FORWARD-BACKWARD ASYMMETRIES
IN HADRONICALLY PRODUCED LEPTON PAIRS

Jonathan L. Rosner
Theoretical Physics Division
Fermi National Accelerator Laboratory, Batavia, IL 60510

and

Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637

ABSTRACT

It has now become possible to observe appreciable numbers of hadronically produced lepton pairs in mass ranges where the contributions of the photon and $Z^0$ are comparable. Consequently, in the reaction $p\bar{p} \rightarrow \ell^- \ell^+ + \ldots$, substantial forward-backward asymmetries can be seen. These asymmetries provide a test of the electroweak theory in a new regime of energies, and can serve as diagnostics for any new neutral vector bosons coupling both to quarks and to charged lepton pairs.

I. INTRODUCTION

The reaction $p\bar{p} \rightarrow \ell^- \ell^+ + \ldots$ is dominated by virtual photons at low energy, by the $Z^0$ at $m(\ell^- \ell^+) = M_Z$, and by photon-$Z$ interference everywhere else. Here $\ell = (e, \mu)$ stands for an isolated charged lepton, i.e., one not due to charm or bottom semileptonic decay. For lepton pair masses between about 60 and 80 GeV/$c^2$, the similar magnitude of photon and $Z$ contributions leads one to expect an asymmetry of about $-50\%$, with three out of four $\ell^+$ having greater rapidity than $\ell^-$ in the direction of the incident proton. For pair masses above 100 GeV/$c^2$, one expects an asymmetry of about $+50\%$, with three out of four $\ell^-$ having greater rapidity than $\ell^+$ in the direction of the proton.

$^1$To be submitted to Phys. Rev. D.
$^2$Permanent address.
Several years ago, when collider experiments at CERN (c.m. energy 540 GeV) and Fermilab (c.m. energy 1.8 TeV) each had accumulated several events per picobarn of cross section, the observation of these asymmetries was estimated to be possible at the 2σ level [2]. Now, with samples from the CDF and D0 detectors at Fermilab of order 100 pb$^{-1}$, it should be possible to observe these interference effects unambiguously. This would be the first study of such effects at masses above the $Z$, a range which has only recently become available to the LEP $e^+e^-$ collider.

In Ref. [2] it was mentioned that new neutral gauge bosons beyond the photon and $Z$ would lead to deviations of the forward-backward asymmetry from that predicted in the standard model [3, 4, 5]. Compositeness (i.e., a new effective four-fermion interaction) also can affect the asymmetry [6]. The present note investigates these points with regard to the reach of the current Fermilab experiments. The effects associated with new gauge bosons $Z'$ are found to be modest until one approaches pair masses $m(\ell^-\ell^+) \simeq M_{Z'}$, where the asymmetries can provide distinction among a number of possibilities. The compositeness signatures in forward-backward asymmetries turn out to be of utility comparable to (but not exceeding) direct searches for excess production cross sections at high lepton pair masses.

In Sec. II we tour of the zoo of extra $Z$'s, noting present limits from direct searches. We then choose in Sec. III a $Z'$ whose mass is compatible with these limits, and ask for its effects on the forward-backward asymmetry. A brief discussion of the achievable limits on compositeness occupies Sec. IV, while Sec. V concludes.

**II. A BRIEF TOUR OF EXTRA $Z$’s**

**A. Unifying groups**

We use the notation of Refs. [3], [4], and [7], which may be consulted for further details. Other discussions of extra $Z$’s may be found in Refs. [8] and [9].

The standard $SU(3) \times SU(2) \times U(1)_Y$ model may be incorporated into an $SU(5)$ [10], with the known quarks and leptons in each family belonging to the representations $5'$ or $10$ of the unifying group. These may be combined into a single 16-dimensional representation of $SO(10)$ [11], with the addition of a right-handed neutrino. The group $SO(10)$ contains $SU(5) \times U(1)$ as a subgroup; we shall denote this $U(1)$ by the subscript $\chi$, and its corresponding gauge boson by $Z_\chi$.

