Combination and QCD analysis of charm quark production at HERA

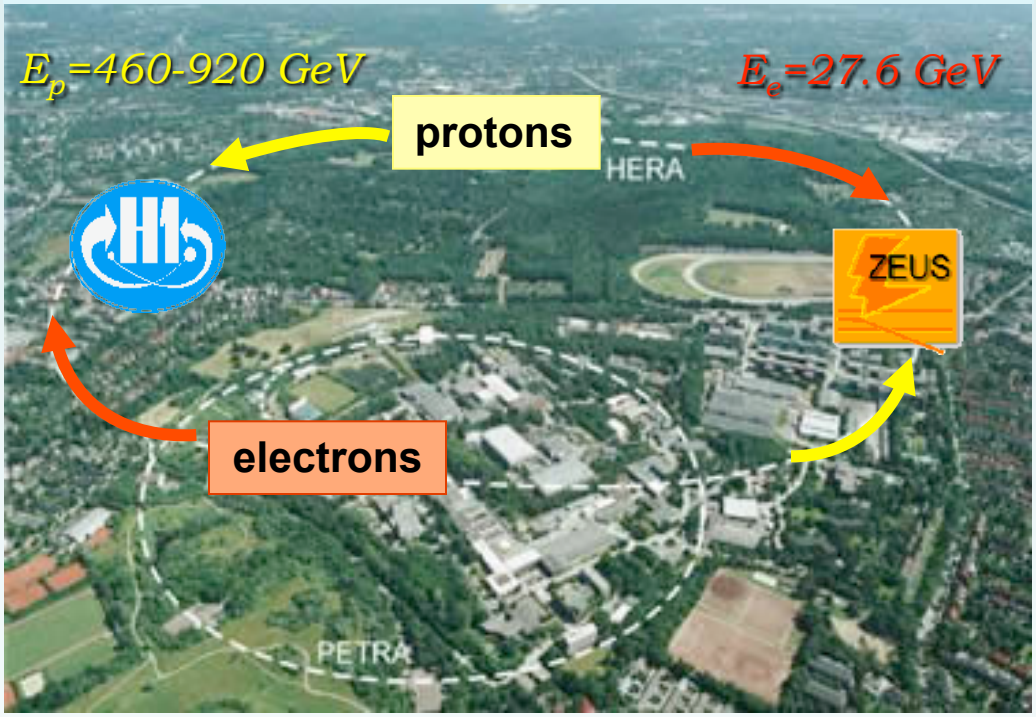
Katerina Lipka, DESY

for the H1 and ZEUS Collaborations

European Physical Society Conference on High Energy Physics 2013

Deep Inelastic Scattering at HERA

World-only ep collider



- HERA I : 1992-2000
- HERA II: 2003-2007
- collider experiments

H1 & ZEUS, $\sqrt{s_{max}} = 318\ GeV$

- integrated Luminosity

$\sim 0.5\ fb^{-1}$/ experiment

HERA switched off June 2007, analyses ongoing on the way to final precision

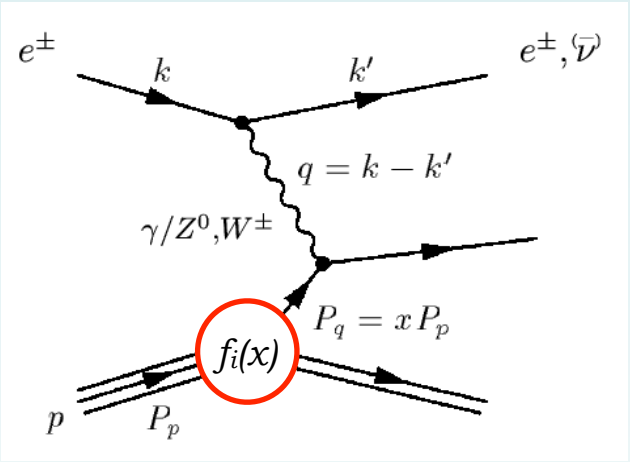
H1 and ZEUS combine experimental data accounting for systematic correlations

HERA performs the QCD analysis of (semi) inclusive DIS data (HERAPDF)

H1 and ZEUS collaborations provide/support the PDF Fitting Tool (HERAFitter)

Deep Inelastic Scattering and Charm Production at HERA

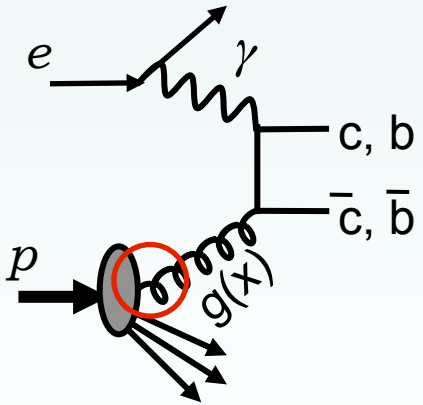
DIS at HERA: clean lepton probe



Kinematics reconstructed from the scattered lepton (or hadronic final state)

$Q^2 = -q^2$	*boson virtuality*
$x = -q^2/2p\cdot q$	*Bjorken scaling variable*
$s = (k+p)^2$	*center of mass energy*
y	transferred energy fraction

Heavy quarks in *ep* scattering produced in boson-gluon fusion



Contribution to total DIS cross section:

charm: ~ 30% at large Q^2

beauty: few % at large Q^2

Gluon directly involved:

cross-check of $g(x)$ from inclusive DIS measurements

Direct test of different heavy flavour treatment schemes

Heavy Quark Schemes in QCD Analysis

Factorisation: $$F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

i - number of active flavours in the proton: defines the factorisation (HQ) scheme

- i fixed : Fixed Flavour Number Scheme (FFNS)

  only light flavours in the proton: i = *3 (4)*

  c- (b-) quarks massive, produced in boson-gluon fusion

  $Q^2 \gg m_{HQ}^2$: can be less precise, NLO coefficients contain terms ~ $ln(\frac{Q}{m_{HQ}})$

- i variable: Variable Flavour Number Scheme (VFNS)

- Zero Mass VFNS: all flavours massless. Breaks down at $Q^2 \sim m_{HQ}^2$

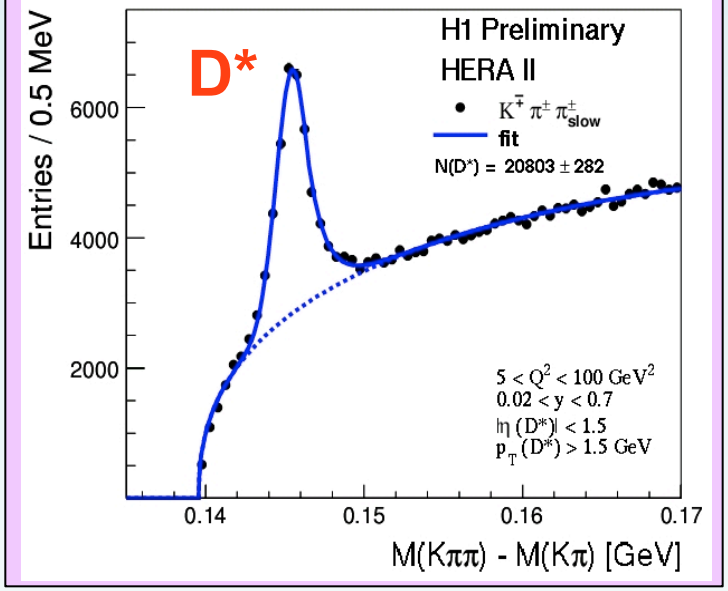
- Generalized Mass VFNS: different implementations provided by PDF groups

  smooth matching with FFNS for $Q^2 \to m_{HQ}^2$ must be assured

Issues in QCD analysis: treatment of heavy quarks, heavy quark mass value

Heavy Quark Tagging Methods at HERA

charmed mesons



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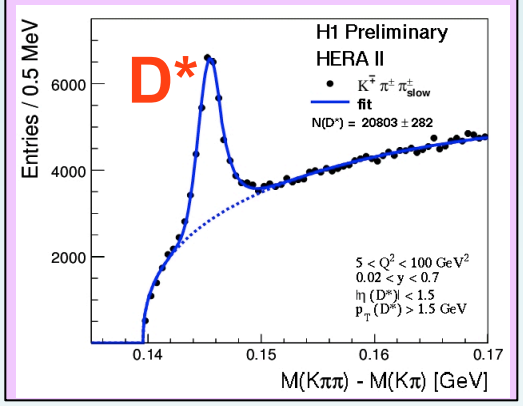
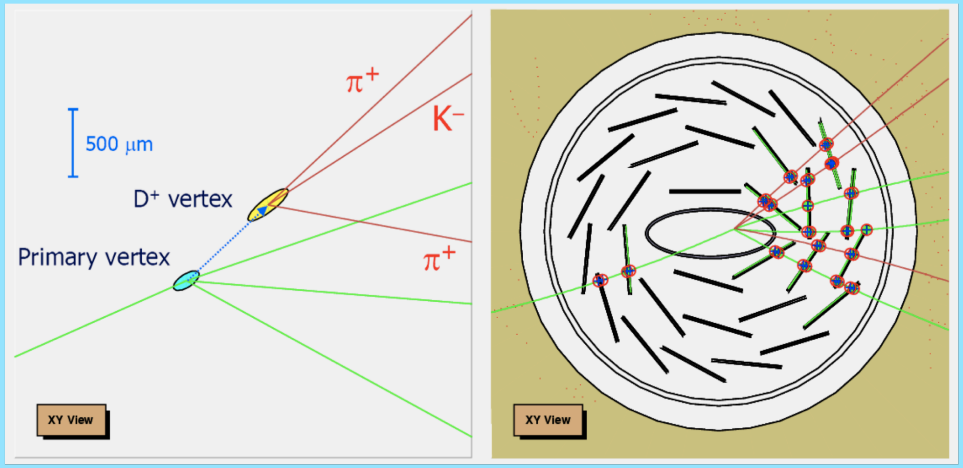


