Combination of Differential $D^{*\pm}$ Cross - Section Measurements in DIS at HERA

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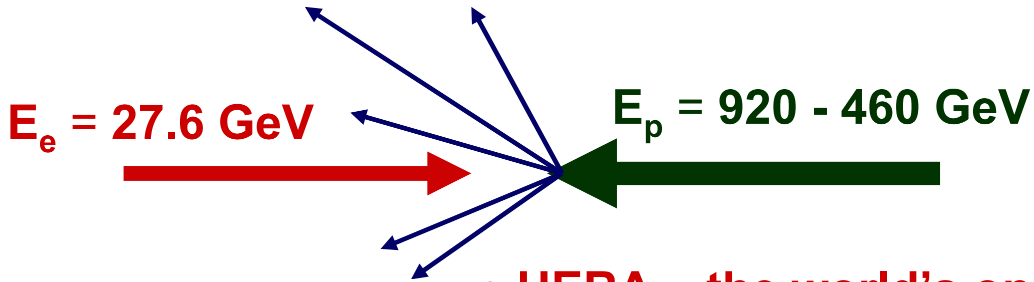
on behalf of the H1 and ZEUS collaborations

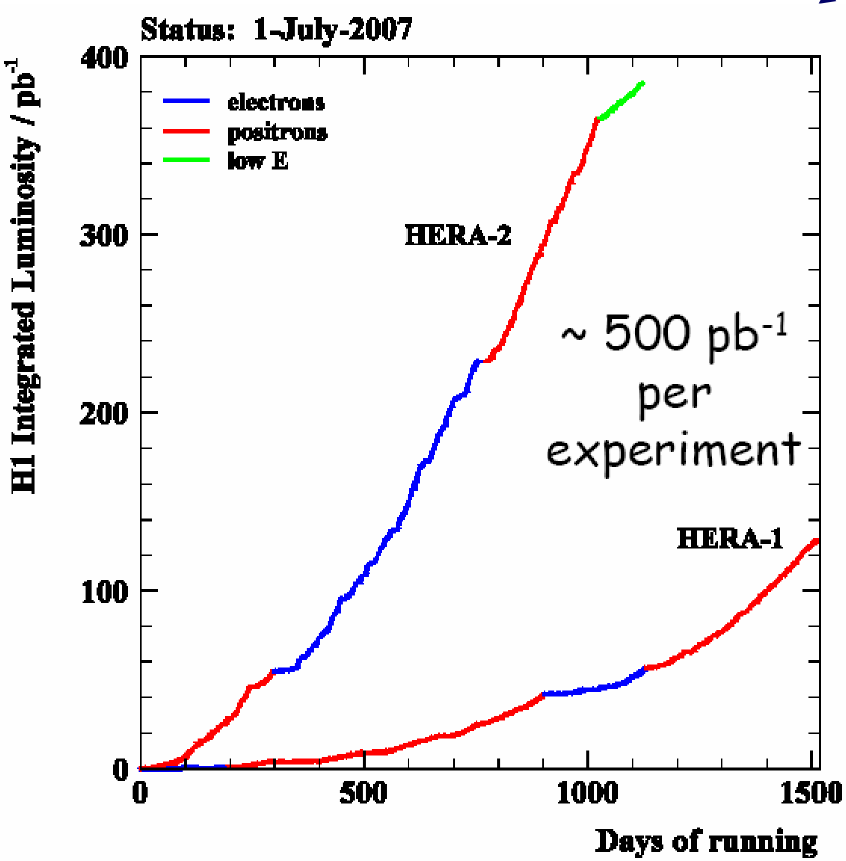
- **Charm production in DIS**
- **Combination of D* differential cross sections measured at HERA**
- **NLO QCD predictions (massive Fixed Flavour Number Scheme)**
- **Data vs. theory predictions**
- **Summary**

Low-x Meeting 2015

Sandomierz, Poland,1-5 September, 2015

HERA





- **HERA – the world's only ep collider**
  operated in 1992-2007 colliding electrons or positrons with protons
- two colliding beam experiments: H1 and ZEUS
- Nominal proton beam energy :

  HERA I (1995-2000)

  E_p = 820 / 920 GeV
  $\sqrt{s}$ = 300 / 318 GeV, L_{int} = 126 pb^{-1}

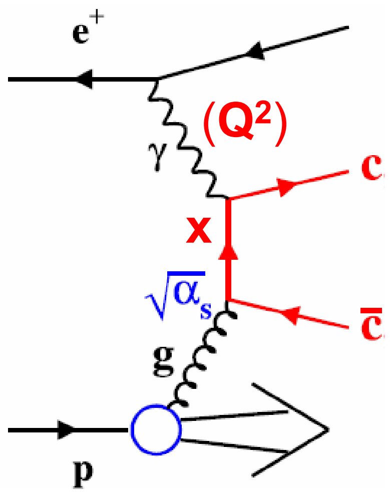
  HERA II (2003-2007)

  E_p = 920 GeV
  $\sqrt{s}$ = 318 GeV, L_{int} = 373 pb^{-1}

- Reduced proton beam energy :

  E_p = 460 GeV, $\sqrt{s}$ = 225 GeV, L_{int} = 12.4 pb^{-1}
  E_p = 575 GeV, $\sqrt{s}$ = 250 GeV, L_{int} = 6.2 pb^{-1}

Charm production in DIS



Boson-Gluon Fusion $\gamma g \rightarrow c\bar{c}$

dominant process of charm production in DIS

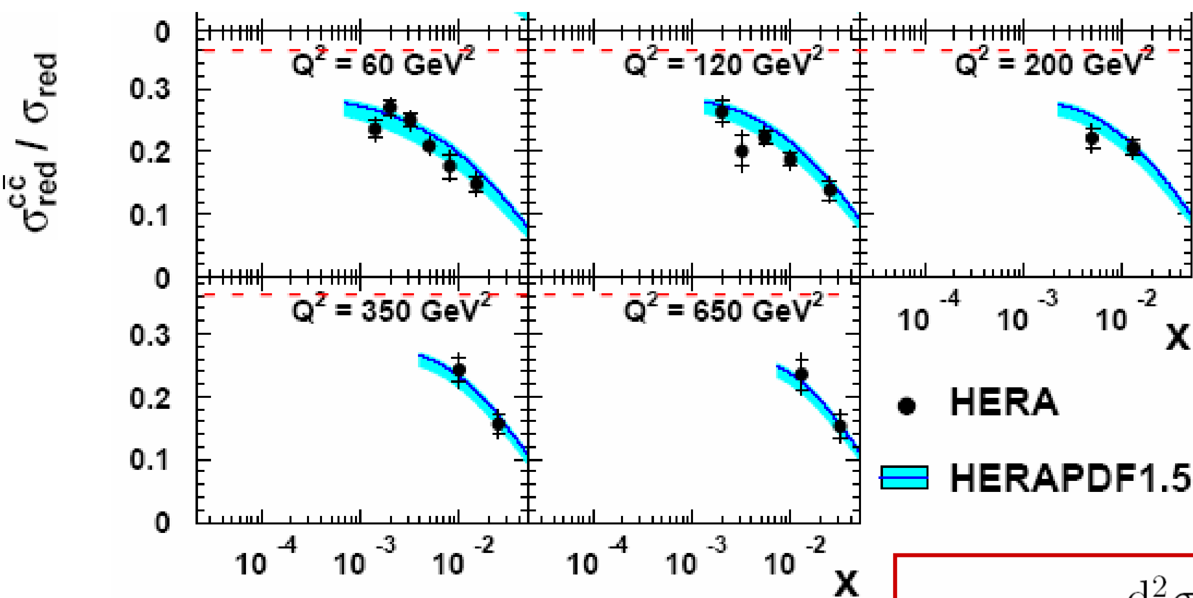
Q^2 |virtuality| of the exchanged boson

x fraction of proton momentum carried by struck quark in Quark Parton Model

y inelasticity, fraction of lepton energy taken by photon in the proton rest frame

