Brief Reports

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Off-peak lepton asymmetries from new Z's

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Neutral heavy gauge bosons have characteristic vector and axial-vector couplings to quarks and leptons. The hadronic process $pp \to (\gamma^*, Z^{0*}, \ldots) + \cdots \to l^- l^+ + \cdots$, where $l = e, \mu, \tau$, exhibits characteristic forward-backward asymmetries whenever the lepton pair is not at rest in the pp center of mass. These asymmetries can be used to probe the couplings of a new boson. Attention is paid to such asymmetries for dilepton masses in the interference region between the new boson and the Z^0.

I. INTRODUCTION

Despite substantial evidence in favor of $SU(2)\times U(1)$ as the electroweak gauge group, present experiments do not say much about new neutral gauge bosons much heavier than the Z^0 (Refs. 1 and 2). Proposed hadron colliders will be able to search for such bosons up to several TeV (Ref. 3). Grand unified[4] and superstring[5] theories lead us to expect a variety of neutral bosons. If one is seen, how can we tell which one it is?

Neutral gauge bosons beyond the photon and Z^0 have characteristic vector and axial-vector couplings to matter reflecting properties of the unifying group.[6] Several tests for these couplings have been proposed recently, including the analysis of neutral-current reactions,[1] the detailed study of branching ratios,[2] and the measurement of forward-backward asymmetries of leptonic decay products. These asymmetries have been discussed both for hadronic[2,4,7–9] and for e^+e^- (Ref. 10) production.

When the dilepton production amplitude receives important contributions from conventional (γ^*, Z^{0*}) as well as new bosons, the interference between the known and unknown amplitudes provides additional information on couplings. Here we study forward-backward lepton asymmetries in the reaction $pp \to l^- l^+ + \cdots$, as a function of dilepton mass, to obtain this information. We shall show that measurement of these asymmetries off resonance peaks is particularly helpful, and investigate the statistical demands made by such a measurement.

We utilize recent discussions of extra Z's motivated by, but more general than, superstring theory. The properties of such extra Z's are reviewed briefly in Sec. II, along with well-known formulas for asymmetries on and off a resonance peak. Our results are contained in Sec. III. Section IV summarizes our work.

II. EXTRA Z's

A. An "extra-Z" primer

We imagine a grand unified theory (GUT) which incorporates SU(5), at least approximately, into the couplings of any new neutral gauge bosons to matter.[6] In E_6 models, of current interest because of superstrings, there are then two such bosons, which we may call Z_ψ and Z_χ. The first of these arises when E_6 breaks down to an $SO(10)\times U(1)$. The second arises when SO(10) breaks down to $SU(5)\times U(1)$. We assume that the lowest-lying "extra Z" is an arbitrary mixture of Z_ψ and Z_χ:

$$Z(\theta) = Z_\psi \cos\theta + Z_\chi \sin\theta \ , \tag{1}$$

where θ is a mixing angle to be determined. We shall take the coupling strengths of the U(1)'s to be the same as that of the weak hypercharge.[1]

Specific values of θ are interesting in GUT and superstring theories. The values $\theta = 0°$, $90°$ correspond to pure Z_ψ, Z_χ. The value $\theta = \arctan(\frac{3}{5})^{1/2} = 37.78°$ describes a boson sometimes denoted[1] Z_η or Z', which arises when E_6 is broken to a rank-5 subgroup at the unification scale in superstring theories. The boson orthogonal to this, corresponding to $\theta = -\arctan(\frac{5}{3})^{1/2} = 127.78°$, is sometimes called[4] Z_I.

B. Vector and axial-vector couplings of neutral gauge bosons

The vector and axial-vector couplings of the gauge boson B_α^μ $(\alpha = \gamma, Z^0, \ldots)$ to a fermion f are denoted $C_{V,A}^{\alpha,f}$, normalized such that

$$\mathscr{L}_{\alpha,f} = -\bar{\psi}_f \gamma_\mu (C_V^{\alpha,f} + \gamma_5 C_A^{\alpha,f}) \psi_f B_\alpha^\mu \ . \tag{2}$$

