Heavy flavour production at HERA

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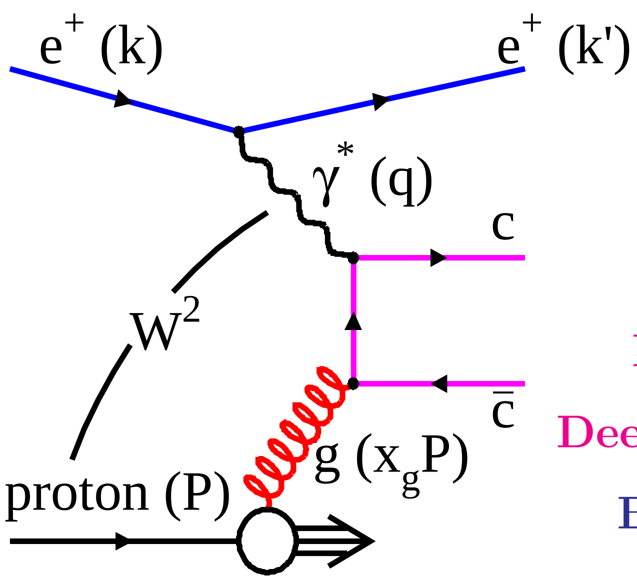
Introduction and experimental set-up



$e^{\pm}(k) + p(P) \rightarrow e^{\pm}(k') + X;$ $\quad s = (P + k)^2$

Photon virtuality: $Q^2 = -q^2 = -(k - k')^2$

Bjorken x: $x = \frac{Q^2}{2q \cdot P}$; $\quad$ Inelasticity: $y = \frac{q \cdot P}{k \cdot P}$

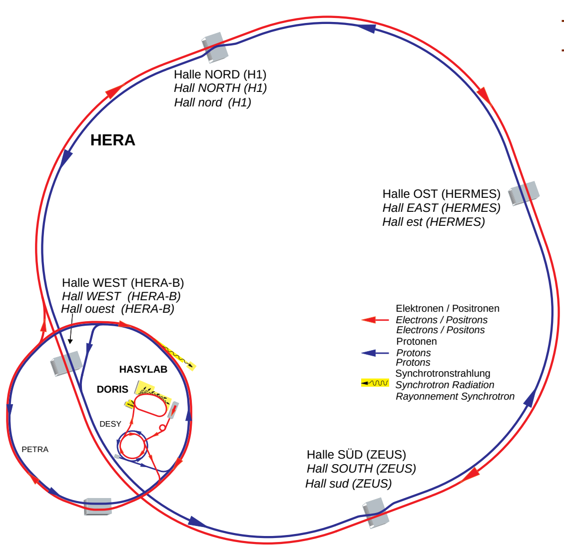
$Q^2 = sxy$; $\quad$ $W = \gamma^* p$ CM energy

Photoproduction (PHP): $Q^2 \simeq 0\, GeV^2$ ($e^{\pm}$ undetected)

Deep Inelastic Scattering (DIS): $Q^2 > 1$ *or* $5\, GeV^2$ ($e^{\pm}$ detected)

BGF: Dominant process for c,b production in DIS

Direct probe of gluon density in proton; Sensitivity to c,b quark masses



HERA: unique $e^{\pm}p$ collider with $E(e^{\pm}, p) = 27.6, 820/920$ GeV

2 main experiments: H1, ZEUS

2 run periods:	HERA I,	HERA II
	1995-2000	2003-2007
$\sqrt{s}$	318 (300)	318 GeV
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	126	$373\, pb^{-1}$

HERA II data taken $\approx$ half e^+p and half e^-p

In 2007 two short runs at lower p energies: $E_p = 575$ GeV; $\quad E_p = 460$ GeV

Theory of heavy quark production

Several QCD NLO schemes for heavy quark (Q=c or b) production:

1)Massive scheme: $Q^2 \approx m_Q^2$ Fixed flavour number scheme (FFNS)

- 3 active flavours in proton; Q-quark not considered as parton in p
- c or b produced perturbatively in hard scattering (see p.2)
- Mass effects correctly included
- Spoiled by large logs of $Q^2/m_Q^2, p_t/m_Q$...

2)Massless scheme: $Q^2 >> m_Q^2$

Zero-mass variable flavour number scheme (ZM-VFNS)

- c or b treated as massless parton
- Resummation of large logarithms of Q^2/m_Q^2
- $\Rightarrow$ c or b density added as 4th flavour like the light quarks

At intermediate Q^2 the 2 schemes should be merged

3) General-mass variable flavour number scheme (GM-VFNS)

- Equivalent to FFNS for $Q^2 \leq m_Q^2$ and to ZM-VFNS for $Q^2 > m_Q^2$
- Interpolation in between (various schemes interpolate differently)
- Used in parton density function (PDF) fits (useful at LHC)

$D^{*\pm}$ photoproduction at 3 CM energies

Clear $D^{*\pm}$ signals seen in $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$ distributions at 3 different CM energies: $\sqrt{s} = 318, 251, 225$ GeV in the kinematic region: $1.9 < p_T^{D^*} < 20$ GeV ; $|\eta^{D^*}| < 1.6$; $Q^2 < 1$ GeV^2 ; $0.167 < y < 0.802$

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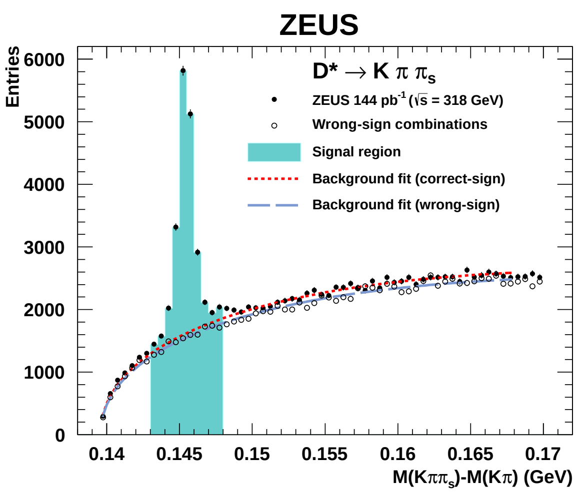
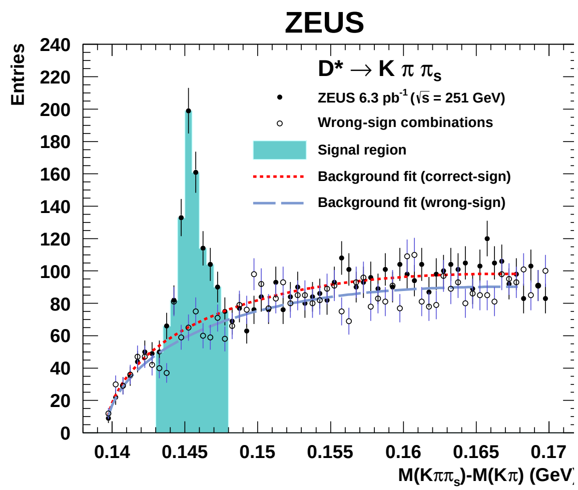
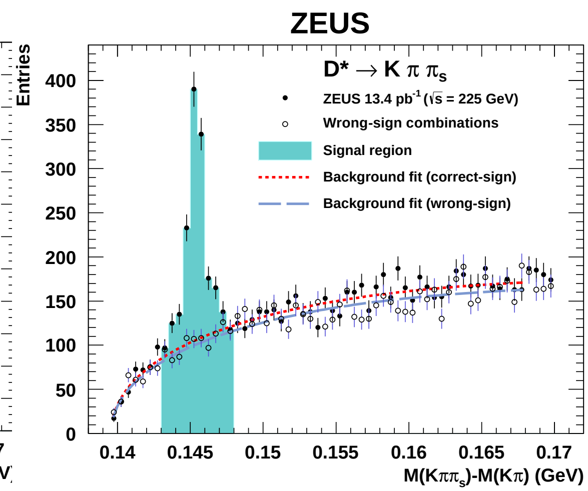
HER: $\mathcal{L} = 144$ pb^{-1} MER: $\mathcal{L} = 6.3$ pb^{-1} LER: $\mathcal{L} = 13.4$ pb^{-1}







