Heavy quarks and prompt leptons in $\bar{p}p$ collider jets

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(i) Large-transverse-momentum $\bar{p}p$ events at $\sqrt{s}=540$ GeV are dominated by two-jet production; the cross section is compatible with the predictions of perturbative QCD. (ii) Large-p_T jets are rich in charm particles. We investigate the implications of these experimental observations. We find a source of heavy quarks and associated prompt leptons which could totally dominate yields conventionally computed from perturbative QCD and which, more importantly, leads to totally different event characteristics. For example, events where both jets contain a heavy-quark fragment ($c\bar{c}+c\bar{c}$, $c\bar{c}+b\bar{b}$, or $b\bar{b}+b\bar{b}$) are the origin of opposite- and same-sign lepton pairs with equal probability. The dileptons are accompanied by four strange particles and occasionally conceal their jet origin by trigger bias. They form a possible source of the "anomalous" dilepton events recently observed by the UA1 experiment.

I. INTRODUCTION

That large-transverse-momentum events observed in $\bar{p}p$ interactions at $\sqrt{s}=540$ GeV follow jet event patterns and cross sections predicted by perturbative QCD is a well-established experimental fact.[1] It is interesting to consider the dominance of two-jet events in conjunction with the recent observation[2] that a significant fraction of the jet fragments are charm particles. We investigate the direct consequences of these experimental results. Although explicit calculations are presented further on, qualitative results are easily anticipated. Large two-jet cross sections will result in a yield of charm particles in excess of those anticipated from perturbative QCD at $\sqrt{s}=540$ GeV. Abundant production of charm (directly or via $b\rightarrow c$ cascade) in jets leads to abundant rates for prompt leptons from their semileptonic decays. Events where both jets contain a $c\bar{c}$ or $b\bar{b}$ pair are not rare. As to a good approximation the jets fragment independently, such events can result in dimuons accompanied by four or more strange particles with $\mu^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\mp}$ charge modes equally probable. It is clear that a detailed understanding of this source of heavy quarks and prompt leptons should be a high priority. This "nonperturbative" source of c,b quarks and their associated prompt leptons constitutes a new background in the search for the t quark or heavier quarks and leptons. It is almost certainly the dominant background (possibly the source) of the "anomalous" dimuon events[3] recently reported by the UA1 experiment.

II. JETS AND HEAVY QUARKS IN JETS

This paper represents an attempt to survey the problem with a minimum of theoretical input beyond the information supplied by experiment. Two-jet cross sections are calculated via perturbative QCD. In the present context the only relevant aspect of the calculation is that it adequately describes high-p_T jet production at collider energies. That it does so is illustrated in Figs. 1(a) and 1(b); the calculation is described in the Appendix. In our attempt to minimize theory and make maximal use of the experimental information we introduce a phenomenological fragmentation function $D_{c/J}$ which describes the