The specific couplings for the photon, the standard Z, and $Z(\theta)$ are shown in Table I. Here

$$g_Z{}^2 \equiv e^2/[x(1-x)],\quad x=\sin^2\theta_W\ ,$$
$$g_\theta{}^2 \equiv \tfrac{5}{3}e^2/(1-x)\ , \tag{3}$$

and[11]

$$A \equiv \cos\theta/(2\sqrt{6}),\quad B \equiv \sin\theta/(2\sqrt{10})\ . \tag{4}$$

C. Partial and total widths of new Z's

The $Z(\theta)$ discussed above can couple to exotic fermions as well as ordinary ones.[1,2,12] If all the decay channels to exotic fermions are open, we find a simple expression for the total $Z(\theta)$ widths,[2] independent of θ:

$$\Gamma(Z(\theta)) = \tfrac{5}{2}\alpha_{\rm EM}M(Z(\theta))/(1-x)\ . \tag{5}$$

This corresponds to $\Gamma/M \approx 2.5\%$. We shall use this value in subsequent discussions.[13] When all exotic channels are closed, the width is about 20—50% of (5), depending on θ (Ref. 2). Thus *new Z's are likely to be fairly narrow.* Their couplings are governed by U(1) strengths, which are weaker than the SU(2) contributing to the Z^0's couplings.

D. Hadronic poduction of new bosons

We use standard Drell-Yan expressions for cross sections and forward-backward asymmetries in lepton-pair production by hadrons.[2,14,15] We define

$$\Delta_\alpha \equiv M^2 - M_\alpha{}^2,\quad \gamma_\alpha \equiv M_\alpha \Gamma_\alpha\ ,$$
$$D_\alpha \equiv (\Delta_\alpha{}^2 + \gamma_\alpha{}^2)^{-1}\ , \tag{6}$$
$$X_{\alpha\beta} \equiv D_\alpha D_\beta(\Delta_\alpha\Delta_\beta + \gamma_\alpha\gamma_\beta)\ ,$$

where M_α and Γ_α are the mass and width of gauge boson α, and M is the effective mass of the lepton pair. The contributions to the cross section for $q\bar{q} \to e^-e^+$ which are symmetric and antisymmetric in $\cos\theta^*$ are proportional to

$$S_q \equiv \sum_{\alpha,\beta} X_{\alpha\beta}(C_V^{q,\alpha}C_V^{q,\beta} + C_A^{q,\alpha}C_A^{q,\beta}) \times (C_V^{e,\alpha}C_V^{e,\beta} + C_A^{e,\alpha}C_A^{e,\beta})\ , \tag{7}$$

$$A_q \equiv \sum_{\alpha,\beta} X_{\alpha\beta}(C_V^{q,\alpha}C_A^{q,\beta} + C_A^{q,\alpha}C_V^{q,\beta}) \times (C_V^{e,\alpha}C_A^{e,\beta} + C_A^{e,\alpha}C_V^{e,\beta})\ . \tag{8}$$

Here θ^* is the c.m. angle of the negative lepton with respect to the quark direction. To calculate the cross section for lepton-pair production in the collision of hadrons A and B, we use the structure functions of Ref. 3. We consider only the effects of u and d quarks. The momentum fractions of the quarks in hadrons A and B are

$$x_A = (M/\sqrt{s}\,)e^y,\quad x_B = (M/\sqrt{s}\,)e^{-y}\ , \tag{9}$$

where $\sqrt{s}$ is the total c.m. energy of the hadrons. Then[15]

$$\sigma_l \equiv \frac{d\sigma(pp \to l^-l^+ + \cdots)}{dM\,dy\,d(\cos\theta^*)} = \frac{Mx_Ax_B}{48\pi}\left[\sum_q [f_q^A(x_A)f_{\bar q}^B(x_B) + f_{\bar q}^A(x_A)f_q^B(x_B)]S_q(1+\cos^2\theta^*) + \sum_q [f_q^A(x_A)f_{\bar q}^B(x_B) - f_{\bar q}^A(x_A)f_q^B(x_B)]2A_q\cos\theta^*\right]\ , \tag{10}$$

where the f's are the structure functions. The forward-backward asymmetry, as a function of y and M, is

$$A^{FB}(y,M) = \sigma^{F-B}(y,M)/\sigma^{F+B}(y,M)\ , \tag{11}$$

where

$$\sigma^{F\pm B}(y,M) = \left[\int_0^1 \pm \int_{-1}^0\right] d(\cos\theta^*)\sigma_l\ . \tag{12}$$

A^{FB} is an odd function of the gauge boson's rapidity y for proton-proton interactions.[4,7]

III. RESULTS FOR ASYMMETRIES

A. Asymmetries at resonance peak

We show[2] in Fig. 1 the forward-backward asymmetry in leptons as a function of y for various values of the mixing angle θ describing the new Z. These asymmetries are small for a wide range of θ. All the vector couplings in Table I vanish for $\theta=0$, so that the on-peak asymmetries

TABLE I. Vector and axial-vector couplings.

