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# Combined measurement of $F_2^{c\bar{c}}$ and effect on PDF fits

Massimo Corradi

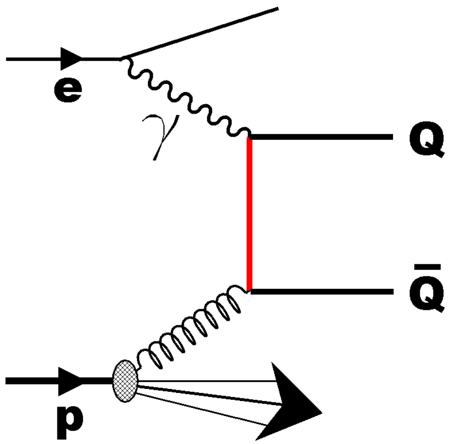
*INFN Bologna*

on behalf of the H1 and ZEUS and collaborations

# Heavy Quark production in DIS

## Fixed Flavour–Number Scheme (FFNS)

c (b)only from hard scattering,
3 (4) active flavours in p



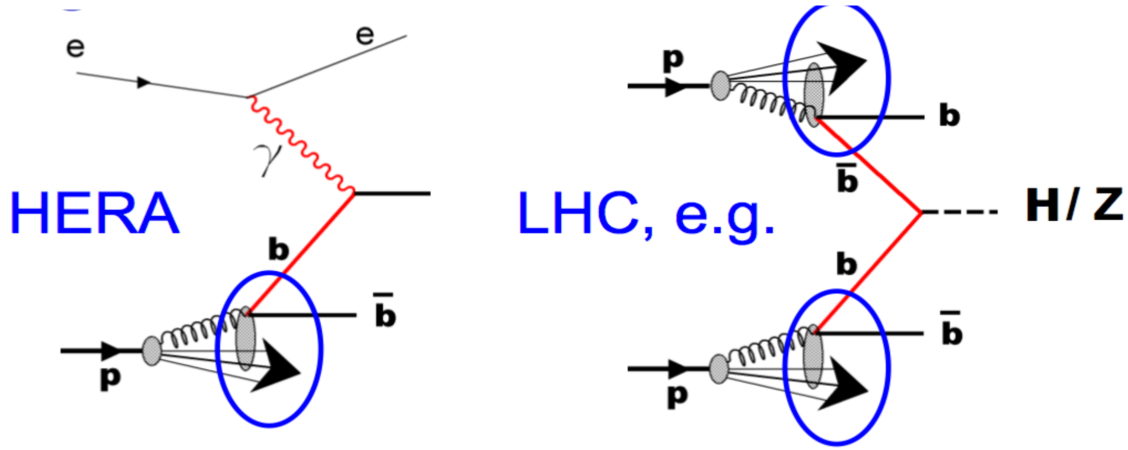

leading order: boson-gluon fusion

Direct access to $g(x)$

FFNS spoiled when $Q^2$, $p_T \gg m_Q$
e.g. large $\log(Q^2/m_Q^2)$

## Zero Mass Variable Flavour–Number Scheme (ZM-VFNS)

$c, b$ active flavours in p




resums $\log(Q^2/m^2)$

c,b: massless partons:
ZM-VFNS fails at $Q^2 \leq \mathcal{O}(m_Q^2)$

needed at high-energy colliders

$c, b$ PDFs can be directly tested in DIS

# PDF fits and charm threshold, GM-VFNS

HERA DIS data are in a $Q^2$ range where the charm mass effects are relevant:
ZM-VFNS can not be used

**Generalised Mass-VFNS (GM-VFNS)**:
interpolates between FFNS at $Q^2 < m_c^2$ and ZM-VFNS at $Q^2 >> m_c^2$
different HQ schemes developed recently

GM-VFNS PDFs have a significant dependence on

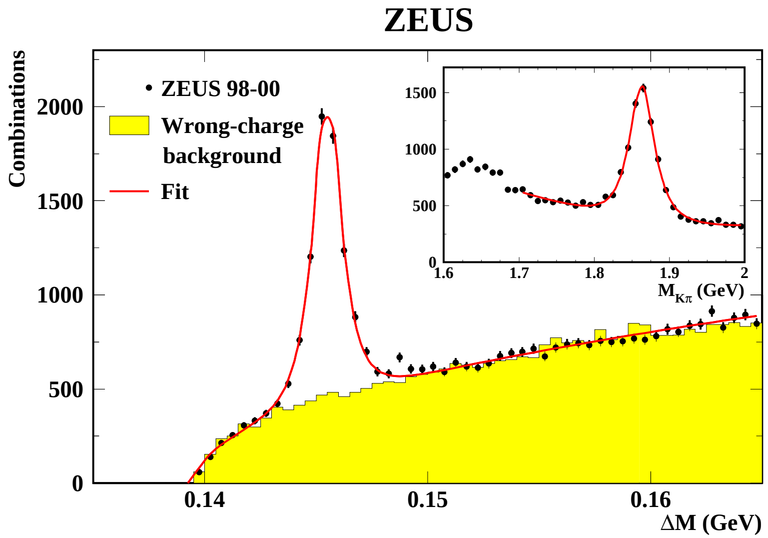
- the HQ scheme
- the charm mass

Impact of different GM-VFNS schemes on W/Z cross section at LHC
up to 3% at NLO

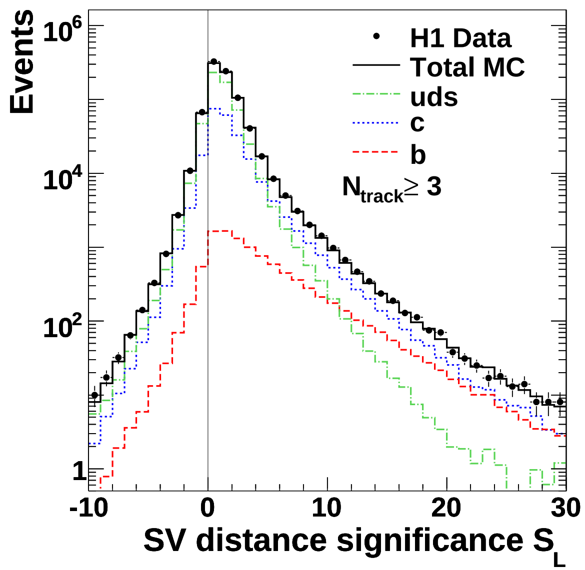
Precise charm DIS data expected to test/constrain these GM-VFN schemes

# Data sets used in the prel. H1-ZEUS combination

- ZEUS, $D^{*+}$, HERA I, L=82+37 $pb^{-1}$ (hep-ex/9908012, hep-ex/0308068)
- H1, $D^{*+}$, HERA I, L=47 $pb^{-1}$ (hep-ex/0608042)
- H1, $D^{*+}$, HERA II prel., L=340 $pb^{-1}$ (high-$Q^2$ part: arXiv:0911.3989)
- ZEUS, $D^+$, $D^0$, 2005 data, L=134 $pb^{-1}$ (arXiv:0704.3562 [hep-ex])
- ZEUS, $\mu$, 2005 data, L=121 $pb^{-1}$ (arXiv:0904.3487 [hep-ex])
- H1, lifetime tag, HERA I, L=57 $pb^{-1}$ (hep-ex/0411046, hep-ex/0507081)
- H1 lifetime tag, HERA II prel, L=189 $pb^{-1}$ (now in arXiv:0907.2643)




$D^{*+}$ signal (ZEUS HERA-I 98-00)




Secondary vertex significance (H1 lifetime tag)

# $F_2^{c\bar{c}}$

$F_2^{c\bar{c}}$ is the part of the $F_2$ structure function with a $c\bar{c}$ in the final state:

$$\frac{d^2\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[ F_2^{c\bar{c}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x, Q^2) \right]$$

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

( note: definition may differ from that used by theorists, see Forte et al. arXiv:1001.2312 )

$D$ mesons (or $\mu$) production measured in “visible” phase space

typically $|\eta(D^*)| < 1.5$, $p_T(D^*) > 1.5$ GeV

$F_2^{c\bar{c}}$ extracted using theory-based correction:

$$F_2^{c\bar{c}}(x, Q^2) = \sigma_{\text{vis,bin}} \frac{F_2^{c\bar{c},\text{theo.}}(x, Q^2)}{\sigma_{\text{vis,bin}}^{\text{theo.}}}$$

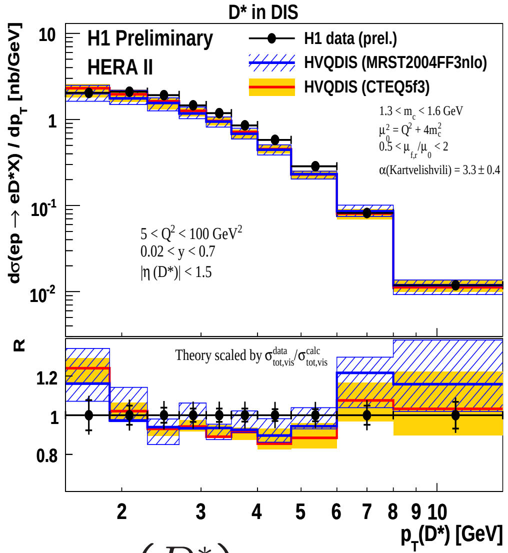
Similarly for inclusive lifetime tagging:
experiments mostly sensitive to events with several central high-$p_T$ tracks

