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Properties and signatures of heavy quarks

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Recent theoretical speculation concerning the mass of the t quark, the charge-2/3 partner of the quark bound in Υ, put it, as well as possible heavier doublets, outside the reach of existing e^+e^- machines. If this speculation is correct, hadron colliders will provide the only means of studying new flavors in the near future. We study (i) the properties of heavy quarks and their bound states, emphasizing the importance of weak effects when $2M_q \gtrsim M_Z$ (mass of the intermediate boson), and (ii) their various experimental signatures in hadronic collisions. Contrary to what one might suspect from past experience with charmed particles, we anticipate that the associated production (and not the e^+e^- or $\mu^+\mu^-$ invariant mass of the quark-antiquark bound state) will provide the most prominent signature via the study of anomalous $e\mu$ events. We expect the background to any leptonic signature to be severe, suggesting the requirement of simultaneous detection of hadrons.

I. INTRODUCTION

The recently observed structure[1] in the 10-GeV mass region has been successfully interpreted in terms of bound states of b quarks, with charge $-\frac{1}{3}$. Such an interpretation accounts for many features of the data such as the production cross sections, leptonic widths, etc. This immediately raises the question whether this quark also has a charge $+\frac{2}{3}$ partner, the so-called t quark, and, if so, what its mass is. There are many speculations regarding the mass of the t quarks. They fall into two categories: One set[2] takes the mass formula suggested by $m_b/m_c \cong m_c/m_s$. Extrapolating to m_t, one expects $m_t/m_b \sim m_b/m_c$, leading to $m_t \sim 15$ GeV. The other class of speculations[3,4] predicts that $m_s/m_b \cong m_c/m_t$, resulting in $m_t \sim 30$ GeV. Various attempts have been made to justify such mass relations by imposing constraints on the Higgs-boson couplings which govern the mass spectrum.

The possibility that $m_t > 20$ GeV raises a very important practical point, viz., that none of the existing e^+e^- colliders will be able to reach threshold for producing $t\bar{t}$ pairs. Hence, for $m_t > 20$ GeV, the only means of producing $t\bar{t}$ in the near future (until completion of LEP) are the p-p and $\bar{p}$-p colliding-beam facilities under construction at Fermilab, CERN, and Brookhaven. With this in mind, we have studied the properties and experimental signatures in hadronic interactions of $t\bar{t}$ pairs with m_t ranging from 15 to 100 GeV. This study is relevant in a different context: These machines cover the kinematic range where the next flavor doublet could be discovered. Calculations regarding the t quark can be directly reinterpreted in terms of a new flavor with corresponding mass. Present speculation[3] puts the mass of the next flavor doublet around 100 GeV, close to the upper limit on fermion masses[5] in the context of the simplest gauge theories on which all our estimates are based.

Quark searches could therefore develop as a major mission of the hadron colliders along with the publicized hunt for weak bosons. Although much attention has been devoted to the production cross sections, signatures, and backgrounds relevant to weak-boson searches,[6,7] a similar effort has not been devoted to the study of new flavors. We feel that important progress in anticipating the detection of weak bosons has been made possible by the advent of perturbative quantum chromodynamics (QCD). It provides us with a definite procedure locked in with existing data, to estimate cross sections, experimental signatures, and backgrounds within one and the same framework.[7]

Therefore, all our calculations are performed in the framework of quantum flavor dynamics, i.e., perturbative quantum chromodynamics and the Weinberg-Salam model. Whereas QCD predicts the observability of the weak bosons in the simplest single-arm lepton search,[7] its implications for quark hunting are far less optimistic and clear cut.

The paper is organized as follows (note that the "technology" of most computations is collected in an appendix): We start by computing the various widths and branching ratios for heavy quarks, drawing attention to the potential importance of weak decays. Indeed when $2M_q \simeq M_Z$, i.e., the mass of the quark-antiquark bound state is not too different from that of the weak boson, decays mediated by W, Z, and Higgs particles play an important role and can eventually contribute the dominant decay channel.[8]

We then compute the production cross section for producing heavy-quark bound states as well as for producing the familiar Drell-Yan dilepton ($l\bar{l}$) background competing with their most prominent signature: enhancements in the invariant mass of lepton pairs. By using scaling laws,[9] which are rather solidly anchored to experimental data, for dilepton yields "on" and "off resonance" and scaling them to larger values of the quark mass (M_q) and collision energy ($\sqrt{s}$), we arrive at rather pessimistic projections regarding the direct observation of the dilepton enhancement from the decay $V \to l\bar{l}$. The situation is further obscured by dileptons originating from the associated production and subsequent leptonic decay of charmed and bottom quarks. At $\sqrt{s} = 540$ GeV such fake dileptons might be more copious than Drell-Yan pairs for invariant masses all the way up to the Z. We conclude that searches with high resolution and very large statistics over the full mass range will be required. This will be a difficult task, especially if one considers the limited luminosity of some of the proposed machines. We also briefly discuss the prospects for dilepton experiments with Fermilab's energy doubler.

This sets the stage for our next investigation: the associated production of unbound flavor. We compute the cross section as a function of the quark mass according to perturbative QCD ideas which successfully account for the observed level of charm production.[10] Despite the optimistic predictions for the total yield and the leptonic branching ratio[11] ($B \simeq 10\%$), the observation of structure in the transverse-momentum distribution of direct single leptons is unlikely because of a combination of (i) the large direct-lepton background predicted by QCD and (ii) the lack of structure in the (dominant) three-body decay distribution. The high-$\langle p_T \rangle$ production predicted by QCD, and the cascading $t \to b \to c \to s$, are expected to wash out all structure in the p_T distribution, even the maximum at $p_T \simeq M_q/3$. This negative result prevails if one observes both leptons from the associated production ($e\mu$ events or like-sign dileptons). The origin of the problem is simple: Every quark is the next quark's fatal background in QCD. Indeed, the drop in cross section one registers for large transverse momentum in a hadron collision is not more than the one that results from the presence of a large mass in the final state. Specifically, any lepton from a decay of say a t quark can be simulated by a high-p_T c, b quark. We actually conclude that angular correlations of the leptons in anomalous e, μ events provide the most promising basis for a systematic experimental search.

