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from

RICE

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I. Overview of Project

We report here on progress made for the period from December 1, 1991 (the date of submission of our previous five-year progress report) to September 1, 1996 for DOE Grant No. DE-FG05-92ER40717. The Bonner Lab High Energy Group presently has major hardware and software design and construction responsibilities in three of the flagship experiments of U. S. High Energy Physics: D0, CMS, and KTeV. These commitments were undertaken after managing boards of the collaborations had evaluated the unique capabilities that we have to offer.

Although fiscal constraints prohibited our participation in the final year of the SMC experiment (1996) on the spin dependent structure functions of nucleons, we played a major role there since it was proposed in 1988. The new results from the SMC data taken in previous years continue to generate a buzz of theoretical activity – and to increase our understanding of the nucleon structure functions and their behavior as a function of Q^2 and x . They have also spawned large new experimental spin physics programs at HERA and at RHIC that ultimately will provide answers to these fundamental questions. This is a direct result of the unprecedented precision and kinematic range of the SMC results. Such precision would not have been possible without the improvement in our knowledge of the muon beam polarization using the Rice-designed beam polarimeter.

In D0 we have been active in data taking, data analysis, upgrade design, and upgrade construction projects. Much of the improvement in D0 will result from the installation of a scintillating fiber tracker. We played a key role in its design, in conceiving and writing the software that will turn the raw data into particle trajectories, and in construction of a test stand for the VLPC's that will turn the fiber light into electrical pulses. We eagerly anticipate the discoveries that lie ahead for this upgraded detector.

In CMS we are responsible for the design and construction of the trigger electronics for one of the crucial subsystems: the end cap muon detectors. We fully expect to take on other responsibilities as the U. S. commitment to LHC projects becomes clearer. Our technical capabilities are well matched to the enormous challenges posed by the physics measurements being contemplated for the CMS detector.

KTeV will be taking data shortly. Rice made major contributions to the construction and commissioning of this experiment.

The long list of publications and presentations during the past five years attests to the fact that the group has been working hard and productively. We hope to see this situation continue for a further five years, and the separate Grant Renewal Proposal is submitted along with this Progress Report for that purpose.

The separation of the experimental projects into two tasks (A and C) is for the purpose of reducing the amount of overhead the grant incurs. Tasks A and B incur the on-campus rate and Task C the considerably lower off-campus rate.

II. Tasks A and C: Experimental High Energy Physics

A. CERN NA47: The SMC Experiment

Introduction and background

There have been two experimental determinations of the spin-dependent structure function $g_1^p(x)$ of the proton during the past 15 years. Both were extracted from measurements of cross section asymmetries in deep inelastic scattering of longitudinally polarized leptons by longitudinally polarized protons. The first was performed at SLAC,¹ using polarized electrons with energies between 6 and 21 GeV and covered the kinematic range $0.1 < x < 0.7$, where x is the Bjorken scaling variable. The second, done at CERN by the European Muon Collaboration (EMC)², used polarized muons of 100 to 200 GeV energy and covered the range $0.01 < x < 0.7$. The result of these experiments disagrees with the prediction of the Ellis-Jaffe sum rule³ and indicates that in the quark-parton model, quarks and antiquarks contribute little to the spin of the proton. In a large number of papers, a variety of new theoretical ideas have been proposed to explain these unexpected results.⁴ Recently two experiments have measured g_1^n from polarized muon-deuteron (SMC⁵ at CERN) and g_1^n from polarized electron-³He scattering (E142⁶ at SLAC). The conclusion from these two experiments appeared to be at variance. However, combined analyses^{7,8,9,10} showed that the experimental data agree in the kinematic region of overlap, and emphasized that the conclusions are very sensitive to the small- x extrapolation of $g_1(x)$ and to higher order and higher twist QCD corrections. Additional data are required to provide a more stringent test of the sum rules and to clarify the contribution of the quark spins to the nucleon spin.

Several experiments are presently being carried out or prepared at CERN (Spin Muon Collaboration),¹¹ SLAC,¹² and DESY¹³ to measure the spin structure functions with improved accuracy. The SMC experiment yielded the first measurement of the spin dependent structure function g_1^n of the neutron¹⁴ and has increased the accuracy of the SLAC-YALE and EMC measurements of g_1^p of the proton¹⁵. From the outset, Rice has taken the lead role in a collaboration with Saclay and Trieste for the construction of the polarimeter which measures the muon beam polarization for the SMC experiment.

The experiment uses a polarized muon beam, a polarized proton/deuteron target, a spectrometer to measure the scattered muon, and a beam polarimeter. A new polarized

¹M. J. Algard *et al.*, Phys. Rev. Lett. 37, 1261 (1976); *ibid.* 37, 70 (1978); G. Baum *et al.*, Phys. Rev. Lett. 51, 1135 (1983); G. Baum *et al.*, Phys. Rev. Lett. 45, 2000 (1980)

²J. Ashman *et al.*, Phys. Lett. B206, 1167 (1988); J. Ashman *et al.*, Nucl. Phys. B328, 1 (1989)

³J. Ellis and R. L. Jaffe, Phys. Rev. D9, 1444 (1974); D10, 1669 (1974)

⁴For a review: H. Rollnik, Proc. 9th Int. Symposium on HE Spin Physics, ed. by K. H. Althoff and W. Meyer, Springer-Verlag, Berlin 1990, Vol. 1, p. 183. E. Reya, Dortmund preprint DO-TH-91/09

⁵SMC, B. Adeva *et al.*, Phys. Lett. B302 (1993) 533.

⁶SLAC E142, D.L. Anthony *et al.*, Phys. Rev. Lett. 71 (1993) 959.

⁷J. Ellis and M. Karliner, Phys. Lett. B313 (1993) 131.

⁸F.E. Close and R.G. Roberts, Phys. Lett. B316 (1993) 165.

⁹G. Altarelli, P. Nason and G. Ridolfi, Phys. Lett. B320 (1994) 152.

¹⁰SMC, B. Adeva *et al.*, Phys. Lett. B320 (1994) 400.

¹¹The Spin Muon Collaboration Proposal, CERN/SPSC 88-47 (SPSC/P242), 1988 (unpublished)

¹²R. Arnold *et al.*, A proposal to measure the neutron spin dependent structure function, SLAC Proposal E142, 1989; E143 Collaboration, SLAC Proposal (unpublished).

¹³The HERMES Collaboration, A Proposal to Measure the Spin-Dependent Structure Functions of the Neutron and the Proton at HERA, DESY-PRC 90/01, 1990 (unpublished)

¹⁴B. Adeva *et al.*, Phys. Lett. B302, 533 (1993)

¹⁵D. Adams *et al.*, Phys. Lett. B329 (1994) 399.

target was built for this experiment. Its design is similar to that used in the earlier EMC proton and SMC deuteron experiments, but with the addition of a new superconducting solenoid with high field uniformity and a dipole magnet for adiabatic spin rotation. The spectrometer was significantly upgraded from the EMC/NMC to reduce systematic uncertainties. The polarimeter is described in detail in the following section.

The quantity that is measured is:

$$A_1(x) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

where $\sigma_{1/2}(\sigma_{3/2})$ is the absorption cross section for polarized virtual photons by polarized nucleons when the total component of angular momentum along the collision axis is $1/2(3/2)$. A_1 is derived from the asymmetry (A) for longitudinally polarized muons scattered by longitudinally polarized nucleons

$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$$

where $d\sigma^{\uparrow\uparrow(\uparrow\downarrow)}$ is the cross section for parallel (antiparallel) muon and nucleon spins. It is derived from the measured asymmetry

$$A = \frac{A_{\text{meas}}}{P_\mu P_T f}$$

where P_μ and P_T are the beam muon and target polarizations and $f(\sim 0.12)$ is the dilution factor arising from unpolarized material in the polarized target. In first order QED, the asymmetry A is related to the virtual γ - nucleon asymmetries A_1 and A_2 by

$$A = D(A_1 + \eta A_2).$$

The depolarization factor D and the coefficient η depend on the event kinematics. In addition, D depends on the unpolarized structure function $R(x, Q^2)$, which was taken from a global fit of the SLAC data. The asymmetry A_2^p arises from the interference between transverse and longitudinal virtual photon polarizations and is constrained by the positivity limit $A_2^p \leq \sqrt{R}$. We have measured A_2^p in a dedicated experiment, where the dipole field was used to hold the proton polarization in a direction perpendicular to the beam. We found A_2^p to be compatible with zero within statistical uncertainty of 0.20, which is a stronger constraint than the one imposed by the positivity limit. In addition, since the coefficient η is small in the kinematic range covered by our experiment, we neglected the term ηA_2^p and included its possible effect in the systematic error. The target polarization was typically 85%(50%) for proton(deuteron), and the beam polarization was measured to be -80% at 190 GeV.

Beam Polarimetry

The muon beam polarimeter was designed at Rice and is shown schematically in Fig. 1a in the decay configuration and Fig. 1b for the μ -e scattering setup. Rice has provided the multiwire proportional chambers (MWPC's) downstream of the bending magnet (MNP26) and the lead glass wall. Trieste has furnished the fast 1 mm beam chambers and Saclay the data acquisition electronics, two Sun workstations for data acquisition and analysis, the trigger scintillation hodoscopes, and the polarized Fe target.

The muon beam polarization is measured by two methods:

- the shape of the energy spectrum of decay positrons in the laboratory system is sensitive to the muon polarization, and
- the muon spin has been analyzed by detecting the elastic scattering of muons from electrons in a polarized iron target.

The decay polarimeter is described in detail in a paper published in NIM.

Fig. 1a. Plan view of the muon decay polarimeter.

Fig. 1b. Layout of the μ -e scattering polarimeter.

Work has continued on improving the decay method. Much high precision data were taken in 1994 and have been analyzed by Rice graduate student Steve Eichblatt. A detailed study of the stability of the beam polarization as a function of time was done. A fraction of the run-by-run analysis is shown in Fig. 2. A comparison is also being made with the results of the μ -e scattering method to determine finally the absolute error on the knowledge of the beam polarization. These analyses constituted part of the Ph.D. thesis of Rice student, Steve Eichblatt.

The beam polarization can be measured by elastic scattering from polarized electrons using the simple spin asymmetry:

$$\frac{N_{\uparrow\downarrow}(y) - N_{\uparrow\uparrow}(y)}{N_{\uparrow\downarrow}(y) + N_{\uparrow\uparrow}(y)} = P_{\mu}P_e A_{th}(y) \text{ where } y = \frac{E_e^{scat}}{E_{\mu}^{inc}}.$$

y is the fractional momentum transferred to the electron and $N_{\uparrow\downarrow}$ and $N_{\uparrow\uparrow}$ are counting rates for spins antiparallel and parallel, respectively. P_{μ} and P_e are the beam and target polarizations. The first order QED spin asymmetry, A_{th} , for fully polarized beam and target is shown in Fig. 3, a plot of:

$$A_{th}(y) = \frac{2y - (2C - 1)y^2}{2 - 2Cy + y^2}; \quad C = 1 + \frac{m_{\mu}^2}{2m_e E_{\mu}}.$$

Fig. 2 (a) Polarization vs. Run for the 1994 Decay data, and (b) histogrammed as a function of the value of the beam polarization.

Fig. 3. Theoretical asymmetry versus y .

