High Energy QCD: Beyond the Pomeron

May 21-25, 2001

Organizing Committee:

John Dainton, Wlodek Guryn, Dmitri Kharzeev, and Yuri Kovchegov

RIKEN BNL Research Center

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are seven Fellows and eight Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program has increased to include ten theorists and one experimentalist in the current academic year, 2001-2002. Beginning this year there is a new RIKEN Spin Program at RBRC with four Researchers and three Research Associates.

In addition, the Center has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are thirty-three proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998.

T. D. Lee
August 2, 2001

* Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.
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QCD overtakes the Pomeron?

In (experimental) pursuit of the Structure, and therefore Chromodynamics, of the Hadronic Interaction

John Dainton
University of Liverpool, GB

Contents

1. Archaeology
2. History
3. Here and Now
4. Conclusion

"We dance around in a ring and suppose, But the secret sits in the middle and knows."

Robert Frost, "The Secret Sits"

Introductory remarks at the International Workshop
"High Energy QCD    Beyond the Pomeron",
May 21 - 25, 2001, Brookhaven, Long Island, NY

1. Archaeology

- strong interaction between nucleons

\[ \Delta t \cdot \Delta E \sim \hbar \quad \Delta x \cdot \Delta p \sim \hbar \]

- space-like \( \equiv \) sum of time orderings

\( \equiv \) emission + absorption

- range \( \propto \frac{1}{\text{mass}} \sim 1 \text{ fm} \)

- high energy?
2. History

- hadron+hadron → X+hadron

analyticity $s \leftrightarrow t \leftrightarrow u$

leading Regge dominance

- universal $1_C$ Regge trajectories $\alpha(t)$

reggeon $IR$: $\rho \alpha_2 f_0$

$\alpha(t) \sim 0.5 + 0.9 \cdot t$

reggeon $IR$: $\pi$ ....

$\alpha(t) \lesssim 0.5 + 0.9 \cdot t$

→ Regge motivated models

exchanged Reggeons → resonances

$IR \rightarrow \quad IP \rightarrow$

↑ mesons

$\alpha_{IR}(t) \sim$ linear, universal

QCD $(q\bar{q})_{sc} +$-string $s_c$

↑

$\alpha_{IP}(t)$?

2 strings $s_c$?

- $IP$, $IR$ in the proton?

Feynman Ingelman-Schlein

$P_{1C/IP} \propto \left( \frac{1}{x_{1C/IP}} \right)^{2\alpha(t)-1} “splitting”$
• helicity dependence

exclusive \( \pi \bar{p} \rightarrow \pi p \) \( \rightarrow R_1 + R_2 + \ldots \)

\[
\begin{align*}
\frac{d\sigma}{dt} - \frac{d\sigma}{dt} &= 0 \quad 1_C = R_1 \\
\frac{d\sigma}{dt} + \frac{d\sigma}{dt} &\neq 0 \quad 1_C = R_1 + R_2 + \ldots \\
\end{align*}
\]

diffraction \( R = IP \) \( \rightarrow T_{\Delta \neq U} \equiv 0 \) \( \rightarrow \) forward peak

reggeon exchange \( R \rightarrow T_{\Delta \lt 0} \) \( \rightarrow \) forward dip

inclusive \( \gamma^* P \rightarrow X Y \) \( X \rightarrow \) hadrons

\begin{align*}
\text{optical theorem} &\quad \text{elastic scattering} \\
\sigma_{pp} \text{ tot}(s) &\sim s^{\alpha_F(0) - 1} \\
\left( \frac{d\sigma_{pp+PP}}{dt} \right)_t &\sim s^{2\alpha_F(t) - 2}
\end{align*}

<table>
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<tr>
<th>( \alpha(t) )</th>
<th>&quot;splitting&quot;</th>
<th>energy dependence</th>
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<tr>
<td>( P_{1C/P} )</td>
<td>( \frac{1}{x_{1C/P}} )</td>
<td>( \sigma \propto s^{2\alpha(t) - 2} )</td>
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<tr>
<td>( &gt; 1 )</td>
<td>falling</td>
<td>rising</td>
</tr>
<tr>
<td>( &lt; 1 )</td>
<td>rising</td>
<td>falling</td>
</tr>
<tr>
<td>with increasing ( x_{1C/P} )</td>
<td>with increasing s</td>
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</table>
- $pp \rightarrow p + 2$-jets

- partons exposed in diffractive exchange ($IP$)

- QCD partons

- chromodynamic spectroscopy

- QCD: non-abelian flux tubes $\rightarrow$ strings

- long distance "string" $V(r) = kr + \text{constant}$

  $\leftrightarrow$ linear meson trajectory

  $J(M^2) = x(0) + \alpha'M^2$

  light quarkonia $u\bar{u}$ $d\bar{d}$ $s\bar{s}$

  $3_C \otimes 8_C \otimes \bar{5}_C \rightarrow 1_C$

  $\alpha' \sim 0.9 \text{ GeV}^{-2}$ (towards)

  gluonia $gg$

  $8_C \otimes \bar{8}_C \rightarrow 1_C$

  $\alpha' \lesssim 0.5 \text{ GeV}^{-2}$
• QCD degrees of freedom at low scale

- Russian resilience – Reggeise your gluons! BFKL

“Reggeised gluon ↔ structure ↔ angular momentum”

elastic diffraction $qq \to qq$

$$T_{qq \to qq} \propto \ldots + \int_{x_1}^{x_P} \frac{g}{x_n} \cdot \int_{x_{n-1}}^{x_n} \frac{g}{x_{n-1}} \ldots \int_{x_1}^{x_n} \frac{g}{x_1} + \ldots$$

$$T_{qq \to qq}(x_P, t) \propto \sum \left( \frac{g}{n!} \ln \frac{1}{x_P} \right)^n = \left( \frac{1}{x_P} \right)^g(t)$$

- Regge form

  - Anati, Fubini, Stangellini, BFKL, Gribov
  - coupling $g \leftrightarrow$ intercept $\rightarrow$ running intercept $\rightarrow$ universal $x_P$?

- $gg, gggg, \ldots J^{PC} = 0^{++} \ldots$ natural $x_P$
  - $ggg, \ldots J^{PC} = 0^{--} \ldots$ unnatural odderon?

- $q\bar{q}$ IR trajectories

  - running intercept?

- reggeon calculus, effective field theory

• the mystery

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<td>$t$ channel gluons?</td>
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<td>gluon ladder(s)?</td>
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<td>running $\alpha_S$</td>
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<td>helicity conserv$^u$?</td>
<td>$q \to gg$ helicity conserv$^u$</td>
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<td>$C + (IP)/-(odderon)$?</td>
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<td>helicity structure?</td>
<td>$q \to gg$ helicity structure?</td>
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Yuri Dokshitzer

Around the Pomeron.

I gave a brief overview of the concept of Pomeron (leading vacuum channel complex angular momentum singularity), the prehistory of the subject ("Before the Pomeron"), and, in particular, the history of muddling through the s-channel unitarity problems ("Inside the Pomeron"). [Given a massive confusion which, as it transpired during the meeting, the Pomeron and related concepts cause to the minds of experimenters and young theorists, I wish someone gave a two-day lecture course on the subject rather than a 30 minutes talk.]

I tried to stress the relation between understanding high energy scattering and understanding confinement.

In the "Besides the Pomeron" part of the talk, I pointed out a number of apparently "anti-Pomeron" phenomena, such as "baryon stopping" (long-range quantum number correlations) and the process dependence of the relative yield of strange hadrons. Comparative studies of pA, heavy ion and pp interactions are of primary importance for understanding both the structure of hadrons and colour dynamics of multiple hadron interactions.
And in QCD?

"Pile-up" of glue $\rightarrow$ increasing Colour field $\rightarrow$ Confinement $\Rightarrow$ Quarks!

How to access the issue?

Theoretically $\Rightarrow$ Best of luck and attention to Gribov

Experimentally $\Rightarrow$ Light Quark Confinement study

- particle production
- fluctuations
- relative yields in $pp / pA / AB$ environment
- $p_\perp$ dependences

Basic Inputs into the $\tau\bar{\tau}$ concept $=$ hinted at

- $\Sigma_{\text{tot}} < \text{Const.} \Rightarrow$ Glue spin-1
- $K_\perp$ limited $\Rightarrow$ $\Delta_s (z) \downarrow$ (As, Fr.)

- short-range quantum # fluctuations

... well, how about baryon stopping
Anti-\( p \) dossie

1. Long-range quantum # fluctuation correlations
   "Baryon stopping" [which ain't any bloody stopping but a proton decay]
   \( p \rightarrow \pi^+\pi^-k^+ \)

   - first observed in heavy ion collisions,
   - then in \( pA \) [stronger than in \( AB \)!]
   - present even in \( pp \)!

As far as final state hadroproduction is concerned, colour dynamics is likely to push us to revise the basic \( p \) picture.

Double-scratch picture of proton scattering

1) \( \rightarrow \)
2) \( \rightarrow \)
3) \( \rightarrow \) the colour field
   \( l+8+8+10 \) (\( \pm 27 \))

A curious painting ampl.

\( q_1 \)
\( q_2 \)
\( A \rightarrow [q_1, q_2, \cdots] \rightarrow \)

\( \rightarrow p \rightarrow 3M \)

Repainted proton projectile
Strange pattern of \textit{strangeness} production

$\pi \to$ increases with centrality in HI.SP.

\textbf{BUT}\hspace{1cm} pA \hspace{1cm} (NA-49)

\textbf{BUT}\hspace{1cm} pp!

(No parallel non-interacting ladders)

Stronger colour fields $\Rightarrow$ larger $p_{T}$

more strange (eventually, charm, ...)

particles, more $e^{+}e^{-}$ pairs, ...

How does the vacuum break up in an unusual colour environment?

e.g. $\bar{q} \to g$

\hspace{2cm} \text{vs.} \hspace{2cm} \bar{q} \to \bar{q}$

"$Z$ is dead, baby. $Z$ is dead."
A precursor to the Feynman parton model:

"Interaction of $\gamma$-quanta and electrons with nuclei at high energies"

V. V. Gribov (1969)

25 years later: Lecture notes on confinement (unpub.

1. "Confinement is older than quarks themselves"

2. "...can be checked on nuclei."

A technical motto that in the \textit{c.m.} frame (light-cone description) the vacuum \textbf{DECOUPLES}

ain't true for WEE, especially in a QFT with inherently unstable infrared dynamics.

To understand \textbf{High Energy Scattering} = \textbf{Confinement} equals
Kovchegov-Mueller Dichotomy

\[ a \frac{ds_A}{dR^2} [x G(x)] = c' d_5 \rho [x G(x)] \cdot L \]

in-medium
multiple scattering:
gluon broadening

\[ M \]
Mackerran-Venugopalan

Fast nucleus \( \Rightarrow \) WW field
\( \Rightarrow \) scattering \( \Rightarrow \) saturation (?)

an alternative/complementary view:

Nucleus at rest \( \Rightarrow \) medium-induced gluon radiation off a fast projectile, and \( p_T \) broadening \( \Rightarrow \) quenching

\[ Q = \rho \int dq^2 q^2 \frac{ds}{dq^2} \]
transport coefficient
THERE ARE TWO POMERONS!

A DONNACHIE + P V LANDSHOFF

SOFT POMERON CONTRIBUTES
\[ F_2(x, Q^2) \sim f_1(Q^2) \times x^{-\varepsilon_1} \]

\[ \varepsilon_1 = 0.08 \quad \text{(DL)} \]

\[ 0.10 \quad \text{(CUDELL et al)} \]

HARD POMERON:
\[ f_0(Q^2) \times x^{-\varepsilon_0} \]

\[ \varepsilon_0 = 0.4 \pm 10\% \text{ OR MORE} \]
\[ \sigma_{\gamma p} = \frac{4\pi \alpha}{Q^2} F_2 \bigg|_{Q^2=0} \]

The real-photon data are an important constraint.

Use them, plus ZEUS + H1 data with \( x \leq 0.001 \quad 0.045 \leq Q^2 \leq 35 \)

**Hard Pom**

\[ X_0 \left( \frac{Q^2}{1 + Q^2/Q_0^2} \right)^{1+\varepsilon_0} \left( 1 + \frac{Q^2/Q_0^2}{2} \right)^{1/2} x^{-\varepsilon_0} \]

3 parameters \( X_0, \varepsilon_0, Q_0 \approx 3 \text{ GeV} \)

**Soft Pom**

\[ X_1 \left( \frac{Q^2}{1 + Q^2/Q_1^2} \right)^{1+\varepsilon_1} x^{-\varepsilon_1} \]

\( \varepsilon_1 = 0.0808 \quad X_1 \) determined by \( \sigma_{\gamma p} \)
\( F_2(x, Q^2) \)

\[ Q^2 = 1.5 \]

\[ \epsilon_0 = 0.437 \]
CHARM STRUCTURE FUNCTION

$F_2^c$

ZEUS

$Q^2 = 1.8 \times 10^7$

$Q^2 = 17.5 \times 10^3$

$Q^2 = 130$

FLAVOUR BLIND:

$\frac{2}{5}$ HARDPOM PART OF $F_2$

$\frac{2}{5} = \frac{4}{9}/\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{1}{9}\right)$

HARD POMERON ONLY!

$Q^2 = 0$

$0.064 (2_{\nu}) 0.437$

16
\[ \gamma p \rightarrow J/\psi p \]

\[ A(s, t) = i \sum_{\ell = 0, 1} \theta_{\ell} F_{1}(t) \left( \alpha_{s}^{(s)} \right)^{\alpha_{s}(t) - \frac{1}{2} \ln(\alpha_{s}(t) - 1)} e^{-\frac{i}{2} \pi (\alpha_{s}(t) - 1)} \]

\[ \frac{d\sigma}{dt} \quad (\text{nb GeV}^{-2}) \]

\[ 0.44 - 1.2 \quad 0.25 - 0.44 \quad 0.13 - 0.44 \quad 0.05 - 0.13 \quad 0 - 0.05 \]

\[ 0.44 - 1.2 \quad 0.25 - 0.44 \quad 0.13 - 0.44 \quad 0.05 - 0.13 \quad 0 - 0.05 \]

**STRAIGHT TRAJECTORIES**

\[ \alpha_{0}' = 0.1 \text{ GeV}^{-2} \]
\[ \alpha_{1}' = 0.25 \text{ GeV}^{-2} \]

\[ \Rightarrow \text{NO SHRINKAGE!} \]
Key questions

- Are there really two separate pomerons?
- Are they simple poles in the $N$ plane?
- Does the hard pomeron contribute already at $Q^2 = 0$?
- Is it really flavour-blind, even at small $Q^2$?
- How do we resum pQCD?
Hard Diffraction and the nature of the QCD Pomeron

Using in an unifying framework S-Matrix and Field-Theoretical properties, we show that 3 different approaches of Hard Diffraction at HERA can be related after some modification. The Soft Color Interaction models (à la Bodwin-Itelson, Ingelman et al.) can be obtained from the QCD dipole formulation with a modified form of the short-distance source of the deep-inelastic interaction. Equivalently, the partonic content of the Pomeron (à la Ingelman-Schlein and followers) is related to the QCD-dipole prescription for the Diffractive Structure function, again with a modified -semi-hard- effective BFKL formula. Consequences for the perturbative/non-perturbative QCD interface and the nature of the QCD Pomeron can be drawn leading to a complementarity of both PQCD/XQCD aspects and a variable effective Pomeron based on an universal kernel.
Hard Diffraction
and the Nature of the QCD Pomeron

R. Petranek, Saslay
Beyond the Pomeron 2001

1) Motivation: the perturbative/non-perturbative QCD Interface

2) 3 models 3 different (?) Interfaces

3) An Unifying Picture: General S-Matrix Field-theory Framework

4) Application: a "Synthetic" Diffractive Structure Function:
   \[ \text{partonic Pomeron} \]
   \[ \text{Soft Color Interaction} \rightarrow \text{QCD Dipole} \]
   with H. Nardell

5) Conclusion / Outlook

S-Matrix Relations

\[ \text{Disc}_1 A(3-3) = \]
\[ \gamma^* \quad \text{Disc}_1 \quad \gamma^* \]
\[ \bar{p} \rightarrow p \quad p \quad \bar{p} \]

\[ \text{Disc}_2 A(3-3) = \]
\[ \gamma^* \quad \text{Disc}_2 \quad \gamma^* \]
\[ \bar{p} \rightarrow p \quad p \quad \bar{p} \]

\[ \text{Disc}_3 A(3-3) = \]
\[ \gamma^* \quad \text{Disc}_3 \quad \gamma^* \]
\[ \bar{p} \rightarrow p \quad p \quad \bar{p} \]

Fig. 2

"Triple Reggie" \[ \Rightarrow \text{Disc}_1 = \text{Disc}_2 = \text{Disc}_3 \]
S. Mann at QCD Descriptions

$\gamma^* \rightarrow \gamma^*$

Partonic Pomeron

$\gamma^* \rightarrow \gamma^*$

Soft Colour Interaction

QCD Dipoles → Soft Color Interaction

Let us perform:

$$\int \frac{d^2y}{y_{\min}} \int dy_1 \int dy_2 \int d^2q = \frac{1}{\lambda} \int dy_0 \left( \gamma^* \right)$$

\text{Fixed } \delta = \gamma^*.

\text{Triplet saddle point in } \theta_1, \theta_2, \theta_3

$\gamma^* \ (\text{solution of } \Delta (\gamma^*) = \pm \frac{1-y^*}{x^*})$

$F(\text{fixed } \gamma^*) = \lambda$

$\Rightarrow$ See Soft Color Interaction

\text{N.B. } F^{\text{BFKL}} (\text{fixed } \gamma^*) \neq F^{\text{BFKL}} (\text{moving } \gamma_{sp})$

$$F^{\text{BFKL}} = N \left( \frac{2 \theta_{sp}}{Q_0} \right) \exp \left\{ -y \Delta (\gamma_{sp}) \right\} \frac{1}{\sqrt{2 \pi \Delta (\gamma_{sp})}}$$

Moving $\gamma_{sp} = \frac{1}{2} \left( 1 - \frac{4 \log Q_{sp}/Q_0}{\Delta (\gamma_{sp})} \right) \neq \gamma^* \text{ fixed, universal}$
QCD Dipoles \rightarrow pertonic Pomeron

\[ I^{(3)}(y, Y; \alpha, Q^2) = \exp\left(2n\Delta(\Delta(1/2)) F_{D}^{\text{\textquotedblleft\textit{harder\textquotedblright}}} (Y, Y; \alpha, Q^2) \right) \]

Model saddle-point in \( y, Y \)

\[ \Delta_y = \Delta(1/2) + \frac{\Delta(1/2)}{8(1+2y)} \quad \geq \Delta(1/2) \]

\[ Y_y = \frac{\eta}{1+2y} \quad \geq 0 \quad \text{but less than } \frac{1}{2} \]

\[ \Delta_{y y}^{-1} \geq \Delta_{y y}^{-1} \quad \geq 2 \Delta_{y y}^{-1} \]

(QCD)

\[ F_{D}^{\text{\textit{diff}}} (y, Y; \alpha, Q^2) = \frac{N_{c}^{2}}{l} \frac{4}{\pi e_{F}} \int \frac{d\gamma_{1} d\gamma_{2} d\gamma_{3}}{2\sin \frac{\pi}{l} \sin \frac{\pi}{l} \sin \frac{\pi}{l}} \Delta \left( Y - y - y' - y'' \right) \cdot \exp \left\{ \eta \left[ \Delta(\Delta(1/2)) + \Delta(1/2) \right] + \Delta(1/2) \Delta(1/2) \right\} \]

\[ \xrightarrow[\text{QCD}]{\text{\textquoteleft\textquoteleft triple-BFKL-Regge formula}} \]

\[ \xrightarrow[\text{\textit{harder}}]{\text{\textquoteleft\textquoteleft intermediate\textquoteright\textquoteright} between Soft and Hard} \]

and depending on "external" variables \( Q^2, Q_0^2 \) and \( \eta = \frac{Y - y}{y} \)
Conclusions

We don't know yet ...

→ PQCD, incomplete
→ $\varphi$QCD, unknown
→ Interface "Variable"

... but our exercise shows interesting features

→ PQCD/$\varphi$QCD complementarity
→ Universality/Diversity of the Parameter
→ Matching of S-Matrix/Field Theoretical Properties
Disentangling Pomeron Dynamics from Vertex Function Effects

Sandy Donnachie

Application of models of the pomeron requires using the wave functions (vertex functions) of the participating particles. These can control many aspects of the dynamics. This is illustrated for

- $\Delta^* p \to V p$, $V = \rho, \phi, \omega$: small $|t| \lesssim 0.5$
  (Donnachie, Gravelis, Shaw: hep-ph/0101221)

- $\Delta p \to VX$, $V = \rho, \phi, \omega$: large $|t| \gtrsim 1.0$
  (Forshaw, Poludniowski: preliminary)

- $F_2, F_2^C, F_T, \sigma_T^\Delta p, \sigma_T^\Delta \rho, F_2^\Delta$ ---- : $t = 0$
  (Donnachie, Dosch: preliminary)

In each case a good simultaneous description of all relevant data is obtained, with a very small number of parameters.
\[ \pi \rightarrow V \nu \] \[ |t| < 0.5 \text{ GeV}^2 \]

Two pomeron, two-gluon exchange: non-perturbative (Diehl) or perturbative (Cudell & Rajan or \( p(dF) \)). Model fixes t-dependence, wave functions (3 parameters in all) and normalization (2 parameters) do the rest. Energy dependence by hand as Donnachie and Landshoff. Excellent global description of all \( p, \phi, J/\Psi \) data.

\[ \pi \rightarrow V \pi \] \[ |t| > 1.0 \text{ GeV}^2 \]

Hard pomeron: \( p(dF) (x, t) \otimes BFKL (LHA, +\theta) \)
Non-relativistic approximation (\( M_V = 2 m_q \)) for wave functions. Two parameters: effective \( q_s \) in BFKL and scale in LHA. Excellent description of \( p, \phi, J/\Psi \) data.

\( F_2, F_3 \rightarrow F_L \text{ etc.} \) \[ t = 0 \]

Dipole picture with two pomeron. Proton treated as a quark-diquark system in dipole. Dipole-dipole cross section obtained from FF scattering. Assume if both dipoles are larger than \( R_c \) only the soft pomeron couples; if at least one dipole is smaller than \( R_c \) the hard pomeron couples. Energy dependence put in by hand, as Donnachie & Landshoff. \( R_c \times 0.28 \text{ fm} \) fixed from \( F_2 (x, Q^2) \).

The rest is prediction.

\( F_2 \) dominated by hard pomeron, even at small \( Q^2 \)
\( F_L \) more sensitive to hard pomeron than \( F_2 \)
\( F_3 \) has comparable sensitivity to hard pomeron as \( F_2 \)
\( F_0 \) dominated by hard pomeron
\( g, \phi \) have significant hard-pomeron component.
Figure 13: $Q^2$ dependence of the $p$-meson cross-section at $W = 75$ GeV in model S2. The data are from: H1 [64]; and ZEUS [51] [60] [62].

Figure 14: $Q^2$ dependence of the $p$-meson cross-section at $W = 1.5$ GeV in model S2. The data are from: NMC [48].

Figure 15: $Q^2$ dependence of the $p$-meson longitudinal to transverse cross-section ratio at $W = 75$ GeV in model S2. The data are from: CHIO [42]; NMC [48]; E665 [37]; H1 [52] [53] [64]; and ZEUS [49] [51] [62].

$\sigma_L/\sigma_T$ is very sensitive to the $P$ wave function. Small changes in $P_0$ produce large changes in the ratio.

The normalization of the soft pomeron term is essentially fixed by the $P$ data, which it dominates.
Figure 25: $Q^2$ dependence of the $J/\psi$-meson cross-section at $W = 90$ GeV in model S2. The data are from H1 [54] [63]; and ZEUS [58] [62].

Figure 26: $Q^2$ dependence of the $J/\psi$-meson cross-section at $W = 14$ GeV in model S2. The data are from EMC [44]; E401 [43]; E516 [45]; NA14 [46]; and E687 [47].

Figure 27: $Q^2$ dependence of the $J/\psi$-meson longitudinal to transverse cross-section ratio at $W = 90$ GeV in model S2. The data are from: H1 [54] [63]; and ZEUS [58] [62].
$\gamma p \rightarrow VX$ at $W = 100$ GeV

J/Psi photo-production

Phi photo-production

Rho photo-production
Figure 2. The soft and hard contribution to structure functions at different values of $x$. Solid line hard contribution from the model; dashed line soft contribution from the model. First row proton structure function $F_2$; second row (p,L) longitudinal proton structure function $F_L$; third row (p,c) charm contribution to the proton structure function $F_{2,c}$, last row photon structure function $F^2_{\gamma}/\alpha$. 

Reflects fit of Donnachie-Landshoff.

Sensitive to hard boson pair in $(x,Q^2)$ range.

Very comparable to $F_2$.
We study the rôle of semi–classical QCD vacuum solutions in high energy scattering by considering
the instanton contribution to hadronic cross sections. We propose a new type of instanton–induced
interactions (“instanton ladder”) that leads to the rising with energy hadronic cross section $\sigma \sim s^\Delta$
of Regge type (the Pomeron). We argue that this interaction may be responsible for the structure
of the soft Pomeron. The intercept $\Delta > 0$ is calculated. It has a non–analytic dependence on the
strong coupling constant, allowing a non-singular continuation into the non-perturbative region.
To obtain the intercept we have to resum powers of the parameter $\exp \left( -\frac{5}{\alpha_s \ln s} \right)$. We derive
the Pomeron trajectory, which appears to be approximately linear in some range of (negative) momentum transfer $t$, but exhibits a curvature at small $t$ and eventually flattens out at some
larger $t$, similar to what is suggested by some phenomenological observations.

I would like to thank Dima Kharzeev and Genya Levin for collaboration on this project.
BFKL pomeron can be viewed as a cascade of gluons:

\[ k_1 \gg k_2 \gg k_3 \gg \ldots \]

\[ \tau_1 \sim \frac{k_1^2}{k_1^2}, \quad \tau_2 \sim \frac{k_2^2}{k_2^2}, \quad \tau_3 \sim \frac{k_3^2}{k_3^2} \]

A small-\(x\) gluon spreads over large longitudinal distances. In the rest frame of a proton \(l \sim \frac{1}{2m_p x} \approx 100 \text{ fm} \) for \(x = 10^{-3}\).

Even in the dilute instanton gas model, it can interact with several instantons (typical size \(s_\text{0} \approx 3 \text{ fm}, \) typical separation \(d \approx 1 \text{ fm}\)).

**OUR PICTURE:**

\[ d_s = d_s(s_\text{0}) \ll 1 \] and gluonic degrees of freedom still make sense.
Consider a ladder diagram with instanton-induced vertices.

Each vertex gives a factor of $e^{-\frac{2\pi}{a}}$, which is a small parameter for $a \ll 1$.

We are resumming leading logs of energy:

$$e^{-\frac{4\pi}{a}} \ll 1, \quad \ln s >> 1$$

We are resumming powers of

$$(e^{-\frac{4\pi}{a}} \ln s)^n \sim 1$$

Since the coherence length of a small-$x$ gluon $\ln 100 \text{fm}$ is $>>$ the typical instanton size $p_0 \sim 0.3 \text{fm}$, we will use point-like instanton vertices.