These conclusions seem to run contrary to our experience with charmed particles: ψ's are a much better signature for charm than associated production of D's. The reason is simple: Charmed particles are too light with $p_T \simeq M_D/3$ giving a lepton signal in a momentum range still clouded by conventional strong-interaction sources for direct leptons.

For very large quark masses any leptonic signature runs into problems with either single W or W^+W^- pair production backgrounds. Indeed, in gauge theories the ZW^+W^- coupling yields a pair production mechanism which is $O(\alpha)$, not $O(G)$, of single W production, and will interfere with e, μ associated flavor production for $M_q \gtrsim M_W$. Bjorken[12] has, however, pointed out that in this case there might be spectacular hadronic signals via $pp \to$ pair of heavy quarks $\to qW\bar{q}W \to$ six high-p_T jets. We discuss the interplay of heavy quarks and weak bosons in the final section.

II. DECAY CHARACTERISTICS OF HEAVY QUARKS

We start by evaluating as a function of the t-quark mass the partial widths and leptonic branching ratio of the vector meson V binding t flavor. The decay rates are calculated according to the standard technology of quantum flavor dynamics; the results are listed in Table I. The parameters in the calculation α_s, the quark-gluon coupling constant, and p, a parameter which phenomenologically represents the dependence of the wave function at the origin on quark mass $[|\psi(0)|^2 \propto M_V^{p-2}]$, are fitted to measured ψ and Υ widths. We obtain $p = 2.07$ and the expression for α_s given in Table I. We are now ready to extrapolate the result to larger quark masses. The resulting widths are given in Table II for representative values of M_q.

It is interesting to notice[8] the large enhancement of the hadronic width due to weak decays for $2M_q \gtrsim M_W$. As a consequence the leptonic branching, which is typically at the 10% level, is suppressed to about 3%.

Although results are shown for $e_q = \frac{2}{3}$ having in mind the t quark, one should have in mind that the next flavor has most likely $e_q = -\frac{1}{3}$, and the result should be rescaled in e_q according to the formulas of Table I. Let us assume for the purpose of illustration that the next charge $-\frac{1}{3}$ quark (b') has mass $M_{b'} = 100$ GeV. Its dominant decay would be $b' \to qW$ with $q = u, c, t$. The total decay rate for b' into a lighter quark q and W is given by[8]

TABLE I. Decays of heavy quarks. Formulas. We use the following notation: γ^* (photon), g (gluon), l (e, μ, τ leptons), V ($t\bar{t}$ bound states), q (quark with charge e_q), $W^\pm$ (weak intermediate boson with $M_W = 82$ GeV), Z (neutral intermediate boson $M_Z = 92$ GeV, $\Gamma_Z = 3$ GeV), H (Higgs boson with $M_H = 10.4$ GeV, $\Gamma_H = 66$ keV), α, G, α_s (electromagnetic, weak, and strong coupling constants), with

$$\alpha_s = \frac{0.193}{1 + (21/12\pi)(0.193)\ln(M_V/M_\psi)^2} .$$

Some of these formulas may be found in Refs. 8 and 13; we assumed $\sin^2\theta_W = \frac{1}{4}$.

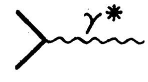
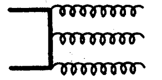
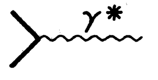
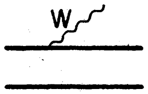
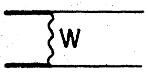
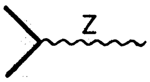
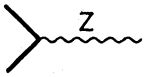
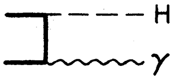
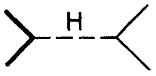
Decay channel	Diagram	Formula
$\gamma^* \to l\bar{l}$		$\Gamma^{\psi}_{l\bar{l}} \frac{e_q^2}{(\frac{2}{3})^2} \left(\frac{M_\psi}{M_V}\right)^{2-p} \ (\equiv \Gamma_{l\bar{l}})$
$3g \to$ hadrons		$\frac{10}{81} \frac{(\pi^2 - 9)}{\pi} \frac{1}{\alpha^2} \frac{\alpha_s^3(M_V)}{e_q^2} \Gamma_{l\bar{l}} \ (\equiv \Gamma_d)$
$\gamma^* \to$ hadrons		$R_h \Gamma_{l\bar{l}} \ (\equiv \Gamma_{\gamma^*})$ with $R_h = \frac{13}{3}\left(1 + \frac{\alpha_s(M_V)}{\pi}\right)$
$t \xrightarrow{W} b$		$\frac{18 G_F^2 M_t^5}{192\pi^3} \frac{1}{(1 + M_t^2/M_W^2)^2} \ (\equiv \Gamma_{W1})$
$t\bar{t} \xrightarrow{W} b\bar{b}$		$\frac{2}{(2e_q)^2} \frac{M_V^4}{(M_W^2 + \frac{1}{4}M_V^2)^2} \Gamma_{l\bar{l}} \ (\equiv \Gamma_{W2})$
$Z \to$ hadrons (u, d, c, s, b)		$\frac{59}{9}\left(\frac{1 - \lvert e_q \rvert}{3e_q}\right)^2 \frac{M_V^4}{(M_V^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \Gamma_{l\bar{l}}$
$Z \to$ leptons $(e, \nu_e; \mu, \nu_\mu, \tau, \nu_\tau)$		$9\left(\frac{1 - \lvert e_q \rvert}{3e_q}\right)^2 \frac{M_V^4}{(M_V^2 - M_Z^2) + M_Z^2 \Gamma_Z^2} \Gamma_{l\bar{l}}$
$t\bar{t} \to H\gamma$		$\frac{G_F M_V^2}{4\sqrt{2}\pi\alpha}\left(1 - \frac{M_H^2}{M_V^2}\right)\Gamma_{l\bar{l}}$
$t\bar{t} \to H \to b\bar{b}$		$\frac{(M_V^2 - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}{(M_V^2 - M_H^2)^2 + M_H^2 \Gamma_H^2} \frac{M_t^2 M_b^2}{M_Z^4} \Gamma_{Z \to b\bar{b}}$

TABLE II. Decays of heavy quarks. Results for $e_q = \frac{2}{3}$. Width of the vector meson binding new quark flavors. Notation is the same as in Table I. Γ_Z represents the sum of the individual contributions to the total width listed in Table I and mediated by Z. B_l is the leptonic branching ratio.

