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LARGE TRANSVERSE MOMENTUM W PRODUCTION AT HADRON COLLIDERS*

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Abstract

Motivated by the recent observation of events in which a large transverse momentum W has been produced together with two energetic jets at the CERN proton-antiproton collider, we consider standard model processes in which a W is created in association with a second weak boson which then decays hadronically into two jets. We find that the production and decay of heavy quark-antiquark pairs can give rise to an observable number of (WW) events in existing collider data samples if the heavy-quark mass is close to the W mass. We calculate the expected event rates for proton-antiproton colliders operating in the energy range 0.6 to 2.0 TeV, and discuss the kinematic properties of the events, and the identity of the heavy quark Q which could be either the top quark, or a down-type quark from a new (fourth) generation.

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1. Introduction

The UA1 collaboration has recently reported the existence of two events at the CERN proton-antiproton collider in which a charged Intermediate Vector Boson (W) has been produced with very large transverse momentum ($p_t \geq m_W$) in association with two energetic hadronic jets [1]. In one event the W decays in the ($e\nu$) channel, and in the other event the W decays in the ($\mu\nu$) channel. In both events the mass of the two-jet system is close to the W mass, and the mass of the (W+jet+jet)-system is in the range 250 - 300 GeV/c^2. In addition to the UA1 events, the UA2 collaboration has also reported events containing a large transverse momentum W candidate, decaying in the ($e\nu$) channel, and produced in association with energetic jet activity [2].

High-p_t W bosons are expected to be produced with associated jet activity at the CERN collider when an incoming quark or antiquark radiates a hard gluon before interacting to produce a W boson. The QCD expectations [3] for this initial state gluon bremmstrahlung give a good description of the experimental data [4] for W bosons with transverse momentum $p_t \leq 40$ GeV/c. However, the expected number of events in the current collider data samples in which a W with $p_t \geq m_W$ is produced in association with two hard gluons (and hence two hadronic jets) is predicted to be small [1]. Furthermore, if we also require the (W+jet+jet)-mass to be greater than 250 GeV/c^2(as it is the case for the two UA1 events), the O(α_s^2) QCD calculation predicts $\leq$ O(10^{-2}) events in the current UA1 data samples[5].

Motivated by these observations in this paper we discuss the production of large transverse momentum W-bosons ($p_t \geq m_W$) at existing hadron colliders, i.e. those operating in the energy range 0.63$\leq \sqrt{s} \leq 2$ TeV.We restrict our attention to processes in which a high-p_t W, which decays in the ($e\nu$) or ($\mu\nu$) channel, is produced in association with a second weak boson (W, Z, or Higgs) which decays hadronically to produce two energetic jets. The cross- sections for (WW), (WZ), and (WH) production at hadron colliders operating with energies ranging from $\sqrt{s} = 0.54\ TeV$ up to the proposed SSC energy, $\sqrt{s} = 40\ TeV$ can be found in refs. [6,7]. At the CERN collider the cross-sections for (i) direct (WW), (WZ), or (WH) production from parton-parton collisions, and (ii) (WW) production from the decay of a massive Higgs boson, are even smaller than the double bremsstrahlung we just mentioned. Indeed, the process with the largest cross-section, W^+W^- pair production from direct parton- parton collisions, is still no more than 0.3 picobarn at $\sqrt{s} = 0.63$ TeV. All the other processes, in this energy range, are smaller by one or more orders of magnitude. Therefore we will not consider these processes further. There is however another standard model process that can give rise to

$$p\bar{p} \rightarrow W + jet + jet + X \tag{1}$$

namely :

$$p\bar{p} \rightarrow Q + \bar{Q} + X \rightarrow W^+q + W^-\bar{q} + X \tag{2}$$

i.e. heavy quark-antiquark production with $m_Q \geq m_W$ so that real (or nearly real) W bosons are produced from the Q and $\bar{Q}$ decays. In the following section we show that if m_Q is close to m_W the cross-section for this process is large enough to have produced several (WW + X) events in the current UA1 data samples (which correspond to 0.7 pb^{-1} in the electron channel). Results are presented for the expected event rates arising from process (2) at the CERN collider ($\sqrt{s}$ = 0.63 TeV), and at the Fermilab collider ($\sqrt{s}$ = 2.0 TeV), together with the associated heavy quark transverse momentum distributions, and the (Q$\bar{Q}$)-mass distributions. Finally, we note that a priori Q could be either the top quark, or the up- or down-type quark from a new (fourth) generation. In section 3 we discuss these possible assignments to Q.