# extraction of $F_2^{c\bar{c}}$

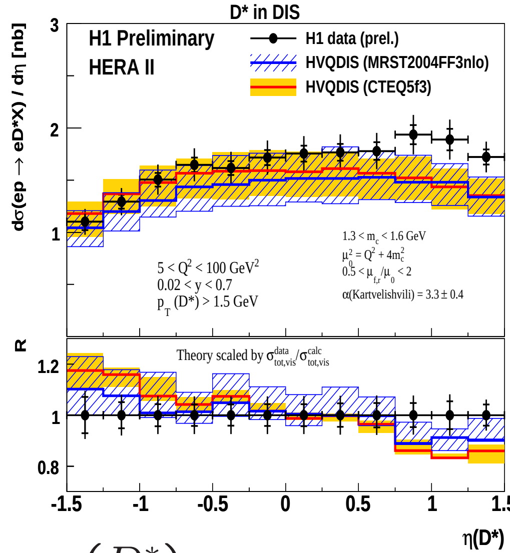
- $F_2^{c\bar{c}}$ re-calculated consistently for $D$, $\mu$ data starting from $\sigma_{\text{vis}}$
- HVQDIS NLO program used (Harris, Smith). good description of $\eta(D)$, $p_T(D)$
- non-perturbative quantities taken from $e^+e^-$ and $ep$ data:
  - fragm. functions
  - fragm. fractions
- Typical kin. acceptances: $\mathcal{A} = \sigma_{\text{vis}}/\sigma_{\text{tot}}$

  $D^*$: $0.25 < \mathcal{A} < 0.70$ for $2 < Q^2 < 200$ GeV$^2$

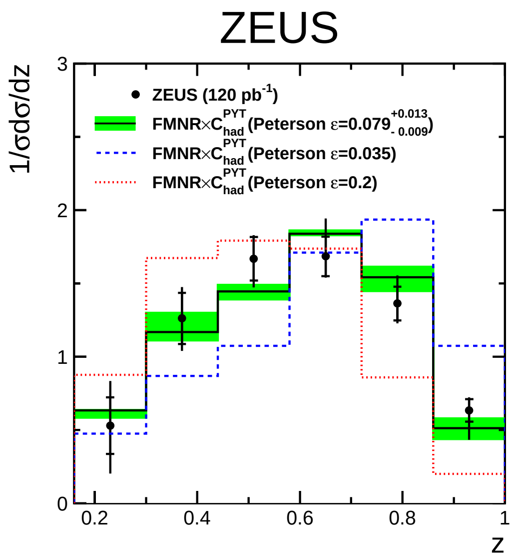
  $\mu$: $0.25 < \mathcal{A} < 0.40$ for $30 < Q^2 < 1000$ GeV$^2$



