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Z^0Z^0 and W^+W^- pair production at supercollider energies

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We present the invariant-mass distributions for the production of Z^0Z^0 pairs by W^+W^- and Z^0Z^0 fusion at 40 TeV. Results are given for Higgs-boson masses of 0.5 and 1.0 TeV and a rapidity cut η_c of 1.5. These calculations, which are performed using the effective-gauge-boson approximation, are compared with the corresponding results for the production of W^+W^- pairs by the same fusion mechanism. A comparison between the approximate calculation and an exact calculation of Z^0Z^0 pair production by W^+W^- fusion is also presented.

I. INTRODUCTION

Since the discovery of the W and Z gauge bosons, efforts to understand the Higgs sector of the standard model have intensified. As has been noted numerous times, the Higgs-boson mass m_H remains almost unconstrained in the model. Proposed experimental signatures of the Higgs boson are, therefore, sensitive to its dominant decay mode in a particular mass range. Roughly speaking, for m_H less than twice the W-boson mass, m_W, Higgs-boson decay into the most massive quark-antiquark pair accessible is dominant.[1] However, if m_H exceeds $2m_W$ the dominant Higgs-boson decay mode is into gauge-boson pairs. This mass regime has recently received considerable attention because the Higgs boson can be produced by gauge-boson fusion,[2] and the entire production-detection process can provide a laboratory for the study of gauge-boson scattering.[3]

In this paper, we present a calculation of the invariant-mass distributions for the process $pp \to Z^0Z^0+X$ which includes contributions from W^+W^- and Z^0Z^0 fusion as well as $q\bar{q}$ annihilation. The W and Z fusion processes are calculated using the effective-gauge-boson approximation for Higgs-boson masses of 0.5 and 1.0 TeV. These results are compared with the corresponding calculation for the W^+W^- final state.

II. CALCULATION OF $pp \to Z^0Z^0+X$

For the range of Higgs-boson masses considered here, production of Z^0 pairs occurs primarily through the channels

$$pp \to q\bar{q} \to Z^0Z^0 , \tag{1}$$

$$pp \to W^+W^- \to Z^0Z^0 , \tag{2}$$

$$pp \to Z^0Z^0 \to Z^0Z^0 , \tag{3}$$

and to some extent through the gluon-fusion channel

$$pp \to gg \to Z^0Z^0 . \tag{4}$$

Processes (1) and (4) constitute backgrounds to Higgs-boson searches. The first of these is the dominant standard-model background, while the second, which occurs through a quark loop, has been shown to be reasonably small.[4]

Without cuts, the cross section for the production of a Z^0 pair of invariant mass m_{ZZ} by gauge-boson fusion is given by

$$\frac{d\sigma}{dm_{ZZ}^2}=\frac{1}{s}\int_{\tau_{\min}}^{1}\frac{d\tau}{\tau}\int_{-\eta}^{\eta}dy\, f(\sqrt{\tau}e^{y})f(\sqrt{\tau}e^{-y})\int_{-\hat{\eta}}^{\hat{\eta}}d\hat{y}\, \hat{f}(\sqrt{\hat{\tau}}e^{\hat{y}})\hat{f}(\sqrt{\hat{\tau}}e^{-\hat{y}})\int_{-1}^{1}dz\frac{d\hat{\sigma}}{dz} , \tag{5}$$

where

$$\tau_{\min}=m_{ZZ}^2/s,\quad \hat{\tau}=\tau_{\min}/\tau,\quad \eta=\ln(1/\sqrt{\tau}),\quad \hat{\eta}=\ln(1/\sqrt{\hat{\tau}}),\quad \text{and}\quad z=\cos\theta . \tag{6}$$