DIS : $Q^2 \geq 1$ GeV^2

Fraction of charm contribution to the inclusive DIS cross section



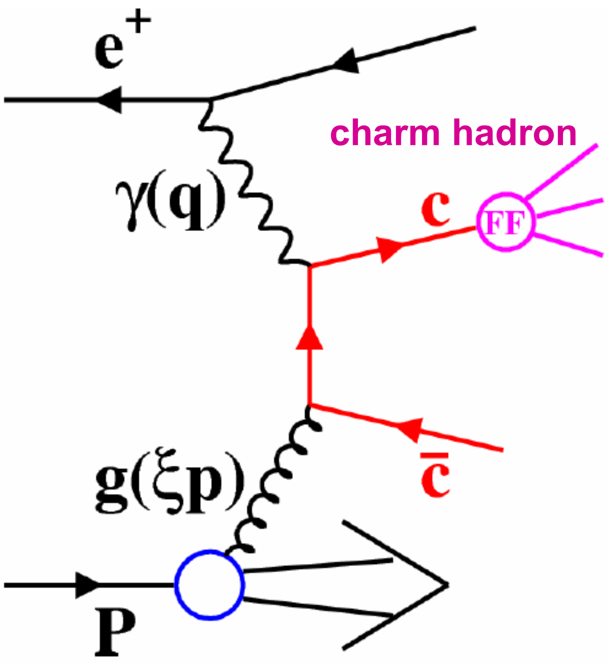
At high Q^2 up to 30% of charm contribution to the HERA DIS cross section

arXiv:1506.07519

reduced charm cross section

$$\sigma_{\mathrm{red}}^{c\bar{c}} = \frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)}$$

Charm production in DIS



- **Tests of perturbative QCD**
  (multiple hard scales m_c, Q^2, $p_T(c)$, various heavy quark mass schemes)
- **Sensitivity to the gluon density in the proton**
- **Constraints on the flavour composition of quarks in the proton**
- **Measurements of c-quark mass and its running**
- **Constraints on the charm fragmentation parameters**
- **Impact on proton parton distribution functions (PDFs)**
  → improvement of predictions for $W^\pm$ / Z and Higgs production cross-sections at the LHC

At HERA different techniques used to measure charm production cross sections :

- **full reconstruction of D or D* mesons**
- **lifetime tagging**
- **tagging of leptons from semi-leptonic decays of heavy-flavour hadrons**

↓

Reduced cross sections $\sigma_{red}^{c\bar{c}}$ for charm production measured by the H1 and ZEUS exp. combined, $2.5 \leq Q^2 \leq 2000$ GeV^2, EPJ **C73** (2013) 2311

(extrapolation from the visible to the full phase space, significant theory related uncertainties)

Combination of $D^{*\pm}$ differential cross sections in DIS

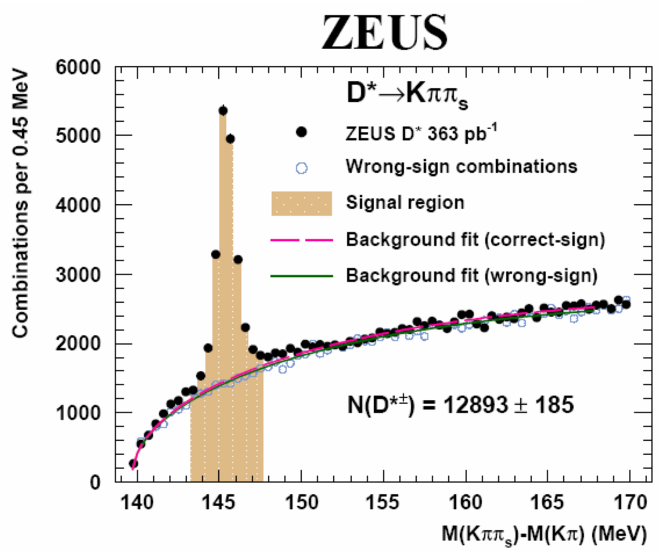
- **analysis of fully reconstructed $D^{*\pm}$ mesons: best signal - to- background ratio**

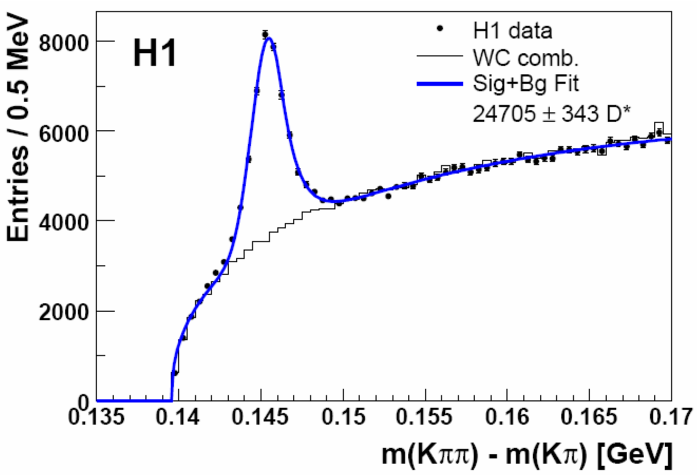
  H1 medium Q^2, $5 \le Q^2 \le 100$ GeV^2, L_{int} = 348 pb^{-1}, EPJ **C71** (2011) 1769
  H1 high Q^2, $100 \le Q^2 \le 1000$ GeV^2, L_{int} = 351 pb^{-1}, PL **B686** (2010) 91
  ZEUS, all Q^2, $5 \le Q^2 \le 1000$ GeV^2, L_{int} = 363 pb^{-1}, JHEP **05** (2013) 097
  ZEUS, HERA I, $1.5 \le Q^2 \le 1000$ GeV^2, L_{int} = 82 pb^{-1}, PR **D69** (2004) 012004 (used only for 2d cross sections)

- **H1 and ZEUS data combined in the visible phase space region → small extrapolation uncertainties**
  ($5 < Q^2 < 1000$ GeV^2, $0.02 < y < 0.7$, $p_T(D^*) > 1.5$ GeV, $|\eta(D^*)| < 1.5$)

- **single and double** ($Q^2 > 1.5$ GeV^2) **differential cross section in various variables**

golden decay channel $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow K^-\pi^+\pi_s^+$

