Tests of the left-right-symmetric model in $p\bar{p} \rightarrow l\bar{l}+X$

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(Received 6 July 1982)

We compare the predictions of the standard model and a recently proposed left-right-symmetric model for dilepton production in $p\bar{p}$ collisions. In particular we compare the predictions of the two models for the forward-backward asymmetry $A_{\rm FB}$ and the average helicity H_A of the outgoing l^-. Although there is some uncertainty due to lack of knowledge of the parton distributions in these predictions, the two models are clearly distinguishable for $\sqrt{s}=540$ GeV.

With the start up of the $p\bar{p}$ collider at CERN it may soon be possible to have direct tests of the nature of the weak interactions through, for example, production of the intermediate vector bosons with masses $\simeq 100$ GeV. The existence of such bosons is a necessary feature of any gauge model of the electroweak interactions and so finding them is a necessary task for present (and future) experiments.

In addition to the production of gauge bosons, the $p\bar{p}$ channel allows for other tests which can be performed to distinguish between the so-called standard model of Glashow, Weinberg, and Salam[1] (GWS) and any competing extended electroweak models[2] based on gauge groups larger than $SU(2)_L \times U(1)$. This is an important feature of $p\bar{p}$ since examining the detailed properties of any gauge bosons such as branching ratios and widths may prove difficult in any hadron-hadron collider with sufficiently low luminosity and large backgrounds. This differs from the case of e^+e^- machines where gauge-bosons signals are much cleaner and backgrounds are more easily controlled.

The Drell-Yan process[3] $p\bar{p} \rightarrow l^+l^-+X$, where l is any charged lepton ($l=e,\mu,\tau,\ldots$) allows, apart from direct production of neutral gauge bosons, comparisons between various extended models by examining the angular distribution and helicity of the outgoing lepton. These data then either rule out extended models (or the standard model) or, at least, greatly limit those extended models which are indeed relevant. In this paper we wish to compare the predictions of the standard GWS model with those of the left-right-symmetry (LRS) model[4] which is consistent with SO(10) grand unification.[5] It should be noted that the work of Mani and Rindoni and of Girardi *et al.* is on completely different left-right-symmetric models than the one considered here.

Recently Beall, Bander, and Soni[6] have considered how a low right-handed mass scale M_R within SO(10) modifies the prediction of the K_L-K_S mass difference; if their analysis is correct, then the second Z boson of the LRS model would be quite heavy ($\gtrsim 1.6$ TeV or so) and so unobservable at CERN or ISABELLE and probably at the Tevatron. However, analyses such as these involve many unknowns (t-quark mass, mixing angles, hadronic matrix elements, corrections from QCD, and long-distance effects) and should be taken with some caution. So, for the present, we will take the philosophy that low M_R is possible within SO(10) but continue to be aware that the K_L-K_S problem may indeed be present for this model.

Unlike the predictions in e^+e^-, theoretical predictions in hadron-hadron collisions are hampered by the lack of detailed information on structure functions[7] and large QCD corrections. Since by looking at helicities and forward-backward asymmetries we are essentially examining ratios of cross sections we hope most of these uncertainties will cancel out. In the structure-function case, we can actually try several different distributions and examine the sensitivity of our results to these unknowns. We will see that the conclusions found here are quite insensitive to the detailed nature of the structure functions used since they are qualitative and/or semiquantitative in nature; a change in the structure functions does not substantially modify the results found here although some changes in detail are expected and are indeed observed. Let us now examine $p\bar{p} \rightarrow l\bar{l}+X$ in an arbitrary extended model.

