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Gluon production of gauge bosons

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We determine the contribution to $pp \rightarrow ZZ+X$ from gluon+gluon$\rightarrow ZZ$ by evaluating the relevant box diagrams.

The intermediate gauge bosons of the standard model $(W^{\pm},Z)$ have been produced in hadron colliders. Their production in supercolliders will be used to study the trilinear gauge coupling, to look for rare decays, to look for extensions of the standard model, and to search for the Higgs boson. The rate of production of pairs of gauge bosons in the parton model is not accurately known because, although the calculation of quark-antiquark annihilation $q\bar{q} \rightarrow ZZ$, W^+W^- is trivial, the calculation of gluon fusion $gg \rightarrow ZZ$, W^+W^- proceeds through box diagrams, and boxes are notoriously difficult. The only previous calculation of $gg \rightarrow ZZ$ was by Pumplin, Repko, and Kane,[1] who calculated the imaginary parts of the longitudinal amplitudes. In this paper, we report the first full calculation of $gg \rightarrow ZZ$ and its contribution to $pp \rightarrow ZZ+X$.

Some parton processes which proceed only through box diagrams have been calculated. A (probably incomplete) list includes $\gamma\gamma \rightarrow gg$ (Ref. 2), $Z \rightarrow gg\gamma$ (Ref. 3), $Z \rightarrow 3g$ (Ref. 4), $gg \rightarrow \gamma\gamma$ (Ref. 5), and $gg \rightarrow \gamma Z$ (Ref. 5). Explicit evaluation of the box diagram is avoided for each of these processes by using a Mandelstam representation as developed for photon-photon scattering by DeTollis.[6] Unfortunately $gg \rightarrow ZZ$ cannot be done this way because the usual form of the Mandelstam representation is not valid when more than one of the external particles has a mass larger than the mass of the internal lines of the box.[7]

In 1979 Veltman addressed the problems of one-loop diagrams by clearly explaining techniques for performing the integrals involved[8] and then by developing a very sophisticated computer code, called FORMF, to evaluate all the needed integrals. The use of the code is described in a paper with Passarino.[9] This is the method we have used to calculate the gluon-gluon contribution to $pp \rightarrow ZZ+X$.

We checked Veltman's code in three ways. (1) Before even attempting $gg \rightarrow ZZ$ we did a complete calculation of photon-photon scattering $\gamma\gamma \rightarrow \gamma\gamma$, and compared it with the classic results of Karplus and Neuman[10] for scattering at right angles. (2) All the four-point integrals can be derived from the integrals with no momenta in the numerator and one, two, three, or four factors in the denominator. We explicitly calculated the most difficult of these, the one with four factors in the denominator, and our result agrees with that given by the code. (3) After calculating $gg \rightarrow ZZ$ we checked gauge invariance by numerically replacing the polarization vector of one of the gluons by its momentum. The result was not exactly zero because of numerical limitations but was always less than 10^{-5} of the result for the physical process. This checks every integral used in the process, as well as our algebraic ability.

Comparison with Karplus and Neuman for $\gamma\gamma \rightarrow \gamma\gamma$ revealed a small problem with our version of the code when it is used for scattering in exactly the forward (or backward) direction. This problem was traced to the factoring of a quadratic equation,

$$ax^2+bx+c=a(x-x_1)(x-x_2) ,$$

where $a \sim (1-z)$ with z the cosine of the scattering angle. Of course if a is zero then the remaining equation is linear and there is no need to factor, but we were not able to determine how to add this branch to the code. However, this was not a problem for $gg \rightarrow ZZ$ because we chose to present the results in terms of an invariant-mass distribution with a cut on the rapidity of the final Z. If the cut in the rapidity y is y_0 then the necessary integrals are an integral of the gluon distribution functions over y from $-y_0$ to y_0 and an integral of the subprocess cross section over z from $-z_0$ to $+z_0$, where z_0 is the smaller of 1 and $(1/\beta)\tanh(y_0-|y|)$, with β the velocity of the final Z. Thus for many values of y_0, z is never ± 1. For those