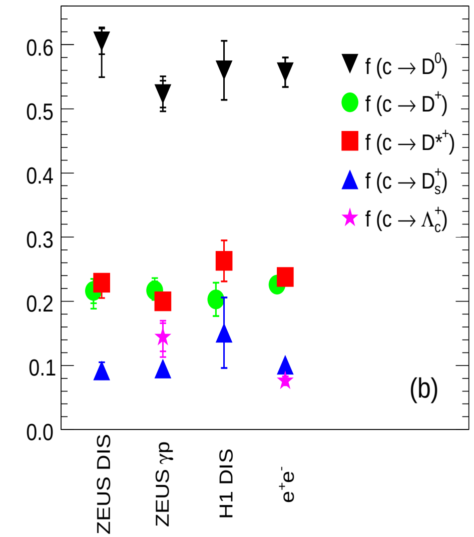

$p_T(D^*)$




$\eta(D^*)$



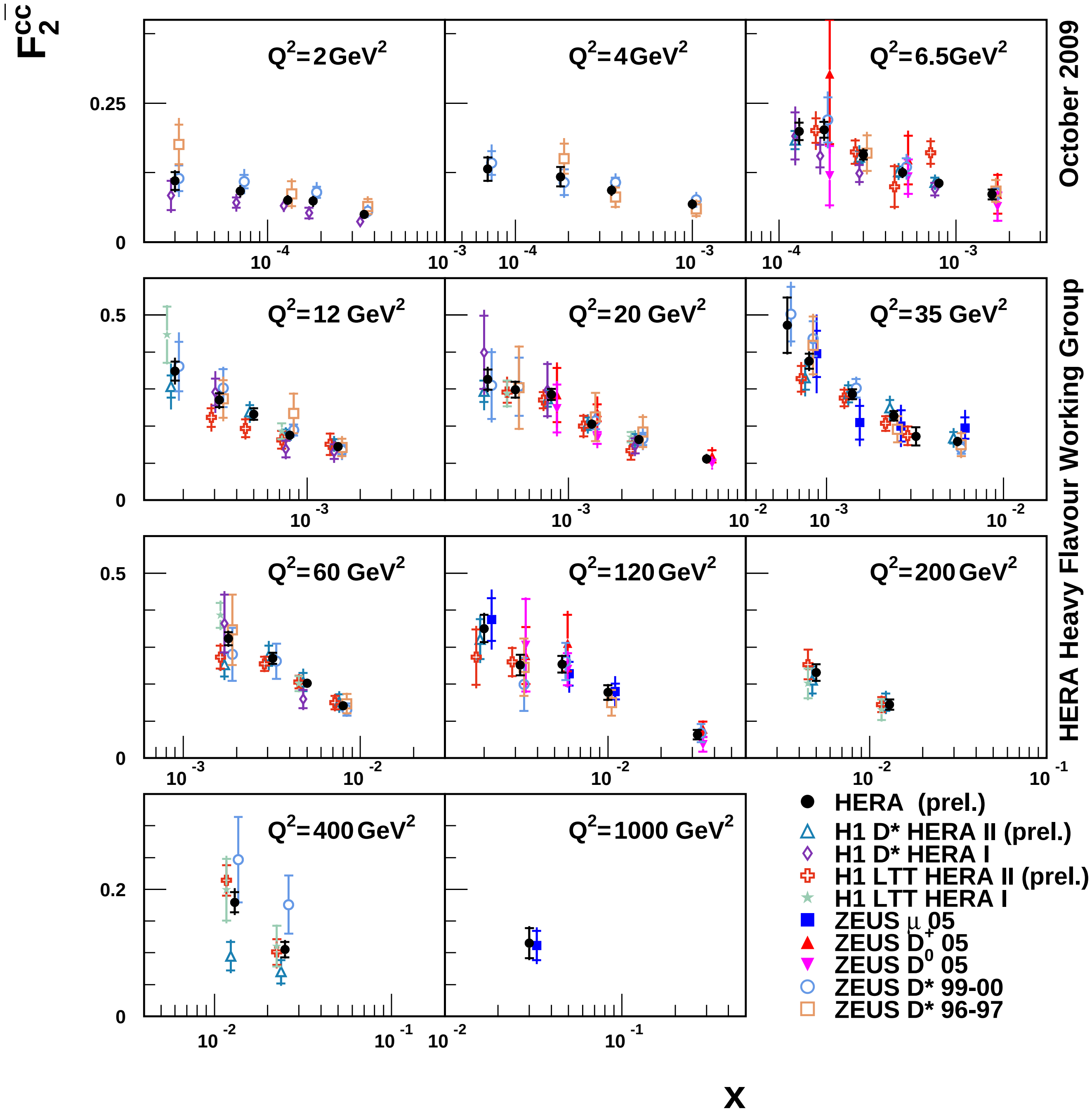

frag. function




frag. fractions

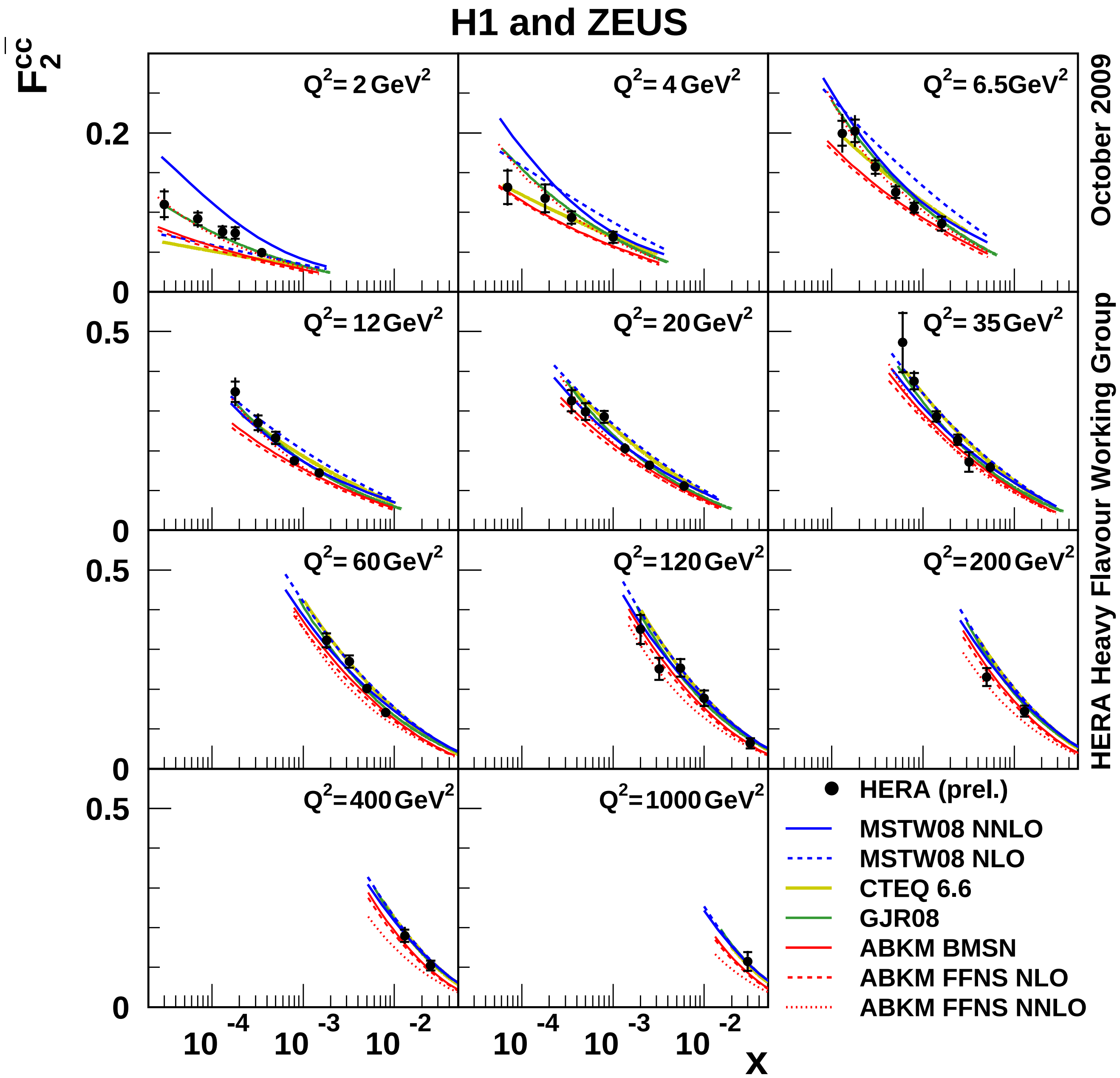
# Combined $F_2^{c\bar{c}}$ compared to single measurements

- method similar to inclusive combination arxiv:0911.0884
- 156 measurements + 54 correl. syst. $\Rightarrow$ 46 combined points
- data are compatible $\chi^2/\text{ndof} = 88/110$
- precision $7-10\%$ for $6.5 \leq Q^2 \leq 60$ GeV$^2$
- $Q^2 \leq 4$ GeV$^2$ $D^*$ HERA-I data
- $Q^2 \leq 20$ GeV$^2$ sizeable correlated theoretical uncertainty



# H1-ZEUS combined $F_2^{c\bar{c}}$ compared to NLO and NNLO calculations

- data can distinguish between different theoretical predictions
- FFNS:
  GJR08
  ABKM FFNS
- GM-VFNS:
  MSTW08
  CTEQ6.6
  ABKM BMSN

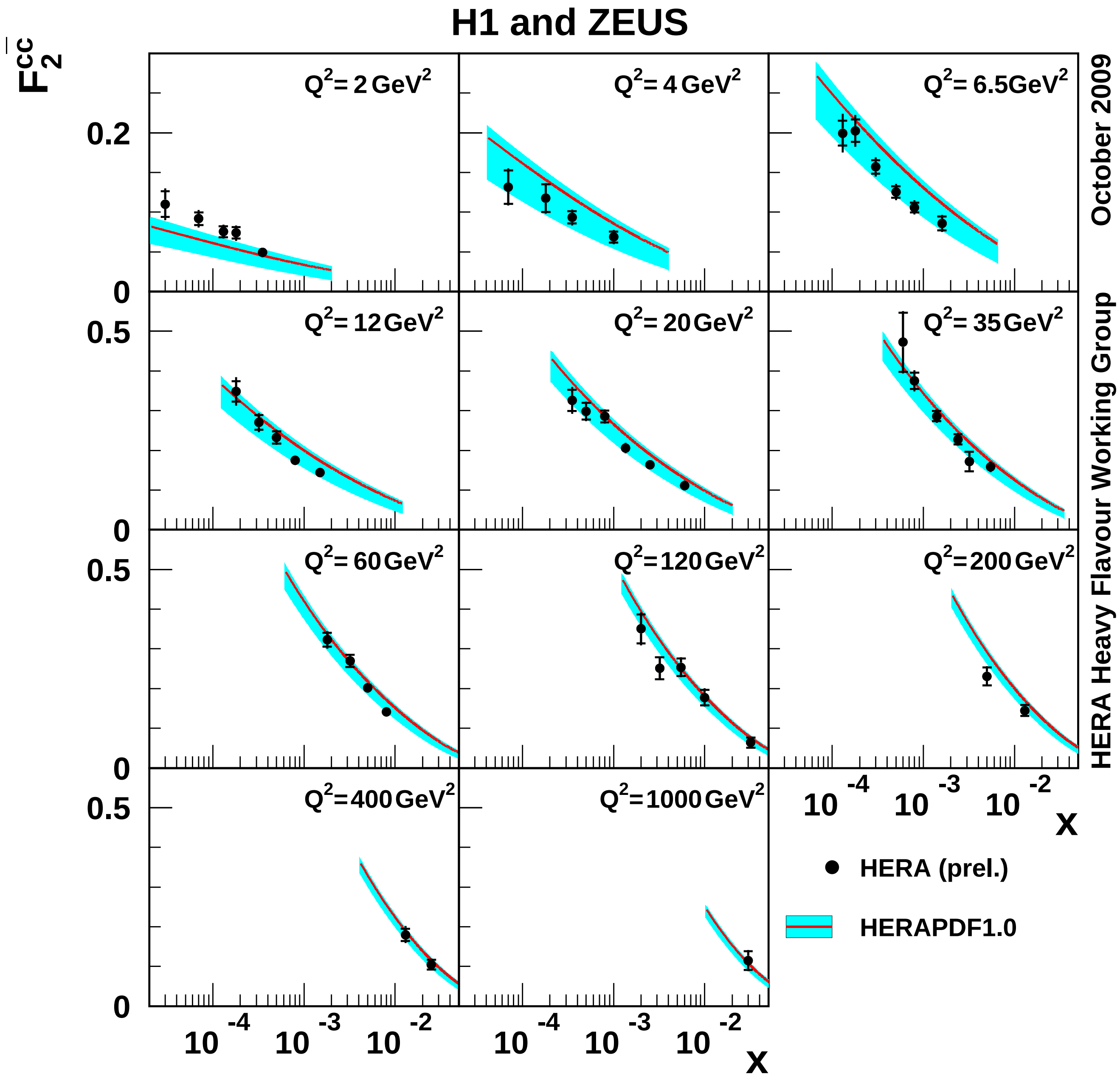


# H1-ZEUS combined $F_2^{c\bar{c}}$ compared to HERAPDF1.0

- HERAPDF 1.0 fit to inclusive HERA I data
- RT GM-VFNS (as MSTW08)
- Central curve: $m_c = 1.4$ GeV

  band:
  $m_c = 1.3$GeV (upper)
  $m_c = 1.65$GeV (lower)

  [pole mass (PDG): $1.47 - 1.83$ GeV]