2. Heavy Quark Production and Decay

The lowest order elementary QCD processes which contribute to heavy quark production are

$$q\bar{q} \rightarrow Q + \bar{Q}$$

and

$$gg \rightarrow Q + \bar{Q}$$

Their cross-sections [8] are respectively :

$$\frac{d\sigma_{q\bar{q}}}{d\hat{t}} = \frac{4\pi\alpha_s^2}{9\hat{s}^2}\left[\frac{(\hat{t}-m_Q^2)^2+(\hat{u}-m_Q^2)^2+2m_Q^2\hat{s}}{\hat{s}^2}\right] \tag{3}$$

and

$$\frac{d\sigma_{gg}}{d\hat{t}} = \frac{\pi\alpha_s^2}{8\hat{s}^2}\left[\frac{6}{\hat{s}^2}(\hat{t}-m_Q^2)(\hat{u}-m_Q^2) - \frac{m_Q^2(\hat{s}-4m_Q^2)}{3(\hat{t}-m_Q^2)(\hat{u}-m_Q^2)} + \right. \tag{4}$$
$$\left. + \left[\left[\frac{4}{3}\frac{(\hat{t}-m_Q^2)(\hat{u}-m_Q^2)-2m_Q^2(\hat{t}+m_Q^2)}{(\hat{t}-m_Q^2)^2} + \frac{3(\hat{t}-m_Q^2)(\hat{u}-m_Q^2)+m_q^2(\hat{u}-\hat{t})}{\hat{s}(\hat{t}-m_Q^2)}\right] + [\hat{t}\leftrightarrow\hat{u}]\right]\right]$$

Taking $Q^2 = 4m_Q^2$, $\Lambda = 0.29$ GeV, and integrating (3) and (4) over the evolved parton densities of ref. [7] (EHLQ set 2), we obtain the Q$\bar{Q}$ production cross-section as a function of m_Q (figure 1) for proton-antiproton collisions in the energy range $0.63 \leq \sqrt{s} \leq 2$ TeV. We emphasize that our numerical results are for the lowest order QCD processes only, and do not include a K-factor which could easily double the calculated cross-sections. The large increase of the cross-section from $\sqrt{s} = 0.63$ TeV to 2 TeV is partly due to the increased contribution from gluon-gluon fusion diagrams. Taking $m_Q = 90$ GeV/c^2, at $\sqrt{s} = 0.63$ TeV the typical incoming partons interacting to produce a $Q\bar{Q}$ pair have a longitudinal momentum $x \approx 0.3$, and the contribution to $Q\bar{Q}$ production from gluon-gluon fusion diagrams is negligible. In contrast to this, at $\sqrt{s} = 2$ TeV the contribution from gluon-gluon fusion is comparable to the contribution from quark-antiquark annihilation. Since extrapolations to much higher energies require the use of gluon densities in a region where the QCD uncertainties are large, we have limited our analysis to the presently available energy range. The broken lines in figure 1 indicate the value of the direct (WW) cross-sections (using evolved parton densities and no K-factor) at the two center-of-mass energies. We notice that at the CERN collider, the production of W pairs from $Q\bar{Q}$ production and subsequent decay dominates direct (WW) production for heavy quark masses $m_Q \leq 120$ GeV/c^2. For heavy quarks with a mass $m_Q = 90$ GeV/c^2 the $Q\bar{Q}$ production cross-section is 4 pb, large enough to have resulted in several (WW) events in the UA1 data samples. Furthermore, for values of m_Q only just above the (W + q) threshold the light quark q (a b-quark if Q is the top-quark) will tend to be produced with little transverse momentum, and will therefore not produce a recognised hadronic jet in the event. If one W subsequently decays in the $(e\nu)$ or $(\mu\nu)$ channel, and the second W decays hadronically, the resulting event will tend to have an isolated lepton + neutrino + two-jets, consistent with the the observed UA1 event topologies.

