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HEAVY QUARK PRODUCTION AT COLLIDER ENERGY

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ABSTRACT

The rather large cross-section reported for Λ_c production at ISR energy suggests that cross-sections for the production of heavier quarks at collider energy could be important. It is then advocated that an interesting kinematical region for the search for leptons associated with t quark formation is $p_T > 5$ GeV/c, $\theta \sim 20 - 30^\circ$.

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At present it is tempting to consider that quarks and leptons occur in recurrent families and that a quark of charge $2/3$ (the t quark) should be associated with the b (charge $-1/3$) quark. The search for such a quark in e^+e^- annihilation has however been unsuccessful in the range of energies now accessible. A lower value for the mass is set at 18 GeV ¹⁾. It is therefore highly worthwhile to explore any promising possibility of detecting the possible production of heavy quarks in hadron collisions with the enormous centre-of-mass energy now available at the CERN $p\bar{p}$ collider, namely 540 GeV . The cross-section for charmed particle production in hadron interactions turns out to be rather large, present information putting it above the $100 \mu\text{b}$ level at ISR energy²⁾. While such a high value still remains a riddle, it can be used as an input to assess production rates for heavier quarks, when the centre-of-mass energy far exceeds the mass value of the relevant hadrons. While the expected cross-sections could then be sizeable ($\sigma \sim 1 \mu\text{b}$ for $M \sim 20 \text{ GeV}$ say), it should be considered against an a priori overwhelming background. The purpose of this note is to elucidate a possible important production mechanism and to discuss the region of phase space where the signal over background ratio would be favourable. We advocate the search for muons (electrons) with $p_T \geq 5 \text{ GeV}/c$ at medium angle ($\theta \sim 20 - 30^\circ$) with respect to either of the incident beams.

We argue in the following that the important mechanism for t quark introduction should be the fragmentation of the incident $p(\bar{p})$ into a leading $\Lambda_t(\bar{\Lambda}_t)$ baryon. This implies the associated production of a $\bar{t}(t)$ meson at typically low x (the Feynman scaling variable) and low p_T . Since the t quark mass is at least 18 GeV , the relatively important Q value for semi-leptonic decays is such that leptons from $t \rightarrow b$ decay with appreciable p_T ($p_T \sim M/4$ hence $p_T \sim 5 \text{ GeV}$ for $M \sim 20 \text{ GeV}$) should be produced when nothing similar is expected from c and b mesons even though they are more abundantly excited through such a mechanism.

Figure 1 shows the (scaling) lepton distribution resulting from such a process. Plotted is quantity $M^2 d^2\sigma/dx_T dy$ at $y = \bar{y}$ where the corresponding yield is expected to be maximum as discussed later. The variable x_T is defined as $x_T = 2p_T/M$, where M is the meson (or quark) mass. The semi-leptonic branching ratio is taken to be 0.1 . The p_T distribution peaks at $M/4$ but is rather wide. For $M \sim 20 \text{ GeV}$ we get $d^2\sigma/dx_T dy|_{y=\bar{y}} \sim 0.1 \mu\text{b}$ practically over the $2 < p_T < 8 \text{ GeV}$ range. The Drell-Yan background at $p_T \sim M/4$ is typically four orders of magnitude lower^{3),4)}. While the lepton background associated with the semi-leptonic fragmentation of c and b quark jets cannot be predicted as precisely, it should not exceed the Drell-Yan contribution by more than two orders

of magnitude³⁾. The expected signal should therefore stand above any expected background. It corresponds to $d\sigma/dp_T \sim 10 \mu\text{b/GeV}$ for $M \sim 20 \text{ GeV}$. The signal could also have some forward-backward asymmetry in charge whereas the expected background should be symmetric. The signal should decrease as M^{-2} with increasing quark mass ($M \ll \sqrt{s}$) while reaching its maximum value at wider and wider angles.

After having presented our main result, we proceed with the analysis. Production of hadrons with high masses has long been considered to be strongly suppressed. The success of statistical models for standard hadrons indeed led one to expect inclusive yields falling exponentially with mass. One can, however, now argue that the production of heavy quarks should be considered in the framework of perturbative QCD and the relevant cross-sections should then decrease only quadratically with mass (up to logarithmic terms)⁵⁾. If one considers $200 \mu\text{b}$ as the correct order of magnitude for charmed particle production at ISR energy, one may expect a sizeable cross-section for b quarks (and for heavier quarks) at collider energy, typically $\sigma \sim 400 \mu\text{b/M}^2$, with M in GeV , valid as long as $M \ll \sqrt{s}$, and in particular in the $20 - 30 \text{ GeV}$ mass range where one may search for the t quark.

