Lepton-pair production in proton-nucleon collisions as a means of testing the standard electroweak model

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We use the standard Glashow-Salam-Weinberg $SU(2)_L \times U(1)$ electroweak theory to calculate the charge asymmetry expected for lepton-pair production in proton-nucleon collisions at various center-of-mass energies. Specifically, we discuss the prospect of measuring charge asymmetry as a means to determine the electroweak mixing parameter $\sin^2\theta_W$, using a proton-beam energy of around 800 GeV. As motivated by the observation that an additional (nonstandard) gauge boson in a low-energy theory appears naturally in the $E_8 \times E_8$ superstring studies, we also adopt an extended $SU(2)_L \times U(1) \times U(1)$ electroweak model. To study manifestations of the nonstandard gauge boson, we consider a fixed-target experiment at a few TeV as well as for a proton-antiproton or proton-proton collider experiment in the few-TeV range. In particular, the behavior of charge asymmetry near the standard Z^0 pole is investigated as a possible means to determine the Z^0 - Z'^0 mixing parameter $\sin\phi$. The possibility of a direct search for the nonstandard gauge boson Z'^0 at Fermilab Tevatron energies is also briefly discussed.

I. INTRODUCTION

It is known¹ that charge asymmetry observed in the unpolarized $e^+ + e^- \rightarrow \mu^+ + \mu^-$ collider experiment provides a means of measuring the electroweak mixing parameter $\sin^2\theta_W$ of the Glashow-Salam-Weinberg (GSW) electroweak theory.² Taking the Mark J experiment (at the DESY electron-positron collider PETRA) as an illustrative example, an analysis of a sample of about 3700 events at the center-of-mass energy $\sqrt{S} = 34.6$ GeV yields¹ a charge asymmetry of $-(11.7 \pm 1.7)\%$, which is somewhat larger in magnitude than the value -8.5% predicted in the GSW theory with $M_{Z^0} = 93$ GeV and $\sin^2\theta_W = 0.22$. Of course, the experimental situation may improve considerably when the CERN e^+e^- collider LEP or the SLAC Linear Collider comes into operation.

Meanwhile, a similar measurement via $\mu^+\mu^-$ production in hadron-hadron collisions, i.e., Drell-Yan processes,³ has so far been lacking, although an experiment with 400-GeV protons was proposed several years ago at Fermilab.⁴ Some theoretical aspects on charge asymmetry in Drell-Yan processes have been addressed briefly by Callaway *et al.*⁵ Theoretically we may define the integrated charge asymmetry $\mathcal{A}$ as

$$\mathcal{A} \equiv \frac{\frac{d\sigma}{dM}(\cos\theta > 0) - \frac{d\sigma}{dM}(\cos\theta < 0)}{\frac{d\sigma}{dM}(\cos\theta > 0) + \frac{d\sigma}{dM}(\cos\theta < 0)}, \quad (1)$$

where $d\sigma/dM$ is the lepton-pair production cross section at the lepton-pair invariant mass M . Note that $\cos\theta$ is defined by

$$\cos\theta \equiv \frac{(l^+ - l^-) \cdot \mathbf{P}}{|l^+ - l^-| |\mathbf{P}|}, \quad (2)$$

where $l^\pm$ are the three-momenta of leptons and $\mathbf{P}$ is the beam momentum in the hadron-hadron center-of-momentum (c.m.) frame. Note that our definition for $\cos\theta$ yields, in the standard GSW electroweak theory, a positive value for the charge asymmetry at low energies (i.e., $M_{\mu^+\mu^-} \ll M_Z$). Specifically, we wish in this paper to focus our attention on high-energy proton-induced collisions, including proton-nucleon (pN), proton-proton (pp), and proton-antiproton ($p\bar{p}$) collisions. However, the results are often rather similar in these cases so that we choose to present the pN results for fixed-target experiments and the $p\bar{p}$ and pp results for collider experiments, unless there is a need to do otherwise.

As should become clear later in the paper, the γ - Z^0 interference in the GSW electroweak theory will give rise to an integrated charge asymmetry of about 5% at $M = 20$ GeV in proton-nucleon collisions for a beam energy of 1 TeV. As illustrated in Figs. 1(a)–1(c), there are other sources for producing a small charge asymmetry. These include (1) interference between one-photon-exchange and Higgs-boson-exchange processes [Fig. 1(a)], (2) interference between one-photon and two-photon-exchange processes [Fig. 1(b)], and (3) interference between the initial- and final-state bremsstrahlung processes [Fig. 1(c)]. For a Higgs particle as given by the standard GSW theory, the contribution due to the first mechanism is proportional to fermion masses and, in the present problem, leads to results which are completely negligible. Note that the treatment of QED contributions due to the second and third mechanisms is the same

FIG. 1. Different sources for producing a small “background” charge asymmetry. These include (1) interference between one-photon-exchange and Higgs-boson-exchange processes (a); (2) interference between one-photon- and two-photon-exchange processes (b); and (3) interference between the initial- and final-state bremsstrahlung processes (c).

for both $e^- + e^+ \rightarrow \mu^- + \mu^+$ and $q + \bar{q} \rightarrow \mu^- + \mu^+$ and it gives rise to an effect of $O(\alpha)$, which exhibits very mild energy dependence.¹ These effects are completely calculable in terms of QED. Since charge asymmetry involves the *ratio* of cross sections, it is expected that a measurement of charge asymmetry in hadron+hadron $\rightarrow \mu^+ + \mu^- + X$ may yield information as clean as the $e^+ + e^- \rightarrow \mu^+ + \mu^-$ charge-asymmetry experiment. In particular, Feynman diagrams for QCD corrections to the Z^0 -exchange graph are analogous to those for the one-photon-exchange graph so that, as a ratio, charge asymmetry may not be sensitive to QCD corrections. This result is suggested by the existing formalism of Altarelli *et al.*,⁶ although further investigation of the problem is very desirable (especially if the proposed experiment will be carried out in the near future). We shall return briefly to this point when we discuss extraction of the electroweak mixing parameter $\sin^2\theta_W$ at the end of Sec. III A.

