# The Charm of HERA

see also plenary talks O. Behnke, V. Radescu, J. Rojo

## Combination and QCD analysis of charm production cross section measurements in DIS at HERA

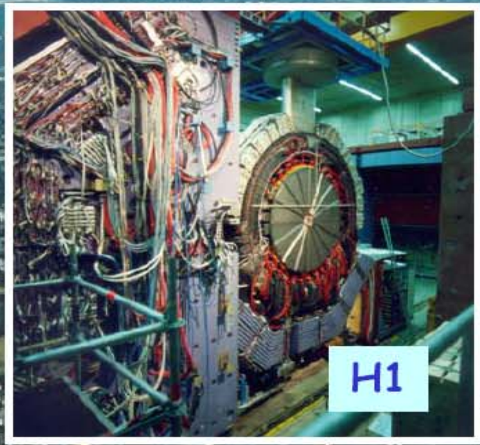

technical details:
DESY 12-172, EPJ C73 (2013) 2311

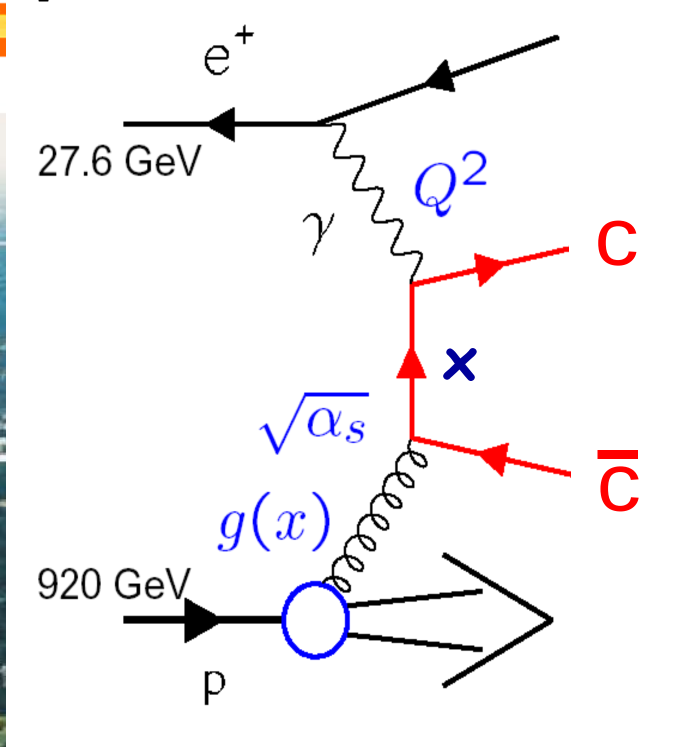
**Achim Geiser, DESY Hamburg**

DIS13, for the ZEUS and H1 collaborations

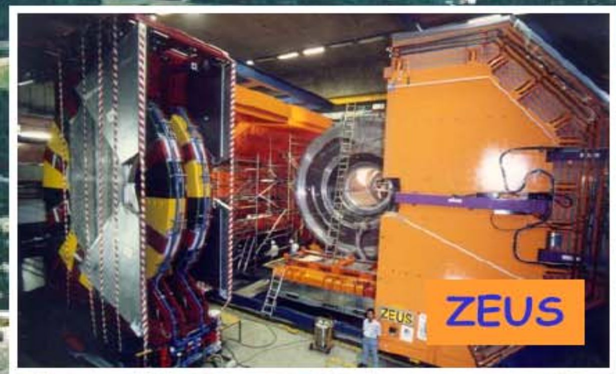
- data combination
- PDF fits
- measurement of $m_c$
- impact on LHC cross sections

# The HERA ep collider and experiments




**up to 30% of cross section**

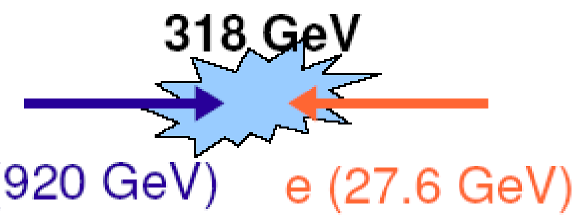



**HERA I: ~ 130 $pb^{-1}$ (physics)**

**HERA II: ~ 380 $pb^{-1}$ (physics)**

**combined: ~ 2 x 0.5 $fb^{-1}$**

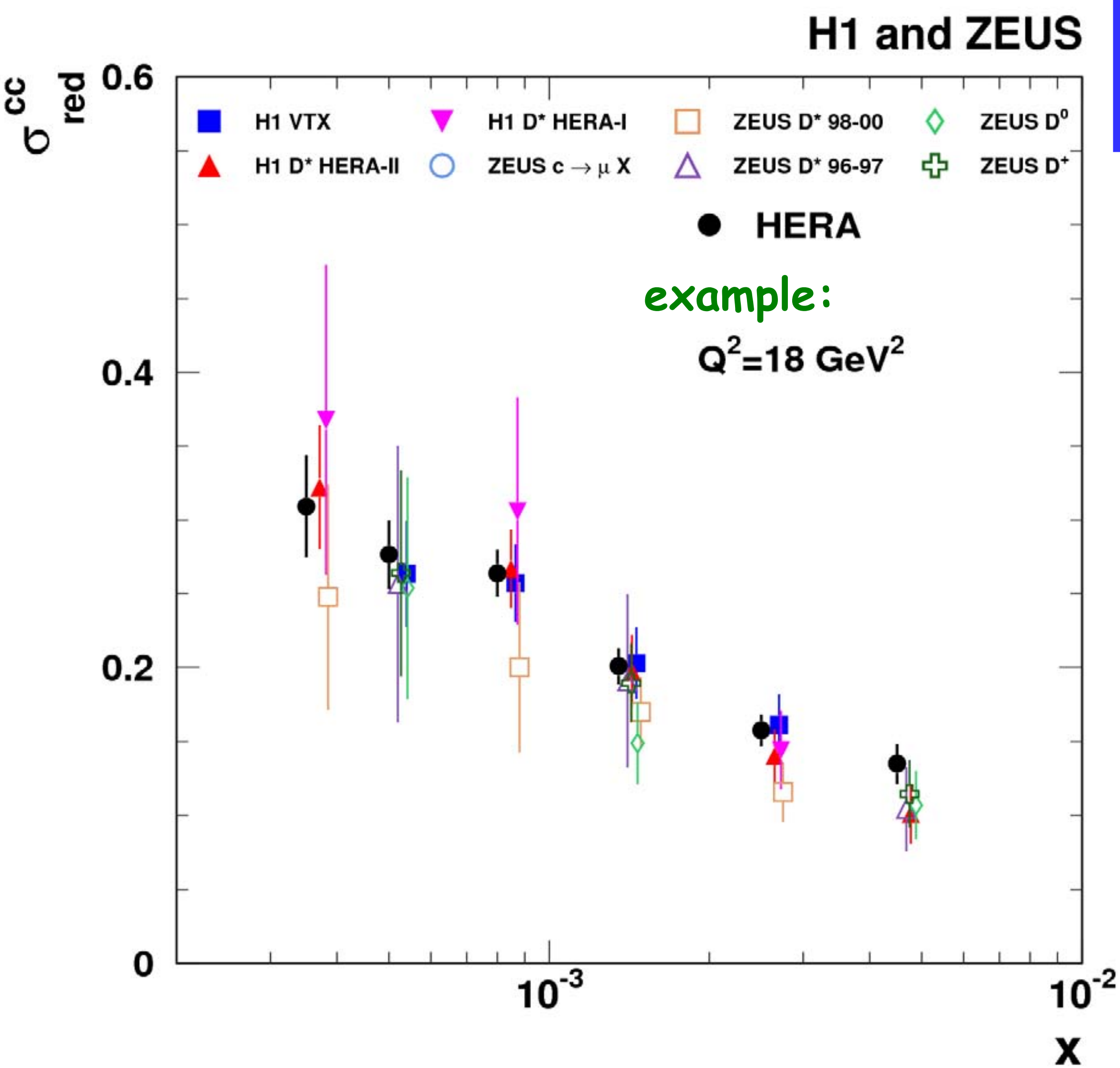
HERA:



