PHYSICAL REVIEW D VOLUME 31, NUMBER 1 1 JANUARY 1985

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Heavy flavors in jets from perturbative QCD

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

R. J. N. Phillips
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

(Received 3 October 1984)

We evaluate the charm and b-flavor content of high-p_T jets in $p\bar{p}$ collisions at $\sqrt{s}=540$ GeV, on the basis of perturbative QCD through order $\alpha_s{}^3$. The resulting charm fraction is of order 5% for jets with $|\eta|\leq 1$ and $10<p_T<50$ GeV, in agreement with estimates based on evolution equations for structure and fragmentation functions, indicating that the much larger value found in a recent experiment by the UA1 collaboration requires a nonperturbative origin.

The heavy-flavor content of QCD jets initiated by light partons is an important question for present and future hadron colliders. There are tentative indications[1] from the CERN $p\bar{p}$ collider that high-p_T jets may contain a substantial charm component. Some investigation of hard $c\bar{c}$ contributions to light-parton-initiated jets has been made using the Altarelli-Parisi equations in the ISAJET program,[2] and using the evolution equations for fragmentation functions directly;[3] these suggest small charm components at the 5–10% level. Possible nonperturbative origins of $c\bar{c}$ pairs have also been suggested.[4] In the present work we concentrate on perturbative calculations of jets, based on explicit Feynman diagrams through order $\alpha_s{}^3$ in the QCD coupling rather than evolution equations: heavy-quark-mass effects then enter directly through the kinematics. We calculate what fraction of jets contain charm quarks, in the rapidity and p_T range of the experimental analysis,[1] and the fractional momentum distribution of the resulting charmed hadrons.

For normalization purposes, we first calculate the cross section for light-quark jets in $p\bar{p}$ collisions from the lowest-order QCD subprocesses[5] $gg\to gg,q\bar{q}$; $g\overset{(-)}{q}\to g\overset{(-)}{q}$; $qq\to qq$; $q\bar{q}\to q\bar{q},gg$; $\bar{q}\bar{q}\to\bar{q}\bar{q}$. We use the parton distributions from model 1 of Ref. 6, with $\Lambda=0.2$ GeV taking $Q^2=\hat{s}$, the subprocess energy squared. The resulting inclusive jet cross section is shown in Fig. 1 versus jet p_T, for c.m. energy $\sqrt{s}=540$ GeV and pseudorapidity cut $|\eta|\leq 1$ corresponding to the UA1 analysis.[1] Note that since the cross section is inclusive, events with two jets within the rapidity cut are counted twice. The fraction of jets due to final gluons is 80% at $p_T=10$ GeV, falling to 50% at $p_T=50$ GeV.

The lowest-order heavy-flavor production subprocesses[7] are

$$q\bar{q}\to Q\bar{Q}\ , \tag{1a}$$

$$gg\to Q\bar{Q}\ , \tag{1b}$$

$$\overset{(-)}{q}Q\to\overset{(-)}{q}Q\ , \tag{1c}$$

$$gQ\to gQ\ , \tag{1d}$$

where q,g indicate light quarks (d,u,s) and gluons, while Q indicates heavy quarks $(c,b,t,\ldots)$; Q may also be replaced by $\bar{Q}$ in (1c) and (1d). The "flavor-excitation" processes (1c) and (1d) require special consideration when we include higher-order processes. They represent processes where a $Q\bar{Q}$ pair has evolved within the incident p or $\bar{p}$; Q undergoes a high-p_T collision while $\bar{Q}$ is left at low p_T [see Fig. 2(a)]. There is a risk of double-counting such processes if we include higher-order contributions, as illustrated in Fig. 2(b). We proceed as follows. We explicitly calculate the next-order $Q\bar{Q}$ production subprocesses from light partons

$$q\bar{q}\to gQ\bar{Q}\ , \tag{2a}$$

$$\overset{(-)}{q}g\to\overset{(-)}{q}Q\bar{Q}\ , \tag{2b}$$

$$gg\to gQ\bar{Q}\ . \tag{2c}$$

These contain soft and collinear singularities, regularized by heavy-quark masses in the kinematics and by requiring the final-state light parton to have $p_T>5$ GeV (as in a previous analysis[8]). They also overlap with the lowest-order flavor-excitation processes; in fact we find that the cross sections from (2b) and (2c) with $p_T(\bar{Q})<5$ GeV (the region where

