Combination and QCD analysis of charm cross sections in DIS at HERA

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on behalf of

arXiv:1211.1182

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Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep-Inelastic ep Scattering at HERA.

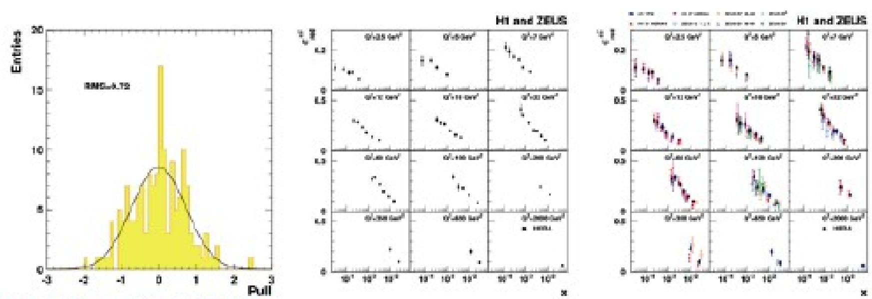
H1 and ZEUS Collaborations (H. Abramowicz (Tel Aviv U.) *et al.*) Show all 484 authors.

Nov 6, 2012 - 46 pages

DESY-12-172
e-Print: arXiv:1211.1182 [hep-ex] | PDF
Experiment: DESY-HERA-H1, DESY-HERA-ZEUS

Abstract: Measurements of open charm production cross sections in deep-inelastic ep scattering at HERA from the H1 and ZEUS Collaborations are combined. Reduced cross sections sigma_red^{c\bar{c}} for charm production are obtained in the kinematic range of photon virtuality 2.5<Q2<2000 GeV2 and Bjorken scaling variable 0.00003<x<0.05. The combination method accounts for the correlations of the systematic uncertainties among the different data sets. The combined charm data together with the combined inclusive deep-inelastic scattering cross sections from HERA are used as input for a detailed NLO QCD analysis to study the influence of different heavy flavour schemes on the parton distribution functions. The optimal values of the charm mass as a parameter in these different schemes are obtained. The implications on the NLO predictions for W^{\pm} and Z production cross sections at the LHC are investigated. Using the fixed flavour number scheme, the running mass of the charm quark is determined.

Note: 46 pages, 14 figures
Keyword(s): INSPIRE: * Automatic Keywords * | charm: production | charm: mass | parton: distribution function | electron p: deep inelastic scattering | mass: energy dependence | scaling: Bjorken | deep inelastic scattering: inclusive reaction | DESY HERA Stor | quantum chromodynamics | scattering | CERN LHC Coll | heavy quark | correlation | kinematics | photon | flavor | quark | ZEUS



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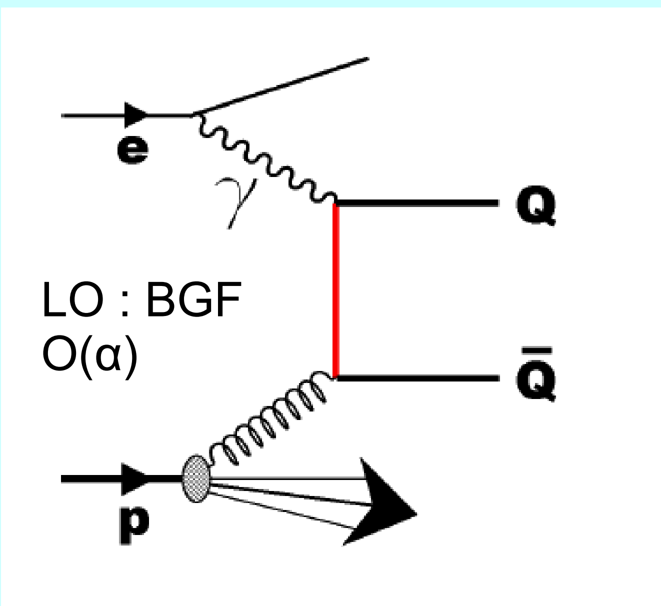
Record created 2012-11-07, last modified 2012-11-15

Heavy quark production in DIS

Fixed Flavour Number Scheme (FFNS)

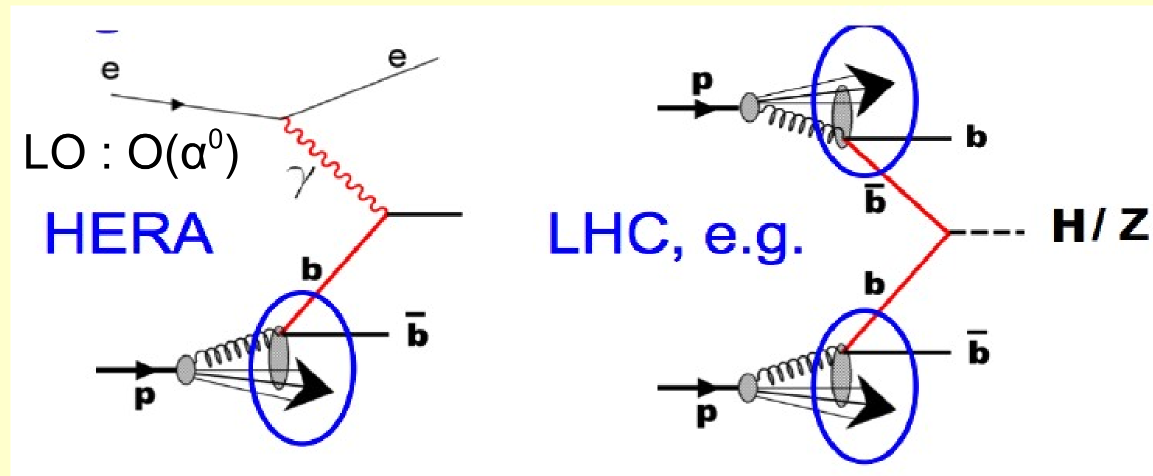
- nf=3 active flavours in p
- heavy-quarks produced in hard scattering
- mass effects correctly included



- spoiled by large logs of Q^2/m^2, p_T/m ...

Variable Flavour Number Scheme(s) (VFNS)

- c, b massless partons for $Q^2>m_c^2$



- simplifies calculations at colliders (neglecting m_c)
- resums large $\log(Q^2/m^2)$

- Zero Mass (ZM) VFNS
  - neglects m_c at all Q^2s

- General Mass (GM) VFNS
  - FFNS at $Q^2<m_c^2$, ZM-FNS at $Q^2>>m^2$
  - Interpolating in between
  - different prescriptions available

Charm production in DIS

Reduced charm cross section defined in analogy to inclusive DIS:

$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4}\, Y_+\, \sigma_{\rm red}^{c\bar{c}}(x, Q^2, s) \qquad Y_+ = 1 + (1-y)^2$$

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

but considering events with charm in the final state

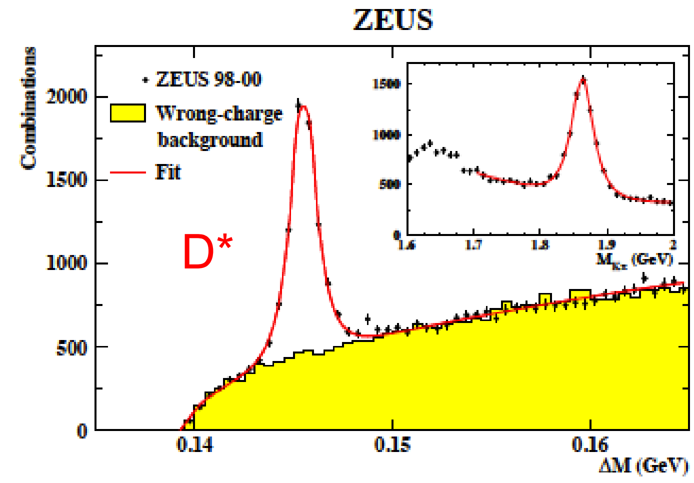
Different definition used by theorists in some case
but differences are small in the HERA range. (up to

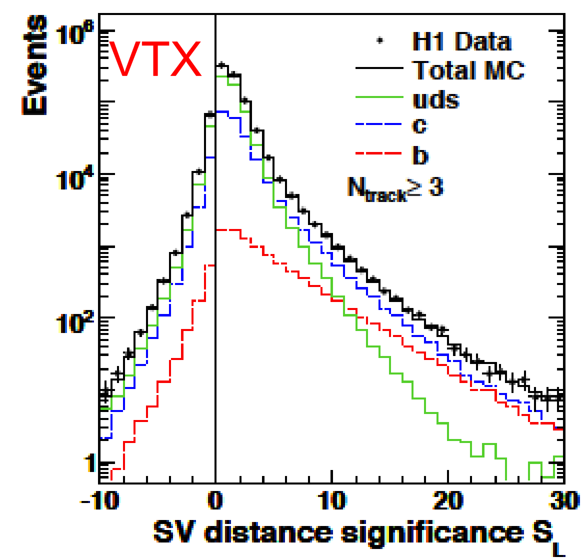
In this analysis we will combine HERA charm production measurements
to extract a combined measurement of $\sigma_{\rm red}^{c\bar{c}}(x, Q^2, s)$

Input data sets

9 data sets used for a total of 155 points

Data Set	Period	$Q^2[GeV^2]$
• 1) H1 VTX	HERA I+II	5 - 2000
• 2) H1 D*	HERA I	2 - 100
• 3) H1 D*	HERA II	5 - 100
• 4) H1 D*	HERA II	100 - 1000
• 5) ZEUS D*	'96-'97	1 - 200
• 6) ZEUS D*	'98-'00	1.5 - 1000
• 7) ZEUS D0	'05	5 - 1000
• 8) ZEUS D+	'05	5 - 1000
• 9) ZEUS μ	'05	20 - 10000





ZEUS HERA II D*, D+, and VTX preliminary not included

Correction to full phase space

D*/D/μ measurements are "visible" D*/D/μ cross sections ($\sigma_{\mathrm{vis,bin}}$)
in bins of Q^2, y (or x), pt, η

Reduced cross sections are obtained as

$$\sigma_{\mathrm{red}}^{c\bar{c}}(x,Q^2) = \sigma_{\mathrm{vis,bin}} \frac{\sigma_{\mathrm{red}}^{c\bar{c},\mathrm{th}}(x,Q^2)}{\sigma_{\mathrm{vis,bin}}^{\mathrm{th}}}.$$

This method accounts for extrapolation to full phase space

The theory used for this "extrapolation" is FFNS at NLO : HVQDIS

Parameters (and systematic variations) used for HVQDIS:

- $m_c = 1.5 \pm 0.15\ \mathrm{GeV}$;
- $\mu_f = \mu_r = \sqrt{Q^2 + 4m_c^2}$, varied up/down by factor 2;
- $\alpha_s^{n_f=3}(M_Z) = 0.105 \pm 0.002$;

- PDF: HERAPDF1.0, FFNS variant
  m_c, μ, α variations done simultaneously in HVQDIS and in PDF fit.