M_q (GeV) Width (keV)	15	30	45	60
Γ_{ll}	5.6	5.9	6.1	6.2
Γ_{γ^*}	25	26	27	27
Γ_d	18	14	12	11
Γ_{W1}	0.3	8	42	124
Γ_{W2}	0.1	2	6	15
Γ_Z	0	1	178	11.5
$\Gamma_{H\gamma}$	0.4	1.8	4	8
Γ_{tot}	61	71	288	215
B_l [a]	9.3%	8.5%	6.1%	3.2%

[a] Note that B_l also includes $\Gamma_{Z \to l\bar{l}}$.

TABLE III. Properties of the vector meson binding the next b quark. $e_q = -\frac{1}{3}$, $M_q = 100$ GeV, a typical expectation for the mass of the next flavor doublet.

Decay channel	Width (keV)
$\gamma^* \to l\bar{l}$	1.6
$3g \to$ hadrons	10.1
$\gamma^* \to$ hadrons	10.8
$b' \xrightarrow{W} q$	$\sum \lvert\epsilon_q\rvert^2 \times 5017$
$b'\bar{b}' \xrightarrow{W} q\bar{q}'$	$\sum \lvert\epsilon_q\rvert^2 \lvert\epsilon_{q'}{}^2\rvert \times 10$
$Z \to$ hadrons	10.4
$Z \to$ leptons	16.3
$b'\bar{b}' \to H\gamma$	8
$b'\bar{b}' \to H \to t\bar{t}$	0.1

$$\Gamma(b' \to q + W) = \sum_q |\epsilon_q|^2 \frac{M_W^2 G_F}{4\pi\sqrt{2}} \frac{(m_{b'}^2 - m_W^2)^2}{m_{b'}^3}\left[2 + \left(\frac{m_{b'}}{m_W}\right)^2\right],$$

where ϵ_q are mixing coefficients of b' with u, c, and t. For $m_{b'} = 100$ GeV we obtain

$$\Gamma(b' \to q + w) = \sum_q |\epsilon_q|^2 \times (4.2\ \text{MeV}).$$

Suppose $\sum_q |\epsilon_q|^2 \sim \frac{1}{10}$; then we obtain $\Gamma \simeq 0.42$ MeV and the b' quark's lifetime would be $\tau \simeq 1.5 \times 10^{-21}$ sec. The properties of the bound state $\bar{b}'b'$ are collected in Table III.

III. EXPERIMENTAL SIGNATURE OF BOUND FLAVOR

Recent experience puts forward the obvious candidate for an experimental scan for new quarks; a search for narrow structure in dilepton invariant mass. We first estimate the signal $B_l\sigma_M$, the production cross section of the heavy-quark–antiquark bound state multiplied by the leptonic branching ratio, as well as the corresponding background, i.e., the lepton pair continuum produced via, for example, the Drell-Yan process. We try to minimize theoretical bias by scaling data in the ψ, Υ mass region. We use the following interpolations[9,14] for the cross sections:

$$M^2\sigma_M(\sqrt{s}) = \left(\frac{\Gamma_d}{M}\right)F\left(\frac{\sqrt{s}}{M}\right), \qquad (1)$$

and for the dilepton background

$$M^3 \frac{d\sigma_{l\bar{l}}}{dM}(\sqrt{s}) = F'\left(\frac{\sqrt{s}}{M}\right). \qquad (2)$$

Equations (1) and (2) would follow from QCD on purely dimensional grounds, although Eq. (1) contains the additional assumption that the production cross section is proportional to the (direct) hadronic width of the vector meson. More important is the additional fact that solid experimental support exists for both. Equation (1) correctly interpolates[14] known yields for ϕ, ψ, ψ' production and correctly predicted that of the Υ. We rewrite it as

$$B_l\sigma_M(\sqrt{s}) = \left|\frac{B_l}{B_l^\psi}\frac{\Gamma_d}{\Gamma_d^\psi}\left(\frac{M_\psi}{M}\right)^3\right| B_l^\psi\sigma\left(\frac{M_\psi}{M}\sqrt{s}\right), \qquad (3)$$

where $M \simeq 2M_q$. Using data on the width and cross section of ψ, we predict $B_l\sigma_M$ using information on B_l and Γ_d given in Tables I, II. The result is shown as a solid line in Fig. 1 at representative values of $\sqrt{s}$, along with data on ψ and Υ production[1,15] at $\sqrt{s} = 27$ GeV. Equation (2) just represents Drell-Yan scaling which is known[1] to hold over a wide range of values of lepton-pair mass M and energy $\sqrt{s}$. Scaling of the data according to Eq. (2) yields the dashed background curves predicting the lepton-pair continuum.

At higher energies another source of dileptons competes with the vector-meson decay signal: associated production of b, c quarks followed by semileptonic decays of both quarks.[16] Our estimates for this background are shown in Fig. 1 as dash-dotted lines. We see that while this source is negligible at present, it exceeds dileptons from the Drell-Yan process at collider energies out to high masses.

