CERN-TH.4209/85

W⁺W⁻ PAIR PRODUCTION IN HIGH ENERGY HADRONIC COLLISIONS:

SIGNAL VERSUS BACKGROUND

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A B S T R A C T

We assess the prospects for measuring the cross sections for the production of W⁺W⁻ pairs in $\bar{p}p$ collisions at very high energy, including those pairs resulting from possible Higgs boson production and subsequent decay. We find that if one of the W's decays hadronically the signal is completely dominated by a background from standard W + two-jet production where the jet-jet mass is order M_W . It would appear therefore that a double leptonic decay is required, with a subsequent loss in rate.

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CERN-TH.4209/85

June 1985

1. - INTRODUCTION

It has been known¹⁾ for some time that the production of gauge boson pairs can provide a decisive test of the structure of the standard electro-weak model. Consider for example the parton level process

$$Q\bar{Q} \rightarrow W^+W^- \quad (1)$$

In the absence of the trilinear γW^+W^- and $Z^0 W^+W^-$ couplings the cross section for this process grows as s/M_W^4 with increasing s and so eventually violates unitarity. Therefore a measurement of this cross section tests the cancellations expected in the various standard model amplitudes. The WW final state is also considered as the most promising channel in which to search for a possible Higgs boson if $M_H > 2 M_W$. This intrinsic interest in weak boson pair production has been recognized in the proposals for very high energy hadron-hadron²⁾ and electron-positron colliders. As the cross sections are not particularly large at realizable energies it is very important to investigate the precise effects of experimental acceptance, cuts, etc., and to assess the relevant backgrounds.

In this letter we shall analyze in some detail the production of W^+W^- pairs in $\bar{p}p$ collisions at high energy. We are particularly interested in the question of whether, to avoid loss of rate, it is possible to identify one W through its hadronic decay, i.e., via $\bar{p}p \rightarrow W(\rightarrow \ell\nu) + W(\rightarrow jj)$ where j stands for a hadronic (light quark) jet. The principal background comes from the QCD parton subprocesses

$$\begin{aligned} Q\bar{Q} &\rightarrow WQ\bar{Q}, \\ QQ &\rightarrow WQQ, \\ QG &\rightarrow WQG, \\ GG &\rightarrow WQ\bar{Q}, \text{ etc.}, \end{aligned} \quad (2)$$

where the mass of the jet pair in the final state is of order M_W . The Feynman diagrams for the W^+W^- "signal" and some of those for the Wjj background are shown in Fig. 1.

The processes (2) have already been analyzed³⁾ in the context of $W+2\text{jet}$ production at the CERN $\bar{p}p$ collider. Here we are interested in jet pairs of much larger invariant mass than those typically observed at the collider and, of course, in a much larger overall centre-of-mass energy. The results of a preliminary study of this mass and energy regime have already been reported^{3,4)}.

In the next section we analyze the signal and background for the $W(\rightarrow \ell \nu) + W(\rightarrow jj)$ final state. We shall conclude that it is unlikely that WW pairs can be detected this way, and thus only double leptonic decays $W(\rightarrow \ell \bar{\nu}) + W(\rightarrow \bar{\ell} \nu)$ lead to an observable signal. Accordingly in Section 3 we present cross-sections for the double leptonic mode. Whether or not this cross-section will in practice be measurable depends on the energy, luminosity, detector acceptance and efficiency, etc., of a given experiment. For illustration we shall present results for a range of energies and acceptances. Section 4 contains some concluding remarks.

2. - ONE LEPTONIC, ONE HADRONIC DECAY

The signal which we wish to investigate is

$$\bar{p}p \rightarrow W^-(\rightarrow e^-\bar{\nu}) + W^+(\rightarrow Q\bar{Q}' \rightarrow j_1 j_2) + X \quad (3)$$

plus its charge conjugate ($\rightarrow e^+\nu + \bar{Q}Q'$). The subprocess amplitudes are calculated from the diagrams of Fig. 1a. We explicitly include the W decays in order that experimental cuts can be properly imposed on the final state. A sum is taken over light quark decays ($u\bar{d}$, $c\bar{s}$).