# Adding combined $F_2^{c\bar{c}}$ to HERAPDF1.0 Fit

- Fit HERA I + $F_2^{c\bar{c}}$

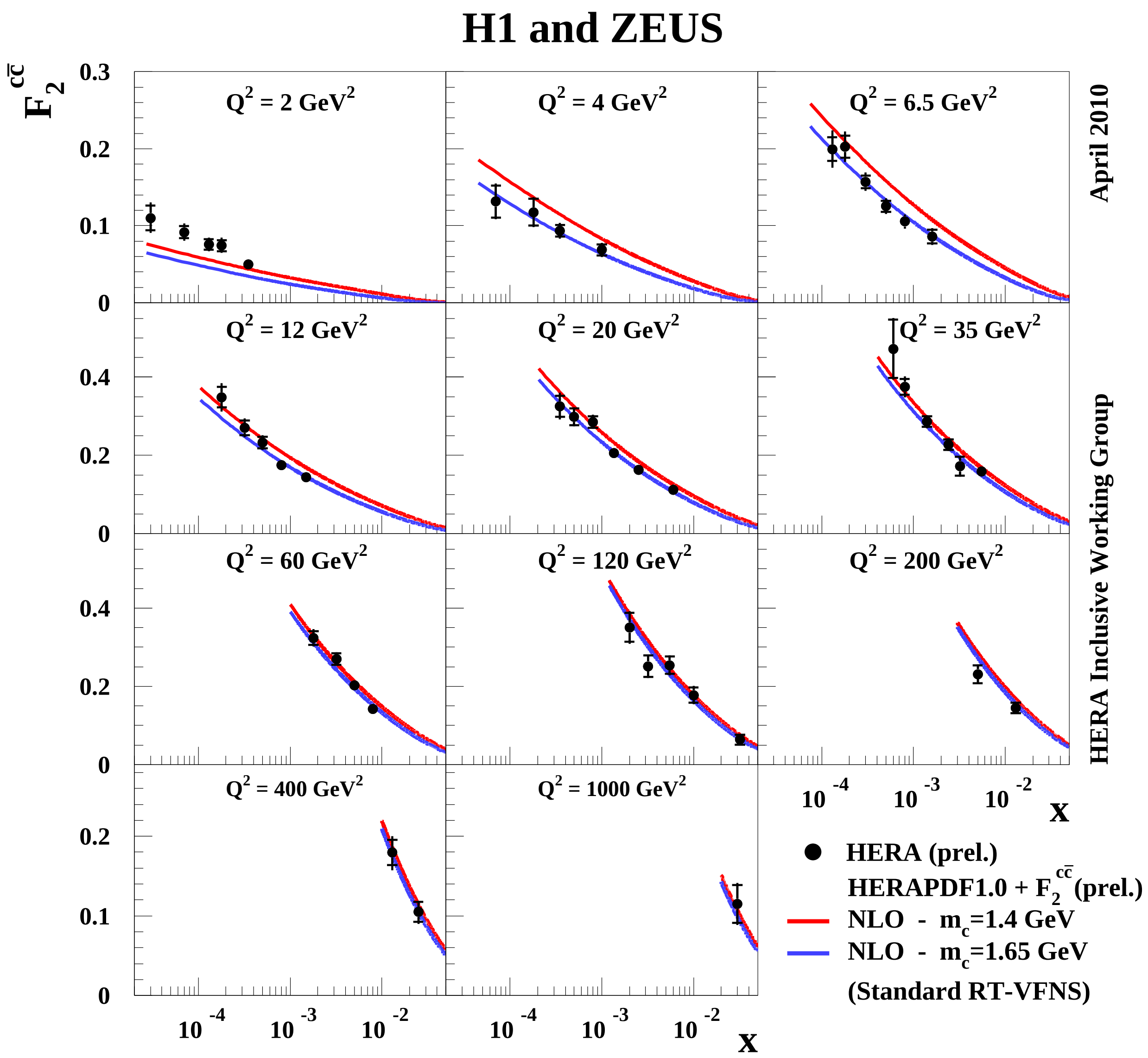
  $Q^2 > 3.5$ GeV$^2$
  ($Q^2 = 2$ GeV$^2$ bin excluded)

  41 charm points

- RT GM-VFNS

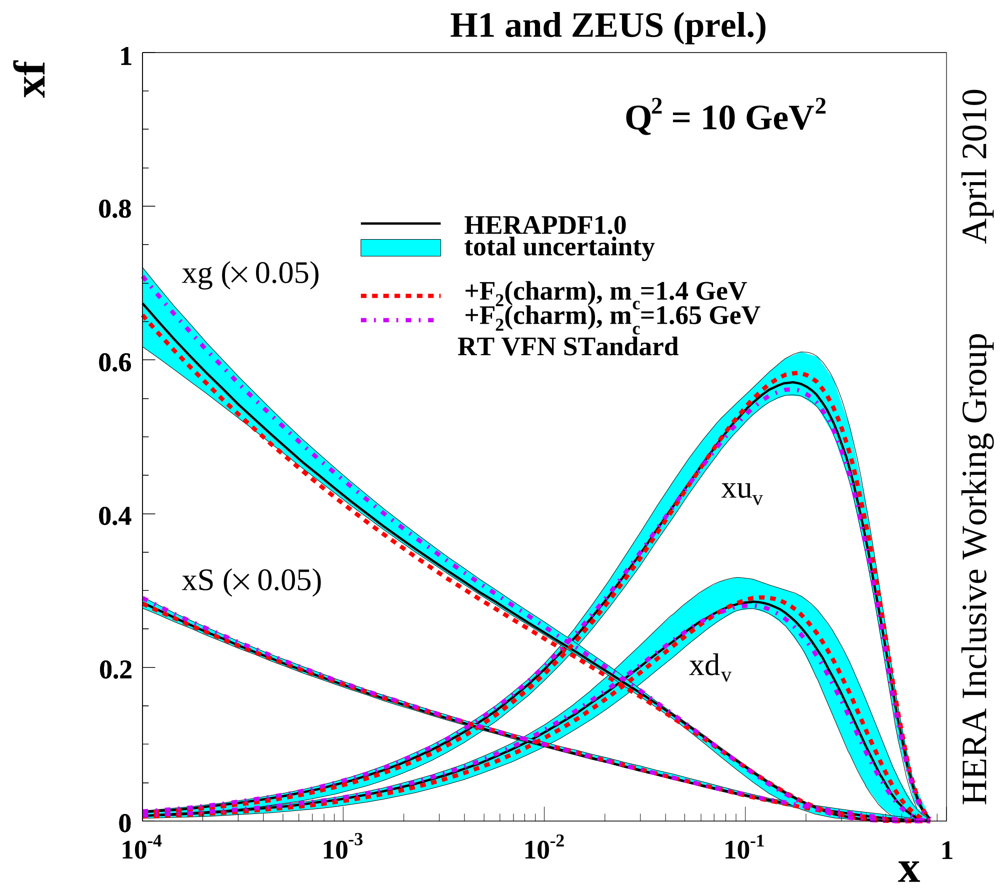
- $m_c = 1.4$ GeV
  $\chi^2_{\text{charm}} = 134.5/41$

  $m_c = 1.65$ GeV
  $\chi^2_{\text{charm}} = 43.5/41$



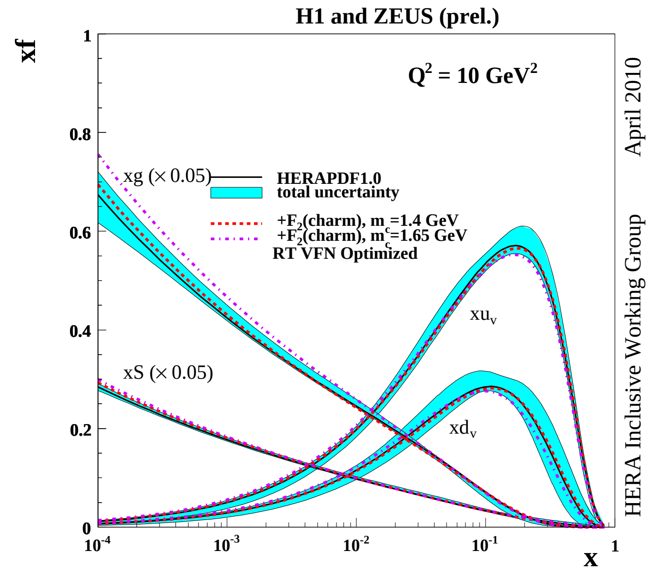
# Effect on PDFs

## Alternative HQ schemes

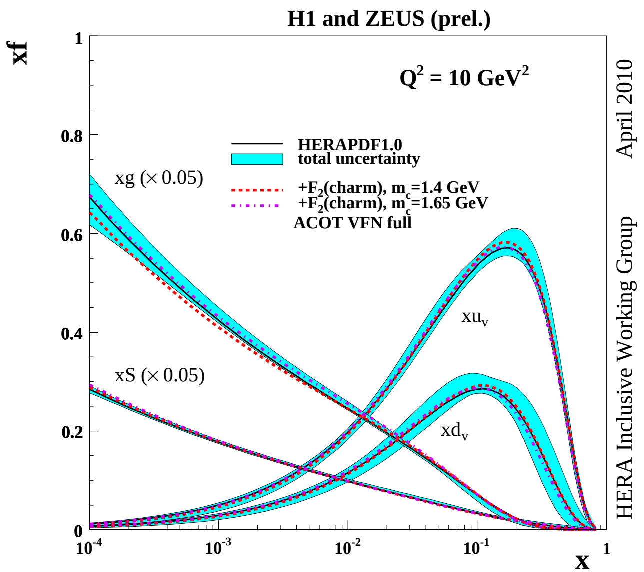



**RT STandard** (MSTW)

- small change in $g(x)$
- dependence on $m_c$ and HQ scheme of the same size of PDF uncertainty