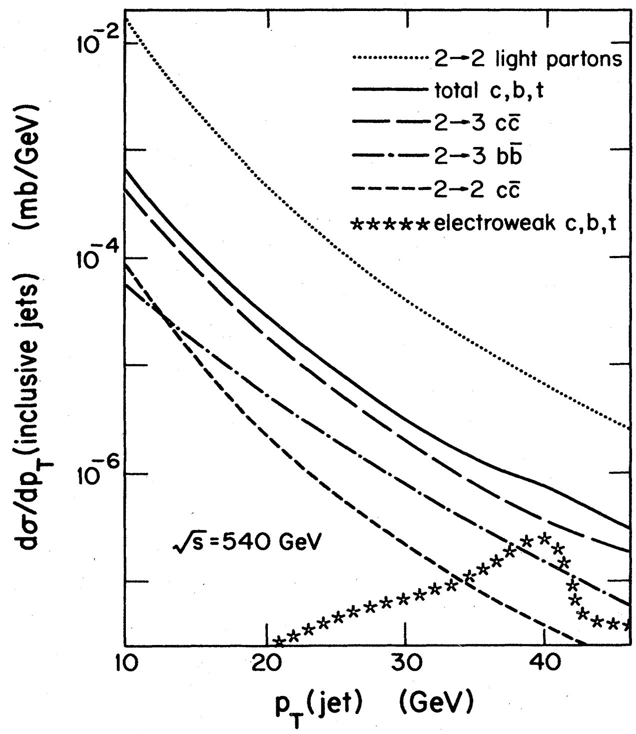

FIG. 1. Inclusive jet cross sections at $\sqrt{s}=540$ GeV with $|\eta|\leq 1$, calculated from low-order Feynman diagrams. The dotted curve denotes the light-parton jets from two-body scattering. The solid curve denotes the full charm cross section (including $b\to c$ decays); the dashed curve and dot-dashed curve are the $2\to 3$ body charm and b-flavor contributions, respectively; the short-dashed curve is the two-body $c\bar{c}$ contribution (the corresponding $b\bar{b}$ contribution being similar). The starred curve is the electroweak contribution to inclusive b and c jets.

the processes may be expected to overlap) are numerically close to the cross sections from (1c) and (1d), respectively, for the case $Q=c$ with the c distribution of Ref. 6. Accordingly, we omit the charm-excitation contributions from processes (1c) and (1d), regarding them as properly included within the calculation of the next-order processes (2b) and (2c). This approach has the advantage that we can address $b\bar{b}$ production in the same spirit [the uncertain kinematics of the missing $\bar{Q}$ quark makes calculations of (1c) and (1d) more questionable as m_Q increases at fixed $\sqrt{s}$]. We calculate the $2\to 3$ processes with full kinematics but using matrix elements in the massless limit,[9] since mass effects are minimal when $p_T{}^2 >> m_Q{}^2$; the full matrix element with $m_Q\neq 0$ has been published[10] for cases (2a) and

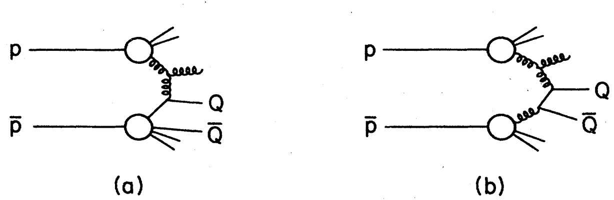

FIG. 2. Typical Feynman diagrams for (a) two-body heavy-flavor Q excitation and (b) $2\to 3$ body $Q\bar{Q}$ production, illustrating the possibility of double-counting between these processes.

