QCD analysis of combined HERA $F_2^{c\bar{c}}$ data and Impact for the LHC

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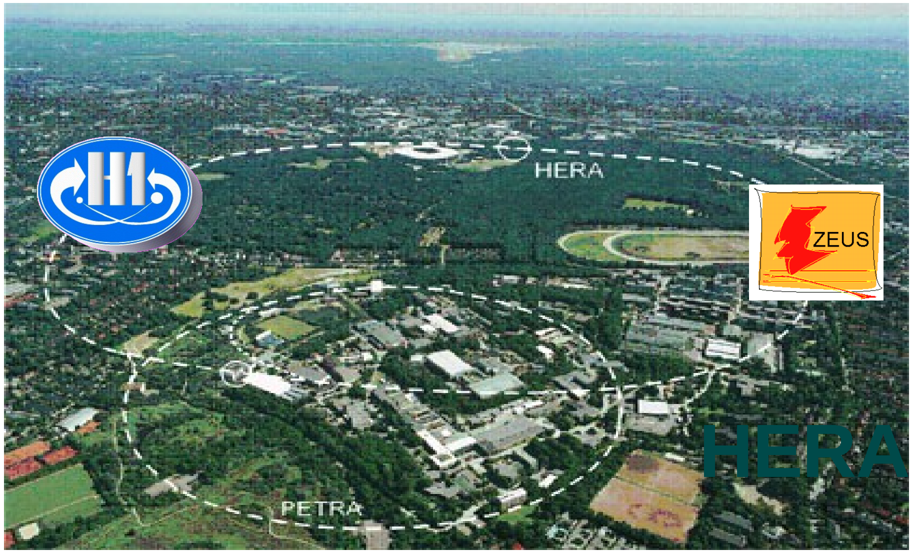
SM Benchmarks at the TEVATRON and LHC
19-20 Nov 2010, Fermilab

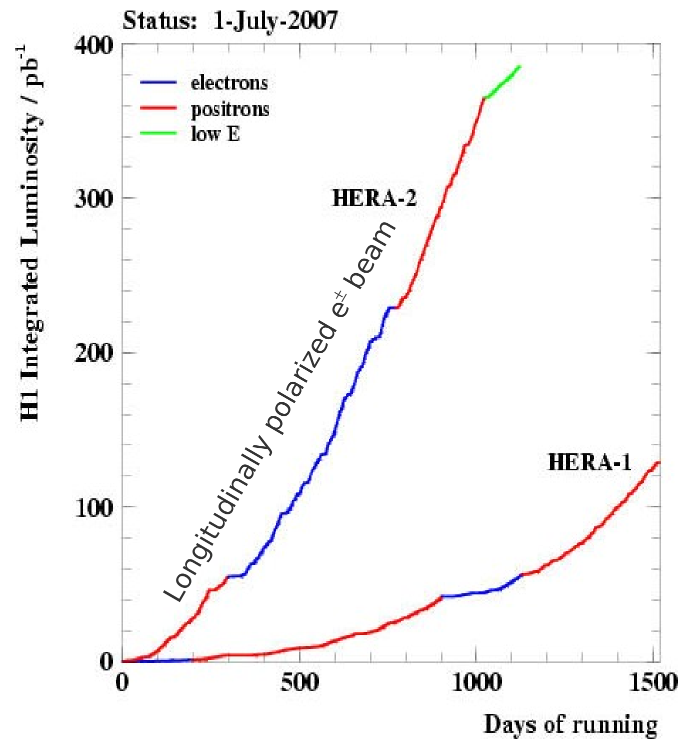
Outline:

- Introduction and motivation
- Scanning of m_c in different heavy flavour schemes
- Predictions of $Z/W^{\pm}$ cross sections at LHC
- Summary

HERA Collider

World's only *ep* collider





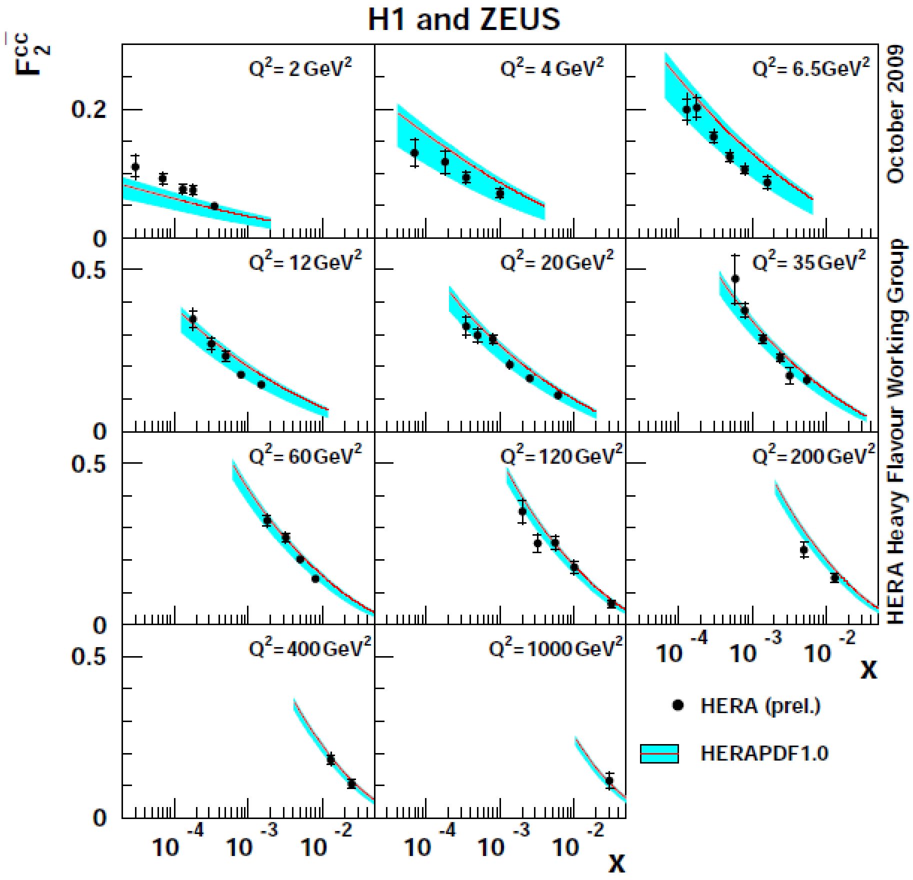
- $e^{\pm}$(27.5 GeV), p(460-920 GeV), $\sqrt{s}$ = 225-318 GeV
- Two large multipurpose detectors: H1 and ZEUS

- 1994-2000: HERA I data
  2003-07 HERA II data with longitudinal $e^{\pm}$ polarisation
- ~0.5 fb^{-1} of luminosity recorded by the each experiment

HERA charm data

Preliminary F_2^{cc} measurement - most precise determination of F_2^{cc} from HERA

- combination of 9 H1 and ZEUS measurement → 5-10% uncertainty
- significant contribution to DIS cross section



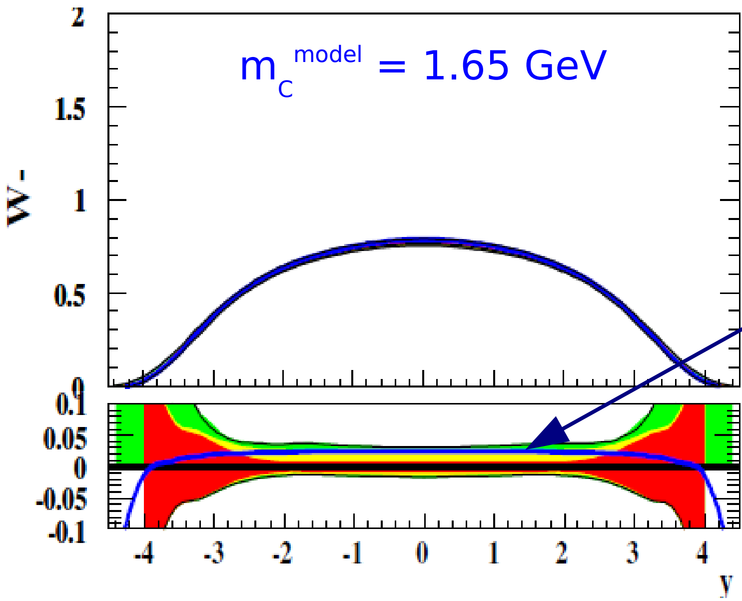
- good agreement of HERAPDF1.0 predictions with F_2^{cc} data

- the band represents HERAPDF1.0 uncertainty from m_c^{model} parameter variation (1.35 – 1.65 GeV)

- data are within the uncertainty band

→ can provide significant constraint on m_c^{model}

Impact on the LHC predictions



- variation of m_c^{model} changes predictions of Z/W cross sections at LHC by ~3%

A.M.Cooper-Sarkar,
PDF4LHC, March 2010

- sensitivity to charm of the LHC cross section predictions comes from flavour sensitivity of the inclusive DIS data

$$xU = xu + xc \quad x\bar{U} = x\bar{u} + x\bar{c} \quad xD = xd + xs \quad x\bar{D} = x\bar{d} + x\bar{s}$$

- where *U* is fixed by F_2 data
  larger m_c^{model} $\rightarrow$ less *c* in sea $\rightarrow$ more *u*

