CHARM CONTENT OF HIGH- $p_{\perp}$ JETS

A. Ali

Deutsches Elektronen Synchrotron, DESY

G. Ingelman

CERN -- Geneva

A B S T R A C T

We find that perturbative processes calculated either by exact QCD matrix elements to order α_s^3 or via parton shower models can not account for the surprisingly large charm meson rate in high- $p_{\perp}$ jets as recently observed by the UA1 collaboration. This has interesting consequences for our understanding of the hadronization process. It may indicate that non-perturbative effects are important at a higher mass scale than usually expected and we investigate a simple model based on such an assumption.

Heavy flavour production is of great interest in many different processes. In several cases it can be understood and quantitatively accounted for by calculations based on perturbative QCD. In others the mechanism is not well understood, like the large charm cross-section observed at the ISR which is believed to have a diffractive origin. In the hadronization process, heavy flavour production is usually thought to be strongly suppressed because of the lack of sizable energy concentrations in the fragmenting colour field and the absence of large enough momentum transfers.

The recent result on the charm particle content of high- $p_{\perp}$ jets reported by the UA1 collaboration [1] at the CERN SPS collider is of interest in this context. Tagging charmed mesons via the decay sequence $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$ (and its charge conjugate) they find the surprisingly large rate $N(D^{*+})/N(\text{jet}) = 0.65 \pm 0.19 \pm 0.33$ for D^{*+} s with fractional momentum $z > 0.1$. Although the jets used in the analysis are from an event sample fulfilling certain conditions of localized electromagnetic energy and global transverse energy, it should essentially be an unbiased sample of central jets, $|\eta| < 1$, in the transverse momentum range 25 to 45 GeV with $\langle p_{\perp} \rangle = 28$ GeV. The fragmentation distribution of the observed D^{*+} sample, see Fig. 1, is very soft in contrast to what is observed in e^+e^- annihilation where charm particles appear through the fragmentation of an initial charm quark. This seems to indicate that the leading charm particle effect is small in the present case.

It is generally expected that collider jets in this kinematic domain are dominantly gluon jets. Based on a standard parametrization of the proton structure functions [2] and the QCD matrix elements for the $2 \rightarrow 2$ processes [3] we find that for central jets ($|\eta| < 1$) the fraction of gluon jets can be well parametrized by $R_g = 0.86 - 0.006 \cdot p_{\perp}$ for $10 < p_{\perp} < 60$ GeV. Thus, in the above jet sample we expect $\approx 70\%$ gluon jets.

Standard models for gluon jet fragmentation do not include production of flavours heavier than strangeness. In the Lund model [4], for example, this is motivated and quantified by the tunneling mechanism which gives a vacuum- $c\bar{c}$ /vacuum- $u\bar{u}$ ratio of the order 10^{-11} . Consequently, nonperturbative mechanisms which predict a strong mass suppression in the colour field can not account for the charm production observed by UA1.

One would therefore first consider perturbative processes as the source of the observed charm production. The lowest order processes giving heavy flavours; i.e. the fusion processes $gg \rightarrow c\bar{c}$, $b\bar{b}$ and $q\bar{q} \rightarrow c\bar{c}$, $b\bar{b}$, are known to contribute very little to the inclusive jet cross-section and would also lead to a much harder charm spectrum similar to e^+e^- annihilation into a leading charm hadron. The result for collider jets with the kinematic constraints of the UA1 data is shown in Fig. 1.

