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QUARKS DECAYING TO REAL W BOSONS

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A B S T R A C T

The reaction $\bar{p}p \rightarrow Q\bar{Q} + \dots$ is just barely capable of producing quarks heavy enough to decay to real W bosons at present SPS energy ($\sqrt{s} = 540$ GeV) and integrated luminosity ($\int Ldt \approx 10^{35} \text{ cm}^{-2}$). One event observed by the UA2 collaboration may be an example of this process. The prospects are studied for collecting more such events at SPS ($\sqrt{s} = 620$ GeV in forthcoming experiments) and Fermilab ($\sqrt{s} = 2$ TeV). At the latter energy, the present UA2 signal, if due to the above process, would be nearly 100 times as strong, and with $\int Ldt = 10^{36} \text{ cm}^{-2}$, quarks heavier than 200 GeV will be within reach.

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Experiments designed to observe the W and Z now appear to be reaching far beyond their mass range, into the area above 150 GeV/c²^{1),2)}. Unusual events which suggest new physics in this mass range include jets and photons opposite missing momentum²⁾ and W bosons opposite high momentum jets¹⁾. In this note we examine the interpretation of one of the latter events as an instance of the process

$$\bar{p} p \rightarrow Q \bar{Q} + \dots ; \quad (1)$$

$$Q \rightarrow W + (\text{light quark}) \\ \quad \quad \quad \hookrightarrow e \nu ; \quad (2)$$

$$\bar{Q} \rightarrow W + (\text{light quark}) \\ \quad \quad \quad \hookrightarrow \text{hadrons}, \quad (3)$$

where Q is a quark just slightly heavier than the W. We find that the cross-section for (1) predicted by QCD is not impossibly low at present SPS energies ($\sqrt{s} = 540$ GeV). Moreover, it is expected to grow rapidly with energy, so that if such a quark exists it should be easily detected in the next round of SPS experiments ($\sqrt{s} = 620$ GeV) and at Fermilab ($\sqrt{s} = 2$ TeV).

In the event "C" of Ref. 1), an electron with $p_{\perp} = 34.4 \pm 3.2$ GeV/c is accompanied by two large jets of $p_{\perp}^{(j_1)} = 38 \pm 5$ and $p_{\perp}^{(j_2)} = 21 \pm 3$ GeV/c and one smaller one of $p_{\perp}^{(j_3)} = 7 \pm 1$ GeV/c, and missing transverse momentum $p_{\perp}^{\nu} = 57 \pm 5$ GeV/c. The transverse mass of the $e\nu$ system is 82 ± 4 GeV/c², consistent with a W, while the effective mass of $j_1 - j_2 - j_3$ is 63 ± 5 GeV/c², also consistent with a W if some small-momentum tracks have been missed.

If the processes (1)-(3) are responsible for this event, the jets associated with the light quark are easily missed if the mass of Q is just above that of W + (light quark). The $e\nu$ and $j_1 - j_2 - j_3$ systems have large $p_{\perp} \approx 36$ GeV/c. For a heavy-quark interpretation, this requires the quarks to be produced with large $p_{\perp}$. As we shall see, for an 85 GeV/c² quark, one expects 2/3 of all the production cross-section to occur for $p_{\perp} > 30$ GeV/c at $\sqrt{s} = 540$ GeV.

Two other events of the form $\bar{p} p \rightarrow W + \text{jet}$ have also been reported in the UA2 experiment¹⁾. We shall not attempt to account for them within the framework of the process (1). Event "A", involving a W candidate produced

opposite a jet of $p_{\perp}(j_1) = 27 \pm 3$ GeV and two small jets, is consistent with a QCD source¹⁾. Event "B" involves a W of transverse momentum 70 GeV/c balanced by a single jet, and is unlikely to come from the processes (1)-(3) unless all but one of the jets in $W \rightarrow$ hadrons have been missed.

The cross-section for the process (1) has been estimated by standard QCD means, taking account both of $q\bar{q} \rightarrow Q\bar{Q}$ ³⁾ and gluon + gluon $\rightarrow Q\bar{Q}$ ⁴⁾ subprocesses^{*}). [Reviews of the limitations of such estimates, and further references, may be found in 5) and 6)]. We make use here of structure functions of Ref. 7), based on CDHS data and extrapolated to large Q^2 using the Altarelli-Parisi equations with $\Lambda = 0.29$ GeV. Results are shown in Fig. 1 for several choices of kinematic cuts. The rapidity limitation $|y_{Q\bar{Q}}| < 1.5$ (solid and dotted curves) ensures that not too many events will be lost in extreme forward or backward configurations. The cut $p_{\perp}(Q) > 15$ GeV/c (solid line) should permit identification of heavy quarks via lepton + jet final states. The cut $p_{\perp}(Q) > 30$ GeV/c (dotted line) does not appreciably suppress very heavy quark production at $\sqrt{s} = 0.54$ TeV.