# HERA charm data combination

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left[1+(1-y)^2\right]\sigma_{red}^{cc}$$



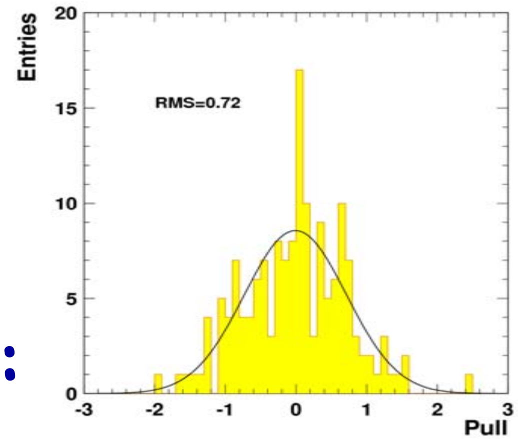

9 data sets
(HERA I, HERA II)

5 charm tagging methods

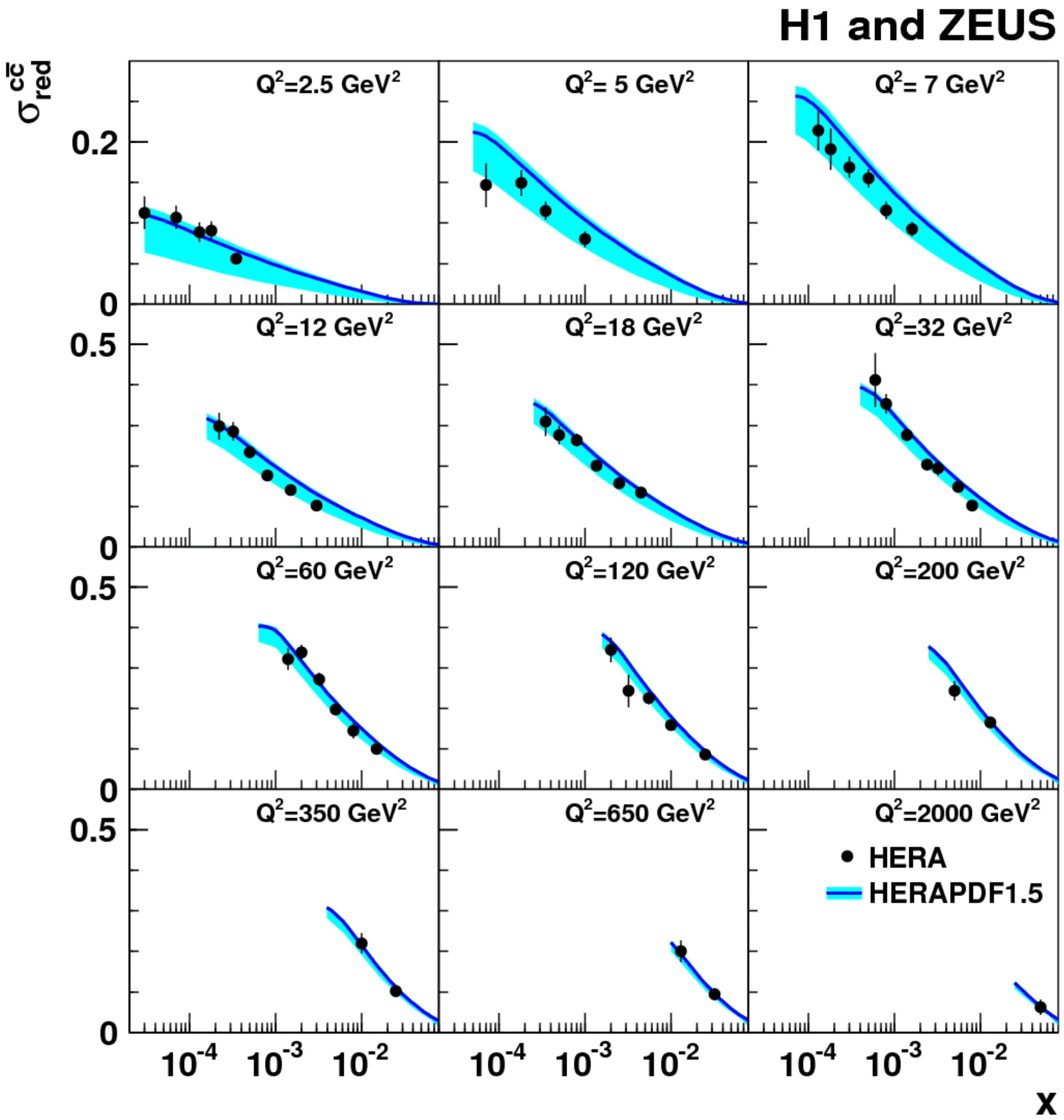
155 -> 52 data points

48 correlated systematic uncertainties

very good selfconsistency of data:



# Combination result



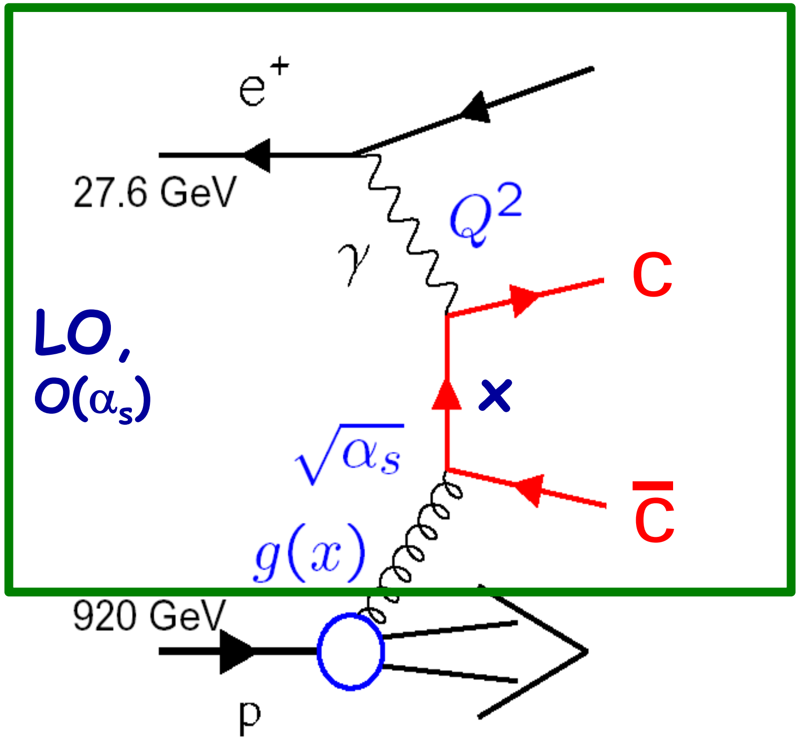

**well described using HERAPDF1.5**

(fitted from inclusive DIS only)

**strong charm mass dependence**

(blue band: 1.35-1.65 GeV)