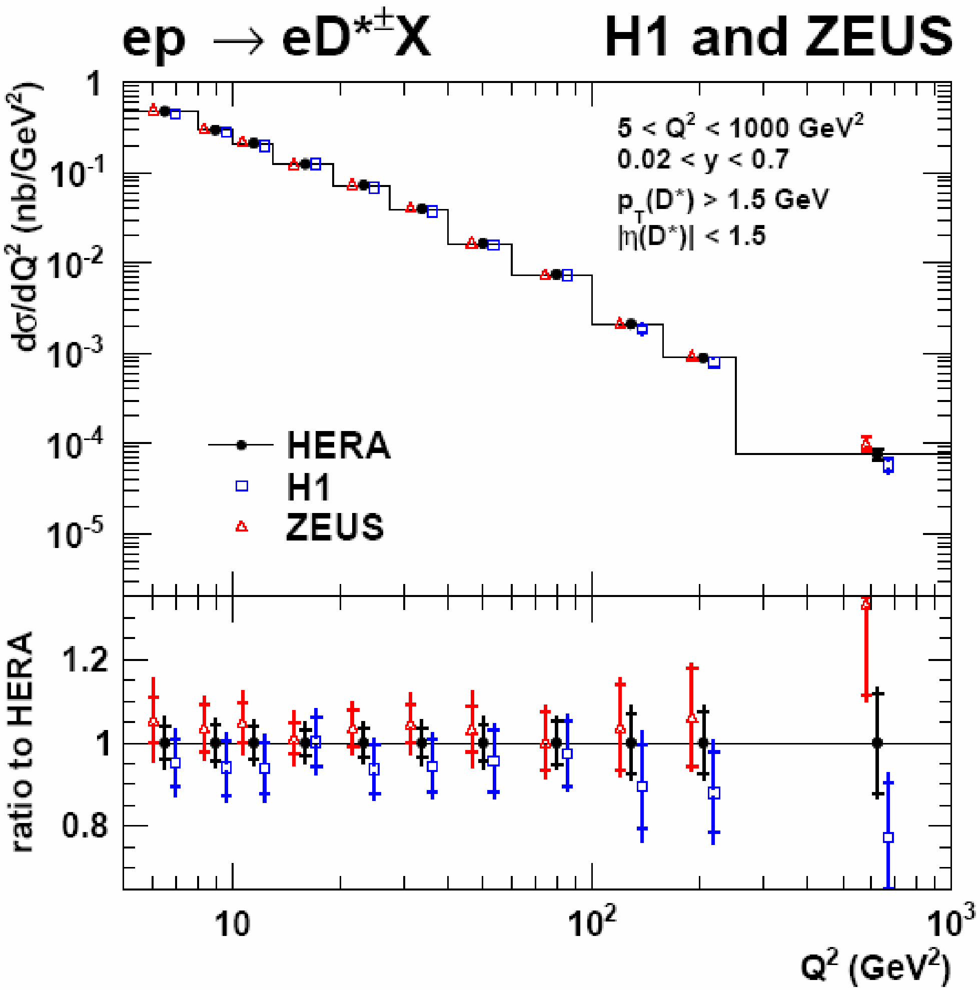




Clean signal in $M(K^-\pi^+\pi^+_s) - M(K^-\pi^+)$ distribution

Combined D*± differential cross section: dσ/dQ²

Combination of most precise D*± visible differential cross sections from full HERA II data-set performed separately for each variable



- Combined data reach precision of ≈ 5% in large fraction of phase space
- data consistent between H1 and ZEUS

► exp. systematic uncertainties independent between H1 and ZEUS

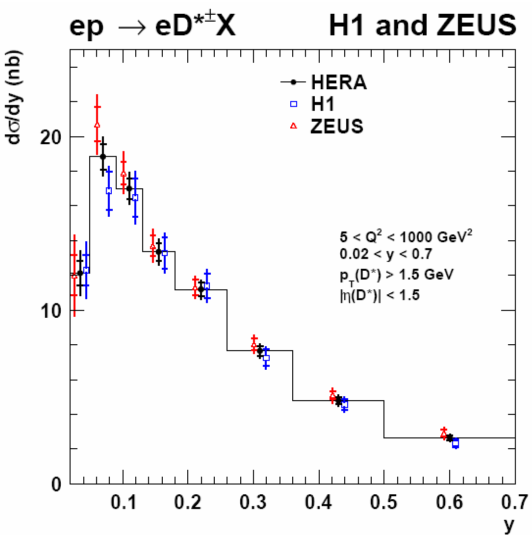
► significantly reduced experimental uncertainties due to :

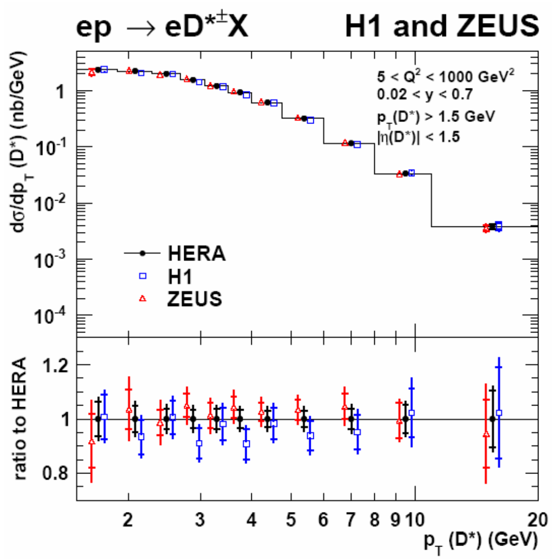
– doubling of statistics
– all correlations of systematic uncertainties taken into account

► negligible theoretical uncertainties [only little extrapolation → (0-10%) of total uncertainty]

arXiv: 1503.06042, to be published in JHEP

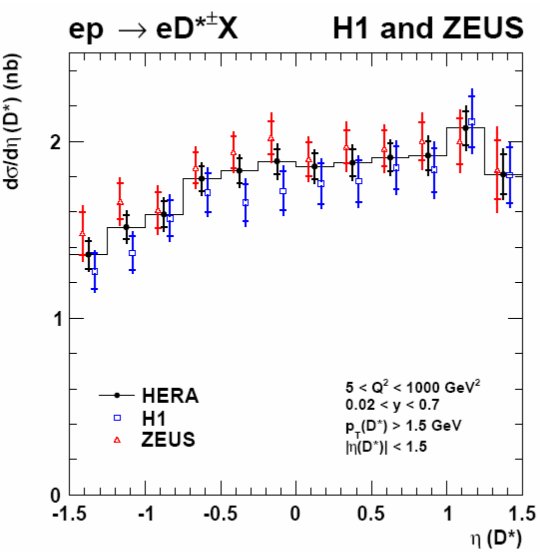
Combined $D^{*\pm}$ differential cross sections vs. y, $p_T(D^*)$, $\eta(D^*)$ and $z(D^*)$

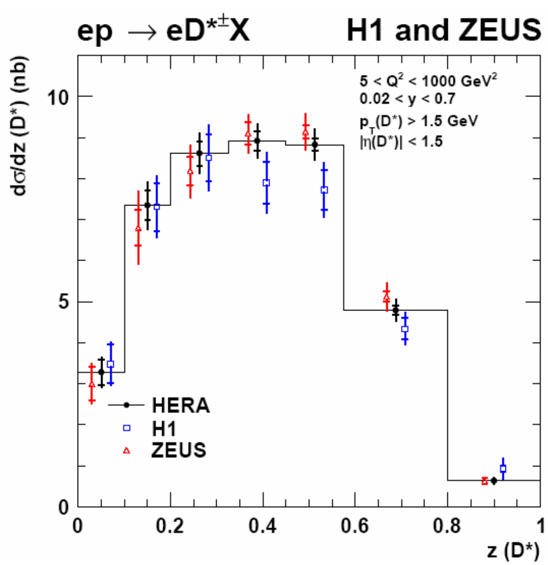




Combination of $D^{*\pm}$ cross sections separately for each variable

- **Combined data reach precision of ≈ 5% in large fraction of phase space**
- **Data consistent between H1 and ZEUS**





