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Electroweak Interference Effects in Two Jet Production at $p\bar{p}$ Colliders

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ABSTRACT

We study the structure of the W and Z resonance peaks in the di-jet invariant mass distribution in $p\bar{p}$ collisions, including the interference effects with QCD two-jet production. These QCD-electroweak interference effects substantially alter both the shape of the invariant mass distribution and the event rate and must be included if the $W, Z \rightarrow$ two-jet rates are to be determined from the measured distribution.

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Previous $p\bar{p}$ collider data¹⁾ showed evidence for the existence of the decays $W, Z \rightarrow 2$ jets in the form of a broad shoulder in the di-jet invariant mass distribution in the region $m_{jj} \sim M_{W,Z}$, but the experimental statistics and jet mass resolution prevented firm conclusions. A major difficulty is that the W, Z signal is overwhelmed by QCD di-jet production arising from the subprocesses $g\bar{g} \rightarrow g\bar{g}, q\bar{q} \rightarrow q\bar{q}, q\bar{q} \rightarrow q\bar{q}$ etc. However the new high statistics $p\bar{p}$ collider data that are becoming available may offer the possibility of isolating the $W, Z \rightarrow 2$ jet signals²⁾ and of then measuring the branching ratios of W, Z decays into hadrons. Due to QCD-electroweak interference effects in the quark scattering processes, the signal in the di-jet mass distribution is not simply a coherent superposition of W and Z Breit-Wigner resonance forms on the rapidly falling QCD background. A detailed study of such interference effects, emphasizing in particular their polarization properties, was originally made in Refs. 3-5.

In this note we give concise formulae for the relevant matrix elements, including all interference effects, and show how this interference should manifest itself in the di-jet mass distribution in $p\bar{p}$ collisions. The Feynman diagrams contributing to the processes

$$q\bar{q} \rightarrow q\bar{q}, \quad (1)$$

and

$$q\bar{q}' \rightarrow q\bar{q}' \quad (2)$$

are shown in Fig. 1a and 1b respectively, and display the origin of QCD-electroweak interference. The six diagrams of Fig. 1a which contribute to the scattering of identical quarks, process (1), subdivide into three with t -channel exchange and three with u -channel exchange. Due to the exchange of anticommuting fermion fields there is a relative minus sign between the u - and t -channel graphs, which ensures that the total amplitude vanishes when the quarks have identical quantum numbers. When the incoming quarks are distinguishable as in process (2) there is no u -channel g, γ and Z exchange, however, a u -channel W may be exchanged if q and q' differ in charge, see Fig. 1b. The crossed processes, $q\bar{q} \rightarrow q\bar{q}$ and $q\bar{q}' \rightarrow q\bar{q}'$, shown in Fig. 1c and 1d, contain physical s -channel Z and W bosons.

The spin and colour averaged matrix element squared for the process $q\bar{q} \rightarrow q\bar{q}$ of Fig. 1a may be written in the form

$$|\overline{\mathcal{M}}_{q\bar{q}}|^2 = \frac{(4\pi)^2}{4 \cdot 9} [T_{g\bar{g}} + T_{Z\bar{Z}} + T_{\gamma\gamma} + T_{gZ} + T_{g\gamma} + T_{Z\gamma}], \quad (3)$$

where T_{ij} denotes the sum of terms originating from particle i and j exchanges; for example T_{gZ} is the sum of the two $g-Z$ interference terms arising from Fig. 1a. The factor 4.9 in

the denominator of Eq. (3) arises from initial state spin and colour averaging. The various contributions to $|\overline{\mathcal{M}}_{q\bar{q}}|^2$ are

$$T_{g\bar{g}} = 16\alpha_s^2 \left(\frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} - \frac{2}{3} \frac{s^2}{ut} \right), \quad (4)$$

$$T_{Z\bar{Z}} = 36\alpha_Z^2 \left[(c_R^4 + c_L^4) \left(\frac{s^2}{t^2} + \frac{s^2}{u^2} + \frac{2}{3} \frac{s^2}{ut} \right) + 2c_R^2 c_L^2 \left(\frac{u^2}{t^2} + \frac{t^2}{u^2} \right) \right], \quad (5)$$

$$T_{\gamma\gamma} = 72\alpha^2 e_q^4 \left(\frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} + \frac{2}{3} \frac{s^2}{ut} \right), \quad (6)$$

$$T_{gZ} = 32\alpha_s \alpha_Z (c_R^2 + c_L^2) \left(\frac{s^2}{ut} + \frac{s^2}{tu} \right), \quad (7)$$

