Heavy-quark production at HERA

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On behalf of the H1 and ZEUS Collaborations

- Introduction : motivation, HERA and DIS
- Measurements of heavy quark production in DIS
- Heavy quark contributions to the structure function, F_2
- Effects on PDF fits and LHC
- Discussion and summary

PDF Working Group, QCD @ LHC 2011 Workshop, St Andrews, 22–26 August 2011

Introduction

Motivation

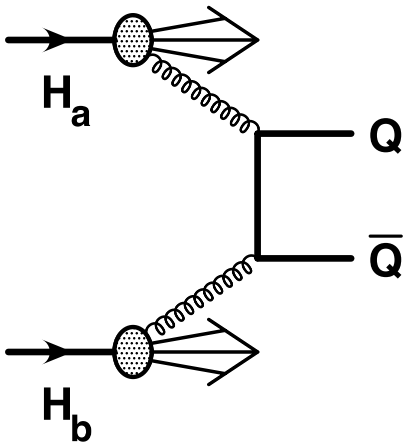
Want to understand the structure of the proton :

• As protons are bound by the strong force, can learn much on the (strong) interaction through study of the structure.

• Provide precise determination of the partonic density functions (PDFs) of the proton to be used at other proton colliders.

• Measure heavy quark cross sections at HERA, combine data and extract PDFs :

- Can we constrain the PDFs in the proton ?
- Effect on gluon and heavy quarks densities in the proton ?
- Can we constrain parameters, e.g. m_Q, or models, e.g. treatment of heavy quarks ?
- What is the impact for the LHC ?



Heavy quark production

For a collision between two hadrons producing heavy quarks, $H_a + H_b \to Q\bar{Q} + X$

$$\sigma(S) = \sum_{i,j} \int dx_1 \int dx_2 \; \hat{\sigma}_{ij}(x_1 x_2 S, m^2, \mu^2) f_i^{H_a}(x_1, \mu) f_j^{H_b}(x_2, \mu)$$

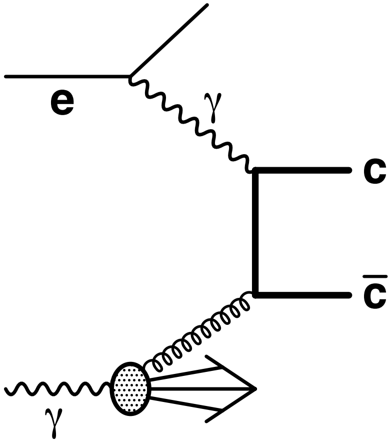
- A convolution of the parton density functions (PDFs) and short distance cross section
- Need to describe fragmentation, transition from a parton to a hadron
- Assume universal, extracting PDFs in deep inelastic scattering at HERA and using for *pp* predictions at the LHC
  - Check scaling violations from QCD fits as directly sensitive to gluon PDFs
  - More precise extractions of the gluon PDFs and better constraints for the heavy quarks PDFs

Heavy quark schemes and PDFs

Treatment of heavy quarks in QCD fits of the proton structure is a crucial assumption

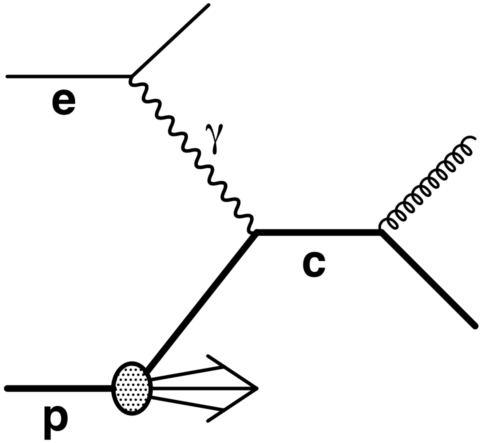
Fixed Flavour Number Scheme (FFNS)

- Heavy quarks massive, produced in Boson-gluon fusion
- Only light flavours and gluon in the proton
- Expected to be less precise for $Q^2 >> m_Q^2$



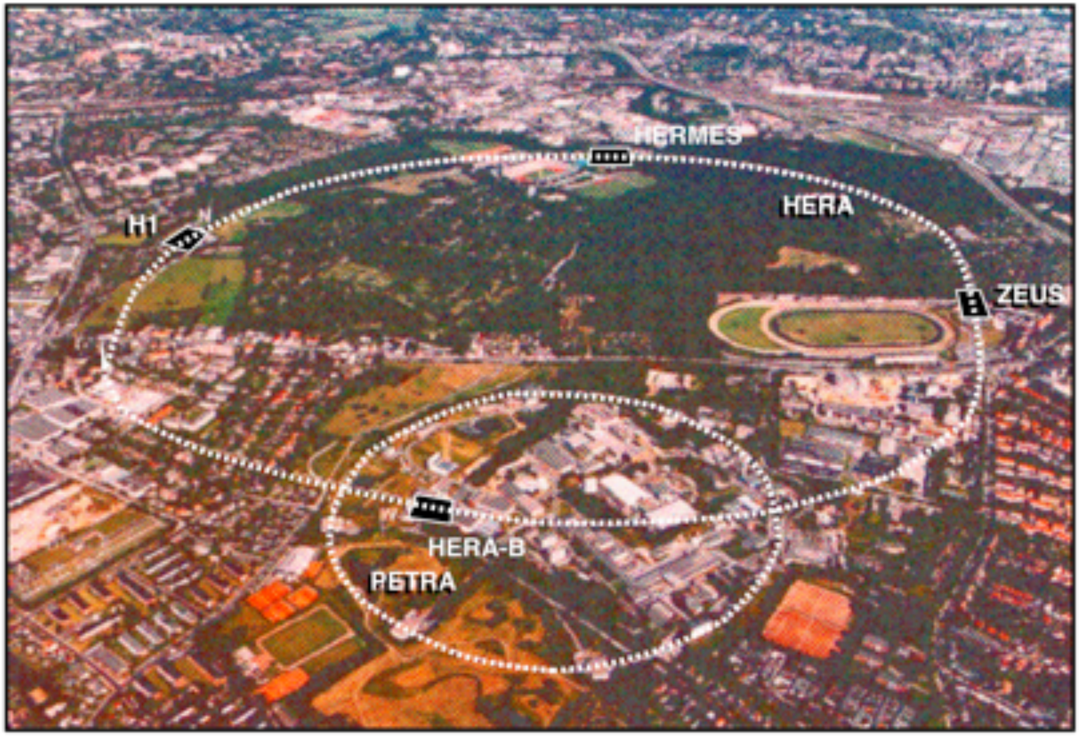
Variable Flavour Number Scheme (VFNS)

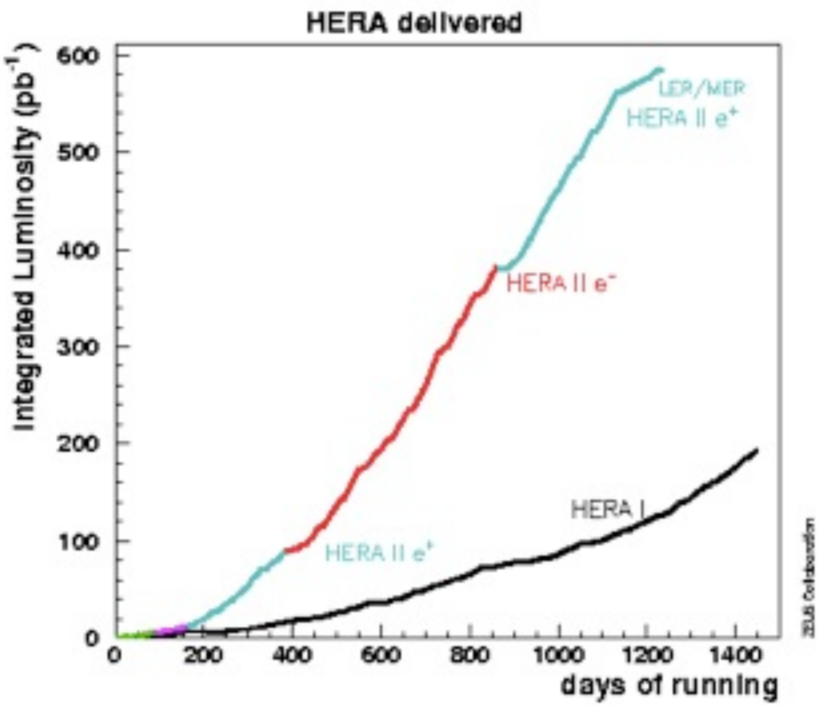
- Zero mass : all flavours massless. Not applicable at $Q^2 \sim m_Q^2$
- Generalised mass : matched scheme where expect applicability for all Q^2