- important at low Q^2 and low x

QCD analysis of F_2^{cc} data

NLO QCD analysis of the preliminary HERA F_2^{cc} data

- together with the published inclusive HERA data (**HERAPDF 1.0**)
- same settings as in HERAPDF 1.0 arXiv:0911.0884

- different implementations of general mass variable flavour number (GM-VFNS) schemes for heavy flavour treatment used in this study:

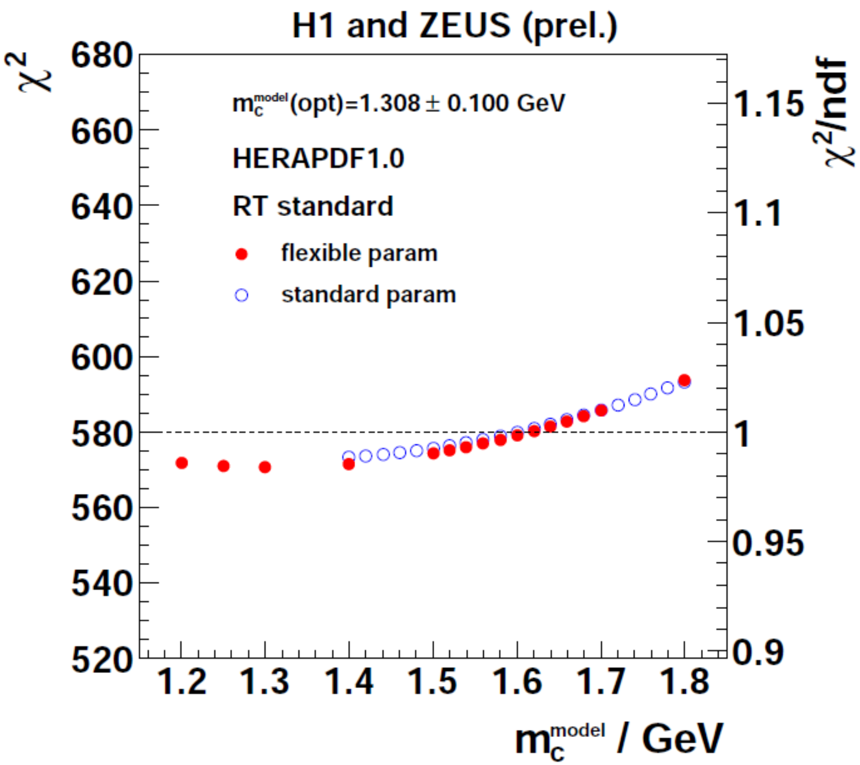
RT standard	used by MSTW08
RT optimised [arXiv:1006.5925]	
ACOT-full	used by CTEQ4,5,6HQ
S-ACOT-χ	used by CTEQ6.5,6.6,CT10
ZMVFNS	used by NNPDF2.0

- the optimal m_c^{model} value is determined for each of these schemes (m_c^{model} (opt)), which gives the best description of the HERA data