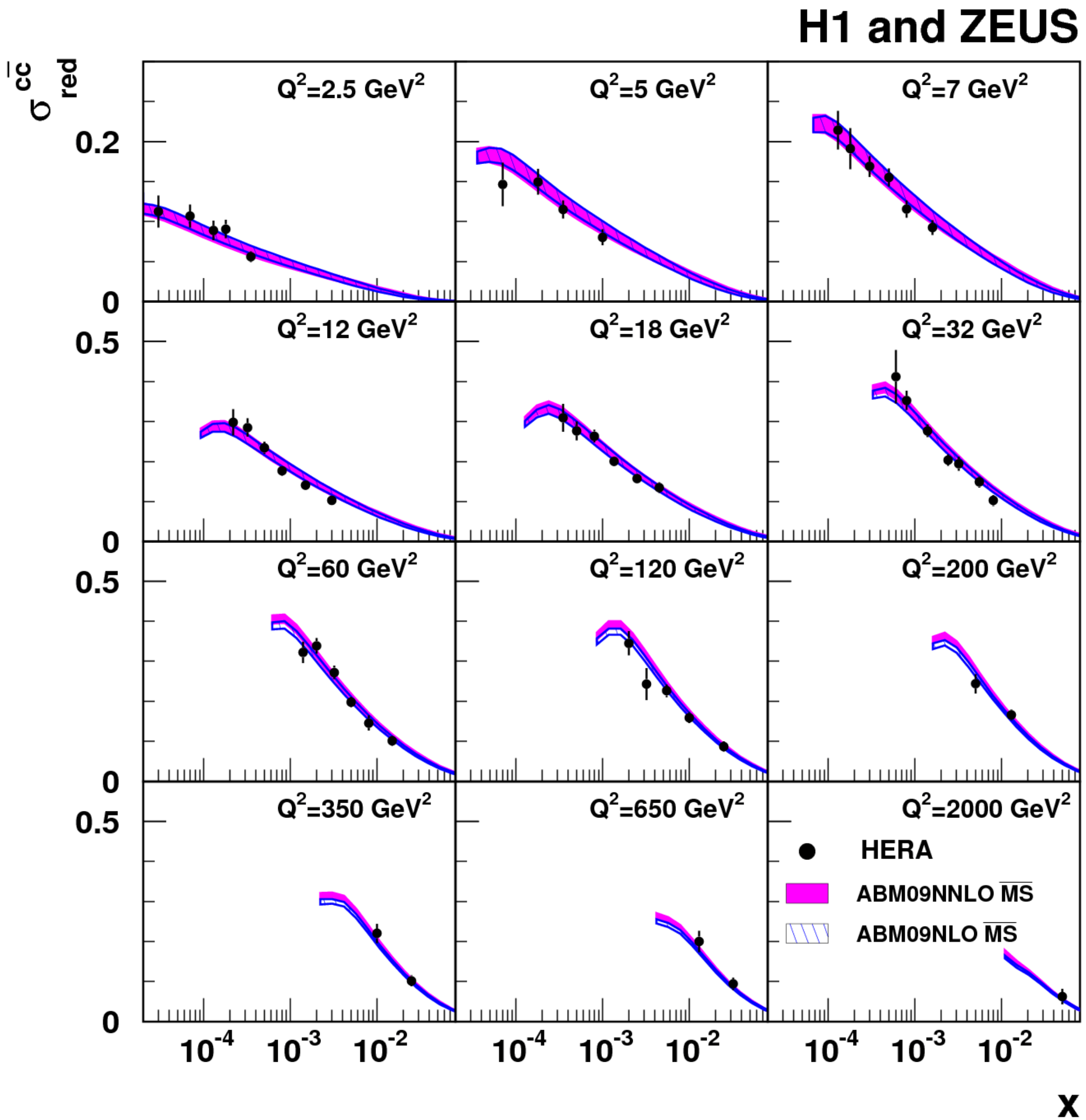
# Fixed Flavour Number Scheme (FFNS)




+ NLO, $O(\alpha_s^2)$
(+partial NNLO, $O(\alpha_s^3)$)
corrections

- no charm in proton
- full kinematical treatment of charm mass
  (multi-scale problem:
  $Q^2$, $p_T$, $m_c$ -> logs of ratios)
- on-shell (pole) or $\overline{MS}$ mass renormalization
- no resummation of logs

# comparison to ABM FFNS



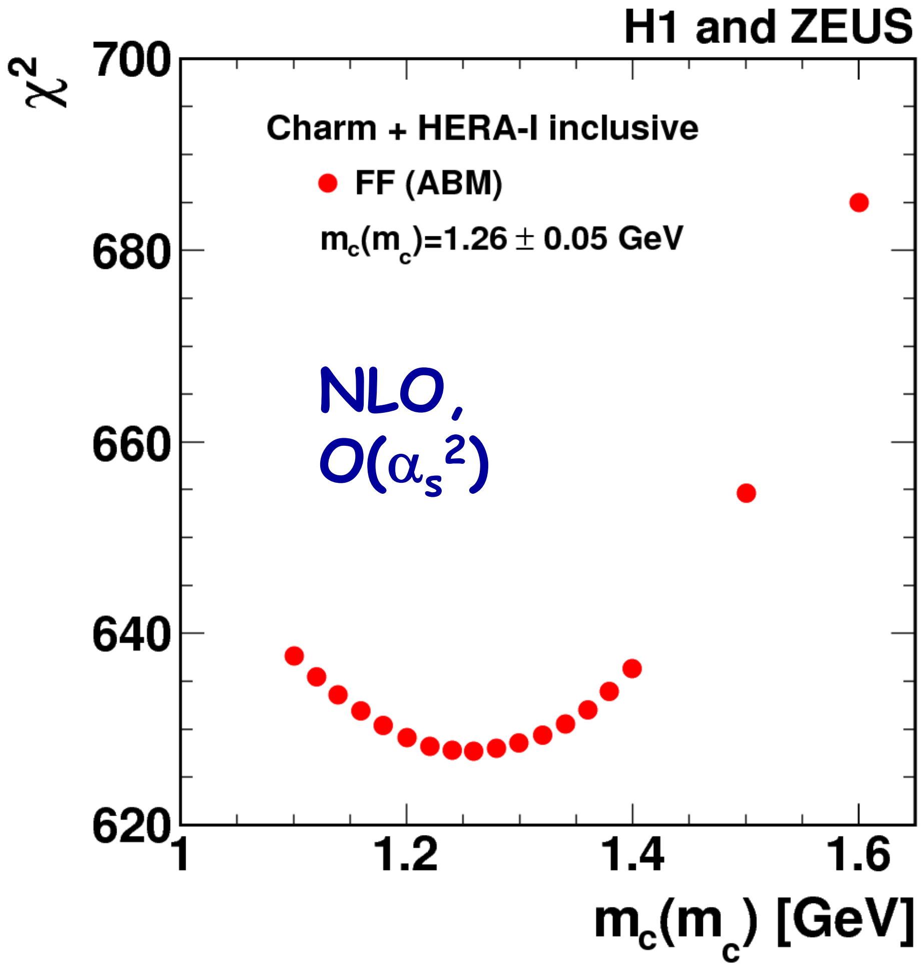

very good description of data in full kinematic range

unambigous treatment of $m_c$ in all terms of calculation

here: $\overline{MS}$ running mass NLO, partial NNLO

(similar predictions for pole mass)

# measurement of $\overline{MS}$ charm mass




**simultaneous fit of combined charm data and inclusive HERA I DIS data** (HERAFitter)

$\chi 2$ = 628/626, 44/47 (charm)

