Measurements of the proton structure at HERA

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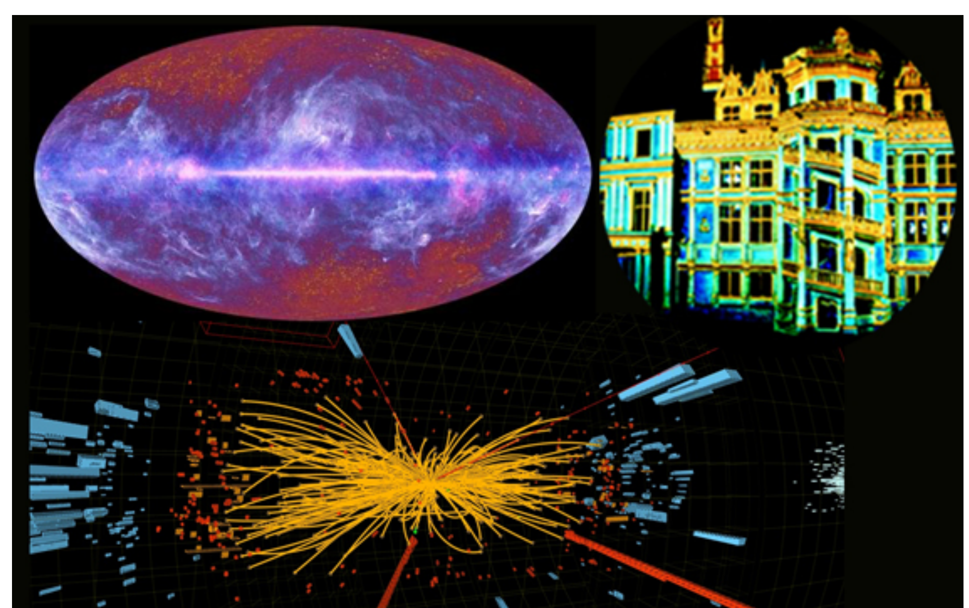
University of Bonn