This asymmetry has a cutoff below $y=1.0$ due to the heavier mass of the muon. Preliminary data were taken with this polarimeter in 1992, and full measurements have been made in 1993 and 1994.

The scattering polarimeter uses the same apparatus as the decay polarimeter except that it includes a magnetized target and another downstream spectrometer arm, which is used to track the scattered muon. The chamber PPC1 is a large 1mm spacing proportional chamber which tracks both the scattered electron and

scattered muon. It was built to track scattered muons which overlapped with the beam as well as provide a high resolution point near the exit of the analyzing magnet. The chamber was built by Saclay, while the electronics and cabling were provided by Rice. The first muon telescope is formed from PPC1 and PBC7, a beam chamber, and is used to track the muons overlapping the beam. The second telescope uses PPC1 and two 2mm chambers to track lower energy muons. After passing through the chambers, the scattered μ^+ passes through 2 m of Fe, and then through a pair of scintillator hodoscopes HMU and HMS. These hodoscopes are part of the trigger and are used for track correlation in the analysis.

The target consists of two 1.32 mm foils of Supermendur (49% Co, 49% Fe, 2% V) placed in a magnetic field of 300 G. This generates a saturation magnetic field within the material of 1.28 T. The resulting polarization is 8.55%. A longitudinal component of the polarization is achieved by tilting the target to an angle of 25° with respect to the

beam, so that the effective polarization is 7.75%. The polarization was flipped by reversing the applied field between spills (every 15 seconds), and the induced emf was measured with a set of coils to monitor the magnetization which is directly related to the electron polarization.

The trigger is formed by requiring a hit in the shower veto (SV) in coincidence with a deposition in the lead glass of more than 10 GeV, as well as a hit in the HMU/S combination.

The tracking analysis consists of 2 distinct parts: upstream and downstream of the analyzing magnet. The first part consists of forming vertices at the target using the beam chambers upstream and downstream of the target. A minimum opening angle is required, as shown in Fig. 4a. We also cut on the vertex position along the beam, accepting only scatters from the target as shown in Fig. 4b. Both of these cuts are rather loose but do reject a lot of background.

Fig. 4a. Vertex opening angle (mrad) showing cut at 3 mrad.

Fig. 4b. Vertex position (mm) showing cut at -10400 ± 500 .

The vertex kinematics and the tracks downstream of the target are then used to 'guess' momenta for the scattered particles. This is used to form roads for point searches in the downstream chambers. Correlations with hits in the downstream chambers are sought on a plane by plane basis with a requirement of at least 3 planes to form a track. The real momentum is then measured using the tracks upstream and downstream of the target for both electron and muon. All calculations are based on the momentum of the muon, since the e^- tends to bremsstrahl as it exits the target. The electron track information is nevertheless valuable, since requiring an e^- track reduces background by a factor of six. We also require a track correlation with the HMU/S combination.

Two corrections have to be made to the raw counting rates: beam flux normalization and the acceptance ratio. The beam flux normalization has been done by both reconstructing random triggers and summing the scaler information from the SV. The ratio of fluxes is then used to correct the counting rates used in the asymmetry. The systematic error is less on the random trigger reconstruction, whereas the statistical error is smaller for the scalers. Since the results are compatible, the scaler result is used. The result is compatible with 1.0, but since the error in normalization gets multiplied by a

factor of 20 when propagated to the error on the polarization, it is important to know this number precisely. Using the scaler information gives a systematic error of 0.6% on the final polarization.

Fig. 5. Beam Polarization for 190 GeV μ^+ using the scattering polarimeter.

The acceptance ratio is actually canceled out by taking data with the target at 2 different angles: 25 ° and 155 °. The acceptance of the two target polarizations is different only because the target has a leakage field which affects the scattered particle trajectories. When we flip the target from 25 ° to 155 ° we flip the longitudinal polarization of the electrons, but we leave the vertical component of the leakage

field unchanged. Therefore when we combine the 2 target angles the effects due to the leakage field cancel.

The measured beam polarization is shown for different bins in y in Fig. 5. A constant good fit is made from $y=0.2$ to $y=0.8$, indicating that the acceptance is well understood over this angular region. Radiative corrections are not applied to these data; applying this correction changes the value by 0.4% to

$$(\text{Rice}) P_{\mu} = -0.757 \pm 0.031 (\text{stat.}).$$

This is to be compared to the result of an independent analysis performed by Saclay of the same data using a different tracking method.

$$(\text{Saclay}) P_{\mu} = -0.772 \pm 0.026 (\text{stat.}).$$

This can be compared with the sample decay values from two years:

$$P_{\mu} = -0.80 \pm 0.023 \pm 0.03 \{1993\}, -0.777 \pm 0.010 \pm 0.020 \{1994\};$$

and the Monte Carlo value $P_{\mu} = -0.785 \pm 0.05$. Analysis of all the 1994 decay data by S. Eichblatt and the μ -e data independently by Trieste and by Saclay are completed, and confirm that the beam polarization is known to better than four percent accuracy, the original stated goal of the polarimeter.

Results and Remarks on Structure Functions

Data on A_1^p were reported in Physics Letters B, covering the kinematic range $1 \text{ GeV}^2 < Q^2 < 60 \text{ GeV}^2$ and $0.003 < x < 0.7$. These values of A_1^p from the SMC and earlier measurements are plotted in Fig. 6. It should be noted that although the error on the beam polarization has been reduced by almost a factor of 2 relative to the EMC, it remains the largest source of systematic error.

The values of g_1^p have been calculated by the relation:

$$g_1^p(x) = \frac{A_1^p(x) F_2^p(x, Q^2)}{2x[1 + R(x, Q^2)]}$$

Fig. 6. Virtual photon-proton asymmetry, statistical errors only. The shaded region indicates size of systematic error.

Fig. 7. The solid circles show xg_1^p , and the open boxes show $\Gamma_1^p(x_{min})$ with statistical errors only. The solid square shows $\Gamma_1^p(x_{min}=0)$ with combined statistical and systematic errors.

The values of $F_2^p(x, Q^2)$ were taken from the NMC parametrization¹⁶ and those of R from a global fit of the SLAC data.¹⁷ The lowest x bin is outside the kinematic region covered by the NMC data, but we have verified that their parametrization extrapolates smoothly to the HERA data. The structure function g_1^p is practically independent of R due to the cancellations between the implicit R dependencies in D and F_2 and the explicit one. The result for the first moment of g_1^p at 10 GeV^2 shown in Fig. 7 is:

$$\Gamma_1^p(10 \text{ GeV}^2) = 0.136 \pm 0.011 \pm 0.011 \text{ (SMC)}$$

The Ellis-Jaffe sum rule, including first order QCD corrections, predicts $\Gamma_1^p = 0.176 \pm 0.006$ (E-J). For $\alpha_s(10 \text{ GeV}^2) = 0.23 \pm 0.02$ corresponding to $\alpha_s(M_Z) = 0.113 \pm 0.004$ and four quark flavors. Our measurement is two standard deviations below this value, and is in good agreement with the EMC result using updated values of F_2 from the NMC. The value for all the above proton data combined is:

$$\Gamma_1^p(10 \text{ GeV}^2) = 0.142 \pm 0.008 \pm 0.011 \text{ (world)}$$

in agreement with the SMC and with the result from SLAC E143. From the combined EMC/SMC/E143 data we obtain:

$$\Delta\Sigma = 0.20 \pm 0.07 \pm 0.10 \text{ and}$$

$$\Delta s = -0.13 \pm 0.02 \pm 0.04.$$

In fact SLAC E142 has the only data in agreement with Ellis-Jaffe, giving a large value of $\Delta\Sigma$, and Δs consistent with zero, and this experiment is being repeated at higher beam energy (lower x).

¹⁶P. Amaudruz *et al.*, Phys. Lett. B295, 159 (1992)

¹⁷L. W. Whitlow *et al.*, Phys. Lett. B250, 193 (1990)

Fig. 8. The current world data on A_1^d and g_1^d at different values of Q^2 .

Fig. 9. The results of the various experiments for Γ_1^n and Γ_1^p .

The current world data on A_1^d and g_1^d are shown in Fig. 8, taken from our preprint which has been accepted for publication in Physics Letters. The results of the various experiments for Γ_1^n and Γ_1^p are shown in Fig. 9, in accord with the previous discussion. Plots comparing the SMC data and the world data to the prediction of the Bjorken sum rule are shown in Fig. 10. The Bjorken sum rule is confirmed by the totality of experiments at the 10% level. More accurate proton and deuteron data are being taken at CERN and SLAC. These data will both test the Bjorken sum rule and measure the quark spin structure of the nucleon with greater accuracy.

In addition to the scattered muon, the spectrometer also detects positively and negatively charged hadrons, mainly pions, produced in the deeply inelastic process. The observed asymmetries for positive and negative hadrons off polarized hydrogen and deuterium targets are shown in Fig. 11. Hadrons are selected so that $z \equiv E_{had} / \nu > 0.2$. It is then assumed that only favored fragmentation of the scattered quark takes place, e.g. $u \rightarrow \pi^+, K^+$ only. The observed asymmetries are then fit to obtain separately the structure functions of the up, down, and sea quarks, under the additional assumption that $\Delta \bar{u} = \Delta \bar{d} = \Delta \bar{q}$ for the sea quark structure function. (Fig. 12) To within the accuracy of these measurements, it seems that the up-quark spin tends to be aligned with that of the proton, the down-quark spin antialigned, and the sea unpolarized. The integrated values overall are:

$$\begin{aligned}\Delta u &= +1.01 \pm 0.19 \\ \Delta d &= -0.57 \pm 0.22 \\ \Delta \bar{q} &= -0.02 \pm 0.09\end{aligned}$$

where the errors are statistical. This constitutes the combined proton and deuteron data for four years of running the SMC experiment. The much cleaner and higher precision data on Δu , Δd , $\Delta \bar{u}$, $\Delta \bar{d}$, Δg that can be obtained at future spin physics facilities, such as polarized RHIC, are clearly necessary for an understanding of the detailed spin structure of the proton.

B. FNAL D0: Experiment and Upgrade

The D0 collaboration has completed taking data for run 1 of the FNAL collider. The analysis of this data is well in hand and we are now working on preparing for run 2 which will take place after the upgrade of the Tevatron main injector. Rice joined D0 after the construction of the run 1 detector but has participated in the taking and analysis of data from that run. Rice has played and will continue to play an important role in the design and construction of the tracking system for the run 2 detector. Here we report on our contributions to both runs.

Physics Goals and Current Status

D0 is a large general purpose detector for studying $\bar{p}p$ collisions at 1.8 TeV at the Tevatron. The detector design emphasizes the following capabilities:

1. good electron and muon identification over the full solid angle (leptons are excellent signatures for new physics),
2. precision calorimetry with fine segmentation and uniform, stable response (for good resolution in jet energy and position, high multi-jet efficiency, and single photon detection),
3. high resolution tracking, and
4. excellent missing transverse energy resolution (for detection of neutrinos and other non-interacting particles).

The general layout of the run 1 D0 detector is shown in Fig. 1. The central detector (CD) consists of a vertex detector, a set of transition radiation detectors, a central tracking chamber and forward tracking chambers. The CD is surrounded by three uranium-liquid argon calorimeters for electromagnetic and hadronic particle identification and energy measurement. The calorimeters are segmented to form towers of pseudorapidity and azimuth of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The full calorimeter coverage extends out to $|\eta| = 4.1$. Outside the calorimeters there is the muon system which consists of three large and two small magnetized toroids together with three layers of proportional drift tube chambers.

