UNIVERSITY
of
GLASGOW

Department of Physics & Astronomy
Experimental Particle Physics Group
Kelvin Building, University of Glasgow,
Glasgow, G12 8QQ, Scotland
Telephone: +44 (0)141 339 8855 Fax: +44 (0)141 330 5881

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Heavy Quark Production

D H Saxon
Dept. Physics and Astronomy, University of Glasgow,
Glasgow, G12 8QQ, Scotland

Abstract

The quality of the data on charm and beauty production is improving fast, with new techniques reported at HERA and the TeVatron. Charm fragmentation at HERA looks the same as at LEP. There is evidence for charm content in the photon and fair agreement between theory and data in DIS. Beauty production at LEP agrees with astounding precision with theory, but at TeVatron and HERA there are 70% discrepancies between theory and results. Future accelerator running with the upgraded detectors will lead to a great improvement in understanding.

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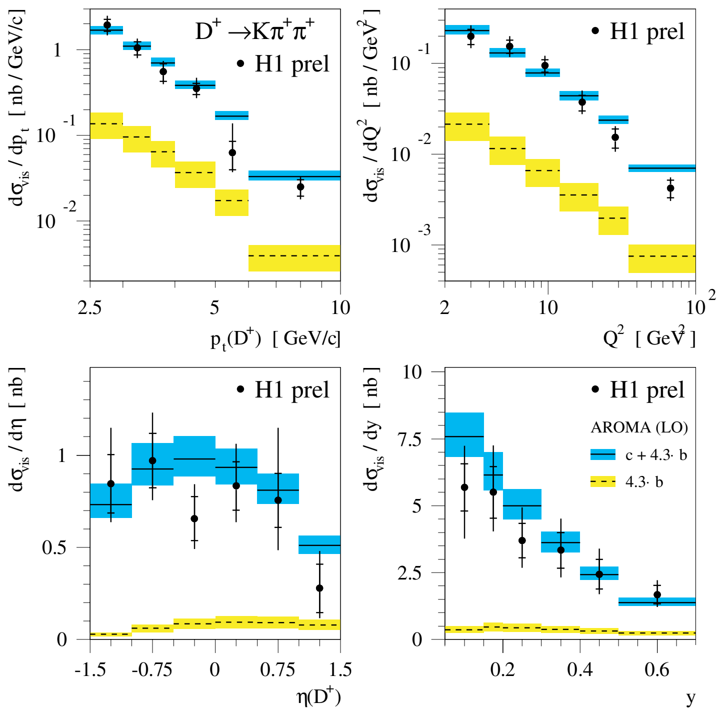

Figure 1: D^+ *inclusive distributions in deep inelastic scattering compared to Monte Carlo calculations*

1 Introduction

This article is an experimental review of open heavy flavour production, principally in ep collisions, but with some reference to TeVatron and LEP results, concentrating on results which are new since the review by Bussey[1]. (Theoretical aspects are dealt with in the talk by Nason in these proceedings.) There has been considerable progress in technique. In charm-finding H1 use decay length tagging as well as mass peaks, and the CDF two-track trigger will greatly increase charm samples. In beauty-finding results are available using muon impact parameter as well as $p_{\rm T}^{\rm rel}$ of the muon relative to jets and for the first time also $D^*\mu$ correlations. The situation on charm measurements is relatively healthy. Comparison of the increasing number of beauty results to theory still leaves more questions than answers.

2 Charm production

The traditional method of identifying charm events is through the decay chain $D^{*+} \to D^0\pi_s^+, D^0 \to K^-\pi^+$, looking for a peak in the $K^-\pi^+$ mass spectrum in events with a tagged by $\Delta m = (m(K^-\pi^+\pi_s^+) - m(K^-\pi^+))$ close to 145 MeV. Charm signals are also seen in the $K^-\pi^+$ mass spectrum without the D^* tag. H1 see a modest peak in $D^+ \to K^-\pi^+\pi^+$ on a huge combinatorial background. This is massively improved using the H1 silicon tracker to add a decay length tag, and charm signals are seen for D^+, D^0, D_s and D^{*+} in DIS for $2 < Q^2 < 100$ GeV^2, typically for $p_{\rm T} > 2.5$ GeV and $|\eta(D)| < 1.5$. Leading order plus parton shower Monte Carlos such as Aroma[2] provide a good description in normalisation and shape of the distributions in $p_{\rm T}, Q^2, \eta$ and y.(see figure 1.)

