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ep Physics at the CBA

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ep Physics at the CBA

In this report we explore the physics potential of a high energy electron proton colliding beam facility where 20 GeV electrons collide with 400 GeV protons at the CBA. Such a facility will dramatically extend lepton nucleon scattering up to momentum transfers where weak processes have strengths commensurate with electromagnetic process ($Q^2 \approx M_W^2$). The study of lepton nucleon scattering in this particularly timely kinematic regime by fixed target experiments will have to await the advent of 20 TeV accelerator beams. In highlighting the physics potential of a high energy ep collider we have drawn heavily on the myriad of proposals intended for CERN,^{1,2} Fermilab,^{3,4} and BNL.⁵ These proposals discuss a large number of important technical details concerning both the design of an ep collider and the extraction of the physics summarized here using realistic detectors.

As we shall show throughout this report, the physics explored by a high energy ep collider tends to be complementary to, rather than competitive with, the physics of either hadron-hadron or electron-positron colliders. Both hadron-hadron and electron-positron physics tends to concentrate on the production of new states; whereas ep scattering tends to concentrate on the t-channel study of particle interactions and particle structure. A high energy ep collider experiment will provide several crucial tests of the standard electroweak theory and QCD. Low energy lepton nucleon scattering experiments have demonstrated that the standard model correctly describes electro-weak phenomena at low Q^2 . These ideas are summarized in reference 6. These tests indicate that the standard model describes the coupling constants of electro-weak interactions, although the predicted propagator Q^2 dependence is untested. In a high energy ep collider, the effect of the charged current propagator on the counting rate will be sufficiently dramatic to offer a precision measurement of the W mass (± 5 GeV). The level of scattering asymmetry observed in polarized ep scattering at SLAC (10^{-4}) will grow to about 25% at the momentum transfers accessible to a high energy ep collider before being damped by the Z propagator. Measurement of the Q^2 dependence of such weak-electromagnetic effects will provide an estimate of the Z mass to about 10% which can then be compared to the more accurate measurement of the Z mass through direct production in either e^+e^- annihilation or hadron-hadron collisions to provide a critical test of electroweak theory, and especially the hypothesis of a single Z^0 .

Modifications can be made to the standard model which match present data at low Q^2 but diverge from the standard model at the momentum transfer than can be explored with an ep collider. For example, the presence of multiple Ws and Zs with masses below about 200 GeV would distort the expected single propagator Q^2 dependence of lepton nucleon scattering in a measurable way. The charged current process, which is measured to be lefthanded at low Q^2 , might become ambidextrous at high momentum transfers

due to either the presence of new vector bosons or new heavy electrons. The ability to control the incident electron polarization in an ep collider provides a powerful tool in searching for righthanded charged current couplings. The effects of a new righthanded, charged current mediating vector boson with a mass of more than 200 GeV will be substantially suppressed relative to the standard W at presently explored momentum transfers, but will grow increasingly more important at higher Q^2 . In a moderate duration ep run, the effects of righthanded mediating Ws of masses below 300 GeV will be detectable. An alternative ambidextrous model might involve a massive neutral heavy electron which couples to righthanded electrons with the standard W propagator. Such righthanded electron coupling would be unobserved in present charged current data which is below threshold for production of this new heavy lepton. The experimental signature for such a heavy electron is striking and offers sensitivity to heavy electrons with masses up to 100 GeV in a modest duration ep run.

High energy electron proton scattering will provide several important tests of QCD. The expected QCD scale breaking of neutral current structure functions can be studied with reasonable precision up to momentum transfers that are 30 times larger than the range accessible to fixed target accelerators of the foreseeable future. Because of the large center of mass energy that is available in a ep collider, scaling violations can be studied in a kinematic region free from the effects of heavy quark thresholds, higher twist corrections and the like. The study of scale breaking in the region of momentum transfers up to 10^4 GeV^2 provides an important test of the present ideas inherent in QCD corrections to the deep inelastic scattering process. These concepts indicate that scale breaking should grow logarithmically in Q^2 . Observations of a power law scaling violation would suggest the onset of new phenomena such as possible quark substructure or additional interactions between quarks and leptons. Even if such phenomena did not occur, the measurement of quark and gluon structure functions at the large momentum transfers accessible to an ep collider will provide information pertinent to the interpretation of parton scattering phenomena in hadron-hadron colliders.

In addition to providing tests of QCD at high Q^2 , a high energy ep collider would test QCD through the high ν , low Q^2 virtual photoproduction process. An ep collider with 20 GeV electrons on 400 GeV protons would produce a virtual photon spectrum in the proton rest frame which is identical to the spectrum produced by a 17 TeV electron fixed target bremsstrahlung beam. Both heavy flavor photoproduction and the QCD Compton process provide potentially powerful test of QCD in detail.