The physics goals of the D0 experiment include the following topics.

1. *Search for the top quark.* At the Tevatron the top quark is produced mostly in pairs, with each top decaying into a W and a b quark. The cleanest signature for top production is a final state with two large p_t leptons ($ee, e\mu, \mu\mu$) + missing E_t + jets. These channels have small branching ratios (1-2%) but are essentially free of backgrounds. The final state consisting of a single large p_t lepton + jets has a 30% branching ratio but suffers from larger physics backgrounds (W + jets) and instrumental backgrounds (jets faking electrons). The final state with six or more jets is very difficult due to QCD background. A signal was observed in run 1—run 2 will be used to confirm this observation and improve the precision of the mass measurement.
2. *Precision studies of electroweak physics.* Topics include production properties of W and Z (mass, width, cross-section, p_t dependence) using both electrons and muons. For example, D0 hopes to measure the W mass to within 0.25%. This mass combined with that of the top quark will constrain the Higgs mass. Other topics to be pursued are charge asymmetries in $W \rightarrow \mu + \nu$ and $Z \rightarrow \mu + \mu$.
3. *QCD studies / jet production.* D0 is able to measure inclusive jet cross-sections over a wide angular range, out to $|\eta| = 3.7$. This allows precision tests of QCD well outside

the central region. Multi-jet production and direct photon production are studied over the same range.

Fig. 1. Layout of the D0 detector

4. Search for new physics. D0 looks for evidence for supersymmetry (squarks, gluinos, ...), leptoquarks and for new heavy W's and Z's. In the absence of signals new search limits are established for these particles.

The D0 experiment started taking physics data in September 1992. Run 1a was completed in May 1993. Run 1b started in November 1993 and was completed last summer. The last run (1c) was completed in February 1996. We recorded an integrated luminosity of 115 pb^{-1} to tape.

The Rice D0 group presently includes faculty David Adams, Hannu Miettinen, Paul Padley and Ed Platner. In addition, Pablo Yepes and Geary Eppley have made contributions in the past. All are resident at Rice. We had a postdoc in residence at FNAL up until the middle of 1996 but are not presently looking to fill that position.

In D0, each group is expected to provide some amount of service work, *i.e.* contributions to the day-to-day running of the experiment beyond data analysis. These activities have included the following:

1. Representing the QCD analysis group on the Offline Computing Policy Board, serving as head of the University of D0 (which arranges weekly talks), serving on the Reconstruction and Analysis committee and numerous other committees;
2. Participating in data-taking shifts and
3. Membership on numerous editorial boards which review proposed publications.

Our biggest service contributions have related to detector upgrade with special emphasis on the tracking system. These are detailed in later sections.

Data analysis for all of run 1 is well advanced in all five physics subgroups (top, QCD, W/Z, B physics, new phenomena). Twenty-four papers have been published (most in PRL), another four submitted and numerous reports have been presented in various conferences and workshops.

The Rice group has participated in this analysis effort in the following physics subgroups: W/Z, top, and QCD. We were responsible for carrying out analyses and writing papers on W' and Z' searches. We have developed new multivariate analysis techniques which are now being applied to the top quark search and mass determination. We have carried out dijet searches for W and Z bosons and for new particles. These analyses are discussed in more detail below.

W' and Z'

Numerous extensions of the standard model predict additional gauge bosons. We have performed a direct search for a heavy charged gauge boson, W' , using the decay channels $W \rightarrow e\nu$ and $W' \rightarrow \tau\nu \rightarrow e\nu\nu\nu$. The data used in the analysis were collected during run 1a with an integrated luminosity of $13.9 \pm 0.8 \text{ pb}^{-1}$. Assuming that the neutrino from W' decay is stable and has a mass significantly less than that of the W' , we set an upper limit at the 95% confidence level on the cross section times branching ratio for $W' \rightarrow e\nu$. A W' with the same couplings to quarks and leptons as the standard model W boson is excluded for $m_{W'} < 610 \text{ GeV}/c^2$ (see Fig. 2a).

Fig. 2a. Limit for $W' \rightarrow e\nu$ compared to theory.

Fig. 2b. Limit for $Z' \rightarrow ee$.

We have also searched for evidence of a heavy neutral gauge boson, Z' , using the decay channel $Z' \rightarrow ee$. The data for this analysis represents an integrated luminosity of $14.9 \pm 0.9 \text{ pb}^{-1}$. We set a limit at the 95% confidence level on the cross section times branching ratio for $Z' \rightarrow ee$. We exclude the existence of a Z' with mass less than $490 \text{ GeV}/c^2$, assuming a reference model Z' with the same couplings to quarks and leptons as the standard model Z boson.

G. Eppley and P. Yepes were the principal authors of a paper from the D0 collaboration presenting the results of the W' search, which was published in Physics Letters B in September 1995. G. Eppley is the principal author of the Z' paper which has been accepted for publication in Physics Letters B. Data from Run 1b, corresponding to an integrated luminosity of 90 pb^{-1} , have been analyzed, extending the limit to $660 \text{ GeV}/c^2$ (See Fig. 2b). This data may be combined with the previous data to set a limit $M_{Z'} > 670 \text{ GeV}/c^2$. This latest result was first presented by G. Eppley at the 11th Topical Workshop on Hadrons in Collision, Padua, Italy, May, 1996.

Top Quark and Multivariate Analysis

During the past several years we have worked extensively on developing, testing, and applying multivariate analysis techniques for high energy physics. We have applied Neural Nets (NN) to top quark physics, in particular to cross section analysis of $\text{top} \rightarrow \text{lepton} + \text{jets}$, as documented in several D0 notes. We have developed an entirely new multivariate analysis method, the PDE (Probability Density Estimation) method, which is a conceptually simple, nonparametric method competitive with NN. A paper on the PDE method has been published in Computer Physics Communications.¹⁸ We have demonstrated that both NN and PDE methods outperform conventional analysis. Our NN/PDE analysis of $\text{top} \rightarrow \text{electron} + \text{jets}$ gave the first indication of the top quark signal at D0 in January of 1994, more than a year before the "official" discovery. The PDE method has been "blessed" by the D0 Collaboration and results obtained with the method have been approved for presentation in several major international conferences by us¹⁹ and by others at D0.²⁰ We have put together a PDE package (a stand alone FORTRAN program implementing the method) and written a PDE Primer describing the package and its usage.²¹ Numerous talks related to this work have been given at D0 by two of us (GE, HEM).

During the last year or so we have extended the PDE method to the realm of mass analysis, applicable to top quark and other mass analysis problems. The basic idea is to replace the PDE discriminant function $D(x)$ by a mass function $m(x)$ which computes the "best" top quark mass for a candidate event, given the values of some kinematic variables x . A paper describing the mass analysis method is in preparation, intended for Computer Physics Communications. We are currently applying this method to the run 1 data sets.

¹⁸ "A New Multivariate Technique for Top Quark Search", L. Holmstrom, S. Sain, and H.E. Miettinen, Computer Physics Communications 88, 195 (1995).

¹⁹ "Top Quark Search with Probability Density Estimates and Neural Networks", H.E. Miettinen, Fourth International Workshop on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics (AIHENP-95), Pisa, Italy, April 1995; "Top Quark Results from D0", H.E. Miettinen (for the D0 Collaboration), Fourth International Workshop on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics (AIHENP-95), Pisa, Italy, April 1995.

²⁰ "Search for Top at D0 using Probability Density Estimation", P. Virador (for the D0 Collaboration), General Meeting of the American Physical Society, Washington, D.C., April 1995.

"Multivariate Searches for the Top Quark", P. Bhat (for the D0 Collaboration), 10th Topical Workshop on Proton-Antiproton Collider Physics, Fermilab, IL, May 1995.

"Top Physics at D0", B. Klima (for the D0 Collaboration), 17th International Symposium on Lepton-Photon Interactions, Beijing, China, August 1995.

²¹ "PDE Primer", G. Eppley, H.E. Miettinen, and P. Virador, D0 Note 2526, April 1995.

Preliminary results, presented partially at the 1996 Snowmass Summer Study, suggest that the statistical precision on the top quark mass obtained with this method is significantly better than that from conventional analysis. Bruce Knuteson, a Rice undergraduate who has been working with us for over a year, has made significant contributions to this project.

We have recently improved upon the original PDE method by implementing "adaptive kernel estimation" for both discriminant and mass analyses. We continue to seek other ways of improving multivariate methods, and we are exploring other application areas as well. For example, the PDE mass analysis method can be easily applied to problems such as W mass determination, and we hope to attack this problem in the near future.

Dijet searches

The predictions of the Standard Model of particle physics have been confirmed by current high energy experiments with no significant observed deviations from the theory. Many extensions of the standard model predict the existence of new massive objects (e.g. additional vector bosons and excited quarks) that couple to quarks and gluons and will form resonant structures in the dijet mass spectrum.

A search for these resonances ($X \rightarrow jj$) was carried out using a data sample of 91 pb^{-1} . The data show no resonances and are in good agreement with NLO QCD as reported in D0 note 2864. The QCD dijet signal was fit by a smooth monotonically decreasing function plus a line shape representing the decay of a massive particle X . Limits on the number of $X \rightarrow jj$ events were then determined from this fit and are used to calculate 95% confidence limits on the cross-section of new particles. Excited quarks (qg) were ruled out up to a mass of 720 GeV as were W' bosons over the range $350 < M < 700 \text{ GeV}$ and Z' over various mass ranges. These results were reported at ICHEP 96 and have been submitted to DPF 96. Also see D0 note 2849.

Progress on the D0 Upgrade

Upgraded Detector Capabilities

Now that run 1 has been completed and most of the data analysis is completed or well underway, the attention of the of the D0 collaboration has turned to the detector upgrade planned for run 2. Considerable effort has been expended to design an upgraded detector which will maintain existing capabilities and still be able to deal with the ten-fold increase in luminosity planned for the next run. This increase in luminosity will enable us to extend the mass reach for particle searches and allow us to accumulate significantly more statistics in established channels. Important upgrades are planned for all subsystems of the D0 detector but the biggest modification is the central tracking system which will be completely replaced. The new tracker will include a solenoid (the current system is non-magnetic) to enable measurement of the transverse momentum of charged particles. This and a pre-shower system will allow D0 to maintain its excellent electron identification capabilities. A precise vertex detector coupled with the magnetic field will provide the tagging of B-quarks and other states produced from displaced vertices. Rice has played a major role in the design of this tracking system and in the evaluation of its expected performance.

The upgrade tracker is made up of an inner silicon microstrip detector and outer scintillating fiber system surrounded by a superconducting solenoid. The detector is described in D0 notes 1933, 2169 and 2542. The silicon system is made up of interleaved barrels and disks to provide hermetic coverage for $|\eta| < 3$. There are four barrels, 12 central disks and two endcap disks at each end. The four barrels are broken up into six

segments along z. All layers include strips parallel to the beam axis (i.e. measuring ϕ) and the second and outermost barrels are double-sided with a two degree stereo angle. The remaining barrel will have 90 degree stereo in the central region. The disks are double-sided with a 30 degree angle between the strip directions which are approximately radial.