Assuming that QED and QCD corrections do not seriously affect interpretation of the charge-asymmetry measurement in hadron+hadron $\rightarrow \mu^+ + \mu^- + X$ experiment, it is important to note that an experiment of very high statistics will become available in Drell-Yan processes if we can go to higher beam energies without losing the

overall luminosity. In particular, proton-nucleon collisions at a proton-beam energy of 800 GeV yields a cross section for muon pairs of 12-GeV invariant mass about an order of magnitude larger than that for 400-GeV protons. An experiment with 800-GeV protons should then give a statistical precision much better than that which may be accomplished in an experiment with 400-GeV protons, proposed several years ago.⁴ This is a trivial but important point since the charge asymmetry caused by γ - Z^0 interference increases with the invariant mass of the muon pair and the number of low-mass muon pairs is irrelevant for our purpose. Of course, the cross-section consideration will favor utilization of a proton beam at the highest energy possible. It is also interesting to note that, unlike in $e^+ + e^- \rightarrow \mu^+ + \mu^-$ experiments, the functional dependence of the measured charge asymmetry on $M_{\mu^+\mu^-}$ can be obtained in a *single* hadron-induced $\mu^+\mu^-$ production experiment.

At Fermilab Tevatron energies (e.g., $\sqrt{s} = 2$ TeV) or at CERN SPS collider energies, the calculated charge asymmetry becomes order of unity for $M_{\mu^+\mu^-} \geq 50$ GeV (with corresponding cross sections of a significant size). In this case, charge-asymmetry measurements are relatively straightforward. The behavior of the charge asymmetry near the Z^0 pole (i.e., 93 GeV) may be of particular interest since it is a direct measure of how the standard gauge boson Z^0 couples to quarks and leptons. For the GSW electroweak theory, the predicted charge asymmetry crosses zero at a few GeV away from the pole position. The exact behavior of the charge asymmetry will be sensitive to the presence of nonstandard gauge bosons or nearby vectorlike quarkonium states [e.g., $^3S_1(t\bar{t})$ bound states].

A charge-asymmetry measurement should also be considered as a tool for probing manifestations of the nonstandard gauge boson, the existence of which has been suggested by recent studies of superstring models.⁷ For instance, the detailed behavior of charge asymmetry near the Z^0 pole may reveal some signature for the existence and/or absence of the nonstandard gauge boson. The effect caused by Z^0 - Z'^0 mixing is considerably amplified in this region.

Therefore, we wish in this paper to make predictions on the charge asymmetry $\mathcal{A}$ in Drell-Yan processes both in the standard GSW electroweak theory and in the $SU(2)_L \times U(1) \times U(1)$ model. In Sec. II we review briefly some ingredients of the electroweak models which are relevant for the purpose of this paper. In Sec. III we study charge asymmetry in a few cases, including (1) $\mu^+\mu^-$ production in proton-nucleon collisions at a proton beam energy of 800 GeV and of a few TeV and (2) $\mu^+\mu^-$ production in a $p\bar{p}$ or pp collider experiment at the center-of-mass energy of a few hundred GeV up to a few TeV. A brief summary of the paper is given in Sec. IV.

II. GLASHOW-SALAM-WEINBERG ELECTROWEAK THEORY AND AN EXTENDED MODEL

In the GSW electroweak theory we may write the neutral-current interaction⁸ L_{NC} as

$$L_{\text{NC}} = e A_\mu J_\mu^{\text{em}} + \frac{e}{\sin\theta_W \cos\theta_W} Z_\mu^0 N_\mu, \quad (3)$$

where $e^2/4\pi (\equiv \alpha)$ is the fine-structure coupling constant and (A_μ, Z_μ^0) are the photon and standard Z-boson fields, respectively. The electromagnetic and standard weak neutral currents $(J_\mu^{\text{em}}, N_\mu)$ are specified by

$$J_\mu^{\text{em}} = \frac{2}{3} i \bar{u} \gamma_\mu u - \frac{1}{3} i \bar{d} \gamma_\mu d - i \bar{e} \gamma_\mu e, \quad (4a)$$

$$N_\mu = i \bar{u}_L \frac{1}{2} \gamma_\mu u_L - i \bar{d}_L \frac{1}{2} \gamma_\mu d_L + i \bar{\nu}_L \frac{1}{2} \gamma_\mu \nu_L - i \bar{e}_L \frac{1}{2} \gamma_\mu e_L - \sin^2\theta_W J_\mu^{\text{em}}. \quad (4b)$$

Here we include only the *first* generation of fermions for the sake of simplicity and generalization of the results to incorporate other generations of fermions is obvious.

In a specific $\text{SU}(2)_L \times \text{U}(1) \times \text{U}(1)$ electroweak model which is inspired by $\text{E}_8 \times \text{E}_8$ superstring studies,⁷ the neutral-current interaction is specified by⁹

$$L_{\text{NC}} = e A_\mu J_\mu^{\text{em}} + \frac{e}{\sin\theta_W \cos\theta_W} Z_{\mu,0}^0 N_\mu + \frac{e}{\cos\theta_W} Z_{\mu,0}' N_\mu', \quad (5)$$

where J_μ^{em} and N_μ are the same as in the GSW theory [Eqs. (4a) and (4b)] and the nonstandard neutral current is given by⁹

$$N_\mu' = \frac{1}{3} (i \bar{u}_L \gamma_\mu u_L + i \bar{d}_L \gamma_\mu d_L) - \frac{1}{6} (i \bar{\nu}_L \gamma_\mu \nu_L + i \bar{e}_L \gamma_\mu e_L) + \frac{1}{3} i \bar{u}_R \gamma_\mu u_R - \frac{1}{6} i \bar{d}_R \gamma_\mu d_R + \frac{1}{3} i \bar{e}_R \gamma_\mu e_R. \quad (6)$$