The next order in α_s , i.e. $2 \rightarrow 3$ processes give additional possibilities through the perturbative $g \rightarrow c\bar{c}$, $b\bar{b}$ splitting. We calculate the charm production rate based on the order α_s^3 QCD matrix elements [5] with the heavy quark mass properly included ($m_c = 1.5$ GeV, $m_b = 5$ GeV) and take charm from bottom decay into account as well. We note that the result depends on the cuts used to avoid the divergences in the matrix elements. To avoid collinear and soft singularities in the processes $p\bar{p} \rightarrow c\bar{c} + \text{jet}$, $b\bar{b} + \text{jet}$ we apply a 10 GeV $p_\perp$ cut off on the additional jet. In addition we demand that the parton-parton invariant masses satisfy the conditions $m_{Q+\text{jet}}, m_{\bar{Q}+\text{jet}} > m_Q + 3$ GeV. This yields a cross-section of ≈ 40 nb for the $2 \rightarrow 3$ processes above, when the UA1 condition of a jet with $p_\perp \geq 24$ GeV and $|\eta| \leq 1$ is also taken into account. Varying the cuts somewhat does not change the cross-sections appreciably. This number is to be compared with the cross-section $\sigma(p\bar{p} \rightarrow c\bar{c} + p\bar{p} \rightarrow b\bar{b}) \approx 13$ nb for the $2 \rightarrow 2$ processes. The larger $2 \rightarrow 3$ cross-section is partly a result of the experimental jet definition. The point is that the $p_\perp$ of a single parton can be quite a bit smaller, yet the sum $p_{\perp i} + p_{\perp j}$ of the partons i and j lying within a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leq 1.0$ still satisfies the experimental condition of a jet with $p_\perp \geq 24$ GeV. The resulting $D^{*\pm}$ spectrum is shown in Fig. 1. We note the considerably softer nature of the $2 \rightarrow 3$ process. The total inclusive yield from the $2 \rightarrow 2$ and $2 \rightarrow 3$ subprocesses is $N(D^{*\pm})/N(\text{jet}) \approx 0.02 \pm 0.005$. Although the cuts applied in the calculations reported in [6] are different from ours the overall rates are in reasonable agreement.

Higher order QCD matrix elements have not been calculated exactly, but their magnitude can be estimated by the recently developed parton cascade evolution formalisms [7-10]. Bremsstrahlung gluons may split perturbatively into quark-antiquark pairs and provided that the gluon virtuality is above the charm pair production threshold, they would give rise to $c\bar{c}$ pairs. Using the Monte Carlo implementation of ref. [10], we show in Fig. 2 the rate of heavy

quark pairs per event initiated either by a gluon-gluon or quark-antiquark system at a given invariant mass, Q , which give the offshellness scale for the QCD radiation process. As expected, a gluon-initiated jet radiate more than a quark jet which leads to a larger charm rate. The result is not particular for this specific model [10]; we have verified that essentially the same result is obtained in the alternative formalism of ref. [8]. We note that the values chosen for the parameters used in these models, such as the charm quark mass and the parton shower cut off, are not crucial for this result.

To be more quantitative and in order to take the hard scattering kinematics as well as experimental cuts into account we combine the shower Monte Carlo program of ref. [10] with one that properly describes the hard $2 \rightarrow 2$ scattering subprocess [11] (and which serves as the starting point for the parton cascade evolution). We choose the offshellness scale, Q , for the cascade to be $Q = \sqrt{\hat{s}}$, i.e. the invariant mass of the hard parton-parton scattering system. This choice maximizes the amount of radiation, but in the kinematic region of interest (central jets) the difference between possible choices is not crucial. Using e.g. $Q^2 = 2 \cdot \hat{s} \cdot \hat{t} \cdot \hat{u} / (\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$ would lower the charm rate given below by $\approx 25\%$.

The resulting charm quark and D^* (scaled) energy distributions are shown by the dashed curves in Fig. 1. The D^* -distribution was obtained using the $c \rightarrow D^*$ fragmentation function of Peterson et al. [12] $D(z) = 1/\{z \cdot [1 - 1/z - \epsilon/(1-z)]^2\}$ with $\epsilon = 0.18$ and the probability of producing a charged D^* , $P(c \rightarrow D^{*\pm}) = 0.45$ based on TASSO data [13]. The parton shower evolution gives a larger inclusive charm rate than the perturbative calculation to order α_s^3 , since in the former case more gluons are emitted which can decay into $c\bar{c}$ pairs. However, since only those gluons with virtuality above the charm pair production threshold can contribute, the gain in the inclusive charm rate is not large for present collider energies. We note that, due to the multiple gluon bremsstrahlung, the fragmentation function of the charmed hadrons becomes somewhat softer and is in fact in reasonable agreement in shape with the UA1 data. The overall rate from the shower model [10], however, is $N(D^{*\pm})/N(\text{jet}) = 0.027$, still a factor 10-20 too small compared to the UA1 data. From this we conclude that if the present high charm meson production rate as reported by the UA1 collaboration [1] persists, then it can not be understood in terms of perturbative QCD alone. One is therefore led to consider possible non-perturbative effects.

