Comment on $Z'$s and the H1 and ZEUS High $Q^2$ Anomalies

Stephen Godfrey

Ottawa-Carleton Institute for Physics

Department of Physics, Carleton University, Ottawa CANADA, K1S 5B6

We investigate the effects of extra neutral gauge bosons on the high $Q^2$ region of the $e^+p \rightarrow e^+X$ cross section at $\sqrt{s} = 300$ GeV. We found that the only models with electroweak strength coupling, typical of extended gauge theories, that give a better fit to the H1 and ZEUS high $Q^2$ data than the standard model, are ruled out by existing data from the Tevatron. From general scaling arguments, using the allowed contact interactions, the only allowed models with $Z'$s would be those with strong couplings although even in this case the statistical evidence is not compelling.

The H1 [1] and ZEUS [2] experiments at HERA have observed an excess of events in $e^+p \rightarrow e^+X$ at $Q^2 > 15,000$ GeV$^2$ compared to Standard Model expectations in 34.3 pb$^{-1}$ of accumulated luminosity. These observations have led to considerable speculation [3,4]. Although these observations cannot be ruled out to be statistical fluctuations the two collaborations estimate that this is unlikely. Some of the more popular interpretations of the high $Q^2$ excess are that it signals the existence of leptoquarks [3], squarks [4], or contact interactions of quarks and leptons [5,6]. In the latter case, a number of authors have suggested that the contact interaction represents a low energy effective interaction which parametrizes the t-channel exchange of an extra neutral gauge boson ($Z'$) [5,8]. In this note we explore the viability of this explanation of the HERA high $Q^2$ anomaly.
Extra neutral gauge bosons are a feature of many extensions of the standard model such as grand unified theories, left-right symmetric models, excited weak vector bosons, and a strong Higgs sector \[ 1-18 \]. \( Z' \)'s contribute to \( ep \) cross sections via t-channel exchange and the resulting interference with standard model contributions \[ 19 \]. The expressions for the resulting cross sections have been given elsewhere so for brevity we do not reproduce them here but refer the interested reader to previously published results \[ 19 \].

To quantify the effect of a \( Z' \) on the HERA cross sections we compare the cross section with a \( Z' \) to the combined H1 and ZEUS data combined bin-by-bin for bins starting at \( Q^2 = (5000, 10000, 15000, 20000, 25000, 30000, 35000) \text{ GeV}^2 \) with each bin being 5000 GeV\(^2\) wide except the last which goes from \( Q^2 = 35000 \text{ GeV}^2 \) to the kinematic limit. The calculated results were corrected for detection efficiencies of 80\% and include an average QCD K-factor of 1.1. We use a log-likelihood procedure with Poisson statistics, appropriate for small numbers of events, to fit \( M_{Z' \psi} \) for a large number \( Z' \)'s arising from models with extended gauge groups \[ 11-13, 16 \].

In only two models did including a \( Z' \) improve the fit and in no case would we argue that the improved fit was statistically distinguishable from the standard model\[ 1 \]. In Fig. 1 we plot the \( e^+ p \) differential cross sections as a function of the minimal \( Q^2 \) value for the standard model and two cases, \( M_{Z' \psi} = 150 \text{ GeV} \[ 12 \] \) and \( M_{Z' \mu \nu \pi} = 420 \text{ GeV} \[ 13 \] \) along with the HERA results which are corrected for detector efficiencies of 80\% and divided by an average QCD K-factor of 1.1 so that we show leading order cross sections.

---

\(^1\)We note that using a \( \chi^2 \) analysis results in a lower \( M_{Z'} \) and implies a better fit than the log-likelihood approach. However the log-likelihood approach is more appropriate for low statistics.

\(^2\)Varying \( \theta_{E_6} \), a parameter of \( E_6 \) GUTS \[ 19 \], we obtain the best fit for \( \theta_{E_6} = \pi/2 \) which correponds to \( Z_{\psi} \).
Fig 1: Integrated cross sections versus a minimum $Q^2$ for $e^+p \rightarrow e^+X$ for the SM (solid curve), $M_{Z_\psi} = 150$ GeV (dotted curve), $M_{Z_{HY,P}} = 420$ GeV (medium-dashed curve) and the contact interactions with $\eta_{LR}^u = \eta_{RL}^u = +1$ for $\Lambda = 3$ TeV (dot-dot-dashed curve), $\Lambda = 4$ TeV (long-dashed curve), and $\Lambda = 5$ TeV (dot-dashed curve). The data points are combined H1 and ZEUS measurements.