Having these four channels available allows one to compare charm fragmentation parameters in DIS with those found at LEP. H1 find $R(u/d) = 1.26 \pm 0.11 \pm 0.04$, $\gamma_s = 0.36 \pm 0.10 \pm 0.04$ and $V/(P+V) = 0.693 \pm 0.045 \pm 0.006$ or $0.613 \pm 0.061^{+0.033}_{-0.088}$, depending on the assumptions made about u/d universality. These are in reasonable agreement with the world averages of $1.00 \pm 0.09, 0.26 \pm 0.07$ and 0.601 ± 0.032 respectively. ZEUS have compared the distribution in $z = (E + p_{\|})/2E_{\rm jet}$ with LEP and CLEO data and find agreement within the modest errors on all these.[3] One concludes that charm fragmentation in DIS looks like charm fragmentation in e^+e^- annihilations.

The NLO-DGLAP model HVQDIS[4] (with the gluon ladder ordered in $k_{\rm T}$) describes differential cross-section distributions well, but double differential distributions such as the rapidity spectrum of D^* for different

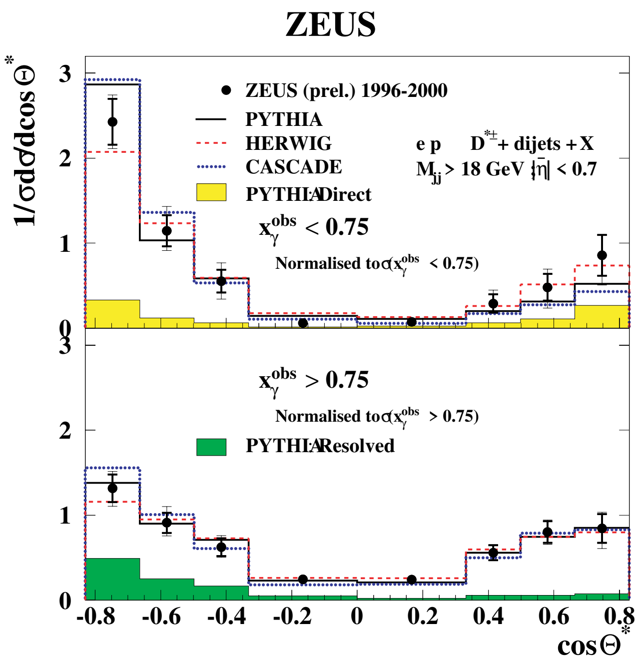

Figure 2: *Photoproduced D^* angular distribution in $\gamma^* p$ centre of mass*

p_{T} bins are less well described. HVQDIS lies below the forward D^* data. Cascade (using CCFM parton shower distributions, where the gluon ladder is ordered in rapidity) seems to do better.[5]

The structure function $F_2^{c\bar{c}}$ can be determined from the D^* rate. There is a large extrapolation to reach full acceptance, so one has to watch the model assumptions made in doing this. Both ZEUS and H1 have done this in the NLO DGLAP scheme. The scaling violations have a steeper Q^2 dependence than F_2, such that charm contributes about 50% of the scaling violation in F_2. One can make further assumptions and calculate the gluon distribution $xg(x)$ from D^* production in DIS and photoproduction. H1 find results very consistent with $xg(x)$ obtained from scaling violations in DIS.[6] H1 have also calculated $F_2^{c\bar{c}}$ in the CCFM scheme.The extrapolation factors are smaller (which is good) and the value of $F_2^{c\bar{c}}$ found tends to be lower. To understand this fully presumably needs a lot of work on F_2^{CCFM}, comparable to that over the years on F_2^{DGLAP}. Watch this space.

ZEUS have studied D^{*+} photoproduction for $1.9 < p_{\mathrm{T}} < 20$ GeV, $|\eta| < 1.6$ and $130 < W < 285$ GeV looking at distributions of p_{T}, η, W and $z(D^*)$. Theory (NLO or FONLL) agrees reasonably in shape but lies somewhat below the data in normalisation.