The physics discussed in this report is predicated on the existence of a 20 GeV on 400 GeV electron proton collider capable of delivering an average luminosity of $2-4 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. Several independent reports have concluded that such a facility is technically feasible at the CBA.^{5, 7} With advanced planning it may even prove possible to collide electrons on protons at one or two of the CBA intersection regions while simultaneously colliding protons on protons at the other intersection regions. Much of the physics summarized in this report presumes a run of net

luminosity per $5 \times 10^{38} \text{ cm}^{-2}$ which would be collected in a reasonable period of dedicated ep running. Some of the physics discussed here requires colliding positrons as well as electrons with protons; some of the physics requires incident leptons with longitudinal polarization. We assume that 80% polarization is possible in an ep collider supplemented with suitable magnetic spin rotator gymnastics.⁵

Because some of the physics potential of an ep collider depends on measurements of hadronic jets, we assume that a general detector with large solid angle electromagnetic and hadronic calorimetry would exist that is similar to those detectors being built for other particle collider facilities. Many of the ep simulation presented here assume a resolution of 40 mrad on jet angle and a $.60\sqrt{E_{\text{jet}}}$ resolution on jet energy. These values are typical of resolutions that have been achieved with present calorimeter technology.

The Neutral Current Process

In this section we discuss the physics result that may follow from a study of the neutral current contributions to high energy ep collisions which are depicted in Fig. 1a. In neutral current interactions, the incident electron emits a boson which is absorbed by a quark carrying a fraction x of the incident proton momentum (see Fig. 1c). In high Q^2 collisions, it is believed that the final hadronic state will separate into the current jet (four momentum $xP+q$) at wide angle and a forward jet (four momentum $(1-x)P$) which is identified with the fragmentation of the forward proton. The kinematic variables x ($x = \frac{Q^2}{2 P \cdot q}$), and Q^2 ($Q^2 = -q^2$) can be measured by measuring the energy and polar angle of the scattered electron. The quantities x and Q^2 can be determined also by measuring the current jet but with different precision. x could be independently measured by the proton fragmentation jet using a forward calorimeter downstream to deflect the fragmenting protons. A useful kinematic variable is $y = \frac{P \cdot q}{P \cdot K}$ which is the fraction of the incident electron energy which is transferred to the proton in the proton rest frame. The variables x , y , and Q^2 are not independent but are related through the relation $Q^2 = s x y$, where $\sqrt{s}$ is the total center of mass energy ($s = 4 E_e E_p$, at high energies).

The major interest in studying the neutral current processes at high energies lies in the study of deep inelastic structure functions, weak-electromagnetic interference, and virtual photoproduction. With the exception of virtual photoproduction at low Q^2 , largely, the interest is in studying scattering at high Q^2 . In Fig. 2 we compare the high Q^2 neutral current yield obtainable in an ep collider to the yield of events in the projected Tevatron muon beam. Clearly the kind of collider discussed here will extend the kinematic regime studied by foreseeable fixed target experiments in a dramatic way.

Structure Function

In this section we describe the x and Q^2 range where the neutral current structure function can be measured with precision in the life of the collider. The cross section for the one photon contribution can be written in the form:

$$d\sigma = \frac{4\pi\alpha^2}{Q^2} \left[1 - \frac{Q^2}{sx} + \frac{1}{2} \left(\frac{Q^2}{sx} \right)^2 \right] F_2(x, Q^2) \frac{dx}{x} \frac{dQ^2}{Q^2}$$

The s dependence in the above expression comes from the bracketed factor which only varies by a factor of two over the full kinematic range $0 < Q^2 < sx$. We reach the conclusion that although increasing s increases the range of Q^2 that is accessible at a given x , increasing s does not appreciably increase the yield of events in a given accessible x and Q^2 bin.

In order to determine the range of x and Q^2 in which we can profitably study $F_2(x, Q^2)$, we set up criteria of bin size and number of events per bin. Because QCD scale breaking grows logarithmically in Q^2 , a natural Q^2 binning scheme is to bin in $d(\log Q^2) = dQ^2/Q^2$; we postulate a bin size is $dQ^2/Q^2 = .1$. $F_2(x, Q^2)$ changes most rapidly near $x = 0$, and so we suggest that $dx/x = .1$ bins are also desirable. Our cross section expression above gives our event yield in a given $dQ^2/Q^2 = .1$ and $dx/x = .1$ bin of:

$$\text{yield per bin} = \frac{2.6 \times 10^6}{Q^2} F_2(x, Q^2)$$

For a mature ep run of 10^{39}cm^{-2} integrated luminosity.

