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Face Pages:	
A. "Results from SMC on the Deuteron Spin Structure Function," Mark Lowe for the Spin Muon Collaboration, Hadron '93 Conference, Como, Italy, June, 1993, to be published in <i>Nuovo Cimento</i> .	
B. "Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron," B. Adeva and the SMC collaboration, <i>Phys. Letts. B302</i> , 533 (1993).	
Preprints:	
A "A High Energy Muon Beam Polarimeter," <i>The SMC Collaboration</i> , submitted to <i>Nucl. Inst. & Meth.</i> , October, 1993.	
B. "Combined Analysis of World Data on Nucleon Spin Structure Function," to be submitted to <i>Physics Letters B</i> , B. Adeva and the Spin Muon Collaboration.	

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The D0 Collaboration at FNAL
The E683 Collaboration at FNAL

Project Abstract and Overview

We report here on progress made for the period from December 1, 1992 (the date of submission of our latest progress report) to November 30, 1993 for DOE Grant No. DE-FG05-92ER40717. The new results from the SMC experiment have generated a buzz of theoretical activity. Our involvement with the D0 experiment and the upgrade has increased substantially during the past two years so that we now have six people heavily committed and making what can only be described as a large and disproportionate impact on D0 physics output. Some of the new developments made here at Rice in Neural Network and Probability Density Estimation techniques for data analysis promise to have applications both in D0 and beyond. We report a load of new results from our high- p_t jet photoproduction experiment. In addition we have been working on KTeV, albeit without having adequate funding for this work.

Progress on the theoretical front has been nothing short of amazing, as is reported herein. In a grand lecture tour during this sabbatical year, Paul Stevenson has already reported his breakthroughs at ten institutions, including CERN, Oxford, Cambridge, Rutherford Lab, Imperial College, and Durham University.

The group at Rice University has had an exceptionally productive year and we are justifiably proud of the progress which is reported here.

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 has been proposed to explain these unexpected results.⁴ Several experiments are presently being carried out or prepared at CERN (Spin Muon Collaboration),⁵ SLAC,⁶ and DESY⁷ to measure the spin structure function of the neutron and to repeat the proton measurement with improved accuracy. The SMC experiment yielded the first measurement of the spin dependent structure function g_1^n of the neutron⁸ and is currently increasing the accuracy of the SLAC-YALE and EMC measurements of g_1^p of the proton. 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. For measurements taken so far, the target and the spectrometer are based on the apparatus built by the EMC, but have been upgraded to reduce systematic uncertainties. A new polarized target has also been installed for running in 1993 and beyond.

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

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, see e.g.: H. Rollnik, Proc. 9th Int. Symposium on High Energy 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

⁵The Spin Muon Collaboration (SMC), Measurement of the Spin-Dependent Structure Functions of the Neutron and Proton, CERN/SPSC 88-47 (SPSC/P242), 1988 (unpublished)

⁶R. Arnold *et al.*, A proposal to measure the neutron spin dependent structure function, SLAC Proposal E142, 1989 (unpublished); E143 Collaboration, R. Arnold *et al.*, Measurements of the Nucleon Spin Structure at SLAC in End Station A, SLAC Proposal E143 (unpublished)

⁷The 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)

⁸B. Adeva *et al.*, Phys. Lett. **B302**, 533 (1993)

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

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

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

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

To a good approximation $A_1 = A/D$ where D is the depolarization factor that depends on the event kinematics. A possible contribution from the transverse asymmetry A_2 is constrained by a positivity limit which is included in the systematic error. The target polarization is typically 40% for deuterons and 85% for protons, and the beam polarization is measured to be -82% at both 100 and 200 GeV. For deuterons $f \approx 0.2$ and $A_{meas} = f P_\mu P_T A \approx 10^{-3}$.

This experiment measures the proton and deuteron asymmetries A_1^p and A_1^d . The neutron asymmetry A_1^n can be extracted from the proton and deuteron asymmetries A_1^p and A_1^d by the relation

$$A_1^n = \frac{1 + \left(\frac{F_2^p}{F_2^n}\right)}{1 - 1.5 W_D} A_1^d - \left(\frac{F_2^p}{F_2^n}\right)$$

where W_D represents the D-state probability of the deuteron ($\sim 5\%$). The polarization is measured using 10 NMR coils embedded in the target material. The integrated NMR absorption signals were calibrated in thermal equilibrium at 1.1 K. This allows us to measure the polarization to an accuracy of about ± 0.02 . In order to minimize systematic errors, we have reversed the polarization directions in the two target halves at regular intervals. For most of our data the spins were reversed every 8 hours by rotating the field direction using the 0.2 T transverse field of a superconducting dipole coil wound on the microwave cavity. In addition, the relative orientation of the solenoid field and the target polarization was changed once or twice per week with DNP.

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 iron target.

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

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

The muon beam polarization has been measured by two methods:

- (1) the shape of the energy spectrum of decay positrons in the laboratory system is sensitive to the muon polarization; this dependence is shown in Fig. 2, and
- (2) 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 a detailed paper (copy included in the appendix) which has been submitted to NIM. Briefly, downstream of the muon spectrometer, a 30 m long muon decay

Fig. 2. Dependence of the energy spectrum of the decay positrons on the muon polarization.

Fig. 3. Corrected muon decay Michel spectrum fitted to obtain muon beam polarization.

Fig. 4. Muon - electron elastic scattering peak.

path is defined between a shower veto hodoscope which identifies the μ^+ and a dipole magnet where the momentum of the e^+ is measured using multiwire proportional chambers. Identification of the decay positrons is done using the energy deposited in a lead glass calorimeter. Radiative corrections are taken into account. For 100 GeV positive muons the beam polarization is found to be $P_\mu = -0.83 \pm 0.03$ (syst.) ± 0.035 (stat.) in 20 hours, in good agreement with Monte Carlo simulations of the beam transport. Fig. 3 shows the measured Michel spectrum with the calculated fit using this value for the muon beam polarization. The decay polarimeter has been routinely used to measure the beam polarization at 200 GeV in 1993; although to obtain the comparable statistics to 100 GeV about 4 times the operating time is required. Rice Postdoc Mark Lowe has been in residence at CERN for the entire experiment and from the outset has led this data analysis effort. The decay polarimeter will be the main topic of the thesis for Rice student Tom Gaussiran.

The μ -e scattering polarimeter, which requires considerably more equipment, has now been installed. A short test run took place in 1992 and it is in operation for the current run. A plot of the μ -e elastic signal from 1992 is shown in Fig. 4. The difference between the incident muon momentum and the sum of the scattered muon and electron momenta is plotted along with the Monte Carlo spectrum calculated from GEANT. The agreement indicates good elastic event reconstruction and shows that the Bremsstrahlung tail on the elastic scattering is well understood. The other sources of systematic error such as internal radiative corrections and beam flux normalization are now being studied. We expect to process all the 100 GeV data to measure the asymmetry and the resulting beam polarization within the next few months. This topic will form the basis for the thesis of Rice student Jack Cranshaw.