- PDFs are propagated to MCFM to calculate $Z/W^{\pm}$ cross section predictions

m_c^{model} scan

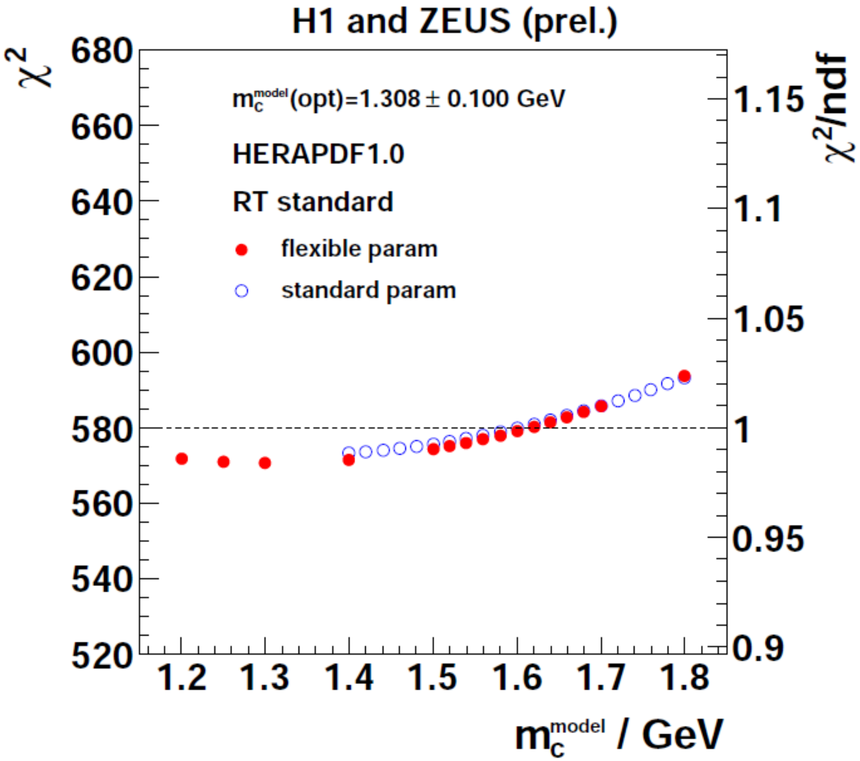
HERA I inclusive

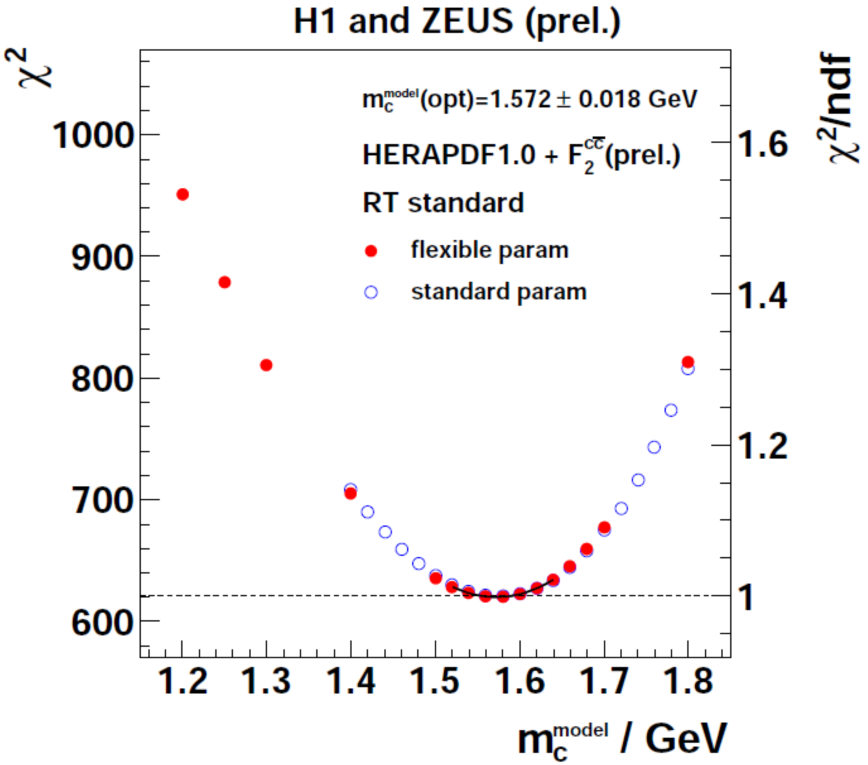


m_c^{model} scan

HERA I inclusive

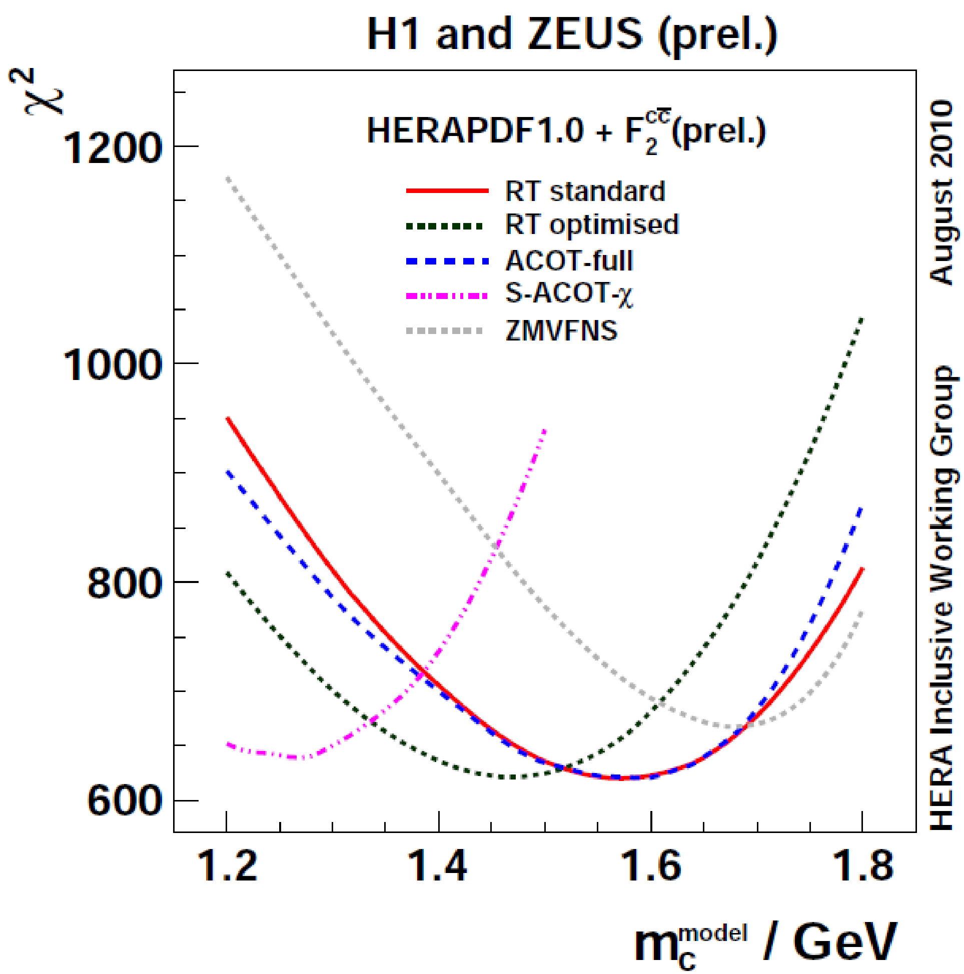
HERA I inclusive + F_2^{cc}





- m_c^{model} (opt) is determined fitting the χ^2 dependance on m_c^{model}

m_c^{model} scan: different HF schemes

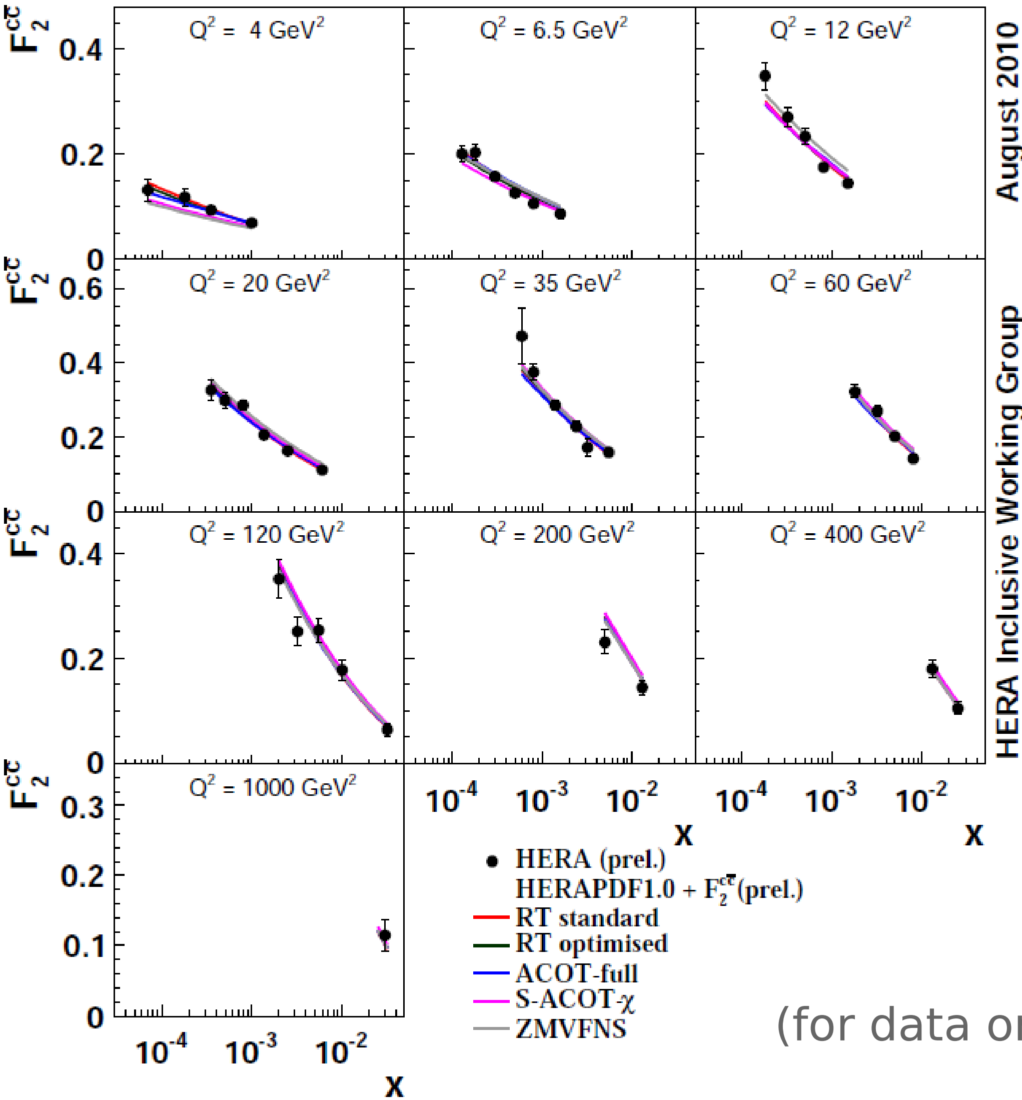


- different schemes have different optimal m_c^{model}

scheme	m_c^{model}(opt)
RT standard	1.58
RT optimised	1.46
ACOT-full	1.58
S-ACOT-χ	1.26
ZMVFNS	1.68

All models yield similar χ^2 values for $m_c^{model} = m_c^{model}$(opt)
except ZMVFNS which returns significantly worse value

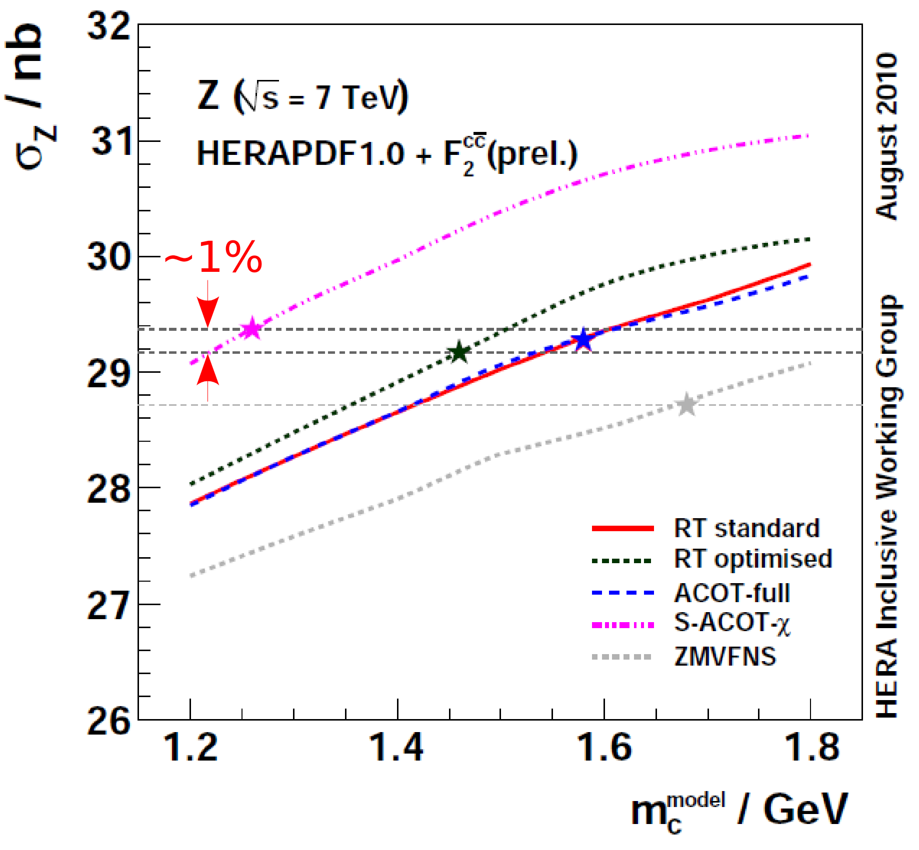
Comparison with data (at m_c^{model}(opt))



- different predictions at m_c^{model} (opt) are similar
- good overall agreement with F_2^{cc} data

(for data only uncorrelated errors shown)

Z/W cross sections at LHC



(★ indicate σ with PDFs at m_c^{model}(opt))