For purely dimensional reasons we compared in Fig. 1 the signal $B\sigma_M$ with background curves $M d\sigma_{l\bar{l}}/dM$. A relevant experimental comparison should take into account the expected dilepton

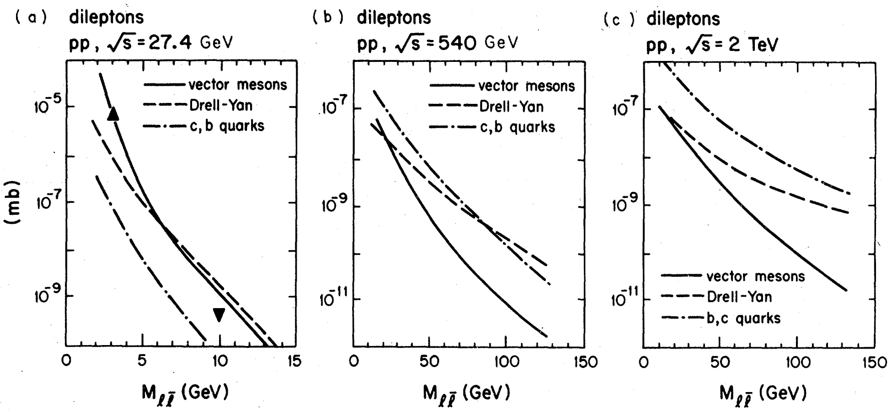


FIG. 1. (a) $B\sigma_M$ for producing a vector meson of mass M (binding heavy quarks of approximate mass $M/2$) in pp interactions ($\sqrt{s} = 27.4$ GeV) is shown as a solid line and compared to data on ψ and Υ production. B is the leptonic branching ratio into a lepton pair $l\bar{l}$. Also shown is the lepton-pair background $M_{l\bar{l}}\, d\sigma/dM_{l\bar{l}}$ from (i) the Drell-Yan process (dashed line); (ii) pair production of c, b quarks followed by leptonic decays of each member of the pair (dashed-dotted line). (b) and (c): Same as (a) for $\sqrt{s} = 0.54$ and 2 TeV.

mass resolution and event rate. This will depend on the specific experimental setup as well as the luminosity of the hadron storage ring. One can, nevertheless, get a feeling for the predictions in Figs. 1(b), 1(c) by first looking at the ψ and Υ points in Fig. 1(a). It is well known that the ψ signal is above Drell-Yan background. The integrated cross section in the Υ region is, however, smaller than the continuum cross section at the same mass, i.e., the signal appears as a "ripple" on the continuum. For the larger masses in Figs. 1(b), 1(c) the signal is, however, suppressed by over one order of magnitude, requiring improved resolution and/or statistics compared to the Fermilab experiment discovering Υ. Especially the second goal might be difficult because of the reduced luminosity of hadron colliders.

We point out that predictions are shown for pp interactions. Although the total rates are expected to be enhanced in $\bar{p}p$ collisions, we do not expect a different signal-to-background ratio. Indeed, the presence of valence antiquarks most likely enhances both in a similar manner.

IV. EXPERIMENTAL SIGNATURE OF NAKED FLAVOR

The associated production of new flavors can be calculated according to perturbative QCD.[10] The result is shown as a solid line in Fig. 2 as a function of M_q at a typical collider energy of $\sqrt{s} = 800$ GeV. This calculation can also be done[14] by rescaling experimental data on dilepton production by $\alpha_s^2(M)/\alpha^2$. The result is shown as the dashed line in Fig. 2, and as expected the two estimates coincide for $2M_q/\sqrt{s}$ not too small and agree in fact remarkably at all M_q. The process

$$(p \text{ or } \bar{p})p \to T\bar{T} + \text{anything}$$
$$\searrow l + \text{anything}$$

will produce an enhancement in the direct-lepton yield at $(p_T)_l \simeq M_q/3$ as three-body channels dominate the semileptonic decay. The Jacobian peak is not expected to be very pronounced. High-mass quarks will be produced with large $\langle p_T \rangle$ in QCD. Furthermore, the cascade decays $t \to b \to c \to s$ will indeed produce leptonic enhancement at lower-p_T values, making the decay spectrum essentially structureless. The results of an explicit estimate are shown in Fig. 3(a). Several backgrounds compete with the signal: (i) semileptonic decays of c, b quarks produced at high p_T[17]; (ii) direct leptons from the internal conversion of high-p_T real photons[18]; (iii) single leptons from Drell-Yan pairs[19]; (iv) leptons from the leptonic decay of high-p_T ψ's [not shown in the figure, but we calculate that they contribute at the same level as (ii) and (iii)]. In view of the ambiguities in calculating both the signal and the multiple backgrounds, we can safely conclude that we have no arguments for the feasibility of a single lepton search, whatever the value of M_q.

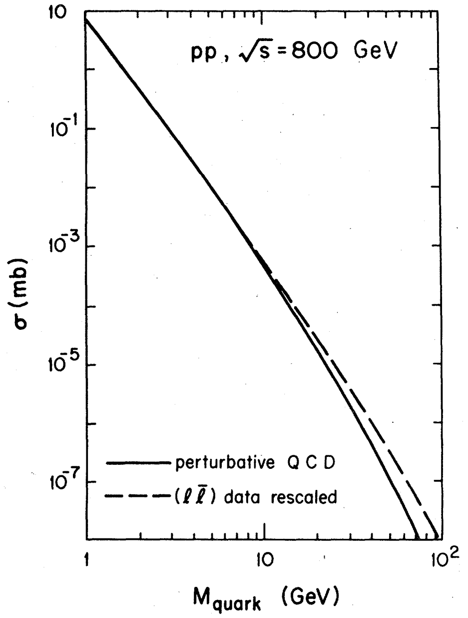


FIG. 2. The cross section for the associated production of heavy quarks is computed as a function of their mass in two different ways: (i) from perturbative QCD (solid line); (ii) by rescaling measured lepton pair yields in coupling constant (dashed line). The calculation is performed for pp interactions with a representative energy $\sqrt{s} = 800$ GeV.

