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$D^*\mu$ correlations in ep scattering at HERA

H1 Collaboration

Abstract

$D^*\mu$ coincidences are studied using data taken with the H1 detector at HERA during the years 1997 to 2000, corresponding to an integrated luminosity of about 90 pb^{-1}. Exploiting the charge and angle correlations between the D^* and the muon, a separation of charm and beauty production is possible. Measurements are performed of the total charm and beauty production cross sections in the kinematic region $p_T(D^*) > 1.5$ GeV/c, $|\eta(D^*)| < 1.5$, $p_T(\mu) > 1.0$ GeV/c, $|\eta(\mu)| < 1.74$ and $0.05 < y < 0.75$, where p_T and η denote, respectively, the transverse momentum and the pseudorapidity of the D^* meson and the muon in the laboratory frame. Differential cross sections of several $D^*\mu$ quantities are compared with the predictions of leading order QCD Monte Carlo simulations, e.g. the squared transverse momentum of the $D^*\mu$ pair.

1 Introduction

In electron-proton collisions heavy quarks are predominantly produced via the photon-gluon fusion (PGF) mechanism, in which a photon emitted by the incoming electron interacts with a gluon in the proton by forming a quark anti-quark pair. Most of these interactions occur via the exchange of an almost real photon, with a virtuality $Q^2 \approx 0$ (photoproduction). In deep inelastic scattering (DIS) Q^2 is large, here $Q^2 > 2$ GeV^2.
The heavy quark cross section in ep production is a convolution of the PGF cross section, calculable in perturbative QCD, the gluon density in the proton and the photon flux. Heavy quark production is, therefore, directly sensitive to the gluon density. As $m_b \approx 3m_c$ and $|Q_b| = \frac{1}{2}|Q_c|$ the beauty production cross section is expected to be about 200 times smaller than the charm production cross section.
The fragmentation and decay of heavy quarks can result in the production of D^* mesons and muons. In this study, both of these signatures are used to "tag" heavy quarks. In the case of double tagging several possibilities exist: D^*D^*, $D^*\mu$ or $\mu\mu$. Using the D^* for the reconstruction of a heavy quark allows a very clean heavy quark sample to be obtained and the D^* provides a good approximation of the kinematic quantities of the corresponding quark. The branching ratios for decay chains which lend themselves to D^* identification are of the order of 1%, however, so the resulting heavy quark sample is small. In the case of muons, the muon and heavy quark momenta are not so closely correlated and the purity of the sample is much lower, but, due to the large branching ratio for the semileptonic decay of heavy quarks of about 10% a relatively large sample is obtained. Therefore the requirement of a D^* and a muon in a double tagging analysis is a compromise between a high statistics sample and a very clean sample. The size of such a sample is at least a factor of 10 smaller than the D^* meson sample in the case of single tagging.
The advantage of double tagging compared to single tagging is the almost complete reconstruction of the heavy quark pair final state, which in principle allows a measurement of the gluon density with smaller theoretical uncertainties. Furthermore, sensitive tests of next-to-leading order (NLO) perturbative QCD can be made. For example, the vectorial sum of the heavy quark transverse momenta in the photon-gluon rest frame obtains its first non-zero contribution at NLO. This quantity can be determined using the transverse momenta of the D^* and muon.

2 Data selection

The data analysed were collected with the H1 detector at HERA and correspond to an integrated luminosity of $\mathcal{L} = 91.2$ pb^{-1}. In this analysis events with at least one D^* and at least one muon are selected. Thus both heavy quarks from the PGF process are detected.
The D^* is reconstructed via the decay channel[1] $D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$. Due to the small difference between the D^* and the D^0 masses, $\Delta M = m_{K\pi\pi_s} - m_{K\pi} = 145.4$ MeV, the momentum of the pion produced by the decay of the D^* is very small, strongly restricting the possible kinematic range of the two decay particles. Therefore the combinatorial background is small and a clear signal is obtained. Muons are identified using the H1 central muon detector.

[1]Henceforth, charge conjugate states are always implicitly included.

