Interference effects and the longitudinal fraction in the process $gg \to ZZ$

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(Received 24 December 1987)

The contribution to $pp \to ZZ + X$ from gluon fusion ($gg \to ZZ$) is determined and combined with the contributions from the subprocesses $q\bar{q} \to ZZ$, $WW \to ZZ$, and $ZZ \to ZZ$ to find the total Higgs-boson signal in ZZ production and the fraction of events where the Z's are longitudinal.

Production and detection of Higgs bosons, or their nonexistence, is the most important problem remaining for the standard model. If this question could be answered definitively it would by itself justify the building of the Superconducting Super Collider (SSC). One signal for the Higgs boson would be a pronounced peak above the background by s-channel Higgs-boson decay into electroweak gauge bosons. To suppress the background the ideal mode of this type is $pp \to ZZ + X$ where the Z's both decay into charged leptons.[1] The branching ratio is small but the final state can be completely reconstructed and the signal can be enhanced by selecting Z's with longitudinal polarization. Thus this process looks very promising for detecting Higgs bosons in the range 300 GeV $\leq M_H \leq 1$ TeV.

The cross section for $pp \to ZZ + X$ from intermediate gauge bosons ($WW \to ZZ$, $ZZ \to ZZ$, generically referred to as W fusion) together with the background $q\bar{q} \to ZZ$ has been calculated by Abbasabadi and Repko[2] and by Duncan[3] using the effective-gauge-boson approximation, and calculated exactly by Dicus, Wilson, and Vega.[4] The background from gluon fusion ($gg \to ZZ$ through box diagrams) has been calculated by Dicus, Kao, and Repko.[5] It is known[6] that gluon fusion can also contribute to the signal by $gg \to H$ through a quark triangle and, in fact, is the dominant mechanism for Higgs-boson production if the top-quark mass is large enough. In this paper I calculate the total ZZ production from gluon fusion ($gg \to H \to ZZ$ through the top quark triangle, $gg \to ZZ$ through quark boxes, and the interference between these contributions) and combine this with the contributions from $q\bar{q} \to ZZ$, $qq \to W^+W^-qq \to ZZqq$, and $qq \to ZZqq \to ZZqq$ as taken from Ref. 4 to find the total Higgs signal and background from $pp \to ZZ + X$.

As in Ref. 5 the method of calculation is to use Veltman's code FORMFACTOR (Ref. 7). The triangle graphs which produce a Higgs boson can be easily evaluated analytically but the box cannot be evaluated so easily, and an analytic expression for it would involve hundreds of Spence functions. FORMFACTOR evaluates these Spence functions numerically and combines them to give values for the various Feynman integrals. It should be emphasized that although the output of FORMFACTOR is a set of numbers the integrals are not done numerically. Here I have also used FORMFACTOR to evaluate the triangle since that is the easiest way to get the interference.

The work that must be done by the practitioner of FORMFACTOR is to combine the integrals in the proper way to get the matrix element for the problem at hand, square, sum over helicities, and integrate over phase space. Near threshold and near the forward and backward directions FORMFACTOR has problems because it must invert a matrix which becomes singular at these points. However it is easy to determine if it is running correctly by checking that it is returning a gauge-invariant amplitude. In any case these points are not a problem here because we are not interested in being too close to threshold and the rapidity cuts, made for other reasons, restrict the evaluation in the forward and backward directions.

Figure 1 shows the various contributions from gluon

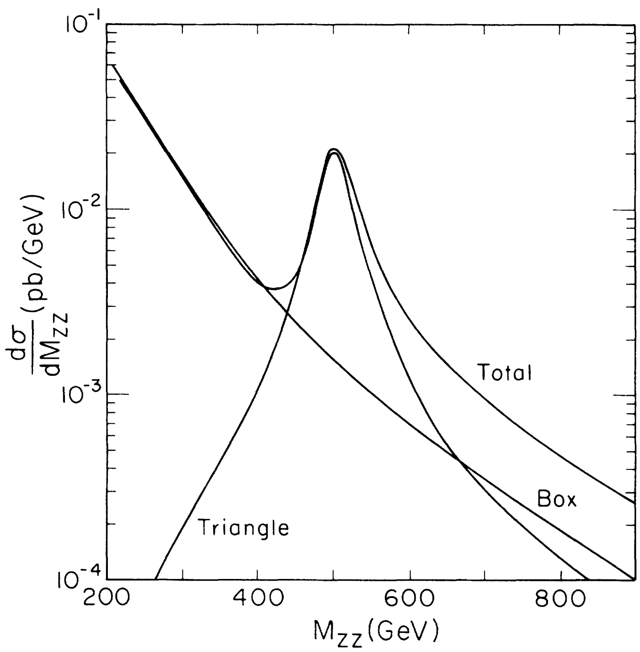

FIG. 1. The invariant-mass cross section for $pp \to ZZ + X$ from gluon fusion. Shown are the contributions from the triangle graphs only, the box graphs only, and the total including interference. The Higgs-boson mass was fixed at 500 GeV and the rapidity was restricted to be less than $y_0 = 1.5$. The triangle graphs have only the top quark whose mass was taken as 100 GeV. The box graphs have the top quark and five light flavors of quarks whose common mass was taken as 1 GeV.