We will discard usual perturbative vertices as $a \ll 1$.
We can plot $\Delta_\rho$ as a function of $\alpha_s$:

$$\Delta_{\text{soft}} = \frac{0.14 d^2 \pi}{(N_c^2 - 1)^2} \left( \frac{2 \pi^2}{d^2} \right)^{\frac{4}{3}} \left( \frac{4 \pi^2}{\alpha} \right)^2 \frac{1}{\alpha^3} \frac{(4\pi)^6}{6 e^2} \frac{E_{\text{soft}}^2 \rho_0^2}{6 \alpha e^2} \frac{1}{\alpha^3} \frac{1}{\alpha^3}$$

$$\Delta_\rho = S \left[ \frac{\pi}{g = 4N_c} \left( m_\pi^2 \rho_0 - \frac{a^2}{4} (0.8 \bar{g} 10) \rho_0^3 \right) \right]_p$$

$S$ ~ factor taking into account virtual corrections:

$$\left[ \frac{\pi}{g = 4N_c} \left( m_\pi^2 \rho_0 - \frac{a^2}{4} (0.8 \bar{g} 10) \rho_0^3 \right) \right]_p^2 \text{ to include quark lines}$$

Even if $\alpha_s \to \infty$ at large distances our pomeron's intercept is finite, $\Delta_\rho \to 0$ as $\alpha_s \to \infty$
After taking into consideration the virtual corrections and the quark contributions the answer for the pomeron's trajectory becomes

$$
\Delta_{soft}(t) = \frac{\pi d^2}{(N_c^2 - 1)^2} \left( \frac{2\pi}{\alpha} \right)^4 e^{-t\frac{\alpha}{\alpha_0}} \frac{4N_c}{\alpha^3} \frac{1}{81} \frac{E_p^2 \rho_0^2}{6n^2} \left[ 2F_2 \left( \frac{g_2^2}{g_1^2}, \frac{n^2}{2}, \frac{n^2}{2}, \frac{n^2}{2} \right) - 1 \right] 
$$

\[ \times \frac{\pi}{256} \left\{ 2e^{t\frac{\rho_0^2}{2}} - e^{t\frac{\rho_0^2}{4}} - \frac{i\rho_0^2}{2} \left[ 2Bi \left( \frac{i\rho_0^2}{2} \right) - Bi \left( \frac{i\rho_0^2}{4} \right) \right] \right\}. \tag{58} \]

The soft pomeron's trajectory of Eq. (59) is depicted in Fig. 8. It is plotted for $\rho_0 = 0.3\text{fm}$, $E_p = 2.4\text{GeV}$, $\delta = 0.31$ and $\alpha \approx 0.75$, i.e., the same values as were used for the estimates of the pomeron's intercept in Sect. IIIC.

$$
\Delta_p(t) = \delta \left[ \prod_{q=u,d,s,...} 1.3 \left( m_q \rho_0 - \frac{2n^2}{3} (0|\bar{q}q|0) \rho_0^2 \right) \right] \Delta_{soft}(t), \tag{59} 
$$

where $\Delta_{soft}(t)$ is given by Eq. (58).

![Fig. 8. Soft pomeron's trajectory. $t$ is measured in the units of $\rho_0^2$.](image)

We can calculate the trajectory of our pomeron by considering non-zero momentum transfer.

$$
\Delta(t) \sim \Delta_{soft} + \Delta' t 
$$

for small $t$.

$\Delta'(t) \approx \Delta_{soft} \cdot \frac{\pi \rho_0^2}{256 \rho_0^2} \frac{\ln \frac{1}{\rho_0^2}}{\rho_0^2} \approx \Delta_{soft} \cdot \rho_0^2 \cdot \ln \frac{1}{\rho_0^2} \approx 0.2 \text{GeV}^{-2}
$$

which is consistent with experimental $x_1 \exp \approx 0.25 \text{GeV}^{-2}$. 

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CONCLUSIONS

I. We have constructed a qualitative model of a pomeron, generated by a strong classical vacuum field.

II. We have quantified our model using the instanton field. The resulting pomeron's intercept has some non-analytic dependence on $d_s$. For reasonably small $d_s \lesssim 0.2-0.3$, the intercept is $\Delta \approx 0.1$. The intercept goes to a finite limit for diverging $d_s$.

III. The slope of the obtained pomeron is $d' / \Delta \approx 2.0 \text{ GeV}^{-2}$, i.e., $d' \approx 2.0 \text{ GeV}^{-2}$, which is in agreement with the experimental $d'_{\text{exp}} = 2.5 \text{ GeV}^{-2}$. We have also plotted the pomeron's trajectory, which is non-linear.
Pomeron at Strong Coupling

Chung-I Tan, Brown U.

21/5/2001

Key Idea:

4d YM Theories at weak coupling is dual to higher dim String Theories with AdS Background

R. C. Brower, S. Mathur, C-I Tan,
hep-ph/0102127; hep-th/0003115;
hep-th/9908196
Outline

• Goal: Non-pert. QCD at HE
• Why Strong Coupling?
• Ancient Lore of QCD at HE and Strings
• Mass Generation and Higher Dimensions
• Maldecena/Witten duality
• Full $J^P_C$ Glueball Spectrum at Strong Coupling
• Pomeron and Pomeron Intercept
• Future Directions
It has been a long held belief that QCD in a non-perturbative setting can be described by a string theory. This thirty-year search for the QCD strings has recently led to a remarkable conjecture: 4-dim QCD is exactly dual to a critical string theory in a non-trivial gravitational background at higher dimensions. In such a framework, Pomeron should emerge as a closed string excitation. We provide here a brief review for the Maldecena duality conjecture, and summarize results for the glueball spectrum and the Pomeron intercept in the strong coupling limit.

We first recall that in the early days of string theory, (or the "dual resonance model" to use the nomenclature that predates both string theory and QCD), one observed that it was reasonable to represent the hadronic spectrum beginning with zero width "resonances" on exactly linear Regge trajectories. With the advent of QCD this approach was reformulated as the $1/N$ expansion at fixed 't Hooft coupling, $g^2 N$. States with vacuum quantum numbers could be assigned to closed-strings, including a massive $2^{++}$ tensor glueball on the leading Pomeron trajectory, $\alpha_P(t) = \alpha_P(0) + \alpha'_P t$. Soon a three-fold crisis appeared: zero-mass states, extra dimensions, supersymmetries. A careful study of negative norm states (i.e ghosts), tachyon cancellation and the consistency of the perturbative expansion at the one loop level led to supersymmetric string theories in 10 space-time dimensions. At the one-loop level unitarity requires that pair creation of two open strings, each contains "zero-mass" spin-1 states, is dual to a vacuum exchange with an intercept $\alpha_P(0) = 2$. This leads to a massless $2^{++}$ state, the graviton. In fact the low energy, perturbative string theory was clearly not QCD but rather supergravity in 10 dimensions!

What is the mechanism which allows our 4-d space/time and yet is able to generate a non-zero mass gap for tensor glueballs? How can one "lower" the Pomeron intercept so that $\alpha_P(0)$ takes on its phenomenological value of $1.1 \sim 1.2$? The key ingredient turns out to be duality, which allows a dual description of QCD involving extra dimensions and a nontrivial background metric which breaks supersymmetries.

This recent development has led to the rebirth of active QCD string studies. A rich glueball spectrum can be computed at strong coupling. In particular, one finds:

$$\alpha_P(0) \simeq 2 - 0.66 \frac{4\pi}{g^2 N} + 0\left(\frac{1}{g^4 N^2}\right).$$

With $N = 3$ and $g^2/4\pi \simeq 0.25$ at a characteristic confinement scale, $\Lambda_{QCD}$, this leads to a value for $\alpha_P(0) \simeq 1.12$. 

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Pomeron in Strong Coupling

A definite line $\rightarrow \frac{1}{\alpha s}$ for high cross-over again?

A question: "lowered" from 2 to finite $\frac{\mu^2}{\alpha S}$

"bounded" from below by 1 ??
Phase Intercept in Strong Coupling:

\[ d_p^{(1)} = d_p^{(0)} + d_p' \tau \]

\[ d_{om} = 2 + d_p' (1 + \kappa_f^2) \]

\[ m_T^2 = \left[ 9.89 + O\left(\frac{1}{g^2} \right) \right] \beta^2 \]

\[ d_p' \approx \left( \frac{24}{5 \pi^2} \right) \left( \frac{1}{g^2} \right) \left[ 1 + O\left(\frac{1}{g^2} \right) \right] \beta^2 \]

\[ \alpha_p(0) = 2 - 0.66 \left( \frac{\alpha_T}{g_\pi^2} \right) + O\left( \frac{1}{g^4} \right) \]
QCD After Brane Revolution

New Chapter for Non-perturbative QCD

- Weak Coupling $\to$ Perturbative QCD
  
  - Non-perturbative QCD: (Duel description)
    - Effective degrees of freedom - masses fields of
      - NS/BrH Background
      - Glueball spectrum in Strong Coupling limit
    
    * Pomeron as Massive Graviton

    - Pomeron intercept in Strong coupling

    \[
    \sigma_{\text{Pom}}^{(0)} = 2 - 0.66 \left( \frac{4\pi}{g^2 N} \right) + O\left( \frac{1}{g^2 N^2} \right)
    \]
Universal Pomeron from High Energy Relativistic Quantum Field Theory

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From the very high energy behavior of Relativistic Quantum Field Theory, it is possible to deduce some essential features of high energy hadron elastic scattering. This was first realized thirty years ago by Cheng and Wu, who investigated massive Quantum Electrodynamics. They were the first to predict the rise of total cross sections, resulting from the existence of the so-called tower diagrams, which generate a term \( S(s) = s^2/(lns)^C \). This is the basic ingredient to build up our Universal Pomeron. In the framework of the impact-picture approach, we assume a factorization property to construct the Born term of the hadron elastic scattering amplitude, as a product of \( S(s) \) and a function \( F(b) \) of the impact parameter \( b \), related to the internal hadronic matter distribution. The eikonalization is done in order to insure unitarity. These considerations have led us to the so-called, Bourrely-Soffer-Wu (BSW) model, which was proposed twenty years ago. It allowed a good description of \( pp \) and \( pp \) elastic scattering up to ISR energies and was able to give very accurate predictions up to CERN SPS collider and Tevatron energies.

Here we present an update version of the BSW model for \( pp \) and \( pp \), including new data and some predictions which can be tested at RHIC-BNL, in the near future by the \( pp2pp \) experiment. We have also extended our approach to describe \( \pi^\pm p \) and \( K^\pm p \) elastic scattering up to the highest available energy, with the same Pomeron. We make predictions in the TeV energy range in view of a possible fixed target physics programme at LHC. Some predictions for \( \gamma\gamma \) and \( \gamma p \) total cross sections are presented and we compare them some with latest LEP and HERA data.
UNIVERSAL POMERON FROM HIGH ENERGY RELATIVISTIC QUANTUM FIELD THEORY

THEORETICAL FRAMEWORK

- Hadron scattering is complicated
  1st simplification: elastic scattering
  2nd simplification: high energy

- Froissart-Martin bound \( T_{\text{max}} < \text{const} \times s^{\frac{1}{2}} \)

THE INSIGHTS FROM HIGH ENERGY BEHAVIOUR OF RPC

DESCRIPTION OF \( \phi \phi \) (\( \bar{\phi}\bar{\phi} \)) ELASTIC SCATTERING AND NUMERICAL RESULTS

DETAILED STUDY OF \( \pi\pi \) ELASTIC SCATTERING

\( \ell \bar{\ell} \) ELASTIC SCATTERING

\( \gamma\gamma \) AND \( \gamma\ell \) TOTAL CROSS SECTIONS

CONCLUDING REMARKS
RESULTS FROM QFT (1970)

PICTURE THREE DECADES AGO

$\Sigma_{\text{tot}} \rightarrow$ finite limit (geometrical size)

CHENG AND WU UNDERTAKE PROGRAMME TO STUDY BEHAVIOR OF QFT AT VERY HIGH ENERGIES USING MASSIVE QED

COMPTON $V + f \rightarrow V + f$

2$^{nd}$ ORDER $\quad \Downarrow$  

4$^{th}$ ORDER $\quad \Downarrow$  

6$^{th}$ ORDER $\quad \Downarrow$  

So 6$^{th}$ order more important than 2$^{nd}$ and 4$^{th}$

Because pair prob. peaks forward

8$^{th}$ ORDER $\quad \Downarrow$

But 10$^{th}$ ORDER $\quad \Downarrow$

14$^{th}$ ORDER $\quad \Downarrow$

MÜLLER $f + f \rightarrow f + f$

8$^{th}$ ORDER $\quad \Downarrow$  

After summation of tower diagrams get

$i e^2/(\lambda s)^2 \rightarrow$ rising $F_{\text{tot}}$

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Fig. 1. Multi-tower diagrams for (a) $pp$ and $\bar{p}p$, (b) $\pi^\pm p$ and (c) $\gamma p$ scattering.
$\sigma_{\text{tot}}(\text{mb})$ vs. $\sqrt{s}$ (GeV)

$\sqrt{s} = 14 \text{ TeV}$

$\sigma_{\text{tot}}(14 \text{ TeV}) = 104.5 \pm 6 \text{ mb}$
Figure 4: $d\sigma/dt$ for $\bar{p}p$ as a function of $|t|$ for $\sqrt{s} = 13.7, 24.3, 53, 546, 630, 1800\text{GeV}$. Experiments [25, 24, 26, 28, 29, 30, 31].

Predict that ISR dip turns into a shoulder at $\bar{p}p$ collider.
C. Concluding Remarks

The high energy behaviour of a QFT has generated a universal Pomeron for the description of $p\bar{p}$, $\pi^+\pi^-$, $K^+\pi^-$ and $\Delta$ scattering.

This impact picture is very successful. It would be desirable to derive from QCD the few parameters which were introduced, namely $c, c'$ for $s$ dependence.

Open problems for the future:
- Polarization
- Inelastic diffractive scattering
\[ \sigma_{\text{tot}}^T (s) = A \alpha \left[ \sigma_{T+T}^T (s) + \sigma_{T^-T}^T (s) \right] \]

\[ A = 0.3342 \]

Figure 16: A plot of total cross sections, $\bar{p}p, \gamma p, \gamma \gamma$ as a function of $\sqrt{s}$(GeV). For $\sigma_{\gamma \gamma}$ two different LEP energies are drawn [42], [43]. Model predictions, solid curve $A = 9.23 \times 10^{-6}$, dashed curve $A = 8.1 \times 10^{-6}$.
Coherence in Nuclear Interactions at RHIC

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In very peripheral collisions (b>2R), nuclei may interact through their electromagnetic and nuclear fields. The exchange particles of the fields couple coherently to the entire nucleus for small momentum transfers. The coherence requirement limits the mass and transverse momentum of the final state to \( \sim 2\gamma h c / R \) and \( \sim \sqrt{2\gamma h c / R} \), respectively. At RHIC, the maximum center of mass is about 6 GeV for a heavy system such as Au+Au. Two-photon, photon-Pomeron, and Pomeron-Pomeron interactions are possible.

The cross sections for coherent vector meson production in heavy-ion interactions at RHIC are large. This is because of the high flux of equivalent photons from the electromagnetic fields of the nuclei and vector meson dominance. The cross sections have been calculated in [1] using the Weizsäcker-Williams method to estimate the equivalent flux of photons. The photonuclear cross sections \( \sigma(\gamma + A \rightarrow V + A) \) have been obtained from a Glauber model calculation with data on \( \sigma(\gamma + p \rightarrow V + p) \) as input. Because of the strong fields, the cross sections for multiple vector meson production, \( A + A \rightarrow A + A + V + V \), are appreciable at RHIC.

It is generally not possible to determine which nucleus emitted the photon and which emitted the Pomeron in a photon-Pomeron interaction. The median impact parameters for producing a vector meson in Au+Au interactions at RHIC range from about 20 to 40 fm. For vector meson transverse momenta \( p_T < \frac{\hbar c}{b} \), interference will occur [2]. The cross section is calculated as an integral over the impact parameter

\[
\frac{d\sigma}{dy dp_T} = \int_{b>2R} |A_1 + A_2|^2 db^2 \tag{1}
\]

where \( A_1 \) and \( A_2 \) are the amplitudes for production off a single nucleus. Since the electric field is antisymmetric and the nuclear density symmetric under spatial inversion, the interference will be destructive. The interference does not affect the overall vector meson production cross sections significantly, but does change the transverse momentum distribution. The change in the transverse momentum distribution should be experimentally observable.

The separation between the nuclei is generally much larger than the \( cr \) of the vector mesons (<b> \sim 40 fm and \( cr = 1.3 \) fm for the \( \rho^0 \)). This means that the vector meson will have decayed before the amplitudes from the two sources can overlap. The system thus works as a two-source interferometer for unstable particles.

The photon from the emitting nucleus may interact incoherently with the target nucleus resulting in break-up of that nucleus. The dominating process is photonuclear excitation of the target into a Giant Dipole Resonance [3]. Coherent vector meson production can occur in coincidence with Coulomb excitation of one or both nuclei. If the photonuclear excitation and the vector meson production are uncorrelated, a vector meson is accompanied by mutual break-up of both nuclei in about 10% of the interactions. Requiring production in coincidence with nuclear break-up reduces the median impact parameters in the interactions by roughly a factor of 2. This should affect the interference discussed above.

Acknowledgements

I would like to acknowledge Spencer Klein, LBNL, Berkeley, my collaborator in the studies of vector mesons and interference. I would like to thank Tony Baltz and Sebastian White, BNL, Brookhaven, for providing the Coulomb interaction probabilities from their paper [3] and for useful discussion.

References

Peripheral Collisions at RHIC

What happens when the nuclei miss each other, $b > 2R$?

Interaction between the electromagnetic and nuclear fields
- EM field: long range
- Nuclear field: short range

For small momentum transfers ($Q < 1/R$), the fields couple coherently to all nucleons.

Enhances cross section: $Z^2, A^2 (A^{4/3})$

Truly coherent interactions: coherent coupling to both nuclei: $\gamma\gamma, \gamma$-Pomeron(meson), Pomeron-Pomeron

Max CM energies at heavy-ion accelerators:

$$W \approx 2 \gamma_{CM} (hc/R)$$

For heavy nuclei (Au/Pb):

<table>
<thead>
<tr>
<th></th>
<th>$\gamma_{CM}$</th>
<th>$W$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL AGS</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>CERN SPS</td>
<td>9</td>
<td>0.5</td>
</tr>
<tr>
<td>RHIC</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>LHC</td>
<td>2,940</td>
<td>160</td>
</tr>
</tbody>
</table>
Experimental consequences of coherence

The coherence requirement limits the angular deflection to
\[ \theta \sim \frac{0.175}{(\gamma \cdot A^{4/3})} \]

At RHIC
- Au \( A=197 \) \( \theta \sim 1 \ \mu\text{rad} \)
- I \( A=127 \) \( \theta \sim 3 \ \mu\text{rad} \)
- Si \( A=28 \) \( \theta \sim 17 \ \mu\text{rad} \)

⇒ Not possible to tag the outgoing nuclei.

Experimental method: Reconstruct the entire event, signal of coherence from low \( p_T \).

Coherent Vector Meson Production

The electromagnetic field of one nucleus corresponds to a stream of photons impinging upon the other nucleus (Weizsäcker-Williams).

\[ \gamma + \text{Pomeron} \rightarrow V \]

The photon may fluctuate into a vector meson (qq-pair) which scatters elastically off the target nucleus.

The cross section can be calculated as the convolution of the WW photon spectrum with the \( \gamma A \) photonuclear cross section.

\[ \sigma(A+A \rightarrow A+A+V) = \int n(\omega) \sigma_{\gamma A}(\omega) \, d\omega \]

Note: This assumes that one can determine which nucleus emitted the photon or the Pomeron.

Not possible in general ⇒
Some interesting quantum mechanical effects.
Experimental signal of coherence – $p_T$ spectrum

Convolution of $p_T$ distributions

$$f_{1,2}(p_T) = \int f_1(p_T') f_2(p_T - p_T') \, dp_T'$$

$$f_1(p_T) = |F(E^2/A^2 + p_T^2)|^2 \gamma (p_T/(E^2/A^2 + p_T^2))^2$$

$$f_2(p_T) = |F(E^2/A^2 + p_T^2)|^2$$

Production off two nuclei

$$\frac{d\sigma}{d\gamma dp_T^2} = \int k_1 \frac{dn}{db} \sigma(\gamma A_2 \rightarrow VA_i) f_{1,2}(p_T) + k_2 \frac{dn}{db} \sigma(\gamma A_2 \rightarrow VA_i) f_{1,2}(p_T) \, db^3$$

Photon flux \quad \left| \int E(b,t) e^{ist} \, dt \right|^2

Impact parameter, $b$, measurable in principle (but not in practice)

Integration over $b$ only valid if $p_T >> 1/b$.

$\Rightarrow$ Add amplitudes

$$\frac{d\sigma}{dy dp_T} = \int |A_1 + A_2|^2 \, db^3$$
**Quantum mechanical aspects of the interference**

- The production is localized to the two nuclei because of the short range of the nuclear force.
  
  $\langle r \rangle < \langle b \rangle$, $c r \sim 1 \text{ fm}$ \hspace{3mm} $\langle b \rangle \sim 40 \text{ fm}$

Transverse plane

- The $\rho$ will have decayed before the amplitudes from the two sources can overlap.
- For interference, the wave function of the pions must retain information about their origin long after the decay.
- A two-source interferometer for unstable particles!

**Electromagnetic dissociation**

The “target” nucleus is excited by a photon from the EM field of the other nucleus and breaks up.

The cross sections are large (Baltz, Chasman, White NIM A417(1998))

- Single dissociation (1 nucleus) \hspace{3mm} $\sigma = 95 \text{ b}$
- Double dissociation (both nuclei) \hspace{3mm} $\sigma = 3.7 \text{ b}$

In a grazing collision ($b=2R$), $P($double dissociation$) = 35\%$
**Vector meson production in coincidence with Coulomb dissociation**

If Coulomb excitation and V.M. production independent:

\[
\sigma = \int (1 - P_{\text{HAD}}(b)) P_C(b) P_V(b) 2\pi \text{d}b
\]

- Easier to trigger on experimentally (at least in experiments primarily designed for central AA collisions, ZDC Calorimeters).

- Dissociation cross sections for emission of 1 neutron vs. any number of neutrons (Au+Au at 200 A GeV)

\[
\begin{align*}
\sigma(X_n,X_n) = 3.7 \text{ b} & \quad \sigma(1n,X_n) = 1.4 \text{ b} & \quad \sigma(1n,1n) = 0.45 \text{ b} \\
\sigma(1n,X_n,p) = 42 \text{ mb} & \quad \sigma(1n,X_n,\rho) = 13 \text{ mb} & \quad \sigma(1n,1n,\rho) = 3.4 \text{ mb}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Vector Meson</th>
<th>$\text{Au} + \text{Au} \rightarrow \text{Au} + \text{Au} + \text{V}$</th>
<th>$\text{Au} + \text{Au} \rightarrow \text{Au}^* + \text{Au}^* + \text{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$\sigma = 590 \text{ mb}$</td>
<td>$\sigma = 42 \text{ mb}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$\sigma = 59 \text{ mb}$</td>
<td>$\sigma = 4 \text{ mb}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$\sigma = 39 \text{ mb}$</td>
<td>$\sigma = 3 \text{ mb}$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\sigma = 0.29 \text{ mb}$</td>
<td>$\sigma = 0.04 \text{ mb}$</td>
</tr>
</tbody>
</table>

Ratios different, e.g.

\[
\frac{\sigma(1\text{n},1\text{n})}{\sigma(1\text{n},\text{X}_\text{n})} = 0.329 \quad (\text{Exp. } 0.34 \pm 0.01)
\]

\[
\frac{\sigma(1\text{n},1\text{n},\rho)}{\sigma(1\text{n},\text{X}_\text{n},\rho)} = 0.268
\]

- Requiring coincidence gives a measure of the impact parameter

\[
\begin{align*}
\rho & \quad <b> = 46 \text{ fm} & \quad 1\text{n},\text{X}_\text{n},\rho & \quad <b> = 18 \text{ fm} \\
1\text{n},1\text{n},\rho & \quad <b> = 20 \text{ fm} & \quad \text{X}_\text{n},\text{X}_\text{n},\rho & \quad <b> = 18 \text{ fm}
\end{align*}
\]
Photon-Pomeron Interactions at RHIC

Falk Meissner * for the STAR Collaboration

In ultra-peripheral heavy ion collisions the two nuclei interact via their long range fields at impact parameters $b > 2\, R_A$, where neither nucleus is disrupted. In exclusive $\rho^0$ production $AuAu \rightarrow AuAu\rho^0$, a virtual photon emitted by one nucleus fluctuates to a $q\bar{q}$ pair, which then scatters diffractively from the other nucleus. Both, the photon and the Pomeron couple coherently to the nuclei with a coupling strength proportional to $Z^2$ for the photon and between $A_0^2 / (\alpha \text{ surface})$ and $A^2 / (\alpha \text{ volume})$ for the Pomeron. It follows, that the cross section for this process is expected to be large: 380 mb or 5% of the hadronic cross section at $\sqrt{s_{NN}} = 130$ GeV\cite{1}. Coherent coupling yields the condition that the interaction takes place only at small transverse momenta $p_T < 2h / R_A \sim 100$ MeV.

Besides photo-nuclear interactions, ultra-peripheral collisions can also involve purely electromagnetic photon-photon processes like $e^+e^-$ pair production; these may be sensitive to non-perturbative QED since the coupling constant $\alpha \approx 0.6$ is large. Purely hadronic double diffractive interactions may produce exotic glue balls. Nevertheless, the cross section for Pomeron-Pomeron processes is expected to be small due to the short range of the strong force.

Exclusive $\rho^0$ meson production at low $p_T$ has a specific experimental signature: the $\pi^+\pi^-$ decay products of the $\rho^0$ meson are observed in an otherwise 'empty' spectrometer; the pion tracks are back-to-back in the transverse plane. The two nuclei remain in their ground state, therefore no signal is detected in the zero degree calorimeters. To detect ultra-peripheral collisions with the STAR detector a low-multiplicity topology trigger was implemented, suppressing background from cosmic rays, beam gas events, and debris from upstream interactions. The central trigger barrel was divided into quadrants. A hit was required in both a South and a North quadrant, while the Top an Bottom quadrants acted as a veto to suppress possible cosmic rays. A fast online reconstruction eliminated events with more than 15 tracks and events with tracks not emerging from the the collision region. Using this trigger, the STAR collaboration collected 7 hours of data in 2000. The level 0 trigger rate varied from 20 to 40 Hz and was reduced to about 1-2 Hz by the level 3 trigger\cite{2}.

The $\rho^0$ analysis selected events with exactly two tracks that formed a primary vertex. The transverse momentum distribution (c.f. slides) for the $\rho^0$ candidates is peaked around $p_t < 100$ MeV, showing the coherent coupling to both nuclei. For pairs within the peak at $p_T < 100$ MeV a clear signal of about 300 $\rho^0$ is observed in the $M_{\pi\pi}$ invariant mass spectrum. For comparison, combinatorial background (modeled by like-sign pairs and shown as the shaded histograms in the plots) shows neither the coherent peak, nor a $\rho^0$ mass peak.

In parallel to the production of a $\rho^0$ meson, the two nuclei can be excited by the exchange of one or more photons yielding the emission of neutrons which are detected in the zero degree calorimeters (ZDC). About 800,000 events with coincident neutron signals in both ZDC's (minimum bias trigger) have been recorded in 2000. About 300 coherent $\rho^0$ events at the characteristic low $p_T$ have been found in this data sample.

In summary, the first observation of coherent $\rho^0$ production in ultra-peripheral heavy ion collisions is reported. The two processes $AuAu \rightarrow AuAu\rho^0$ and $AuAu \rightarrow Au^*Au\rho^0$, i.e. exclusive $\rho^0$ production with and without nuclear excitation, have been observed.

\cite{2} F. Meissner, Ultra Peripheral Collisions, poster presented at Quark Matter 2001.

*Lawrence Berkeley National Laboratory
Photon-Pomerion Interactions at RHIC

Exclusive production of $\rho^0$ mesons $\text{Au}+\text{Au} \rightarrow \text{Au}+\text{Au} + \rho^0$

- Interaction via long range fields
- Large cross section:
  $380 \text{ mb} \text{ for } \text{Au at } 130 \text{ GeV/nucleon} \newline
  5\% \text{ of hadronic cross section}$
- Coherent coupling to both nuclei
  $\Rightarrow$ Small transverse momentum:
  $p_T < 2/R_A \sim 60 \text{ MeV}$
  $\Rightarrow$ Longitudinal component
  $P_L < 2\gamma/R_A \sim 6 \text{ GeV/c} \ll P_{\text{nuclei}}$

**Coupling Strength**

- Nuclei may be mutually excited

**Photon $\propto Z^2$ (only $\propto Z$ for incoherent coupling to single nucleon)**

**Pomerion $\propto A^{4/3} \text{ to } A^2$** (\(A^{4/3} \propto \text{surface, in the limit } \sigma_{\rho^0 N} \rightarrow \infty\);
\(A^2 \propto \text{volume, in the weak limit}\))

**First Goal - Proof of Principle**

Observe exclusive $\rho^0$ production $\text{Au Au} \text{ Collisions}$

Brookhaven, May 2001

Falk Meissner, LBNL
Experimental Signature/Trigger

Only two oppositely charged tracks
- Low total $p_T$
- Back-to-back in transverse plane

Trigger Backgrounds:
- Cosmic rays
- Beam-gas Events
- Debris from upstream events

Typical Event:

Topology Trigger:
- ~7 hours of dedicated data collection
- 30,000 triggers in 2000

Brookhaven, May 2001

Falk Meissner, LBNL
**First Results: Invariant Mass & Transverse Momentum Spectra**

**Peripheral Trigger:**

\[ \text{Au} + \text{Au} \rightarrow \text{Au} + \text{Au} + \rho^0 \]

Peak at low \( p_T \) signature for coherent interaction

**Signal region:** \( p_T < 0.1 \text{ GeV} \)

**Fit of \( \rho^0 \) Lineshape**

(all data: peripherally triggered + minimum bias; c.f next slide)

to \( \rho^0 \) + non resonant \( \pi^+\pi^- \) production

interference is significant

**Brookhaven, May 2001**

Falk Meissner, LBNL
**Nuclear Excitation**

In addition to \( \rho^0 \) production, nuclei can exchange one or more separate photons and become mutually excited.