Such a relatively large cross-section calls for a particular mechanism. As first discussed, simple QCD estimates give too low a value for heavy quark yields and although reliable at large p_T , the calculated rate cannot provide a clear signal for new quarks. While the large mass of the quark may justify a perturbative approach, this can be relatively safely envisaged only at large p_T . In such a case the dominant terms turn out to be $gg \rightarrow Q\bar{Q}$ and to some extent $q\bar{q} \rightarrow Q\bar{Q}$, the maximum yield being at 90° . At large enough p_T ($p_T \gg M$) all inclusive distributions for different flavours become equal provided that $\sqrt{s} \gg \gg M$. The corresponding yields can be calculated⁶⁾. One can then fold the semi-leptonic decay distributions and compute the associated inclusive lepton distributions^{3),4)}. The differential cross-section $d^2\sigma/dp_T dy|_{y=0}$ for μ^+ and μ^- , say associated with b and c jet production in $p\bar{p}$ collisions at $\sqrt{s} = 540 \text{ GeV}$, is of the order of $10^{-5} \mu\text{b/GeV}$ at $p_T \approx 20 \text{ GeV}$. Such a lepton signal stands clearly above the Drell-Yan background (by over an order of magnitude) and should therefore contribute to most of the large p_T prompt leptons seen below $p_T = 30 \text{ GeV}$. Above this value W and Z production should become the dominant source⁴⁾.

This non-controversial signal is however not of much use when searching for new quarks. Yields from c and b quarks cannot be predicted with enough precision to allow one to eventually infer from experiment the presence or absence

of a t component which could contribute fully only at $p_T \gg 20$ GeV. In order to search for t quarks one has then to study associated jet particles in the hope of finding a characteristic cascade³⁾. This is rather difficult with configurations where the trigger lepton is likely to have taken a very large fraction of the jet momentum.

One is then led to consider low p_T production in order to better distinguish between t and b and c quarks using the large mass gap and its related marked difference in Q value. Large p_T leptons ($p_T \sim 5$ to 10 GeV) should be produced by low p_T t hadrons while this should not be the case for b and c hadrons, despite a much larger production rate. This is what we propose, taking advantage of the relatively large cross-section previously mentioned. It should be stressed, however, that extending (a priori reliable) large p_T yields down to low p_T in order to obtain global hadron yields gives only much lower values for the cross-section. While one may justify a perturbative approach on the grounds of the heavy quark mass⁷⁾, there are many ambiguities and uncertainties associated with the low p_T limit. The estimated lepton yield would then be maximum at 90° and the total cross-section is at the level of 10^{-2} μb for $M \sim 20$ GeV only⁷⁾. One therefore has to look for a new mechanism.

From present information²⁾ it seems that the dominant production mechanism is the fragmentation of the incident $p(\bar{p})$ into a leading $\Lambda(\Lambda_c)$ baryon. The search for charm particles at ISR energy has indeed provided evidence for a relatively abundant production of Λ_c with a rather flat x distribution and a global rate which we may take at the level of 200 μb (order of magnitude). This has been interpreted as being due to the presence of a $c\bar{c}$ component (at the 0.01 level) in the quark Fock space of the incident hadron⁵⁾. We prefer to argue for a mechanism whereby a diquark in the incident hadron (with a rather large x value) would pick a low x c quark, appearing through the interaction (Fig. 2) and emerge as a leading Λ_c . Such a mechanism can indeed also be successfully used to interpret polarization effects seen in hyperon production⁸⁾ and the a priori peculiar charge effects found for leading mesons associated with large p_T medium angle triggers⁹⁾. This has been discussed in detail recently^{10), 11)}. We consider such a diquark approach¹²⁾ as respectable enough to be extended to heavier quark production. While the relative weight can be taken as M^{-2} according to perturbative QCD, the production cross-sections are globally scaled according to that known for Λ_c . It is then taken to be $400/M^2$ μb (M in GeV). A meson should be associated with this leading baryon. Its x distribution should be much softer, the heavy quark having but a low x value, in contradistinction to the intrinsic component approach⁵⁾. We take a distribution of the type

$$\frac{d\sigma}{dx} = (f+1) \frac{400}{M^2} (1-x)^f \mu b \quad (1)$$

with M in GeV and f a shape parameter which may be equal to three to five whether we consider empirical D meson distributions²⁾ or counting rules¹³⁾ as the proper approach. The lepton distribution of Fig. 1 hardly changes. There is no x^{-1} factor in (1) in agreement with the fact that the dominant process is baryon-meson associated production and not pair production of heavy mesons. With no constraint on the Λ_t momentum, we focus on an inclusive t meson distribution (1) which is forward-backward symmetric. One may however argue that heavy quark-antiquark pairs will be in configurations which minimize the invariant mass and both the quark and the antiquark would then be either in the proton (Λ_t) or antiproton ($\bar{\Lambda}_t$) direction. In such a case the lepton seen on the proton side should be dominantly negative. Such a charge asymmetry could be present. It should of course prevail in the intrinsic component approach⁵⁾.