fusion, $gg \to ZZ$ for a typical case of a top-quark mass of 100 GeV. Shown are the square of the triangle graphs, the square of the box graphs, and the total including interference between the box and triangle pieces. The interference is seen to be positive for invariant masses greater than the Higgs-boson mass and negative for smaller invariant masses. The triangle contributions are purely $J=0$. From the values shown we can determine $f\cos^2\phi$ where f is the fraction of the box cross section that is $J=0$ and ϕ is the relative phase between the box and the triangle. This quantity varies from near zero on the pole to 0.26 far away from the pole, a variation that is strongly influenced by the obvious variation in ϕ from the Higg's propagator. The object of interest f is thus not determined very tightly. All that can be said is that the box must be at least 26% $J=0$ for some invariant masses.

Figures 2–4 show the total gluon contributions for various top-quark masses as well as the sum of the contri-

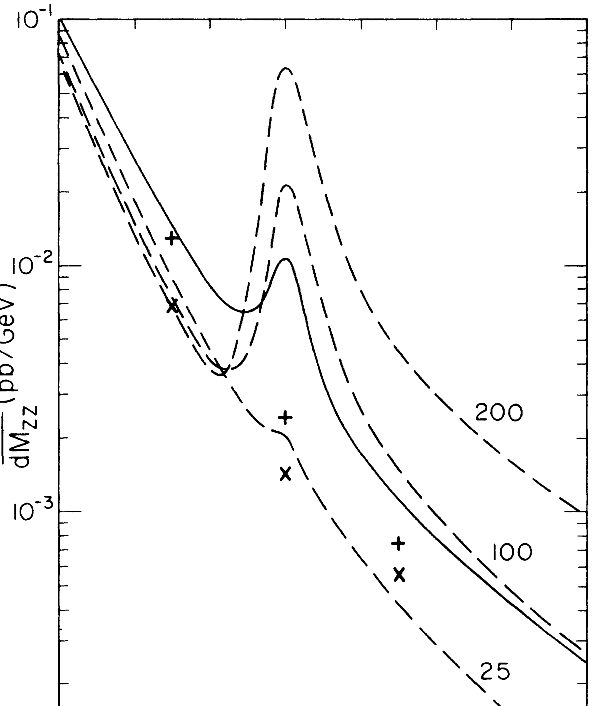

FIG. 2. The cross section for $pp \to ZZ+X$ as a function of the ZZ invariant mass for a Higgs-boson mass of 500 GeV. The rapidity was restricted to be $y_0 \leq 1.5$. The solid curve is the contribution from vector-boson fusion, $WW \to ZZ$ and $ZZ \to ZZ$ plus the contribution from quark annihilation $q\bar{q} \to ZZ$. The dashed lines are the total contribution from gluon fusion $gg \to ZZ$ for a top-quark mass of 25, 100, and 200 GeV. The background to vector-boson fusion, in the absence of a Higgs boson, from $q\bar{q} \to ZZ$ is marked by the plus sign at M_{ZZ} equal 350, 500, and 650 GeV. The background to gluon fusion, from the contributions of the quark boxes only, is given by the X's at 350, 500, and 650 GeV for the case where the top mass is 200 GeV.

