LU TP 99–28
September 1999

Heavy Quark Production Asymmetries

E. Norrbin[1]

Department of Theoretical Physics,
Lund University, Lund, Sweden

Abstract

In the hadroproduction of charm (or heavy flavours in general) in the context of string fragmentation, the pull of a beam remnant at the other end of a string may give a charm hadron more energy than the perturbatively produced one. The collapse of a low-mass string to a single hadron is the extreme case in this direction, and gives rise to asymmetries between leading and non-leading charm hadrons. We study these phenomena within the Lund string fragmentation model and improve the modelling in part by a consideration of hadroproduction data. Applications include heavy quark production in any collision between hadron-like particles such as γp at HERA and pp at HERA-B or the LHC.

[1]emanuel@thep.lu.se

1 Introduction

Several experiments at fixed-target energies have observed asymmetries between leading and non-leading charmed hadrons in π^-p collisions [1]. In [2] we study this effect in the context of the Lund string fragmentation model [3] and find that it is possible to improve the model to obtain a good description of the asymmetry data. In this model, collapses of light colour singlets mainly account for the asymmetry.

We also study single charm spectra and particle/anti-particle correlations and find good agreement between the model and single charm spectra, but fail to describe the correlation data from E791 [4]. This is in contrast to NLO calculations [5], which adequately describe single charm spectra for non-leading particles and some correlations, but fail to describe the asymmetry and leading-particle single charm spectra.

A related effect included in the string model is the non-perturbative 'beam drag'. In this model the produced heavy quarks are connected to the beam remnants by colour singlet strings. Through soft interactions with the beam remnant the charm quark can gain energy and momentum to produce a heavy hadron at a larger rapidity than that of the heavy quark.

2 Model aspects

The asymmetry between D^+ and D^- is described by the asymmetry parameter

$$A = A(x_\mathrm{F}, p_\perp) = \frac{\sigma(\mathrm{D}^-) - \sigma(\mathrm{D}^+)}{\sigma(\mathrm{D}^-) + \sigma(\mathrm{D}^+)} \ , \tag{1}$$

which is observed to be an increasing function of x_F in π^-p collisions. In fig. 1 experimental results are compared to a modified version of the string model as implemented in the Pythia 6.1 [6] event generator. In the Lund string fragmentation model the produced charm quarks are connected to the beam remnants by colour singlet strings as e.g. in fig. 2. The colour of the incoming anti-up quark is inherited by the outgoing anti-charm quark, which forms a colour singlet together with the pion beam remnant down quark. The distribution of $\overline{\mathrm{c}}$-d string masses near threshold is shown in fig. 3, both using the default parameters and with some modifications.

Depending on the mass of a string, different hadronization mechanisms are used:

Large mass ($M_\mathrm{string} > m_\mathrm{c} + m_\mathrm{q} + 1$ GeV) Ordinary string fragmentation with a continuum of phase-space states.

Low mass The colour-singlet system forms a cluster that undergoes two-body decay into two hadrons.

Very low mass If the invariant mass of a cluster is so small that two-body decay is not possible, the cluster is forced to collapse into a single hadron with compatible flavour contents. This gives rise to an asymmetry favouring leading particles.

The qualitative nature of the asymmetry is thus described by the string model. However, the quantitative behaviour depends on the parameters of the model. The model aspects considered are described in more detail in [2], so here we just give a brief summary:

