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HEAVY FLAVOUR PRODUCTION AT HERA

BENNO LIST
For the H1 and ZEUS Collaborations
University of Hamburg, Institute for Experimental Physics,
Luruper Chaussee 149, D–22761 Hamburg

The production of charm and beauty quarks in ep collisions at HERA has been studied by the H1 and ZEUS collaborations. Charm production is generally well described in total rate and in shape by next to leading order (NLO) calculations in perturbative quantum chromodynamics (QCD), although in specific phase space corners the NLO calculations underestimate the observed cross sections. More and more beauty production data are becoming available. For this process, NLO QCD predictions tend to be lower than the measurements.

1 Introduction

The production of charm and beauty quarks has been studied in great detail over the last years at the ep collider HERA by the H1 and ZEUS collaborations. In ep scattering, the main production mechanism of heavy quarks is boson gluon fusion, where a pair of heavy quarks is formed in the collision of a photon emitted by the electron[a] and a gluon out of the proton. The mass of the charm or beauty quark provides a hard scale that makes calculations in perturbative QCD (pQCD) viable even in the absence of additional hard scales that may be provided by the photon virtuality Q^2 or the transverse momentum p_t of the quarks.

Calculations based on pQCD have generally been quite successful in describing charm production data, while beauty production rates tend to be underestimated by such calculations. The challenges faced by theory include the treatment of the quark mass in different kinematic regions, the inclusion of the effects of the intrinsic gluon transverse momentum k_t, and a quantitative description of heavy flavour production in processes where the photon's hadronic structure is resolved.

[a] At different times, HERA ran with electrons or positrons; here we use the term "electron" to denote either.

2 Charm Production

A wealth of charm production measurements at HERA exists, in both photoproduction, where the exchanged photon is quasi–real ($Q^2 \approx 0$), and deep-inelastic scattering (DIS), where the photon virtuality Q^2 is large compared to Λ_{QCD}. Mostly, these measurements are based on D^* tagging, where decays of the D^{*+} meson[b] to $D^0\pi^+$ with subsequent D^0 decays to $K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$ are used to identify charm production. This technique is well understood, but hampered by the rather small branching fractions of the decays involved. Recently, also measurements that exploit lifetime information using vertex detectors have been presented; these measurements profit from larger sample sizes and the possibility to measure charm and beauty production concurrently, but require a vertex detector, whose resolution has to be well understood.

Calculations based on pQCD [1,2], using parton densities of the proton derived from inclusive DIS measurements [3], have been very successful in describing inclusive charm production in photoproduction and DIS over many orders of magnitude in cross sections [4,5,6]. Of particular importance for these calculations is the gluon density, which can be inferred from the scaling violations in the inclusive DIS measurements. Still, at low values of Q^2, the charm production data tends to be higher than the pQCD predictions. The experimental accuracy of these data is now sufficient to further constrain the gluon density; however, theoretical uncertainties in this region are still substantial and thus call for an improved theoretical understanding.

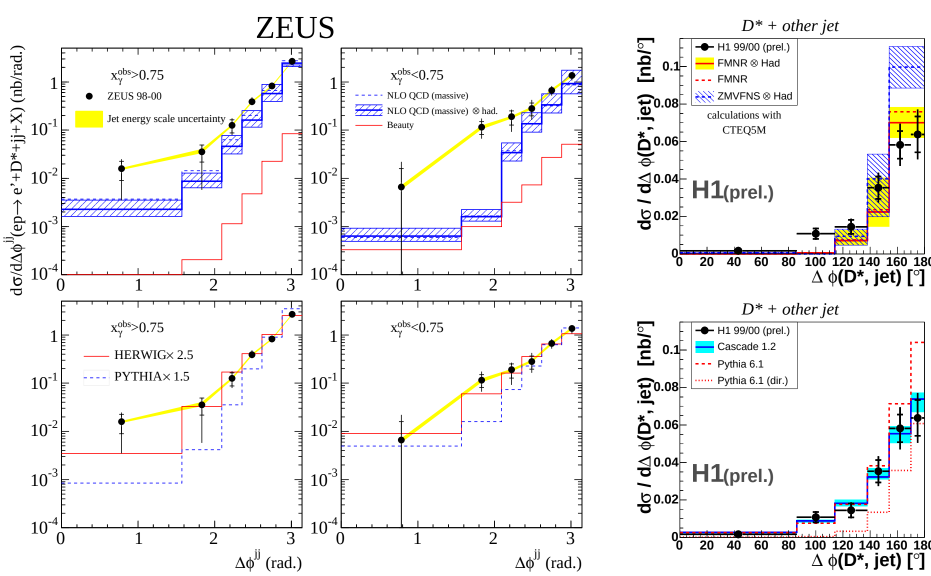

Figure 1: ZEUS [7] (left) and H1 [8] (right) measurements of charm production in events with a D^* meson and jets. Shown is the opening angle $\Delta\phi$ between the jets in the plane perpendicular to the beam, in comparison to NLO QCD calculations (top) and Monte Carlo models (bottom).