$N(D^*) = 12256 \pm 191$ $N(D^*) = 417 \pm 37$ $N(D^*) = 859 \pm 49$

Background estimated by fitting simultaneously correct- and wrong-sign distributions in the range $\Delta M < 0.168$ GeV

$D^{*\pm}$ photoproduction at 3 CM energies

Visible D^* PHP cross sections obtained from: $\sigma_{vis}(D^*) = \frac{N^{data}(D^*)}{A \cdot BR \cdot \mathcal{L}}$

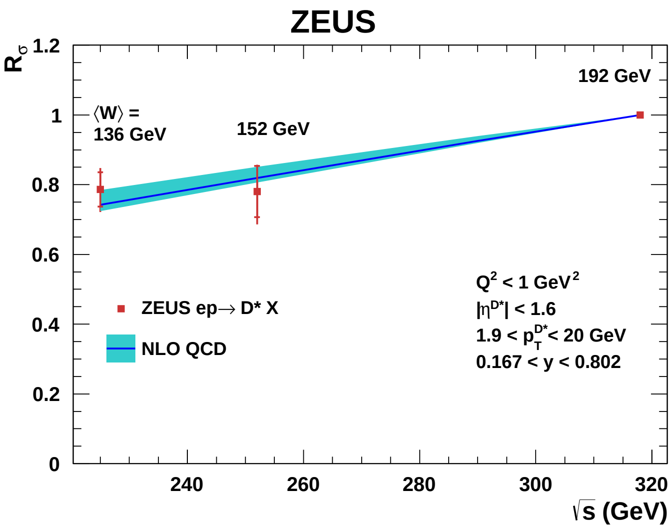
$BR = B(D^* \to D^0\pi) \cdot B(D^0 \to K\pi) = 0.0263$; A = acceptance

Ratio of visible cross sections: $R_\sigma = \frac{\sigma_i}{\sigma_{HER}}; i = HER, MER, LER$

yields higher precision of E-dependence of cross section

since some syst. uncertainties in data and theory cancel

Data compared to FFNS NLO predictions:



Total syst. uncertainty ≈ 5% in data

few % in theory

$< W > =$ mean W from generated MC

MER/LER cross sections similar

HER cross section higher

Cross sections increase with increasing *ep* CM energy

This increase is predicted by NLO QCD

Charm fragmentation fractions in PHP

Fragmentation fractions of c-quarks into charm hadrons:

Probability of c quark to hadronise into a given charm hadron

$f(c \rightarrow charm\ hadron) = \sigma(charm\ hadron)/\sigma(total\ charm\ production)$

Needed to go from partonic QCD to hadronic cross sections

No QCD predictions; crucial to compare pQCD with measurements

Are they the same for c-quarks produced in e^+e^-, ep, pp collisions ?

Test fragmentation universality by measuring all of them

Measurements performed in PHP regime: $Q^2 < 1$ GeV^2

Charm hadrons reconstructed in the range:

$p_T > 3.8$ GeV, $|\eta| < 1.6$, $130 < W < 300$ GeV

Charm hadrons measured: $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$

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

$D_s^+ \rightarrow \phi\pi^+$, $\Lambda_c^+ \rightarrow K^-p\pi^+$

$$\sigma_{tot} = \sigma^{eq}(D^0) + \sigma^{eq}(D^+) + \sigma(D_s^+) + 1.14\ \sigma(\Lambda_c^+)$$

Full HERA II data: 372 pb^{-1}

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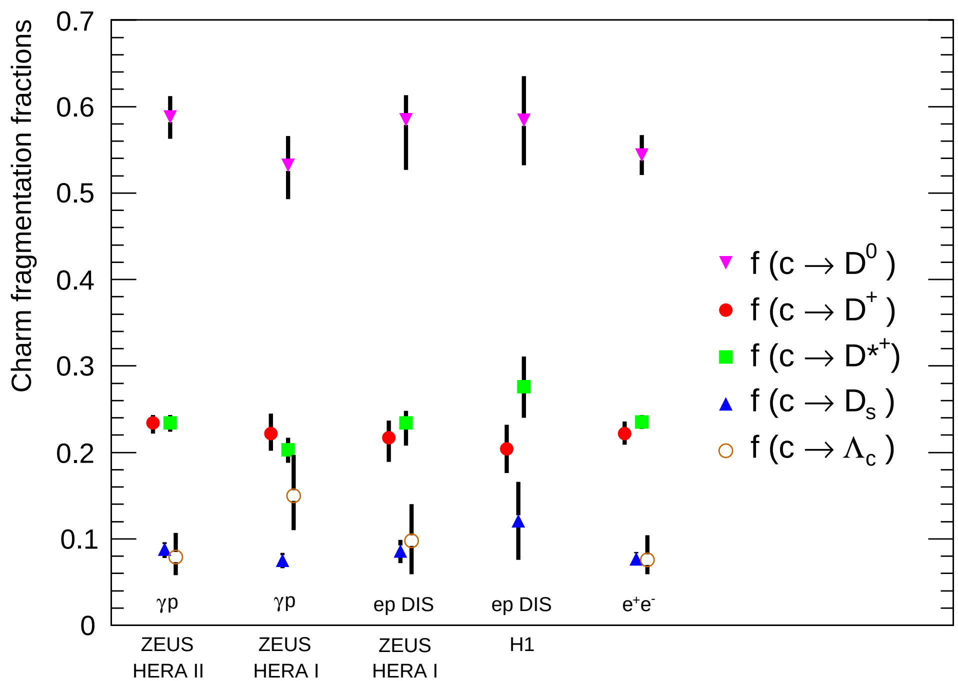
Charm fragmentation fractions in PHP

Silicon-strip detector used for charm vertices

⇒ Clear charm hadron signals for all channals



Charm fragmentation fractions:

Results (left column) in good agreement with previous results:

ZEUS PHP, ZEUS DIS, H1 DIS, $e^- e^-$

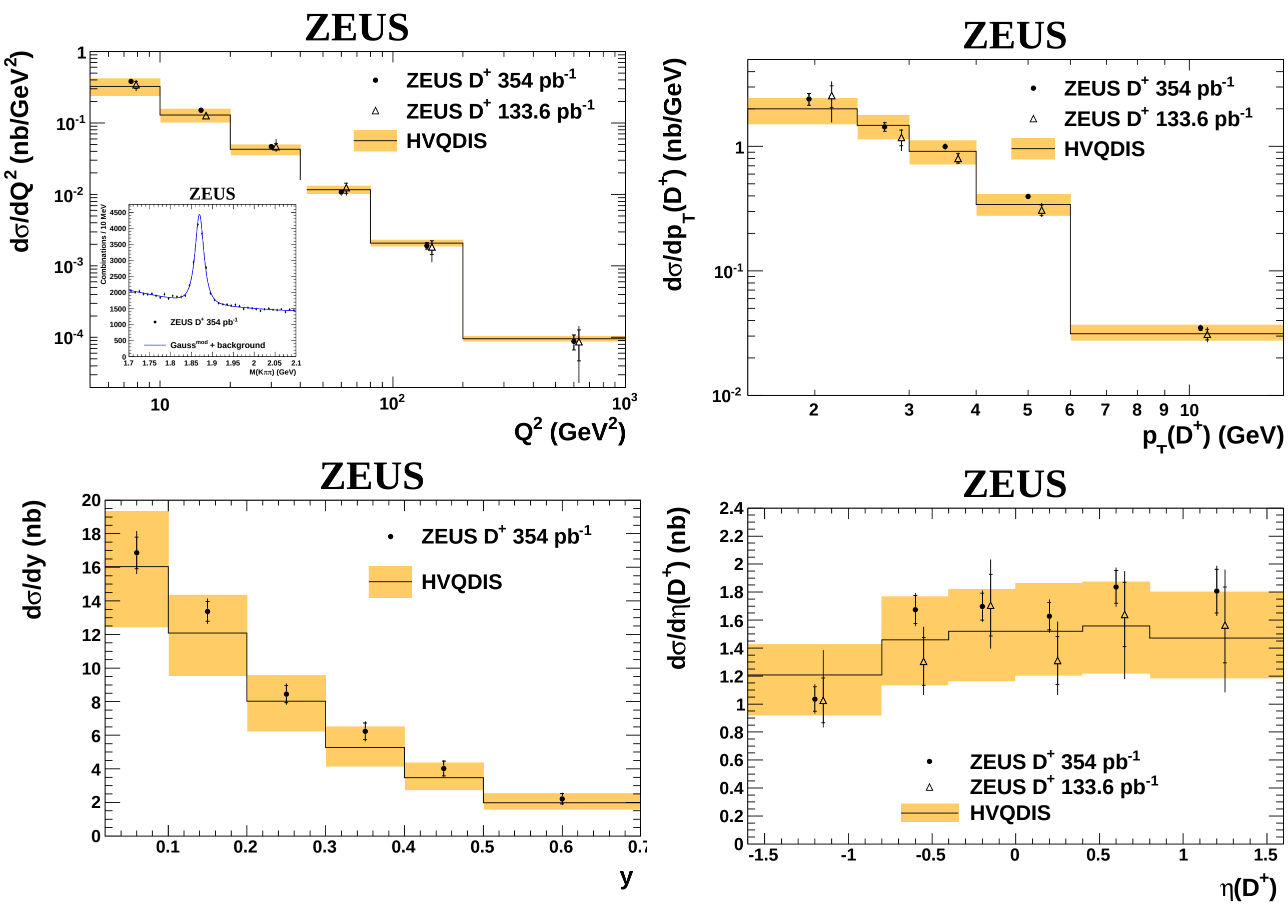
Precision of charm f.f. competitive with combined e^+e^- LEP results