A further embedding into $E_6$ is suggested by some string-theory models [12]; the $U(1)$ which arises when $E_6$ breaks down to $SO(10) \times U(1)$ will be denoted by the subscript $\psi$, and its corresponding boson by $Z_\psi$. The 15 known fermions in each family of the standard model belong to 27-plets of $E_6$, consisting of $16$, $10$, and $1$ representations of $SO(10)$. The $16$, as mentioned, contains the standard fermions and a right-handed neutrino. The $10$ contains weak isosinglet quarks and antiquarks of charge $\pm 1/3$, and weak doublets of leptons and antileptons. The $1$ contains an isosinglet Majorana neutrino.
The most general \( Z' \) within \( E_6 \) then may be parametrized [8] as

\[
Z' = Z_\psi \cos \theta + Z_\chi \sin \theta .
\]  

When \( \theta = \arctan(\sqrt{3}/5) = 37.78^\circ \), the corresponding \( Z' \) is denoted by \( Z_\eta \), and corresponds to a specific breaking of \( E_6 \) suggested by some superstring theories [12].

When \( \theta = \arctan(-\sqrt{5}/3) = 127.78^\circ \), the corresponding \( Z' \) is the one which arises when \( E_6 \) breaks down to \( SU(6) \times SU(2)_I \). The subscript stands for “inert,” since all gauge bosons of \( SU(2)_I \) are neutral. The \( I_{3I} = 0 \) member of the \( SU(2)_I \) triplet is called \( Z_I \).

We shall assume in what follows that a single extra \( U(1) \) beyond the standard model remains unbroken at energies accessible to present accelerators. Slightly different patterns arise from other symmetry breaking schemes, such as \( SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R \to SU(3)_{color} \times U(1)_{B-L} \times SU(2)_L \times U(1)_R \), if the \( SU(4) \) and \( SU(2)_R \) break at different scales. We shall also assume that the mixing between the ordinary \( Z \) and the \( Z' \) remains extremely small. Stringent constraints on this mixing exist, as discussed in some of the more recent Refs. [9].

B. Couplings

The vector and axial-vector couplings \( C_V \) and \( C_A \) of the photon, \( Z \), and \( Z' \) to \( u \) and \( d \) quarks and to charged leptons have been given in Ref. [4]. Equivalently, the left-handed and right-handed couplings \( C_L \equiv C_V - C_A \) and \( C_R \equiv C_V + C_A \) are shown in Table I. Here we denote

\[
g_Z^2 \equiv e^2/[x(1-x)] \quad , \quad x \equiv \sin^2 \theta_W \simeq 0.231 \quad , \]

\[
g_\theta^2 \equiv \frac{5}{3} e^2/(1-x) \quad , \]

\[
A \equiv \cos \theta/2\sqrt{6} \quad , \quad B \equiv \sin \theta/2\sqrt{10} .
\]  

We have assumed a universal \( U(1) \) coupling strength [8] which would be that arising if \( E_6 \) broke in a single step to the standard model \( \times U(1)_\theta \).

C. Decay width

If all members of three 27-plets of \( E_6 \) can be produced in the decay of a heavy \( Z' \), there is a simple expression for its width [5]:

\[
\Gamma(Z') = \frac{5}{2} \alpha(M_{Z'})M_{Z'}/(1-x) \quad ,
\]  

where \( \alpha(M_{Z'}) \) is the electromagnetic fine-structure constant evaluated at \( M_{Z'} \). This corresponds to a ratio \( \Gamma/M \simeq 2.5\% \), so the \( Z' \) should be relatively narrow. Its precise width will depend on the availability of open channels. Some members of
Table I: Left- and right-handed couplings.

| Boson | $u$ quark | $d$ quark | Electron |
|-------|-----------|-----------|----------|
| $\gamma$ | $2\epsilon/3$ | $2\epsilon/3$ | $-\epsilon/3$ | $-\epsilon/3$ |
| $Z$ | $g_Z(-\frac{1}{2} + \frac{2}{3}x)$ | $g_Z(\frac{2}{3}x)$ | $g_Z(\frac{1}{2} - \frac{1}{3}x)$ | $g_Z(-\frac{1}{3}x)$ |
| $Z'$ | $-g_\theta(A + B)$ | $g_\theta(A + B)$ | $-g_\theta(A + B)$ | $g_\theta(A - 3B)$ | $g_\theta(3B - A)$ | $g_\theta(A + B)$ |

the 27-plet could be too heavy to be produced in pairs in the decays of $Z'$, reducing its predicted width. Alternatively, the presence of superpartners could increase the predicted width.

