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INFORMAL REPORT

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QCD Tests and Large Momentum-Transfer reactions at CBA

R. Longacre and M. J. Tannenbaum

The predicted inclusive single particle cross section for a selected group of QCD reactions is shown in Figure 1.[†] The highest rate process is jet production¹ followed in descending order by single particle production $(\pi^0)^2$, direct photon production,¹ $J/\psi + e^+e^-$ production at high P_T ³, and direct photon production with an internal conversion to an e^+e^- pair with mass $1 \text{ GeV} \leq m \leq 9.5 \text{ GeV}$ [ψ region excluded]. At a given P_T these processes span a cross section variation of about 7 orders of magnitude.

On the right hand scale are shown the expected number of events in a reasonable general purpose detector⁴ ($\Delta y = \pm 2$, $\Delta\phi = 2\pi$) for a nominal year's running (10^7 seconds at $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ luminosity) integrated over a constant effective* bin interval of $\Delta P_T \Delta y \Delta\phi = 100 \text{ GeV/c}$. For direct photons a special purpose detector is envisaged⁵ with $\Delta\Omega = 780 (\text{GeV/c})^2 / P_T^2$ so that the expected events should be decreased by a factor of $\approx P_T (\text{GeV/c})$.

If QCD is the correct theory of the strong interactions, the unravelling of quantitative and precise QCD tests from measurements of these cross sections is expected to be very

[†]Note that massive lepton pair production, and even Z^0 production at large P_T also provide significant QCD testing possibilities. These subjects are discussed elsewhere.

*This corresponds to an actual bin width of $\Delta P_T = 5 \text{ GeV/c}$, $\Delta y = 4$ at P_T of 10 to 20 GeV/c ; and $\Delta P_T = 50 \text{ GeV/c}$ $\Delta y = 1$ at $P_T = 250 \text{ GeV/c}$. The effective bin width is defined as the integral of the cross section over the actual ΔP_T interval, divided by the value of the cross section at the lower edge of the bin.

complicated and tedious. Many subprocesses contribute to any individual reaction. Furthermore, detailed knowledge of various structure functions, and in many cases fragmentation functions, as well as their Q^2 evolution, is required to extract the physics of the basic QCD subprocesses from the data. Experimental ingenuity can overcome many of these problems² but at the expense of a long program of measurements of jets and single particles individually, in pairs, and in multiples. Great progress has been made in 12 years of research at the ISR and 5 years at PETRA. This can be expected to continue at CBA. In addition, the availability of polarized beams at CBA will open up the possibility of exploring the nature of the underlying gauge theories of strong and related interactions in which helicity plays as fundamental a role as charge.⁶ To illustrate the frontier opened up by CBA, present information on QCD is based on data with $Q^2 \approx 1000 \text{ GeV}^2$ at PETRA, 500 GeV^2 at the ISR and 200 GeV^2 from inelastic lepton scattering. At CBA, detailed results will be obtained at $Q^2 > 100,000 \text{ GeV}^2$.

It is desirable to try to find fundamental tests of QCD which are sensitive to the specific properties of gluons and the non-Abelian structure of the theory, which would show that the theory is computable above leading order, and which are insensitive to the extraneous parameters such as structure functions, fragmentation functions and the like. Such tests can occur when higher-order corrections produce interference effects which must be zero in lowest order. One such effect⁷ is the linear polarization of direct single photons produced in p-p collisions. It is claimed⁷ that this polarization provides "a rigorous test of perturbative QCD as well as an important check on the color hypothesis." "This latter aspect is particularly attractive because the polarization involves the three-gluon interaction and the equality of the quark-gluon and three-gluon coupling in an essential way."

The linear transverse polarization, P , of directly produced photons can be measured using the decay angular distribution of internally converted e^+e^- (or $\mu^+\mu^-$) pairs.

$$\frac{dW(\cos\theta_d, \phi_d)}{d\Omega_d} = \frac{3}{16\pi} \{1 + \cos^2\theta_d - P \sin^2\theta_d \cos 2\phi_d\}$$

The reaction is assumed to proceed via the Compton subprocess:

$$\begin{array}{c} g + q \rightarrow \gamma + q \\ \quad \quad \quad | \\ \quad \quad \quad \rightarrow e^+e^- \end{array}$$

The predicted value of the polarization at the constituent level is

$$P(\theta^*) = \frac{\alpha_s}{2\pi} [F(\theta^*) + F(\pi-\theta^*)]$$

where

$$F(\theta^*) = \frac{4}{3} \frac{\cos\theta^*(3-\cos\theta^*)}{5 + 2 \cos\theta^* + \cos^2\theta^*}$$

The angle θ^* is the angle between the photon and the gluon in the quark-gluon center-of-mass system. The polarization has been symmetrized because the gluon direction is assumed to be unknown.