The first case is two $Z'$s, $Z_\psi$ and $Z_\eta$ arising from the breaking of the grand unified group E6 [12]. The best fits occur for $M_{Z'} < 100$ GeV which is ruled out by Tevatron data [20]. The second case is for a $Z'$ model that couples to the usual weak hypercharge (HYP) [13] which has a best fit for $M_{Z'} \sim 420$ GeV. Although this particular value of $M_{Z'}$ maximized the log-likelihood function, the variation of $\ln L$ with $M_{Z'}$ is so gradual that this value should be taken as little more than suggestive and is only slightly more than 1$\sigma$ better than the $M_{Z'} \rightarrow \infty$ case which corresponds to the standard model. Because there are no published limits on $Z_{HY,P}$ by the Tevatron collaborations we estimated a limit using the criteria that at least ten dilepton events would be observed in the combined $e^+e^- + \mu^+\mu^-$ channels in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV with a total integrated luminosity of 110 pb$^{-1}$ [10]. We obtain the limit $M_{Z_{HY,P}} > 780$ GeV. Although this limit should not be taken as absolute, we have some faith in its validity since a similar analysis gives results very close to the CDF limits for $Z_\psi$, $Z_\chi$, $Z_\eta$ and $Z_{LR}$. We conclude that the fitted value of $M_{Z_{HY,P}}$ is also ruled out by Tevatron data.
We next ask whether our fitted $Z'$ masses are consistent with the energy scales extracted from the contact interaction fits [5,6]. The standard parametrization of contact interactions is $4\pi \eta_{ij}/\Lambda^2$ where $\Lambda$ is the scale of new physics and $\eta_{ij}$ denotes the chirality of the contact interaction. A very massive $Z'$ arising from a gauge theory contributes a contact term that goes roughly like $e^2/(c\alpha_s^2 s_w^2 M_{Z'}^2)$. The actual expression would depend on the specific model with its predicted ratio of $Z'$ to $Z$ couplings and fermion-$Z'$ couplings. Rearranging this expression so that it is in the same form as that of the contact interaction and taking $M_{Z'} = 420$ GeV we obtain $\Lambda \sim 2$ TeV in reasonable agreement with the value of $\Lambda = 3$ TeV obtained by direct fits to the contact interaction [5]. The agreement would be even better if we had not neglected $Q^2$ dependent propagator effects which should be included for such a low mass exchange object. For comparison purposes we also show in Fig. 1 the $e^+p$ cross section with a contact interaction with $\Lambda = 3$ TeV and $\eta_{uLR}^u = \eta_{uRL}^u = +1$, the value obtained by a number of authors [3]. The choice of the $\eta$'s is constrained by atomic parity violation measurements in cesium. We conclude from this exercise that the HERA data is not compatible with a $Z'$ consistent with Tevatron limits, with the size of couplings expected in a gauge theory, but could only arise from a $Z'$ with strong couplings although even in this case, the statistical evidence is not compelling.

Composite models of gauge bosons satisfy this criteria of strong coupling strength. Two such models of $Z''$s have appeared in the literature; excited weak vector bosons [14] and the breaking electroweak symmetry strongly model (BESS) [15]. Neither model appears to be ruled out by existing data [17,18].

We found that this contact term has a lower $\chi^2$ than the standard model but that the log likelihood function indicates a worse fit. When redoing the fit to $\Lambda$ with $\eta_{uLR}^u = \eta_{uRL}^u = +1$ we found that using the $\chi^2$ criteria we obtained a best fit for $\Lambda \sim 4$ TeV and using the log-likelihood criteria $\Lambda \sim 5$ TeV. We would not regard this latter result to be statistically distinguishable from the SM fit. We also show in Fig. 1 the cross section for $\Lambda = 4$ and 5 TeV.
To conclude, we studied the effects of extra gauge bosons on the high $Q^2$ region of the $e^+p \rightarrow e^+X$ cross section at $\sqrt{s} = 300$ GeV. We found that the only model with electroweak strength coupling typical of extended gauge theories that gives an improved fit over the standard model fit is ruled out by existing data from the Tevatron. From general scaling arguments using the allowed contact interactions, the only allowed models with $Z''$s are those with strong couplings. Two such models, the excited weak boson model [14,17] and the BESS model [15,18] do not appear to be ruled out by current data.

ACKNOWLEDGMENTS

This research was supported in part by the Natural Sciences and Engineering Research Council of Canada. The author thanks Kingman Cheung for helpful communications.
REFERENCES

[1] H1 Collaboration, C. Adloff et al., DESY Report 97-24 (Feb. 1997), hep-ex/9702012.