$p_T(D^*)$, $\eta(D^*)$ and $z(D^*)$ measured in LAB

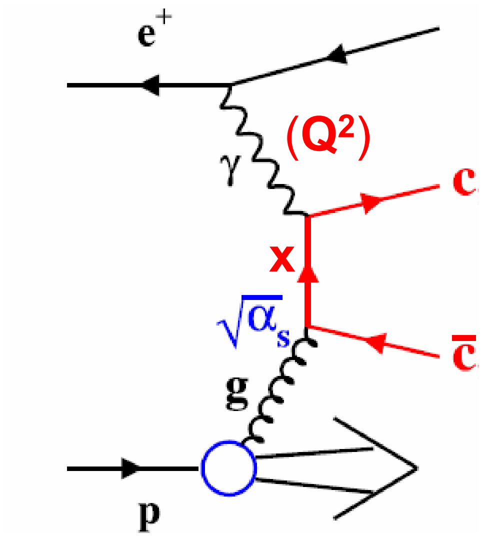
$Z(D^*) = (E(D^*) - p_z(D^*))/(2E_e y)$

arXiv: 1503.06042, to be published in JHEP

NLO QCD predictions – Fixed Flavour Number Scheme (FFNS)

- charm quark is massive at all scales ($Q^2 \approx m_c^2$), mass effects correctly included
- 3 light quark flavours (u, d, s) and g in the proton PDF, no charm in the proton
- heavy quarks produced perturbatively in hard scattering
- no resummation of large logs of Q^2/m_c^2, p_T/m_c , …

Full NLO ($O(\alpha_s^2)$) and partial NNLO ($O(\alpha_s^3)$) calculations of heavy-flavour production in DIS exist



leading order $O(\alpha_s)$ process

Charm production cross section in DIS at HERA best described by NNLO predictions in the massive FFNS scheme

(EPJ C73 (2013) 2311, combined $\sigma_{red}^{c\underline{c}}$, calculations of Alekhin, Blümlein and Moch)

NLO QCD predictions for $D^{*\pm}$ production

- HVQDIS program (B. W. Harris & J. Smith, PR D57 (1998) 2806)

  NLO FFNS predictions for differential x-sec for c-quarks converted to $D^{*\pm}$-meson cross sections using fragmentation function (FF) of Kartvelishvili et al.
  $ep \rightarrow e\, c\underline{c}\, X \rightarrow e\, D^*\, X$

Estimation of theoretical uncertainties :

- $\mu_r^2 = \mu_f^2 = Q^2 + 4m_c^2$, scales changed independently by factors 0.5 and 2
- the pole mass of the charm-quark $m_c = 1.50 \pm 0.15$ GeV
- HERAPDF1.0, FFNS
- $\alpha_s^{nf=3}(M_Z) = 0.105 \pm 0.002$ (corresponds to $\alpha_s^{nf=5}(M_Z) = 0.116 \pm 0.002$)
- uncertainties related to fragmentation:
  - ► fragmentation parameter $\alpha_K(D^*)$ in FF
  - ► $\hat{s}$: photon-parton CMS energy squared

    $\hat{s}_1 = 70 \pm 40$ GeV^2 , $\hat{s}_2 = 324$ GeV^2

$\hat{s}$ range	$\alpha_K(D^*)$
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4
$\hat{s} > \hat{s}_2$	2.67 ± 0.31

  - ► transverse fragmentation $f(k_T) = k_T \exp(-2k_T/\langle k_T\rangle)$; $\langle k_T\rangle = 0.35 \pm 0.15$ GeV
  - ► fragmentation fraction $f(c \rightarrow D^*) = 0.2287 \pm 0.0056$
- HVQDIS : estimation of small beauty contribution to the $D^{*\pm}$ signal ($ep \rightarrow e\, b\underline{b}\, X \rightarrow e\, D^*\, X$)

Customised NLO QCD predictions for $D^{*\pm}$ production

- Find parameters of the HVQDIS calculations providing reasonable description of all D*differential cross sections in shape and normalisation
- Theory uncertaint dominated by variations of scales μ_r and μ_f, c-quark pole mass and fragmentation model

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- ► reduce μ_r by factor 2 : $\mu_r^2 = Q^2 + 4m_c^2$, $\mu_r \rightarrow 0.5 \cdot \mu_r$ → increase of D* cross section
- ► reduce charm-quark pole mass : $m_c = 1.50$ GeV → $m_c = 1.40$ GeV → increase of D* cross section
- ► change parameter $\hat{s}_1$ in longitudinal Kartvelishvili FF

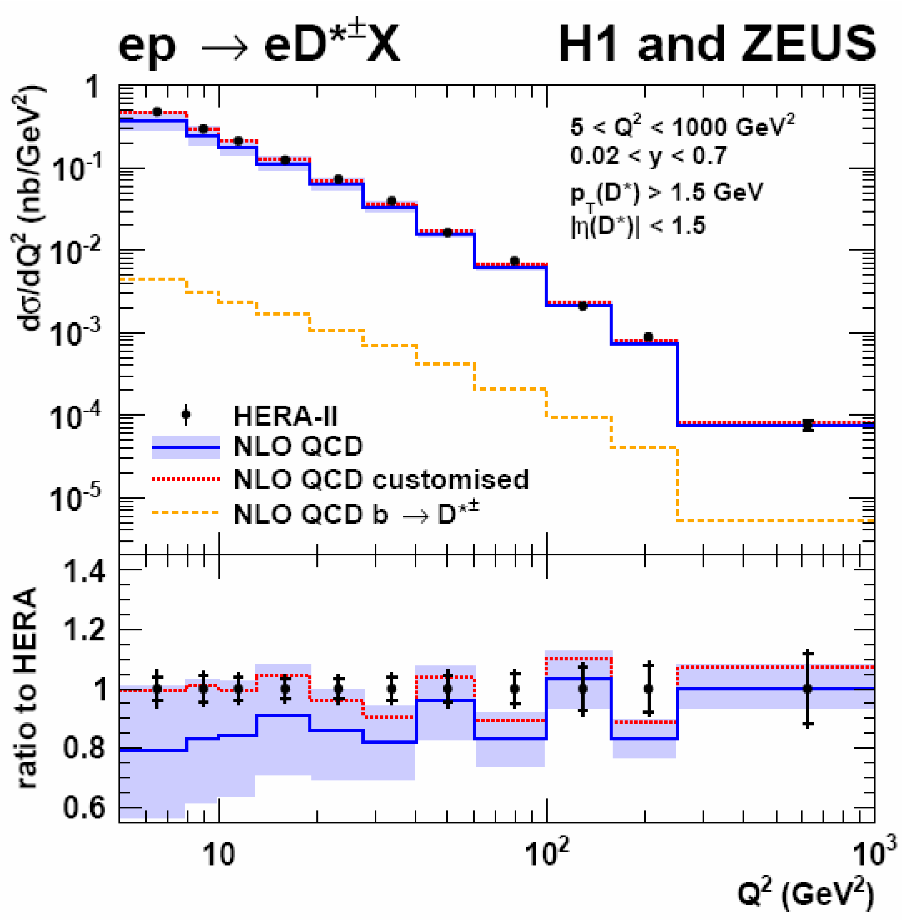
  $\hat{s}_1 = 70$ GeV² → $\hat{s}_1 = 30$ GeV² → soften fragmentation

