ZEUS RESULTS, 1993 DATA: A SEARCH FOR NEW PHYSICS

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Abstract: Searches for resonance states coupling to e^-q, $\nu_e q$, $e^-\gamma$, $\nu_e\gamma$, $\nu_e W^-$, e^-Z, $q\gamma$, qg, qZ, and $qW^\pm$ have been performed using colliding electron-proton beams at HERA up to $\sqrt{s} = 296$ GeV. No evidence for leptoquarks, excited electrons, excited neutrinos, or excited quarks has been found by the ZEUS detector in a sample with an integrated luminosity of $\approx 550\ nb^{-1}$. Limits on couplings and masses between 50 and 230 GeV are presented for these exotic particles. Additionally, the ZEUS measurements of deep inelastic neutral and charged current differential cross sections are presented.

1 Introduction

HERA provides collisions between 26.7 GeV electrons and 820 GeV protons. With $\sqrt{s}$ = 296 GeV and squared four-momentum transfer $Q^2 >$ 40,000 GeV^2, this new realm obligates an experimentalist to seek new phenomena. We present searches for leptoquarks and excited fermions and also show new, high Q^2, differential cross sections in deep inelastic scattering.

In 1993, ZEUS collected an integrated luminosity of $\approx$ 600 nb^{-1}, $\approx$ 550 nb^{-1} of this is presented here. Although a substantial data sample, HERA design luminosity is 1.3 pb^{-1}/day (under continuous running conditions).

The ZEUS collaboration is comprised of 50 institutes from 12 countries. This analysis used several detector[1)] components. The tracking system is comprised of a vertex detector and a cylindrical drift chamber. Outside the tracking system, is the 0.83 radiation lengths thick solenoid, providing a 1.4 T field. Surrounding these detectors, are the FCAL (forward calorimeter), RCAL (rear calorimeter), and BCAL (barrel calorimeter). These calorimeters (covering 99.8% of solid angle) are made of alternating depleted uranium and scintillator layers. They are compensating, giving equal response to hadronic and electromagnetic showers to within (2±2)%. All three are longitudinally segmented into an electromagnetic section of ~25 radiation lengths (projective in BCAL), followed by hadronic sections which have ~6, ~4, and ~3 interaction lengths in FCAL, BCAL, and RCAL, respectively. Behind these, is a backing calorimeter (unused in this analysis) and muon chambers (covering >90% of solid angle).

HERA events naturally fall into three categories: 1) quasi-real photoproduction, 2) neutral current (NC) deep inelastic scattering (DIS), and 3) charged current (CC) DIS.

Photoproduction events consist of a nearly real exchanged photon colliding with the beam proton. As these events all have low Q^2, the scattered electron usually remains in the beam pipe. Since these events balance transverse momentum, they form a negligible background to exotic searches.

NC DIS events, from virtual γ/Z exchange, leave well-isolated electrons in the calorimeter. The isolated e^- serves as the principle selection criterion of NC DIS. Hadronic current jets, and sometimes portions of the beam remnant jet, are also found in the detector.

CC DIS events, from virtual W exchange, leave a neutrino in the final state. Again, hadronic current jets, and portions of the beam remnant jet are found in the detector. The undetected neutrinos yield events characterized by an unbalanced transverse momentum, which is the principle selection criterion for these events.

2 DIS Differential Cross Sections

Using cuts similar to those found in our previous analyses[1)6)14)], we extracted NC and CC samples. Constraints on FCAL and RCAL timing helped remove beam-gas upstream of ZEUS. Differences in top and bottom timing removed most cosmics. Requirements on vertex position and transverse energy deposits near the FCAL beampipe also greatly reduced beam-gas events. Energy-momentum constraints were also used to identify NC events and remove beam-gas.