The basic detection unit of the scintillating fiber tracker is the doublet: two adjacent layers of parallel scintillating fibers offset by half a fiber spacing so that the fibers in one layer cover the gaps in the next. The fiber tracker is made up of eight cylindrical superlayers. Each superlayer has one doublet with fibers parallel to the beam line to measure ϕ and one small-angle (1 mrad/cm) stereo doublet. The previous design with two stereo doublets on every other barrel (and none on the remaining barrels) provided some advantages for pattern recognition but is much more difficult to assemble. The eight well-separated layers are needed so the fiber detector can provide an effective first-level trigger.

Rice has contributed to the design and construction of the upgrade tracking system in many areas. We participated in a number hardware studies at FNAL which demonstrated the capabilities of the fibers, photodetectors (VLPC's) and associated readout electronics. We developed software to simulate the fiber system and to carry out track finding and fitting for the overall tracking system. These contributions are described below. We carried out a number of simulation studies to assess the capabilities of the fiber tracker and the relative merits of various options. These are summarized in a series of D0 notes: 2665, 2779, 2799 and 2869. The first of these shows we can expect close to 100% efficiency and an RMS position resolution of 80-90 microns with an average of 10 detected photons in a doublet (fibers have a diameter of 870 microns). We expect a signal almost twice this size. The other papers focus on the difficulty of doing local pattern recognition (matching axial and stereo fibers). Hardware considerations have driven us to a design where this local matching will be very difficult at high luminosities. D0 notes 2895 and 2918 respectively look at the options of using timing information and adding scintillating pads to help with this problem. Neither looks feasible with the budget constraints for run 2 but we might consider them again for a later run.

Software

The Rice group has developed and maintained two software packages which have been important in the design of the fiber tracker. SFT simulates the response of a scintillating fiber tracking system. Locally we also use it to provide a sensible simulation of a silicon microstrip tracker. The package TRF clusters raw scintillating fiber data to form hit coordinates, performs pattern recognition to link hits into tracks, fits the tracks to evaluate kinematic parameters and associates the found tracks with Monte Carlo tracks for performance evaluation.

The SFT package provides a detailed description of the response of a fiber tracker. The detector is described as a series of plastic disks or cylindrical shells and the input to SFT are the positions of energy depositions within these volumes. An appropriate fraction of this energy is assigned to each crossed fiber and the number of captured photons is proportional to this energy. The number of detected photons is obtained by accounting for the attenuation length of the scintillating fiber and the losses at the couplings, absorption in the optical fiber and the quantum efficiency of the photodetector. SFT has been used extensively for studies both at and away from Rice. It is an important component of the D0 upgrade software framework.

The bulk of our software development effort over the last few years has gone into the TRF package. The software was originally developed for use at the SSC and has been very useful in the study of the D0 detector. Although the luminosity and energy are much lower at D0, the small tracking volume and longer crossing time result in a similar complexity. TRF uses a road-following algorithm with a Kalman filter update. The novel feature is a facility for the user to provide a set of paths at run time. Tracks are found only along these paths and parameters such as the number of missed surfaces and maximum chi-square can be path-dependent. Thus the user may easily tune to trade CPU speed for track-finding performance.

We are still far from finding the "final" solution to the very difficult problem of finding tracks in the upgraded D0 detector at high luminosities. We expect occupancies on the order of 10% in the inner fiber layers with multiple interactions over a long interaction region. We have also had to accommodate frequent changes in the proposed layout of the tracking system culminating in a design optimized for triggering and ease of construction rather than for off-line pattern recognition. Nonetheless, TRF has been a useful tool for understanding the capabilities of the detector. We did carry out one study where we found that TRF performed well for crossings with no background events but found the CPU time increased rapidly as minimum bias background events were added.

TRF in its present form will not be adequate for analyzing the bulk of the D0 data. It has become increasingly difficult to upgrade due to the constraints inherent in its procedural design. Our work over the last year has concentrated on developing an object-oriented design to be implemented in C++. This direction is consistent with the plans for D0 run 2 software and the trends in HEP and commercial computing. The new framework is called TRF++ and is described at <http://www.bonner.rice.edu/adams/trf++/>.

TRF++ provides a much more flexible implementation of the design of its predecessor. The detector is described as a series of surfaces. Paths provide instructions for iteratively finding tracks along ordered lists of surfaces. A path is propagated to the next surface which is searched for nearby hits which are each separately added to the track. The track is refit and the quality is tested to reject ghosts. The algorithms for propagation, searching, fitting and testing are specified individually for each path surface. Replacements for these algorithms are easily added through the mechanism of inheritance. New surface descriptions may be added in the same way.

We have also developed the software package FTF for finding tracks at level 3. This last stage of the trigger only allows 25 ms/event and will not allow full event reconstruction. The Rice software, originally designed for use in the RHIC STAR detector, finds $r\text{-}\phi$ tracks in the fiber detector within this tight time constraint. A detailed description of the code will be soon published in *Nuclear Instruments and Methods* ²². The main features of the algorithm are an optimized data organization and a conformal mapping to speed up fitting procedures. The FTF performance in the D0 environment was studied and published in a D0 note²³. FTF was found to be 90 times faster than the on-line code with slightly deteriorated track finding efficiency and momentum resolution. However the number of fake tracks found by the fast algorithm was substantially larger than in the case of the off-line tracking. We believe this problem can be solved by tuning the program parameters.

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²² Pablo Yepes, *A Fast Track Pattern Recognition*, to be published in *Nucl. Instr. and Meth. In Nuclear Research A* (<http://bonner-pc8.rice.edu/yepes/projects/fft/fft.ps>).

²³ Helio da Motta, Alberto Santoro and Pablo Yepes, *A First Use of a Fast Algorithm in the D0 Upgrade Detector*, D0 Note 2893.

Hardware

VLPC's

VLPC's, an extremely interesting new technology, are able to detect single photons with high quantum efficiency ($>50\%$) and excellent energy resolution (30% single photo-electron resolution). They are solid state pixel devices, each pixel being approximately 1 mm in diameter, and they operate at liquid helium temperatures (~ 5 K). The VLPC pixels will be arranged into "cassettes" of 1024 channels residing in a LHe cryostat. A cassette will be considered operational if each channel passes a set of criteria set out in the purchasing contract with Rockwell. Each cassette will be tested to measure relative quantum efficiency, gain, single photo-electron energy resolution and dark count as a function of temperature and bias voltage. As part of this project, we have been constructing the system that will be used to test the VLPC channels.

VLPC Test Stand Electronics and Software

At Bonner Lab, we have assembled the electronics that will be used for testing VLPC's. They will be read out via VME using a FNAL ASIC, the SVX II. This ASIC will sit in a VME crate which is read out with a Bit 3 VME to PCI interface system into a Pentium PC computer. The SVX II will be driven by a number of pulse generators which will be controlled from the PC via a GPIB interface. The hardware for the initial system has been purchased. The prototype DAQ system will have to be delivered to FNAL in the fall of 1996 for testing of the prototype VLPC cassette.

We have written a preliminary version of the software which will operate the system, acquire the data and analyze it. The software is being written using modern industry standard procedures. This benefits our students who acquire skills which will be of use to them outside the field of particle physics. The software is a Windows based system written in C++. Three undergraduate students have been involved with the project. This system has been used with a GPIB interface from the PC to a CAMAC crate to acquire data from a phototube looking at a prototype light source. We are currently finalizing the VME based system that will be used in the production testing of the VLPC's. The resulting distributions of VLPC data are stored in HBOOK histograms and can be viewed in real time using PAW. In addition it will be possible to download the histograms to remote sites so that physicists in different locations can look at the data and study the progress of VLPC testing.

This data acquisition system is a prototype of the hardware that will be used in the completed D0 upgrade detector. All the hardware we are using (with the exception of the computer) consists of devices that will be used in the D0 detector. Thus the data acquisition system we are building is an important test for these devices. As part of this project have been heavily involved in debugging these devices. In the past year Iain Bertram oversaw the work of engineers and technicians at FNAL developing and testing some of these systems. A number of studies of the SVX II chip were completed using the charge injector described in the next section and the results will be published.

The SVX II was connected to an operating VLPC chip and the results look good. Fig. 3 shows the relationship between the number of photoelectrons and the SVX channel for two different SVX II preamp settings. This is for HISTE IV VLPC's being lit by a LED pulser. We expect 3 times more gain for HISTE V VLPC's. Fig. 4 shows a spectrum for a preamp setting of 8 with the first four photopeaks fitted to gaussians.

FemtoCoulomb Charge Injector

We designed and built a 4 channel prototype femtoCoulomb charge injector which produces simulated VLPC signals, a schematic of which is shown in Fig. 5. We are presently designing a 32 channel VME based version of the system. This circuit board has been used in the testing of electronics, data acquisition systems and triggering for both the fiber and silicon tracking systems of the upgrade. Simulating the small signals produced by the VLPC system represented a significant engineering challenge which we at Rice were proud to accomplish.

Central Fiber Tracker (CFT) Stereo Board:

The CFT board is responsible for reading out the stereo layers of the Central Fiber Tracker. Presently we are involved in the design of a prototype version of the board that incorporates most of the features of the final board that will be used in the upgraded D0 detector. This is a 9U VME board conforming to the D0 custom backplane which will read out the VLPC's, amplify and digitize the signals using the SVX II chip and pass the results along to the DAQ system. This version of the board will be used for the VLPC test stand DAQ system. It is a prototype of the board that will reside on the VLPC cassettes in the final design.

Fig. 5. Schematic of VME femtoCoulomb charge injector

C. CERN LHC: CMS

Introduction

At Rice, we remain optimistic that high energy hadron colliders will be a very important tool in making progress on the many open questions in particle physics today. The standard model of strong and electroweak interactions provides impressive agreement with all known high-energy physics observations, but many physicists believe that it must be incomplete, as many experimental parameters, including the quark and lepton masses, the quark mixing angles, and the nature of the Higgs sector, need to be inserted by hand.

Physics beyond the standard model, such as supersymmetry, grand unification, and superstrings, is capable of predicting many of these parameters from fundamental principles. New phenomena predicted in the mass range accessible at the LHC includes a complete elucidation of the Higgs sector and the likely discovery of many new particles, i.e., the superpartners of the Standard Model quarks, leptons, and gauge bosons. These potential discoveries, and more probably those yet to be imagined, will most likely occur at a hadron collider with a detector which emphasizes high quality lepton detection. Such a detector is the one being designed for use at the LHC: the Compact Muon Solenoid (CMS) detector.

Discovery Potential for New Physics

The CMS detector is designed to detect many of the diverse signatures of new physics by identifying and precisely measuring muons, electrons and photons over a large energy range and at high luminosity. For instance, a standard model (SM) Higgs boson with mass between 95 and 150 GeV would be discovered via its two photon decay after an integrated luminosity of about $3 \times 10^4 \text{ pb}^{-1}$. The same integrated luminosity gives a discovery range of 135 to 525 GeV in the four lepton decay modes of the Higgs. An integrated luminosity of 10^5 pb^{-1} would allow discovery in these channels in the range 85 to 700 GeV. Adding the two lepton two jet channels extends the discovery range for the Higgs up to 1 TeV.

The two photon and four lepton channels are also crucial for the discovery of a Higgs boson in the Minimal Supersymmetric Standard Model (MSSM). The excellent detector resolution and good acceptance can be used to search for the narrow intermediate mass Higgs bosons predicted by such models. In addition events with multiple high energy jets and large missing transverse energy are the most obvious model independent signatures in searches for the supersymmetric partners of quarks and gluons. The background in CMS due to jet events faking missing E_T because of cracks or tails in the energy resolution is found to be well below that from physics backgrounds.