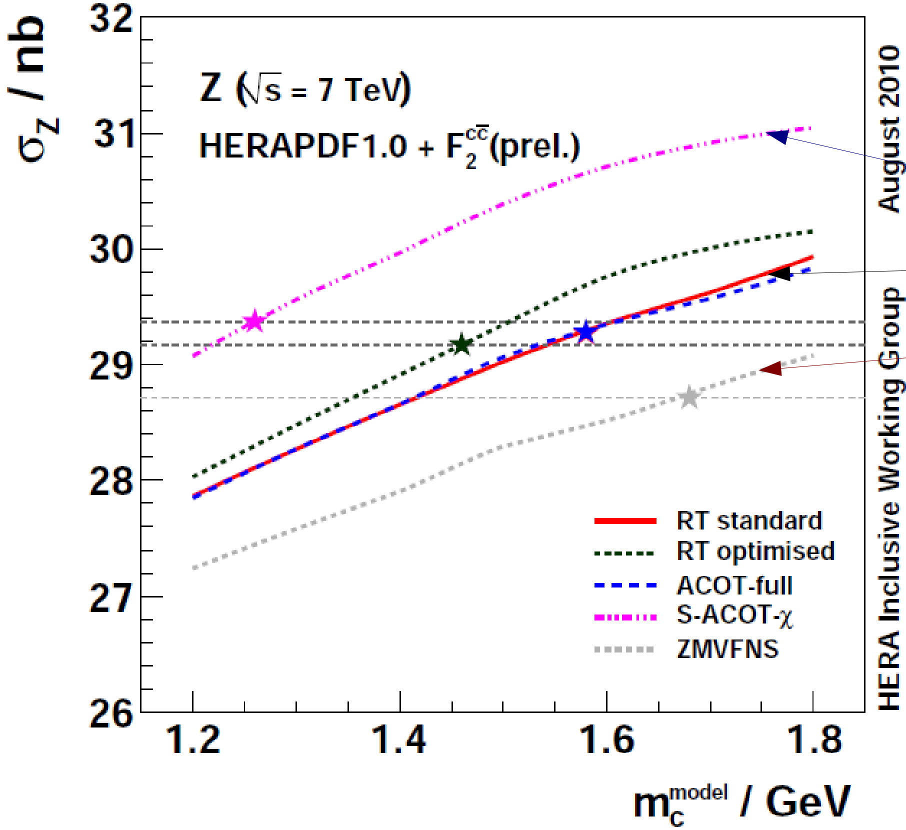
- cross section predictions for each scheme vary ~7% for 1.2 < m_c^{model} < 1.8 GeV

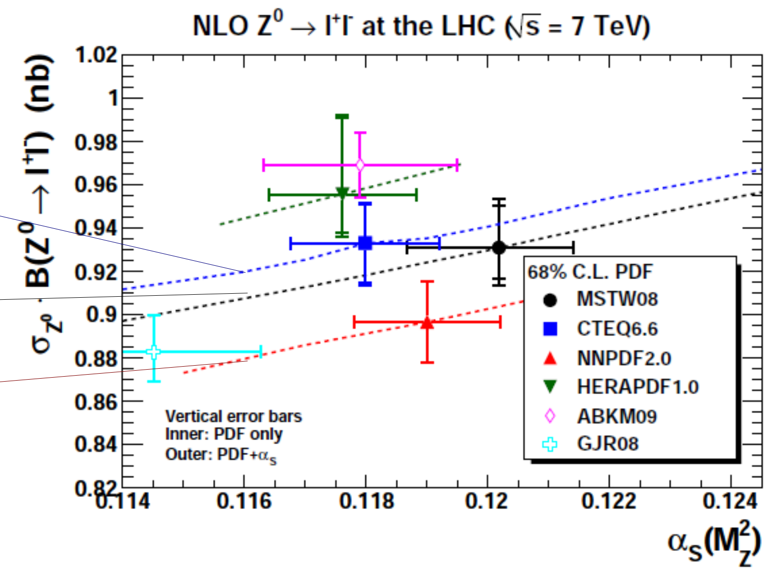
- predictions for all schemes vary ~7% for given m_c^{model}

BUT:

- predictions for m_c^{model} (opt) has much smaller spread: <1% (~2% with ZMVFNS)

Z/W cross sections at LHC





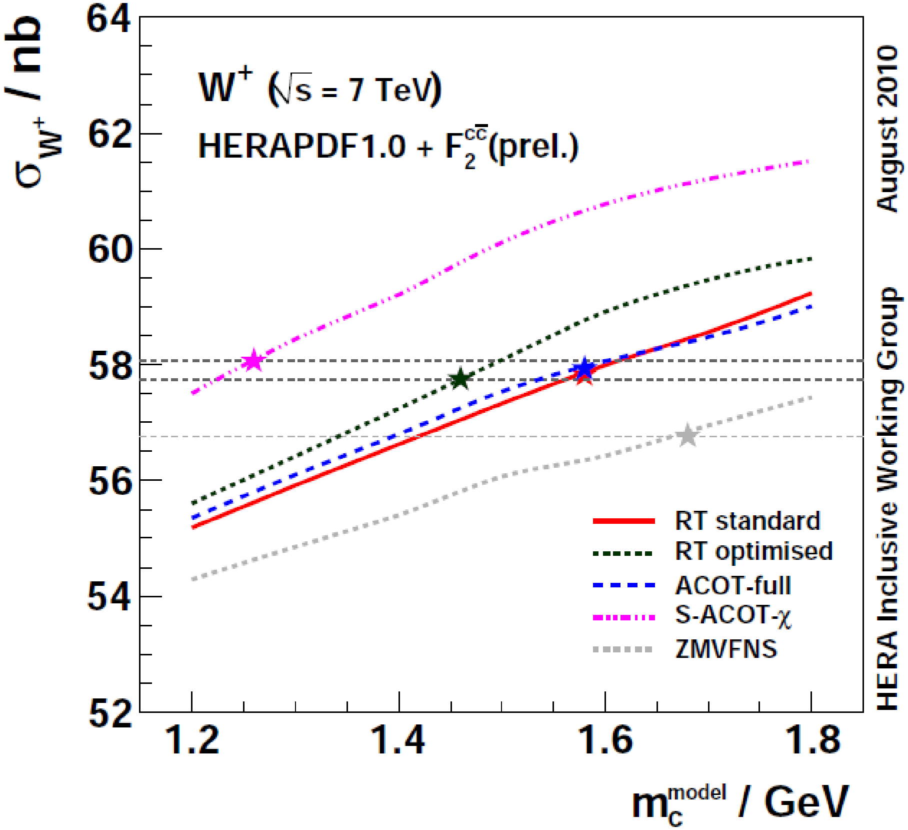
- comparison of Z cross sections as a function of $\alpha_S(M_Z^2)$ G.Watt, PDF4LHC 26.03.201

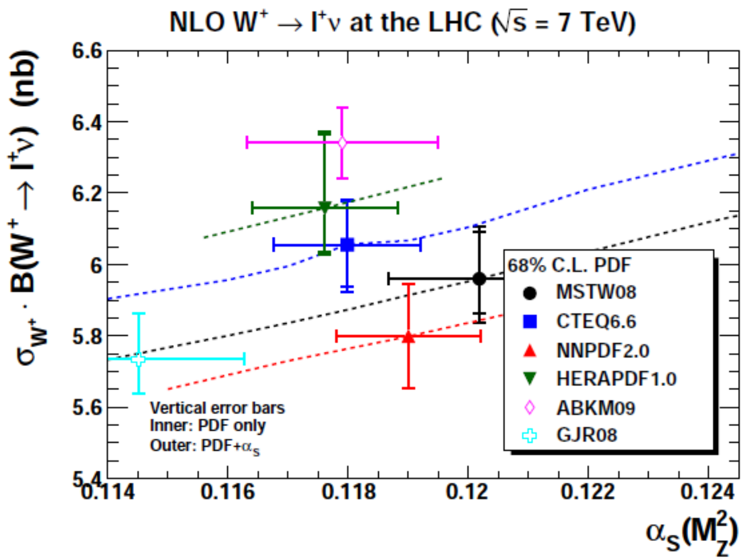
(★ indicate σ with PDFs at m_c^{model}(opt))