Use the measurements to help discriminate between schemes and constrain the PDFs

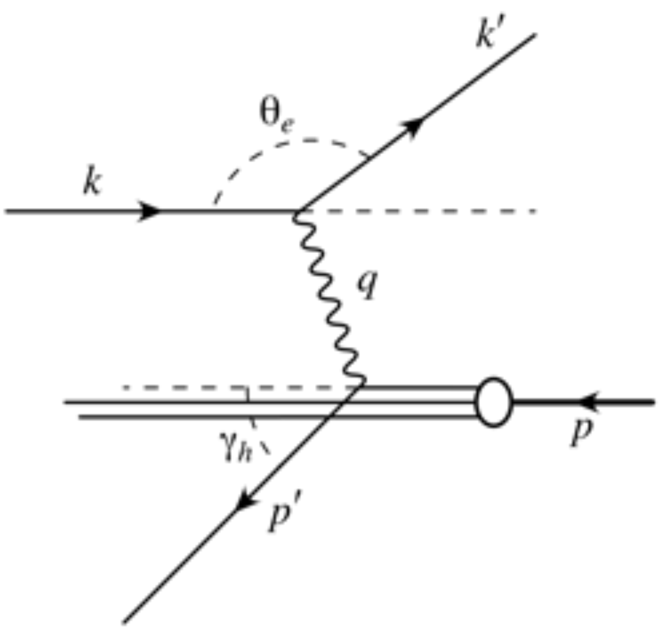
The HERA collider

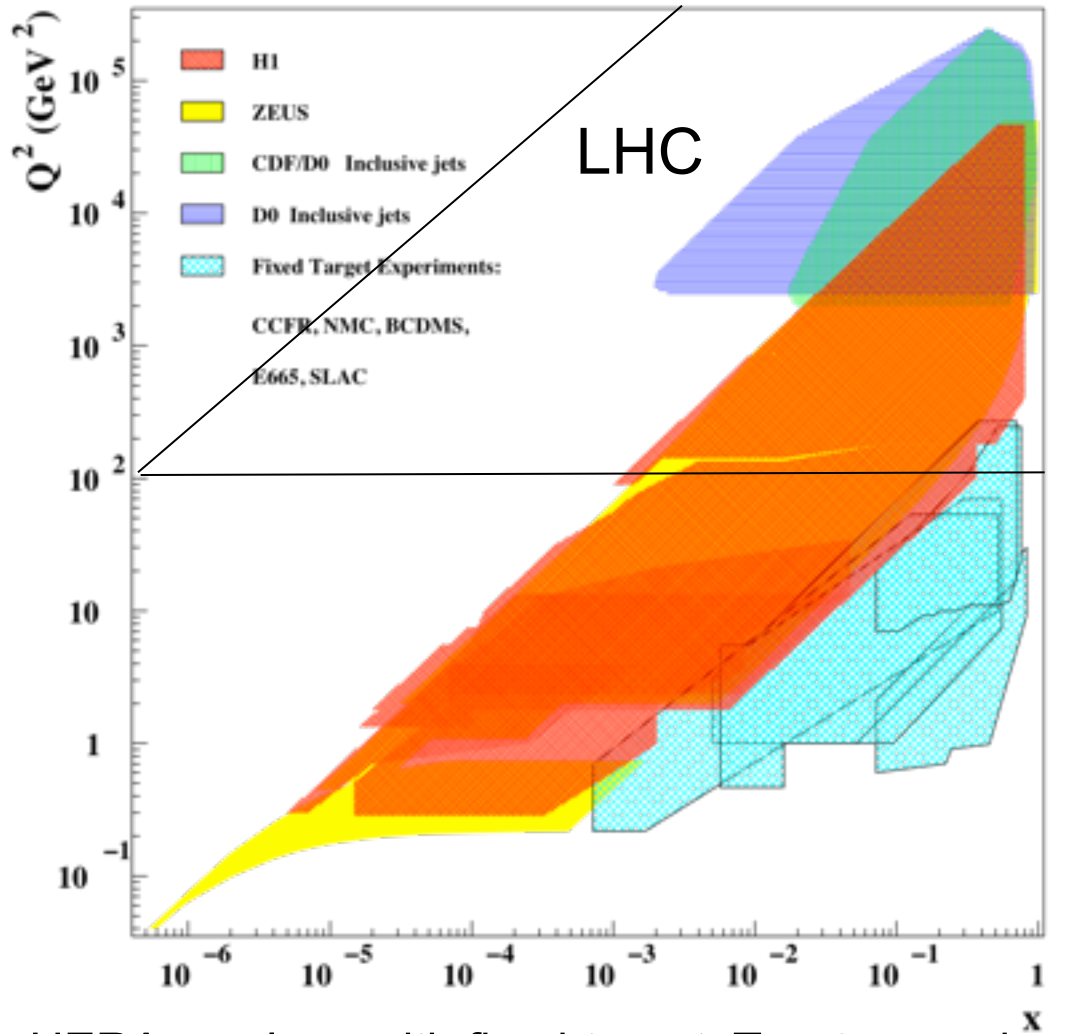




- During 1992–2007, mainly E_e = *27.5 GeV*, E_p = *920 GeV* giving $\sqrt{s}$ ~ *320 GeV*.
- Colliding-beam experiments collected combined sample ~ *1* fb^{-1}.

Deep inelastic scattering : definitions





Momentum transfer :

$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction carried by struck parton :

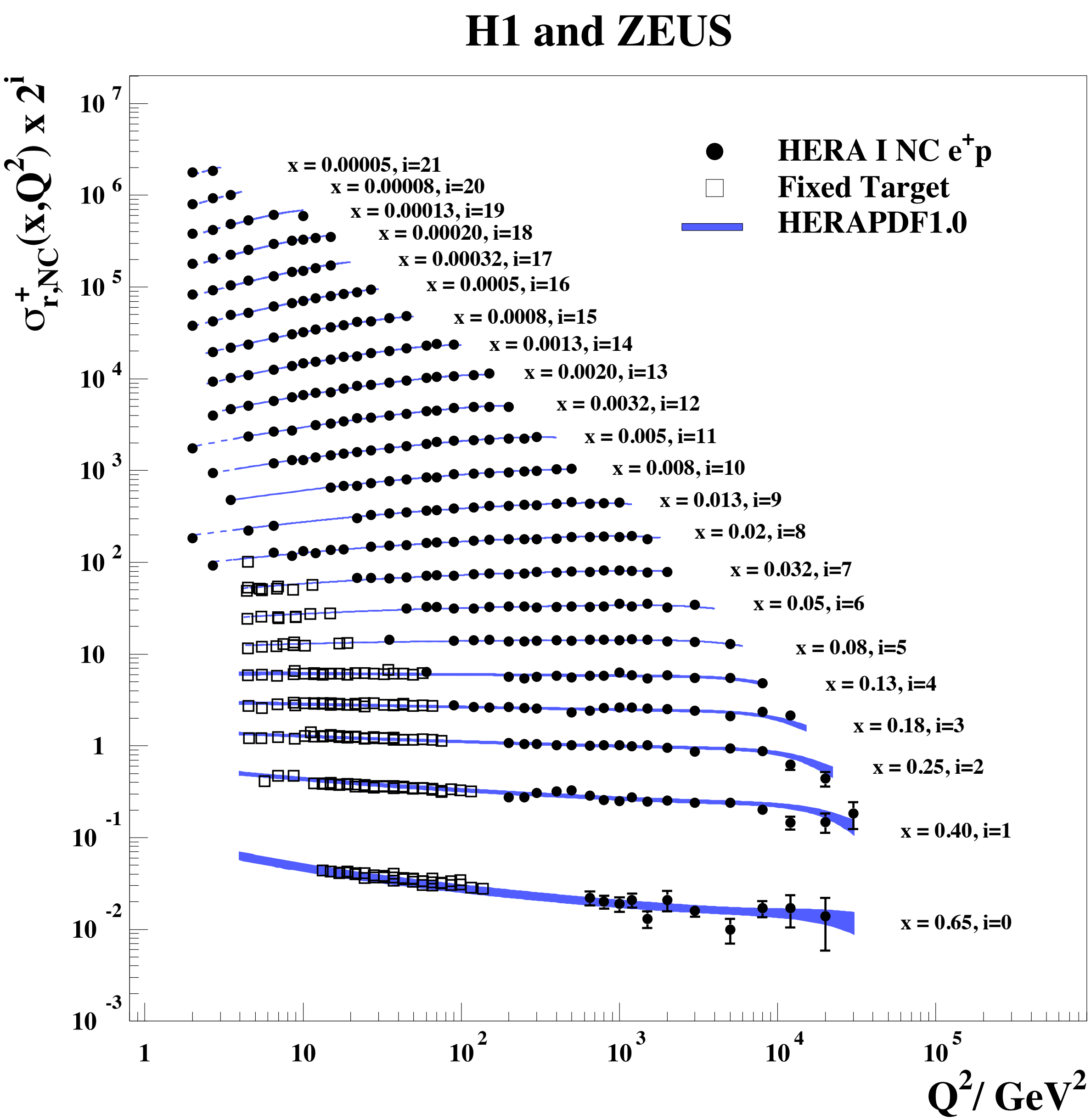
$$x = Q^2/(2p\cdot q)$$

Inelasticity :