Other physics will also be possible with this general purpose detector. For example the copious production of B mesons allows for the measurement of CP violating effects in the B system. Also it will be possible to search for the quark gluon plasma using Upsilon production when the LHC is running as a heavy ion collider.

Detector Characteristics

The design goals of the CMS experiment are enumerated below:

- 1) a very good and redundant muon system
- 2) the best possible electromagnetic calorimeter
- 3) a high quality central tracker

4) a financially affordable detector

The resulting detector design is shown in **Fig. 1**. The tracking system consists of a silicon pixel detector close to the interaction region and gas microstrip detectors. Surrounding the tracking system is a $PBWO_4$ electromagnetic calorimeter read by photomultipliers. Next comes a hadronic calorimeter which consists of sandwiches of copper plates and plastic scintillator with embedded WLS fibers. This is surrounded by the return yoke of the magnet, which contains the muon detection system.

The Rice participants in CMS include David Adams, Marj Corcoran, Hannu Miettinen, Jay Roberts, Ed Platner, and Paul Padley. We are making use of our technical expertise in electronics design, track finding, and collider physics in general to design the electronics and trigger system of the muon endcap (EMU) and the overall tracking software. The experience of Ed Platner, Mitch Wright, and Paul Padley with detector electronics is a welcomed and needed addition to the collaboration. David Adams is writing the software for the inner tracking, building on his work with the SDC and D0. The experience of Adams and Padley with object oriented software will be important for the overall software development for CMS. The collider physics experience of Hannu Miettinen as well as Pablo Yepes and Geary Eppley from the Bonner Lab Nuclear Physics Group will also prove useful.

End Cap Muon System (EMU)

An appropriate match between our long term physics interests and adequately challenging our technical capabilities is found in the End Cap Muon System, to which we are expected to make a major contribution. EMU is a crucial component of the CMS detector. For example, 60% of Higgs to four muon decays will have a track in the EMU. The design of the EMU is such that there are four layers of muon chambers embedded within the magnet's return yoke. Each muon chamber subtends either 10 or 20 degrees of azimuth and consists of 6 layers of cathode strip chamber, each with a 9.53 mm gas gap. Each layer of a chamber has cathode strips running in the radial direction. There will be 80 strips in a 10 degree section. Anode wires will be strung perpendicular to the anode strips. The wires will have 3.175 mm spacing and will be read out in groups of 16. Both views are read out, which allows the construction of a 3 dimensional muon track stub when the 6 layers of the chamber are used. Fig. 2 shows the arrangement of chambers for one end cap.

Fig. 2. Arrangement of chambers for one muon end cap.

Fig. 3. Equipotentials in the muon chambers as originally proposed.

Fig. 4. Equipotentials for the arrangement which we proposed for the muon chambers. Note that the addition of potential wires in between the anode wires reduces the size of the dead region significantly.

Our first study was of the electrostatics of the chamber configuration. Fig. 3 shows a Garfield plot of the field for the nominal chamber design. Clearly there is a region of small field variation between the sense wires which will have long drift times. These drift times can be significantly longer than the beam crossing time and so a method (described below) is needed to associate a track stub with a particular bunch crossing.

We examined the possibility of eliminating this problem by changing the field configuration of the chamber. Fig. 4 shows what happens when potential wires are added between the anode wires. The size of the dead region is significantly reduced. Fig. 5 shows the efficiency for detecting a hit within a certain time window for different configurations of the field. While there is a clear advantage to using field wires from this standpoint, other issues such as difficulty of construction will also have to be taken into consideration in order to reach a decisive conclusion.

An important component of this discussion is the use of fast amplifier shaper electronics that allows detection of the first electron that enters the avalanche region. Fortunately, such an amplifier shaper system

was developed for the SDC at the SSC. This electronics is now sufficiently mature that it is in use in two applications where fast timing is required (E-896 drift chamber at the

AGS and the MWC trigger for STAR - both systems being developed here at Rice).

We have proposed to CMS that this ASIC be used for the anode wire read out regardless of the field configuration of the chambers. The only modification that would be required is to the input impedance of the chip to make it optimal for the EMU CSC's.

Fig. 5 Efficiency of recording a hit as a function of the time in ns. Four plots are shown corresponding to different spacings of wires, with and without additional field wires.

capped at a few kHz. For a P_t threshold of 20GeV/c, a momentum resolution of 30% is required to achieve this limit. This can be achieved if track hits can be localized to within half a cathode strip width. This is done using a comparator network as diagrammed in Fig. 6.

The digital signals generated by the comparator network are fed into the front end trigger processor card, called the LCT. There are 4 or 5 such cards per chamber, each

Fig. 6. The strip comparator circuit. If $Q_{n-1} > Q_{n+1}$ then track is on the left side of strip n for $Q_n > \text{Threshold}$, $Q_n > Q_{n-1}$ and $Q_n > Q_{n+1}$.

looking at an azimuthal section of the chamber. The LCT card sees the signals from all 6 layers of a chamber within a fraction of the azimuth. It uses a combination of FPGA's and memory lookup tables to link hits from the different layers to form a track stub. Since a track above the momentum threshold can deviate at most 2.5 strips within a chamber the number of possible strip combinations easily fits within a memory look up. This includes combinations with noise and missing hits. A similar card performs the same steps for the anode wires. Currently the design of the LCT cards allows for only one muon

stub to be passed up the trigger chain from each card. At Rice, we are doing a Monte Carlo study to determine the consequences of this decision. Preliminary results indicate that there is no significant loss of physics potential by imposing this restriction.

The front end LCT processor cards will pass their track stubs to the trigger mother board. Fig. 7 shows the arrangement of front end cards and the mother board on a muon chamber. Fig. 8 is a schematic of EMU SC Trigger scheme. The mother board will match the information from the anode and cathode LCT cards and pass the information up the trigger chain to a "consolidator" card. There will be one mother board for each muon chamber and one "consolidator" for each 30 degree azimuthal sector of the muon chamber system. The Rice group has studied how many tracks each motherboard needs to pass on up the trigger chain and has found that at least two track stubs should be passed on. This is a preliminary result and the work is continuing. Our group will design and build the trigger mother board.

CMS Software Progress

Our major contribution to the CMS software environment so far has been the design of an object-oriented track finding system. This is being designed with both D0 and CMS in mind and is described in the D0 software section of this document. An early version was presented and was well received at the June CMS week at CERN.

Fig. 7. View of a 10 degree muon chamber showing the arrangement of front end cards and the mother board.

Fig. 8. Schematic of EMU CSC trigger scheme.

D. FNAL E832 and E799 Phase II: KTeV

Introduction

Fermilab experiment E832 will study CP violation in the neutral kaon system, and E799 will study a wide range of rare K decays. These experiments, referred to as KTeV (Kaons at the Tevatron), are just beginning first data-taking in August of 1996. Although CP violation was discovered in the neutral kaon system in 1964, its origin still eludes us. In the standard model with three generations of quarks, CP violation arises from a non-zero phase in the CKM matrix element V_{ub} . Standard model predictions for $\text{Re}(\varepsilon'/\varepsilon)$ range from $3-10 \times 10^{-4}$, using the current best value of the top mass. However, other models, such as Wolfenstein's superweak model, have not been ruled out. CP violation has yet to be seen outside the neutral kaon system, although experiments to look for CP violation in the neutral B system are under construction.

The object of E832 is to measure the CP violating parameter $\text{Re}(\varepsilon'/\varepsilon)$ to a precision of 10^{-4} , which will put strong constraints on parameters of the standard model. A non-zero value for $\text{Re}(\varepsilon'/\varepsilon)$ would be definitive evidence for direct CP violation, in which a CP eigenstate of one sign decays directly into a CP eigenstate of the opposite sign. The best measurement of $\text{Re}(\varepsilon'/\varepsilon)$ is $7.4 \pm 5.2 \text{ (stat)} \pm 2.9 \text{ (sys)} \times 10^{-4}$ from FNAL E731, a value consistent with zero. CERN experiment NA31 reported $33 \pm 7 \text{ (stat)} \pm 8 \text{ (sys)} \times 10^{-4}$,²⁵ which disagrees with the E731 result by about 2.5 standard deviations. Both groups are pursuing more precise experiments. E832 will also extend the limits on certain CPT violating parameters. These measurements are pertinent since string theories, unlike quantum field theories, allow CPT violation.

In addition to CP studies, KTeV will study a wide range of rare decays of the K_L , reaching sensitivities of 10^{-11} for many modes. One day of KTeV data will be equivalent to the entire world's sample from all other experiments for many of these modes. We at Rice are particularly interested in lepton-number violating modes such as $K_L \rightarrow \pi^0 \mu e$ and $K_L \rightarrow \mu e$. As an example, we expect an improvement in the single event sensitivity for $K_L \rightarrow \pi^0 \mu e$ from 2.7×10^{-9} , the E799-I result, to about 7×10^{-11} for E799-II.

Current Status of KTeV

The KTeV detector consists of a state-of-the-art CsI electromagnetic calorimeter to measure the neutral decays of the K^0 and a precision spectrometer to measure the charged decays. There are two parallel neutral beams. For the $\text{Re}(\varepsilon'/\varepsilon)$ measurement a fully active regenerator moves from one beam to the other every spill. An array of photon vetoes both in the decay region and in the spectrometer detects decay products which miss the CsI. Fig. 1 is a plan view of the detector.

We began installation in the experimental hall in August of 1995. Most of the detector was staged in other areas of the lab, so that installation is now complete and all major subsystems are working. We received first muon beam on July 31, 1996. Due to preparation and testing beforehand, the detector came up quickly. We expect first hadron beam in late August of 1996, with first physics-quality data a month later. A problem with CsI readout electronics will necessitate a replacement of one chip in each channel of the CsI array. Useful data can be taken before the replacement is done and we expect to have replacement chips by mid to late September. KTeV is on track for exciting physics results sometime in 1997.

²⁴ L. K. Gibbons et al, Phys. Rev. Letters, 70, 1203 (1993).

²⁵ H. Burkhardt et al, Phys. Lett, B206, 169 (1988).

Fig. 1. Plan view of the KTeV detector. Note the greatly expanded vertical scale compared to the horizontal scale. The Mask Anti, immediately upstream of the regenerator, vetoes on beam halo particles. Ring counters (RC6-RC10) and spectrometer anti-counters (SA2-SA4 and CSI) veto events in which particles miss the chambers or calorimeter. C1-C4 are the drift chambers. TRD1-8 are transition radiation detectors for particle identification for E799.

KTeV Drift Chambers

The Rice group joined KTeV in March of 1992. Our hardware contribution to the experiment was the rebuilding of the four large drift chambers in the spectrometer. These chambers were used in two previous experiments at Fermilab, where they achieved excellent spatial resolution (80 microns), but had problems with failure of cathode wire solder joints, making them unreliable during the run. This was solved by replacing the Be-Cu wires with gold-plated aluminum wires strung at lower tension, a change having the additional advantage of reducing multiple scattering in the chambers. In over three years we have not had a single failure of the new cathode wires. We also had problems with sense wire failures due to the tungsten wire pulling out of the gold plating. These problems were solved by reinforcing the solder joint with a brass pin which holds the wire in place with friction. No failures of the sense wires have occurred since the "pin" technique was adopted a year and a half ago.