$$T_{g\gamma} = 128\alpha_s \alpha e_q^2 \frac{s^2}{ut}, \quad (8)$$

$$T_{Z\gamma} = 72\alpha_Z \alpha e_q^2 \left[(c_R^2 + c_L^2) \left(\frac{s^2}{tu} + \frac{s^2}{ut} + \frac{1}{3} \left(\frac{s^2}{ut} + \frac{s^2}{tu} \right) \right) + 2c_R c_L \left(\frac{u^2}{tt} + \frac{t^2}{uu} \right) \right], \quad (9)$$

where α_s, α and

$$\alpha_Z = \frac{\alpha}{\sin^2 \theta_W \cos^2 \theta_W} \quad (10)$$

are the strong, electromagnetic and Z -boson coupling constants, respectively, and θ_W is the Weinberg angle. In the following we use $\alpha = \alpha(M_W) = 1/128$ and $\sin^2 \theta_W = 0.23$. The coefficients of the Z coupling to right- and left-handed quarks of charge e_q are

$$\begin{aligned} c_R &\equiv c_R^q = -2e_q \sin^2 \theta_W, \\ c_L &\equiv c_L^q = 2T_3^q - 2e_q \sin^2 \theta_W. \end{aligned} \quad (11)$$

s, t and u are the usual Mandelstam variables and

$$t_Z \equiv t - M_Z^2, \quad u_Z \equiv u - M_Z^2. \quad (12)$$

$T_{g\bar{g}}$ of Eq. (4) is the well known⁶⁾ QCD contribution to $q\bar{q} \rightarrow q\bar{q}$. It is interesting to note the different origin of the $\pm \frac{2}{3}$ factors which occur in the interference terms in $T_{g\bar{g}}, T_{Z\bar{Z}}$ and $T_{\gamma\gamma}$. The $-\frac{2}{3}$ associated with the interference between t - and u -channel gluon exchange is the trace over the colour matrices $\text{Tr}(T^a T^b T^a T^b)$, whereas $+\frac{2}{3}$, rather than 2, occurs because the other two interference terms are diluted by a factor of 3 on account of colour, that is interference only occurs when all quarks have identical colour. This dilution factor was omitted in Ref. 5.

The matrix element squared $|\overline{\mathcal{M}}_{q\bar{q}}|^2$ describing the crossed channel process $q\bar{q} \rightarrow q\bar{q}$ can be obtained from Eqs. (3)-(10) by interchanging s and u . In addition the Z width must be included as the u -channel pole crosses into the physical s -channel. In summary

$$s \leftrightarrow u, \quad \frac{1}{u_Z} \rightarrow \frac{s_Z}{s_Z^2 + \Gamma_Z^2 M_Z^2}, \quad \frac{1}{u_Z^2} \rightarrow \frac{1}{s_Z^2 + \Gamma_Z^2 M_Z^2}, \quad (13)$$

where $s_Z \equiv s - M_Z^2$.

In analogy to (3), the $qq' \rightarrow qq'$ matrix element squared can be expressed in the form

$$|\overline{\mathcal{M}}_{qq'}|^2 = \frac{(4\pi)^2}{4 \cdot 9} [T_{gg}^* + T_{WW}^* + T_{ZZ}^* + T_{\gamma\gamma}^* + T_{gW}^* + T_{WZ}^* + T_{W\gamma}^* + T_{Z\gamma}^*] \quad (14)$$

where

$$T_{gg}^* = 16\alpha_s^2 \left(\frac{s^2 + u^2}{t^2} \right), \quad (15)$$

$$T_{WW}^* = 9\alpha_W^2 |V_{qq'}|^4 \frac{s^2}{u_W^2}, \quad (16)$$

$$T_{ZZ}^* = 36\alpha_Z^2 \left[(c_R^2 c_L^2 + c_L^2 c_L^2) \frac{s^2}{t_Z^2} + (c_R^2 c_L^2 + c_R^2 c_L^2) \frac{u^2}{t_Z^2} \right], \quad (17)$$

$$T_{\gamma\gamma}^* = 72\alpha^2 e_q^2 e_{q'}^2 \left(\frac{s^2 + u^2}{t^2} \right), \quad (18)$$

$$T_{gW}^* = 16\alpha_s \alpha_W |V_{qq'}|^2 \frac{s^2}{tu_W}, \quad (19)$$

$$T_{WZ}^* + T_{W\gamma}^* = 12\alpha_W |V_{qq'}|^2 \frac{s^2}{u_W} \left[c_L c_L' \alpha_Z \frac{1}{t_Z} + e_q e_{q'} \alpha \frac{1}{t} \right], \quad (20)$$

