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Drag effects in charm photoproduction

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Abstract: We have refined a model for charm fragmentation at hadron colliders. This model can also be applied to the photoproduction of charm. We investigate the effect of fragmentation on the distribution of produced charm quarks. The drag effect is seen to produce charm hadrons that are shifted in rapidity in the direction of the beam remnant. We also study the importance of different production mechanisms such as charm in the photon and from parton showers.

In previous work [1] we studied and refined a model for the hadronization of a low-mass string in the framework of the Lund string fragmentation model [2]. The model was used to describe the leading particle effect that has been observed at fixed-target experiments [3]. With a leading charmed meson defined as having the light quark in common with the incoming beam, an asymmetry has been observed between leading and non-leading charmed mesons, favouring leading particles in the beam fragmentation region. In a string fragmentation framework this is understood in the following way. Because of the colour flow in an event, the produced charm quarks normally are colour-connected to the beam remnants of the incoming particles. This results in the possibility for a charmed hadron to gain energy and momentum from the beam remnant in the fragmentation process and thus be produced at a larger rapidity than the initial charm quark. The extreme case in this direction is when the colour singlet containing the charm quark and the beam remnant has a small invariant mass, e.g. below or close to the two-particle threshold. Then the colour singlet, called a *cluster*, will be forced to collapse into a meson, giving a hard leading particle. The corresponding production mechanism for non-leading particles involves sea-quarks and is therefore suppressed.

The qualitative nature of the asymmetry can thus be understood within the string model. The quantitative predictions, however, depend on model parameters. The model has been tuned to reproduce data on both asymmetries and single-charm spectra at fixed target energies [1]. Here we wish to apply the model to γp physics at HERA. The asymmetries are small in this case because of the higher energy and the flavour neutral photon beam. Therefore the emphasis will be shifted towards beam-drag effects, consequences of the photon structure and higher-order effects.

The photon is a more complicated object than a hadron because it has two components, one *direct* where the photon interacts as a whole and one *resolved* where it has fluctuated into a $\mathrm{q\overline{q}}$ pair before the interaction. This will result in very different event structures in the two cases. This study is constrained to real photons (photoproduction) as modeled by Schuler and Sjöstrand [4] and implemented in the PYTHIA [5] event generator. We include the photon flux and use cuts close to the experimental ones. We first examine the leading-order charm spectra for direct and resolved photons, estimate the cross section in the two cases, and study how the fragmentation process alters the charm spectra in the string model. Then we add some higher-order processes (flavour excitation and quark splitting) and find that they give a significant contribution to the charm cross section, especially for resolved photons.

We consider charm photoproduction in an $\mathrm{e^{\pm}p}$ collision (820 GeV protons and 27.5 GeV electrons) with real photons ($Q^2 < 1$ GeV), $130 < W_{\gamma\mathrm{p}} < 280$ and some different $p_\perp$-cuts. The analysis is done in the γp center of mass system using true rapidity ($y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$) as the main kinematical variable. The photon (electron) beam is incident along the negative z-axis.

To leading order, the massive matrix elements producing charm are the fusion processes $\mathrm{q}\gamma \to \mathrm{c\overline{c}}$ (direct), $\mathrm{gg} \to \mathrm{c\overline{c}}$ and $\mathrm{q\overline{q}} \to \mathrm{c\overline{c}}$ (resolved). Fig. 1 shows the distribution of charmed quarks and charmed hadrons separated into these two classes. For direct photons the hadrons are shifted in the direction of the proton beam, since both charm quarks are colour-connected to the proton beam remnant. In a resolved event the photon