Note that the overall normalization for the above nonstandard neutral weak current is given by, e.g., Durkin and Langacker⁹ and such normalization was used incorrectly (with a factor of 2 too large) by Barger *et al.*⁹

In the $2+2+1$ Higgs-boson scenario^{9,10} we denote the vacuum expectation values of the two Higgs-boson doublets and one Higgs-boson singlet as (v, v', x) , respectively. The Z^0 - Z'^0 mass matrix is of the form

$$\begin{pmatrix} A & C \\ C & B \end{pmatrix}, \quad (7a)$$

where we have

$$A \equiv \frac{1}{4} [g^2 + (g'/2)^2] (|v|^2 + |v'|^2), \quad (7b)$$

$$B \equiv \frac{1}{4} \frac{(g'')^2}{144} (16|v|^2 + |v'|^2 + 25|x|^2), \quad (7c)$$

$$C \equiv \frac{1}{4} \frac{g''}{6} \sqrt{g^2 + (g'/2)^2} (4|v|^2 - |v'|^2). \quad (7d)$$

Note that g , g' , and g'' are coupling constants, respectively, for the $\text{SU}(2)_L$ and the two $\text{U}(1)$'s. We may diagonalize the Z^0 - Z'^0 mass matrix by introducing

$$Z_\mu^0 \equiv \cos\phi Z_{\mu,0}^0 + \sin\phi Z_{\mu,0}', \quad (8a)$$

$$Z_\mu'^0 \equiv -\sin\phi Z_{\mu,0}^0 + \cos\phi Z_{\mu,0}'. \quad (8b)$$

We find,¹⁰ with M_Z and $M_{Z'}$ the (diagonalized) physical

masses for the two bosons:

$$\tan 2\phi = \frac{C}{A-B}, \quad (9a)$$

$$M_Z^2 + M_{Z'}^2 = A+B, \quad (9b)$$

$$(M_Z^2 - M_{Z'}^2)^2 = (A-B)^2 + C^2. \quad (9c)$$

The neutral-current interaction as given by Eq. (5) becomes

$$L_{\text{NC}} = A_\mu e J_\mu^{\text{em}} + \frac{e}{\sin\theta_W \cos\theta_W} Z_{\mu}^0 N_{\mu,\text{new}} + \frac{e}{\cos\theta_W} Z_{\mu}^{'0} N_{\mu,\text{new}}', \quad (10)$$

with

$$N_{\mu,\text{new}} = \cos\phi N_\mu + \sin\theta_W \sin\phi N_\mu', \quad (11a)$$

$$N_{\mu,\text{new}}' = \cos\phi N_\mu' - \frac{\sin\phi}{\sin\theta_W} N_\mu. \quad (11b)$$

It is clear that there are *only* two *new* parameters in the present theory: namely, $\sin\phi$ and $M_{Z'}$. Although there are other competitive models on the basis of simple Higgs-boson-mechanism considerations,¹⁰ we shall employ only the above $\text{SU}(2)_L \times \text{U}(1) \times \text{U}(1)$ electroweak model to illustrate the role played by the nonstandard gauge boson.

III. CHARGE ASYMMETRY IN DRELL-YAN PROCESSES

For the sake of simplicity we recast Eq. (3) or (10) as

$$L_{\text{NC}} = A_\mu e J_\mu^{\text{em}} + g_0 Z_\mu^0 N_\mu + g_0' Z_\mu^{'0} N_\mu', \quad (12)$$

where we note that N_μ and N_μ' stand for the “new” neutral currents as defined by Eqs. (11a) and (11b). We write, *explicitly* for muon-pair production in Drell-Yan processes,

$$N_\mu = \sum_i i \bar{Q}_i \gamma_\mu (h_V^i + h_A^i \gamma_5) Q_i + i \bar{\mu} \gamma_\mu (g_V + g_A \gamma_5) \mu + \dots, \quad (13a)$$

$$N_\mu' = \sum_i i \bar{Q}_i \gamma_\mu (h_V^{'i} + h_A^{'i} \gamma_5) Q_i + i \bar{\mu} \gamma_\mu (g_V' + g_A' \gamma_5) \mu + \dots. \quad (13b)$$

Here “...” stands for contributions from other leptons and Q_i runs over quarks of different flavors ($u, d, \dots$). It is a *trivial* task to obtain the various couplings h_V^i , h_A^i , etc., for both models described in the previous section. For example, $g_V = -\frac{1}{4} + \sin^2\theta_W$ and $g_A = -\frac{1}{4}$ in the standard GSW electroweak theory.

Setting aside for the moment the question related to QCD corrections, muon-pair production in Drell-Yan processes may proceed via the Feymann diagrams illustrated in Fig. 2, where the interference between diagrams are possible. The differential cross section for muon-pair production in proton-nucleon collisions is then given by

$$\begin{aligned}
\frac{d\sigma}{dM^2 d\Omega_\xi}(p+N \rightarrow \mu^+ + \mu^- + X) = & \int_0^1 dx_1 \int_0^1 dx_2 \delta(M^2 - x_1 x_2 S) |\xi|^2 \frac{1}{\sqrt{(x_1+x_2)^2 - (x_1-x_2)^2 \cos^2 \theta}} \frac{1}{6\pi^2 \sqrt{S} M} \\
& \times \left[\sum_i [f_{q_i/P}(x_1) f_{\bar{q}_i/N}(x_2) + f_{\bar{q}_i/P}(x_1) f_{q_i/N}(x_2)] \Lambda_+^i \right. \\
& \times \left[\frac{1}{4} x_1 x_2 S + M^2 x_1 x_2 \frac{\cos^2 \theta}{(x_1+x_2)^2 - (x_1-x_2)^2 \cos^2 \theta} \right] \\
& + \sum_i [f_{q_i/P}(x_1) f_{\bar{q}_i/N}(x_2) - f_{\bar{q}_i/P}(x_1) f_{q_i/N}(x_2)] \Lambda_-^i \\
& \left. \times x_1 x_2 \sqrt{S} M \cos \theta \frac{1}{\sqrt{(x_1+x_2)^2 - (x_1-x_2)^2 \cos^2 \theta}} \right], \quad (14)
\end{aligned}$$

where $\xi \equiv \frac{1}{2}(I^+ - I^-)$ and the structure functions such as $f_{q_i/P}(x)$ are understood in the ordinary sense (the probability of finding a quark q_i with longitudinal-momentum fraction x inside the proton p). Note that $\cos \theta$ is already defined earlier by Eq. (2). Note also that, in $p\bar{p}$ collisions, the variable x_1 will be reserved for partons in the proton (not the antiproton) so that the predicted charge asymmetry at low energies will again be positive.