Of course, within our simple QCD approach especially background (i) presents a major obstacle as almost any high-p_T lepton originating from the semileptonic decay of a heavy quark can be simulated by the semileptonic decay of a ligher quark produced with a relatively larger transverse momentum. In lowest-order perturbative QCD the two keep matching each other's cross sections.

This leaves us with what we anticipate to be the most promising leptonic search for the t or any other new quark flavor: anomalous e, μ events. Requiring observation of a second high-p_T lepton signalling the presence of a leptonic decay of the associatively produced quark suppresses the cross section by B_l, i.e., about 10%. On the contrary the competing backgrounds are now suppressed dramatically except for (i). The fact that leptons from heavy-quark decay are screened by those from c, b semileptonic decays hold true for opposite side $e\mu$ events. However, when observing both leptons, their angular correlation can be

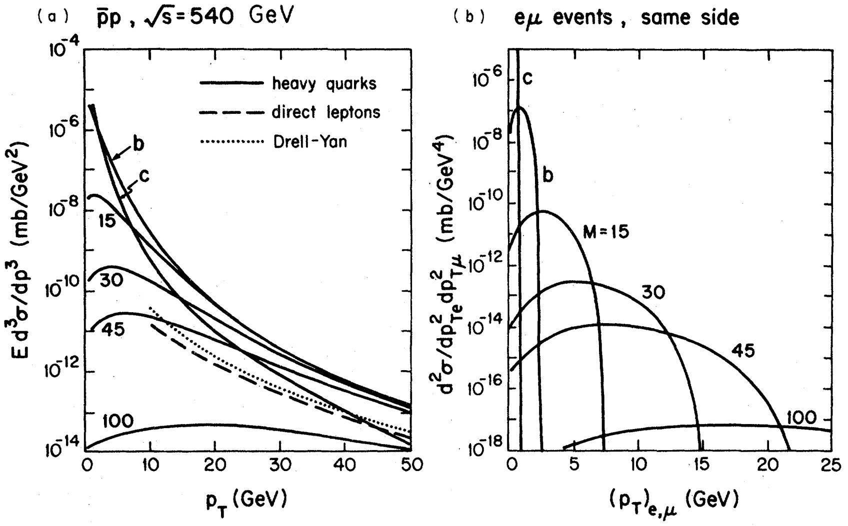


FIG. 3. (a) The transverse-momentum spectrum at rapidity $y=0$ of leptons originating from the production and subsequent semileptonic decay of c, b quarks and heavy quarks with $M_q=15$, 30, 45, and 100 GeV. Also shown is the same cross section for leptons resulting from the Drell-Yan process (dotted line) and the internal conversion of photons with large p_T (dashed line). Other sources of single leptons are discussed in the text. Calculations are performed for $\bar{p}p$ interaction at $\sqrt{s}=540$ GeV. (b) Transverse-momentum spectrum of $e\mu$ events from associated production and semileptonic decay of c, b quarks and heavy quarks with $M_q=15$, 30, 45, and 100 GeV. For illustration we have chosen both leptons to have rapidity $y=0$ and $(p_T)_e=(p_T)_\mu$. Calculations are performed for $\bar{p}p$ interactions at $\sqrt{s}=540$ GeV.

used to enhance the signal. Consider, for example, events with the e and μ on the same side with $p_{Te}=p_{T\mu}$. Because of the $2\to 2$ kinematics inherent in $O(\alpha_s)$ QCD, such events cannot be simulated by b, c decays. Indeed, the parent of a very-high p_T ($\simeq M_t/3$) lepton from charm decay was necessarily produced with high transverse momentum. Therefore, the associated charmed particle and its decay lepton must necessarily be on the opposite side to balance overall transverse momentum. On the other hand, in the case of a genuine production of a pair of heavy quarks, requiring that the second lepton follows the first does not create a momentum imbalance and only suppresses the cross section $\sim B_l/4\pi$. This is borne out by an explicit estimate shown in Fig.

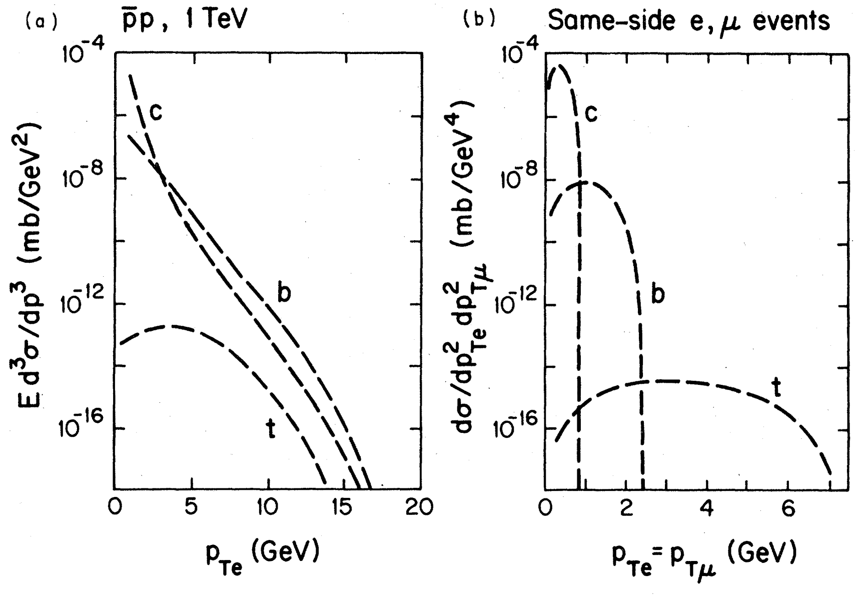


FIG. 4. Same as Fig. 3 for $p_{lab}=1$ TeV, the energy of Fermilab's doubler. We have chosen $M_t=15$ GeV.

3(b), which also illustrates the fact that the joint spectrum has a kinematic cutoff at $M_q/2$.