Figure 3 shows the $Q^2 - x$ contours where the yield per bin is greater than 100 for our ep run of 10^{39}cm^{-2} . We see from Fig. 3 that in the low x region do we measure structure functions up to the kinematic limit, but elsewhere we are luminosity limited. In light of the fact that increasing s does not appreciably increase the yield in a given $x - Q^2$ bin, we conclude that incremental increases in luminosity outweigh incremental increases in s for the measurement of structure functions. For these reasons a dedicated 20 x 400 GeV ep facility at the CBA is expected to do a better job with structure function measurement than a part time 10 x 1000 GeV ep facility at Fermilab.

QCD Scale Breaking

The central prediction of QCD, when applied to lepton-nucleon scattering, is related to the momentum transfer (Q^2) dependence of structure functions. QCD predicts that structure functions should vary logarithmically as a function of Q^2 for fixed x . The interaction of quarks and gluons causes an evolution in the structure function at higher Q^2 which is predicted to enhance the structure functions at small x and to suppress the structure functions at large x . This variation with Q^2 reflects the increasingly important role of sea quarks in the neutral current process as the momentum transfer increases. Figure 4 shows simulated structure functions in the low x region which could be measured easily at our ep collider. The rise in $\log(Q^2)$ for low data will reflect into F_2 rather dramatically for this choice of scale breaking parameters. The value $\Lambda = .5 \text{ GeV}^2$ was used in the calculations of Fig. 4, although recent data indicate that this value may be too large, even so the effect is clear. We note that the kinematic limit for neutral current scattering at $x = 0.1$ at the Tevatron is only at $Q^2 = 200 \text{ GeV}^2$, whereas the limit for a $20 \times 400 \text{ GeV}$ ep collider is at Q^2 of 3200 GeV^2 , at least an order of magnitude higher. As Fig. 4 demonstrates, the study of scale breaking at low x at an ep collider will not be statistically limited. At the DPF Snowmass Workshop on Future Facilities⁸ it was estimated that an ep run of 5×10^{38} integrated luminosity would determine Λ to $\pm 30\%$ if $\Lambda = 100 \text{ MeV}$ and $\pm 20\%$ if $\Lambda = 300 \text{ MeV}$. A 30% measurement of Λ translates to a 6% measurement of α_s .

Non-QCD Scale Breaking

An ep collider offers the chance to measure the Q^2 dependence of structure functions over 3 orders of magnitude, providing a powerful tool searching for possible power law contributions to scale breaking. Such anomalous scale breaking would signify the onset of exciting new phenomena in lepton nucleon scattering.

In the past, when lepton nucleon scattering experiments began to reach the energies of a few hundred MeV, nucleons no longer scattered like pointlike objects, but instead appeared to have a substructure that was described by a form factor. As electron energies were increased, a new simplicity emerged as the scaling of deep inelastic structure functions was explained eventually as a manifestation of electron-quark scattering. As the energy regime that is accessible with a high energy ep collider is reached, one may find that quark themselves may have substructure. An indication of substructure would emerge as the power law scale violation from the multiplicative quark form factor of the type:

$$|F(q)|^2 = \left(\frac{M^2}{Q^2 + M^2} \right)^2$$

where M represents the reciprocal distance scale of the subquarks. Such a form factor would produce an x independent pattern of scaling violations contrasted to the x dependent scaling violations of QCD. Figure 5 shows how a quark form factor would affect the measurements of the neutral current structure of F_2 . The error bars reflect the statistical precision appropriate to an ep run of $5 \times 10^{38} \text{ cm}^{-2}$ integrated luminosity. The two curves correspond to a range of x between .1 and .3 and between .3 and .5. With this luminosity we would be sensitive to M values of up to 300 GeV.

The presence of non-logarithmic scale violations as we illustrate in Fig. 5 are only one indication of quark substructure. Dramatic differences in the appearance of the hadronic final state would occur in the transition from the regime of photon-quark scattering to photon subquark scattering. Early indications of such an effect would be a substantial broadening of the current jet at large Q^2 . QCD jet broadening is only expected to grow logarithmically in Q^2 from conventional effects. Such anomalous effects will be easily detectable at an ep facility since the current jet direction is predicted from the scattered electron energy and angle.

Quark substructure effects should also be observable at high energy e^+e^- colliders through variations in the ratio of hadronic to the point-like cross section as a function of E_{cm} . Of course, in e^+e^- annihilation, the analysis of R is complicated by the E_{cm} s -channel production of new states. Hence the interpretation of a s dependence of R in e^+e^- annihilation is inevitably cloudy.

Polarized Proton Structure Functions

As discussed extensively in Ref. 15, the ability to collide electrons and positrons with polarized protons at the CBA adds a new dimension to deep inelastic scattering. We list four of the many possible measurements.