D. Scattering amplitudes

The vector- and axial-vector nature of the interaction with gauge bosons implies that the annihilation process $f\bar{f} \rightarrow e^-e^+$ may be uniquely specified by the helicities of the initial fermion $f$ and final electron $e^-$. We may then express the corresponding amplitudes, generalizing the result of Ref. [2], as

$$A_{ij} \equiv A(f_i \bar{f} \rightarrow e^-_j e^+) = -Qe^2 + \frac{\hat{s}}{\hat{s} - m_Z^2 + iM_Z \Gamma_Z} C_i^Z(f) C_j^Z(e)$$

$$+ \frac{\hat{s}}{\hat{s} - m_{Z'}^2 + iM_{Z'} \Gamma_{Z'}} C_i^{Z'}(f) C_j^{Z'}(e) .$$

(5)

Here $\hat{s}$ denotes the square of the c.m. energy, while the coefficients are those given in Table I for $(i, j) = (L, R)$. The differential cross section for $f\bar{f} \rightarrow e^-e^+$ is then

$$\frac{d\sigma(f\bar{f} \rightarrow e^-e^+)}{d\cos\theta^*} = \frac{1}{128\pi} \hat{s}(|A_{LL}|^2 + |A_{RR}|^2)(1 + \cos\theta^*)^2$$

$$+ (|A_{LR}|^2 + |A_{RL}|^2)(1 - \cos\theta^*)^2 .$$

(6)

The forward and backward cross sections $\sigma_F$ and $\sigma_B$ are those obtained by integrating (6) over positive and negative values of $\cos\theta^*$. The forward-backward asymmetry is then

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} \frac{|A_{LL}|^2 + |A_{RR}|^2 - |A_{LR}|^2 - |A_{RL}|^2}{|A_{LL}|^2 + |A_{RR}|^2 + |A_{LR}|^2 + |A_{RL}|^2} .$$

(7)
E. Present experimental limits and available data

The CDF Collaboration [13] has published lower limits on various types of $Z'$ bosons including the ones of the type considered here. The 95% c.l. lower limits on $(Z\psi, Z\eta, Z\chi, ZI)$ masses are (415, 440, 425, 400) GeV/$c^2$, respectively. In this data set, based on 19.7 pb$^{-1}$, there are 40 $e^+e^-$ events above an invariant mass of 125 GeV/$c^2$. The present data sample is approximately 5 times as large, and one can make use of dimuon as well as dielectron data. All told, one can expect at least a factor of ten statistical improvement with respect to the results of Ref. [13] once the current run concludes, or an improvement with respect to the results noted in Ref. [2] by a factor of about 40. What can one learn from such a data sample?

First of all, the asymmetry below the $Z$ (in the 60 - 80 GeV/$c^2$ range) should be very pronounced. (See especially Figs. 3(c) and 4(b) of Ref. [2].) However, it is necessary to take account of radiative corrections in order to compare data with predictions. The asymmetry at the $Z$ itself is small [14] and rapidly varying with lepton pair mass. If an electron or positron initially in the $Z$ peak loses energy through undetected radiation, it can appear to belong to a lower-mass pair. The observation of an asymmetry at lepton pair masses above the $Z$ is much less dependent on radiative corrections. Here, as we shall see in Sec. III and has been shown in Ref. [2], the asymmetry is expected to be large and slowly varying with pair mass. With a few hundred lepton pairs anticipated above a mass of 125 GeV/$c^2$, there should be no problem in measuring the predicted $\sim 50\%$ asymmetry to about 10% of its value. Thus, effects of new physics should be at least this large to be observable.