The semi-leptonic decay of the meson gives a lepton energy distribution of the type

$$\frac{dN}{d\omega} \sim \frac{M^2 - m^2 - 2M\omega}{M(M-2\omega)} \omega^2 \quad (2)$$

where M and m stand for the initial and final meson (quark) masses respectively. In practice $m \ll M$. From (1) and (2) one can calculate the differential cross-section for lepton production (assuming a branching ratio of 0.1). Since the parent meson has a non-uniform rapidity distribution determined by (1), the lepton yield will be maximum where the meson rapidity distribution peaks. This occurs at $\bar{y} = \ln \sqrt{s}/(f+1)M$. At relatively small x [neglecting the variation of the $(1-x)^f$ factor in (1)] one gets a rather simple expression:

$$\left. \frac{d^2\sigma}{dx_T dy} \right|_{y=\bar{y}} = \frac{10^3}{M^2} \int_{x_T}^1 \frac{z_T(1-z_T)}{\sqrt{1 - \frac{x_T^2}{z_T^2}}} dz_T \quad (3)$$

which exhibits the Jacobian peak effect. The scaling distribution obtained from (3), but using the full x dependence (1), is presented in Fig. 1. We have defined $3T = 2\omega/M$ and $x_T = 2p_T/M$. The value of $\bar{y}$ depends on the parameter f . For $\sqrt{s} = 540$ GeV and $M = 20$ GeV, the corresponding angle is $\theta = 17^\circ$ (25°) for $f = 3(5)$. The distribution at $\bar{y}$ does not depend appreciably on the thus chosen value for f .

In the central region ($y \sim 0$), the lepton yield is smaller by a factor $\sqrt{s}/(f+1)M$ which can be sizeable. However, there should also be some contribution from meson pair production which peaks there. Extrapolating from present information about charmed baryon production, it is worth focusing first on those mesons produced in association with a baryon and which should give a sizeably large p_T ($p_T > 5 \text{ GeV}/c$) lepton yield at medium angle. This is where one may look for a signal from t hadron production.

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REFERENCES

- 1) B. Wiik, Rapporteur talk, High Energy Physics Conference, Madison 1980, eds. L. Durand and L. Pondrom.
Physics with high energy electron-positron colliding with the Mark J detector: the Mark J Collaboration, Physics Reports 63 (1980) 337.
- 2) K.L. Giboni et al., Phys. Lett. 85B (1979) 437;
W. Lockman et al., Phys. Lett. 85B (1979) 443;
D. Drijard et al., Phys. Lett. 85B (1979) 452.
For a recent review see:
"Excitation of new flavours", ISR discussion meeting 2-4 (1981) - M.G. Albrow and M. Jacob, CERN report.
Evidence for Λ_b production has also been reported:
M. Basile et al., CERN EP/81-38.
- 3) S. Pakvasa et al., Phys. Rev. D20 (1978) 2862.
- 4) R. Horgan and M. Jacob, Physics at Collider Energy, CERN 81-04.
- 5) S.J. Brodsky et al., SLAC PUB 2660 (1981).
- 6) R. Horgan et al., Nucl. Phys. B179 (1981) 441.
- 7) B.L. Combridge, Nucl. Phys. B151 (1979) 429.
- 8) O. Overseth, High energy physics with polarized beams and polarized targets, Lausanne (1980)
- 9) D. Hanna et al., Phys. Rev. Lett. 46 (1981) 398;
D. Beavis et al., Phys. Rev. to be published (1981).
- 10) M. Jacob, "Quark-quark interactions", invited papers at Physics in Collision Blacksburg (1981), Plenum Press, to be published.
- 11) P.V. Landshoff, Rapporteur talk, EPS High Energy Physics Conference, Lisbon (1981).
- 12) A. Donnachie, Z. Phys. C4 (1980) 161.
- 13) J.F. Gunion, UCD 79-4 and references therein; Phys. Lett. 88B (1979) 150.

FIGURE CAPTIONS

- Figure 1 : Scaling differential cross-section $M^2 d^2\sigma/dx_T dy|_{y=\bar{y}}$ for leptons originating from the decay of a meson produced in association with a leading baryon. The inclusive distribution is proportional to $(1-x)^5$. The value of $\bar{y}$ is $\ln \sqrt{s}/6M$.
- Figure 2 : Diquark-quark fusion mechanism corresponding to the production of a leading heavy baryon.

Fig. 1

Fig. 2