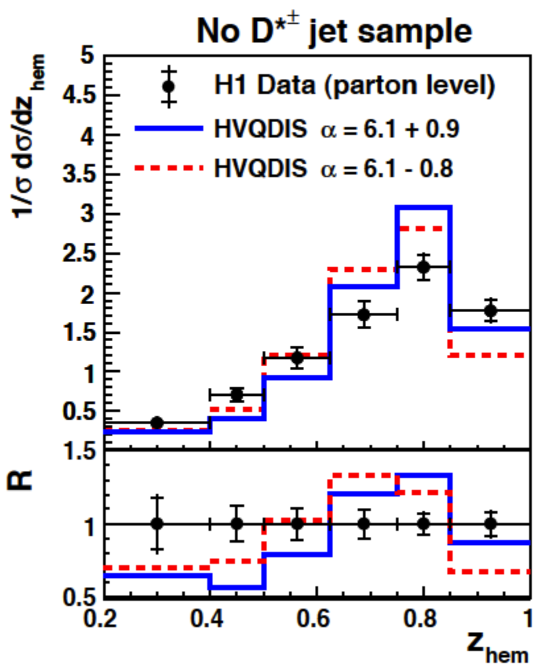
Fragmentation model

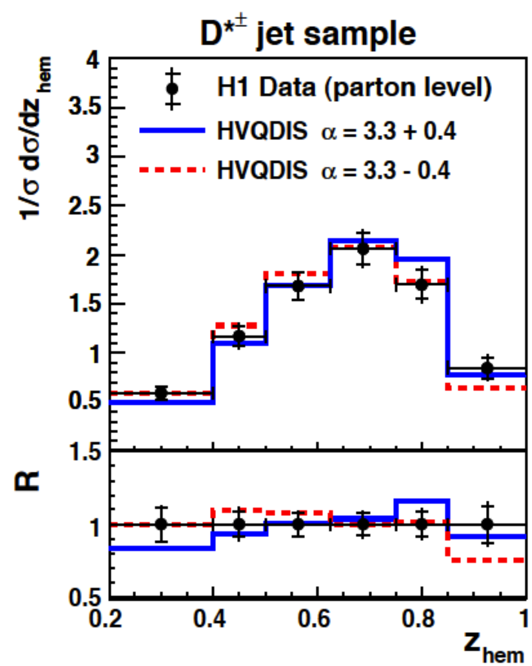
To produce visible D*, D, μ cross section a fragmentation model is used:

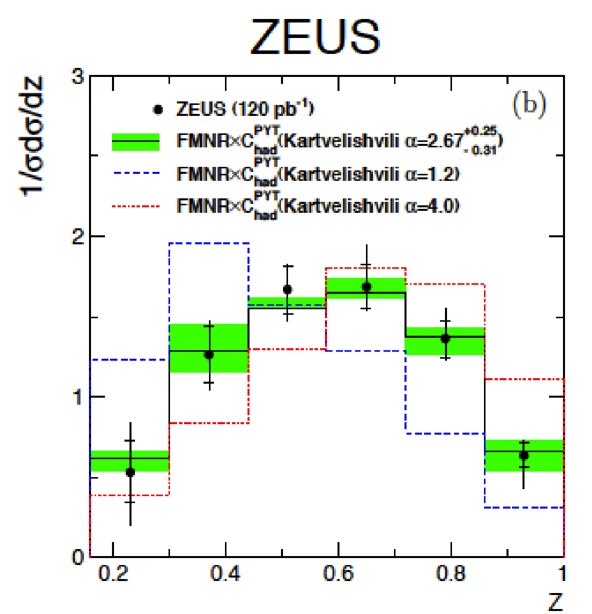
- Longitudinal fragmentation function : Kartvelishvili with variable α_K ($\hat{s}$)
  $\hat{s}$ = γ*g cms energy squared,
  based on D* fragmentation mesurements in ep:

$\hat{s}$ range	$\alpha_K(D^*)$	α_K(g.s.)	Measurement
$\hat{s} \leq \hat{s}_1$	6.1 ± 0.9	4.6 ± 0.7	[47] D^*, DIS, no-jet sample
$\hat{s}_1 < \hat{s} \leq \hat{s}_2$	3.3 ± 0.4	3.0 ± 0.3	[47] D^*, DIS, jet sample
$\hat{s} > \hat{s}_2$	2.67 ± 0.31	2.19 ± 0.24	[11] D^* jet photoproduction

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







More fragmentation

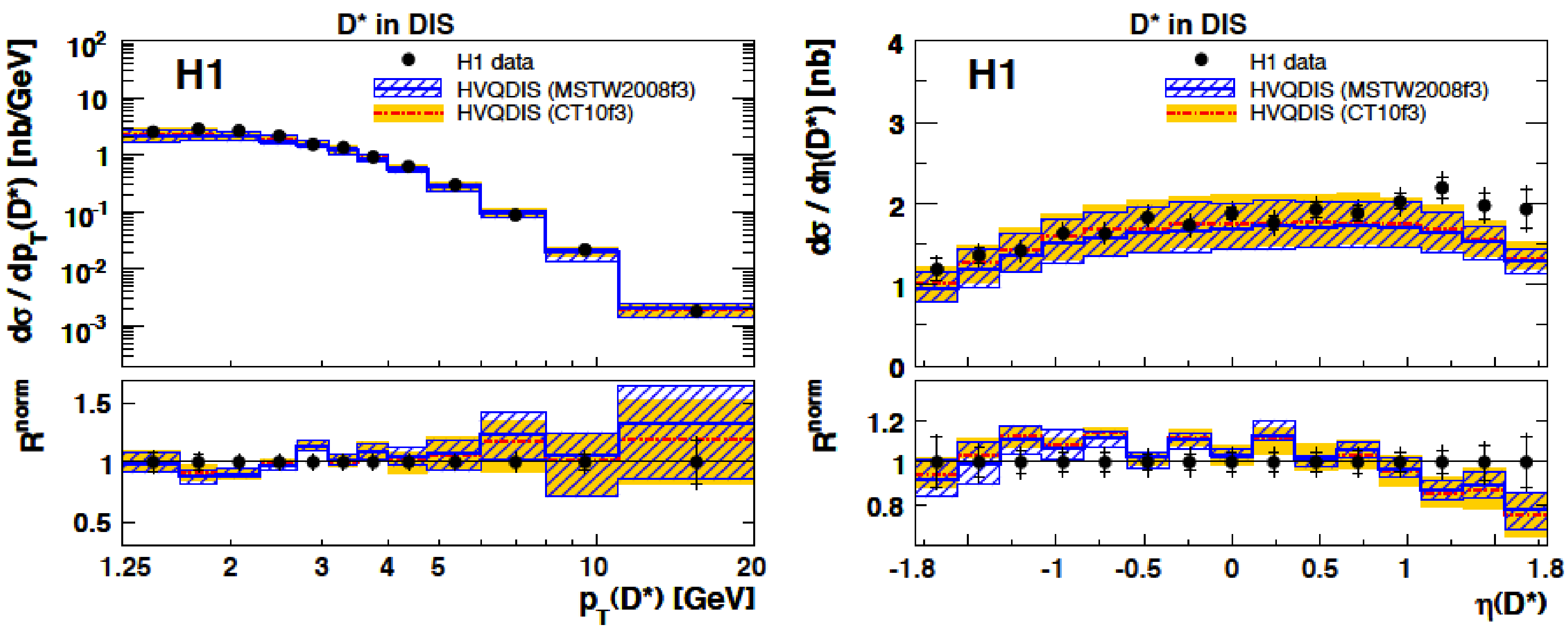
- Fragmentation for ground-state D meson was softened wrt D* to account for D* decays (based on e+e- data and kinematics)

- transverse fragmentation (kT of D wrt c direction): based on e+e- data: <kt> = 0.35 +- 0.15 GeV

- Fragmentation fractions, updated average of e+e- and ep data (arXiv:1112.3757)

$f(c \to D^{*+})$	0.2287 ± 0.0056
$f(c \to D^{+})$	0.2256 ± 0.0077
$f(c \to D^{0,\mathrm{not}D^{*+}})$	0.409 ± 0.014
$B(c \to \mu)$	0.096 ± 0.004

Good description of measured cross sections



Combination

- The H1 VTX data are already given as $\sigma_{\rm red}^{c\bar{c}}$

- 155 measurements are combined into 52 x,Q^2 points

- combination: measurements at the same x,Q^2 point must come from the same true $\sigma_{\rm red}^{c\bar{c}}$

- the combination is done similarly to the inclusive HERA combination, by minimizing

correlated systematic errors

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right)^2}{(\delta_{i,stat}\,\mu^i)^2 + (\delta_{i,unc}\,m^i)^2} + \sum_j b_j^2$$

statistical errors

uncorrelated systematic errors

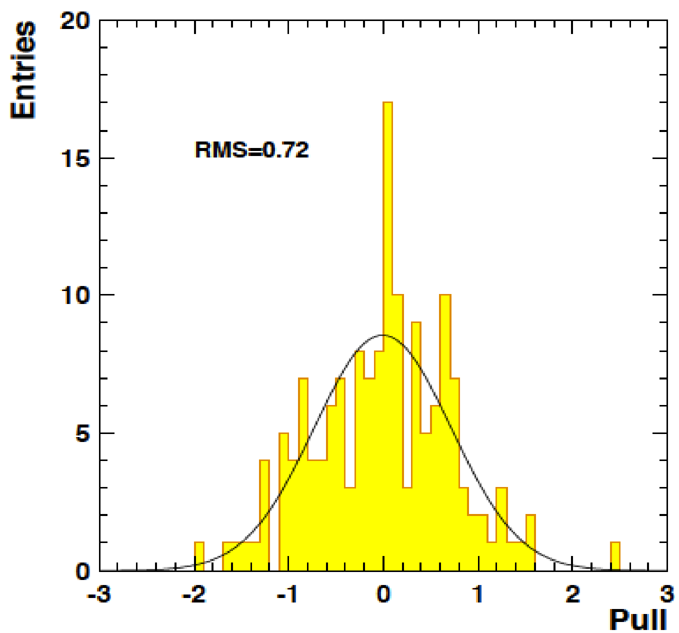
- the main difference is that the statistical error is taken as constant rather than proportional to sqrt of cross section, since in charm case the bkg contribution is large