	Fermion					
	u quark		d quark		Electron	
Boson	C_V	C_A	C_V	C_A	C_V	C_A
γ	$2e/3$	0	$-e/3$	0	$-e$	0
Z^0	$g_Z(-\frac{1}{4}+2x/3)$	$g_Z/4$	$g_Z(\frac{1}{4}-x/3)$	$-g_Z/4$	$g_Z(\frac{1}{4}-x)$	$-g_Z/4$
$Z(\theta)$	0	$g_\theta(A+B)$	$-2g_\theta B$	$g_\theta(A-B)$	$2g_\theta B$	$g_\theta(A-B)$

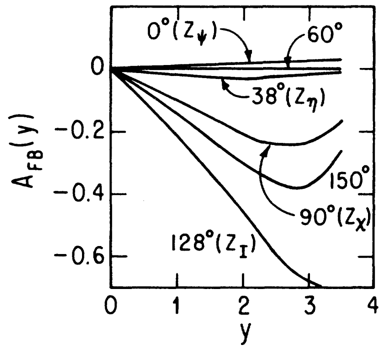

FIG. 1. Forward-backward asymmetries in $pp \to Z(\theta) + \cdots \to l^- l^+ + \cdots$ for $\sqrt{s}=40$ TeV, as a function of rapidity. Here $M(Z(\theta))=1$ TeV. Interference with γ^*, Z^* has been taken into account.

vanish there. A second zero of the asymmetries[1,2] occurs at $\tan\theta=(\frac{5}{3})^{1/2}$ ($\theta=52°$), for which the *axial-vector* couplings of the d quark and lepton vanish.

B. Off-peak asymmetries

One learns more about the vector and axial-vector couplings of new gauge bosons by measuring asymmetries of lepton pairs produced *off* the resonance peak. This suggestion[16] seems feasible at the proposed Superconducting Super Collider (with $\sqrt{s}=40$ TeV) for gauge bosons up to about a TeV in mass. Above this value, the statistical power of the method is limited by the low cross section[2,15] in the interference region between the standard and new Z.

We show in Fig. 2 the $F \pm B$ contributions (12) to the cross section, evaluated at $y=2$. For bosons with small on-peak asymmetries, the off-peak asymmetries are larger. For these cases one evaluates the asymmetries not at the resonance peak, but over a wide mass range on one side of the peak.

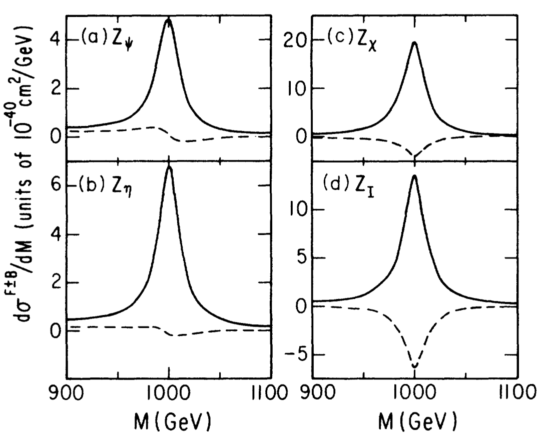

FIG. 2. Forward±backward cross sections at $y=2$ as a function of dilepton mass, for reaction considered in Fig. 1. (a) $\theta=0°$ (Z_ψ); (b) $\theta=38°$ (Z_η); (c) $\theta=90°$ (Z_χ); (d) $\theta=128°$ (Z_I). Solid curves, $F+B$; dashed curves, $F-B$.

