New results on charm production at HERA

Uri Karshon
Weizmann Institute of Science, ISRAEL
On behalf of the H1 and ZEUS Collaborations

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O U T L I N E

Introduction and motivation
Experimental set-up
Theory of heavy quark production: charm
$D^{\pm}$ production in deep inelastic scattering
$D^{*\pm}$ production in deep inelastic scattering
Charm fragmentation fractions in photoproduction
HERA charm data combination in deep inelastic scattering
Summary

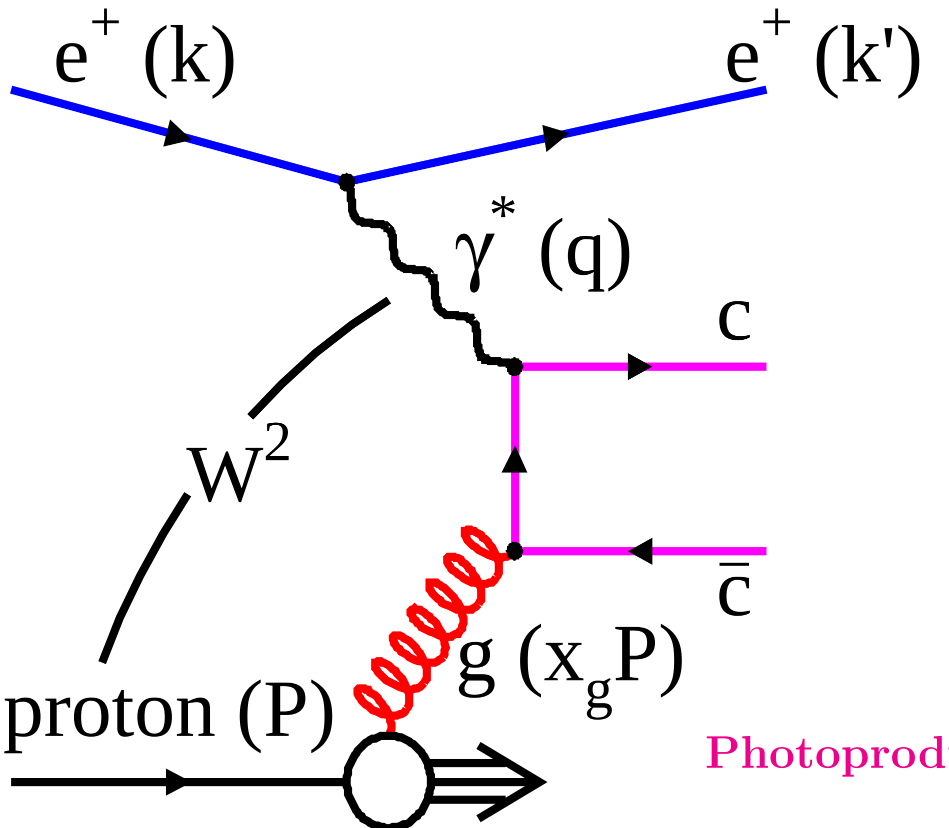
Introduction and motivation

Production of ground-state charm mesons D and D^* extensively studied at HERA

$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\bar{D}^0 = \bar{c}u$, $D^- = \bar{c}d$

Charm quark c (charge $\frac{2}{3}$): Coupling to γ stronger than d, s, b quarks (charge $-\frac{1}{3}$)

$\Rightarrow$ Large charm production cross section at HERA



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

Photon virtuality:

$\boldsymbol{Q^2 = -q^2 = -(k - k')^2}$

Bjorken x: $\boldsymbol{x = \frac{Q^2}{2q \cdot P}}$

Inelasticity: $\boldsymbol{y = \frac{q \cdot P}{k \cdot P}}$

$\boldsymbol{Q^2 = sxy}$

$\boldsymbol{W = \gamma p}$ **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)

Photon-gluon fusion

Introduction and motivation

Boson-gluon fusion (BGF): Dominant process for charm in DIS

Charm contribution to inclusive DIS cross section
is up to 30% at HERA

Direct probe of the gluon density of the proton

Sensitivity to c-quark mass

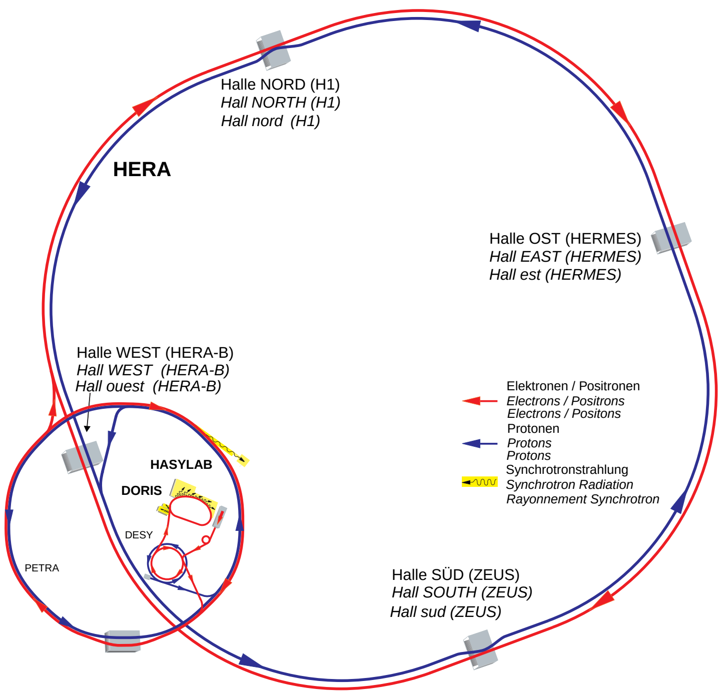
Test of QCD by comparing data to
next-to-leading order (NLO) predictions

Multiple scales ($Q^2, m_c, p_T(c)$): perturbative calculations possible

Can extract charm contribution to the proton structure function F_2

Fractions of charm quarks hadronising to charm hadrons
can test fragmentation fraction universality

Experimental set-up



HERA is a unique $e^{\pm}p$ collider

Tunnel $< \frac{1}{4}$ Circumference of LHC Tunnel

Asymmetric Detector(along beam)

Many TWO's

2 Collider Rings: Lepton and Proton

2 Lepton Beams: e^- or e^+

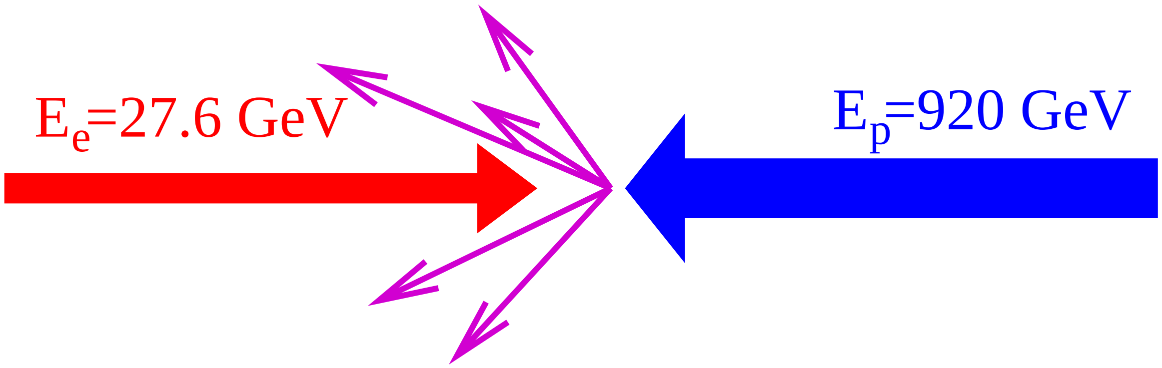
2 Proton Beam Energies: $820, 920\ GeV$

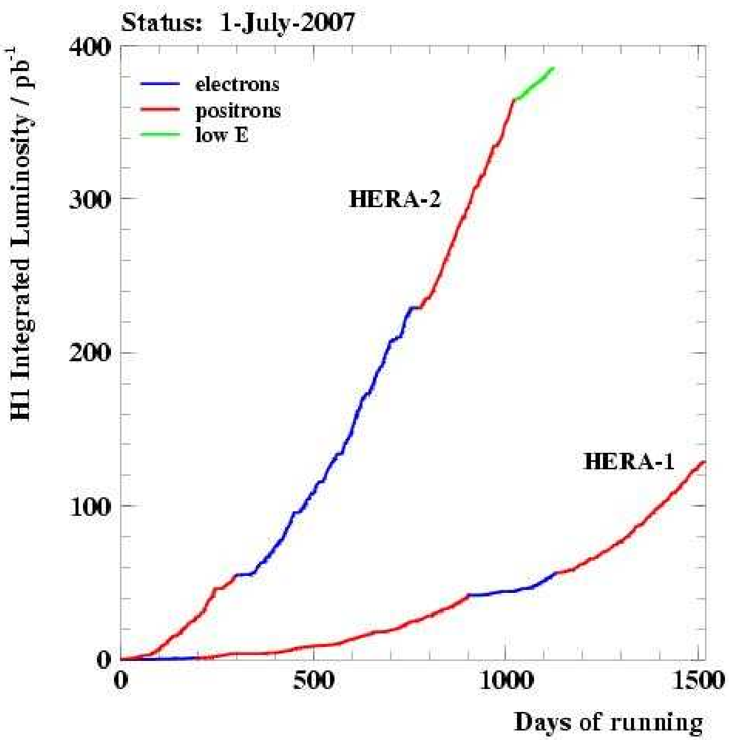
2 Main Experiments: H1, ZEUS

2 Run Periods: HERA I, HERA II

2 Event Types: DIS, Photoproduction

Experimental set-up





	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	$373\, pb^{-1}$

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

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

Theory of heavy quark production: charm

Several QCD NLO schemes for charm production:

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

3 active flavours in proton; c-quark not considered as parton in p

Charm produced perturbatively in hard scattering (see p.2)

Mass effects correctly included

Spoiled by large logs of $Q^2/m^2, p_t/m$...