We wish to remind the reader of the fact that, in the quark-antiquark c.m. frame, the cross section is propor-

tional to $R_{\mu\mu}(1 + \cos^2 \theta^*) + 2B_\mu \cos \theta^*$, a form already known in the case of $e^+ + e^- \rightarrow \mu^+ + \mu^-$. This means that the charge asymmetry evaluated at a specific angle $\theta = 60^\circ$ is already slightly larger than the integrated charge asymmetry. An optimized experiment carried out at an angle near 0° allows for investigation of an asymmetry which is about $\frac{8}{3}$ times of the integrated one. It is clearly of importance to consider such an optimized experiment in an effort to measure $\sin^2 \theta_W$.

The complete expressions for $\Lambda_\pm^i$ are given, for a quark of flavor i , by

$$\begin{aligned}
\Lambda_+^i \equiv & \left[\frac{e^2}{M^2} \right]^2 Q_{q_i}^2 + g_V^2 g_V h_V^i \frac{e^2 Q_{q_i} 2(M^2 - M_Z^2)}{M^2[(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]} + \frac{g_0^4 (g_V^2 + g_A^2)(h_V^{i2} + h_A^{i2})}{(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
& + g_V^2 g_V' h_V'^i \frac{e^2 Q_{q_i} 2(M^2 - M_Z^2)}{M^2[(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]} + \frac{g_0^4 (g_V'^2 + g_A'^2)(h_V'^{i2} + h_A'^{i2})}{(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
& + 2g_0^2 g_V'^2 (g_V g_V' + g_A g_A')(h_V^i h_V'^i + h_A^i h_A'^i) \frac{X}{X^2 + Y}, \quad (15a)
\end{aligned}$$

$$\begin{aligned}
\Lambda_-^i \equiv & g_V^2 g_A h_A^i \frac{e^2 Q_{q_i} 2(M^2 - M_Z^2)}{M^2[(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]} + \frac{4g_0^4 g_V g_A h_V^i h_A^i}{(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
& + g_V^2 g_A' h_A'^i \frac{e^2 Q_{q_i} 2(M^2 - M_Z^2)}{M^2[(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]} + \frac{4g_0^4 g_V' g_A' h_V'^i h_A'^i}{(M^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
& + 2g_0^2 g_V'^2 (g_V g_A' + g_A g_V')(h_V^i h_A'^i + h_A^i h_V'^i) \frac{X}{X^2 + Y}, \quad (15b)
\end{aligned}$$

with

$$X = (M_Z^2 - M^2)(M_Z^2 - M^2) + M_Z M_{Z'} \Gamma_Z \Gamma_{Z'}, \quad (15c)$$

$$Y = [(M_Z^2 - M^2)M_{Z'} \Gamma_{Z'} - (M_Z^2 - M^2)M_Z \Gamma_Z]^2. \quad (15d)$$

We use Eqs. (14), (15a), and (15b) to make predictions on charge asymmetry in different cases. Note that the sign switch for the charge-asymmetric effect under quark-antiquark interchange signifies differences among the pN , pp , $p\bar{p}$ collisions. This sign indicates that the quark and the antiquark cannot be both in the "sea," thus emphasizing the importance of the valence distributions. Setting the $M_{Z'}$ mass to a very large value or making all the "primed" couplings to zero, we can make predictions in the case of the standard $SU(2)_L \times U(1)$ electroweak model.

FIG. 2. Feynman diagrams for muon-pair production in hadron-hadron collisions.

In what follows we wish to describe sample results for (a) proton-nucleon collisions at $E_p=800$ GeV; (b) proton-nucleon collisions at a proton beam energy of a few TeV; and (c) behavior of charge asymmetry near the Z^0 pole in a $p\bar{p}$ and pp collider experiment.

A. Proton-nucleon Collisions at $E_p=800$ GeV

In Fig. 3(a) we plot the predicted charge asymmetry (in %) as a function of the dimuon invariant mass M (in GeV) for proton-nucleon collisions at a proton beam en-

FIG. 3. (a) The predicted charge asymmetry (in %) shown as a function of the dimuon invariant mass M (in GeV) for proton-nucleon collisions at a proton beam energy of 800 GeV (corresponding to the center-of-mass energy $\sqrt{s}=38.8$ GeV). (b) The predicted charge asymmetry (in %) as a function of the dimuon invariant mass m (in GeV), respectively, for pN , pp , and $p\bar{p}$ collisions at a proton beam energy of 800 GeV. (c) The predicted charge asymmetry (in %) as a function of x'_F for a dimuon invariant mass M of 12 GeV at a proton beam energy of 800 GeV.