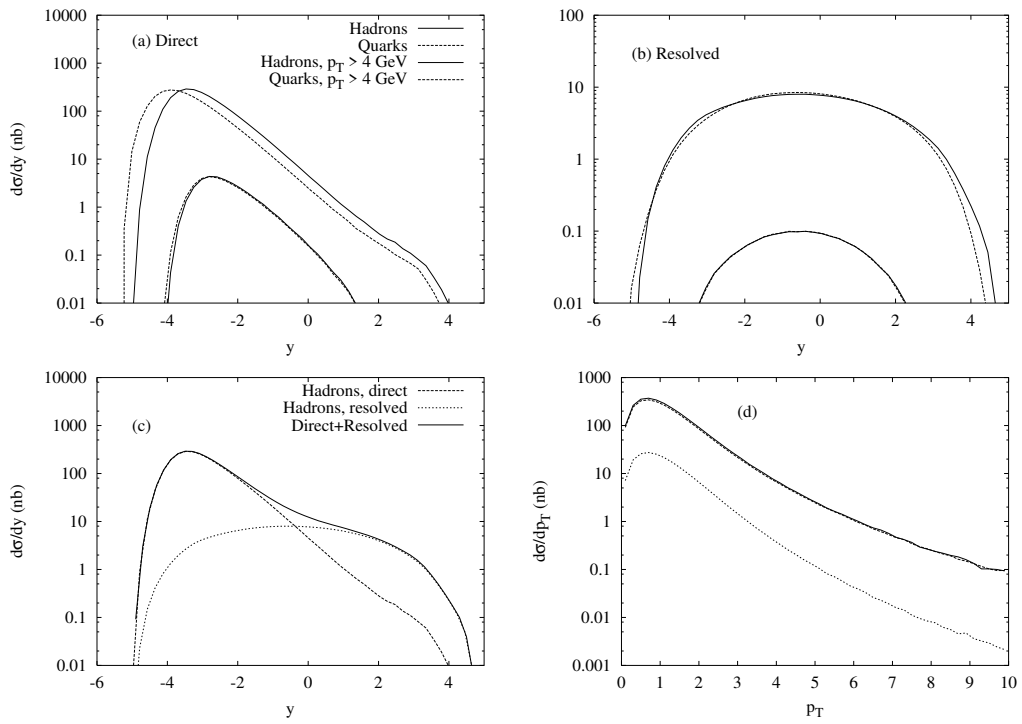

Figure 1: *Distribution of charmed hadrons and quarks in rapidity: (a) direct and (b) resolved photons. Comparison of resolved and direct processes in (c) rapidity and (d) transverse momentum.*

also has a beam remnant, so the charmed hadron is shifted towards the beam remnant it is connected to. Also note that the drag effect is a small-$p_\perp$ phenomenon. A jet at high $p_\perp$ will not be much influenced by the beam remnant.

The drag effect is illustrated in Fig. 2 where the average rapidity shift in the hadronization, $\langle \Delta y \rangle = \langle y_{\mathrm{Hadron}} - y_{\mathrm{Quark}} \rangle$, is shown as a function of y_{Hadron}. For direct photons and central rapidities the shift is approximately constant. The increasing shift for large rapidities is due to an increased interaction between the proton remnant and the charmed quark when their combined invariant mass is small. At large negative rapidities there is no corresponding effect because there is no beam remnant there. The drop of $\langle \Delta y \rangle$ in this region is a pure edge effect; only those events with below-average Δy can give a very negative y_{Hadron}. For resolved photons the shift is in the direction of the proton and photon beam remnants. Note that what is plotted is only the mean. The width of Δy is generally larger than the mean, so the shift can go both ways. For example the quarks at very small rapidities ($y \lesssim -5$) in Fig. 1b will all be shifted with $\Delta y > 0$ but hadrons produced there will, on the average, come from quarks produced at larger rapidities (i.e. $\Delta y < 0$). Hence the apparent contradiction with Fig. 2b by these edge effects.