The background comes from the processes depicted in Fig. 1b, i.e.,

$$\bar{p}p \rightarrow W^-(\rightarrow e^-\bar{\nu}) + [QQ', Q\bar{Q}', \bar{Q}Q', QG, \bar{Q}G, GG] + X \quad (4)$$

plus its charge conjugate where again we take the leptonic decay of the W explicitly into account. For both the signal and the background we restrict the final state parton (jet) pairs to have an invariant mass M_{jj} in the range

$$M_W - \Delta < M_{jj} < M_W + \Delta. \quad (5)$$

For the signal this corresponds to integrating over the W resonance while for the background a small Δ - say $O(10 \text{ GeV})$ - guarantees that the jet pair mimics a true two jet W decay⁵⁾. For the background we sum over all possible light quark (u, d, s, c, b) and gluon combinations. We are explicitly assuming that it is impossible to reliably distinguish quark jets of different flavour and gluon jets. This appears to be the case at the CERN $\bar{p}p$ collider. Otherwise, of course,

the background could be substantially reduced by rejecting all pairs of incorrect flavour.

As in our previous work we are representing the final state jets in terms of massless partons. While this procedure certainly contains uncertainties³⁾, it does provide an adequate overall description of the CERN $\bar{p}p$ collider data on W , Z^0 + jets. Thus it is certainly satisfactory for a preliminary examination of the signal versus background question where, in any case, jet reconstruction efficiencies will tend to cancel in the comparison. A precise quantitative analysis of the absolute rates would require a full detector simulation with a hadronization model (see, e.g., Ref. 5)).

In order to keep the analysis as general as possible we shall use a set of representative cuts which are typical of present collider experiments. In particular we assume 100% detection efficiency for final state leptons and jets which have

- (a) a minimum transverse momentum

$$P_T^L, P_T^J > P_T^0 ;$$

- (b) a maximum pseudorapidity

$$|\eta^L|, |\eta^J| < \eta_0 ;$$

and (c) a minimum mutual angular separation

$$\Delta r(\ell, j), \Delta r(j_1, j_2) > r_0$$

with $\Delta r^2 = \Delta\phi^2 + \Delta\eta^2$ where ϕ is the azimuthal angle. From the standpoint of comparing signal and background the precise values of P_T^0 and r_0 (and the standard model parameters M_W , M_Z , α , ...) are not particularly crucial. We shall use $P_T^0 = 10$ GeV/c and $r_0 = 1$ for illustration. As expected, there is greater sensitivity at very high energy to the pseudorapidity cut η_0 . Unless otherwise stated we use $\eta_0 = 2.5$, which corresponds to detection down to an angle of 9.4° from the beam direction. All the cross sections in this letter are calculated using the structure functions of Eichten et al.¹⁾ (set I, $\Lambda = 200$ MeV) which have been specifically developed for high $\sqrt{s}$ (low x) studies.

Figure 2 shows the cross sections for the $e\nu j_1 j_2$ final state from the signal (WW) and background (Wjj) processes using the cuts defined above for

both. Also shown is the WW cross section with no cuts imposed on the final state, i.e., $\sigma_{\text{tot}}^{\text{WW}} * 2 * B(W^- \rightarrow e^- \nu) B(W^+ \rightarrow Q \bar{Q}')$. Apart from the branching ratios, this corresponds to the total cross-section as calculated originally by Brown and Mikaelian⁶⁾. We see immediately that the background completely dominates the signal at all relevant values of $\sqrt{s}$.

Before concluding that the situation is hopeless, we must consider whether there are any additional cuts which could reduce the background to signal ratio. A priori there are two obvious possibilities:

(i) Decrease the pseudorapidity interval. Recall that the QCD Wjj cross sections are singular when the final state partons are collinear with the incoming partons. The jet rapidity distribution for the background is therefore broader than that for the jets from WW decay, which have no analogous beam direction singularity. Figure 3 shows, however, that although decreasing η_0 has qualitatively the right effect, the improvement in the signal to background ratio is too small to be of any use.