Fragmentation fractions of c-quarks independent of production

Support hypothesis of universality of heavy-quark fragmentation

Universality supported also by new LHC pp data (ALICE + LHCb)

$D^{\pm}$ production in DIS



Full HERA II data: 354 pb^{-1}

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Clean D^+ signal

$N(D^+) = 8356 \pm 198$

D^+ differential cross sections w.r.t $Q^2, y, p_T(D^+), \eta(D^+)$ in kinematic region

$5 < Q^2 < 1000$ GeV^2,

$1.5 < p_T(D^+) < 15$ GeV,

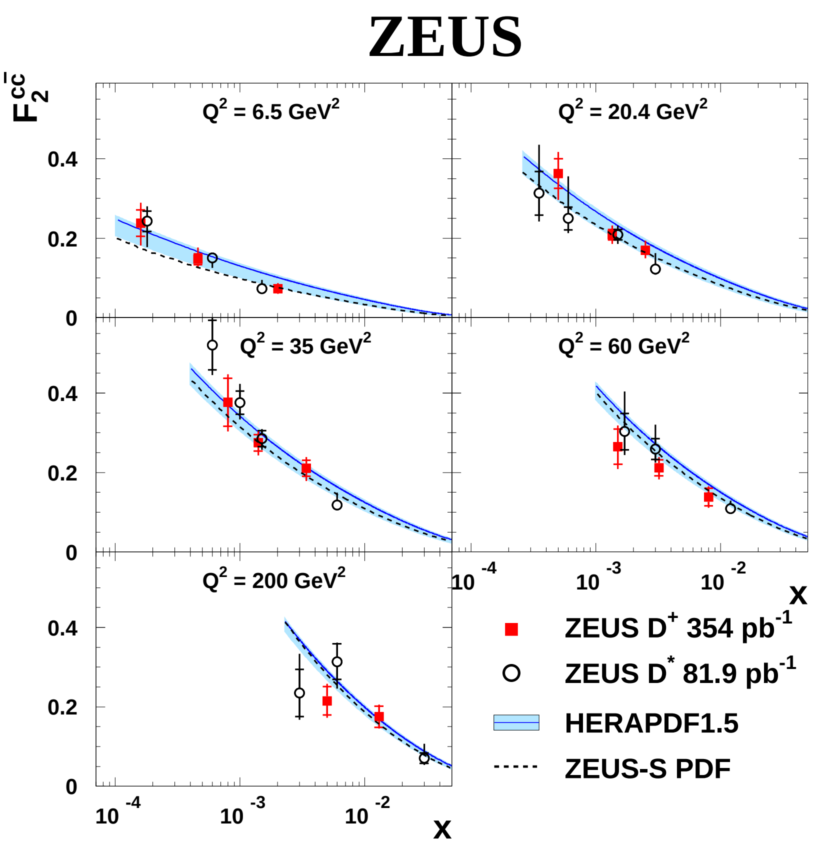
$|\eta(D^+)| < 1.6$,

$0.02 < y < 0.7$

NLO QCD predictions based on FFNS describe data well up to $Q^2 \approx 1000$ GeV^2

Similar agreement for double differential cross sections $d\sigma/dy$ for different Q^2 ranges

$D^{\pm}$ production in DIS



Charm contribution to proton structure function:

Express double differential cross section as:

$$\frac{d^2\sigma^{c\bar{c}}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^{c\bar{c}} - y^2 F_L^{c\bar{c}}]$$

$F_2^{c\bar{c}}, F_L^{c\bar{c}}$ are charm contributions to proton structure functions F_2 and F_L

$d\sigma/dy$ for different Q^2 bins used to extract $F_2^{c\bar{c}}$ at reference points x_i, Q_i^2 for each bin i using

$$F_{2,meas}^{c\bar{c}}(x_i, Q_i^2) = \sigma_{i,meas}\frac{F_{2,theo}^{c\bar{c}}(x_i,Q_i^2)}{\sigma_{i,theo}}$$

$F_{2,theo}$ and $\sigma_{i,theo}$ calculated at NLO in FFNS with HVQDIS program

$D^{\pm}$ results compared to previous ZEUS D^* results and to predictions of GM-VFNS based on HERAPDF1.5 parton densities and of FFNS based on ZEUS-S PDF

HERAPDF1.5 uses HERA *ep* data to provide NLO predictions compatible with other PDF groups

The NLO calculations describe new precise data well

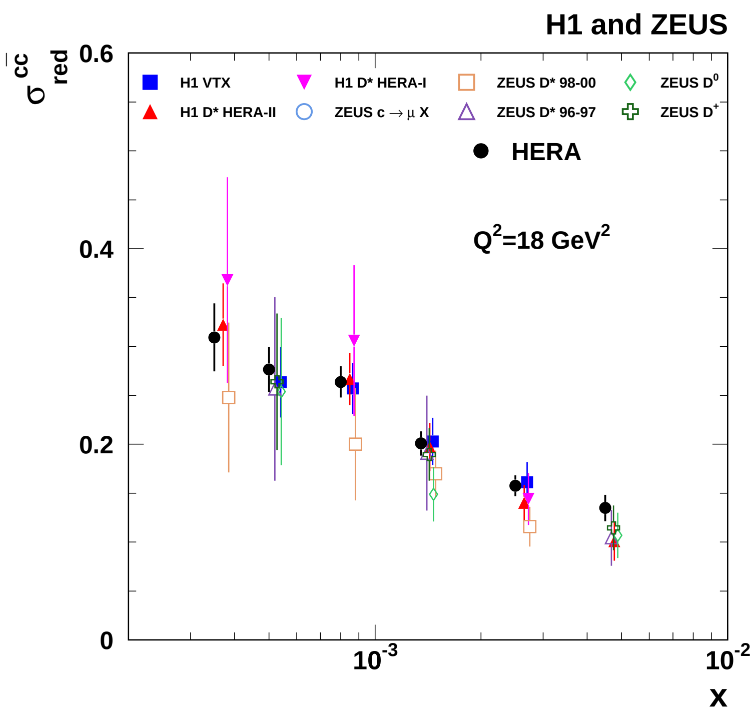
HERA charm data combination in DIS

Combined 9 data sets of D^*, D^+, D^0, μ and liftime tag data
with 155 H1 and ZEUS cross section measurements
from various HERA I and HERA II analyses EPJ C73 (2013) 2311

Charm reduced cross section, $\sigma^{c\bar{c}}_{red}$, obtained in kinematic range:

$$2.5 < Q^2 < 2000 \text{ GeV}^2;\ 3 \cdot 10^{-5} < x < 5 \cdot 10^{-2}$$

$$\frac{d^2\sigma^{c\bar{c}}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1 + (1 - y)^2)\sigma^{c\bar{c}}_{red}]$$