In order to isolate the drag effect we plot the rapidity shift in the direction of 'the other end of a string'. This is accomplished by studying $\langle \Delta y \cdot \mathrm{sign}(y_{\mathrm{Other\ end}} - y_{\mathrm{Quark}}) \rangle$ as a function of y and $p_\perp$ as shown in Fig. 3. In this case the difference between direct and resolved events are less marked, showing the universality of string fragmentation. The

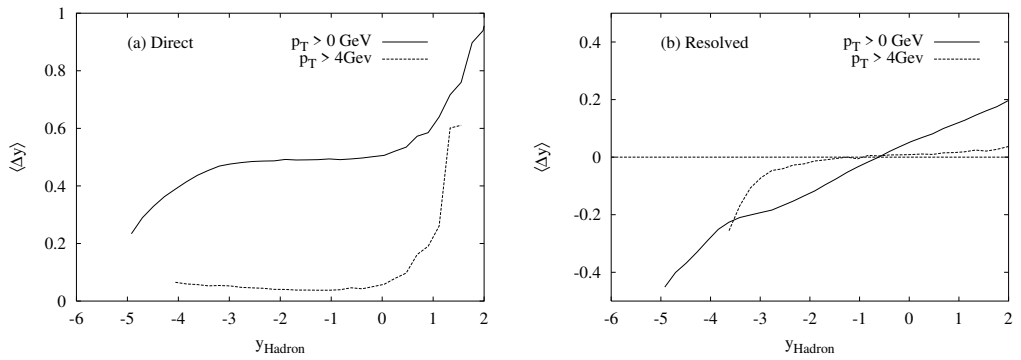

Figure 2: *Rapidity shift* $\langle \Delta y \rangle = \langle y_{\mathrm{Hadron}} - y_{\mathrm{Quark}} \rangle$ *for (a) direct and (b) resolved photons as a function of rapidity.*

remaining differences stem from the different distributions of string masses in the two cases.

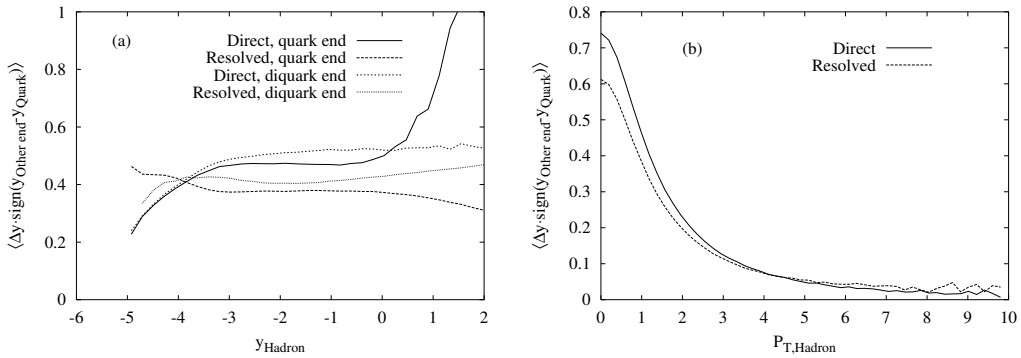

Figure 3: *Rapidity shift* $\langle \Delta y \cdot sign(y_{Other\ end} - y_{Quark}) \rangle$ *as a function of (a) rapidity and (b) transverse momentum. The shift for a hadron produced from a string containing a diquark in the other end is separated from those containing a quark. No* $p_\perp$ *cut is applied.*

Higher-order effects can be included in an event generator through flavour excitation (e.g. $\mathrm{cq} \to \mathrm{cq}$) and parton showers (gluon splitting, $\mathrm{g} \to \mathrm{c\overline{c}}$). This approach is in some ways complementary to full NLO calculations. A NLO calculation of the charm cross section contains all diagrams up to order α_{s}^3 ($\alpha_{\mathrm{s}}^2 \alpha_{\mathrm{em}}$ for direct photons) whereas a Monte Carlo event generator simulating parton showers/flavour excitation contains all diagrams of order α_{s}^2 ($\alpha_{\mathrm{s}} \alpha_{\mathrm{em}}$ for direct photons) and an approximation to all higher orders. In this way some processes that are not included in a NLO calculation are approximated. Some examples are $\gamma \mathrm{q} \to \mathrm{c\overline{c}qg}$, $\mathrm{g}\gamma \to \mathrm{q\overline{q}c\overline{c}}$ and $\mathrm{gg} \to \mathrm{c\overline{c}c\overline{c}}$.