Fig. 5. Results from SMC and SLAC E142 on the spin structure function of the deuteron. The E142 data on the neutron was added to the EMC proton data to get a result for the deuteron.

Fig. 6. Results from SMC and SLAC E142 on the spin structure function of the neutron. The neutron result was obtained from the SMC deuteron data by using the EMC proton data.

Results and Remarks on Structure Functions

Data on A_1^d have been reported in Physics Letters B, covering the kinematic range $1 \text{ GeV}^2 < Q^2 < 30 \text{ GeV}^2$ and $0.006 < x < 0.6$. The values of g_1^d have been calculated by the relation:

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

We adopt here the convention that g_1^d and F_2^d are the average structure functions of the nucleon in the deuterium nucleus. We have taken $F_2^d(x, Q^2)$ and $R(x, Q^2)$ at $Q^2 = 4.6 \text{ GeV}^2$, which is the average Q^2 of the data. The values of $F_2^d(x, Q^2)$ were taken from the NMC parameterization⁹ and those of R from a global fit of the SLAC data.¹⁰

SMC results for A_1^d are plotted in Fig. 5 along with the sum of the SLAC E142 neutron (He^3) and the EMC proton results. Only statistical errors on the SMC are shown since the systematic errors are small by comparison. Note that there is good agreement of the world data on the measured asymmetry A_1 . The neutron structure function g_1^n extracted from the A_1 values is plotted in Fig. 6. The world data on $xg_1(x)$ are shown in Fig. 7.

Some remarks on the comparison of the world data on structure functions are appropriate. The sum rules on the first moments $\Gamma_1 = \int_0^1 g_1(x) dx$ of g_1 are:

⁹P. Amaudruz *et al.*, Phys. Lett. **B295**, 159 (1992)

¹⁰L. W. Whitlow *et al.*, Phys. Lett. **B250**, 193 (1990)

World Data on Spin Structure Functions Low X Extrapolation

Fig. 7. A compilation of all existing data on spin structure functions.

Ellis Jaffe:

$$\Gamma_1^{p(n)[d]} = (\pm) \left(1 - \frac{\alpha_s}{\pi}\right) + \frac{1}{3} \frac{\frac{F}{D} - 1}{\frac{F}{D} + 1} \left[5 - \left(1 + 4 \frac{\alpha_s}{\pi} \frac{33 - 8N_F}{33 - 2N_F}\right)\right] = 0.176(-0.016)[+0.085]$$

Bjorken:

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_s}{\pi} (1 + 0.342 + 0.184) \right] = 0.183$$

evaluated to all perturbative orders at $Q^2 = 5 \text{ GeV}^2$. Using the SMC data we calculate $\int_{0.005}^0.6 g_1^d(x) dx = 0.024 \pm 0.020(\text{stat.}) \pm 0.014(\text{sys.})$. Extrapolating outside the measured region, we obtain $\Gamma_1^d = 0.023 \pm 0.020 \pm 0.015$ (SMC) to be compared with the theoretical value $\Gamma_1^d = 0.085 \pm 0.005$ (EJ). The EMC data gave $\Gamma_1^p = 0.126 \pm 0.018$ (EMC) also in disagreement with the EJ value $\Gamma_1^p = 0.176 \pm 0.006$ (EJ). Combining the two sets of data gives $\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05$ (EMC + SMC) in agreement with the BJ value $\Gamma_1^p - \Gamma_1^n = 0.183 \pm 0.002$ (BJ).

On the other hand, SLAC E142, using the extrapolation shown in Fig. 7, obtain $\Gamma_1^p = 0.022 \pm 0.011$ in agreement with the EJ prediction $\Gamma_1^p = 0.016 \pm 0.006$ (EJ). Combining these data with the EMC one obtains a 2 standard deviation violation of the fundamental Bjorken sum rule.

However, one should take note of the following observations:

(1) For the EMC proton data, $\langle Q^2 \rangle = 10.7 \text{ GeV}^2$, whereas $\langle Q^2 \rangle = 2 \text{ GeV}^2$ for SLAC E142. Thus, perturbative QCD corrections should be made before the two data sets can be combined to obtain the Bjorken sum.

(2) E142 data must be extrapolated further than the SMC and EMC to obtain Γ_1^p . As shown in Fig. 7, the E142 extrapolation goes to zero at a larger x than that of the SMC data. This is perhaps better illustrated in Fig. 6, in which the SMC data, despite the larger statistical errors, tends to remain non-zero to smaller x than does the E142 extrapolation.

Although there is no statistically significant disagreement between the two sets of data, at present an unsatisfactory situation exists. This can only be resolved by higher precision data at small x from the SMC and from SLAC E143, which begins taking data shortly. The data from the SMC on A_1^p which are currently being analyzed will be available in early 1994. The improved knowledge of the beam and target polarization of the SMC experiment are critical for obtaining the needed higher precision for testing the fundamental Bjorken sum rule.

B. FNAL D0 — Experiment and Upgrade

As members of the D0 experiment at FNAL, the Rice group is participating both in the current D0 program and in the D0 upgrade. The first part of our report focuses on the physics goals and current status and the second part on the upgrade.

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: 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 resolutions in jet energy and position, high multijet efficiency, and single photon detection); 3) High resolution tracking; 4) Excellent missing E_T resolution (for detection of non-interacting particles).

Fig. 8. Layout of the D0 detector.

The general layout of the D0 detector is shown in Fig. 8. The central detector (CD) consists of a vertex detector, a set of transition radiation detectors (not yet operational), a central tracking chamber and a pair of forward and backward 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 $d\eta \times d\phi = 0.1 \times 0.1$; 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.* The mass of the top quark is believed to be around 130 ± 40 GeV. At the Tevatron it is produced mostly in pairs, with each t decaying into a $W + b$ quark. The cleanest signature for top production is a final state with a large p_T electron + large p_T muon + jets. This channel has only a 2% branching ratio but is essentially free of background. For an integrated luminosity of 25 events/pb (goal for the present run), one expects about 10 such events if the mass is 130 GeV. Roughly half of these would be detected in D0, thus constituting a discovery. The final state consisting of a single large p_T lepton + jets has a 30% branching ratio but suffers from a larger background ($W + \text{jets}$). The final state with six or more jets is considered to be “hopeless” due to QCD background.
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 1/4 %. This will help to pin down the top mass within the standard model. Other topics to be pursued are charge asymmetries in $W \rightarrow \mu + \nu$ and $Z \rightarrow \mu + \mu$.
3. *QCD studies / jet production.* D0 will be able to measure inclusive jet cross-sections over a wide angular range, out to $|\eta| = 3.7$. This will allow precision tests of QCD well outside the central region. Multi-jet production will be studied over the same range.
4. *Search for new physics.* D0 will look for evidence for supersymmetry (squarks, gluinos, ...) and for new heavy W 's and Z 's. In the absence of signals new search limits will be established for these particles.