To investigate the dependence of the $Q\bar{Q}$ event topology and kinematics on m_Q we calculate the invariant mass spectrum of the electron-neutrino pair arising from the semileptonic decay of one of the heavy quarks. The partial width for the weak decay of a heavy quark Q into the three body final state $(qe\nu)$ has been recently shown [9] to be given by :

$$\Gamma(Q \to q + W(\to e\nu)) = \frac{{G_F}^2 m_Q^5}{192\pi^3} |U_{Qq}|^2 f\left(\frac{m_Q^2}{m_W^2}, \frac{m_q^2}{m_Q^2}, \frac{\Gamma_W^2}{m_W^2}\right)$$

with

$$f(\rho,\mu,\gamma) = 2\int_0^{(1-\sqrt{\mu})^2} \frac{dx}{(1-x\rho)^2+\gamma}\left[(1-\mu)^2+(1+\mu)x-2x^2\right]$$
$$\times\sqrt{1+\mu^2+x^2-2(\mu+\mu x+x)}$$

The invariant mass distribution of an electron-neutrino pair produced in this way is given by :

$$\frac{d\sigma}{dm_{e\nu}} = 2\sigma(Q\bar{Q})\frac{dP}{dm_{e\nu}}B(W \to e\nu)$$

where $\sigma(Q\bar{Q})$ is the production cross-section shown in figure 1, B is the branching ratio for W-decay in the $(e\nu)$ channel, and

$$\frac{dP}{dm_{e\nu}} = \frac{2m_{e\nu}}{m_Q^2}\frac{1}{\Gamma}\frac{d\Gamma}{dx}$$

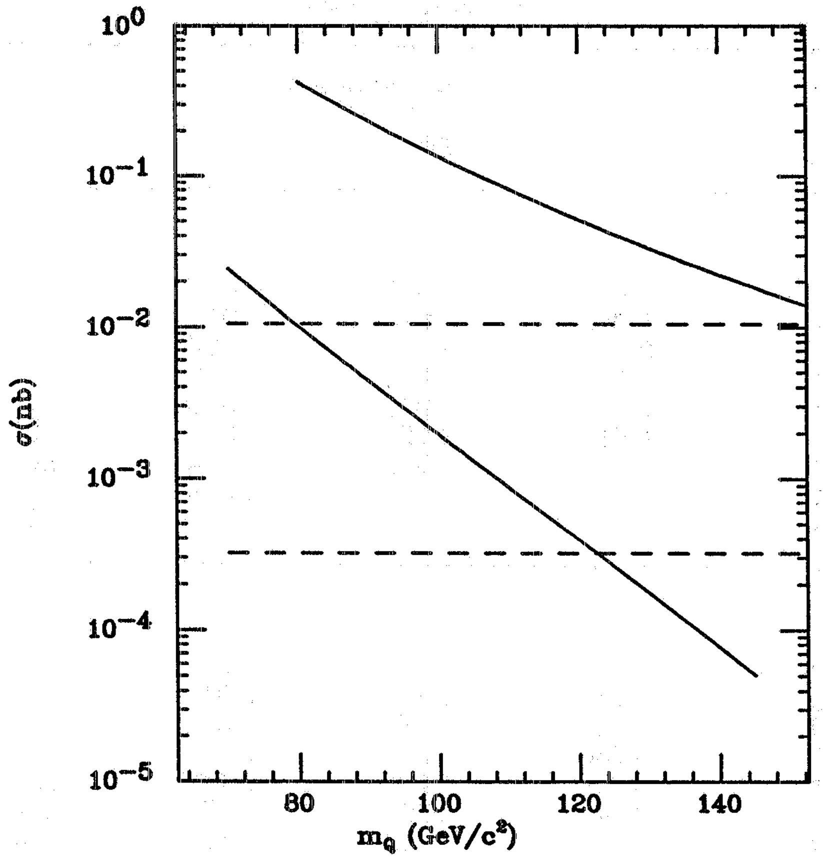

Fig. 1 Total production cross-section for process (2) as a function of the heavy quark mass m_Q, shown for the proton-antiproton collider energies $\sqrt{s} = 0.63$ and 2.0 TeV. The broken lines show the cross-section for direct W^+W^- production from parton-parton interactions at the three energies.