similar decomposition in predictions

→ could explain part of existing differences between PDFs

Z/W cross sections at LHC

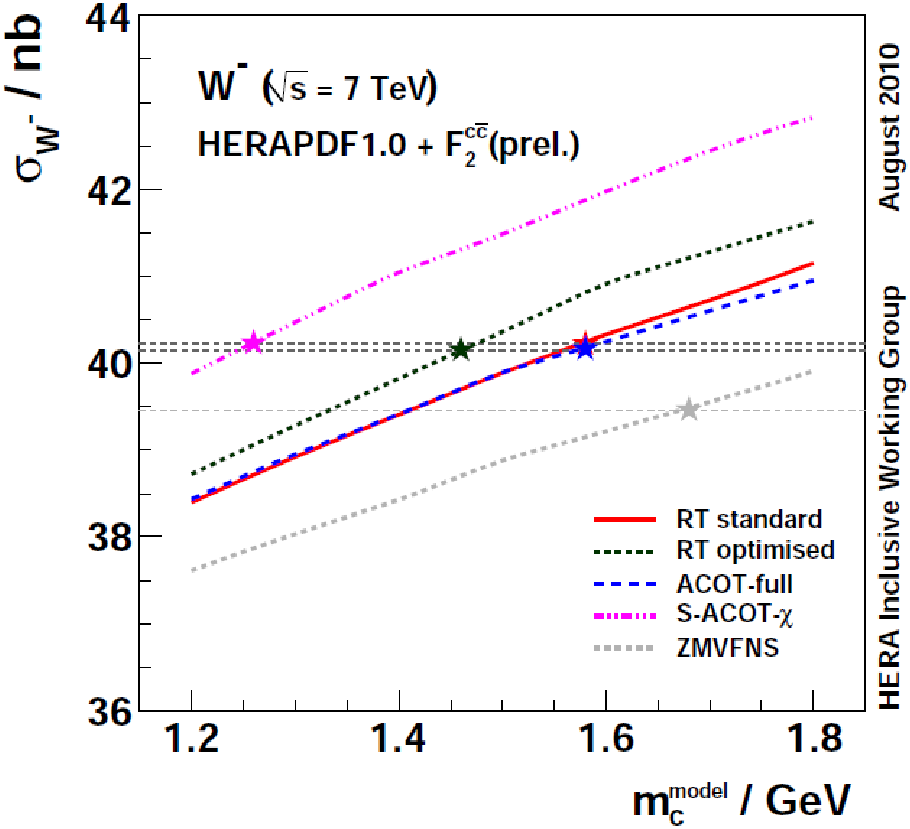


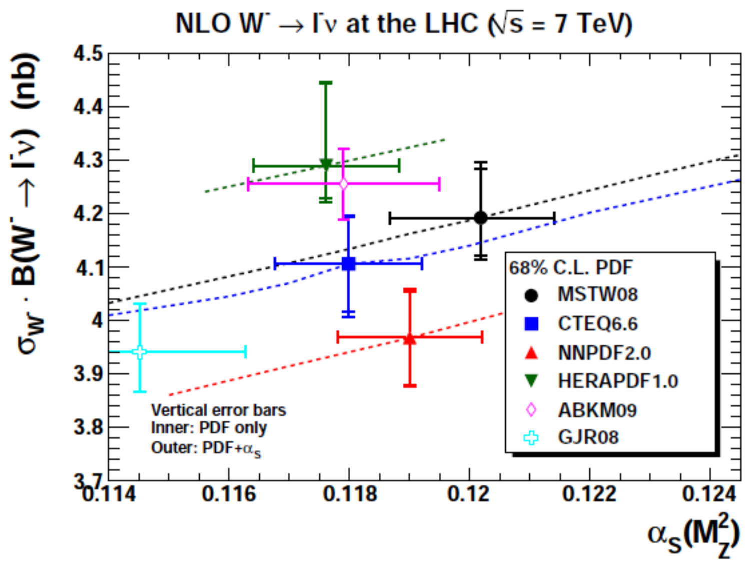


- comparison of W^+ cross sections as a function of $\alpha_S(M_Z^2)$
  G.Watt, PDF4LHC 26.03.201

(★ indicate σ with PDFs at m_c^{model}(opt))

Z/W cross sections at LHC





- comparison of W^- cross sections as a function of $\alpha_S(M_Z^2)$
G.Watt, PDF4LHC 26.03.201

(★ indicate σ with PDFs at m_c^{model}(opt))

Summary

A NLO QCD analysis of F_2^{cc} data using various HF schemes was presented

- m_c^{model} (opt) determined for each HF scheme with full uncertainty
- PDFs with m_c^{model} (opt) were used to predict Z/W production cross sections at the LHC

$\rightarrow$ uncertainty on the Z/W cross section predictions at LHC is reduced to below 1%

More details can be found:

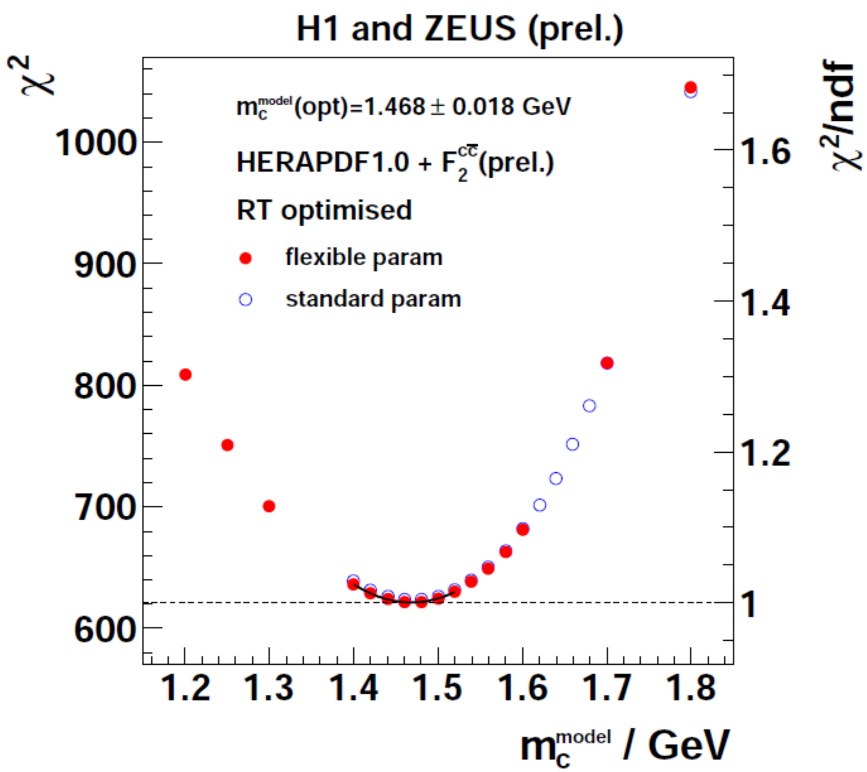
H1prelim-10-143, ZEUS-prel-10-019

https://www.desy.de/h1zeus/combined_results/heavy_flavours/MCScan/charmfit.pdf

Back-up slides

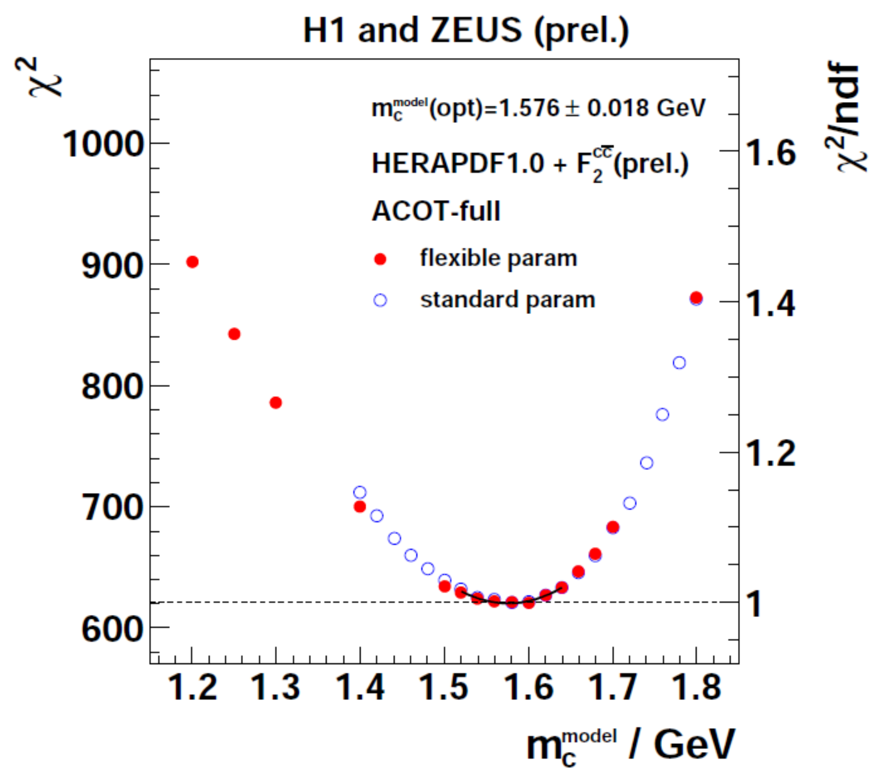
m_c^{model} scan: different HF schemes

RT optimised



m_c^{model} (opt) = 1.47 ± 0.02 GeV

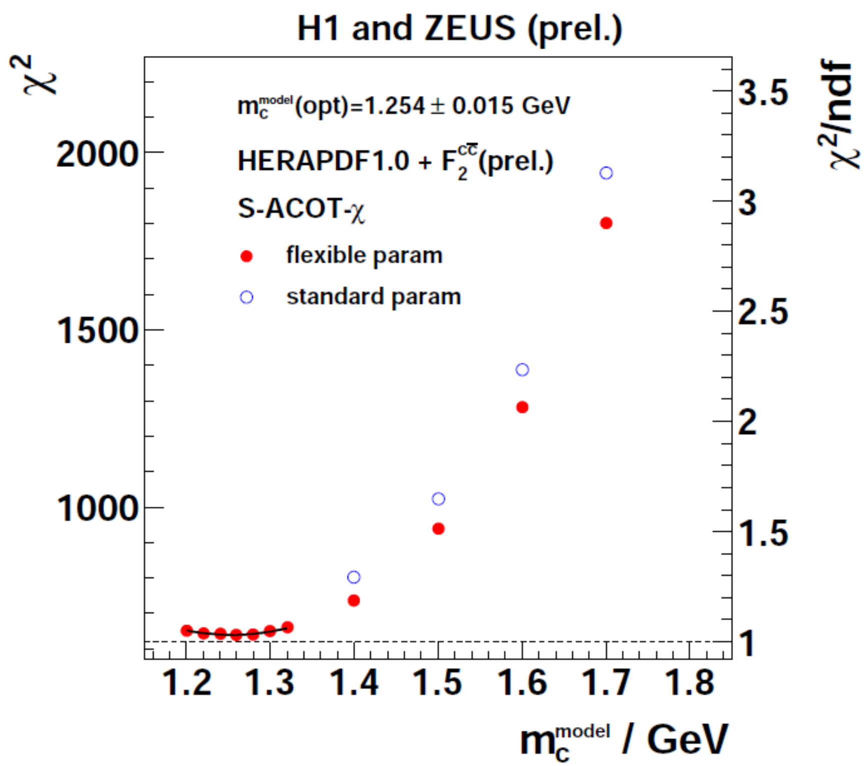
ACOT-full



m_c^{model} (opt) = 1.58 ± 0.02 GeV

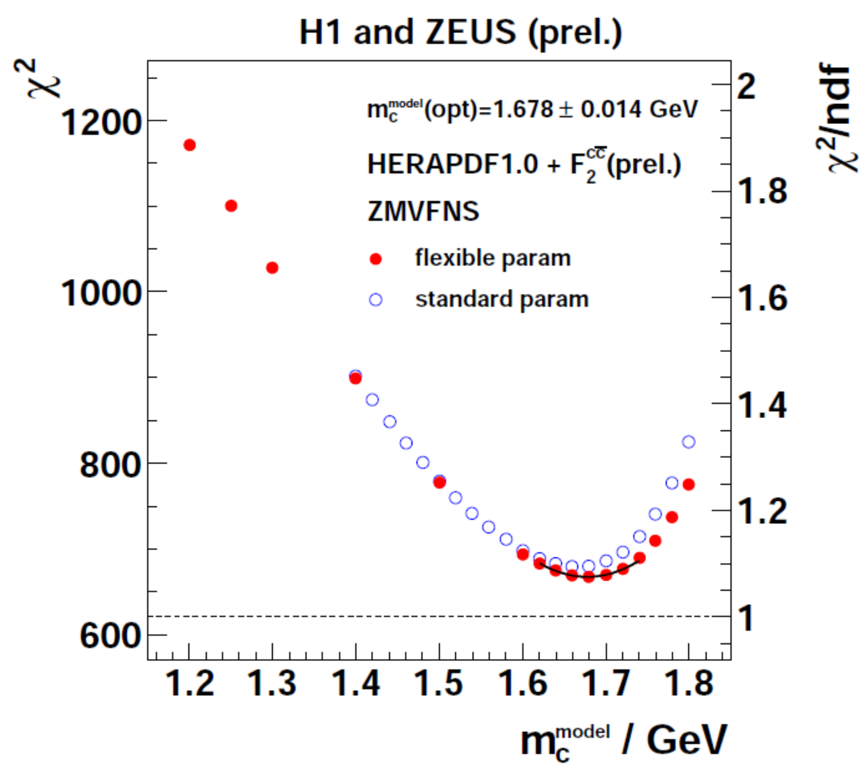
m_c^{model} scan: different HF schemes

S-ACOT-χ



m_c^{model} (opt) = 1.25 ± 0.02 GeV

ZMVFNS



m_c^{model} (opt) = 1.68 ± 0.01 GeV

Analysis Settings

NLO QCD analysis of the preliminary HERA F_2^{cc} data

- together with the published inclusive HERA data (HERAPDF1.0,arXiv:0911.0884)

- standard **HERAPDF1.0** settings used **(qcdnum17.0,** arXiv:1005.1481**)**
  (α_S =0.1176, scale $\mu_R=\mu_F=Q^2$, Q^2_{min}= 3.5 GeV^2)

with two parametrisation assumptions:

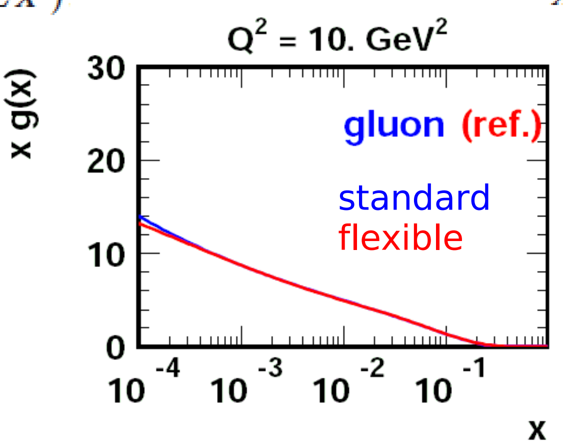
standard:

$$xf(x) = Ax^B(1-x)^C(1+Ex^2)$$

flexible:

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{25}$$

(allows for a negative gluon contribution at low x)



Q^2_0=1.9 GeV^2,
m_C^{model} scan: 1.4 – 1.8 GeV

Q^2_0=1.4 GeV^2,
m_C^{model} scan: 1.2 – 1.8 GeV

PDF determination in HERAPDF 1.0

DGLAP at NLO → QCD predictions

PDFs parametrised (at starting scale Q^2_0) using standard parametrisation form:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

A: overall normalisation

B: small x behavior

C: x→1 shape

The optimal number of parameters chosen by saturation of the χ^2

- central fit with 10 free parameters

xg, xu_v, xd_v, $x\bar{U}$, $x\bar{D}$

where $x\bar{U}=x\bar{u}$ and $x\bar{D}=x\bar{d}+x\bar{s}$ at the starting scale ($x\bar{s}=f_s x\bar{D}$ with $f_s=0.31$)

A_g, A_{uv}, A_{dv} are fixed by sum rules

extra constrains for small x behavior of d- and u-type quarks:

$B_{uv}=B_{dv}$, $B_{\bar{U}}=B_{\bar{D}}$, $A_{\bar{U}}=A_{\bar{D}}(1-f_s)$ for $\bar{u}=\bar{d}$ as $x\to 0$

Heavy Quark treatment in PDFs

Factorisation:

$$F_2^{V,h}(x,Q^2) = \sum_{i=f,\bar{f},g} \int_x^1 dz \cdot C_2^{V,i}\left(\frac{x}{z},\frac{Q^2}{\mu^2},\frac{\mu_F^2}{\mu^2}\alpha_S(\mu^2)\right) f_{i/h}(z,\mu_F,\mu^2)$$

i - number of active flavours in the proton m_c=1.5, m_b=4.7 GeV

QCD analysis of the proton structure: treatment of HQ essential

Different prescriptions how to treat heavy quarks in PDF fits (HQ schemes):

Fixed Flavour Number Scheme (FFNS) *i-fixed*

c(b) quarks massive, only light flavours in the proton i=3(4)

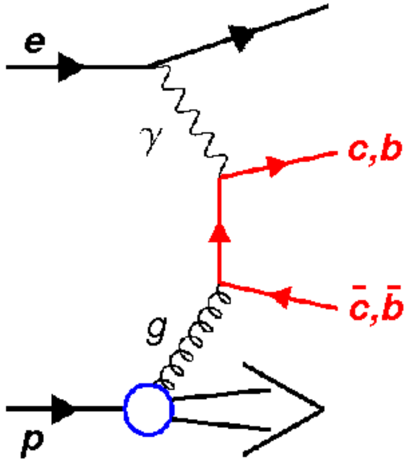
General-Mass Variable Flavour Number Scheme (GM-VFNS) *i-variable*

matched scheme, different implementation used by fit groups $\rightarrow m_c^{model}$

Zero-Mass Variable Flavour Number Scheme (ZMVFNS)

all flavours massless (breaks at $Q^2 \sim m_{HQ}^2$)

Heavy Quarks at HERA



Heavy quarks at HERA are produced mainly in boson-gluon fusion

- test of pQCD, access to the gluon

Charm contribution to total DIS cross section
- up to 30% at high Q^2

Measure heavy qyark structure functions

- direct test of HQ schemes in PDF fits, e.g. charm structure function:

$$\sigma^{cc} \propto F_2^{cc}(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L^{cc}(x,Q^2)$$

