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# Properties of hadron distributions in reactions - containing very heavy quarks*



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# PROPERTIES OF HADRON DISTRIBUTIONS IN REACTIONS CONTAINING VERY HEAVY QUARKS*

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## ABSTRACT

We study, in the framework of the naive quark-parton model, production and decay dynamics for processes containing a very heavy quark Q of a new flavor, decaying via weak interactions. We argue that

(i) The event-by-event distribution of hadrons is similar to what would exist in a similar direct process involving the same produced partons (with the same momenta), but not involving a cascade decay.

(ii) For neutrino production, electroproduction, and $e^+e^-$ annihilation, at energies far above threshold, the inclusive momentum distribution of a stable hadron H containing the Q peaks near the maximum momentum, i.e., at values of the scaling variable $z \sim 1$.

(iii) For events containing a nonleptonic decay of Q into ordinary quarks via $Q \rightarrow q\bar{q}q$, the leading hadron distribution is characterized by multiplicity ~3 times normal multiplicity, as well as abnormally large transverse momenta.

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## I. INTRODUCTION

Recent experiments[1,2,3] have hinted at the existence of a new quark Q of mass of ~5 GeV or greater. If there does exist such a quark, or others of even higher mass, it becomes important to have some understanding of the gross characteristics of hadron distributions relevant to production and decay processes involving such superheavy quarks. The quark-parton model has in the past provided a useful guide in this regard.[4] According to present theoretical ideas there seems to be no obvious reason to doubt its applicability to processes involving new quarks, other than rather straightforward considerations associated with the modified kinematics. It is the purpose of this note to discuss such issues.[5] We consider the rather idealized limiting case of an extremely massive quark Q which decays weakly into ordinary quarks q or leptons $\ell$; schematically

$$\begin{aligned} Q &\rightarrow q q \bar{q} \\ Q &\rightarrow q \ell \bar{\ell} \quad . \end{aligned} \tag{1}$$

We shall consider production of Q in colliding-beam processes, and in deep-inelastic lepton-hadron interactions. Having done this much, the reader should be able to draw his own conclusions on the implications for hadron-hadron collisions. The main conclusion to be reached here is that the configuration of final hadrons in a typical event is indistinguishable from what one would get were the hadron jets which are associated with the "ordinary" quarks to be produced directly instead of in the cascade decay of Q. For example, final state hadrons in an event with the basic parton description

$$\begin{array}{l} e^+e^- \rightarrow Q\bar{Q} \\ \qquad\quad |\; \bar{Q} \rightarrow \bar{q}\ell\bar{\ell} \\ \qquad\quad Q \rightarrow qq\bar{q} \end{array} \tag{2}$$

would have very similar average properties (for the same parton momenta) as in the hypothetical direct process

$$e^+e^- \to q\bar{q}q\bar{q}\ell\bar{\ell} \quad . \tag{3}$$

A related conclusion is that the inclusive distribution dN/dz of produced hadrons containing a new superheavy quark Q of mass $m_Q$ is peaked near z=1 (here $z = p/p_{max}$). A crude guess is

$$\langle z \rangle \sim 1 - \frac{1\ \mathrm{GeV}}{m_Q} \quad . \tag{4}$$

## II. PRODUCTION OF Q

We begin the argument by considering colliding-beam processes. For $e^+e^- \to q\bar{q}$ there is in the center-of-mass frame a two-jet system, with each jet possessing a dp/p inclusive momentum-spectrum extending to a maximum momentum $p_{max} \sim \frac{1}{2}\sqrt{s}$. The total multiplicity is thus $n \sim 2c \log \sqrt{s} \sim c \log s$, with c a constant which empirically is ~2. Now replace one q by a superheavy Q ($m_Q$ > 100 GeV??); for example consider the process $\bar{\nu} + e \to q + \bar{Q}$. At energies far above threshold, both q and $\bar{Q}$ have <u>ab initio</u> momenta $\sim \frac{1}{2}\sqrt{s}$ in the center-of-mass frame. However, to study the evolution of the final state, it is clearest to first look at it in the frame where Q is at rest. This is accomplished by a Lorentz boost in the direction of flight of q, with $\gamma \sim \sqrt{s}/2m_Q$. Hence the momentum of the q now becomes $p \sim \gamma \frac{\sqrt{s}}{2} \sim s/4m_Q$. In this frame the emitted hadrons will be predominantly in the direction of flight of the parton q (with dp/p spectrum). There may also be produced a few wee hadrons associated with the dressing of the superheavy quark into a superheavy hadron H*, and a few more wee hadrons associated with possible cascade decays of H* into its ground state H. Thus the total multiplicity, proportional to the length in rapidity of the hadron plateau, is given by

$$n \sim c \log\left(\frac{s}{4m_Q}\right) + O(1) \sim c\left[\log\frac{s}{(1\ \mathrm{GeV})^2} - \log\frac{m_Q}{1\ \mathrm{GeV}}\right] + O(1) \quad . \tag{5}$$