(ii) Decrease the jet-jet mass window Δ . While decreasing Δ certainly reduces the background faster than the signal (the variation is approximately linear for the former), the actual benefit is minimal as indicated in Fig.4. Notice that as expected the signal is little affected until Δ decreases to $O(\Gamma_W)$. In reality, the value of Δ will be determined by how well a given detector and jet algorithm can reconstruct the mass of a W from its hadronic decay. Present experience suggests that a Δ value of 10 GeV is not unreasonable.

Our pessimistic conclusion does not imply that there are no corners of phase space where the background is less important. However, there is little advantage in choosing cuts which at the same time substantially reduce the signal. Note, for example, that at $\sqrt{s} = 20$ TeV the signal is already reduced by an order of magnitude going from $\eta_0 = 2.5$ to $\eta_0 = 1$. At this point it is better to return to the double leptonic decay.

3. - DOUBLE LEPTONIC DECAY

Consider now the QCD background free double leptonic decay mode $W(\rightarrow \ell \bar{\nu}) + W(\rightarrow \bar{\ell} \nu)$. For illustration, we show in Fig. 5 some typical cross sections as a function of centre-of-mass energy. We have summed over the final states $[e^-e^+, e^-\mu^+, \mu^-e^+, \mu^-\mu^+] +$ two neutrinos. For representative cuts we require that the charged leptons should have $|\vec{p}_T^\ell| > 10$ GeV/c and pseudorapidity less than 2.5 (dashed line) or 1.5 (dot-dashed line). We also require that the missing transverse momentum $|\vec{p}_{T_{\nu_1}} + \vec{p}_{T_{\nu_2}}|$ be greater than 10 GeV/c. Note that when similar cuts are applied to a single electron and missing neutrino in the UA1 data⁷⁾, the resulting signal seems to be clearly dominated by single W leptonic decay. Thus we anticipate that the signal defined by these cuts will be dominated by the decay of WW states even though the precise mass of the WW state may be difficult to reconstruct (due to the fact that 2 neutrinos are missing). Also shown (solid line) is the cross-section with no cuts. We see that, as expected, the rapidity cuts become more effective at higher energy. For an integrated luminosity of 10^{39} cm⁻² at $\sqrt{s} = 40$ TeV the expected numbers of events are 5800 (no cuts), 2500 (cuts, $|\eta| < 2.5$) and 1120 (cuts, $|\eta| < 1.5$). Note that we have not included the (small) contribution to the $e^-e^+ + 2\nu$ and $\mu^-\mu^+ + 2\nu$ final states from double Z^0 production and decay: $\bar{p}p \rightarrow Z^0(\rightarrow e^-e^+, \mu^-\mu^+) + Z^0(\rightarrow \nu\bar{\nu}) + X$. The same channels could also in principle be contaminated with single Z^0 production and leptonic decay with a missing energy fluctuation in the underlying event or from $Z^0 \rightarrow \tau\tau \rightarrow (\ell + \bar{\ell}' + \nu's)$ ⁸⁾. Of course charged lepton pairs with a mass in the vicinity of M_Z could be vetoed with not much loss in rate to remove all but the last background process listed.