The cross section for this process is very small (Figure 1), but nevertheless 100,000 events per year can be expected at $P_T \approx 15$ GeV/c. The virtual photon emission angle in the constituent center-of-mass system can be found to a precision $\Delta\cos\theta^* = 0.03$ RMS by the simple algorithm of defining the rapidity of the recoiling jet as the rapidity of the highest transverse momentum recoiling particle with $P_T > 3$ GeV/c. This algorithm is 62% efficient for the nominal detector,⁴ mostly due to the limited rapidity acceptance of the

detector compared to the maximum available rapidity at $P_T \approx 15$ GeV/c.

For the purpose of this report the polarization is measured by the asymmetry

$$\varepsilon = \frac{n_{\perp} - n_{\parallel}}{n_{\perp} + n_{\parallel}}$$

where $n_{\parallel}$ is the number of events with azimuthal angle within $\pm 45^\circ$ of the decay plane and $n_{\perp}$ are the rest. Because of the $\sin^2\theta_d$ factor in the decay distribution, the polarization sensitivity is diluted by the asymmetric decays. Thus for this preliminary estimate, the asymmetry ε is computed by averaging over all events with $\sin^2\theta_d \geq 0.5$, which gives a polarization error:

$$\sigma_P = \frac{1}{\sqrt{n}} \frac{\pi}{2} \times 1.78 = \frac{2.8}{\sqrt{n}}.$$

Here, n is the total number of events integrated over all decay angles θ_d , ϕ_d ; the first factor is due to the azimuthal average and the second factor due to the $\sin^2\theta_d$ cut and average. This simplified estimate is considered adequate at this time since possible systematic effects have been ignored.

The predicted polarization and the expected (statistical) measurement errors are shown in Figure 2 for a nominal year of running. An overall detection efficiency of 60% is assumed for events within the acceptance of the detector. The outer error bars are for 60,000 events, $P_T \approx 16$ GeV/c, and the inner error bars for 130,000 events, $P_T \approx 12$ GeV/c. While polarizations at the level of 10% could be reasonably measured for $|\cos\theta^*| < 0.5$, the QCD prediction of $\leq 3\%$ is clearly too small for the expected sensitivity. Another potential problem is that the x_T values of 0.03 to 0.05 may be too small for meaningful perturbative QCD predictions. At P_T of ≈ 50 GeV/c, $x_T \approx 0.125$, the rate is down by another factor of 100

which would increase the polarization error by a factor of 10, to about 30%.

Increasing the machine energy would not help improve the feasibility of this QCD polarization test. In fact, decreasing the energy might be more appropriate since then x_T would increase for a fixed $P_T \approx 15$ GeV/c without much of an effect on the cross section. In order to do this type of measurement at CBA at the level predicted, a luminosity scale of $10^{36} \text{ cm}^{-2} \text{ sec}^{-1}$ is more appropriate than 10^{33} .

A particularly important feature of high P_T phenomena is that they are a probe of very large momentum transfers. The four-momentum-transfer for constituent scattering is approximately $Q^2 = 2 P_T^2$. For the reactions shown in Figure 1, momentum transfers of $60,000 (\text{GeV}/c)^2$ can be probed with inclusive single particle production and $140,000 (\text{GeV}/c)^2$ with inclusive jet production. One would hope that such momentum transfers are high enough to knock a quark out of a proton or to reveal a substructure of the quarks.

In order to make quantitative estimates of the effects to be expected from quark substructure, it is convenient to use a model.⁸ Eichten, et al.⁹ have proposed that the strong force which binds the subconstituents in quarks produces a contact interaction between quarks which becomes visible once the center-of-mass energy $\sqrt{s}$ becomes comparable to the characteristic scale of compositeness, Λ . The contact interaction gives a nearly isotropic angular distribution for identical quark scattering:

$$\frac{d\sigma}{dx} = \frac{4}{3} \frac{\pi \Lambda^2}{\Lambda^2} \frac{\hat{s}}{\Lambda^2} \times \frac{3}{16} \left[1 + x^2 + \frac{4}{3} \right]$$

where $x = \cos\theta^*$, the quark-quark center-of-mass scattering angle and $\Lambda = \pm 1$. The total cross section for the contact interaction is

$$\sigma_{TOT} = \frac{4}{3} \frac{\pi}{\Lambda^2} \frac{\hat{s}}{\Lambda^2}$$

There is also an interference term between the contact interaction and QCD which gives an additional term to the angular distribution:

$$\frac{d\sigma}{dx} = \frac{-16}{9} \frac{\pi \Lambda}{\Lambda^2} \frac{\alpha_s}{1-x^2}$$