The DIS differential cross sections as a function of Q^2 are of interest. We used the above samples, combined with acceptances obtained from Monte Carlo programs, to calculate differential cross sections. In Figure 1, the preliminary 1993 DIS differential cross sections are shown as a function of Q^2. The vertical error bars represent only statistical errors. Also displayed, is the NC sample from the structure function analysis, which extended to low Q^2. Systematic errors in these analyses include a luminosity uncertainty of $\pm$ 5%, and an acceptance uncertainty of $\pm$ 6%. The NC sample also has a background contamination of 3-5%. There is also a bin to bin uncertainty of $\pm$7-15% due to the energy scale uncertainty. If one takes the bin by bin ratio of the NC and CC cross sections, the systematic uncertainties will be reduced.

The data agree well with theoretical expectations (not shown). At low Q^2, the NC differential cross section is dominated by photon exchange while at high Q^2, Z exchange is significant. One expects, from propagator effects, the two differential cross sections to cross in the region of $Q^2 \approx M_B^2$ where B is the heavy boson. This is the first time an experiment has measured the two differential cross sections becoming equal in this high Q^2 region.

3 Excited Leptons and Quarks

The existence of three generations of leptons and quarks is a puzzle which would be naturally explained by lepton and quark substructure. Excited leptons or quarks would be a clear compositeness signature. HERA provides a unique place to search for such substructure.

We have searched the 1993 data sample for decaying excited fermions (f*). The cross section[2)] for producing a spin-1/2 f*, assuming magnetic coupling mediated by the gauge bosons (γ, Z, and W), can be written quite generally as:

$$\sigma(ep \to \mathrm{f}^*\mathrm{X}) = \frac{|\mathrm{c}|^2 + |\mathrm{d}|^2}{\Lambda^2}\sigma_0(\mathrm{M}_{\mathrm{f}^*}) \tag{1}$$

where c and d are vector and axial vector coupling constants, Λ is the compositeness scale, and σ_0 is a mass dependent reference cross-section. The excited lepton would then decay into a normal lepton plus a gauge boson.

Before HERA, the best direct limits on excited lepton production came from LEP searches for ($e^+e^- \rightarrow ll^*$) and ($e^+e^- \rightarrow l^*\bar{l}^*$) (see Figure 5).[3] LEP t-channel measurements of $e^+e^- \rightarrow \gamma\gamma$ give a lower limit of $M_{e^*} > 116$ GeV.[3] Further e* limits come from a model dependent analysis of $\nu_\mu e \rightarrow \nu_\mu e$ scattering,[4] and measurements of g-2.[5] Both the H1 and ZEUS collaborations have published direct searches for f* using their 1992 data samples.[6][7]

The obvious channel in which to seek an e* is $e^* \rightarrow e\gamma$. We have sought e*'s in NC DIS events by requiring a second energetic electromagnetic cluster in addition to the scattered electron. Electromagnetic Compton scattering (ep$\rightarrow e\gamma$X) is a natural background to e* $\rightarrow e\gamma$. Quasi-elastic Compton scattering (X=p; $Q^2 \approx 0$), tends to leave 2 electromagnetic showers at large values of θ. For an incident electron beam energy E_e, the energies of the electromagnetic showers associated with the electron and photon (E_1, E_2) are related by:

$$2E_e = E_1(1 - cos(\theta_1)) + E_2(1 - cos(\theta_2)) \tag{2}$$

where the polar angle θ is defined as zero in the incident proton beam direction (near FCAL). In the limit of low energy transfer (i.e. most cases), where θ values are large, $E_1 + E_2$ peaks near the incident electron beam energy. Figure 2 shows the distribution of this sum peaking near E_e as expected. The invariant mass distribution of these events is shown in Figure 3.

The Compton selection criteria were tightened in the search for e* $\rightarrow$e γ by requiring that

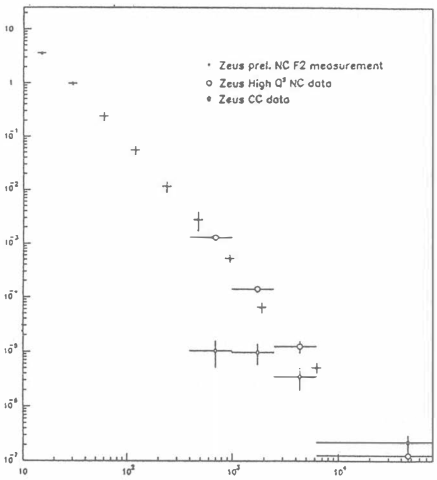

Figure 1: $d\sigma/dQ^2$ (nb/GeV^2) as a function of Q^2 (GeV).