The D0 experiment took physics data from September 1992 until June 1993. By all accounts, the run was a great success for D0. The detector and all its subsystems worked exceedingly well. The data taking efficiency was approximately 80% when the main ring was not in operation (54% overall, including losses beyond the control of D0). The total data sample acquired by D0 corresponds to an integrated luminosity of 16.7 pb^{-1} on tape. Three of us from Rice participated in data taking by running regular shifts in the calorimeter, tracking, and muon system subgroups.

Data analysis is proceeding full speed in all five physics subgroups (top, QCD, W/Z , B physics, new phenomena). Preliminary results have been presented in numerous conferences and workshops; a sampling of the topics is given in Ref.¹¹ A paper on

¹¹“ W and Z Decays to Electrons in D0”, Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 387. D0 Collaboration, presented by N.A. Graf.

“ W and Z Decays to Muons in D0”, Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 390. D0 Collaboration, presented by D. Wood.

leptoquark search¹² has been submitted to Phys. Rev. Letters. We set a mass limit of 120-130 GeV on first generation leptoquarks, assumed to be produced in pairs and to decay into an electron + quark. Two other PRL's will be submitted shortly, one on top quark search,¹³ and another on jet events with rapidity gaps.¹⁴ In the former paper we set a new lower limit of 130 GeV on the top quark mass, and discuss the properties of an interesting event for which expected backgrounds are small. In the latter paper we set an upper limit on the fraction of events containing no particles between two large E_T jets which are well separated in pseudorapidity. About a dozen other papers are at various stages of preparation.

The Rice group has participated in this analysis effort in the W/Z and top physics subgroups. We are responsible for carrying out analyses and writing papers on Z' and W' searches. We have developed new analysis techniques to be applied to the top quark search and to other topics (e.g. B physics). This work is discussed in some detail below.

The discovery of the heavy intermediate bosons, W and Z, in 1983 at CERN was a spectacular confirmation of the standard model of particle physics. The model has withstood many experimental tests but there is still room for extensions which allow or require the existence of additional such bosons referred to as the W' and Z'. These models do not predict specific masses and so a high energy hadron collider such as that at FNAL is the ideal place to carry out such a search. Rice has been heavily involved in making use of the existing D0 data to carry out searches for both W' and Z', the latter being a topic of the Ph.D. dissertation of Rice student Geary Eppley.

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- "Top Quark Search in D0 from the Lepton + Jets Mode", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 453. D0 Collaboration, presented by B. Klima.
 - "Search for the Top Quark in Dilepton Events with D0", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 456. D0 Collaboration, presented by R. Partridge.
 - "Dimuon Production in D0", Proceedings of the Fermilab Meeting DPF92, i World Scientific (1993), p. 753. D0 Collaboration, presented by S. Igarashi.
 - "Direct Photon Production from D0", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 971. D0 Collaboration, presented by G.R. Snow.
 - "Inclusive Jet Cross Sections at the D0 Detector", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 993. D0 Collaboration, presented by R.V. Astur.
 - "Two Jet Energy and Rapidity Distributions", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 996. D0 Collaboration, presented by G.C. Blazey.
 - "Production of Jets in Association with W Vector Bosons in the D0 Detector", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1094. D0 Collaboration, presented by J. Yu.
 - "A Search for Squarks and Gluinos in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV with the D0 Detector", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1228. D0 Collaboration, presented by M. Paterno.
 - "A Search for Scalar Leptoquarks in D0", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1265. D0 Collaboration, presented by K.W. Merritt.
 - "Triggering the D0 Experiment", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1641. D0 Collaboration, presented by J.T. Linnemann.
 - "Electron Identification in the D0 Detector", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1678. D0 Collaboration, presented by M. Narain.
 - "Low Energy Response of the D0 Calorimeter and Jet Energy Measurement", Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1681. D0 Collaboration, presented by P.C. Bhat.
 - ¹²"First Generation Leptoquark Search in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi *et al.*
 - ¹³"Search for the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," to be submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi, *et al.*
 - ¹⁴"A Search for Jet Events with Rapidity Gaps in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," to be submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi *et al.*

W' Limits

Fig. 9. Number of expected W' events as a function of the mass of the W' for two different analyses.

Due to the rather complicated environment in proton-antiproton colliders, the W' search has been performed in a clean leptonic channel, this is $W' \rightarrow e + \nu$. The analysis requires an isolated and energetic electron and a large amount of missing momentum, carried away by the neutrino. The electron was identified with the excellent D0 calorimeter system. W' particles should produce events with an extremely large neutrino E_T and missing energy. Some candidates with large values of those two variables were found, but our analysis showed they were compatible with the expected background from ordinary W . This lack of signal allowed us to set limits on W' production with coupling equal to those of the standard model. Fig. 9 shows the number of expected W' events as a function of $m_{W'}$ for two different analyses. A W' with a mass below 600 GeV is excluded at 95% CL. This is the highest limit yet obtained for the W' mass. The W' analysis is near completion and a draft for publication will soon be written.

We have searched for evidence for new heavy neutral gauge bosons, Z' , decaying into two electrons. We require two isolated electromagnetic clusters with transverse energies greater than 25 GeV in the fiducial region of the calorimeter, with matching tracks in the central detector. The total efficiency for the selection criteria is about 20%, yielding 716 events from 15.4 pb^{-1} of data. There are 14 events with a di-electron invariant mass greater than 125 GeV. This is consistent with the expected signal from $Z \rightarrow ee$, Drell-Yan production of ee pairs, and QCD background from dijets faking electrons. We can therefore exclude a Z' of mass below 440 GeV at the 95% confidence level, assuming standard model couplings to quarks and leptons (see Fig. 10).

During the past year our group at Rice has worked extensively on developing and testing new techniques for multidimensional data analysis. Specifically, we have been interested in developing methods which are well suited for the task of identifying rare signals such as $top \rightarrow lepton + missing E_T + jets$, and which are more efficient than conventional analyses. Two such techniques have been studied in detail: Artificial Neural Networks (NN) and Multivariate Probability Density Estimation (PDE). The latter method is an entirely new technique which we have developed in collaboration with two mathematicians from the Department of Statistics at Rice. Our work is documented in three D0 notes; below we briefly discuss each of these notes.

Z' Limits

Fig. 10. Number of expected Z' events as a function of the Z' mass for two different pair mass cuts.

In the first note¹⁵ we studied the performance of some simple neural networks which could be used to search for $top \rightarrow lepton + missing E_T + jets$. Monte Carlo generated top events (signal) and $W + jets$ events (background) were used for training and testing. We found that simple architectures with only a few input variables work surprisingly well, and that such NN are very robust in that their performance depends only weakly on internal net parameters. This offers hope that modest networks with relatively few weights can be effective in identifying rare signals masked by large backgrounds.