1. The polarized structure function of the proton has been measured at low Q^2 in deep inelastic ep scattering. The measurements are sensitive to $A_u(x)$ --the degree of polarization transfer from the proton to the up quark. The results of these experiments were both interesting and unexpected. High Q^2 measurements would determine the scaling behavior of $A_u(x)$.
2. The proton polarization asymmetry in positron-proton charged current interactions is directly proportional to $A_d(x)$. This important quantity has never been measured. While $A_u(x)$ is predicted to be large and positive, $A_d(x)$ should be smaller and negative--that is the polarization of the d quark should be opposite to the polarization of the proton.

3. The proton polarization asymmetry of longitudinally polarized electrons on transversely polarized protons is sensitive to $R = \sigma_L/\sigma_T$. This important parameter is quite difficult to measure by other means. The parton model predicts $R = 0$ for scattering from spin 1/2 constituents and $R = \infty$ for scattering from spin 0 constituents.
4. The current algebra Bjorken sum rule:

$$\int \frac{dx}{x} \left(\frac{A_p F_p(x)}{1 + R_p} - \frac{A_n F_n(x)}{1 + R_n} \right) = \frac{1}{3} \frac{|G_a|}{|G_v|} \left(1 - \frac{\alpha_s}{\pi} (Q^2) + \dots \right)$$

could be tested by measuring the quantities on the lefthand side of the equation directly. This is a fundamental test of QCD.

Weak-Electromagnetic Interference

The asymmetry in low Q^2 electron proton scattering observed at SLAC gave the first compelling evidence for the existence of weak and electromagnetic interference in the neutral current process. Photon exchange continues to overwhelm Z exchange even at the Q^2 accessible to an ep collider, but even so the asymmetry measurement continues to be the best means to observe the effects of the Z. The predictions for A, from the standard model, for the asymmetry between the electron and positron scattering cross section is:

$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \\ \equiv \frac{2\sqrt{2} G_F}{e^2} \frac{Q^2}{1 + Q^2/M^2} \frac{f^-}{f^+} \frac{x F_3^{\text{INT}}(x, Q^2)}{F_2^{\text{em}}(x, Q^2)}$$

where $f^\pm = \frac{1 \pm (1-y)^2}{2}$ and $\frac{x F_3^{\text{INT}}}{F_2^{\text{em}}}$ is the ratio of the structure functions and their interference term. Present data indicates that this ratio of structure function should be constant to within 1% over the Q^2 range of interest here. We see from the above equation that the asymmetry parameter grows linearly with Q^2 until it is damped by the Z propagator at a Q^2

comparable with the squared mass of the Z. The mass of the Z can be measured to ± 15 GeV with a luminosity of 5×10^{38} . We feel that the major contribution of ep scattering in this area is not in the precision measurement of the Z mass, but rather as a test of the standard model in the extreme spacelike region. Deviations from the expected Q^2 dependence of the asymmetry parameter A could signify the presence of additional neutral vector bosons which are more massive than the standard Z.

Virtual Photoproduction

In the low Q^2 limit, an ep facility can be viewed as an intense high energy virtual photon beam. The virtual photon spectrum, when viewed in the rest frame of the incident protons, will resemble the bremsstrahlung photon beam generated when 17 TeV incident electrons impinge on a thin radiator. Hence an ep collider will allow the study of photoproduction at the highest energies, before the existence of 20 TeV fixed target accelerator beams. In this section we discuss the virtual photoproduction of heavy quark states and the study of the high energy QCD Compton process. Particles produced by the high energy photoproduction process tend to be produced within 20 degrees of the incident proton direction, so one might consider dedicating one interaction region of an ep facility to building a detector optimized for photoproduction. Such a detector might resemble the detectors built for fixed target photoproduction, consisting of a magnetic spectrometer interspersed with particle identifiers and a downstream calorimeter.

The Williams-Weizsacker formula gives the effective luminosity of the ep virtual photon beam for a given ep luminosity in terms of Q^2 and y . The y variable is significant in the virtual photoproduction limit ($Q^2 \ll s$) since the s , the total squared photon-proton center of mass energy, is given by $s = s y$. The Williams-Weizsacker virtual photon luminosity is:

$$dL_\gamma = \frac{\alpha L_{ep}}{2\pi} (1 + (1-y)^2) \frac{dQ^2}{Q^2} \frac{dy}{y}$$

where dL_γ represents the equivalent virtual photon-proton luminosity for a given dy, dQ^2 bin, and L_{ep} represents the ep luminosity. We compute rates from this formula integrating over Q^2 from a Q^2_{min} dictated by an assumed minimum scattered electron tagging angle of 3 degrees to a Q^2_{max} which we take as .1s.