- Believed to factorize as function of impact parameter
- Decay yields neutrons in Zero Degree Calorimeter (ZDC) -> minimum bias trigger
- Data set: \(~800,000\) events with minimum bias trigger

\[
\text{Au} + \text{Au} \rightarrow \text{Au}^* + \text{Au}^* + \rho^0
\]

---

**Transverse Momentum**

- \( \pi^+ \pi^- \)
- \( \pi^0 \pi^+ \), \( \pi^- \pi^- \)

**Signal region:** \( p_T < 0.1 \text{ GeV} \)

**Invariant Mass for \( p_T < 0.1 \)**

- \( \pi^+ \pi^- \)
- \( \pi^0 \pi^+ \), \( \pi^- \pi^- \)

**Preliminary**

Brookhaven, May 2001

Falk Meissner, LBNL
Compare ZDC Signals
(for two track events)

Ultra Peripheral Trigger

- Pedestal peak at ADC sum = 4
- Higher ADC values usually in east or west only (beam gas events)

Minimum Bias Trigger

- Single neutron peak around ADC = 9 coincident in east and west
- Higher ADC values from hadronic peripheral events

Summary:

Observe two different processes!

\[ \text{Au+Au} \rightarrow \text{Au+Au} + \rho^0 \quad \text{and} \quad \text{Au+Au} \rightarrow \text{Au}^*+\text{Au}^* + \rho^0 \]

First observation of Ultra-Peripheral Collisions in heavy ion interactions

RHIC is a good place to study diffractive processes in heavy ion and polarised (!) proton-proton collisions

Brookhaven, May 2001

Falk Meissner, LBNL
The \( \text{PP}^2\text{PP} \) Experiment at RHIC

S. Bültmann (Brookhaven National Laboratory)
E-Mail: bueltmann@bnl.gov

Summary

The \( \text{PP}^2\text{PP} \) experiment at RHIC is going to measure elastic and total cross-sections in (un-)polarized proton-proton scattering. The experiment is located at the 2 o'clock interaction region of the RHIC complex. Elastic scattering at the RHIC energies, \( \sqrt{s} = 200 \text{ GeV/c} \) and possibly 500 GeV/c during the first year, requires detection of the scattered protons at very small angles. At a few locations along the beam line, the scattering angle is directly proportional to the measured distance between the scattered proton and the beam axis, \( \Theta = \frac{y_{\text{Det}}}{L_{\text{eff}}} \). One of these locations, suitable for measurements at the four-momentum transferred, \( -t \), in the range 0.003 to 0.100 (GeV/c)^2, is at \( L_{\text{eff}} = 20 \text{ m} \).

Elastic scattering requires the detection of the two collinearly scattered protons in coincidence. We are planning to use four planes of silicon microstrip detectors, two of each measuring the position of the scattered proton along one direction perpendicular to the beam momentum, together with one trigger scintillator, per detector package. The detector packages will be mounted inside Roman Pots above and below the beam line. The two pots will allow to move the detector packages vertically to positions about 15 mm above and below the beam centre. The setup will feature additional scintillator counters close to the interaction region to tag non-elastic scattering events. These veto counters can also be used to detect single- and double-diffractive scattering events. They cover a pseudo-rapidity range of \( 2.6 < \eta < 5.6 \).

During the Year-2001 engineering run of \( \text{PP}^2\text{PP} \) the main focus of the measurements will be on the total cross-section difference between the two transverse helicity states of the beam, \( \Delta \sigma_T \), the single and double transverse spin asymmetries, \( A_N \) and \( A_{NN} \), and the energy dependence of the nuclear slope, \( b \). Running for about two days at a reduced luminosity of about \( 10^{28} \text{ cm}^{-2} \text{ sec}^{-1} \), would enable us to measure \( A_N \) and \( A_{NN} \) to about 5% relative accuracy and \( \Delta \sigma_T \) to about 0.3 mb. This should allow to distinguish between different exchange models brought forward for example in

We will also measure the total cross section, \( \sigma_{\text{tot}} \), providing data at \( \sqrt{s} = 200 \text{ GeV/c} \), a region between the existing data measured at ISR on the lower energy side and Fermilab at higher energies. A measurement at \( \sqrt{s} = 500 \text{ GeV/c} \) would add a data point to the region of Fermilab's measurements and could enable us to distinguish between models calling for saturation of the cross-section at higher energies and Pomeron exchange models. A measurement at \( \sqrt{s} = 500 \text{ GeV/c} \) would also allow us to measure the elastic differential cross-section, \( d\sigma/dt \), up to a \( -t \) of 1.0 GeV^2/c^2. A dip in \( d\sigma/dt \) around a \( -t \) of 0.8 GeV^2/c^2 is expected. This region is very sensitive to spin exchange. On the lower \( -t \)-side of the dip region the \( C \)-parity is positive (+1), while on the higher \( -t \)-side it is negative (-1).

In case of longitudinal beam polarization being available at our interaction point, also the longitudinal spin asymmetry, \( A_{L} \), together with the cross-section difference, \( \Delta \sigma_L \), could be measured. Including the above mentioned measurements, the s-channel helicity amplitudes could be extracted.

---

**pp2pp Physics Programme**

Study of total and elastic cross-sections in proton-proton scattering over a large kinematic range

\[ 50 \leq \sqrt{s} \leq 500 \text{ GeV/c} \]
\[ 4 \times 10^{-4} \leq |t| \leq 1.5 \text{ (GeV/c)}^2 \]

- Measurements with transverse and longitudinally polarized protons to determine
  - the s-channel helicity amplitudes \( \Phi_i \)
    \[ \Phi_1 \sim <\uparrow\downarrow > M \uparrow \uparrow \]  
    \[ \Phi_2 \sim <\uparrow\downarrow > M \uparrow \downarrow \]  
    \[ \Phi_3 \sim <\uparrow\downarrow > M \downarrow \uparrow \]  
    \[ \Phi_4 \sim <\uparrow\downarrow > M \downarrow \downarrow \]  
    \[ \Phi_5 \sim <\uparrow\downarrow > M \uparrow \downarrow \]  
  - determine the nature of the mediator of the elastic interaction
- Measurements with unpolarized protons
- Measurements with (un-)polarized deuterons and helium
- Diffractive Scattering

---

**Experimental Setup**

![Experimental Setup Diagram]

- BRAHMS & PP2PP
- PHENIX
- STAR
- RICH
- AGS
- LINA Booster
- 200 MeV Polarimeter
- RF Dipoles
- 70% Polarization
- \( 50 < \sqrt{s} < 500 \text{ GeV} \)
- \( L_{\text{tot}} = 2 \times 10^{32} \text{s}^{-1} \text{cm}^{-2} \)
- \( \varepsilon = 20 \pi \text{ mm mrad} \)

---

Stephen Büttmann

The pp2pp Experiment at RHIC
Principle of Measurement

For small scattering angles the position of the protons at the detection point are directly proportional to the angle via the beam transport matrix:

\[ y_{\text{det}} = a_{jj} y^* + L_{\text{eff}} \theta_{\text{sc}} \]

Parallel to point focusing: \( a_{jj} = 0 \) and \( L_{\text{eff}} \) large

\[ t_{\text{min}} \propto \frac{k^2 \varepsilon^2}{\beta^*} \]

\( \Rightarrow \) need large \( \beta^* \) and small \( \varepsilon \)

For Coulomb region special tune is required:

\[ \beta^* = 195 \text{ m} \text{ and low emittance } \varepsilon = 5\pi \text{ mm mrad} \]
Silicon Detector Package in Roman Pot

- 400 micron thick silicon microstrips covering 5 x 8 cm
- 70 micron wide strips with 100 micron pitch
  (good track resolution and limited occupancy)
- 2 X-detectors (768 strips of 45 mm length)
- 2 Y-detectors (512 strips of 75 mm length)
- High and uniform efficiency
- Close proximity of detector to beam (14 mm)

- 8 mm thick trigger scintillator behind silicon planes

**RHIC Run 2001**

No special conditions required:

$L_{off}$ = 20 m, Roman Pot position at 57 m from IP

Minimum experimental setup:

- One Roman Pot station in each outgoing beam pipe
- Veto counter system around IP

Kinematic coverage:

- at 100 GeV/c: [Image]
- at 250 GeV/c: [Image]
  (if running at this energy takes place)
Measurements in 2001

- Study CNI region, $\sigma_{tot}, A_N, A_{NN}$
- $s$ dependence of the nuclear slope, $b$
- Measurement of $A_N$ over large -$t$ range to find suitable kinematic region for polarimetry

Expected Run Plan

- Total Proton Intensity = $5 \cdot 10^{10} - 10^{11}$
  \[ \Rightarrow L \approx 1.2 \cdot 10^{28} \text{ cm}^{-2} \text{ sec}^{-1} \]
- 100 events/sec for $\sim$10 mb elastic cross-section
- 1.4 million events for 10 hour ring filling (assume 40% efficiency)
- One or two days of special running most practical for us
- Accuracy $\delta A_N \approx 0.002 - 0.003$
- Accuracy $\delta A \sigma_{tot} \approx 0.3 \text{ mb}$

Outlook

2003

- Extend measurements to $0.1 < -t < 1.3 \text{ (GeV/c)}^2$

Beyond 2003

- Measure in CNI region, requiring special tune $0.0004 < -t < 0.12 \text{ (GeV/c)}^2$
- Measure in large -$t$ region $1.3 < -t < 5 \text{ (GeV/c)}^2$
- Elastic scattering of proton-deuteron, deuteron-deuteron, and proton-$^4\text{He}$ also possible
DO Hard Diffraction in Run I and Prospects for Run II

Andrew Brandt

University of Texas at Arlington

One of the most interesting new results from Tevatron Run I was the existence of large rapidity gaps in events with a hard scattering (Slide 1). DO published several papers on events with a central rapidity gap between jets [1] and have several more papers submitted or in preparation on related topics, including diffractive production of jets [2], diffractive production of W and Z bosons, and hard double pomeron exchange. Slides 2 and 3 summarize some of the recent results. Improved understanding of the new field of hard diffraction, which probes otherwise inaccessible details of the strong force and vacuum excitation, requires new detectors for tagging and measuring scattered protons.

To improve its capabilities for hard diffraction studies, DO is adding a Forward Proton Detector (FPD) [3] for Run II as shown in Slide 4. The FPD consists of momentum spectrometers that make use of accelerator magnets along with points measured on the track of the scattered proton to calculate the proton’s momentum and scattering angle. Tracks are measured using scintillating fiber detectors located in vacuum chambers positioned in the Tevatron tunnel 20–60 meters upstream and downstream of the central D0 detector. The vacuum chambers were built by Brazilian and Dutch collaborators and have been installed in the Tevatron. The scintillating fiber detectors are being assembled at the University of Texas at Arlington. Most of the FPD electronics has been installed and commissioned and data taking will begin soon (see Slide 5).

The FPD has acceptance for a large range of proton (anti-proton) momenta and angles. The combination of spectrometers maximizes the acceptance for protons and anti-protons given the available space for locating the detectors. Particles traverse thin steel windows at the entrance and exit of each Roman pot (the stainless steel vessel that houses the detector). The pots are remotely controlled and can be moved close to the beam (within a few mm) during stable beam conditions and retracted otherwise. The scintillating fiber detectors are read out by multi-anode photomultiplier tubes and are incorporated into the standard D0 triggering and data acquisition system.

The FPD will allow new insight into an intriguing class of events that are not currently understood within the Standard Model. It allows triggering directly on events with a scattered proton, anti-proton, or both, along with activity in the D0 detector. In addition to improved studies of recently discovered hard diffractive processes, the new detector will allow a search for glueballs and exotic phenomena. The FPD will also provide improved luminosity measurements, which are an important component to all D0 analyses.

Bibliography of Literature


DO Hard Diffraction in Run I 
and Prospects for Run II 

Andrew Brandt 
DO / University of Texas, Arlington 

- Intro and Run I Hard Diffraction Results 
- Forward Proton Detector 

Beyond the Pomeron 
May 22, 2001 
Brookhaven National Lab
### DØ Single Diffractive Results

#### Gap Fraction (%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Data</th>
<th>Hard Gluon</th>
<th>Flat Gluon</th>
<th>Soft Gluon</th>
<th>Quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s(β) ∝ )</td>
<td>β(1 − β)</td>
<td>const.</td>
<td>(1 − β)⁵</td>
<td>β(1 − β)</td>
<td></td>
</tr>
<tr>
<td>1800 Fwd</td>
<td>0.65 ± 0.04</td>
<td>2.2 ± 0.3</td>
<td>2.2 ± 0.3</td>
<td>1.4 ± 0.2</td>
<td>0.79 ± 0.12</td>
</tr>
<tr>
<td>1800 Cent</td>
<td>0.22 ± 0.05</td>
<td>2.5 ± 0.4</td>
<td>3.5 ± 0.5</td>
<td>0.05 ± 0.01</td>
<td>0.49 ± 0.06</td>
</tr>
<tr>
<td>630 Fwd</td>
<td>1.19 ± 0.08</td>
<td>3.9 ± 0.9</td>
<td>3.1 ± 0.8</td>
<td>1.9 ± 0.4</td>
<td>2.2 ± 0.5</td>
</tr>
<tr>
<td>630 Cent</td>
<td>0.90 ± 0.06</td>
<td>5.2 ± 0.7</td>
<td>6.3 ± 0.9</td>
<td>0.14 ± 0.04</td>
<td>1.6 ± 0.2</td>
</tr>
</tbody>
</table>

#### Ratio of Gap Fraction

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>630/1800 Fwd</td>
<td>1.8 ± 0.2</td>
<td>1.7 ± 0.4</td>
<td>1.4 ± 0.3</td>
<td>1.4 ± 0.3</td>
<td>2.7 ± 0.6</td>
</tr>
<tr>
<td>630/1800 Cent</td>
<td>4.1 ± 0.9</td>
<td>2.1 ± 0.4</td>
<td>1.8 ± 0.3</td>
<td>3.1 ± 1.1</td>
<td>3.2 ± 0.5</td>
</tr>
<tr>
<td>1800 Fwd/Cent</td>
<td>3.0 ± 0.7</td>
<td>0.88 ± 0.18</td>
<td>0.64 ± 0.12</td>
<td>30. ± 8.</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>630 Fwd/Cent</td>
<td>1.3 ± 0.1</td>
<td>0.75 ± 0.16</td>
<td>0.48 ± 0.12</td>
<td>13. ± 4.</td>
<td>1.4 ± 0.3</td>
</tr>
</tbody>
</table>

Within the *Ingelman-Schlein* model, DØ data can be reasonably described by a pomeron composed dominantly of quarks.

For the model to describe DØ data as well as other measurements, a reduced flux factor convoluted with a gluonic pomeron containing significant soft and hard components is required.

hep-ex/9912061
Series of 18 Roman Pots forms 9 independent momentum spectrometers allowing measurement of proton momentum and angle.

\[ \xi = 1 - x_p = \frac{\Delta P}{P} \quad t = (P_{\text{Beam}} - P_F)^2 \]

1 Dipole Spectrometer (\( \vec{p} \)) \( \xi > \xi_{\text{min}} \)
8 Quadrupole Spectrometers (\( p \) or \( \bar{p} \), up or down, left or right) \( t > t_{\text{min}} \)
Hard Color-Singlet Exchange

Count tracks and EM Calorimeter Towers in $|\eta| < 1.0$

Measure fraction of events due to color-singlet exchange

Measured fraction (~1%) rises with initial quark content:
Consistent with a soft color rearrangement model preferring initial quark states Inconsistent with two-gluon, photon, or U(1) models

Long Range Plan

• Install 8 more detectors (total of 10) during September shutdown

• Begin data taking with full DØ detector and trigger list in October

• Demonstrate working system, usefulness of horizontal plane, and secure funding for remaining MAPMT in 2002

• Early papers:
  NIM
  Elastic t-distribution
  Single diffraction distributions
  Diffractive jet production
  Double tagged double pomeron exchange
Hard Diffraction at CDF

Anwar Ahmad Bhatti
The Rockefeller University
CDF Collaboration

SOFT DIFFRACTION
1) Soft single diffraction PRD 50 (1994) 5550
2) Soft double diffraction NEW RESULT

RAPIDITY GAP RESULTS
3) Diffractive $W$ PRL 78 (1997) 2698
4) Diffractive Dijets PRL 79 (1997) 2636
6) Diffractive $J/\psi$ NEW RESULT


ROMAN POT RESULTS
10) Diffractive Dijets 1800 PRL 84 (2000) 5043
11) Diffractive Dijets 630 COMING SOON!
Gluon Fraction and Factorization

\[ D = 0.19 \pm 0.04 \]

\[ f_g = 0.54^{+0.16}_{-0.14} \]
Measurement of diffractive structure function
Comparison with expectations from H1 results

\[ D = \frac{\int_{\log \beta = 0}^{\log \beta = -1.4} F_{jj}^D(\beta; CDF) d\beta}{\int_{\log \beta = 0}^{\log \beta = -1.4} F_{jj}^D(\beta; H1) d\beta} \]

\[ = \begin{cases} 
0.06 \pm 0.02 & \text{for fit-2} \\
0.05 \pm 0.02 & \text{for fit-3}
\end{cases} \]

CDF normalization uncertainty = ±26 %

\( Q^2 = -q^2 \)

\( W^2 \)

\( M^2 \)

\( p \)

\( e \)

\( s \)

\( \beta \)

\( \xi \)

\( E_T^{jet,1,2} \geq 7 \text{ GeV} \)

\( Q^2 = 75 \text{ GeV}^2 \)

\( 0.035 \leq \xi \leq 0.095 \)

\( |t| \leq 1.0 \text{ GeV}^2 \)
Diffractive $J/\psi$ Production

Ratio of SD to ND cross sections versus $x_{bj}$

$$x_{bj}^{\pm} = \frac{1}{\sqrt{s}} \times p_T^{J/\psi} \left( e^{\pm \eta^{J/\psi}} + e^{\pm \eta^{ot}} \right)$$

![Graph showing the ratio of SD to ND cross sections versus X-Bjorken.](image)

- J/$\psi$ Data
- Roman Pot Dijets

\[
\left( \frac{R_{JJ}}{R_{J/\psi}} \right)_{exp} = \frac{g^D + \frac{4}{9} q^D}{g^{ND} + \frac{4}{9} q^{ND}} / \frac{g^D}{g^{ND}} = 1.17 \pm 0.27 \text{ (stat)}
\]

Gluon fraction: $f_g^D = 0.59 \pm 0.15 \text{ (stat } \oplus \text{ syst)}$
Double Pomeron Exchange : Test of Factorization

\[
\begin{align*}
\sigma_{ND} &= \sigma_0 F(x, Q^2) F(x, Q^2) \\
\sigma_{SD} &= \sigma_0 F(x, Q^2) F^D(x, \xi, Q^2) \\
\sigma_{DP} &= \sigma_0 F^D(x, \xi, Q^2) F^D(x, \xi, Q^2)
\end{align*}
\]

\[
\frac{R_{SD}}{R_{ND}} = 0.15 \pm 0.02 \text{(stat)} \pm 0.03 \text{(norm)}
\]

\[
\frac{R_{DPE}}{R_{SD}} = 0.80 \pm 0.26 \text{(stat)}
\]

\((10^{-2.8} < x < 10^{-2})\)

Breakdown of Factorization

\[
7 < E_T^{jet1, 2} < 10 \text{ GeV} \\
0.035 < \xi_F < 0.095 \\
0.01 < \xi_F < 0.03 \\
|t_F| < 1.0 \text{ GeV}^2
\]
**DD Cross Sections at $\sqrt{s} = 630$ and 1800 GeV**

$\sqrt{s} = 1800$ GeV \hspace{0.5cm} \sigma_{DD}(\Delta\eta > 3) = 6.32 \pm 0.03\text{(stat)} \pm 1.7\text{(syst)}\text{mb}$

$\sqrt{s} = 630$ GeV \hspace{0.5cm} \sigma_{DD}(\Delta\eta > 3) = 4.58 \pm 0.02\text{(stat)} \pm 1.5\text{(syst)}\text{mb}$
The effective Pomeron trajectory and Double-Pomeron-Exchange Reaction in UA8

Samim Erhan

University of California, Los Angeles, California 90095, USA.

In this talk, UA8 final results from the analysis of a double-Pomeron-exchange data sample were presented. Results were also summarized from our earlier work [S. Erhan et al. (UA8 Collaboration), Nucl. Phys. B 514 (1998) 3, and S. Erhan & P. Schlein, Phys. Lett. B 481 (2000) 177], where we have shown that the Triple-Regge parametrization fits all available single-diffractive data at ISR, SPS and Tevatron, provided that the effective Pomeron trajectory intercept, \( \alpha(0) \), is \( s \)-dependent and decreases with increasing \( s \), as expected from unitarization (multi-Pomeron-exchange) calculations. \( \alpha(0) = 1.10 \) at the lowest ISR energy, 1.03 at the SPS-Collider and perhaps smaller at the Tevatron.

Despite the complications of multi-Pomeron exchange, factorization of Pomeron emission and interaction seems to be valid to a high degree. The UA8 parametrization of single-diffraction as the product of a “Flux Factor” of the Pomeron in the proton, \( F_{P/p}(t, \xi) \), and a proton-Pomeron total cross section \( \sigma_{pp}^{\text{total}} \) has the form:

\[
\frac{d^2\sigma_{dd}}{d\xi dt} = [0.72 F_1(t)^2 e^{1.1t} \xi^{1-2\alpha(t)}] \cdot [(s')^{0.1} + 4.0(s')^{-0.32}].
\]

where: \( s' = s \xi \) and \( \xi = 1 - x_p \). The constant, 0.72, is the product of \( F_{P/p}(t, \xi) \) and \( \sigma_{pp}^{\text{total}} \) normalizations.

The effective Pomeron trajectory, \( \alpha(t) \), has a linear form with a quadratic term added to allow for a flattening of the trajectory at high-\( |t| \), as required by the data:

\[
\alpha(t) = 1 + \epsilon + \alpha't + \alpha''t^2
\]

A further analysis of inelastic diffraction data at the ISR and SPS-Collider confirms the relatively flat \( s \)-independent Pomeron trajectory in the high-\( |t| \) domain, \( 1 < |t| < 2 \) GeV\(^2\), reported earlier by Erhan et al. At \( |t| = 1.5 \) GeV\(^2\), \( \alpha = 0.92 \pm 0.03 \) is in agreement with the trajectories found in diffractive photoproduction of vector mesons at HERA. This suggests a universal fixed Pomeron trajectory at high-\( |t| \).

We have isolated double-Pomeron-exchange interactions in events in which one or both of the final state \( p \) and/or \( \bar{p} \) are detected in Roman-pot spectrometers. The central system is detected in the calorimeter system of the UA2 experiment, and is separated from \( p \) and \( \bar{p} \) by pseudo-rapidity gaps, \( 2.3 < |\eta| < 4.1 \). Assuming the validity of factorization in double-Pomeron-exchange interactions, we have extracted the Pomeron-Pomeron total cross section, \( \sigma_{pp}^{\text{total}}(M) \), using the above parametrization of the \( F_{P/p}(t, \xi) \) factor and the effective Pomeron Regge trajectory. For masses above 10 GeV, \( \sigma_{pp}^{\text{total}}(M) \) agrees with the factorization prediction of \( \approx 0.1 \) mb. However, for smaller masses, it exhibits an intriguing enhancement, \( \sigma_{pp}^{\text{total}}(M) \approx 1.0 \) mb, which is much larger than expected from a breakdown of factorization. The low-mass enhancement of the invariant mass distribution of the central system may be an evidence for resonant Pomeron-Pomeron interactions (e.g., glueball production) in the few-GeV mass region, although the invariant mass resolution is inadequate to observe any structure.

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2Supported by U.S. National Science Foundation Grant PHY94-23142
Key Results:

- No s-dependence of trajectory at high-t
- Intercept and slope exhibit s-dependence

Agreement between:

HERA $\rho^0, \phi^0$ photo-production
pp/p$\bar{p}$ inelastic diffraction

May 22, 2001
Samim Erhan - "Beyond the Pomeron" (BNL)
\[ \alpha(t) = 1.035 + 0.165 \, t + 0.06 \, t^2 \]
\[ \chi^2/DF = 4.2 \]

Integral is total \( \sigma_{\text{dif}} \).

The data require a smaller intercept and slope.

Trajectory at high-\( t \) agrees with UA8 results.

\[ \alpha(t) = \varepsilon + \alpha' \, t + \alpha'' \, t^2 \]

6-parameter fit:
\[ \varepsilon = 0.10 - 0.02 \log(s/549) \]
\[ \alpha' = 0.22 - 0.03 \log(s/549) \]
\[ \alpha'' = 0.06 - 0.01 \log(s/549) \]

Similar \( s \)-dependent \( \varepsilon \).

(starts within ISR range) and flattening at high-\( t \).
Pomeron-Pomeron Total Sigma

Red line is factorization prediction: about 0.1 mb.

- High mass points appear to agree with prediction
- $\sigma_{pp}$ low mass enhancements in both data sets.

May 22, 2001    Samim Erhan - "Beyond the Pomeron" (BNL)
DPE "AND" Event Selection

\[ \Phi_{p+\bar{p}} \]

Minimum \( P^+ \) acceptance is 1 GeV/c.

DPE "OR" Calorimeter \( \Sigma P_{\text{longitudinal}} \)

DPE "OR" Extracted from Diffractive trigger
Rapidity gaps, 2.3 - 4.1
DIF \( \times \)
DPE \( \checkmark \)

\( \Rightarrow \) Rap. gaps produce symmetry in calorim.
DPE "AND" data

- $N^0 = 0.5 N^{\pm}$
- No anomalous behavior

DPE "AND" Longitudinal Structure

$\cos \theta$ for hit calorimeter cells in c.m. of $M_x$

- $M_x < 5$ GeV: isotropic
- $M_x > 5$ GeV: polar peaked

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Soft
Diffractive Scattering
and
QCD Instantons
BNL 01'

(Nowak + Chiu+ Zahed)
Set up

Abelian: \[WW\]

Non-Abelian: SVM, Strings, Instantons, ...
Scales

$\sin^2 \theta_2 - G^2 \gammaordsim 1 \text{ GeV} / \text{fm}^2$

$\chi^2$-min. $\sigma = \frac{1}{2\pi \alpha'} < 1 \text{ GeV} / \text{fm}$

Justification: $k_0 = n_0 \rho_0 \propto 10^{-2}$

$S \propto \frac{1}{\text{fm}^{-4}} \frac{1}{\sqrt{3}} \text{ fm}$. 

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\[ \cos \Theta \rightarrow \cosh = \frac{1}{\sqrt{1-v^2}} = \frac{z}{2m} - i \]

\[ T(e, b) \rightarrow T(x, b) \]
Results

\[ \frac{1}{s^2} \left\{ \begin{array}{c}
\int \\
\end{array} \right\} \frac{1}{2} 12 \left( \frac{\pi}{s} \right) \left( \frac{\alpha_s}{\pi} \right)^2 \]

\[ \frac{1}{s^2} \left\{ \begin{array}{c}
\int \\
\end{array} \right\} \frac{1}{2} 12 \pi \frac{s}{s_0} k_0^2 \]

\[ \frac{1}{s^2} \left\{ \begin{array}{c}
\int \\
\end{array} \right\} \frac{1}{2} 12 \pi \frac{s}{s_0} k_0 \ln s \]

\[ \frac{\sigma_{QG}}{\sigma_{QGP}} = 12 \left( \frac{\pi k_0}{\alpha_s} \right)^2 = \left( \frac{\pi 10^{-2}}{\sqrt{s}} \right) \times 10^{-2} \]

\[ \sigma_{BKFL} = \pi \left( \frac{\alpha_s}{\pi} \right) \ln s \]

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String Fluctuations, AdS/CFT and the Soft Pomeron

Romuald A. Janik

In this talk we summarize the results obtained in [1,2] on the application of the AdS/CFT correspondence as a tool for studying nonperturbative high energy scattering in gauge theories.

The AdS/CFT correspondence provides an exact equivalence between certain types of gauge theories and appropriate ‘dual’ string theories on a curved (‘Anti-de-Sitter’-like) background. In particular strong coupling properties of gauge theories get mapped to (semi-)classical properties of the relevant string theory.

Scattering amplitudes in the eikonal approximation can be expressed as correlation functions of Wilson lines (resp. loops) following classical straight line quark trajectories (resp. trajectories of a quark-antiquark pair). We perform the calculation of these correlation functions in Euclidean space, express them as a function of the relative euclidean angle \( \theta \), and then we perform an analytical continuation into Minkowski space. We use the AdS/CFT correspondence in the first ‘Euclidean’ step.