Here $\sqrt{s}$ is the collider energy, f and $\hat{f}$ are the quark-number distribution and gauge-boson distribution functions, respectively, and $\hat{\sigma}$ is the cross section for the elementary scattering process. The introduction of a rapidity cut η_c on both Z^0's imposes the constraint

$$| y+\hat{y}\pm y^* | \le \eta_c , \tag{7}$$

where

$$y^*=\text{arctanh}(\beta z) \tag{8}$$

is the rapidity of a Z^0 in the center of mass and $\beta=(1-4m_Z^2/m_{ZZ}^2)^{1/2}$. This constraint modifies the limits of the dy, $d\hat{y}$, and dz integrals.[5]

In this calculation, we use the Eichten-Hinchliffe-Lane-Quigg[6] (EHLQ) quark-number distribution functions. The gauge-boson distribution functions[7–10] are those of Ref. 9. Processes (1) and (2) are discussed in Ref.

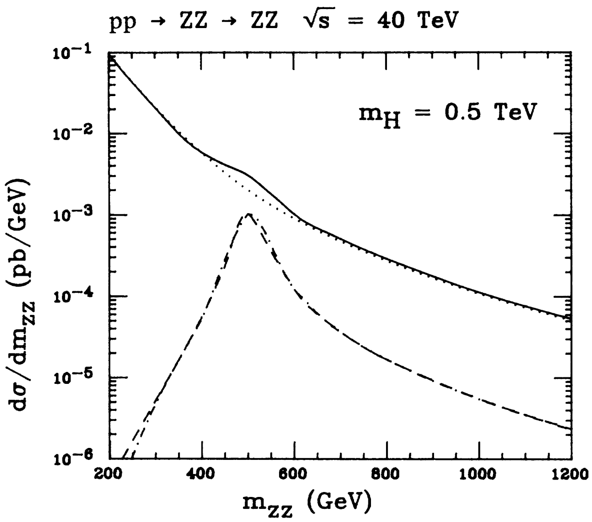

FIG. 1. The invariant-mass distribution for Z^0Z^0 pair production by Z^0Z^0 fusion subject to a rapidity cut $\eta_c = 1.5$ is shown. The dashed-dotted curve is the contribution from initial and final longitudinal Z^0's only. The dashed curve is the contribution from all polarizations of Z^0's, the dotted curve is the background from $q\bar{q} \to Z^0Z^0$, and the solid curve is the sum of the previous two.

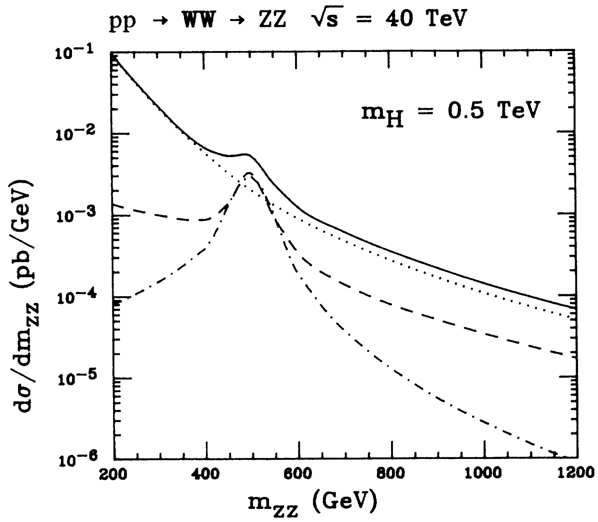

FIG. 3. The invariant-mass distribution for Z^0Z^0 pair production by W^+W^- fusion subject to a rapidity cut $\eta_c = 1.5$ is shown. The dashed-dotted curve is the contribution from longitudinal initial W's and longitudinal final Z^0's only. The dashed curve is the contribution from all polarizations of W's and Z's, the dotted curve is the background from $q\bar{q} \to Z^0Z^0$, and the solid curve is the sum of the previous two.