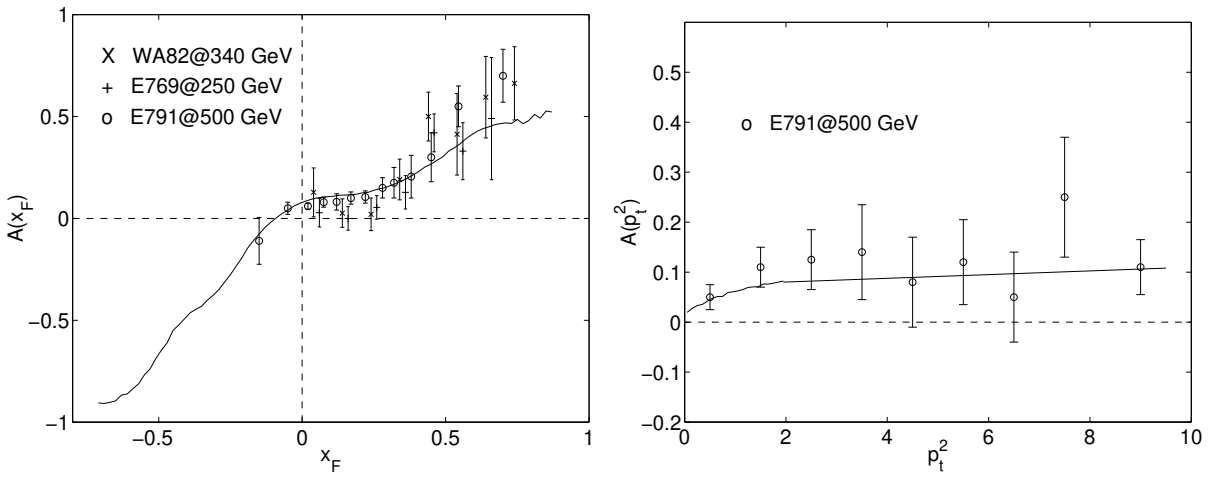

Figure 1: Experimental results on asymmetries compared to the modified version of PYTHIA 6.1 described in this note. Data is from π^-p fixed-target experiments, where $x_{\rm F} > 0$ is the pion fragmentation region.

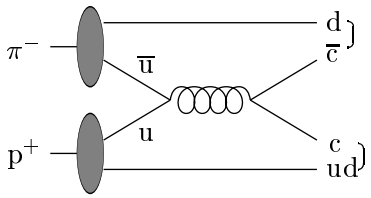

Figure 2: String configuration in a π^-p collision with quark fusion charm production.

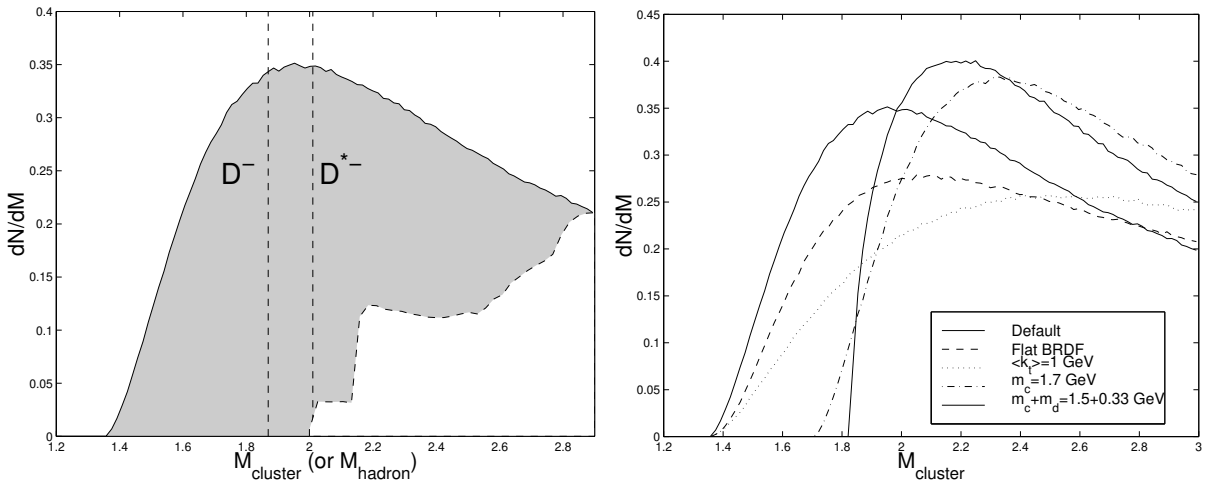

Figure 3: Distribution of $\overline{\rm c}$-d colour singlet masses in a π^-p collision using different parameters of the model. The dashed curve in the first figure is the distribution of invariant mass of the hadronic system produced from the colour singlet string or cluster. Below the two-particle threshold only the one-particle states $\rm D^-$ and $\rm D^{*-}$ are available.