**Optimized RT** (smoother at $Q^2 = m_c^2$, Thorne DIS2010)



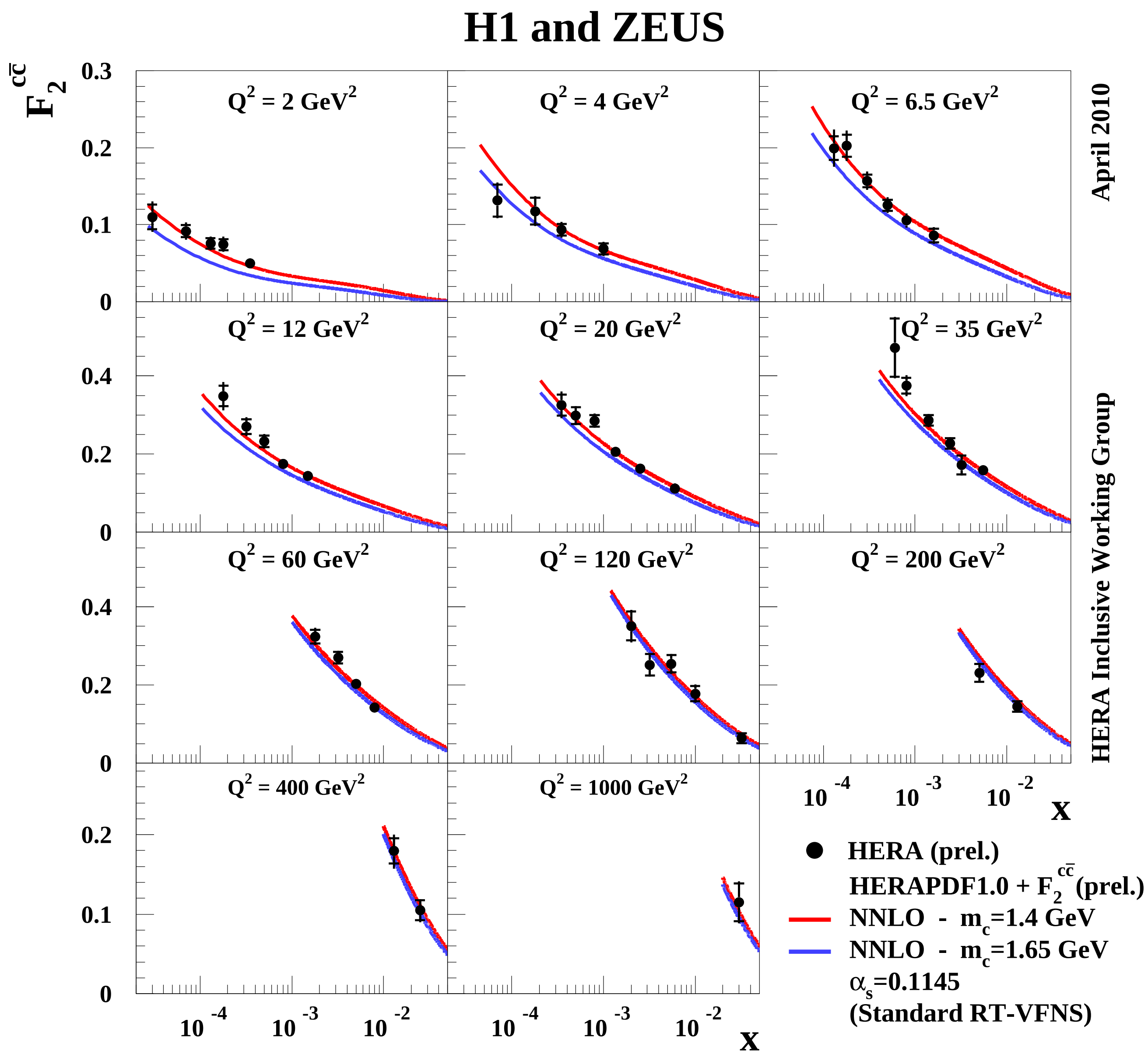

**ACOT** (as in CTEQ6.6)

# NNLO Fit

- "approximated" NNLO RT GM-VFNS (MSWT)
- expected to be less dependent on HQ scheme
- better agreement at $Q^2 = 2$ GeV$^2$

  Overall agreement similar to NLO
- $m_c = 1.4$ GeV $\chi^2_{\text{charm}} = 54/41$

  $m_c = 1.65$ GeV $\chi^2_{\text{charm}} = 186/41$



# Conclusions

- Preliminary combination of H1 and ZEUS $F_2^{c\bar{c}}$ data
- data from $Q^2 = 2$ GeV$^2$ to 1000 GeV$^2$
- precision of $7 - 10\%$ on a wide kinematic range
- data more precise than spread between different theor. predictions
- $F_2^{c\bar{c}}$ fits well with inclusive HERA data
- significant dependence of the fit on $m_c$ and HQ scheme.

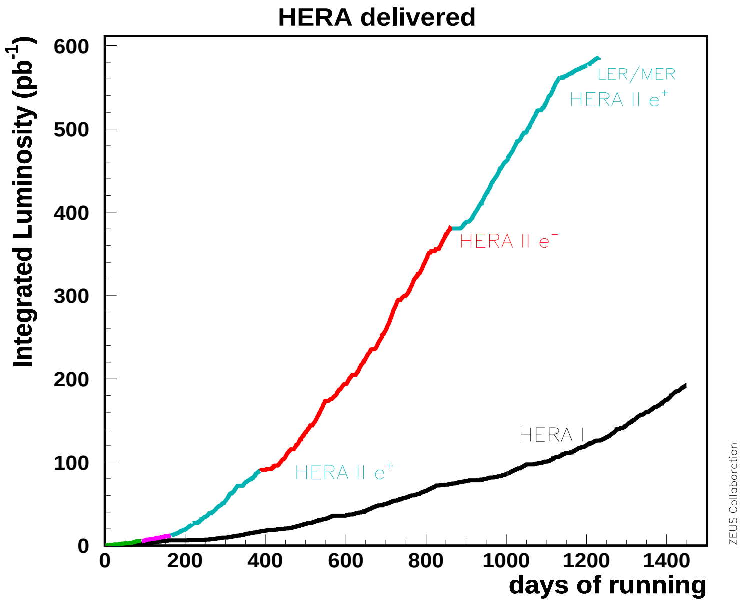
**BACKUPS**

# HERA, H1 and ZEUS

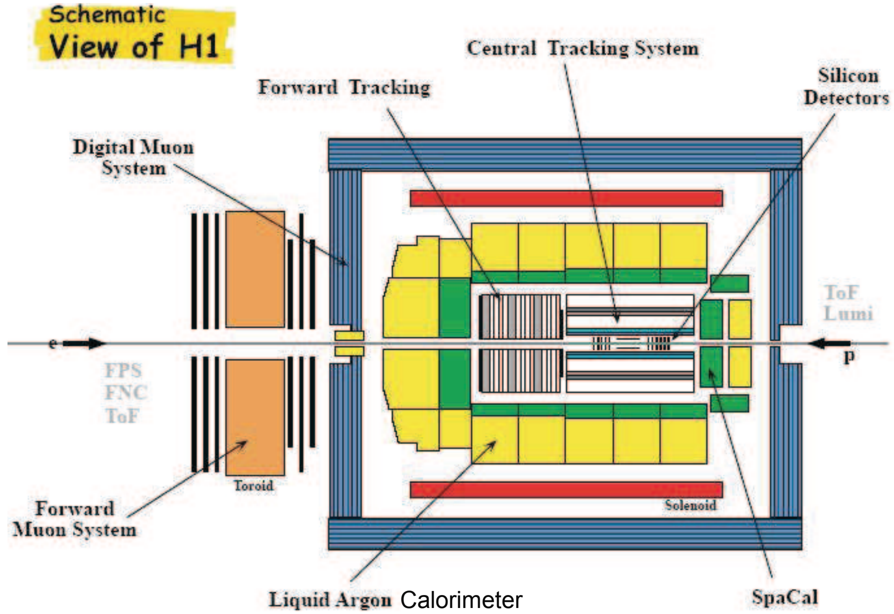
HERA

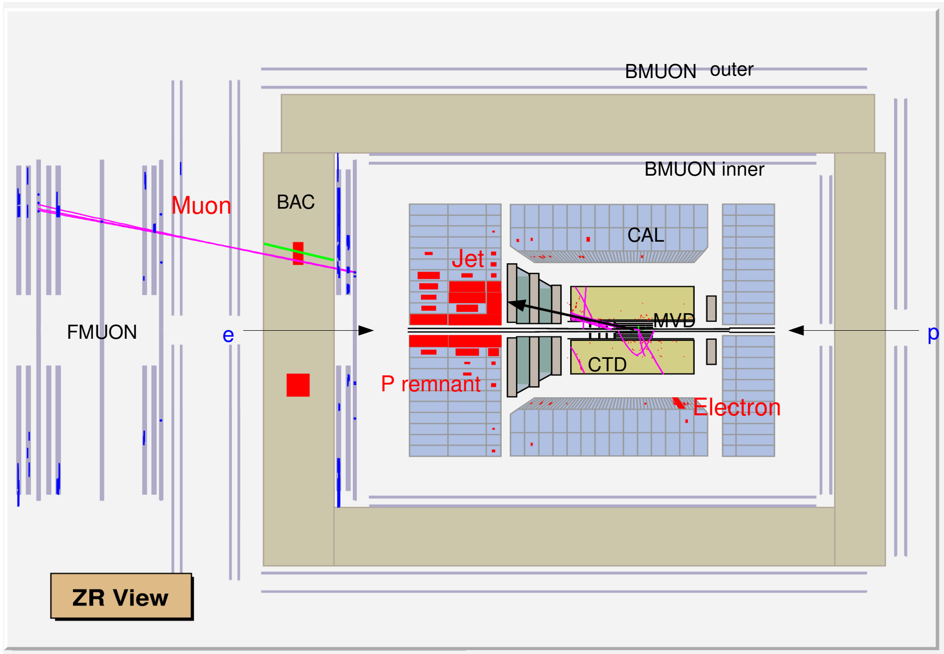
- $E(e^{\pm}) = 27.5\text{GeV}$
  $E(p) = 920\text{GeV}$

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




- $\mathcal{L} \simeq 0.5\text{fb}^{-1}$ (per experiment)



# Combination method

Combination done taking into account correlated exp. and theo. uncertainties

Similar method as for inclusive combination: find the values of the "true" $F_2^{c\bar{c}}$ $(m^i)$ and of the "systematic shifts" $(b_j)$ that minimize the function

correlated systematic errors

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

statistical errors

uncorrelated systematic errors

(where $\mu^i$=$i^{\text{th}}$ measurement)