The subprocess differential cross section for $q\bar{q} \rightarrow l\bar{l}$ can be written as (in the $q\bar{q}$ center-of-mass frame)

$$\frac{d\sigma(q\bar{q})}{dz^*}=NQ_q{}^2[A_q(1+z^{*2})+2B_qz^*]\ ,$$

where N is a normalization factor, Q_q is the charge of the quark q in units of e, and $z^* \equiv \cos\theta^*$ is the $q\bar{q}$ center-of-mass scattering angle. For an arbitrary extended model, A_q and B_q are defined via

$$A_q \equiv 1 + \sum_i \frac{v_{l_i} v_{q_i}}{-Q_q}\left[\frac{s}{s-M_{Z_i}{}^2}\right] + \sum_{i,j} \frac{(v_{l_i}v_{l_j} + a_{l_i}a_{l_j})(v_{q_i}v_{q_j} + a_{q_i}a_{q_j})}{Q_q{}^2}\left[\frac{s}{s-M_{z_i}{}^2}\right]\left[\frac{s}{s-M_{z_j}{}^2}\right],$$

$$B_q \equiv 2\sum_i \frac{a_{l_i}a_{q_i}}{-Q_q}\left[\frac{s}{s-M_{z_i}{}^2}\right] + \sum_{i,j}\frac{(v_{l_i}a_{l_j} + v_{l_j}a_{l_i})(v_{q_i}a_{q_j} + v_{q_j}a_{q_i})}{Q_q{}^2}\left[\frac{s}{s-M_{z_i}{}^2}\right]\left[\frac{s}{s-M_{z_j}{}^2}\right].$$

Here v_{li} and a_{li} (v_{qi} and a_{qi}) represent the vector and axial-vector couplings of the lepton (quark) to the ith Z^0 boson in units of the center-of-mass energy of the $q\bar{q}$ subprocess, i.e., $\tau = \hat{s}/s$.

To obtain the differential cross section for $p\bar{p} \to l\bar{l} + X$ we merely fold in the appropriate parton distribution functions and multiply by the appropriate kinematic factors; we then merely sum over the various partons inside the proton (anti proton):

$$\frac{d\sigma(p\bar{p})}{dM^2 dz^* dx_F} \sim \sum_q \frac{x_a x_b}{(x_F{}^2 + 4\tau)^{1/2}}[f_q^p(x_a)f_{\bar{q}}^{\bar{p}}(x_b) + f_{\bar{q}}^p(x_a)f_q^{\bar{p}}(x_b)]\frac{d\sigma(q\bar{q})}{dz^*},$$

where M^2 is the invariant mass squared of the $l\bar{l}$ system and

$$x_{a,b} = \tfrac{1}{2}[(x_F{}^2 + 4\tau)^{1/2} \pm x_F]$$

with x_F being the standard Feynman variable

$$-1 + \tau \le x_F \le 1 - \tau .$$

To obtain the laboratory differential cross section we must convert from the $q\bar{q}$ scattering angle θ^* to the $p\bar{p}$ center-of-mass scattering angle θ; these are related through ($z = \cos\theta$)

$$z^* = \frac{(x_a - x_b) - (x_a + x_b)z}{(x_a - x_b)z - (x_a + x_b)}$$

so that

$$\frac{d\sigma}{dz^*} = \frac{d\sigma}{dz}\frac{dz}{dz^*} = \frac{d\sigma}{dz}\cdot\frac{1}{4\tau}[(x_a + x_b) - (x_a - x_b)z]^2 .$$

If we make this change of variable and integrate over x_F we find (for fixed $\sqrt{s}$) the double differential cross section $d\sigma(p\bar{p})/d\tau\, dz$.

The forward-backward asymmetry $A_{\rm FB}$ is now defined as

$$A_{\rm FB} = \frac{\int_0^1 dz \frac{d\sigma(p\bar{p})}{d\tau\, dz} - \int_{-1}^0 dz \frac{d\sigma(p\bar{p})}{d\tau\, dz}}{\int_{-1}^1 dz \frac{d\sigma(p\bar{p})}{d\tau\, dz}}$$

and is a function of τ (or $\sqrt{\tau}$)