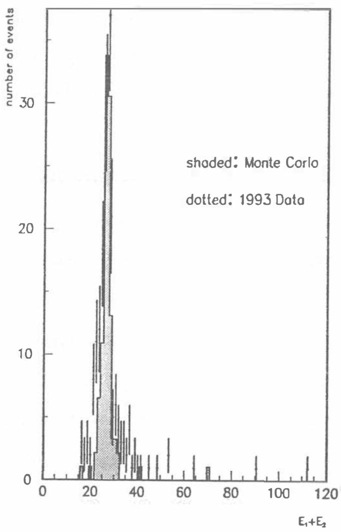

Figure 2: Compton scatter energy sum (GeV).

one of the electromagnetic showers have polar angle < 2.62 radians. This is because kinematics require any object whose invariant mass exceeds $2E_e$ to be boosted towards FCAL in the lab. The resulting highest invariant mass event was at $\sim$ 50 GeV, corresponding to a slight weakening (for eγ) of the limit in Figure 4.

Since the f* branching ratios into fermions and gauge bosons depend on the couplings c and d, [2] we have searched for several decay modes. Our searches included final states with W and Z decaying hadronically ($\approx$ 70 % of their branching ratios). Such decays would have large hadronic transverse energies compared to backgrounds, and thus are easily recognized.

As an example, the selection criteria in the search for e* $\rightarrow$eZ were: 1) $30 < E - p_z < 60$ GeV, 2) $E_{e-m} > 10$ GeV, 3) $\theta_{e-m} < 2$ radians, 4) $E_T > 60$ GeV. The "e-m" designates the highest energy electromagnetic shower in the event, and E_T designates the transverse energy, excluding the ring of calorimeter cells closest to the FCAL beampipe and the highest energy electromagnetic shower. Were a signal present, we would reconstruct the Z mass. Figure 5 shows the reconstructed Z mass for Monte Carlo events with 150 GeV e* mass. The Z typically travels forward and since the calorimeter cells nearest the FCAL beampipe were excluded from this reconstruction, the mass is systematically low.

We have also searched for excited quarks (q^*). The most stringent limits on q^* are from the CDF collaboration[8] with limits $M_{q^*} > 550$ GeV. However, if the q^* couples predominantly through the electromagnetic interaction, it would not have been seen at CDF. While hadron collider experiments are sensitive to qgq^* vertices, HERA is mainly sensitive to $q\gamma q^*$ vertices. In a preliminary analysis of the 1993 data sample, we sought the decay $q^* \rightarrow q\gamma$ and found one candidate with an expected background of 0.83 events. Although q* production is expected to be γ propagator dominated at HERA, we also sought the decay mode $q^* \rightarrow qX_{hadronic}$ (in the forms of qg, qZ, and q'W$^\pm$), and found two candidate events for an expected background of 1.26 events. Thus, no evidence for q^* decay is found.

Shown in Table 1 are the results from the searches for all f* modes. There is good agreement in all modes between expected background and the observed number of candidates.

Table 1: Preliminary 1993 search results for the ZEUS f* analysis σ limits are in pb.