Reduced cross sections $\sigma^{c\bar{c}}_{red}$
as function of x for fixed Q^2 values:

Example for $Q^2 = 18$ GeV^2

Combined results - filled circles

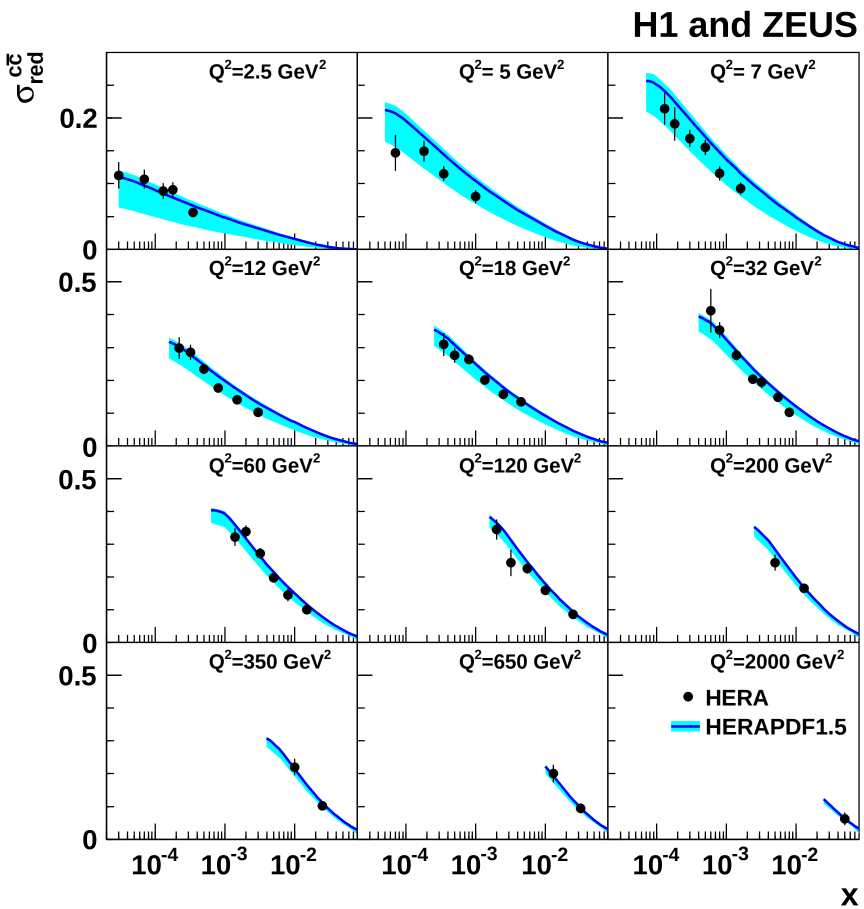
Correlated systematics fully taken into account

Combined results uncertainty ≈ factor 2
better than each most precise data set
in the combination

HERA charm data combination in DIS

How well does the mixed massive-massless scheme GM-VFNS work?

Reduced cross sections $\sigma_{red}^{c\bar{c}}$ as function of x for fixed Q^2 values



Combined inclusive DIS data (HERA I+II) compared to NLO predictions based on HERAPDF1.5 extracted in RT standard scheme

Lines are predictions with $M_c = 1.4$ GeV

M_c = effective (not physical) mass parameter in GM-VFNS

Large theory uncertainty dominated by M_c variation

Within uncertainties NLO GM-VFNS describe data well

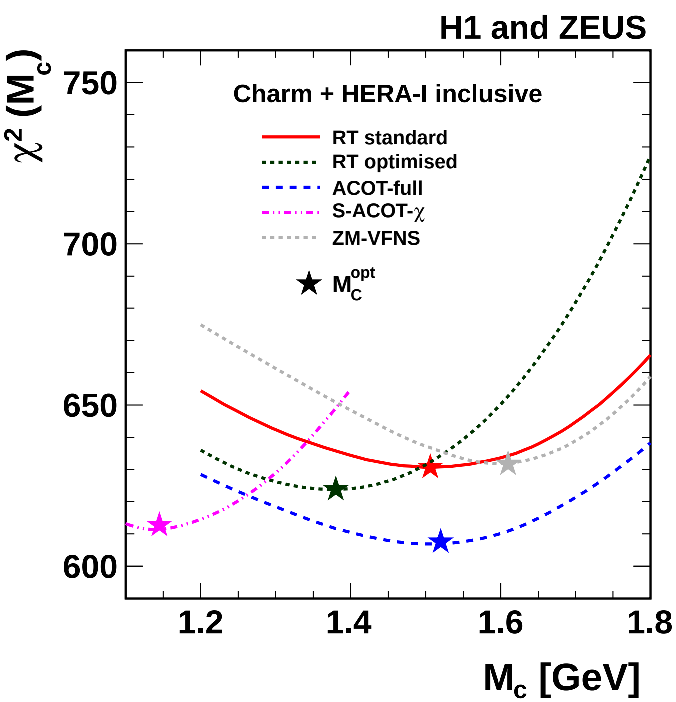
HERA charm data combination in DIS

Combined NLO analysis with $\sigma_{red}^{c\bar{c}}$ and inclusive DIS cross sections

in kinematic range: $W > 15$ GeV, $x < 0.65$, $Q^2 > 3.5$ GeV^2

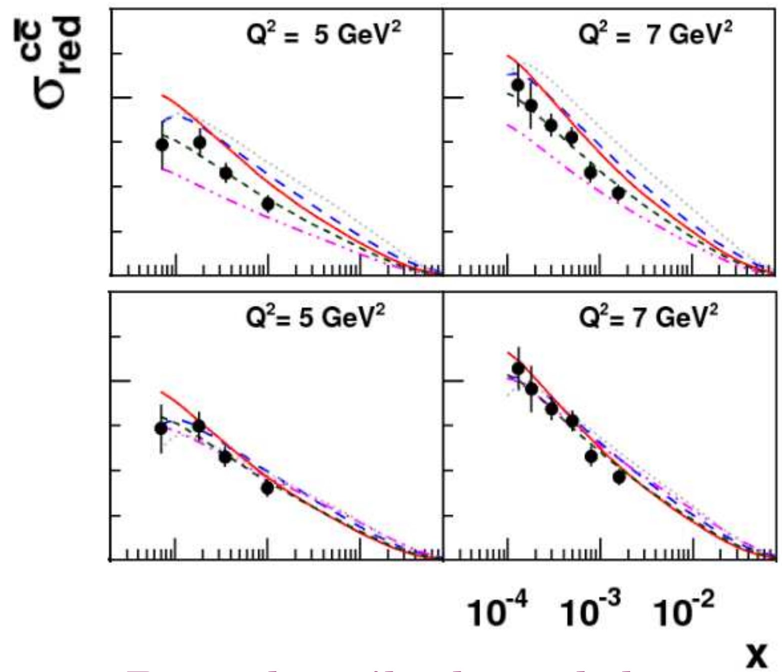
For each HFL scheme, PDF fits performed with $1.2 < M_c < 1.8$ GeV

χ^2 values vs. M_c from PDF fits for various HFL schemes



Minimal χ^2 values observed for each scheme at different M_c^{opt}

VFNS predictions for $\sigma_{red}^{c\bar{c}}$ with $M_c = 1.4$ GeV (up) and $M_c = M_c^{opt}$ (down)