5, where W^+W^- fusion was treated in the simplest approximation of retaining only longitudinal initial W's. For this paper, we have included all initial gauge-boson polarizations in order to assess the contribution of transverse degrees of freedom away from the Higgs-boson peak. The contribution of process (3), which only involves Higgs-boson exchanges, is presented here for the first time.[11]

III. RESULTS FOR Z^0Z^0 FINAL STATES

The contribution to the Z^0 pair cross section $d\sigma/dm_{ZZ}$ from Z^0 fusion is shown in Figs. 1 and 2. From these figures, the dominance of the Higgs-boson coupling to longitudinal Z^0's is evident. Notice that the contribution from purely longitudinal Z^0's (the dashed-dotted line) accurately accounts for the Higgs-boson peak. In addition, this contribution is virtually indistinguishable from that of all polarization states, which is given by the dashed line. In Figs. 3 and 4, the corresponding contribution to $d\sigma/dm_{ZZ}$ from W^+W^- fusion is illustrated. Here, too, the longitudinal degrees of freedom provide an excellent description of the Higgs-boson peak. However, away from the peak the transverse degrees of freedom make a substantial contribution.

The result of combining Z^0 pairs from sources (1)–(3) is illustrated in Figs. 5 and 6. All polarization states are

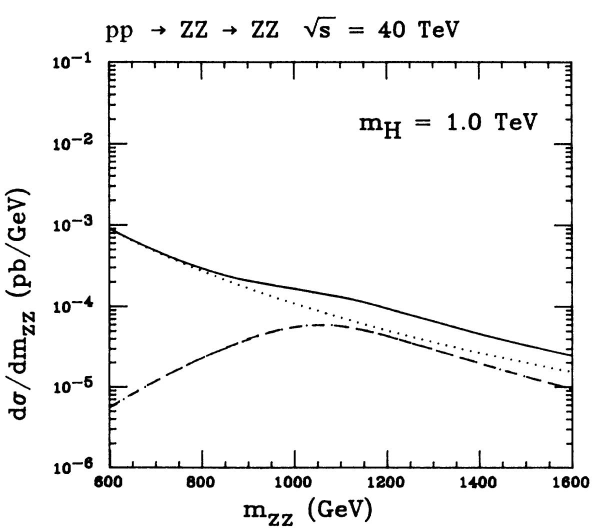

FIG. 2. Same as Fig. 1 except for the value of m_H.

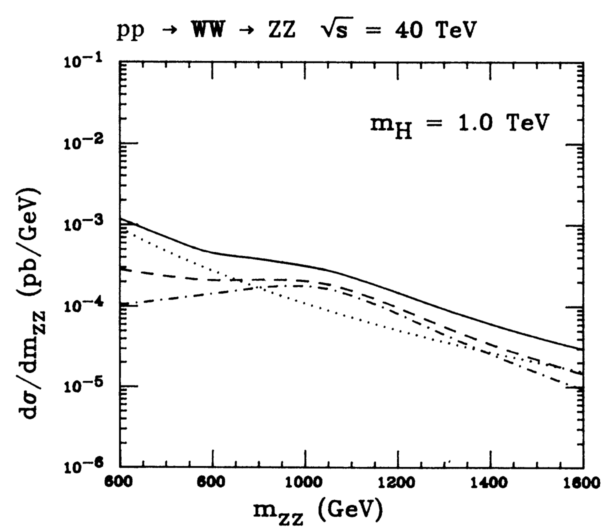

FIG. 4. Same as Fig. 3 except for the value of m_H.