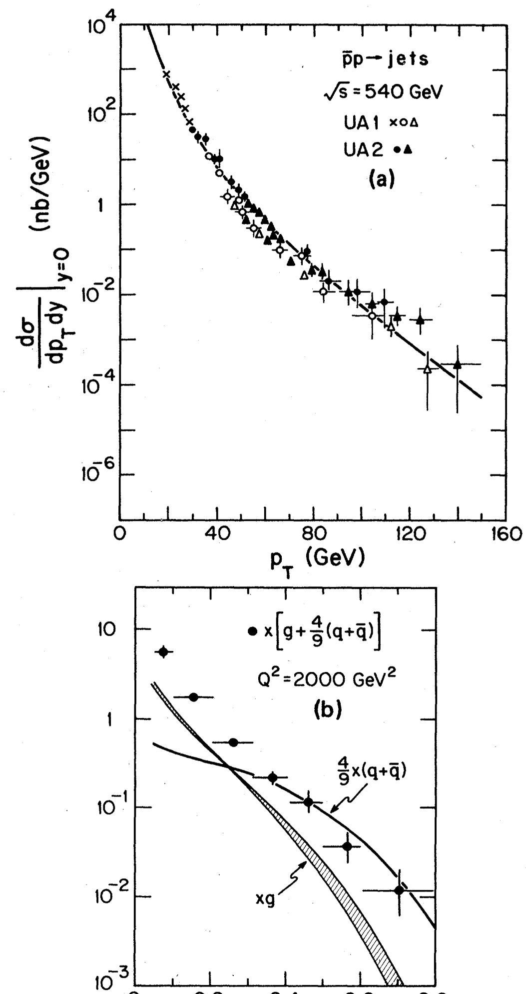

FIG. 1. (a) Transverse-momentum distribution of two-jet events at rapidity y (collider c.m. system)$=0$ for $\sqrt{s}=540$ GeV. The solid curve is our theoretical prediction, outlined in the Appendix. The data are taken from Ref. 1. (b) Effective parton distribution $xF(x)=xg+\frac{4}{9}x(q+\bar{q})$ entering the factorized two-jet calculation compared with data obtained by the UA1 collaboration (Ref. 1). The shadowed region for $xg(x)$ is bound by the softer Owens-Reya (Ref. 14) distribution and the harder Duke-Owens I (Ref. 15) distribution.

charm content in jets [without attempting to differentiate between the quark and (predominantly) gluon jets produced in $\bar{p}p$ collisions]. We suggest a fragmentation function of the form

$$(D_1)_{c/J}(z)=\frac{1.012}{z}(1-z)^{5/2} . \quad (1)$$

Although the experimental information is fragmentary (only D^*s are observed via the $D^*\to D\pi$ transition, and the sample of jets studied is not unbiased), Eq. (1) describes the UA1 data[2] as shown in Fig. 2(a). Parametrization (1) is also consistent with the experimental result that $\langle z\rangle=0.2$ for $z>0.1$. The multiplicity of charm particles in a jet corresponding to fragmentation function (1) is shown in Fig. 2(b) as a function of the jet energy E_J. Notice that $N(c)/N(\text{jet})\simeq 1$ for $E_J>20$ GeV. The sample of jets studied in the experiment was subjected to the same cut; the experimenters find $N(D^{*\pm})/N(\text{jet})=1.2\pm 0.2 \pm 0.7$, which is therefore within large errors compatible with our parametrization.

Before proceeding with the calculation, we comment on this "abundant" charm content of jets and argue that it is not totally unexpected. Equation (1) is compatible in shape and to better than a factor 2 in multiplicity with the charm content in gluon jets calculated from the Webber Monte Carlo program.[4] According to Eq. (1) the average fractional momentum carried by a charm particle in a jet is $\langle z\rangle\simeq 0.3$. This is in fact the result expected from flavor democracy

$$\frac{c+(b\to c)}{u+d+s+c+b}=\frac{2}{5} . \quad (2)$$

Equation (2) assumes that the momentum of the fragmenting jet is equally shared by all flavors and takes into account that b quarks decay back to charm. Flavor democracy therefore implies $\langle z_c\rangle=0.4$. The momentum of the D^* is softened by the fragmentation function[5] of the charm quark and therefore $\langle z_{D^*}\rangle\simeq\frac{2}{3}\langle z_c\rangle\simeq 0.3$. This is exactly the result anticipated from Eq. (1). Also, the shape of Eq. (1) is in line with theoretical expectations.

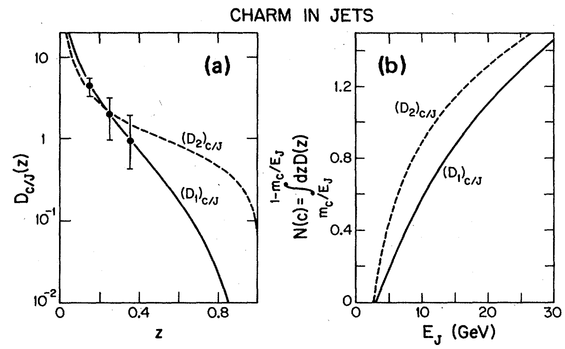

FIG. 2. (a) Fragmentation function for charm in jets. The data are from the UA1 collaboration (Ref. 2) for D^* mesons in jets. The curves denoted by D_1 and D_2 correspond to the parametrization given in Eqs. (1) and (3), respectively. (b) Multiplicity of charm pairs in jets as a function of the parent-jet energy for the two parametrizations of the fragmentation function.

From counting rules[6] we expect

$$D_{c/J}\sim\frac{1}{z}(1-z)^n$$

with $n=2$ (3) for a quark (gluon)$\to c\bar{c}$. We have treated the gluon as a $q\bar{q}$ pair.

