New Standard-Model Test for Future Colliders

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We point out that for W-pair production from e^+e^- or $q\bar{q}$ beams, the correlation between the decay planes of the W's is numerically negligible (at tree level) in the standard model. This occurs for the production of WW via intermediate fermions or gauge bosons and independently for WW produced via Higgs-boson exchange, and is not restricted to two-body diagrams. In general, the correlation need not vanish, and so a nonzero correlation would be a clear signal of physics beyond the standard model. Definition of the W-decay plane should be fairly straightforward from the decay $W \rightarrow f\bar{f}$ and, hence, the correlation measurement is experimentally feasible.

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Particle physics today is in the fortunate state of having the standard model (SM), a workable theory which is consistent with all confirmed experimental data. In spite of that, many people feel that the situation is not fundamentally satisfactory. This feeling arises because the Higgs boson required by the theory has not been found and the physics of the Higgs sector is not well understood. In addition, we do not know why the theory takes the form it does, why it has so many parameters such as masses, why the unification is less complete than appears possible, and the reason for the observed number of flavors. Although most of these questions take us beyond the SM, those involving the Higgs sector are a part of the SM, and are thus a central problem today in particle physics.

As was first emphasized some years ago,[1] a productive way to study the physics of the Higgs sector is with beams of W bosons (W includes $W^{\pm}, Z^0$; we will mention particular charge states where needed). This observation has led to studies of how to generate beams of W's using W's emitted from quarks or leptons, and to calculations of the W structure functions.[2–4] Thus for any constituent cross sections involving W interactions it is now known how to write the parton-model cross sections for leptonic or hadronic beams.

We have carried out an extensive program[5] in which we examine how to study W interactions experimentally at future colliders, and how to extract information from the data. In this note we report on one unanticipated and interesting standard-model prediction. In the following we first state the result and how to measure it, then explain how it is derived, and finally comment on its significance.

Consider production of a pair of W's in the SM, starting with e^+e^- or $q\bar{q}$ or qq in hadrons. Assume massless initial fermions. At tree level there are contributions from s-channel γ, Z^0 and from crossed-channel fermions, as in Fig. 1(a). In addition, there are contributions from s-channel or t-channel Higgs bosons. These may be attached to a quark loop or to a W pair which originates from the quarks or leptons, as in Figs. 1(b)–1(d). Clearly, it is of interest to investigate the correlation between the planes of the W's.

This is easy to do in practice, both theoretically and experimentally. The W's decay into $f\bar{f}$ most of the time. Even when the W's are very energetic, the opening angle between the f and $\bar{f}$ is not too small. The minimum opening angle varies from 31° at $m_{WW} = 600$ GeV to 9.2° at $m_{WW} = 2000$ GeV, and for a velocity $\beta = 0.99$ ($m_{WW} \simeq 1150$ GeV), 80% of the longitudinal W's give opening angles from 16.5° to 21°, while 80% of the transverse W's give opening an-

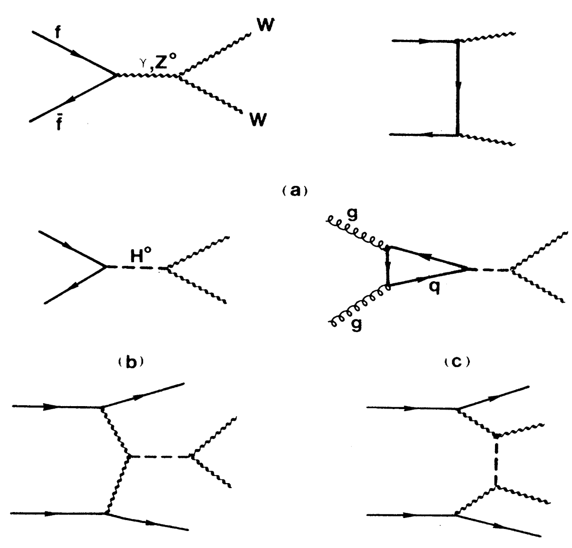

FIG. 1. Diagrams for processes resulting in a WW final state.

gles from 16.5° to 31°. Thus, in practice, it is easy to define experimentally the normal to the W-decay plane, $\hat{\mathbf{n}}_i$ for W_i (see Fig. 2).

The relevant angle is then $\cos\chi = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2$. As we show below, if we take account of the symmetry of the situation, the joint distribution integrated over polar angles must be of the form

$$F(\chi) = 1 + D\cos 2\chi.$$

Then it turns out that all the contributions of Fig. 1 give D of order $(m_W^2/m_{WW}^2)^2$ times a (known) number of order unity or less (specifically, if $m_{WW} > 200$ GeV, then $|D| < 0.02$). This is an important consequence of the SM which, as far as we are aware, has not been previously discussed.