It is smaller than the usual value by an amount proportional to log $m_Q$. Boosting back into the center-of-mass frame, we find[5] the average maximum momentum of an ordinary hadron in the jet formed by $\bar{Q}$ is only a fraction $\sim 1\ \mathrm{GeV}/m_Q$ of the momentum carried by the produced "stable" superheavy hadron H containing $\bar{Q}$. In other words the inertia carried originally by $\bar{Q}$ is retained by the hadron $H=q\bar{Q}$, because the ordinary hadrons are mainly produced with velocity (or, better, $\gamma$) less than or of order that possessed by $\bar{Q}$. Hence their share of the momentum and energy is diminished[6] by a factor $\sim 1\ \mathrm{GeV}/m_Q \ll 1$. This is all illustrated in Fig. 1.

Evidently a similar situation holds for an energetic Q electroproduced or neutrino-produced from fixed targets. In the laboratory frame, the process may be described[7] as follows: After Q leaves the target, an inside-outside cascade of hadrons develops, in conjunction with a "polarization cloud" containing a $\bar{q}$, which accompanies the Q and is accelerated by it. When the momentum of $\bar{q}$ (and emitted hadrons) is a fraction $\sim(1\ \mathrm{GeV}/m_Q)$ that of the Q, the $\bar{q}$ and Q will have low relative velocity (or $\gamma$) and can readily bind to form a superheavy hadron H*, terminating the process. Thus there emerges the same conclusion as before.

## III. DECAYS OF Q

In the semileptonic decay $Q \to q\ell\bar{\ell}$, considered in the rest frame of Q, we will evidently have a hadron jet of typical multiplicity $\sim c \log\frac{m_Q}{3}$. A wee hadron in this jet, when Lorentz boosted into a frame where Q is relativistic, is in the same region of phase space as the most leading ordinary hadrons originally produced in association with the Q and H*:

$$p_{\text{hadron}} \sim (1\ \text{GeV}/m_Q)\, p_{H*} \sim \gamma_Q\ \text{GeV} \quad . \tag{6}$$

Evidently the rest of this decay jet does not in general[9] overlap in phase-space with the production-jet, and represents an extension of it. To visualize the situation better, suppose the decay jet is emitted (as is typically the case) in the Q rest frame at an angle $\sim 90^{\circ}$ relative to the Q direction of flight. Then in the lab frame all particles in the decay jet have decay angle $\theta \sim \gamma^{-1} \sim m_Q/E_Q$. The leading particle in the decay jet has energy $\sim \gamma \frac{m_Q}{3} \sim \frac{E_Q}{3}$, while the leading particles in the produced-hadron jet (as well as the slowest particles in the decay jet) have energy $\sim(1\ \text{GeV}/m_Q)\, E_Q \sim \gamma_Q$ GeV. The angles of the individual members of the produced-hadron jet fluctuate by an amount at least of order $\gamma^{-1} \sim \theta$ because of their nonvanishing transverse momenta. Hence we may make a rotation of coordinates by an amount $\gamma^{-1}$ into the direction of the decay jet components without affecting the angles of the produced hadron components significantly. Upon doing this we see that the produced-hadron jet and decay jet really comprise <u>one</u> collinear jet with the maximum momentum $\sim E_Q/3$ and a wee minimum momentum. This shows that the hadron configuration is essentially what one would obtain from consideration of a direct production process

$$\nu + Q \rightarrow \ell + \bar{\ell} + \ell + q \tag{7}$$

instead of the two-step process

$$\begin{array}{l} \nu + q \rightarrow \ell + Q \\ \qquad\qquad\quad \llcorner\!\!\rightarrow \bar{\ell} + \ell + q \quad . \end{array} \tag{8}$$

This is illustrated in Fig. 2. It should be clear that this line of argument is of general validity.