+ vertex reconstruction



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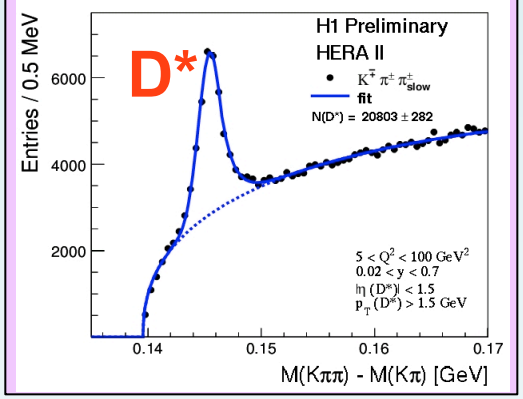

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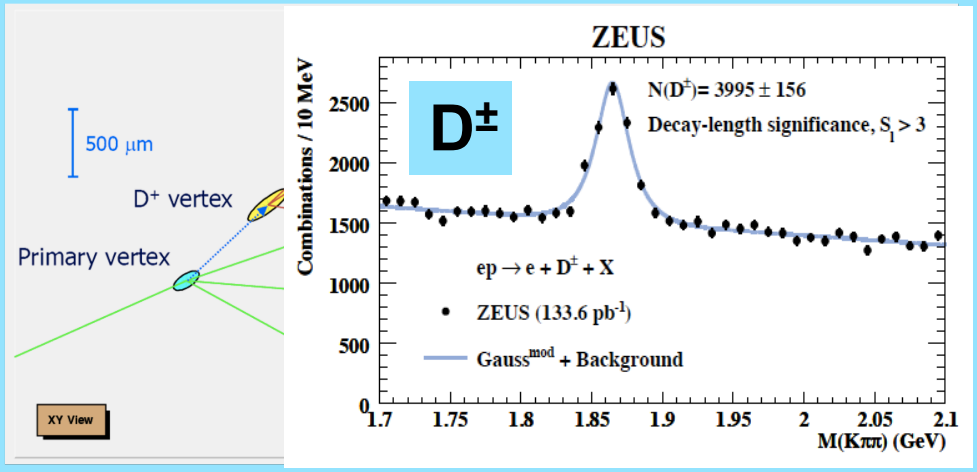

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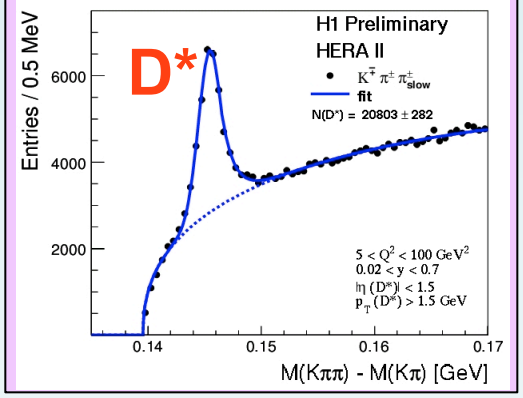
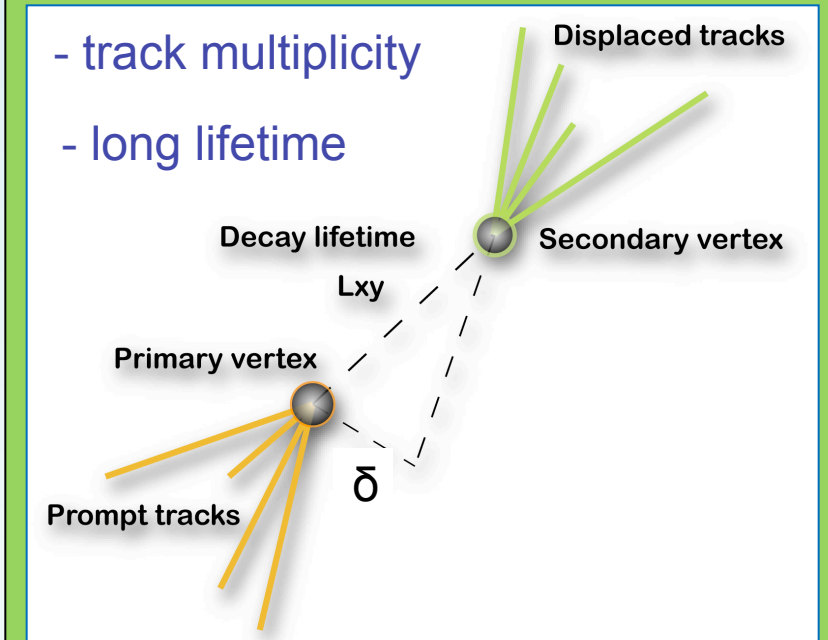


properties of c-, b- hadrons:

- track multiplicity
- long lifetime



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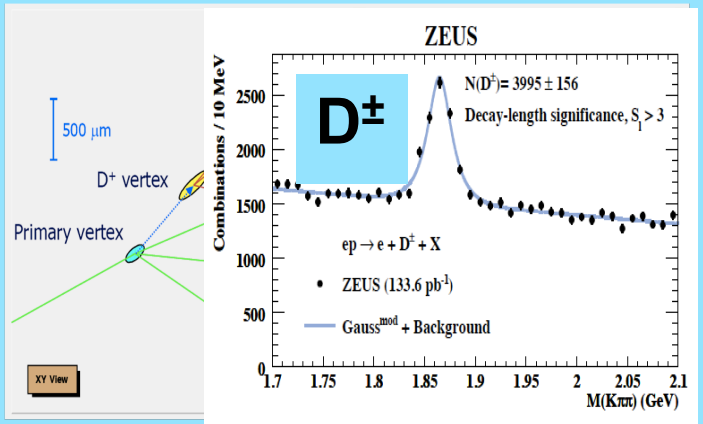

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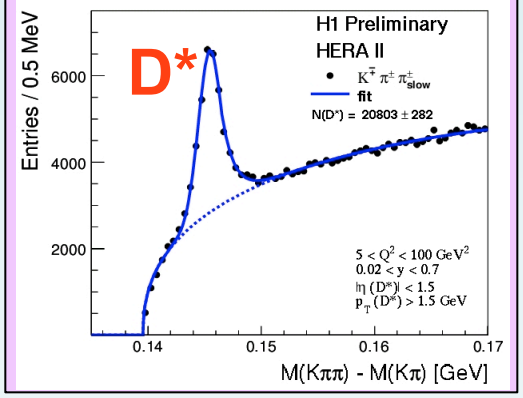
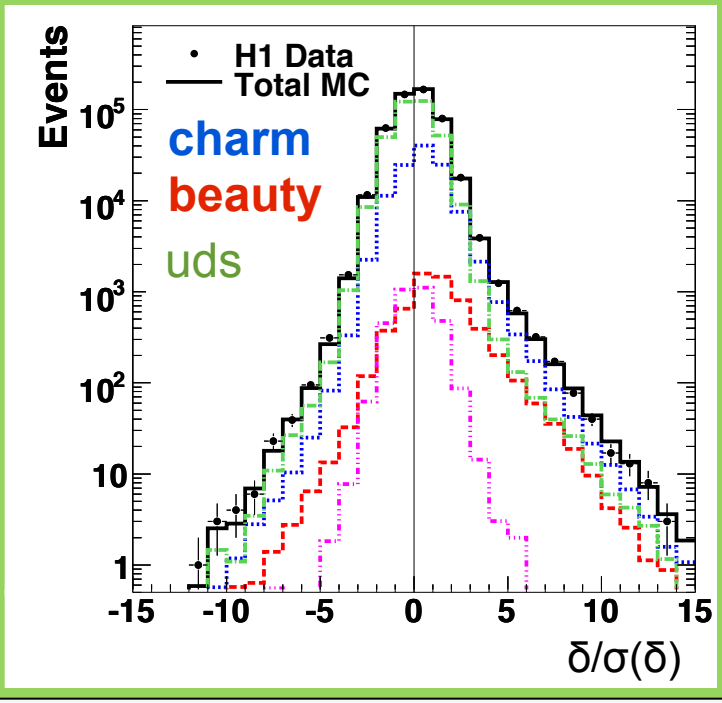


track displacement significance



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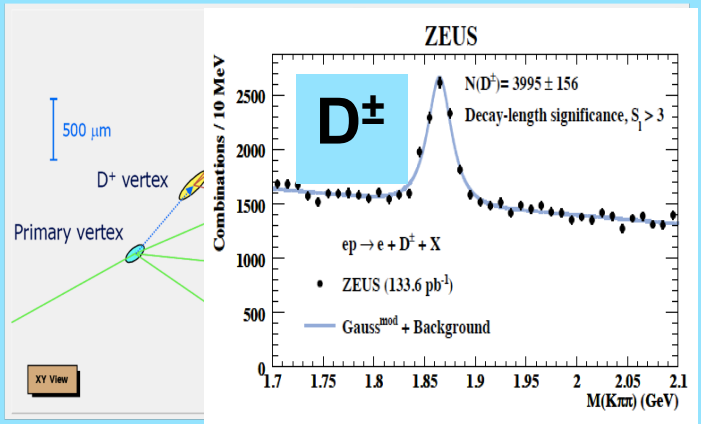