Figure 1 shows the distribution of the mass difference ΔM for the full $D^* \mu$ sample with the requirements $p_T(D^*) > 1.5$ GeV/c, $|\eta(D^*)| < 1.5$, $p_T(\mu) > 1.0$ GeV/c, $|\eta(\mu)| < 1.74$ and $0.05 < y < 0.75$. Here p_T and η denote, respectively, the transverse momentum and the pseudorapidity of the D^* meson and the muon in the laboratory frame. Events in the whole Q^2 range are selected, about 25% of which are DIS events. The number of $D^*\mu$ events is obtained from a simultaneous fit to right ($D^{*+} \rightarrow K^-\pi^+\pi_s^+$) and wrong ($D^{*+} \rightarrow K^+\pi^+\pi_s^-$) charge combination ΔM distributions. The signal is described by a gaussian and the shape of the background is parametrized by a function of the form $a \cdot (\Delta M - m_\pi)^{1/2}$. The beauty fraction is strongly enhanced in the kinematic region selected, in particular as a result of the requirement that $p_T(\mu) > 1$ GeV/c.

3 Charge and angle correlation

The separation of charm and beauty production is possible by exploiting the charge and angle correlations of the D^* and the muon. In the photon-proton centre-of-mass frame, leading order QCD predicts that the two heavy quarks are produced "back-to-back", i.e. the vectorial sum of their transverse momenta is zero. In the case of charm only one correlation condition for the $D^*\mu$ pair is possible, namely $\Delta\Phi \approx 180°$ and $Q(D^*) \neq Q(\mu)$, where $\Delta\Phi$ denotes the azimuthal angle difference between the D^* and the muon and $Q(D^\star)$ and $Q(\mu)$ represent the charge of the $D^\star$ and the muon, respectively. Both the fragmentation and the semileptonic decay processes can smear these conditions; $\Delta\Phi$ can deviate significantly from $180°$. In the case of beauty three possible correlation conditions exist. The muon can either come from the semileptonic decay of a hadron containing a b, referred to here as a "direct" decay, or from the "cascade" decay of a charmed hadron produced in the decay of the original b quark.
The correlations between the D^* and muon directions and their charges are not clear-cut in the laboratory for DIS events due to the relative transverse motion of the laboratory and photon-proton (γp) reference frames. Hence a Lorentz transformation is made to the γp frame[2], in which the correlations are investigated. Perturbative effects like gluon radiation and also a possible non-zero initial "intrinsic" transverse momentum of the interacting partons smear the correlations further. Here, four regions are defined using the charge and topology of the identified $D^*\mu$ events:

1. $\Delta\Phi^* < 90°$ and $Q(D^*) = Q(\mu)$.
2. $\Delta\Phi^* < 90°$ and $Q(D^*) = -Q(\mu)$.
3. $\Delta\Phi^* > 90°$ and $Q(D^*) = Q(\mu)$.
4. $\Delta\Phi^* > 90°$ and $Q(D^*) = -Q(\mu)$.

The expected population of these regions with heavy quark events is sketched in table 1. $B^0-\bar{B}^0$ mixing has a slight influence on the population of the four correlation regions, which is taken into account in this study.

[2] Quantities in the γp frame are marked with a superscript *

	$\Delta\Phi^* < 90^\circ$	$\Delta\Phi^* > 90^\circ$
$Q(D^*) = Q(\mu)$	few b events, no c	mainly "direct" b events, no c
$Q(D^*) = -Q(\mu)$	mainly "direct" b, few c	mainly "cascade" b and c

Table 1: The correlations between the topology and charge of the D^* mesons and muons in $D^*\mu$ events and the flavours of heavy quark event that can populate each of the investigated regions.

4 Separation of charm and beauty

The topology and charge correlations in the $D^*\mu$ events allow a separation of the charm and beauty contributions to the $D^*\mu$ sample. These contributions are identified by performing a likelihood fit in the four regions defined above to the right and wrong charge combination ΔM distributions. The fit describes the data well, as shown in figure 2. The result of the fit is presented in figure 3. The contributions resulting from hadrons mis-identified as muons and muons resulting from the decays of light hadrons are evaluated using Monte Carlo calculations and subtracted from the data. For charm the fraction of such muons is about 30% and for beauty it is about 5%. For the total visible $D^*\mu$ production cross sections values of $\sigma^c_{vis}(ep \rightarrow e'D^*\mu X) = (720 \pm 115\ (stat.) \pm 245\ (syst.))$ pb and of $\sigma^b_{vis}(ep \rightarrow e'D^*\mu X) = (380 \pm 120\ (stat.) \pm 130\ (syst.))$ pb are obtained for charm and beauty production, respectively. The values are larger than the leading order (LO) + parton shower (PS) predictions by a factor of 1.8 for charm and a factor of 3.6 for beauty. These measurements are compatible with previous results [2],[3].