In order to study the interplay of confinement and reggeization we use a version of the AdS/CFT correspondence which exhibits confinement — Witten’s black hole background. The prescriptions for calculating the expectation values of Wilson loops is to find a minimal surface in the curved geometry which is spanned on the loop/loops. For large impact parameters (w.r.t. the confinement scale) the minimal surface is well approximated by the helicoid [1]. The resulting Euclidean formula has a branch cut structure, which, through the analytic continuation to Minkowski space gives rise to (i) inelastic amplitudes and (ii) linear Regge trajectories. The intercept in this case is 1.

In [2] we studied quadratic fluctuations of the string worldsheet around the helicoid. The resulting Euclidean expression was again continued to Minkowski space and through the branch cut structure gave rise to a shift of the intercept proportional the number of effective transverse dimensions \( n_\perp \) of the dual string theory (the intercept becomes equal to \( 1 + n_\perp/96 \)).

The main result is that a (numerically small) shift of the intercept arises naturally through analytical continuation of a Lüscher-like term for the helicoid, it is independent of variations of the string tension and gives a surprisingly similar trajectory to the experimental soft pomeron for \( n_\perp = 7, 8 \).

MOTIVATION

• GAUGE THEORY SCATTERING
  \( s \to \infty \)
  \( t \) FIXED/SMALL

• QUESTIONS:
  Amplitudes \( \sim s^k \)
  AT STRONG COUPLING

  - BEHAVIOUR WITH \( t \)
    (REGGERIZATION/TRAJECTORIES)

  - INTERPLAY WITH CONFINEMENT

• USE \( \text{AdS/CFT} \) CORRESPONDENCE

(SYM GAUGE THEORY) \( \equiv \) SUPERSTRINGS ON A 'AdS_5 \times S^5' BACKGROUND

  PROPERTIES AT
  \( \leftrightarrow \)
  'EASY' PROBLEMS

STRICT COUPLING

• THERE EXIST VARIANTS FOR CONFINING THEORIES.
• **Analytical Continuation**  
  Euclidean ↔ Minkowski

\[ A_{\theta_e, L} = \langle \quad \uparrow \quad \theta_e \quad \rangle \]  

**Euclidean**

**Analytically Continue**

\[ \theta_e \rightarrow -i \chi = -i \log \frac{s}{2m^2} \]

\[ A(s, L) = A_{-i \log \frac{s}{2m^2}, L} \]

1. **Using the AdS/CFT Correspondence Calculate**  
   Euclidean correlator \( A_{\theta, L} \)

2. **Within Gauge Theory Perform Analytical Continuation**  
   \[ \theta \rightarrow -i \log s \]
CALCULATION FROM ADS/CFT

- Confining Theory
  \[ \downarrow \]
  Witten's BH Geometry

\[ z = R_0 \]
\[ z = 0 \]

- LARGE IMPACT PARAMETERS
  \[ \downarrow \]
  EVERYTHING HAPPENS NEAR THE HORIZON

- METRIC NEAR THE HORIZON FLAT

- FIND MINIMAL SURFACE IN FLAT SPACE
\[ \frac{L^2}{\theta} \log \left[ \ldots \right] \quad \rightarrow \quad \frac{L^2}{2\pi} \ln \frac{2\pi}{\log s} \]

Amplitude = \( i \leq e^{-\frac{1}{\alpha_{\text{eff}}} \frac{L^2}{\log s}} \)

\text{FOURIER TRANSFORM}

\[ \int \! d^2q \, e^{iLq} \quad q^2 = -t \]

Amplitude = \( i \left( \log s \right) \leq 1 + \frac{\alpha_{\text{eff}}}{4} t \)

- \text{INTERCEPT} = 1
- \text{LINEAR TRAJECTORY}

\text{SMALL IMPACT PARAMETERS}

\[ \downarrow \]

\text{DIFFERENT GEOMETRY}

\[ \downarrow \]

\text{DIFFERENT BEHAVIOUR}

\( / \text{SOFT} - \text{HARD} \quad \text{TRANSITION} \)
RESULT:

\[ S \uparrow 1 + \frac{n}{96} + \frac{d'_\text{eff}}{4} \cdot t \]

Logs...

\[ n = 7 \quad \mapsto \quad S \quad 1.073 \]

\[ n = 8 \quad \mapsto \quad S \quad 1.0833... \]

SOFT POMERON?

\[ S \quad 1.08 + 0.25t \]

- \( d'_\text{eff} \) IS NOT PREDICTED BUT IS DEFINED THROUGH
  STATIC \( q\overline{q} \) POTENTIAL

PHENOMENOLOGICAL VALUE: \( d'_\text{eff} \approx 0.8 \ldots \text{GeV}^{-2} \)

SLOPE \( \sim 0.2 \text{ GeV}^{-2} \)

- NATURAL COUPLING TO SINGLE QUARKS
- INDEPENDENCE OF \( d'_\text{eff} \)

CAUTION:

\( \uparrow \) PREFACTOR
\( \uparrow \) FERMIONS (SHOULD BE MASSIVE)
\( \uparrow \) CUT-OFF
Inclusive diffraction: $F_2^D$ and the partonic interpretation

A closer look:
- Energy flow and thrust

Diffractive final states in DIS:
- Dijet and 3-jet production, open charm

... and in hadron-hadron(like) interactions:
- Dijets in diffr. photoproduction [and at the Tevatron]
Summary and Conclusions

Diffractive dijet production (and $F_2^D$):

- Diffr. Dijets tightly constrain diffractive gluon distribution $g^D$ (shape and norm.), in contrast to $F_2^{D(3)}$ measurements.

- Data favour diffr. PDF’s, evolving with DGLAP, strongly dominated by gluons with momentum distribution rel. flat in $z$ ("H1 fit 2")

- Consistent picture from $F_2^{D(3)}$ and jet measurements: Concept of factorizing diffr. PDF’s in DIS [Collins] works.

- Consistent with factorizing $x_{\perp\perp}$ dependence with $\alpha_{\perp\perp}(0) = 1.17$ ("Regge factorization")

- SCI and Semiclassical models not yet able to simultaneously give correct shape and normalizations of jet cross sections

- Improved models calculations based on 2-gluon exchange can describe part of dijet cross section

Indications for breakdown of Factorization?

- Suppression of open charm ($D^*$)

- Suppression of $x_\gamma < 1$ dijets for $Q^2 \approx 0$
Diffractive Dijet Production in DIS

Motivation:

- Direct sensitivity to $g^D$ through $\mathcal{O}(\alpha_s)$ process (boson gluon fusion):
- Jet $P_T$ provides second hard scale

Kinematics (in partonic picture):

$M_{12}$

- Invariant mass of two leading jets

$z_{IP}^{(jets)} \approx \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$

- Momentum fraction of exch. entering hard scattering

Diffractive Gluon Distribution

Dijets directly constrain shape and normalization of $g^D$:

- H1 fit 2: very good agreement with data
- H1 fit 3: overshoots at high $z_{IP}$
- ACTW-D: too high

[res. $\gamma^*$, IR and quark contributions small]

Proton rest frame picture: $q\bar{q}g \gg q\bar{q}$ states
Soft Colour Neutralization

- Soft Colour Interactions SCI (Edin, Ingelman, Rathsman) original version and "generalized area law" (Rathsman)
- Semiclassical Model (Buchmüller, Gehrmann, Hebecker)

H1 Diffractive Dijets

- tiny $q\bar{q}$ contribution
- BJLW $\sim$ OK if $p_{T,g} > 1.5$ GeV
- Saturation Model too low $p_{T,rem}$ not able to discriminate :-(

$\omega_F < 0.01 \Rightarrow$ avoid IR exch.; P PDF's $g$-dominated

$\Rightarrow$ Sensitivity to differences between models which all (have been tuned to) describe $E_2^{D(3)}$ !
Diffractive $D^*$ Production

$\Rightarrow$ H1 fit predicts three times higher cross section!
$\Rightarrow$ Broken factorization (Errors still large)?
$\Rightarrow$ 2-gluon, $q\bar{q} + q\bar{q}g$ calculation (Bartels et al.) OK at small $x_F$, high $z_F$!

High Energy QCD, BNL Brookhaven, May 2001

Dijets in Diffr. Photoproduction ($Q^2 \approx 0$)

$\alpha_\gamma$ dependence of cross section

- Resolved $\gamma$ similar to hadron-hadron
- Suppression factor $S = 0.6$ at small $\alpha_\gamma$ necessary!
- Factorization broken? (Large errors...)

[New measurement in progress...]

High Energy QCD, BNL Brookhaven, May 2001

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POMERON PHYSICS STUDIED WITH THE ZEUS DETECTOR

M. Derrick
Argonne National Laboratory

This talk covers four areas of HERA physics studied with the ZEUS detector:

a) The $Q^2$ and $x$ dependence of the proton structure function $F_2$ is presented, emphasizing the transition that occurs at about $Q^2 = 1 \text{ GeV}^2$ from pQCD behaviour, described by DGLAP evolution in $Q^2$, to a Regge-type behaviour parametrized by a simple vector dominance model at the lowest $Q^2$ values. The cross sections extrapolation to photoproduction agrees reasonably well with those directly measured.

b) About 10% of the DIS events are diffractive. The general properties can be understood either in terms of the exchange of a pomeron in the t-channel or by the interaction of $q\bar{q}$ and $q\bar{q}g$ dipoles in the proton rest system. The data are consistent with factorizing into a pomeron flux times a pomeron structure function. The scaling violations show that the pomeron is gluon dominated. However, the resulting parton distributions are not universal, failing to account for hadronic diffraction at the Tevatron collider. The cross section data indicate a larger pomeron intercept than seen in soft hadronic diffraction. New data with diffractive masses above 20GeV show a clear three-jet structure as expected from the $q\bar{q}g$ partonic state that dominates this region.

c) Vector meson production dominates the low mass region. Both the light, $\rho$, $\omega$ and $\phi$, as well as the heavy, $J/\psi$ and upsilon, mesons have been observed. The energy dependence of the light mesons in photoproduction is similar to hadronic reaction, but the $t$ dependence, as a function of $W$, is different. The $J/\psi$ in photoproduction and the $\rho$ in electroproduction have a much steeper $W$ dependence leading to different pomeron trajectories. The $t$ slope of the data shows a change from a large to a small dipole size with increase of the hard scale. Production ratios approach the SU(4) photon wave function value at high $Q^2$.

d) The data are compared to the saturation model of Golec-Biernat and Wuesthoff.
- ZEUS QCD01 & REGGE97 shown in fitted $Q^2$ range
- Is the slope changing?
- Quantify this from the slope $dF_2/d\log(Q^2)$
• Ingelman-Schlein factorisable model → Pomeron with partonic structure (quark and gluon densities)

\[ P_{NP}(z, \mu^2) \]

\[ \mu^2 = 4.5 \text{ GeV}^2 \]

\[ \mu^2 = 12 \text{ GeV}^2 \]

\[ \mu^2 = 75 \text{ GeV}^2 \]

HERA data ⇒ Pomeron dominated by gluons.

• pQCD inspired models (\(\gamma\)-dissociation picture)
  → Pomeron described as two-gluons exchange

\[ q\bar{q}g \text{ contribution dominates at low-}\beta \ (\beta = \frac{Q^2}{Q^2 + M_Z^2}) \].
\[ 5 < Q^2 < 100 \text{ GeV}^2 \]
\[ 200 < W < 250 \text{ GeV} \]
\[ x_F < 0.025 \]
\[ 23 < M_X < 40 \text{ GeV} \]
\[ \eta_{\text{hadron}}^{\text{max}} < 3.0 \]
\[ N_{\text{jet}} = 3 \ (y_{\text{cut}} = 0.05) \]
\[ -2.3 < \eta_{\text{jet}} < 2.3 \]
\[ (L = 39 \text{ pb}^{-1} \rightarrow 678 \text{ evts.}) \]

\[ x_i = \frac{2 \cdot E_i^{\text{jet}}}{M_X} \]
\[ x_1 \geq x_2 \geq x_3 \]
\[ x_1 + x_2 + x_3 = 2 \]

\[ x_i = \underbrace{2 \cdot \sin \theta_i}_{\sin \theta_1 + \sin \theta_2 + \sin \theta_3} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image}
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\includegraphics[width=\textwidth]{image}
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\includegraphics[width=\textwidth]{image}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{image}
\end{figure}
Exponential fall characteristic of diffractive processes

\[ \frac{d\sigma}{dt} \propto e^{-b|t|} \]

ELASTIC

similarity with diffraction of light by a circular aperture \( b \propto R^2 \)

\( b \) related to transverse size of the interaction

\[ b = \frac{R^2}{R_0^2} \]

\[ R^2 = R_S^2 + R_V^2 \]

\[ 5 \text{ GeV}^{-1} = 1 \text{ fm} \]
$\alpha_P(t)$ FROM $\rho$ AND $J/\psi$

**Diagram**

- $\rho Q^2 = 0.5 GeV^2$ ZEUS 94-95, H1 94, Omega 82
- $\rho Q^2 = 3.5 GeV^2$ ZEUS (prel.) 96-97
- $\rho Q^2 = 10 GeV^2$ ZEUS (prel.) 96-97
- $J/\psi Q^2 = 0 GeV^2$ ZEUS (prel.) 96-97

**Text**

No universal Pomeron.
GB&W Description of $\sigma_{tot}^{\gamma^*p}$

Dotted line: GB&W model (3 parameter fit) $\sigma_0 = 23.03 \, \text{mb}$
Solid line: MRST NLO QCD fit $\Delta_0 = 1.6 \, \text{GeV}$, $\lambda = 0.288$

$\Rightarrow$ What about $dF_2/d\log(Q^2)$ of NLO DGLAP fits....
ABSTRACT
Diffractive processes at hadron colliders and at HERA exhibit similar but not identical behaviour to that expected for conventional Pomeron exchange. We present the experimental evidence for beyond the standard Pomeron properties of diffraction and review a phenomenological model in which a Pomeron-like behaviour emerges from the quark-gluon sea of the nucleon. Experimental data on soft and hard diffraction are compared with predictions based on this model.

- Introduction
- Elastic and total cross sections
  - Regge approach
  - Parton model approach
- Soft diffraction and multi-gap cross sections
- Hard diffraction
**$M^2$-scaling in diffraction**

**Single Diffraction**

K. Goulianos and J. Montanha

PRD D59, 114017 (1999)

The $M^2$ dependence of the $pp$ single diffraction differential cross section at $t = -0.05$ GeV$^2$ does not depend on the $s$-value ($M^2$-scaling). This is contrary to the Regge theory $s^2$-behaviour and in agreement with the Pomeron flux renormalization prediction of the above reference.

**Double diffraction**

The CDF central rapidity gap data agree in shape with the Monte Carlo prediction for double diffraction dissociation based on Regge theory and factorization.

The $\sigma_{DD}$ agrees with the prediction of the renormalized rapidity gap model based on $M^2$-scaling (KG, hep-ph/9806384), contrary to the $s^2$ expectation from Regge theory.
Multi-gap cross sections

\[ \Delta y_1 \quad \Delta y'_1 \quad \Delta y_2 \quad \Delta y'_2 \quad \Delta y_3 \quad \Delta y'_3 \quad \Delta y_4 \]

\[ y'_1 \quad y_2 \quad y'_2 \quad y_3 \quad y'_3 \]

\[ \Delta y \equiv \sum_{i=1}^{4} \Delta y_i \]

Rules for calculating multi-gap cross-sections

The high energy cross section for a multi-gap process can be calculated from the parton-model scattering amplitude

\[ \text{Im} f(t, \Delta y) \sim e^{(\varepsilon + \alpha't)\Delta y} \]

- For the rapidity regions \( \Delta y' = \sum \Delta y'_i \), where there is particle production, the \( t = 0 \) parton model amplitude is used and the sub-energy cross section is given by \( C \cdot e^{\varepsilon \Delta y'} \).

- For rapidity gaps, \( \Delta y \), which can be considered as resulting from elastic scattering between clusters of particles, the square of the full parton-model amplitude is used, \( e^{2(\varepsilon + \alpha't_i)\Delta y_i} \), and the form factor \( \beta^2(t) \) is included for a surviving (anti)proton.

- The gap probability (product of all rapidity gap terms) is normalized to unity.

- A color factor \( \kappa \) is included for each gap.

Calculation of the 4-gap differential cross section of the above figure:

- There are 10 independent variables, \( V_i \), shown below the figure.

\[ \frac{d^{10} \sigma}{dV_1 dV_2} = P_{gap} \times \sigma \text{(sub-energy)} \]

\[ \sigma \text{(sub-energy)} = \kappa^4 \left[ \beta^2(0) \cdot e^{\varepsilon \Delta y'} \right] \quad (\Delta y' = \sum_{i=1}^{3} \Delta y'_i) \]

\[ P_{gap} = N_{gap} \times \Pi_{i=1}^{4} \left[ e^{(\varepsilon + \alpha't_i)\Delta y_i} \right]^2 \times [\beta(t_1)\beta(t_4)]^2 \]

\[ P_{gap} = N_{gap} \cdot e^{2\varepsilon \Delta y} \cdot f(V_i)_{i=1}^{10} \quad (\Delta y = \sum_{i=1}^{4} \Delta y_i) \]

- \( N_{gap} \): factor that normalizes \( P_{gap} \) over all phase space to unity.
**Diffractive DIS**

Inclusive DIS \(\frac{d^2 \sigma}{dx \, dQ^2} \sim \frac{1}{x} \cdot F_2(x, Q^2)\)

Diffractive DIS \(\frac{d^4 \sigma}{dt \, d\xi \, d\beta \, dQ^2} \sim \frac{1}{\beta} \cdot F_2^D(t, \xi, \beta, Q^2)\)

\(x - \beta \xi\)

\(F_2^D(t, \xi, \beta, Q^2) = f_c \cdot F^{\text{sub-energy}}(\beta, Q^2) \cdot P_{\text{gap}}(t, \xi, Q^2)\)

\[\Delta y = \ln \frac{1}{\xi} \Rightarrow \frac{d \Delta y}{d \xi} = \frac{1}{\xi}\]

\[P_{\text{gap}} = N_{\text{gap}} \cdot \frac{1}{\xi} \cdot \left[ e^{[\epsilon + \alpha' t]} + \lambda(Q^2) \ln \frac{1}{\xi} \right] \cdot \beta^2(t)\]

\[N_{\text{gap}}^{-1}(Q^2, \xi_{\text{min}}) = \int_{\xi_{\text{min}}}^{1} \xi^{-[1+ \epsilon + \lambda + \alpha' t]} \beta^2(t) \, dt \, d\xi\]

\[\xi_{\text{min}} = \frac{x_{\text{min}}}{\beta} = \frac{Q^2/s}{\beta} \Rightarrow N_{\text{gap}} = f \left( Q^2, \frac{Q^2}{s\beta} \right)\]

Ignoring \(t\) \(\Rightarrow \quad N_{\text{gap}} = (\epsilon + \lambda) \cdot (Q^2/s\beta)^{\epsilon} \cdot \lambda\)

To guarantee factorization at large \(Q^2\):
\((n = \epsilon + \lambda, \quad C = N_{\text{fact}})\)

\[F_2^D(\xi, \beta, Q^2) = C \cdot \frac{n}{\xi^{1+n}} \cdot \left[ 1 - e^{-\frac{1}{C}(Q^2/s\beta)^{n}} \right] \cdot f_c \cdot \frac{A_{\lambda}}{\beta^\lambda}\]

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Comparison with HERA data

Dependence of $\alpha^P(0)$ on $Q^2$:

$$\alpha^P(0) = 1 + \frac{1}{2} [\epsilon + \lambda(Q^2)] \quad \text{(use } \epsilon = 0.1 \text{ and } \lambda = 0.1 + 0.053 \ln Q^2)$$

ZEUS 1994

Diffractive structure function prediction (hep-ph/0001092)

H1 DATA:
$Q^2 = 45 \text{ GeV}^2$
$F_2(Q^2 = 50, x = 0.00133) = 1.46$
$\Rightarrow F_2(x) = 0.2/x^{0.3}$
$\xi \approx 0.01$

$\epsilon = 0.1$
$\lambda = 0.3$

The solid curve in the figure is predicted using the above data/parameters and $f_c = 0.5$. 
CONCLUSIONS

• Soft diffraction
  - A parton-model approach to diffraction was presented based on the observed $M^2$-scaling ($s$-independence) in single and double diffraction $\bar{p}p$ differential cross sections, $d\sigma/dM^2$.
  - This approach leads to unitarized cross sections without the need to introduce multi-Pomeron exchanges to account for saturation effects (screening, survival-probability ...).
  - Multi-gap differential cross sections are predicted.

• Hard diffraction
  - Diffractive structure function in DIS:
    \[ F_2^D(\xi, \beta, Q^2) \sim \frac{1}{\beta^3} \frac{1}{\xi^{1+\epsilon} + \lambda} \times N_{gap}(Q^2, \beta) \]
  - Dependence of Pomeron intercept on $Q^2$:
    \[ \alpha(0) = 1 + \frac{1}{2}[\epsilon + \lambda(Q^2)] \]
  - Ratio of diff/non-diff structure functions at the Tevatron:
    \[ R \sim 1/x^{\epsilon + \lambda} \]
Scaling Properties of
High-Energy Diffractive Vector-Meson Production
at High Momentum Transfer

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May 23, 2001

Abstract

Recent results on the diffractive production of vector mesons in photon-proton reactions at HERA
are challenging contemporary understanding of diffractive processes and of hadron structure. Fol-
lowing a brief overview of selected results obtained from the measurement programs of the H1 and
ZEUS collaborations during the first eight years of operation, we concentrate on the experimental and
phenomenological particulars relating to a recent observation of power-law scaling with momentum
transfer in semi-exclusive vector-meson photoproduction. The combination of the observed power
and the polarization of the vector meson appear to violate the helicity selection rules of perturbative
QCD. This observation fits into a pattern of HERA results pointing to contributions from a point-like
transverse-to-transverse vacuum-exchange transition which is difficult to reconcile with QCD.
Scaling Properties of High-Energy Diffractive Vector-Meson Production at High Momentum Transfer

Selected Results from HERA

Surprise in $\rho^0$ Photoproduction at High Momentum Transfer

J. A. Crittenden
Deutsches Elektronen-Synchrotron

General Remarks on Exclusive VM Production at HERA

Investigation of vacuum-exchange processes
Vacuum exchange has a complicated, poorly understood structure

Study properties of strong interaction
  → Soft interactions
    - Forward, total cross sections
    - Exponential $t$-slopes, shrinkage
    - Helicity rules
  → Hard interactions
    - Short-distance vacuum exchange
    - Scale definition
    - Sensitive to $|xG(\mu,x)|^2$
    - Helicity rules

The hard/soft transition can be studied in $Q^2, M^2, |t|

Exclusivity allows study of helicity structure
  → The VM helicity state is directly related to the expected scaling behavior
  → The spin-density matrix elements are directly related to meson structure
Quick Review (IV):
\( \sigma_L/\sigma_T \) in Elastic \( \rho^0 \) Electroproduction

\[
R = \frac{1}{1 - \frac{\Delta^2}{1 - \frac{\Delta^2}{1 - \left(\frac{r_{00}}{r_{04}}\right)^2}}}
\]

\( \Delta \) now known to be small

The dominance of \( \sigma_L \)

was an early prediction of pQCD

Remarkably hard scaling behavior for \( \sigma_T \)

(The \( Q^2 \) dependence is even weaker than \( Q^{-6} \))

Quick Review (VI):
\( \sigma_L/\sigma_T \) in Elastic \( \rho^0 \) Electroproduction

A. Kreisel at DIS2001

ZEUS

\( n=1.89\pm0.03 \)

\( n=2.72\pm0.03 \)
Main Topic:
VM Photoproduction at High \(|t|\)

Photoproduction Tagging at \(W \approx 100\ \text{GeV}\)

**ZEUS detector**

\[Q^2 < 0.02\ \text{GeV}^2\]
\[23 < E_{e'} < 25\ \text{GeV}\]
\((\Rightarrow 80 < W < 120\ \text{GeV})\)

**ZEUS 1996/97 preliminary**

Integrated luminosity: 24 pb\(^{-1}\)

\[\rho^0: \approx 18k\]
\[\phi: \approx 2k\]
\[J/\psi: \approx 150\]

Proton-dissociative process dominates at \(|t| > 1\ \text{GeV}^2\)

\[x = \frac{t}{t-M_{c}^{2}}\]

Cross sections \(\frac{d\sigma}{dt}\) are integrated over \(0.01 < x < 1\)

**Diffractive \(\rho^0\) Photoproduction (III)**

\((-t)^n \times \frac{d\sigma}{dt}\)

Multiplying with \((-t)^n\)

**BNL Workshop**
23 May 2001

J.A. Crittenden
DESY
Diffractive $\phi$ Photoproduction (II)

\[ (-t)^n \times \frac{d\sigma}{dt} \]

\[ \begin{align*}
(-t)^4 \\
(-t)^3 \\
(-t)^2 \\
\end{align*} \]

Multiplying with $(-t)^n$

Momentum Transfer $(-t)$ [GeV$^2$]

Decay-Angle Analysis (II)

Talk by A. Kowal at DIS2001

ZEUS

Transverse polarization dominates

Helicity breaking clearly measured at level of few %

(But why no dependence on $t$?)

Also significant double-flip contribution


BNL Workshop
23 May 2001

J.A. Crittenden
DESY
Some general remarks
(and some questions)

These are the first measurements of light-vector-meson photoproduction at values of $t$ comparable to the $Q^2$ values in DIS which led to the discovery of charged proton constituents in 1967.

BUT this is presumably a strong interaction, rather than electromagnetic.

We observe an extremely hard $t$ dependence
$\Rightarrow$ low-order process (first order ?)
$\Rightarrow$ What about the meson form factor ?

The QCD helicity selection rules appear to be violated.

These values for $t$ exceed the mass scales for $\rho$ and $\phi$ and exceed $\Lambda_{QCD}^2$
$\rightarrow$ Asymptotic region

The $t$ dependence characterizes the interaction.

Perturbative field theory
for vacuum exchange in the strong interaction (?)

What is the exchanged field?
What is the "charge"?
(Strength about $1/100$ of confinement)
What is the reacting proton constituent?

Are there point-like interactions of hadronic bound states?

At tempted Synthesis

There appears to be increasing evidence for a point-like $T \rightarrow T$
vacuum-exchange transition which is difficult to reconcile with QCD

A QCD description requires chiral-symmetry breaking, for example, quark-mass effects.

This requirement results in a $t$ dependence stronger than observed.

This $T \rightarrow T$ transition contributes to VM electroproduction well into the $Q^2$ region where pQCD successfully describes the production of longitudinal vector mesons.

It is the dominant VM-photoproduction process at high momentum transfer.

The successful field theoretical description of this process will be a prime candidate for a theory which can be used in higher orders to describe diffractive processes at low momentum transfer, elastic and total hadronic cross sections.
Abstract: For Multiplicities, Cross Sections and Diffraction Dissociation

W.D. Walker – Duke University

In figure 1 we see the multiplicity distributions for a range of $\sqrt{s}$ values. The solid curve is the distribution for lower energies (ISR) where KNO multiplicity scaling holds. The quantity $x$ is the charged multiplicity $n/<n_1>$ where $<n_1>$ is the average multiplicity for a single parton-parton collision. KNO scaling works for a part of each of the multiplicity distributions. Figure 2 shows the result of subtracting the solid curve from each of the experimental distributions. The result is a group of curves which peak at a value of $n/<n_1> = 2$. The distributions widen as $\sqrt{s}$ increases.

To begin to understand the position of the energy threshold for double (and triple) parton-parton collisions we use the energy required $\sqrt{s}$, for making the multiplicity $<n_1>$ charged particles from $e^+e^-$ annihilation. This formulation predicts a threshold for two collisions of about $\sqrt{s} = 100$ GeV for p-pbar interactions. The results of the calculations and observations are shown in the Table. The quantity $<n_1>$ is measured and nicely fitted by an expression of the form $<n_1> = A \log(\sqrt{s}) + B$ over the range of $\sqrt{s}$ of 60 to 1800 GeV. We note that the threshold for 3 collisions should be in the neighborhood of 500 GeV. We show the decomposition of the multiplicity distribution at 1800 GeV. in Figure 3. We have extrapolated our results to LHC energies. We find that the multiparton collisions account for almost all of the increase in the non-single diffractive cross section, $\sigma_{NSD}$, in the collider energy range. We predict that multi-parton collisions will have a cross section of about an equal magnitude with that for single parton-parton collision at the LHC energy. This is shown in figure 4. Remarkably the cross section for single parton-parton, $\sigma_1$, seems to be nearly constant as the energy is increased.