The D^* content of quark, gluon, c, and b jets can be calculated perturbatively using the Altarelli-Parisi equation for fragmentation functions. Evolved fragmentation functions have a very different shape from the one suggested by counting rules and Eq. (1). Guided by a recent calculation[7] we use as an alternative parametrization

$$(D_2)_{c/J}(z)=\frac{0.35}{z}(1-z)^{1/2}(2+15z^2)e^{-2z} . \quad (3)$$

It is also consistent with the data as shown in Fig. 2.

Using the parton-model descriptions of jet production (see Appendix) and of the charm content of jets [Eqs. (1) or (3)], it is now straightforward to compute charm production via jets

$$\frac{d\sigma^c}{dp_{Tc}}=\int_{(p_{T\,\min})^2}^{(\sqrt{s}/2)^2}dp_T{}^2\int_{y_1^a}^{y_1^b}dy_1\int_{y_2^a}^{y_2^b}dy_2\left[F(x_1)F(x_2)\frac{d\hat{\sigma}}{dp_T{}^2}D_{c/J}\left[z=\frac{p_{Tc}}{p_T}\right]\frac{1}{p_T}\theta\left[\frac{(\hat{s})^{1/2}}{2}-2m_c\right]\right.$$
$$\left.\times\,\theta\left[1-z-\frac{2m_c}{(\hat{s})^{1/2}}\right]\theta\left[z-\frac{2m_c}{(\hat{s})^{1/2}}\right]\right] . \quad (4)$$

Structure functions, cross sections, and jet kinematics are described in the Appendix. We take $m_c=1.5$ GeV, $(p_{T\,\min})^2=3$ GeV^2. The charm cross section as a function of the p_T of the charmed particle is shown in Fig. 3. It is totally insensitive to the cutoff $p_{T\,\min}$ introduced to regularize the two-jet cross section and can therefore be considered a direct consequence of the data described in Figs. 1 and 2(a). In experiments a cut $p_{T\,\min}>10$ GeV is routinely imposed in order to guarantee good jet identification. We will impose the same cut on the calculation when computing observables relevant to collider experiments.

We next calculate the prompt-lepton cross section resulting from the semileptonic decay of heavy quarks in jets. We compute the decay at the quark level in the collinear approximation,[8] i.e., we define a structure function $D_{l/c}$ for leptons in charm particles, in the standard model

$$D_{l/c}(z)=2B(1+2z)(1-z)^2 , \quad (5)$$

where B is the branching ratio $c\to sl\bar{\nu}$. The prompt-

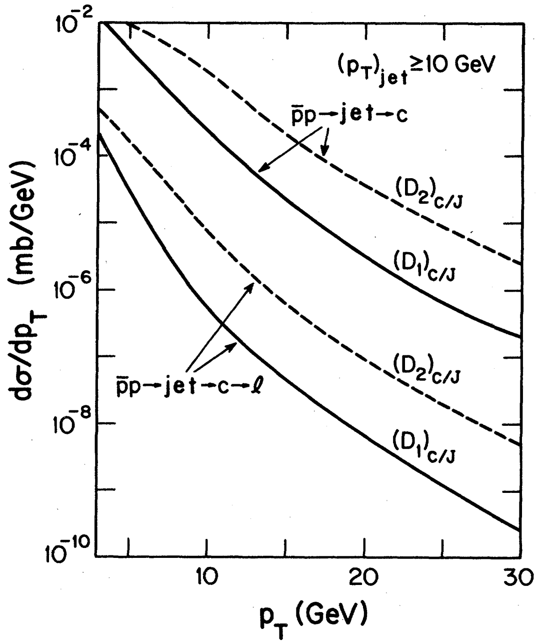

FIG. 3. Transverse-momentum distribution of charm particles (leptons) in events where one of the jets fragments into charmed particles (leptons), as described by Eq. (4) [Eq. (4) with $D_{c/J}(z)$ replaced by $D_{l/J}(z)$, Eq. (6)] for the two parametrizations Eqs. (1) and (3).