$\hat{s}$ range	$\alpha_K(D^*)$
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4
$\hat{s} > \hat{s}_2$	2.67 ± 0.31

- ► all other parameters are left at their default values

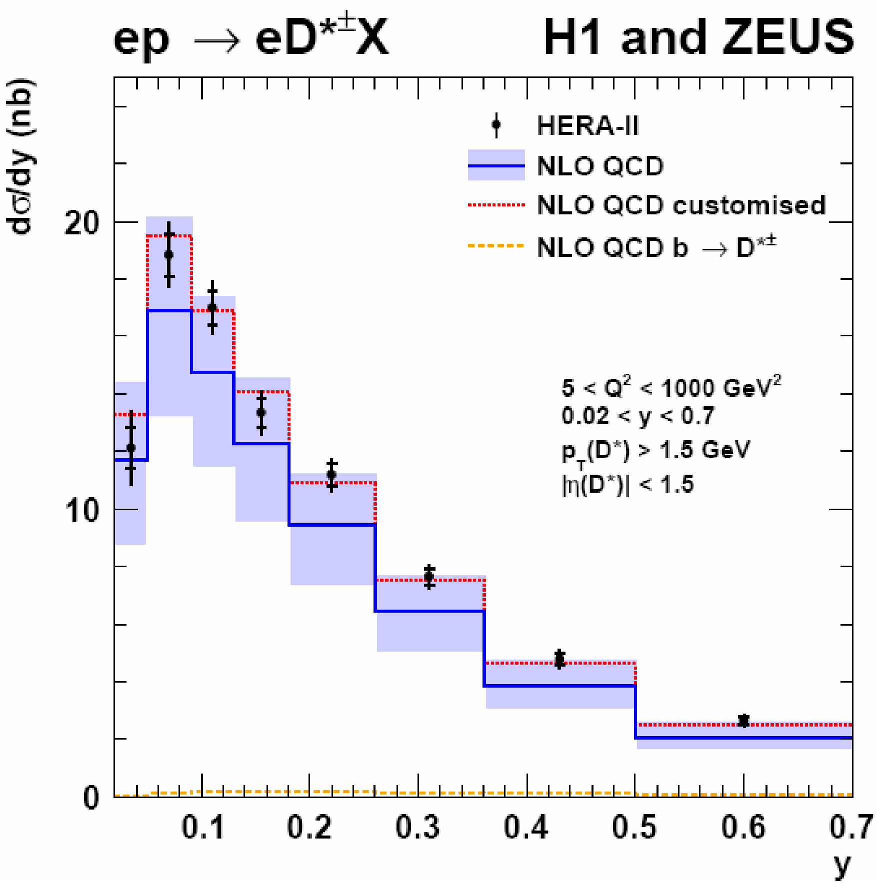
This adjustment is not a prediction but may give hints in which direction to develop theory

$d\sigma/dQ^2$ vs. NLO QCD prediction



- Data are more precise than theory predictions
  - data reach precision of ≈ 5%
  - theoretical uncertainties from (30- 40)% at low Q^2 to 10% at high Q^2
- NLO QCD predictions describe data reasonably within large uncertainties
- NLO QCD customised describe data very well
- Higher order calculations will reduce theory uncertainties

dσ/dy vs. NLO QCD prediction



- Data yield much higher precision than theory
  - precision of data ≈ 5%
  - typical theoretical uncertainty (10- 30)%
- NLO QCD predictions describe data reasonably within large uncertainties
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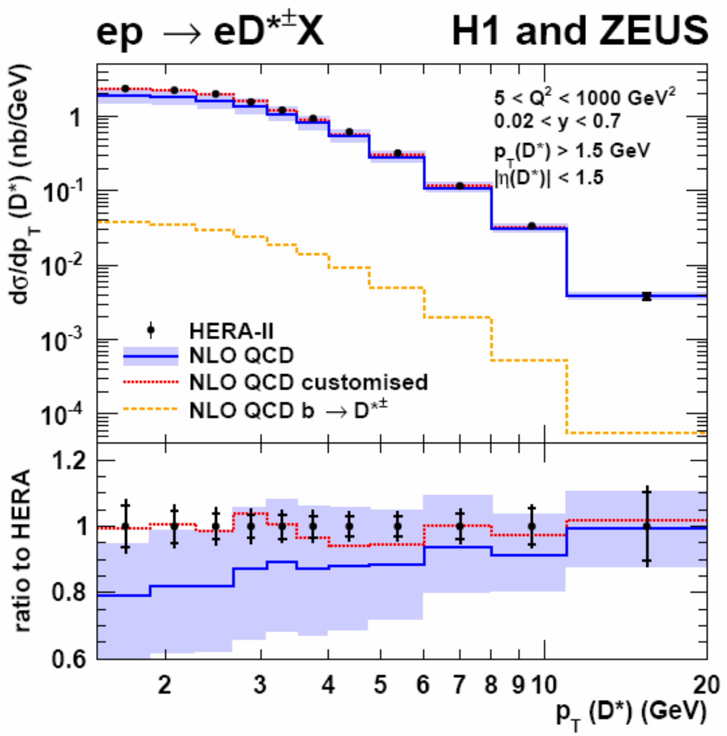
dσ/dp$_T$(D*) vs. NLO QCD prediction