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

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

Charm treated as massless parton

Resummation of large logarithms of Q^2/m_c^2

$\Rightarrow$ Charm density added as 4th flavour like the light quarks

At intermediate Q^2 the 2 schemes should be merged

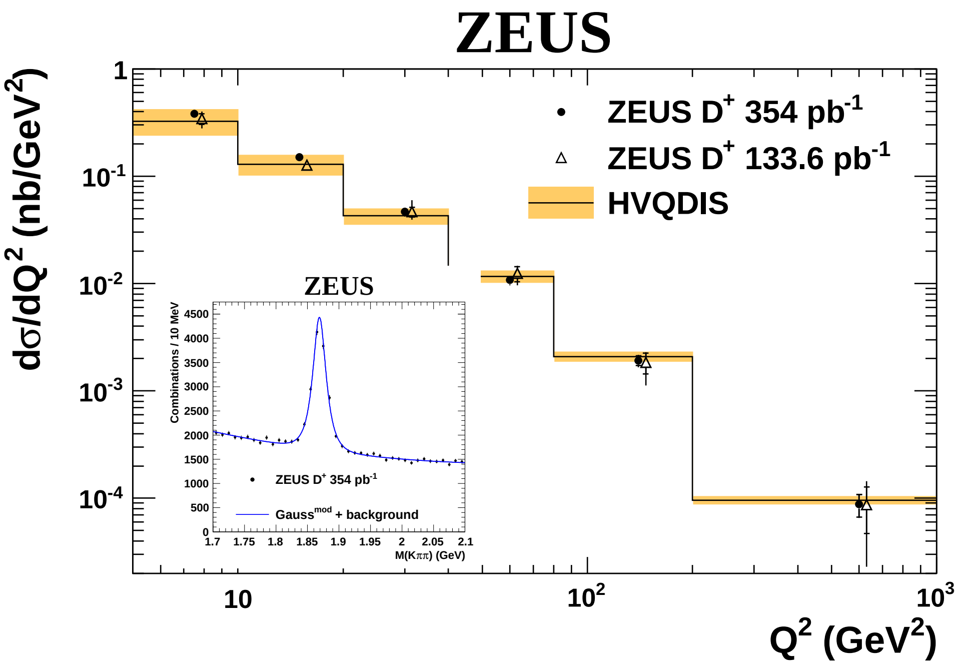
3) General-mass variable flavour number scheme (GM-VFNS)

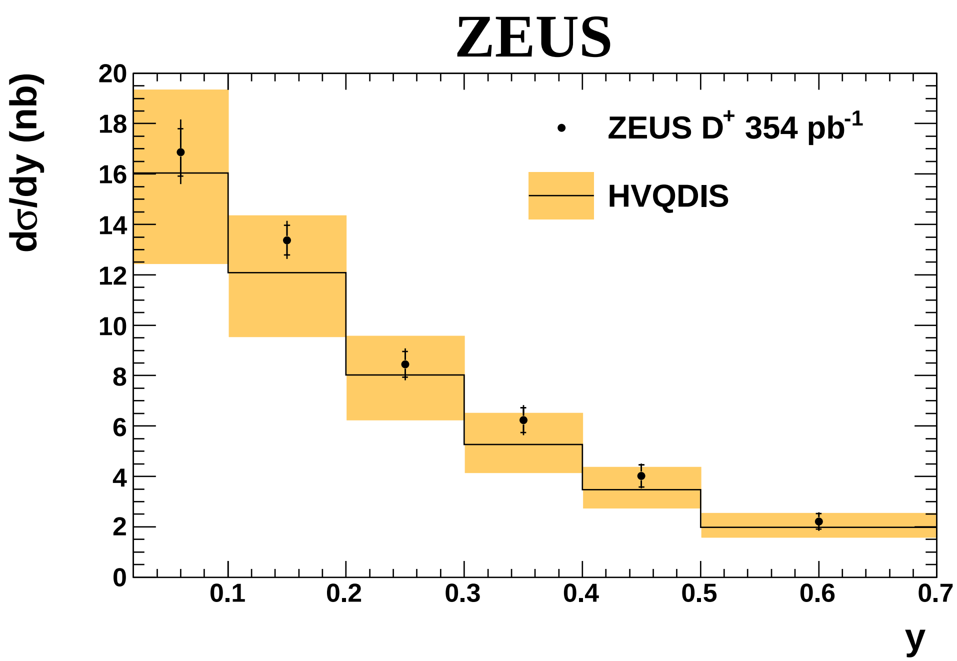
Equivalent to FFNS for $Q^2 \leq m_c^2$ and to ZM-VFNS for $Q^2 > m_c^2$

Interpolation in between (various schemes interpolate differently)

Used in parton density function (PDF) fits (useful at LHC)

$D^{\pm}$ production in DIS





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

JHEP 05 (2013) 023

Clean D^+ signal in $M(K^-\pi^+\pi^+)$ dist.

Charge-conjugate states are included

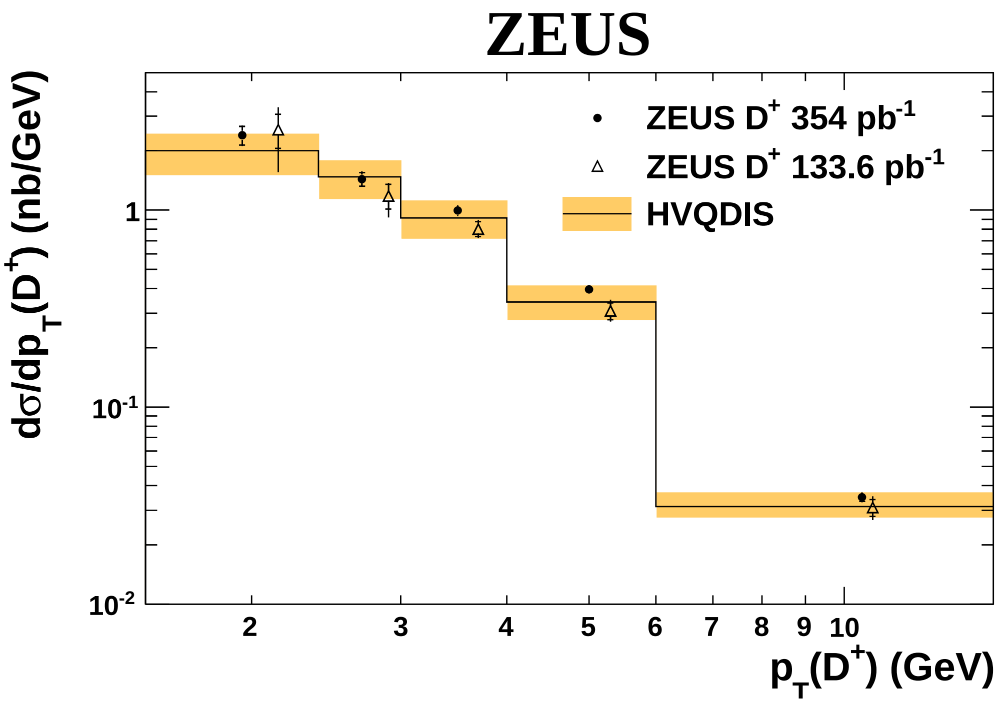
$$N(D^+) = 8356 \pm 198$$

D^+ differential cross sections in $ep \to e'c\bar{c}X \to e'D^+X'$ w.r.t Q^2, y in kinematic region $5 < Q^2 < 1000$ GeV^2, $1.5 < p_T(D^+) < 15$ GeV, $|\eta(D^+)| < 1.6$, $0.02 < y < 0.7$