$$y = (q\cdot p)/(k\cdot p)$$

HERA overlaps with fixed-target, Tevatron and LHC experiments

Inclusive DIS data and HERAPDF fit

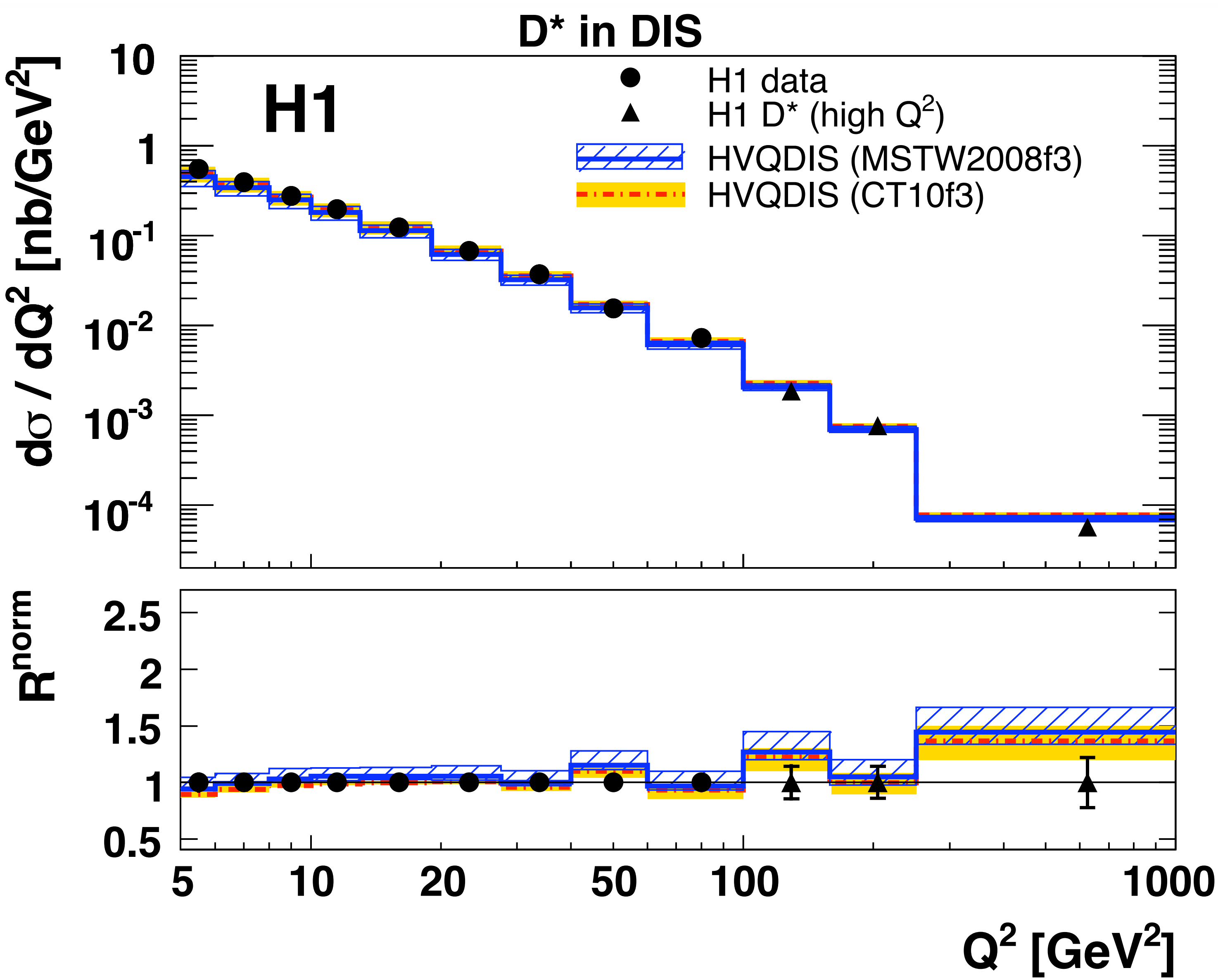


Impressive results for inclusive DIS.

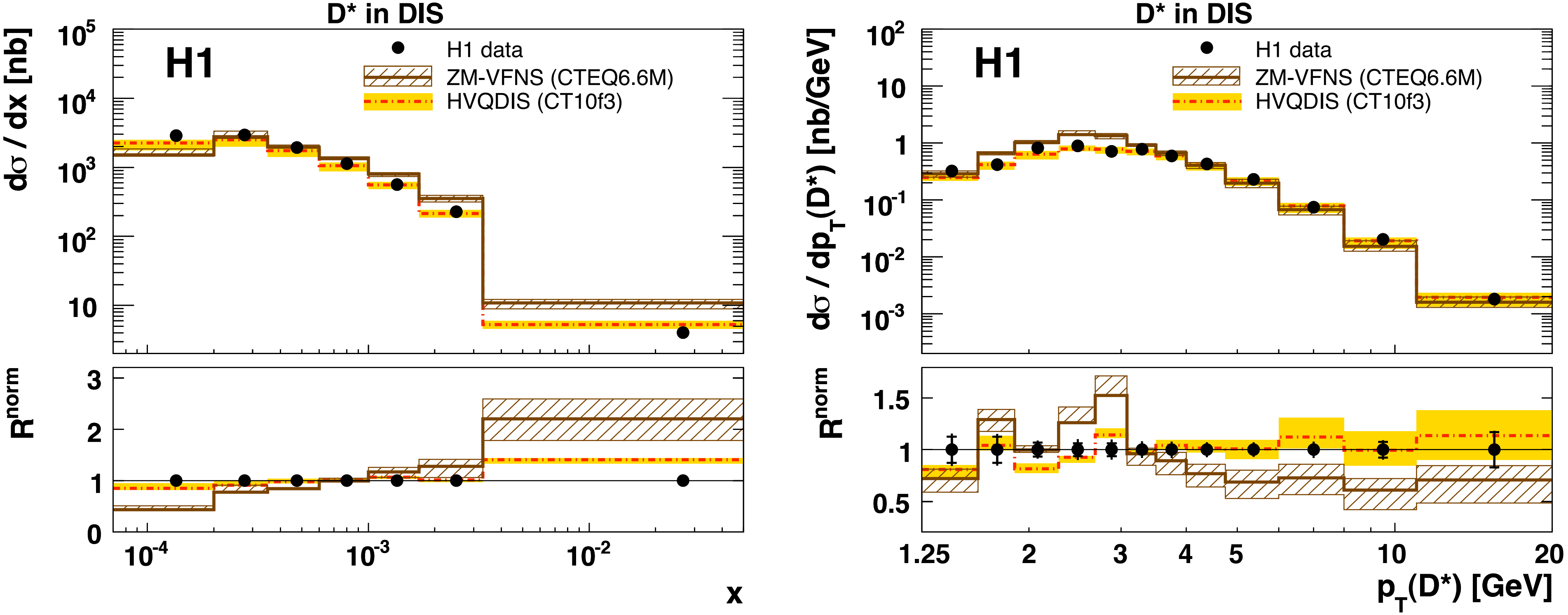
What can measurements of heavy quarks contribute ?

Measurements of heavy quark production in DIS

Charm cross sections

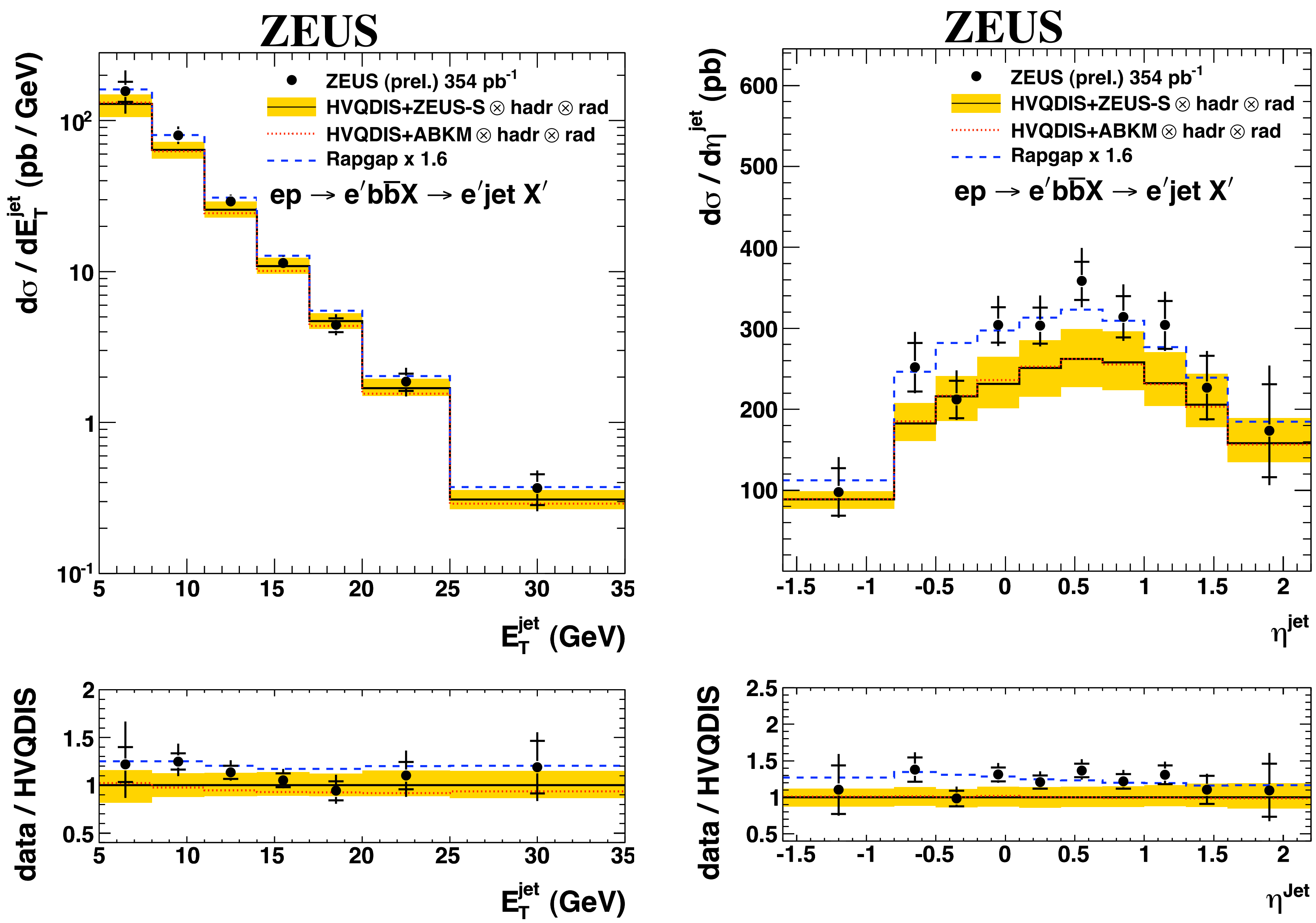


Charm cross sections



- In general, FFNS scheme describes data well and better than VFNS does
- Also relevant given extrapolation to full D^* phase space
- Various other measurements from H1 and ZEUS of charm in different decay channels, kinematic regions, etc. to be combined.