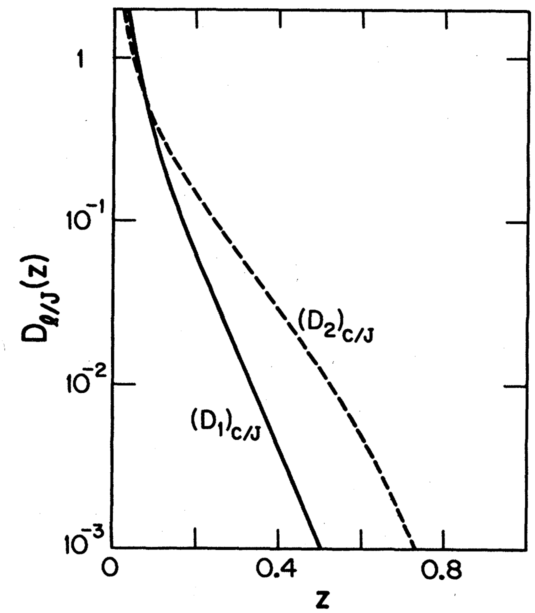

FIG. 4. Fragmentation function $D_{l/J}$ for a lepton in a jet, according to Eqs. (1) or (3), (5), and (6).

lepton content in jets is now readily obtained by[8]

$$D_{l/J}(z)=\int_z^1 \frac{dy}{y} D_{c/J}(y) D_{l/c}\left[\frac{z}{y}\right], \tag{6}$$

where $D_{c/J}$ is given by Eqs. (1) or (3). The resulting distribution is shown in Fig. 4. The prompt-lepton yield in $\bar{p}p$ interactions from heavy-flavor fragments of jets is shown in Fig. 3. It is obtained by substituting $D_{l/J}$ for $D_{c/J}$ in Eq. (4).

The latter result can be used to illustrate the potential importance of these considerations. Notice that for a luminosity of 120 nb^{-1} we expect from Fig. 3 about $1 \sim 100$ events with two jets $[(p_T)_{\text{jet}} > 10$ GeV$]$ and a lepton with $p_T > 15$ GeV. We checked that rapidity cuts do not significantly change this number.[9] This is exactly the event signature for the t quark[10] in the decay $W \to t(\to bl\nu)\bar{b}$. This background is removed by the requirement that the lepton be isolated from the jets.[11] This is one of many possible examples of how this new source of c,b (possibly t) quarks and associated prompt leptons warrants a complete reconsideration of background estimates in heavy-quark, lepton, or new particle searches and of the efficiency of any form of flavor tagging.

Finally, we calculate the cross section for producing a charmed particle pair in both final-state jets

$$\begin{aligned}\frac{d\sigma^{2c}}{dp_{T1}dp_{T2}} = \tfrac{1}{2} \int_{(p_T\,\min)^2}^{(\sqrt{s}/2)^2} dp_T^2 \int_{y_1^a}^{y_1^b} dy_1 \int_{y_2^a}^{y_2^b} dy_2 \\ \times \left[D_{c/J}\left[z_1=\frac{p_{T1}}{p_T}\right] D_{c/J}\left[z_2=\frac{p_{T2}}{p_T}\right] F(x_1)F(x_2)\frac{d\hat{\sigma}}{dp_T^2}\frac{1}{p_T^2}\theta\left[\frac{(\hat{s})^{1/2}}{2}-2m_c\right] \right. \\ \left. \times\, \theta\left[1-z_1-\frac{2m_c}{(\hat{s})^{1/2}}\right]\theta\left[1-z_2-\frac{2m_c}{(\hat{s})^{1/2}}\right]\left[z_1-\frac{2m_c}{(\hat{s})^{1/2}}\right]\theta\left[z_2-\frac{2m_c}{(\hat{s})^{1/2}}\right]\right]. \end{aligned} \tag{7}$$

The result is shown in Fig. 5 as a function of p_{T1} for $p_{T2} > 5$, 10 GeV, values relevant to our later discussion of anomalous dimuon events. Also shown is the same distribution for a lepton rather than a charm particle in each jet. It is again obtained by substitution of $D_{l/J}$ for $D_{c/J}$ in Eq. (7).