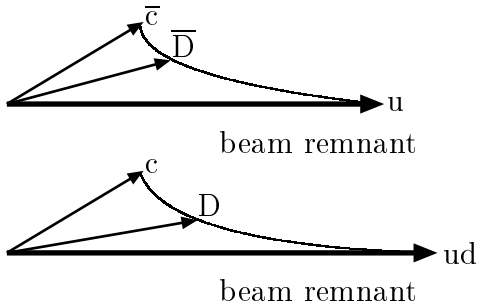

Figure 4: The ud diquark of the proton remnant has, at least in the average, a larger energy/momentum than the lone u quark. Because the diquark is in a colour singlet with the c-quark, in average, we will have $\langle y_{\mathrm{D}} \rangle > \langle y_c \rangle$ and $\langle y_{\mathrm{D}} \rangle > \langle y_{\overline{\mathrm{D}}} \rangle$ for $y_{\mathrm{beamremnant}} > 0$.

- The masses used for the light and heavy quarks regulate the fraction of collapses. More collapses gives rise to a larger asymmetry. We use $m_{\mathrm{c}} + m_{\mathrm{q}} = 1.5$ GeV + 0.33 GeV, i.e. constituent masses and the charm mass that gives the best fit to the total charm cross section.

- Width of the primordial $k_\perp$ distribution. A larger intrinsic $k_\perp$ of the partons entering the hard interaction gives rise to an asymmetry also at larger $p_\perp$ which is in agreement with data. We use a Gaussian with $\langle k_\perp \rangle = 1$ GeV.

- Beam remnant distribution functions. The energy-momentum of the beam remnant has to be split between the constituent quarks. This aspect is varied by using different beam remnant distribution functions parameterizing the fraction of energy-momentum taken by the constituents. We use an intermediate scenario.

- Threshold behaviour between collapse and decay of a cluster. The transition between cluster collapse and cluster decay as the cluster mass is increased can be slow or fast. We use an intermediate scenario.

- Energy conservation in collapse. When a string with a very low mass collapses into a hadron, both energy and momentum cannot be conserved simultaneously. We consider different ways to shuffle energy between strings and partons in an event, but find that observable quantities are not sensitive to this aspect.

3 Beam drag

Beam remnant drag is a different, less obvious, source of asymmetry. In an independent fragmentation scheme the rapidity of a charm quark is preserved, on the average, during fragmentation. This is not necessarily so in string fragmentation, where the produced hadron inherits energy and momentum from both endpoints of the string. The resulting hadron will then have a rapidity that, on the average, is shifted in the direction of the other end of the string. An example with a proton beam remnant is shown in fig. 4.

This is why the asymmetry for negative x_{F} in fig. 1 is negative, even though D^- is a leading particle also in this region. This behaviour is strongly dependent on the choice of beam remnant distribution functions, see [2].