5 Differential cross sections

Normalized differential $D^*\mu$ cross sections for $p_T^2(D^*\mu)$, $\hat{y}(D^*\mu)$, $M(D^*\mu)$ and $\Delta\Phi$ are shown in figure 4 together with the predictions of a Monte Carlo model based on leading order perturbative QCD matrix elements matched to parton showers. $p_T(D^*\mu)$, $M(D^*\mu)$ and $\hat{y}(D^*\mu)$ denote the transverse momentum, which is defined via $p_T(D^*\mu) = |\vec{p}_T(D^*) + \vec{p}_T(\mu)|$, the invariant mass and the rapidity of the $D^*\mu$ pair. No separation of charm and beauty is performed in the different bins. For charm the LO + PS prediction is multiplied by a factor 1.8 and for beauty by 3.6. The quantities $p_T(D^*\mu)$, $\Delta\Phi$ and $\hat{y}(D^*\mu)$ can be used to study both perturbative and non-perturbative QCD effects in heavy quark production, whereas $M(D^*\mu)$ and $\hat{y}(D^*\mu)$ are needed in the determination of the fraction of the proton's momentum carried by the gluon entering the PGF process, x_g. The LO QCD model describes the shape of the various distributions quite well.

6 Conclusions

An analysis is presented of events containing both D^* mesons and muons produced in ep scattering in the H1 experiment at HERA. The events result largely from the production of heavy quark anti-quark pairs via the photon-gluon fusion process. Exploiting the charge and angle correlations between the D^* and the muon allows a separation of the contributions of beauty and charm to the sample. The total charm and beauty $D^*\mu$ cross sections are compatible with previous results. Monte Carlo predictions based on leading order QCD matrix elements matched to parton showers underestimate the charm cross section by a factor of 1.8 and the beauty cross section by a factor of 3.6. The Monte Carlo model provides a reasonable description of the shape of various kinematic variables describing the $D^*\mu$ final state.

References

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[3] C. Adloff et al. (H1 Collaboration), Nucl. Phys. B545 (1999) 4, Phys. Lett. B467 (1999) 156, Phys. Lett. B528 (2002) 199