As a practical matter it is necessary to carry out a separation of W's and jets to perform this test. Further, the f and $\bar{f}$ in a given W decay will have different energies in general because of the Lorentz transformation from the W rest frame. Occasionally, one of them is soft enough to make it difficult to determine the W-decay plane. Such questions have been considered in some detail at various studies for future accelerators. For example, Fig. 4 of Fernandez *et al.*,[6] based on ISAJET studies including detector effects, indicates that in principle it should be possible to select out $W \to q\bar{q}$ events and define the W-decay plane (and thus its normal). Further discussion of experimental aspects, and some consideration of possible background problems, which are not trivial but are not expected to be extreme, will be given in Ref. 5.

To derive the result, consider the process $X \to W_1 W_2$ followed by $W_1 \to f_1 \bar{f}_1$ (e.g., $W^+ \to u\bar{d}$ or $Z^0 \to u\bar{u}$) and $W_2 \to f_2 \bar{f}_2$, where X can be any single- or multiple-particle state. Following Trueman,[7] define final angles as follows (see Fig. 3). In the rest frame of X, choose the z axis along the W_1 direction. Boost along z to the W_1 rest frame to define the decay angles θ_1, ϕ_1 of f_1. Boost to the W_2 rest frame to define θ_2, ϕ_2. Then if we label helicities by a,b,c,d, the joint decay distribution is given by

$$W(s,t,\theta_1,\phi_1,\theta_2,\phi_2) = \sum_{abcd} \rho_{cd}^{ab} A_{ca}^{(1)}(\theta_1,\phi_1) A_{db}^{(2)}(\pi-\theta_2,-\phi_2),$$

where the production density matrix is

$$\rho_{cd}^{ab} = \frac{1}{N} \sum_{\text{spins}} M(X \to W_1^a W_2^b) M^*(X \to W_1^c W_2^d),$$

$$N = \sum_{ab} \sum_{\text{spins}} |M(X \to W_1^a W_2^b)|^2,$$

and the $A^{(i)}$ are $W \to f\bar{f}$ decay density matrices. The angle χ between the two decay planes is then $\chi = \phi_2 - \phi_1$, and we define $\Phi = (\phi_1 + \phi_2)/2$. Then the correlation between the planes, integrated over θ_1, θ_2, and Φ, is (for unpolarized beams)

$$F(\chi) = 2\pi \int W(s,t,\Omega_1,\Omega_2)\, d\cos\theta_1\, d\cos\theta_2\, d\Phi,$$

and is normalized to unity when integrated over $\chi/2\pi$. A short calculation gives[8]

$$F(\chi) = 1 + D\cos 2\chi, \quad D = \tfrac{1}{4}(\rho_{--}^{++} + \rho_{++}^{--}).$$

To illustrate what happens, first consider the contribution of Fig. 1(a) to D. Examining the $++$ (or $--$) amplitude, one finds for $e^+e^- \to W^+W^-$ (and similarly for $q\bar{q} \to WW$) an s-channel Z^0 contribution $s\beta\sin\theta/4(m_Z^2 - s)$, and a t-channel ν-exchange contribution $\sin\theta(1 + m_W^2/t)/4\beta$, where θ is the scattering angle. To leading order in s these cancel. D is essen-

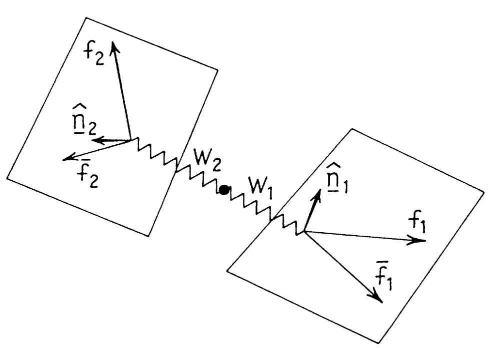

FIG. 2. Illustration of the decay plane correlation.

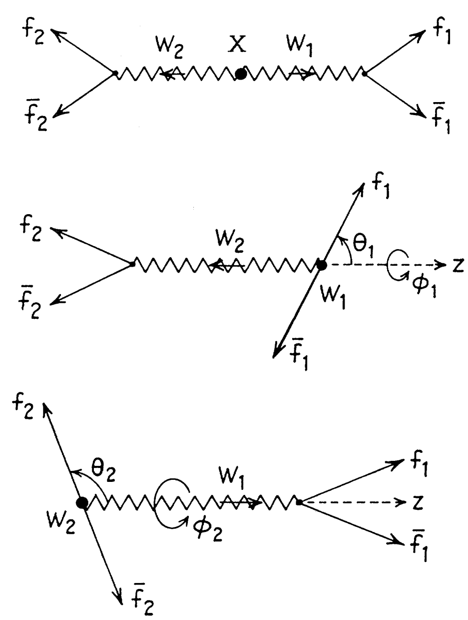

FIG. 3. Definitions of the decay angles for $WW \to f_1\bar{f}_1 + f_2\bar{f}_2$.