[2] ZEUS Collaboration, J. Breitweg, et al., DESY Report 97-25 (Feb. 1997), hep-ex/970215.

[3] J. Blümlein, hep-ph/9703287; J. Kalinowski, R. Rückl, H. Spiesberger, and P.M. Zerwas, hep-ph/9703288; D. Choudhury and S. Raychaudhuri, hep-ph/9703270; J.L. Hewett and T.G. Rizzo, hep-ph/9703337; G.K. Leontaris and J.D. Vergados, hep-ph/9703338; Z. Kunszt and W.J. Stirling, hep-ph/9703427; I. Montvay, hep-ph/9704280.

[4] G. Altarelli et al., hep-ph/9703276; H. Dreiner and P. Morawitz, hep-ph/9703279; J. Kalinowski, R. Rückl, H. Spiesberger, and P.M. Zerwas, hep-ph/9703288; D. Choudhury and S. Raychaudhuri, hep-ph/9703363.

[5] V. Barger, K. Cheung, K. Hagiwara, and D. Zeppenfeld, hep-ph/9703311; N. Di Bartolomeo and M. Fabbrichesi, hep-ph/9703375.

[6] K.S. Babu, C. Kolda, J. March-Russell, and F. Wilczek, hep-ph/9703293; M.C. Gonzalez-Garcia and S.F. Novaes, hep-ph/9703346; G. Altarelli et al., hep-ph/9703270.

[7] B.A. Arbuzov, hep-ph/9703460; K. Akama, K. Katsuura, and H. Terazawa, hep-ph/9704327.

[8] W. Marciano, talk given at the Pheno'97 International Symposium, Madison WI, March 17-19, 1997.

[9] For a recent review of $Z'$ physics see M. Cvetic and S. Godfrey, to be published in Electroweak Symmetry Breaking and Physics Beyond the Standard Model, eds. T. Barklow, S. Dawson, H. Haber, and J. Seigrist (World Scientific, 1996) hep-ph/9504216.
[10] S. Godfrey, Phys. Rev. D51, 1402 (1995).

[11] J.L. Hewett and T.G. Rizzo, Phys. Rev. D45, 161 (1992) gives a good summary of the couplings of the various models.

[12] For a detailed review see J.L. Hewett and T.G. Rizzo, Phys. Rep. 183, 193 (1989) and references therein.

[13] K.T. Mahanthappa and P.K. Mohapatra, Phys. Rev. D42, 1732 (1990); 42, 2400 (1990).

[14] U. Baur et al., Phys. Rev. D35, 297 (1987); M. Kuroda et al., Nucl. Phys. B261, 432 (1985);

[15] R. Casalbuoni it et al., Phys. Lett. B155, 95 (1985); Nucl. Phys. B310, 181 (1988); M. Bilenky, J.-L. Kneur, F.M. Renard, and D. Schildknecht, Phys. Lett. B316, 345 (1993).

[16] R.N. Mohapatra, Unification and Supersymmetry (Springer, New York, 1986); H. Georgi, E. Jenkins, and E.H. Simmons, Phys. Rev. Lett. 62 2789 (1989); V. Barger and T.G. Rizzo, Phys. Rev. D41 956 (1990); D. Chang, R. Mohapatra, and M. Parida, Phys. Rev. D30, 1052 (1984); R. Foot and O. Hernández, Phys. Rev. D41, 946 (1990); R. Foot, O. Hernández, and T.G. Rizzo, Phys. Lett. B246, 183 (1990); E. Ma, Phys. Rev. D36, 274 (1987); K.S. Babu et al., Phys. Rev. D36, 878 (1987); J.F. Gunion et al. Int. J. Mod. Phys. A2, 118 (1987); T. G. Rizzo, Phys. Lett. B206 133 (1988); A. Bagneid, T.K. Kuo, and N. Nakagawa, Int. J. Mod. Phys. A2 1327 (1987); 2, 1351 (1987).

[17] J. Layssac, F.M. Renard, and C. Verzegnassi, Phys. Lett. B287, 267 (1992); Z. Phys. C53, 97 (1991).

[18] R. Casalbuoni it et al. [hep-ph/9702323].

[19] S. Capstick and S. Godfrey, Phys. Rev. D35, 3351 (1987); Phys. Rev. D37, 2466 (1988).

[20] K. Maeshima, Fermilab-Conf-96/412-E.