III. HEAVY QUARKS IN JETS VERSUS ASSOCIATED PRODUCTION BY FUSION

In perturbative QCD heavy quarks are produced by the fusion of light quarks and gluons inside the colliding hadrons, i.e., $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$. The resulting total cross

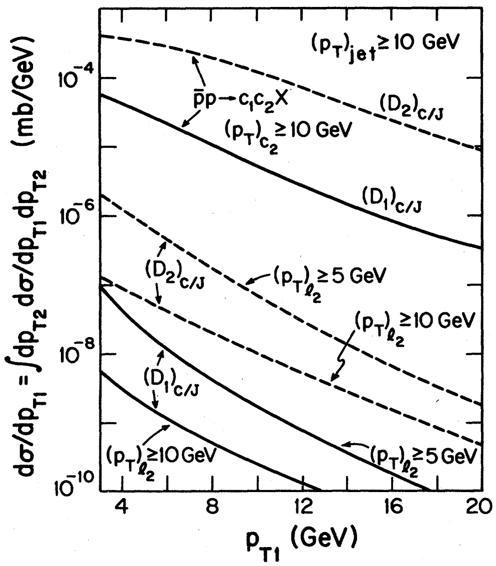

FIG. 5. Transverse-momentum distribution of charmed particles (leptons) when both jets fragment into charmed particles (leptons), as described by Eq. (7) [Eq. (7) with $D_{c/J}(z)$ replaced by $D_{l/J}(z)$, Eq. (6)] for the two parametrization Eqs. (1) and (3). Note the trigger condition on the transverse momentum of the second charmed-particle pair.

section[12] for charm production is shown in Fig. 6. It is difficult to confront this result with the cross section for charm in jets obtained by integrating Eq. (4). This calculation, unlike any previously presented, depends indeed on the value of the cutoff $(p_{T\,\min})^2$ introduced to regularize the two-jet cross section. A handle on this cutoff can be obtained by computing from Eq. (A5) the two-jet contribution to the $\bar{p}p$ total cross section

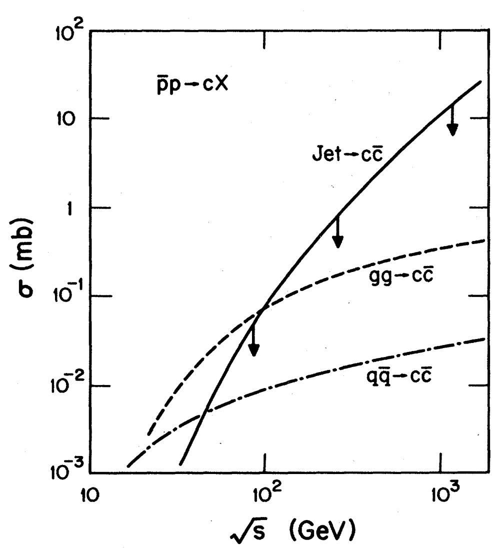

FIG. 6. Comparison of total cross sections of QCD-motivated charm-particle sources and the fragmentation source discussed here. For the curve denoted jet$\to c\bar{c}$ we have chosen $(p_{T\,\min}^{\rm jet}) = \sqrt{3}$ GeV. Note the very small contribution of the fragmentation source to σ(charm) for $\sqrt{s} \sim 63$ GeV and below.

$$\sigma^{2\,\rm jet} = \frac{1}{2}\int_{(p_{T\,\min})^2}^{(\sqrt{s}/2)^2} dp_T{}^2 \frac{d\sigma^{2\,\rm jet}}{dp_T{}^2} \,. \tag{8}$$

The result is shown in Fig. 7(a) and, not surprisingly, depends critically on the value of the cutoff chosen. Although it is dangerous to use our two-jet results down to $p_T = 1.5$ GeV, it is easy to check[13] that in doing so one generates an inclusive hadron distribution which nicely fits inclusive charged-particle cross sections down to relatively low-p_T values. It is tempting[13] to associate the ra-