More information about the origin of charm in photoproduction is obtained by studying $\gamma p \to c\bar{c}X$ in events with two jets and a D^* tag. Experimentally one histograms the fraction of the energy in each event which is contained in the two highest-E_{T} jets, $(x_\gamma^{obs} = (\Sigma_{j=1,2} E_{\mathrm{T},j} e_j^{-\eta})/2yE_e)$. The region $x_\gamma^{obs} > 0.75$ is dominated by direct photon-gluon fusion with a hard quark exchange. In the γp centre-of-mass frame this leads to a jet angular distribution proportional to $1/(1-\cos\theta^*)$. The $x_\gamma^{obs} < 0.75$ region includes the possibility of a $c\bar{c}$ pair being resolved within the structure of the photon. One of these is struck by a hard gluon and recoils from the photon with an angular distribution of $1/(1+\cos\theta^*)^2$. A strong backward peak is found in the data, providing clear evidence for charm content in the photon.[7] (see figure 2.) Monte Carlo calculations based on Pythia, Herwig or Cascade describe the distributions fairly well.

The ratio, $(R = \sigma(x_\gamma^{obs} < 0.75)/\sigma(x_\gamma^{obs} > 0.75))$, for ($\gamma p \to$ two jets) events is sensitive to the resolved photon structure. For all two-jet events this ratio exceeds 1 for photoproduction (rising to 2 for jets at lower E_{T}) and falls to around 0.3 (depending on E_{T}) for $Q^2 > 100$ GeV^2. For events with a charm tag the ratio is flat at about 0.6 independent of Q^2.This result is described by various approaches: SAS1D describe it in terms of γ^* structure. Cascade and Aroma avoid assumptions on γ^* structure and produce low values of x_γ^{obs} by parton shower evolution. Aroma, using DGLAP evolution, somewhat under-predicts this effect. Cascade, using CCFM evolution, lies closer to the data.

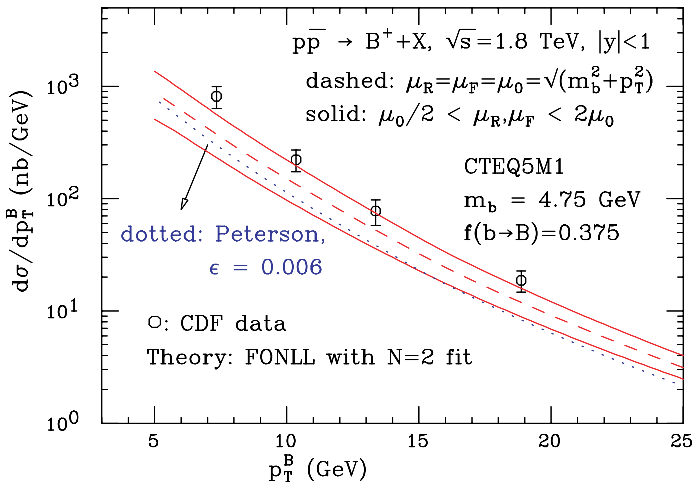

Figure 3: *CDF results on B^+ production compared to calculations*

There is a curious anomaly reported by ZEUS in that D^* production in e^+p is less than in e^-p at the highest x and Q^2 values. The result (a factor of two over several bins) persists after checks for many types of experimental error. It is not understood.[7]

ZEUS report on D^* production in diffractive DIS,[7] selecting events on the basis of the most forward energy deposit, ($\eta_{\max} < 3.0$.) This includes $(6.3 \pm 0.6^{+0.3}_{-0.7} \pm 0.3)\%$ of all D^* in DIS. Seven distributions are studied and described by models either having a gluon structure within the Pomeron (where the result falls between the $c\bar{c}$ and the $c\bar{c}g$ models of BJLW,) or using gluon ladders or higher order processes instead of an explicit Pomeron.

CDF report first results from their new two-track trigger, which is producing a step increase in quality of data. beautiful signals are seen for $D^0 \to KK$, $D^0 \to \pi\pi$, $D^+ \to \phi\pi^+$ and $D_s \to \phi\pi^+$. Exclusive beauty hadronic decays such as $B^\pm \to D^0\pi \to K\pi\pi$ are found after selecting on the D^0 impact parameter. We may expect significant new physics results on charm and beauty production in the future.[8]

3 Beauty production

Beauty production in e^+e^- annihilation is extraordinarily precisely measured and agrees astoundingly well with theory and model predictions. The b-fraction and the b-fragmentation are exemplary, and 2% effects on gluon emission are used to measure precisely m_b.[9] It is therefore something of a shock to realise that in pp and ep collisions there are big discrepancies between theory and data.