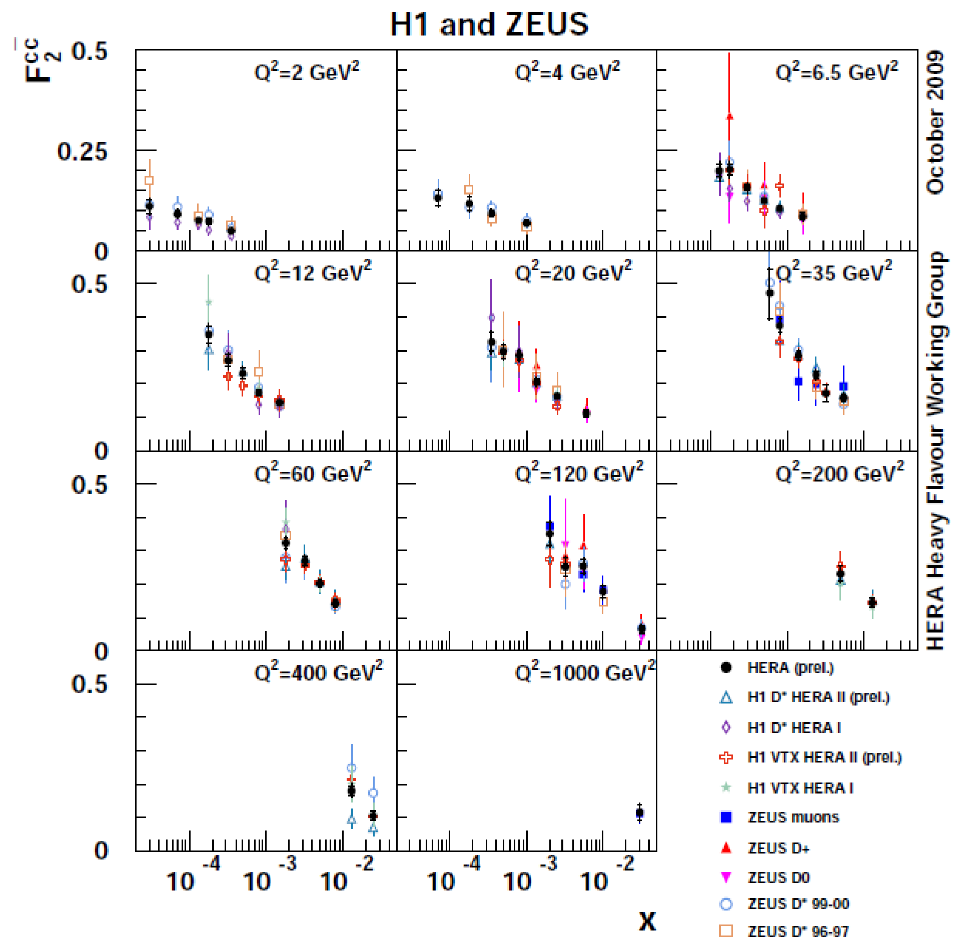
Introduction

Preliminary HERA F_2^{cc} measurement

H1 prelim-09-171
ZEUS-prel-09-015

https://www.desy.de/h1zeus/combined_results/index.php?do=heavy_flavours

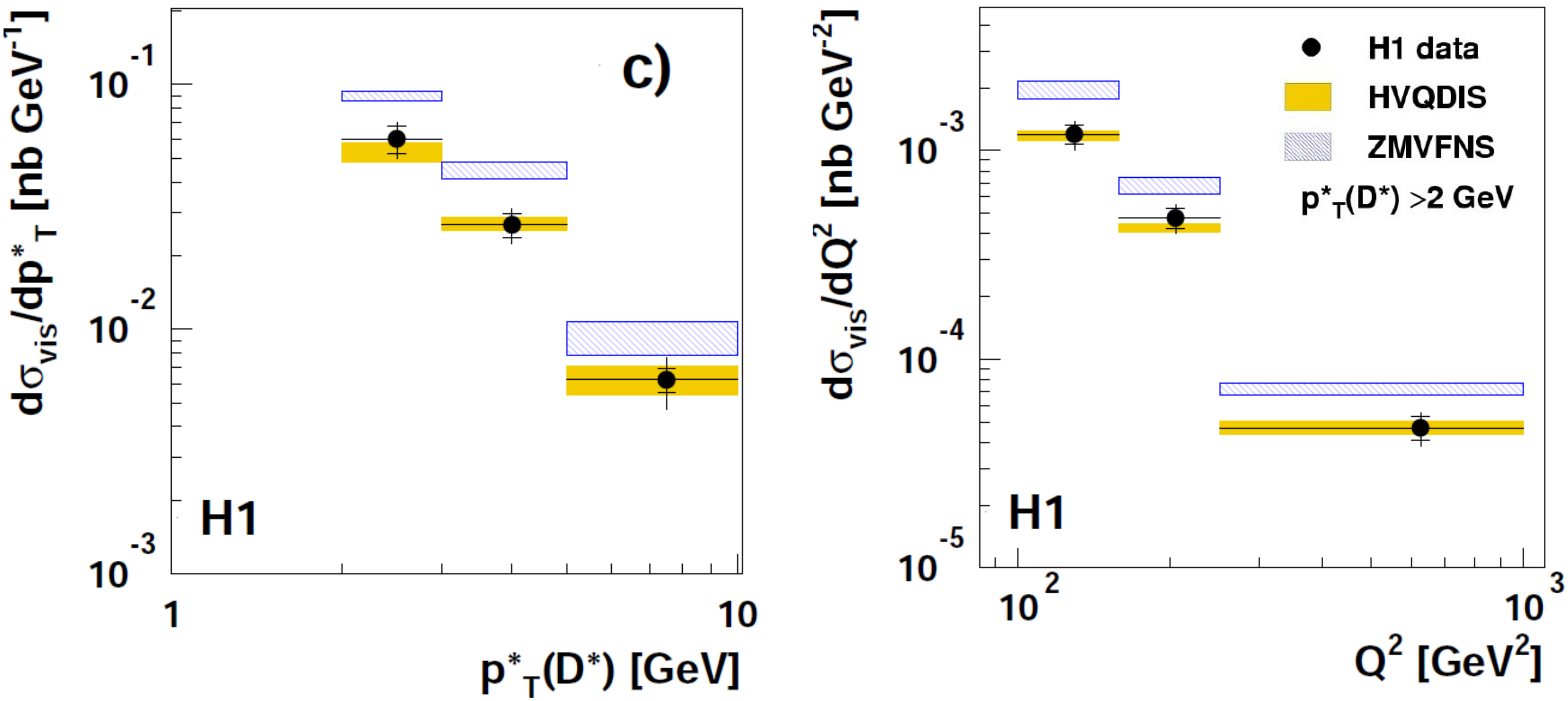
- significant contribution to DIS cross section
- most precise determination of F_2^{cc} from HERA
  - combination of 9 H1 and ZEUS measurements (HERA I + part of HERA II)
  - different charm tagging methods
  - covers $2 < Q^2 < 1000$ GeV^2 and $10^{-5} < x < 10^{-1}$
  - 5-10% uncertainty



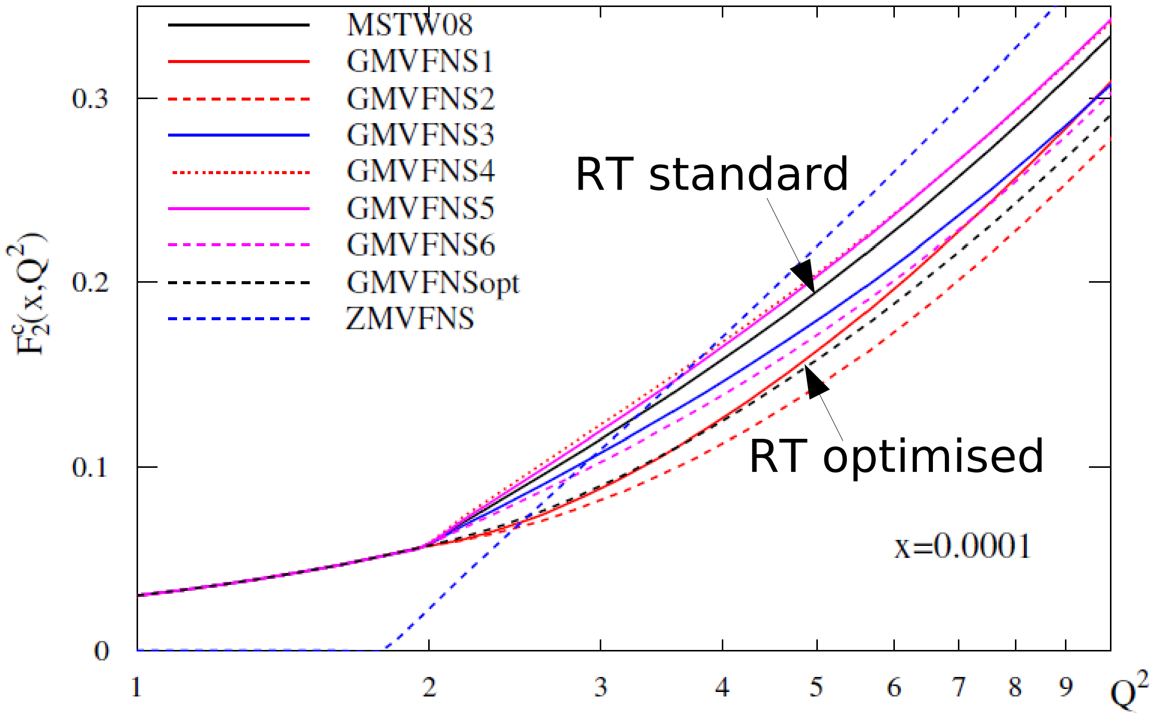
Charm measurement: ZMVFNS

Charm measurement at HERA:

- ZMVFNS doesn't describe heavy flavour data



RT scheme (standard vs optimised)