Data described much better with M_c^{opt} than with fixed M_c

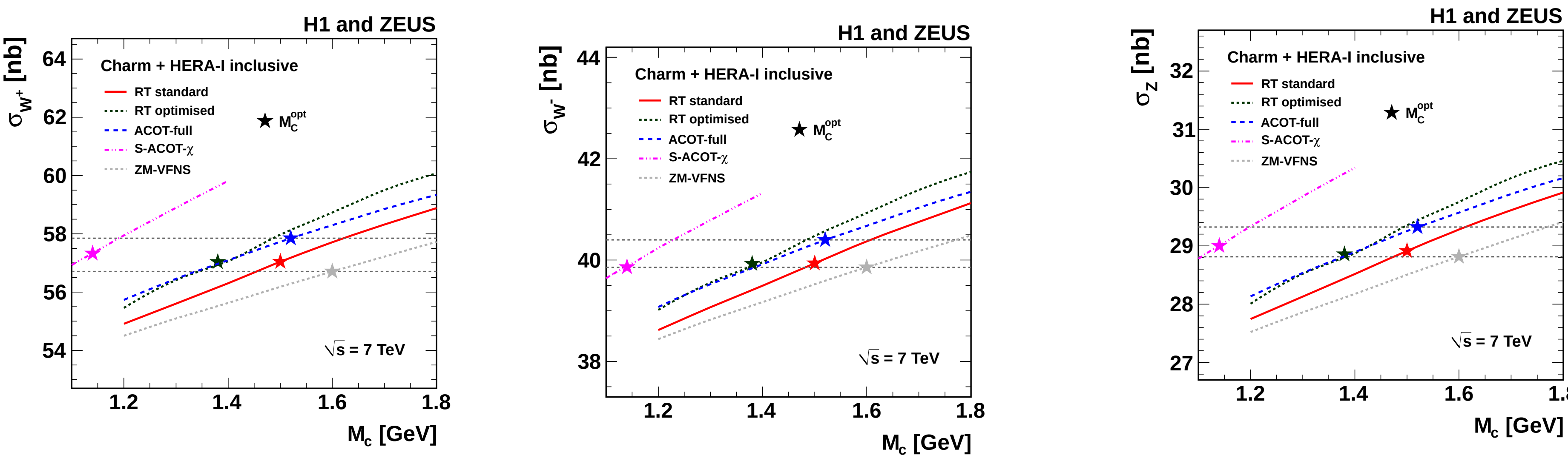
Predictions of all schemes are very similar for $Q^2 \geq 5$ GeV^2

HERA charm data combination in DIS

Implications on NLO predictions for W, Z production at LHC

W^+, W^-, Z^0 cross section predictions for LHC at $\sqrt{s} = 7$ TeV

Calculated for each scheme for $1.2 < M_c < 1.8$ GeV in 0.1 GeV steps



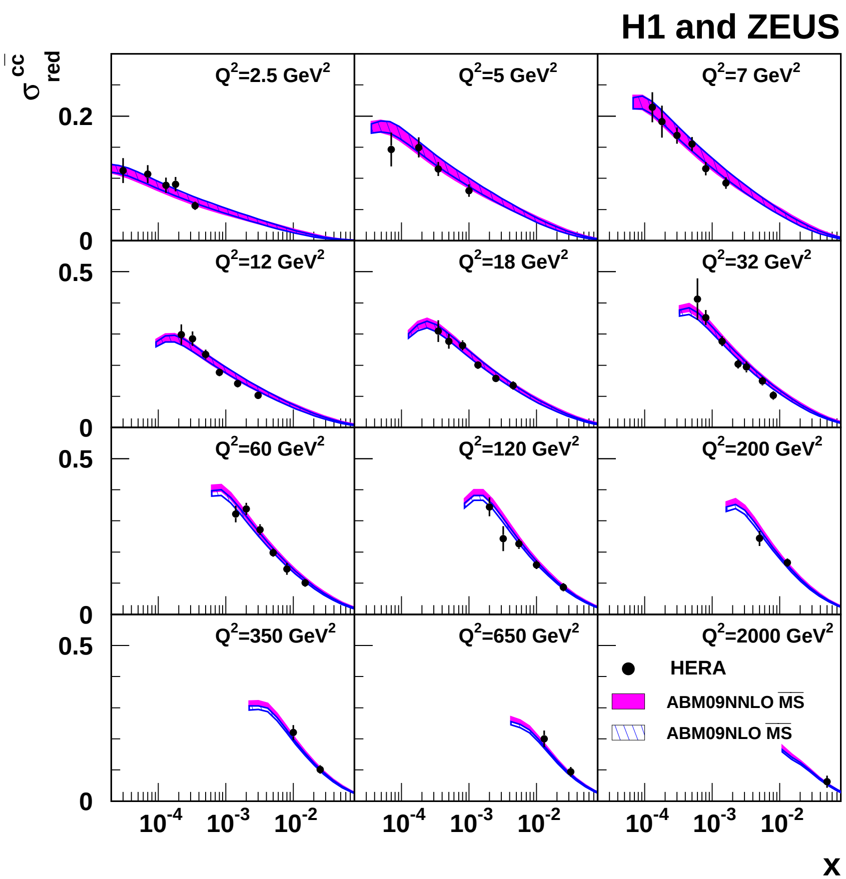
All cross sections rise monotonically with M_c

Significant spread of $\approx 6\%$ between predictions for any fixed M_c

Reduces to $\approx 1.4 - 2\%$ when taking M_c^{opt} for each scheme

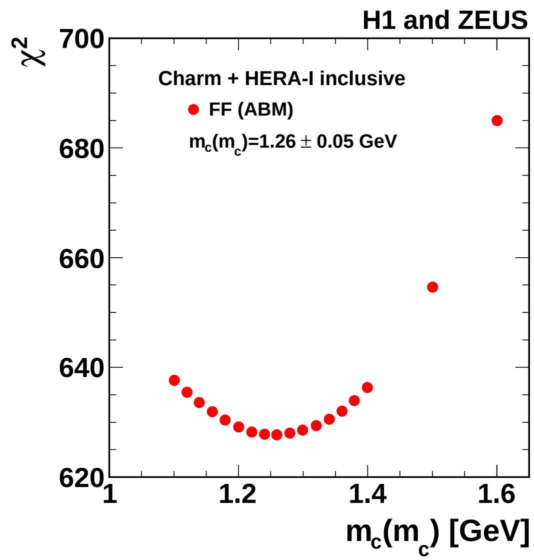
HERA charm data combination in DIS

Combined charm data vs. ABM FFNS prediction: Uses instead of pole mass the running mass definition in $\overline{MS}$ scheme



$m_c(m_c)$ extraction in $\overline{MS}$ scheme:

Same minimisation procedure as for VFNS



Data well described in full kinematic region

Similar NLO/NNLO predictions

Less sensitivity to higher order corrections)

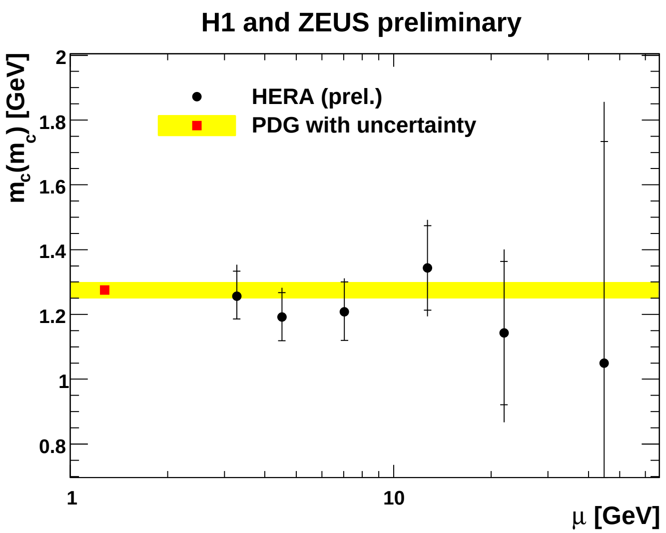
$$m_c(m_c) = 1.26 \pm 0.05_{exp.} \pm 0.03_{mod.} \pm 0.02_{param.} \pm 0.02_{\alpha_s}\ GeV$$

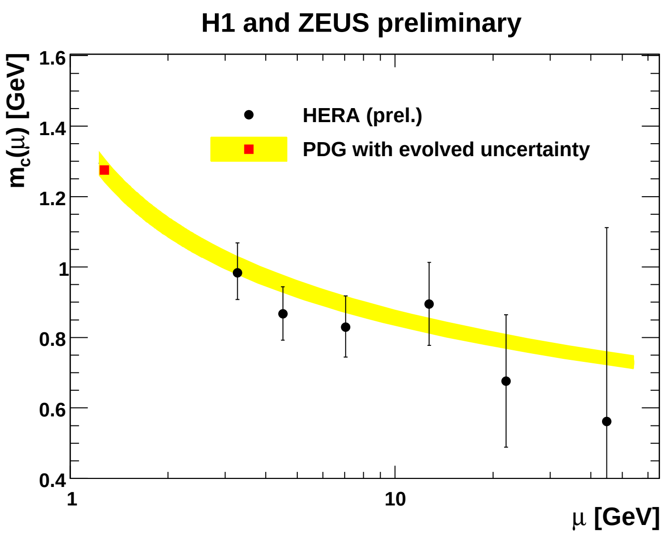
Uncertainties are experimental, model, parametrisation and α_s