In the second note¹⁶ we introduced a new analysis technique based on Multivariate Probability Density Estimation (PDE). This technique is a precise, conceptually simple, non-parametric technique which requires little optimization. The basic idea is to estimate the probability density functions for signal and background events (generated by a Monte Carlo) by means of simple analytic kernels, and then apply a cut on the ratio of these functions to select signal event candidates in real data. The method works directly in the d-dimensional "feature space" of d physical variables chosen to characterize events of interest. A linear mapping of the feature space is applied to find uncorrelated linear combinations of the original d variables; these transformed variables are then used in

subsequent calculations. Correlations between variables are thus taken into account and analyzed in a well-defined manner.

We applied the PDE method to the processes $t\bar{t} \rightarrow e + missing E_T + jets$ (signal) and $W + jets \rightarrow e + missing E_T + jets$ (background), and compared its performance with that of NN. We found that the two methods yield very similar results in terms of attainable signal-to-background ratios and signal efficiencies. We demonstrated that this similarity is in fact to be expected once the significance of the NN output is properly understood.

Aside from the question of performance, the PDE method offers both conceptual and practical advantages which appear to make it well suited for many feature recognition problems. In the near future we will apply this method to D0 data to search for the processes $t\bar{t} \rightarrow e + missing E_T + jets$ and $t\bar{t} \rightarrow all jets$. In addition, physicists in the B physics group at D0 are interested in applying the PDE method to b-quark tagging and to identifying various b-quark production mechanisms; work on the latter topic has already

¹⁵H.E. Miettinen and R. Ou, "Searching for Top with Neural Nets, I. Optimization of NN Parameters", D0 note 1842, 7/10/93

¹⁶H.E. Miettinen, R. Ou, L. Holmstrom, and S. Sain, "Searching for Top with Neural Nets. II. NN versus Probability Density Estimation", D0 Note 1931, November 1993.

begun. A paper on the PDE method will be submitted shortly to Computer Physics Communications.

In the third note¹⁷ we address the question of which physical variables for the process $top \rightarrow lepton + missing E_T + jets$ are best suited for analyses which make use of the NN or PDE method. The importance of many commonly used variables is evaluated with both methods. A systematic search for optimal sets of up to 13 such variables is carried out. Results obtained with NN and PDE techniques are compared with those from a conventional analysis which relies on 1-dimensional cuts. We find that, typically, such cuts can be tuned to yield equally good signal-to-background ratios, but the NN and PDE techniques yield signal efficiencies which are considerably higher than those attained with standard analysis. Work on this paper is still in progress.

Progress on D0 Upgrade

Although the D0 collaboration is very busy taking and analyzing data with the detector in its present configuration, considerable effort has been expended to design an upgraded detector which will maintain and expand its capabilities for future Fermilab collider runs.¹⁸ Significant increases in luminosity will allow us to extend the mass reach for particle searches and allow us to accumulate significantly more statistics in established channels. The calorimeter and muon system electronics will be modified and scintillators will be added to the latter. The major change is a complete replacement of the central tracker. The new tracker will include a solenoid (the current system is non-magnetic) to allow us to measure 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 allow us to study B production, decay, mixing and eventually CP violation. Rice has played a major role in the design of this tracking system.

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 shown in Fig. 11 and is described in D0 notes 1426, 1733 and 1933. The silicon system is made up of interleaved barrels and disks to provide hermetic coverage past $\eta = 3$. There are four barrels, 14 central disks and four endcap disks at each end. The four barrels are broken up into seven 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 disks are double-sided with a 30 degree angle between the strip directions which are approximately radial.

The basic measuring unit of the scifi system 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 scifi tracker is made up of four cylindrical superlayers. Each superlayer has two doublets with fibers parallel to the beam line to measure ϕ and two opposite-angle stereo doublets with a pitch of 0.001 rad/cm (approximately 2 degree stereo). The ϕ doublets are spaced by 1.5 cm to provide some pointing information. The stereo doublets are outside and adjacent to the outer ϕ doublet.

The current schedule and resources do not allow us to construct this full system in time for the beginning of collider run II. A descoped design that does meet the current

¹⁷H.E. Miettinen, R. Ou, L. Holmstrom, and S. Sain, "Searching for Top with Neural Nets. III. Selection of Input Variables", D0 Note in preparation.

¹⁸"E823 (D0 Upgrade) Step 1 and Beyond", D0 Collaboration, D0 note 1426, 5/20/92; "E823 (Upgrade)", D0 Collaboration, D0 note 1733, 5/19/93; "E823 (D0 Upgrade): Magnetic Tracking", D0 Collaboration, D0 note 1933, 10/12/93

schedule and budget is shown in Fig. 12. Most of the silicon disks and the readout electronics for the outer scifi superlayer are omitted. The descoped system gives up some of the forward coverage while maintaining most of the capability in the central region which is critical to high p_T physics. We hope to find additional funds or, if the run is delayed, to use budgets from later years to complete the detector before run II. If the schedule and budget are not changed, then we will begin with the descoped detector and add the missing pieces during or after that run. Rice plays an important role in understanding the capabilities of both the full and descoped systems.

Fig. 11. Tracking system designed for the D0 upgrade.

Fig. 12. The descoped D0 tracker that is expected to be constructed for run II.

One of the major efforts of the Rice D0 group is the design and demonstration of the upgrade tracking system. We participate in a large-scale scintillating fiber test at FNAL. We maintain software for track-finding and reconstruction (TRF) and for simulating the response of the scintillating fiber tracker (SFT). Most important, we use these software tools to carry out studies to assess the potential performance of the upgrade tracking system.

The goal of the Fermilab cosmic ray test is to demonstrate the feasibility of operating a many-channel scintillating fiber tracking system. The system will eventually include many thousand channels. Presently all the pieces are in place and we hope to begin reading out a few channels early next year. Rice has contributed to the general construction of the system and has provided software for the data acquisition system. Our former Postdoc, John Skeens, was in residence at FNAL during the past year participating in the cosmic ray test. Our new Postdoc, Iain Bertram, is expected to continue this while in residence at FNAL. He will also participate in the current run and data analysis.

We have modified the scifi response package SFT to allow the user to specify a fraction of channels which randomly turned off and a fraction which are randomly turned on. Typically 2% of the channels are turned off providing a conservative estimate of the number of non-functional channels expected in the final system. The fraction of channels on is usually set to zero or 1% to simulate background from the calorimeter and other sources. Both of these parameters can be easily varied to study the robustness of the system.