In analogy with $e^+e^- \to \mu^+\mu^-$ we can also examine the helicity of the outgoing lepton assuming that the initial p and $\bar{p}$ beams are unpolarized (i.e., as far as the $q\bar{q} \to l\bar{l}$ subprocess is concerned the q and $\bar{q}$ are unpolarized). In the $q\bar{q}$ center-of-mass frame the helicity of the outgoing lepton is given by (as a function of $\cos\theta^*$ and for a given flavor of quark q)

$$H(\cos\theta^*) = \frac{-2[\Sigma_1^q(1 + \cos^2\theta^*) + 2\Sigma_2^q \cos\theta^*]}{A_q(1 + \cos^2\theta^*) + 2B_q \cos\theta^*}$$

To calculate $H(\cos\theta)$ for the $p\bar{p}$ interaction we must multiply both numerator and denominator by the quark distribution functions and appropriate kinematic factors; we then must sum each over quark flavors and integrate each over x_F. (As in the case of $A_{\rm FB}$, we must also convert from the $q\bar{q}$ scattering angle $\cos\theta^*$ to the laboratory angle $\cos\theta$.)

Σ_1^q and Σ_2^q are given by (in any extended model)

$$\Sigma_1^q = \sum_i \frac{v_{q_i}a_{l_i}}{-Q_q}\left[\frac{s}{s-M_{Z_i}{}^2}\right] + \sum_{i,j}\frac{(v_l a_l)_i (v_q{}^2 + a_q{}^2)_j}{Q_q{}^2}\left[\frac{s}{s-M_{z_i}{}^2}\right]\left[\frac{s}{s-M_{z_j}{}^2}\right],$$

$$\Sigma_2^q = \sum_i \frac{v_{l_i}a_{q_i}}{-Q_q}\left[\frac{s}{s-M_{z_i}{}^2}\right] + \sum_{i,j}\frac{(v_q a_q)_i (v_l{}^2 + a_l{}^2)_j}{Q_q{}^2}\left[\frac{s}{s-M_{z_i}{}^2}\right]\left[\frac{s}{s-M_{z_j}{}^2}\right].$$

Below we will consider the angular-averaged helicity H_A in comparing the two models; to obtain this we merely integrate separately the numerator and denominator of the expression for $H(\cos\theta)$ over the angular variables. We thus obtain, as in the case of $A_{\rm FB}$, H_A simply as a function of τ. To proceed with the calculation one now only needs the quark and antiquark distribution functions of the proton and antiproton and the couplings and masses of the Z bosons of the models under study. Our couplings are normalized such that in the GWS model we have, for any fermion f,

$$v_f = \tfrac{1}{2}(T_3^f - 2x_W Q_f)[x_W(1-x_W)]^{-1/2} ,$$

$$a_f = \tfrac{1}{2}T_3^f[x_W(1-x_W)]^{-1/2}$$

with $x_W = \sin^2\theta_W \simeq 0.225$ and Q_f (T_3^f) being the charge third component of the weak isospin of the fermion f.

In the LRS model[4,5] these couplings are given by

$$v_{f_1} = \tfrac{1}{2}(T_3^f - 2x_W Q_f)(c+ds)[x_W(1-x_W)]^{-1/2}$$

$$a_{f_1} = \tfrac{1}{2}T_3^f(c-s/d)[x_W(1-x_W)]^{-1/2} ;$$

$$d \equiv (1-2x_W)^{-1/2}$$

for v_{f_2} and a_{f_2} we let $c \to -s$ and $s \to c$ where s $(\equiv \sin\phi)$ and c $(\equiv \cos\phi)$ represent mixings in the Z-boson mass matrix. (Note that as $M_{Z_2} \to \infty$, $\cos\phi \to 1$ and we recover the standard GWS model.) In the LRS model, consistent with SO(10) grand unified theory with low M_R,[5] we have $x_W \simeq 0.27$; this is the value we will use below together with $\phi \simeq 9.33 \times 10^{-2}$ as found from our previous analysis. A detailed presentation of this model has been given elsewhere; we merely note that the masses of the two neutral gauge bosons are[5]

$$M_{Z_1} = 81.3 \text{ GeV} , \quad M_{Z_2} = 241.2 \text{ GeV} .$$

We now turn to the results of our calculation which are presented in Figs. 1—4. Figure 1 shows the prediction for A_{FB} in the standard model for $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV. The shaded area gives the representative size of the uncertainty due to lack of detailed knowledge of the parton distribution function of the proton; this area is probably somewhat larger than that estimated here.