Consistent with PDG: 1.275 ± 0.025 GeV

HERA charm data combination in DIS

Measurement of running m_c





Extract $m_c(m_c)$ separately for 6 different kinematic ranges in

$$\mu = \sqrt{< Q^2 > + 4m_c(m_c)^2}$$

$< Q^2 >$ is the logarithmic average Q^2 of the subset

Red points at scale m_c and bands are PDG average

$m_c(m_c)$ translated to $m_c(\mu)$ by:

$$m_c(\mu) = m_c(m_c)\frac{(\frac{\alpha_s(\mu)}{\pi})^{\beta_0^{-1}}}{(\frac{\alpha_s(m_c)}{\pi})^{\beta_0^{-1}}}$$

$\beta_0 = 9/4$ for $N_f = 3$

Data consistent with expected QCD running

First measurement of $m_c(\mu)$ from combined HERA charm reduced cross section data

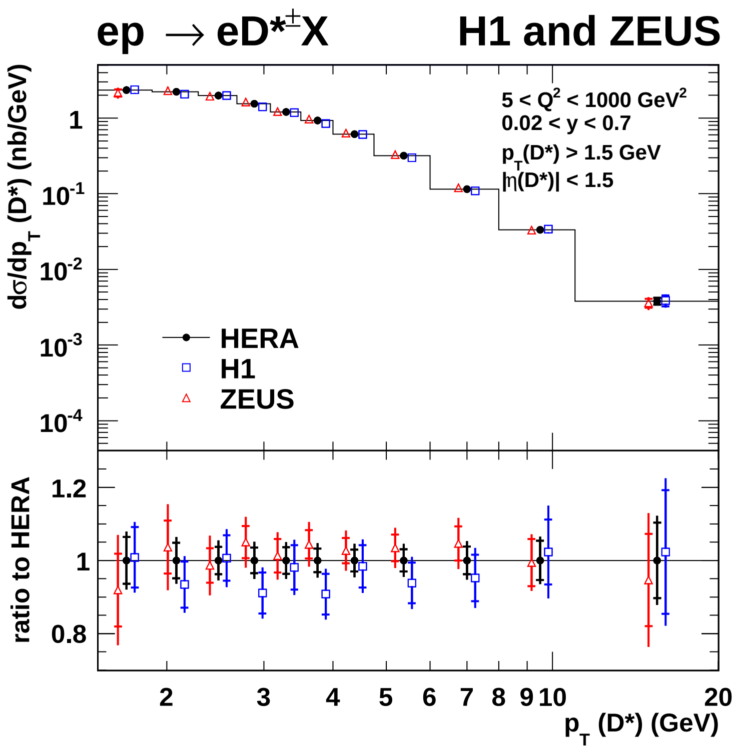
Important consistency check, similar to running m_b at LEP

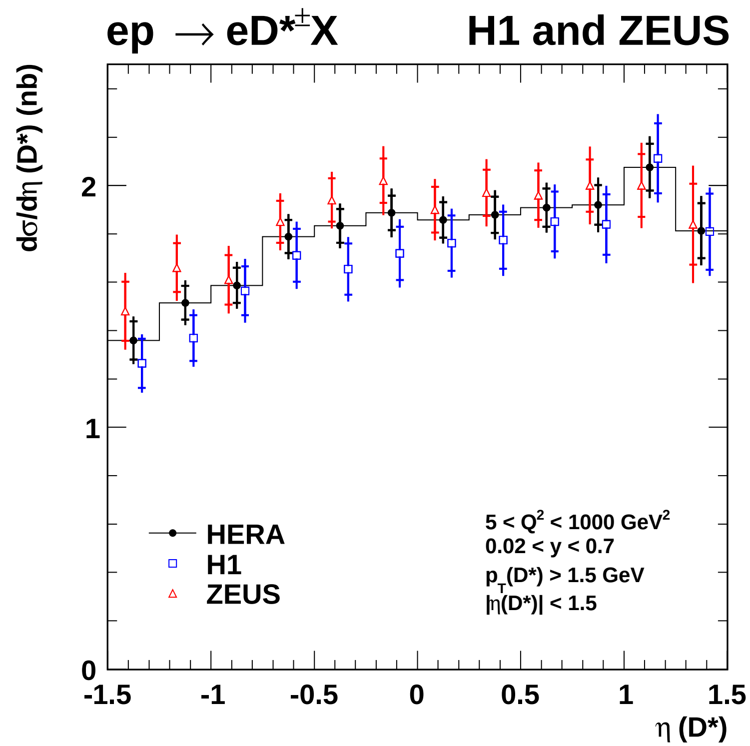
EPJ C55 (2008) 525

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

Combined H1+ZEUS D^{*+} visible differential cross sections w.r.t $p_T^{D^*}, \eta^{D^*}$

hep-ex 1503.06042; JHEP to be published





Correlations in systematic uncertainties fully taken into account

Impressive reduction of uncertainties in the combined results

Precision of combined data ≈ 5% in large fraction of phase space

Similar results and precision obtained for $d\sigma/dQ^2$ and $d\sigma/dy$

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

Differential cross sections compared to NLO predictions: HVQDIS

HVQDIS setup for $ep \rightarrow c\bar{c}X \rightarrow D^{*}X$ uses some arbitrary variable definition

e.g. $\mu_r = \mu_f = \sqrt{Q^2 + 4m_c^2}$; $m_c^{pole} = 1.5$ GeV

Try to change parameters such that normalisation and shapes of all differential cross sections describe the data well

Found this to happen with $\mu_r = 0.5\sqrt{Q^2 + 4m_c^2}$; $m_c^{pole} = 1.4$ GeV and with some softening of the fragmantation function used

(Kartvelishvili et al.)

All other parameters left at default values

The value of $m_c^{pole} = 1.4$ GeV was also found to describe better the data in the study of $\sigma_{red}^{c\bar{c}}$ (p.14)