ergy of 800 GeV (corresponding to the center-of-mass energy $\sqrt{s}=38.8$ GeV). Here we have used the Z^0 mass and width reported by the UA1 Collaboration:¹¹

$$M_Z = 93 \text{ GeV}, \quad \Gamma_Z = 3.4 \text{ GeV}. \quad (16)$$

Unless specified otherwise we choose to fix¹² the electroweak mixing parameter $\sin^2\theta_W$ to be 0.225 and will vary the Z^0 - Z'^0 mixing parameter $\sin\phi$ and the Z'^0 mass $M_{Z'}$. In Fig. 3(a) we choose $M_{Z'}=2$ TeV and $\sin\phi=0$, which *effectively* turns off effects of Z'^0 . Note that we use two different sets of parton distribution functions: (1) the first set proposed by Duke and Owens¹³ and (2) the one proposed by Eichten, Hinchliffe, Lane, and Quigg¹⁴ (EHLQ; set 1 as recorded in an erratum¹⁴ to the original paper). Although the predicted Drell-Yan cross sections based on these two distributions may differ from each other by as much as about 30%, the predicted charge asymmetries in the two cases are extremely close. For $x'_F=0.2$ with $x'_F \equiv (x_1-x_2)/(1-\tau)$ and $\tau \equiv M^2/S$, the difference revealed by Fig. 3(a) is negligible. For $x'_F=0.5$, the two predicted curves almost coincide so that we plot only the one for the Duke-Owens distribution. As a numerical example, with $x'_F=0.5$, $M_{\mu^+\mu^-}=12$ GeV, and the K factor set to unity, the Duke-Owens distributions yield 9.6×10^{-8} $\mu\text{b}/\text{GeV}$ for the cross section and +1.41% for the charge asymmetry while the EHLQ distributions yield 7.4×10^{-8} $\mu\text{b}/\text{GeV}$ and +1.40%, respectively.

It may be useful to note that the observed charge asymmetry in the Υ region should exhibit dips since the $^3S_1(b\bar{b})$ quarkonium states couples to photons [and so to $(\mu^+\mu^-)$ or $(q\bar{q})$] and such couplings produce charge-symmetric cross sections. We wish to return to this interesting aspect when we consider the behavior of charge asymmetry near the Z^0 pole.

In Fig. 3(b) we plot the predicted charge asymmetry (in %) as a function of the dimuon invariant mass M (in GeV), respectively, for pN , pp , and $p\bar{p}$ collisions at a proton beam energy of 800 GeV. At $x'_F=0.2$, the predictions in the three cases differ from one another. At $x'_F=0.5$, the predictions for pN and pp are very close to the $p\bar{p}$ prediction.

To exhibit the major difference among pN , pp , and $p\bar{p}$ collisions, we show in Fig. 3(c) the predicted charge asymmetry (in %) as a function of x'_F for a dimuon invariant mass M of 12 GeV at a proton beam energy of 800 GeV. In view of the sign switch in Eq. (14) under quark-antiquark interchange, the charge asymmetry in the pp case vanishes at $x'_F=0$. For the same reason, the charge asymmetry in the pN is relatively small in this region. However, the charge asymmetry in these two cases rises fairly rapidly to almost coincide with the prediction in the $p\bar{p}$ case, which is pretty much independent of x'_F .

Having learned from Figs. 3(a)–3(c) that the predicted charge asymmetries do not vary much with the input parton distribution functions and the dependence on the parameter x'_F follows a fixed pattern, we wish to use only the pN case with the Duke-Owens distributions at $x'_F=0.5$ as our primary example (unless specified otherwise).

In Fig. 4 the charge asymmetry as a function of $M_{\mu^+\mu^-}$ is shown for two additional values of $\sin^2\theta_W$. It is clear that a 10% change in this parameter produces a change of the same order of magnitude in the predicted charge asymmetry. To measure this important parameter in Drell-Yan processes, it is useful to keep in mind that a simultaneous measurement of the *slope* will add *independent* information concerning the Z^0 parameters. [See, e.g., Eqs. (14) and (15) and III C below.]

We have also considered the prospect of using a nuclear target in the proposed charge-asymmetry measurement. In this case the luminosity can be increased considerably but we need to examine whether the effect observed by the European Muon Collaboration (EMC), i.e., *modification* of nucleons in nuclear medium, could jeopardize the precision nature of the experiment. In Fig. 5 we plot the ratio of the charge asymmetry predicted with two sample EMC models, namely, rescaling¹⁵ and quark cluster,¹⁶ to the predicted charge asymmetry in the absence of the EMC effect. Note that we have amplified the scale in order to display effects of less than a percent. The ratio at $x'_F \sim 0.5$ is extremely close to unity for the rescaling model since at this value of x'_F the contribution near $x_2 \sim 0.2$ dominates (where the rescaling effect is negligible). As another example for the rescaling model we note that the deviation of the ratio from unity is about +0.3% for $x'_F=0.2$ and $M_{\mu^+\mu^-}=10$ GeV. In any event, it is clear that the issue related to the EMC effect is negligible here.

To extract the electroweak mixing parameter from charge-asymmetry measurements in $pN \rightarrow \mu^+\mu^- X$, we need to consider whether there is a substantial QCD correction to the simple formulas, Eqs. (14) and

FIG. 4. The charge asymmetry at 800 GeV shown as a function of $M_{\mu^+\mu^-}$ for several values of $\sin^2\theta_W$.

FIG. 5. The ratio of the charge asymmetry predicted with two sample EMC models, namely, rescaling (Ref. 15) and quark cluster (Ref. 16), to the predicted charge asymmetry in the absence of the EMC effect. Note that we have amplified the scale in order to display rather small effects.

(15a)–(15d). QCD corrections to Drell-Yan and Z^0 -production mechanism, Fig. 2, have been investigated by Altarelli *et al.*⁶ for integrated cross sections. Although QCD corrections to individual diagrams are of numerical importance, the ratio of the integrated cross sections for Drell-Yan and Z^0 -production processes turns out to be insensitive to large QCD corrections. (For integrated cross sections, QCD corrections account for the observed deviation of the K factor from unity. Experimentally, the K factor is seen to be fairly insensitive to the value of $M_{\mu^+\mu^-}$ or of x'_F .) Of course, there are problems associated with the formalism of Altarelli *et al.* (as discussed in the work of Hwang and Kisslinger⁶). In addition, QCD corrections to differential cross sections, including both charge-symmetric and charge-asymmetric ones, may exhibit some unexpected kinematic dependence. Accordingly we feel that QCD corrections to the present charge-asymmetry calculation need to be investigated further, although it does not seem likely that the problem of QCD corrections would prevent extraction of the electroweak mixing parameter from the proposed charge-asymmetry measurements in $pN \rightarrow \mu^+\mu^-X$. We should also mention that, from an experimental point of view, it will always be useful to measure charge asymmetry in $pN \rightarrow \mu^+\mu^-X$ if such measurement can be made with great precision. (See below.) If the extracted value of $\sin^2\theta_W$ agrees well with the value obtained by other means, it suggests that perturbative QCD corrections cancel out, as in the work of Altarelli *et al.*⁶ Should a substantial disagreement exist between the data and the

prediction presented here, it would signify the importance of perturbative QCD corrections in charge asymmetry, which after all can be and will be scrutinized thoroughly (even though it is a very complicated subject). In the following we take the result of Altarelli *et al.*² and assume that QCD corrections can be summarized into an overall K factor (and so drop out in a ratio of cross sections, such as charge asymmetry).