(2b) and we have confirmed numerically that those mass corrections are not important.

Figure 1 shows our calculated inclusive charm and b-flavor jet cross sections versus p_T(jet) from the $2\to 2$ processes (1a) and (1b) and the $2\to 3$ processes (2a)–(2c), calculated with $m_c=1.5$ GeV and $m_b=4.6$ GeV. Since b flavor decays dominantly by $b\to c$, each b jet necessarily contains a charm hadron contributing to the charm signal. Isolated final-state partons are regarded as generating single jets with the same momentum. When two final partons come close in orientation, such that

$$(\phi_1-\phi_2)^2+(\eta_1-\eta_2)^2\leq 1 \quad ,$$

where ϕ_i and η_i are the azimuthal angles and pseudorapidities, respectively, they are regarded as a single jet and their momenta are combined (following the UA1 jet algorithm). In the inclusive c (b) jet cross section, a jet containing a $c\bar{c}$ ($b\bar{b}$) pair is counted twice, since it yields twice the number of corresponding heavy hadrons compared to a single c (b) jet.

Figure 1 shows that $2\to 3$ $c\bar{c}$ processes dominate in the kinematic region considered; this echoes the familiar result in heavy-flavor production,[11] that flavor excitation tends to dominate over $q\bar{q}$ and gg fusion. The $2\to 3$ $b\bar{b}$ contributions are also significant; this is not surprising since at $p_T >> m_b$ the kinematical suppression relative to $c\bar{c}$ is not large.

In principle, t-quark production also contributes to charm in jets via $t\to b\to c$, but the calculated rates for $m_t=40$ GeV are too small to show in Fig. 1. More significant additional sources of charm in high-p_T jets are the electroweak processes $q\bar{q}'\to W\to c\bar{s},t\bar{b}$ and $q\bar{q}\to Z\to c\bar{c},b\bar{b}$. These contribute significantly to the heavy-quark fraction near $p_T=40$ GeV, as seen in Fig. 1, but are negligible in the range $p_T=16$–20 GeV of the UA1 study.[1] The $q\bar{q}\to W,Z\to q\bar{q}$ contributions are negligible compared to the light-parton QCD contributions in Fig. 1.

The $2\to 2$ $c\bar{c}$ processes give hard charm, in the sense that the c quark carries the whole jet momentum; subsequent fragmentation to a charm hadron [e.g., by the model of Peterson, Schlatter, Schmitt, and Zerwas[12] (PSSZ)] gives a relatively hard distribution in the longitudinal momentum fraction:

$$z=\vec{p}(\text{hadron})\cdot\vec{p}(\text{jet})/[\vec{p}(\text{jet})]^2 \quad . \tag{3}$$

Similarly the $2\to 2$ $b\bar{b}$ processes give a hard b-quark distribution, but after b fragmentation and $b\to c$ decay, the resulting c-quark distribution is much softer. (Incidentally, experiment indicates[13] that the subsequent $c\to D$ fragmentation does not soften the distribution any further; the PSSZ model is apparently inapplicable in the environment of B-hadron decay where there is relatively little energy release.)

In contrast, the $2\to 3$ processes give several different sorts of heavy-flavor jets:

(a) Isolated Q jets, giving hard distributions as above. For charm jets in the range $p_T=16$–20 GeV, these are about 40% of the contribution.

(b) $Q+g$, $Q+q$, $Q+\bar{q}$ jets, where the Q component is softer. For the charm sample above, these are about 10%.

(c) $Q\bar{Q}$ jets, with softer individual Q or $\bar{Q}$ components. For the charm sample above, these give about 50% of the inclusive signal.

For $2\to 3$ $b\bar{b}$ production, the final charm distribution is softened further by the B-hadron decay process, as before.