Recently, a new D^* measurement has been published by the ZEUS collaboration [7] that focuses on charm photoproduction with jets, and H1 has presented similar preliminary data [8]; here, the jet p_t provides a hard scale that dominates over the charm quark mass. In addition, the jets lead to additional observables whose distributions may be confronted with theoretical preditions. Of particular interest here is x_γ, which in a leading order picture corresponds to the fraction of the photon's momentum that enters the hard interaction; the measured observable is defined as $x_\gamma^{obs} = (E - p_z)_{jets}/(E - p_z)_{had}$, i.e. the fraction of $E - p_z$ of the two leading jets compared to the total $E - p_z$ of the hadronic final state. This quantity is expected to be close

[b] Charge conjugate states are implicitly included in this text.

to 1 for "direct" processes, where the photon couples pointlike to the heavy quark, while events where the photon's hadronic structure is resolved tend to lie at lower values of x_γ^{obs}.

The ZEUS collaboration has also measured the opening angle $\Delta\phi^{jj}$ in the transverse plane, which is expected to be π in leading order (order α_s) QCD, while radiation of additional gluons leads to smaller opening angles. Thus, this measurement tests effects of order α_s^2, so that "NLO" calculations are in fact leading order for this observable. H1 has performed a similar measurement with events that contain a D^* meson plus a separate jet, where H1 has measured the opening angle between the D^* and the jet directions. Both measurements are shown in Fig. 1. While the region of large opening angles is well described by the calculations, the NLO predictions fall below the data when the jets are not completely back-to-back anymore, in particular in the resolved regime ($x_\gamma^{obs} < 0.75$), as the ZEUS measurement shows. In contrast, Monte Carlo models, which approximate higher orders by additional parton showers, are more successful in describing these distributions. A significant improvement is hoped for when Monte Carlo programs will become available for ep scattering processes that mach NLO calculations with parton showers, such as MC@NLO [9].

3 Beauty Production

The measurement of beauty production is considerably more difficult compared to charm production due to the smaller cross section and the absence of easily identifiable decay channels with sizeable branching fractions. Beauty production can be identified by the observation of events with muons that have a large relative transverse momenta $p_{t,rel}$ with respect to a nearby jet, or by the exploitation of lifetime information; these techniques have also been combined.

Both, the ZEUS and H1 collaborations, have published results [10,11] for visible beauty production cross sections in events with muons and jets, which are characterized by restrictions on the p_t and pseudorapidity η of the muons and jets. Event with D^* mesons and muons [12] or dimuons [13] have also be used to extract beauty cross sections.

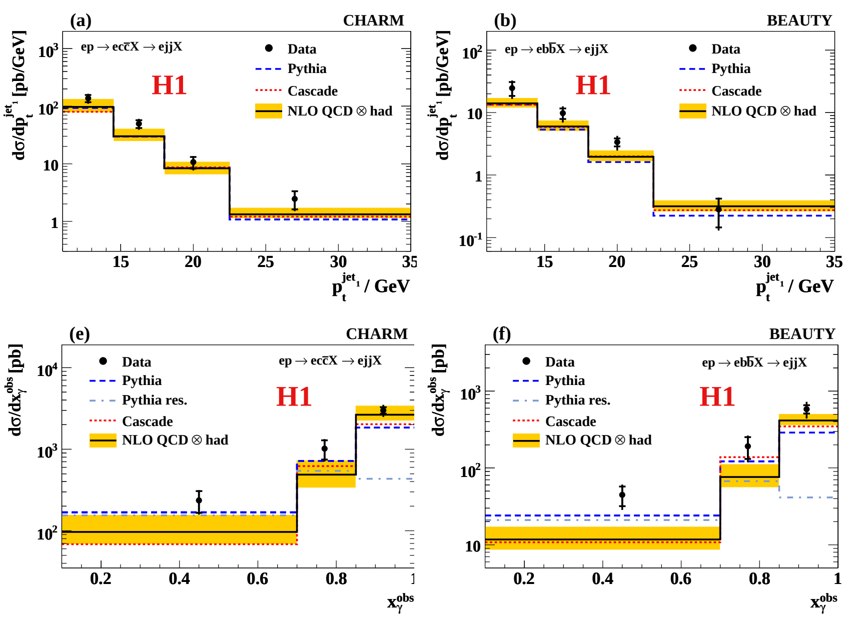

Figure 2: H1 measurements [14] of inclusive charm and beauty production in photoproduction with two jets.

Recently, the H1 collaboration has also published inclusive beauty production cross sections in DIS [5,6], and in photoproduction with two jets [14], based solely on lifetime information; the ZEUS collaboration has also presented preliminary beauty production measurements based on their micro vertex detector [15]. This is also the first heavy flavour result from the HERA-II running phase, while the other results discussed in this presentation were achieved with HERA-I data.

The inclusive beauty production measurements in DIS are well discribed by the NLO QCD calculations, and approach a precision that is sufficient to discriminate between different parametrizations of parton densities in the proton. It is encouraging to see also NNLO calculations of beauty production appear [16], which agree well with the DIS measurements. On the other hand, the rate of beauty photoproduction with two jets is significantly underestimated by the theory calculations, as shown in Fig. 2. The discrepancy is again particularly large in the region of small $x_\gamma^{obs} < 0.85$.

In general, a large fraction of the beauty production measurements show higher cross sections than predicted by QCD calculations; among observations where the discrepancy is particularly significant are the H1 measurement of visible b cross sections with muons and jets in DIS and photoproduction [11], the new H1 dijet measurement in photoproduction [14], a measurement using $D^*\mu$ correlations [12], and a ZEUS measurement of visible b cross sections with muons and jets in DIS [10]. However, essentially all measurements are compatible with cross section values that are approximately a factor 1.5 to 1.7 larger than the NLO QCD prediction, and several new measurements [5,6,17] are also consistent within errors with a ratio between data and theory of 1.

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