A similar situation occurs for nonleptonic decays, except that there are three decay-hadron jets, each of which merges with the leading produced hadrons (which have momentum $\sim\gamma_Q$ GeV). If we focus attention only on momentum distributions and not angle or $p_\perp$ distributions, we should have the situation described in Fig. 2d,with the mean multiplicity of leading hadrons ~3 times the normal amount. This does not mean a higher density of leading hadrons in phase space; indeed event by event the three jets are in distinguishable regions of momentum space. A better description is that the mean transverse momentum of the leading hadrons is much larger ($\sim m_Q/3$) than normal. Thus a signal for production of high energy superheavy flavored hadrons decaying nonleptonically is (a) abnormally high (factor ~3) multiplicity of leading hadrons, and (b) abnormally high transverse momenta of such hadrons ($p_\perp \lesssim m_Q/3$).

There are of course some immediate implications of this picture for charmed hadron production by neutrinos, as well as by electron-positron annihilation. It would appear that a charmed-quark mass $m_c \sim 1.2$ to 1.6 GeV is large enough for at least seeing an initial trend for the mean z of charmed mesons in neutrino reactions to be larger than for uncharmed mesons. While calculations do exist which argue that this behavior is ruled out,[10] the argumentation is indirect, and it may be better to await the additional data we can expect in the near future. In $e^+e^-$ annihilation, there is not really high enough energy to make a clear test, although the large yield of D*'s of high momentum at the highest $e^+e^-$ energies[11] may be some encouragement.

However, it must be remembered that much of our argument presumed existence of jets with energy high enough so that a central plateau structure exists; this in turn implies very high, quite possibly unrealistically high, energy and mass scales ($m_Q > 100$ GeV??). Thus what happens in the interesting mass region of 5 to 100 GeV may not be easy to describe quantitatively from these considerations alone. Nevertheless, for quarks Q of mass greater than 5 GeV, the properties we have discussed should become apparent, at least qualitatively and perhaps semiquantitatively.

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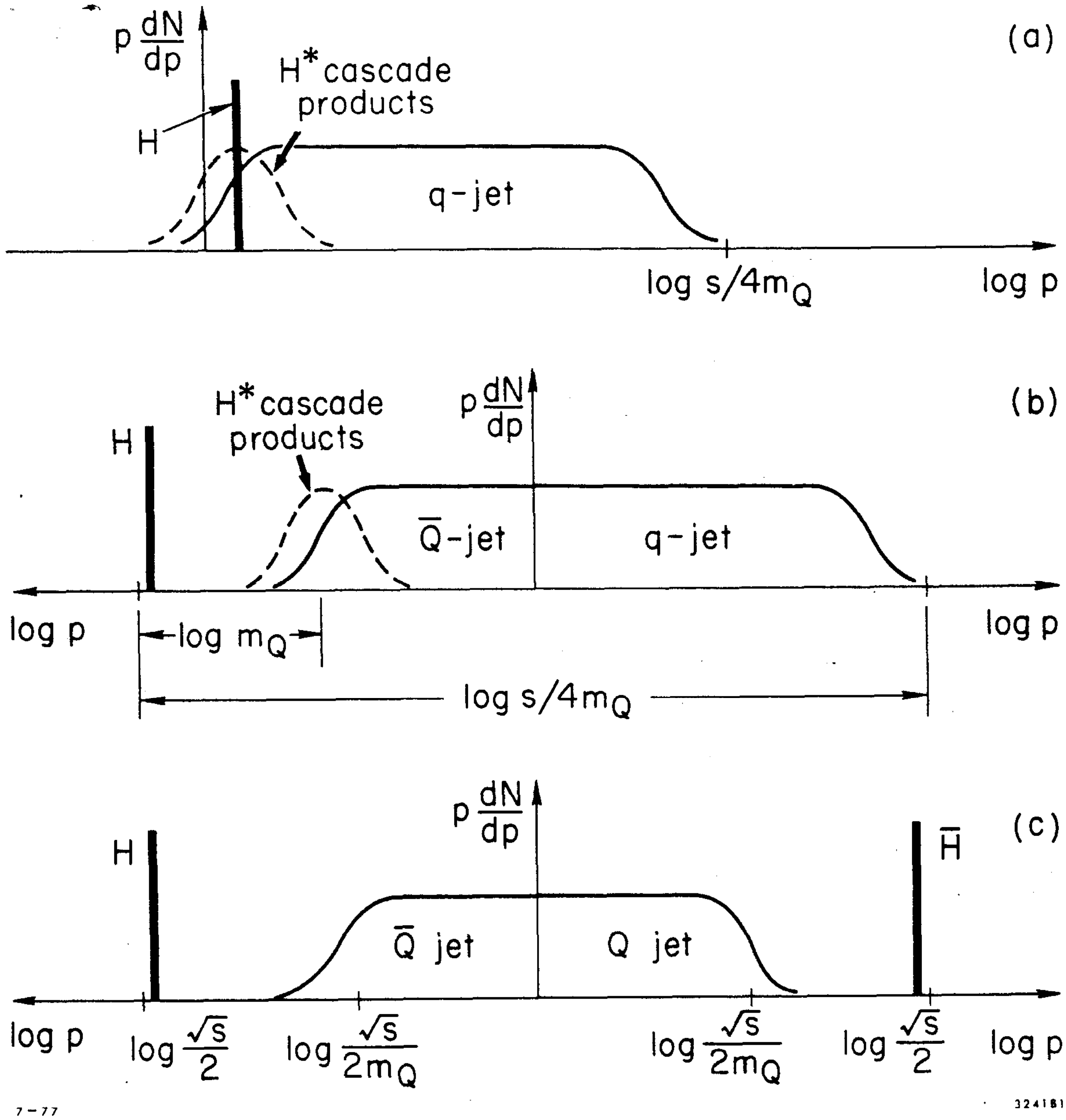
## REFERENCES