Taking $m_W = 85$ GeV/c^2, $\Gamma_W = 3$ GeV, and $|U_{Qq}| = 0.97$, the resulting differential ($e\nu$)-mass spectrum is tabulated in table 1 for heavy quark masses in the range $70 \leq m_Q \leq 110$ GeV/c^2, and for the two cases, $m_q = 5.3\ GeV/c^2$ at $\sqrt{s} = 0.63\ TeV$ and $m_q = 1.5\ GeV/c^2$ at $\sqrt{s} = 2\ TeV$. If we require energetic electrons and neutrinos [($e\nu$)-mass close to m_W] the highest rate of events at the CERN Collider corresponds to $m_Q =$ 90 GeV/c^2. In the remainder of this paper we have therefore choosen this value of m_Q for illustration.

We next discuss the transverse momentum distribution of the heavy quark. If

$$m_Q \approx (m_W + m_q)\ and\ m_Q >> m_q$$

the W p_t- distribution arising from the heavy quark will be similar to the heavy quark p_t-distribution. The inclusive differential cross-section for producing a heavy quark within

Table 1 : Differential cross-section for producing an electron-neutrino pair of invariant mass $m_{e\nu}$ from process (2) for (a) $\sqrt{s} = 0.63$ TeV, $m_q = 5.2$ GeV/c^2, and (b) $\sqrt{s} = 2$ TeV, $m_q = 1.5$ GeV/c^2.

$d\sigma/dm_{e\nu}$ (pb GeV^{-1})				
$m_{e\nu}$	m_Q (GeV/c^2)			
(GeV/c^2)	70	80	90	100
(a)				
10	0.026	0.006	-	-
20	0.055	0.013	0.001	-
30	0.091	0.021	0.002	-
40	0.127	0.032	0.003	-
50	0.145	0.045	0.005	-
60	0.097	0.058	0.008	0.001
70	-	0.053	0.014	0.002
80	-	-	0.054	0.018
90	-	-	-	0.002
(b)				
10	0.72	0.19	0.02	-
20	1.55	0.41	0.04	-
30	2.53	0.69	0.07	0.01
40	3.54	1.04	0.11	0.02
50	4.12	1.47	0.17	0.03
60	3.08	1.90	0.27	0.06
70	-	1.98	0.49	0.13
80	-	-	2.09	0.99
90	-	-	-	0.10

the rapidity interval $|y| \leq 2.5$ is given by :

$$\frac{d\sigma}{dp_t} = 2\sum_{ij}\int_{-2.5}^{+2.5} \frac{p_t^2\ coshy\ dy}{\sqrt{m_Q^2 + p_t^2 cosh^2 y}} \int_{x_{min}}^{1} \frac{dx_1}{\left(x_1 - x_\perp \frac{\chi + cos\theta}{2sin\theta}\right)} \tag{5}$$

$$\times F_i(x_1, 4m_Q^2) F_j(x_2, 4m_Q^2) \frac{d\sigma_{ij}}{d\hat{t}}$$

where $F_i(x, Q^2)$ are the non-singular parton densities, and

$$x_{min} = \frac{x_\perp \frac{\chi + cos\theta}{sin\theta}}{2 - x_\perp \frac{\chi - cos\theta}{sin\theta}},\ x_2 = \frac{x_1 x_\perp \frac{\chi - cos\theta}{sin\theta}}{2x_1 - x_\perp \frac{\chi + cos\theta}{sin\theta}}, \chi = \sqrt{1 + \frac{4m_Q^2 sin^2\theta}{x_\perp^2 s}},\quad sin\theta = \frac{2e^{-y}}{1 + e^{-2y}}$$

The elementary parton cross-sections $\frac{d\sigma_{ij}}{dt}$ are given in expressions (3) and (4). Expression (5) is correct if the incoming partons are collinear and have no initial transverse momentum. However, soft initial state gluon bremmstrahlung is expected to destroy the collinearity of the colliding partons and produce an overall $< p_t >_{Q\bar{Q}} \approx \alpha_s \frac{\sqrt{\hat{s}}}{2}$. To correct the transverse momentum distribution of the heavy quark Q for this effect we use [10] :

$$\frac{d\sigma^{corr}}{dp_t} = \int_0^{p_t} \frac{d\sigma^{naive}}{dk_t} d\mathbf{P}(p_t - k_t) \tag{6}$$

where σ^{naive} is the first order cross-section [eq. (5)], and the soft gluon bremsstrahlung transverse momentum distribution is given by :

$$\frac{d\mathbf{P}}{K_\perp dK_\perp} = \int b db J_0(K_\perp b) e^{-h(b,m_Q)}$$

with

$$h(b,m_Q) = \frac{8}{3\pi} c_{ij} \int_0^{m_Q} \frac{dk_\perp}{k_\perp} \alpha_s(k_\perp^2)(1 - J_0(k_\perp b)) \ln \frac{m_Q + \sqrt{m_Q^2 - k_\perp^2}}{m_Q + \sqrt{m_Q^2 - k_\perp^2}}$$

