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Combination of $\mathrm{D}^{*\pm}$ differential cross-section measurements in deep inelastic ep scattering at HERA

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H1 and ZEUS have published differential cross sections for D^* production from their respective final data sets in a very similar phase space. These fiducial cross sections were combined, taking into account all relevant correlations, thereby significantly reducing the uncertainties. Next-to-leading-order QCD predictions were compared to the results

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1. Introduction

Measurements of open-charm production in deep inelastic electron[1]-proton scattering (DIS) at HERA provide important input for stringent tests of QCD.

Both the H1 [1, 2] and ZEUS [3] collaborations have recently published measurements in a similar phase space of differential cross sections for D^* production using the full HERA II sets. Previously, open-charm production cross sections extrapolated to the full phase space have been partially combined [4] at the level of the charm reduced cross sections. This procedure introduced an additional non-negligible theory uncertainty due to extrapolation but allowed combination of measurements performed with different charm-tagging techniques.

The recent analysis [5] concentrates on the combination of cross sections for D^* [1–3] at the visible level which can be compared directly to differential next-to-leading-order (NLO) cross-section predictions without the need for extrapolation. The combination is based on the procedure described in [6–8], including a full treatment of the correlated uncertainties, similar to the one used for the reduced-cross-section combination [4]. This yields a significant reduction of the overall uncertainty of the measurements.

Combinations are made for the single-differential cross sections in terms of the exchanged-photon virtuality, Q^2, the inelasticity y, the transverse momentum, $p_T(D^*)$, and pseudorapidity, $\eta(D^*)$, of the outgoing D^* mesons, and the D^* inelasticity $z(D^*) = (E(D^*) - p_Z(D^*))/(2E_e y)$, where E_e is the incoming electron energy. The double-differential cross sections in Q^2 and y are also combined.

The massive fixed-flavour-number scheme (FFNS) is used for theory predictions throughout this note, since it is the only scheme for which fully differential calculations [9] are available at NLO in QCD. All D^* cross sections always include contributions from both charm and beauty production.

2. QCD calculations

Charm-production predictions were obtained at next-to-leading order in QCD ($\mathscr{O}(\alpha_s^2)$) using HVQDIS [9] in the 3-flavour FFNS scheme.

The following parameters were used in the calculations and the corresponding variations were used to estimate the associated uncertainties

- **pole mass of the charm quark** $m_c = 1.5 \pm 0.15\,\mathrm{GeV}$;
- **renormalisation and factorisation scales** $\mu_f = \mu_r = \sqrt{Q^2 + 4m_c^2}$, varied simultaneously up or down by a factor of two for the extrapolation from $Q^2 < 100\,\mathrm{GeV}^2$ to $Q^2 < 1000\,\mathrm{GeV}^2$, for which only the shape was relevant, and varied independently by a factor of two for the absolute predictions, with the restriction that the ratio of the two scales never exceeds 2;
- **strong coupling constant** $\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$, corresponding to $\alpha_s^{n_f=5}(M_Z) = 0.116 \pm 0.002$;

[1] Hereafter "electron" is used to denote both electron and positron, if not otherwise stated.

- **the proton PDF** was described by a series of FFNS variants of the HERAPDF1.0 set [8] at NLO, evaluated for $m_c = 1.5 \pm 0.15\,\text{GeV}$, $\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$ and for different scale choices. Charm data were not included in these fits. The effect of the PDF uncertainties was evaluated according to the HERAPDF1.0 prescription [8].

- **charm fragmentation** was treated as detailed in [4].

These predictions were used for comparison to the data as well as to make a very small extrapolation to a common fiducial phase space. The theory uncertainty induced in this procedure is small compared to the experimental uncertainties.

The small beauty contribution needed a detailed treatment of b hadron to D^* decays and was therefore obtained from the RAPGAP [10] MC, normalised to independent measurements as detailed in [2, 3]. The sum of the HVQDIS charm and scaled RAPGAP beauty predictions is referred to as NLO predictions in the following.