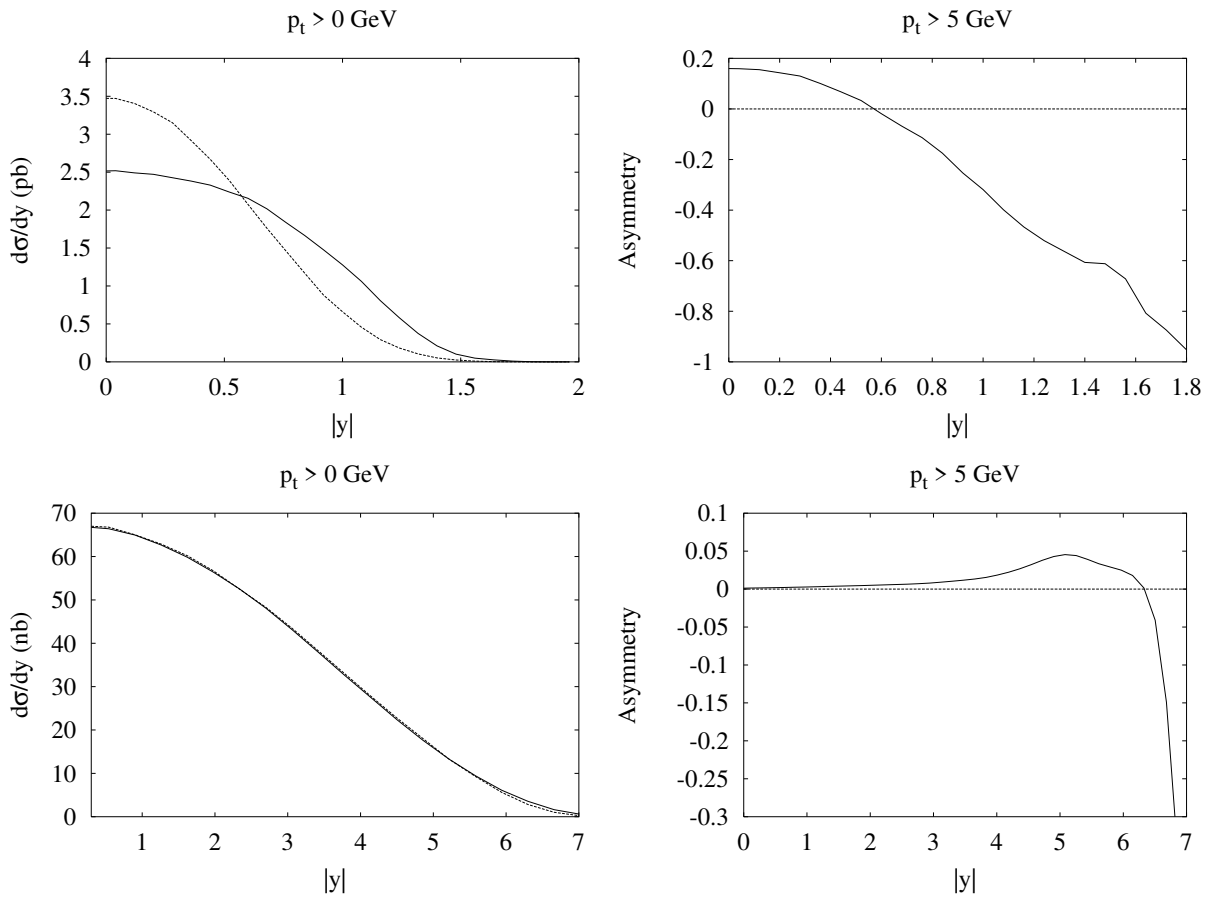

Figure 5: B^0 (dashed) and $\overline{B}^0$ (full) distribution and the resulting asymmetry, $A = (\sigma(B^0) - \sigma(\overline{B}^0))/(\sigma(B^0) + \sigma(\overline{B}^0))$ at HERA-B (top) and the LHC (bottom).

4 Applications

We have tuned the parameters of the model from a consideration of fixed target charm production data. Other applications include any collision between hadron-like particles e.g. γp, pp or p$\overline{\text{p}}$. This sections gives just a few examples.

Asymmetries in the $B^0\overline{B^0}$ system at pp colliders must be considered as a background to asymmetries from CP-violation [7]. Fig. 5 shows the bottom asymmetry as a function of rapidity for HERA-B and LHC energies (pp at 40 GeV and 14 TeV respectively). At HERA-B the effect is as large as in fixed-target charm experiments and a measurement of the effect would be feasible. At 14 TeV on the other hand, effects are at the 1% level and will be hard to see. Because most strings at the LHC are very massive, collapses will be rare. Only the drag effect for large rapidities is of any importance, as can be seen from the figure. At higher energies, higher order effects will become important – e.g. at the LHC, less than half of the total heavy quark cross section comes from the leading order fusion processes included in fig. 5.

We also show some examples of charm photoproduction in γp collisions. In this case the study is further complicated because of the photon structure, which can be classified as direct or resolved. In the direct case, the photon interacts as a point particle in the hard scattering subprocess. If the photon has fluctuated into a q$\overline{\text{q}}$ pair it can interact as a meson and therefore you need to know the parton distribution of the photon. These two