To proceed further, we should mention that, with the K factor set to unity, the *calculated* Drell-Yan cross section is $9.6 \times 10^{-8} \mu\text{b}/\text{GeV}$ for an 800-GeV beam at $M_{\mu^+\mu^-} = 12 \text{ GeV}$ and becomes $8.8 \times 10^{-9} \mu\text{b}/\text{GeV}$ for a 400-GeV beam at $M_{\mu^+\mu^-} = 12 \text{ GeV}$, an order of magnitude smaller although the predicted charge asymmetry is about the same. Rutherford *et al.*³ has made extensive feasibility studies in a possible charge-symmetry measurement in $pN \rightarrow \mu^+\mu^-X$ at $E_p = 400 \text{ GeV}$. They assume for simplicity that the high-precision asymmetry data below $M_{\mu^+\mu^-} = 8 \text{ GeV}$ will be used for studies of systematic effects and to extract higher-order em asymmetries [Figs. 1(b) and 1(c)]. Then the data above $M_{\mu^+\mu^-} = 8 \text{ GeV}$ can be used to determine the weak-coupling constant. For an integrated proton flux of 6×10^{17} protons (corresponding to a running time of about 100 days at Fermilab), they have obtained a conservative estimate for the statistical precision of the measured asymmetry:

$$\frac{\delta \mathcal{A}}{\mathcal{A}} = 0.087. \quad (17)$$

Now, the statistics at $E_p = 800 \text{ GeV}$ is better than that at $E_p = 400 \text{ GeV}$ by more than an order of magnitude (due to the enhancement of Drell-Yan cross sections at large $M_{\mu^+\mu^-}$), pushing the expected statistical precision to the level of ~ 0.02 . Accordingly, Fig. 4 suggests that a measurement at $E_p = 800 \text{ GeV}$, performed in a way as suggested by Rutherford *et al.*,³ yields a statistical precision of about 4% on the measured electroweak parameter $\sin^2\theta_W$. The accuracy is clearly better than that which has been achieved in charge-asymmetry measurements¹ in $e^+e^- \rightarrow \mu^+\mu^-$ (and which is 10–15%) if the proposed experiment of Rutherford *et al.* can be carried out at $E_p = 800 \text{ GeV}$.

The present discussion indicates that another experiment using a beam of energy 2 TeV or higher will improve the statistics by *at least an order of magnitude*, provided that the beam intensity remains and the apparatus works equally well. Numerically, we find that, with the K factor set to unity, the *calculated* Drell-Yan cross section is $5.5 \times 10^{-9} \mu\text{b}/\text{GeV}$ for an 800-GeV beam at $M_{\mu^+\mu^-} = 16 \text{ GeV}$ and becomes $7.8 \times 10^{-8} \mu\text{b}/\text{GeV}$ for a 2-TeV beam at $M_{\mu^+\mu^-} = 16 \text{ GeV}$, an order of magnitude larger although the predicted charge asymmetry in both cases is about 2.5%. Furthermore, as the beam energy increases, the number of high-mass lepton pairs, with an increasing charge asymmetry, is considerably enhanced so that it is possible to perform a better measurement of $\sin^2\theta_W$ (provided of course that we do not lose in luminosity).

Once a precision measurement of $\sin^2\theta_W$ is at hand, it

may be possible to detect manifestations of the nonstandard gauge boson. It is clear that, to this end, we will have to consider the kinematic region where the dimuon invariant mass M is not too far below the Z^0 mass. In a fixed-target experiment, this will not be easy since it is important to make $\sqrt{S}$ large enough to make the predicted Drell-Yan cross section significant while maintaining the desired luminosity. We consider this possibility briefly in Sec. III B. In a collider experiment we gain a lot on the maximal $\sqrt{S}$ available to us but the luminosity in general poses a serious problem. In Sec. III C we consider briefly this interesting possibility.

B. Proton-nucleon collisions at a proton beam energy of a few TeV

We wish to consider briefly the prospect of carrying out a fixed-target experiment using a proton beam of a few TeV in energy, although there is not any major accelerator facility that delivers such a beam at present.

In Fig. 6 the predicted asymmetry in proton-nucleon collisions at a proton beam energy of 2 TeV is plotted as a function of the dimuon invariant mass $M_{\mu^+\mu^-}$. We note that, with the K factor set to unity, the *calculated* Drell-Yan cross section is $3.5 \times 10^{-6} \mu\text{b/GeV}$ at $M_{\mu^+\mu^-} = 8 \text{ GeV}$ and becomes $4.1 \times 10^{-11} \mu\text{b/GeV}$ at $M_{\mu^+\mu^-} = 32 \text{ GeV}$, the latter completely negligible for practical purpose. It is clear that the cross section for high-mass lepton pairs (e.g., $M_{\mu^+\mu^-} \geq 16 \text{ GeV}$) is significant, allowing for a precision measurement of

$\sin^2\theta_w$ at this energy. In this figure the solid curve is obtained with $\sin\phi=0$ and $M_{Z'}=2 \text{ TeV}$, the dashed curve with $\sin\phi=0$ and $M_{Z'}=200 \text{ GeV}$, and the dash-dot curve with $\sin\phi=-0.10$ and $M_{Z'}=200 \text{ GeV}$, the first one being used as an approximation for complete absence of the Z'^0 boson. In all cases we use $\Gamma_{Z'}=\Gamma_Z$ for simplicity. Unfortunately, predictions in the three cases presented do not differ very much from one another. In fact, the sensitivity to Z'^0 mass can hardly be noticed (for $M_{Z'}$ greater than 200 GeV). The hope to pin down the Z'^0 - Z^0 mixing parameter $\sin\phi$ is also slim.