An order-of-magnitude estimate is possible on the basis of the amplitude (5) and the couplings (2). The extra factor of $x \equiv \sin^2 \theta_W$ in $g_Z^2$ relative to $g_Z^2$ occurs for any $Z'$ coupling to a U(1) charge. For a lepton pair mass of 125 GeV/$c^2$, the fractional effect on the scattering amplitude is no larger than $x(125 \text{ GeV}/c^2/M_{Z'}^2)^2$, or a couple of percent for $M_{Z'} = 400 \text{ GeV}/c^2$. In the next section we shall illustrate this estimate with some explicit examples.

III. EFFECTS OF A 500 GeV $Z'$

We assume $M_{Z'} = 500 \text{ GeV}/c^2$, beyond the published mass limits [13], and calculate the expected forward-backward asymmetries in $f\bar{f} \rightarrow e^-e^+ + \ldots$ for $f = u, d, \mu$. (The most convenient formalism for incorporating parton-level results into a calculation with up-to-date structure functions and realistic detector acceptance is given in Ref. [4]. The case $f = \mu$ is relevant for the process $e^-e^+ \rightarrow \mu^-\mu^+$ at a next-generation linear collider.) The results are shown in Figs. 1–3.

In these figures the first point to note is the relative insensitivity to a 500 GeV $Z'$ of physics at or below 200 GeV. This is in part a feature of our assumption that the standard $Z$ and the $Z'$ are very weakly mixed with one another, and in part stems from the relatively weak coupling assumed for the $Z'$. 
Figure 1: Parton-level forward-backward asymmetries for $u\bar{u} \rightarrow e^- e^+$. Solid line: standard model. Dashed line: $500 \text{ GeV}/c^2 Z_\chi$ added. Dotted line: $500 \text{ GeV}/c^2 Z_\psi$ added. A $Z_I$ does not couple to $u$ quarks and does not change the standard model prediction.
When the lepton pair mass approaches $M_{Z'}$, the characteristic interferences differ substantially from one another for various kinds of $Z'$. These patterns can be very helpful in diagnosing the nature of a new neutral gauge boson [4].

The asymmetries in $u\bar{u} \to e^-e^+$ are the same for the standard model and when a $Z_I$ is added, since that boson does not couple to $u$ quarks.

The asymmetries when a $Z_\psi$ is added are very small at the pole, since a $Z_\psi$ couples purely axially to the ordinary quarks and leptons.

The most likely place where asymmetries due to a $Z'$ will first be observed is at the pole mass. Accordingly, in Fig. 4 we have shown the asymmetries for $f\bar{f} \to e^-e^+$ at a subenergy of 500 GeV due to a $Z'$ of mass 500 GeV/c$^2$, parametrized by the
Figure 3: Same as previous figure for $\mu^-\mu^+ \rightarrow e^-e^+$. 

angle $\theta$ in Eq. (1). Also shown is the ratio

$$r \equiv \frac{(C_u^L)^2 + (C_d^R)^2}{(C_u^L)^2 + (C_d^R)^2}$$

(8)

describing the relative strengths of $u$ and $d$ quark couplings. The ratio $r$ reaches its maximum of 2 at $\theta = \arcsin(\sqrt{5/2}/4) \approx 23.28^\circ$, and vanishes for $\theta = \theta_I \equiv \arctan(-\sqrt{5/3}) \approx 127.78^\circ$, i.e., for $Z' = Z_I$. In the latter case, $Z'$ production in hadronic colliders is due entirely to $d\bar{d}$ annihilation, and the large negative asymmetry in $d\bar{d} \rightarrow e^-e^+$ will be reflected in a similar asymmetry in $p\bar{p} \rightarrow e^-e^+ + \ldots$. To some extent this is also true of the $Z_\chi$, for which $r$ is only 1/5. With no more than about a dozen events of $p\bar{p} \rightarrow Z_\chi, I \rightarrow \ell^-\ell^+$, it should therefore be possible to demonstrate a convincing forward-backward asymmetry very different from that due to the photon and $Z$. 