3. Combined D^* cross sections

Input measurements are presented at the QED Born level (using running α) and include both the charm and beauty contributions to D^* production. The total expected beauty contribution is small ($\sim 3\%$). The overall phase space for the combined cross sections is given by

- $5 < Q^2 < 1000\,\text{GeV}^2$,
- $0.02 < y < 0.7$,
- $1.5 < p_T(D^*) < 20\,\text{GeV}$,
- $|\eta(D^*)| < 1.5$.

In order to make the input data sets compatible to the chosen phase space and with each other, a small extrapolation was applied before the combination. From the two sets of measurements in [2], the one compatible with the cuts on $p_T(D^*)$ and $\eta(D^*)$ quoted above was chosen. Since this measurement extended only up to $Q^2 < 100\,\text{GeV}^2$ it was extrapolated to $Q^2 < 1000\,\text{GeV}^2$ using the shape of the HVQDIS [9] prediction, normalised to the cross-section measurement for $100 < Q^2 < 1000\,\text{GeV}^2$ taken from [1]. All measurements were updated with the D^* branching ratio from the latest PDG value [11].

The combination of the data sets used the χ^2 minimisation method developed for the combination of inclusive DIS cross sections [6 – 8], as implemented in HERAverager [12]. The χ^2 function was defined as described in [4] and took into account the correlated systematic uncertainties for the H1 and ZEUS cross-section measurements. The statistical uncertainties were treated as uncorrelated, while most of the systematic uncertainties were treated as point-to-point correlated within each dataset. Asymmetric systematic uncertainties were symmetrised before averaging. Only the branching ratio uncertainty was treated as correlated source between H1 and ZEUS. Each combined point consisted of the combination of exactly two measurements.

Since the data were statistically correlated between the different distributions, each distribution had been combined separately. The individual data sets as well as the results of the combination for

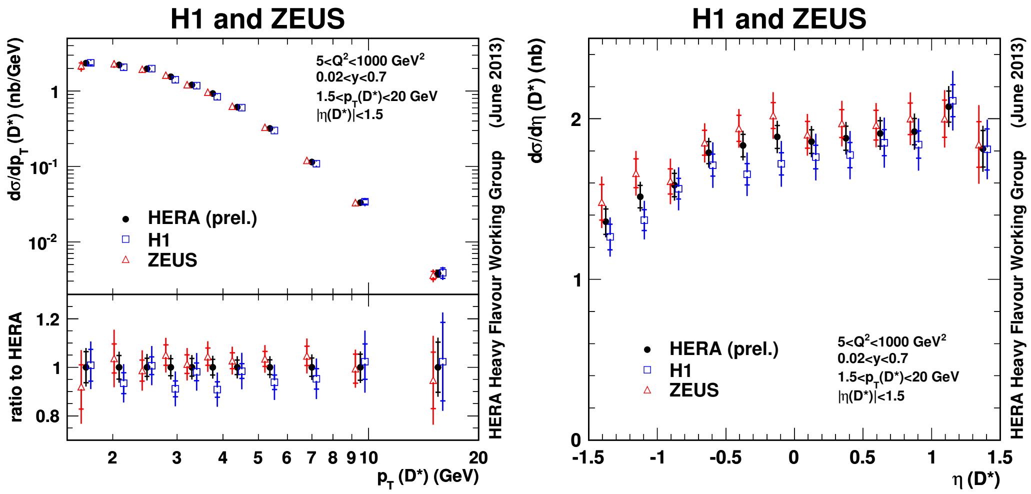

Figure 1: Differential D^* cross section as a function of $p_T(D^*)$ and $\eta(D^*)$. The open symbols show the individual measurements, shown with a small horizontal offset for visibility. The filled points are the combined cross sections. The bottom part shows the ratio of these cross sections with respect to the central value of the combined cross sections.

two selected distributions are shown in Fig. 1. The combination in the different variables had the p-values corresponding to χ^2 varying between 0.15 and 0.85, i.e. the two data sets are consistent.