- 48 correlated systematics, 9 of which related to Hvqdis+Fragmentation

- 1 procedural uncertainty from using different definitions of χ^2

Results

- $\chi^2/n_{\mathrm{dof}} = 62/103$
  uncertainties a bit conservative



- Systematics fluctuate reasonably,
  (only 1 by more than 1 σ)

- uncertainty on some syst of improved
--> cross-calibration of different data sets

source	data sets	name	shift [σ]	Reduction factor [%]
δ_1	1	H1 vertex resolution	-0.1	94
δ_2	1–4	H1 CJC efficiency	-0.3	82
δ_3	1	H1 CST efficiency	0.0	98
δ_4	1	B multiplicity	-0.3	96
δ_5	1–9	c longitudinal fragmentation	-0.9	84
δ_6	1, 3, 4	photoproduction background	0.2	94
δ_7	1	D^+ multiplicity	0.0	99
δ_8	1	D^0 multiplicity	0.0	99
δ_9	1	D_s multiplicity	0.1	98
δ_{10}	1	b fragmentation	0.0	100
δ_{11}	1	H1 VTX model: x-reweighting	-0.4	95
δ_{12}	1	H1 VTX model: p_T-reweighting	0.3	74
δ_{13}	1	H1 VTX model: $\eta(c)$-reweighting	-0.3	87
δ_{14}	1	H1 VTX uds-background	0.0	53
δ_{15}	1	H1 VTX ϕ of c-quark	0.2	90
δ_{16}	1	H1 hadronic energy scale	-0.1	89
δ_{17}	1	H1 VTX F_2 normalisation	-0.2	97
δ_{18}	3, 4	H1 Primary vertex fit	0.1	99
δ_{19}	2–4	H1 electron energy	0.6	69
δ_{20}	2–4	H1 electron polar angle	0.3	77
δ_{21}	3, 4	H1 luminosity (HERA-II)	-0.9	80
δ_{22}	3, 4	H1 trigger efficiency (HERA-II)	-0.3	98
δ_{23}	3, 4	H1 fragmentation model in MC	-0.1	89
δ_{24}	2–7	$BR(D^* \to K\pi\pi)$	0.1	98
δ_{25}	2–6	$f(c \to D^*)$	0.1	94.
δ_{26}	2, 3	H1 efficiency using alternative MC model	0.4	73
δ_{27}	2–9	NLO, m_c	0.5	72
δ_{28}	2–9	NLO, scale	-1.2	66
δ_{29}	2–9	c transverse fragmentation	-0.2	78
δ_{30}	2–9	NLO, PDF	0.2	97
δ_{31}	2–9	NLO, $\alpha_s(M_Z)$	-0.2	95
δ_{32}	2	H1 luminosity (1998-2000)	-0.1	97
δ_{33}	2	H1 trigger efficiency (HERA-I)	-0.2	95
δ_{34}	2	H1 MC alternative fragmentation	-0.1	70
δ_{35}	9	ZEUS μ: B/RMUON efficiency	-0.1	92
δ_{36}	9	ZEUS μ: FMUON efficiency	0.2	97
δ_{37}	9	ZEUS μ: energy scale	0.0	85
δ_{38}	9	ZEUS μ: P_T^{miss} calibration	0.0	72
δ_{39}	9	ZEUS μ: hadronic resolution	0.6	71
δ_{40}	9	ZEUS μ: IP resolution	-0.2	97
δ_{41}	9	ZEUS μ: MC model	0.1	86
δ_{42}	9	$B(c \to \mu)$	0.1	97
δ_{43}	7, 8	ZEUS lifetime significance	0.5	52
δ_{44}	7	$f(c \to D^0)$	0.3	97
δ_{45}	8	$f(c \to D^+) \times BR(D^+ \to K\pi\pi)$	-0.6	91
δ_{46}	7–9	ZEUS luminosity (2005)	-0.1	95
δ_{47}	5	ZEUS luminosity (1996-1997)	0.4	96
δ_{48}	6	ZEUS luminosity (1998-2000)	0.3	90