tially $|M(++)|^2/\sigma$, and in σ no such cancellation occurs. An independent cancellation occurs in the electromagnetic current (when it is present), i.e., the γ contribution cancels the part of the Z^0 containing $\sin^2\theta_W$. The cancellation occurs *separately* for the H^0 contribution (see below). Thus numerically $D \leqslant (m_W^2/m_{WW}^2)^2$ so that D is negligible for $m_{WW} \gtrsim$ a few hundred gigaelectronvolts; specifically, for $m_{WW} > 200$ GeV, $|D|$ is $< 2\%$ for any process. An analogous cancellation occurs for the similar cases $f\bar{f} \to Z^0 Z^0$ and $f\bar{f} \to Z^0 W$.

Next, consider a possible contribution from the decay of a spin-0 particle into W pairs. The general amplitude is of the form

$$M(ab) = A k_1 \cdot k_2 \epsilon_{1a}^* \cdot \epsilon_{2b}^* + B k_1 \cdot \epsilon_{2b}^* k_2 \cdot \epsilon_{1a}^* + iC \epsilon_{\mu\nu\lambda\rho} \epsilon_{1a}^{*\mu} \epsilon_{2b}^{*\nu} k_1^\lambda k_2^\rho .$$

Then a calculation gives

$$D = 2x^2[(A^2 - C^2)(1-4x) + 4A^2x^2]/T,$$

where

$$T = 8x^2[(A^2 + C^2)(1-4x) + 4A^2x^2] + [(A+B)(1-4x) + 4Ax^2]^2, \quad x = m_W^2/m_H^2.$$

D is therefore negligible for small x unless $A + B = 0$. This can happen if $A = B = 0$, i.e., a pseudoscalar coupling, which gives $D = -\frac{1}{4}$, or if $A = -B$ and $C = 0$, i.e., a scalar coupled to transverse modes, where $D = \frac{1}{4}$. (Numerically, the contribution from a hypothetical spin-0 particle would be reduced below $|D| = \frac{1}{4}$ because of the SM background.) For any other case, and in particular for a Higgs boson with a $g_{\mu\nu}$ coupling to W's (i.e., $B = C = 0$), one finds $D \leqslant 3(m_W^2/m_H^2)^2$. Thus all the diagrams of Fig. 1 give $D \leqslant \text{const}(m_W^2/m_{WW}^2)^2$. Note that not all the diagrams are two-body processes.

To understand better the origin of the cancellation one can look at an SU(2)-symmetric theory of $W^\pm, Z^0, e, \nu$, with arbitrary Lorentz-invariant couplings at the $W^+W^-Z^0$ vertex, and consider (for example) $e^+e^- \to W^+W^-$. The seven independent ZW^+W^- couplings reduce to one, giving the usual gauge-invariant theory, simply by imposition[9,10] of the unitarity constraint which requires the amplitudes involving W_L to be well behaved as $s \to \infty$. At the same time, a cancellation in $M(++)$ automatically occurs between the s- and t-channel contributions. Although the amplitudes involving longitudinal polarizations are independent of $M(++)$ in general, in a unitary, gauge-invariant Lagrangean theory (where couplings factorize) the relations are strong enough[11] so that $M(++)/M(00) \sim m_W^2/m_{WW}^2$. Additional contributions due to new physics could affect $M(++)$ and $M(00)$ differently, leading to nonzero D. In particular, any physics which gives only transverse W's and contributes to leading order in m_{WW}^2 would give nonzero D.

That D should be $\leqslant (m_W^2/m_{WW}^2)^2$ is a test of the SM which is effectively independent of the usual tests such as the shape of $\sigma(m_{WW}^2)$. D is sensitive to contributions to the amplitudes $M(++)$ or $M(--)$, while the cross section is dominated by the amplitudes $M(+-)$, $M(-+)$, and $M(00)$. It is possible to arrange nonstandard physics contributions giving a significant D but contributing negligibly to σ, such as a new scalar with gauge-invariant transverse couplings. Thus D is an excellent probe of physics beyond the standard model—any value observed above a percent or so when $m_{WW} \gtrsim$ a few times m_W must be due to a new effect.[12] It is important that detectors for future colliders be segmented finely enough to see the two-core $W \to f\bar{f}$ decay and define the decay plane.

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[12]The suppression of the ++ amplitude could be altered when one-loop strong corrections are included. Should this occur, the SM expression for D might involve a term of order $(m_W^2/m_{WW}^2)\alpha_s$, which is still negligible. We are investigating this possibility.