The combined cross sections as a function of $p_T(D^*)$, $\eta(D^*)$ and $z(D^*)$, and the double differential cross sections in Q^2 and y are shown in Figs. 2 to 3 and compared to the FFNS NLO QCD predictions. The predictions described the data very well within uncertainties. The data reached a precision of about 5% over a large fraction of the measured phase space, while the typical theory uncertainty ranged from 30% at low Q^2 to 10% at high Q^2. Therefore, higher-order massive-scheme NNLO calculations and improved fragmentation model for these predictions would be very helpful to match the data precision.

Both in the single-differential (not shown) and in the double-differential distributions the central theory prediction showes a somewhat softer y distribution than the data. The central prediction for $z(D^*)$ is a bit wider than the measured distribution.

4. Conclusions

Measurements of D^* production in deep inelastic ep scattering by the H1 and ZEUS experiments were combined in the fiducial phase space, accounting for the correlated systematic correlations. The data sets were found to be consistent, and the combined data have significantly reduced uncertainties. The combined data were compared to massive-scheme NLO QCD predictions. The predictions described the data very well, but also gave some hints for possible future improvements.

References

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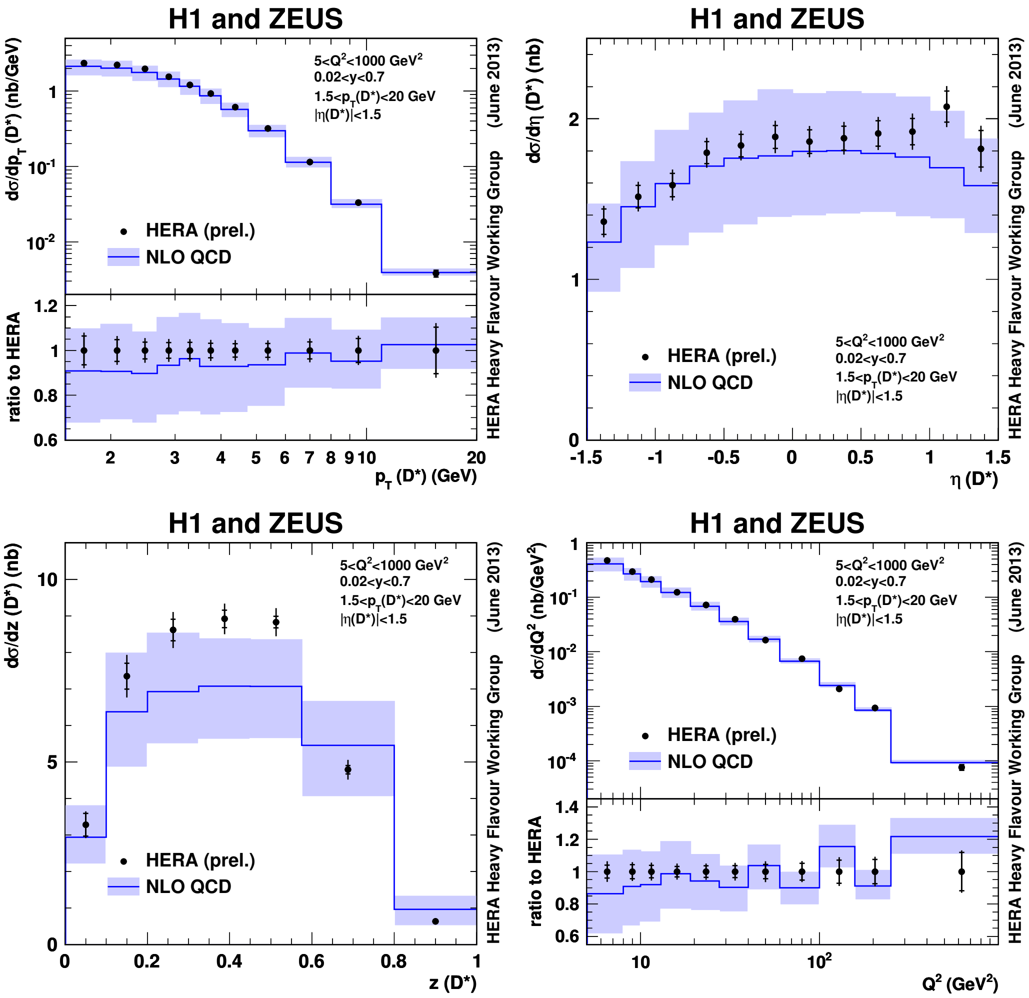