Previous ZEUS results also shown

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

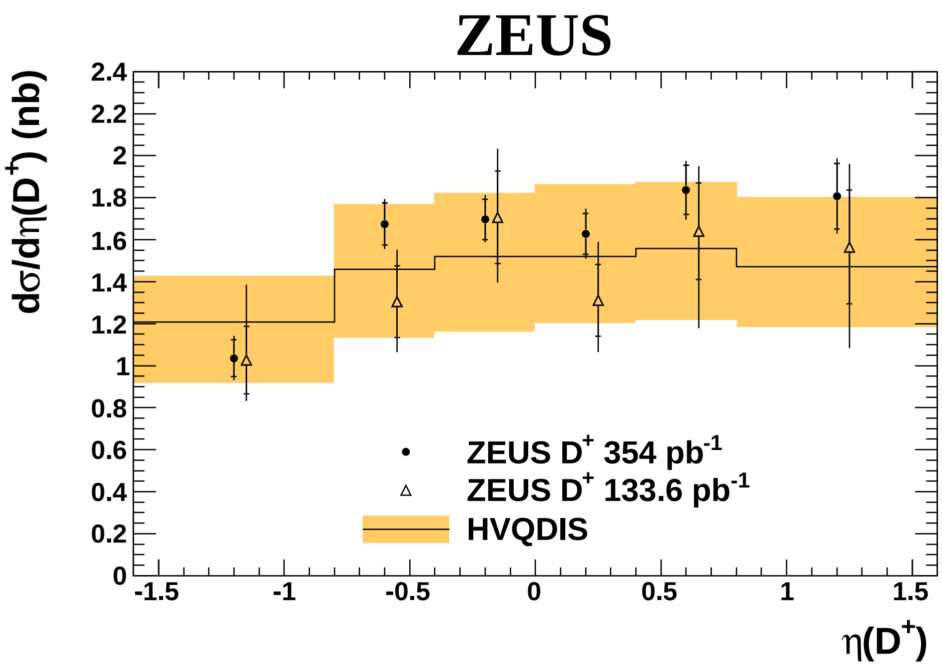
$D^{\pm}$ production in DIS



D^{+} differential cross sections w.r.t $p_T(D^+), \eta(D^+)$

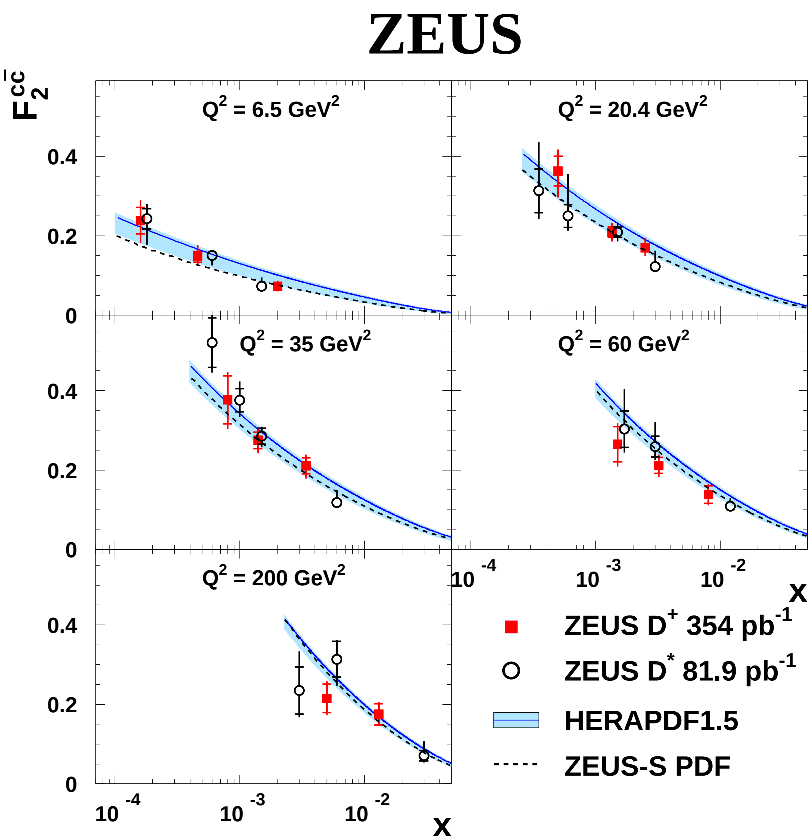
ll

HVQDIS predictions describe data



Similar agreement for double differential cross sections $d\sigma/dy$ for different Q^2 ranges (not shown)

$D^{\pm}$ production in DIS



Charm contribution to proton structure function:

Express double differential cross section as:

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

$F_2^{c\bar{c}}, F_L^{c\bar{c}}$ 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

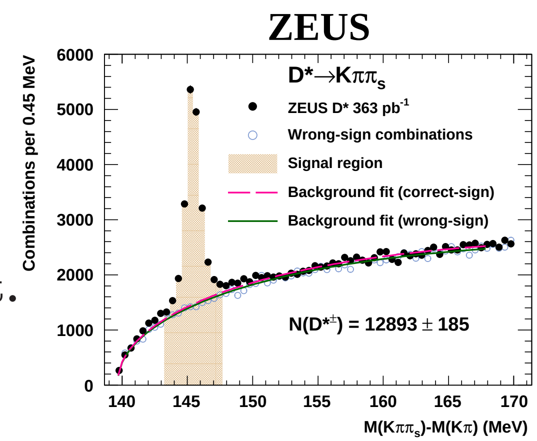
$$F_{2,meas}^{c\bar{c}}(x_i, Q_i^2) = \sigma_{i,meas} \frac{F_{2,theo}^{c\bar{c}}(x_i, Q_i^2)}{\sigma_{i,theo}}$$

$F_{2,theo}$ 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

The NLO calculations describe new precise data well

$D^{*\pm}$ production in DIS

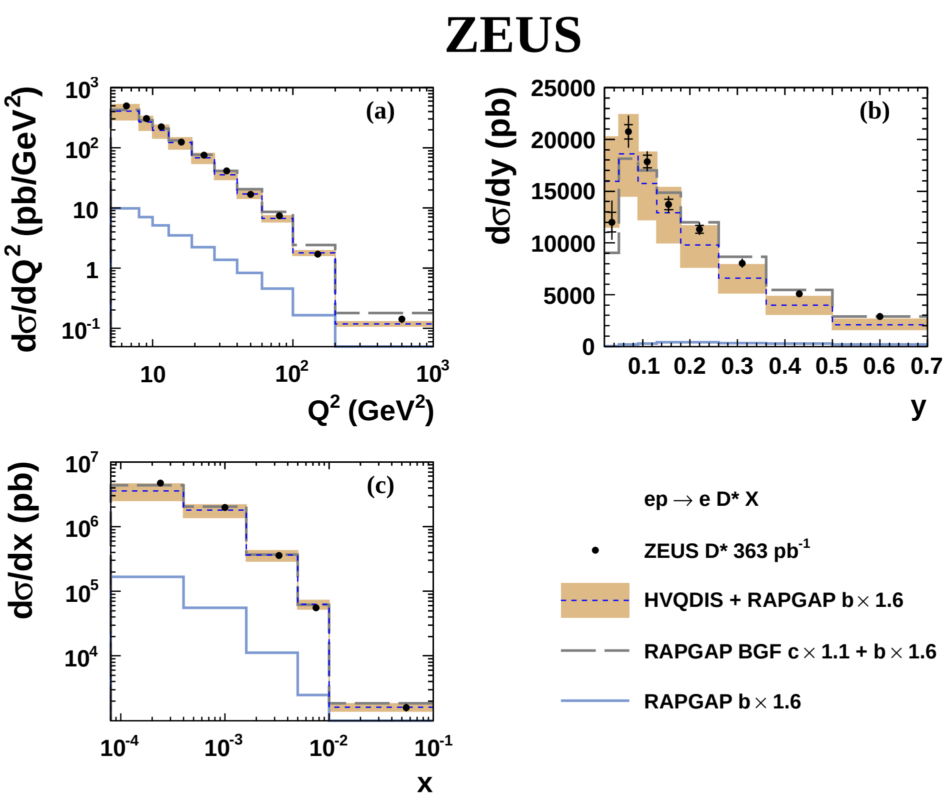


Full HERA II data: 363 pb^{-1}

JHEP 05 (2013) 097

Clean D^{*+} signal in $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$

$N(D^{*+}) = 12893 \pm 185$



D^{*+} differential cross sections in $ep \to e' c\bar{c}X \to e' D^* X'$ w.r.t Q^2, y, x in kinematic region $5 < Q^2 < 1000$ GeV^2, $1.5 < p_T(D^+) < 20$ GeV, $|\eta(D^+)| < 1.5$, $0.02 < y < 0.7$