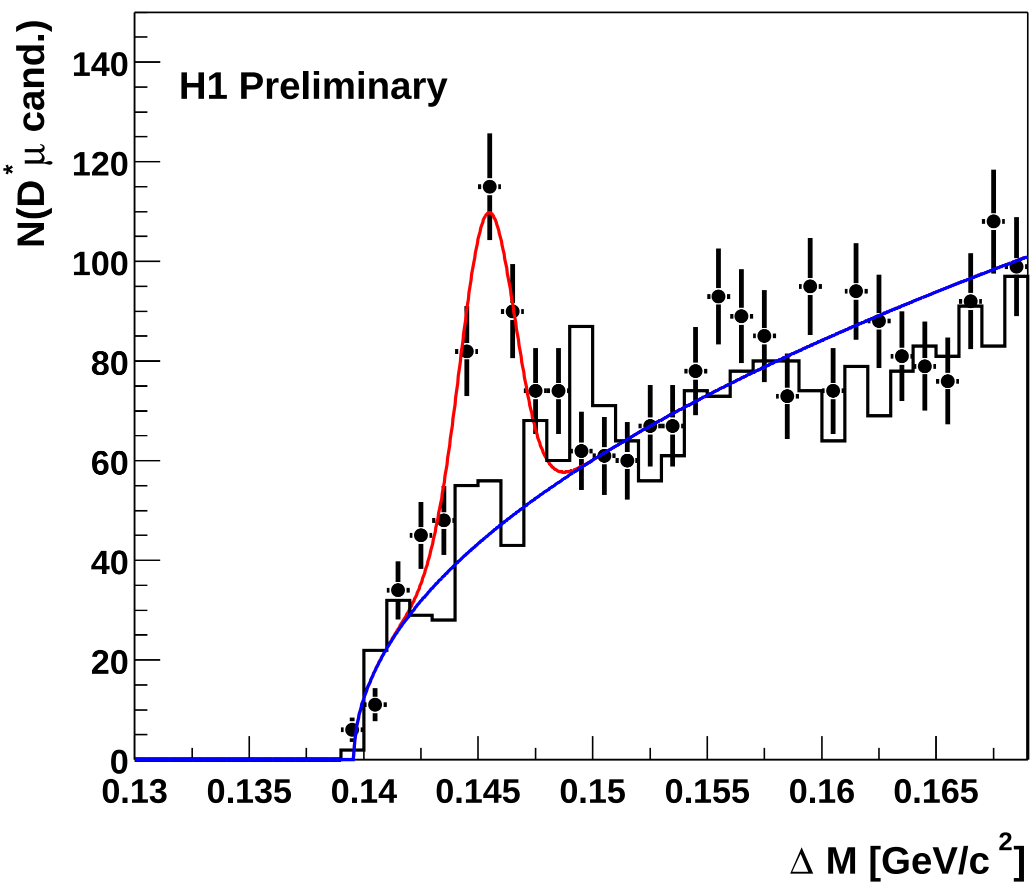

Figure 1: Distribution of the mass difference $\Delta M = m_{K\pi\pi_s} - m_{K\pi}$ for the full sample in which a D^* and a muon are reconstructed. The histogram indicates the background as obtained from wrong charge combinations in the D^* reconstruction. The solid lines represent the simultaneous fit of a Gaussian for the D^* signal plus a backgound term, describing both the right and wrong charge combinations.