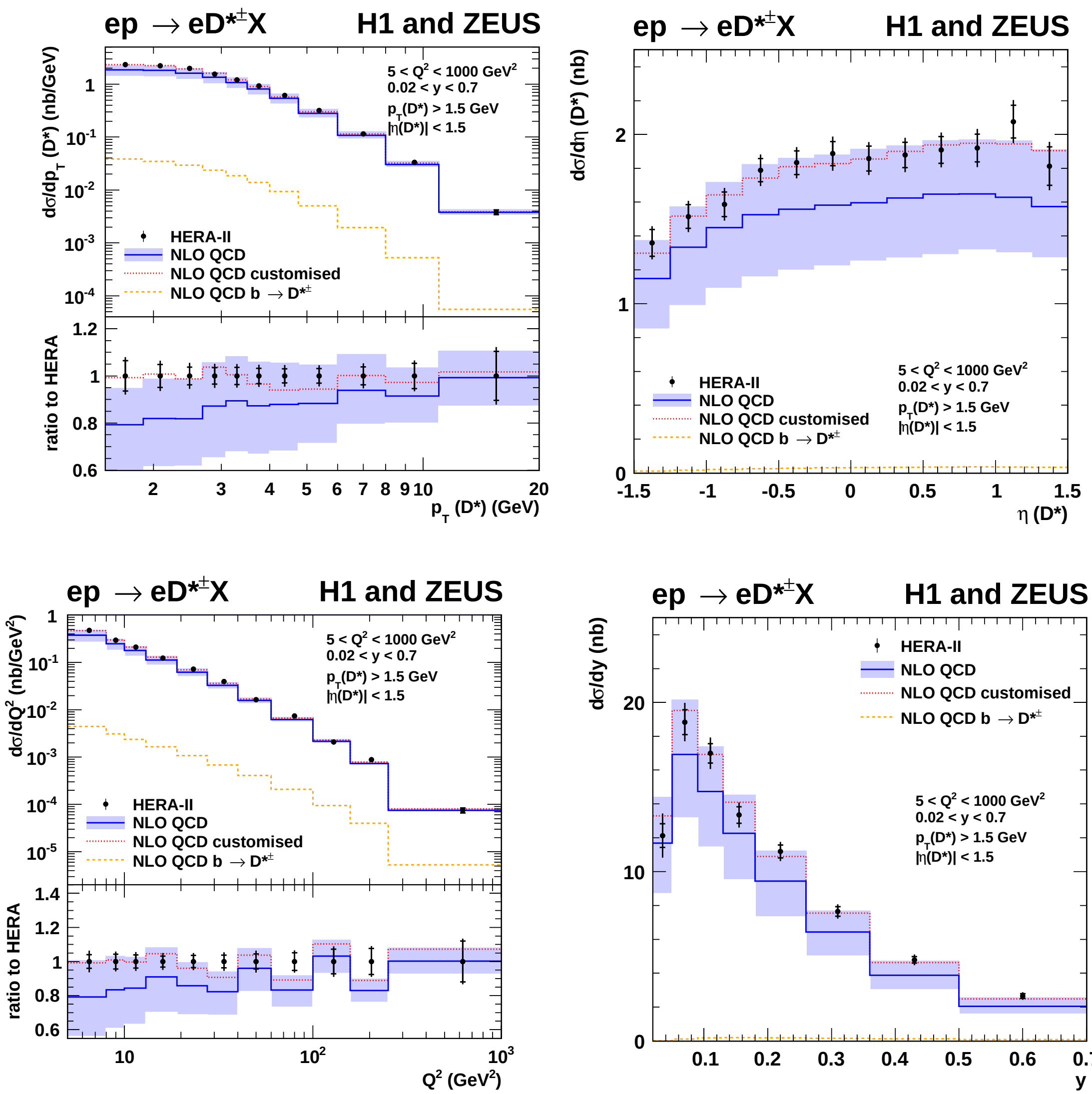
"NLO QCD customised" shown as red dots in the following plots

This is NOT a prediction, but may hint at which direction theory can be improved

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

HERA D^{*+} differential cross sections w.r.t $p_T^{D^*}, \eta^{D^*}, Q^2, y$ vs. theory (HVQDIS)

Negligible theoretical uncertainties in data points, since no extrapolation



Combined data reach precision of $\approx 5\%$

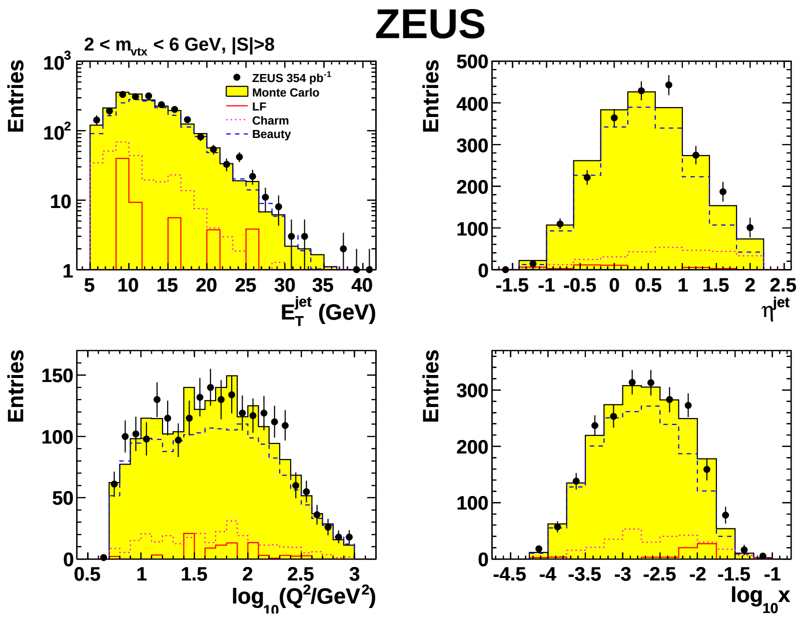
NLO describe data within large uncertainties ($\approx 10-30\%$)

NLO customised describe data very well

NNLO calculations and improved fragmentation models may help

Similar conclusions for D^* double-differential cross sections in Q^2, y

Beauty production in DIS



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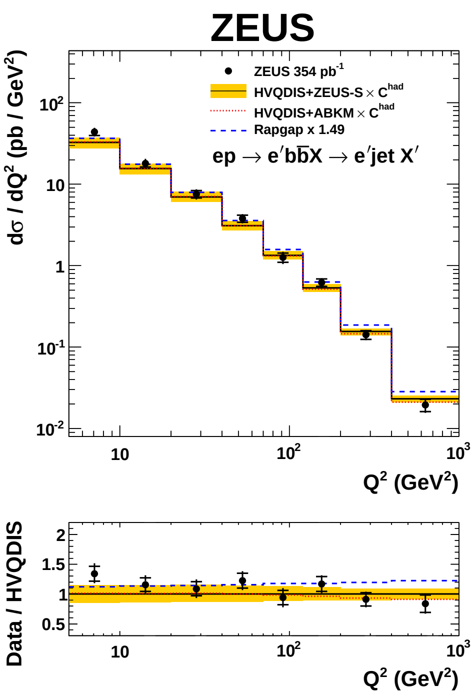
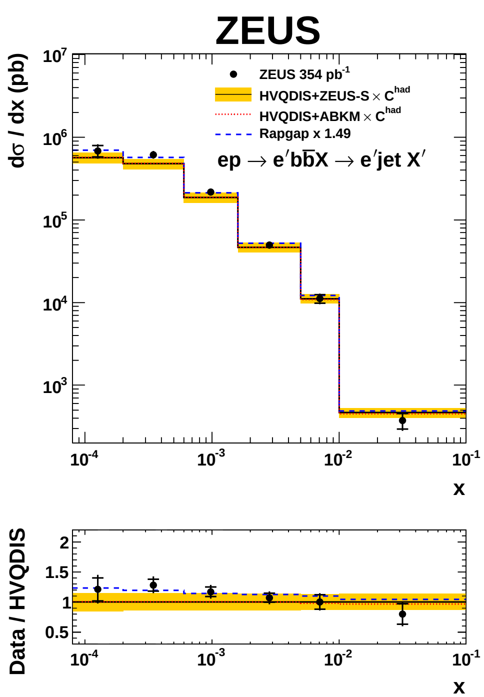
Beauty cross section at HERA much smaller than charm

With a micro-vertex detector at HERA II, lifetime information can be used

$E_T^{jet}, \eta^{jet}, Q^2, x$ distributions of sec. vertices for b-enriched sample with $2 < m_{vtx} < 6$ GeV and $|S| = |d/\delta d| > 8$ d=decay length