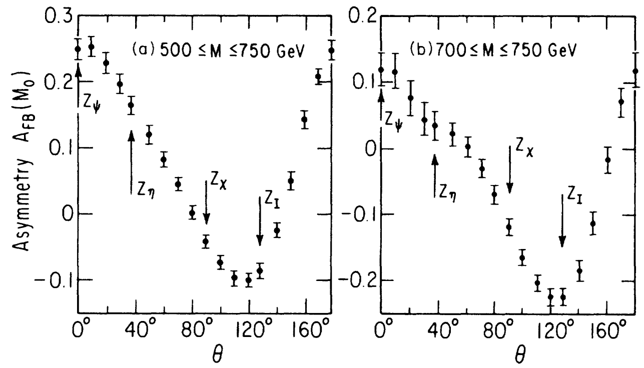

FIG. 3. Forward-backward asymmetry as a function of mixing angle θ, integrated over ranges of dilepton mass M. Here $M(Z(\theta))=750$ GeV.

We have explored the mass range over which it makes sense to measure asymmetries. If the lower limit M_0 of this range is too close to the Z^0, all the information about the new boson will be washed out by the contribution of the virtual photon and Z^0. For a 750-GeV/c^2 boson, we have found that this lower limit is about 500 GeV/c^2. We show in Fig. 3 two examples of an integrated asymmetry of the form

$$A_{FB}(M_0)=\sigma^{F-B}(M_0)/\sigma^{F+B}(M_0) , \tag{13}$$

where

$$\sigma^{F\pm B}(M_0)\equiv \int_{M_0}^{M(Z(\theta))} dM \left[\int_0^{y_{\max}} \pm \int_{y_{\min}}^{0} \right] \times dy\, \sigma^{F\pm B}(y,M) . \tag{14}$$

The error bars correspond to the statistical precision possible with an integrated luminosity of 10^4 pb^{-1}. Convincing asymmetries can be measured both for the Z_ψ (the case $\theta=0$) and for the Z_η, as well as for most other values of θ. In the absence of any other contributions, the asymmetry at the Z_ψ peak would vanish, since all the couplings of the Z_ψ to ordinary matter are axial-vector couplings. For the Z_η the asymmetry has also been shown negligible at the resonance peak.[9]

IV. CONCLUSIONS

A. Comparison of on-peak and off-peak asymmetries

What is gained by measuring off-peak asymmetries, when the rates at the resonance peak are so much greater? A comparison of Fig. 3 with the on-peak asymmetries implied by Fig. 1 shows that there is a wide range of couplings (essentially $-10° < \theta < 70°$) for which the on-peak asymmetries will be very small, as a result of their double zeros at $\theta=0°$ and 52°. The off-peak asymmetries, on the other hand, have single zeros in θ whose positions depend on the dilepton mass range. The virtual Z and photon thus provide important reference amplitudes, permitting sensitive studies of couplings over the whole range of θ.

B. Implications for detectors

1. Lepton acceptance

The lepton asymmetries in $pp \to Z(\theta)+\cdots \to l^-l^+$ (see Fig. 1) are most significant for large gauge-boson rapidity.[2,4,7,17] At large $|y|$, a gauge boson must be formed from a quark-antiquark annihilation in which one parton has large x and the other has small x. [See, e.g., Eq. (10).] The large-x parton is much more likely to be a quark than an antiquark, since valence quarks have much harder distributions than sea antiquarks in the proton. Thus, in a pp collider, measurement of forward-backward asymmetries in Z decays demands *good acceptance for leptons at small angles to the beam.* Such acceptance is most easily obtained for muons.[7,18]

2. Mass resolution

The widths of new Z's likely to arise in GUT's and superstring theories are expected to be small—from 0.5% to 2.5% of their mass.[13] These widths provide key information on the number of open decay channels.[2] Good mass resolution is needed to detect the off-peak asymmetries in Fig. 2, since some of them are rapidly varying at or near the resonance mass. For 1-TeV muons, it appears possible to get 10% mass resolution.[18] Doing better appears hard but not impossible.[19]

3. Lepton signs

The measurement of lepton asymmetries demands sign information. This will be unavailable for high-energy electrons. Again, muons appear to be the leptons of choice. (Asymmetries in τ decays may also be of some help.[8])

C. Summary

Lepton asymmetries in hadronic collisions can be informative not only at the resonant peaks of new gauge bosons, but also for dilepton effective masses sensitive to interference between old and new bosons. We have cited examples based on an extended gauge group motivated by superstrings, but the method is more general. Adequate and possibly specialized muon detection is essential to reap the benefits of this approach at high-energy hadron colliders.

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