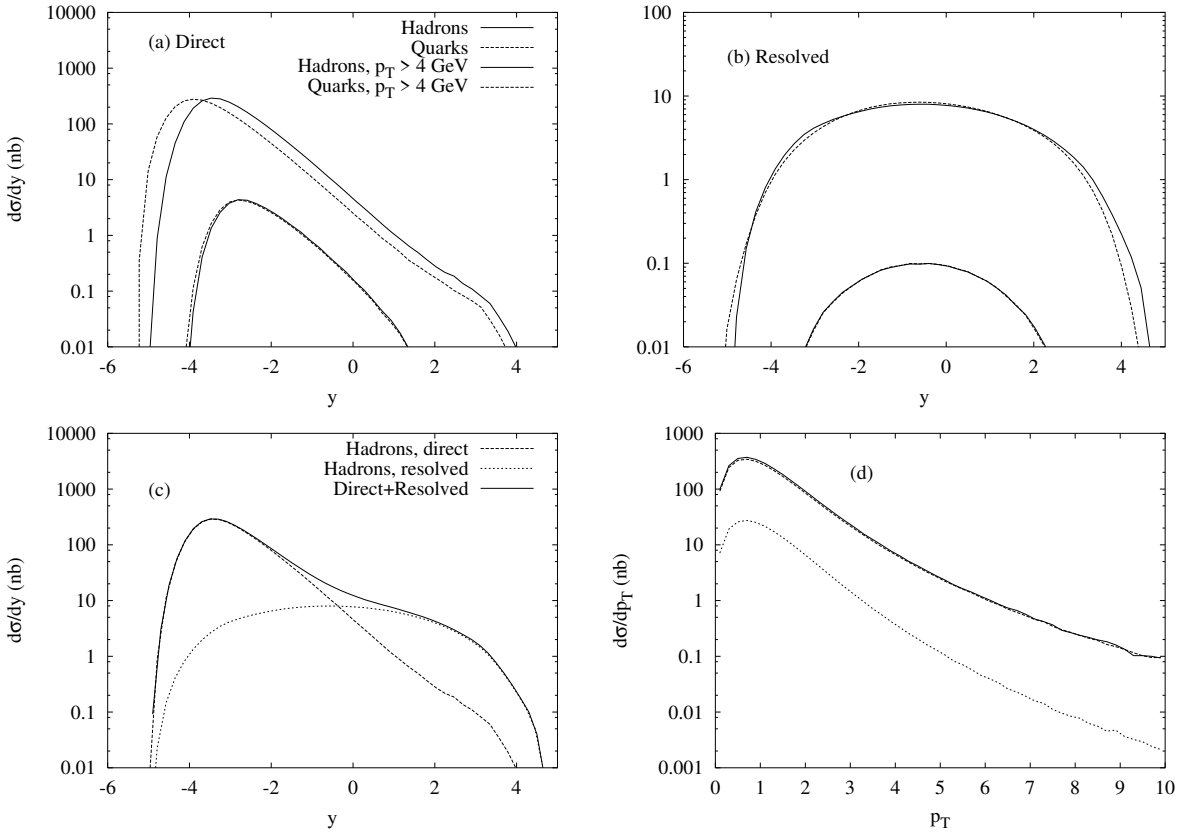

Figure 6: Charm cross section for direct and resolved photons with different $p_\perp$ cuts.

classes of events give rise to fairly different event structures, see fig. 6. The drag effect shifts the hadron spectrum in the direction of the proton beam remnant.

5 Summary

We have studied some non-perturbative effects in heavy quark production within the framework of the Lund string fragmentation model. We find some agreement with data if specific parameters are used. We also apply the model to pp and γp physics and arrive at predictions of bottom-asymmetries at HERA-B and the LHC.

References

[1] WA82 Collaberation, M. Adamovich et al.,
Phys. Lett. B **305** (1993) 402;
E769 Collaboration, G.A. Alves et al.,
Phys. Rev. Lett. **72** (1994) 812;
E791 Collaboration, E.M. Aitala et al.,
Phys. Lett. B **371** (1996) 157

[2] E. Norrbin and T. Sjöstrand,
Phys. Lett. B **442** (1998) 407

[3] B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, *Phys. Rep.* **97** (1983) 31

[4] E. Norrbin, *Heavy Quarks at Fixed Target*, edited by H. Cheung and J. Butler

[5] P. Nason, S. Dawson and R.K. Ellis,
Nucl. Phys. D **327** (1989) 49;
W. Beenakker, R. Meng, G.A. Schuler, J. Smith and W.L. Van Neerven,
Nucl. Phys. B **351** (1991) 507

[6] T. Sjöstrand, *Comput. Phys. Commun.* **82** (1994) 74

[7] M. Chaichian and A. Fridman, *Phys. Lett.* B **298** (1993) 218