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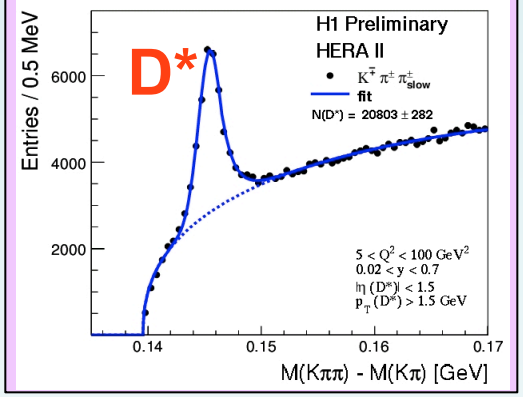
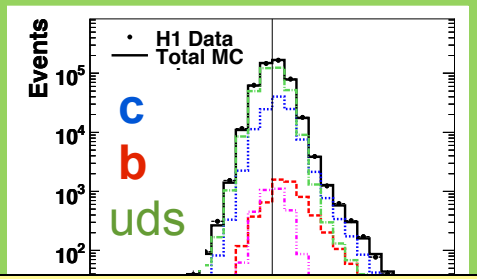
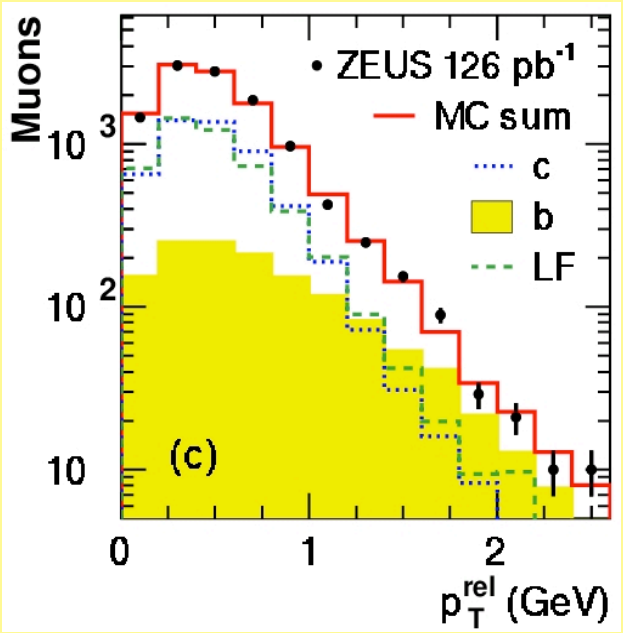
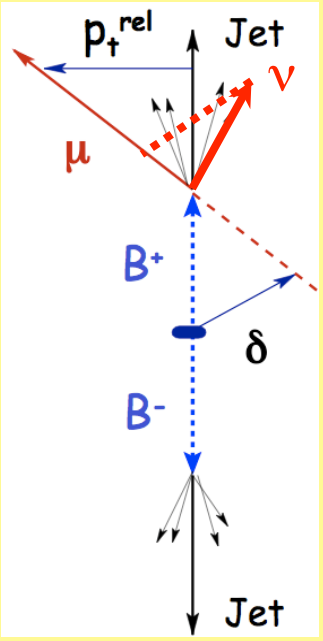


track displacement

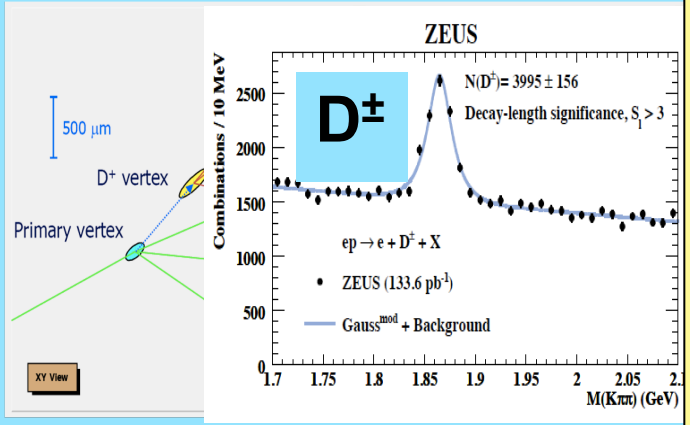


semi-leptonic decays of c and b



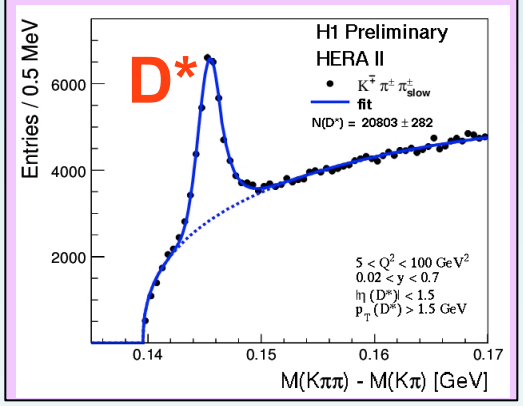


+ vertex reconstruction



Heavy Quark Tagging Methods at HERA

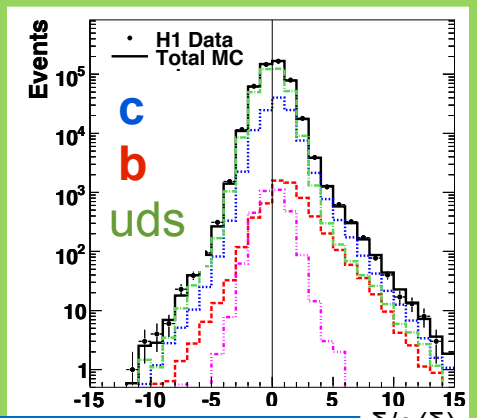
charmed mesons



different tag methods

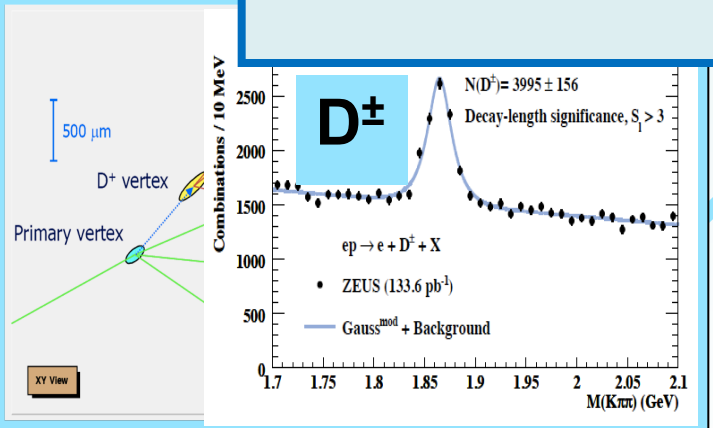
orthogonal systematics

track displacement

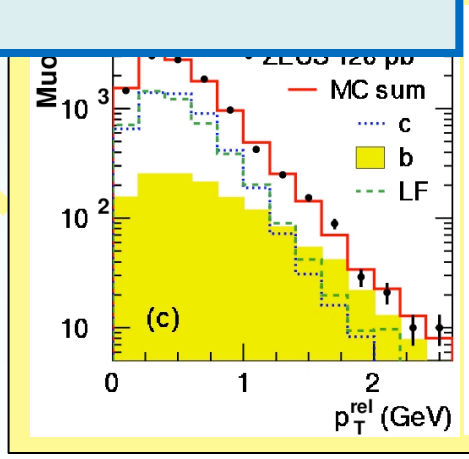


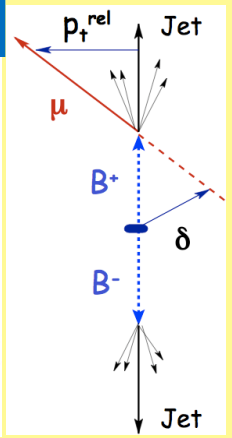
Combination of all measurements

+ ver



ys of c, b





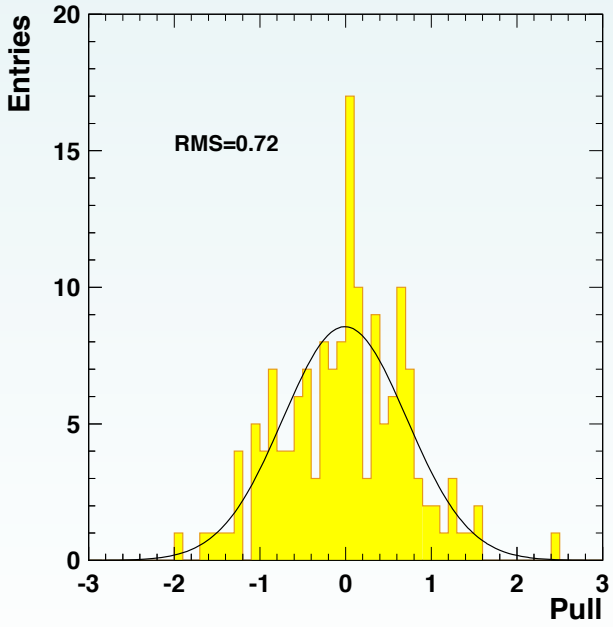
HERA Combined Charm Cross-Sections

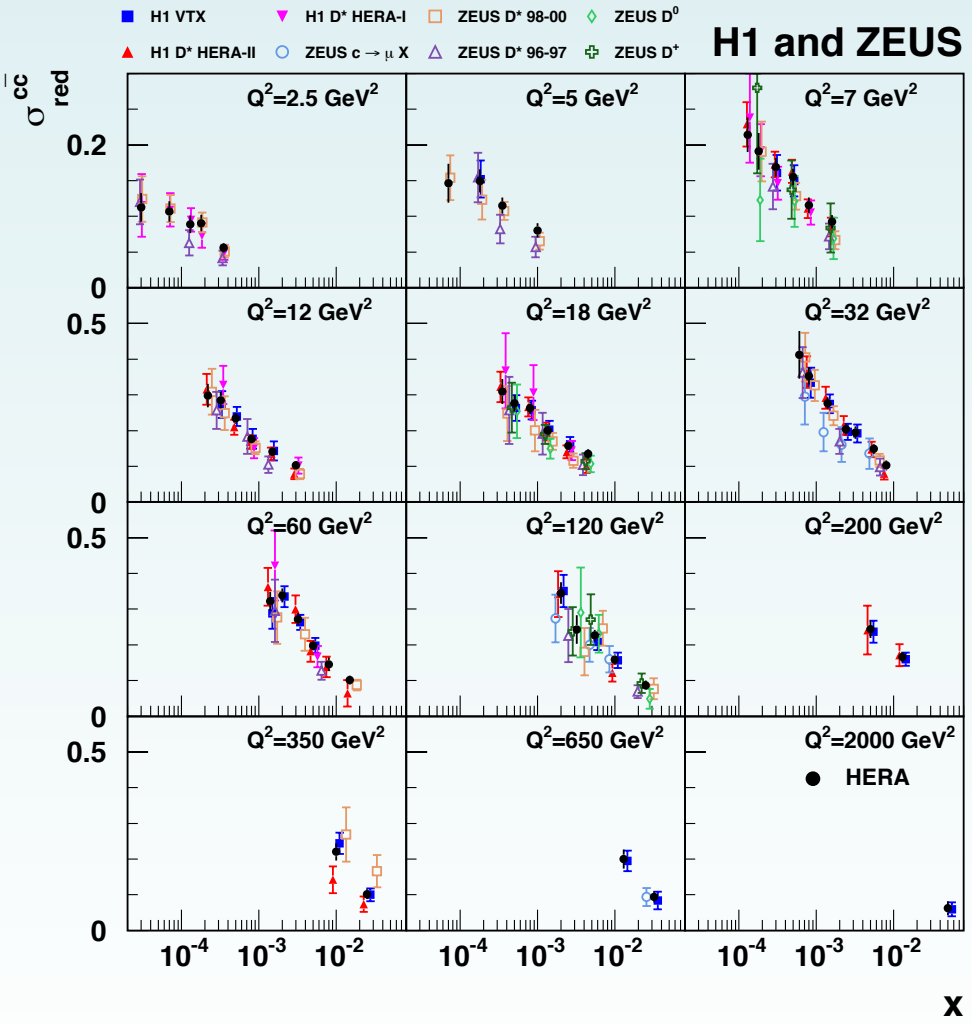
9 data sets, 155 measurements
5 charm tagging methods
consistent theory treatment for all data