The development of the track-finding and reconstruction package TRF continues at Rice inspired by our desire to simulate the tracker at an increasing level of detail. An iterative road-following algorithm is used: the current track parameters are used to predict the position at the next layer and then an attempt is made to add each of the nearby hits to the track, updating the track parameters with a Kalman filter. If the new chi-square is below a preset limit, then a new track is created. Tracks are deleted if they miss (fail to pick up hits) in more than a few layers. This technique is well suited to a system like ours where there are a small number of highly efficient layers. One recent important upgrade is the addition of path definitions: the user provides a list of allowed paths through the detector and the searches for new hits are restricted to those consistent with these paths. This addition has allowed us to deal efficiently with the seven segments in the silicon barrels. Considerable work has also been done to improve the fitting and to overcome some numerical problems in the Kalman filter algorithm.

We carried out two rounds of simulation studies last year. The first culminated in the May 1993 D0 upgrade tracker design.¹⁹ That design has the same general features as the current one but had fewer silicon barrels, more silicon disks and did not have any stereo in the silicon barrels. The scifi barrels were slightly longer and had five degree stereo. The high- p_T muon track-finding efficiency with the phi-measuring layers alone was quite high (99%) even in $t\bar{t}$ events but there was significant confusion in the stereo layers and the efficiency dropped below 90% when they were added.

Another round of studies were carried out for the present tracker design. We now define a track reconstruction efficiency which imposes a tight limit (20.0) on the match chi-square. This match chi-square is defined to be the difference between the reconstructed and true track parameters weighted by the track error matrix. We have also added more detail to the silicon system: gaps covering 5% of the surface and an intrinsic inefficiency of 3%. For $t\bar{t}$ events with W's decaying to muons, we find that the full reconstruction efficiency for these muons is 95%. About half of the missing 5% are tracks that are found but fail the match chi-square requirement. The ratio of false tracks to reals is only 0.1%. If we are very conservative and add 1% noise to the scifi and silicon, then the efficiency drops to 88% and the false/real ratio climbs to 0.6%. We conclude that the system is adequate but that we are sensitive to the noise levels and must work to keep them well below this level. Work is in progress to understand all losses in detail and to determine what fraction of the missing tracks can be recovered with better software.

¹⁹"E823 (Upgrade)", D0 Collaboration, D0 note 1733, 5/19/93

C. FNAL E683 — Photoproduction of High p_t Jets

Introduction

The purpose of Fermilab experiment E683 is the study of photoproduction of jets using the Wide Band photon beam. Rice is the lead institution on this experiment. Collaborating institutions are Ball State University, Fermilab, University of Iowa, University of Maryland, University of Michigan, Vanderbilt University and University of Wisconsin. The Wide Band Beam at Fermilab provides the world's highest energy tagged photon beam, with usable photon fluxes extending to 400 GeV. This beamline can also supply a pion beam, and for comparison purposes we took about 10% of our data with 250 GeV negative pions. The large-solid-angle coverage of our calorimeters, including full coverage in the forward direction, provides us with a unique opportunity to study the interactions of the photons with partons in the target nucleons. The first-order QCD processes of interest are the diagrams in which the photon couples directly to the parton. These are the QCD Compton and photon-gluon fusion diagrams. In some cases, the photon first dissociates into a quark-antiquark pair before it interacts, the so-called "extended photon." Events of this type will allow us to obtain new information on the photon structure function. When higher order QCD processes are considered, the direct coupling and extended photon processes are not distinct, so a thorough understanding of high p_t photoproduction requires a higher order QCD calculation. A complete second-order calculation is being done by Jeff Owens of Florida State, and should be available within a few months.

In addition to studying jet photoproduction with a hydrogen target, the A -dependence of jet photoproduction is of particular interest. We took data with a liquid deuterium target and six solid nuclear targets ranging from Be to Pb. We know from our previous experiment E609 that large A -dependent effects are seen in jet production in p - A interactions, and we expect similar effects in γ - A interactions.

Fig. 13a. Plan view of the experiment, showing the positions of beam and main calorimeter.

Fig. 13b. Beam's eye view of the main calorimeter, showing segmentation.

A plan view of the experimental apparatus is shown in Fig. 13a. The most important part of our apparatus is a sampling calorimeter, the segmentation of which is shown in Fig. 13b. Each tower consists of one layer of lead-scintillator sandwich, followed by three layers of iron-scintillator sandwich. Both the EM and hadronic energy resolutions are important and were carefully calibrated with electrons and pions of various energies. Analysis of the calibration data is complete. We are currently compiling time-dependent gain shifts using LED and pulser data.

The energy resolution of the calorimeter is parameterized in the usual way: $(\sigma(E)/E)^2 = (N/\sqrt{E})^2 + K^2$, where K is a constant term in the resolution, and N

characterizes the energy dependence. For electromagnetic particles, $N \approx 35\%$ and $K \approx 2\%$. For hadrons, $N \approx 80\%$ and $K \approx 5\%$. The e/h ratio is measured to be about 1.25.

Fig. 14. (a) Azimuthal angle between the two jets in dijet events produced in $\gamma\gamma$ interactions..

Fig. 14. (b) E_1 flow. The azimuthal angle of the higher p_T jet defines $\phi=0$. Each calorimeter tower is plotted at the appropriate ϕ , weighted by the tower E_T .

Recent Results

The first results from our jet analysis have been summarized in a paper which has been submitted to Physical Review Letters. A contributed paper was also submitted to the Photon-Lepton conference held in August at Cornell University. These papers summarize the evidence for jet structure and discuss the forward energy flow both for $\gamma\gamma$ and $\pi\pi$ interactions. Fig. 14a shows the distribution in azimuthal angle between the jets for dijet events with average $p_T > 4$ GeV. Fig. 14b shows the E_1 flow for these events. Both distributions show clear evidence for the dijet structure and excellent agreement with Monte Carlo expectations.

Fig. 15 shows the forward hadronic energy into the beam calorimeter for $\gamma\gamma$ interactions along with the Monte Carlo expectations from the various contributing subprocesses. Contrary to naive expectations, the direct and resolved photon contributions do not have markedly different forward energy distributions. Fig. 16 compares the forward energy flow for $\gamma\gamma$ and $\pi\pi$ dijet events. The $\gamma\gamma$ and $\pi\pi$ forward energy distributions are remarkably similar, again contrary to naive expectations.

Fig. 15. Forward hadronic energy into the beam calorimeter for $\gamma\gamma$ dijet events with average jet p_T greater than 4 GeV. Also shown are the Monte Carlo expectations for the forward energy for the three contributing processes, the direct coupling, resolved photon, and vector meson dominance processes.

Fig. 16. Forward hadronic energy for dijet events with average jet p_t greater than 3.8 GeV. γp and πp data are compared.

However, γp and πp dijet events do show significant differences in other distributions. Figs. 17a and 17b compare $\Delta\phi$ between the jets and E_t flow for the two data sets. Two features are immediately clear. The pion data has considerably more "underlying event", that is, more E_t not associated with either jet, and the jets are considerably more acoplanar for πp compared to γp .