Table I gives the total rates for heavy flavor production for a run with an ep luminosity of $5 \times 10^{38} \text{ cm}^{-2}$. This table assumes that the virtual photon-heavy quark cross section depends on Q^2 , and v , the virtual photon energy in the proton rest frame according to:

$$\sigma = \sigma_0 \left(\frac{M_v^2}{M_v^2 + Q^2} \right)^2 \left(1 - \frac{v_{\text{THR}}}{v} \right)$$

where the Q^2 damping comes from an assumed vector meson dominance propagator (M_v is the heavy vector meson mass), and the v dependence cuts off the cross section smoothly near N_{THR} . The asymptotic heavy flavor production cross sections σ_0 ($\approx 500\text{nb}$) are scaled from the measured charm photoproduction cross section according to $(Q_q/M_q)^2$ where Q_q and M_q are the charge and mass of the heavy quark. The underlying ideas of this simple VMD model, $(Q_q/M_q)^2$ scaling, and the threshold v dependence, are in agreement with observed features of vector meson photoproduction data from the ρ to the J/ψ ,

TABLE I
Virtual Photoproduction of Heavy Quark States

	Expected Yield*
1) $\gamma^* \rightarrow D\bar{D}$	4.9 M
2) $\gamma^* \rightarrow B\bar{B}$	440 K
3) $\gamma^* \rightarrow t\bar{t}$	79 K
(20 GeV top)	
4) $\gamma^* \rightarrow t\bar{t}$	3.1 K
(50 GeV top)	
5) $\gamma^* \rightarrow t\bar{t}$	1.1 K
(60 GeV top)	

* Yield for $5 \times 10^{38} \text{ cm}^{-2}$ integrated luminosity.

Particle spectroscopy and production model studies form the major physics motivations for investigating high energy photoproduction of heavy quark states. The large yield of beauty states shown in Table I will enable one to find new mesons and baryons and study their lifetimes and decay modes. The ability to measure the cross section for heavy quark production over a range in v will allow one to test QCD motivated models of photoproduction such as the photon-gluon fusion model in a definitive way.

The semileptonic decay of heavy quark states provides a major signal for heavy quark photoproduction by creating events with anomalous leptons and large missing p_T . Although the heavy quark states will have momentum vectors which are nearly along the direction of the incident proton, simulations show the heavy quark state decay products emerge at reasonably large angles in the laboratory, and semileptonic decay leptons are generally well separated from other tracks in the event. Vector mesons containing heavy quarks may be observed through the reconstruction of their mass through dilepton decay products. The large mass Bethe-Heitler background should be very small. Unfortunately the yield for heavy quark vector meson production should be several orders of magnitude less than the yields presented in Table I. Lastly if the mass of the top quark is over one half the mass of the Z, a high energy ep collider may be the cleanest way to observe top states before LEP II.

The study of the high energy QCD Compton process depicted in Fig. 6a provides another motivation for virtual photoproduction studies.⁹ This process, where a high energy photon scatters off a quark in the proton creating a wide angle gluon jet and a wide angle quark jet, is the inverse of one of the mechanisms that is thought to be responsible for direct photon production in hadron-hadron collisions. In the kinematic regime where the final quark and gluon jet emerge with a large p_T (say $p_T > 15$ GeV), the cross section calculation should be reliable, and hence measurements of the process will serve as tests of QCD. The ratio of the QCD Compton cross section over the QED Compton cross section (which would have a high p_T photon against a quark jet) serves as a direct and independent measurement of α_s strong. Correlations are expected¹⁰ between the plane defined by the quark and gluon jet and the polarization of the virtual photon which serves to directly test the form of the quark gluon coupling. For example, this angular correlation is expected to have the opposite sign as the correlation predicted for the QED Compton process.

The QCD Compton process is a low Q^2 process with two high p_T jets, and it will produce events which can be distinguished from neutral current events which consist of a single large p_T jet and a large Q^2 scattered electron. The light quark photon-gluon fusion contribution of Fig. 6b, however, produces a background with the same topology as the QCD Compton process. It is possible to suppress the photon-gluon fusion process relative to the QCD Compton process by demanding that the parton which collides with the virtual photon has a large fraction of the incident proton momentum. A lower cut on the parton energy fraction suppresses the gluon initiated process of Fig. 6b relative to the quark initiated process of Fig. 6a since gluons tend to carry a much smaller fraction of the proton momentum than the valence quarks. Energy balance can be used to find ξ , the fraction of momentum of the incident proton carried by the parton which collided with the virtual photon for a given two jet event.

$$\xi = (E_{j1} + E_{j2} + E_e - E_e)/E_p \quad ,$$

where E_{j1} and E_{j2} are the lab energies of the two jets, E_e and E_e' are the energy of the incident and scattered electron, and E_p is the energy of the incident proton.