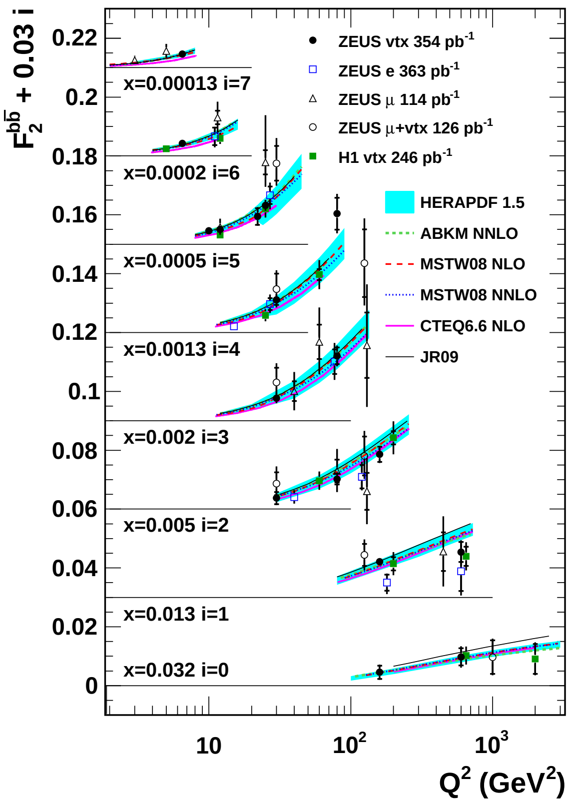


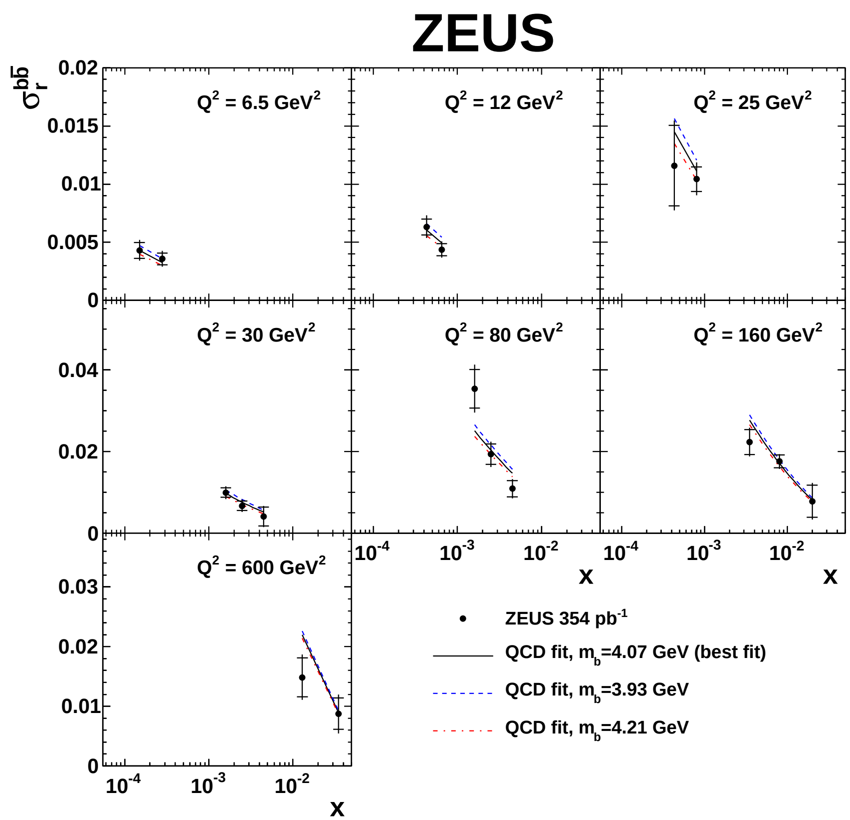


Differential cross sections for inclusive jet production in b-events as function of Q^2 and x

Good description of the data by the NLO FFNS HVQDIS prediction

Beauty production in DIS





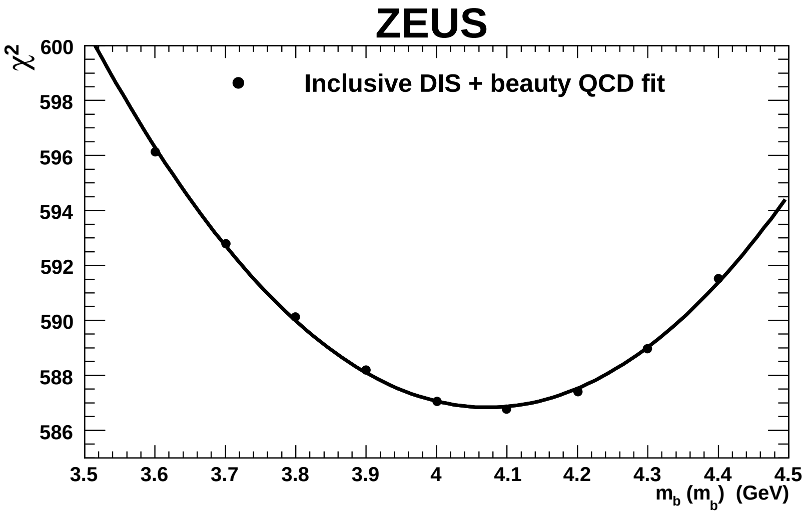
Left: Structure function $F_2^{b\bar{b}}$ as function of Q^2 for fixed x values in good agreement with FFNS and GM-VFNS NLO and NNLO predictions

Right: Reduced b cross section $\sigma_r^{b\bar{b}}$ as function of x for fixed Q^2 values used to determine b-quark mass in a QCD fit as done for the c-quark mass

Lines are results with $m_b = 4.07$ (best fit), 3.93 and 4.21 GeV

Sensitivity to m_b comes mostly from low Q^2

Beauty production in DIS

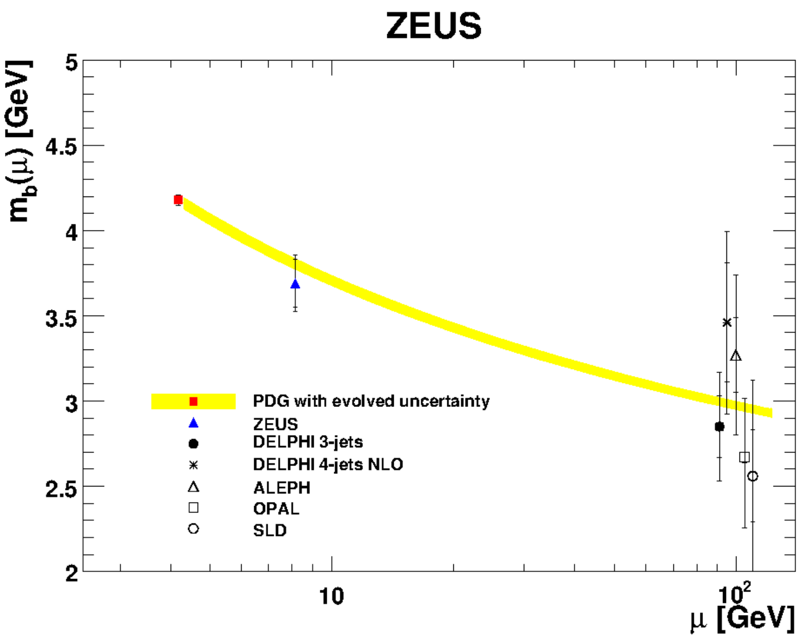


Extraction of $m_b(m_b)$ from NLO FFNS fit using $\overline{MS}$ scheme

Uncertainties are from fit, model, PDF parametrisation and theory

$$m_b(m_b) = 4.07 \pm 0.14(fit)^{+0.01}_{-0.07}(mod.)^{+0.05}_{-0.00}(param.)^{+0.08}_{-0.05}(theo.)\ GeV$$

PDG: 4.18 ± 0.03 GeV from lattice QCD + time-like processes



$m_b(m_b)$ translated, as for $m_c(m_c)$, to $m_b(\mu)$ with $\mu = 2m_b$ and compared to PDG and LEP results

Mass running is consistent with QCD

Summary

H1 and ZEUS still providing new charm(ing) and beauty(full) results
with full HERA data $\Rightarrow$ tighter constraints on QCD

$\sigma(D^*)$ in PHP vs. ep CM energy measured for the first time at HERA.
The D^* cross sections increase with $\sqrt{s}$ as predicted by NLO QCD

New precise charm fragmentation fractions measurements in PHP competitive
with e^+e^- collisions; support fragmentation universality

New DIS charm measurements and HERA charm data combination
provide constraints on PDFs and on QCD heavy quark calculations

Most HERA DIS charm data were combined:

- Consistent data sets extracted using different methods; reduced uncertainties
- Data are well described by FFNS and GM-VFNS QCD predictions
- Optimal M_c parameter for different VFNS improves predictions of $\sigma_{W,Z}$ at LHC
- Running charm mass in $\overline{MS}$ FFNS: $m_c(m_c) = 1.26 \pm 0.06$ GeV agree with PDG
- First measurement of the charm-mass running at HERA

Combination of D^* visible cross sections:

- Negligible theory uncertainties (no extrapolation)
- Challenge to theory and fragmentation models

New precise b-jet measurement + lifetime tag in DIS using secondary vertices:

- Data well described by NLO QCD
- b mass measured in $\overline{MS}$ scheme: $m_b(m_b) = 4.07 \pm 0.17$ GeV agree with PDG
- b mass running consistent with QCD