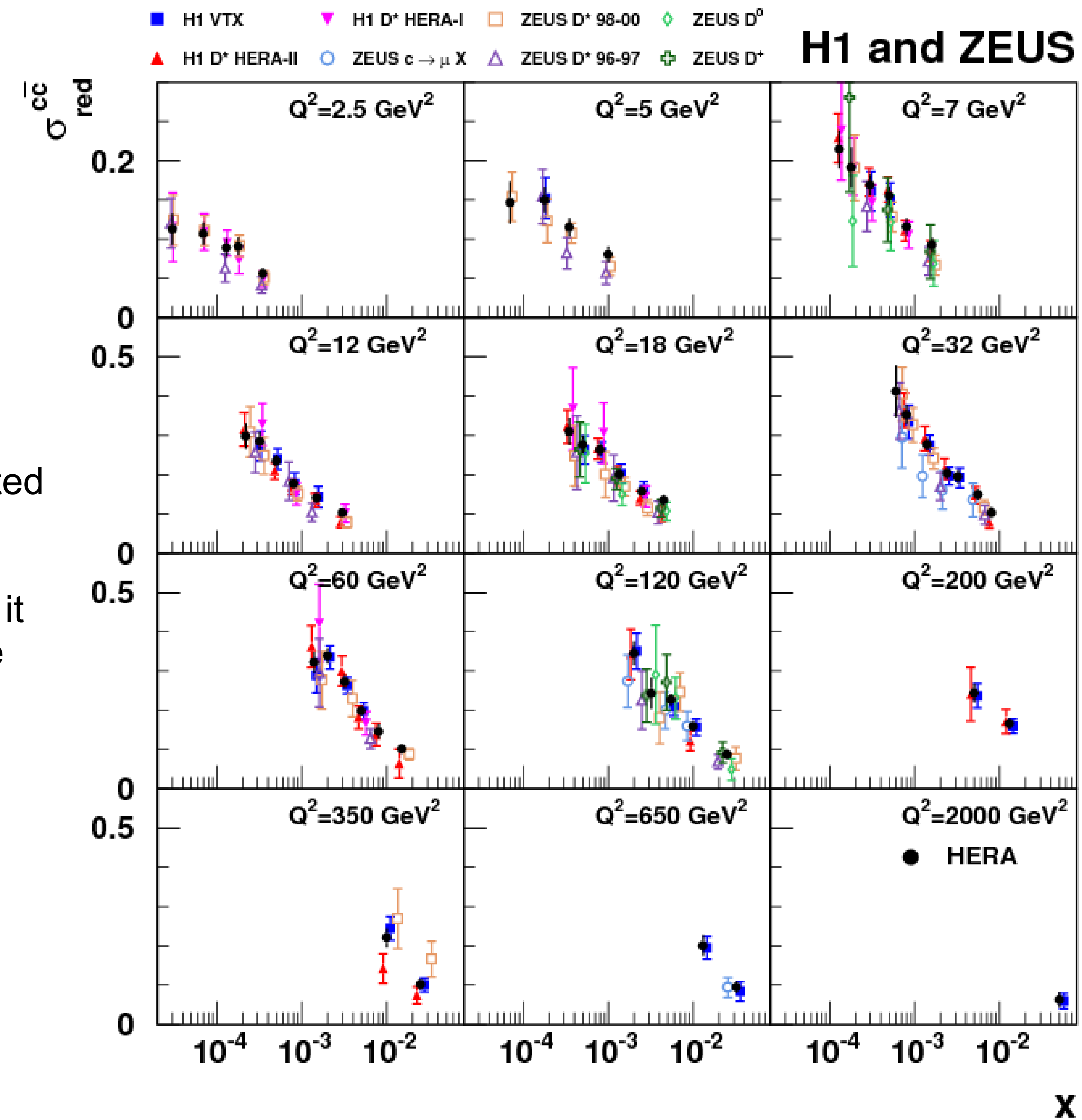
Results compared to single measurements

- Combined data more precise than single data sets

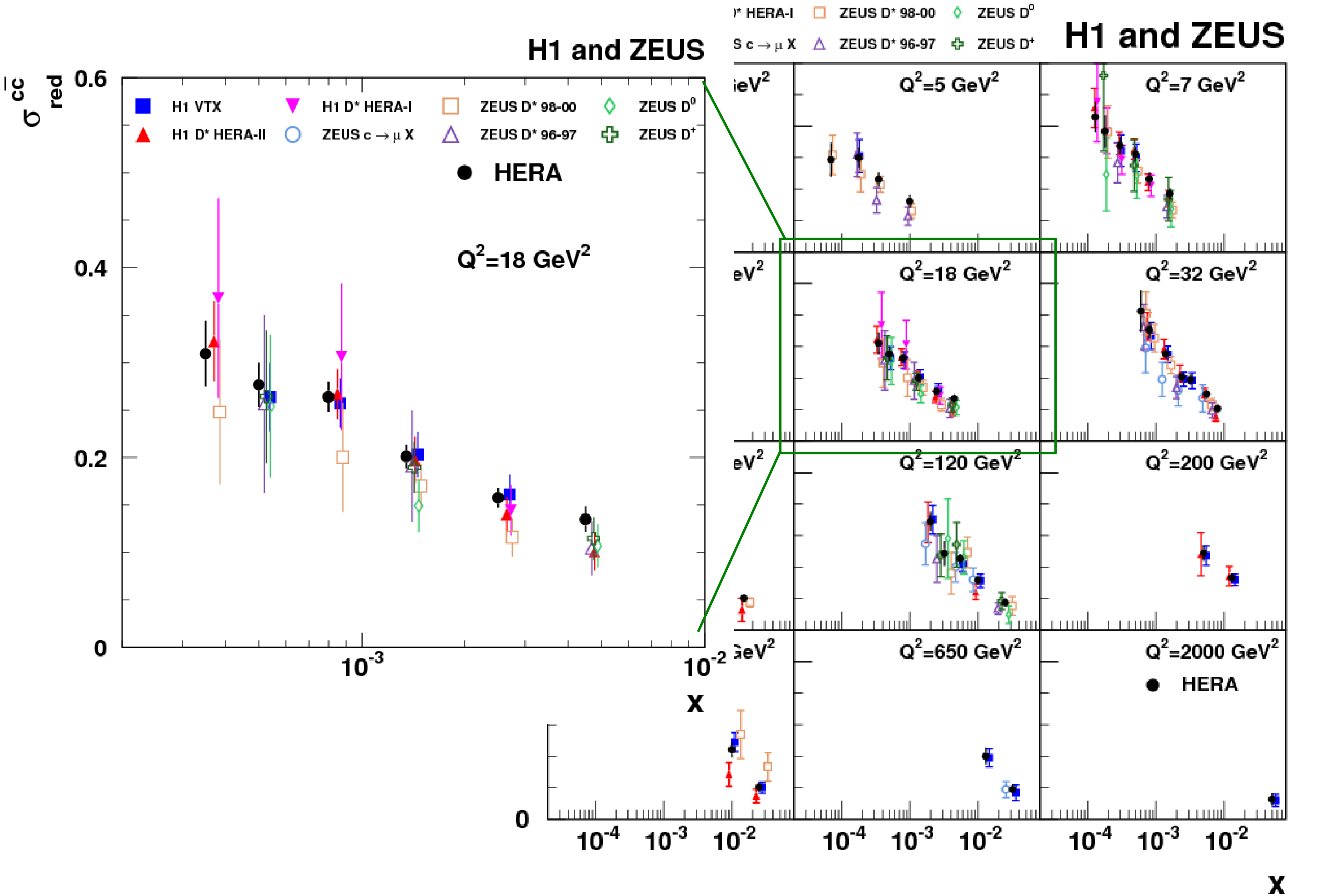
- Total uncertainty ~6% at medium x and $12 < Q^2 < 60$ GeV^2

- Correlated uncertainty similar size of uncorrelated
  --> full correlation matrix provided
  --> very important to use it (in contrast with inclusive ccombination)

- Procedural errors small except at Q^2=350 GeV^2 (4-5%)



Results compared to single measurements



Comparison with HERAPDF1.5

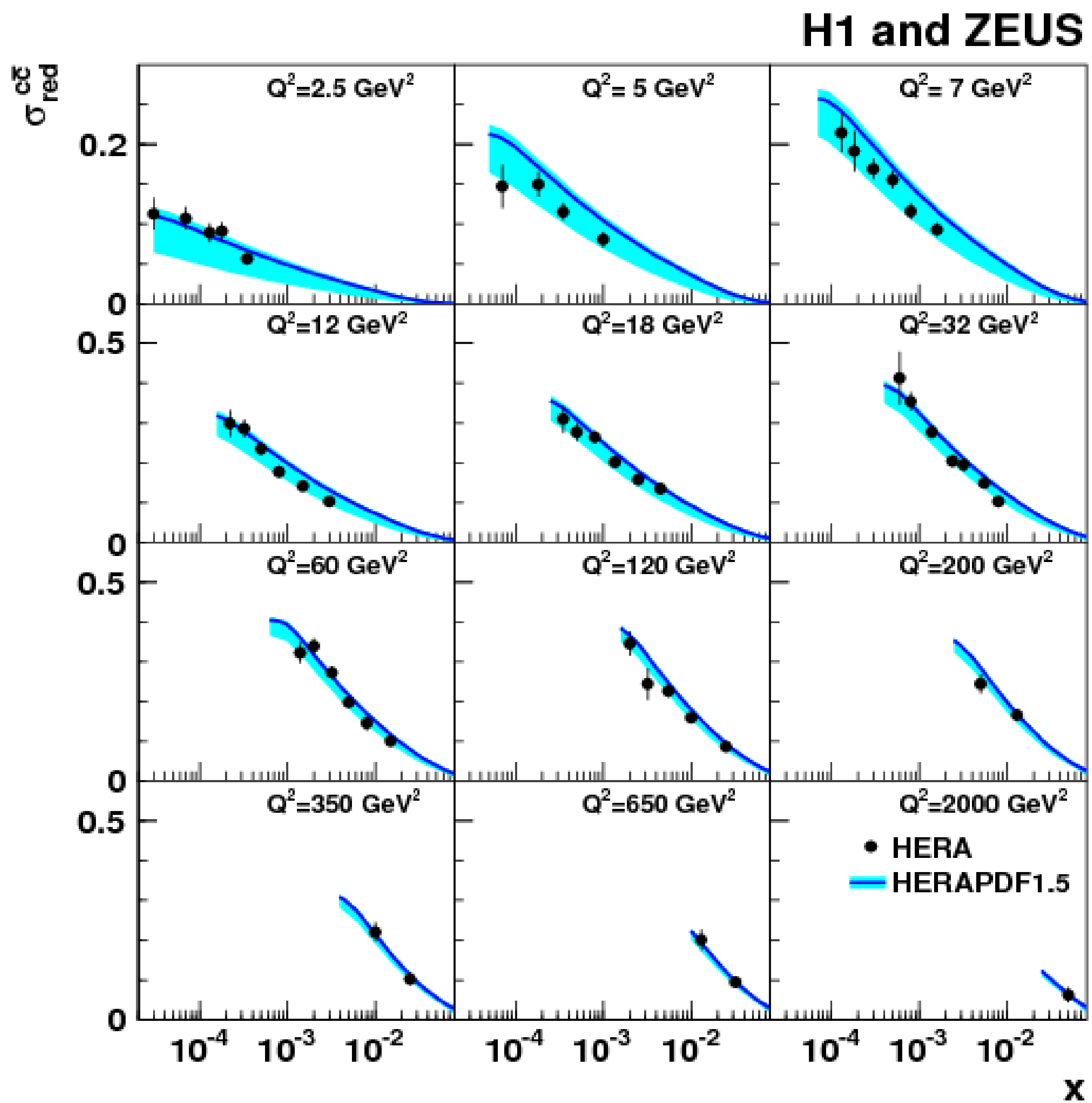
- GM-VFNS
  (RT-standard variant)
  $O(\alpha_s^{\ 2})$ for FFN part
  $O(\alpha_s)$ for VFN part

- PDF : HERAPDF1.5
  (no charm data included)

- Central line for
  m_c=1.4 GeV (pole)

- Main uncertainty from
  model variation
  $1.35 < m_c < 1.65$ GeV

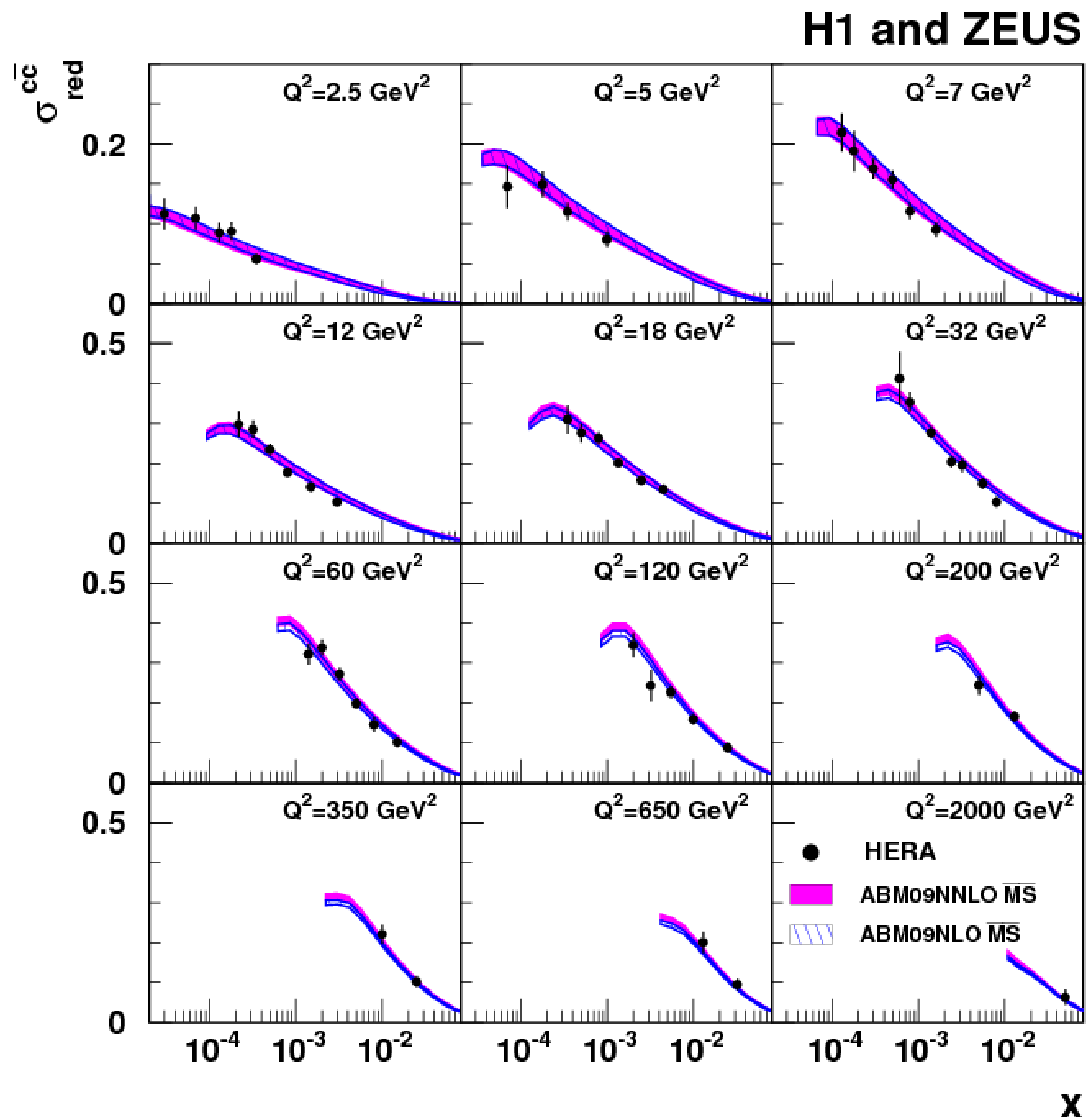
- Consistency of charm data
  with inclusive fit