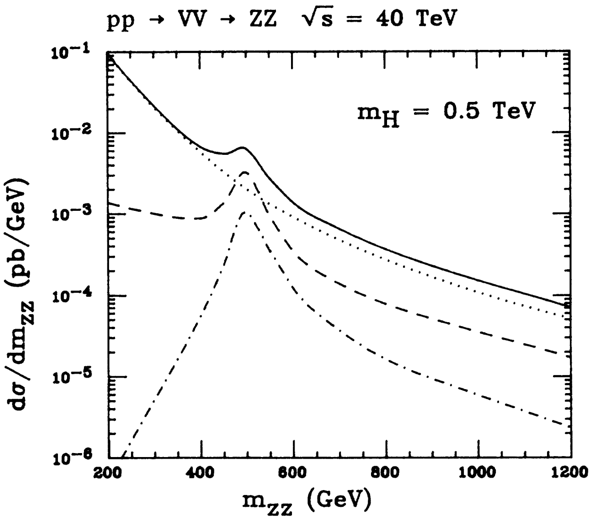

FIG. 5. The invariant-mass distribution for Z^0Z^0 pair production by vector-boson fusion subject to a rapidity cut $\eta_c = 1.5$ is shown. The dashed-dotted curve is the contribution from Z^0Z^0 fusion, the dashed curve is the contribution from W^+W^- fusion, and the dotted curve is the background from $q\bar{q} \rightarrow Z^0Z^0$. The solid curve is the total contribution.

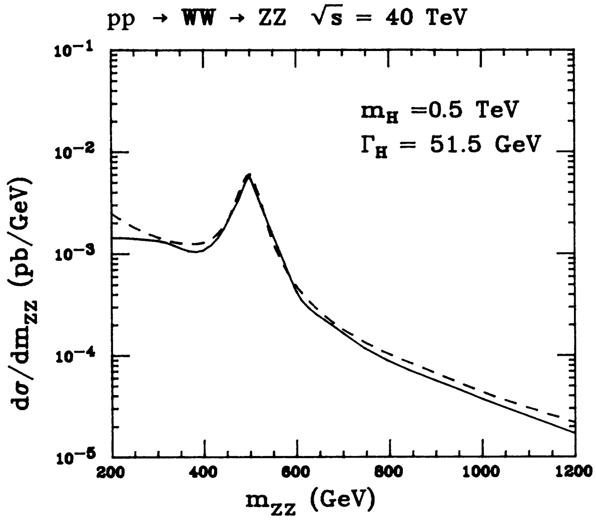

FIG. 7. A comparison of the effective-gauge-boson calculation (dashed line) and the exact calculation of $d\sigma/dm_{ZZ}$ (solid line) is shown for a rapidity cut $\eta_c = 1.5$.

included in these figures. For the case of $m_H = 0.5$ TeV and $\Gamma_H = 0.06$ TeV, a bin of width Γ_H contains about 3000 Z^0 pair events using a integrated luminosity 10^{40} cm^{-2}. Of these events, about 1200 are from the $q\bar{q}$ annihilation background. In the case of $m_H = 1.0$ TeV and $\Gamma_H = 0.5$ TeV, there are about 1200 pair events in the peak, 600 of which are background. By increasing the rapidity cut to $\eta_c = 2.5$, the number of events in the peaks increases by about a factor of 2.

The results presented here can be compared with an exact perturbative calculation of $pp \rightarrow W^+W^- \rightarrow Z^0Z^0$ performed by Dicus, Wilson, and Vega.[12] Although these authors use slightly different values for several input parameters, the agreement between the two calculations is quite satisfactory. This is illustrated in Fig. 7, which was obtained using the same values for α_{EM}, m_W, and Γ_H used in Ref. 12.

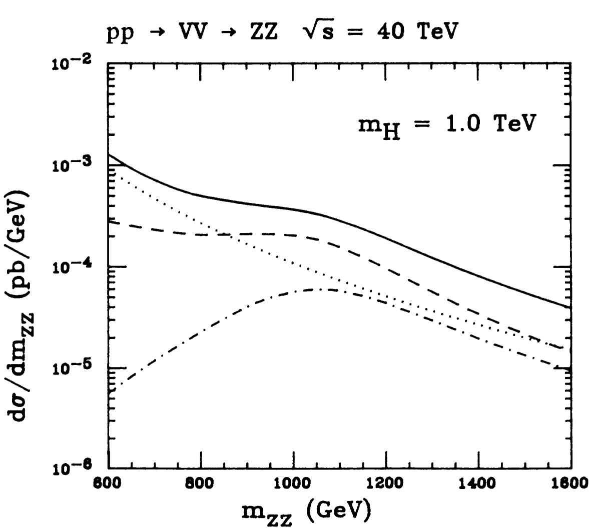

FIG. 6. Same as Fig. 5 except for the value of m_H.