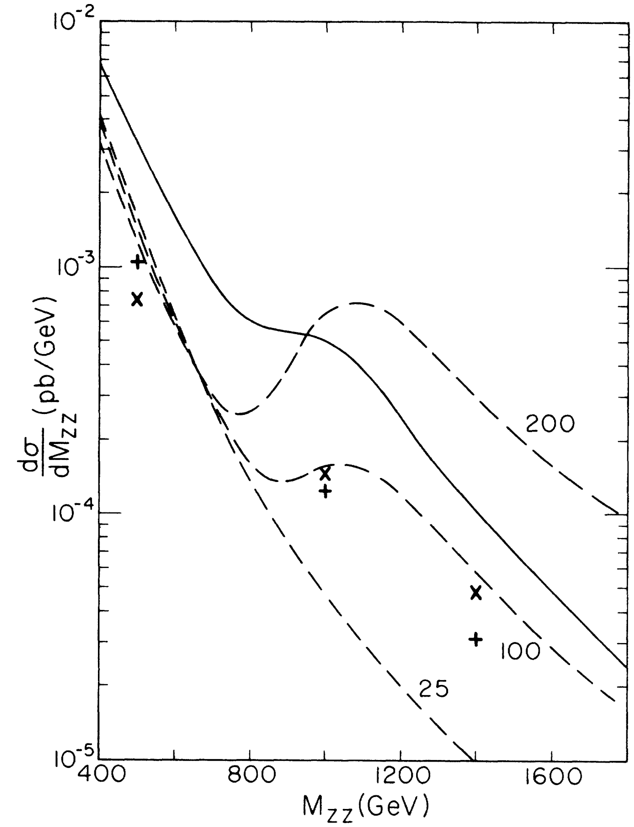

FIG. 3. The invariant-mass cross section for $pp \to ZZ+X$ as in Fig. 2, but for a Higgs-boson mass of 1 TeV.

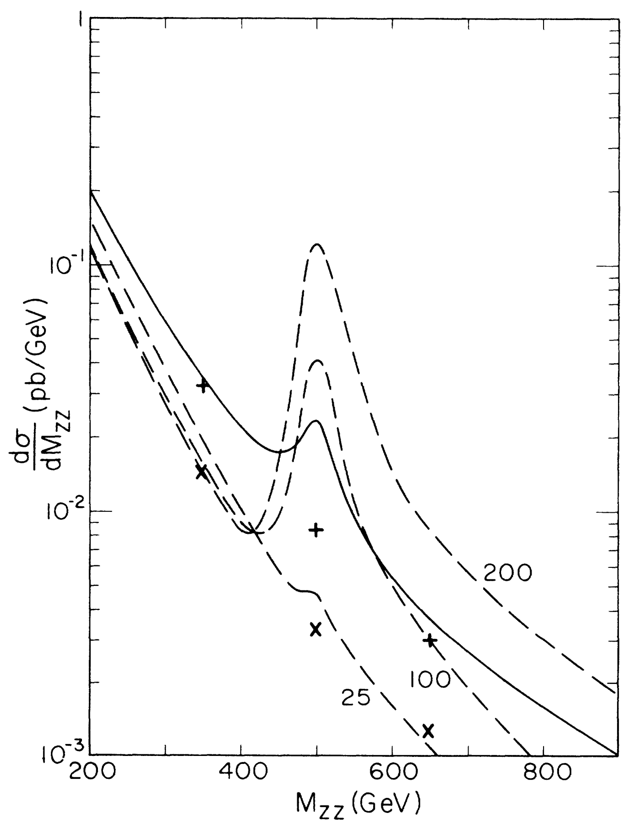

FIG. 4. The invariant-mass cross section for $p+p \to Z+Z+X$ as in Fig. 2 but for a rapidity cut of $y_0 \leq 2.5$.

butions from $q\bar{q}\rightarrow ZZ$, $qq\rightarrow W^+W^-qq\rightarrow ZZqq$, and $qq\rightarrow ZZqq\rightarrow ZZqq$ (Ref. 4) for a Higgs-boson mass of 500 GeV or 1 TeV and a rapidity cut of 1.5 or 2.5. The rapidity cut of 2.5 is included for completeness although it may allow too much background from $qq\rightarrow ZZqq$ where the quarks exchange a gluon and the Z's are radiated off the quark lines.[8] Backgrounds in the absence of a Higgs boson are given in the figures.

All calculations shown in the graphs were done at the SSC energy of 40 TeV. A calculation of W^+W^- production ($WW\rightarrow WW$) at the energy of the CERN Large Hadron Collider (LHC) (17 TeV) shows that the Higgs peak is barely visible above the background.[9] Gluon fusion at LHC energy has both the signal and background reduced by about the same amount. A graph at 17 TeV using the other parameters of Fig. 3 would look just like Fig. 3 with all the cross-section values reduced by a factor of approximately 4. In the present calculations, as well as those of Ref. 4, we used $\sin^2\theta_W=0.22$, $\alpha=\frac{1}{128}$, and set 1 of the distribution functions of Duke and Owens.[10]

If gluon fusion can be separated from W fusion by the detection of the quark jets in the final state of W fusion then Figs. 2–4 tell the whole story. If, however, only the Z's in the final state are detected then the quantity of interest is the total of W fusion and gluon fusion at the appropriate top-quark mass. In this case the relevant quantities in Figs. 2–4 would be the sum of the gluon curves with the vector boson curve.

Although the Higgs boson gives a pronounced peak in Figs. 2–4 the number of events above background is not very large particularly when we insist that the Z's decay into leptons. The authors of Refs. 2 and 3 noted that the Z's from $qq\rightarrow ZZ$ are almost entirely transversely polarized while those from Higgs decay tend to be longitudinally polarized. Therefore the signal can be greatly enhanced if the polarization of the Z's can be detected. The gluon-fusion processes add some longitudinal Z's when the gluons fuse to form a Higgs boson but also some transverse Z's when the gluons fuse into the box. The box gives primarily transverse Z's except for the contribution from the top quark when its mass is not small.