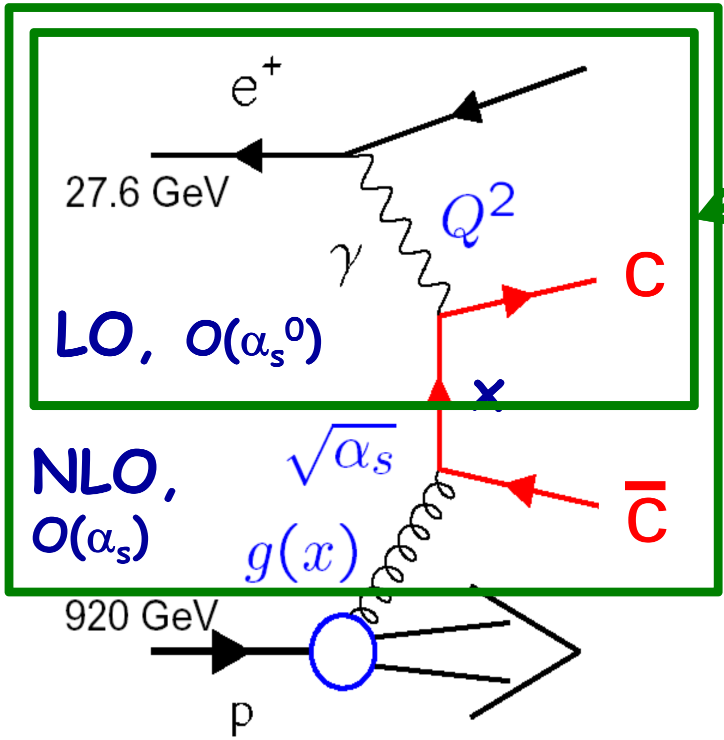
(see also talk S. Alekhin)


**mod:** vary $f_s$, $m_b$, $Q^2_{min}$, PDF param

**$m_c(m_c)$ = 1.26 ±0.05$_{exp}$ ±0.03$_{mod}$ ±0.02$_{\alpha s}$ GeV**

**PDG: 1.275 ±0.025 GeV (lattice QCD + time-like processes)**

# Variable Flavour Number Scheme (GM-VFNS)




+ NNLO, $O(\alpha_s^2)$
corrections

**very high $Q^2$:**

- massless charm in proton
- resummation of $\log(Q^2/m^2)$ etc.

**very low $Q^2$:**

- massive calculation (pole mass)

**in between** (almost everywhere):

- kinematic interpolation and/or correction terms

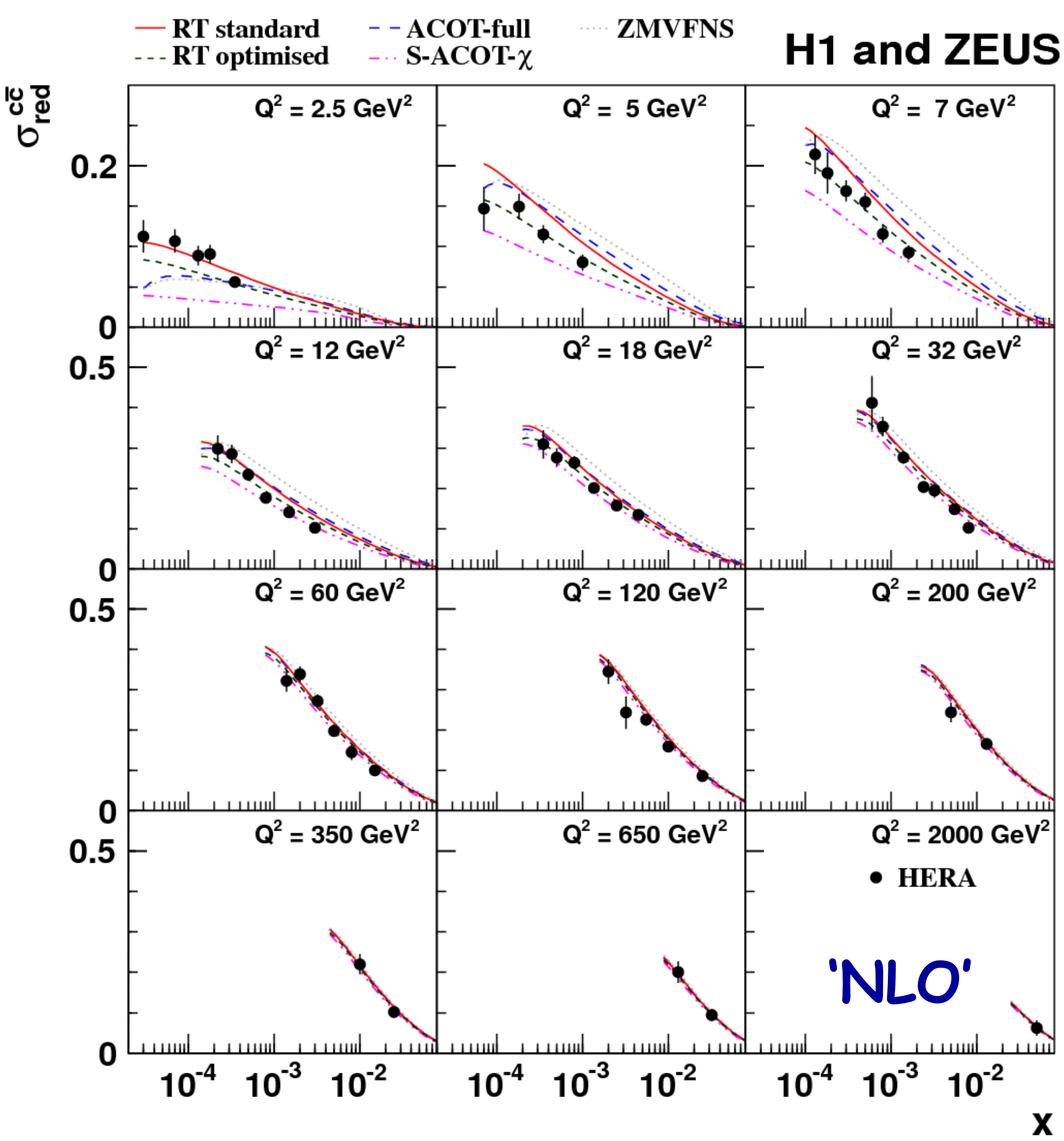
# Table of different schemes

| Theory (PDF) | 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-$\chi$ | [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.-$\mathcal{O}(\alpha_s^3)$ | - | | | |

Table 6: Calculations from different theory groups as shown in figures 5-8. The table shows the heavy flavour scheme used and the corresponding reference, the respective $F_{2(L)}$ definition (section 2), the value and type of charm mass used (equation (3)), the order in $\alpha_S$ of the massive and massless parts of the calculation, the value of $\alpha_s$, the renormalisation and factorisation scale, and which HERA charm data were included in the corresponding PDF fit. The distinction between the two possible $F_{2(L)}$ definitions is not applicable (n.a.) for $\mathcal{O}(\alpha_s)$ calculations.

# comparison to various VFNS

more comparisons see paper




as implemented in HERAFitter (talk R.Placakyte)