MC experiments show that this is an unbiased estimator

156 original measurements

54 correlated uncertainties

46 combined $F_2^{c\bar{c}}$ points

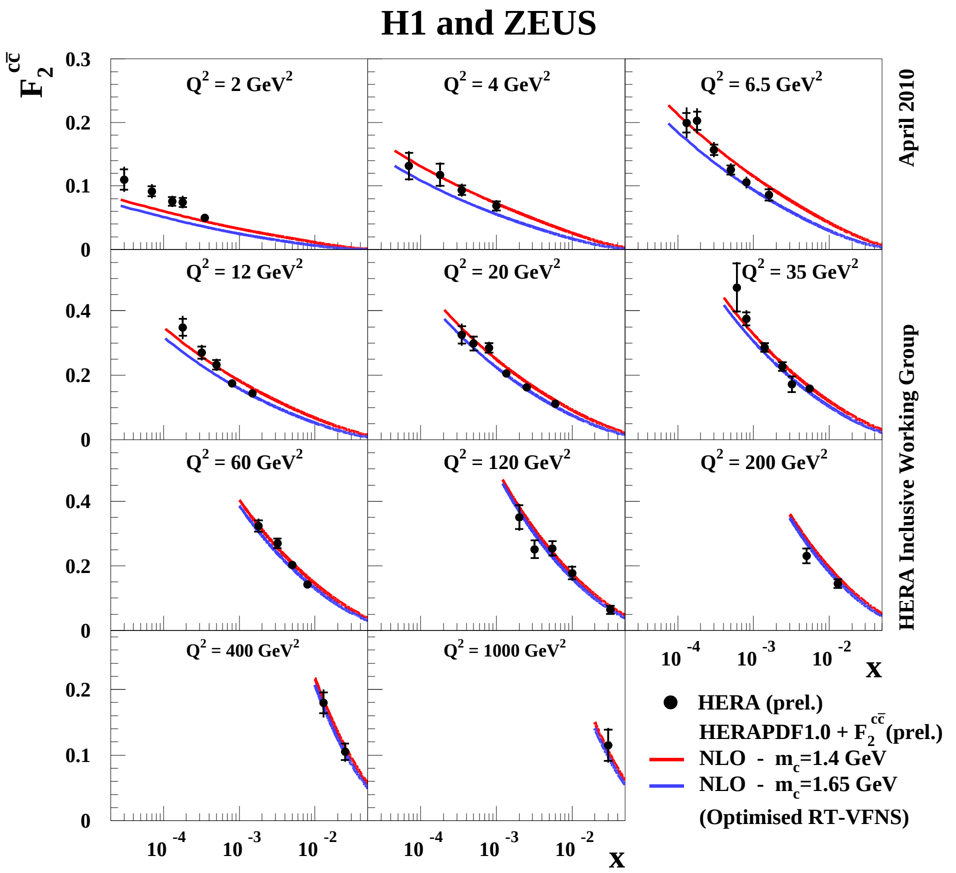
Exp. syst. independent between H1 and ZEUS

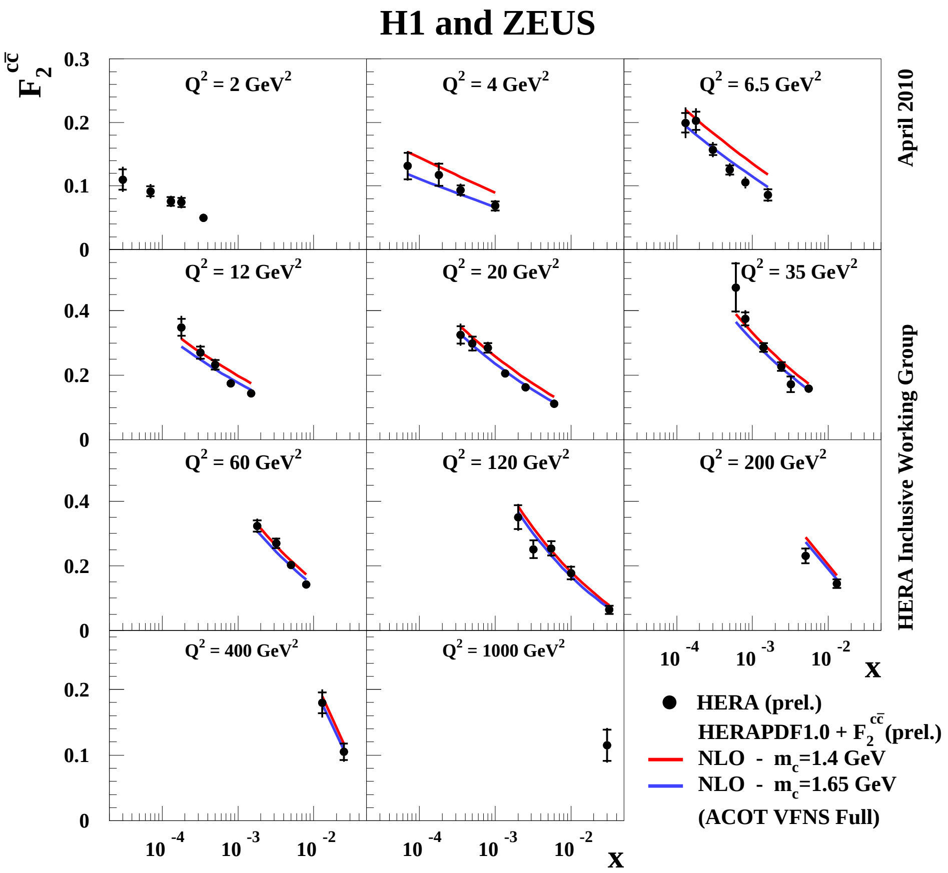
Theor. unc. correlated between data sets:

- fragmentation function
- fragmentation fractions
- HVQDIS: $\mu_f = \mu_r = \sqrt{Q^2 + m_c^2}$ varied by fact. 2, $m_c$, PDFs

Procedural unc. on the $\chi^2$ function form

# Fits With Different HQ schemes: RT-Optimized, ACOT



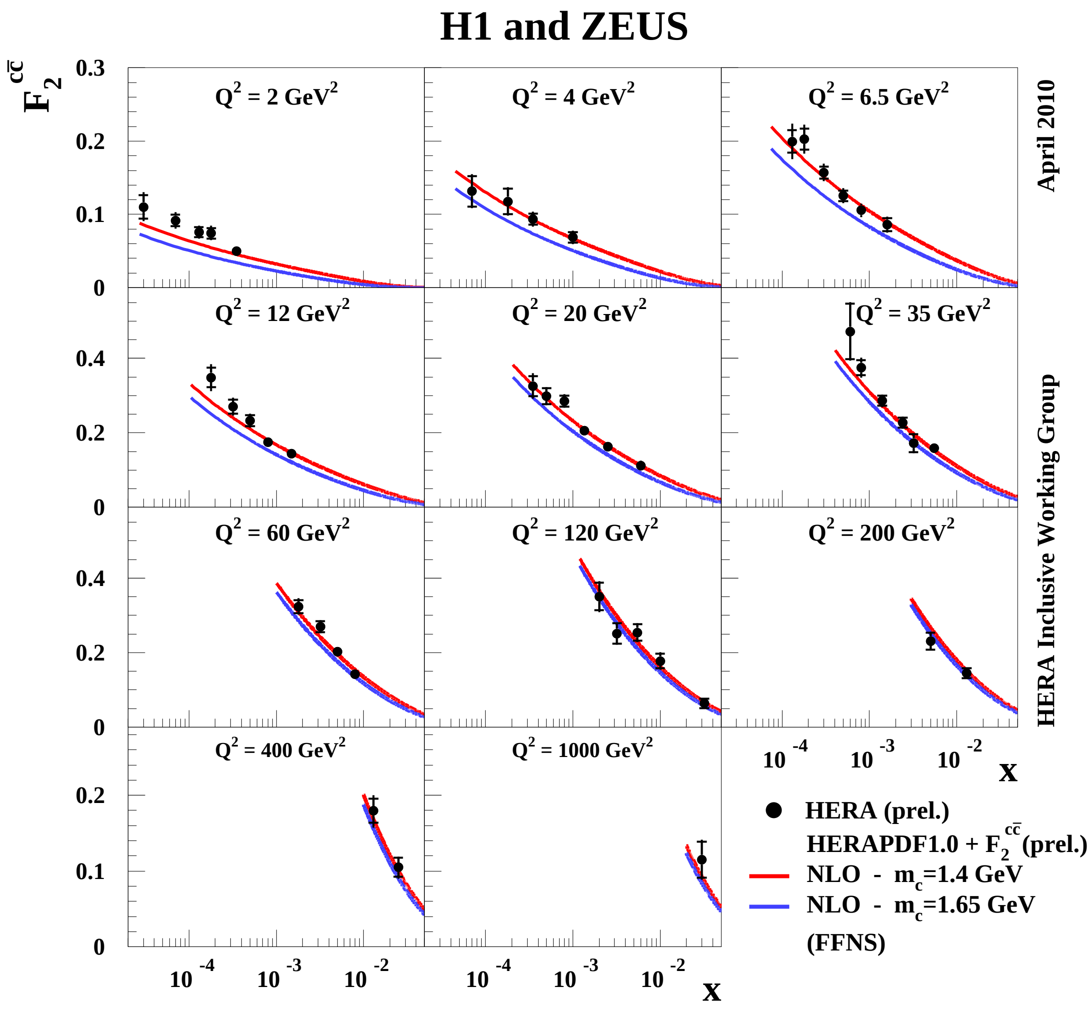

RT-optimized: smoother FFNS-VFNS transition (see R. Thorne, DIS 2010)