An especially intriguing feature of composite models of quarks and leptons is that the interactions generally violate parity.⁸ "There is no reason why they should not; the left-and-right handed electron are completely different species above the scale of $SU(2) \times U(1)$ breaking." In fact, the example given above is an explicit parity violating left-left interaction. For this and other parity violating interactions,¹⁰ the availability of longitudinally polarized beams in CBA will provide dramatically enhanced sensitivity.¹¹

The effect of the above contact interaction on the inclusive jet cross section at $\sqrt{s} = 800$ GeV is shown in Figure 3 for $\Lambda = -1$ and $\Lambda = 2.0$ TeV (solid line compared to dotted line). There is perhaps a 15% effect at $P_T = 250$ GeV/c. This would be a 3 standard deviation effect compared to the statistical error, but would be overwhelmed by experimental and theoretical systematic uncertainties such as: energy scale uncertainty, energy resolution smearing, and the uncertainties of the quark and gluon structure functions.

By contrast, the parity violating longitudinal asymmetry for scattering

$$\sigma_{--} - \sigma_{++}$$

by two left handed or two right handed longitudinally polarized proton beams is also shown in Figure 3 including the contact interaction (dot-dash line).⁶ This should be compared to the

effect expected from the parity-violating interference between $W^\pm$ and Z^0 exchange and the ordinary QCD processes¹¹ (dashed line). The beams are taken to be 100% polarized for this figure*, whereas the actual beam polarization is expected to be 70%.^{6,10} The statistical errors on the contact interaction asymmetry would be invisible on the scale of Figure 3 except at the highest P_T .

The measured asymmetry is defined as

$$\varepsilon \equiv \frac{\sigma_{--} - \sigma_{++}}{\sigma_{--} + \sigma_{++}}$$

$\sigma_{--} + \sigma_{++}$ is taken equal to $2\sigma_{\text{unpol}}$, where σ_{unpol} is given in Figure 3. The magnitude of the asymmetry can be calculated and compared to the statistical error expected in one nominal running year ($L = 10^{40} \text{ cm}^{-2}$) in bins approximately 10% wide in P_T and 1 unit full width in rapidity (Table I). The systematic errors are expected to be less than 10^{-2} and hopefully less than 10^{-3} . At this level, the effect is clearly visible for $P_T \geq 140 \text{ GeV}/c$ and can be precisely measured to determine Λ . Taking Table I at face value for $P_T > 140 \text{ GeV}/c$ implies a 7% measurement of Λ^{-2} or a 3.5% measurement of Λ for $\Lambda = 2 \text{ TeV}$ and $A = -1$. Values of Λ much above 3 TeV would be difficult to observe because the quark substructure effect becomes comparable to the QCD-weak interference.

It is clear that the parity violating polarization asymmetry will provide a major advance in the study of quark substructure and any other new physics.

*Since the parity violation is actually only a single beam asymmetry, the effect is proportional to the sum of the beam polarizations rather than the product.

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Table I

P_T GeV/c	$\langle P_T \rangle$ GeV/c	σ_E Statistical Error (%)	(100% Polarized Beams)			(70% Polarized Beams)
			ϵ Total Asymmetry (%)	ϵ_W QCD-Weak Asymmetry (%)	$(\epsilon - \epsilon_W)/\sigma_E$	$(\epsilon - \epsilon_W)/\sigma_E$
100-110	104.7	0.06	1.2	0.6	9.8	6.0
140-150	144.7	0.23	3.4	1.2	9.4	6.6
150-167	157.6	0.27	4.1	1.5	9.8	6.8
167-184	174.7	0.39	5.3	1.8	8.9	6.3
184-200	191.3	0.67	7.8	2.2	8.4	5.9
200-225	210.7	1.05	10.1	2.5	7.2	5.0
225-250	235.7	2.4	13.5	2.6	4.5	3.2
250-300	268.9	4.8	17.5	3.0	3.0	2.1

Figure 2

Figure 3