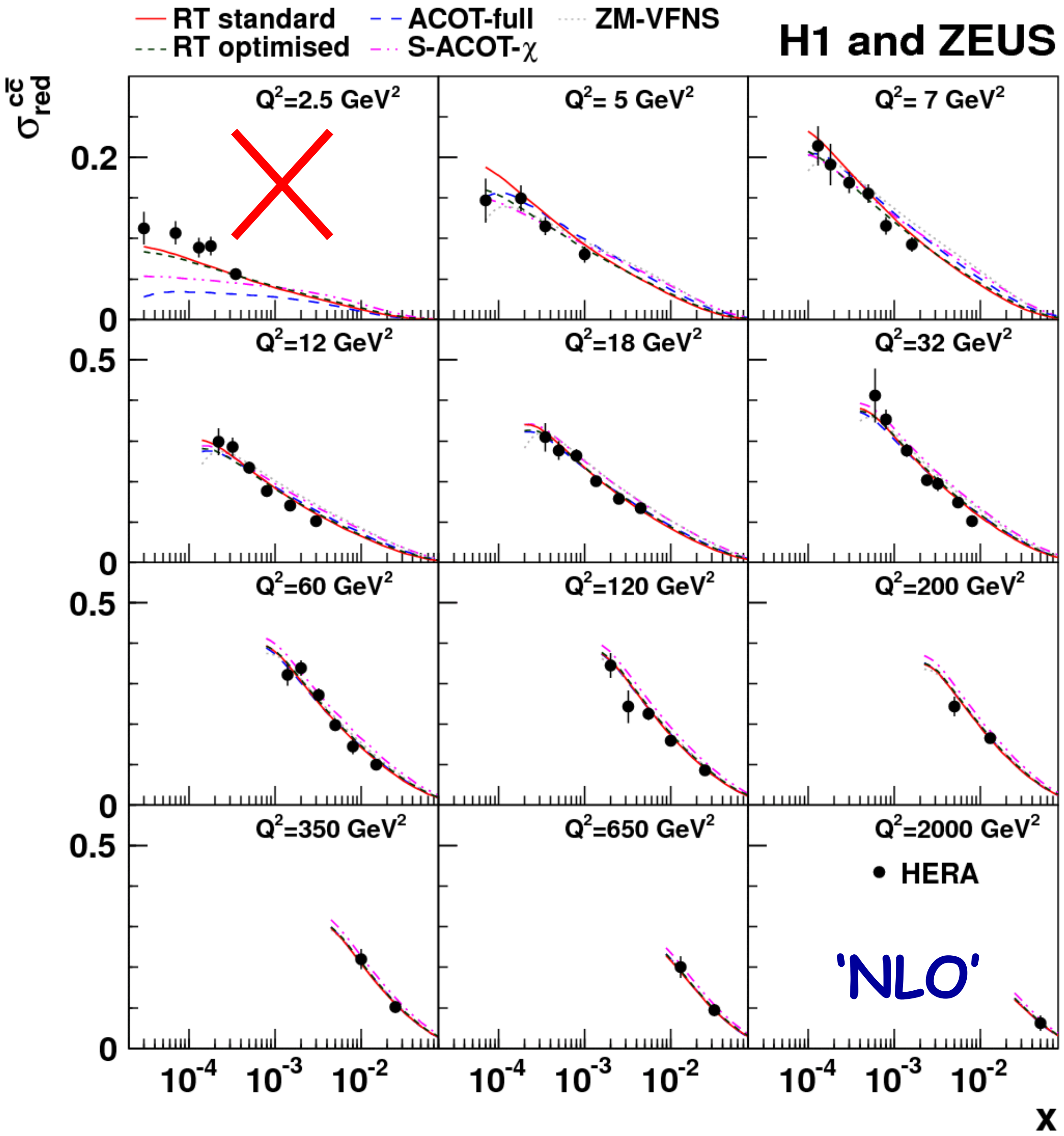
$m_c$ (pole) fixed to 1.4 GeV

differences mainly due to different matching schemes of massive and massless parts

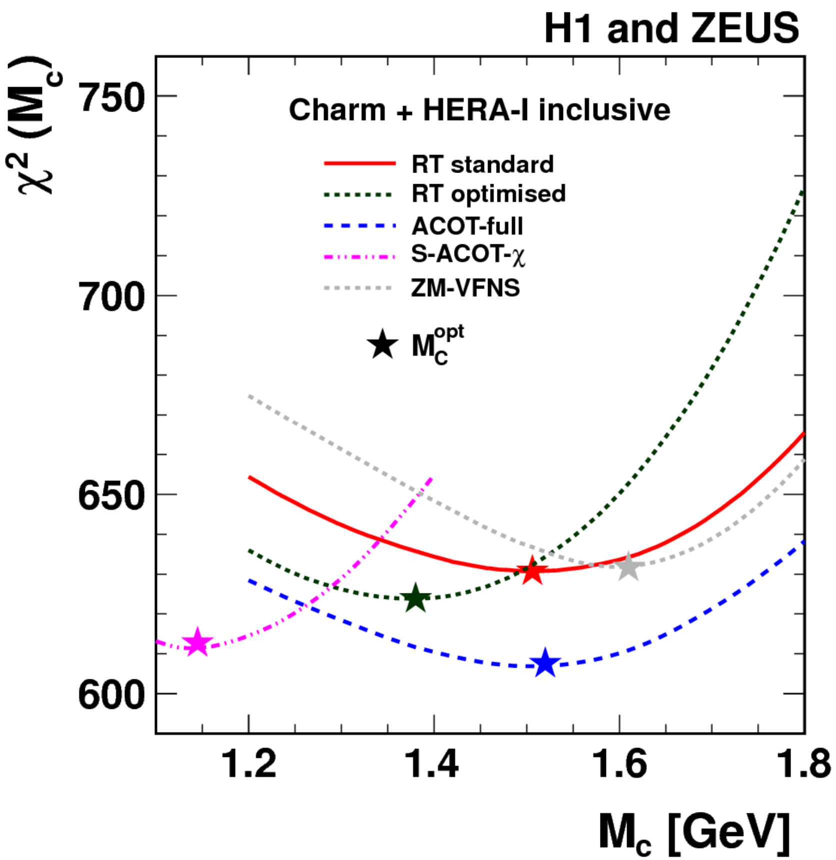
+ corresponding additional parameters in interpolation terms