Beauty cross sections



$F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

Extraction of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

Defining the DIS cross section and charm structure functions as :

$$\frac{d^2\sigma^{c\bar{c}}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\{[1+(1-y)^2]F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}(x,Q^2)\}$$

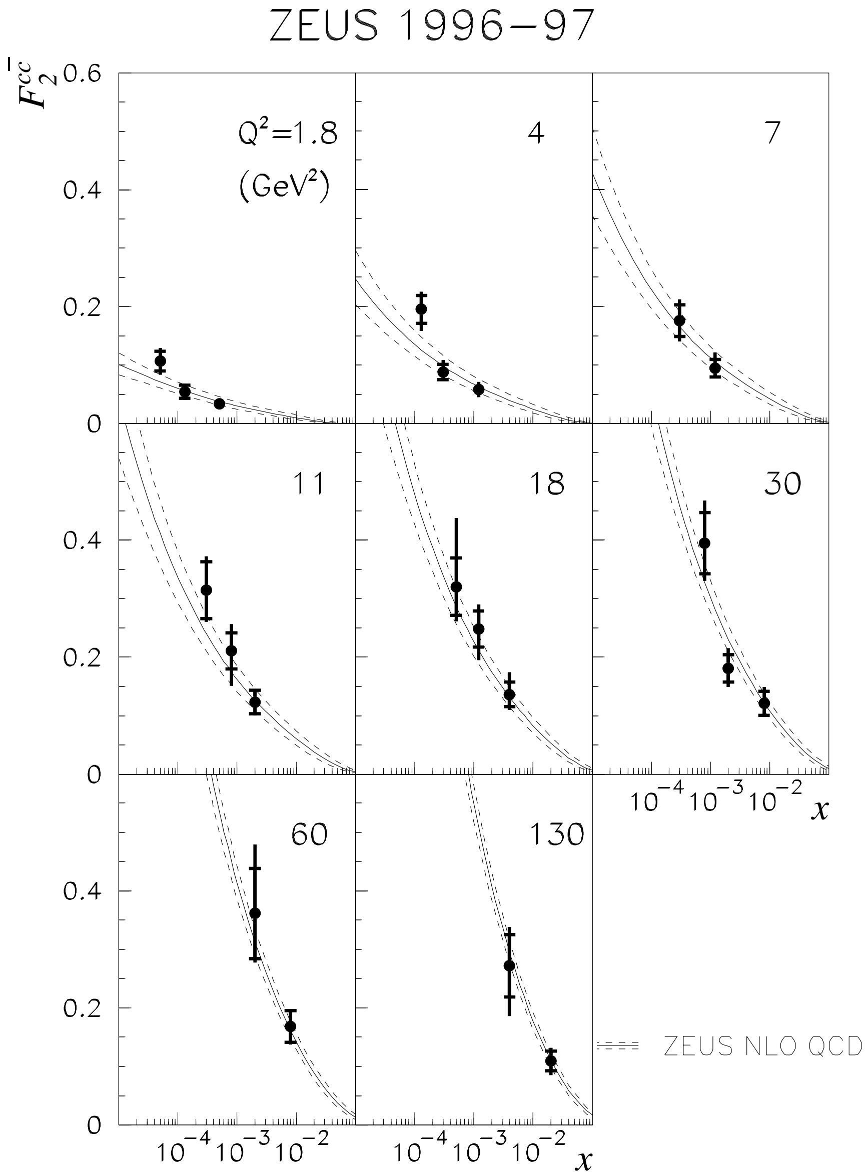
Extraction of (extrapolation to) $F_2^{c\bar{c}}$ performed by :

$$F_{2,\mathrm{meas}}^{c\bar{c}}(x_i,Q_i^2) = \frac{\sigma_{i,\mathrm{meas}}(ep \to D^* X)}{\sigma_{i,\mathrm{theo}}(ep \to D^* X)} F_{2,\mathrm{theo}}^{c\bar{c}}(x_i,Q_i^2)$$

Extrapolations are subject to (unknown) uncertainties; remedy :

- Measure in wide phase-space
- Use different decay channels / experimental techniques

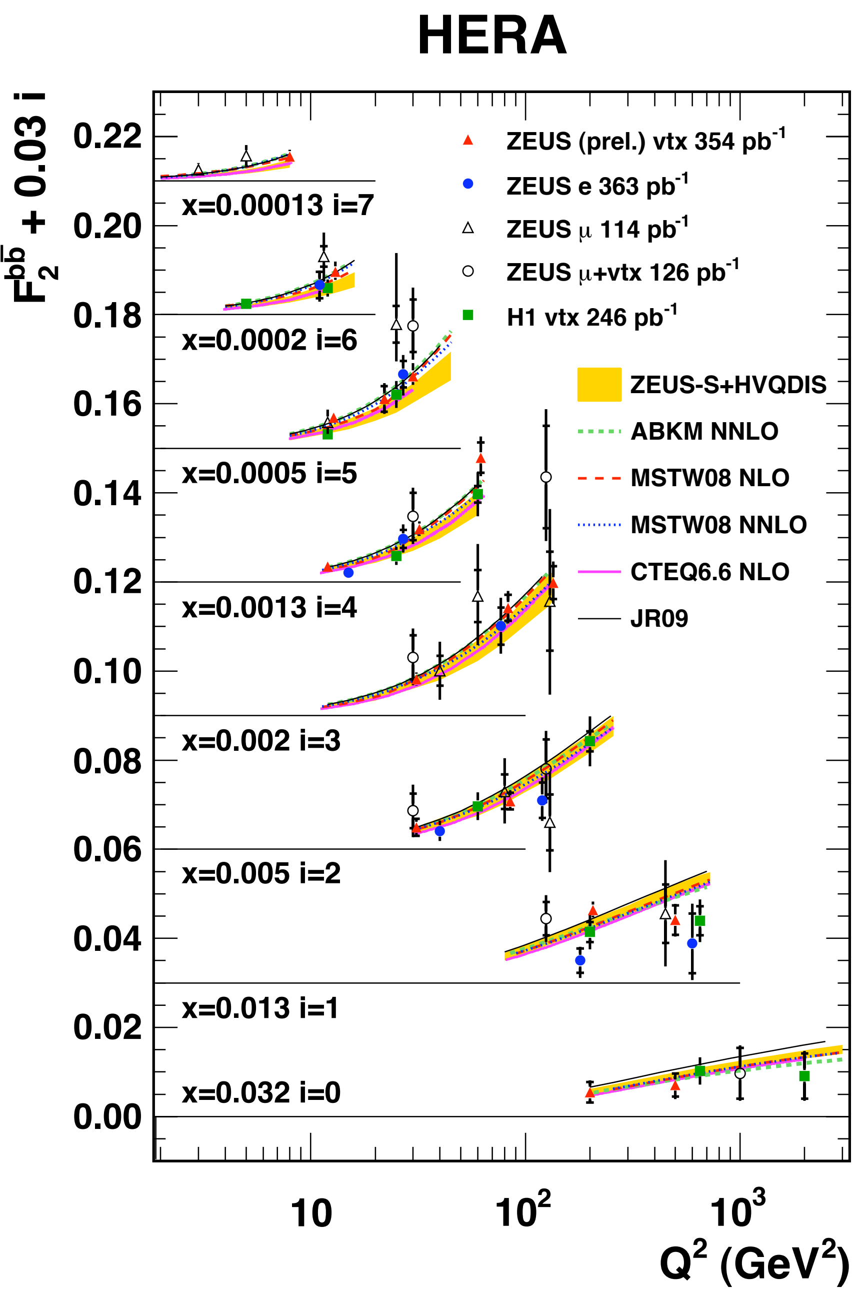
Early measurements of $F_2^{c\bar{c}}$



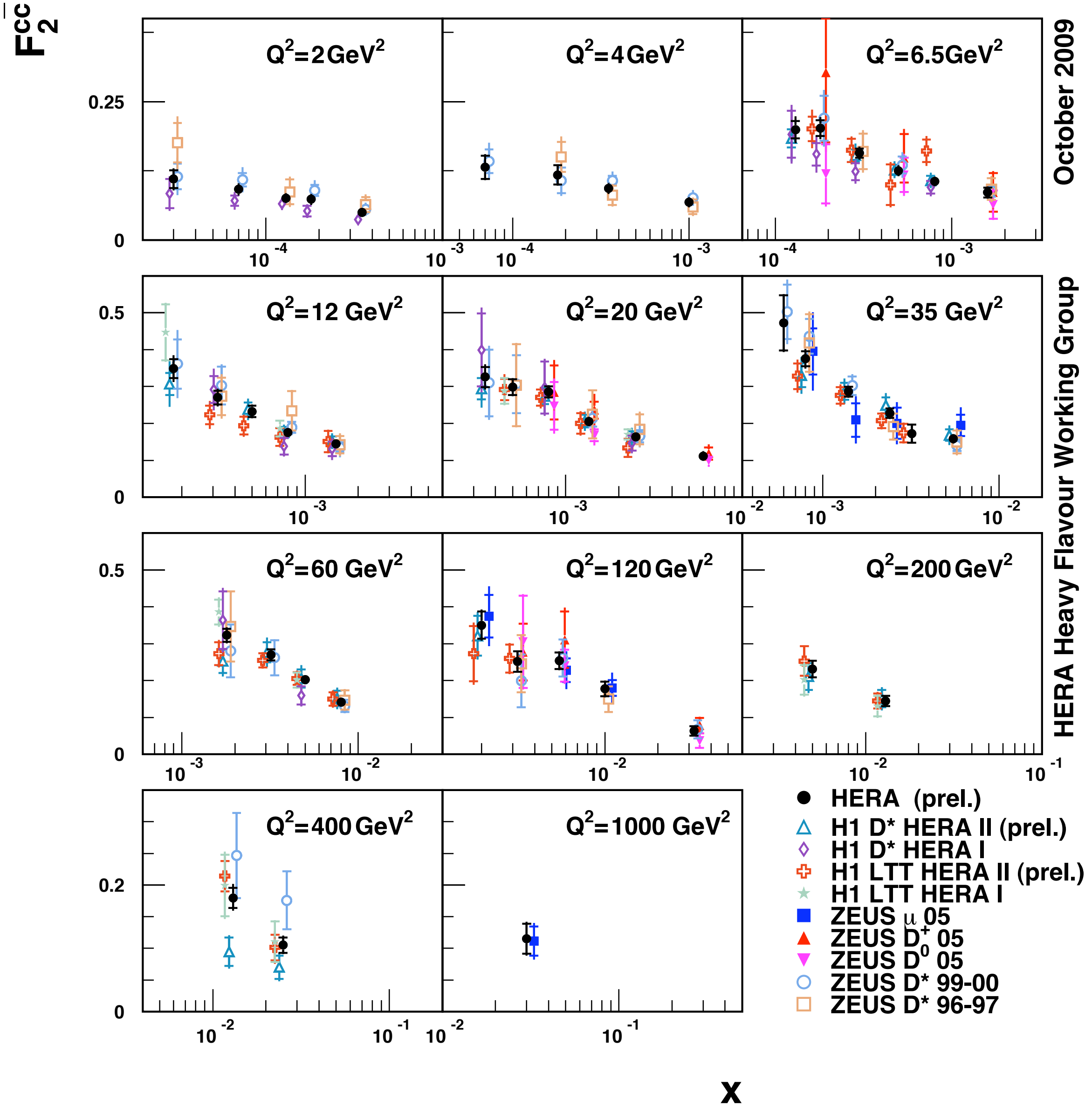
- Measurements showed :
  - Strong rise to low x
  - Scaling violations
  - Charm up to about 30% of total cross section
- Early results established basic procedure
- Extraction basis for future measurements
- Lots involved in such a “simple” extrapolation