The behavior of the curve of A_{FB} is very similar to that found in the reaction $e^+e^- \to \mu^+\mu^-$ (Ref. 8); this is not wholly unexpected since the underlying subprocess $q\bar{q} \to l\bar{l}$ is so similar to that of the $e^+e^- \to \mu^+\mu^-$ channel except for the value of the coupling constants. We see that on either side of the Z^0 mass $(\sqrt{\tau} \simeq 0.17)$, A_{FB} is going through a rather rapid change in sign essentially resulting from a change in sign of the Z^0 propagator $(s - M_Z{}^2)^{-1}$. Note A_{FB} peaks just before and after the Z^0 at roughly $|A_{FB}| \simeq 0.6$; it should also be noted that when $\sqrt{\tau} = M_Z/\sqrt{s}$ the uncertainty in A_{FB} due to our poor knowledge of the structure functions vanishes. This is due to the fact that we are here producing a Z^0 resonance with a given cross section (which *does* depend on the structure function); the

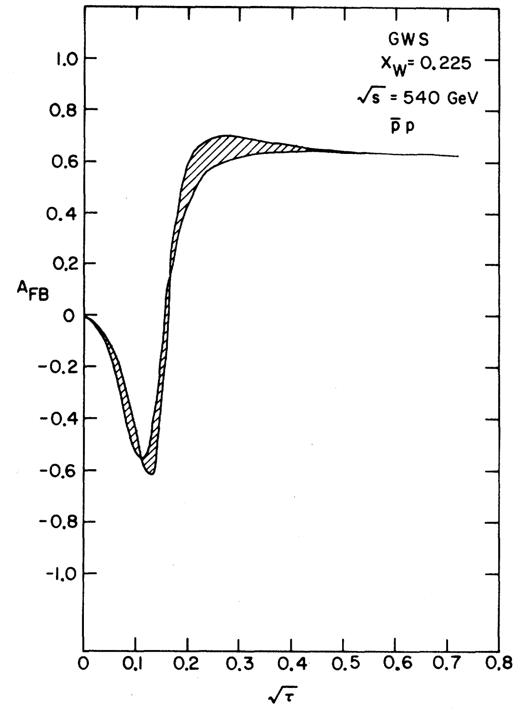

FIG. 1. The forward-backward asymmetry A_{FB} in the standard model for $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV as a function of $\sqrt{z}$.

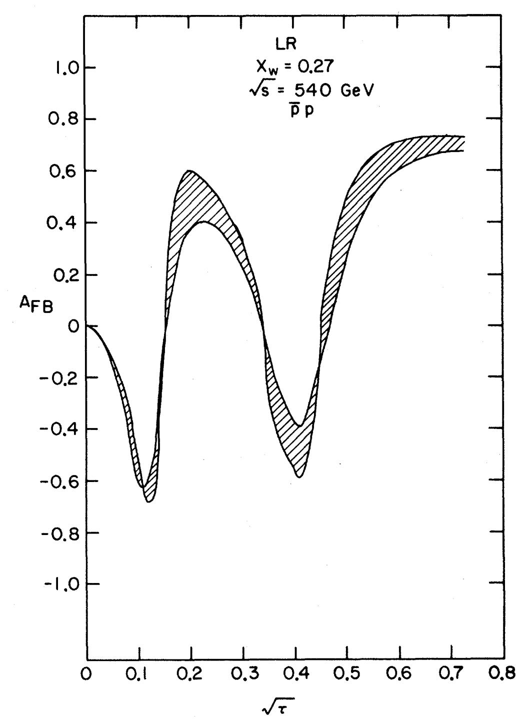

FIG. 2. Same as Fig. 1 but for the left-right-symmetric model.