We have calculated the z distribution of charm hadrons arising from the jet contributions described above for the particular range $16 < p_T$ (jet) < 20 GeV and $|\eta(\text{jet})| \leq 1$. We calculate primary c- and b-quark fragmentation by the PSSZ model[12] in the laboratory frame, B-hadron decay by $b \rightarrow cd\bar{u}$ $V-A$ matrix elements, and assume a $c \rightarrow D$ fragmentation $\delta(1-z)$ for the decay product. The results are shown in Fig. 3, normalized by the lowest-order light-parton jet cross section; they are compared with the apparent distribution deduced from $D^{*\pm}$ production in the same p_T and η range. It is interesting that about half of the produced charm in Fig. 3 comes from jets containing both c and $\bar{c}$ (from $2 \rightarrow 3$ processes); i.e., such jets are about $\frac{1}{4}$ of all charm jets in our calculation for $16 \leq p_T \leq 20$ GeV and $|\eta| \leq 1$.

It can be seen that the perturbative contributions lie far below the UA1 signal at small z. At large z, however, where there are no measurements at present, it may still be that the low-order perturbative contributions are close to the true result.

Our results cannot consistently be changed very much. If α_s and the parton distribution functions were scaled with $p_T{}^2 \sim \frac{1}{4}\hat{s}$ rather than $\hat{s}$, the $2 \rightarrow 3$ processes would be relatively enhanced but only by a factor close to 1. If the light-parton p_T cutoff were reduced, the $2 \rightarrow 3$ processes would again be enhanced; however, any big enhancement from this quarter cannot be believed, because it would come from soft and collinear singularities and they make the perturbation calculation unreliable. We have used no empirical K-factor enhancement in the light-parton contributions so the latter may in fact be underestimated. The $2 \rightarrow 2$ light-parton curve in Fig. 1 agrees well with published jet data[14] if an enhancement factor $K \simeq 1.5$ is applied; an equal enhancement would be expected for charm jets, however, leaving the ratio unchanged.

Some degree of uncertainty attends the UA1 charm signal. It includes an electron trigger requirement, which is usually satisfied by hadrons but could somewhat favor jets containing heavy quarks. Also, the branching fraction used for $D^0 \rightarrow K^-\pi^+$ may require some revision upward.[15] There is also an $E_T > 50$ GeV requirement which may add bias when studying jets of only 16–20 GeV in p_T. On the other hand, the UA1 signal is based on $D^{*\pm}$ production alone and could plausibly be doubled (or more) to allow for D^{*0} and other charm hadrons. Barring accidents, a large qualitative discrepancy at small z seems unavoidable.

We conclude the following.

(i) Low-order QCD cross sections for charm production in jets are at the 5% level for the range $10 \leq p_T(\text{jet}) \leq 50$ GeV with $|\eta(\text{jet})| \leq 1$. This agrees qualitatively with estimates of charm production based on evolution equations.[2,3] To explain the UA1 signal, nonperturbative effects seem to be needed.