-> we treat mass in VFNS as effective parameter

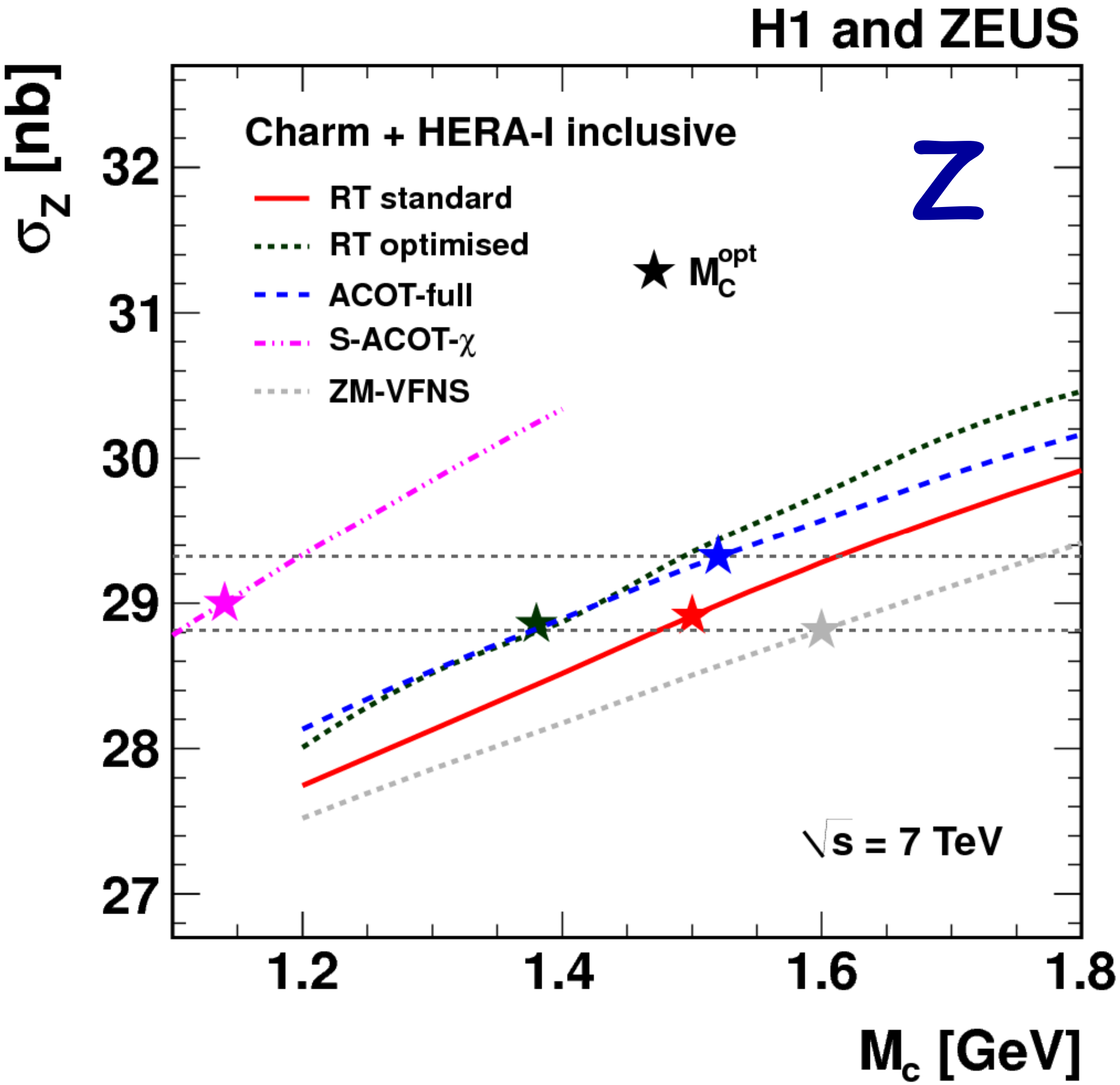
# comparison to various VFNS

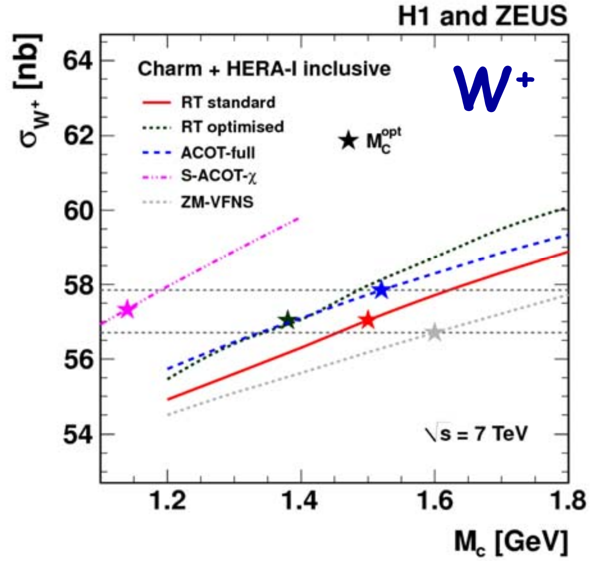


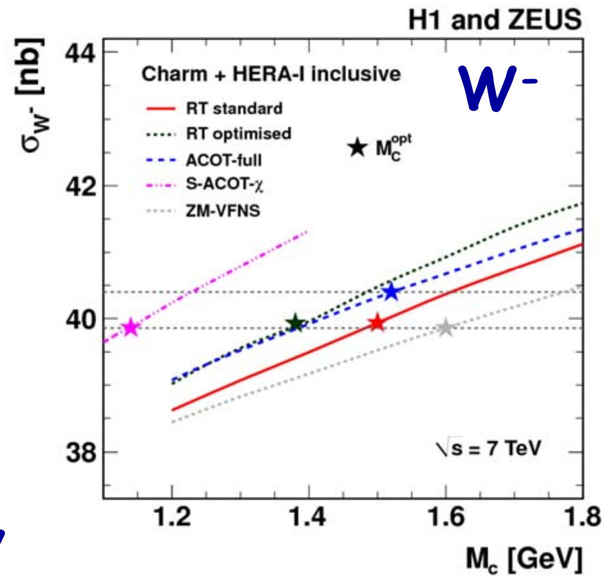

**fit optimal mass for each scheme** ($Q^2 > 3.5$ GeV$^2$)
(see also talk M. Guzzi for S-ACOT-$\chi$)



# Z, W cross section predictions for LHC



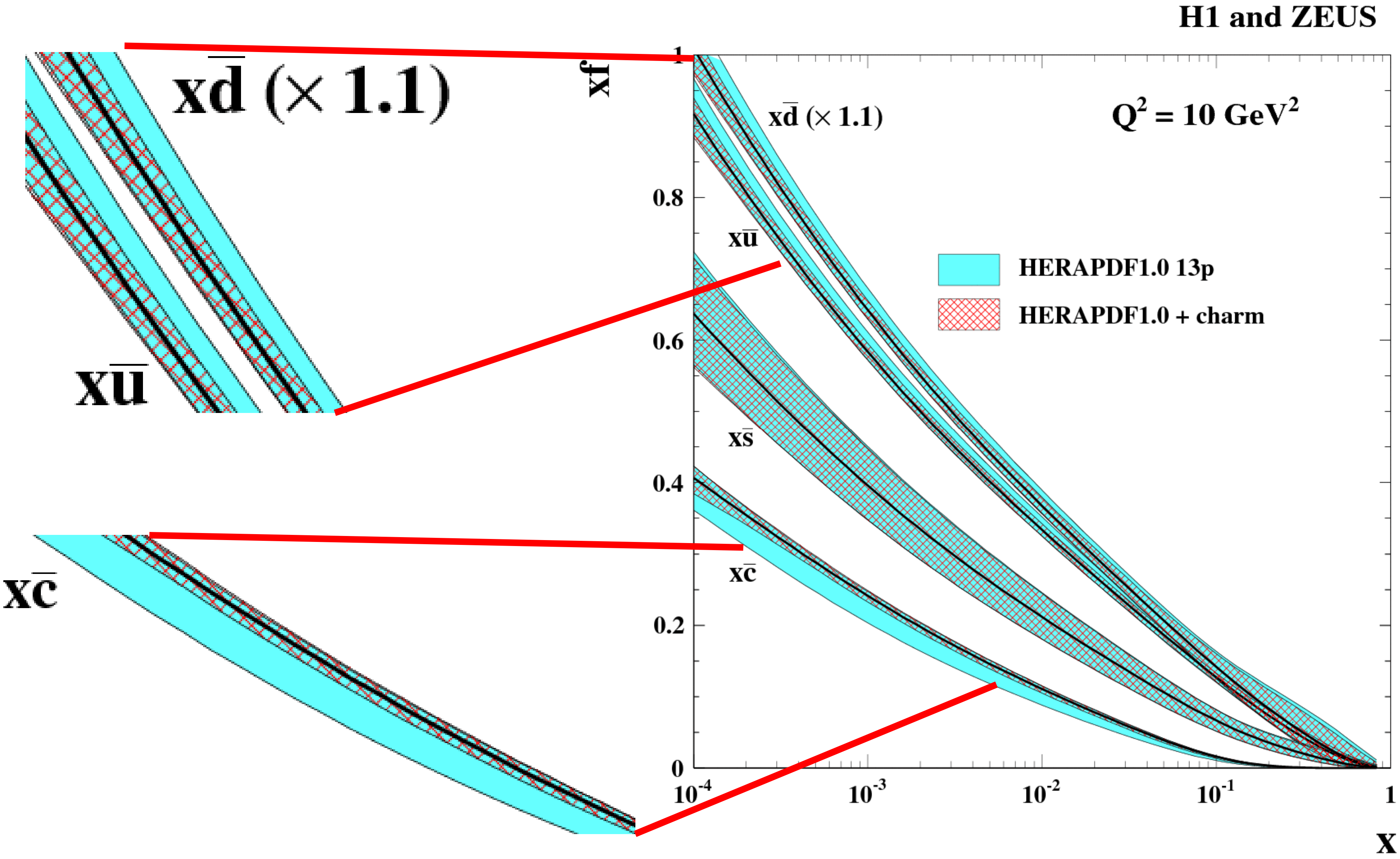




**optimal $M_c$ significantly reduces uncertainty**

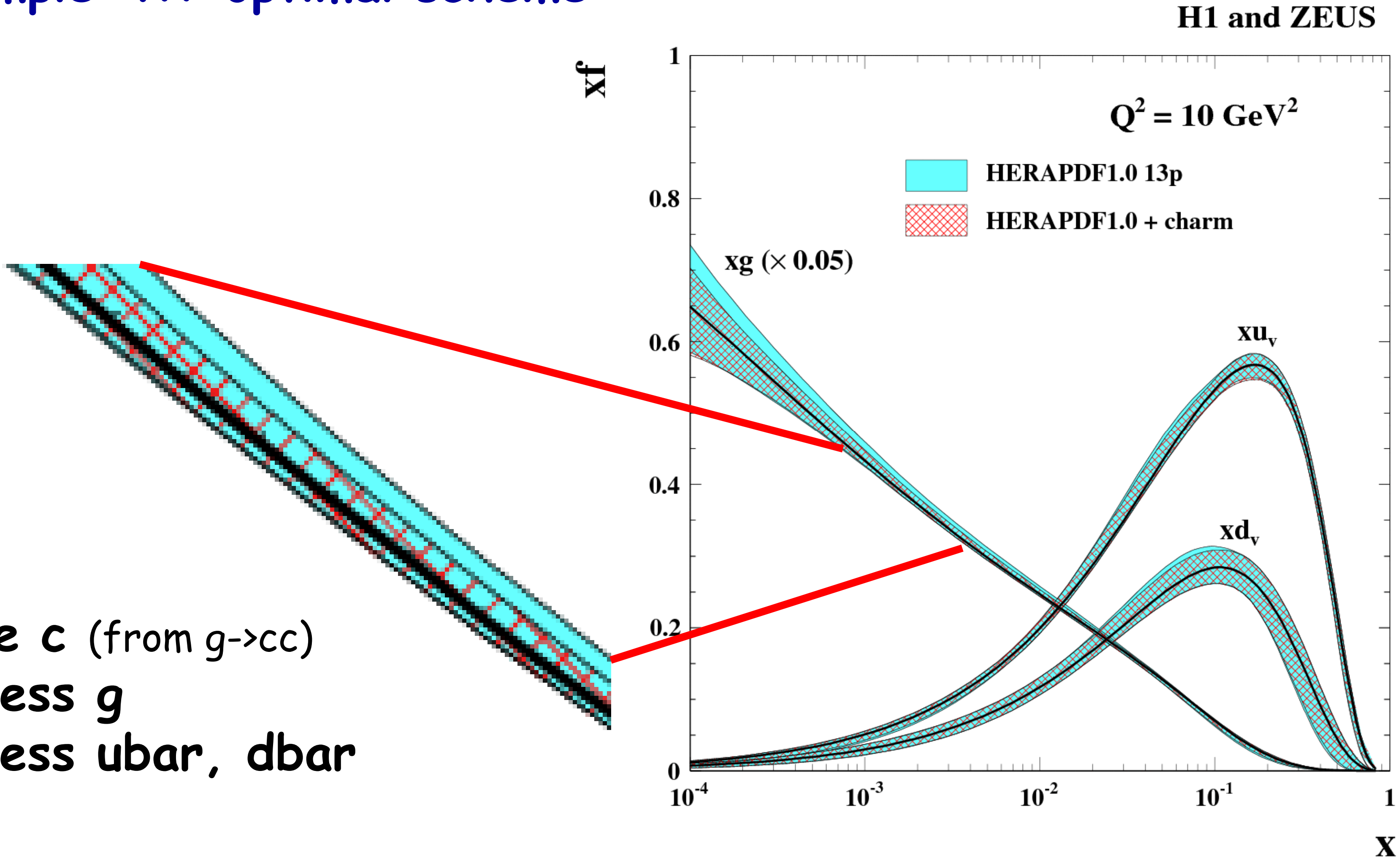
# Charm data stabilize sea flavour composition

**example: RT optimal scheme**



# and reduce gluon uncertainty

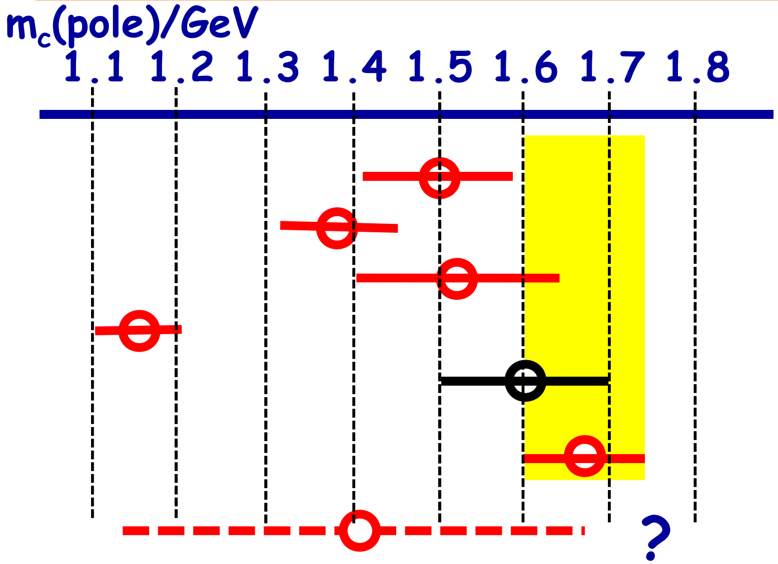
**example: RT optimal scheme**




**more c** (from g->cc)
**-> less g**
**-> less ubar, dbar**

**-> expect reduced uncertainty also for Higgs cross section**

# some personal closing remarks

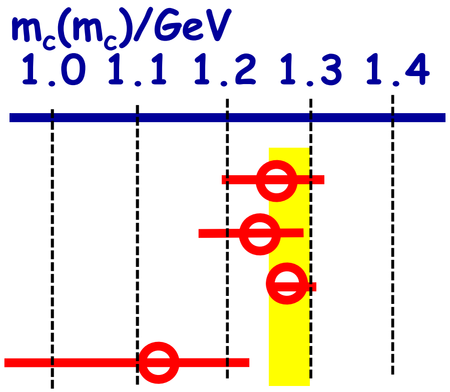



**this work, 'NLO'**

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

**PDG pole mass**

effect smaller at 'NNLO', but will not disappear (see below)
-> in VFNS not obvious to use world average to reduce uncertainties
-> use "effective" mass values, or live with large(r) $m_c$ uncertainty?