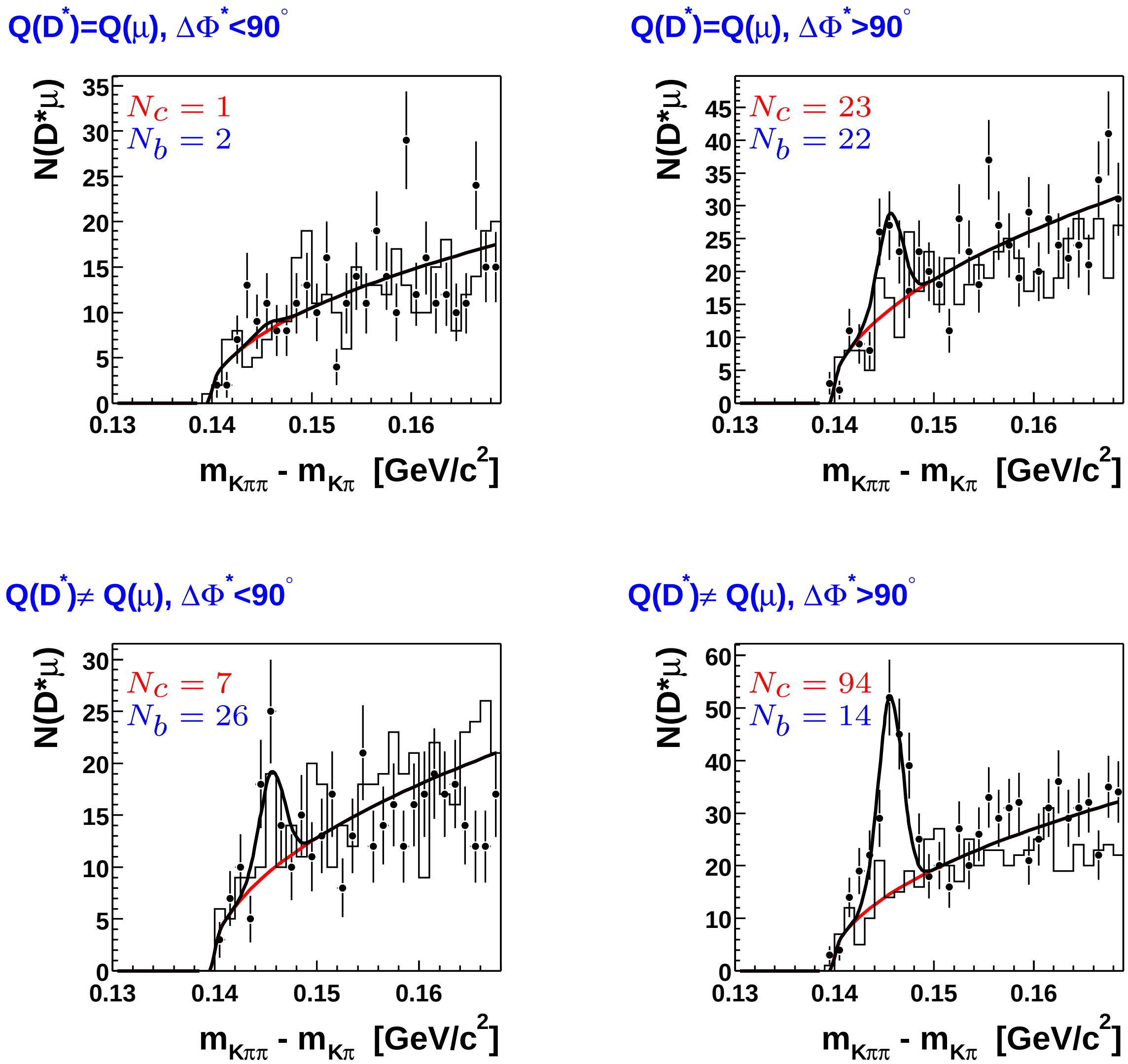

Figure 2: Distributions of the mass difference $\Delta M = m_{K\pi\pi_s} - m_{K\pi}$ in the four correlation regions considered, given by the relative charges of the D^* and the muon and the azimuthal angle $\Delta\Phi^*$ between them. The points represent the data, the histogram indicates the background as estimated from wrong charge combinations. The solid lines are the result of a simultaneous fit of right and wrong charge combinations to all four correlation regions to extract the beauty and charm contributions.

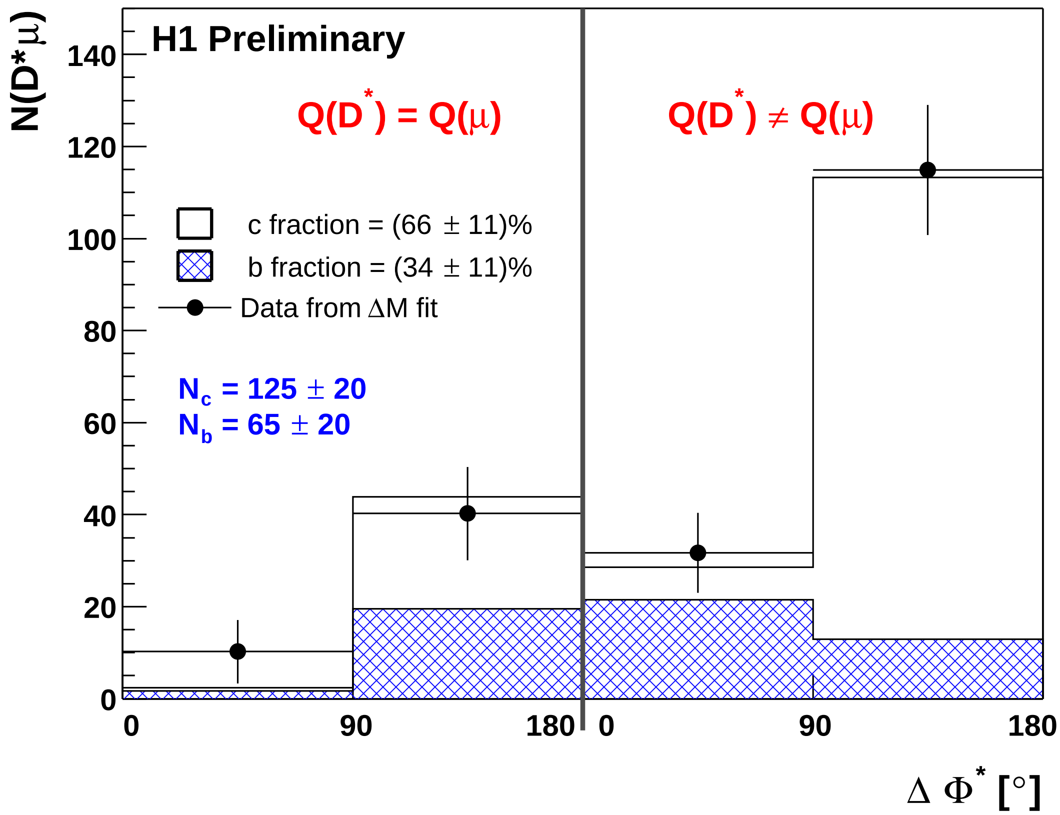

Figure 3: Estimated decomposition of the uncorrected data in the four correlation regions, given by the charge of the D^* and the muon and the azimuthal angle $\Delta\Phi^*$ between them. The solid points are the result of a fit to the ΔM distribution in each correlation region. The solid line gives the sum of the charm and beauty $D^*\mu$ signal events as obtained from the fit. The hatched histogram represents the beauty contribution. The distributions still contain background from hadrons misidentified as muons and muons from the decays of light hadrons, which is corrected for separately. This background to the muon selection represents about 30% of the charm signal and about 5% of the beauty signal.