combined to 52 data points
48 sources of correlated systematics

Eur. Phys. J. C 73:2311 (2013), [arXiv:1211.1182]

very good consistency of the data





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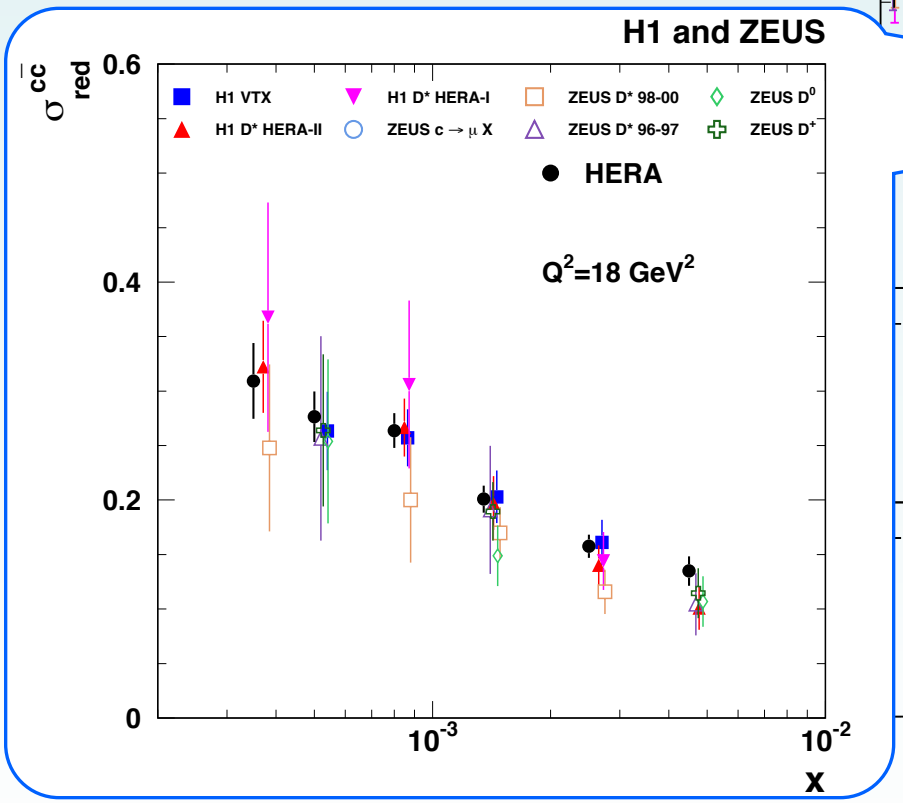
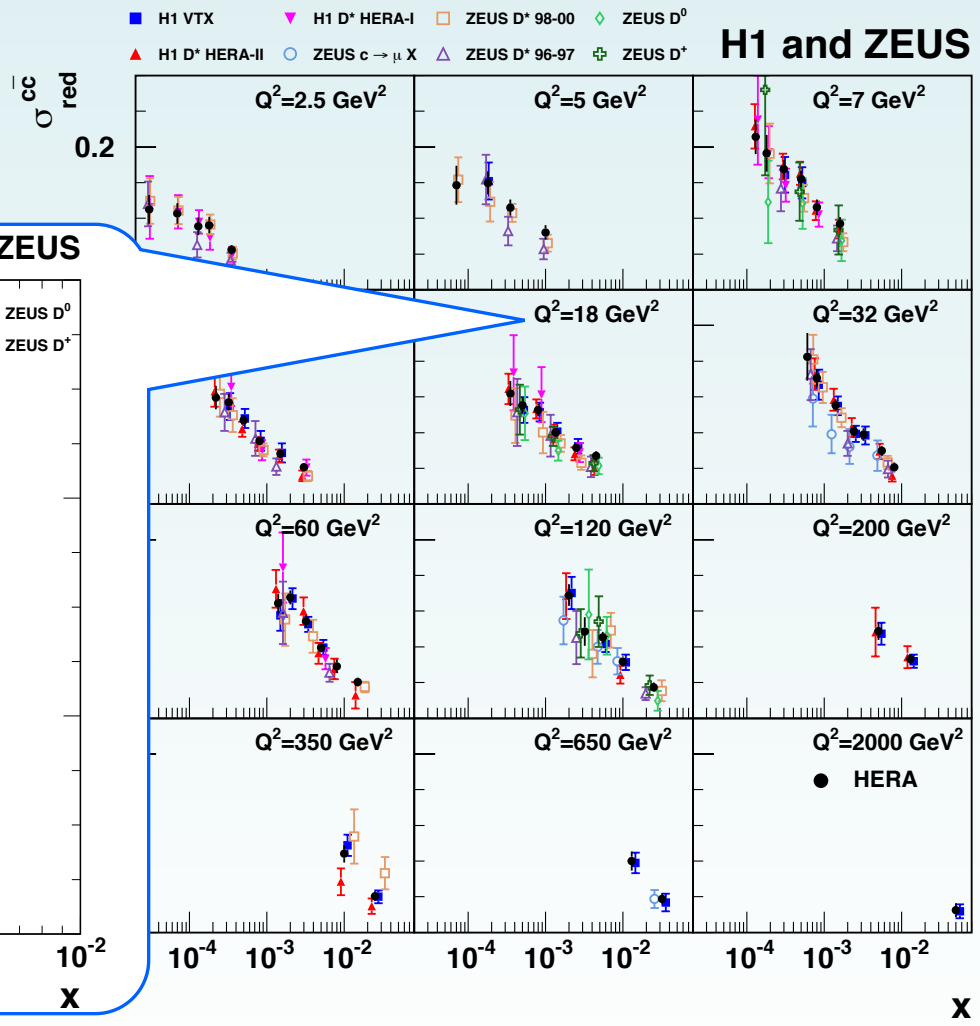