To examine whether the situation improves with the beam energy, we give a similar plot in Fig. 7 for a proton beam energy of 10 TeV. Again, we note that, with the K factor set to unity, the *calculated* Drell-Yan cross section is $1.5 \times 10^{-6} \mu\text{b/GeV}$ at $M_{\mu^+\mu^-} = 12 \text{ GeV}$ and becomes $4.9 \times 10^{-10} \mu\text{b/GeV}$ at $M_{\mu^+\mu^-} = 48 \text{ GeV}$, the latter already negligible for practical purpose. Here we see again that the presence of the nonstandard gauge boson does not give rise to significant effects. It is clear that, although the nonstandard gauge boson *does* contribute to the charge asymmetry, the accuracy required to detect its presence by such measurement makes the proposed experiment extremely difficult, if not impossible. For this reason we turn our attention to investigate the behavior of the charge asymmetry near the Z^0 pole, where we shall see that the charge asymmetry is of order of unity and crosses zero near the pole position. If the luminosity is high enough in a collider experiment, this may turn out to be an ideal way to look for some manifestation of the nonstandard gauge boson.

FIG. 6. The predicted asymmetry in proton-nucleon collisions at a proton beam energy of 2 TeV is plotted as a function of the dimuon invariant mass $M_{\mu^+\mu^-}$.

FIG. 7. The predicted asymmetry in proton-nucleon collisions at a proton beam energy of 10 TeV is plotted as a function of the dimuon invariant mass $M_{\mu^+\mu^-}$.

C. Behavior of charge asymmetry near the Z^0 pole

We wish to describe some numerical results which indicate that a $p\bar{p}$ or pp collider experiment with the center-of-mass energy $\sqrt{s}$ in the range of a few TeV is a better place to examine the interesting behavior of the charge asymmetry near Z^0 pole. A possible direct search

for the nonstandard gauge boson will also be discussed.

Using pp collisions as our illustrative example, we note that, with $M_{Z'}=200$ GeV, $\sin\phi=-0.10$, $M_{\mu^+\mu^-}=93$ GeV (i.e., on the Z^0 pole), and the K factor set to unity, the calculated Drell-Yan cross sections is 1.2×10^{-9} $\mu\text{b}/\text{GeV}$ (with Z^0 and Z'^0 neglected) or 3.1×10^{-7} $\mu\text{b}/\text{GeV}$ (with Z bosons included) at $x_F=0.5$ and

FIG. 8. The predicted asymmetry in proton-antiproton and proton-proton collisions at a center-of-mass energy of 600 GeV is plotted as a function of the dimuon invariant mass $M_{\mu^+\mu^-}$ near the Z^0 pole.

FIG. 9. The predicted asymmetry in proton-antiproton and proton-proton collisions at a center-of-mass energy of 2 TeV is plotted as a function of the dimuon invariant mass $M_{\mu^+\mu^-}$ near the Z^0 pole.

$\sqrt{S}=600$ GeV and it becomes $2.2 \times 10^{-8} \mu\text{b}/\text{GeV}$ (with Z bosons neglected) or $7.9 \times 10^{-6} \mu\text{b}/\text{GeV}$ (with Z boson included) at $x'_F=0.2$ and $\sqrt{S}=2$ TeV. Thus, the Z^0 -production cross section at $\sqrt{S}=2$ TeV is higher than that at $\sqrt{S}=600$ GeV by about an order of magnitude. Further, the dimuon production cross section near the Z^0 pole is enhanced by at least 2 orders of magnitude compared to the continuum background (i.e., if the Z^0 were not there), making a charge-asymmetry measurement a real possibility.

In Figs. 8(a) and 8(b) we display the behavior of the charge asymmetry near the Z^0 pole by focusing the energy range ± 10 GeV around the pole position, which is assumed to be 93 GeV, respectively, for $p\bar{p}$ and pp collisions at $\sqrt{S}=600$ GeV. The dash-dot curve represents the results for $\sin\phi=-0.10$ and $M_{Z'}=200$ GeV while the dashed curve is that for $\sin\phi=0$ and $M_{Z'}=200$ GeV. In Figs. 9(a) and 9(b), we plot analogous results at $\sqrt{S}=2$ TeV. The results for $\sin\phi=0$ and $M_{Z'}=2$ TeV are very close to those for $\sin\phi=0$ and $M_{Z'}=200$ GeV, indicating the insensitivity of the predicted charge asymmetry near the Z^0 pole to the Z^0 mass. Figures 8 and 9 indicate that the charge asymmetry is of order of unity and crosses zero near the pole position. An inspection of the basic formulas [Eqs. (14) and (15)] indicates *both that* the sizable symmetry at the pole position is dominated by the second term in Eq. (15b) and thus provides a measurement of the quantity $g_{0g}^4 g_A h_V h_A / (M_{Z'}^2 \Gamma_{Z'}^2)$ and *that*, at a given x'_F , the *slope or the position of zero crossing* varies with the Z^0 - Z'^0 mixing parameter $\sin\phi$. This provides a means of measuring $\sin\phi$ if charge asymmetry in this region can be pinned down to an accuracy of a couple of percent.

FIG. 10. The Z^0 production cross section near the *assumed* Z^0 pole for both $p\bar{p}$ and pp collisions at $\sqrt{S}=2$ TeV. $\Gamma_{Z'}=\Gamma_Z=3.4$ GeV is used for the sake of illustration.