This conclusion follows from calculations to lowest order in α_s. In higher orders $c\bar{c}$ and $b\bar{b}$ can be produced on the *same* side at high p_T, from a high-p_T gluon, for example. If both quarks produce mesons which decay semileptonically, then we have a background to the same-side lepton pair signal. We have not estimated this, and can simply put our faith in perturbation theory.

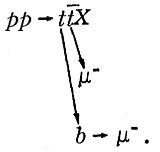
We conclude this section with some comments.

Figure 4 reproduces the estimate of Fig. 3 for experiments with Fermilab's energy doubler.[20]

High-p_T b quarks cascading $b \to ce\nu$ followed by $c \to s\mu\bar{\nu}$ can produce same-side $e\mu$ events. We feel not only that a fail-safe heavy-quark detector should measure e, μ with good resolution, but also that further observation of the associated hadrons would certainly provide important, possible crucial, additional information.

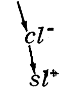
The angular asymmetry between positive and negative leptons may provide a possible signature for heavy quarks. The existence of such an asymmetry, which comes about from the interference between one- and two-gluon exchange in $qq \to Q\bar{Q}$, and between initial- and final-gluon bremsstrahlung in $q\bar{q} \to Q\bar{Q}$ (in analogy to the asymmetry in $e^+e^- \to \mu^+\mu^-$), has been discussed in Ref. 21. This asymmetry depends on the mass of the heavy quark Q, and a detailed measurement may be able to isolate the effects of a new heavy quark.

An alternative signature to $e\mu$ is provided by same-sign dileptons

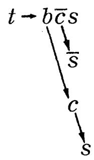


We expect $\sigma(\mu^-\mu^-) \simeq 10^{-2}\sigma(t\bar{t})$. This signal is inferior in two respects: One μ is necessarily degraded in p_T because of the $t \to b \to \mu^-$ cascade; B^0-$\bar{B}^0$ mixing could be quite large, especially if the t quark is heavy,[22] and therefore $b\bar{b}$ production could simulate equal-sign dileptons from the associated production of a t quark.

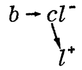
Other obvious signatures[23] of $t\bar{t}$ production are via the cascade decays



events with six charged leptons and via



with six strange particles. The rate for six-lepton events is expected to be $\sim 10^{-6}$ and for six strange particles can be as high as $\sim 10^{-1}$ of the $t\bar{t}$ production cross section. The main background for six-lepton events would be from $b\bar{b}$ production with



plus an additional pair of leptons emitted radiatively, or coming from additional $c\bar{c}$ or $b\bar{b}$ production and decay. This background rate is $\sim 10^{-6}$ times the $b\bar{b}$ production cross section and is close to the expected signal. Corresponding backgrounds for six-strange-particle signal are expected to be more severe.

The pair production of heavy leptons[24] through the Drell-Yan process $pp \to L^+L^-X$ is significantly suppressed compared to the production of quarks of a corresponding mass. For example, for $M_L \simeq M_q \simeq 10$ GeV we have $\sigma B_l{}^2 \simeq 10^{-5}$ mb for quark production, whereas $\sigma(pp \to L\bar{L}X) \simeq 10^{-7} \sim 10^{-8}$ mb. In fact, the dominant production mechanism for producing heavy leptons in hadron colliders would be via the decay of possible heavier-quark flavors.

V. THE INTERPLAY OF HEAVY QUARKS AND WEAK BOSONS

When $M_q \simeq M_W$, weak decays not only suppress the leptonic decays of the quark (see Table II), a confusing interplay between heavy-quark and W production will appear.

When $M_q \simeq M_W$, $\sigma(M_q \simeq M_W) \simeq 10^{-7} \sim 10^{-8}$ mb (see Fig. 2). Because of the non-Abelian character of the Weinberg-Salam model, W pairs can be produced via Z leading to a pair production cross section[25] which is $O(\alpha)$, not $O(G_F)$ of the single W yield. Therefore,

$$\sigma(pp \to W^+W^-X) \simeq 10^{-7}-10^{-8} \text{ mb} \simeq \sigma(M_q \simeq M_W) .$$

As also the leptonic branching ratios of W's and quarks as heavy as M_W are similar (see Tables I, II), the detection of quarks will be difficult. The situation is similar to the one for flavor bound states with $M_V = 2M_q = M_Z$. Such V states predominantly decay via Z and are hidden under the Z peak.

Conversely leptons from all heavy-quark decays provide background leptons in a W, Z search. Figure 5(a) shows dileptons from Z decay along

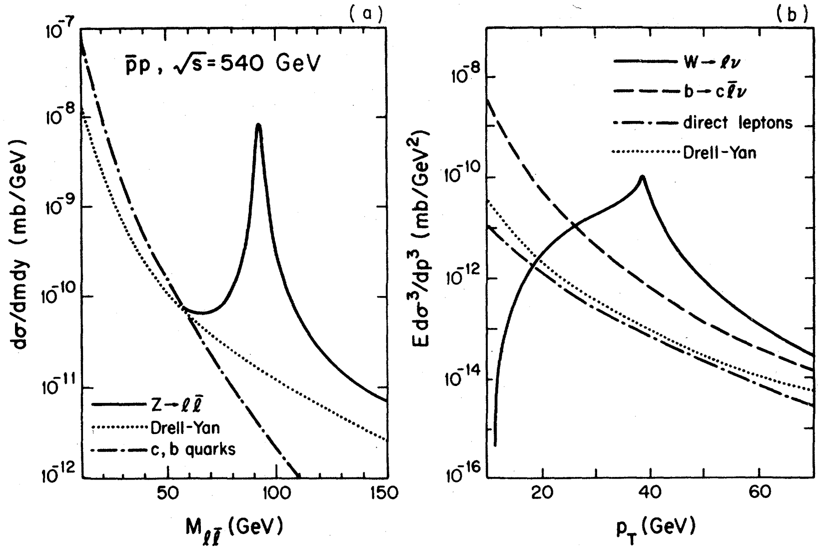


FIG. 5. (a) Lepton pairs in $\bar{p}p$ interactions ($\sqrt{s}=540$ GeV, $y=0$) from prominent sources: (i) production and leptonic decay of the weak boson Z (solid line); (ii) Drell-Yan (dotted line); (iii) pair production of c, b quarks followed by leptonic decays of each member of the pair (dashed-dotted line). (b) Single-lepton transverse-momentum spectrum in $\bar{p}p$ interactions ($\sqrt{s}=540$ GeV, $y=0$) from prominent sources: (i) production and leptonic decay of the weak boson W^+ (solid line); (ii) production and semileptonic decay of b quarks (dashed line); (iii) the Drell-Yan process (dotted line); (iv) the internal conversion of real photons (dashed-dotted line). Other sources are discussed in the text.