Measurements of $F_2^{b\bar{b}}$

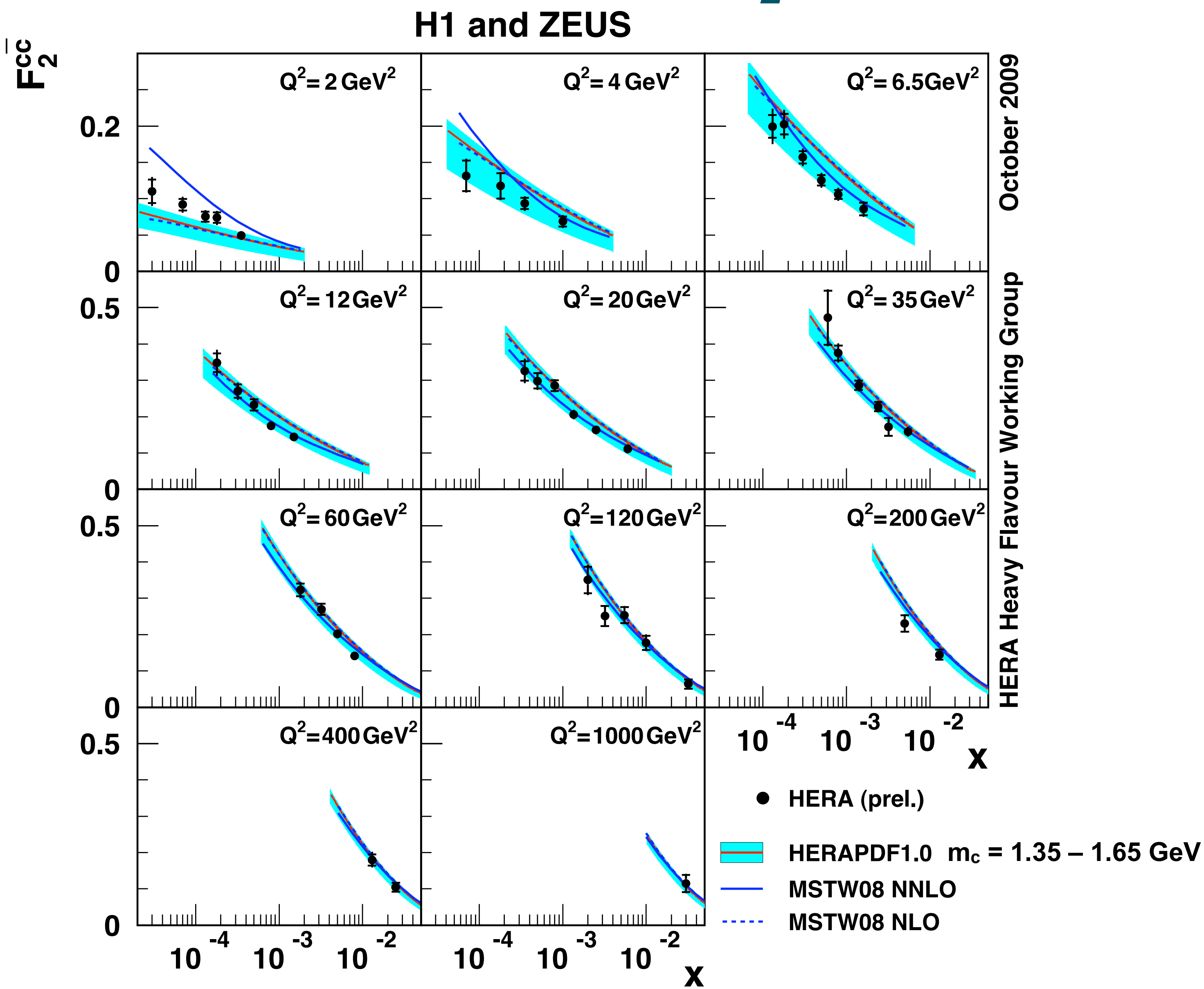
- Clear observation of scaling violations
- Similar precision to early charm measurements
- Can discriminate PDFs
- Possibility to discriminate m_b
- Need to combine data



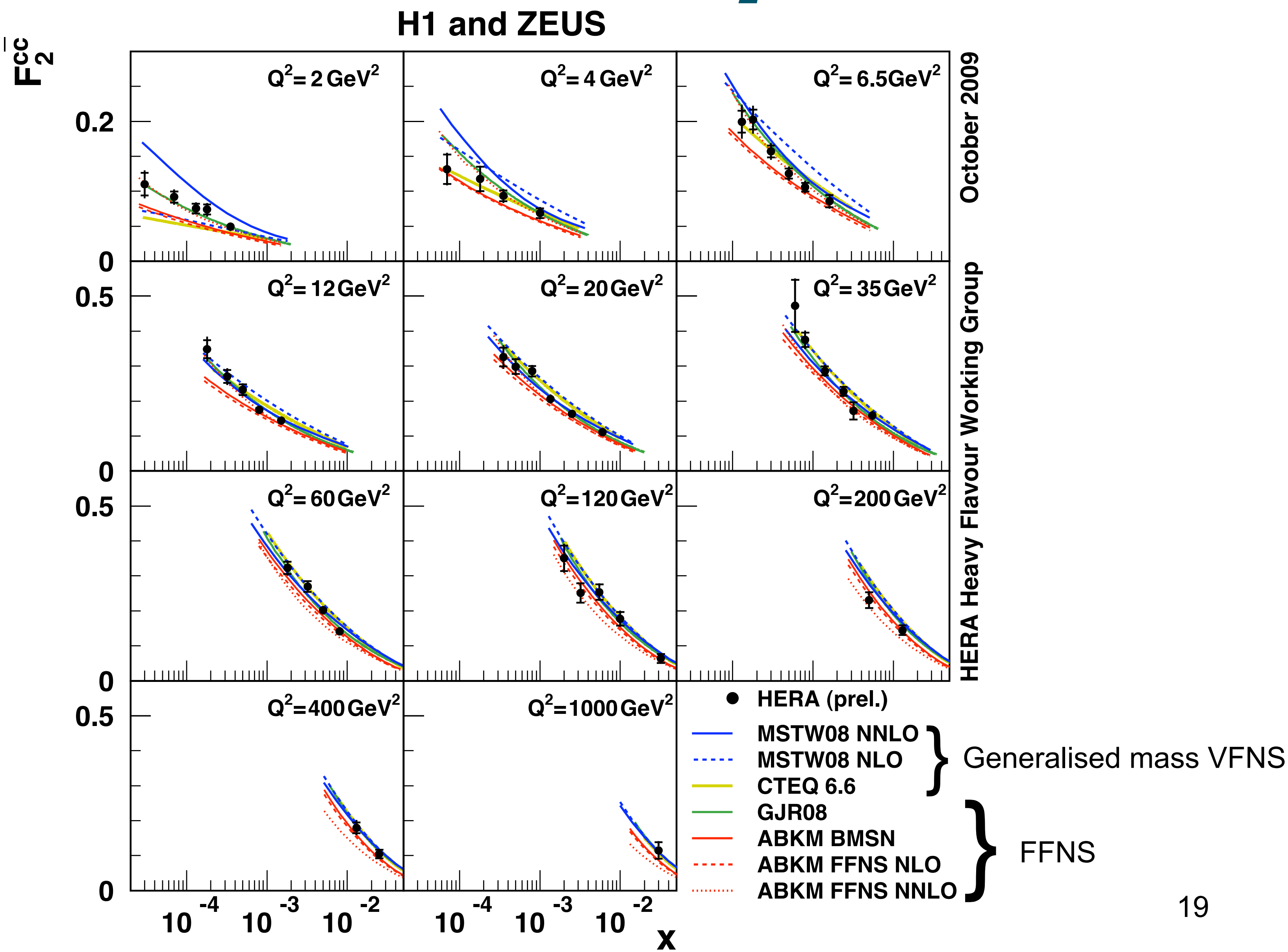
Combined measurements of $F_2^{c\bar{c}}$