Process	MC	Data	$\sigma <$	Process	MC	Data	$\sigma <$	Process	MC	Data	$\sigma <$
e* $\rightarrow$ e γ	4.6	5	7.2	$\nu^* \rightarrow \nu\gamma$	0.6	2	9.6	$q^* \rightarrow q\gamma$	0.8	1	11.3
e* $\rightarrow$ e Z	4.2	2	12.5	$\nu^* \rightarrow \nu$ Z	2.0	2	15.6	$q^* \rightarrow qX_h$	1.3	2	23.0
e* $\rightarrow \nu$ W	2.0	4	21.9	$\nu^* \rightarrow$ eW	6.0	2	12.5				

Using Monte Carlo to estimate the signal acceptance, ϵ, as a function of mass, and selecting N events (with N the largest number of events consistent at the 95% confidence level with the number of events observed in a mass region) for as an upper limit ($u.l.$) on the number of events observed, one may calculate for a luminosity $\mathcal{L}$, upper limits on f* cross sections:

$$\sigma_{u.l.}(M) = \frac{N_{u.l.}(M)}{\epsilon(M)\mathcal{L}}. \tag{3}$$

With no evidence for excited fermions, preliminary 95% confidence level limits (in Figure 5) were calculated. Excited neutrino limits are less stringent due to the large virtuality of the massive W^- propogator.

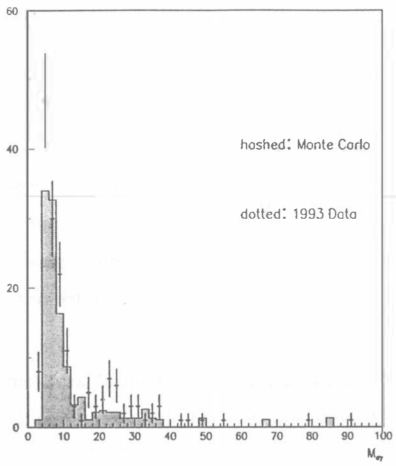

Figure 3: Compton scatter invariant mass (GeV) of the eγ system.
After imposing tighter cuts for the e* search, only 1 event ~ 50 GeV remained.

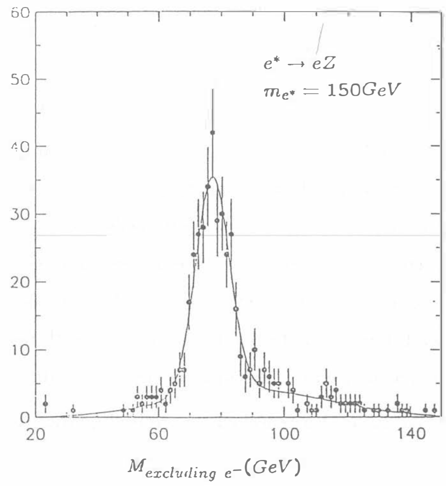

Figure 5: Reconstructed Monte Carlo Z mass.

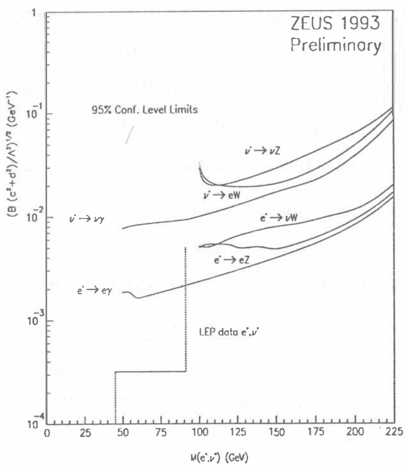

Figure 4: l* limit (coupling*B.R.) as a function of l* mass GeV. q^* limits (not shown for clarity) lie directly under e* limits.

4 Leptoquarks

A leptoquark (LQ) would be a fundamental, color-triplet boson coupling to a lepton and a quark, with fractional charge and both lepton and baryon number. Leptoquarks arise naturally in models attempting to unify nature by invoking fermion substructure, or in models postulating symmetries linking hadronic and leptonic sectors.[9] At HERA, a LQ would be produced as an s-channel resonance through electron-quark coupling. Thus, a LQ would be signaled by a narrow peak in the Bjorken x distribution at $x = M_{LQ}^2/s$. The total cross section[9] for LQ production in the narrow width approximation is:

$$\sigma = \frac{\pi}{4s}(J+1)(\lambda_L^2 + \lambda_R^2) f_q(x) \tag{4}$$

where J is the spin of the leptoquark, $f_q(x)$ is the quark probability density function, and $\lambda_L(\lambda_R)$ is the left(right) handed coupling. Within this theoretical framework, leptoquarks are uniquely specified by: 1) spin (scalar or vector), 2) charge, 3) weak isospin, and 4) whether the leptoquark couples to e$^-$, e$^+$, u, d, $\bar{u}$, or $\bar{d}$.