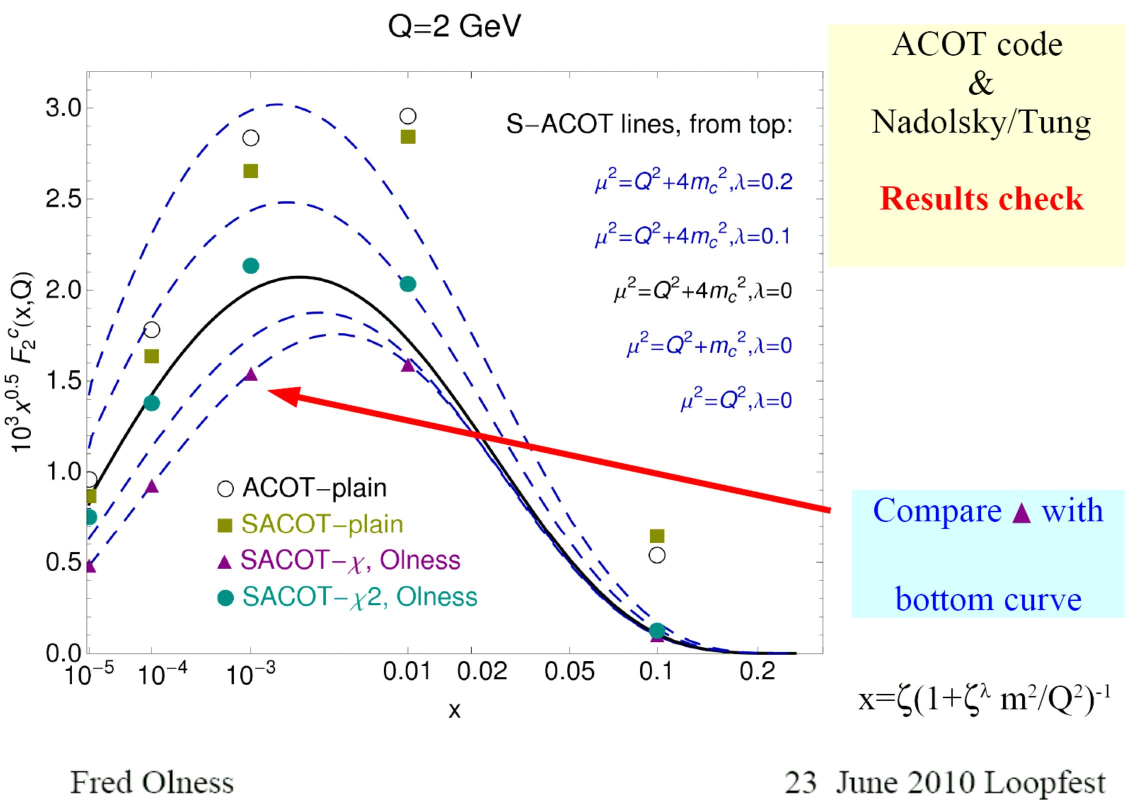
R.S. Thorne, PoS (DIS 2010) 053

- compared to standard RT optimised scheme is smooth at threshold

S-ACOT-χ scheme

ACOT full with generalised slow rescaling = ACOT χ $\quad \chi = x\left[1+\frac{(\mathbf{n}m_c)^2}{Q^2}\right]$

Comparison of ACOT code with CTEQ (Nadolski/Tung)



- same ACOT code is implemented in h1fitter
- fit results were confirmed by Voica with independent code from Fred Olness
- ACOT χ scheme is (again) used for m_c scan studies

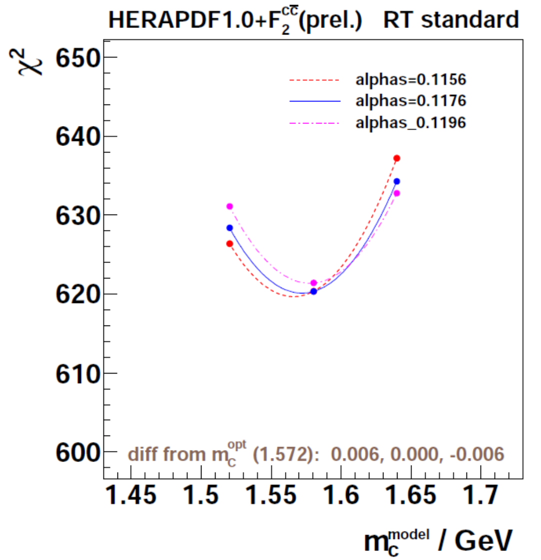
Systematic uncertainty on m_c^{model}

- to determine systematic uncertainty on m_c^{model} HERAPDF1.0 prescription was used:

  - α_s variation (± 0.002)
  - vary parametrisation (e.g. $Bu_v \neq Bd_v$)
  - vary model parameters ($f_s, m_B, Q^2_{min}, Q^2_0$)

Variation	Standard	Lower	Upper
fs	0.31	0.23	0.38
m_B	4.75	4.3	5
Q^2_{min}	3.5	2.5	5
Q^2_0	1.4	-	1.9

(uncertainty from Q^2_0 assumed to be symmetric and treated as procedural)



Systematic uncertainties on m_c^{model} obtained for each heavy flavour scheme →

scheme	m_c^{model}*(opt)*
RT standard	$1.58^{+0.02}_{-0.03}$
RT optimised	$1.46^{+0.02}_{-0.04}$
ACOT-full	$1.58^{+0.03}_{-0.04}$
S-ACOT-χ	$1.26^{+0.02}_{-0.04}$
ZMVFNS	$1.68^{+0.06}_{-0.07}$

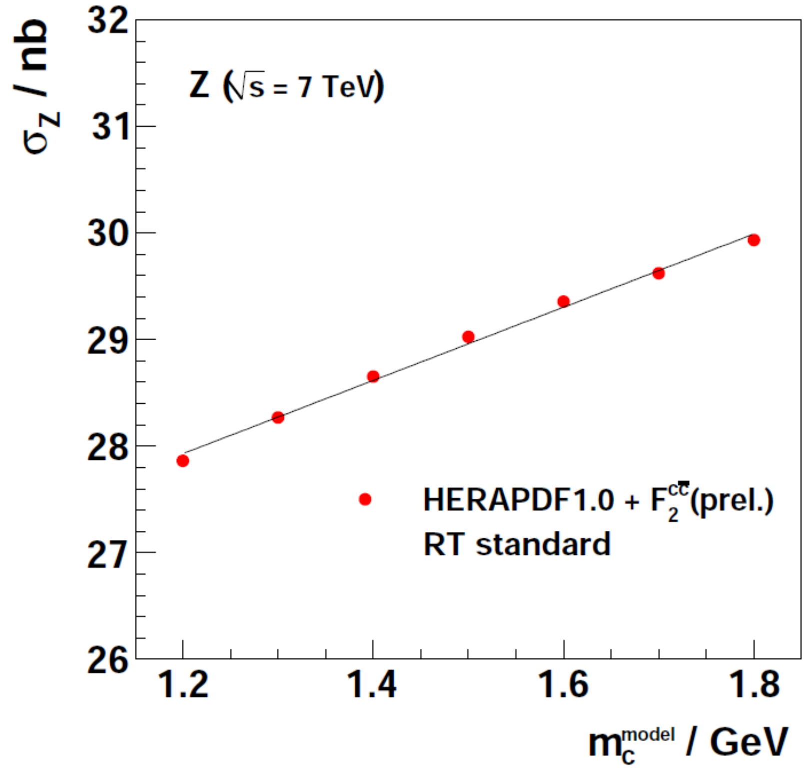
Application of m_c^{model} scan: Z/W cross sections at LHC

Z/W cross sections calculated with MCFM 5.7

- same conditions as for the PDF4LHC benchmarking at √s = 7 TeV

- uncertainty from m_c^{model} propagated to Z/W cross sections

scheme	m_c^{model}*(opt)*	σ_Z*(nb)*
RT standard	$1.58^{+0.02}_{-0.03}$	$29.27^{+0.07}_{-0.11}$
RT optimised	$1.46^{+0.02}_{-0.04}$	$29.17^{+0.07}_{-0.13}$
ACOT-full	$1.58^{+0.03}_{-0.04}$	$29.28^{+0.10}_{-0.13}$
S-ACOT-χ	$1.26^{+0.02}_{-0.04}$	$29.37^{+0.08}_{-0.15}$
ZMVFNS	$1.68^{+0.06}_{-0.07}$	$28.71^{+0.19}_{-0.20}$



Z/W cross sections at LHC: summary

scheme	m_c^{model}(opt)	χ^2/dof	χ^2/ndp (F_2^{cc})	σ_Z(nb)	σ_{W^+}(nb)	σ_{W^-}(nb)
RT standard	$1.58^{+0.02}_{-0.03}$	620.3/621	42.0/41	$29.27^{+0.07}_{-0.11}$	$57.82^{+0.14}_{-0.22}$	$40.22^{+0.10}_{-0.15}$
RT optimised	$1.46^{+0.02}_{-0.04}$	621.6/621	46.5/41	$29.17^{+0.07}_{-0.13}$	$57.75^{+0.14}_{-0.26}$	$40.15^{+0.10}_{-0.18}$
ACOT-full	$1.58^{+0.03}_{-0.04}$	621.2/621	59.9/41	$29.28^{+0.10}_{-0.13}$	$57.93^{+0.18}_{-0.24}$	$40.16^{+0.12}_{-0.16}$
S-ACOT-χ	$1.26^{+0.02}_{-0.04}$	639.7/621	68.5/41	$29.37^{+0.08}_{-0.15}$	$58.06^{+0.16}_{-0.30}$	$40.23^{+0.11}_{-0.21}$
ZMVFNS	$1.68^{+0.06}_{-0.07}$	667.4/621	88.1/41	$28.71^{+0.19}_{-0.20}$	$56.77^{+0.33}_{-0.34}$	$39.46^{+0.24}_{-0.25}$
			max diff:	0.7%	0.5%	0.2%
			(with ZMVFNS)	2.3%	2.3%	2.0%

- same conclusions with HERAPDF1.5
 (preliminary combined inclusive HERA I+II data)

Systematic uncertainty on m_c^{model}