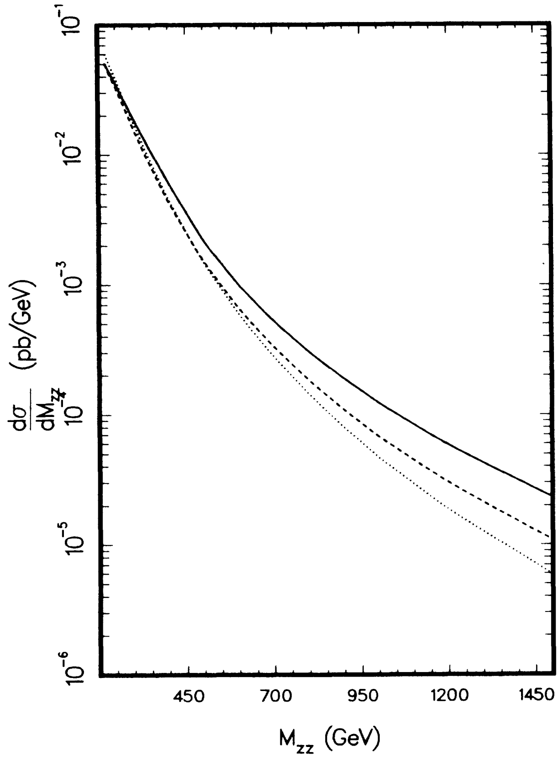

FIG. 1. The contributions to $pp \to ZZ+X$ from the parton processes $q\bar{q} \to ZZ$ (solid line) and $gg \to ZZ$. The dashed line is the contribution from $gg \to ZZ$ for a top-quark mass of 100 GeV, the dotted line is for a top mass of 40 GeV. $\sqrt{s}$ is 40 TeV while the rapidity cut was taken to be $y_0 = 1.5$. Also included in the loop are five light quarks with a mass of 1 GeV each. The Z mass was taken as 93.3 GeV corresponding to $\sin^2\theta_W = 0.22$. The quark and gluon distribution functions used were those of Duke and Owens with $\Lambda = 0.2$.

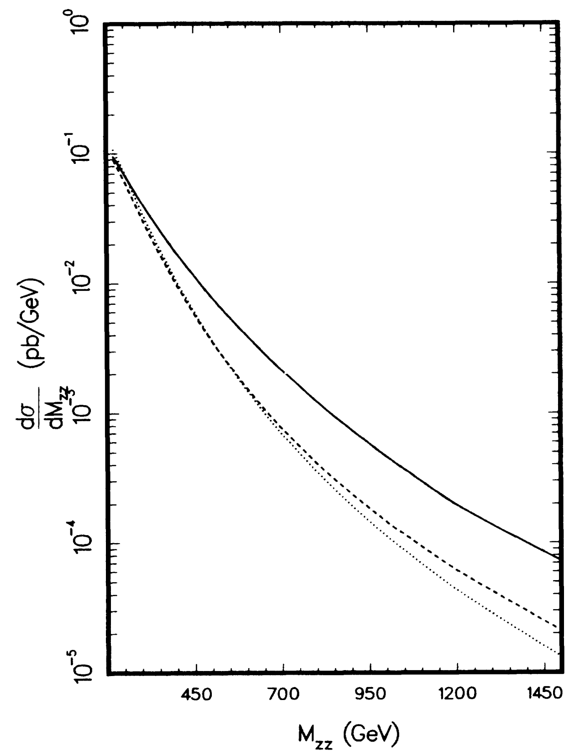

FIG. 2. The contributions to $pp \to ZZ+X$ as in Fig. 1 except that $y_0 = 2.5$.

values of y_0 where z can reach ± 1 we have cut the z integral off at 0.9999 after checking that the result was insensitive to this cutoff.

The results are shown in Fig. 1 for $\sqrt{s} = 40$ TeV, $y_0 = 1.5$, in Fig. 2 for $\sqrt{s} = 40$ TeV, $y_0 = 2.5$, and in Fig. 3 for $\sqrt{s} = 10$ TeV, $y_0 = 1.5$. The contribution from the quark in the box is almost completely independent of the quark's mass as long as the mass is less than about 20 GeV. The figures were done for two light up quarks and three light down quarks with a common mass of 1 GeV, and the top quark. The results do depend on the mass of the top quark as is shown in the figures.

Not shown in the figures is the relative contribution to the total from the different helicities of the Z. The light quarks produce only transverse Z's. This occurs because the longitudinal-polarization vector equals the momentum vector plus terms of order M/E, where M and E are the Z mass and energy. But dotting the momentum vector of the Z into the amplitude gives zero up to terms proportional to the quark mass. A heavy top will, however, produce a significant number of longitudinal Z's. For a top mass of 100 GeV and an invariant mass of 1000 GeV the longitudinal-longitudinal-polarization state is approxi-