All four chambers were rebuilt at Rice with these and other improvements. The chambers returned to Fermilab in July of 1995 and underwent a system test with the full electronics, TDC's, and DAQ system before installation in the KTeV hall. The Rice group worked closely with the Rutgers group, who built the new electronics, in this system test. Since installation in March of 1996, the chambers have been running stably, with low dark current, and without a single failure. The Rutgers electronics allows us to run the chambers 150V lower than previously, providing greater stability and longer lifetime. The chambers were tested with cosmic rays before we received first muons. We could therefore reconstruct tracks as soon as we had real particles through the chambers. Fig. 2 shows a reconstructed muon in the KTeV detector.

Aluminum Wire Tension Loss

A known effect with aluminum wire is a long-term tension loss, or "creep". We have observed such an effect over a time scale of over two years in the aluminum cathode wire used to restring the drift chambers. We see a loss in tension from the original 140g to 100g over this time period. Based on our own measurements and the measurements of other groups, we can expect a small additional loss in tension over the next two years to about 90-95g. We have studied the effects of this loss both with measurements on a test chamber and with field calculations done with the CERN library package POISSON. We conclude that there will be no observable effect on chamber operation at least down to a cathode wire tension of 70g, and probably no effect down to 50g, considerably less than the 90g we expect at the end of the experiment. Fig. 3 shows the measured tension in a sample of 15 cathode wires over a period of about two years.

Fig. 3. Wire tension vs. time for a sample of aluminum cathode wires used in the KTeV drift chambers.

Analysis Efforts

During the past year we have begun Monte Carlo studies of the lepton number violating modes $K_L \rightarrow \pi^0 \mu e$ and $\pi^0 \rightarrow \mu e$. These studies were the subject of senior theses for Rice physics majors Angela Bellavance and Michelle Chabot. Now that installation and commissioning are nearly complete we expect to devote more time to analysis of both data and Monte Carlo.

Personnel involved in this effort are Marj Corcoran and Paul Padley. Graduate student Julius Barnes received an MA degree in June of 1995 based on work on the KTeV drift chambers. A total of five Rice physics majors have done senior research on this project. One of these, Angela Bellavance, is remaining at Rice for graduate school with the intention of working on KTeV. There is a strong possibility of another graduate student in the incoming class in the fall of 1996. In addition to these students, five other Rice undergraduates received valuable research experience working with us. One Rice senior physics major plans to do his senior thesis on KTeV during the 1996-97 academic year.

E. FNAL E683: Photoproduction of High p_t Jets

Introduction

In Fermilab E683 we have studied the photoproduction of high p_t jets. Rice is the lead institution on this experiment with Marj Corcoran as spokesperson. Collaborating institutions are Ball State University, Fermilab, University of Iowa, University of Maryland, University of Michigan, and Vanderbilt University. The experiment took data in 1991.

The Wide Band Photon Beam at Fermilab provides the world's highest energy tagged photon beam, with useable photon fluxes up to 400 GeV. Fig. 1 shows a plan view of the detector. The calorimeter covers about 2 units of η with full azimuthal coverage. At our low $\sqrt{s}$, leading order (LO) QCD predicts $\sim$ equal contributions from the direct (point like) and resolved (photon is $q\bar{q}$) processes. Information on the photon structure function is potentially measurable in this experiment. However, at next-to-leading order (NLO), the distinction between direct and resolved processes becomes blurred. In fact, the NLO direct process is topologically equivalent to the LO resolved process. Fig. 2 shows examples of the LO direct and resolved processes of interest to E683

First order QCD calculations for these processes are available from a variety of sources. A NLO calculation for the direct processes, combined with the first order resolved processes, has been available for some time from J. Owens and coworkers. A NLO calculation which includes both direct and resolved processes is expected soon from Owens and Harris.

Physics results from E683

1. By triggering on total E_t , we observe a sudden shift in event topology with increasing E_t . A much weaker shift in event topology is observed in πp interactions under identical conditions. Similar results have been seen in pp interactions at much higher energies, but ours is the first such observation at fixed-target energies. Our

observations are consistent with known differences between photons and hadrons, given the harder structure functions of photons.

2. Observed jet structure for γp interactions agrees well with calculations for distributions such as jet E_T - flow, azimuthal angle between the jets, and forward energy flow. Even the underlying event is well described by a LO Monte Carlo, which is often not the case for πp or pp interactions. We observe that πp interactions in the same kinematic region exhibit more underlying event and larger acoplanarity between the jets. However the forward energy is surprisingly similar for γp and πp interactions.

3. A-dependent effects similar to those seen in $pA \rightarrow \text{jets}$ are seen in both γA and πA interactions, but at a somewhat reduced level, particularly in the photon case. A nuclear enhancement to jet p_T imbalance or " k_T " is seen in our data.

4. Both single jet inclusive and dijet cross sections have steeper p_T dependence than would be expected from first-order QCD calculations, indicating a substantial NLO contribution.

5. The fraction of the beam momentum that appears in the jets is called x_T , even though it is not a complete parton distribution function due to triggering and acceptance effects. LO processes predict $x_T = 1$. Including acceptance and kinematic cuts, a LO Monte Carlo indicates that the observed x_T distribution is softer than expected, with no peak or enhancement at $x_T = 1$. A higher order calculation (with detector acceptance and smearing included) is much closer to our data, although still not perfect.

E683 has been the thesis experiment for six M. A. degrees, four Ph.D.'s, with another four anticipated within the next year.

Fig. 2. (a) QCD point like processes. (b) Example of a resolved process where the photon is a $q\text{-}\bar{q}$.

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Publications

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- "SDC Technical Design Report," Solenoidal Detector Collaboration, SDC-92-201, SSCL-SR-1215 (1992).
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- "Measurements of the Photon Structure Function," D. Lincoln for the E683 Collaboration, *The Fermilab Meeting, Proceedings of DPF 92*, World Scientific, Singapore, 1993.
- "The A-dependence of the K_T of Photoproduced Jets," D. Naples for the E683 Collaboration, *The Fermilab Meeting, Proceedings of DPF 92*, World Scientific, Singapore, 1993.
- "A Study of Photon-Nucleus Collisions at High Transverse Energy," Q. Zhu for the E683 Collaboration, *The Fermilab Meeting, Proceedings of DPF 92*, World Scientific, Singapore, 1993.
- "Detecting Beam Pileup for High Rate Particle Beams," D. Lincoln and D. Naples, Nucl. Instrum. and Meth. A 332, 23 (1993).
- "Preliminary Results in Measurement of Inclusive Jet Photoproduction Cross Section at Fermilab Wideband Photon Lab," P. Birmingham for E683 Collaboration, submitted to *The Albuquerque Meeting Proceedings of DPF 94*.
- "Preliminary Dijet Photoproduction Cross Section," C. Halli for E683 Collaboration, submitted to *The Albuquerque Meeting Proceedings of DPF 94*.
- "Observation of Jet Production by Real Photons. E683 Collaboration, D. Adams *et al.*, Phys. Rev. Letters 72, 2337 (1994).
- "A Dependence of Photoproduced Dijets," E683 Collaboration, D. Naples *et al.*, Phys. Rev. Lett. 72, 2341 (1994).
- "A Hidden Bias in a Common Calorimeter Calibration Scheme," D. Lincoln, G. Morrow and P. Kasper, Nucl. Instrum. Meth. A 345, 449 (1994).
- "The Emergence of Jet Dominance in γ - p Interactions at Fixed Target Energies," E683 Collaboration, D. Alton *et al.*, submitted to Phys. Rev. Lett.
- "Photon Structure Function at $\sqrt{s} = 21$ GeV," G. Morrow, submitted to *The Minnesota Meeting, Proceedings of DPF 96*, Minneapolis, August 12-17, 1996.
- "The Emergence of Jet Dominance in γ - p Interactions at Fixed Target Energies," D. Alton for E683 Collaboration, submitted to *The Minnesota Meeting Proceedings of DPF 96*.

Presentations:

- "The Physics Research Program at the Bonner Lab," B. Bonner, Physics Department Colloquium, Rice University, November 6, 1991.

- "Spin Asymmetries in Hadron Scattering and the Spin of the Proton," J. Roberts, High Energy Physics Seminar, University of Trieste, February 18, 1992.
- "Calibration of the E683 Main Calorimeter," G. Morrow for the E683 Collaboration, Fall Meeting of the Texas Section of the American Physical Society, Rice University, November 1992.
- "E683 - Photoproduction of Jets," W. Davis for the E683 Collaboration, Fall Meeting of the Texas Section of the American Physical Society, Rice University, November 1992.
- "On Determining x_{Bj} from Jet Measurements," D. Lincoln for E683 Collaboration, The Fermilab Meeting DPF92, Fermilab, November 10-14, 1992.
- "A Study of Photon-Nucleus Collisions at High Transverse Energy," Q. Zhu for E683 Collaboration, The Fermilab Meeting DPF92, Fermilab, November 10-14, 1992.
- "First Results from Fermilab E683," M. Corcoran, High Energy Physics Seminar, Argonne National Lab, February, 1993.
- "The Spin of the Nucleon," J. B. Roberts, Physics Colloquium, Rice University, April 17, 1993.
- "Results from SMC on the Spin Structure Function of the Deuteron," M. Lowe for the Spin Muon Collaboration, Hadron 93, Como, Italy, June 25, 1993.
- "Results from Fermilab E683," M. Corcoran, High Energy Physics Seminar, University of Chicago, October, 1993.
- "Photoproduction of Jets: Fermilab E683," D. Lincoln, Fermilab Joint Experimental and Theoretical Seminar, Fermilab, October, 1993.
- "Novel Approaches to the Top Search," H.E. Miettinen, D0 Collaboration meeting, Fermilab, March 24, 1994.
- "Hard Scattering Processes," M. D. Corcoran, invited talk at the Washington Meeting of the APS, April 1994.
- "The SMC Experiment," J. B. Roberts, invited talk, The Albuquerque Meeting, DPF 94, Albuquerque, August 2-6, 1994.
- "Search for New Gauge Bosons at D0," G. Eppley, The Albuquerque Meeting, DPF 94, Albuquerque, August 2-6, 1994.
- "Performance of a Large Scale Scintillating Fiber Tracker using VLPC Readout," I. Bertram, The Albuquerque Meeting, DPF 94, Albuquerque, August 2-6, 1994.
- "Searching for Top with Multivariate Techniques," H.E. Miettinen, High Energy Physics Seminar, Michigan State University, Lansing, December 2, 1994.
- "Results from the D0 Experiment at Fermilab," H.E. Miettinen, Physics Colloquium, University of Jyväskylä, Jyväskylä, Finland, January 1995.
- "The Search for Additional Heavy Gauge Bosons at the D0 Experiment," G. Eppley, D0 Collaboration Meeting, Fermilab, January 27, 1995.
- "Top Quark Results from D0," H. E. Miettinen, Fourth International Conference on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics, Pisa, Italy, April 3-8, 1995.
- "Top Quark Search with Probability Density Estimates and Neural Networks," H. E. Miettinen, Fourth International Conference on Software Engineering and Artificial Intelligence for High Energy and Nuclear Physics, Pisa, Italy, April 3-8, 1995.
- "Discovery of the Top Quark," H. E. Miettinen, Physics Colloquium, Rice University, April 12, 1995.
- "Photoproduction of Jets, Results from E683," M. Corcoran, HEP Seminar, University of Texas, Austin, April 1995.
- "Why Bother with Particle Physics," P. Padley, Physics Colloquium, University of Edinburgh, May 4, 1995.
- "Rapidity Gaps Between Jets at D0 and CDF," I. A. Bertram, 10th Topical Workshop on Proton Antiproton Collider Physics, Fermilab, May 9-13, 1995.
- "Observation of the Top Quark," P. Yepes, XXIII International Meeting on Fundamental Physics, Comillas, Spain, May 23, 1995.
- "Why Bother with Particle Physics," P. Padley, Physics Colloquium, Rice University, September 27, 1995.
- "Hard Scattering Nuclei," M. Corcoran, Fields Fest, 65th Birthday Celebration for Tom Fields, Argonne, IL, October 1995.
- "Photoproduction of Jets, Results from E683," M. Corcoran, HEP Seminar, University of Wisconsin, Madison, November 1995.
- "The KTeV Experiment," M. Corcoran, University of D0, Fermilab, March 1996.
- "The KTeV Experiment," M. Corcoran, Southern Methodist University, April 1996.
- "Searches for New Particles at D0," G. Eppley, 11th Topical Workshop on Hadrons in Collision, Padua, Italy, May 26 - June 1, 1996.
- "Multivariate Methods Applied to Top Quark Physics," B. Knuteson and H. E. Miettinen, Snowmass Summer Study on Future Directions for High Energy Physics, Snowmass, June 24 - July 12, 1996.
- "Photon Structure Function at $\sqrt{s} = 21$ GeV," G. Morrow, The Minnesota Meeting, DPF 96, Minneapolis, August 12-17, 1996.