**this work, FFNS NLO, $\Delta\chi^2=1$**
**Alekhin et al., FFNS appr. NNLO**
**PDG $m_c(m_c)$, MS** **-> can use as external constraint?**
**Gao, Guzzi, Nadolsky, GM-VFNS NNLO, $\Delta\chi^2\sim15\text{-}50$**

# Summary and conclusions

- **HERA DIS Charm data have been combined**
  (except most recent, see talks O. Zenaiev, O. Bachynska)
  **very good consistency, reduced uncertainties**

- **very well described by NLO QCD in FFNS**
  **-> measure running charm mass ($\overline{MS}$)**
  $m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{\alpha s}$ GeV

- **different VFNS variants prefer different optimal charm masses**
  (additional parameters for interpolation between massless and massive calculations)
  **-> good description of data with 'optimal' mass in all variants**

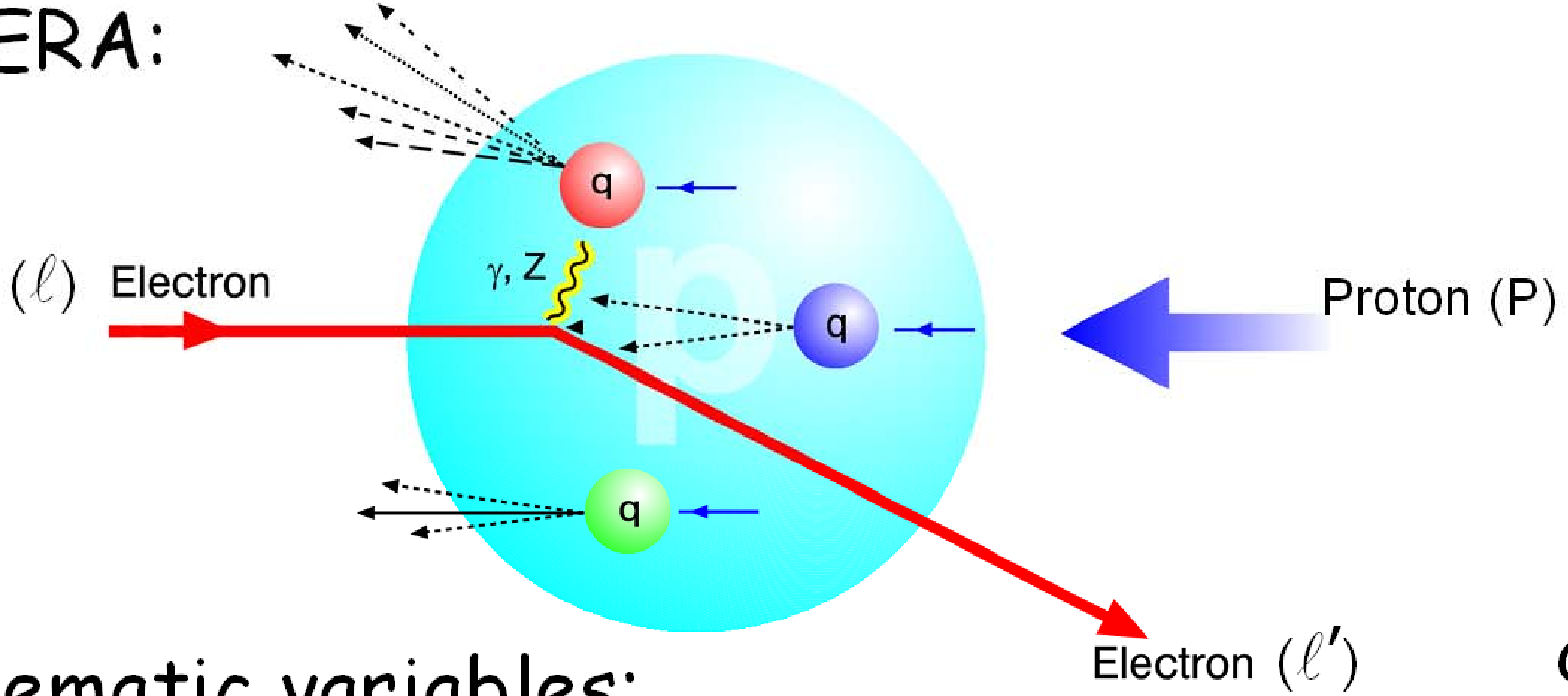
- **PDF fits using optimal mass significantly reduce uncertainties for W and Z production at LHC (stabilization of flavour composition) and reduce uncertainty on gluon distribution**

- **-> towards including charm data in HERAPDF2.0**

# Backup

# Deep Inelastic ep Scattering at HERA

HERA:




$q = \ell - \ell'$

kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

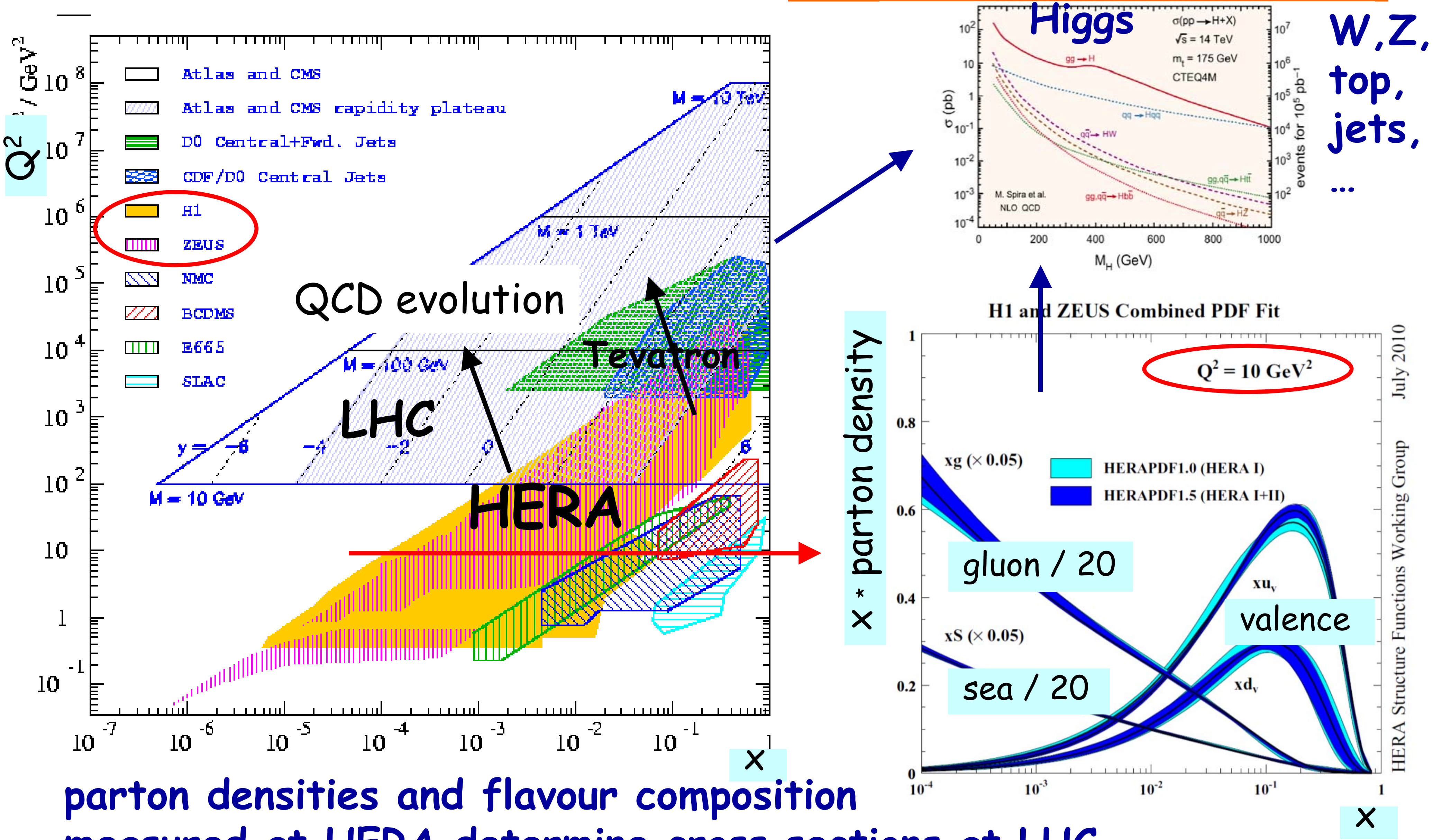
$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

$y = \frac{qP}{\ell P}$ inelasticity,
$\gamma$ momentum fraction (of e)

$Q^2 \lesssim 1\ GeV^2$:
photoproduction

$Q^2 \gtrsim 1\ GeV^2$:
DIS

# Parton density functions (PDF)




**parton densities and flavour composition measured at HERA determine cross sections at LHC**