Collisions with nuclei will likely obey a different set of rules than single nucleon-nucleon collisions. This makes such studies seem very inviting.
\[ \sqrt{s} = 200 \text{ GeV} \]
\[ \sqrt{s} = 546 \text{ GeV} \]
\[ \sqrt{s} = 900 \text{ GeV} \]
\[ \sqrt{s} = 1800 \text{ GeV} \]
# TABLE-COLLISION CHARACTERISTICS

<table>
<thead>
<tr>
<th>$\sqrt{s}$-GeV</th>
<th>$&lt;n_1&gt;$</th>
<th>$x' = \sqrt{s'}/\sqrt{s}$</th>
<th>$\sigma_{\text{NSD}}$</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>14</td>
<td>.58</td>
<td>30.3</td>
<td>31.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>20.0</td>
<td>.40</td>
<td>35.2</td>
<td>33.5</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>546</td>
<td>25.2</td>
<td>.30</td>
<td>40.2</td>
<td>30.8</td>
<td>9.5</td>
<td></td>
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<tr>
<td>900</td>
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<td>.24</td>
<td>43.0</td>
<td>31.7</td>
<td>10.2</td>
<td>1.5</td>
</tr>
<tr>
<td>1800</td>
<td>31.5</td>
<td>.18</td>
<td>47.0</td>
<td>31.9</td>
<td>12.5</td>
<td>2.7</td>
</tr>
<tr>
<td>14000</td>
<td>42.2</td>
<td>.10</td>
<td>62.0</td>
<td>30.6</td>
<td>17.2</td>
<td>13.9</td>
</tr>
</tbody>
</table>
Decomposition - 1.8 TeV

Normalized Cross Section

$x = \langle n / n_1 \rangle$
\( \sigma (\text{mb}) \) vs. \( \sqrt{s} \) (GeV)

- \( \sigma_1 \)
- \( \sigma_2 \)
- "\( \sigma_3 \)"

\( \sigma_{\text{NSD}} = 32 \text{ mb} \)
Study of Diffractive Dijet Production at CDF

Kenichi Hatakeyama

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CDF Collaboration

We have studied single diffractive dijet production at $\sqrt{s} = 630$ and 1800 GeV using events triggered on a leading antiproton detected in a Roman Pot spectrometer. In this study, the diffractive structure function of the antiproton is measured and compared between $\sqrt{s} = 630$ and 1800 GeV. We find agreement in the $\beta$ dependence of the measured diffractive structure functions ($\beta$ is the momentum fraction of Pomeron carried by the struck parton), and a ratio in normalization of

$$R[\frac{630}{1800}] = 1.3 \pm 0.2(stat) \pm 0.4(syst)$$

in the region of $0.1 < \beta < 0.5$, $0.035 < \xi < 0.095$, where $\xi$ is momentum fraction of the $\bar{p}$ carried by the Pomeron, and 4-momentum transfer squared $|t| < 0.2$ GeV$^2$. This ratio is in general agreement with predictions from the renormalized Pomeron flux model, soft color interaction model, and gap survival model.

We have also studied some characteristics of the diffractive structure function using the higher statistics 1800 GeV data sample. In the region $\beta < 0.5$, $0.035 < \xi < 0.095$ and $|t| < 1$ GeV$^2$, the measured diffractive structure function can be fitted with the form

$$F_{ij}^D(\beta, \xi) = C \cdot \beta^{-n} \cdot \xi^{-m}$$

The fit yields $n = 1.04 \pm 0.01(stat)$ and $m = 0.92 \pm 0.02(stat)$. In the framework of Regge theory, the Pomeron, Reggeon and Pion exchanges have $\xi$ dependences of $\xi^{-1.2}$, $\sim \xi^0$ and $\sim \xi$, respectively. The measured value of $m = 0.92 \pm 0.02(stat)$ indicates that single diffractive dijet production is dominated by Pomeron exchange.

Comparisons are made with results from the UA8 collaboration, which studied single diffractive dijet production and the structure function of the Pomeron in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV at the CERN SppS collider. To compare the CDF 630 GeV data with the UA8 results, the CDF 630 GeV data sample was re-analyzed in a similar way to that used by the UA8 collaboration. The $x(2 - j\ell) \equiv x_{bj}(proton)$ distribution for the UA8 data, from which UA8 evaluated the Pomeron structure function, agrees with that for the CDF 630 GeV data reasonably well.
Diffractive Dijets with Leading Antiproton

Physics Motivation:

1. Measure the diffractive structure function
   
   \[ F_{jj}^D(\beta, \xi, Q^2, t) \]

   \[ F_{jj}^D(x, \xi, Q^2, t) = x \left[ g^D(x, \xi, Q^2, t) + \frac{4}{9} q^D(x, \xi, Q^2, t) \right] \]

   \[ F_{jj}^D(x, \xi, Q^2, t) \rightarrow F_{jj}^D(\beta, \xi, Q^2, t) \]

   \[ \frac{\partial^5 (p\bar{p} \rightarrow pj j X)}{\partial x_p \partial \beta \partial \xi \partial t \partial p_T^2} = \frac{F_{jj}(x_p, Q^2)}{x_p} \frac{F_{jj}^D(\beta, \xi, Q^2, t)}{\beta} \frac{d\sigma_{gg \rightarrow gg}}{dp_T^2} \]

2. Test QCD factorization by comparing
   (a) \[ F_{jj}^D(\beta, \xi, Q^2, t) \] between \( \sqrt{s} = 630 \) and 1800GeV
   (b) \[ F_{jj}^D(\beta, \xi, Q^2, t) \] with expectation from the measurements of diffractive DIS at HERA

3. Test Regge factorization

   \[ F_{jj}^D(\beta, \xi, Q^2, t) \]

   \[ F_{jj}^D(\beta, \xi, Q^2, t) = f_{P/P}(\xi, t) \]

   \[ x_{\bar{p}} = p_{g,q}/p_{\bar{p}}, \quad x_p = p_{g,q}/p_P \]

   \[ \xi = 1 - x_F = p_P/p_{\bar{p}}, \quad \beta = p_{g,q}/p_P \]
Diffractive dijet and Inclusive Events (630 GeV)

- Diffractive dijet events favor larger $\xi$ values
- The ratio of dijet to inclusive events has a flat $t$-dependence
  Consistent with 1800 GeV results
Diffractive Structure $F_{jj}^D(\beta)$: 630 vs. 1800 GeV

$$F_{jj}^D(x_{\bar{p}}, \xi) = R_{SD}^{ND}(x_{\bar{p}}, \xi) \times F_{jj}^D(x_{\bar{p}})$$

$$F_{jj}^D(x_{\bar{p}}, \xi) \rightarrow F_{jj}^D(\beta, \xi)$$
$$\beta = \frac{x_{\bar{p}}}{\xi}$$

Distributions are fitted to

$$F_{jj}^D(\beta) = B \times (\beta/0.3)^{-n}$$

$$0.1 < \beta < 0.5$$

with a common "n" value

$$R_B[630 \text{ GeV}] = 1.3 \pm 0.2 (\text{stat})^{+0.4}_{-0.3} (\text{syst})$$

CDF Preliminary

- 630 GeV
  - $E_{T1,2}^{\text{Jet}} > 7 \text{ GeV}$
  - $E_T^* > 10 \text{ GeV}$
  - $0.035 < \xi < 0.095$
  - $|t| < 0.2 \text{ GeV}^2$

- 1800 GeV
Diffractive Structure $F_{jj}^D(\beta, \xi) : (1800 \text{ GeV})$

$$F_{jj}^D(\beta, \xi) = C \times \beta^{-n(\xi)}$$
$$\langle n \rangle = 1.04 \pm 0.01(\text{stat})$$

$$F_{jj}^D(\beta, \xi) \propto 1/\xi^m$$
$$m = 0.92 \pm 0.02(\text{stat})$$

(at $\beta = 0.1$)

$\xi, \beta$-factorization:

$$F_{jj}^D(\beta, \xi) = C \cdot \frac{1}{\beta^m} \cdot \frac{1}{\xi^m} \quad (10^{-3}/\xi < \beta < 0.5 \text{ and } 0.035 < \xi < 0.095)$$
Comparison with UA8 (630 GeV)

UA8 has more events at low-\(\xi\) than CDF due to different Roman Pot acceptance

\(\Rightarrow\) Weight events in CDF data so that the \(\xi\) distribution becomes similar to that of UA8
Diffractive $J/\psi$ production at CDF

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(for the CDF Collaboration)

Abstract

We report the first observation of diffractive $J/\psi(\rightarrow \mu^+\mu^-)$ production in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV. Diffractive events are identified by their rapidity gap signature. In a sample of events with two muons of transverse momentum $p_T^\mu > 2$ GeV/c within the pseudorapidity region $|\eta| < 1.0$, the ratio of diffractive to total $J/\psi$ production rates is found to be $R_{J/\psi} = [1.45 \pm 0.25]\%$. The ratio $R_{J/\psi}(x)$ is presented as a function of $x$-Bjorken. By combining it with our previously measured corresponding ratio $R_{jj}(x)$ for diffractive dijet production we extract a value of $0.59 \pm 0.15$ for the gluon fraction of the (anti)proton diffractive structure function.
Diffractive $J/\psi$ Production in $\bar{p}p$ Collisions

- $J/\psi$ mesons are mostly produced through $gg$ fusion
- Diffractive $J/\psi$ production provides measurement of gluonic content of the Pomeron
- Challenging test for the phenomenological models describing $J/\psi$ *anomaly* and diffractive production
Diffractive Event Signal in Dimuon Sample

Rapidity gap definition

- No energy above noise in the forward calorimeters
- No hit in the BBC on the side of calorimeter gap
**Fraction of Diffractive $J/\psi$ Events**

\[
R_{J/\psi} \times A_{\text{gap}} = \frac{N_{J/\psi}^{\text{SD}}}{N_{J/\psi}^{\text{ND}}} \times \frac{\varepsilon_{1\text{vtx}}^{\text{ND}}}{\varepsilon_{1\text{vtx}}^{\text{SD}}} \times \frac{1}{\varepsilon_{\text{Live}}}
\]

\[
= \frac{67.5 \pm 10.4}{13339 \pm 128} \times \frac{0.57 \pm 0.04}{0.86} \times \frac{1}{0.80 \pm 0.03}
\]

\[
R_{J/\psi} \times A_{\text{gap}} = (0.42 \pm 0.07)\%
\]

$N_{(0,0)}^{\text{SD}} = N_{(0,0)} - N_{(0,0)}^{\text{ND}}$

\[
= (87.4 \pm 9.7) - (19.9 \pm 3.9)
\]

\[
= 67.5 \pm 10.4
\]

$A_{\text{gap}}$ is defined as the fraction of single-diffractive interactions having a rapidity gap in the region of $2.4 \leq |\eta| \leq 5.9$. 

\( R_{J/\psi} \) as a Function of Bjorken-X

From the detected jet, we calculate:

\[
X_{bj} = p_{g,q} / p_{p(\bar{p})} = \frac{p_T J/\psi \cdot e^{-\eta_{J/\psi}} + F_{T \text{jet}} \cdot e^{-\eta_{\text{jet}}}}{2 \cdot p_0 p(\bar{p})}
\]

\[
\approx \frac{p_T J/\psi (e^{-\eta_{J/\psi}} + e^{-\eta_{\text{jet}}})}{\sqrt{s}}
\]
Gluon Content of Pomeron

Ratio of diff. to non-diff. dijet production

\[ R_{JJ}(x) = \frac{F^{D}_{JJ}(x)}{F_{JJ}(x)} = \frac{g^{D}(x) + \frac{4}{9} q^{D}(x)}{g(x) + \frac{4}{9} q(x)} = \frac{g^{D}(x)}{g(x)} \times \frac{1 + \frac{4}{9} \frac{g^{D}(x)}{g(x)}}{1 + \frac{4}{9} \frac{g(x)}{g(x)}} \]

Since

\[ R_{J/\psi}(x) = \frac{g^{D}(x)}{g(x)} \Rightarrow \frac{R_{JJ}(x)}{R_{J/\psi}(x)} = \frac{1 + \frac{4}{9} \frac{g^{D}(x)}{g(x)}}{1 + \frac{4}{9} \frac{g(x)}{g(x)}} \]

\[ \frac{R_{JJ}}{R_{J/\psi}}_{\exp} = 1.17 \pm 0.27 \text{(stat)} \quad @ \bar{x} = 0.0063, \bar{Q} = 6 \text{ GeV/c} \]

From the proton PDF-set GRV94 LO

\[ \frac{q(x)}{g(x)} = 0.274 \quad @ \quad x = 0.0063, Q = 6 \text{ GeV/c} \]

\[ \rightarrow \quad \text{Gluon fraction} \quad @ \quad \bar{x} = 0.0063 \text{ and } \bar{Q} = 6 \text{ GeV/c} \]

\[ f^D_g = 0.59 \pm 0.14 \text{(stat)} \pm 0.06 \text{(syst)} \]

\[ \Rightarrow \quad \text{From diff. } W, b\bar{b} \text{ and dijet production} \]

\[ f^D_g = 0.54^{+0.16}_{-0.14} \]
MATCHING of SOFT and HARD P O M E R O N S

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May 24, 2001


The main goal: We want to find out how large the contribution of the non-perturbative QCD to the parameters of the phenomenological "soft" Pomeron (Donnachie-Landshoff Pomeron): \( \Delta_R = 0.08 \pm 0.1 \) and \( \alpha'_R = 0.25 \text{GeV}^{-2} \).

Key idea: "Soft" Pomeron \( \rightarrow \) nonperturbative QCD but at sufficiently short distances

\[
\frac{r_\perp(Pomeron)}{r_\perp(separation)} \gg \frac{1}{\Lambda}
\]

The results:

- The high energy asymptotic is due to exchange of the resulting Pomeron - Regge pole with the intercept close to 1;
- The pQCD contribution to the resulting Pomeron is essential;
- pQCD leads to
  - Considerable increase of the soft Pomeron intercept: \( \Delta_{SH} \approx 3 \Delta_S \);
  - Decrease of the slope of the soft Pomeron trajectory \( \alpha'_{SH} \approx \frac{1}{2} \alpha'_S \);
- The result crucially depends on the value of the intercept for the soft Pomeron \( \Delta_S \);
- The result is sensitive to our assumption on the values of scales: the nonperturbative scale of the soft Pomeron and the separation scale for the hard (BFKL) Pomeron;

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Scales of QCD

High density QCD

$Q_s(x)$

- Saturation scale

- $pQCD$

$\approx 2\, \text{GeV}$

- Scale anomaly (Size of instantons?)

- $pQCD$

$+\,$

- instantons

$\approx 1\, \text{GeV}$

- Separation scale

- instantons

$\approx 200 - 300\, \text{MeV}$

- Confinement scale (Size of hadrons)

- $npQCD$

"Matching of soft and hard Pomerons"
- The NLO BFKL kernel: $K_{BFKL}(q^2, q'^2) = \alpha_S(r)
K(r - r')$ where $r = \ln(q^2/\Lambda^2)$ and $r' = \ln(q'^2/\Lambda^2)$

- The Mellin image of $K(r - r') K(f)$ has a form:
  $K(f) = \Delta_H(\alpha_S) + D(\alpha_S)(f - \frac{1}{2})^2$

"Matching of soft and hard Pomerons"
Our approach:

- \( K(q^2, q'^2) = \Delta_S \phi(q^2) \phi(q'^2) \)
- \( \Delta_S \phi(q^2) \phi(q'^2) \) → \( s^{\Delta_S} \);

- \( K(q^2, q'^2) = \Delta_S \phi(q^2) \phi(q'^2) \) → diffusion in impact parameters \( (b_t) \);

- \( K(q^2, q'^2) = \Delta_S \phi(q^2) \phi(q'^2) \) → \( R = \alpha'_P \ln s \)
  where \( R \) is the radius of interaction;

- \( K(q^2, q'^2) = \Delta_S \phi(q^2) \phi(q'^2) \) → \( \alpha'_P \propto 1/q_0^2 \);

"Matching of soft and hard Pomerons" E. Levin
Matching of soft and hard Pomerons

E. Levin
Solution to the two channel problem

\[ \Delta_{SH} - \Delta_S = 4 \Delta_S^2 \sqrt{r_S/4D\pi\omega} \left( \frac{4\omega}{D r_H} \right)^{\frac{1}{6}} \]

\[ F \left( \left( \frac{4\omega}{D r_H} \right)^{\frac{1}{6}} \cdot \left( r_S - r_H \frac{\Delta_H}{\omega} \right) \right) \text{ where } r_S = \log \left( \frac{1}{r_{\text{ScaleAnomaly}}^2} \right) \]

\[ H = \log \left( \frac{1}{r_{\text{separation}}^2} \right); \text{ and } F(z) = \int_0^\infty \frac{dt}{\sqrt{t}} \exp \left( -zt - \frac{t^3}{3} \right). \]

"Matching of soft and hard Pomerons"  

E. Levin
Semihard Component of the Soft Pomeron

B. Kopeliovich (MPI Heidelberg)
in collaboration with
I. Potashnikova
B. Povh
E. Predazzi

Outline

- Large mass diffraction ⇒
- Two-scale structure of hadrons ⇒
- A specific form of energy dependent $G_{\text{tot}}(s)$ ⇒
- Phenomenology and elastic data in the impact parameter representation

Why large mass diffraction is suppressed?

Why the triple-Pomeron coupling is so small

$$\sigma_{pp} = \Omega (50 \text{ mb?}) \quad \sigma_{pp} \approx 2 \text{ mb}$$

To explain this one has to assume that the Pomeron has a small size $r_P$.

Why diffractive gluon bremsstrahlung is suppressed?

Only gluon radiation can provide the large mass behavior $\frac{d\sigma_{dd}}{dM^2} \propto \frac{1}{M^2}$

Excitation of the quark system leads to $\frac{d\sigma}{dM^2} \propto \frac{1}{M^3}$

It is easy to disentangle between these two processes.
Diffractive radiation by a quark

\[ \text{\includegraphics[width=0.5\textwidth]{dihadron}} \]

Take a simple form in impact parameter representation at \( \alpha_s \ll 1 \)

\[
M^2 \frac{d\sigma(qN \rightarrow gGN)}{d^2 k_T} \bigg|_{k_T=0} = \frac{1}{16\pi} \int d^2 q_T \left| \Psi_G(q_T) \bar{G}(q) \right|^2
\]

A. Schäfer

B. K.

A. Tarasov


\[ \sigma(q_T) = \frac{9}{8} \sigma_{qg}(q_T) \]  

\[ \hat{s} = 5 \text{MeV}^2 \]

PQCD calculations (with regularized \( \alpha_s(q^2) \) at small \( q^2 \)) overestimate the diffractive cross section by an order of magnitude.

\[ \sigma(qN \rightarrow gGN) \propto \langle r_g^4 \rangle \]

In the strong quark-gluon interaction regime

\[
\left. \Psi_G(q_T, \kappa_r) \right|_{q_T=1} = -\frac{2}{\pi} \sqrt{\frac{\alpha_s}{3}} \frac{\hat{s}^{1/2}}{r_g^2} e^{-r_g^2/2r_0^2}
\]

The data can be explained if \( r_0 = 0.3 \text{ fm} \)

Two sizes in light hadrons:

- the quark separation \( R_q \gg r_0 \)
- the quark separation \( R_q \ll r_0 \)

E. Shuryak

V. Braun et al.

A. Di Giacomo et al.

The small size of the gluon clouds makes it difficult to shake them off, either diffractively (\( \propto r_0^4 \)) or nondiffractively (\( \propto r_0^2 \))

What happens if \( r_0 \rightarrow 0 \)?

- no gluon radiation is possible, however the inelastic cross section doesn't vanish

\[ \text{or } \frac{q_e}{q_b} \rightarrow \frac{q_e}{q_b} \]

or

\[ \text{or } q_e \rightarrow q_e \]

or

\[ q_e \rightarrow q_e \]
Since gluon radiation is the only source of energy dependence, in this limit of $r_0 \to 0$
\[ \mathcal{O}_{\text{tot}} = \text{const} = \tilde{\mathcal{O}}_0 \]
if $r_0 \neq 0$, but small
\[ \mathcal{O}_{\text{tot}}(s) = \tilde{\mathcal{O}}_0 + r_0^2 f(s) \quad \text{vanishes} \quad \mathcal{O}_0(\tilde{s}_0) \quad \text{at} \quad r_0 \to 0 \]
\[ \Rightarrow \tilde{\mathcal{O}}_0 + r_0^2 K \cdot (\tilde{s}_0)^{\Delta} \]
\[ \Delta = \frac{4 \Delta_s}{3 \pi} \approx 0.17 \]
\[ K = \frac{g}{C} \approx 16.2 \]

Only one parameter $\tilde{\mathcal{O}}_0$ which cannot be evaluated perturbatively.

It needs just one experimental point for $\mathcal{O}_{\text{tot}}$ to fix this parameter.

Unitarization:
\[ \text{Im} \Gamma_P(b, s) = \frac{f}{D(s)} \left[ 1 - e^{-D(s)} \text{Im} \mathcal{Y}_P(b, s) \right] \]

Here
\[ \mathcal{Y}_P(b, s) = \sum_{n=0}^{\infty} \mathcal{Y}_n(b, s) \]
\[ D(s) = 1 + \frac{\mathcal{O}_{\text{pp}}^{pp}(s)}{\mathcal{O}_{\text{ee}}^{pp}(s)} \]

We have only one free parameter $\tilde{\mathcal{O}}_0^{PP}$ which we fix adjusting $\mathcal{O}_{\text{tot}}^{PP}$
at $\sqrt{s} = 546$ GeV.

Then we are in position to predict the energy dependence and the slope of elastic scattering:
\[ \mathcal{O}_{\text{tot}}^{PP} = 2 \int d^2 b \quad \text{Im} \Gamma(b, s) \]
\[ B_{ee}^{PP} = \frac{1}{2} \langle b^2 \rangle = \frac{1}{\mathcal{O}_{\text{tot}}^{PP}} \int d^2 b \quad b^2 \quad \text{Im} \Gamma(b, s) \]
$\sigma_{\text{tot}}(\text{mb})$

$B_{e1}(\text{GeV}^{-2})$

Fully predicted
How to get rid of the absorptive/unitarity corrections?

AGK cutting rules for inclusive cross sections $\rightarrow$ Mueller theorem

\[ \frac{d\sigma_{\text{inel}}}{dy} = \sigma_0 + \sigma_1 \left( \frac{E}{\sqrt{s}} \right)^{\Delta} \]

The energy dependence of the inclusive cross section is given by the bare Pomeron, no unitarization is needed.

Fit to available data by A. Likhoded et al.

- $d\sigma_{\text{inel}}/dy = \sigma_0 + \sigma_1 \left( \frac{E}{\sqrt{s}} \right)^{\Delta}$
- Both terms are demanded by the fit
- $\Delta = 0.17$!
Summary

- High mass diffraction is extremely sensitive to the size of the gluon clouds of valence quarks and fixes it at $r_0 = 0.3$ fm.
- In the case of $r_0^2 \ll R_h^2$ the cross section consists of two terms:
  \[ \sigma_{\text{tot}}(s) = \sigma_0(R_h) + \sigma_1(s, r_0) \]
  with $\sigma_1(s, r_0) \propto r_0^2$ and $\sigma_0(R_h)$ independent of $s$.
- There is only one unknown parameter in the model $\sigma_0$.
  \[ \sigma_1(s, r_0) \propto r_0^2 (s/s_0)^{0.17} \]
  is calculated.
- Available elastic scattering data translated to the impact parameters are well reproduced.
- The forthcoming data from the pp$\rightarrow$pp experiment are expected to have a sufficient precision to disentangle between $\sigma_{\text{tot}} \propto (s/s_0)^{\Delta}$ and $\sigma_{\text{tot}} = \sigma_0 + \sigma_1(s/s_0)$.
The CKMT approach to the Pomeron puzzle*

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The CKMT model for the parametrization of the nucleon structure function $F_2$ is a model based on Regge theory which phenomenologically takes into account the Regge cuts and the decrease of their contribution with $Q^2$, and which describes the experimental data on $F_2$ in the region of low $Q^2$.

An explicit theoretical model which leads to the above pattern of energy behavior, now confirmed by a simultaneous description of diffractive production by real and virtual photons, is also presented.

The CKMT model taken as an initial condition for the NLO evolution equations in perturbative QCD, provides a good description of the experimental data of $F_2$ in the whole available kinematical region of $x$ and $Q^2$, in particular when these data are presented in the form of the logarithmic slopes.

THE CKMT MODEL PLB 337 (1994) 358

We propose the following parametrization of the structure functions of the nucleons at moderate $Q^2$:

$$F_2(x,Q^2) = A \frac{Q^2}{Q^2 + \Delta(Q^2)} \left( 1 + \frac{Q^2}{Q^2 + \Delta(Q^2)} \right) x \left( 1 - x \right)^{n(Q^2) + 4}$$

Sea quarks

$$+ B \frac{Q^2}{Q^2 + \Delta(Q^2)} x \left( 1 - x \right)^{n(Q^2)}$$

Valence quarks

Where

$$\Delta(Q^2) = \Delta(0) \left( 1 + \frac{Q^2}{Q^2 + \Delta(0)} \right)$$

$$\Delta(0) \approx 0.07 - 0.08$$

$$\Delta(0) \approx 0.21 - 0.24$$

The behaviour at $x \to 1$ is given by the factors $(1-x)$

$$n(Q^2) = \frac{3}{2} \left( 1 + \frac{Q^2}{Q^2 + C} \right)$$

Small $Q^2$: $n \approx 1.5$

Large $Q^2$: $n \approx 3$

Dimensional counting rules

The separate contribution of the $u$ and $d$ valence quarks is given by

$$\beta \cdot (1-x)^{n(Q^2)} = \beta_u \cdot (1-x)^{n(Q^2)} + \beta_d \cdot (1-x)^{n(Q^2) + 1}$$

Where $\beta_u$, $\beta_d$ are fixed by the normalization condition for valence quarks.

The second factor in the two terms accounts for the connection with real photons.

CKMT -> A. Capella, A.B. Kaidalov, C.M. and J. Tran Thanh Van
A.B. Kaidalov, C. Merino and D. Pertermann

We compute $F_2$ and its derivatives

$$\frac{dF_2}{db \omega^2} \quad \text{and} \quad \frac{d \ln F_2}{d \ln (1/x)}$$

by using the CKMT model:

- $0 < \omega^2 \leq \omega_0^2$ (e.g., $\omega_0^2 = 2 \text{ GeV}^2$)

CKMT model without perturbative evolution

- $\omega_0^2 < \omega^2 \leq \text{charm threshold}$

NLO ($\overline{\text{MS}}$) evolution of the $F_2$ CKMT parametrized

$u, d, s \rightarrow pdf$

with $m_g = 3$.

- \text{charm threshold} < $\omega^2 < \infty$

NLO ($\overline{\text{MS}}$) evolution of the $F_2$ CKMT parametrization

$u, d, s, c \rightarrow pdf$

with $m_g = 4$. 
Diffraction

The CKMT model uses Regge factorization.

Proton structure

P.R(f)

P, p, p

Pomeron structure

P.R(f)

p, p, p

Triple Regge vertices

\[ F_2^{p}\left(x, Q^2, x_p, t\right) = \frac{[g_{pp}(t)]}{16\pi} \cdot x_p \cdot 1 - 2q_p(t) \cdot F_p\left(\beta, Q^2, t\right) \]

\[ \text{Flux factor} \quad \text{Pomeron structure function} \]

The Pomeron structure function depends on the choice of the flux factor (e.g., Annamalai & Landshoff flux factor).

\[ \text{differs from ours by } \frac{2}{11\pi} \]
The function $F_2^d = \frac{1}{2}(F_2^p + F_2^n)$ can be related to the deuteron structure.

In the CKMT model (PLB 343 (1995) 403, PRO 53 (1996) 2369),

\[
F_p(\beta, Q^2) = F_2^d(\beta, Q^2; A \rightarrow eA, B \rightarrow eB, m \rightarrow m-2)
\]

is a parametrization of $F_p$ valid in the region $1 \leq Q^2 \leq 5 GeV^2$

with

\[
\begin{align*}
\epsilon &= \frac{\rho_{pp}(0)}{\rho_{nn}(0)} \\
\delta &= \frac{\rho_{pp}(0)}{\rho_{np}(0)}
\end{align*}
\]

The $t$ dependence of $F_p$, which is expected to be very small, is factored out from soft diffraction with absorptive corrections.

\[
\epsilon \approx \delta \approx 0.07
\]

The values of $\epsilon$ and $\delta$ have some uncertainties, the largest being in the value of $\delta$.

We use this parametrization of $F_p(\beta, Q^2)$ as initial condition for QCD evolution.

Numerical calculations have been performed using the QCD evolution program of Devoto et al., Ajrenche et al. and Engel et al.