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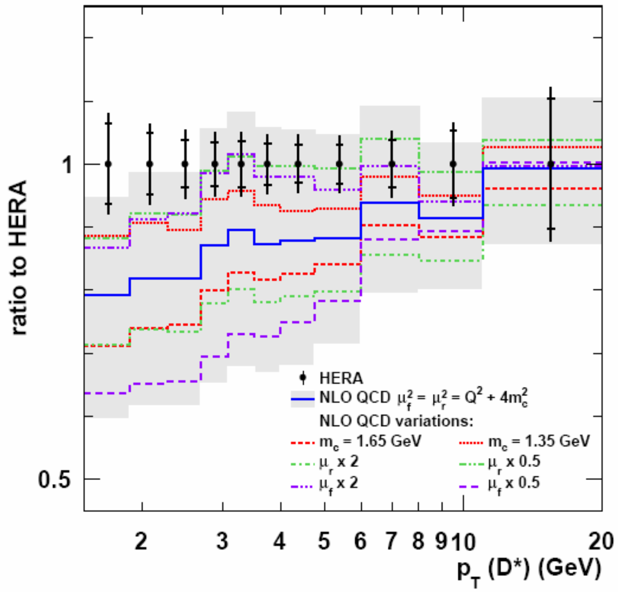
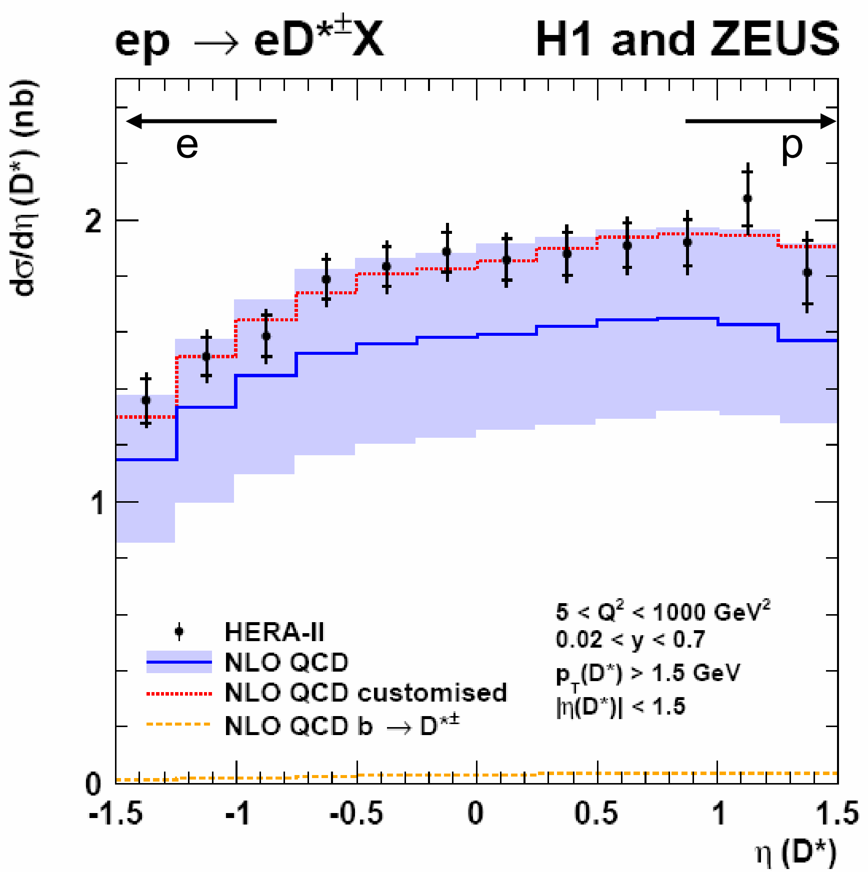


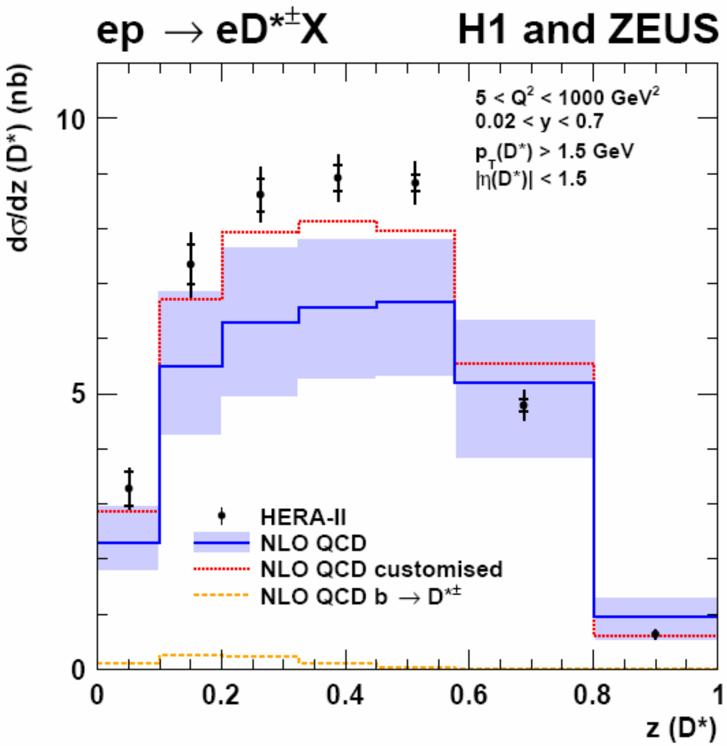
NLO predictions (ratio to data) with different variations of parameters → preference for a reduced renormalisation scale μ_r

dσ/η(D*) vs. NLO QCD prediction



- **Data yield much higher precision than theory**
  - **precision of data ≈ 5%**
  - **typical theoretical uncertainty (10- 30)%**
- **NLO QCD predictions describe data reasonably within large uncertainties**
- **NLO QCD customised describe data very well**

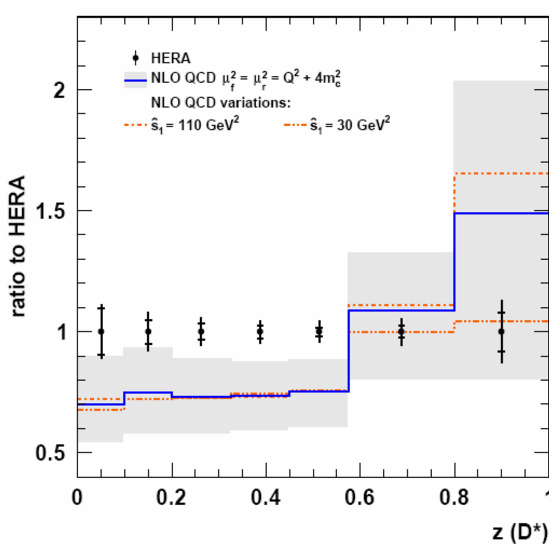
dσ/z(D*) vs. NLO QCD prediction

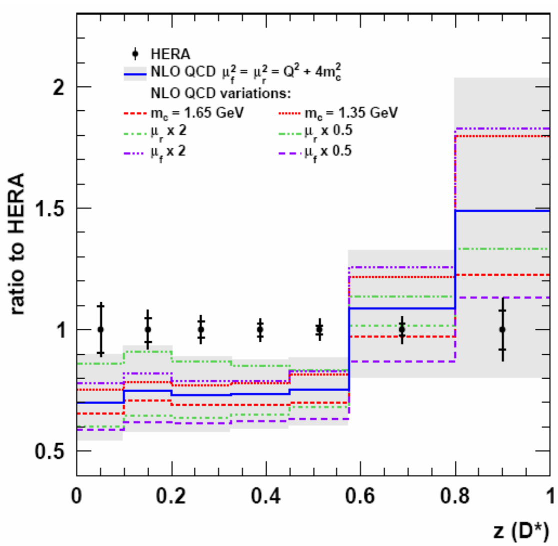


- Data yield much higher precision than theory
- NLO QCD predictions harder than data
- NLO QCD customised describe data better but not perfect
- NNLO calculations and improved c-quark fragmentation models may help