Before HERA, the best direct limits on leptoquark production came from pair production searches at LEP and FNAL. For comparison with other experiments, the coupling is traditionally,[10] but arbitrarily, set to $\sqrt{4\pi\alpha_{EW}} = .31$ and an upper mass limit is quoted. LEP limits[11] are based on searches for Z $\rightarrow LQ\overline{LQ}$ and limit $M_{LQ} > 44$ GeV. FNAL limits,[12] which are based on searches for $g \rightarrow LQ\overline{LQ}$, yield $M_{LQ} > 133$ GeV. An indirect limit also arises from searches for the rare decay $\pi^+ \rightarrow e^+\nu_e$ [13] limiting $M_{LQ} > 10\sqrt{\lambda_L\lambda_R}$ TeV. Therefore, we search for leptoquarks with purely left or right handed couplings. Finally, both H1 and ZEUS have published leptoquark searches using their 1992 data samples.[7][14]

The data samples used for the $eq \rightarrow LQ \rightarrow eq$ search consisted of a data sample which was almost identical to the NC DIS sample. As this final state will appear identical to an NC DIS event, we refer to this as an NC-type LQ. We were aided by the fact that the y (in fixed target experiments y is the fraction of the energy lost by the incident e$^-$ in NC DIS) distribution of NC DIS is radically different from that of a hypothetical leptoquark. A HERA NC DIS data sample has a cross section proportional to $1/y^2$. In the leptoquark rest frame, $y = (1-\cos\theta)/2$ where θ is the decay angle of the electron. Thus, a scalar leptoquark would be flat in y, while a vector leptoquark would be distributed as $(1-y)^2$. To improve the signal to noise ratio, based on Monte Carlo studies, we have imposed a cut on y as a function of M_{LQ} to obtain optimum limits.

The preliminary 1993 ZEUS leptoquark sample (see Figure 6) is shown as a function of

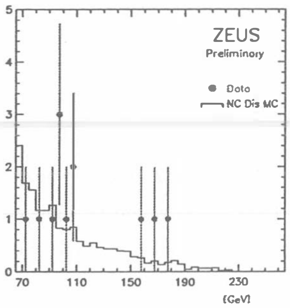

Figure 6: Number of events as a function of invariant mass (GeV) for NC LQ candidates.

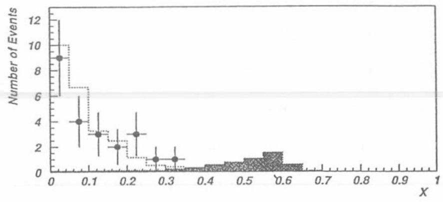

Figure 7: Distribution of x ($M_{LQ} = 296\sqrt{x}$) for CC LQ candidates. Data: dots; dashed line: CC DIS MC; shaded: 240 GeV CC LQ MC.

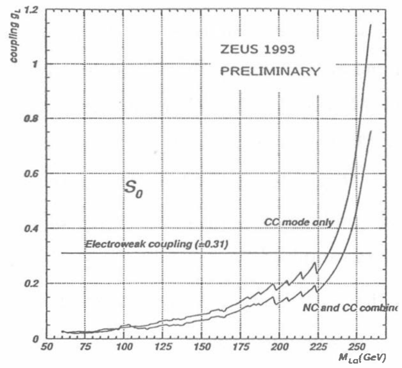

Figure 8: NC and CC LQ limits as a function of LQ mass (GeV). The limits equal the electroweak coupling strength near 230 GeV.