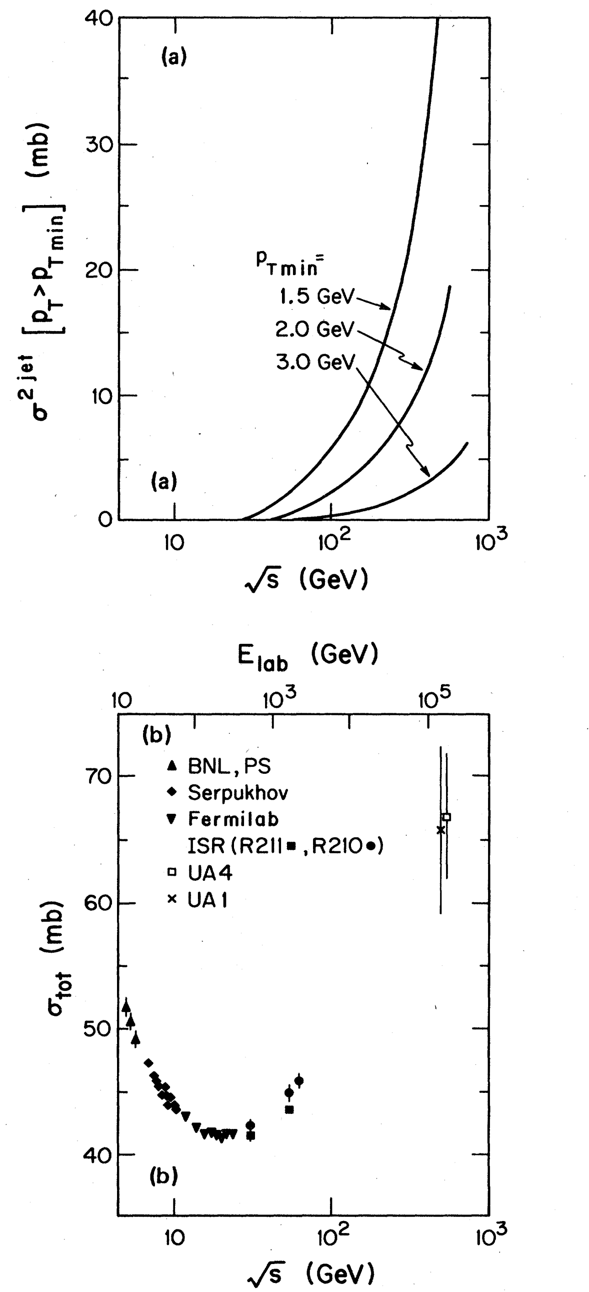

FIG. 7. (a) Total two-jet cross section as a function of $\sqrt{s}$ and its dependence on the cut $p_{T\,\min}^{\rm jet}$ in Eq. (8). (b) Experimental results on the total $p\bar{p}$ cross section as a function of $\sqrt{s}$. Compare the drastic rise in $\sigma_{\rm tot}(p\bar{p})$ with the rise of the total two-jet cross section, given in Fig. 7(a).

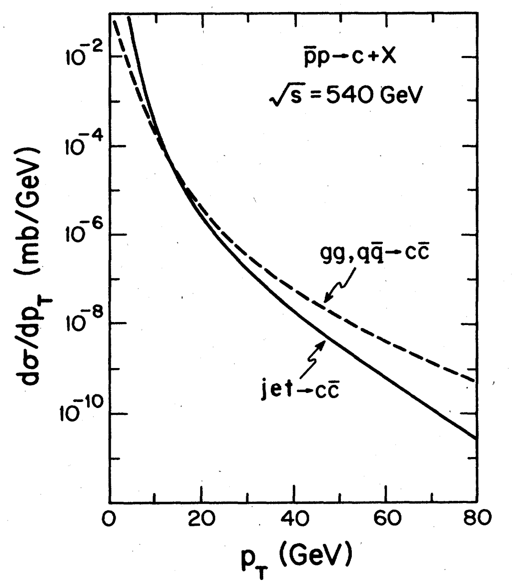

FIG. 8. Comparison of the p_T distribution of charmed particles produced conventionally ($gg,q\bar{q}\to c\bar{c}$) and by fragmentation (jet$\to c\bar{c}$). The steeper slope of the jet$\to c\bar{c}$ curve is a consequence of Eq. (1), fitted to the softer D^* fragmentation function.

pid increase[14] of $\sigma^{2\text{jet}}$ with energy with the corresponding increase in σ_{tot} shown in Fig. 7(b). The juxtaposition shown in Fig. 7 clearly requires that $p_{T\,\text{min}}>1.5$ GeV. This leads to an upper limit on the charm-in-jet cross section shown in Fig. 6. It is interesting to notice that this upper limit allows for large effects at $\sqrt{s}=540$ GeV but is nevertheless dominated by the perturbative QCD result for $\sqrt{s}=63$ GeV and below.[15] The upper limit could well represent a realistic cross section, but a large fraction of the cross section results from very soft charmed particles and will be removed by cuts in most measurements. It is therefore more relevant to compare the production rates at large transverse momenta (where moreover the value of $p_{T\,\text{min}}$ becomes inconsequential). Such a comparison is shown in Fig. 8. For $p_T>10$ GeV the inclusive charm cross sections from charm in jets and charm from parton fusion[16] are equal within the rather large ambiguities of each calculation.