8
Figure 4: Parameters as a function of the mixing angle $\theta$ for a 500 GeV/$c^2$ $Z'$, as measured on the peak. (a) Forward-backward asymmetries at the parton level. Solid line: $u\bar{u} \rightarrow e^- e^+$; dashed line: $d\bar{d} \rightarrow e^- e^+$; dotdashed line: $\mu^- \mu^+ \rightarrow e^- e^+$. (b) Ratio $r$ of sums of squares of $u$ and $d$ production coefficients.
The suppression of the couplings of a $Z'$ to $u$ quarks over a wide range of $\theta$ indicated in Fig. 4(b) implies that the decays of the $Z'$ may be enriched in the charge $-1/3$ quarks $d$, $s$, $b$. Moreover, as one can see from the couplings in Table I, there is the potential for $|C_d^d| \ll |C_d^d|$, leading to a characteristic forward-peaking in the process $d\bar{d} \rightarrow Z' \rightarrow (d, s, \text{or } b) + (\bar{d}, \bar{s}, \text{or } \bar{b})$. It may be worth while looking for such an effect by studying the angular distribution of jets produced at high transverse momentum using momentum-weighted jet charge methods.

The asymmetries at the pole for $d\bar{d} \rightarrow e^-e^+$ and $\mu^+\mu^- \rightarrow e^-e^+$ vanish at $\theta = 0$ (where the couplings to the $Z'$ are purely axial) and $\theta = \arctan(\sqrt{5}/3) \simeq 52.24^\circ$, where they are purely vector. Aside from small effects due to interference with the photon and $Z$, these asymmetries are always of the same sign: negative for $d\bar{d} \rightarrow e^-e^+$ and positive for $\mu^+\mu^- \rightarrow e^-e^+$.

The peak in the asymmetry for $u\bar{u} \rightarrow e^-e^+$ at $\theta = \theta_f$ is due to the vanishing of the $Z'$ contribution, whereupon the large positive standard model value is attained.

**IV. REMARKS ON COMPOSITENESS**

Analyses similar to those carried out for extra neutral gauge bosons can be performed when the $f\bar{f} \rightarrow e^-e^+$ scattering amplitude is modified by a term due to exchange of a very heavy strongly-coupled boson, such as that which would arise in certain composite models. Specifically, in Ref. [6] the amplitude for $f_L\bar{f} \rightarrow e^-_Le^+$ was taken to be

$$A_{LL} \equiv A(f_L\bar{f} \rightarrow e^-_Le^+) = -Qf e^2 + \frac{\hat{s}}{\hat{s} - m_Z^2 + iM_Z\Gamma_Z} C^Z_L(f)C^Z_L(e) + \xi g_Y^2 \frac{\hat{s}}{2 \hat{s} - M_V^2},$$

(9)

where $\xi = \pm 1$, and $g_Y$ is a new coupling constant associated with the exchange of a hypothetical vector meson $V$ with mass taken to equal $2 \text{ TeV}/c^2$. Other scattering amplitudes were taken to have standard form. The fractional effect on the amplitude should be of order $(\alpha_Y/2\alpha)(\hat{s}/M_V^2)$, or roughly $\alpha_Y/4$ for $\sqrt{\hat{s}} = 125 \text{ GeV}$. Thus with a 10% measurement of asymmetries above a lepton pair mass of $125 \text{ GeV}/c^2$ one could exclude a value of $\alpha_Y(2 \text{ TeV}/M_V)^2$ above 0.4, or a value of $M_V$ below about $3.2 \text{ TeV}/c^2$ for $\alpha_Y = 1$. This is comparable to values set in other searches at present.

In contrast to models with extra neutral gauge bosons, the composite model discussed in Ref. [6] also predicts appreciable effects in charged-current lepton pair production, such as $p\bar{p} \rightarrow e^- + \nu + \ldots$. Even with $\alpha_Y(2 \text{ TeV}/M_V)^2$ as small as 0.1, one expects deviations by up to a factor of two from the standard model predictions for the cross section for production of single charged leptons above a transverse momentum of $200 \text{ GeV}/c$. 