We have computed the yield of high p_t dijet events due to both the QCD Compton and photon-gluon fusion process for an ep collider. The elementary cross sections of the processes depicted in Fig. 6 are taken from the literature.^{10 12} In computing the photon-gluon fusion we use a gluon distribution of the form:

$$g(\xi) = \frac{n+1}{2} (1-\xi)^n$$

with $n=5$. The photon-gluon fusion calculation is summed over all 6 quark species. In computing the QCD Compton cross sections we use the Buras-Gaumer parameterization of the quark momentum fraction distribution. We compute the virtual photon flux using the Williams-Weizsacker formula.

Figure 7 shows the p_t distributions of either of the two jets created by the QCD Compton process (curves B and C) and the photon-gluon fusion process (curves A and D) for a 20 x 400 ep collider with a total integrated luminosity of $5 \times 10^{38} \text{ cm}^{-2}$. All curves assume a minimum electron tagging angle of e degrees. Curves A and B have not cut on ξ ; while curves C and D have the cut $\xi > 0.6$. We see that the ξ uncut gluon fusion model dominates over the QCD Compton process except at the very largest p_t . However the cut $\xi > .6$ reduces the photon-gluon fusion background to about 10% while still leaving about 1300 relatively pure Compton events with $p_t > 15 \text{ GeV}$.

The Charged Current Process

In this section we discuss the physics inherent in a study of the charged current process depicted in Fig. 1b. The major physics goals of ep charged current physics include measurement of the W mass through the charged current propagator, and a search for the effects of righthanded charged currents.

In the normal charged current process an electron will scatter from a quark via W exchange leaving a neutrino and a wide angle current jet in the final state. The neutrino will escape detection, and the event kinematic variables x and Q^2 (or alternatively x and y) must be determined through the measurement of the current jet energy and angle. Throughout this section, we assume that the jet angle can be measured to $\pm 40 \text{ mrad}$, and the jet energy can be measured to $\pm .60 \sqrt{E_{\text{jet}}}$. These current jet measurement errors are substantially larger than the errors associated

with measuring the scattered electron to determine x and Q^2 of a neutral current process. Hence while resolution issues played only a small role in the neutral current physics presented earlier, this is not true of the charged current physics to follow.

In addition to resolution effects, any analysis of ep charged current data will be complicated by the possible contamination of the charged current data sample by the much more copious neutral current data sample. The entire charged current yield in a 5×10^{38} luminosity run of a 20×400 GeV ep collider is about 9000 events if that luminosity is split equally between electron and positron running and is unpolarized. The neutral current yield for this run is over 10 million events. Simulations⁵ have shown that possible contamination can be controlled by putting suitable cuts on Q^2 and the angle of the current jet. The primary signature for a charged current event is the absence of a final state electron. A realistic detector will have holes in its fiducial volume, so that a measurement of the current jet must demonstrate that in a given "electronless" ep event the final state electron did not leave through a hole. These constraints must guarantee that the final lepton direction can be predicted with precision so that neutral current contamination of the charged current data sample is eliminated.

In this section we make plots that incorporate the effects of jet resolution and contamination, and are drawn with statistical error bars appropriate to a run of total integrated luminosity of $5 \times 10^{38} \text{ cm}^{-2}$ which is divided into 4 equal subruns with left and righthanded polarized electrons, and left and righthanded polarized positrons. We note that these running conditions cost about a factor of 3 in total charged current yields over the yield obtained in a single $5 \times 10^{38} \text{ cm}^{-2}$ run with lefthanded polarized electrons. We feel, however, that these run conditions would exploit the physics potential in the neutral current as well as the charged current sector.

The W Propagator

Figure 8 shows the evolution of the charged current propagator with error bars appropriate to our standard ep run. As Q^2 grows, the resolution in Q^2 due to error in jet measurement deteriorates, and the yield for a given Q^2 bin diminishes. In light of these effects we have cut off Fig. 8 at a Q^2 of about 4500 GeV^2 since beyond this point the events in a given Q^2 bin are substantially contaminated by mismeasured low Q^2 events. The simulated data of Fig. 8 could be used to determine the mass of the W to within $\pm 5 \text{ GeV}$ even with a 20% uncertainty in ep luminosity.

By fitting the shape of the W propagator, we will be sensitive to the possible effect of multiple W s. If several W s exist, the mass and coupling of the lightest W may be shortly determined from $p\bar{p}$ experiments. If the known mass of the lightest W is used as an input to a fit of the effective charged current propagator determined in an ep collider, the presence of a second W can be determined up to a higher mass of 200 GeV.

Righthanded Charged Currents

At momentum transfers that have been explored, the charged current is known to couple only to lefthanded fermions and righthanded antifermions. This fact is embodied in the standard model, and leads to a striking prediction for an ep collider--that there is no weak scattering of righthanded electrons or protons in a collider. However, there are several possible scenarios which allow for an ambidextrous charged current interaction at sufficiently large Q^2 . The charged current interaction could ultimately be left-right symmetric at high Q^2 due to the presence of new, high mass vector bosons or neutral heavy electrons. We consider the possibility of a high mass, righthand charged current vector boson first.