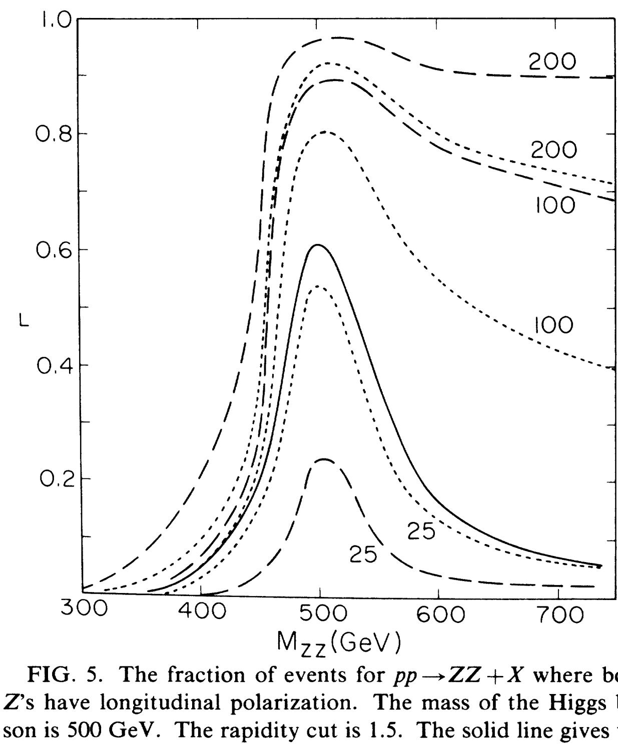

FIG. 5. The fraction of events for $pp\rightarrow ZZ+X$ where both Z's have longitudinal polarization. The mass of the Higgs boson is 500 GeV. The rapidity cut is 1.5. The solid line gives the fraction from $q\bar{q}\rightarrow ZZ$ and $WW\rightarrow ZZ$ contributions. The dashed lines give the longitudinal fraction of gluon-fusion events for a top mass of 25, 100, or 200 GeV. The dotted lines give the longitudinal fraction when W fusion and gluon fusion are combined.

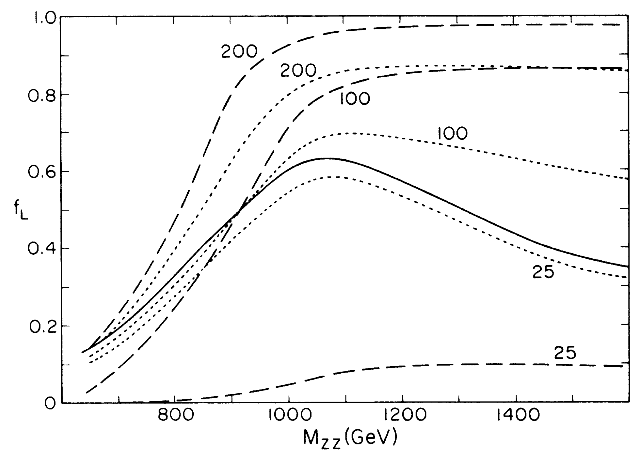

FIG. 6. The fraction of events were both Z's are longitudinal as in Fig. 5 except the Higgs-boson mass is 1 TeV.

Figures 5 and 6 show the fraction of Z's that are longitudinally polarized, $f_L=d\sigma(LL)/d\sigma(\text{total})$. f_L is a sensitive function of the top-quark mass but, for top masses greater than about 80 GeV, gluon fusion produces longitudinal Z's even more efficiently than W fusion. Figures 5 and 6 show f_L for both the case of separate gluon fusion and W fusion and the case where only the combination is detected. If the top quark has a small mass the longitudinal fraction from gluon fusion is small but, in that case, gluon fusion does not produce many Z's so that f_L for the total remains large.

In summary, all the obvious contributions to $pp\rightarrow ZZ+X$ have now been included and it remains a good candidate for finding the Higgs boson. Inclusion of the gluon fusion reactions increases both the signal and the background in a way that depends on the value of the top-quark mass. Gluon fusion, by itself, may not produce a usable signal if the top quark is too light. But if the top quark is reasonably heavy the signal will be considerably enhanced and, for any top-quark-mass value, the total signal-to-background ratio from gluon fusion plus W fusion is not seriously degraded.

It is a pleasure to thank Chung Kao, Wayne Repko, Scott Willenbrock, Sandy Wilson, and especially Roberto Vega for a great deal of help. I also wish to acknowledge the support of the University of Texas Center for High Performance Computing and the University of Texas Computation Center. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG05-ER8540200.

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