1. A. Benvenuti *et al.*, Phys. Rev. Letters **36**, 1478 (1976).
2. A. Benvenuti *et al.*, Phys. Rev. Letters **38**, 1110 (1977).
3. S. Herb *et al.*, Phys. Rev. Letters (to be published).
4. See for example, R. P. Feynman, *Photon-Hadron Interactions* (W. A. Benjamin, New York, 1972).
5. At least some of the ideas underlying this discussion already reside in the literature; much of the rest is quite possibly folklore. See for example, M. Suzuki, preprint LBL-6173 (1977).
6. The choice 1 GeV, rather than 0.5 or 2 GeV, for the constant is only guesswork; we use 1 GeV mainly for its didactic convenience.
7. For expositions of this point of view, see J. D. Bjorken, Proceedings of the SLAC Summer Institute on Particle Physics, SLAC-167 (1973); also J. D. Bjorken, SLAC-PUB-1756 and *Lecture Notes in Physics*, No. 56, ed. by J. G. Komer, G. Kramer, and D. Schildknecht (Springer-Verlag, Berlin, 1976); p. 93.
8. A. Casher, J. Kogut, and L. Susskind, Phys. Rev. Letters **31**, 792 (1973).
9. An exception is backward decay; however, at large $\gamma$ this becomes a highly improbably configuration.
10. V. Barger, T. Gottschalk, and R. Phillips, University of Wisconsin preprint COO-601.
11. G. Feldman *et al.*, Phys. Rev. Letters (to be published).

FIGURE CAPTIONS

1. (a) Momentum distributions for hadrons produced in the process $\bar{\nu}+e \rightarrow q+Q$, with Q superheavy, as viewed in the rest frame of Q. The H is a $\bar{Q}q$ meson stable under strong interactions. (b) Same as (a), viewed in the $\bar{\nu}e$ center-of-mass frame. (c) Momentum distribution of hadrons produced in $e^+ + e^- \rightarrow \bar{Q} + Q$, viewed in the $e^+e^-$ center-of-mass frame.

2. (a) Rapidity distribution of electroproduced or neutrino-produced hadrons in processes which involve production of a superheavy quark, as viewed in the laboratory frame. (b) Hadron spectrum from semileptonic decay of the $\bar{H}$ as produced as in (a), again in the laboratory frame. (c) Composite spectrum. The distribution is very similar to that of a single q-jet of momentum $\sim E_Q/3$. (d) Composite spectrum as in (c), now for the non-leptonic decay of H via $\bar{Q} \rightarrow \bar{q}\bar{q}q$.



p dN/dp
(a)
H* cascade products
H
q-jet
log s/4m_Q
log p
H* cascade products
p dN/dp
(b)
H
Q̄-jet
q-jet
log p
log m_Q
log p
log s/4m_Q
p dN/dp
(c)
H
H̄
Q̄ jet
Q jet
log p
log √s/2
log √s/2m_Q
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Fig. 1