Combined measurements of $F_2^{c\bar{c}}$

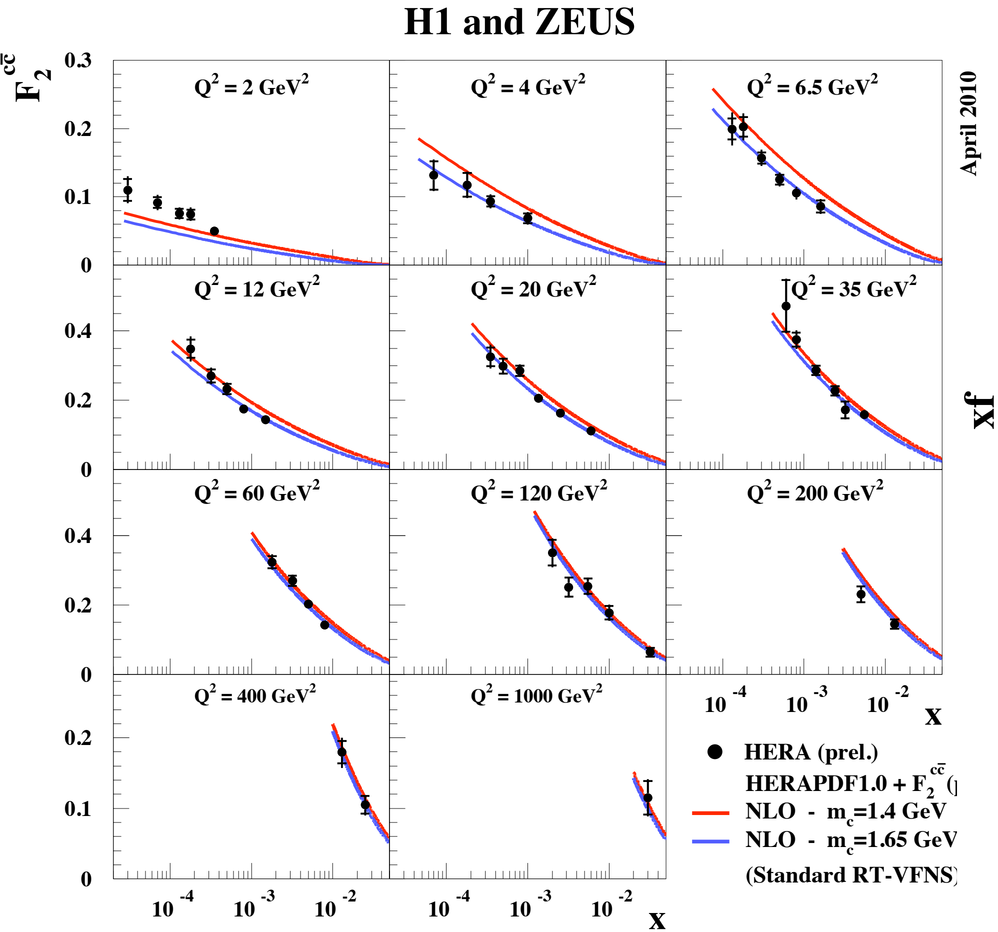


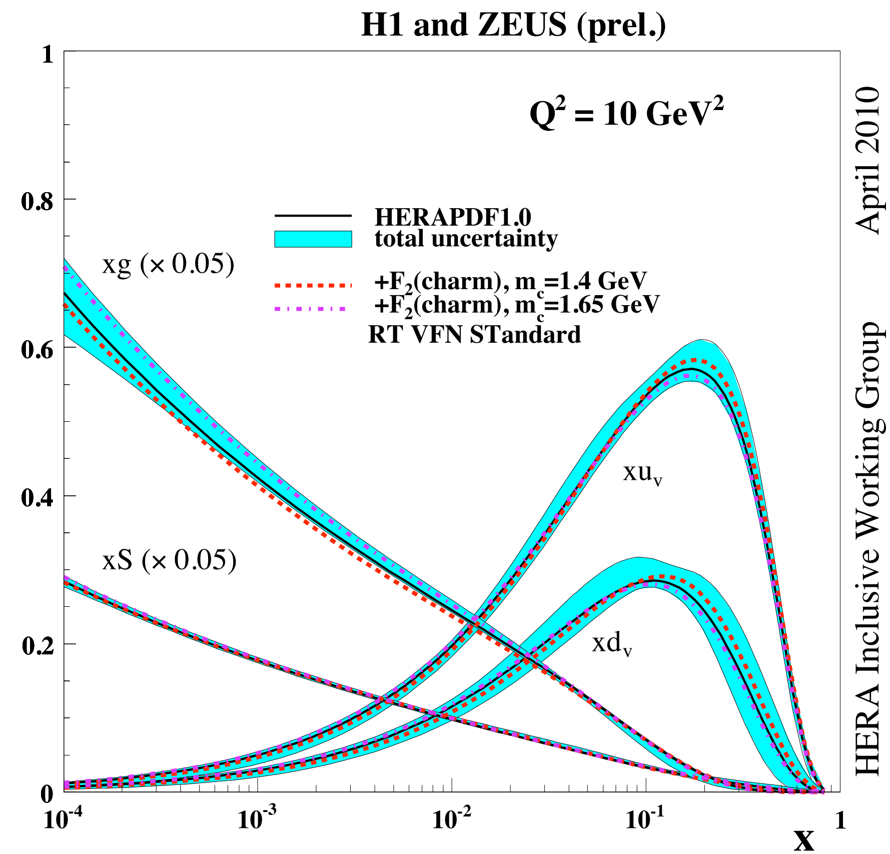
Combined measurements of $F_2^{c\bar{c}}$