Figure 2: Differential D^* cross section as a function of $p_T(D^*)$, $\eta(D^*)$, $z(D^*)$ and Q^2. The filled points show the combined cross sections. The inner and outer error bars indicate the uncorrelated and total uncertainties, respectively. Also shown are the NLO predictions from HVQDIS (solid line) with a small b-quark contribution obtained with RAPGAP. The filled band shows the theoretical uncertainty.

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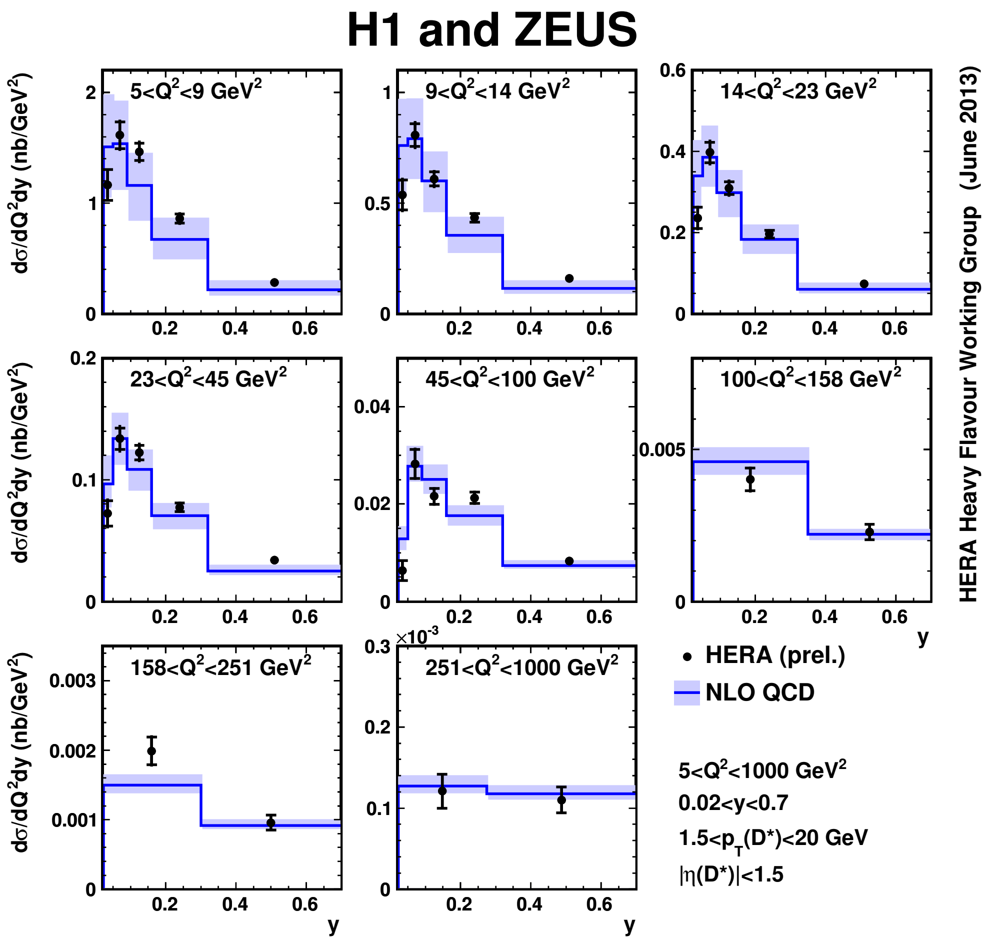

Figure 3: Double-differential D^* cross section as a function of of Q^2 and y. Other details as in Fig. 2.

[12] https://wiki-zeuthen.desy.de/HERAverager/