$$T_{Z\gamma}^* = 72\alpha_Z \alpha e_q e_{q'} \left[(c_R c_R' + c_L c_L') \frac{s^2}{tt_Z} + (c_R c_L' + c_R' c_L) \frac{u^2}{tt_Z} \right], \quad (21)$$

with $u_W \equiv u - M_W^2$, $c_{L,R} \equiv c_{L,R}^q$ of Eq. (11) and $c_{L,R}' \equiv c_{L,R}^{q'}$. $V_{qq'}$ denotes the qq' element of the weak mixing matrix and

$$\alpha_W = \frac{\alpha}{\sin^2 \theta_W} \quad (22)$$

is the W coupling constant. Due to colour, there is no $g - Z$ or $g - \gamma$ interference term in $\mathcal{M}_{qq'}$ of Eq. (14). Also W exchange terms only occur when q and q' can be coupled via a weak mixing matrix element $V_{qq'}$.

The two crossed processes

$$q\bar{q}' \rightarrow q\bar{q}', \quad q\bar{q} \rightarrow q'\bar{q}', \quad (23)$$

containing either a physical W or Z boson are obtained by making the substitutions

$$s \leftrightarrow u, \quad \frac{1}{u_W} \rightarrow \frac{s_W}{s_W^2 + \Gamma_W^2 M_W^2}, \quad \frac{1}{u_W^2} \rightarrow \frac{1}{s_W^2 + \Gamma_W^2 M_W^2} \quad (24)$$

and

$$s \leftrightarrow t, \quad \frac{1}{t_Z} \rightarrow \frac{s_Z}{s_Z^2 + \Gamma_Z^2 M_Z^2}, \quad \frac{1}{t_Z^2} \rightarrow \frac{1}{s_Z^2 + \Gamma_Z^2 M_Z^2} \quad (25)$$

respectively. Finally we must include the important contribution from the subprocess

$$qq' \rightarrow q'' q''' \quad (26)$$

in which all four quarks are distinct, e.g. $us \rightarrow cd$. Here only u -channel W exchange can occur and

$$|\overline{\mathcal{M}}|^2 = \frac{(4\pi)^2}{4 \cdot 9} 9\alpha_W^2 |V_{qq''}|^2 |V_{qq''}|^2 \frac{s^2}{u_W^2}. \quad (27)$$

As before, the crossed process, $qq''' \rightarrow q'' q'$, is obtained by making the substitutions of Eq. (24).

Using all the above $qq \rightarrow qq$ matrix elements, together with those for the pure QCD subprocesses $gg \rightarrow gg$ and $gg \rightarrow q\bar{q}$,⁶⁾ we calculate the $p\bar{p} \rightarrow 2$ jet cross section as a function of the invariant mass m_{jj} of the di-jet system. For the parton structure functions we use set 1 of Duke and Owens,⁷⁾ evaluated at $Q^2 = p_{Tj}^2$, where p_{Tj} denotes the jet transverse momentum. For the masses and widths of the weak bosons we take $M_Z = 91$ GeV, $M_W = M_Z \cos \theta_W = 79.85$ GeV, $\Gamma_Z = 2.51$ GeV and $\Gamma_W = 2.09$ GeV, corresponding to a top quark of mass $m_t > M_W - m_b$. The K factor is assumed to be equal to one.

The detailed electroweak interference structure is displayed in Fig. 2 where we show the modification of the QCD two jet mass distribution at the CERN $p\bar{p}$ collider and the Tevatron arising from the presence of the W and Z bosons

$$\frac{d\sigma_{EW}}{dm_{jj}} \equiv \frac{d\sigma_{tot}}{dm_{jj}} - \frac{d\sigma_{QCD}}{dm_{jj}} \quad (28)$$

which in addition to the purely electroweak terms also contains the QCD-electroweak interference contributions (solid lines). To exhibit the effect induced by the nonresonant

electroweak terms and the interference between QCD and electroweak amplitudes we also include the pure s -channel W and Z resonance cross sections (dashed lines). Finally, the dotted lines represent the pure QCD two jet cross section, scaled by a factor 10^{-2} .