Effects on PDF fits and LHC

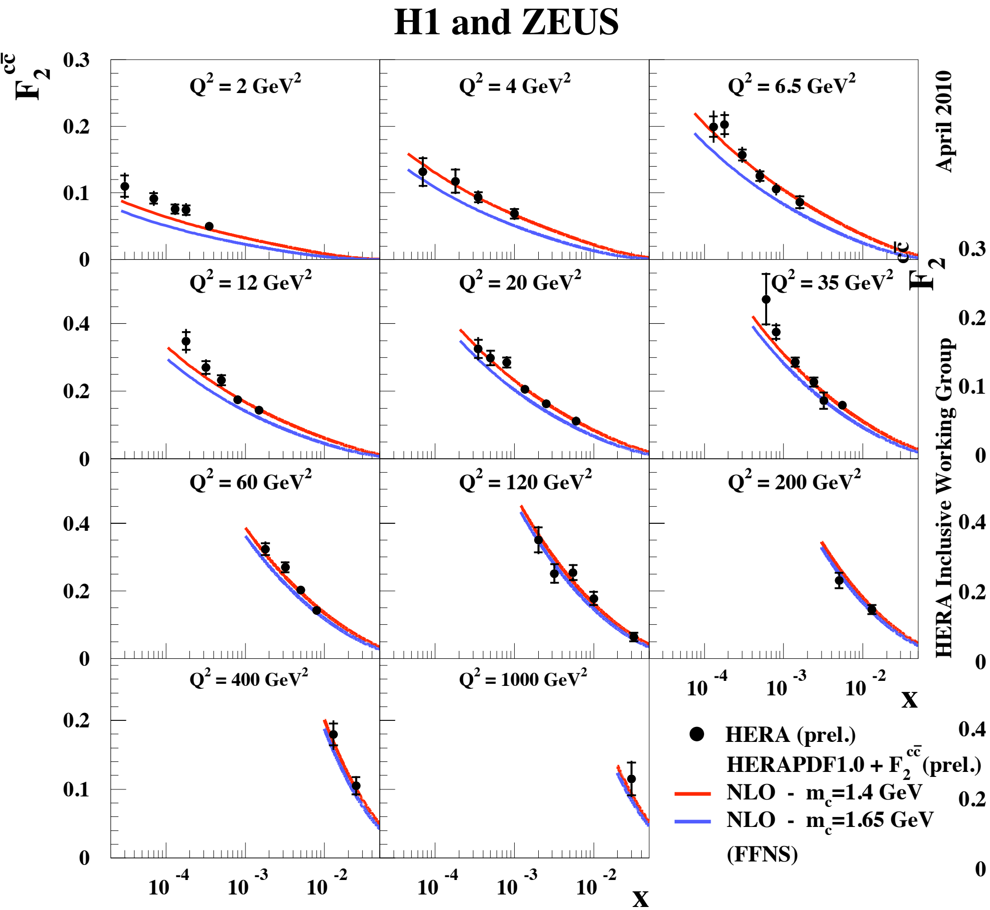
Using $F_2^{c\bar{c}}$ in NLO QCD fits





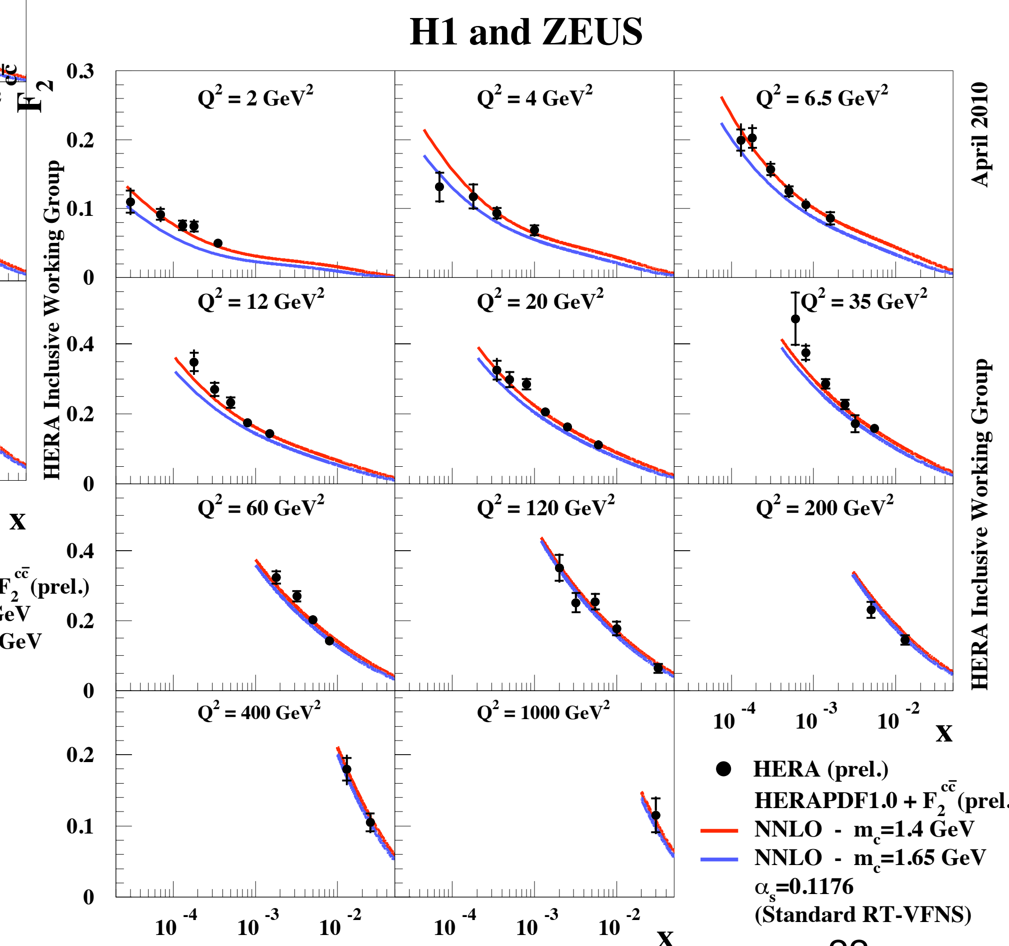
Clear preference for m_c = *1.65 GeV*

Using $F_2^{c\bar{c}}$ in (N)NLO QCD fits



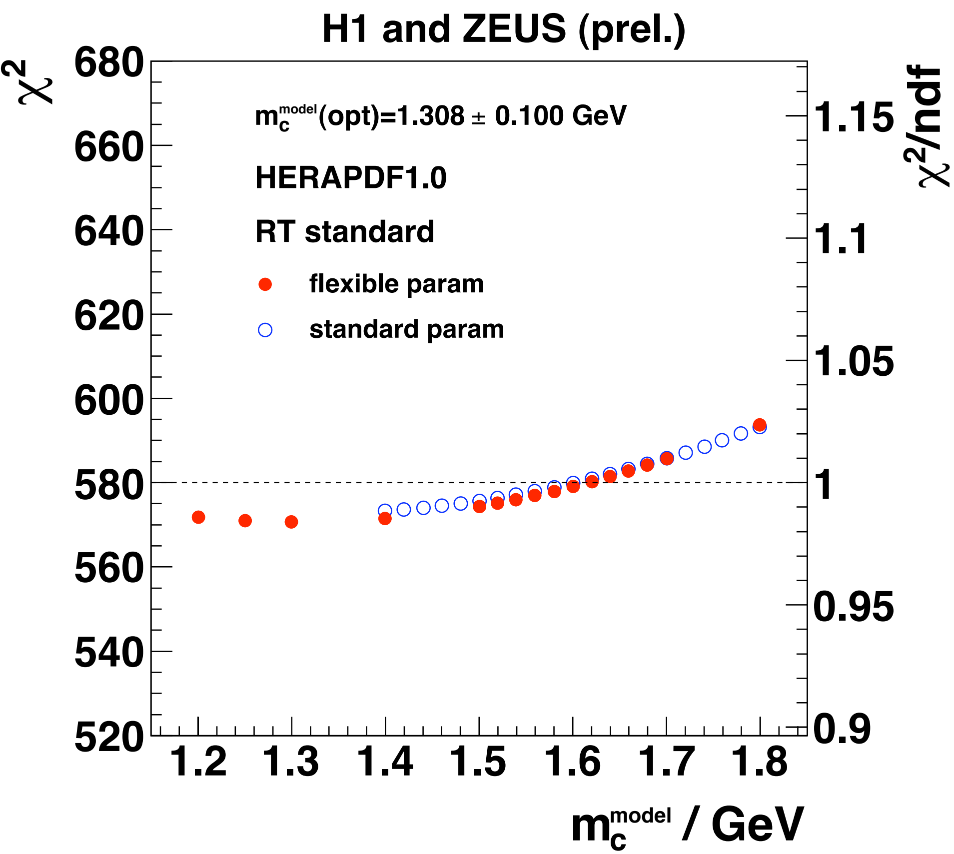
FFNS

NNLO

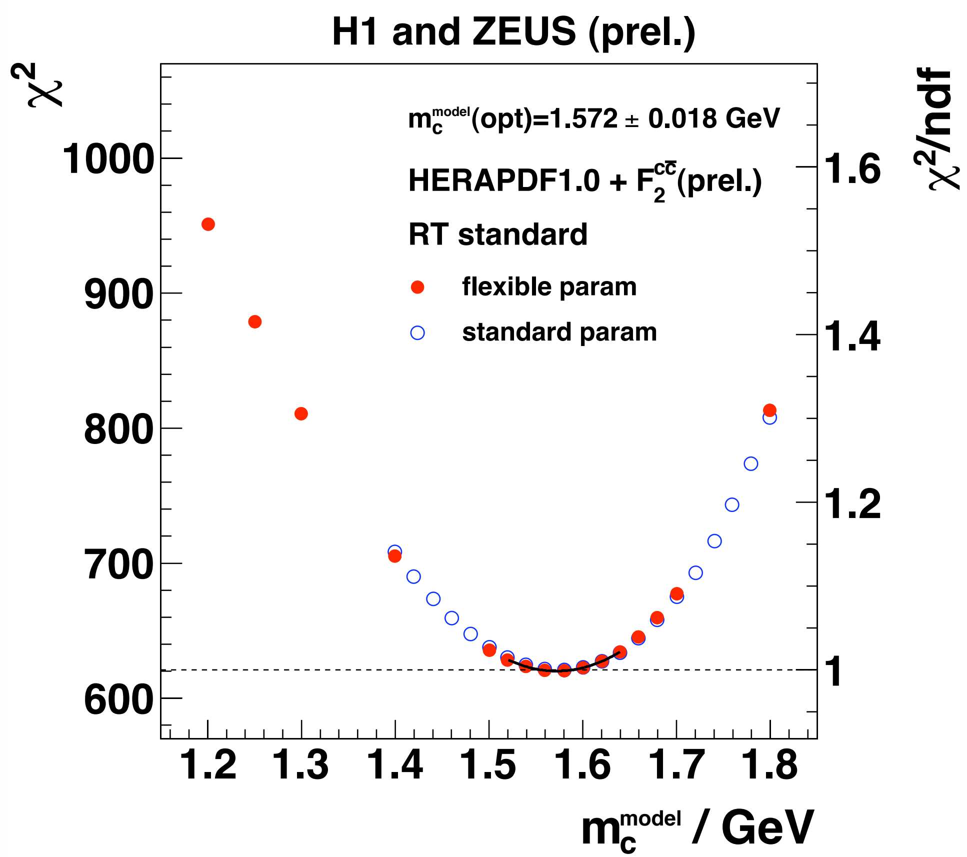


Clear preference for m_c = *1.4 GeV*

Variation of m_c in QCD fits

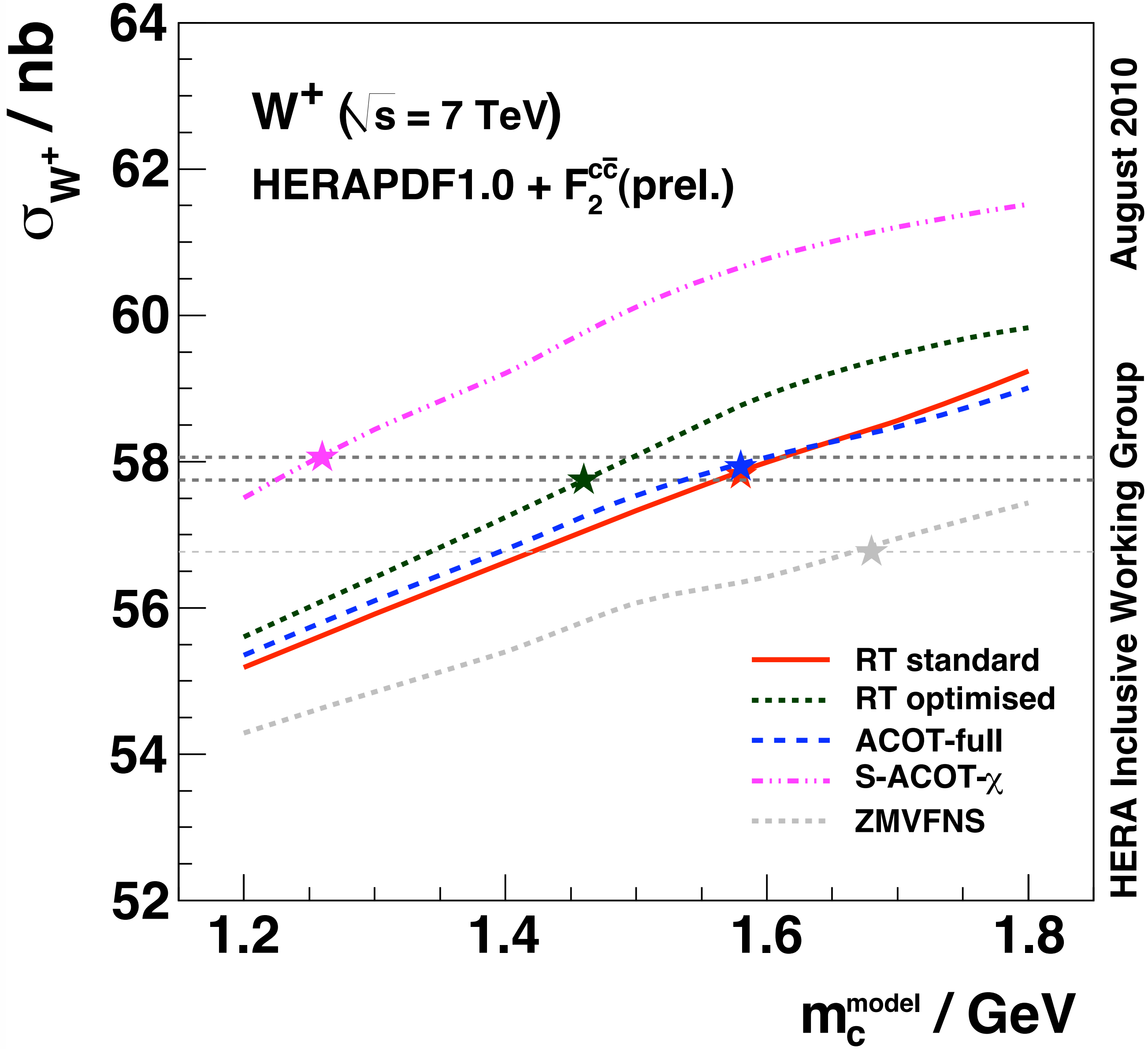


No charm data in fit



Include charm data in fit

Effect on LHC predictions



Discussion and summary

Discussion

• Collaborations producing new high-precision measurements of both charm and beauty structure functions

• Publish current combined data and include new measurements for final $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

$$F_{2,\mathrm{meas}}^{c\bar{c}}(x_i, Q_i^2) = \frac{\sigma_{i,\mathrm{meas}}(ep \to D^* X)}{\sigma_{i,\mathrm{theo}}(ep \to D^* X)} F_{2,\mathrm{theo}}^{c\bar{c}}(x_i, Q_i^2)$$

• Common parameters and uncertainties needed for extraction :

- PDF, e.g. HERAPDF1.0 FFNS
- m_c, e.g. $m_c = 1.50 \pm 0.15$ GeV
- μ_F and μ_R, e.g. $\mu_F = \mu_R = (Q^2 + 4\, m_c^2)^{1/2}$ and vary by factor of 2
- Fragmentation function, e.g. Kartvelishvilli with $\alpha = 3 \pm tbd$
- Fragmentation fraction, e.g. $f(c \to D^*)$ = combined HERA/CDF/LEP value

• Then have the most precise charm and beauty data to be used in PDF fits

Summary

• Many precise measurements of heavy quark production at HERA

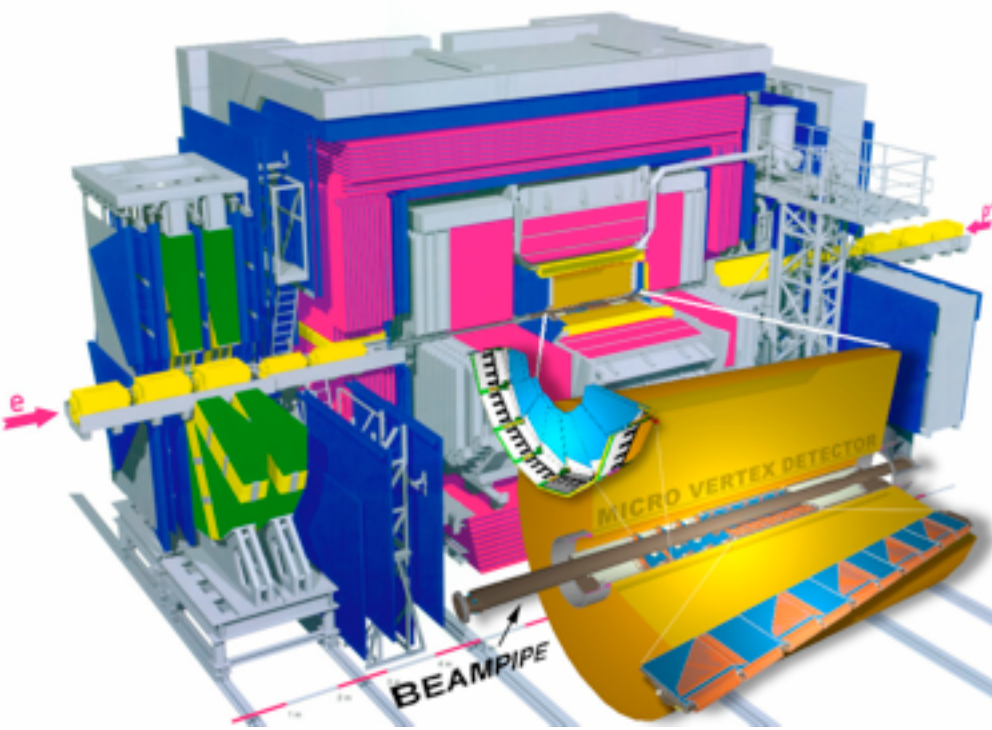