$Z(D^*) = (E(D^*) - p_z(D^*)) / (2E_e y)$

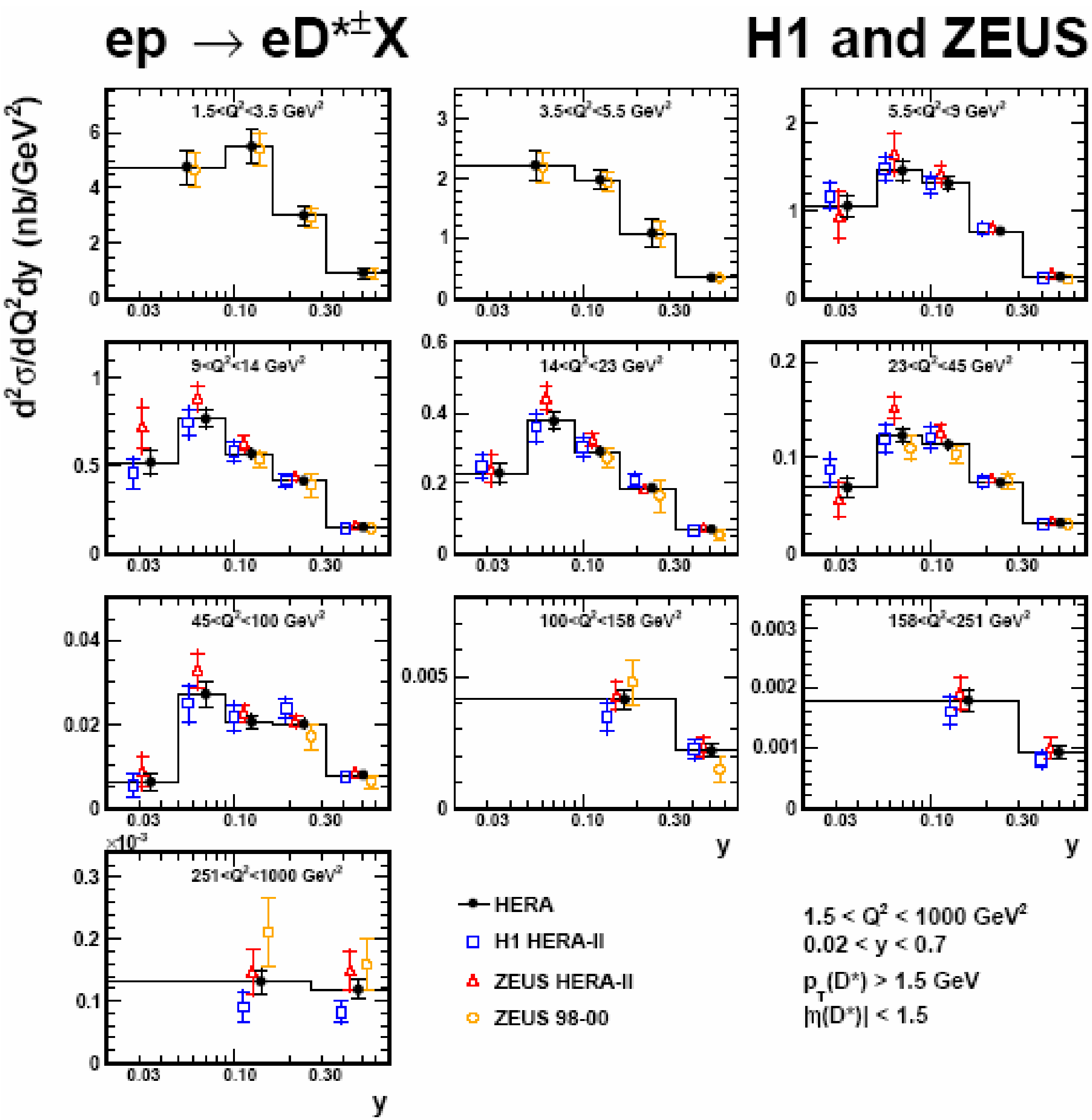
Ratio of NLO predictions to data with different variation of parameters





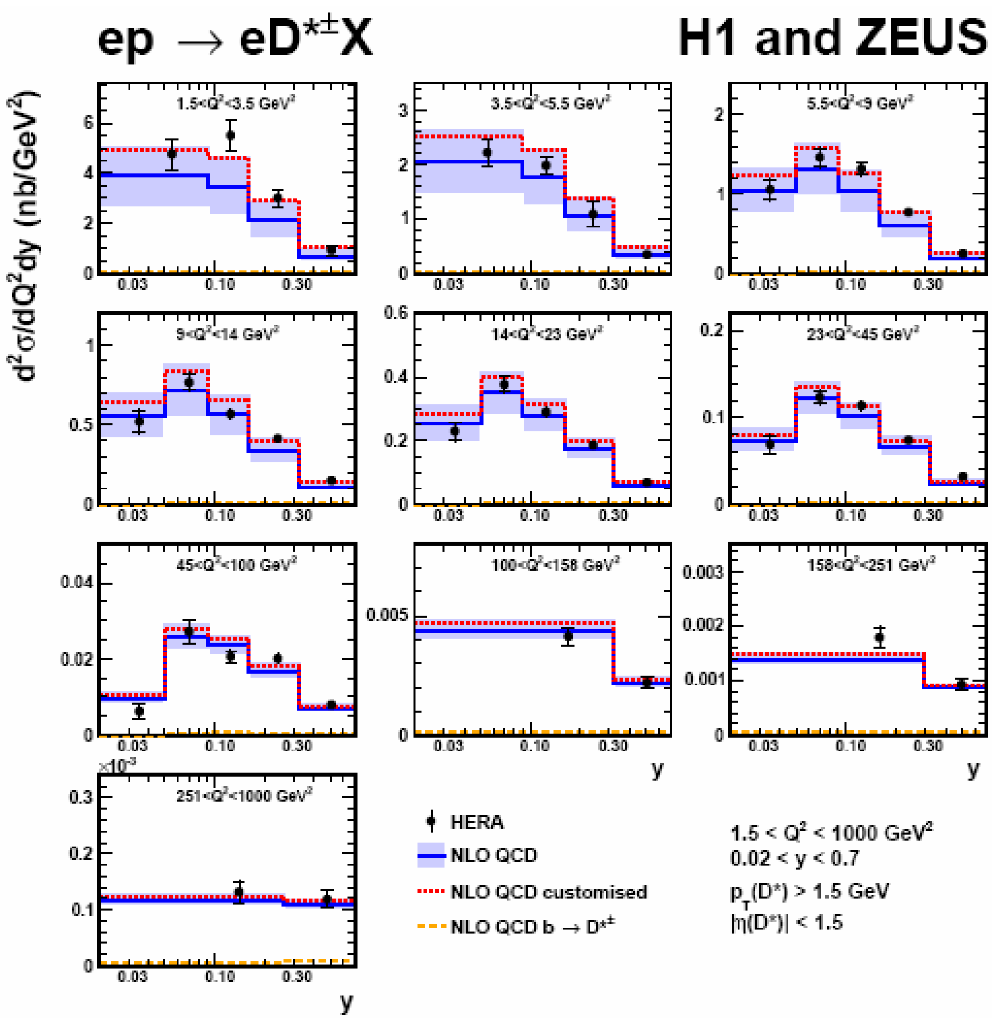
- preference for a reduced renormalisation scale
- sensitivity to fragmentation parameters

Combined double - differential D* cross sections $d^2\sigma/dQ^2dy$



- **Combined data reach precision of ≈ (5-10)% in large fraction of phase space**
- **Data consistent between H1 and ZEUS**

$d^2\sigma/dQ^2dy$ vs. NLO QCD predictions



- **Data are more precise than theory predictions**
  - data reach precision of ≈ (5-10)%
  - theoretical uncertainties from 30% at low Q^2 to 10% at high Q^2
- **NLO QCD predictions describe data well within large uncertainties**
- **NLO QCD customised describe data well**