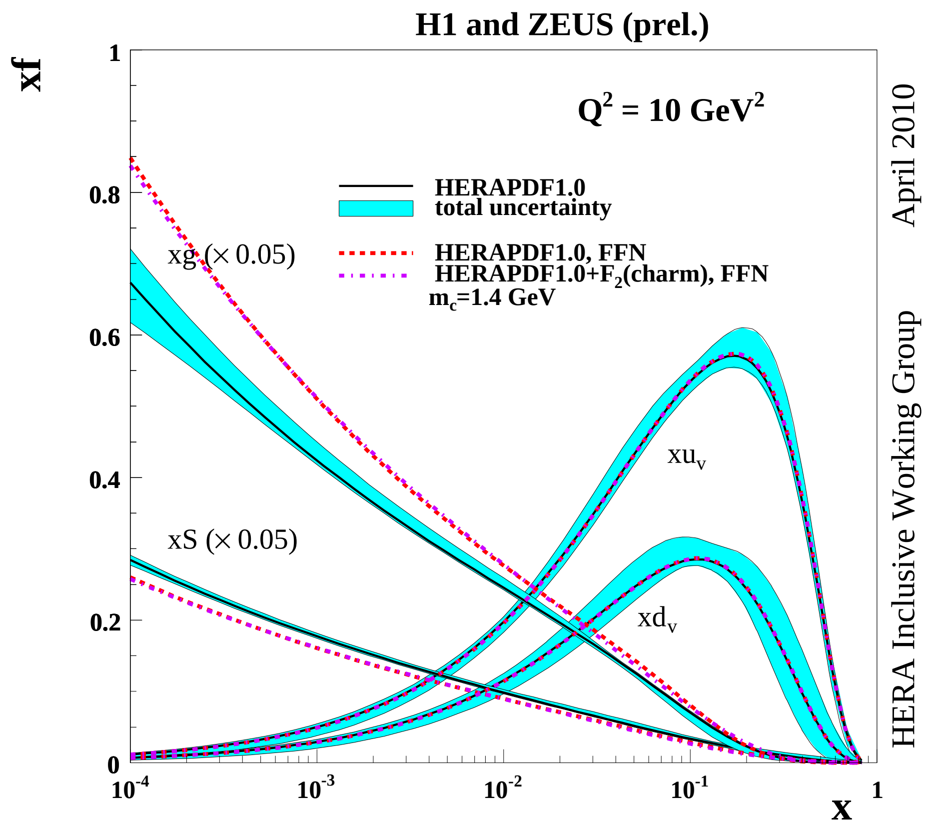
- $m_c = 1.4$ GeV : $\chi^2_{\text{charm}} = 64/41$
- $m_c = 1.65$ GeV : $\chi^2_{\text{charm}} = 100/41$

ACOT-full (as used by CTEQ)

- $m_c = 1.4$ GeV: $\chi^2_{\text{charm}} = 89/41$
- $m_c = 1.65$ GeV: $\chi^2_{\text{charm}} = 41/41$

# HERAPDF1.0+$F_2^{c\bar{c}}$ FFNS FIT

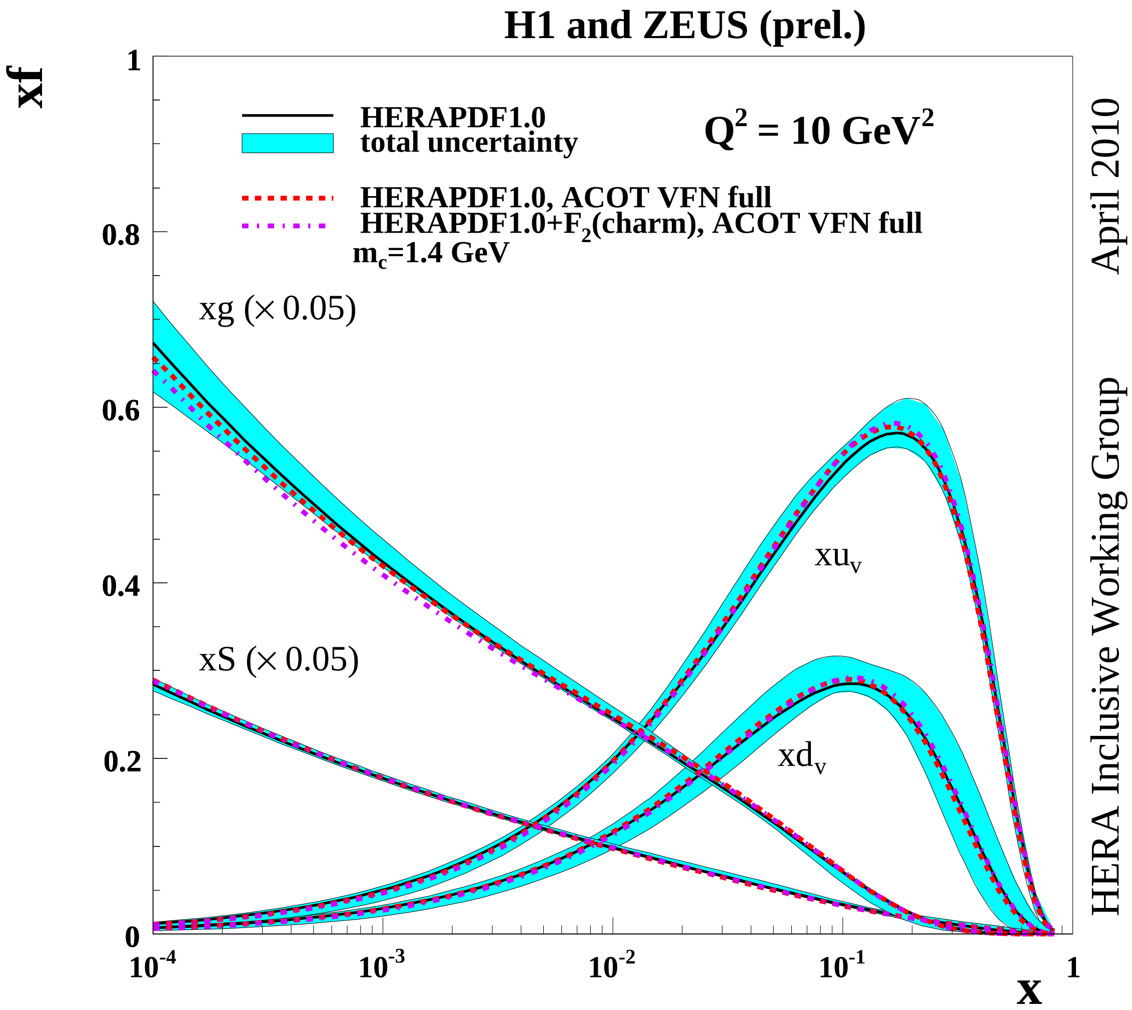


## $\chi^2$ of fits with different HQ schemes:

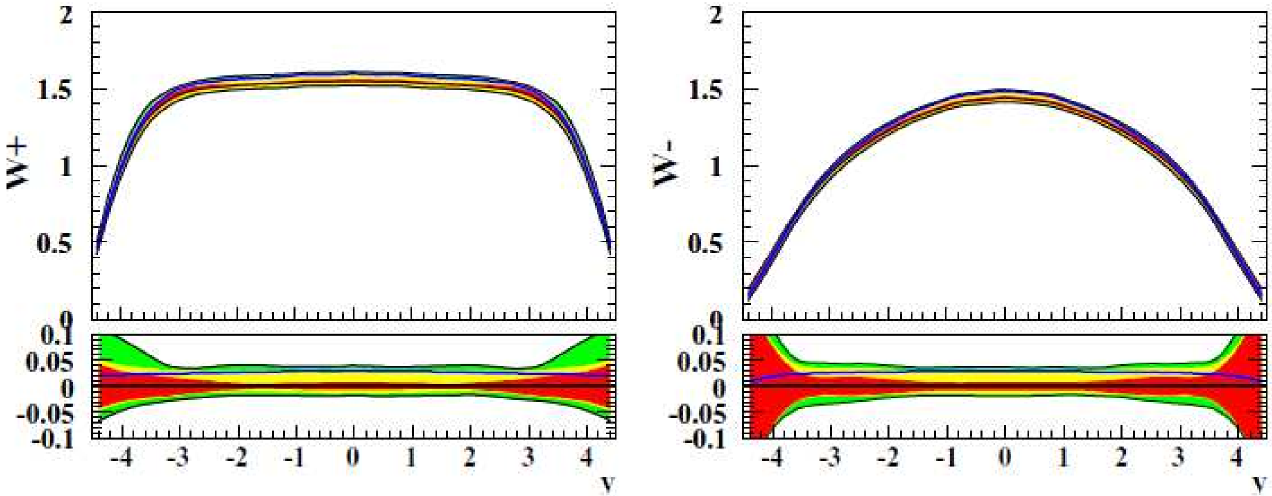
| HQ scheme | $m_c = 1.4$ GeV | $m_c = 1.65$ GeV |
|---|---|---|
| NLO: | | |
| RT STandard | $\chi^2_{\text{charm}} = 134/41$ | $\chi^2_{\text{charm}} = 43/41$ |
| RT Optimized | $\chi^2_{\text{charm}} = 64/41$ | $\chi^2_{\text{charm}} = 100/41$ |
| ACOT | $\chi^2_{\text{charm}} = 89/41$ | $\chi^2_{\text{charm}} = 41/41$ |
| FFNS | $\chi^2_{\text{charm}} = 52/41$ | $\chi^2_{\text{charm}} = 249/41$ |
| NNLO: | | |
| RT STandard | $\chi^2_{\text{charm}} = 54/41$ | $\chi^2_{\text{charm}} = 186/41$ |