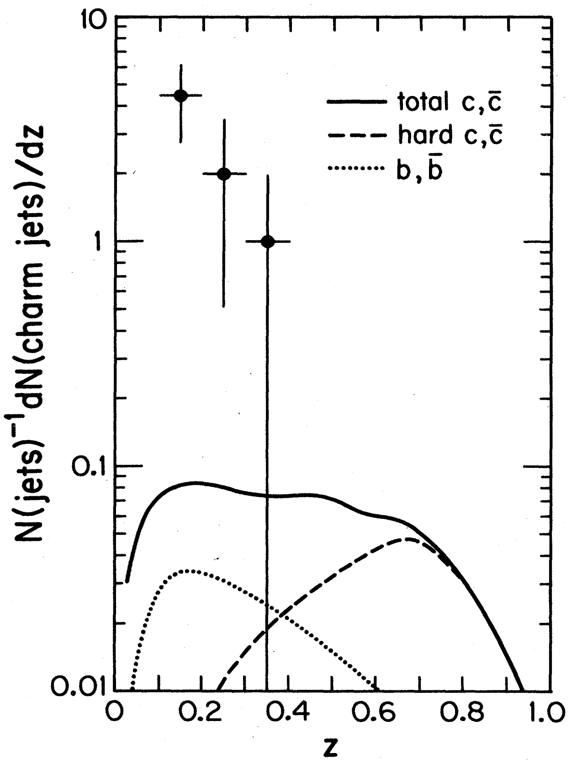

FIG. 3. Normalized z dependence of charm production. N(all jets)$^{-1}$ dN(charm jets)$/dz$ is plotted vs z for our calculations at $\sqrt{s} = 540$ GeV, $p_T(\text{jet}) = 16$–20 GeV, $|\eta(\text{jet})| \leq 1$. The data points represent the UA1 results (Ref. 1). The solid curve is the net charm contribution. The dashed curve is the contribution from hard c and $\bar{c}$ (i.e., jets from isolated $c,\bar{c}$ jets) and the dotted curve is the contribution from b and $\bar{b}$ jets with $b \rightarrow c$ decay.

(ii) The corresponding low-order contributions to the z distribution are considerably harder than the UA1 signal. However, they may correctly describe the high-z behavior, which has not yet been measured.

(iii) Our study provokes further interesting questions for hadron collider experiments: What fraction of jets contain c or $\bar{c}$ alone? What fraction of jets contain $c\bar{c}$ pairs? What fraction of c in jets comes from b decay (or t decay)? What is the charm production at large z? The eventual answers could shed more light on jet structure and the application of perturbative calculations.

We thank K. Hagiwara for discussion. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the Department of Energy under Contract No. DE-AC02-76ER0081.

[1]UA1 collaboration, G. Arnison *et al.*, Phys. Lett. **147B**, 222 (1984).

[2]F. E. Paige, BNL report, 1984 (unpublished); and in *Proceedings of the 1982 DPF Summer Study on Elementary Particle Physics and Future Facilities, Snowmass, Colorado,* edited by R. Donaldson, R. Gustafson, and F. Paige (Fermilab, Batavia, Illinois, 1982); B. R. Webber, in Proceedings of VIIth European Symposium on Antiproton Interactions, Durham, 1984 (unpublished).

[3]K. Hagiwara and S. Jacobs, University of Wisconsin Report No. MAD/PH/192 (unpublished).

[4]F. Halzen and F. Herzog, Phys. Rev. D **30**, 2326 (1984); University of Wisconsin Report No. MAD/PH/190 (unpublished).

[5]B. L. Combridge, J. Kripfganz, and J. Ranft, Phys. Lett. **70B**, 234

(1977); R. Cutter and D. Sivers, Phys. Rev. D **17**, 196 (1978); J. Owens, E. Reya, and F. Gluck, *ibid* **18**, 1501 (1978).
[6]D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).
[7]J. Babcock, D. Sivers, and S. Wolfram, Phys. Rev. D **18**, 162 (1978); B. L. Combridge, Nucl. Phys. **B151**, 429 (1979).
[8]V. Barger *et al.*, Phys. Rev. D **29**, 1923 (1984).
[9]See, e.g., F. A. Berends *et al.*, Phys. Lett. **103B**, 124 (1981).
[10]Z. Kunszt, E. Pietarinen, and E. Reya, Phys. Rev. D **21**, 733 (1980).
[11]See, e.g., F. Halzen, J. Phys. C **3**, 381 (1982); V. Barger, F. Halzen, and W. Y. Keung, Phys. Rev. D **25**, 112 (1982).
[12]C. Peterson *et al.*, Phys. Rev. D **27**, 105 (1983).
[13]J. Green *et al.*, Phys. Rev. Lett. **51**, 347 (1983).
[14]UA1 collaboration, G. Arnison *et al.*, Phys. Lett. **123B**, 115 (1983); **132B**, 214 (1983); UA2 collaboration, P. Bagnaia *et al.*, Z. Phys. C **20**, 117 (1983); Phys. Lett. **138B**, 430 (1984).
[15]R. Schindler (Mark III collaboration), report to Leipzig Conference, 1984 (unpublished).