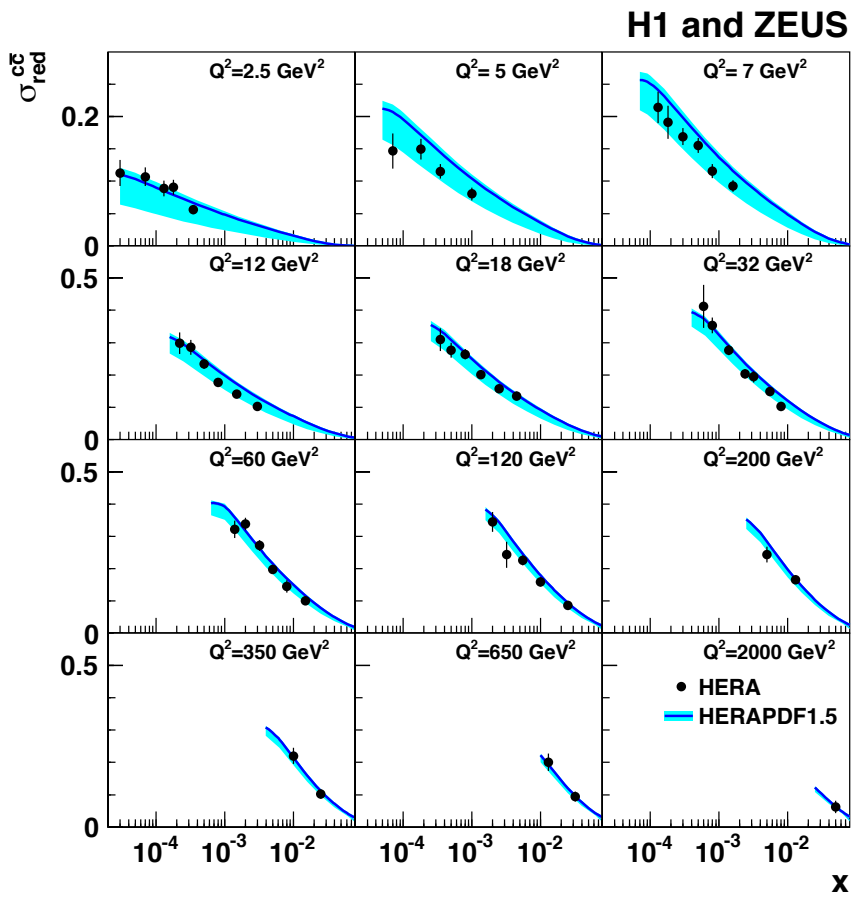
Precision ~ 5% at medium Q^2 reached

HERA Charm Data test PDFs obtained with inclusive DIS

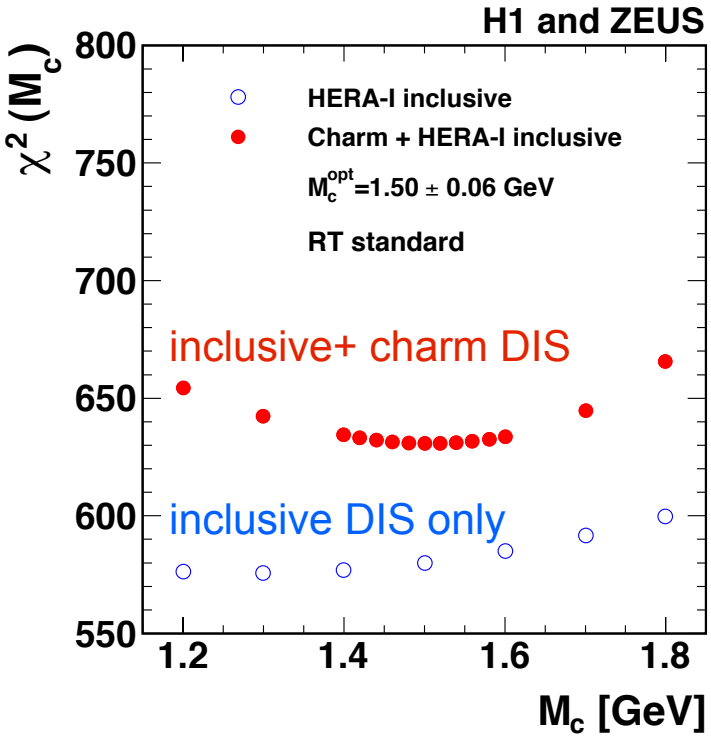
HERAPDF is obtained using only **inclusive** HERA DIS NC and CC data, use VFNS

Describes charm cross-sections very good

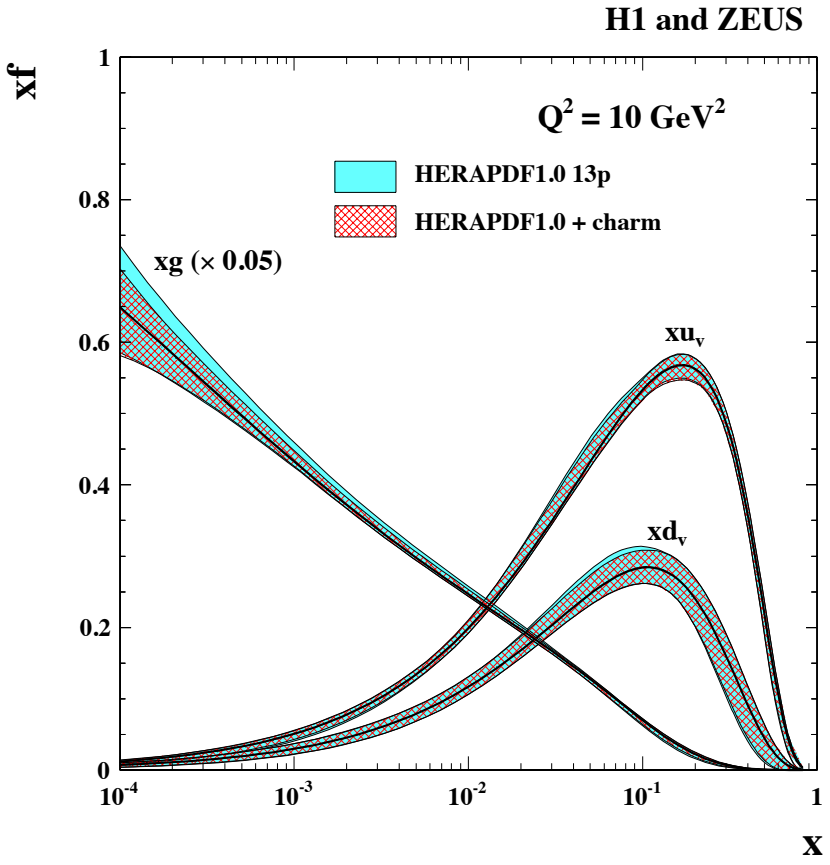
Uncertainty band mostly due to variation of charm quark mass in PDF: $1.35<m_c<1.65$ GeV

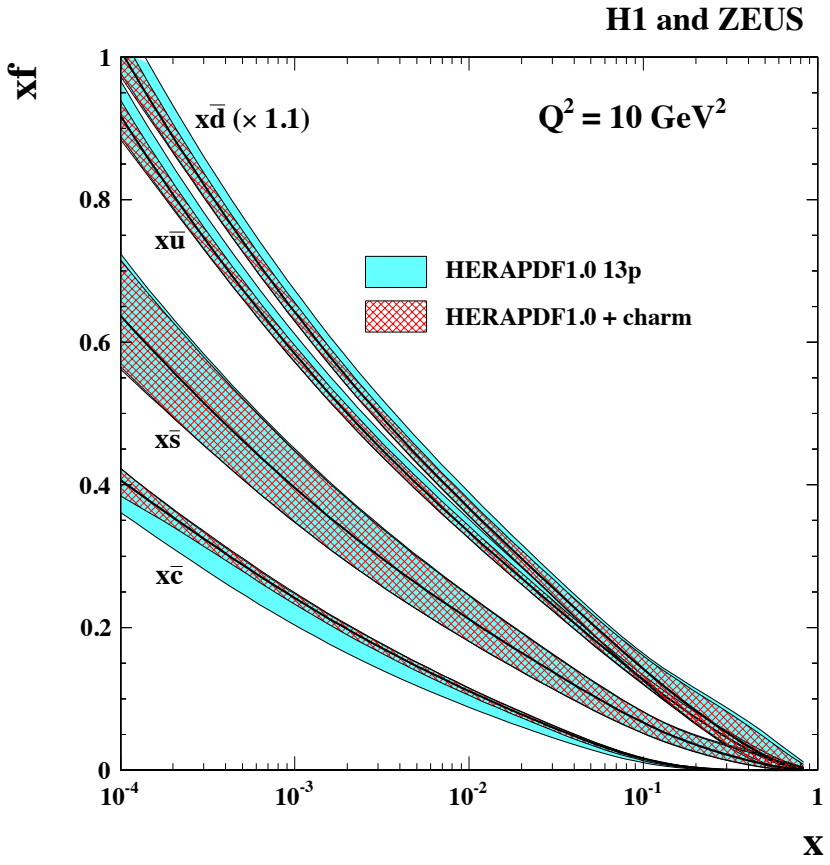


Sensitivity to charm mass in PDF fit increased once HERA charm data used together with inclusive DIS data