Theses:

- "Design and Construction of a Large Area Multi-wire Proportional Chamber," S. Eichblatt, M.A. Thesis, Rice University, April 1992.
- "Simulating $Z' \rightarrow e^+e^-$ Events at $\sqrt{s} = 40$ TeV to Evaluate a Proposed Silicon-Scintillating Fiber Tracking System for SDC," G. Eppley, M.A. Thesis, Rice University, April 1992.
- "A Study of Photon-Nucleus Collisions at High Transverse Energy," Q. Zhu, Ph.D. Thesis, Rice University, September 1992.
- "Calibration of the E683 Main Calorimeter," G. Morrow, M.A. Thesis, Rice University, April 1993.
- "Design & Construction of a γ Shower Position Detector," J. Xu, M.A. Thesis, Rice University, April 1993.
- "Observation of Jet Photoproduction and Comparison to Monte Carlo Simulation," D. Lincoln, Ph.D. Thesis, Rice University, August 1993.
- "Measurement of the Polarization of the Muon Beam for the SMC Experiment," T. Gaussiran, Ph. D. Thesis, Rice University, April 1994.
- "The SMC μe Elastic Scattering Polarimeter," J. Cranshaw, Ph.D. Thesis, Rice University, March 1995.
- "Drift Chambers for KTeV," J. Barnes, M.A. Thesis, Rice University, April 1995.
- "Search for Additional Gauge Bosons at D0," G. Eppley, Ph.D. Thesis, Rice University, April 1995. (Awarded the Rice Physics Department's H. A. Wilson prize for the outstanding Ph. D thesis.)
- "Search for Evidence of Photoproduction of Higher-Twist QCD Events at Experiment 683 at Fermi National Accelerator Laboratory," M. Traynor, Ph.D. Thesis, Rice University, October 1995.
- "A Precise Measurement of the Polarization of a 200 GeV Muon Beam in a Polarized deep Inelastic scattering experiment at CERN," S. Eichblatt, Ph.D. Thesis, Rice University, June 1996.

III. Task B: Theoretical High Energy Physics

A. Progress on Theoretical Topics: Paul Stevenson

$\lambda\Phi^4$ Theory

We have continued to advocate our ideas, developed in collaboration with M. Consoli, concerning $\lambda\Phi^4$ theory. In our picture the continuum limit of the theory is "trivial" (in the sense that all scattering amplitudes vanish), but it does not correspond to just taking the $\lambda_R \rightarrow 0$ limit of renormalization-group-improved perturbation theory (RGIPT). The importance of this work is that it implies very different phenomenological consequences for the Standard Model, allowing a very heavy Higgs that is nevertheless relatively narrow.

Our picture violates a number of existing theoretical prejudices, and there have been many objections from referees. We have been at pains to answer these fully, and to re-examine, re-check, and clarify our arguments in every way possible. A paper devoted entirely to criticizing our work has appeared in print²⁶ and we have written a detailed rebuttal to this. Firstly, the constant-field re-scaling that the author considers is not the same as ours, so his results have no relevance to our work. Secondly, his discussion is wholly based on results obtained from RGIPT - and we have already clearly stated that our nonperturbative approach and conventional RGIPT are not compatible.

This controversy has focused our attention on a really crucial distinction between our approach and the conventional one. The RGIPT approach assumes that spontaneous symmetry breaking (SSB) is a second-order phase transition; that is, the transition occurs when the physical mass in the symmetric phase becomes exactly zero, so that the origin changes from a minimum to a maximum of the effective potential. Our results say that the transition is actually first order; the SSB phase appears while the symmetric-phase mass is still positive; i.e., while the origin is still a local minimum of the effective potential. (The subtlety is that the symmetric-phase mass m is vanishingly small in units where the SSB-phase mass m_h is finite.) Obtaining a continuum limit of a lattice theory requires $(\text{correlation length})/(\text{lattice spacing}) \rightarrow \infty$ or equivalently, $(\text{physical mass})/(\text{cutoff}) \rightarrow 0$. If the transition is second order, then one can obtain a continuum limit, for any value of the bare coupling, just by tuning the bare mass-squared to its critical value. However, for a first-order transition, the continuum limit requires not only tuning the bare mass-squared, but also sending the bare coupling to zero in a particular way (like $1/\ln(\text{cutoff})$).

Our picture makes the striking prediction that the *exact* form of the effective potential is given by a sum of ϕ^2 , ϕ^4 , and $\phi^4 \ln \phi^2$ terms (with the ϕ^2 term being absent in the classically-scale-invariant case). This form shows the first-order character of the transition, in contrast to the predictions of RGIPT. Data from lattice simulations²⁷ provides a stringent test of these predictions. Our form fits the data to high precision, while it is not possible to get an acceptable fit with any the RGIPT formulas to be found in the literature. The lattice evidence continues to grow in precision and range of parameters studied.

²⁶ R. Tarrach, Phys. Lett. B 367, 249 (1996)

²⁷ A. Agodi, G. Andronico, and M. Consoli, Z. Phys. C 66, 439 (1995); P. Cea, L. Cosmai, M. Consoli, and R. Fiori, hep-th/9505048 and 9603019.

We have also searched for fresh ways of approaching the $\lambda\Phi^4$ problem, so as to put a new perspective on the debate. We have found such an approach by taking a “particle” viewpoint and exploiting the connection with the atomic-physics problem of a weakly interacting, dilute Bose gas. As is well-known, the nonrelativistic limit of $\lambda\Phi^4$ theory corresponds to particles interacting via a $\delta^{(3)}(\vec{r})$ potential²⁸. Our crucial insight is that, relativistically, the interparticle potential also has a $-1/r^3$ component arising from particle-pair exchange via the “fish” diagram. This attractive, long-range potential provides an energy gain that can offset the repulsion and rest-mass energy costs, causing a finite particle density to be favored over the empty vacuum. This corresponds to the SSB phase transition. The important point is that it occurs when the original particle’s physical mass is sufficiently small, but still non-zero. That is, the SSB transition is first order.

Briefly, the energy density associated with a density n of particles with zero 3-momentum has three terms; nm from the rest-mass cost, an n^2 term from the pairwise $\delta^{(3)}(\vec{r})$ repulsions, and an $n^2 \ln n$ term from the pairwise attractions. The $\ln n$ arises because a $-1/r^3$ interaction would give an infinitely negative contribution, but for the fact that intervening particles “screen” the interaction, providing a long-distance cutoff proportional to the density. Translation into QFT language can be made, recognizing that n is proportional to ϕ^2 , the background field strength. The energy density as a function of ϕ (the effective potential) is made up of ϕ^2 , ϕ^4 , and $\phi^4 \ln \phi^2$ terms. This reproduces our previous prediction, but from a quite different perspective.

B. Publications, Presentations & Theses (1992 - 1996): Stevenson

Publications

- “Variational Calculations of the Effective Potential with Non-Gaussian Trial Wavefunctionals”, R. Ibañez-Meier, A. Mattingly, U. Ritschel, and P. M. Stevenson, *Phys. Rev. D* **45**, 2893 (1992).
- “Variational Principle for Effective Action and Prospects for Nonlinear Optimization”, R. Ibañez-Meier, L. Polley, and U. Ritschel, *Phys. Lett. B* **279**, 106 (1992).
- “Unconventional Large-N Limit of the Gaussian Effective Potential and the Phase Transition in $\lambda\Phi^4$ Theory”, U. Ritschel, I. Stancu, and P. M. Stevenson, *Z. Phys. C* **54**, 627 (1992).
- “QCD Perturbation Theory at Low Energies”, A. C. Mattingly and P. M. Stevenson, *Phys. Rev. Lett.* **69**, 1320 (1992).
- “Nonperturbative N-point Functions from the Gaussian Effective Action and Renormalization of $\lambda\Phi^4$,” R. Ibañez-Meier, *Phys. Lett. B* **295**, 89 (1992).
- “Autonomous renormalization of the one-loop effective potential and a 2 TeV Higgs in $SU(2) \times U(1)$,” R. Ibañez-Meier and P. M. Stevenson, *Phys. Lett. B* **297**, 144 (1992).
- “Resolution of the $\lambda\Phi^4$ puzzle and a 2 TeV Higgs boson,” M. Consoli and P. M. Stevenson, Rice preprint DE-FG05-92ER40717-5, hep-ph/9303256
- “ τ decay and the QCD infrared fixed-point,” A. C. Mattingly, Rice preprint DE-FG05-92ER40717-8, submitted to *Phys. Rev. D*.
- “Optimization of $R(e^+e^-)$ and ‘freezing’ of the QCD couplant at low energies,” A. C. Mattingly and P. M. Stevenson, *Phys. Rev. D* **49**, 437-450 (1994).
- “The non-trivial effective potential of the trivial $\lambda\Phi^4$ theory: a lattice test,” M. Consoli and P. M. Stevenson, *Zeit. Phys. C* **63**, 427-436 (1994).
- “The $16\frac{1}{2} - N_f$ Expansion and the Infrared Fixed Point in Perturbative QCD,” *Phys. Lett. B* **331**, 187-192 (1994).
- “Scheme dependence, optimization, and ‘freezing’,” P. M. Stevenson, in proceedings of the DPF QCD Working Group Meeting; University of Wisconsin-Madison, April 1994.
- “‘Triviality’ and the Perturbation Expansion in $\lambda\Phi^4$ Theory,” M. Consoli and P. M. Stevenson, Rice preprint DE-FG05-92ER40717-13, hep-ph/9403299.