If we assume that the righthanded mediating W couples to the righthanded leptons and righthanded quarks in a fashion analogous to the lefthanded coupling of the standard W , the cross-section for righthanded couplings will be of the form:

$$\frac{d\sigma}{dx dy} = \frac{G_F^2 s}{\pi} \left(\frac{M_W^2}{M_{RW}^2 + Q^2} \right)^2 [W_1 + (1-y)^2 W_2]$$

where M_{RW} is the mass of the righthanded mediating W , and M_W is the mass of the standard W , W_1 is a sum over the charge $2/3$ quark momentum distributions, and W_2 is a sum over the charge $1/3$ antiquark momentum distributions.

The same expression applies to the scattering of lefthanded positrons; W_1 is the sum over the charge $-2/3$ antiquark distributions and W_2 is the sum over charge $-1/3$ quark distributions. Alternatively, the new righthanded mediating W may couple to righthanded electrons and lefthanded quarks. In this case one can get the righthanded electron cross-section by exchanging W_1 for W_2 in the above expression.

We can search for the presence of a righthanded charged current by looking for a Q^2 dependence in R_p which is defined as the ratio of the yield of charged current events from righthanded polarized electrons over the yield from lefthanded polarized electrons. For the case of completely polarized electrons, this ratio would be zero and stay zero in

the absence of righthanded charged current couplings. If there were a massive righthand mediating W , the ratio would be very small at low Q^2 and grow to unity as Q^2 became much larger than the squared mass of the standard W as well as the new righthanded W . We believe that 80% longitudinal polarization can be achieved in one ep intersection area through proper spin chromaticity matching. This will result in a righthanded polarized beam consisting of 90% righthanded electrons and 10% lefthanded electrons. Hence in our righthanded current model, R_p would grow from $R_p = .10/.90 = .11$ at low Q^2 to unity at very high Q^2 . This growth is shown in Fig. 9, for the case of a righthanded lepton-righthanded quark coupling (Fig. 9a), and a righthanded lepton-lefthanded quark coupling (Fig. 9b). The error bars reflect the precision appropriate to our standard ep run; contamination cuts and resolution effects have been included. Figure 9 indicates that we will be sensitive to a M_{RH} mass of 300 GeV for righthanded lepton-righthanded quark couplings, and a mass of 350 GeV for righthanded lepton-lefthanded quark couplings.

An alternative mechanism for a righthanded charged current coupling to the electron requires the existence of a neutral righthanded partner of the electron. The presence of such a new heavy lepton would not be observable at low energies if the heavy lepton were sufficiently massive. Figure 10 shows the yield of such a righthanded heavy lepton as a function of M_L , the heavy lepton mass for a $5 \times 10^{38} \text{ cm}^{-2}$ ep run. Figure 10 assumes that the electron- W -heavy lepton coupling is identical to the standard electron- W -neutrino coupling. Copious production of such heavy leptons will occur up to masses of 100 GeV.

Such a new heavy lepton could decay via the charged current interaction into $e^- \mu^+ \nu$, $e^- e^+ n$, or $e^- u \bar{d}$, or possibly via the neutral current into $\nu \mu^+ \mu^-$, or $\nu q \bar{q}$. The final states will typically have anomalous leptons or anomalous jets with large missing P_T . Even in the case of a heavy lepton decaying into final states with missing neutrinos, the heavy lepton mass can be reconstructed from the observed lepton decay products and the current jet. Such a reconstruction is illustrated in Fig. 11 for the case of a 40 GeV heavy lepton. Once such a heavy lepton is observed, its righthanded character can be established by comparing the yield with righthanded polarized incident electrons to the yield with lefthanded polarized electrons.

Leptoquarks

Some models¹² which construct quarks and leptons from constituents predict the existence of narrow leptoquarks with masses in the vicinity of 100 GeV. Grand Unified Theory also predicts the existence of leptoquarks, but at stratospheric mass scales. Because leptoquarks or leptogluons will appear as s-channel resonances in a ep collider, experimental signatures are dramatic and unambiguous. The formation of an s-channel leptoquark and its subsequent decay will produce events which are

topologically similar to those from ordinary high Q^2 neutral current events. However, the leptoquark events will produce a peak in the measured x distribution at an $x = M_{LQ}^2/s$. This peak is illustrated in Fig. 12 for the case of 100 GeV leptoquark produced at an $s = 40,000 \text{ GeV}^2$ ep collider. The width of the peak is dominated by the gluon P_t distribution within the proton, and the area of the peak depends strongly on Λ , the reciprocal distance scale of quark-lepton compositeness. Figure 12 assumes a leptoquark yield of:

$$\sigma = 4\pi^2 \alpha_s \frac{M_{LQ}^2}{\Lambda^4} Z f_g(Z); \quad \Lambda = \frac{M_{LQ}}{s}$$

where $f_g(Z)$ is the gluon distribution within the proton. A 20 x 400 GeV ep collider should be sensitive to vector leptoquarks and leptoquarks with masses of up to about 150 GeV under these assumptions.