At HERA energies, higher-order effects give large contributions to the cross section. In Fig. 4 the cross section is divided into different production channels for direct and resolved photons. We note that now the cross sections are of the same order of magnitude and the major contribution in the resolved case is flavour excitation. The details of course depend on the parameterization of the photon structure.

The double peak structure in the flavour excitation process for direct photons is because the charm quark in the beam remnant at low $p_\perp$ is also included. This peak disappears when a $p_\perp$ cut is introduced (Fig. 4c).

The physics discussed here has consequences also for b-production at HERA-B. Because of the larger mass of the b-quark, drag/collapse effects are expected to be smaller. However, this is compensated by the smaller CM-energy when the HERA proton beam is used on a fixed target, giving non-negligible effects as shown in Fig. 5. An understanding of these aspects are important when studying CP violation in the $B^0\overline{B^0}$ system [6].

In summary we have improved the modelling of charm in the PYTHIA event generator by a consideration of charm hadroproduction data [1]. In this note we study beam-drag effects at HERA and it should be interesting to look for experimental signatures, e.g. differences between NLO and data. We also show that higher order effects give important contributions to the charm production spectra at HERA energies, especially for resolved photons.

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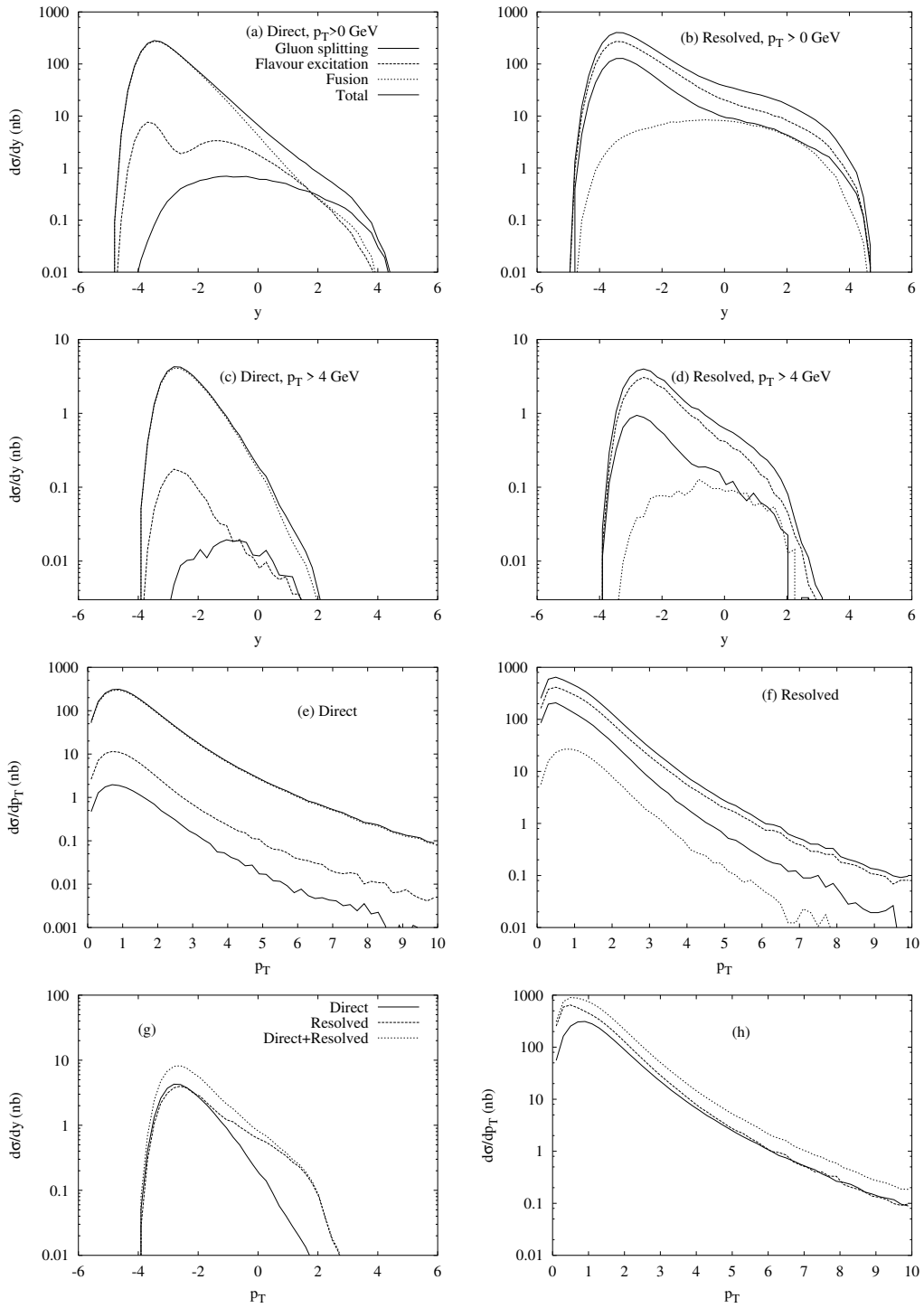