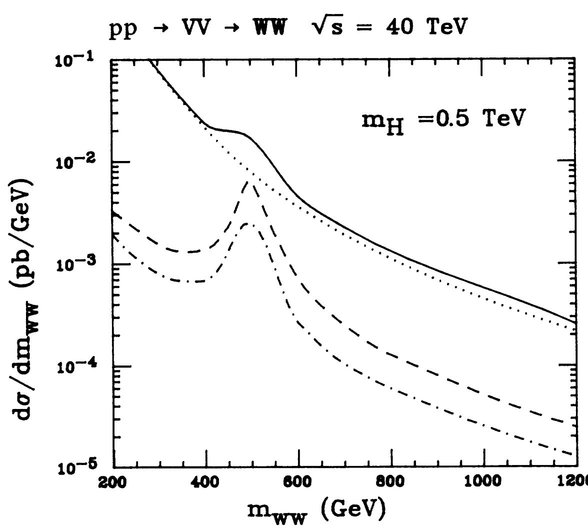

FIG. 8. The invariant-mass distribution for W^+W^- pair production by vector-boson fusion subject to a rapidity cut $\eta_c = 1.5$ is shown. The dashed-dotted curve is the contribution from Z^0Z^0 fusion, the dashed curve is the contribution from W^+W^- fusion, and the dotted curve is the background from $q\bar{q} \rightarrow W^+W^-$. The solid curve is the total contribution.

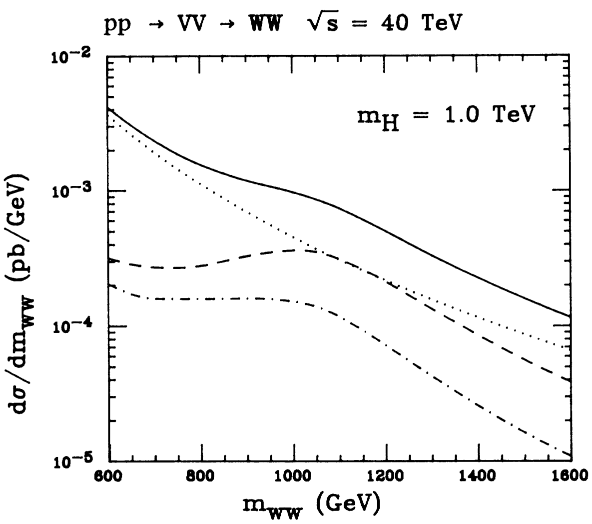

FIG. 9. Same as Fig. 8 except for the value of m_H.

character of the Higgs-boson coupling. It is also satisfying to see the close agreement between the exact calculation of Ref. 12 and the effective-gauge-boson approximation. This is of practical importance since the approximate calculation is much simpler computationally.

Finally, for comparison purposes, in Figs. 8 and 9 we show the cross sections $d\sigma/dm_{WW}$ for the processes

$$pp \to q\bar{q} \to W^+W^- \ , \tag{9}$$

$$pp \to W^+W^- \to W^+W^- \ , \tag{10}$$

$$pp \to Z^0Z^0 \to W^+W^- \ . \tag{11}$$

The yield of W^+W^- pairs is higher than in the Z^0-pair case. For example, with $m_H = 0.5$ TeV and $\Gamma_H = 0.06$ TeV, a bin of width Γ_H centered at the peak contains about 9000 pair events of which approximately 4800 are due to $q\bar{q}$ annihilation. In this case, too, the comparison between an exact calculation[13] and the approximate calculation[14] presented here is quite good.[15]

IV. DISCUSSION

From Figs. 3 and 4, it is clear that the W-boson fusion process receives significant contributions from the initial transverse polarization states. As expected, the effect of the transverse-polarization states is most pronounced away from the Higgs-boson peak due to the longitudinal

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