There is an interesting possibility that the positions of the yet-to-be-observed vectorlike ($t\bar{t}$) quarkonium states may in fact be close to the Z^0 pole. As indicated earlier, such states couple indirectly to $\mu^+\mu^-$ and $q\bar{q}$ and such couplings produce charge-symmetric cross sections. The

FIG. 11. The predicted charge asymmetry near the Z'^0 pole, which is assumed to be 200 GeV, respectively, for $p\bar{p}$ and pp collisions at $\sqrt{S}=2$ TeV. The dash-dot curve represents the result for $\sin\phi=-0.10$ and $M_{Z'}=200$ GeV while the dashed curve is that for $\sin\phi=0$ and $M_{Z'}=200$ GeV.

behavior of the charge asymmetry near a resonance can be used to distinguish between a neutral gauge boson and a vectorlike quarkonium state, since it is a *direct* measure of how the vectorlike resonance couples to quarks and leptons.

To close this section it may be useful to present a couple of results near the assumed Z'^0 pole. Of course, there is not any experimental indication that the Z'^0 boson exists. For the sake of illustration we take Z'^0 mass to be 200 GeV which is not inconsistent with the current experimental low bounds.⁹ In fact, absence of an additional gauge boson not too far away from the standard one will spell serious trouble for the superstring idea.⁷ On the other hand, if such a speculative object is indeed found, it will be of immediate importance to use the observed charge asymmetry to establish a link with the one suggested by superstring models.⁷

In Fig. 10 we show the Z'^0 production cross section near the *assumed* Z'^0 pole for both $p\bar{p}$ and pp collisions at $\sqrt{S}=2$ TeV, using $\Gamma_{Z'}=\Gamma_Z$ for the sake of illustration. Our investigation indicates that the magnitude of the predicted cross section, which is of order 10^{-7} $\mu\text{b}/\text{GeV}$ at $x_F \sim 0.2$, is somewhat larger at $x_F \sim 0$ and falls off rapidly beyond $x_F \sim 0.4$. As a numerical example, it is found that, with $x_F=0$, $M_{\mu^+\mu^-}=M_{Z'}=200$ GeV, $\sin\phi=0$, and the K factor set to unity, the predicted $\mu^+\mu^-$ production cross section in $p\bar{p}$ collisions is 6.0×10^{-7} $\mu\text{b}/\text{GeV}$ with Z'^0 *included* and 1.8×10^{-9} $\mu\text{b}/\text{GeV}$ with Z'^0 *excluded*. Further, a reduction of the predicted cross section by 2 orders of magnitude is need if, instead of 200 GeV, we have adopted 700 GeV for the Z'^0 mass (and for $M_{\mu^+\mu^-}$). Combining the predicted cross section with the luminosity (about $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$) expected at the Fermilab Tevatron $p\bar{p}$ collider, we find that there will be only a couple of Z'^0 produced in a month of running time, should the Z'^0 mass is about 200 GeV. The situation becomes almost hopeless, should the Z'^0 mass be greater than 300 GeV (which, according to the work of Marciano and Sirlin,¹⁷ may indeed be the case).

In Figs. 11(a) and 11(b) we plot the behavior of the charge asymmetry near the Z'^0 pole by focusing the energy range ± 10 GeV around the pole position, which is assumed to be 200 GeV, respectively, for $p\bar{p}$ and pp collisions at $\sqrt{S}=2$ TeV. The dash-dot curve represents the results for $\sin\phi=-0.10$ while the dashed curve is that for $\sin\phi=0$. Because of the specific nature of the assumed Z'^0 boson in the $2+2+1$ Higgs-boson scenario,^{9,10} the predicted charge asymmetry near the assumed Z'^0 pole is very sensitive to the value of $\sin\phi$. Comparison between Figs. 10 and 11 indicates that, granting the validity of the $2+2+1$ Higgs-boson scenario, the Z^0 - Z'^0 mixing parameter $\sin\phi$ will be much better determined in a charge-asymmetry measurement. However, it is of importance to emphasize that the ob-

served charge asymmetry near the pole position can vary from the ones indicated by Figs. 8 and 9 to the present ones, or to even a flat line, all depending how the Z'^0 boson couples to quarks and leptons. Thus, if the Z'^0 boson is indeed discovered through detection of lepton pairs, it will be imperative to use the geometry of these events to sort out the charge asymmetry, thereby providing critical information about the nature of the object. This is an important point since a resonance behavior such as displayed by Fig. 10 may arise for a *new* $^3S_1$ toponium state or other vector particles (which will be a remarkable discovery by itself). In other words, it takes more than just discovering a resonance to demonstrate existence of an interaction of a *new* type, which the conjectured non-standard gauge boson Z'^0 is all about.

IV. SUMMARY

In this paper we have studied the charge asymmetry expected for lepton-pair production in pN , $p\bar{p}$, and pp collisions at different center-of-mass energies, using the standard Glashow-Salam-Weinberg $\text{SU}(2)_L \times \text{U}(1)$ electroweak theory and an extended $\text{SU}(2)_L \times \text{U}(1) \times \text{U}(1)$ electroweak model. Both models were briefly outlined in Sec. II. For a proton beam energy of 800 GeV, we have considered in Sec. III A the prospect of measuring charge asymmetry as a means to pin down $\sin^2\theta_W$. We have also considered in Secs. III B and III C the possibility of detecting manifestations of the nonstandard gauge boson in both fixed-target and collider experiments. Specifically, we have considered in Sec. III C the behavior of charge asymmetry near the Z^0 pole which may allow for a measurement of the Z^0 - Z'^0 mixing parameter $\sin\phi$. A possible direct search for the nonstandard gauge boson Z'^0 has also been discussed.

Notes added. After completing this paper we learned of a related paper¹⁸ by Rosner, who has examined off-peak lepton asymmetries from new Z bosons, and another paper by Ash *et al.*,¹⁹ who measured charge asymmetry in hadron jets from e^+e^- annihilation at $\sqrt{S}=29$ GeV. Additional references may be found in Rizzo,²⁰ who examines mixing effects on Z -boson properties, and in Capstick and Godfrey,²¹ who considered comparison of discovery limits for E_6 neutral gauge boson at future colliders.

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