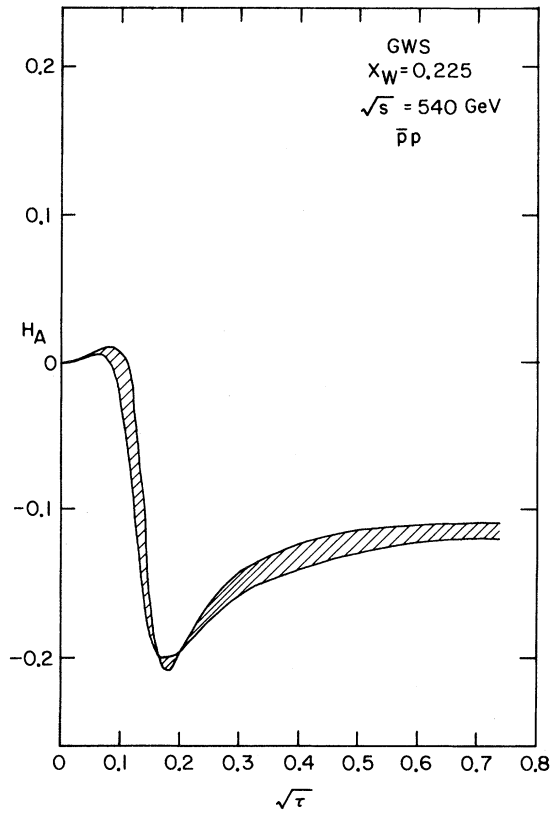

FIG. 3. The angular-averaged helicity of the outgoing lepton H_A, in the standard model for $\bar{p}p$ collisions at $\sqrt{s}=540$ GeV as a function of $\sqrt{\tau}$.

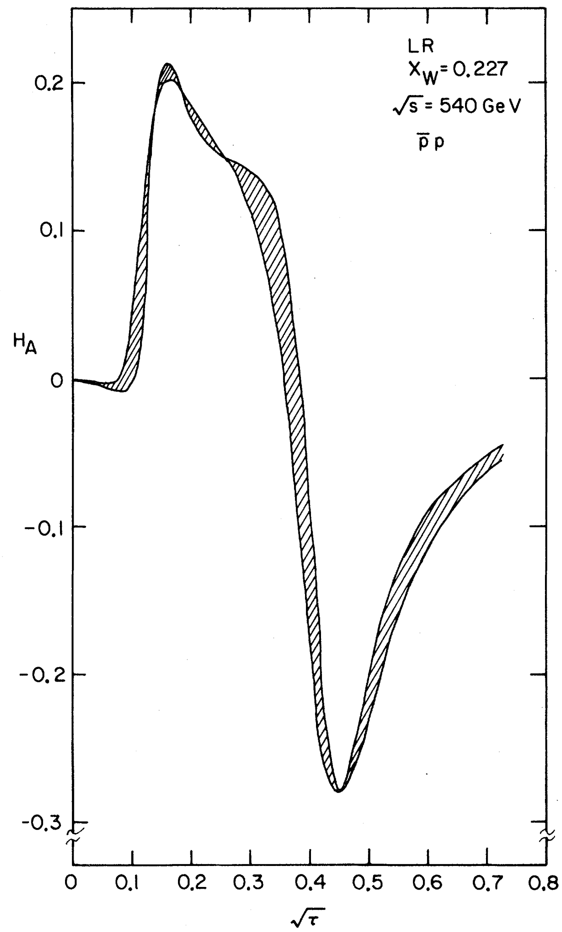

FIG. 4. Same as Fig. 3 but for the left-right-symmetric model.

Z^0 resonance then decays into a lepton pair resulting in an asymmetry. Obviously the asymmetry is then structure-function independent since it results from the Z^0 decay itself and is production-mechanism independent.