IV. DILEPTON EVENTS

The outstanding feature of the mechanism for generating charm particles discussed in this paper is, however, the large rate for multilepton events, especially same-sign dileptons. First, let us point out that dileptons on the same side of the beam can result from the semileptonic decay of both charm particles in a high-p_T jet. In perturbative QCD such events are almost impossible to generate and they have been suggested[8] as a signature for $t\bar{t}$ production. This is just one illustration of the fact that charm in jets will seriously interfere with most forms of flavor tagging. The complete event structure will have to be considered to eliminate these events. More interesting, however, is the fact that events where both high-p_T jets contain a charm- or b-flavor-particle pair are not rare; see Fig. 5. Such events contain four charm or b-flavor particles and four strange particles result from their decay. Dileptons from such events have an equal probability to have the same or opposite sign. As an illustration we estimate that for a luminosity of 100 nb^{-1} there is ~ 1 event of this type where one lepton has $p_{T1}=10$ GeV and the other $p_{T2}\geq 10$ GeV; see Fig. 5. These events contain a lepton pair $l^{\pm}l^{\pm}$ (with equal probability) and four strange particles. Due to trigger bias the leptons will carry a large fraction of the jet energy, i.e., $\langle z_{l/J}\rangle$ observed will be much larger than what is implied by Fig. 4. We estimate that $\langle z_{l/J}\rangle \simeq 0.5$ for $p_{Tl}>15$ GeV. This effect is familiar from high-p_T production. As a result a large fraction of the events will be quiet in associated hadron activity. It is clear that the anomalous dilepton events[3] recently discovered by the UA1 experiment could very well correspond to the class of events just described. Their events are indeed rich in strange particles and especially those containing same-sign leptons have defied any description in terms of perturbative QCD.[17] The leading source of same-sign dileptons in the fusion model is $b\bar{b}$ production with $b\to c\to sl^+\nu$ and $\bar{b}\to \bar{c}l^+\nu$. For p_T values of order 10 GeV the rate for these events is roughly one order of magnitude smaller than the one estimated from charm production via jets. Also $l^{\pm}l^{\pm}/l^{\pm}l^{\mp}\simeq 0.1$ and can be at best increased to 0.3 by introducing maximal B^0-$\bar{B}^0$ mixing.[17,18]

To establish whether heavy quarks in jets are the origin or just the dominant background of these fascinating events will most likely require more statistics. It is important to remember, however, that a fraction of the charm particles in jets have a b-quark origin, i.e., also $c\bar{c}b\bar{b}$ or $b\bar{b}b\bar{b}$ events are expected. They are included in our calculation [see, e.g., Eq. (2)] but cannot be separately considered in the absence of a detailed understanding of jet fragmentation.

Glancing at Fig. 6 one might speculate that t quarks could be buried in the debris of the very-high-momentum jets.

ACKNOWLEDGMENTS

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APPENDIX: FACTORIZED CALCULATION OF LARGE-p_T JET CROSS SECTIONS

In calculating the $\bar{p}p\to J_1J_2$ cross section we make use of the factorization[19] of the two-jet cross section into a function $F(x_1)F(x_2)$ which depends only on the fractional momenta x_i of the partons inside the colliding hadrons and a cross section describing the (almost) universal p_T dependence of the $2\to 2$ QCD partonic subprocesses

$$\frac{d\hat{\sigma}}{dp_T{}^2}=K\frac{8\pi\alpha_s{}^2}{9}\frac{1}{\hat{s}^2(1-4p_T{}^2/\hat{s})^{1/2}}\times(\chi^2+\chi+1+\chi^{-1}+\chi^{-2})\,, \tag{A1}$$

with

$$p_T{}^2=\frac{\hat{t}\hat{u}}{\hat{s}} \tag{A2}$$

and

$$\chi\equiv\frac{\hat{u}}{\hat{t}}=e^{y_1-y_2} \,. \tag{A3}$$

Here p_T, y_1, y_2 are the transverse momentum and rapidities of the two jets and $\hat{s},\hat{u},\hat{t}$ are the usual Mandelstam variables defined for the $2\rightarrow 2$ partonic subprocess. The K factor in (A1) represents possible nonleading perturbative corrections. We choose

$$\alpha_s=\alpha_s(\hat{s})=\frac{12\pi}{(33-2n_f)\ln(\hat{s}/\Lambda_n)} \,. \tag{A4}$$