with Drell-Yan pairs as well as lepton pairs from associated production and twin leptonic decay of b, c quarks. Note that for our particular estimates[26] the Drell-Yan process becomes unobservable at collider energies [see also Figs. 1(b), 1(c)]. Figure 5(b) shows the corresponding situation for single leptons from charged W's. The background now also includes direct leptons from the internal conversion of prompt photons.

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APPENDIX

The calculations presented in this paper are in principle straightforward, although in practice some of them involve complex Monte Carlo calculations. In view of the combined ambiguities in the calculation of the properties of heavy quarks and their production rates one can, without any real loss in reliability of the final estimate, introduce a set of approximations which allow analytic and almost "back of the envelope" type estimates of the results. We present the procedure in this appendix.

Three-body decay function $N(k)$

For a heavy quark of mass M decaying into three massless particles, e.g., $t\to be^+\bar{\nu}$, we have in the rest frame of the quark

$$k\frac{d^3N}{dk^3}=\frac{24}{\pi}\frac{B}{M^4}k(M-2k)\,, \tag{A1}$$

where k is the lepton momentum and B the leptonic branching ratio. This distribution satisfies the desired features: (i) It vanishes as $k\to 0$ and $k\to M/2$; (ii) it has a maximum at $k=M/3$; (iii) it is normalized to the branching ratio

$$\int\frac{d^3k}{k}\frac{kd^3N}{dk^3}=B\,. \tag{A2}$$

Single-lepton decay spectrum

Take the same quark when produced in a hadron collision with cross section $Ed^3\sigma/dp^3$; then the lepton momentum spectrum is given by

$$k\frac{d^3N}{dk^3}=\int_{E_0}^{\sqrt{s}/2}dE(E^2-M^2)^{1/2}\int_{\cos\theta_0}^{1}d(\cos\theta)\int_0^{2\pi}d\phi\,E\frac{d^3\sigma}{dp^3}(E,p_T)k'\frac{d^3N}{dk'^3}(k')\,. \tag{A3}$$

θ is the angle between $\vec{k}$ and $\vec{p}$, ϕ the angle between the plane $(\vec{p},\vec{k})$ and $(\vec{p}$, collision axis). In Eq. (A3)

$$p_T{}^2=\left(p\sin\theta\frac{k_T}{k}+p\sin\theta\cos\phi\frac{k_L}{k}\right)^2+p^2\sin^2\theta\sin^2\phi\,. \tag{A4}$$

Here

$$p=(E^2-M^2)^{1/2}, \tag{A5}$$

$$k=(k_L{}^2+k_T{}^2)^{1/2}, \tag{A6}$$

where L and T denote longitudinal and transverse components with respect to the collision axis. Furthermore,

$$k'=\frac{s-M^2}{2M}, \tag{A7}$$

with

$$s=M^2-2Ek+2kp\cos\theta\,. \tag{A8}$$

The integration limits in Eq. (A3) are

$$\begin{aligned}&\text{for } k<\frac{M}{2},\quad E_0=M\,,\\&\text{for } k>\frac{M}{2},\quad E_0'=k+\frac{M^2}{4k}\,,\end{aligned} \tag{A9}$$

$$\begin{aligned}&\text{for } k<M/2 \text{ and } E<E_0',\quad \cos\theta_0=-1\,,\\&\text{otherwise},\quad \cos\theta_0=\frac{2Ek-M^2}{2pk}\,.\end{aligned} \tag{A10}$$

These equations can be trivially generalized for nonvanishing masses in the final state and simplify significantly if one observes the decay lepton at 90° in the center-of-mass system, i.e., $k_L=0$ and $k_T=k$.

For $Ed^3\sigma/d^3p$ we use lowest-order QCD calculation of the Feynman-x_F $(=2E/\sqrt{s})$ and p_T dependence of the heavy-quark production cross section. It turns out that for $k_L=0$ (i.e., $\theta_{\text{c.m.}}=90°$) the calculation is relatively insensitive to the x_F dependence of $Ed^3\sigma/dp^3$. One can, therefore, limit the evaluation of Eq. (A3) to the transverse degrees of freedom

$$\frac{d\sigma}{dk^2}=\int_{k-M^2/4k}^{\sqrt{s}/2}dp_T{}^2\left(\frac{d\sigma}{dp_T{}^2}\right)_{x_F=0}\frac{dN}{dk_l{}^2}\,(s=M^2-2kE+2kp_T)\,, \tag{A3$'$}$$

with s defined as in Eqs. (A7), (A8) and $E=(M^2+p_T{}^2)^{1/2}$. Equation (A3$'$) can be readily generalized to the e, μ correlation

$$\left(\frac{d\sigma}{dk_e{}^2dk_\mu{}^2}\right)_{k_e=k_\mu=k}=\int_{-(k-M^2/4k)}^{(k-M^2/4k)}dp_T{}^2\left(\frac{d\sigma}{dp_T{}^2}\right)_{x_F=0}\frac{dN}{dk^2}(s=M^2-2kE+2kp_T)\frac{dN}{dk^2}(s'=M^2-2kE-2kp_T)\,. \tag{A11}$$

Calculations in the paper are based on Eqs. (A3) and (A11).