Comparison with FFNS (ABM)

- ABM FFNS
  describe data well in the
  full HERA range

- $m_c(m_c)$=1.18 GeV ($\overline{MS}$)



Comparison with CT10 GM-VFNS

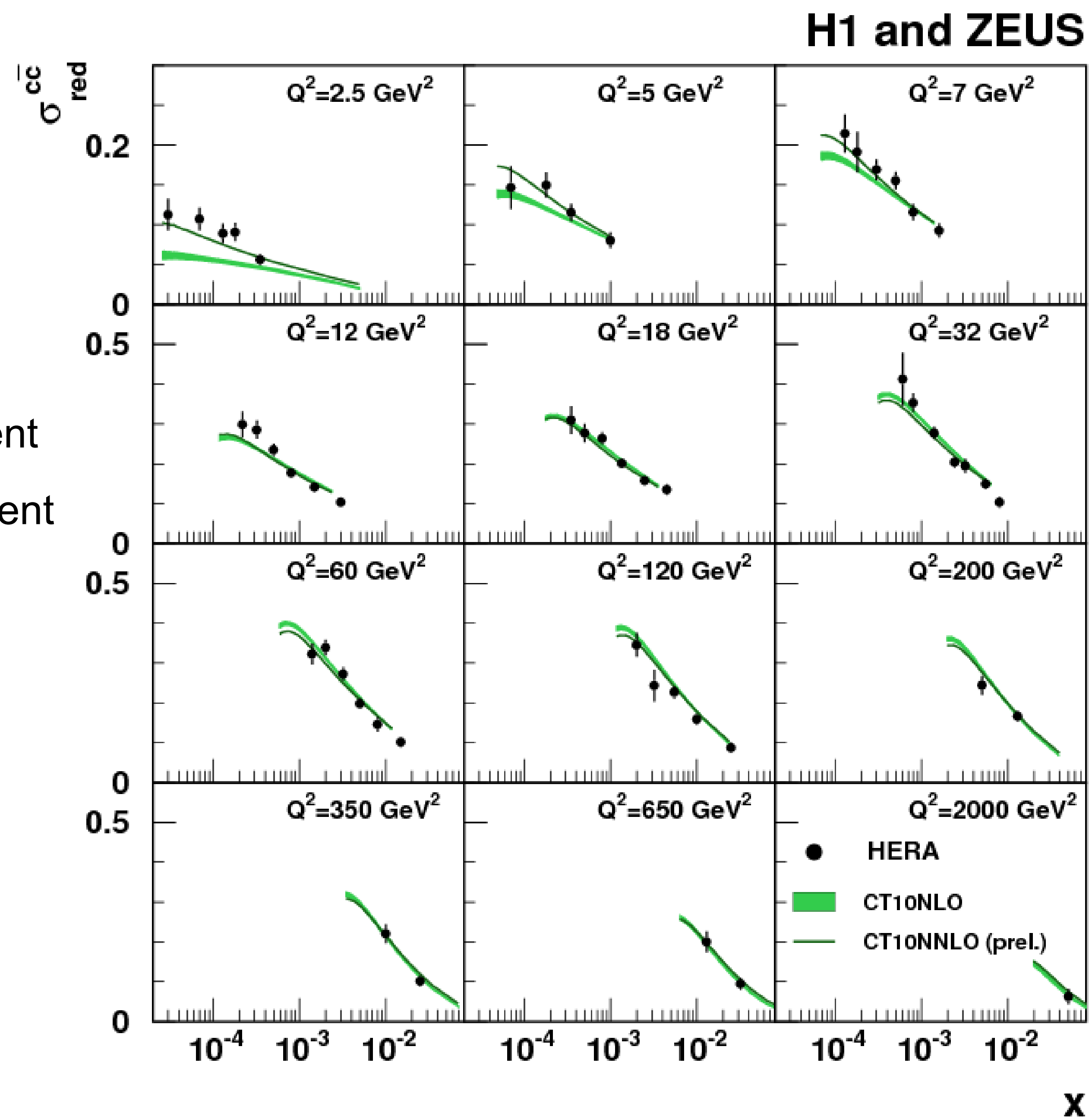
Comparison to CT10

GM-VFNS
S-ACOT-χ scheme:

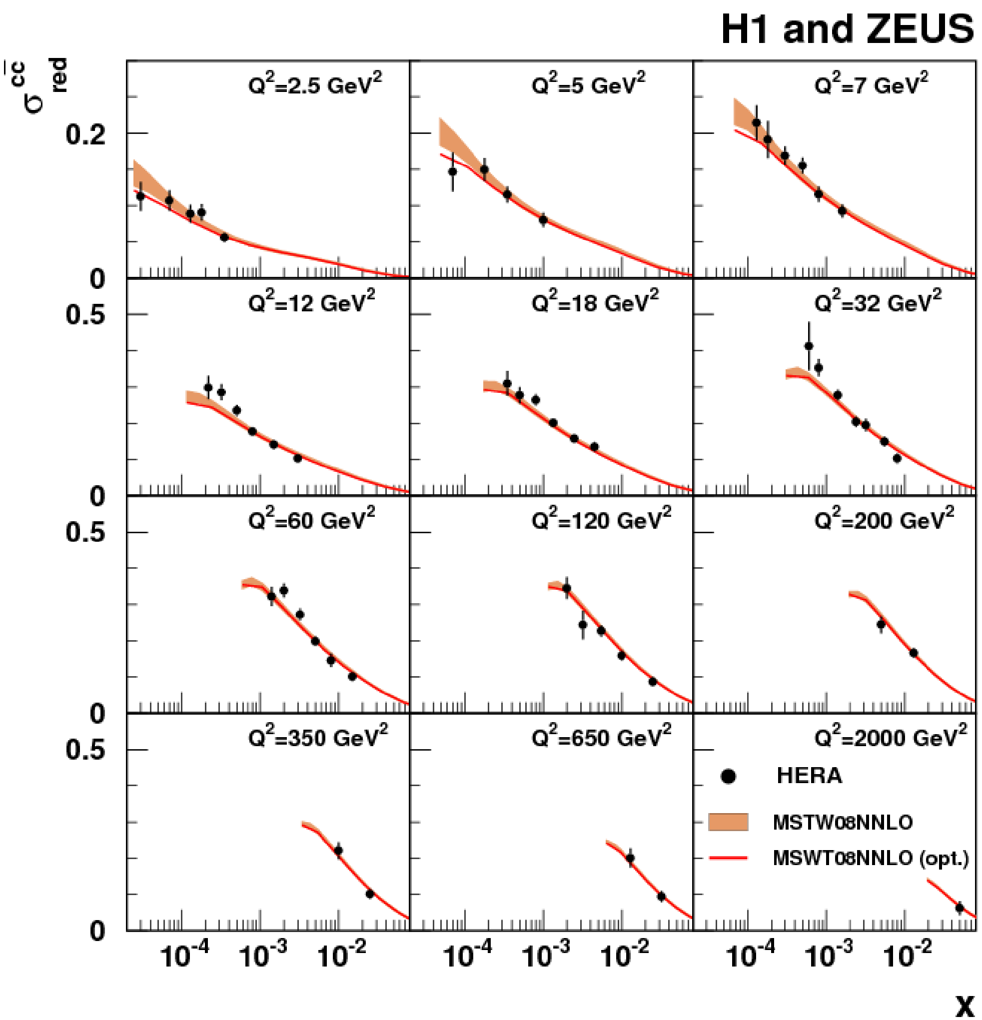
- NLO : $O(\alpha_s)$ -> poor agreement
- NNLO : $O(\alpha_s^2)$ -> fair agreement

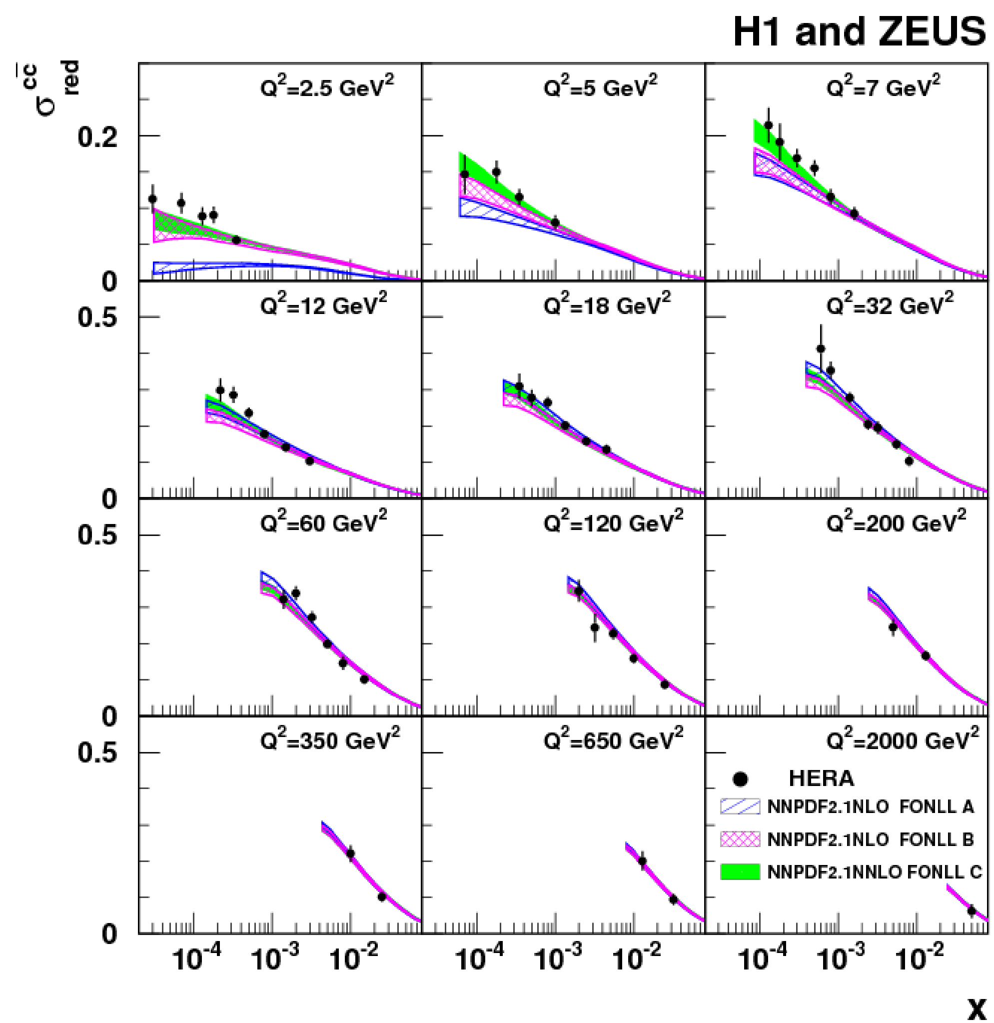
m_c = 1.3 GeV (pole)

Agreement improves going to higher order.