The number of active flavors n_f is increased at each threshold. The continuity of α_s is maintained by the choice of Λ_n with $\Lambda_4=0.3$ GeV and $m_b=5$ GeV, $m_t=35$ GeV. The two-jet cross section in its factorized form is then given by

$$\frac{d\sigma^{2\,\mathrm{jet}}}{dp_T{}^2}=\int_{y_1^a}^{y_1^b}dy_1\int_{y_2^a}^{y_2^b}dy_2F(x_1,Q^2)F_2(x_2,Q^2)\frac{d\hat{\sigma}}{dp_T{}^2} \tag{A5}$$

with

$$F(x)=u(x)+d(x)+\tfrac{9}{4}g(x) \,. \tag{A6}$$

In (A6) the dependence on Q^2 is not displayed but all structure functions are evolved to $Q^2=\hat{s}$. In (A5) we integrate over the jet rapidities; they are related to x_1, x_2 by

$$x_1=\frac{p_T}{\sqrt{s}}(e^{y_1}+e^{y_2}) \,,\qquad x_2=\frac{p_T}{\sqrt{s}}(e^{-y_1}+e^{-y_2}) \,. \tag{A7}$$

The Jacobian is already properly included in $\hat{\sigma}$ as given by (A1) and

$$y_1^{a,b}=\ln\frac{a(\mp)(a^2-4)^{1/2}}{2} \,,\qquad y_2^{a,b}=(\mp)\ln\frac{2-x_Te^{(\mp)y_1}}{x_T} \,, \tag{A8}$$

with

$$a=\frac{\sqrt{s}}{p_T}\equiv\frac{2}{x_T} \,. \tag{A9}$$

That Eqs. (A1)—(A9) adequately describe the $\bar{p}p$ data[1] is shown in Figs. 1 and 2. Figure 2 displays the factorized structure function [defined by (A6)] extracted from the UA1 data.[1] It is compared to our choice of structure functions used to evaluate the jet cross section shown in Fig. 1, i.e., u,d valence and sea quarks from Ref. 20; the gluon structure function is the first solution presented in Ref. 21. A good description of the data with these structure functions requires $K=2$ in (A1).

We also define a total cross section for jet production as

$$\sigma^{2\,\mathrm{jet}}=\frac{1}{2}\int_{(p_{T\,\min})^2}^{(\sqrt{s}/2)^2}\frac{d\sigma^{2\,\mathrm{jet}}}{dp_T{}^2} \,. \tag{A10}$$

Except for some speculations in Sec. III related to the total charm yield from c quarks in jets, none of the results presented in this paper depend on the *ad hoc* cutoff $p_{T\,\min}$ introduced in the definition of $\sigma^{2\,\mathrm{jet}}$.

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[4]B. R. Webber, in Proceedings of the XVth Symposium on Multiparticle Dynamics, Lund, 1984 (unpublished).

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[9]The errors on this and the following calculations are large. They are a direct consequence of the limited experimental information on the charm content of jets. It is not so much the multiplicity but the shape of the $D_{c/J}$ function that will have to be measured accurately in order to do quantitative calculations. We do not differentiate c and b quarks thus underestimating the lepton yield at high p_T.

[10]M. Della-Negra, in Proceedings of the XVth Symposium on Multiparticle Dynamics, Lund, 1984 (unpublished).

[11]We expect this background to dominate the background from the production of acollinear $b\bar{b}$ pairs, followed by the semileptonic decay of either b or $\bar{b}$. A detailed estimate of the former is, however, difficult as it involves details of jet fragmentation.

[12]For a review, see F. Halzen, in *Proceedings of the 21st International Conference on High Energy Physics, Paris, 1982,* edited by P. Petiau and M. Porneuf [J. Phys. (Paris) Colloq. C3-401 (1982)].

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