Fig. 17 (a) Comparison of dijet events produced in γp and πp interactions. Plot of azimuthal angle between the two jets for events with average jet p_t greater than 4 GeV.

Fig. 17. (b) Comparison of dijet events produced in γp and πp interactions.. Plot of E_t flow, as shown in Fig. 15.

The first results on the A-dependence studies are presented in a paper which has been submitted to Physical Review Letters. We study the A-dependence by calculating the quantity $K_{t\phi}$, which measures the p_t imbalance of the jets in the transverse plane. Fig. 18 shows $K_{t\phi}$ vs. A for both pion and photon data. We expect several contributions to $K_{t\phi}$, including primordial transverse momentum of the partons bound in the proton, gluon radiation effects, experimental effects such as calorimeter granularity and energy resolution, and nuclear effects. The difference in $K_{t\phi}$ between pion and photon data can be understood

Fig. 18. The A-dependence of $K_{T\phi}$ for dijet events produced in γp and πp interactions with average jet p_t greater than 3 GeV. The curves shown are fits to the form $C_0 + C_1 A^\alpha$. For the γp data, the fitted values are $C_0 = 1.85 \pm 0.10$; $C_1 = 0.24 \pm 0.10$ and $\alpha = 0.32 \pm 0.08$. For the πp data the fitted values are $C_0 = 3.54 \pm 0.22$; $C_1 = 0.27 \pm 0.21$ and $\alpha = 0.39 \pm 0.15$.

values of α measured by different experiments. This paper explains at least some of the confusion as simply due to acceptance effects.

In the last year two students have received Ph.D. degrees from this experiment. They are Donna Naples from the University of Maryland, and Don Lincoln from Rice University.

at least partially by the increased underlying event in the pion data. All of the non-nuclear effects can be lumped into one constant, and we fit the data to the form $K_{T\phi}^2 = C_0 + C_1 A^\alpha$. For both the photon and pion data, α is consistent with 1/3, as would be expected from a multiple scattering model.

There has been recent theoretical interest in the A-dependence of jet photoproduction by M. Luo, J. Qiu and G. Sterman, who have used perturbative QCD to relate our measurements to the color force experienced by a parton moving through nuclear matter.

One final recent result relating to A-dependent effects in hard scattering is a Physical Review Letter co-authored by Tom Fields and Marj Corcoran. This paper discusses discrepancies in α measurements from earlier dihadron experiments. Different experiments had quite different acceptances, and this paper shows how the different acceptances lead to different measured values of α . There has been a great deal of confusion in the literature about the conflicting

D. FNAL E832 and E799 Phase II — KTeV

Fermilab E832/E799 (KTeV) will take data during the next fixed-target cycle at Fermilab, currently scheduled for mid 1995. These experiments will study CP violation in the neutral kaon system as well as a wide range of rare K decays. This experiment will measure the CP violating parameter $Re(\epsilon'/\epsilon)$ to a precision of 10^{-4} . A non-zero value for $Re(\epsilon'/\epsilon)$ 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 current best measurement of $Re(\epsilon'/\epsilon)$ is from Fermilab E731, which measured $(7.5 \pm 5.2 \text{ (stat)} \pm 2.9 \text{ (syst)}) \times 10^{-4}$, a value consistent with zero. A CERN experiment NA31, has measured a nonzero value, $(33 \pm 7 \text{ (stat)} \pm 8 \text{ (syst)}) \times 10^{-4}$, a value which disagrees with the E731 result by ~ 2.5 standard deviations. Both groups are pursuing more precise experiments.

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. The Rice group is responsible for refurbishing the four drift chambers which are the heart of the spectrometer. These chambers were used in two previous experiments at Fermilab, where they achieved excellent spatial resolution (80 microns), but had mechanical problems. The cathode wires have had the problem of pulling out of the solder joint, shorting to ground, and bringing the chamber and the entire experiment down. The problem is thought to arise from stress on the solder joint caused by excessive tension used in stringing the cathode wires. This problem will be solved by replacing the beryllium-copper cathode wires with gold-plated aluminum. The aluminum wires will be strung at significantly less tension than the old cathode wires (150 g vs. 420 g), thereby alleviating the problem of pull-out from the solder. This solution also has the desirable consequence of significantly reducing the multiple scattering in the chambers.

The chamber work for KTeV has proceeded on schedule in the past year. The smallest of the four chambers was shipped to Rice during the fall of 1992. A variety of tests was done on this chamber in order to gain familiarity with it, as well as to determine the effects of helium contamination in the gas. These tests influenced the design of the helium bags which are located between all chambers to reduce multiple scattering. A new clean room facility was built at Rice for the KTeV chamber work. Over the summer of 1993 part of this chamber was restrung with the gold-plated aluminum cathode wire and standard gold-plated tungsten sense wire. The aluminum wire has proved fairly easy to work with, and the problem of wire pull out from the solder seems to be solved. Three hundred cathode wires have been in place for three months, and no wires have yet pulled out of solder joints. Our goal is to have all four chambers restrung by the end of the summer of 1994, so that they can be shipped to Fermilab and be prepared for installation.

Marj Corcoran is leading this effort. Graduate student Julius Barnes will write his Master's thesis based on the chamber work. During the past summer and this semester Rice undergraduates have received valuable research experience working with us on these chambers. In spite of the progress we have made, we very much need a post doctoral research assistant to help with the chamber work as well as participate in other aspects of the KTeV project. For example, we would like to participate in the rare-K decay Monte Carlo studies currently being carried out by the collaboration, but are unable to without additional manpower.

E. Publications, Presentations, and Theses

Publications:

- "A high energy muon beam polarimeter," submitted to Nuclear Instruments and Methods, with B. Adeva and the SMC Collaboration.
- "Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron," B. Adeva and the SMC collaboration, Phys. Letts. B302, 533 (1993).
- "Results from the SMC on the Spin Structure Function of the Deuteron," to be published in Nuovo Cimento, M. Lowe and the Spin Muon Collaboration.
- "Combined Analysis of World Data on Nucleon Spin Structure Function," submitted to Physics Letters B, B. Adeva and the Spin Muon Collaboration.
- "First Generation Leptoquark Search in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi *et al.*
- "Search for the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," to be submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi, *et al.*
- "A Search for Jet Events with Rapidity Gaps in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV," to be submitted to Phys. Rev. Letters, D0 Collaboration, S. Abachi *et al.*
- "Searching for Top with Neural Nets. I. Optimization of NN Parameters," H. E. Miettinen and R. Ou, D0 Note 1842, July 1993.
- "Searching for Top with Neural Nets. II. NN versus Probability Density Estimation," H. E. Miettinen, R. Ou, L. Holmstrom, and S. Sain, D0 Note 1931, November 1993.
- "Detecting Beam Pileup for High Rate Particle Beams," Nuclear Instruments and Methods A332, 23 (1993). D. Lincoln and D. Naples.
- "Observation of Jet Photoproduction by Real Photons," submitted to Phys. Rev. Lett., E683 Collaboration.
- "A-Dependence of Photoproduced Jets," submitted to Phys. Rev. Lett., E683 Collaboration.
- "Nuclear Rescattering Effects in Massive Dihadron Production," Phys. Rev. Lett. 70, 143 (1993), T. Fields and M. Corcoran.