CDF run I measured b-production via $B^+ \to J/\psi K^+$ for $p_{\rm T} < 20$ GeV and found a signal 2.9 times theory. Revisiting the theory,[8] with revised fragmentation functions and updating the calculation (FONLL) has reduced this ratio to 1.7. A similar story is found in D0. Jung reports a new fit using Cascade (CCFM-based) that goes well through the data points.[5] We can expect an improvement in the data with the upgrades to the TeVatron detectors. The high b-tagging efficiency means we can look at $b\bar{b}$ correlations. Studies of angular differences between two tagged jets will discriminate between different production mechanisms.

Beauty production at HERA has been studied using muons close to jets and using the $p_{\rm T}^{\rm rel}$ of the muon relative to the jet. ZEUS and H1 report event samples which are $(27 \pm 3)\%$ beauty with a large fake muon component. H1 have shown results also using the muon impact parameter. The method is partially independent, and yields similar purity $(26 \pm 5)\%$. For photoproduction with $p_{\rm T}^{\mu} > 2$ GeV, $35° < \theta < 130°$ and $k_{\rm T}$-jets with $E_{\rm T} > 5$ GeV, H1 report a cross section of $(160 \pm 16 \pm 29)$ pb, which is a factor 2.4 to 4 times higher than NLOQCD(FMNR), Cascade, or Aroma prediction. ZEUS show differential cross-sections in rapidity (range -1.6 to 2.3) and $p_{\rm T}^{\mu}$ (range 3 to 10 GeV), and find a cross-section 1.9 times FMNR and well outside the errors.[10]

In deep inelastic scattering H1, (using $p_{\rm T}^{\rm rel}$ and impact parameters,) again find a value exceeding various calculations by a factor 2.6 to 4.3. ZEUS studied a sample of 836 events from 60 pb^{-1} of data with a $(25 \pm 5)\%$

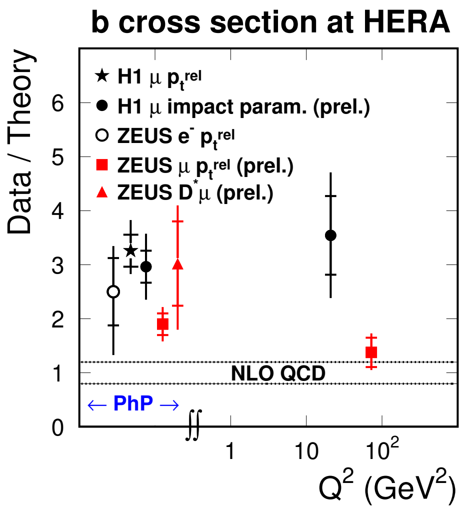

Figure 4: *Summary of b-production comparisons of data and theory*

purity. They find the spectra $p_\mu, \eta, E_{\mathrm{T,jet}}^{\mathrm{Breit}}$, well described by Monte Carlo. Their result for $\sigma(ep \to eb\bar{b}X \to e$ jet $\mu X)$ is 1.4 times HVQDIS and only 1.0 S.D. high.[11]

First results are reported from a new technique of looking for events containing both D^* and muon. $c\bar{c}$ production produces these with opposite charge and in opposite hemispheres in the γg rest frame. $b\bar{b}$ production also produces opposite charges in the same hemisphere, same charge in opposite hemisphere. The statistics are modest but the background suppression is impressive (34 beauty events in the same hemisphere opposite charge, on a background of only 3). Results again lie above theory.[12] Figure 4 summarises the state of our knowledge.

In all these beauty studies the efficiencies are low and acceptance corrections large. Measurements are made in different kinematic regions and model assumptions are needed to reconcile them. Most of the results lie well above the theoretical expectation. All will benefit from detector upgrades to H1 and to ZEUS for HERA-II.

Results[13] have been reported by L3 and by OPAL on $\gamma\gamma \to c\bar{c}X$, $b\bar{b}X$. L3 use both electron and muon signatures and have lower false-lepton backgrounds. The result is reminiscent of HERA. There is good agreement with QCD calculations for charm, but for beauty the data lie a factor of about three above the predictions. Clearly beauty production is fertile ground for future study both experimentally and theoretically.

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