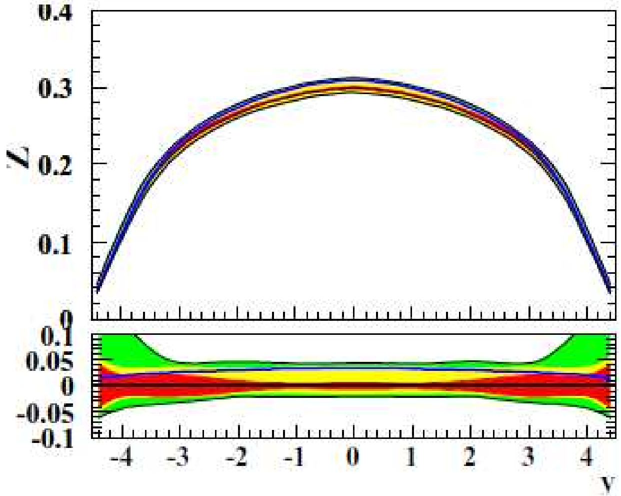
# ACOT scheme with/without $F_2^{c\bar{c}}$ data



Thanks to Amanda Cooper Sarkar

## W and Z rapidity distributions



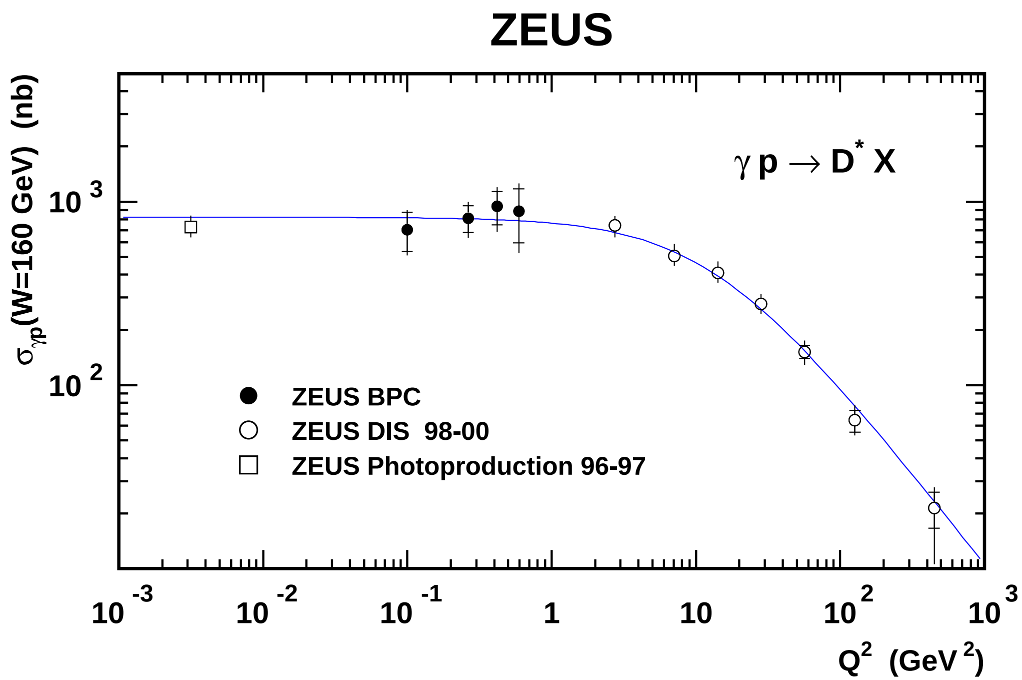




**Predictions from HERAPDF1.0 for W+ W- and rapidity distributions at the LHC 14 TeV ($m_c$=1.4GeV)**

**The blue line shows the shi for $m_c$=1.65 GeV**

| σ(W⁺).B $_{W\to l\nu}$ (nb) | σ(W⁻) .B $_{W\to l\nu}$ (nb) | σ(Z) .B $_{Z\to ll}$ (nb) |
|---|---|---|
| **$m_c$=1.4 GeV**<br>12.44±0.01<br>+0.31 -0.08<br>+0.23 -0.06 | 9.28±0.05<br>+0.25 -0.07<br>+0.21 -0.04 | 2.076±0.014<br>+0.059 -0.015<br>+0.045 -0.009 |
| **$m_c$=1.65 GeV**<br>12.76 | 9.52 | 2.13 |

# Charm production from $Q^2 \sim 0$ to 400 GeV$^2$

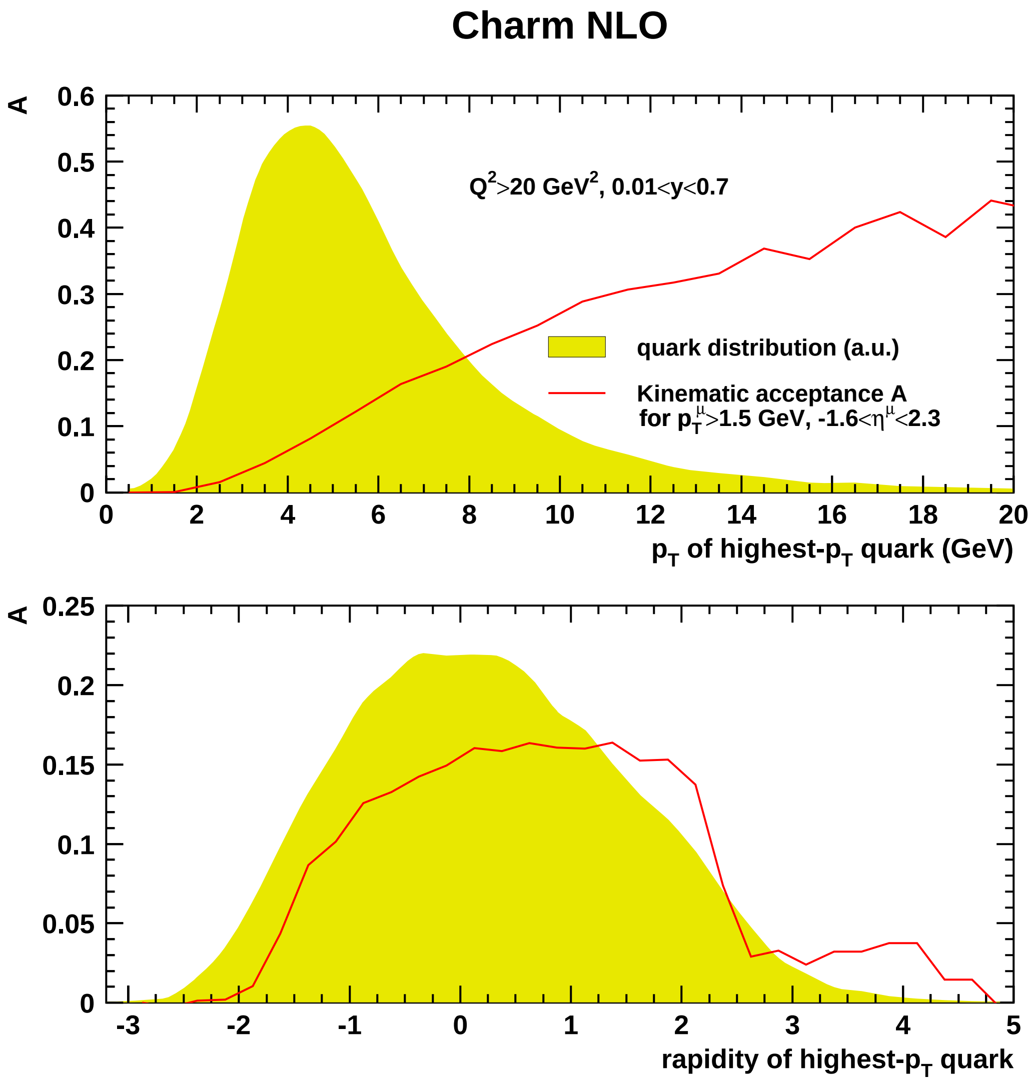



$\sigma(\gamma^* p \to D^{*\pm} X)$
for $p_T(D^*) > 1.5$ GeV$^2$, $|\eta(D^*)| < 1.5$

$d\sigma(ep \to D^* X)/dQ^2 \propto 1/Q^2$ for $Q^2 \ll m_c^2$

$d\sigma(ep \to D^* X)/dQ^2 \propto 1/Q^4$ for $Q^2 \gg m_c^2$

# Acceptance of ZEUS muon analysis




$$A = \frac{N(\mu; p_T > 1.5, -1.6 < \eta < 2.3)}{N(\mu)}$$

versus $p_T$ or $y$
of the highest-$p_T$ $c/\bar{c}$ quark