Most precise ZEUS D^* DIS results

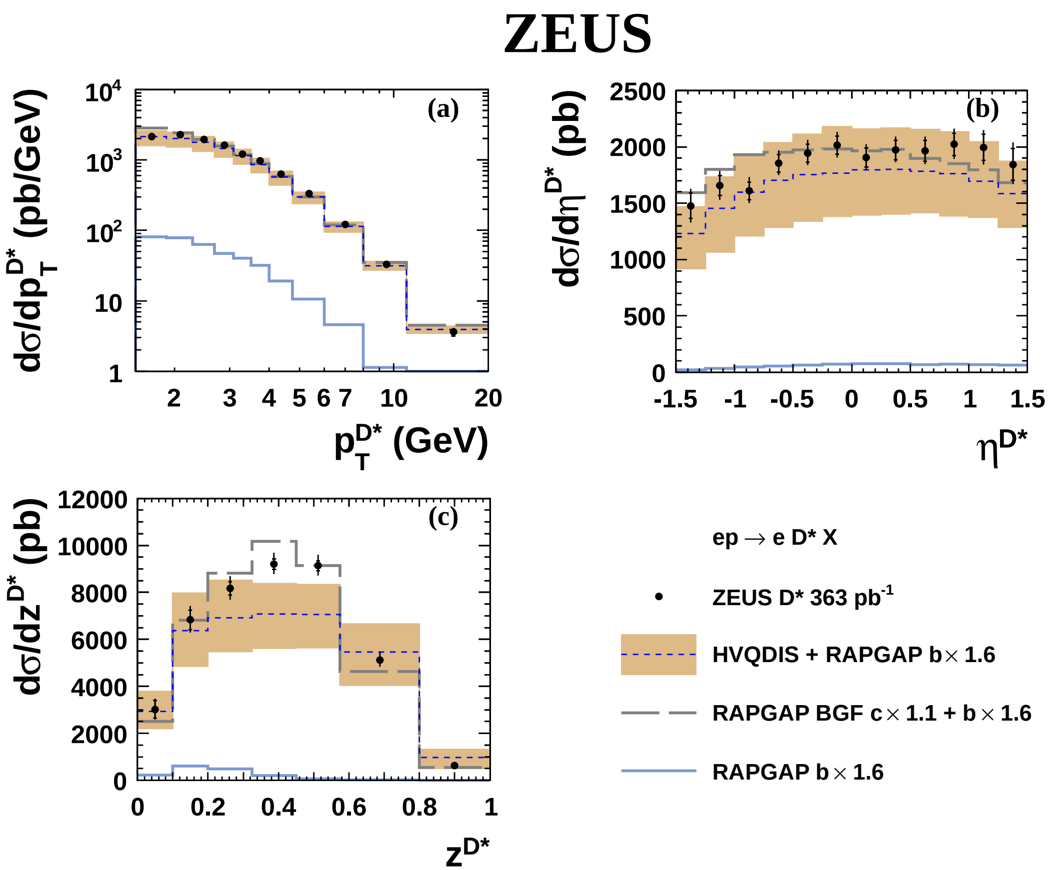
Results compared to NLO HVQDIS and to RAPGAP MC based on LO matrix elements via BGF

NLO calculations describe data well

RAPGAP roughly reproduce data shape

$D^{*\pm}$ production in DIS

D^{*+} differential cross sections w.r.t $p_T^{D^*}, \eta^{D^*}, z^{D^*}$



$z^{D^*} = E(D^*)/E(\gamma^*)$
in p rest frame

Results compared to HVQDIS and to RAPGAP MC

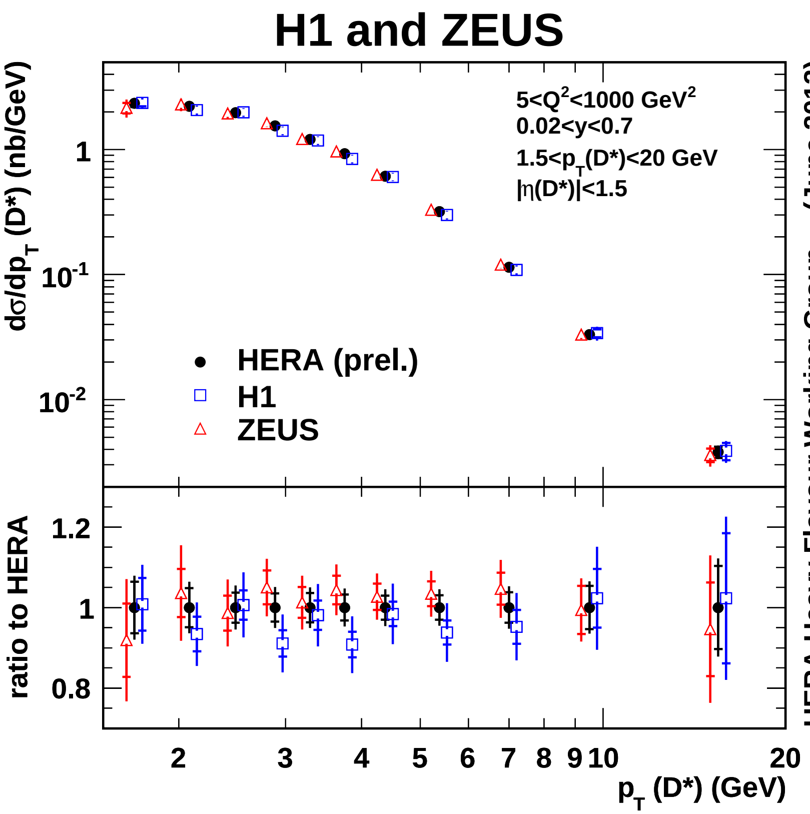
Reasonable description by massive NLO

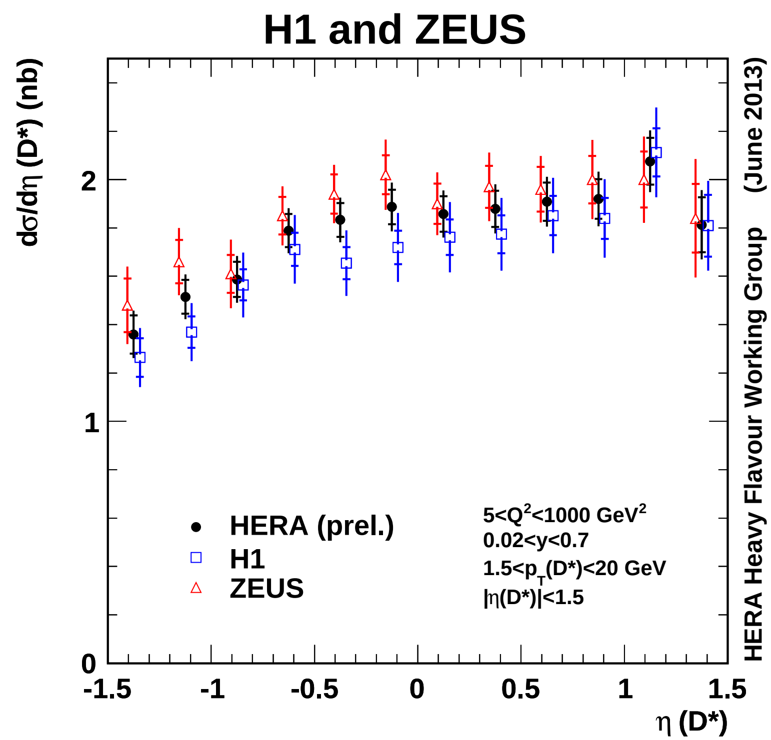
RAPGAP roughly reproduce data shape

Similar agreement for double differential cross sections $d\sigma/dy$ for different Q^2 ranges (not shown)

$D^{*\pm}$ production in DIS

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

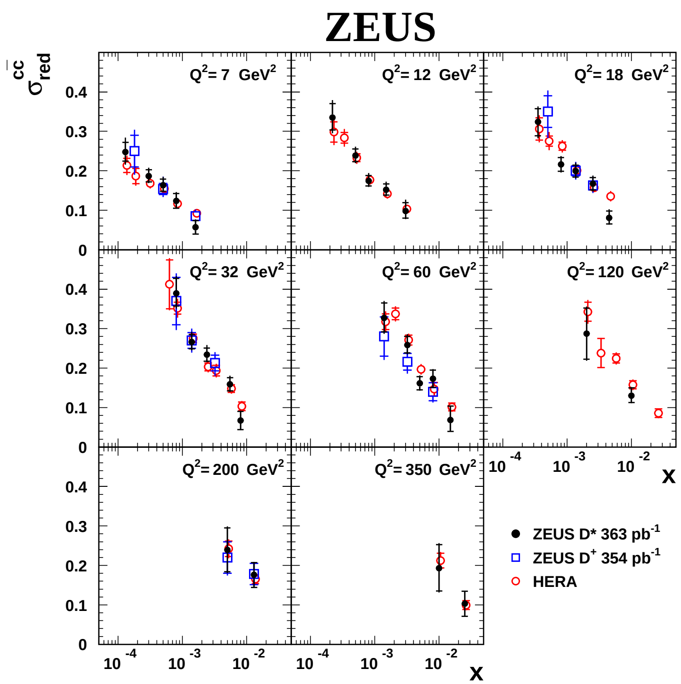




All relevant correlations are taken into account

Impressive reduction of uncertainties in the combined results

$D^{*\pm}$ production in DIS



Charm contribution to proton structure function:

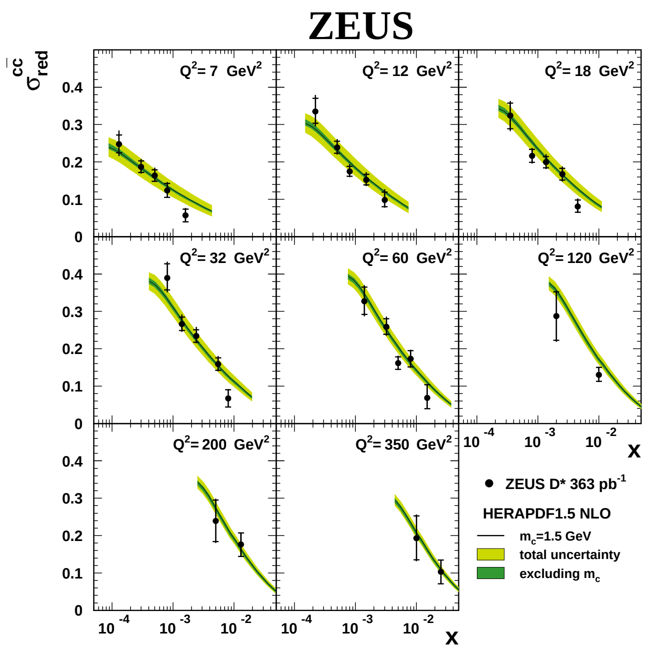
Define charm reduced cross section as:

$$\sigma_{red}^{c\bar{c}}(x, Q^2, s) = F_2^{c\bar{c}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x, Q^2)$$

$$Y_+ = 1 + (1 - y)^2$$

$D^{*\pm}$ results compared to ZEUS D^+ results and to combined H1+ZEUS results

All 3 measurements are in good agreement



$D^{*\pm}$ results compared to GM-VFNS based on HERAPDF1.5 parton densities

The NLO calculation describe data well

Charm fragmentation fractions in PHP

Fragmentation fractions of c-quarks into charm hadrons:

Probability of c quark to hadronise into a given charm hadron

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

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: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$

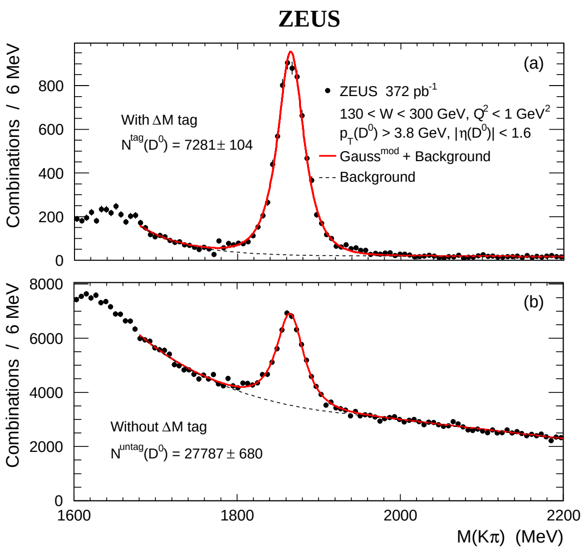
$D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$

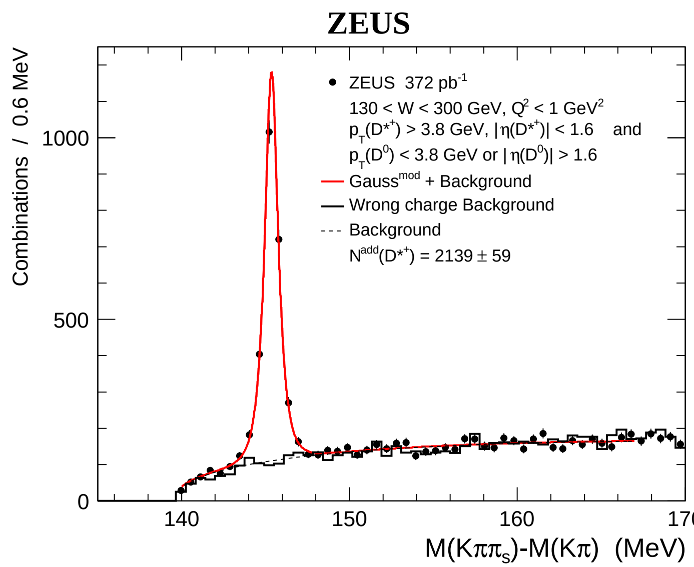
$D_s^+ \to \phi\pi^+$, $\Lambda_c^+ \to K^-p\pi^+$

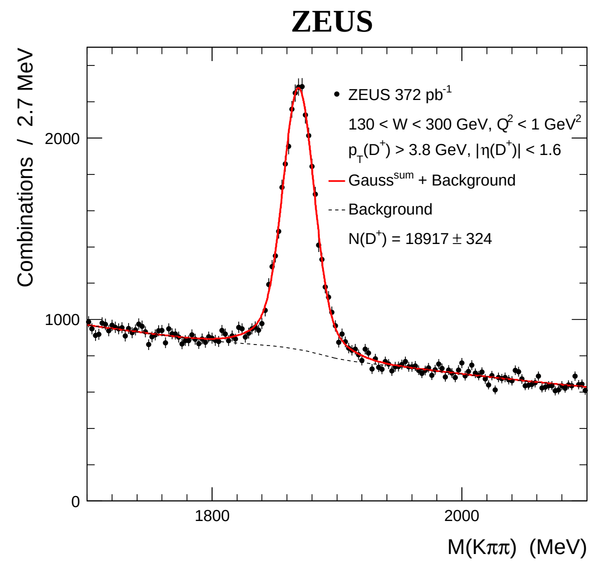
$$\sigma_{tot} = \sigma^{eq}(D^0) + \sigma^{eq}(D^+) + \sigma(D_s^+) + 1.14\ \sigma(\Lambda_c^+)$$