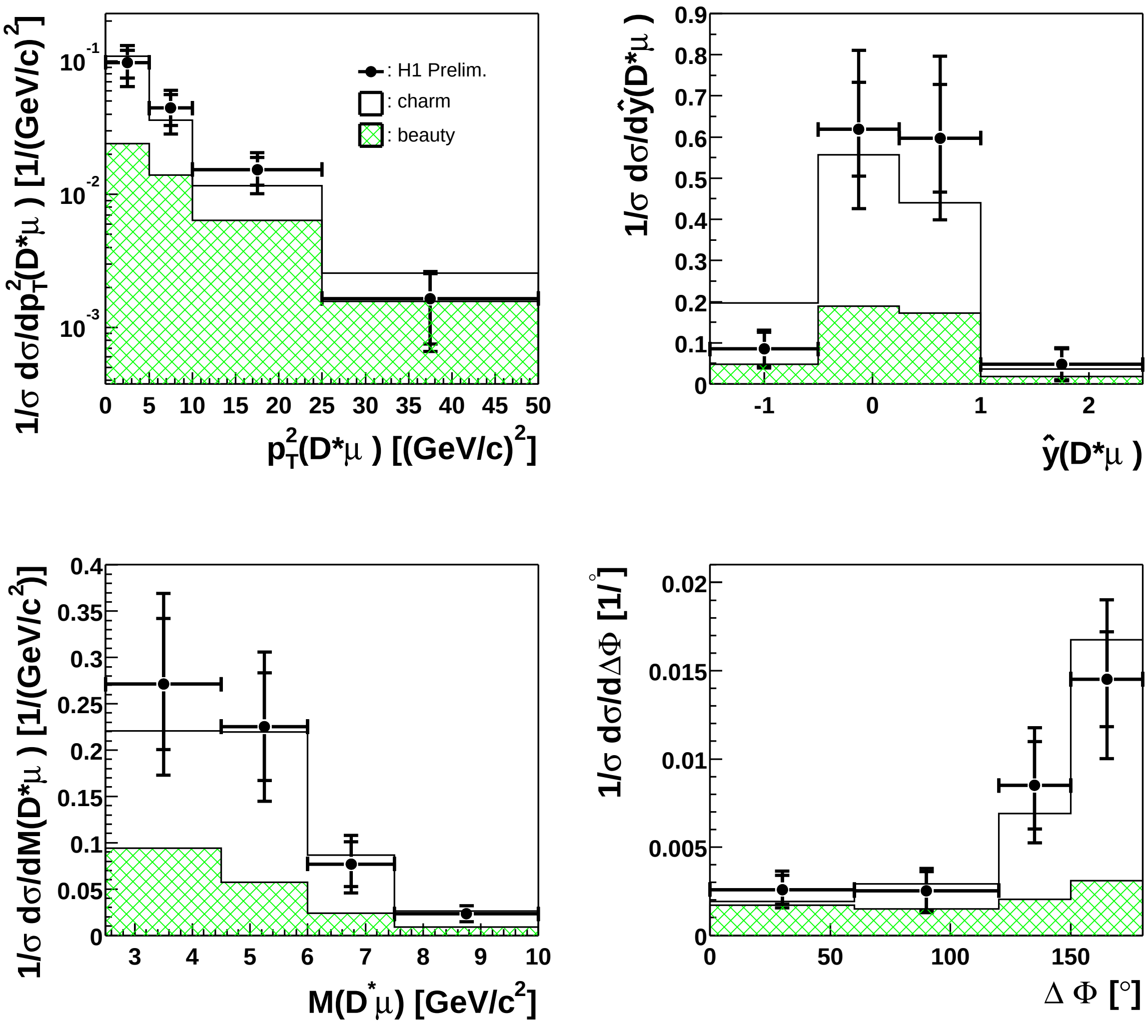

Figure 4: The data points show cross sections for $D^*\mu$ production normalised to the total cross section in the visible range ($p_T(D^*) > 1.5$ GeV/c, $|\eta(D^*)| < 1.5$, $p_T(\mu) > 1.0$ GeV/c, $|\eta(\mu)| < 1.74$ and $0.05 < y < 0.75$). The measurements are shown as a function of the kinematic variables $p_T^2(D^*\mu)$, $\hat{y}(D^*\mu)$, $M(D^*\mu)$ and $\Delta\Phi$, determined all in the lab frame. Also shown are the scaled predictions of the AROMA Monte Carlo program which uses leading order QCD matrix elements and parton showers. The charm cross section predicted by AROMA is multiplied by a factor 1.8 and the beauty cross section by a factor 3.6.