D functions

In the limit where the mass of the parent hadron is negligible compared to the transverse momentum of the detected lepton, we may simplify the kinematics from three-dimensional phase space to one-dimensional longitudinal phase space, neglecting transverse momentum. For the fragmentation $a\to c+X$ we write, as usual,

$$\frac{dN}{dz}=D_{c/a}(z)\,, \tag{A12}$$

where z is the fractional momentum of a which c carries. For a two-step fragmentation, $a\to b\to c$,

$$D_{c/a}(z)=\int_z^1\frac{dy}{y}D_{b/a}(y)D_{c/b}(z/y)\,. \tag{A13}$$

For the particular choice of three-body decay described above, we find that (M is a meson, l a lepton, and B the leptonic branching ratio)

$$D_{l/M}(z)=2B(1+2z)(1-z)^2\,, \tag{A14}$$

so that

$$\int_0^1 D_{l/M}(z)dz=B\,. \tag{A15}$$

For heavy quarks fragmenting into a meson, we consider two possibilities:

$$D_{M/Q}(z)=1\,, \tag{A15a}$$

$$D_{M/Q}(z)=\delta(1-z)\,. \tag{A16b}$$

We use (a) for charmed-quark decay, and (b) for anything heavier.[27] Note that both fragmentation functions are normalized to unity. We can now convolute these with the leptonic decay to find the fragmentation function for $Q\to M\to l$. We find

$$D_{l/Q}(z)=(3z^2-\tfrac{4}{3}z^3-\tfrac{5}{3}-2\ln z)B\,, \tag{A17a}$$

$$D_{l/Q}(z)=2B(1+2z)(1-z)^2\,. \tag{A17b}$$

Single leptons at high p_T

To find the single-lepton spectrum at high p_T, one convolutes two ingredients. The first is the cross section for producing a heavy quark at high p_T, $E d\sigma^Q/d^3p$, which is calculated in perturbative QCD. The second is the fragmentation function for the heavy quark to fragment into a lepton. Note that for this procedure to be valid we require $p_T \gg m_Q$. Then the lepton cross section is

$$E\frac{d\sigma^l}{d^3p}(p_T,\theta)=\int_1^{p_T^{\max}/p_T} D\left(\frac{1}{z}\right)E\frac{d\sigma^Q}{d^3p}(zp_T,\theta)dz\,. \tag{A18}$$

We have verified that this procedure is consistent with the full calculation using three-body decay kinematics.

Dileptons from heavy quarks

Dileptons can be produced from a heavy $Q\bar{Q}$ pair if both decay semileptonically. If the mass of the lepton pair is much greater than the mass of the quark Q, we may again use the longitudinal fragmentation approximation to carry out the calculation of the dilepton spectrum.

We find that the cross section for producing a lepton pair of mass m at squared center-of-mass energy s is

$$\frac{d\sigma}{dm^2}=\int_{x_1x_2\geq m^2/s} dx_1dx_2f^B(x_1)f^T(x_2)\frac{d\sigma^{\rm SP}(x_1x_2s)}{dm^2}, \tag{A19}$$

where $f^B(f^T)$ is the parton density in the beam (target), and the subprocess cross section is

$$\frac{d\sigma^{\rm SP}(\hat{s})}{dm^2}=\frac{\sigma_{Q\bar{Q}}(\hat{s})}{\hat{s}} \times\int D_{l/Q}(z_1)D_{\bar{l}/\bar{Q}}(z_2)\delta\left(z_1z_2-\frac{m^2}{\hat{s}}\right)dz_1dz_2\,. \tag{A20}$$

Here $\sigma_{Q\bar{Q}}(\hat{s})$ is the cross section for heavy-quark production calculated in perturbative QCD.[10]

Single leptons from ψ

A ψ produced at high p_T produces single leptons via the decay $\psi\to l^+l^-$ with one lepton undetected. The D function for the decay, for an unpolarized ψ, is simply a constant, equal to the branching ratio B.

A model for producing high-p_T ψ's has been presented in Ref. 28. The high-p_T ψ cross section is given by

$$E\frac{d\sigma^\psi}{d^3p}=fC\frac{\alpha_s^2}{\langle e^2\rangle\alpha^2}\int_{2m_c}^{2m_D}E\frac{d\sigma^{l\bar{l}}}{d^3p\,dm}dm\,, \tag{A21}$$

where $f\simeq\frac{1}{8}$ is a factor which accounts for the number of states a $c\bar{c}$ pair can make below naked charm threshold, $C=\frac{2}{3}$ is a color factor, and $\langle e^2\rangle\simeq 0.2$ is the average squared quark charge in the lepton-pair production cross section $\sigma^{l\bar{l}}$. This model is consistent with available high-p_T ψ and Υ data.

At sufficiently high energy, we may assume that the main m dependence in the lepton-pair cross section comes from the photon propagator, and ignore any m dependence in the virtual-photon high-p_T cross section, between $m=0$ and $m=m_\psi$. We take

$$\frac{d}{dm}=\frac{2\alpha}{3\pi m}\,, \tag{A22}$$

enabling the integral in (A21) to be evaluated.

Finally we note that the D function for an almost real photon to produce a single lepton at high p_T is

$$D(z)=\frac{\alpha}{2\pi}\ln\left(\frac{p_T^2}{4m_l^2}\right)[z^2+(1-z)^2]\,. \tag{A23}$$

This is approximately constant.

In terms of the approximations we have made, the cross section for leptons from ψ is simply proportional to the cross section for leptons from direct photons:

$$\frac{\sigma(\psi\to l)}{\sigma(\gamma\to l)}\simeq\frac{4BfC\alpha_s^2\ln(m_D/m_c)}{3\alpha^2\langle e^2\rangle\ln(p_T^2/4m_l^2)}\,. \tag{A24}$$

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