4. - DISCUSSION

In a sense it is not surprising that the W + two-jet background dominates the WW signal. Recall that it is just as difficult to detect single W production via the hadronic (two-jet) decay of the W again because of the QCD two-jet background. The reason is simply that there are many $2 \rightarrow 2$ subprocesses - involving all flavours of quarks and gluons - which contribute to two-jet production. It would appear that the requirement of an additional W in the final state does not change this situation qualitatively. For example, in the present case, if we simply count the contributions which come in coherently and then square the result and sum over all incoherent contributions, we find a characteristic measure of order 600 for the process $W(\rightarrow \ell \nu) + 2$ QCD jets and only

order 30 for $W(\rightarrow \ell \nu) + W(\rightarrow Q\bar{Q})$. It is also important to note the calculations discussed here indicate that at the lowest energies discussed (630 GeV) the QQ (plus $Q\bar{Q}$ and $\bar{Q}\bar{Q}$) and the QG (plus $\bar{Q}G$) initial states make comparable contributions (~50% each) with GG giving less than 1% while at the highest energy (40 TeV) the dominant contribution comes from QG plus $\bar{Q}G$ (~85%) with both QQ (plus $Q\bar{Q}$ and $\bar{Q}\bar{Q}$) and GG less than 10% each. This is to be contrasted with purely QCD processes at similar sub-energies where GG is expected to be dominant.

A very important question⁹⁾ concerns the possibility of detecting a Higgs boson produced in high energy hadronic collisions via its W^+W^- decay (the dominant mode for $M_H > 2 M_W$). A detailed study, taking into account all possible Higgs boson masses, is beyond the scope of the present letter. Nevertheless the conclusion is rather clear. In the analysis of Ref. 1), the W^+W^- "signal" of the present work is taken as the background to the process

$$(-)_p \rightarrow H(\rightarrow W^+W^-) + X \quad (6)$$

when the mass of the W pair is of order M_H . Again, one might wish to exploit the hadronic decay of one of the W's. The relevant quantity is then the ratio of $W + \text{two-jets}$ to $W + W(\rightarrow \text{two-jets})$ as a function of the $W + \text{jets}$ invariant mass. This is shown in Fig. 6 for $\sqrt{s} = 40$ TeV where the upper histogram corresponds to the background process and the lower to the signal. The signal to background ratio of $O(10^{-2})$ noted above is seen to be approximately independent of the invariant mass of the produced system, at least up to masses of 1 TeV. Also shown in the figure, as shaded histograms, are the extra contributions to the lower curve which would arise if a standard Higgs boson existed at a mass of 200 or 400 or 600 GeV/c². The Higgs boson is assumed to be produced via a combination of GG fusion¹⁾ and WW + ZZ fusion¹⁰⁾. The widths of these resonances are determined by the calculated Higgs width at the stated mass value. It is clear, as already noted in Ref. 1), that Higgs boson production and decay into WW is, at most, only comparable to the continuum WW production rate integrated over an appropriate range in M_{WW} for these values of M_H . The new result here is that both processes are overwhelmed in the $W(\rightarrow \ell \nu) + W(\rightarrow jj)$ decay channel by the QCD background. Again, the double leptonic mode $H \rightarrow WW \rightarrow \ell \bar{\nu} \ell' \nu$, even with the ambiguity in reconstructing the WW mass, and the mode $H \rightarrow Z^0 Z^0 \rightarrow (\ell \bar{\ell})(\ell' \bar{\ell}')$, appear to be more realistic possibilities. A more detailed study is in progress.

Finally notice that for simplicity and brevity we have been considering proton-antiproton collisions only. This is appropriate for the present generation of hadron colliders. At much higher energies, the differences between the pp and $\bar{p}p$ cross sections become smaller and we have checked that our conclusions are exactly the same for W pair production in proton-proton collisions. For completeness we should also note that the WW and Wjj production rates will also receive contributions from double scattering processes¹¹⁾ which are interesting in their own right. However, we anticipate³⁾ that such double parton collision processes will constitute a relatively small contribution to the processes discussed here even at the highest energies of interest.

ACKNOWLEDGEMENTS

We acknowledge many helpful discussions with our colleagues at CERN. Special thanks go to R. Cahn, M. Jacob and S. Geer.

NOTE ADDED: After the completion of the work described here we learned that a similar analysis using similar techniques to focus on the background to Higgs boson detection due to the $GG \rightarrow Q\bar{Q}W$ subprocess has been performed by J.F. Gunion, Z. Kunszt and M. Soldate, preprint OITS-298(1985).