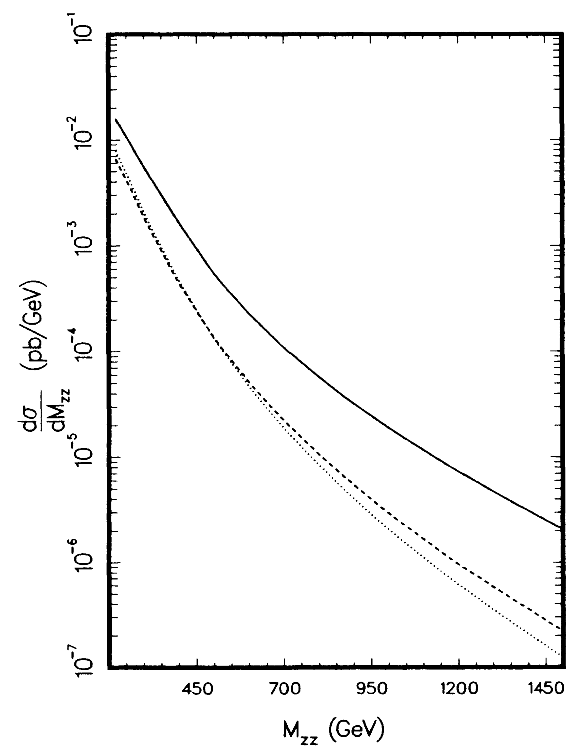

FIG. 3. The contributions to $pp \to ZZ+X$ as in Fig. 1 but with $\sqrt{s} = 10$ TeV.

mately $\frac{1}{3}$ of the total; the transverse-longitudinal states are still only about 1% of the total. For a top-quark mass of 40 GeV the fractions are about 4% and less than 1%, respectively.

Figures 1-3 show that the relative contribution to $pp \rightarrow ZZ+X$ from initial gluons decreases as the invariant mass increases, but is, in fact, larger than the contribution from quark-antiquark for small invariant masses and small top-quark masses. To illustrate this more clearly we show in Fig. 4 the ratios of the contributions given in Figs. 1 and 2. These results are all consistent with previous calculations of other processes.[2-5] The gluon contribution is not small and does give an important and annoying background in searches for new effects such as the production of the Higgs boson by W^+W^-, ZZ in $pp \rightarrow ZZ+X$.[11] In fact, the box is a factor of 10-20 greater than one would expect from a naive counting of couplings, color factors, and luminosities. This also agrees with previous calculations. This background is not so large, however, as to make invisible new effects in ZZ production.

This determination of gluon production of pairs is the beginning of a larger program. The interference of this process with Higgs-boson production from gluon fusion, $gg \rightarrow H \rightarrow ZZ$, will determine whether gluon fusion can be used to search for the Higgs boson. Here we have concentrated on the ZZ final state because it is the most interesting for detection of the Higgs boson. But other final states are important as well, and $gg \rightarrow W^+W^-$, $gg \rightarrow ZH$, $gg \rightarrow HH$, $gg \rightarrow gH$, as well as a more detailed examination of $gg \rightarrow \gamma\gamma$ and $gg \rightarrow Z\gamma$, will be reported in future publications.

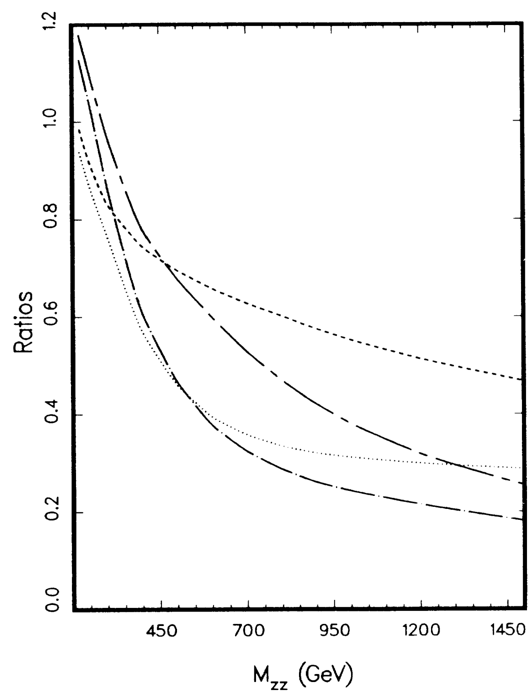

FIG. 4. The ratio of the contribution to $pp \rightarrow ZZ+X$ from $gg \rightarrow ZZ$ to that from $q\bar{q} \rightarrow ZZ$. $\sqrt{s}$ is 40 TeV. The dashed line is for $y_0=1.5$ and a top mass of 100 GeV. The long dash-short dash line is for $y_0=1.5$ and a top mass of 40 GeV. The other two lines have $y_0=2.5$ and a top mass of 100 GeV (dotted line) or 40 GeV (dot-dash line).

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