A highly virtual parton will radiate gluons (and to a lesser extent $q\bar{q}$ pairs) to reduce its virtuality. This is a perturbative process. At large Q^2 (short distances) the evolution of a parton is governed by perturbation theory. The interesting question in the present context is: What happens when the parton virtuality is degraded sufficiently so that it is comparable to the charm pair production threshold? In the usual formulation of the QCD shower models, the standard assumption is that the evolution of a virtual parton is controlled by perturbation theory all the way down to a very small scale, thus typically $Q_F \approx 1$ GeV. After the perturbative cascade colour neutral objects are formed which have typically small masses and hence will dominantly fragment into light hadrons. We would like to argue that the UA1 D^* data [1] suggest that this may not be the case. On the contrary, a virtual parton may enter the hadronization phase at a much earlier stage, i.e. $Q_F \gg 1$ GeV. We present below a simple model for non-perturbative production of heavy flavours in a jet based on the hypothesis that the hadronization scale Q_F is indeed a large number.

The first step towards a realistic model is to produce a set of partons (quarks and gluons) which arise as a result of a hard scattering and thus have non-zero virtuality. To obtain the mass spectrum of such virtual partons we use the parton shower Monte Carlo of ref. [10] in combination with the hard scattering Monte Carlo [11] to implement the kinematic conditions of the experiment. A jet initiated by a high- p_T parton with large virtuality thus evolves perturbatively into a set of partons, mostly gluons, which may have non-zero virtuality. For example, the gluon initiating a high- p_T jet at collider energies has a mass spectrum as shown by the dotted curve in Fig. 3. (When plotted as relative mass, m_{gluon}/Q , the shape is rather insensitive to the actual energy scale Q .) We now assume, for simplicity, a fixed value Q_F such that partons in the shower evolution with virtuality $m_{\text{parton}} > Q_F$ are allowed to radiate further but those with $m_{\text{parton}} < Q_F$ are not. This gives a set of final state gluons with mass spectrum as given in Fig. 3 for two representative values, $Q_F = 5$ GeV and 10 GeV. (The peak near zero mass reflects the possibility that a gluon does not emit any radiation and is then put on mass shell by the Monte Carlo algorithm.)

Of course, for a given center of mass energy, the gluon multiplicity decreases with increasing Q_F , shown by the curve marked g in Fig. 4, but the number of gluons with virtuality above the charm pair production threshold increases slowly and becomes constant as

shown by the curve marked g' in Fig. 4. Nevertheless, the choice of Q_F is not specified by the theory and is therefore somewhat arbitrary. We would, however, like to argue that a reasonable quantity to characterize the scale Q_F is probably the invariant mass, m_{jet} , of a jet, defined, for example, using the Serman-Weinberg criterion and measured accordingly. Typical numbers for m_{jet} at PETRA/PEP [14] are in the range 5-10 GeV. Comparison with perturbative estimates clearly indicate that a significant contribution to m_{jet} is non-perturbative. Thus, a value of Q_F in the range of 5 GeV looks reasonable.

The hadronization of offshell partons has, to our knowledge, not been discussed earlier. In the following we apply the well known and simple idea that a gluon splits into a quark-antiquark pair (on mass shell) with energies given by the usual Altarelli-Parisi splitting function $P_{g \rightarrow q\bar{q}}(z) \sim z^2 + (1-z)^2$. Since the coupling $g \rightarrow q\bar{q}$ is flavour independent we make the ansatz of choosing flavours according to the same threshold function as for the production of a heavy quark pair from a virtual photon, i.e. $v_q(3-v_q^2)/2$, where $v_q^2 = 1-4m_q^2/m_g^2$. This gives a probability for charm production, $P_c = v_c(3-v_c^2)\theta(v_c^2)/\sum_i v_i(3-v_i^2)\theta(v_i^2)$, which above threshold quickly approaches 1/4. Using the same fragmentation model as above we obtain the charm production rate as a function of the parameter Q_F shown in Fig. 4. The maximum $c\bar{c}$ yield is for $Q_F \approx 10$ GeV but the yield for $Q_F \geq 5$ GeV is still appreciable.

The result in Fig. 4 is for gluon jets produced at the CERN collider energies in the kinematic range of interest. Quark jets give much less gluons with virtuality large enough for charm pair production. Therefore, having the proper mixing of quark and gluon jets gives a maximum rate $N(D^{*\pm})/N(jet) \approx 0.12$ and the z -spectrum shown by the solid lines in Fig. 1. Maximizing the charm production within this model thus makes the D^* rate consistent with the reported rate [1] when the large experimental errors are taken into account.