We present the results in an one-loop approximation but we have checked that practically the same results are obtained in two loops.
**EXPLICIT MODEL WITH THE CKMT PATTERN OF ENERGY BEHAVIOR:**

A. CAPELLA, E.G. FERREIRO, A.B. KADANLY, AND C.A. SALGADO

**QUARK-PARTON PICTURE**

The virtual photon $\gamma^*$ dissociates into a $q\bar{q}$ pair of size $\xi$ which has multiple interactions with the target.

- **Two kinds of $q\bar{q}$ pairs:**
  - $L \to$ LARGE SIZE CONFIGURATION
  - $S \to$ SMALL SIZE CONFIGURATION

**Complicated Non-Perturbative System $\to$ Regge Phenomenology**

$Q^2 \rho = \rho(2S, 0^2) \to$ Perturbative QCD

Applicable when $\xi \ll L$

$\xi_0 = 0.2 \ \mathrm{fm}$ (fit in agreement with the correlation length of non-perturbative interactions from lattice calculations)

It uses eikonal approximation with the standard Regge form for the singularities.

- Correct description of inelastic distortion of both real and virtual photons.
The gluon and quark in QCD are reggeized. Pomeron, Odderon and other colourless reggeons are composite states of the reggeized gluons. The Regge trajectories and couplings for gluons and quarks can be calculated with the use of an effective action. In the generalized leading logarithmic approximation the intercept for the contributions of diagrams with several reggeized gluons is expressed in terms of the ground state energy for the corresponding Schrödinger equation. In the multi-colour QCD this equation turns out to be completely integrable. The problem is reduced to finding the Baxter function satisfying the Baxter equation. It is shown, that this function is meromorphic and its residues satisfy a recurrent relation. The intercept for the composite state of the reggeized gluon is expressed in terms of
Beyond the Pomeron: Reggeized gluons and quarks.

Is it possible to hear the form of a drum? (Rae)
Yes, by the use of the spectral analysis.

Is it possible to establish if the "elementary" particle is elementary or not? (For example -iggs boson)
Yes, by measuring the Regge trajectory with the corresponding quantum numbers.

Are the gluons and quarks point-like particles?
Not, because they lie on the Regge trajectories.

\[ W(t) = g^2 \frac{d^2}{d^2} + g^4 \frac{d^4}{d^4} \]

\[ W(-x^2) = -\frac{N_c}{16\pi^2} \int \frac{d^2 k}{2\pi^2} \frac{d^2}{d^2} \]

\[ W_{BFKL} (1975) \]
\[ W_{Fadin+Kho} (1992) \]

What are their constituents? - Reggeized gluons and quarks

Is there a solution of the bootstrap equations?

\[ \chi = \sum \phi \phi \phi \phi \cdots \]
Integral of the reggeon interactions by $N^\infty$

Normalization conditions:

\[ \|7^5\|_1^2 = \sum_{k=1}^n \|\pi^k\|^2 \|\pi_{\bar{k}}\|^2 \|\pi_k\|^2 \|\pi_{\bar{k}}\|^2 < \infty \]

\[ \|7^5\|_2^2 = \sum_{k=1}^n \|\pi^k\|^2 \|\pi_{\bar{k}}\|^2 \left( \|\pi^k\|^2 + \|\pi_{\bar{k}}\|^2 \right) < \infty \]

Hermicity properties:

\[ \hbar = \Pi_{k=1}^n \hbar (\hbar \pi_{\bar{k}})^{-1} \]

\[ \hbar^T = (\hbar \pi_{\bar{k}})^{-1} \hbar \pi_{\bar{k}} \]

The integral of motion:

\[ [A, \hbar] = 0 \quad A = \Pi_{k=1}^n \pi_{\bar{k}} \]

Generating function for the integrals of motion:

\[ t^2(u) = t^2(\lambda^1(u), \lambda^2(u), \ldots, \lambda^n(u)) = \sum_{z=0}^n q_z u^{n-z} \]

transfer matrix

\[ q_0 = 2, \quad q_1 = 0, \quad q_2 = \frac{1}{\lambda^2}, \quad q_n = A \]

\[ L_k = \begin{pmatrix} u + \epsilon_k P_k - P_k \\ \epsilon_k P_k - u - \epsilon_k P_k \end{pmatrix} \]

\[ [t^2(u), t^2(v)] = 0 \quad \hat{t}^2(u), \hbar] = 0 \]

Monodromy matrix

\[ T(u) = L^1(u) L^2(u) \ldots L^n(u) = Y \]

Yang-Baxter equation.

\[ X = X \]

Bethe ansatz
Yang-Baxter equation, Bethe ansatz, Baxter equation

Monodromy matrix is parametrized as follows

\[
T(u) = \begin{pmatrix}
A(u) & B(u)

C(u) & D(u)
\end{pmatrix} = \frac{1}{u}
\]

Yang-Baxter equation:

\[
\frac{\partial}{\partial u} G(u,v,w) = \frac{\partial}{\partial v} G(u,v,w) = \frac{\partial}{\partial w} G(u,v,w)
\]

mean, bilinear commutator between \( A, B, C, D \)

Solution of the Y-B equation = Bethe ansatz

Faddeev, Khochemovsky (1979): \( \Theta_0 = 0 \), \( \Theta_0 \)-pseudovacuum state

\[
\Theta_0 = \begin{pmatrix}
\theta_{1}^{20}
\theta_{2}^{20}
\theta_{3}^{20}
\theta_{4}^{20}
\end{pmatrix}
\]

because \( \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \)

Algebraic Bethe ansatz:

\[
\Theta_0 = B(u_1) B(u_2) \ldots B(u_n) \Theta_0
\]

(Alp. Dv.) \( \Theta_0 = \Lambda(u) \Theta_0 \), \( \Lambda(u) \)-eigenvalue of \( T(u) \)

only if \( u_1, u_2, \ldots, u_n \) satisfy the Bethe equations

\[
(u_{2}+i)^{n} \prod_{t=1}^{n} \left( u_{2}+i-u_{t} \right) + (u_{2}-i)^{n} \prod_{t=1}^{n} \left( u_{2}-i-u_{t} \right) = 0
\]

then \( \Lambda(u) = (u+i)^{n} \prod_{t=1}^{n} \frac{u+i-u_{t}}{u-u_{t}} + (u-i)^{n} \prod_{t=1}^{n} \frac{u-i-u_{t}}{u-u_{t}} \)

Baxter function: \( Q(u) = \prod_{t=1}^{n} (u-u_{t}) \), \( m = k \) (nontrivial)

Baxter equation:

\[
\left( u_{1}+i \right)^{n} Q(u_{1}+i) + \left( u_{1}-i \right)^{n} Q(u_{1}-i)
\]

\[
\left( Faddeev, \text{Khochemovsky, } 1979 \right)
\]

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V(\lambda) \phi(\alpha) = (\lambda+i)^n \phi(\alpha+i) - 2\lambda^n \phi(\alpha) + (\lambda-i)^n \phi(\alpha-i)

V(\lambda) = \frac{m(m-1)}{\lambda^2} + \frac{c_2}{\lambda^3} + \ldots + \frac{c_h}{\lambda^h}, \quad m = \frac{1}{2} + \frac{\nu + \frac{n}{2}}{2}

Symmetry: \quad \phi_{k} \rightarrow (-1)^k \phi_{k}, \quad \lambda^n \phi(\alpha) \rightarrow (-\lambda)^n \phi(-\alpha)

Two solutions with the poles at \lambda = 0, +i, +2i, \ldots \quad \text{or at} \quad \lambda = 0, -i, -2i, \ldots

\phi_{e} \quad \text{and} \quad \phi_{o}

\phi(\alpha) = \sum_{n=1}^{\infty} \frac{c_n}{\lambda^n}, \quad c_n \text{ satisfy the recurrence relation}

The sum is convergent for \left| \frac{\alpha}{2} \right| < \frac{1}{2}

Zeros of \phi(\alpha) are situated on the imaginary axis between the poles

\phi(\alpha) = \prod_{k=1}^{n} \left( 1 + \frac{\alpha}{1 + i \frac{\alpha}{2}} \right)

Holomorphic energy:

\varepsilon = i \lim_{\lambda \rightarrow 1} \left[ \phi(\alpha-i \lambda^n \phi(\alpha)) \right]

The poles of \phi(\alpha) are a consequence of the complicated analytic properties of \pi(p, \rho, \phi, \ldots \lambda).

In \pi(p, \rho, \phi, \ldots \lambda), these poles are cancelled providing that \rho_2, \rho_3, \ldots \rho_h are quantized.
**Pomeron and Odderon in the \( \lambda \)-representation**

Pomeron odd function in \( \lambda \)-representation

\[
Z_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}) = \Phi_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}}) = \Phi_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}})
\]

\[
\lambda = \delta + i \frac{\pi}{2}
\]

- Quantization of the Baxter function

\[
Z_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}})
\]

**Odderon odd function in the \( \lambda \)-representation**

\[
Z_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}}, \vec{P}_{\lambda_{3}})
\]

\[
\Phi_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}})
\]

\[
X_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}})
\]

**Poles in \( \delta \)** in \( Z_{\lambda_{1}, \lambda_{2}}(\vec{P}, \vec{x}_{\lambda_{1}}, \vec{P}_{\lambda_{2}}) \) are cancelled.
Perturbative Radiation in Gap Events
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Rapidity gap events in the presence of hard scattering are one of the striking features of hadronic final states at HERA and the Tevatron. Although the formation of a gap cannot be a purely perturbative process, it must be consistent with perturbative analysis, where the latter applies. Examples include evolution in diffractive DIS structure functions, and the case considered here, the flow of energy, \( Q_\Omega \), into region \( \Omega \) of rapidity \( (\eta) \) and azimuthal angle \( (\phi) \) between two high-\( p_T \) jets. This cross section possesses a standard collinear factorization form.

\[
\frac{d\sigma_{AB \to J}}{dp_T dQ_\Omega} = f_{n/A} \otimes f_{h/B} \otimes \frac{d\hat{\sigma}_{ab}}{dp_T dQ_\Omega},
\]

with corrections of order \( \Lambda_{QCD}^2 / Q_\Omega^2 \), in terms of normal parton distributions \( f \), and hard-scattering functions \( d\hat{\sigma} \), where \( p_T \) stands for any fixed kinematic variables of the jet(s). The hard-scattering cross section itself may be refactorized into short-distance functions at the scale \( p_T \), and a cross section computed in eikonal approximation, into which all \( Q_\Omega \)-dependence goes.

\[
\frac{d\hat{\sigma}_{ab}}{dp_T dQ_\Omega} = \sum_{IJ} h^*_I(p_T, \mu') h_I(p_T, \mu') \sigma^{(\text{eik})}_{IJ}(Q_\Omega / \mu').
\]

The variable \( \mu' \) is an arbitrary factorization scale that separates the short-distance functions \( h \) and eikonal cross sections \( \sigma^{(\text{eik})} \), both of which are infrared safe. The indices \( I \) and \( J \) label the color exchange content of the short-distance functions.

The refactorization of the cross section (2) allows us to quantify the idea of color exchange [1]. As the refactorization scale \( \mu' \) changes, so does the color exchange. In this sense, Eq. (2) interpolates between “two-gluon exchange” and “soft color” models for gap formation. Radiation into \( \Omega \) is a result of evolution between the scales \( p_T \) to \( Q_\Omega \). This evolution is characterized by a set of anomalous dimension matrices, which depend on both \( p_T \) and the choice of \( \Omega \). In general, reactions involving gluons involve more radiation, and hence a lower gap fraction, that those involving quarks. This is consistent with comparisons of 630 and 1800 GeV data from the Tevatron.

An analysis of energy flow, rather than of multiplicity, leads to a constellation of predictions in terms of \( s \), jet \( p_T \) and rapidity, as well as \( Q_\Omega \) [2].

References


PQCD can help with:

- **Evolution** - as in $F_2^D$

- **Energy Flow**

$$\frac{d\sigma_{AB\rightarrow f}}{d\Omega} = f \otimes f' \otimes \frac{d\sigma}{d\hat{Q}_2^2}$$

energy into region $\Omega$

\[\Omega\]

$Q_\Omega$ distribution computable via factorization as long as $Q_\Omega \gg \Lambda_{QCD}$

c.f. Marchesini Webber 88

(brems. vs underlying event)

- **Same Applies to Factorized Diffractive Cross Section**

- **See How Short-time QCD 'ALLows' Gaps**
OSKETCH OF METHOD

• Cross section at measured $E_{\text{gap}} \gg \Lambda$
  is factorizable in standard way:

$$\frac{d\sigma_{AB}}{d\cos \theta_j dQ_c} (s, E_t, \Delta y) = \sum_{\text{Partons}} \phi_i/A \otimes \phi_j/B \otimes \frac{d\hat{\sigma}_{ij}}{d\cos \hat{\theta}_j dQ_c} (\hat{s}, \hat{t}, \Delta y, \chi_c(-\hat{t})) + \mathcal{O}(\Lambda^2/Q_c^2) \uparrow \text{partonic}$$

• For $Q_c^2 \ll -t$ but still perturbative
  separate two scales in the
  partonic cross section:

$$Q_c \frac{d\hat{\sigma}_{ij}}{d\cos \hat{\theta}_j dQ_c} = H_{\text{IL}}^{ij}(\hat{s}, \hat{t}, \mu, \alpha_s(\mu^2)) \uparrow \text{IL}$$

$I, L = \text{singlet}, \text{octet}...$

$\mu$: new factorization scale

defines color exchange $I, L$
  in hard scattering ($s$)

virtuality $< \mu$

Forward $y$

Backward $y$

virtuality $\gg \mu$
For any $\Omega$: $q\bar{q}: I, J$

$$\frac{\mu d S}{d\mu} \sim \sum_q^{n} \frac{\Omega_{k}}{k_{0} = \mu} \cdot \left( \frac{X_{k}}{X_{J}} \right)^{*} + \sum_{\Omega_{k}}^{n} \frac{\Omega_{k}}{k_{0} = \mu} \cdot \left( \frac{X_{k}}{X_{J}} \right)^{*}$$

As $\mu$ increases, these corrections shift from $S$ to $H$

$$\frac{\mu d S}{d\mu} = - \Gamma^{+}_{IK} \Omega_{k} \Delta S_{k, I} - \Omega_{I} \Gamma_{k, I}$$

$$\Gamma = \Gamma(\Omega, \theta^{*})$$

$$= \Gamma(\Omega, \theta^{*}) + \cdots$$
\[ \alpha = \frac{\partial}{\partial \ln \mu} \left( \frac{X^4 + X^2}{2} \right) \Omega^{\text{eik}} \]

\[ \beta = \frac{\partial}{\partial \ln \mu} \left( X^3 + X \right) \Omega^{\text{eik}} \]

\[ \gamma = \frac{\partial}{\partial \ln \mu} \left( X^4 + X^2 \right) \Omega^{\text{eik}} \]

\[ \Gamma_{q \bar{q}}^{\omega} = \left( \begin{array}{cc} C_F \beta & \frac{C_F}{2N_c} (\alpha + \delta) \\ \frac{C_F}{2N_c} (\alpha + \delta) & C_F \alpha - \frac{1}{2N_c} (\kappa + \beta + 2\delta) \end{array} \right) \]
\[
\frac{d\hat{\sigma}^{ij}}{d\cos\theta_d Q_c} = H_{ij}^{sss} \left( \frac{t}{\mu^2} \right) S_{i}^{ij} \left( \frac{Q_c}{\mu} \right)
\]

- Once we know evolution of \( S \) and \( H \), we can fix \( \mu^2 = -t \), and compute \( S(\frac{Q_c}{\mu}) \).

- Because \( \Gamma_{3, 1}, \Gamma_{1, 8} \neq 0 \), singlet/octet exchange do not evolve independently (unless \( s/t \to \infty \ldots ! \)) De Buca Tang

- Linear combinations of \( 1, 8 \) exchange do evolve independently \( \Gamma(\Delta g, \Delta g) \).

- Eigenvectors of \( \Gamma \) determine distribution of energy flow.

- Large eigenvalue \( \to \) high \( \Gamma \).
  Small eigenvalue \( \to \) low \( \Gamma \).

- Single-gluon exchange has projection onto 'small' eigenvalue color combination \( \Gamma \) as lowest order prediction of gap probability (perturbative.)
The HERMES Effect

G.A. Miller

What is the HERMES Effect?

Our Theory

Coherent Contributions of Nuclear Mesons to Electroproduction—HERMES Effect

Gerald A. Miller, S.J. Brodsky M. Karliner


What is the HERMES Effect?

CALLAN-GROSS relation severely violated \( \Rightarrow \) bosons are the partons!

**Mesons in nucleus!**
• Fitted values of $R_A/R_D$:

![Graph showing fitted values of $R_A/R_D$ for different $Q^2$ values with experimental data points from HERMES, HERMES(3He/D), NMC(C/D), and NMC(4He/D).]

• Conclusion:

$$R_A > R_D \text{ at } x < 0.06 \text{ and } Q^2 < 1.5 \text{ GeV}^2$$
\[ \mathbf{F}_1 = \frac{g_e}{2m_w} F^{\mu \nu} (w^\nu \partial_\mu \sigma - w_\mu \partial_\nu \sigma) \]

\[ J^\mu - \frac{g_e}{m_w} P^\mu w^0 F_v(Q^2) \]

Form factor

\[ q = ?? \]

\[ \text{BR} (\omega \rightarrow \pi^+ \pi^- \gamma) \leq 3.6 \times 10^{-3} \Rightarrow \frac{g^2 e^2}{s_{\pi}} \leq 2d \]

large

\[ \frac{8\pi^{\theta}}{A} \nu^3 (g\omega)^2 A^{1/3} F_v^2(Q^2) \]

harmonic oscillator

\[ \frac{\sigma_L(A)/A}{\sigma_L(0)/2} = 1 + \frac{Q^4}{\nu (\nu^2 + Q^2)} \frac{8\pi^{\theta}}{F_v^0 R_0} \]

\[ F_v(Q^2) \quad \text{from Itô & Gross or dipole} \]

\[ q < \text{Max} \quad \omega^0 \quad \text{from Wakamatsu model} \]
\[ \sigma_T = \frac{g_{\pi NN}}{2M_0} \left[ V^{\mu\nu} - \frac{1}{2} \left( V^{\mu\nu} - V^\nu \right) \right] \]
Summary

-27.5 GeV $Q^2$ HERMES

$O_{1}(A)$ enhanced by nuclear vector mesons
$O_{7}(A)$ depleted by nuclear scalar mesons

dynamics assumed consistent with nuclear binding, densities, Deep Inelastic Scattering (DIS) Ordway

Verification needed

Meson-$\gamma^*$ Interactions (many choices, I haven't explored) more exotic needed

Significant nuclear coherent production of $\pi$ Mesons (ITIT) $I=0$ pairs

$O_{7}(A)$ depends strongly on $x_1, Q^2, A$

see it effects at $x=0.1, 0.2, Q^2=0.56 GeV^2$

enhanced or

Can't rule out HERMES DATA with our theory -

Nuclear mesons may play unanticipated role - fundamental constituents at low $Q^2$
Unitarity corrections to the BFKL Pomeron

G. Korchemsky (Orsay)

1. Why does the BFKL Pomeron violate the unitarity?

2. Unitarization procedure in QCD:
   - "weak" unitarization
   - "strong" unitarization

3. Regge effective theory in QCD

4. Comparison with the dipole model
I. Onium–onium scattering at high energy

\[ q_1^2 \sim q_2^2 \ll s = e^Y \]

\[ \alpha_s \, \text{fixed, } \, \alpha_s \, \text{small} \]

Structure of the QCD corrections

\[ \sigma(s) = \sigma_{LO}(\alpha_s h s) + \alpha_s \sigma_{NLO}(\alpha_s h s) + \ldots \leq \text{const. } h_s^2 \]

**Leading order = BFKL approximation**

\[ \sigma_{LO} = \sum_{\text{rungs}} \frac{(\nu - 1) h_s^2}{(\pi \Gamma(3) \alpha_s N_c h_s)^\nu} \]

Leading log's comes from planar diagrams only

Large-$N_c$ limit reproduces correctly \[ \sigma_{LO}(\alpha_s N_c h_s) \]

**BFKL approximation = Dipole model = \sigma_{LO}**
I. Why the unitarity is broken to the leading order

- Two limits $\alpha_s \to 0$ and $b_s \to \infty$ do not commute

- Unitarity corrections become important as

$$Y \sim \frac{g}{\alpha_s b_s^{1/2}}, \quad \sigma_0 \sim \alpha_2 \sigma_{1/2}^{\mu \nu \rho}$$

- Unitarity corrections come from subleading corrections both in $\alpha_s$ and $\sigma_0$.

? Does the dipole model reproduce the QCD unitarity corrections? ...not obvious

? How to calculate unitarity corrections in QCD?

Feynman-Grigov theorem: "Unitarity constraints allow to reconstruct the loop diagrams out of the Born level graphs."

Unitarity constraint $SS^+ = 1$, $S = 1 + iT$

$$T - T^+ = iT T^+$$

QCD ansatz:

$$T_{\alpha\beta} = \cdots = \alpha_s T^{(3)} + \alpha_s^2 T^{(5)} + \cdots$$
Unitarity constraints
\[ T^{(a)} = (T^{(a)})^+, \quad T^{(b)} = (T^{(b)})^+; \ T^{(a)} (T^{(a)})^+, \ldots \]

- S-matrix in the BFKL approximation

\[ T^{(a)} = \begin{pmatrix} a_s T^{(a)} & i \frac{1}{2} (a_s T^{(a)})^2 \\ \end{pmatrix} \]

Reggeized gluon + multi-Regge kinematics

\[ S_{BFKL} = 1 + i a_s T^{(a)} + \frac{1}{2} (i a_s T^{(a)})^2 + 0 \]

BFKL Pomeron

\[ \mathcal{S} = \text{color charge} \]

\[ < \gamma_A \gamma_B | S_{BFKL} | \gamma_A \gamma_B > \]

\[ \text{BFKL Pomeron model in the Regge kinematics} \]

\[ \text{Unitarity is broken:} \]

\[ S_{BFKL} \neq 1 \]

Korchemsky \text{ correction in ACD:}

- Unitarization procedure in ACD:
  - Add the minimal set of corrections to \( S_{BFKL} \)
  - To restore unitarity
Unitarity constraints:

- "Weak": only in the main channels
- "Strong": in all energy subchannels $s_{ij}$

"Weak" unitarity

$$ S_{\text{BFKL}} = 1 + i (\alpha_s T^{(n)}) + \frac{1}{2} (i \alpha_s T^{(n)})^2 \rightarrow S_{\text{weak}} = \exp (i \alpha_s T^{(n)}) $$

Lowest order correction $\sim (T^{(n)})^4$

\[
= c_1 \left[ \alpha_s^2 e^{(\nu_4-1)Y} \right]^2 + c_2 \alpha_s^4 N_c^2 e^{(\nu_4-1)Y} \\
\text{double BFKL exchange} \quad \text{4 new 4-reggeon state}
\]

BKP equation

\[
= \sum_{n=4} \text{4 reggeon compound state} e^{(\nu_4-1)Y}
\]
- "Weak" unitarity corrections do not have a natural small parameter

- BFKL states are supplemented by higher \((N=1, 2, \ldots)\) reggeon compound states

- \(N\) reggeon states obey "extended" symmetry of integrable Heisenberg magnet

\[
\text{BFKL} + \text{weak unitarity} = \sum_{N_1 \ldots N_k} N_1 \ldots N_k \text{ Quantum Mechanic of } N=2, 4, \ldots \text{ reggeon compound states}
\]

"strong" unitarity

\[
\begin{array}{c}
\text{A} \\
\text{B} \\
\text{C} \\
\text{D} \\
\text{E} \\
\text{F} \\
\text{G} \\
\text{H} \\
\end{array}
\begin{array}{c}
\text{I} \\
\text{J} \\
\text{K} \\
\text{L} \\
\text{M} \\
\text{N} \\
\text{O} \\
\text{P} \\
\end{array}
\]

- Number of reggeons is not conserved
- Creation/annihilation of reggeons is allowed

- A new element of the effective theory: reggeon number changing vertices

\(V_2 \to 4, V_2 \to 6, \ldots\)
Explicit form

\[ V_{2\rightarrow 4} = - - \]

Lowest order correction

\[ \text{transition between } N=2 \text{ and } N=4 \text{ states} \]

\[ \text{triple BFKL vertex} \]

- Reggeon compound states start to interact

- Interaction is local in "time" $\tau$ and is conformal invariant

\[ \text{BFKL weak approximation} \xrightarrow{\text{unitarity of reggeon states}} \text{Quantum Mech.} \xrightarrow{\text{unitarity of interacting reggeon states}} \text{Effective field theory} \]

\[ 2 \]

\[ 1 \quad 2 \quad \ldots \quad 4 \]

\[ 4 \]
Calculation of triple BFKL vertex

\[
\begin{align*}
\text{BFKL states} & \quad \xrightarrow{\gamma} \quad \text{bfkl states} \\
\text{reggeon transition vertex} & \quad \xrightarrow{\gamma} \quad \text{bfkl states}
\end{align*}
\]

Feynman diagram representation

- Planar contribution agrees with the dipole model prediction
  - Mueller, Bielas, Navelet, Peschanski
- Emerging Regge effective theory is different from the dipole model
- Dipole model does not take into account
  - contribution of higher compound reggeon states
  - neglects nonplanar corrections to the effective vertices

[Beware of the AFS cancellation - planar contribution may be zero after all]
Effective Field Theory for the Small-$x$ Evolution

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Deep inelastic scattering in QCD

\[ \sum_{\text{hadrons}} q \gamma^* \]

Bjorken limit:
\[ \begin{align*}
Q^2 &\equiv -q^2 \to \infty \\
x &\equiv \frac{Q^2}{2pq} \text{ fixed}
\end{align*} \]

\[ W_{\mu\nu} = \left( \frac{q_\mu q_\nu}{q^2} - g_{\mu\nu} \right) F_1(x, Q^2) \]
\[ + \frac{1}{pq} (p_\mu - q_\mu \frac{pq}{q^2})(p_\nu - q_\nu \frac{pq}{q^2}) F_2(x, Q^2) \]

Optical theorem
\[ W_{\mu\nu} = \frac{1}{\pi} \text{Im} T_{\mu\nu} \]
\[ T_{\mu\nu} = i \int d^4z e^{izq} \langle p | T \{ j_\mu(z) j_\nu(0) \} | p \rangle \]

EFT for the small-\(x\) 26 June 2001
Emission of partons $\sim \rho$ (density)
Annihilation of partons $\sim \frac{\alpha_s}{Q^2}\rho^2$
(the amplitude of the annihilation of two partons in the cascade is $\frac{\alpha_s}{Q^2}$)

⇒

The equilibrium between emission and annihilation (saturation) should be described by simple non-linear equation

$$\frac{d\rho}{d \ln(1/x)} = \frac{N_c\alpha_s}{\pi} \left( K^{BFKL} \otimes \rho - const \times \frac{\alpha_s}{Q^2} \times \rho^2 \right)$$

EFT for the small-$x$  

26 June 2001
Small-$x$ DIS from the nucleon

Fast quark moves along the straight line $\Rightarrow$

quark propagator reduces to the Wilson line collinear to quark's velocity

$$\begin{align*}
U(x_\perp, \eta) &\equiv [\infty n_\eta + x_\perp, -\infty n_\eta + x_\perp] \\
[x, y] &\equiv \text{Pexp} \left\{ ig \int_0^1 dv (x - y)^\mu A_\mu (vx + (1 - v)y) \right\}
\end{align*}$$

EFT for the small-$x$ 26 June 2001
Non-linear evolution equation

\[ \frac{\partial}{\partial \eta} \mathcal{U}(x_\perp, y_\perp) = \]

\[ -\frac{\alpha_s N_c}{4\pi^2} \int dz_\perp \{ \mathcal{U}(x_\perp, z_\perp) + \mathcal{U}(z_\perp, y_\perp) - \mathcal{U}(x_\perp, y_\perp) \]

\[ + \mathcal{U}(x, z)\mathcal{U}(z, y) \} \frac{(x - y)_\perp^2}{(x_\perp - z_\perp)^2(z_\perp - y_\perp)^2} \]

\[ \mathcal{U}(x_\perp, y_\perp) \equiv \frac{1}{N_c} (\text{Tr}\{U(x_\perp)U^\dagger(y_\perp)\} - N_c) \]

LLA for DIS in pQCD \( \Rightarrow \) BFKL
LLA for DIS in sQCD \( \Rightarrow \) NL eqn
(s for semiclassical)

Example - LLA for the structure functions of large nuclei: \( \alpha_s \ln \frac{1}{x} \sim 1, \alpha_s^2 A^{1/3} \sim 1 \)
\[ \pi \to \partial_\perp^2 \pi \Rightarrow \]

\[ U^{\eta_A}(x_\perp) \otimes U^{\eta_A}_{\dagger}(y_\perp) = \int_{\Omega_{1,2}(\eta_0)=1} D\pi_1(z,\eta) D\pi_2(z,\eta) D\Omega_1(z,\eta) D\Omega_2(z,\eta) \]

\times \Omega_1^{\dagger}(x_\perp,\eta_A) U^{\eta_0}_{x} \Omega_2(x_\perp,\eta_A) \otimes \Omega_2^{\dagger}(y_\perp,\eta_A) U^{\eta_0}_{y} \Omega_1(y_\perp,\eta_A)

\times \exp \left\{ \int_{\eta_0}^{\eta_A} d\eta \int d^2z \left[ \sum_{g=1,2} \frac{1}{g} \sum_{i=1,2} \delta^2 \pi_i^a(z,\eta) (\Omega_i^{\dagger}(z,\eta) \frac{\partial}{\partial \eta} \Omega_i(z,\eta))^a 

- \frac{1}{4\pi} \pi_1^a(z,\eta) \delta^2 (\Omega_1^{\dagger}(z,\eta) U^{\eta_0}_{z} \Omega_2(z,\eta))^a_{\Omega_2} \pi_2^b(z,\eta) \right] \right\} \]

The action is now local.