Presentations:

- "W and Z Decays to Electrons in D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 387. D0 Collaboration, presented by N. A. Graf.
- "W and Z Decays to Muons in D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 390. D0 Collaboration, presented by D. Wood.
- "Top Quark Search in D0 from the Lepton + Jets Mode," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 453. D0 Collaboration, presented by B. Klima.
- "Search for the Top Quark in Dilepton Events with D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 456. D0 Collaboration, presented by R. Partridge.
- "Dimuon Production in D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 753. D0 Collaboration, presented by S. Igarashi.
- "Direct Photon Production from D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 971. D0 Collaboration, presented by G. R. Snow.
- "Inclusive Jet Cross Sections at the D0 Detector," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 993. D0 Collaboration, presented by R. V. Astur.
- "Two Jet Energy and Rapidity Distributions," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 996. D0 Collaboration, presented by G. C. Blazey.

- "Production of Jets in Association with W Vector Bosons in the D0 Detector," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1094. D0 Collaboration, presented by J. Yu.
- "A Search for Squarks and Gluinos in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV with the D0 Detector," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1228. D0 Collaboration, presented by M. Paterno.
- "A Search for Scalar Leptoquarks in D0," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1265. D0 Collaboration, presented by K. W. Merritt.
- "Triggering the D0 Experiment," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1641. D0 Collaboration, presented by J. T. Linnemann.
- "Electron Identification in the D0 Detector," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1678. D0 Collaboration, presented by M. Narain.
- "Low Energy Response of the D0 Calorimeter and Jet Energy Measurement," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 1681. D0 Collaboration, presented by P.C. Bhat.
- "First Results from Fermilab E683," M. Corcoran, High Energy Physics Seminar, Argonne National Lab, February, 1993.
- "The A-Dependence of Jet Photoproduction," D. Naples, Presented at the Moriond Conference, March, 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.
- "On Determining x_{Bj} from Jet Measurements," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 926. E683 Collaboration, presented by D. Lincoln.
- "The A-Dependence of K_{T0} for Photoproduced Jets," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 948. E683 Collaboration, presented by D. Naples.
- "A Study of Photon-Nucleus Collisions at High Transverse Energy," Proceedings of the Fermilab Meeting DPF92, World Scientific (1993), p. 945. E683 Collaboration, presented by Q. Zhu.
- "Results from the SMC on the Spin Structure Function of the Deuteron," M. Lowe, Hadron 93, Como, Italy, June 25, 1993.
- "The Spin of the Nucleon," J. B. Roberts, Physics Colloquium, Rice University, April 17, 1993.

Theses:

- "Observation of Jet Photoproduction and Comparison to Monte Carlo Simulation," Don Lincoln, Ph.D. Thesis, Rice University, August, 1993.
- "Calibration of the E683 Main Calorimeter," Gregory P. Morrow, M.A. Thesis, Rice University, April, 1993.

TASK B – Theoretical High Energy Physics

A. Progress on Theoretical Topics

Our work on the “optimization” of the third-order QCD calculation for $R(e^+e^-)$ was completed and is now in press with Physical Review D. We find, as reported in our Physical Review Letter of last year, that the effective couplant, $\bar{\alpha} = \alpha_s / \pi$, “freezes” to an essentially constant value 0.26 below an energy of about 300 MeV. This number is obtained entirely theoretically and is a direct consequence of applying the “optimization” procedure proposed in 1981²⁰ to the third-order perturbative QCD calculation of $R(e^+e^-)$ ²¹. There is an extensive literature, reviewed briefly in our paper, that assumes “freezing” of the couplant as a phenomenological hypothesis and extracts low-energy values of α_s / π from experimental data in a wide variety of ways. Remarkably, these values agree quite well with each other and with our value, 0.26. Furthermore, the theoretical and experimental $R(e^+e^-)$ agree very well down to zero energy if both are ‘smeared’ in the manner proposed by Poggio, Quinn, and Weinberg²².

Alan Mattingly has extended this work to the τ -decay case. Because of the “freezing” of the couplant, one can make a perturbative prediction for the differential decay rate $d\Gamma/ds$ into hadrons with total invariant-mass-squared s , where $0 < s < M_\tau$. Integrating over s gives a result for the total decay rate which agrees well with the directly obtained result that involves only the effective couplant at the scale M_τ .

A breakthrough in our work on $\lambda\phi^4$ theory has been achieved in collaboration with Maurizio Consoli of the INFN, Catania, Italy. We have realized that our earlier Gaussian-effective-potential results are, in fact, perfectly compatible with the ‘triviality’ of $\lambda\phi^4$ theory, for which there is strong evidence from rigorous inequalities and from lattice simulations. ‘Triviality’ means that the particles of the theory have no physical interaction; all scattering amplitudes vanish in the continuum limit. However, it does not mean that spontaneous symmetry breaking is impossible. Indeed, for a ‘trivial’ theory the effective potential should be given exactly by the classical potential plus the free-field zero-point energy of the shifted field; i.e., by the one-loop effective potential. When this is renormalized in a simple, but nonperturbative way, one finds that the shifted field does indeed become non-interacting as the cutoff goes to infinity. Because there are no physical interactions the one-loop effective potential should be effectively exact. This is confirmed by the fact that the Gaussian approximation leads to exactly the same result.

For a classically scale-invariant $\lambda\phi^4$ theory one finds $m^2 = 8\pi^2 v^2$ for the physical particle mass, m , in terms of the renormalized vacuum expectation value of the field, v . Since the phenomenological value of v is 246 GeV (from the Fermi constant $G_F = 1/\sqrt{2}v^2$), this formula predicts a 2.2 TeV Higgs boson.

Crucial to this picture is an unconventional wavefunction renormalization in which the constant background field (the mode with zero 4-momentum) renormalizes differently from the fluctuation field (the finite-momentum modes). Since this decomposition is Lorentz invariant, this procedure does not violate any sacred principles. There is a close analogy with Bose-Einstein condensation, where the lowest energy mode must be treated separately, since it has a macroscopic occupation number.

²⁰ P.M. Stevenson, Phys. Rev. D **23**, 2916 (1981).