Full HERA II data: 372 pb^{-1} JHEP 09 (2013) 058

Charm fragmentation fractions in PHP







$M(K^-\pi^+)$

Upper: with ΔM tag

$N(D^0) = 7281 \pm 104$

Lower: without ΔM tag

$N(D^0) = 27787 \pm 680$

$M(K^-\pi^+\pi_s^+) - M(K^-\pi^+)$

for additional D^{*+}

$N^{add}(D^{*+}) = 2139 \pm 59$

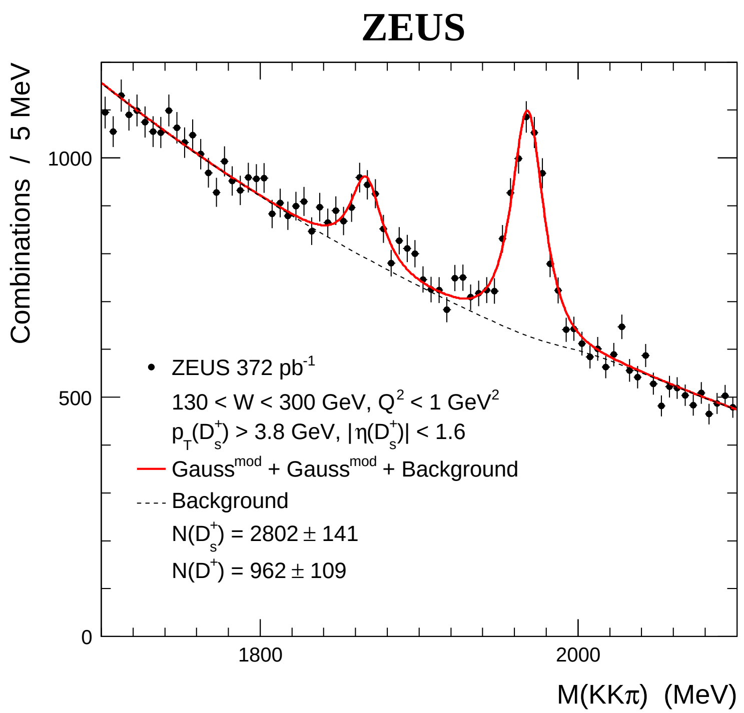
$M(K^-\pi^+\pi^+)$

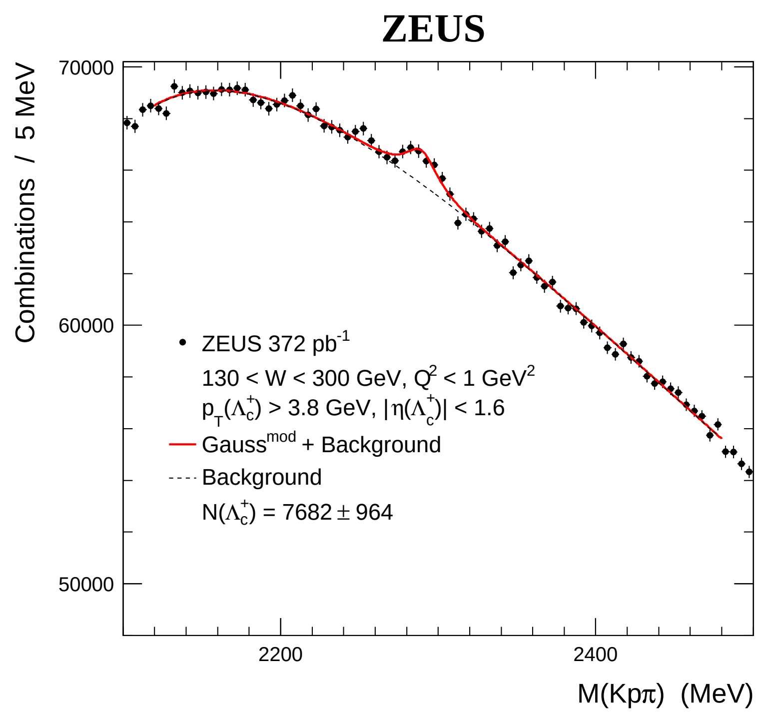
$N(D^+) = 18917 \pm 324$

Silicon-strip detector used for charm vertices

⇒ Clear charm hadron signals for all channals

Charm fragmentation fractions in PHP





$M(\phi\pi^+) \quad \phi \to K^+K^-$

$N(D_s^+) = 2802 \pm 141$

$N(D^+) = 962 \pm 109$

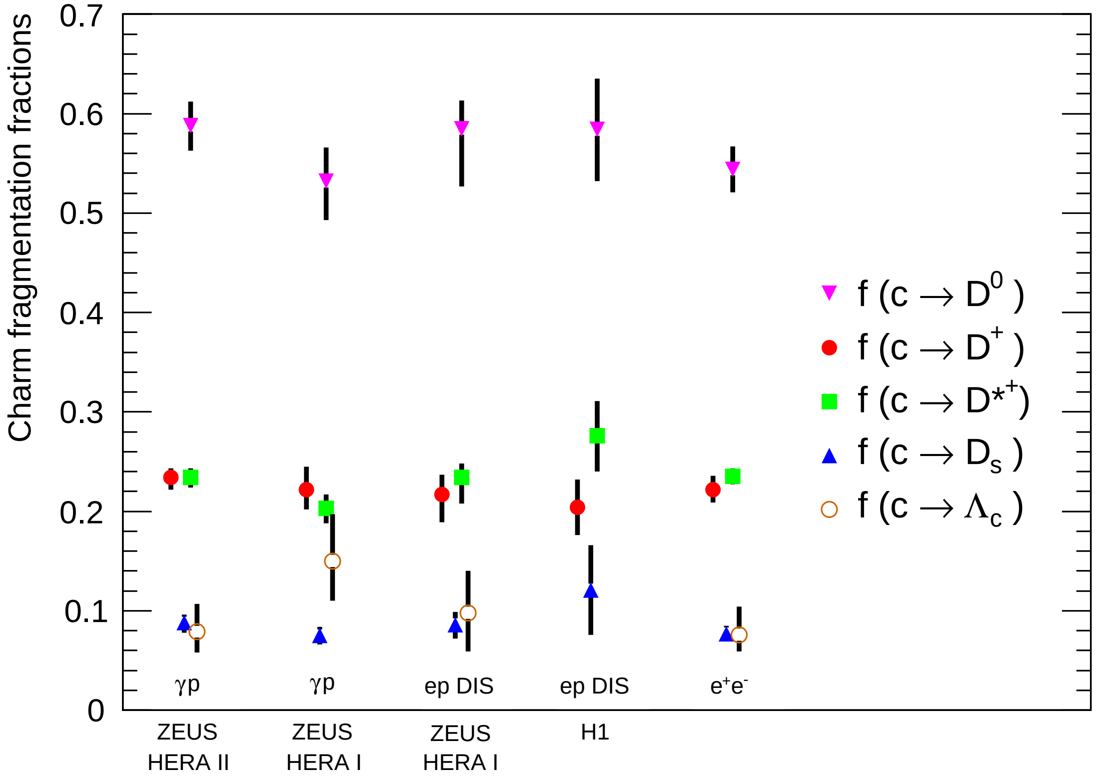
$M(K^-p\pi^+)$

$N(\Lambda_c^+) = 7682 \pm 964$

Charm-strange baryons accounted for by term $1.14\ \sigma(\Lambda_c^+)$

Charm fragmentation fractions in PHP

Charm fragmentation fractions:



Results (left column) in good agreement with previous results

Precision competitive with combined e^+e^- LEP results

Fragmentation fractions of c-quarks independent of production

Support hypothesis of universality of heavy-quark fragmentation

HERA charm data combination in DIS

Combined charm DIS production cross sections from H1 and ZEUS

Data sets correspond to 155 cross section measurements from various HERA I and HERA II analyses EPJ C73 (2013) 2311

Reduced cross sections $\sigma_{red}^{c\bar{c}}$ obtained in kinematic range:

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

Combined charm + inclusive DIS HERA cross sections:

Input for NLO analysis to study influence of heavy flavour (HFL) schemes on PDFs

Charm mass in GM-VFNS treated as effective mass parameter M_c

M_c does not correspond directly to a physical mass

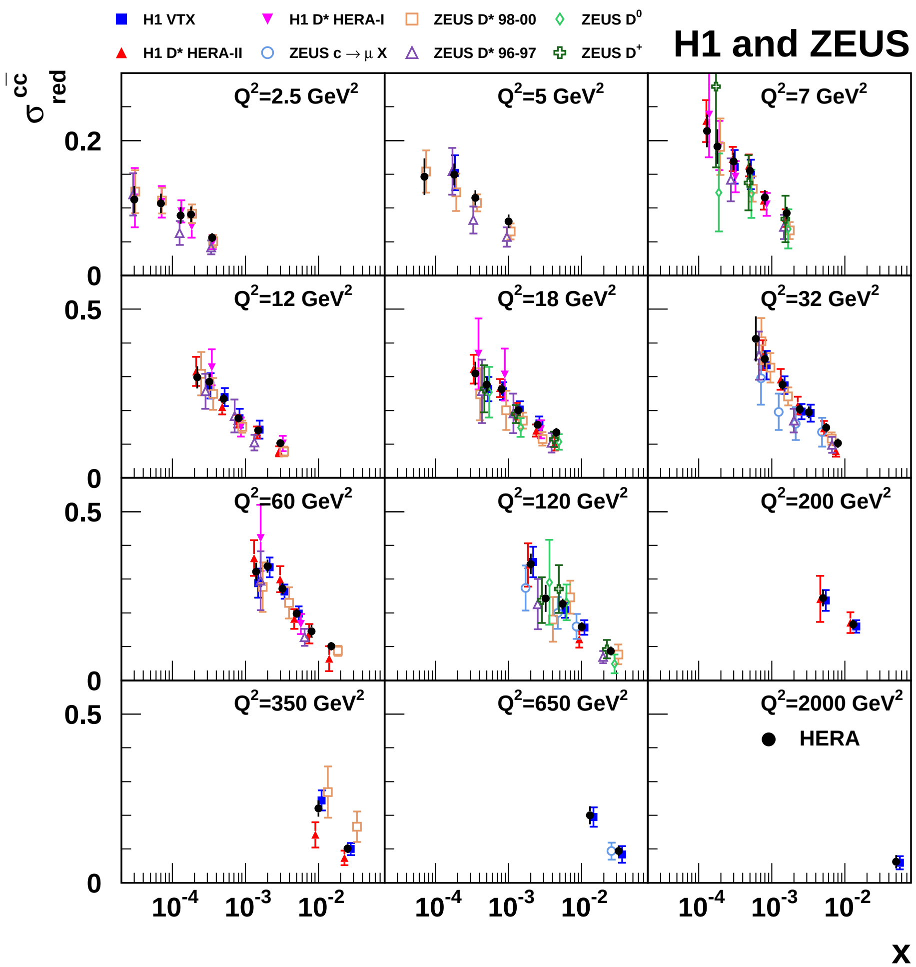
Different optimal M_c values are obtained in various schemes

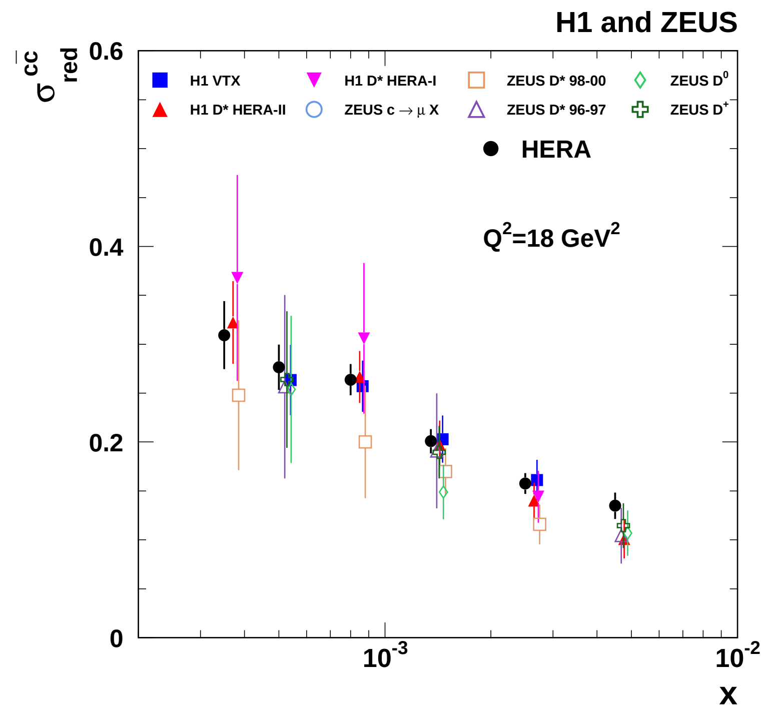
Implications on NLO predictions for W, Z production at LHC