Comparison with MSTW08 and NNPDF2.1





GM-VFNS, qualitatively similar behaviours

Detailed comparison not simple as different groups use different parameters, schemes, data...

Differences between predictions

Theory	Scheme	Ref.	$F_{2(L)}$ def.	m_c [GeV]	Massive ($Q^2 \lesssim m_c^2$)	Massless ($Q^2 \gg m_c^2$)	$\alpha_s(m_Z)$ ($n_f=5$)	Scale	Included charm data
MSTW08 NLO	RT standard	[28]	$F^c_{2(L)}$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108	Q	[1,4–6,8,9,11]
MSTW08 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
MSTW08 NLO (opt.)	RT optimised	[31]			$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108		
MSTW08 NNLO (opt.)					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
HERAPDF1.5 NLO	RT standard	[55]	$F^c_{2(L)}$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.1176	Q	HERA inclusive DIS only
NNPDF2.1 FONLL A	FONLL A	[30]	n.a.	$\sqrt{2}$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.119	Q	[4–6,12,13,15,18]
NNPDF2.1 FONLL B	FONLL B		$F^c_{2(L)}$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$			
NNPDF2.1 FONLL C	FONLL C		$F^c_{2(L)}$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
CT10 NLO	S-ACOT-χ	[22]	n.a.	1.3	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.118	$\sqrt{Q^2+m_c^2}$	[4–6,8,9]
CT10 NNLO (prel.)		[56]	$F^{c\bar{c}}_{2(L)}$	1.3 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
ABKM09 NLO	FFNS	[57]	$F^{c\bar{c}}_{2(L)}$	1.18 ($\overline{\text{MS}}$)	$\mathcal{O}(\alpha_s^2)$	-	0.1135	$\sqrt{Q^2+4m_c^2}$	for mass optimisation only
ABKM09 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	-			

- Different perturbative orders of FFN / VFN parts
- Different matching prescriptions between FFN and VFN parts
- Different mc, α_s
- Different scales
- Different fitted data sets (in general including some HERA charm data)

QCD analysis

- Fit of charm and inclusive HERA data using different GM-VFNS schemes and FFNS
- Same inclusive data as in HERAPDF1.0 + charm data with Q^2 >3.5 GeV^2
- More flexible 13 parameter parametrization:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g} \cdot (1-x)^{C_g} - A'_g x^{B'_g} \cdot (1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} \cdot (1-x)^{C_{\overline{U}}}, \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} \cdot (1-x)^{C_{\overline{D}}}.
\end{aligned}
$$

A_g, A_{u_v}, A_{d_v} fixed by sum rules

$B_{\overline{U}} = B_{\overline{D}}$

$A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$, $f_s = 0.31$

$C'_g = 25$

- Different GM-VFNS schemes used:

- RT NLO with “standard” and “optimal” matching between FFN/VFN parts (as in MSTW)

(*$O(\alpha_s^2)$ for FFN part, $O(\alpha_s)$ for VFN part*)

- ACOT-full NLO and S-ACOT-χ NLO (as in CT10 NLO, *all $O(\alpha_s)$*)

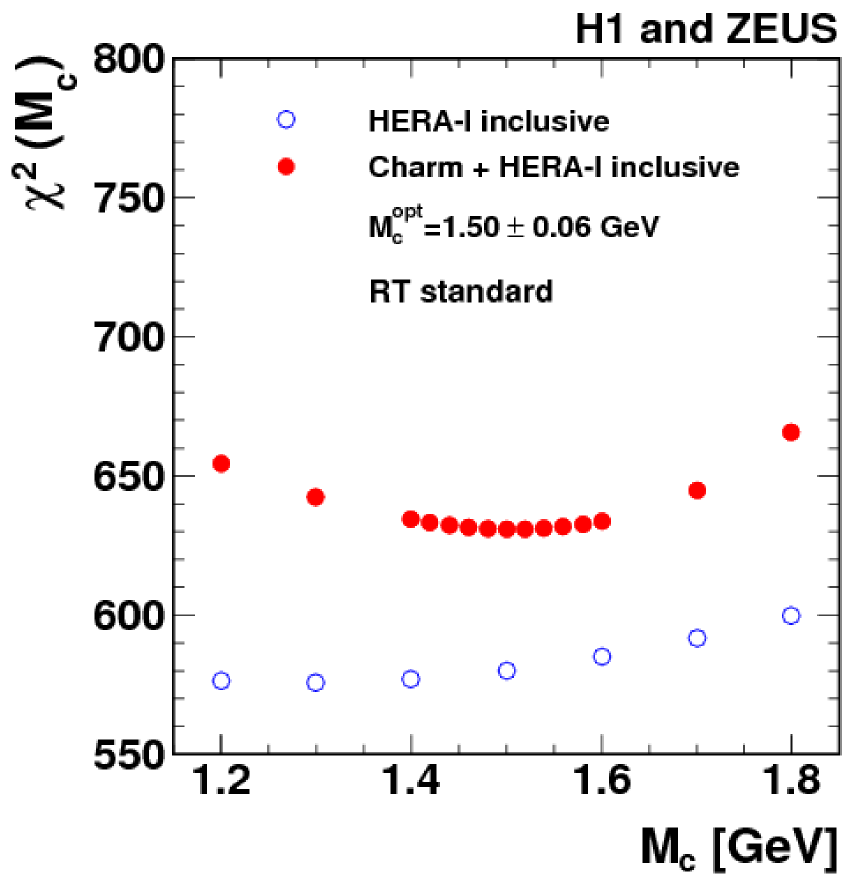
- ZM-VFNS NLO (*$O(\alpha_s)$*)

GM-VFNS Fit results

- results depend mainly on :
  1) heavy-flavour scheme of GM-VFNS
  2) the charm mass value

- Approach used :
  The charm mass is treated as a free parameter of the fit, Mc, different for each heavy-flavour scheme

- In contrast to the fit to inclusive data only, a minimum of χ2 is found



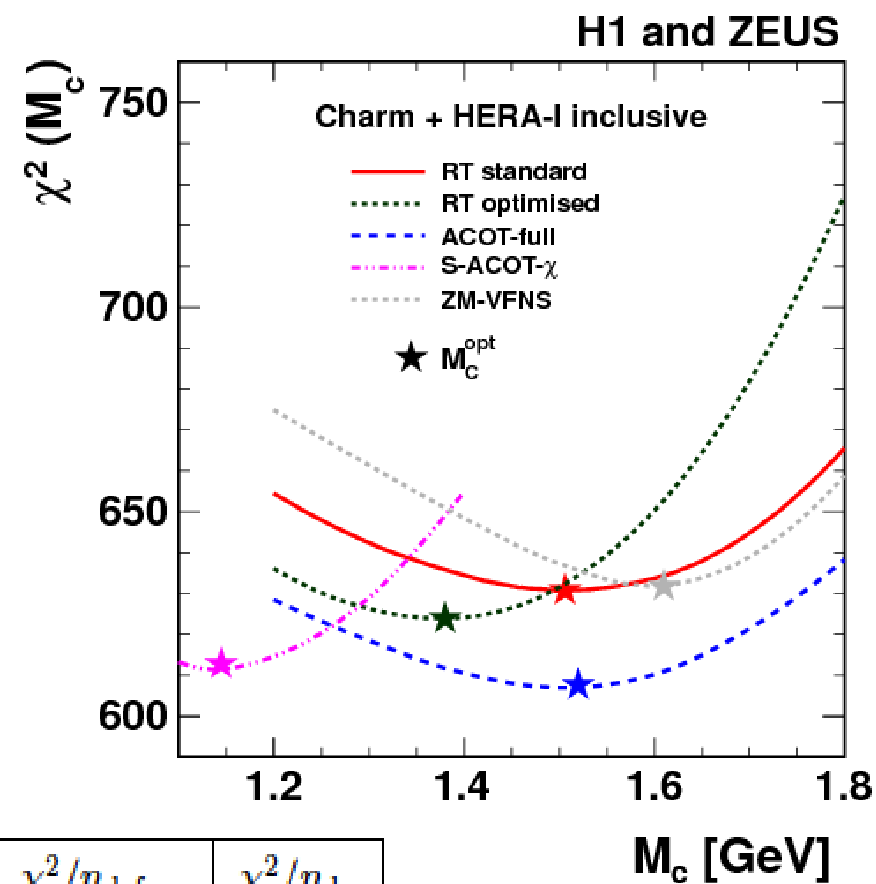
Optimal Mc for differen schemes

Best fit Mc^{opt} differs for different approaches:

- Best global fit : ACOT-full

- Best fit to charm data : RT standard

- Systematics calculated similarly to HERAPDF fit

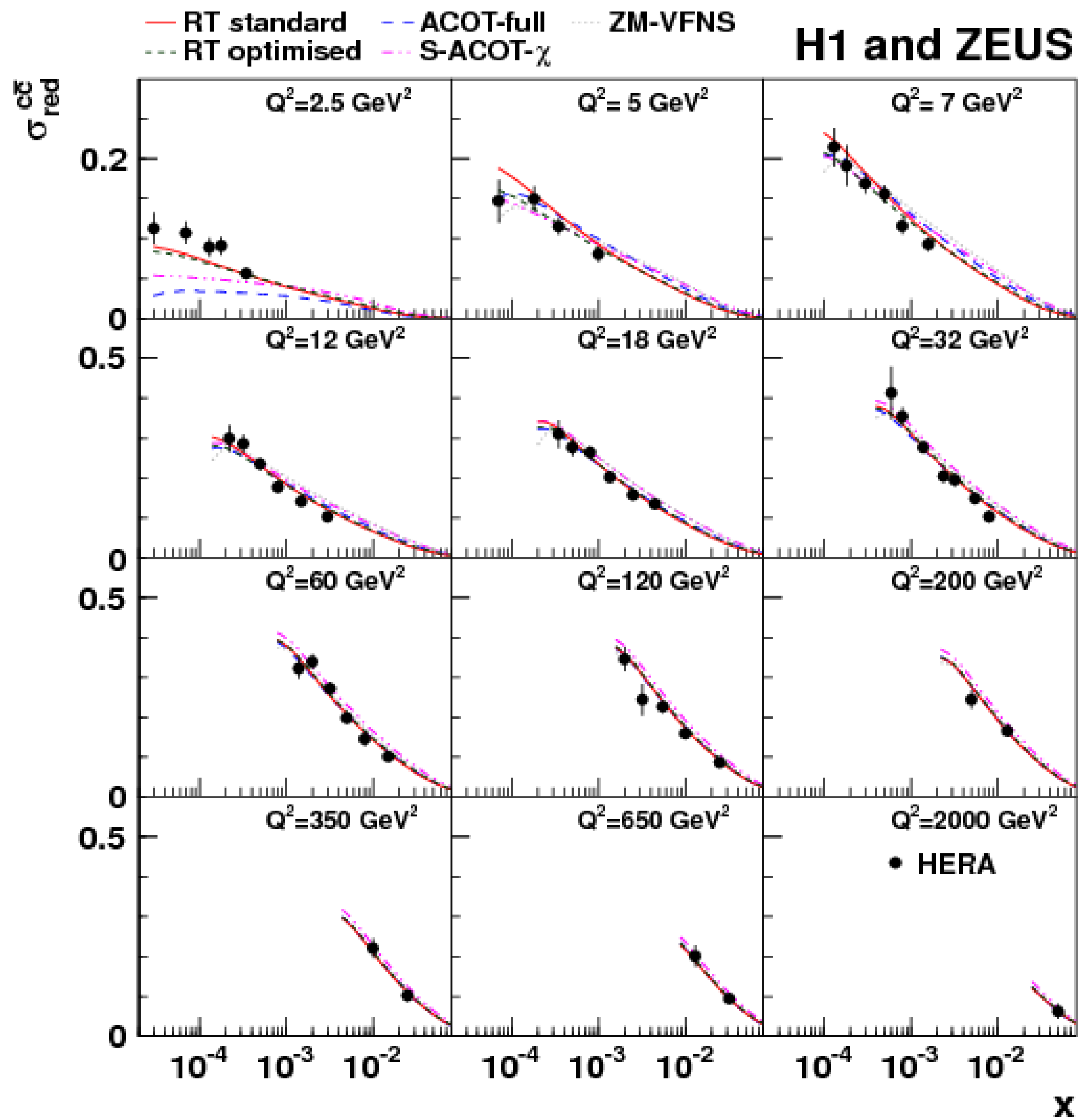


scheme	M_c^{opt} [GeV]	χ^2/n_{dof} $\sigma_{red}^{NC,CC}+\sigma_{red}^{c\bar{c}}$	χ^2/n_{dp} $\sigma_{red}^{c\bar{c}}$
RT standard	$1.50 \pm 0.06_{exp} \pm 0.06_{mod} \pm 0.01_{param} \pm 0.003_{\alpha_s}$	$630.7/626$	$49.0/47$
RT optimised	$1.38 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.01_{param} \pm 0.01_{\alpha_s}$	$623.8/626$	$45.8/47$
ACOT-full	$1.52 \pm 0.05_{exp} \pm 0.12_{mod} \pm 0.01_{param} \pm 0.06_{\alpha_s}$	$607.3/626$	$53.3/47$
S-ACOT-χ	$1.15 \pm 0.04_{exp} \pm 0.01_{mod} \pm 0.01_{param} \pm 0.02_{\alpha_s}$	$613.3/626$	$50.3/47$
ZM-VFNS	$1.60 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.05_{param} \pm 0.01_{\alpha_s}$	$631.7/626$	$55.3/47$

Fit results compared to charm data

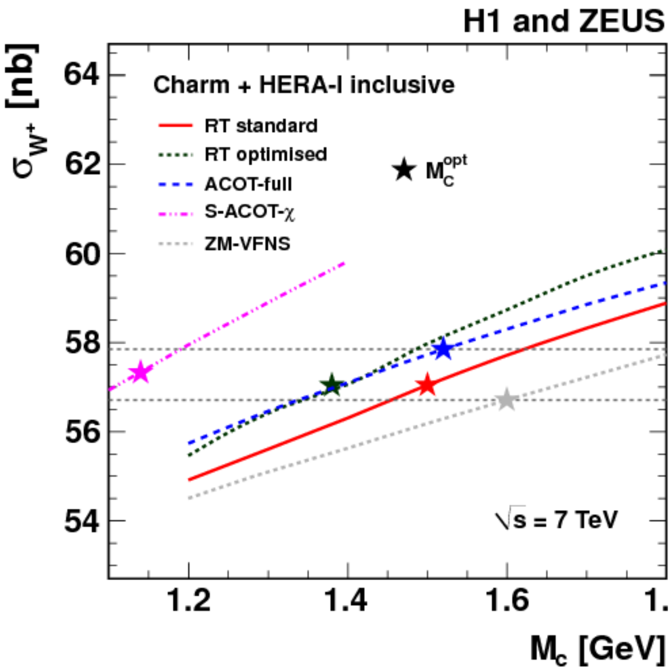
- Using the optimized Mc
  all the fits describe data
  reasonably well,
  including ZM-VFNS

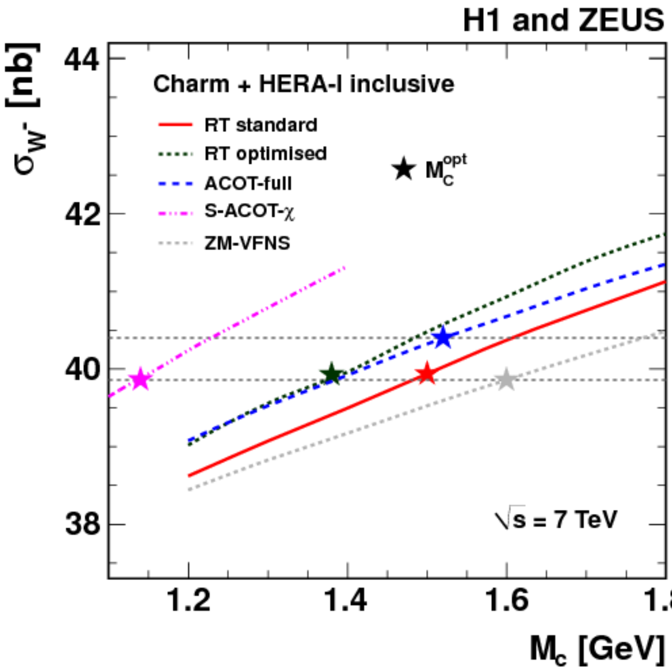
- Largest deviations observed
  In the lowest Q^2 bin
  (not included in the fit)

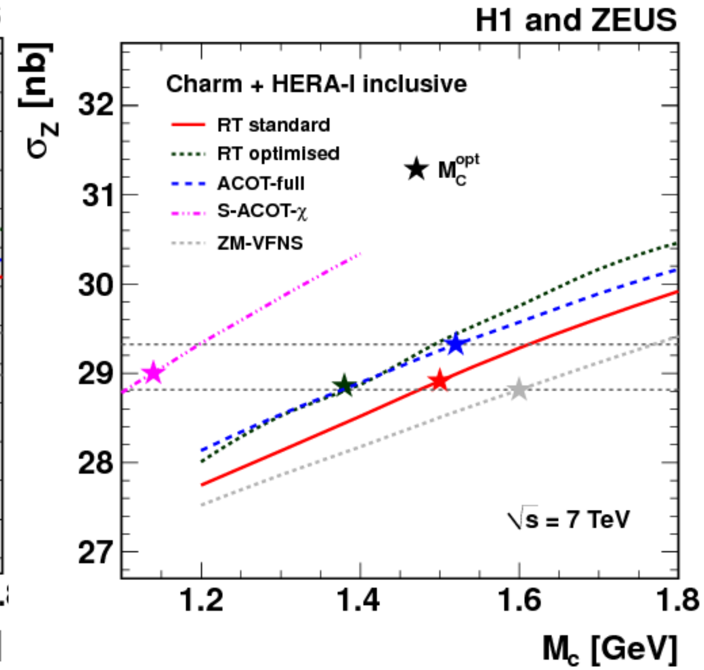


Impact on LHC cross sections

- Cross sections for W+,W-,Z production at LHC as a function of Mc







- For fixed Mc there is a significant spread among different schemes (~ 6%)

- Using optimized Mc the spread is reduced (1.8% for Z at Mc=1.4 GeV)