While QCD estimates for total charm production fall short by at least a factor of 10 in pp collisions at $\sqrt{s} = 28$ GeV^{5),6)}, there is some reason to hope that they may be better for the high $p_{\perp}$ regime, when perturbation theory should be more reliable. This should be testable in the near future in multi-lepton events⁸⁾ coming from $b\bar{b}$ and possibly $t\bar{t}$ production⁹⁾. Thus we expect a "calibration" of Fig. 1 to be possible using SPS data.

Turning now to the case of a quark heavy enough to decay to (real W) + (light quark), we present cross-sections for its production in more detail in the Table. As mentioned earlier, nearly 2/3 of the cross-section at $\sqrt{s} = 540$ GeV for $p\bar{p} \rightarrow Q\bar{Q} + \dots$ ($m_Q = 85$ GeV/c²) lies at $|y_{Q\bar{Q}}| < 1.5$, $p_{\perp} > 30$ GeV/c. The total cross-section is about 2 pb. To estimate the probability of observing the processes (2) and (3), we must multiply this value further by appropriate branching ratios $2B_{ev} B_n \approx 2(1/12)(3/4) \approx 1/8$. Thus we would estimate via QCD that the cross-section for the processes (1)-(3) is about 0.3 pb. In the experiment of integrated luminosity $\int L dt = 116 \text{ nb}^{-1}$ ¹⁾, one would then have expected to see such an event with about a 3% probability. This is about four times larger than the estimated QCD background of 7×10^{-3} event¹⁾, so it is at least a hypothesis worthy of consideration. Moreover, it is quite possible that there is still a deficiency

^{*}) I am grateful to E. Berger for providing the code for these subprocess cross-sections.

in our understanding of heavy quark production. The above-mentioned "calibrations" using $b\bar{b}$ and possibly $t\bar{t}$ production will help settle this last point.

At $\sqrt{s} = 540$ GeV, the subprocess $q\bar{q} \rightarrow Q\bar{Q}$ is the dominant source of a quark with mass 85 GeV/c². The gluonic subprocess has become dominant by $\sqrt{s} = 2$ TeV, leading to a nearly hundred-fold increase in the cross-section. Even at $\sqrt{s} = 620$ GeV (the projected energy for the next SPS run), the predicted cross-section has increased from its value at $\sqrt{s} = 540$ GeV by about a factor of 2.

An experiment of $\int L dt = 10^{36}$ or 10^{37} cm⁻² is ultimately expected to be realizable at $\sqrt{s} = 2$ TeV. From Fig. 1 it appears that a wide range of quarks decaying to real W's are capable of being produced if they exist. Within the uncertainty of present estimates^{*)}, and allowing for some luck, it is possible that such a quark may already have been observed.

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^{*)} Cross-sections about a factor of 2 higher are estimated by A. Ali, whom I thank for several detailed discussions of his results prior to publication.

	$\sigma_{q\bar{q}}$ (pb)	σ_{gg} (pb)	σ_{tot} (pb)
<u>$\sqrt{s} = 0.54$ TeV</u>			
No cuts	2.2	0.06	2.3
$p_{\perp}(Q) \geq 15$ GeV/c; $ y_{Q\bar{Q}} \leq 1.5$	2.0	0.05	2.0
$p_{\perp}(Q) \geq 30$ GeV/c; $ y_{Q\bar{Q}} \leq 1.5$	1.4	0.03	1.4
<u>$\sqrt{s} = 0.62$ TeV</u>			
No cuts	4.3	0.2	4.5
$p_{\perp} \geq 15$ GeV/c; $ y_{Q\bar{Q}} \leq 1.5$	3.8	0.2	4.0
<u>$\sqrt{s} = 2$ TeV</u>			
No cuts	83	109	192
$p_{\perp}(Q) \geq 15$ GeV/c; $ y_{Q\bar{Q}} \leq 1.5$	75	100	175

Table - Cross-sections for production of a quark Q with
 $m_Q = 85$ GeV/c².

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FIGURE CAPTION

Cross-sections for $p\bar{p} \rightarrow Q\bar{Q} + \dots$ at $\sqrt{s} = 0.54$ and 2 TeV (labels on curves). Solid lines: $p_{\perp}(Q) > 15$ GeV/c; $|y_{Q\bar{Q}}| < 1.5$. Dashed lines: no cuts. Dotted line: $p_{\perp}(Q) > 30$ GeV/c, $|y_{Q\bar{Q}}| < 1.5$ (0.54 TeV only).