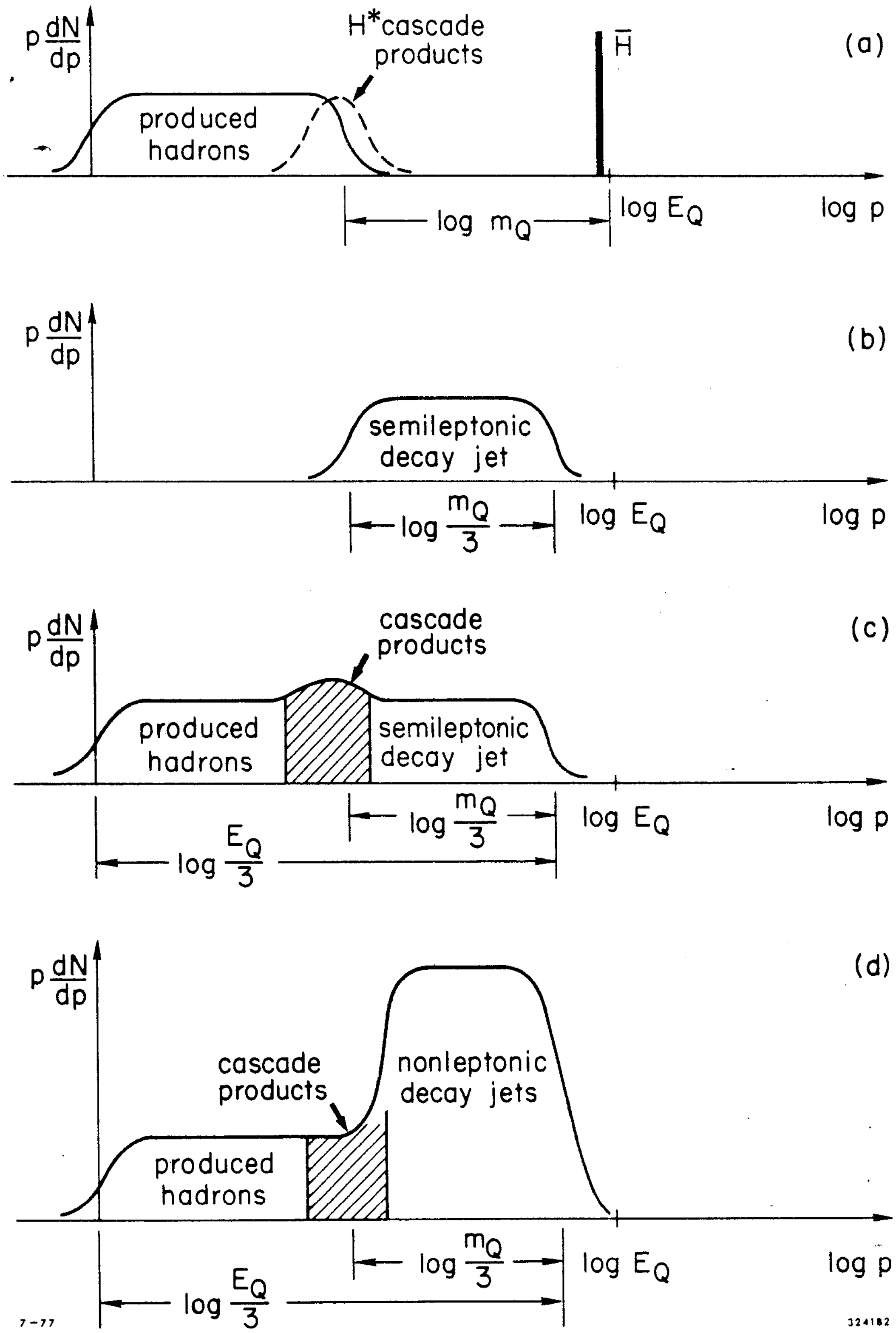
p dN/dp
(a)
H*cascade products
$\bar{H}$
produced hadrons
log $m_Q$
log $E_Q$
log p
(b)
semileptonic decay jet
log $\frac{m_Q}{3}$
(c)
cascade products
log $\frac{E_Q}{3}$
(d)
nonleptonic decay jets
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Fig. 2