The colour factors are $c_{ij} = 1$ for $q\bar{q}$ and $\frac{9}{4}$ for gluon-gluon interactions respectively, and we have taken the value m_Q for the maximum energy carried by a single gluon [10]. Expression (6) is only approximately correct. In principle the Born parton-parton cross-section should be folded with the bremsstrahlung probability and then integrated over the parton densities. However, given the other uncertainties associated with the calculation (the K-factor, and the uncertainty in our knowledge of the parton densities) we feel that expression (6) is a reasonable approximation. For $Q\bar{Q}$ production at the CERN collider the "naive" heavy quark transverse momentum distribution given by eq. (5), and the soft gluon bremsstrahlung corrected p_t-distribution given by eq. (6), are shown in figure 2 for $m_Q = 90$ GeV/c^2. After correcting for soft gluon radiation the average heavy quark transverse momentum is found to be :

$$< p_t > = 66\ GeV/c\ ,\quad for\ m_Q = 90\ GeV/c^2\ \ at\ \sqrt{s} = 0.63\ TeV.$$

Integrating the differential p_t distribution for heavy quark transverse momenta in excess of 80 GeV/c we obtain a cross-section of 0.9 pb for the production of a high-p_t heavy quark with mass $m_Q = 90$ GeV/c^2 at the CERN collider.

To complete our analysis of the $Q\bar{Q}$ event kinematics we next consider the $(Q\bar{Q})$-mass distribution which, fixing $m_Q = 90$ GeV/c^2, can be obtained by folding expressions (3) and

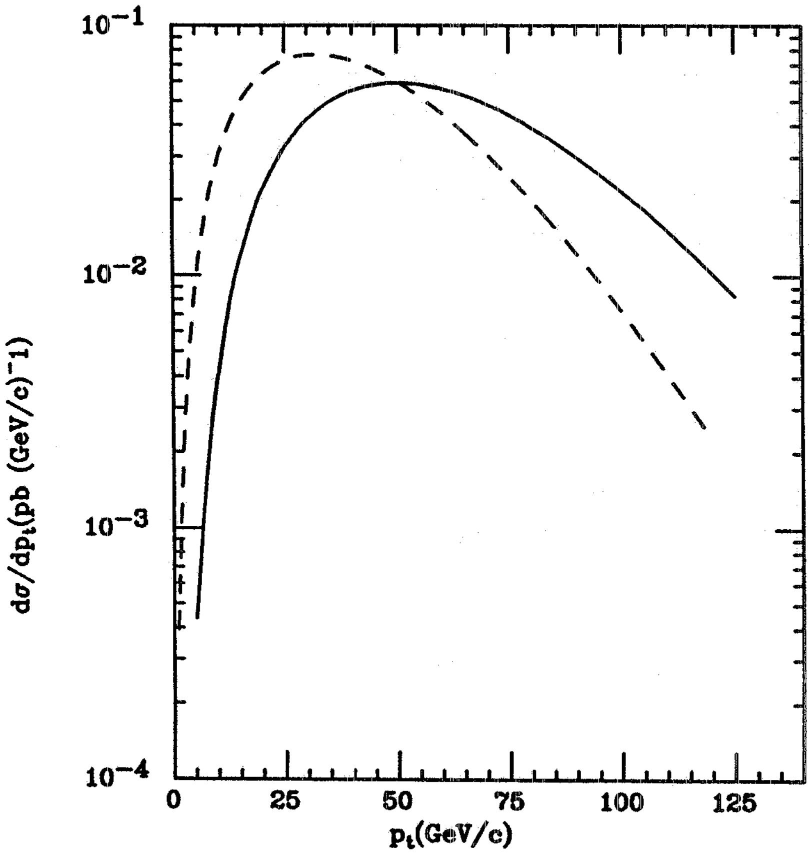

Fig. 2 Heavy quark transverse momentum distribution from $Q\bar{Q}$ production and decay at the CERN collider ($\sqrt{s} = 0.63$ TeV). The heavy quark mass has been taken to be 90 GeV/c^2. The curves show the result before (broken curve) and after (solid curve) the correction for soft initial state gluon radiation.