Figure 2 shows the prediction for $A_{\rm FB}$ in the LRS model with the parameters given above; the curve here also behaves quite similarily to that found for $e^+e^-\to\mu^+\mu^-$. Contrary to the standard-model case, we see that the curve goes through several extrema, two with each Z^0 boson. Owing to the uncertainty in the structure function for $\sqrt{\tau}\lesssim 0.2$ one cannot easily distinguish between the LRS and standard models; at the first Z^0 pole however we see that $A_{\rm FB}\simeq -0.12$ in the LRS while we find roughly the same magnitude but opposite sign in the standard model. The reason for this is easy to see, since at a Z^0 pole $A_{\rm FB}$ is proportional to

$$v_{l_i}a_{l_i}\left[\sum_q v_{q_i}a_{q_i}\right] \text{ for } Z_i^0 .$$

While none of the quark coupling constants change sign when we go from the standard to LRS models (and neither does the lepton axial-vector coupling) the lepton vector coupling does change sign due to $x_W\simeq 0.225\to x_W\simeq 0.27$. We thus would expect that if $c+ds\cong 1$ (which it is) $A_{\rm FB}({\rm GWS})\simeq -A_{FB}({\rm LRS})$ which is what we see from the figure. Note that although there is some uncertainty due to the structure functions the general behavior of the curves is quite insensitive to this lack of knowledge.

Figure 3 shows the angular-averaged helicity H_A in the GWS model where, again, we see behavior very similar to that found in $e^+e^-\to\mu^+\mu^-$. For small $\sqrt{\tau}$ ($\lesssim 0.1$), H_A is positive and quite tiny ($\simeq 0.01$) making it essentially unobservable. As $\sqrt{\tau}$ grows, H_A becomes negative and grows substantially larger in magnitude being $\simeq -0.20$ at the Z^0 pole. As $\sqrt{\tau}$ increases further $\sqrt{\tau}$ decreases in magnitude to $\simeq -0.11$ and remains essentially featureless and smooth as a function of $\sqrt{\tau}$. We see that, as in the case of $A_{\rm FB}$, the structure-function uncertainties in H_A vanish at the Z^0; the reasoning here is the same as above.

In order to measure H_A, it will be necessary to stop the outgoing lepton and observe its weak decay; this may be much easier to do with τ's than with μ's since they are more massive and less penetrating. Heavier sequential leptons would make the situation even easier; however in this case the work here would have to be redone since terms of order $m_l/\sqrt{s}$ would be important.

Figure 4 shows H_A in the LRS model; note that for small $\sqrt{\tau}$ ($\lesssim 0.2$) H_A in this model has roughly the same magnitude but the sign opposite to that of the GWS model. The origin of this sign difference is again due to the sign difference found in v_l in the two models. This difference in sign clearly allows us to distinguish these two models for any value of $\sqrt{\tau}$; note that the H_A curve is again very similar to that found in the $e^+e^- \to \mu^+\mu^-$ process.

H_A is quite large near either Z^0 pole and should be easily measured. It should be noted that whereas many extended models exist with two (or more) Z^0 bosons a clear, distinguishing feature will be the values of $A_{\rm FB}$ and H_A. The observation of a second Z^0 alone will probably not point out any particular extended model (or group of models) unless *all* of the possible neutral-current parameters are measured.

In this paper we have examined the predictions for the forward-backward asymmetry $A_{\rm FB}$ and the angular-averaged lepton helicity H_A in $p\bar{p}$ reactions at $\sqrt{s} = 540$ GeV in the left-right-symmetric model. We have then compared these predictions to those of the standard GWS model and found quite significant differences in the two predictions which can provide a further test of the left-right-symmetric theory. Although lack of detailed knowledge prevents an extremely accurate calculation of these quantities in any electroweak model the general features we find are insensitive to these unknowns and thus are sufficiently well determined to provide such tests. We look forward to seeing such tests performed in the near future at the CERN $p\bar{p}$ collider.

This work was supported by the U. S. Department of Energy, Contract No. W-7405-Eng-82, Office of Basic Science (KA-01-01), Division of High Energy Physics and Nuclear Physics.

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