• Data impacting on QCD fits : constraining the PDFs, distinguishing between schemes and determining the masses

• More data to come and more precise combined results expected

• We will learn more about QCD and provide more precise predictions (for the LHC)

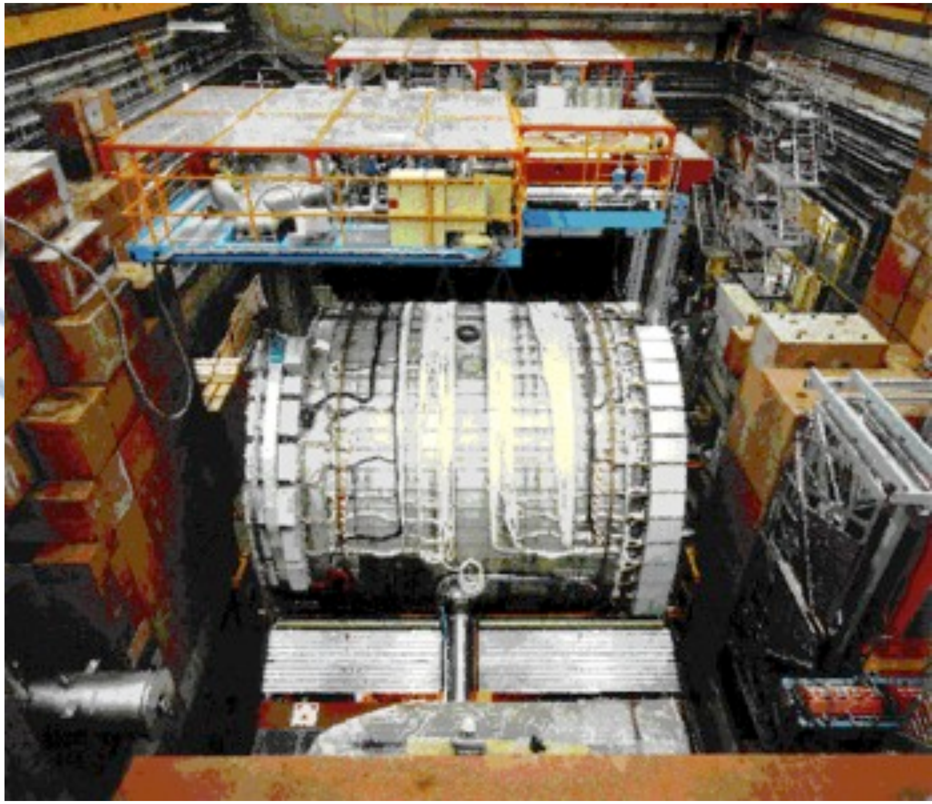
Back-up

The H1 and ZEUS detectors



Both large general-purpose detectors:

- Almost hermetic
- Similar to LEP, Tevatron, etc.
- More instrumentation in proton direction



Sub-detectors consist of:

- Electromagnetic and hadronic calorimeters
- Tracking detectors
- Micro-vertex detectors
- Luminosity monitors
- Muon chambers
- …

Extraction of parton densities—HERAPDF

$$\sigma_{DIS} \sim f_P \otimes \sigma_{pert}$$

f_P : proton parton density function evolved with Q^2 by DGLAP equations.

σ_{pert} : short distance cross section calculable in pQCD.

- The structure of (parton densities in) the proton extracted from fits to DIS data.
- Use next-to-leading order (NLO) QCD, a series expansion in α_s with e.g. hard scale Q^2 and assumptions : heavy quark masses, the starting scale, the strong coupling, the functional form of the parton density functions, etc..

Data used :

- HERAPDF1.0 : NC, CC ($Q^2 > 100\ GeV^2$); NC ($Q^2 > 0.045\ GeV^2$) [JHEP 01 (2010) 109]
- HERAPDF1.X : Low-E_p data ($Q^2 > 2.5\ GeV^2$); HERA II high Q^2 data; charm data [prel.]

Uncertainties :

- Experimental—using $\Delta\chi^2 = 1$
- Model—heavy quark masses, minimum Q^2 and strange quark distribution
- Parameter—envelope of parameter variations.