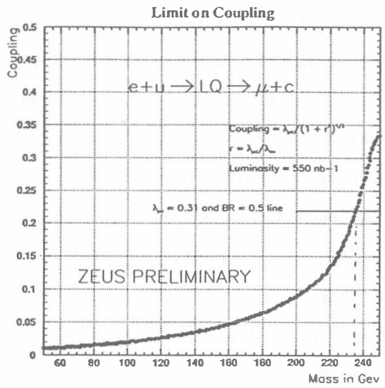

Figure 9: Generation changing LQ limit as a function of mass (GeV). The limit equals the electroweak coupling strength near 235 GeV, with an assumed branching ratio of 50%.

M_{LQ}. Points with error bars represent data while the histogram is from a NC DIS Monte Carlo. One sees an excess of events near 100 GeV. In these three bins, 6 events are observed while 2.4 events are expected. To detewrmine the significance of this enhancement, we have fitted the data to a Gaussian (width constrained) and a smooth falling background. Interpreted as a resonance signal, this enhancement has a significance of only about 1.2 σ. Thus, with no clear evidence for a leptoquark signal, we have calculated 95% Confidence Level Limits on Coupling vs M_{LQ} using the measured luminosity, data, estimated background, and LQ cross section (equation (4)). (See figure 7.)

We searched also for leptoquarks in the reaction ($e^- q \to LQ \to \nu q'$). With a neutrino in the final state, these limits are applicable to left handed couplings only (λ_L). Because this LQ final state will be identical to the final state of a CC DIS event, we refer to this as a CC-type LQ. The data sample used is an almost complete overlap of the 23 CC DIS data events discussed earlier (2 events are different). The data and CC DIS Monte Carlo agree well with no enhancement at any M_{LQ}. (See Figures 7 and 8.) Assuming electroweak coupling strength (λ_L=0.31), we set a preliminary 95% confidence level limit of $M_{LQ} > 232$ GeV.

Additionally, we have performed a preliminary analysis using the 1993 data sample to search for generation changing leptoquarks. A candidate event for the 2nd generation decay, $e^- + u \to LQ \to \mu + c$, would have a large imbalance in its transverse momentum since the muon deposits little energy in the ZEUS calorimeter. Thus, the data sample used for this search consists of the 23 data events discussed earlier for the CC-type LQ. We searched this sample for a muon and found no candidate events. Assuming electroweak coupling strength ($\lambda_{\mu c} = \lambda_{eu} = 0.31$), and a branching ratio of 0.5, we set a preliminary 95% confidence level limit for this mode of $M_{LQ} > 235$ GeV. (See Figure 9.)

To look for 3rd generation decays, $e + d \to LQ \to \tau + b$, ZEUS has optimized an analysis to find both leptonic and hadronic decays of the τ. These events, once again, have large transverse energy imbalance since there is a ν_τ in the final state. One event is observed in the final data sample when 0.63 events are expected from Monte Carlo. This allows ZEUS, assuming electroweak coupling ($\lambda_{\tau b} = \lambda_{eu} = 0.31$) and a branching ratio of 0.5, to set a preliminary 95 % confidence level limit for this mode of $M_{LQ} > 208$ GeV.

5 Outlook

The future of searches for new phenomena at HERA lies in precision measurements of DIS differential cross sections, which, at $Q^2 > 1000$ GeV^2, should prove sensitive to new physics.

Much as the NC and CC DIS differential cross sections become equal at Q^2 near the square of the heavy boson masses, new interactions coupling to the electron and the partons should manifest themselves in deviations from the predicted differential cross sections. Such deviations are quite generally parameterized as contact interactions. HERA should begin polarized beam running in the second half of this decade allowing such precision polarized measurements with sensitivity up to compositeness scales of 7 TeV.[15)]

Even with small integrated luminosity, ZEUS has proven to have a powerful ability to search for new particles and set limits on their couplings. HERA's 1994 run is expected to produce about five times the integrated luminosity of the 1993 data samples shown.

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