10
V. CONCLUSIONS

We have considered the effects of two new types of physics on forward-backward asymmetries of high-mass charged lepton pairs produced in proton-antiproton collisions at the Fermilab Tevatron.

(1) A new neutral gauge boson ("Z'") can modify scattering amplitudes at the parton level, but its effects will probably not be visible through interference with the photon and Z contributions in the current sample of data. A handful of events at the peak of a new Z can, however, already exhibit asymmetries strikingly different from those in the standard model for a range of possible forms of the Z'.

(2) Composite models can give rise to effective contact terms, whose fractional contribution to electroweak amplitudes can probably be ruled out or discovered at the 10% level in the current round of experiments. For coupling strengths of order $\alpha_Y = 1$, these would correspond to compositeness scales of order 5 TeV, comparable to those probed in other current experiments. In one class of models \cite{6}, such terms are expected to be particularly prominent in charged-current lepton pair production, such as is studied in searches for excited W bosons \cite{15}.

ACKNOWLEDGMENTS

I am grateful to H. Frisch for stimulating me to undertake this investigation and for helpful discussions. This work was supported in part by the United States Department of Energy under Grants No. DE AC02 76CH03000 and DE FG02 90ER40560.

References

[1] S. D. Drell and T.-M. Yan, Phys. Rev. Lett. 25, 316, 902(E) (1970); Ann. Phys. (N.Y.) 66, 578 (1971).
[2] J. L. Rosner, Phys. Lett. B 221, 85 (1989).
[3] P. Langacker, R. W. Robinett, and J. L. Rosner, Phys. Rev. D 30, 1470 (1984).
[4] J. L. Rosner, Phys. Rev. D 35, 2244 (1987).
[5] V. Barger, N. G. Deshpande, J. L. Rosner, and K. Whisnant, Phys. Rev. D 35, 2893 (1987).
[6] J. L. Rosner and D. E. Soper, Phys. Rev. D 45, 3206 (1992).
[7] R. W. Robinett, Phys. Rev. D 26, 2388 (1982); R. W. Robinett and J. L. Rosner, Phys. Rev. D 25, 3036 (1982); 26, 2396 (1982).
[8] D. London and J. L. Rosner, Phys. Rev. D 34, 1530 (1986).
[9] L. S. Durkin and P. Langacker, Phys. Lett. 166B, 436 (1986); U. Amaldi et al., Phys. Rev. D 36, 1385 (1987); F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. B287, 457 (1987); J. L. Hewett and T. G. Rizzo, Phys. Rep. 183, 193 (1990); P. Langacker and M. Luo, Phys. Rev. D 45, 278 (1992); P. Langacker, in Precision Tests of the Standard Model, edited by P. Langacker (World Scientific, Singapore, 1995), p. 883; M. Cvetič and S. Godfrey, in Electro-weak Symmetry Breaking and Beyond the Standard Model, edited by T. Barklow, S. Dawson, H. Haber, and J. Siegrist (World Scientific, Singapore, 1995), and references therein; M. Cvetič and P. Langacker, Institute for Advanced Study report IASSNS-HEP-95/90, [hep-ph/9511378](http://arxiv.org/abs/hep-ph/9511378) (unpublished).

[10] H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974).

[11] H. Georgi in Proceedings of the 1974 Williamsburg DPF Meeting, ed. by C. E. Carlson (New York, AIP, 1975) p. 575; H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93, 193 (1975).

[12] E. Witten, Nucl. Phys. B258, 75 (1985); E. Cohen, J. Ellis, K. Enqvist, and D. V. Nanopoulos, Phys. Lett. 165B, 76 (1985); J. L. Rosner, Comments on Nucl. Part. Phys. 15, 195 (1986).

[13] CDF Collaboration, F. Abe et al., Phys. Rev. D 51, 949 (1995).

[14] CDF Collaboration, F. Abe et al., Phys. Rev. Lett. 67, 1502 (1991).

[15] CDF Collaboration, F. Abe et al., Phys. Rev. Lett. 67, 2609 (1991); Phys. Rev. Lett. 74, 341 (1995); 74, 2900 (1995).