(4) with the relevant parton densities, and for each $\hat{s}$ integrating over the allowed interval of $\hat{t}$. The resulting mass distribution is shown in figure 3. Integrating the differential cross-section for ($Q\bar{Q}$)-masses in excess of 250 GeV/c^2 we obtain a cross-section of 0.5 pb for massive-($Q\bar{Q}$) production (with m_Q = 90 GeV/c^2) at the CERN collider. Finally, taking the branching ratio of the W into two jets to be 2/3 (assuming no $t\bar{b}$ decays) and the branching ratio for the decay in the ($e\nu$) channel to be 1/9 we estimate the (e+ν+jet+jet) cross-section at the CERN collider to be 0.04 pb, where the p_t of the ($e\nu$)-system (identified with the p_t of the underlying quark Q) is in excess of 80 GeV/c, and the mass of the (e+ν+jet+jet)-system (identified with the $Q\bar{Q}$ mass) is in excess of 250 GeV/c^2. We have assumed that all of the cross-section in the region $p_t \geq 80$ GeV/c is associated with $Q\bar{Q}$ pairs with mass $\geq$ 250 GeV/c^2. Taking into account both the ($e\nu$) and ($\mu\nu$) channels, this cross-section corresponds to 0.06 events in the current UA1 data samples. We note that the experimental trigger and selection efficiencies will tend to reduce this number, whilst the effect of the experimental resolution on the fastly falling transverse momentum and mass distributions, will tend to increase the number of events passing the cuts.

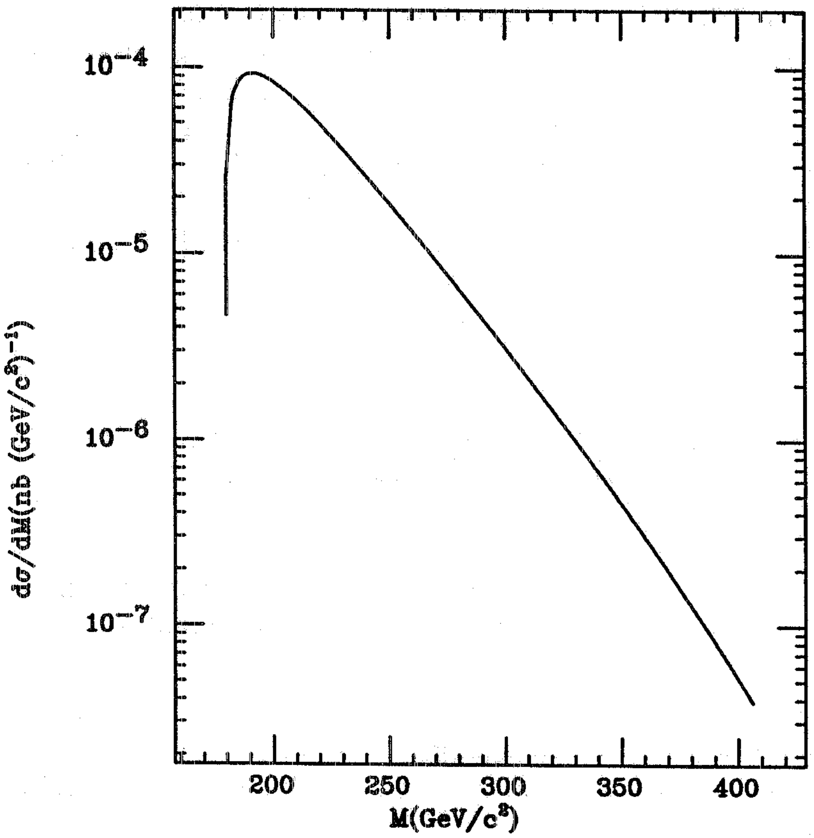

Fig. 3 $Q\bar{Q}$ mass distribution for heavy quark-antiquark production at the CERN collider, at $\sqrt{s} = 0.63 GeV$, with $m_Q = 90$ GeV/c^2.