Summary

In this report we have tried to demonstrate how a 20 x 400 GeV ep facility at the CBA will complement the physics of high energy e^-e^+ and hadron-hadron colliders. An ep collider will extend tests of the standard model by about an order of magnitude in spacelike momentum transfer, and extend our knowledge of electro-weak processes to a remarkable degree. It will be especially interesting to see if the lefthanded nature of the charged current observed at low spacelike momentum transfers persists to large, spacelike momentum transfers. A high energy ep collider is unique in the opportunity to investigate QCD through the scale breaking at high Q^2 the high P_t QCD Compton process.

In addition to probing small distance behavior in kinematic regions orthogonal to other collider facilities, an ep facility will generate data ultimately crucial to the understanding of the physics of e^+e^- and hadron-hadron collisions. The current jet that is produced in the high energy ep neutral current process recoils against a single electron which can be used to predict the momentum of the quark which gives rise to the jet. The central problem in jet physics of deducing the kinematics of a quark by measurement of its hadronization jet can be studied under uniquely controlled circumstances. Finally the high Q^2 structure functions of the proton which are essential in understanding hard processes in hadron-hadron scattering can only be cleanly measured in an ep collider.

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Figure 1.

- (a) two contributions to the neutral process
- (b) the charged current process
- (c) the hadronic final state divides into two jets as shown.

Figure 2.

Comparison of ep neutral current rate with
fixed target muon beam neutral current rate.

Figure 3.

Neutral current luminosity boundary. For a luminosity of 10^{39} cm^{-2} , the enclosed area has a rate of greater than 100 counts in a $dx/x = .1$, $dQ^2/Q^2 = .1$ bin.

Figure 4.

F_2 as a function of Q^2 for very low values of x corrected for acceptance, resolution, and binning effects using the method of Appendix III. The plots assume $\Lambda^2 = 0.2$. The low x scale breaking predicted by QCD will be experimentally evident.

Figure 5.

The Q^2 dependence of F_2 for events with $0.1 < x < 0.3$ and $0.3 < x < 0.5$ in the absence of quark substructure (unlabeled curves) and in the presence of quark substructure with characteristic mass scales of 100 and 300 GeV. We will be sensitive to up to mass scales of 300 GeV.

(a)

(b)

Figure 6.
Sources of High P_t dijet events
(a) QCD Compton process
(b) Photon-gluon fusion process

Figure 7.

High p_T jet yield for $5 \times 10^{38} \text{ cm}^{-2}$ luminosity
 A and D are photon-gluon fusion
 B and C are QCD Compton
 C and D have $\xi > .6$ cut

Figure 8.

The Q^2 evolution of the charged current propagator for different W masses corrected for acceptance and binning effects. We can measure the W mass to ± 5 GeV.

Figure 9.

(a) The ratio of 80% polarized righthanded electron events to 80% polarized lefthanded electron events in a model with a new W of mass M which has a $V+A$ coupling to leptons and a $V+A$ coupling to quarks. We will be sensitive to these effects up to masses of 300 GeV. (b) The ratio of 80% polarized lefthanded positron events to 80% polarized righthanded positron events in a model with a new W of mass M which has a $V+A$ coupling to leptons and a $V-A$ coupling to quarks. We will be sensitive to these effects up to masses of 350 GeV.

Figure 10.

Expected yield of neutral heavy electrons for our assumed run as a function of heavy electron mass.

Figure 11.

Heavy electron mass resolution for 40 GeV heavy electrons decaying into final states with one missing neutrino.

- (a) $E^0 \rightarrow e^-e^+\nu$
- (b) $E^0 \rightarrow e^- \mu^+ \nu$
- (c) $E^0 \rightarrow \nu q \bar{q}$

Figure 12.

The effects of a 100 GeV leptogluon on the yield of $Q^2 > 2500 \text{ GeV}^2$ neutral current events as a function of x . If the leptogluon compositeness scale is 1 TeV, about 10000 signal events will be produced in a run of $5 \times 10^{38} \text{ cm}^{-2}$ integrated luminosity of an $S = 40000 \text{ GeV}^2$ ep collider. These signal events will form a peak at $x = .25$ in the neutral current yield which will lie over a smooth background of ordinary neutral current events.

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