FFNS used to determine running mass of the c-quark, $m_c(m_c)$

HERA charm data combination in DIS

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





Enlarged plot for $Q^2 = 18$ GeV^2

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

Combine 8 data sets of D^*, D^+, D^0, μ and lifetime tag data

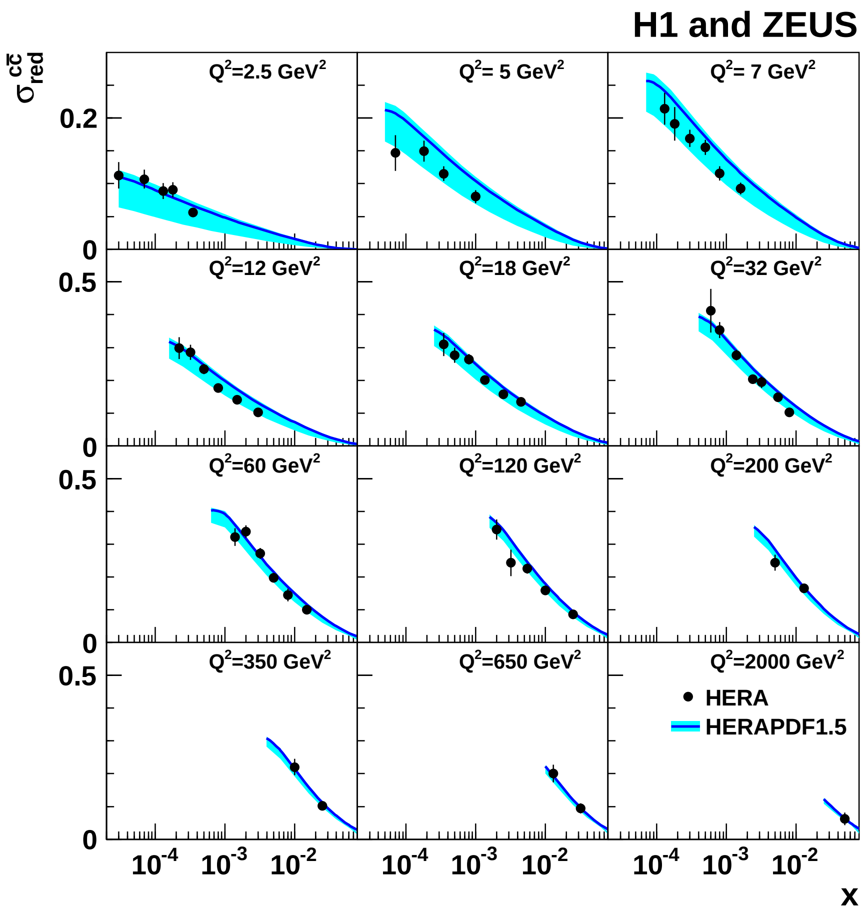
Combined results - filled circles

Correlated systematics fully taken into account

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

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

Lines are predictions with $M_c = 1.4$ GeV

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 performed using $\sigma_{red}^{c\bar{c}}$ together with combined inclusive DIS cross sections

Due to sizeable charm contribution to inclusive cross section this analysis reduces uncertainties related to charm production

Kinematic range of analysis: $W > 15$ GeV, $x < 0.65$, $Q^2 > 3.5$ GeV^2

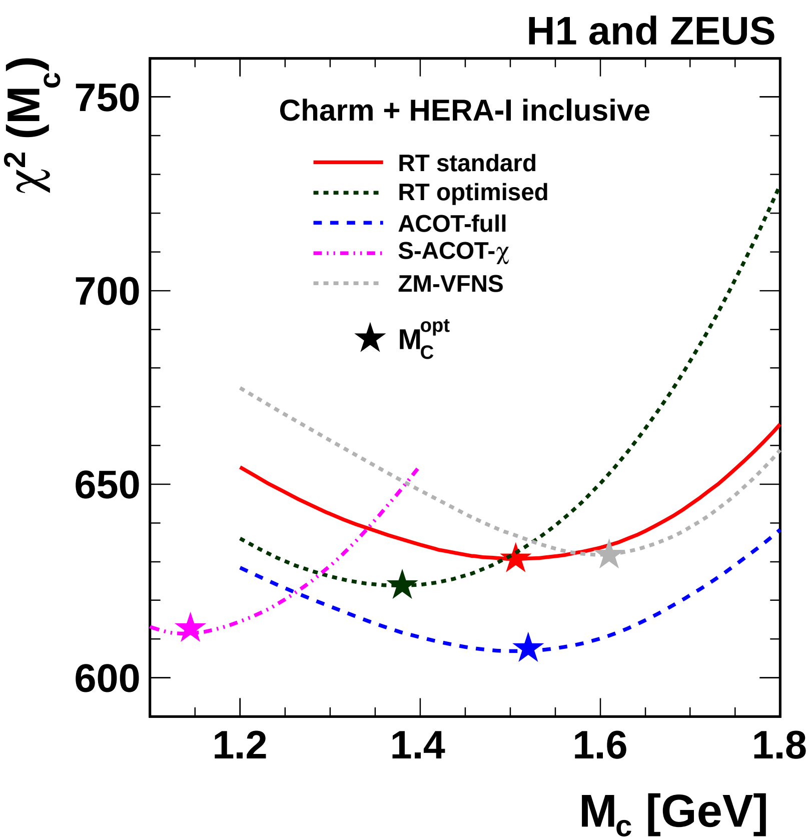
For each HFL scheme, PDF fits performed with $1.2 < M_c < 1.8$ GeV

For each fit, $\chi^2(M_c)$ is calculated and M_c^{opt} is determined from parabolic fit

Clear χ^2_{min} is seen when charm data are added to inclusive DIS data

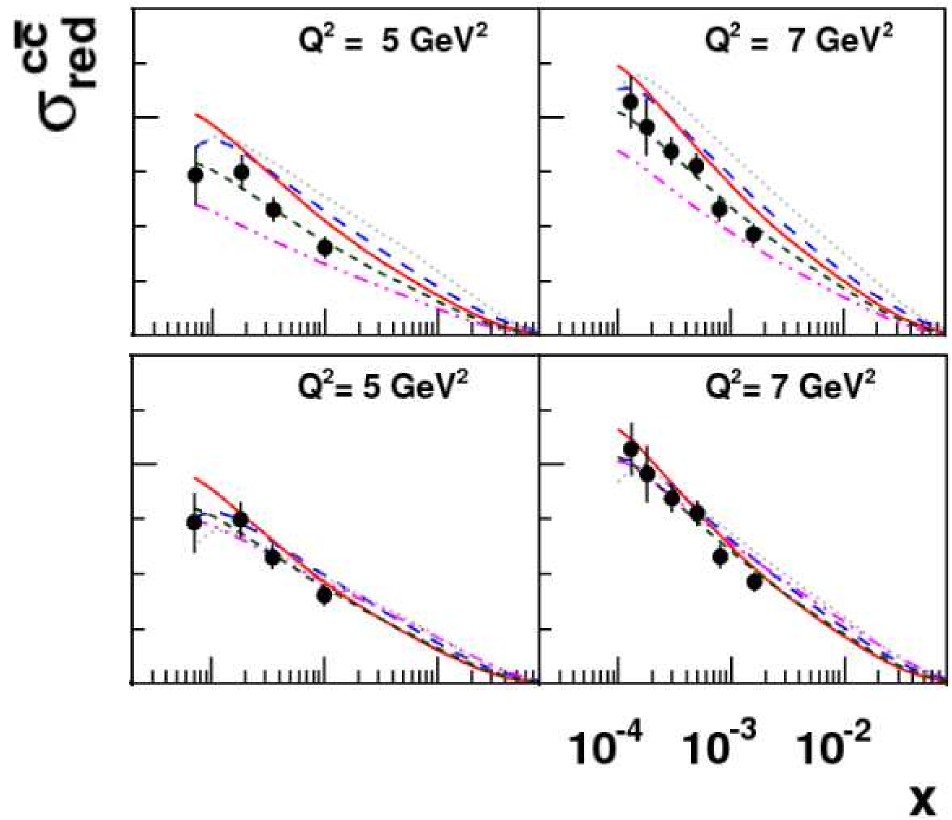
HERA charm data combination in DIS

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)



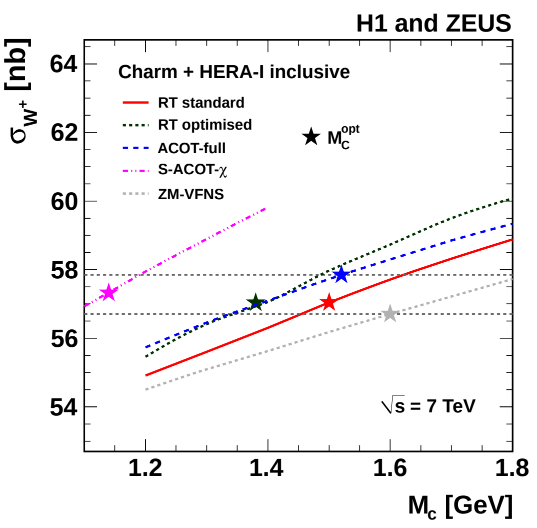
Data described much better with M_c^{opt} than with fixed M_c