Perturbation theory

\[ \Omega_1(z,\eta) = e^{-ig\phi_1(z,\eta)}, \quad \Omega_2(z,\eta) = e^{-ig\phi_2(z,\eta)} \]

Propagators:

\[ \phi_i^a(x_\perp,\eta) \pi_j^b(y_\perp,\eta') = -i\delta_{ij}\delta^{ab}\theta(\eta - \eta')(x_\perp | \frac{1}{\partial_\perp^2} | y_\perp), \]

\[ \phi_i^a(x_\perp,\eta) \phi_j^b(y_\perp,\eta') = 0, \quad \pi_i^a(x_\perp,\eta) \pi_j^b(y_\perp,\eta') = 0 \]
After integration over canonical momenta $\pi_i$

\[
U^{\eta_A}(x_\perp) \otimes U^{\dagger \eta_A}(y_\perp) \\
= \int_{\Omega_{1,2}(\eta_0)=1} D\Omega_1(z,\eta) D\Omega_2(z,\eta) \Omega_1^{\dagger}(x_\perp,\eta_A) \\
\times U^{\eta_0}(x_\perp) \Omega_2(x_\perp,\eta_A) \otimes \Omega_2^{\dagger}(y_\perp,\eta_A) U^{\dagger \eta_0}(y_\perp) \Omega_1(y_\perp,\eta_A) \\
\times \exp \left\{ -\frac{1}{\alpha_s} \int_{\eta_0}^{\eta_A} d\eta \int d^2z [\partial^2_\perp(\Omega_{1}^{\dagger}(z,\eta) U^{\eta_0}_z \Omega_2(z,\eta))]_{ab}^{-1} \\
\times \partial^2_\perp(i\Omega_{1}^{\dagger}(z,\eta) \dot{\Omega}_1(z,\eta))^a \partial^2_\perp(i\Omega_{2}^{\dagger}(z,\eta) \dot{\Omega}_2(z,\eta))^b \right\},
\]

where $\dot{\Omega} \equiv \frac{\partial}{\partial \eta} \Omega$

The action is local (and real). Given the initial conditions

\[
\langle p_B | U^{\dagger \eta_0}(zx_1) U^{\dagger \eta_0}(z_2) \ldots U^{\dagger \eta_0}(z_n) | p_B \rangle,
\]

this functional integral can be calculated.
Summary of the talk Direct Solutions to Kovchegov Equation
Leszek Motyka, Uppsala and Kraków

The Kovchegov equation describes the evolution of the color dipole density in an onium state and is capable to include multiple scattering of the dipoles off the target. It is compatible with QCD in the leading logarithmic log(1/x) approximation and large Nc limit. It may be viewed as a minimal extension of the BFKL equation in which the unitarity of the scattering amplitude is preserved. Therefore the properties of the equation and the applications in the high energy phenomenology call for a detailed study. Besides that I want to test whether the solutions of Kovchegov equation are able to explain the recently reported phenomenon of geometric scaling in $\sigma(\gamma p)$.

I focus on the Kovchegov equation for small dipoles and for the cylindrical nucleon, which has a particularly simple form

$$\frac{\partial \hat{N}(k, Y)}{\partial Y} = \alpha_s K_{BFKL} \left( 1 + \frac{\partial}{\partial \log k^2} \right) \hat{N}(k, Y) - \alpha_s [\hat{N}(k, Y)]^2$$

(1)

where

$$K_{BFKL}(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1 - \gamma), \quad Y = \log(1/x)$$

(2)

Now I substitute

$$n(k, Y) = \frac{\hat{N}(k, Y)}{k^2}$$

(3)

which reduces the equation to the BFKL-like form. This equation was solved numerically by the discretization method with the use of set of orthogonal polynomials. The nonlinear term has is local in k which makes it straightforward to generalize the standard method used in the linear case. After the discretization one obtains a set of nonlinear differential equations of the first order. The initial condition function is usually assumed to be defined by the Glauber-Mueller Ansatz.

I demonstrate that the unintegrated gluon distribution $f_g(k, Y)$ may be obtained from the solution $\hat{N}(k, Y)$ by the following formula

$$f_g(k^2, Y) = \frac{35T}{4\pi^2\alpha_s} k^4 \Delta_k \hat{N}(k, Y)$$

(4)

with $\Delta_k$ used for the 2-dimensional Laplace operator in the k space.

I consider both the fixed and running $\alpha_s$ in the Kovchegov equation. The running coupling (RC) constant case is particularly interesting because the BFKL equation with RC requires an explicit infra-red cut-off (about 1 GeV) due to the Collins-Kwiecieński bound for the BFKL pomeron intercept. In the Kovchegov equation the cut-off may be lowered substantially without loosing the stability of the equation. This happens because the growth of the gluon density at low $k^2$ (and successively for all k) is tamed by the nonlinear term - the infrared cut-off is now generated by the equation itself. However, the evolution in x is still to rapid and the resulting gluon distributions for low x is by order of magnitude too large in comparison with the existing parametrisations. The potential source of the failure is probably the missing non-leading corrections to the BFKL part of the kernel which would slow down the evolution. The approximate geometric scaling is found to hold for $x < 0.01$.

I also study the Kovchegov equation with $\alpha_s$ fixed to 0.1 in order to guarantee the evolution to be slow. The solving function in the low x region may be approximately expressed as

$$\hat{N}(k, Y) \sim \log(1 + (Q_s/k)^\beta)$$

(5)

with the saturation scale $Q_s(x)$ growing towards small x as $x^{-0.2}$ and $\beta \sim 1.5$. The solutions is also consistent with the geometric scaling, however it is different from the Glauber-Mueller input and therefore from the corresponding distribution from the Golec-Biernat–Wüsthoff model. The gluon following from the solution agrees reasonably with the accepted parametrisations. The amount of shadowing is investigated by comparing the gluon from the nonlinear and linear equation. It is found, that the shadowing corrections for the gluon are at the level of 30% for $x \simeq 10^{-4}$ and $10^{-2}$ for $Q_s^2 = 100, 10$ and 1 GeV$^2$, respectively.

As the main conclusion we confirm, that a reasonable phenomenology may be constructed on the basis of the Kovchegov equation with a small coupling constant and that the nonleading corrections should be included for the equation with the running coupling constant.
Solution to Kovchegov equation for fixed $\alpha_0 = 0.1$
and $Y = 0, 2, 4, \ldots, 16$

\[ N(k, Y) \sim \log(1 + (Q/k_T)^\beta) \]

\[ Q^2 \sim Q_0^2 \exp(\alpha Y) \]

$\alpha \sim 0.4 \quad \beta \sim 1.5$
Test of geometric scaling for fixed $\alpha_s = 0.1$

Scaling variable: $t = k_T \exp(-0.2Y)$

All $Y$, all $k_T$

$Y > 4$, all $k_T$
Gluon from Kovchegov equation with $\alpha_s = 0.1$
Shadowing from Kovchegov equation with $\alpha_s = 0.1$
Comparison of solutions with running and fixed $\alpha_s$ at high $Y$
Total and differential cross sections for high energy and small momentum transfer elastic hadron-hadron scattering are studied in QCD using a functional integral approach. The hadronic amplitudes are governed by vacuum expectation values of lightlike Wegner-Wilson loops, for which a matrix cumulant expansion is derived. The cumulants are evaluated within the framework of the Minkowskian version of the model of the stochastic vacuum. Using the second cumulant, we calculate elastic differential cross sections for hadron-hadron scattering. The agreement with experimental data is good.

We calculate high-energy photoproduction of the tensor meson $f_2(1270)$ by odderon and photon exchange in the reaction $\gamma + p \rightarrow f_2(1270) + X$, where $X$ is either the nucleon or the sum of the $N(1520)$ and $N(1535)$ baryon resonances. Odderon exchange dominates except at very small transverse momentum, and we find a cross section of about 20 nb at a centre-of-mass energy of 20 GeV. This result is compared with what is currently known experimentally about $f_2$ photoproduction. We conclude that odderon exchange is not ruled out by present data. On the contrary, an odderon-induced cross section of the above magnitude may help to explain a puzzling result observed by the E887 experiment.

E. Berger, O. N. hep-ph/9808320
E. Berger et al. hep-ph/0001270
H. Dosch et al. P.R. D50, 1992 (94)
1 Introduction

- Ideas on non-trivial vacuum structure of QCD
  (Savvidy '77, Shifman, Vainshtein, Zakharov '78, Shuryak, Nielsen, Ambjorn, Oleson, ...)
  spaghetti-vacuum, instanton vac. ...

- Consequences for high-energy scattering?
  (Ellis, Guillard, Zakrzewski '79, Doria, Frenkel, Taylor '80, Reiter, O.N. '84)

  • soft hadronic reactions
  • hard reactions: Drell-Yan process
  • soft photons in hadronic reactions
  • electromagnetic form factors of hadrons at small $Q^2$
Scatt. ampl. \propto W(C_+) W(C_-) - 1

\[ W(C_{\pm}) = \text{Tr} \ \text{Pexp} \left[ -ig \int dx^\mu G_\mu(x) \right] \]
\[ M_1(P_1) + M_2(P_2) \rightarrow M_1(P_3) + M_2(P_4) \]

\[ \tilde{T}' = -2i \times \int d^2b_T e^{i\frac{\vec{Q}_T}{b_T}} \]

\[ \int d^2x_T d^2y_T \omega_1(\vec{x}_T) \omega_2(\vec{y}_T) \]

\[ \left\langle W_+ \left( \frac{1}{2} \vec{b}_T, \vec{x}_T \right) W_- \left( -\frac{1}{2} \vec{b}_T, \vec{y}_T \right) \right\rangle \]

-1

Gluon average

- Scattering amplitude

\sim \text{correlation function of lightlike Wegner Wilson loops}
$\frac{d\sigma}{dt}$ in $\text{mb/GeV}^2$

$pp: \sqrt{s} = 23 \text{ GeV}$
$S_p = 0.87 \text{ fm}$

Proton structure: quark - diquark
<table>
<thead>
<tr>
<th>parameter</th>
<th>lattice calc., quenched</th>
<th>SVM stat. pot.</th>
<th>high energy scattering</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\text{string tension})^{\frac{1}{2}}) (\sqrt{s}) / MeV</td>
<td>420</td>
<td>415</td>
<td>435</td>
</tr>
<tr>
<td>gluon cond. (G_2^{1/4}) / MeV</td>
<td>486 ± 6</td>
<td>486</td>
<td>(529)</td>
</tr>
<tr>
<td>non abelian par. (\alpha)</td>
<td>0.89 ± 0.02</td>
<td>0.89</td>
<td>0.74</td>
</tr>
<tr>
<td>correlation length (\alpha / \text{fm})</td>
<td>0.33 ± 0.01</td>
<td>0.33</td>
<td>0.32</td>
</tr>
</tbody>
</table>

\[\text{---} : \text{input}\]
The Instanton/Sphaleron Mechanism
of High Energy Hadronic and Heavy Ion Collisions

Edward V. Shuryak
Department of Physics and Astronomy
State University of New York, Stony Brook, NY 11794-3800

We argue that if the growing part of hadron-hadron cross section (described phenomenologically by the $\alpha(0) - 1$ of soft Pomeron) is due to instanton/sphaleron mechanism, as suggested recently. In essence, if the parton collisions happens nearby tunneling event (described semiclassically by instantons) some wee partons can be absorbed by it. The resulting field configuration is close to sphaleron-like spherically symmetric gluomagnetic cluster, which then explodes into several gluons.

New element of the talk is discussion of quark effects. We conjecture that sphaleron decay should go into the same hadronic states as do instanton-induced decays of of $J^P = 0^+, 0^-$ colorless objects: (i) the scalar glueball candidate $f_0(1710)$ who decay mostly into $\eta, \eta$ and $KK$; or (ii) as suggested by Bjorken, $\eta \rightarrow KK\pi, eta\pi, eta'\pi$. Common signature of these final states is unusually large fraction of “delayed pions” coming from $\eta, eta', KS$ decays. This correlates well with experimentally observed but unexplained decrease of HBT correlation parameter $\lambda$ from its usual value $\approx 0.5$ to $\approx 0.2$ in high multiplicity events.

Instanton mechanism should be even more important for high energy heavy ion collisions in the RHIC energy domain, where it is no longer a rare process, due to very large number of parton-parton collisions. We predict production of of the order of a hundred produced sphalerons per unit rapidity. Unlike perturbative gluons (or mini-jets), these classically unstable objects promptly decay into several gluons, quarks and antiquarks, leading to very rapid entropy generation. This may help to explain why the QGP seem to be produced at RHIC so early. We further argue that this mechanism cannot be important at higher energies (LHC), where the relevant scale is expected to go above 1 GeV and the perturbative description should apply.
Instanton/sphaleron mechanism
of high energy hadronic and heavy ion collisions
E.V. Shuryak
SUNY Stony Brook

- Introduction: the "substructure scale"
- Instanton liquid, properties, counting rules
- Elastic scattering
- Inelastic scattering: multi-gluon production, unitarization
- Evaluating Soft Pomeron parameters, $\Delta, \alpha'$
- The Sphaleron and its decay
- Instanton/sphaleron mechanism for heavy ion collisions at RHIC

- Sphaleron + (fermions from 't Hooft vertex)
  - What are hadronic final states?
  - Do they have special features?
  - Can those be found experimentally
Qualitative Pictures

Quark moves through the instanton vacuum. (Note: Sea quarks are opposite in flavor and chirality!) and becomes a constituent quark, $m_{\text{eff}} \approx 400$ MeV.

If 2 partons collide, \[ \Rightarrow \]
Instantons transform some of their field into a different form which is called a sphaleron

Two quarks collide near the instanton

Low energy \[ \rightarrow \nu_L \]

Optimal energy

High energy

At zero energy, instantons cannot produce $\rho$, $E^2 = B^2, E \cdot B = 0$

"Unitarization" (a la Shifman, Nair, \textit{et al.})

\[ \rho \rho \rightarrow \rho \rho + \rho \rho \rho \rho + \cdots \]
• What the instanton-induced clusters should look like? (in NN, not AA)

\[ J^P = 0^+, 0^- \text{ but not } 2^+ \]

\[ (G^i), (G^i) \]

large for instanton \( \to 0 \) for instanton fic

• Color \( 8 \otimes 8 \), even if multi-gluon processes zero actually both gluons \( \in \) to one SU(3) \( (NSG) \)

\[ 3 \otimes 3 = 1 + \bar{3} + 5 \]

\[ J^{PC} = 1^+ \]

For color singlet we have phenom. info:

\[ 0^+ \]

\[ J/\psi + (gg) \]

\[ (G^i), (G^i) \]

scattered glueball

• Prominent resonance (Mark III) with very strong coupling to \( \eta \eta \) large \( KK \) large \( \pi \pi \) seen but small

\[ \eta_c \] is especially interesting

\[ N_c \]

J. Bjorken, hep-ph/01

• All multiparticle modes, except the following 3:

\[ \eta \eta \pi \pi \{ \eta \eta \}\]

\[ (u\bar{u}) (d\bar{d}) (s\bar{s}) \]

Fits to 4' 't Hooft Lagrangian
• Is there any special signature of instanton-induced clusters? (Distinct from mini-jets?)
• If so, can it be observed?

Yes
• Presence of SS and strong dominance of PS meson leads to KK, or $\gamma'$, $\gamma$
• All of them lead to delayed pions
  $K_s K_s \rightarrow \pi \pi \quad \gamma \rightarrow 3\pi \quad \gamma' \rightarrow \pi \pi \pi \pi \rightarrow 5\pi$

Unable to participate in HBT correlations with promptly produced pions! Prob(delayed $\pi$) $\approx 0$

For comparison: In the usual string breaking
there are also produced, but much less prominently

$\text{Prob (delayed } \pi \text{) } \approx 0.3 \quad \leftrightarrow \quad \lambda_{\text{HBT}} = (1 - 0.3)^2 \approx 0.5$

G.d.m. significantly from $\omega \rightarrow 3\pi$

Indeed observed in the usual pp, heavy ions, etc. Always the same!

So, let us look at $\lambda_{\text{HBT}}$ as multiplicity goes up

From Buschbeck et al
hep-ex/0003029

Huge effect has been seen already?
(no other explanation???)

$\lambda = 0.2$ means $\text{Prob(delayed } \pi \text{) } = 0.55$
Phenomenological Summary

Mini-jets vs Instanton-induced Clusters

- In hh'
  - Both can explain growth of $\sigma(s)$, multiplicity size
  - Mini-jets can be looked for as clusters in $(\Theta, \Phi)$ statistically ...
  - Instanton-induced clusters, $M = 2.5-3$ GeV, isotropic $\Delta y \sim 1$, $\Delta \Phi \sim 2\pi$
  - Mini-jets are expected to fragment as string fragments
    - Standard $\lambda \approx 0.5$ and standard $\eta'/\pi$, $\eta'/\pi$, $\eta$, $\kappa$
    - Enhanced $\eta', \eta, \kappa$, $\lambda_{HBT}$ decreases, as observed!

- In AuAu etc
  - Both can explain multiplicity growth, and why there appears new component at RHIC $\sim N_{coll}(A)$
    - Instead of $\sim N_{part}(A)$
  - Mini-jets with a cutoff from pp fit (HIJING) lead to $\frac{dy}{dy}$ ~ 200 mini-jets (central AuAu at RHIC)
    - It is not enough for collective effects and jet quench
  - Instanton-induced reactions (into QGP, no hadrons, with similar cross section)
    - Leads to much higher entropy!
    - And may solve quark production problem
Classical Gluon Production in Hadronic Collisions

Gregory W. Carter

Department of Physics and Astronomy, SUNY Stony Brook, NY 11794-3800.

Abstract

The instanton liquid model of the QCD vacuum has been rather successful in describing low-energy phenomenology. Recent work suggests these localized, classical solutions of the gauge field play a role in the semi-hard processes relevant to hadron-hadron and heavy ion collisions. Specifically, the high-energy growth in inelastic partonic cross sections might be due to partons probing instantons. Excited by the energetic partons, an instanton may be transformed from a Euclidean vacuum tunneling event into a color magnetic configuration which sits atop the barrier – a sphaleron – and decays into perturbative gluons.

We have derived and solved the field equations for the initial sphaleron state and, drawing from work done on electroweak sphaleron decays, estimate its decay will produce roughly 6 gluons after a time of 1.5 fm/c.

Based on work done in collaboration with E. V. Shuryak.
THE INITIAL STATE

A STATIC, UNSTABLE CLASSICAL SOLUTION:

AS THE SPHAERON ROLLS DOWN THE HILL TO $V_1$, IT DECAYS INTO GLUONS.

TOPOLOGICAL CHARGE:

$$Q_{\text{LIE}} = \pm 1$$

$$Q_{\text{SPH}} = \pm \frac{1}{2}$$
THE STATIC, CLASSICAL SOLUTION:

USING WITTEN'S NOTATION [PR 38 (1977) 121.]

\[
A^a_0 = \frac{x^a}{r} A_0
\]

\[
A^a_j = \frac{1 + \phi^2}{r^2} \varepsilon_{jak} x_k + \frac{\phi}{r^3} \left( \delta_{ij} r^2 - x_a x_j \right) + A_i \frac{x^a x_j}{r^2}
\]

ONE HAS

\[
S = -\frac{1}{4i} \int d^4 x \, F^2
\]

\[
= -8\pi \int_0^{\alpha} d\tau \int_0^{\sigma} dt \int_0^{\pi} d\theta \int_0^{2\pi} d\phi \left[ \frac{1}{2} r^2 F_{\mu\nu}^2 + \frac{1}{2} (D_\mu \phi_i)^2 + \frac{1}{4r^2} \left( 1 - \phi_1^2 - \phi_2^2 \right)^2 \right]
\]

\[
\mu, \nu = 0, 1 \quad i = 1, 2 \quad D_\mu \phi_i = \partial_\mu \phi_i + \varepsilon_{ij} A_\mu \phi_j
\]

\[
F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu
\]

SIMILAR TO 2-D ABELIAN HIGGS.

FOR A COLOR MAGNETIC SOLUTION, WE CONSIDER

\[
A_0 = A_1 = \phi_i = 0, \quad \partial_0 \phi_2 = 0
\]

AND SOLVE FOR \( \phi_2 \) IN 1+1 D.
TIME EVOLUTION

OUR SOLUTION RESEMBLES THAT OF
KLINHÄMER + MANTON PRD 30 (1984) 2212
FOR ELECTROWEAK PHYSICS.

DECAY WAS STUDIED BY ZADROZNY PLB 204 (1988) 11

THE SPHALERON EXPANDS AS A SHELL;
FREE FIELD BEHAVIOR IS EVENTUALLY
OBSERVED $\Rightarrow W^\pm, Z, \text{AND HIGGS BOSONS.}$
Comparing our result with the electroweak, we can estimate $N_{\text{gluons}}$

**Energy (calculated numerically)**

$$E_{\text{EW}} \approx 10^8 \text{ MeV}$$

$$E_{\text{QCD}} = 63 \frac{\text{MeV}}{\text{fm}}$$

**Particle Numbers**

$$N_{\text{EW}} = 51 \approx \frac{1}{2} \frac{E_{\text{EW}}}{M_{\text{W}}}$$

So

$$N_{\text{gluons}} \approx \frac{1}{2} \frac{E_{\text{QCD}}}{m}$$

$$N_{\text{gluons}} \approx 5 - 6$$

**Decay Time**

$$\tau_{\text{EW}} \approx 4.5 \text{ fm}^{-1}$$

$$\leq \tau_{\text{QCD}} \approx 4.5 \text{ fm}^{-1}$$

$$\tau_{\text{QCD}} \approx 1.5 \pm 0.5$$
NOW WE SPECULATE:

HOW MANY IN A-A COLLISIONS?

\[
\frac{dN_{\text{prompt}}}{dy} \approx 200
\]

SHURYAKOV MAXIMAL ESTIMATE FOR CENTRAL COLLISIONS AT RHIC

TOTAL GLUON PRODUCTION:

\[
\frac{dN_{\text{gluons}}}{dy} \approx 1000
\]

THIS, AN ESTIMATE OF THE MAXIMUM PRODUCTION FROM THE SPHALERON MECHANISM, IS IN LINE WITH THE RHIC DATA.

THUS OUR ESTIMATES SUGGEST THAT THE DECAY OF TOPOLOGICAL OBJECTS IN QCD MIGHT PLAY A ROLE IN GLUON PRODUCTION IN HIGH-ENERGY COLLISIONS.
Saturation 101 (Discussion: Thursday, 5/24/01)

\[ \sigma_{g^*g^*} \approx \int d^2x_1 \, dz \, \phi^{g^*g^*g^*g^*}(x_1, z) \cdot \Delta_{g^*g^*} (x_1, w^2) \]

At very high \( w^2 \) the cross sections saturate.

The transition is described by "saturation scale" \( g_s \).

\[ Q_s^2(w^2, A) \sim (w^2)^{(d_f - 1)/3} \, A^{1/3} \gg A_{QCD}^2 \]
What does this mean for gluon distributions?

$\frac{\partial \rho_0(k)}{\partial k_t}$

$Q_s^2$ 

$\Lambda_{QCD}^2$

$\frac{k_t \rho_0}{Q_s^2}$

$\Lambda_{QCD}^2$

$Q_s^2$

$\Rightarrow$ Most gluons have $k_t \sim Q_s \gg \Lambda_{QCD}$ thus the gluon distribution is insensitive to non-perturbative region, and $d_s(k_t \sim Q_s) \ll 1$ allowing us to calculate things analytically from first principles QCD!

$\Omega \frac{1}{x}$

$Q_s^2(x)$

$\uparrow$ BFKL

$\rightarrow$ DGLAP

$Q^2$
Experimental signals of (no) saturation at HERA (et al).

$\Rightarrow$ All small-$x$ and small-$Q^2$ data could be described by saturation models (as well as by DGLAP and/or Pomeron). The difference is that unlike DGLAP-based approach saturation does not assume much about non-perturbative region and unlike Pomeron/Reggeons is QCD-based.

1. DGLAP-based fits work, but usually have \( x G(x, Q^2 \sim 1 \text{GeV}^2) \lesssim 0 \). \( Q_s = Q_s(W^2) \)?

Is this good / consistent / reasonable?

2. Saturation predicts \( F_2 \sim Q^2 R^2 \ln \frac{1}{x} \) (small $x$, small $Q^2$)

(i) With diffusion \( F_2 \sim (R + a \ln \frac{1}{x})^2 \ln \frac{1}{x} \sim \ln \frac{3}{x} \)

(other models? hard to distinguish ... ?)

D. Keidt

has a parameter

maybe not unique (?)

223
(12) \( F_2 \sim Q^2 \), \( \frac{2F_2}{\Delta A Q^2} \sim Q^2 \) (small \( Q^2 \))

\( Q^2 < Q_s^2 \)

gauge invariance?

vector mesons?

\( \sim W^2 (e^{-1}) \)

in saturation the region \( Q^2 < Q_s^2 \sim A^{1/3} \) unlike?

need an \( QA \) collider?

(3) Diffraction: \( \frac{\sigma_D}{\sigma_{\text{tot}}} \sim \text{const.}(W^2) \)

\( \frac{\sigma_D}{\sigma_{\text{tot}}} \) fixed \( Q^2 \)

Saturation: \( \sigma_D \sim \int \frac{dx}{x} \left( \frac{x^2}{x_s^2} \right)^2 \sim \left( \frac{x}{x_s} \right)^2 \sim x \xi \)

\( \xi \sim Q_s^2 \sim x \xi \)

as \( Q_s^2 \sim x \xi \)

since \( \sigma_{\text{tot}} \sim x \xi \ln \frac{Q^2}{Q_s^2} \Rightarrow \)

\( \frac{\sigma_D}{\sigma_{\text{tot}}} = \frac{1}{2 \ln \frac{Q^2}{Q_s^2}} \)

Simple explanation of GBW fit.
4. \( \frac{d\sigma^D}{dM_x^2} \) predicts leveling off or even a turnover at high \( W^2 \) at lower (but still large) \( M_x^2 \).

5. \( \frac{\sigma_L}{\sigma_T} \) saturates prediction.

6. Saturation \( \Rightarrow \) strong gluonic fields \( A_n \sim \frac{1}{g} \)

→ strangeness enhancement in both \( pA \) and \( AA \)

\( \text{NA49} \quad \text{NAS0} \)

even in \( pp \) (with large multiplicity \( \Rightarrow \) extreme conditions)

→ \( J/\psi \) production/suppression

\( m_{c} \sim 1.5 \text{ GeV} \quad m_{J/\psi} \sim 36 \text{ GeV} \)

\( Q_{s}^{2} \sim z_{c} \text{ GeV}^{2} \)
4. Scaling: \( \sigma = \sigma \left( \frac{Q}{Q_0(w^2)} \right) \) (Motyka's talk)

8) Slope of vector meson production

Shrinkage of diffractive peak

\( \sigma^p \) does not vanish at large \( Q^2 \).
Summary of the Discussion on Pomeron Physics Program at RHIC

Summary by Wlodek Guryn, BNL

(Discussion leader Dima Kharzeev, BNL)

The general questions for the discussion were:

1. What (if any) are the fundamental physics questions that make diffractive interactions at high energies worth studying?

2. What (if any) are the measurements that can be done at RHIC to address these questions?

3. How (if at all) will the measurements with p1p1, pA, AA advance the field?

At present the diffraction studies at RHIC are focused around pp2pp experiment. Some of the questions are addressed in the approved physics program of the pp2pp experiment. Some, like central glueball production, could be addressed by combining the Roman pots of the pp2pp experiment with the existing HI RHIC detectors. A dedicated study of this was strongly endorsed by the workshop participants.

In the following are specific questions and the summary of the discussion.