The well known ratio of $\sigma_Z/\sigma_W \simeq 1/3$ is evident from Fig. 2. The W , Z signals appear small on account of the large QCD background which is dominated by gluon induced subprocesses. Integrating over twice the $W(Z)$ width, we find that the background dominates over the $W(Z)$ signal by about a factor 40(80) at CERN collider energies. At $\sqrt{s} = 1.8$ TeV this ratio is increased to 200(300), see Fig. 2b. Thus, extraction of the W , Z signal at the Tevatron will be much more difficult than at the CERN collider. While QCD-electroweak interference terms are positive below the $W(Z)$ mass, they are negative for invariant masses larger than M_W , M_Z . As a result the differential cross section $d\sigma/dm_{jj}$ is increased for $m_{jj} < M_W$ and decreased for $m_{jj} > M_Z$. Between the two peaks the interference effects from the W and the Z partly cancel and $d\sigma/dm_{jj}$ is only little affected. Furthermore, the interference effects shift the W and Z peak downwards by about 0.3 GeV.

The invariant mass spectrum shown in Fig. 2 does not yet include effects induced by the finite jet mass resolution of the detector in an actual experiment. In the UA2 experiment, for example, m_{jj} can be determined with an accuracy of about 10%.^{1,2)} Figure 3 shows $d\sigma_{EW}/dm_{jj}$ (solid line) and the pure s -channel W and Z resonance cross sections (dashed line) for the CERN $p\bar{p}$ collider when the experimental jet mass resolution, simulated by Gaussian smearing of m_{jj} with standard deviation $\Delta m = 0.1 \times m_{jj}$, is taken into account. Since Δm is much larger than Γ_W and Γ_Z in the W , Z mass region the resonance peaks are considerably broadened and the maximal cross section is strongly reduced. Furthermore, the individual W and Z peaks can no longer be resolved. The observable W , Z signal in the two-jet channel thus consists of a broad enhancement in $d\sigma/dm_{jj}$ in the mass region $65 \text{ GeV} \leq m_{jj} \leq 100 \text{ GeV}$ with a maximum around M_W .

It is evident from Fig. 3 that interference effects between QCD and electroweak amplitudes affect the shape of the observable W , Z signal substantially. For $m_{jj} < 84 \text{ GeV}$ the cross section is significantly larger than the rate from pure s -channel W and Z resonance production. The total event rate in the di-jet invariant mass range $65 \text{ GeV} \leq m_{jj} \leq 100 \text{ GeV}$ which is attributable to W , Z production is increased by 17% when non-resonant electroweak contributions and interference effects are included. Below $m_{jj} = 60 \text{ GeV}$ $d\sigma_{EW}/dm_{jj}$ begins to increase slowly. This effect is caused by s -channel photon exchange which, as the di-jet mass is decreased, becomes more and more important.

In conclusion, we have calculated electroweak interference effects in two jet production at $p\bar{p}$ colliders in the W , Z mass range. The shape of the two jet invariant mass distribution is found to be affected significantly in the resonance region when the finite experimental jet mass resolution is taken into account. Due to the increased experimental statistics at the CERN collider it should soon be possible to isolate the W , $Z \rightarrow 2$ jet signal. Our results show that effects caused by the interference between electroweak and QCD amplitudes must be taken into account when data are compared with theoretical predictions.

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FIGURE CAPTIONS

1. Feynman diagrams for (a) $q\bar{q} \rightarrow q\bar{q}$ and (b) $q\bar{q}' \rightarrow q\bar{q}'$ scattering. The crossed processes $q\bar{q} \rightarrow q\bar{q}$ and $q\bar{q}' \rightarrow q\bar{q}'$ are shown in (c) and (d) respectively.
2. The di-jet invariant mass distribution in the W and Z resonance regions at (a) the CERN collider ($p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV) and (b) the Tevatron ($p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV). The solid and dashed lines show $d\sigma_{EW}/dm_{jj}$ (see Eq. (28)) and the pure s -channel W and Z resonance contributions, respectively. The dotted line gives the QCD two-jet cross section, scaled by a factor 10^{-2} . To roughly simulate detector response transverse momentum and pseudorapidity cuts of $p_{Tj} > 12$ GeV and $|\eta_j| < 0.7$ at the CERN collider, and $p_{Tj} > 20$ GeV and $|\eta_j| < 1.4$ at the Tevatron are imposed. The K -factor is assumed to be equal to one.
3. The di-jet invariant mass distribution in the W and Z resonance regions at the CERN collider for a jet-jet invariant mass resolution of $\Delta m = 0.1 \times m_{jj}$. A transverse momentum cut of $p_{Tj} > 12$ GeV and a pseudorapidity cut of $|\eta_j| < 0.7$ are imposed. The solid and dashed line show $d\sigma_{EW}/dm_{jj}$ (see Eq. (28)) and the pure s -channel W and Z resonance contributions, respectively. A K -factor equal to one is assumed.

Fig. 1

Fig. 2a

Fig. 2b

Fig. 3