QCD Analysis of Charm Data



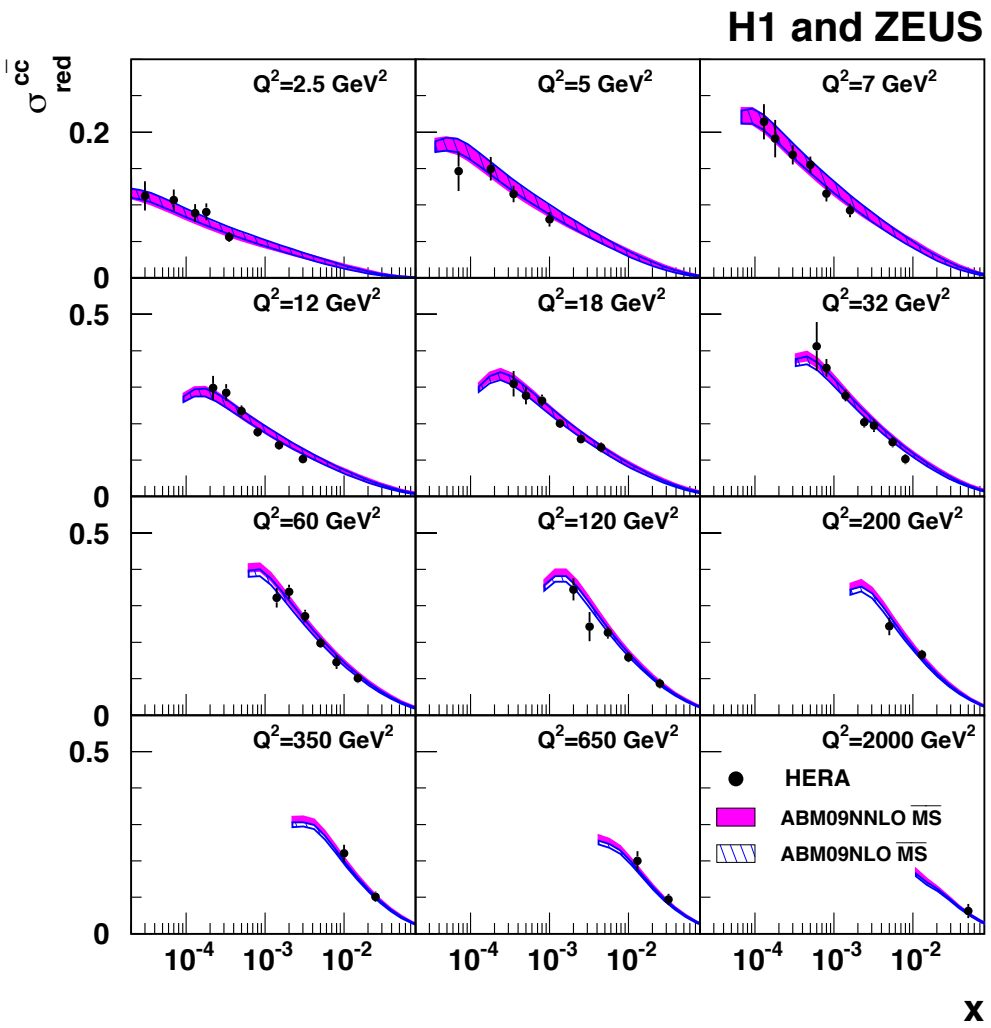


Inclusion of charm: reduced uncertainty on gluon, charm and light sea

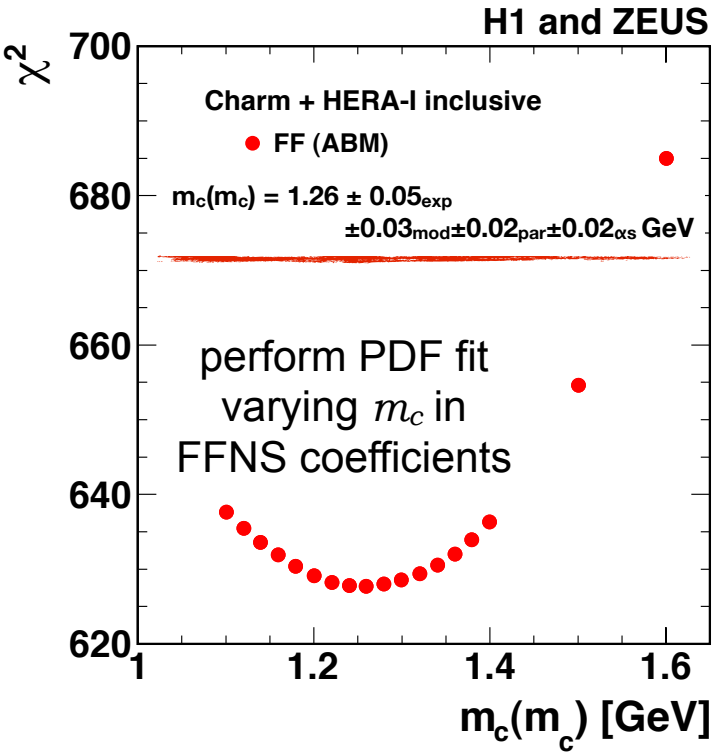
...mostly due to better constrained charm-quark mass

HERA Charm Data vs QCD Analysis in FFNS

QCD Predictions at NLO (~α_s^2) and NNLO (~α_s^3) describe data very well
Running mass of charm quark is used in coefficient functions in QCD analysis



Determine $m_c(m_c)$ in $\overline{MS}$ at NLO

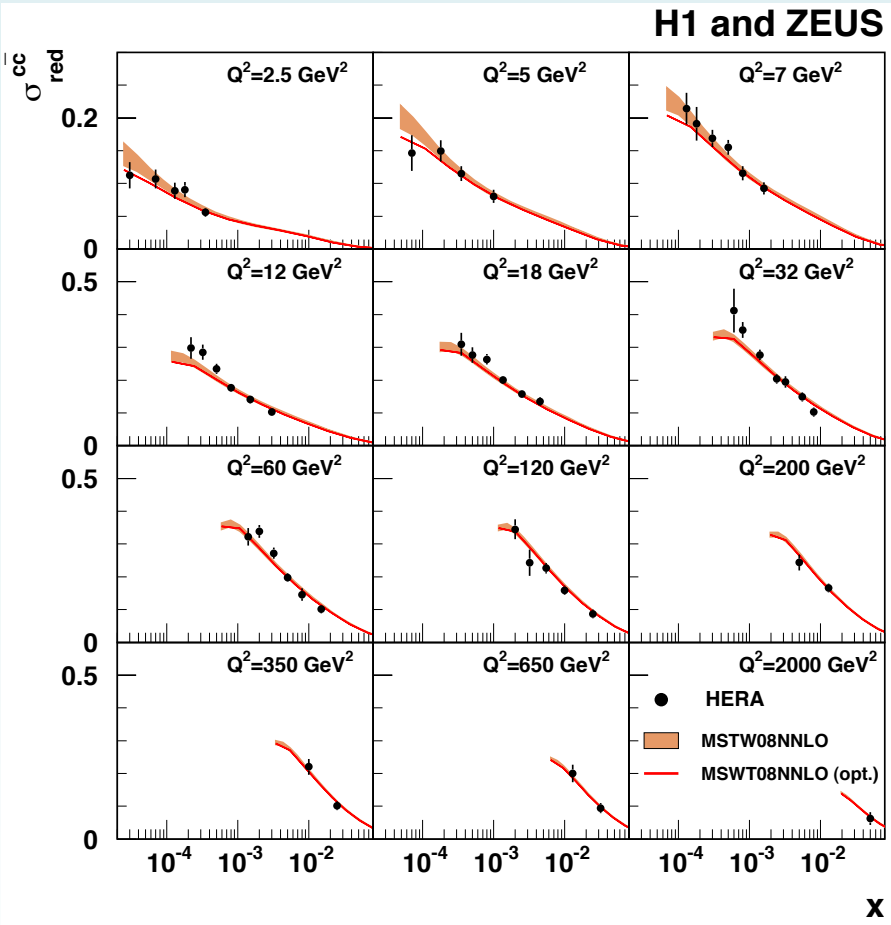


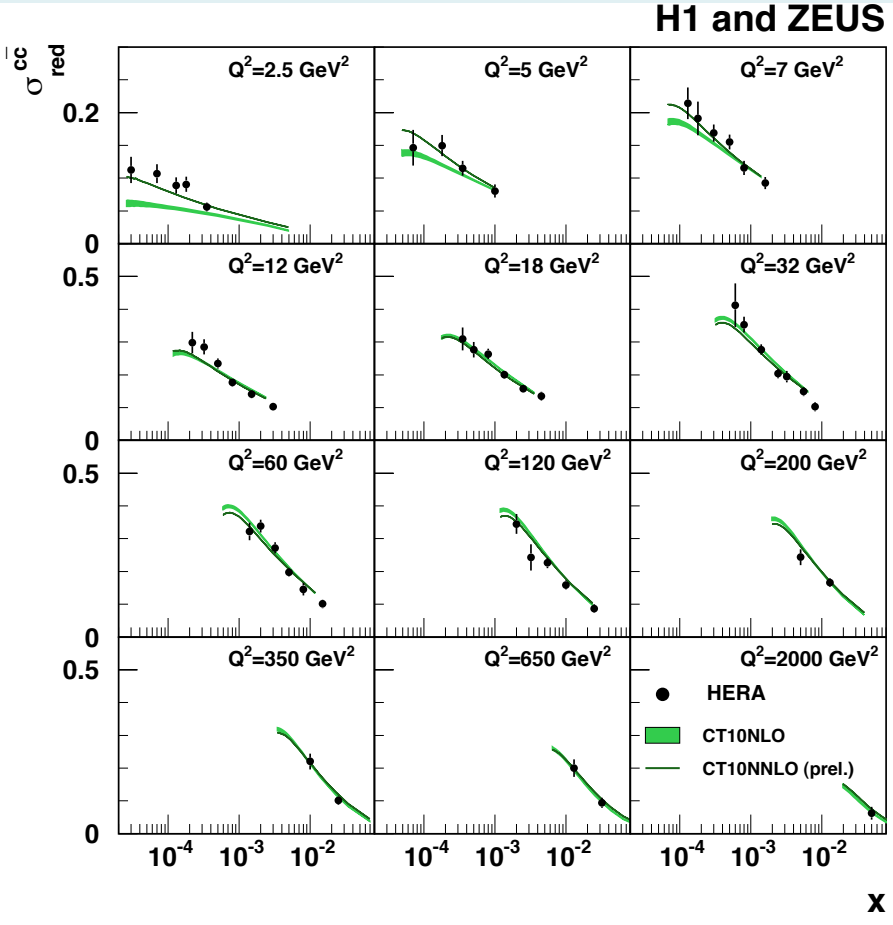
Consistent with the world average

$m_c(m_c)_{wa}$ = 1.275 ±0.025 GeV

HERA Charm Data vs QCD Analysis in VFNS

Data are confronted to predictions using Variable-Flavour Number Scheme at NLO (α_s) and NNLO (α_s^2)

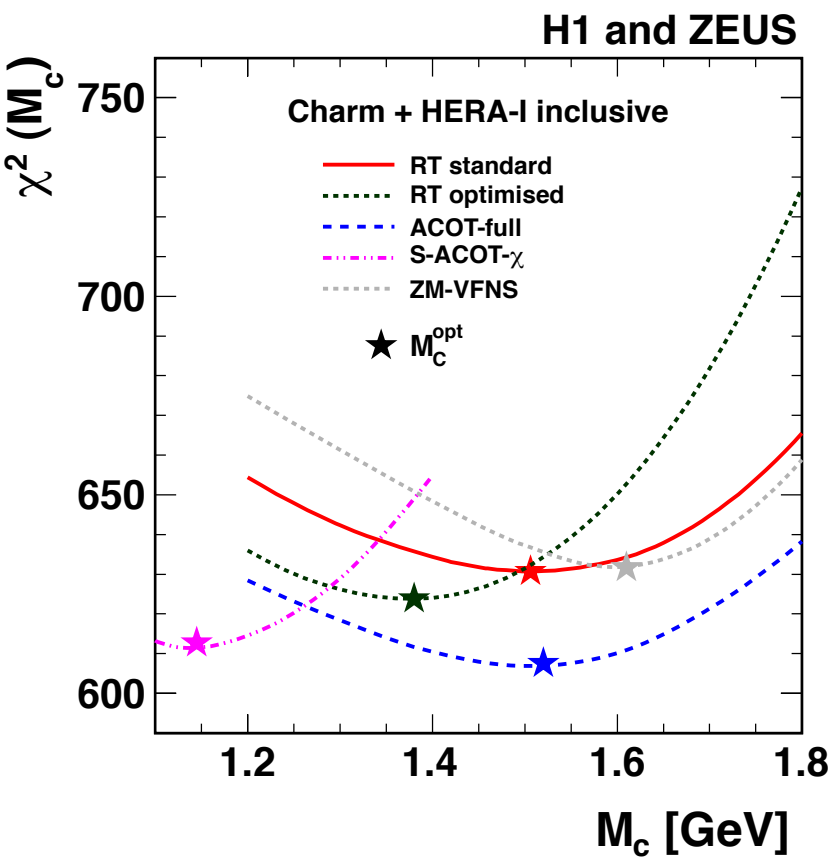




Predictions using heavy quark coefficients at higher order describe data better at lower Q^2