We note that the UA1 charm result [1] is based on a very small statistics (20 D^* in total) and that a smaller D^* yield would be preferred theoretically. It is therefore very important that the reported charm rate is confirmed by higher statistics and also to establish that the D^* is indeed a fragment of a jet and not a beam fragment. Obvious observables to test this point are correlations in azimuthal angle and rapidity between the D^* and the jet, as well as

the transverse momentum distribution of the D^* measured with respect to the jet direction. In order to verify that the effect is related to gluon jets primarily, one should observe a decrease in the D^* -yield as the $p_{\perp}$ of the jet is increased, since the sample would then be dominated by quark jets which are expected to have much less gluon radiation and hence also less D^* production.

One may worry that a large D^* rate [1], which is at least an order of magnitude larger than perturbative QCD estimates, is inconsistent with the inclusive lepton and dilepton measurements by the UA1 and UA2 collaborations [15] which are in agreement with calculations based on perturbative QCD [16]. However, the point here is that due to the softness of the observed D^* spectrum, with $\langle p_{\perp} \rangle \approx 5$ GeV, the leptons from the semileptonic decays $D^{*\pm} \rightarrow \mu^{\pm} X$ will not contribute significantly in the large $p_{\perp}$ range. Lowering the lepton $p_{\perp}$ trigger, a significant enhancement in the low- $p_{\perp}$ region should appear and a measurement in that region would therefore serve as an independent confirmation of the large charm production rate. Perhaps we should remark that a significant production of $c\bar{c}$ pairs in the fragmentation of a gluon jet may also contribute to the same-sign dimuons, recently measured by the UA1 collaboration [15]. However, all of these events will necessarily have large accompanying hadronic activity and will therefore not be able to survive the hadronic energy isolation criterion, which characterize the UA1 same-sign data. We hope to come back to these issues in the future.

We have presented above a model which could serve as the starting point for studies of non-perturbative heavy flavour production. The hypothesis that the gluon jets have a significant non-perturbative $c\bar{c}$ production is testable in a number of ways. One should observe an increase in the $c\bar{c}$ yield in the toponium decays $J_{\top} \rightarrow ggg$, $\Upsilon_{gg} \rightarrow$ hadrons and $\eta_{\top} \rightarrow gg \rightarrow$ hadrons. An additional test would be that the gluon jets in $e^+e^- \rightarrow 3$ -jet events at the highest PETRA/PEP energies should show enhanced charm particle production compared to a quark jet of comparable energy. Equivalently, hadronic events with large sphericity should show increased $c\bar{c}$ production compared to events with small sphericity in e^+e^- annihilation. This would lend support to the hypothesis that indeed a large scale is involved in the fragmentation process and that the gluon jets are in fact different from quark jets, at least in their heavy flavour content.

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FIGURE CAPTIONS

- Figure 1: Distributions in $z = \vec{p} \cdot \vec{p}_{\text{jet}} / p_{\text{jet}}^2$. The data points (with statistical error bars only) are the $D^{*\pm}$ spectrum observed by UA1 [1]. The dotted curves give the result of exact QCD matrix elements $p\bar{p} \rightarrow c^+X$ to order α_s^2 (2→2 processes) and α_s^3 (2→3 processes) combined with the fragmentation $c \rightarrow D^{*\pm}$. The dashed curves are the charm quark and $D^{*\pm}$ spectra obtained from a parton shower model and the full curves the result when combined with our model for non-perturbative charm production.
- Figure 2: Rates of heavy flavour pair production, $c\bar{c}$ or $b\bar{b}$, from a parton cascade evolution starting from a gluon-gluon or quark-antiquark system of invariant mass Q .
- Figure 3: Mass spectrum for gluons initiating a high- $p_{\perp}$ jet (dotted curve) and for final state gluons obtained by parton cascade evolution down to a scale Q_F as reconstructed from a parton shower Monte Carlo [10] for a gluon-gluon system (of invariant mass Q) at collider energies.
- Figure 4: Gluon multiplicity (right-hand scale) in total (g) and with gluon virtuality above charm pair production threshold (g'). Also shown are the charm quark and $D^{*\pm}$ multiplicity (left-hand scale) of a collider gluon jet as a function of the mass scale Q_F below which partons are assumed to enter the nonperturbative phase of the model discussed in the text.

FIG. 1

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