3. The Identity of Q

In this section we discuss the possible identities of the two quarks (Q and q) in the decay :

$$Q \rightarrow W + q$$

where $m_Q \approx m_W$. We first notice that the most likely assignment for q is that it is a known light quark, i.e. $m_q \leq m_b$. If this were not the case, current limits from e^+e^- experiments [11] would suggest that $m_q \geq 23$ GeV/c^2. Choosing $m_q = 23$ GeV/c^2, $m_Q = (m_W + m_q)$, and recomputing the cross-sections for producing a (WW) event at the CERN collider, we obtain a cross-section of 1 pb, a factor of four smaller than for the case considered in section 2. Furthermore, if we wish to explain the UA1 high-p_t W-events we must have only two hadronic jets ($p_t \geq 10$ GeV/c) in the final state. If m_q becomes too large higher jet multiplicities will become more likely, suppressing the observed rate of (W + two-jet)-events further. For these reasons a known light quark assignment to q seems more reasonable than a top-quark- or a fourth-generation-quark- assignment.
We are then left with basically only two possibilities:

(i) The light quark q is a b-quark and the heavy quark Q is the top-quark. The cross-sections presented in section 2, where m_q was taken to be m_b, are then applicable.

This hypothesis is attractive, but must overcome two difficulties. Firstly, the UA1 collaboration has reported [12] the existence of six events, recorded in 1983, in which an isolated electron or muon has been produced in association with two hadronic jets, and a small missing transverse energy. One possible interpretation of these events is that they arise from W production followed by decay in the $(t\bar{b})$ channel. The mass range, for the top quark, would then be $\approx 30 \div 60$ GeV, i.e. quite different from the one suggested here, $m_t \approx m_W$. We must await further results before we know whether this interpretation of the six UA1 events is correct. Secondly, the recently improved measurements [13] at the CERN collider of the ratio

$$R = \frac{B(W^{\pm} \to e\nu)\sigma(p\bar{p} \to W^{\pm} + X)}{B(Z \to e^+e^-)\sigma(p\bar{p} \to Z + X)}$$

favour a top mass $m_t \leq m_W$ [14], although within the current experimental errors and theoretical uncertainties $m_t \approx m_W$ cannot be completely excluded.

(ii) The light quark q is a known up-type quark (u or c) and Q is the down-type quark from a new generation. The u-quark decay mode will be more supressed by powers of the Cabibbo angle than the c-quark decay mode. We therefore consider the decay :

$$Q \to c + W$$

The decay kinematics for this process is essentially identical to the kinematics discussed in section 2 and illustrated in table 1 and figures 2 and 3 (to the extent that $m_q =$ 5.2 GeV/c^2 is almost the same as $m_q = m_c$ given that $m_Q = 90$ GeV/c^2). However, the cross-section for W^+W^- production will be different. Defining

$$F = \frac{\Gamma(Q \to W + c)}{\Gamma(Q \to \tilde{W} + t)}$$

where $\tilde{W}$ indicates a virtual off-mass-shell W-boson, and taking

$$m_Q = 90\ GeV/c^2, \quad m_t = 50\ GeV/c^2, \quad \frac{|U_{Qc}|^2}{|U_{Qt}|^2} \leq 0.01$$

we estimate that the ratio of widths F $\leq$ 0.94. The cross-section for W^+W^- production is then supressed relative to the rates presented in section 2 by the factor :

$$\beta = \frac{1}{1 + \frac{1}{F}} \leq 0.5$$

4. Conclusions

We have investigated the hypothesis that the high transverse momentum W bosons recently observed by UA1 and UA2 at the CERN proton - antiproton collider signal the production of a heavy quark with a mass near to the W mass. The heavy quark can either be the top quark or a new down-type quark belonging to a fourth generation. Although these hypothesis are consistent with existing standard model results, the predicted final state mass and heavy quark transverse momentum distributions, calculated from first order QCD but including soft initial state bremsstrahlung, do not favour mass and p_t values as high as the ones reported by the CERN groups. Requireing the heavy quark transverse momentum to exceed 80 GeV/c^2, the heavy quark interpretation we have discussed gives essentially the same event rate as the QCD double bremsstrahlung process discussed in the introduction. We would like to stress that the very distinctive signature of high p_t-W's ($p_t \approx m_W$) can be used to investigate the presence of heavy quarks with mass $m_Q \geq m_W$ at present and future colliders.

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