Charm mass in Variable Flavor Number Scheme

Study charm mass choice in PDF using different VFNS implementations using HERAFitter



different implementation of VFNS
use m_c^{pole} in the HQ coefficients

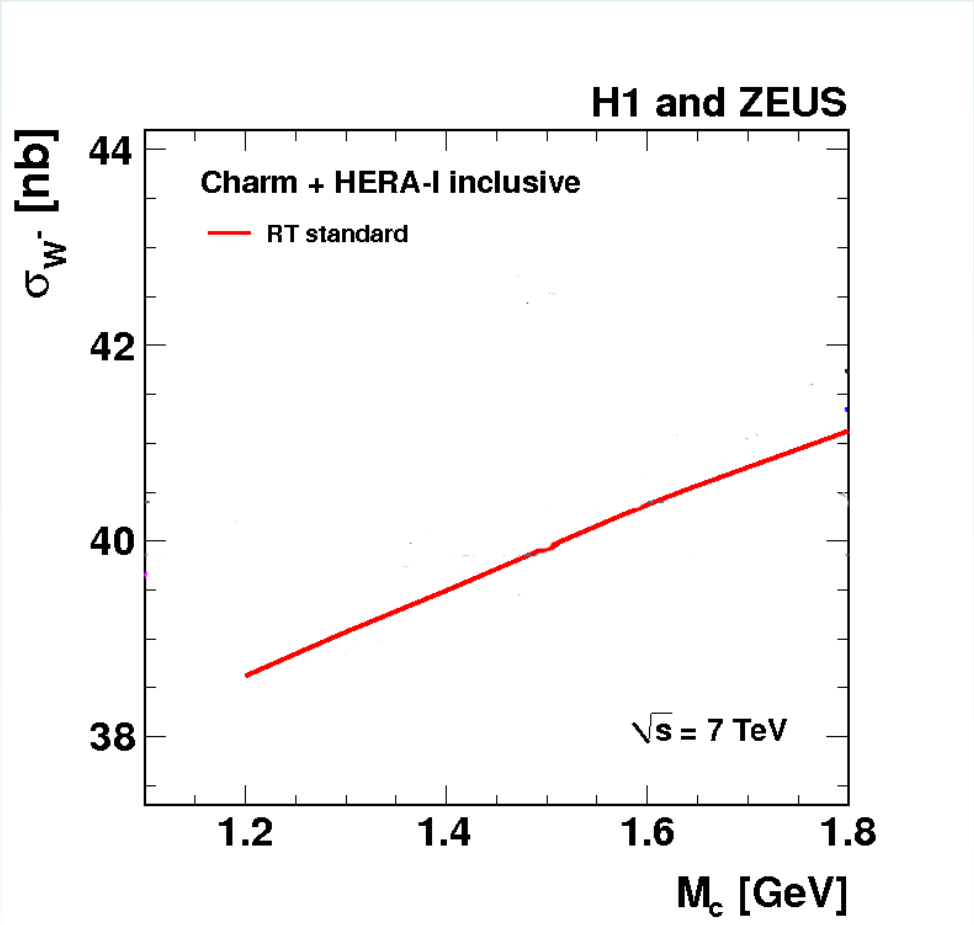
matching between N_{flavor} to $N_{flavor+1}$,
(*choosing an interpolation approach and different methods for truncation of the perturbative series*)
→ definition of m_c(pole) gets as uncertain as matching conditions: $m_c^{pole} \rightarrow M_c$

parameter M_c is implicitly used in predictions for the LHC processes using VFNS PDFs (CTEQ, MSTW, NNPDF, HERAPDF)

Different schemes prefer different M_c

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

NLO prediction for W^+ (W^-, Z) production at the LHC: dependence on charm mass in PDF

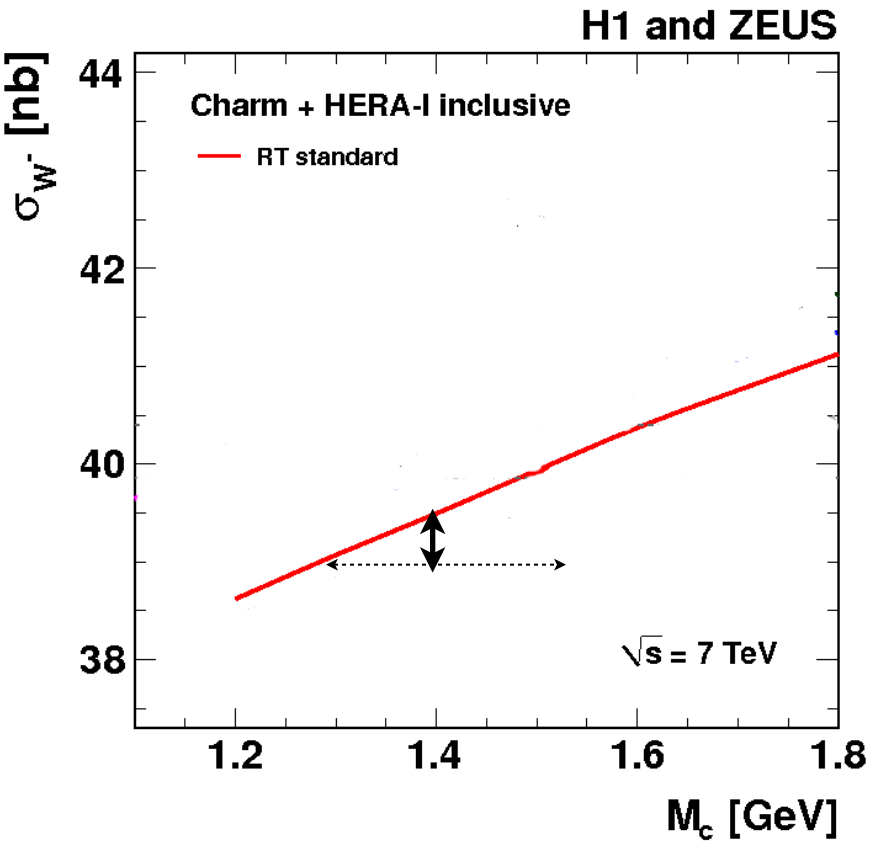


Larger M_c → more gluons, less charm → more light quarks → larger σ_W

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

NLO prediction for W+ (W-, Z) production at the LHC: dependence on charm mass in PDF

Only one HQ scheme



M_c variation in PDF

$1.3 < M_c < 1.5$ GeV

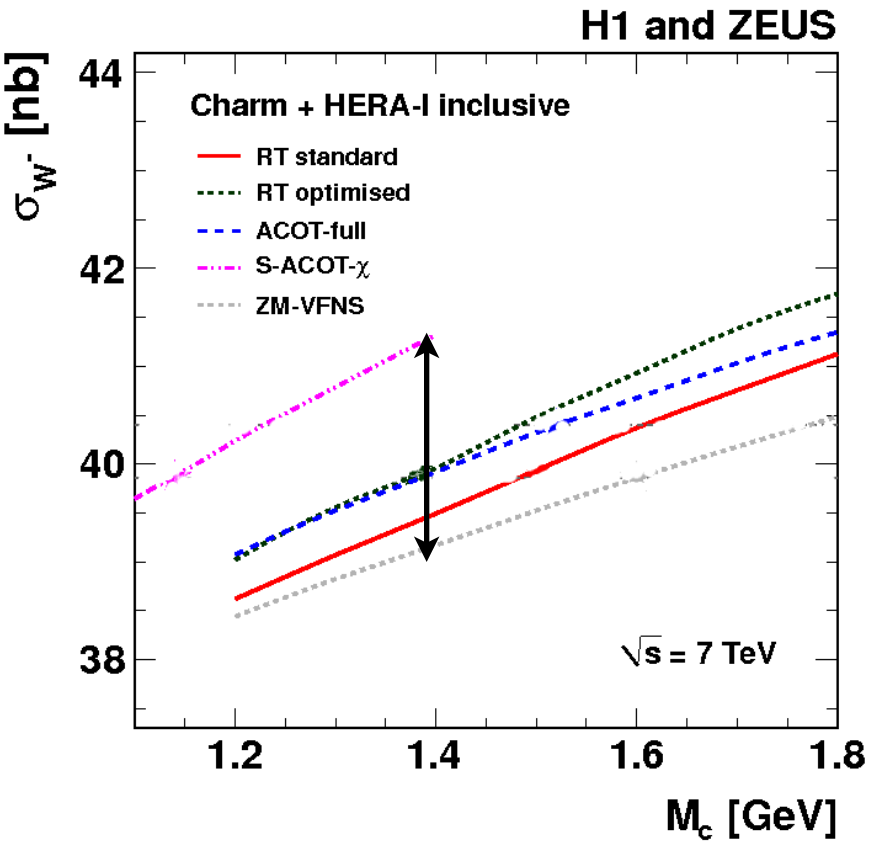
3% uncertainty on W prediction

Larger $M_c \rightarrow$ more gluons, less charm $\rightarrow$ more light quarks $\rightarrow$ larger σ_W

Effect of charm mass in VFNS PDF on σ(W, Z) at NLO

NLO prediction for W^+ (W^-, Z) production at the LHC: dependence on charm mass in PDF

Several HQ schemes



M_c variation in PDF

$1.3 < M_c < 1.5$ GeV

3% uncertainty on W prediction

Using different HQ schemes:

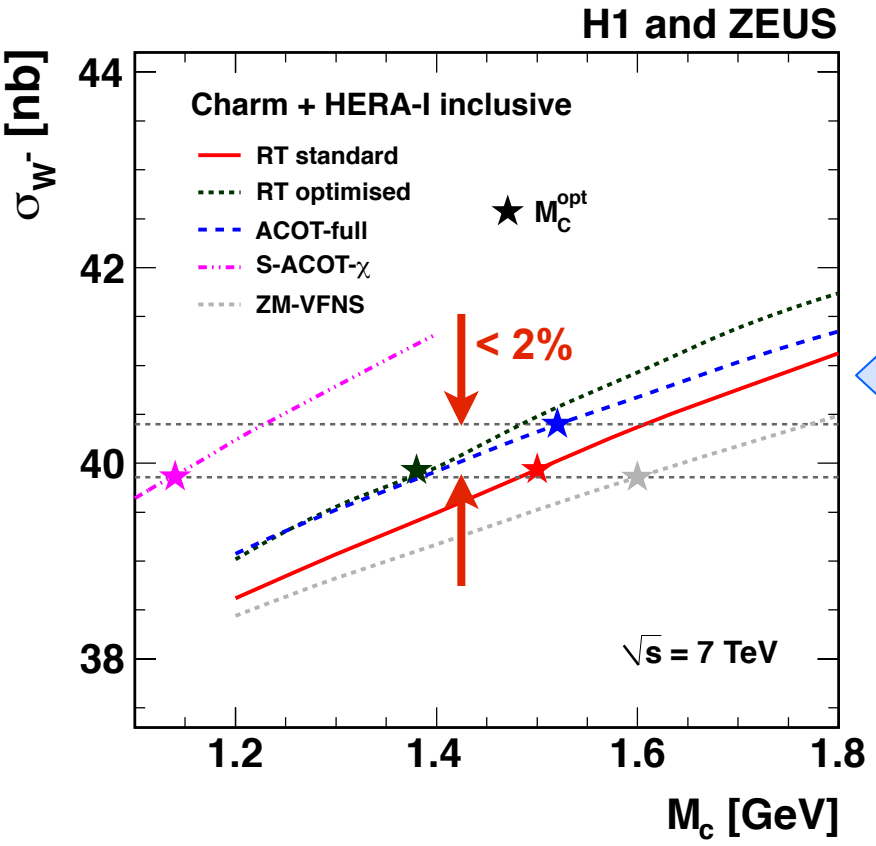
+ 7% uncertainty

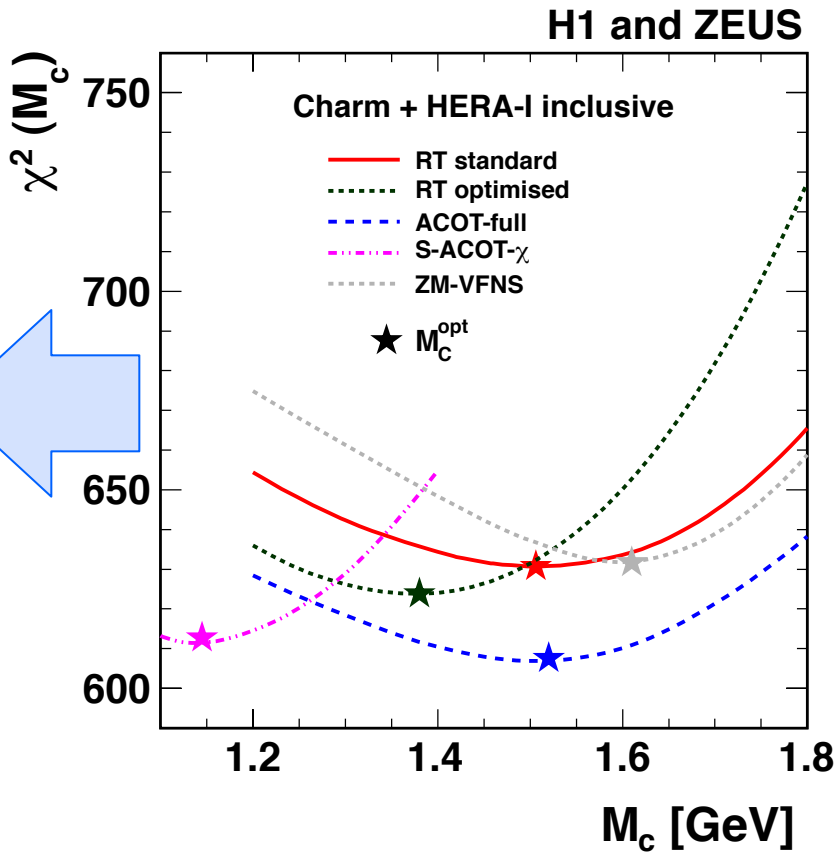
Larger $M_c \rightarrow$ more gluons, less charm $\rightarrow$ more light quarks $\rightarrow$ larger σ_W

Data sensitivity to different heavy quark treatments in PDFs

NLO prediction for W^+ (W^-, Z) production at the LHC: dependence on charm mass in PDF

Use optimal M_c in each scheme

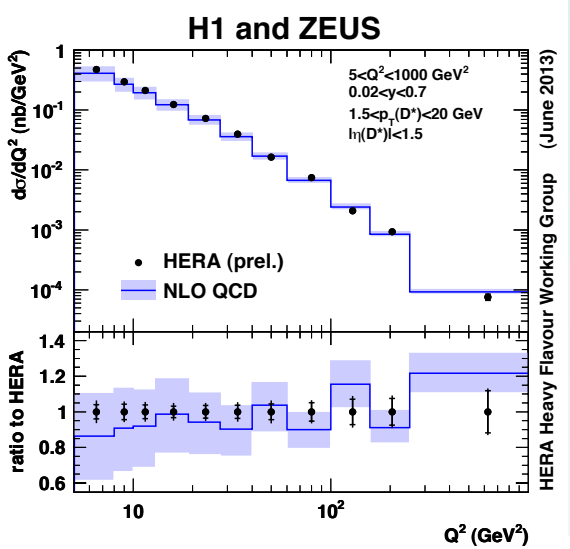


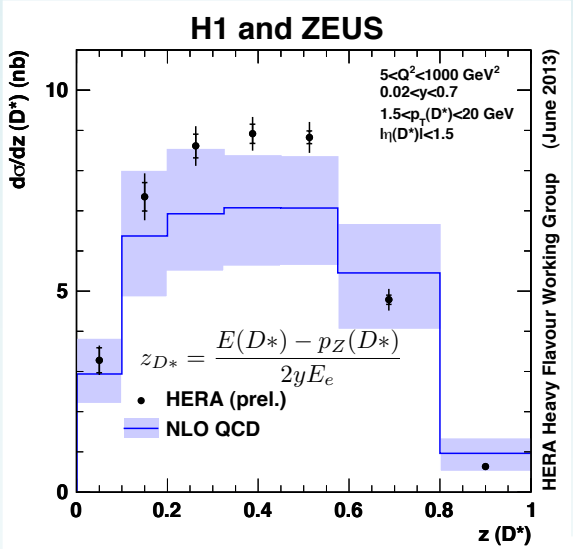


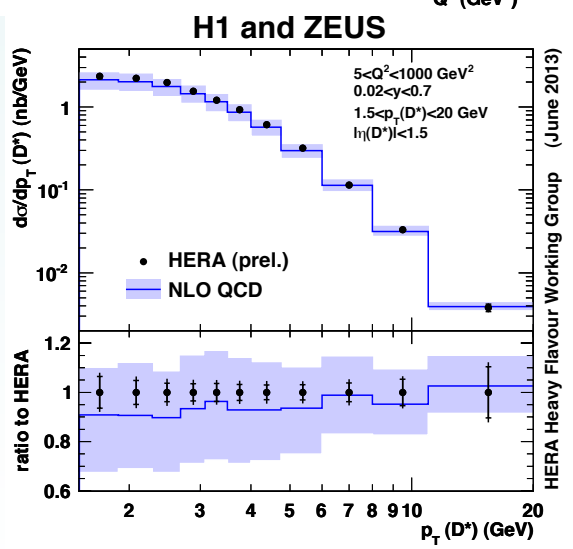
Uncertainty due to differences in charm treatment in PDFs significantly reduced by using optimal M_c in each HQ scheme in PDF

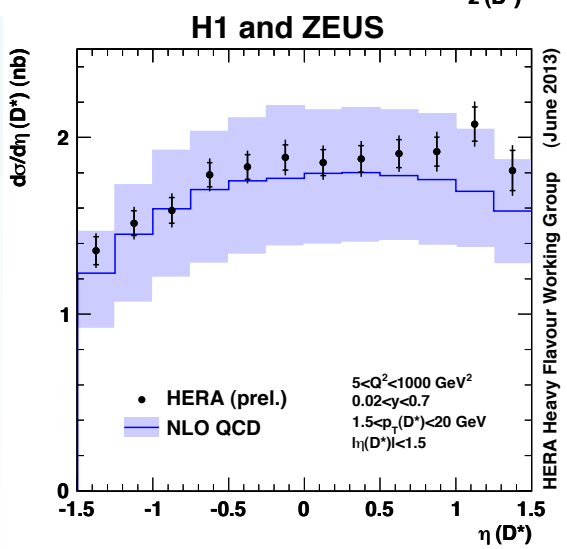
NEW: combined D* differential cross sections

shapes of the D* kinematic distributions sensitive to m_c in NLO QCD and fragmentation model
combined HERA D* differential cross sections can be used for further theory constraints









H1prelim-13-141, ZEUS-prel-13-002

[H1 Collaboration], Phys. Lett. B686, **(2010) 91**
[H1 Collaboration], Eur. Phys. J. C71 **(2011) 1769**
[ZEUS Collaboration], DESY-13-054

NLO QCD (HVQDIS)
m_c=1.5±0.15 GeV

$\mu^2_r = \mu^2_f = \mu^2_0\ Q^2+4m^2_c$

scales varied independent
¼ $\mu^2_0 < \mu^2_r \neq \mu^2_f < 4\mu^2_0$

PDF: HERAPDF1.0 FFNS

Kartvelischwili fragmentation,
details in Eur. Phys.J.C 73:2311 (2013)

Summary

HERA combined open charm cross section measurement

- important milestone in HERA DIS program accomplished
- precision of 5% reached at medium Q^2

Combined charm measurements included in QCD analysis

Sensitivity to assumption of charm quark mass in PDF fit improved

Running mass of charm quark, $m_c(m_c)$ determined in FFNS at NLO

- consistent with previous analysis at NLO *S. Alekhin et al,.Phys. Lett. B 718 (2012) 550*
- consistent with PDG world average at NNLO

Optimal charm mass in PDF, M_c, using different VFNS determined

- improved prediction of W and Z cross sections at the LHC

Differential cross sections of D* mesons at HERA combined

- experimental precision is challenging to the theory