1. What is the high energy asymptotics of strong interactions: does it satisfy Froissart-Martín bound, which requires that \( \sigma_{\text{tot}} < \pi/m^2 \log^2 s \)?

The most popular fit to the present data shows that \( \sigma_{\text{tot}} \) grows like \( s^\Lambda \), violating Froissart-Martín bound. One of the reasons why the simple parametrization \( \sigma_{\text{tot}} \sim s^\Lambda \) is successful describing data is poor accuracy of high-energy points. It is important to point out that even though there are higher energy data available from Tevatron at \( \sqrt{s} = 1800 \) GeV, the two existing data points differ significantly enough so that the ambiguity in terms of asymptotic behavior of total cross sections persists. In short there is a great need for accurate pp data from RHIC. Given that maximum \( \sqrt{s} = 500 \) GeV at RHIC, which is in the range where one expects that \( \sigma_{\text{tot}} \) is measurably different from \( \sigma_{\text{tot}} \), a very precise measurement of both \( \sigma_{\text{tot}}(pp) \) and \( \rho \) parameter may reveal that a different functional form is needed for the fit, which could ultimately satisfy Froissart-Martín bound.

2. What is the difference between high-energy interactions of particles and antiparticles? The Pomeranchuk theorem predicts that asymptotically, with increasing energy the total cross sections for particle-particle and particle-antiparticle converge to be the same. Odderon question?
As mentioned earlier RHIC energy range in where a sizable difference between pp and pp interaction exists. So it is the best place to study those differences, which are expected to show in the shape of differential cross section, especially in the dip region where the contribution of the Odderon exchange, the C odd partner of the Pomeron, is expected to show up. In addition cross sections for meson (photon) and nucleon – nucleus scattering can be studied as important part of the program of hadron-hadron interactions.

3. How does the range of strong interaction depend on energy? What is the size of the gluon cloud around the nucleon? How does it show in the slope of the Pomeron trajectory?

This question is studied at RHIC by measuring the energy dependence of \( \sigma_{\text{tot}}(pp) \), \( d\sigma/dt \), \( d^2 \sigma_{\text{diff}}/dtd\phi \). Also in the polarized proton elastic scattering the hadronic spin-flip will be measured by measuring analyzing power \( A_n(t) \) in the Coulomb Nuclear Interference (CNI) region.

4. What is the high parton density, high color strength asymptotic behavior of strong interactions?

These questions can be addressed by studying diffraction in pp, pA (p+ A?), AA, \( \gamma A \), "Meson"A collisions. This area of research is unique to RHIC because of its energy range and ability of using variety of colliding beams. However a detector in addition to Roman pots of pp2pp experiment to detect production of \( J/\Psi \), \( \eta_c \) and other open charm particles would be needed. Also inclusive cc production with polarized proton beams could provide answers to the question.

5. Is the proton polarization transferred to the “wee” coherent gluon field?

The following measurements, which can be done uniquely at RHIC, will address the above question.

- Spin asymmetries in pp elastic scattering.
- Azimuthal correlations in \( p^+ p^- \rightarrow pp + X \), where \( X = \Lambda \Lambda \), a self analyzing channel or investigating spectroscopy of \( X \), in particular where \( X \) is a glueball.

6. What traces the baryon number (B) in high-energy interactions?

Few mechanisms of baryon number (B) transfer over large rapidity interval compete. The B of the projectile can be transferred to the central rapidity region either by a diquark, a valance quark or even by gluons. Available data for pp collisions from the ISR at CERN are limited by \( \sqrt{s} = 62.8 \) GeV. New data at much higher energies are desperately needed to clarify relative role of different mechanisms. Good understanding of this dynamics is vital to our understanding of baryon stopping mechanism in heavy ion collisions.
Following is a table summarizing the discussion:

<table>
<thead>
<tr>
<th>Physics Question</th>
<th>Can RHIC answer this question?</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What is the high-energy asymptotics of strong interactions: does it satisfy Froissart bound requiring that $\sigma_{\text{tot}}&lt;\frac{\pi}{m_{\pi}^2}\log^2 s$? How about the unitarity of the total cross-sections?</td>
<td>Maybe</td>
<td>Given Tevatron data, surprise is possible. pp2pp experiment</td>
</tr>
<tr>
<td>2. What is the difference between high-energy interactions of particles and antiparticles?</td>
<td>Yes</td>
<td>pp2pp experiment</td>
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<td>3. How does the range of strong interaction depend on energy? What is the size of the gluon cloud around the nucleon? (How does it show in the slope of Pomeron trajectory?)</td>
<td>Yes</td>
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<td>4. What is the high parton density, high color strength asymptotic behavior of strong interactions?</td>
<td>Yes, Unique</td>
<td>Requires “Central” Detector and Roman pots</td>
</tr>
<tr>
<td>5. Is the proton polarization transferred to the “wee” coherent gluon field?</td>
<td>Yes, Unique</td>
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<tr>
<td>6. What traces the baryon number in high-energy interactions?</td>
<td>Yes</td>
<td>Requires Central Detector</td>
</tr>
</tbody>
</table>
HIGH ENERGY QCD
BEYOND THE POMERON
WORKSHOP SUMMARY

George Sterman
THE POMERON
(Through the mists of time)

• Heuristics of the Pomeranchuk Theorem

Elastic Scattering

\[ f_{ab}(s,t) \]

• Dispersion

\[ f_{ab}(s,0) \sim \int \frac{ds'}{2\pi i} \frac{\text{Im} f_{ab}(s,0)}{s-s'} \]

• Crossing

\[ f_{ab}(s,0) - f_{\bar{a}b}(s,0) \text{ bounded} \]

• Optical Theorem

\[ \sigma_{ab}^{\text{tot}}(s) \sim \text{Im} f_{ab}(s,0) \]

\[ \sigma_{ab}^{\text{tot}}(s) = \sigma_{\bar{a}b}^{\text{tot}}(s) \xrightarrow{s \to \infty} 0 \]
$$\bar{p}p : 21.70 s^{0.0808} + 98.39 s^{-0.4525}$$

$$pp : 21.70 s^{0.0808} + 56.08 s^{-0.4525}$$
**Spin and S-dependence**

Tree exchange for particle spin $\sigma$

\[
\frac{f_{ab}}{(s,t)} = \frac{s}{t} \sim \frac{1}{t} p_{\mu_1} \cdots p_{\mu_r} E^{\nu_1} \cdots \nu_0 \cdot p'_{\nu_1} \cdots p'_{\nu_0}
\]

\[
\sim \frac{s^\sigma}{t}
\]

**Regge Generalization**

\[
\frac{1}{t} s^x(+) = \frac{1}{t' - t_N}
\]

\[
\alpha(+N) = N
\]

'Reggeon'

(Linear) Trajectory

\[
\alpha(t) = \alpha(0) + b t^r
\]
REGGEONS FROM FIELD THEORY

Basic process (scalars)

\[ \sum \frac{dk^+ d^2 k'_+}{2k^+} \left| \begin{array}{c} k' \\ k \end{array} \right|^2 \sim g^2 \ln \frac{k^+_{\text{max}}}{k^+_{\text{min}}} \sum \frac{d^2 k'_+}{(k'_+^2 + m^2)^2} \alpha(\infty) \sim \frac{1}{m^2} \]

Ladders

\[ S \rightarrow \left| \begin{array}{c} \vdots \\ \vdots \\ \vdots \\ \vdots \end{array} \right|^2 \quad \Rightarrow \quad S \alpha(\infty) = \frac{\alpha(\infty)}{n!} \ln \frac{n}{m} \frac{S}{m} \]

QCD

\[ \sum \frac{dk}{m^2} \left| \begin{array}{c} k_{i+1} \\ k_i \end{array} \right|^2 \sim g_s^2 \ln \frac{k_{i+2}^+}{k_i^+} \sum \frac{dk_i^2}{k_i^2} \sim \text{dimensional} \quad \text{dimensionless} \]
ENTER: THE REAL WORLD

Experiment

\[ \sigma_{pp} \sim \sigma_{pp} \sim s^{0.08 + x'1} + \# S^{-1/2} \]

\[ x' \sim 0.25 \text{ GeV}^2 \]

Donnachie
Landskoff

Hypothesis

This behavior due to the exchange of the 'Pomeron' \( (P) \)

\( P: \sigma_{pp} \sim \sigma_{pp} \rightarrow 'vacuum' \) quantum nos

\( P: \text{reggeon with } x(0) \sim 1 \)

\( P: \text{`pure' carrier of strong interactions} \)

\( P: \text{No quantum numbers... Is it dull?} \)

\[ \text{Not at all...} \]
REGGE INERENCE

See this: \( S^{(4)-1}_P \)  
Means this

And this

(2++ glueball?)

\( \alpha_{pp}(?) = 2 \)

Encodes this

AND

\[ \text{Im} \quad \ldots \text{=} \sum \left| \chi \right|^2 \quad n = p, \bar{p}, \pi, K, \ldots \]

By carrying no label, \( \bar{P} \) encodes all of the strong interactions...

... including confinement
THE POMERON PROGRAM IN A NUTSHELL

Approach IP from...

1. Outside
   
2. Inside
   
3. Inside and Out
   
4. Inside-Out
POMERON N.B.'s

- $\alpha > 0 \Rightarrow$ violation of unitarity (eventually)
  is our $\not P$ the 'real' $P$?

- diffractive $\sigma$: only 'part' of $P$ at diffractive end
  may affect $\alpha, \alpha'$

- $\gamma^*$ and other off-shell particles
  how to relate to $\not P$ of 'normal' hadrons?

Each issue a center of theoretical debate, experimental tests...

- Is $\not P$ 'wrong end of the stick':
  just 'shadow' of everything
  that can happen?
Seeking Out the Pomeron

- Rapidity

\[ y = \frac{1}{2} \ln \frac{E + p_3}{E - p_3} \quad (\sim \eta = \ln \cot \frac{\theta}{2}, \quad m/E \to 0) \]

\[ a + b \to a + b \quad \text{(forward scattering)} \]

\[ p_b = -p_a \]

\[ Y = y_a - y_b \approx 2y_a = \ln \frac{5}{m^2} \quad \text{(maximum y)} \]

\[ S^x = e^{2\alpha Y} e^{-\alpha Y} \]

- Any large \( Y \)-interval \( \to \)

no particles but momentum transfer: diffraction; 'P' physics

Rapidity Gap

240
• Gap events have twice the power!

\[
\frac{d\sigma}{dM^2} \sim |\Delta y|^{2a} \sim e^{2(a-1)\Delta y}
\]

(very cooperative)

• Role of high-multiplicity events:

\[2<n>, 3<n> \ldots\]

William Walker
Yuri Dokshitzer
• THE SOFT-HARD DICHOTOMY
  (more general than '2-1P model
  (Landshoff
  Donnachie)

  \[ \alpha(0) + \alpha' \]
  \[ S \]
  hadron-hadron

  • data: \( \alpha(0) \approx 0.08 \)  \( \text{ 'SOFT IP' } \)
  \( \alpha' \approx 0.25 \text{ GeV}^{-2} \)

  • gluon ladders (BFKL IP)

  \[ \alpha(0) = \frac{4\pi}{N_c \ln z} \alpha_s \quad \text{ 'large'} \]

  \[ \sim 3 \alpha_s \quad \text{ 'HARD IP'} \]

  \[ \alpha', \text{ 'small'} \]

Expectation: Replace 1 or both hadrons by short-distance scattering but keep \( \Delta y \)

\[ \Larger \alpha \]

\[ \text{smaller} \alpha' \]
ELASTIC and TOTAL CROSS SECTIONS

\[ \sigma_{\text{tot}} \] (Tevatron) measured to much higher energy than \( pp \) (cf. \( P \)-theorem)

\( \rightarrow pp \rightarrow 2pp \) at RHIC

Stephen Buelteman

• elastic \& independent of \( Re, Im \) \( f_{pp} \)

\[ Re f_{pp} - Re f_{p\bar{p}} \rightarrow 0 \] (\(^{1}\)Pallowed')

'odderon' (not yet seen)

Nachtman's other tests/signals

• polarization: open territory
Single Transverse Spin Asymmetry $A_N$

\[
A_N(t) = \frac{1}{P \cos \phi} \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)}
\]

with $\phi$ the azimuthal angle
and $P$ the proton polarization

THE SPIN DEPENDENCE OF HIGH-ENERGY PROTON SCATTERING.
N.H. Buttimore, B.Z. Kopeliovich, E. Leader, J. Soffer, T.L. Trueman

Stephen Büttmann

The pp2pp Experiment at RHIC
Small-\(x\) DIS; Saturation

\[ F_2 \sim |\frac{\sigma}{w} Q^2| \sim \text{Im} \left( \frac{\sigma}{\mu^2} \right) \]

\[ W^2 \sim \frac{Q^2}{x} (1-x) \rightarrow S \]

\[ \ln \frac{1}{x} \sim \ln s = \ln W^2 \]

\[ \Delta Y \sim \ln \frac{1}{x} \]

Large \(Q^2\): \(P\) 'squeezed at one end

How does this affect \( x_{\text{DIS}}(W^2) \) ?

Study \( x G(xA) \sim \frac{F_2(xA)}{x} \)

\[ f_{g/P}(x) \rightarrow \frac{1}{x^{\lambda_A}} \]
- Why is $F_2$ so convenient?
  \[
  \frac{1}{x g(x)}: \text{ vary } x, Q \text{ in one exp. in large range}
  \]
  \[\lambda \sim 0.2 - 0.4 \text{ 'Hard } P',\]
  For $x \lesssim 10^{-4-5}$ begin to knock on door of unitarity, through

- Saturation of gluon density $Q_s(x)$: saturation scale

\[
\left(\frac{x G(x, Q_s)}{R_H^2}\right) \frac{1}{Q_s^2} = 1 \quad \Rightarrow \quad R_H^2
\]

\[
x G \sim \frac{1}{Q_s^2}
\]

At $Q_s \rightarrow$ turnover to NP

Hard $P \rightarrow$ Soft $P$

\[\text{eA Seen... but no clear } x \text{-dependence (HERMES)} \quad \text{Jerry Miller: VM's as parton low } Q^2\]
HARD DIFFRACTION(s)

- A remarkable discovery in the 80's and 90's
  UA8 ... DO, CDF, ZEUS, H1

- DIS, Photoproduction ~10% of events!

- Inclusive

\[ \gamma, \gamma^* (Q^2) \rightarrow \text{low } M_{\pi}^2 (\text{Jets},) \]
\[ \rightarrow \text{high } M_{\pi}^2 (b \bar{b} \ldots) \]
\[ \rightarrow \text{gap } \Delta y \rightarrow e^{2(\alpha-1) \Delta y} \]
\[ \rightarrow \text{low } M^2 \]

(Super, Berera
  C.J. Collins)

Factorization:
- Gap formation soft physics
- Incoherent from hard scatter (universal)

\[ d\sigma^{D}_{p\gamma} = \sum_a f_{q/p}^{\text{diff}} \otimes d\sigma_{xg}^{\text{diff}} \]
\[ a=q,g \]

\[ \mu \frac{d}{d\mu} f_{q/p}^{\text{diff}} (x, \mu) = P_{ab} (x, \mu^{2}) \otimes f_{b}^{\text{diff}} (x, \mu) \]

Evol., universality -> many predictions \{ dijets, bb \}
QCD Factorization @ Work

Predict diffr. dijet cross sections with PDF's obtained from inclusive $F_2^{D(3)}$ measurement:

[resolved $\gamma^*$ component included]

H1 Diffractive Dijets

$\Rightarrow$ Consistent with QCD factorization in diffr. DIS!

High Energy QCD, BNL Brookhaven, May 2001
Pomeron distributions

\[ f_{q/p} (x, Ax) = f_{q/P} (\beta) \otimes f_{P/B} (x_P) \]

\[ x = \beta x_P \]

+ Reggeons...

H1's choice...
• **Exclusive Vector Meson**

\[ Q \rightarrow m_V \sim 2m_q; \quad q = u, d, s, \rho, \omega \]

\[ P' (Q, m_V, t, M_V) \]

\[ M_V \geq m_p \]

**General trend:**

more localized \( P' \) → harder \( IP' \) \( \alpha, m_V, t \)

\((x\, up, \alpha'\, down)\)

• Relation to \( f_{G/p} \) for \( M_V = m_p, t \rightarrow 0 \)

\[ p \quad \sim \quad x \quad G(x); \quad small \quad x \quad \sim 10^{-3} \]

• \( t \)-dependence, polarization:

'Anomaly' in exclusive \( \rho \)

production at high \( t \)

why \( \sigma_t > \sigma_L \)?
Fit of $\rho^0$ Lineshape

ZEUS $\gamma p \rightarrow (\rho^0 + \pi^+\pi^-)p$

STAR $\gamma Au \rightarrow (\rho^0 + \pi^+\pi^-)Au$

Fit all data to $\rho^0 + \pi^+\pi^-$
interference is significant
$\pi^+\pi^-$ fraction is high (background?)

Set = 0 for STAR

Brookhaven, May 2001

Falk Meissner, LBNL
Photon + IP at RHIC

Joakim Nyström
Falk Meissner

$\gamma \text{Au} \rightarrow (\rho^0, \pi^\mp \pi^\pm) \text{Au}$
- Hadron-hadron

- Single-diffractive

- Double pomeron

- Single-gap dijet

\[
\sigma_{pp}^{\text{diff}} = f_{p}^{\text{diff}} \otimes f_{\bar{p}}^{\text{diff}} \otimes \hat{\sigma}
\]

- \( J_{alp}^{\text{diff}} \) from DIS \( \rightarrow \) too large by 5-10

- \( \sigma_{AB}^{\text{diff}} \) does not enjoy collinear-factorization (Collins Fruton...)

- Gap formation of 2 (protons, pp... not mceherent)
- Rapidity Gaps in pQCD

- not natural for 1-gluon exchange

\[ t=0 \]

\[ \text{even at } t=0 \]

- quark need new Coulomb field!
- Radiates
- Fills Gap

\[ -t \gg \Lambda^2_{QCD} \rightarrow \text{two gluon color singlet exchange} \]

\[ \text{no problem} \]

\[ -t \gg \Lambda^2_{QCD} \rightarrow \text{soft color picture} \]

- kinematics
- statistical color equilibration
• pQCD in H-H Diffraction

• Jets look like jets in inclusive events initiated by 'normal' collinear partons.

• Parton distributions in $x$ should not interfere with gap (re)formation of outgoing $p$, $\bar{p}$,$\ldots$N$^*$,$\ldots$)

  fits to diffractive PDFs 'make sense', but will not be same as in DIS, & may not factor between $p$, $\bar{p}$

  (overall constant?)

• Perturbative treatment of soft radiation into dijet gaps: find evolution in color exchange. Replaces 2-gluon/soft color dichotomy.
THEORETICAL APPROACHES

- Modelling the Pomeron
  - Peter Landshoff
  - Sandy Donnachie
  - Carlos Mendez
  - Jacques Soffer

2-IP model

\[ F_2(x, Q^2) = f_1(Q^2) \frac{x^{\alpha_1}}{1 + \frac{Q^2}{Q_0^2}} + f_0(Q^2) \frac{x^{\alpha_0}}{1 + \frac{Q^2}{Q_0^2}} \]

\[ \alpha_1 = 0.06 \]
\[ \alpha_0 = 0.4 \]

Fit to DIS, VM and γp data

Gegna Leun: Matching with EVOLM.

CKMT: Include EVOLM, in fit to PDFs.

Also: fit to hadronic data

Soffer

Dipole-based models (calculable)

\[ \sigma_{\gamma p} \sim \int d^2r_1 d^2r_2 \frac{1}{4s} (2 \delta(z, r_1)) \frac{1}{r_2 \sqrt{1 + \frac{r_2^2}{4R_s^2}}} \]

Golec-B. Wusthoff

Saturation

Boris Kopelevich: Semi-hard component:

\[ \sigma \sim \sigma_0 + \frac{\delta}{Q} \]
Nonperturbative Approaches I: QCD Vacuum

Instanton-mediated elastic ↓ Spaleron-inelastic (RHIC)

Ismail Zahed
Edward Shuryak
Gregory Carter

Instanton-ladders Stochastic Vacuum

Yuri Kovchegov

Otto Nachtmann
NP II: Partons $\rightarrow$ Reggeons

Lev Lipatov
Gregory Korchemsky

Generalizes BFKL ladder

Reggeized gluon ($g^\ast_{C(t)}$)
a new player in effective field theory

Connection to exactly solvable models!

$\gamma_2^t = H_{\text{eff}}^t$

eigenstates: pomeron, odderon.

true behavior: an infinite series
NP III: RESUMMED DIPOLE CROSS SECTIONS

another BFKL generalization

Robi Peschanski
Ian Balitsky
Leszek Motyka
Genya Levin

Balitsky-Kovchegov Eq. of density $n(k, Y)$

$$\frac{\partial n}{\partial Y} = \alpha_s N_\gamma n - \alpha_s N^2 \frac{\overline{k}^2}{k^2}$$

BFKL pomeron ↑

'rescattering overlap!

A theory of saturation...

NP IV: STRING-BASED POMERONS

'Duality' (a rule to calculate)

QCD ($g_s \to \infty$, $N_c \to \infty$) from
classical supergravity in
> 4 dimensional curved space

Tao! gluon trajectory
Janik! Wilson lines
Chung-I Tao
Romuald Janik

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CONCLUSION:
TRANSCENDING THE POMERON

The Pomeron is:
- An organizing theme
- An intellectual guide
- A range with many peaks
  (Foothills have been climbed)
- A doorway to a unified dynamics of QCD
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# High Energy QCD: Beyond the Pomeron

**Physics Department, Brookhaven National Laboratory**

**May 21-25, 2001**

## Agenda

### Monday, May 21 ---- Small Seminar Room

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>8:30</td>
<td>Registration</td>
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<tr>
<td>9:00</td>
<td><strong>Opening Session</strong></td>
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<td>9:00 - 9:15</td>
<td>Włodek Guryn</td>
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<td>9:15 - 9:50</td>
<td>John Dainton</td>
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<td>9:50 - 10:30</td>
<td>Yuri Dokshitzer</td>
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<td>10:30 - 11:00</td>
<td>Coffee Break</td>
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<tr>
<td>11:00 - 11:40</td>
<td>Peter Landshoff</td>
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<td>11:40 - 12:20</td>
<td>Robi Peschanski</td>
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<td>12:20 - 12:30</td>
<td>Lunch</td>
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**Non-Perturbative Approaches to Pomerons I**

<table>
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<tr>
<th>Time</th>
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<tr>
<td>2:00</td>
<td><strong>Chair: Boris Kopeliovich</strong></td>
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<tr>
<td>2:00 - 2:30</td>
<td>Sandy Donnachie</td>
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<td>2:30 - 3:00</td>
<td>Yuri Kovchegov</td>
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<td>3:00 - 3:30</td>
<td>Coffee Break</td>
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### Chair: Jerry Miller

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<thead>
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<tr>
<td>3:30</td>
<td><strong>Chung-I Tan</strong></td>
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<td>4:00</td>
<td><strong>Jacques Soffer</strong></td>
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<td>4:30</td>
<td><strong>Formation of Discussion and Working Groups</strong></td>
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<td>5:30</td>
<td>&quot;Welcoming Reception, Large Seminar Room Lounge, Physics Department&quot;</td>
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<tr>
<td>5:30</td>
<td><strong>Tom Kirk</strong></td>
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*Welcome from BNL*
Tuesday, May 22 ---- Large Seminar Room

RHIC Experiments

Chair: Peter Landshoff

9:00 - 9:30 Joakim Nystrand  Coherence in Nuclear Interactions at RHIC
9:30 - 10:00 Falk Meissner  Photon Pomeron Interactions at RHIC
10:00 - 10:30 Stephen Bueltman  pp2pp experiment at RHIC
10:30 - 11:00 Coffee Break

Collider Experiments I

Chair: John Dainton

11:00 - 11:30 Andrew Brandt  D0 Hard Diffraction in Run I and Prospects in Run II
11:30 - 12:00 Anwar Bhatti  Diffractive Results from CDF
12:00 - 12:30 Samim Erhan  The Effective Pomeron Trajectory and Double-Pomeron Exchange in UA8
12:30 - 2:00 Lunch

Non-Perturbative Approaches to Pomerons II

Chair: Konstantin Goulianos

2:00 - 2:30 Ismail Zahed  Non-Perturbative QCD and High-Energy Scattering
2:30 - 3:00 Romuald Janik  String Fluctuations, AdS/CFT and the Soft Pomeron
3:00 - 3:30 Coffee Break
3:30 - 6:30 Discussion

Wednesday, May 23 ---- Small Seminar Room

Collider Experiments II

Chair: Sandy Donnachie

9:00 - 9:30 Frank-Peter Schilling  Hard Diffraction: Results from H1 at HERA
9:30 - 10:00 Malcolm Derrick  Pomeron Physics Studied with the ZEUS Detector
10:00 - 10:30 Konstantin Goulianos  Beyond the Conventional Pomeron
10:30 - 11:00 Coffee Break
**Wednesday, May 23 ---- Small Seminar Room, continued**

**Chair:** Yuri Kovchegov

11:00 - 11:30 James Crittenden  
Scaling Properties of High-Energy Diffractive Vector-Meson Production at High Momentum Transfer

11:30 - 12:00 William Walker  
Analysis of Hadron Multiplicities and Diffraction Dissociation

12:00 - 12:15 Kenichi Hatakeyama  
Study of Diffractive Dijet Production at CDF

12:15 - 12:30 Andrei Solodsky  
Diffractive J/ψ Production at CDF

12:30 - 2:00 Lunch

**Non-Perturbative Approaches to Pomerons III**

**Chair:** Dmitri Kharzeev

2:00 - 2:30 Eugene Levin  
Matching of Soft and Hard Pomerons

2:30 - 3:00 Boris Kopeliovich  
Semihard Components of the Soft Pomeron

3:00 - 3:30 Carlos Merino  
The CKMT Approach to the Pomeron Puzzle

3:30 - 4:00 Coffee Break

4:00 - 6:00 Discussion

**Thursday, May 24 ---- Large Seminar Room**

**Perturbative and Non-Perturbative QCD I**

**Chair:** Otto Nachtmann

9:00 - 9:30 Lev Lipatov  
Solution of the Baxter Equation for the Composite States of the Reggeized Gluons in QCD

9:30 - 10:00 George Sterman  
Perturbative and Non-Perturbative Radiation

10:00 - 10:30 Gerald Miller  
The HERMES Effect

10:30 - 11:00 Coffee Break

**Chair:** Eugene Levin

11:00 - 11:30 Gregory Korchemsky  
Unitarity Corrections to the BFKL Pomeron

11:30 - 12:00 Ian Balitsky  
Effective Field Theory for the Small-x Evolution

12:00 - 12:30 Leszek Motyka  
Direct Solutions to Kovchegov Equation

12:30 - 2:00 Lunch

2:00 - 3:30 Discussion

3:30 - 4:00 Coffee Break

4:00 - 5:30 Discussion

7:00 - Workshop Dinner
Friday, May 25 ---- Large Seminar Room

Perturbative and Non-Perturbative QCD II

Chair: Raju Venugopalan

9:00 - 9:30 Otto Nachtmann
9:30 - 10:00 Edward Shuryak
10:00 - 10:30 Gregory Carter
10:30 - 11:00 Coffee Break
11:00 - 12:30 Discussion
12:30 - 2:00 Lunch

Chair: Yuri Dokshitzer

2:00 - 3:00 George Sterman
3:00 - Conference Adjourns

High Energy Hadron-Hadron Scattering in a Functional Integral Approach
Instanton/Sphaleron Mechanism in Hadronic Nuclear Collisions
Classical Gluon Production in Hadronic Collisions

Summary
Photographs
from
Workshop Dinner

May 24, 2001

Painters’ Restaurant
416 South Country Road
Brookhaven Hamlet, NY 11719
Additional RIKEN BNL Research Center Proceedings:

Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105

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Additional RIKEN BNL Research Center Proceedings:

Volume 4 – Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics – BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722
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Homepage: http://quark.phy.bnl.gov/www/riken.html  
High Energy QCD:
Beyond the Pomeron
May 21 - 25, 2001

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:
I. Balitsky
J. Crittenden
S. Erhan
G. Korchemsky
F. Meissner
J. Nystrand
A. Solodsky
A. Bhatti
J. Dainton
K. Goulianos
Y. Kovchegov
C. Merino
R. Peschanski
G. Sterman
A. Brandt
M. Derrick
K. Hatakeyama
P. Landshoff
G. Miller
F.-P. Schilling
C.-I. Tan
S. Bueltman
Y. Dokshitzer
R. Janik
E. Levin
L. Motyka
E. Shuryak
W. Walker
G. Carter
S. Donnachie
B. Kopeliovich
L. Lipatov
O. Nachmann
J. Soffer
I. Zahed

Organizers: John Dainton, Wlodek Guryn, Dmitri Kharzeev, and Yuri Kovchegov