Summary

- **Precise differential D* mesurements in DIS by the H1 and ZEUS experiments combined:**
  - **distributions of inclusive DIS variables and kinematic variables of D*-mesons**
  - **significantly reduced overall uncertainties**
  - **combination in the visible phase space**
    → negligible theoretical uncertainties

- **Massive-scheme NLO QCD predictions describe data reasonably within large theory uncertainties**

- **Higher order QCD corrections and improved heavy-quark fragmentation models would be desirable to exploit the precision of the HERA data**

Backup slides

Theory of heavy quark production

Massive Fixed Flavour Number Scheme (FFNS)

- charm quark is massive at all scales ($Q^2 \approx m_c^2$), mass effects correctly included
- 3 light quark flavours (u, d, s) and g in the proton PDF, no charm in the proton
- heavy quarks produced perturbatively in hard scattering
- no resummation of large logs of Q^2/m_c^2, p_T/m_c , …

Zero Mass Variable Flavour Number Scheme (ZM-VFNS)

- $m_c = 0$ in matrix elements and kinematics calculations
- flavour threshold $Q^2 \sim m_c^2$:

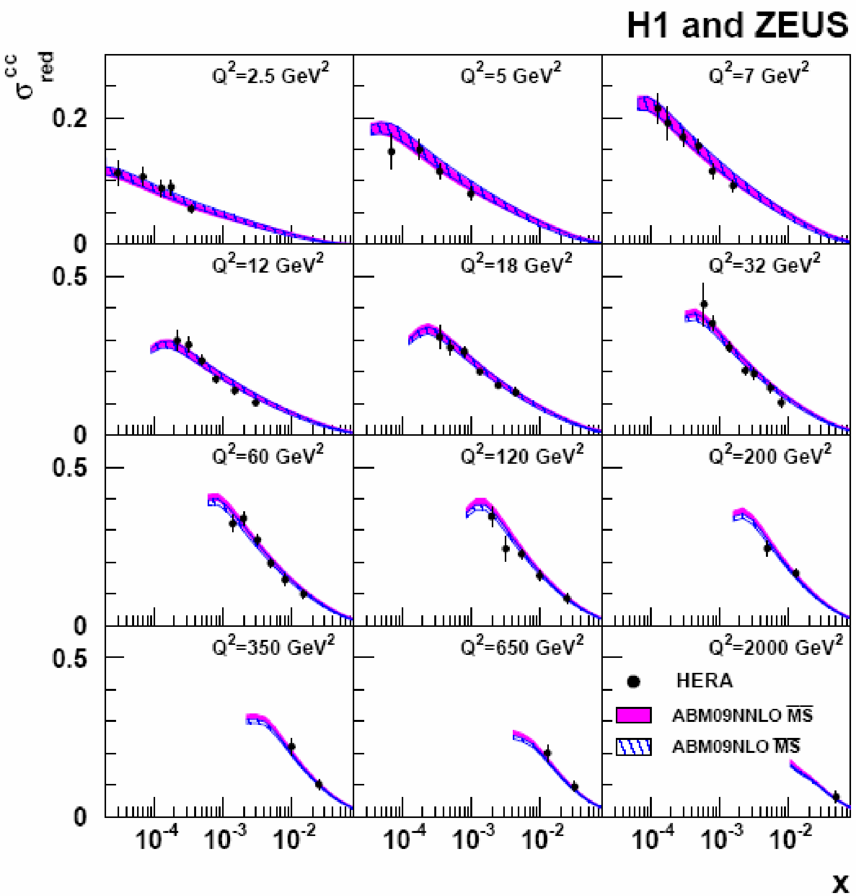
  $Q^2 < m_c^2 \rightarrow$ charm production cross section vanishes, 3 light flavours in the proton PDF

  $Q^2 > m_c^2 \rightarrow$ charm as massless parton in the proton in addition to u, d, s (heavy-quark PDF)
- resummation of large logs of Q^2/m_c^2

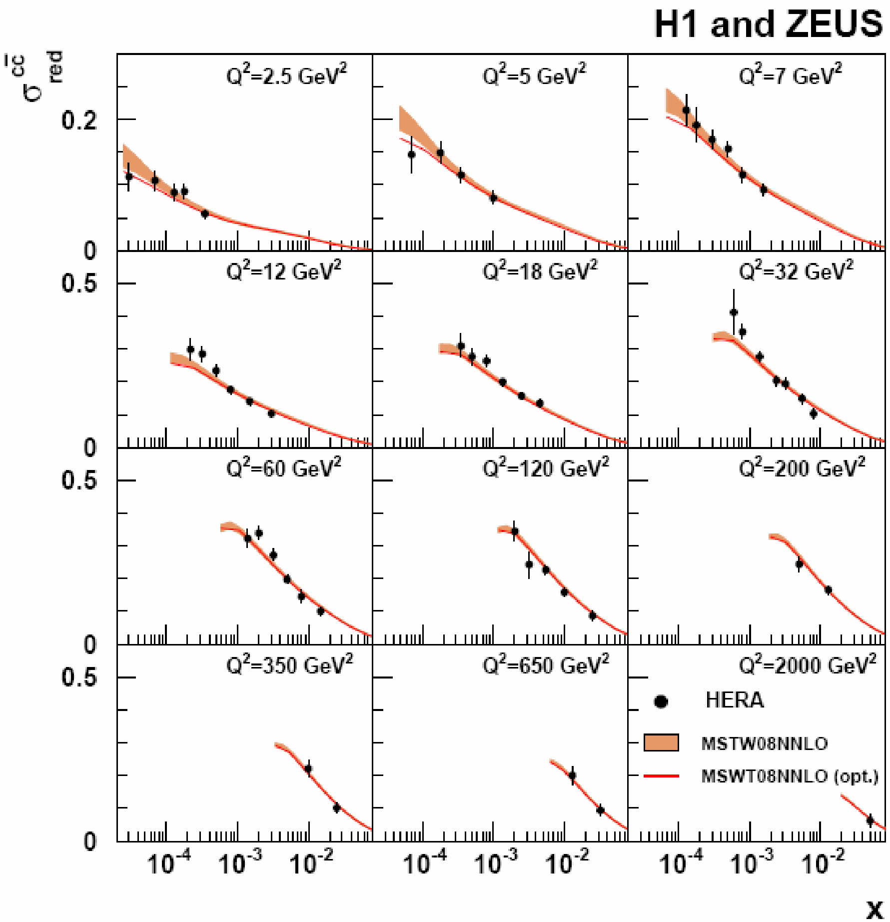
General Mass Variable Flavour Number Scheme (GM-VFNS)

- low Q^2 ($Q^2 \leq m_c^2$) : charm production in FFNS approach (mass efects largest)
- high Q^2 ($Q^2 > m_c^2$):charm production in ZM-VFNS (important resummation effects)
- at intermediate scales interpolation between 2 schemes
- used in PDF fits

HERA charm data combination in DIS, EPJ C73 (2013) 2311



σ_{red}^{cc} vs. NLO and NNLO FFNS predictions of the ABM group (Alekhin, Blümlein and Moch)



σ_{red}^{cc} vs. NNLO GM-VFNS predictions of the MSTW group (Martin, Stirling, Thorne and Watt)

NLO (NNLO) FFNS predictions give a good description of the HERA charm data.

NNLO GM-VFNS predictions also provide a good description of charm reduced cross sections.