- The choice of the optimized Mc stabilizes the PDFs

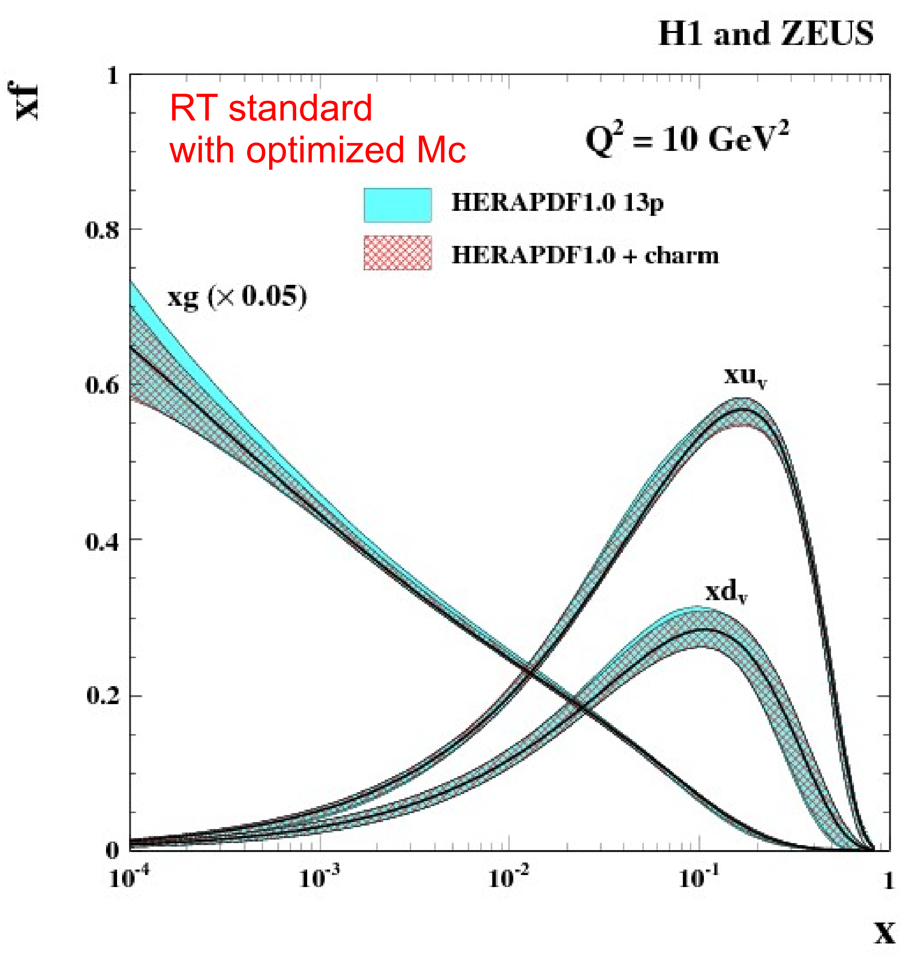
Impact on PDFs

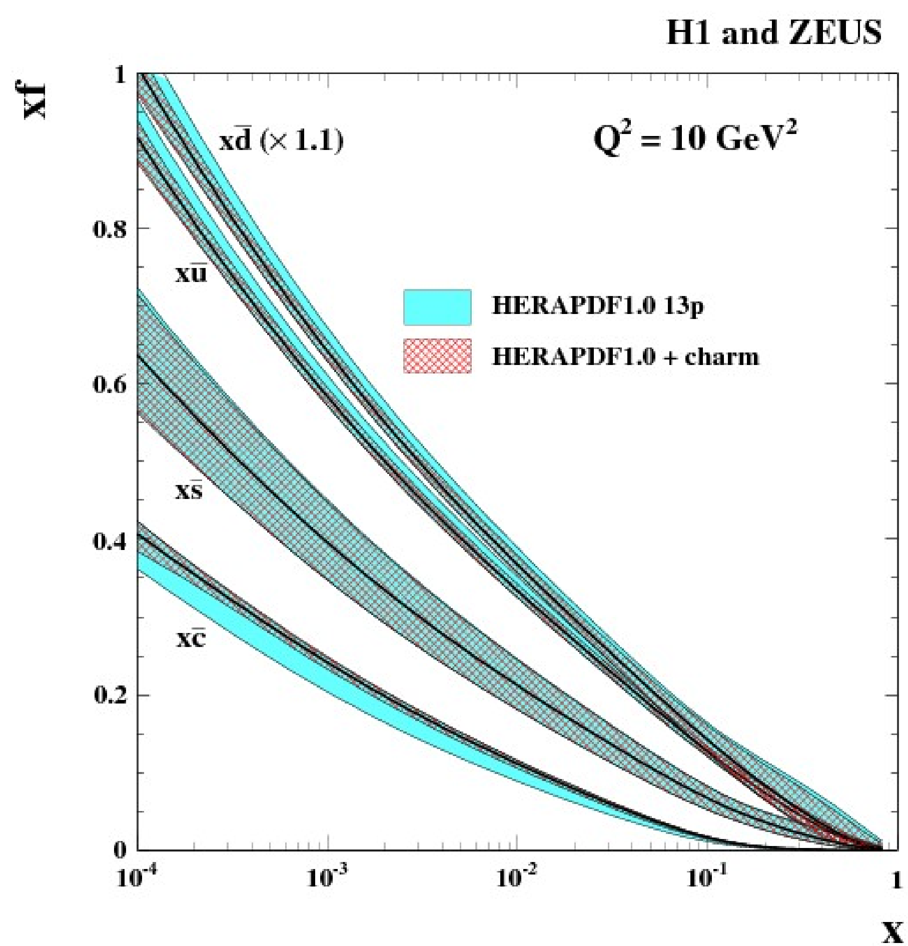
RT "standard" fit, with optimized Mc

- Uncertainty on g(x) reduced due to the reduced range allowed for Mc variation in the parametrization uncertainty

- Uncertainty on c(x) reduced significantly

- Uncertainty on light sea reduced because of reduced uncertanty of charm component

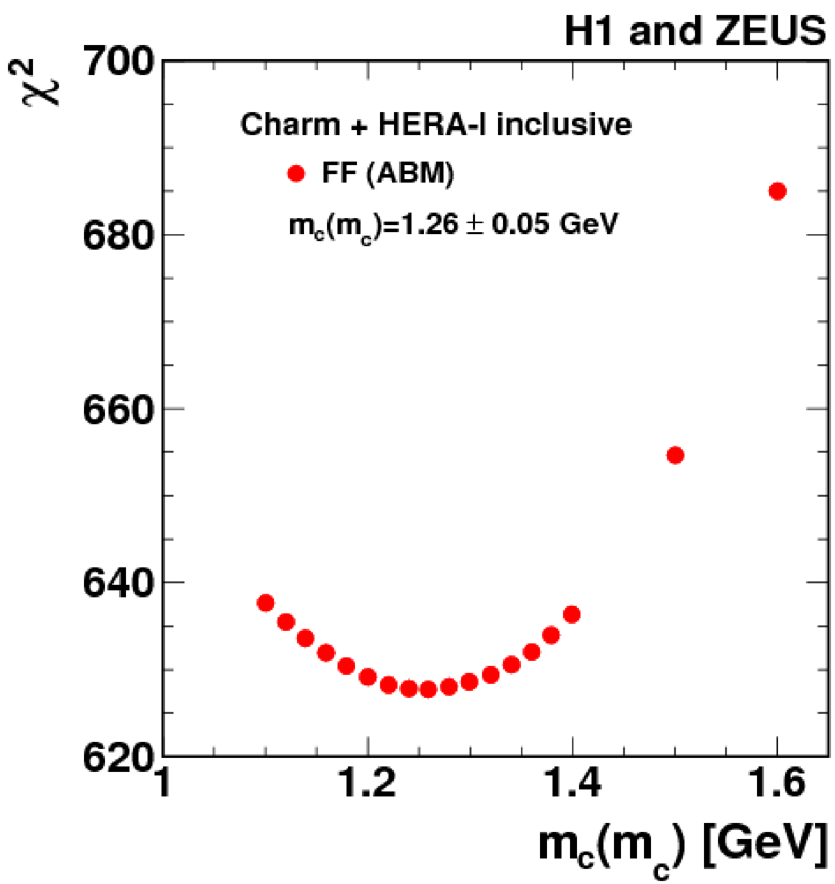




FFNS fit and measurement of m_c

The QCD fit was also done in the FFNS at $O(\alpha^2)$

- FFNS (nf=3) gives a good fit of HERA data
- ABM version with $m_c(Q)$ in $\overline{\text{MS}}$ scheme
- No dependence on GM-VFNS matching scheme
  -> can be used to measure the charm mass



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

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

Conclusions

- **H1-ZEUS charm data have been combined**:

  - consistent extraction of $\sigma_{\mathrm{red}}^{c\bar{c}}$

  - different data sets are compatible,

  - uncertainty ~6% at mid-x, mid-Q^2 , significant correlations.

- **Inclusive + charm GM-VFNS fits:**

  fitting optimal Mc for each scheme

  - reduces the differences between different schemes

  - reduces the uncertainty on c(x), g(x), $\bar{u}$(x), $\bar{d}$(x)

- **FFNS NLO measurement of m_c**

- Still more data to be combined ...

BACKUPS

LHC cross sections, errors correspond to optimal Mc uncertainty

scheme	σ_Z [nb]	σ_{W^+} [nb]	σ_{W^-} [nb]
RT standard	28.91 ± 0.30	57.04 ± 0.55	39.94 ± 0.35
RT optimised	28.85 ± 0.24	57.03 ± 0.45	39.93 ± 0.27
ACOT-full	29.32 ± 0.42	57.84 ± 0.74	40.39 ± 0.47
S-ACOT-χ	29.00 ± 0.22	57.32 ± 0.42	39.86 ± 0.24
ZM-VFNS	28.81 ± 0.24	56.71 ± 0.40	39.86 ± 0.25

Systematics of QCD fit

- Model uncertainties:
  - strange : $0.23<fs<0.38$
  - beauty : mb = 4.75 +- 0.25 GeV
  - Low-Q2 selection : Q2_min for inclusive data from 3.5 to 5 GeV2

- Parametrization uncertainties:
  - single parameters added in turn to the PDF parametrizations
  - starting scale Q20 from 1.4 to 1.9 GeV2

- αs(Mz) = 0.1176 +-0.002 [0.105 for FFNS]

Charm measurements at HERA

Many different measurements:

- Wide kinematic range
  0 < Q2 < 10000 GeV2

- Different methods to tag charm:
  - Full reconstruction of D and D* mesons,
  - Semileptonic decays,
  - Inclusive lifetime

  very different systematics and sensitivities

- We present here a combination of
  all DIS data (Q2>1GeV^2) published so far

- Improvements wrt preliminary result released in 2008:
  - all data sets used are final
  - consistent approach for kinematical acceptance