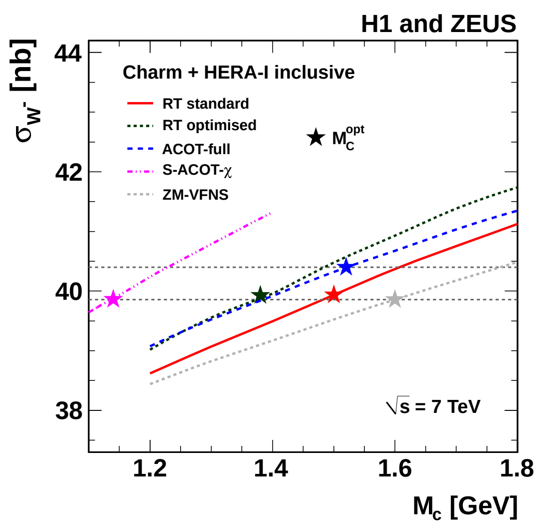
Predictions of all schemes are very similar for $Q^2 \geq 5$ GeV^2

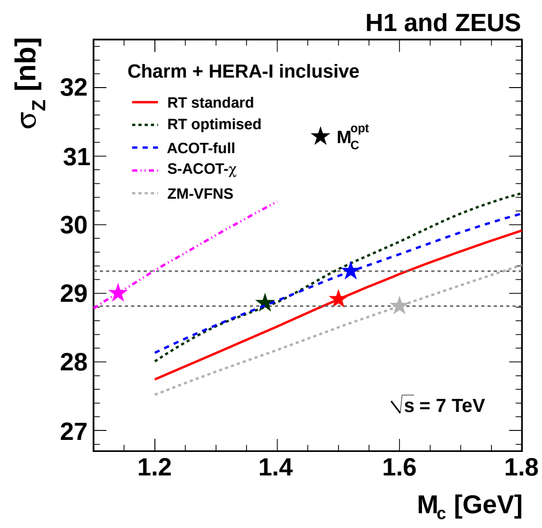
HERA charm data combination in DIS

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

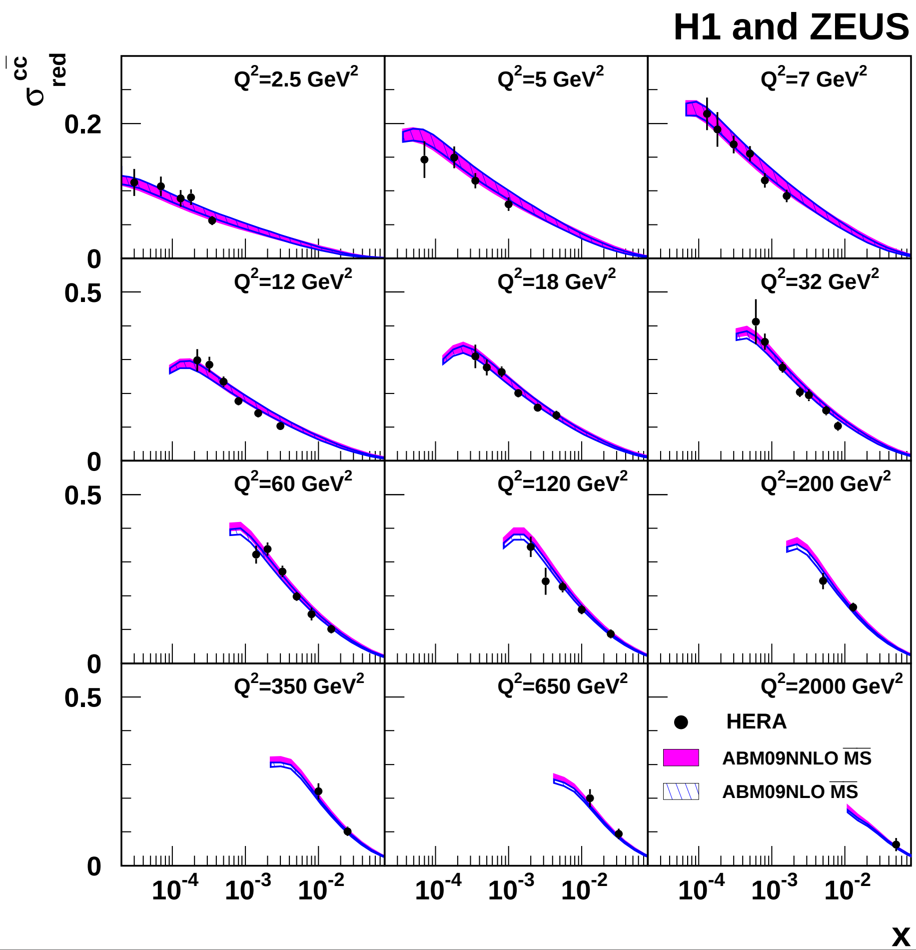
Significant spread of $\approx 6\%$ between predictions for any fixed M_c
Reduces to $\approx 1.4 - 2\%$ when taking M_c^{opt} for each scheme

HERA charm data combination in DIS

How well does the rigorous massive scheme FFNS work ?

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

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



Reduces cross section sensitivity to higher order corrections

Improves theoretical precision of mass definition

NLO and NNLO predictions are very similar

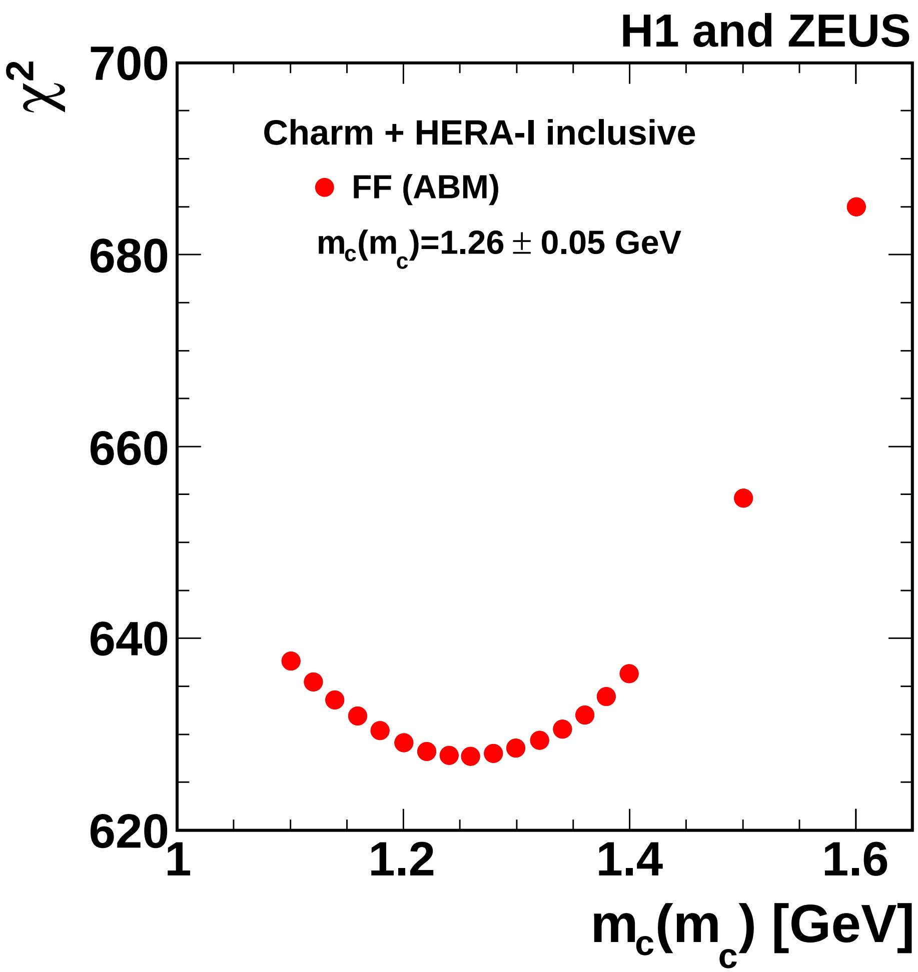
Data described very well in whole kinematic range

HERA charm data combination in DIS

Extraction of charm running mass $m_c(m_c)$ using $\overline{MS}$ scheme:

Fit combined charm and inclusive DIS data using NLO analysis in FFNS scheme of ABM group

Same minimisation procedure as for VFNS analysis



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

Errors are experimental, model, parametrisation and α_s

Consistent with PDG:

$m_c(m_c) = 1.275 \pm 0.025$ GeV

Summary

Differential cross sections for the production of $D^{\pm}$ and $D^{*\pm}$ mesons in DIS were measured with the full HERA II data

NLO QCD predictions based on FFNS describe the data well

Charm contributions to the proton structure function, $F_2^{c\bar{c}}$ or $\sigma_{red}^{c\bar{c}}$, agree with GM-VFNS predictions based on PDF fit HERAPDF1.5

Charm fragmentation fractions measurements in PHP support fragmentation universality and are competitive in precision with e^+e^- collisions

HERA combined charm data in DIS provide new constraints on description of the proton structure and allow a precise charm mass measurement

Combined data compared to QCD predictions in GM-VFNS, FFNS:
For each VFNS variant an optimal charm mass, M_c^{opt}, is determined
Its use significantly reduces PDF uncertainties
FFNS at NLO provides best description with $\overline{MS}$ running mass:
$m_c(m_c) = 1.26 \pm 0.06$ GeV in agreement with world average