²⁸ M.A.B. Bég and R.C. Furlong, *Phys. Rev. D* **31**, 1370 (1985); K. Huang, *Intl. J. Mod. Phys. A* **4**, 1037 (1989); R. Jackiw, in *Bég Memorial Volume*

- "'Triviality' made easy: the real $(\lambda\phi^4)_4$ story," M. Consoli and P. M. Stevenson, Rice preprint DE-FG05-92ER40717-14, hep-ph/9407334.
- "The $\lambda\phi^4$ Miracle: Lattice data and the zero-point potential," P. M. Stevenson, submitted to J. Phys. G.
- "Gaussian Effective Potential for the U(1) Higgs Model", R. Ibañez-Meier, I. Stancu, and P. M. Stevenson, Zeit. Phys. C 70, 307 (1996).
- "Response to Tarrach's 'Mode Dependent Field Renormalization and Triviality'," submitted to Phys. Lett. B.
- "Landau Poles, Ultraviolet Fixed Points, and 'Triviality' in the Perturbative Expansion of $\lambda\phi^4$ ", M. Consoli and P. M. Stevenson, submitted to Int. J. Mod. Phys.

Presentations

- "Particle Astrophysics", P. M. Stevenson, Prairie View Summer Science Academy, Prairie View A&M University, Texas, June, 1992.
- "QCD Perturbation Theory at Low (Yes, Low!) Energies", P. M. Stevenson, Imperial College, London, June 1992.
- "Applying Optimized Perturbation Theory to QCD at Low Energies", A. C. Mattingly, DPF Meeting, Fermilab, November 1992.
- "Optimization of Perturbation Theory in QCD," P. M. Stevenson, University of Catania, Italy Sept. 22, 1993.
- "Resolution of the $\lambda\phi^4$ puzzle and a 2 TeV Higgs boson," P. M. Stevenson, presented in colloquia at the following institutions:
  - University of Catania, Italy, Sept. 24, 1993
  - CERN, Geneva, Switzerland, Sept. 29, 1993
  - Rutherford Laboratory, England, Oct. 6, 1993
  - Durham University, England, Oct. 8, 1993
  - Cambridge University, England, Oct. 14, 1993
  - Imperial College, London, England, Oct. 28, 1993
  - Birkbeck College, London, England, Nov. 3, 1993
  - Oxford University, England, Nov. 4, 1993
  - Bremen-Groningen-Oldenburg mini-workshop, Oldenburg University, Germany, Nov. 12, 1993
  - University College, Swansea, Wales, Nov. 18, 1993
  - Texas A&M University, January 1994.
  - University of Wisconsin Madison; March 1994.
  - University of Wisconsin Madison, April 1994.
  - University of Kansas, Lawrence, Kansas, February 9th, 1996.
- "Scheme dependence, optimization, and 'freezing'," P. M. Stevenson, DPF QCD Working Group meeting, University of Wisconsin Madison, April 1994.
- "'Freezing' of the QCD couplant at low energies," P. M. Stevenson, Physics Doesn't Stop: Recent Developments in Phenomenology meeting, University of Wisconsin Madison, April 1994.
- "Understanding 4-dimensional scalar field theory," P. M. Stevenson, INFN, Catania, Italy, June, 1995.
- "Hadron-Nucleus Collisions; an opaque subject?," P.M. Stevenson, Department of Physics, University of Catania, Italy, June 1995.
- " $\lambda\phi^4$ Field Theory in a Particle-Gas picture", P. M. Stevenson, INFN, Catania, Italy, July 16th, 1996.
- "The Principle of Minimal Sensitivity and Its Applications", P. M. Stevenson, INFN, Catania, Italy, July 18th, 1996.

Theses

- "Linear and Non-Linear Field Transformations and Their Application in the Variational Approach to Nonperturbative Quantum Field Theory", R. Ibañez-Meier, Ph.D. Thesis, Rice University, April 1992. (Awarded the Physics Department H. A. Wilson award for the most outstanding Ph.D. thesis of 1992.)
- "Variational' methods in quantum field theory," A. C. Mattingly, Ph.D. Thesis, Rice University, May, 1993. (Awarded the H. A. Wilson award for the most outstanding Ph.D. thesis of 1993.)

C. Progress on Theoretical Topics: Jorge Lopez

This progress report covers the period during which Jorge has been a member of the Bonner Nuclear Lab: August 1995 - August 1996. His research has followed the following four correlated tracks.

Low-energy supersymmetry

The measurement of $R_b = \Gamma(Z \rightarrow b\bar{b}) / \Gamma(Z \rightarrow \text{hadrons})$ at LEP had for some time fallen about three standard deviations above the Standard Model prediction. It had been speculated that the Minimal Supersymmetric Standard Model may account for this excess should the superpartners had some special properties (i.e., light charginos and top squarks). We showed that the recent LEP 1.5 run together with a large array of phenomenological constraints limited the possible contribution of supersymmetry to R_b and could therefore not account for the perceived discrepancy. Recent experimental reanalyses, most notably by ALEPH, have shown that the discrepancy may now be largely reduced if not removed altogether. This is welcome news, as the better motivated supersymmetric theories based on grand unification and supergravity predict that the measured value of R_b should agree with the Standard Model prediction within the experimental uncertainty. (Paper #6)

We have shown that supersymmetry may affect the top-quark production cross section at the Tevatron at the one-loop level in a measurable way (i.e., shifting the Standard Model prediction by as much as 35%) should certain relations among the superpartner masses hold. Such effects may be discernible when the Main Injector upgrade becomes operational. (Paper #10)

Unified and supergravity models

Unified supersymmetric theories are able to predict the value of the strong gauge coupling (α_s) at the electroweak scale, once the other two Standard Model couplings are input ($\sin^2 \theta_w$ and α). This prediction exceeds all experimentally acceptable values of α_s in the case of traditional unified theories [such as SU(5)]. In contrast, we have shown that in flipped SU(5) the prediction for α_s can easily agree with experiment, in which case the proton decay mode $p \rightarrow e^+ p^0$ should be observable at Superkamiokande. (Paper #2)

Flipped SU(5) also provides a new and interesting way of reconciling the unification scale deduced from electroweak measurements (10^{16} GeV) with that predicted in string models (10^{18} GeV). In the process various intermediate scales are determined in a self-consistent way. (Paper #5)

The observation by CDF of a single event consisting of two electrons, two photons, and missing energy has been taken by some as the first direct evidence for the existence of supersymmetry. We have proposed a model based on no-scale supergravity with a light gravitino that is described in terms of a single parameter and can naturally explain both the kinematics and dynamics of the event (Paper #12). We have also completed an extensive study of additional signals that this model predicts at the Tevatron and at LEP. Ongoing runs at LEP 2 searching for acoplanar photon pairs should soon support or disfavor the model. (Paper #14)

String model building

Flipped SU(5) finds its most compelling motivation in superstring model building. We have updated the experimental predictions of a string-derived flipped SU(5)

model, which has as one of its virtues the first-principles prediction for the top-quark mass of 175 GeV. (Paper #8)

We have also investigated the possibility of a leptophobic Z' gauge boson in the context of string-derived flipped SU(5), where one finds that leptophobia is a natural property (in contrast with other unified models). Such a Z' may have escaped detection at the Tevatron, as the traditional searches concentrate on the unavailable leptonic decay channel. A leptophobic Z' in flipped SU(5) violates parity maximally and may be detected at RHIC via its contribution to the parity-violating asymmetry A_{PV} . (Paper #9)

Tests of CPT symmetry

A generic consequence of strings is the violation of certain sacrosanct principles, such as the conservation of CPT symmetry or the constancy with time of the fundamental constants of nature. CPT violation can be parametrized by additional contributions to the Liouville equation describing the density matrix of the neutral kaon system. These contributions arise from string effects and effectively 'open' the quantum mechanical system. We have analyzed the data obtained by CPLEAR on certain two-pion and semileptonic decay asymmetries in the context of this type of CPT violation, and determined upper bounds on the CPT-violating parameters that are very close to the theoretically expected range (Paper #3). We have also studied the effects of a thin regenerator placed inside the CPLEAR detector, which may enhance the signal in certain cases (Paper #15).

Additional activities

I have completed an especially-commissioned review article on the subject of supersymmetry (Paper #7), and have been a co-author of a study of the physics potential for a high-luminosity upgrade of the Tevatron collider (Paper #11).

D. Publications and Presentations: Lopez

Publications

1. Vanishing $Str M^2$ in the presence of anomalous $U_A(1)$, J. L. Lopez and D. V. Nanopoulos, Physics Letters B 369 (1996) 243.
2. Lowering α_s by flipping SU(5), J. Ellis, J. L. Lopez, and D. V. Nanopoulos, Physics Letters B 371 (1995) 65.
3. Tests of CPT symmetry and quantum mechanics with experimental data from CPLEAR, The CPLEAR Collaboration, J. L. Lopez, et. al., Physics Letters B 364 (1995) 239.
4. Flipped SU(5): A grand unified superstring theory (GUST) prototype, Jorge L. Lopez and D. V. Nanopoulos, to be published in Proceedings of the 33rd International School of Subnuclear Physics, Erice, July 1995.
5. A new scenario for string unification, Jorge L. Lopez and D. V. Nanopoulos, Physical Review Letters 76 (1996) 1566.
6. Supersymmetry and R_μ in the light of LEP 1.5, J. Ellis, J. L. Lopez, and D. V. Nanopoulos, Physics Letters B 372 (1996) 95.
7. Supersymmetry: from the Fermi scale to the Planck scale, J. L. Lopez, Reports on Progress in Physics 59 (1996) 819.
8. Experimental constraints on a stringy SU(5)xU(1) model, J. L. Lopez, D. V. Nanopoulos, and A. Zichichi, Physical Review D 53 (1996) 5253.
9. Leptophobic Z' in stringy flipped SU(5), Jorge L. Lopez and D. V. Nanopoulos, to be published in Physical Review D.
10. Enhanced supersymmetric corrections to top-quark production at the Tevatron, J. Kim, J. L. Lopez, D. V. Nanopoulos, and R. Rangarajan, to be published in Physical Review D.
11. Future Electroweak Physics at the Fermilab Tevatron: Report on the TeV-2000 Study Group, D. Amidei, et. al., FERMILAB-PUB-96-082.
12. A supergravity explanation of the CDF $ee\gamma\gamma$ event, Jorge L. Lopez and D. V. Nanopoulos, submitted to Physical Review Letters.

13. String unification and leptophobic Z' in flipped SU(5), J. L. Lopez, to be published in Proceedings of the Fourth International Conference on Supersymmetry (SUSY96), University of Maryland, May 1996.
14. Experimental consequences of no-scale supergravity in light of the CDF $ee\gamma\gamma$ event, Jorge L. Lopez and D. V. Nanopoulos, submitted to Physical Review D.
15. Regenerator test of CPT symmetry in the neutral kaon system, J. Ellis, J. L. Lopez, N. Mavromatos, and D. V. Nanopoulos, to be submitted to Physics Letters B.

Presentations

- "Flipped SU(5): a Grand Unified Superstring Theory (GUST) Prototype," Bonner Nuclear Lab, Rice University, November 3, 1995.
- "Recent developments in stringy flipped SU(5) phenomenology," SLAC Theory Seminar, Stanford University, February 28, 1996.
- "Lessons for unified models from precise sparticle spectroscopy," Plenary Session Talk, Physics with e^+e^- colliders, SLAC, February, 29, 1996.
- "String Unification and Leptophobic Z' in flipped SU(5)," Plenary Session Talk, Fourth International Conference on Supersymmetry (SUSY96), University of Maryland, May 31, 1996.