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- 4) W.J. Stirling in the Proceedings of the 5th Topical Workshop on Proton-Antiproton Collider Physics, (St. Vincent, Italy, February 1985) and S.D. Ellis, R. Kleiss and W.J. Stirling preprint CERN-TH. 4185/85 (1985).
- 5) Note that the background discussed here is largely distinct from the $W + 1$ jet (plus fragmentation) channel studied in detail by E. Fernandez, et al., Proceedings of the 1984 DPF Summer Study on Design and Utilization of the SSC, (Snowmass, CO, June-July 1984), page 107. The various mass and shape cuts used to such advantage in that study to separate $W \rightarrow Q\bar{Q}$ from single jet fragmentation will not be so effective in controlling the 2 jet background discussed here.
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- 7) See, e.g., G. Arnison, et al., Phys. Lett. 129B(1983)273.
- 8) We thank S. Geer for pointing out this background source.
- 9) For a recent study see L. Roberts, preprint ITP-SB-85-16(1985). See also Ref. 1).
- 10) R.N. Cahn and S. Dawson, Phys. Lett. 136B(1984)196; R.N. Cahn, preprint LBL-18736(1984). We thank R. Cahn for explaining the techniques of this latter paper to us.
- 11) See, for example, B. Humpert, Phys. Lett. 135B(1984)179.

FIGURE CAPTIONS

- 1) (a) Feynman diagrams which contribute to W^+W^- production in hadronic collisions.
 (b) Examples of Feynman diagrams for the background process $\bar{p}p \rightarrow W + 2 \text{ jets} + X$.
- 2) Cross sections for $\bar{p}p \rightarrow e\nu j_1 j_2 + X$ as a function of the collision energy $\sqrt{s}$. The solid line is the background contribution $\bar{p}p \rightarrow W(\rightarrow e\nu) + j_1 j_2 + X$ and the dashed line is the signal $\bar{p}p \rightarrow W(\rightarrow e\nu) + W(\rightarrow j_1 j_2) + X$, both calculated using the jet and lepton cuts described in the text. The WW contribution with no cuts is also indicated as the dashed-dotted line.
- 3) Dependence of the signal (dashed line) and background (solid line) contributions of Fig. 2 on the pseudorapidity acceptance $|\eta| < \eta_0$ of the final state electron and jets at collision energies $\sqrt{s} = 2, 20$ TeV.
- 4) Dependence of the signal (dashed line) and background (solid line) contributions of Fig. 2 on the mass window for accepting a jet pair as (if) coming from a W decay, i.e., $M_W - \Delta < M_{j_1 j_2} < M_W + \Delta$ at $\sqrt{s} = 2, 20$ TeV.
- 5) Cross sections for the double leptonic decay mode, $\bar{p}p \rightarrow W(\rightarrow \ell \bar{\nu}) + W(\rightarrow \bar{\ell}' \nu') + X$, as a function of the collision energy $\sqrt{s}$. A sum is taken over ee, e μ , $\mu\mu$ final states. The curves correspond to (a) no final state cuts (solid line) and (b) pseudorapidity and transverse momentum cuts as described in the text: $|\eta| < 2.5$ (dashed line) and $|\eta| < 1.5$ (dash-dotted line).
- 6) Distributions in the invariant mass M of the $e\nu j_1 j_2$ final state at $\sqrt{s} = 40$ TeV in $\bar{p}p$ collisions. The lepton and jet cuts are the same as those in Fig. 2. Also shown as the shaded histograms are the contributions to the same final state from Higgs production and decay, $H \rightarrow W(\rightarrow e\nu) + W(\rightarrow j_1 j_2)$, for three choices of the Higgs mass: $M_H = 200, 400$, and 600 GeV.

- Figure 1 -

- Figure 2 -

- Figure 3 -

- Figure 4 -

- Figure 5 -

- Figure 6 -