²¹ S. G. Gorishny, A. L. Kataev, and S. A. Larin, Phys. Lett. B **259**, 144 (1991); M. A. Samuel and L. R. Surguladze, Phys. Rev. Lett. **66**, 560 (1991)

²² E. C. Poggio, H. R. Quinn, and S. Weinberg, Phys. Rev. D **13**, 1958 (1976).

In our latest paper with Consoli we have begun to consider how our picture can be definitively tested in lattice simulations.

B. Publications, Presentations and Thesis

Publications:

- "Nonperturbative N-point functions from the Gaussian effective action and renormalization of $\lambda\phi^4$," R. Ibañez-Meier, Phys. Lett. **B295**, 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. **B297**, 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, submitted to Physical Review D.
- "Optimization of $R(e^+e^-)$ and "freezing" of the QCD couplant at low energies," A. C. Mattingly and P. M. Stevenson, Rice preprint DE-FG05-92ER40717-7; Phys. Rev. D (in press).
- " τ decay and the QCD infrared fixed-point," A. C. Mattingly, Rice preprint DE-FG05-92ER40717-8, submitted to Phys. Rev. D.
- "The non-trivial effective potential of the 'trivial' $\lambda\phi^4$ theory: a lattice test," M. Consoli and P. M. Stevenson, Rice preprint DE-FG05-92ER40717-9, submitted to Zeitschrift für Physik C.

Presentations:

- "Applying Optimized Perturbation Theory to QCD at Low Energies," A. C. Mattingly (presenter) and P. M. Stevenson, DPF92 meeting (Fermilab, Nov. 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

Thesis:

- "'Variational' methods in quantum field theory," A. C. Mattingly, Ph.D., May, 1993. (Awarded the Rice Physics Department's H. A. Wilson award for the most outstanding Ph.D. thesis.)

Face Pages and Preprints of Selected Publications

Face Pages

- A. "Results from SMC on the Deuteron Spin Structure Function," Mark Lowe for the Spin Muon Collaboration, Hadron '93 Conference, Como, Italy, June, 1993, to be published in *Nuovo Cimento*.
- B. "Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron," B. Adeva and the SMC collaboration, *Phys. Letts. B* **302**, 533 (1993).

Preprints

- A "A High Energy Muon Beam Polarimeter," *The SMC Collaboration*, submitted to *Nucl. Inst. & Meth.*, October, 1993.
- B. "Combined Analysis of World Data on Nucleon Spin Structure Function," to be submitted to *Physics Letters B*, B. Adeva and the Spin Muon Collaboration.

Preprints removed

Results from SMC on the Deuteron Spin Structure Function

Mark Lowe
for
The Spin Muon Collaboration (SMC)

Abstract

The spin-dependent structure function g_1^d of the deuteron has been measured in the deep inelastic scattering of polarised muons on polarised deuterons in the kinematical range $Q^2 > 1 \text{ GeV}^2$, $0.006 < x < 0.6$. The first moment $\Gamma_1^d = \int_0^1 g_1^d dx = 0.023 \pm 0.020(\text{stat.}) \pm 0.015(\text{syst.})$ is smaller than the prediction of the Ellis-Jaffe sum rules. Using earlier measurements of g_1^p , the first moment of the spin-dependent neutron structure function g_1^n can be inferred. The difference $\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05(\text{stat.}) \pm 0.04(\text{syst.})$ agrees with the Bjorken sum rule $\Gamma_1^p - \Gamma_1^n = 0.183 \pm 0.004$.

1 Introduction to Spin Dependent Structure Functions

In the single photon approximation, the difference in cross sections for deep inelastic scattering of a muon polarised parallel and antiparallel to a longitudinally polarised nucleon can be expressed as:

$$\left(\frac{d^2\sigma}{dQ^2 d\nu} \right)^{||} - \left(\frac{d^2\sigma}{dQ^2 d\nu} \right)^{\perp} = \frac{4\pi\alpha^2}{E^2 Q^2} [M(E + E' \cos\theta) G_1(Q^2, \nu) - Q^2 G_2(Q^2, \nu)] \quad (1)$$

In this expression, the spin-independent structure functions of the hadronic tensor have cancelled and we are left with an expression in terms of the spin-dependent structure functions, $G_1(Q^2, \nu)$ and $G_2(Q^2, \nu)$. In the scaling limit (i.e. $Q^2, \nu \rightarrow \infty$), G_1 and G_2 reduce to

$$M^2 \nu G_1(Q^2, \nu) \rightarrow g_1(x) \quad M \nu^2 G_2(Q^2, \nu) \rightarrow g_2(x) \quad (2)$$

where x is the Bjorken scaling variable, defined as:

$$x = \frac{Q^2}{2M\nu} \quad (3)$$

where M is the mass of the nucleon.

For the case of parallel or antiparallel target and lepton polarisations, the influence of g_2 is small. Experimentally, one measures an asymmetry

$$A = \frac{d\sigma^{||} - d\sigma^{\perp}}{d\sigma^{||} + d\sigma^{\perp}} \quad (4)$$

To relate this measured asymmetry to the structure function, one extracts the virtual photon asymmetry A_1 via the relation

$$A \cong D A_1 \quad (5)$$

Measurement of the spin-dependent structure function $g_1(x)$ of the deuteron

Spin Muon Collaboration (SMC)

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We report on the first measurement of the spin-dependent structure function g_1^d of the deuteron in the deep inelastic scattering of polarised muons off polarised deuterons, in the kinematical range $0.006 < x < 0.6$, $1 \text{ GeV}^2 < Q^2 < 30 \text{ GeV}^2$. The first moment, $\Gamma_1^d = \int_0^1 g_1^d dx = 0.023 \pm 0.020 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$, is smaller than the prediction of the Ellis-Jaffe sum rules. Using earlier measurements of g_1^p , we infer the first moment of the spin-dependent neutron structure function g_1^n . The difference $\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$ agrees with the prediction of the Bjorken sum rule, $\Gamma_1^p - \Gamma_1^n = 0.191 \pm 0.002$.

In the past 15 years, two experimental determinations of the spin-dependent structure function $g_1^p(x)$ of the proton were made from measurements of cross section asymmetries in deep inelastic scattering of longitudinally polarised leptons by longitudinally polarised protons. The first was an experiment at SLAC [1] in which polarised electrons with energies between 6 and 21 GeV were used and which covered the kinematic range $0.1 < x < 0.7$, where x is the Bjorken scaling variable. The second was an experiment at CERN [2] in which polarised muons of 100, 120 and 200 GeV energy were used, and which covered the x range $0.01 < x < 0.7$. The result of these experiments disagrees with the prediction of the Ellis-Jaffe sum rule [3] for the proton and indicates that in the quark-parton model, the spins of quarks and antiquarks contribute little to the spin of the proton. In a large number of papers, a variety of theoretical ideas were proposed to explain this unexpected result [4]. Several experiments are presently being carried out or prepared at CERN [5], SLAC [6], and DESY [7] to measure the spin structure function of the neutron

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