Figure 4: *The cross section divided into different production mechanisms and different photon structure. (a) Direct and (b) resolved photons with* $p_\perp > 0$ GeV. *(c) Direct and (d) resolved photons with* $p_\perp > 4$ GeV. *(e) Direct and (f) resolved photons in* $p_\perp$. *We add the components together for (g) rapidity (*$p_\perp > 4$ GeV*) and (h) transverse momentum.*

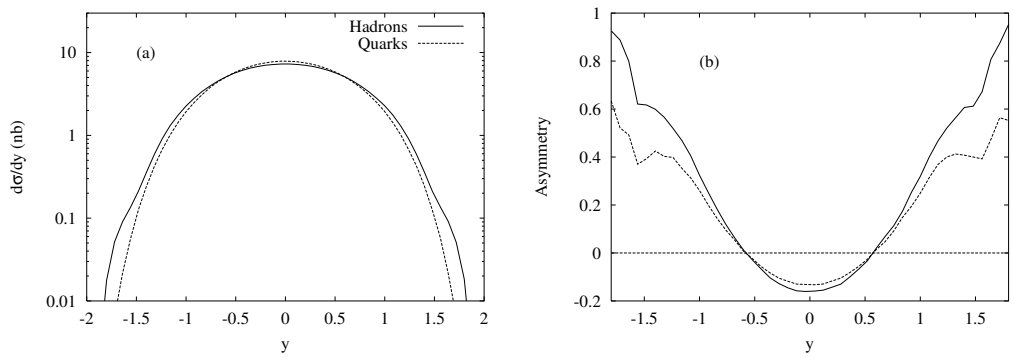

Figure 5: *(a) Distribution of bottom quarks and hadrons at HERA-B (pp at 40* GeV *CM-energy, i.e. no nuclear target effects included). (b) Asymmetry* ($A = (\sigma(\overline{\mathrm{B}^0}) - \sigma(\mathrm{B}^0))/(\sigma(\overline{\mathrm{B}^0}) + \sigma(\mathrm{B}^0))$ *as a function of rapidity for two parameterizations of the beam remnant distributions (full=uneven, dashed=even) [1]. This asymmetry is due to drag effects where hadrons containing bottom quarks have been shifted more towards the beam remnant than those containing anti-quarks. The diquark with, on the average, larger energy/momentum than the quark of the proton beam remnant, is colour connected to the bottom quark, thus shifting it more than the anti-quark.*