Blois 2014



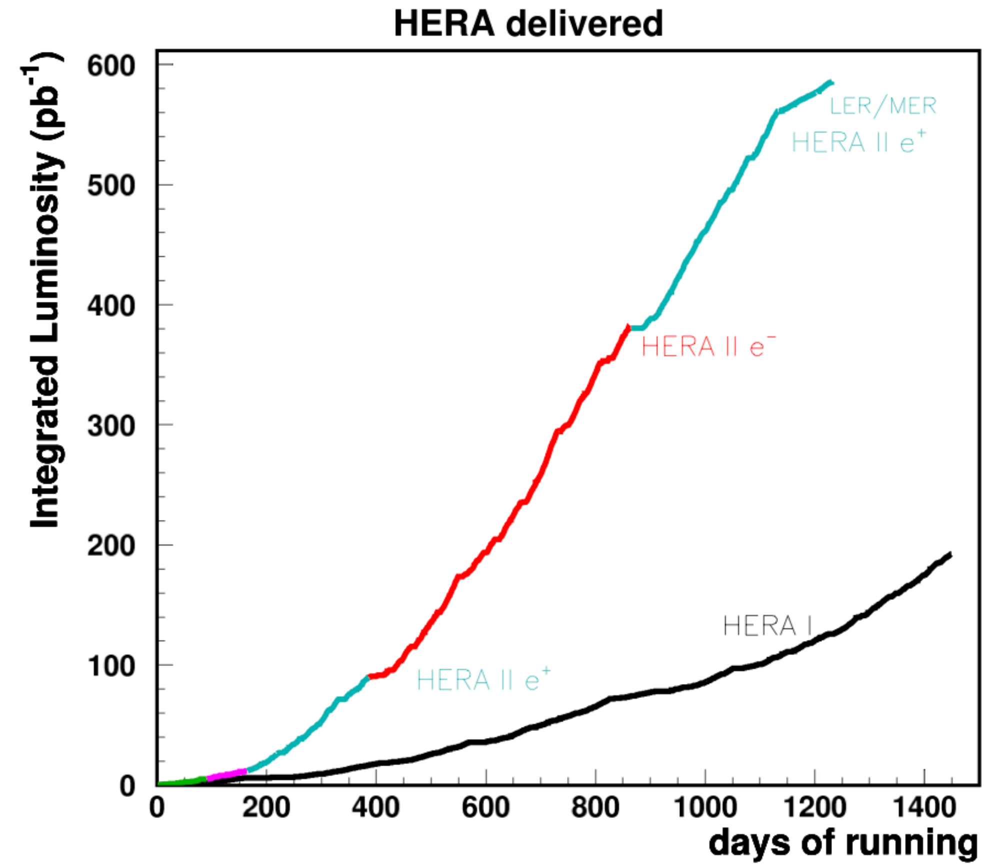
Outline

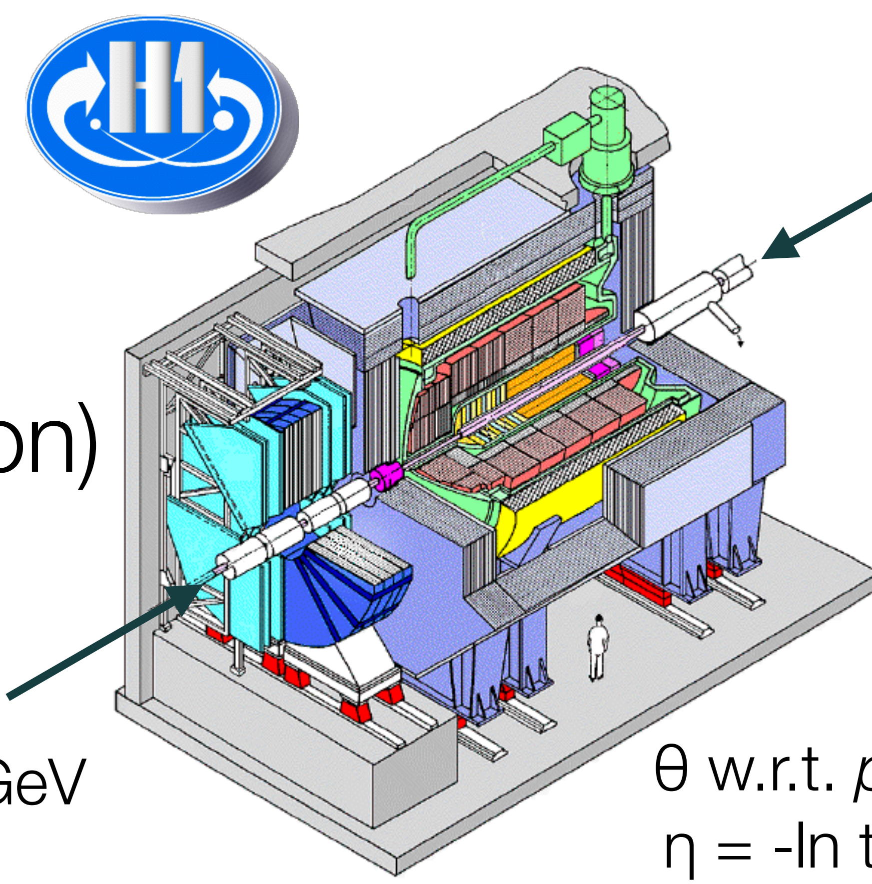
- Introduction
- Recent F_L measurements
- ZEUS and H1 NC/CC combinations
- HERAPDF 2.0
- F_2^b and F_2^c
- Summary

Many interesting and
recent measurements not
discussed due to lack of time:
22 papers in ZEUS/H1 combination!

HERA

- $e^{\pm}\, p$ collisions at $\sqrt{s}$ = 318 GeV
  - ~0.5 fb^{-1} per experiment
- HERA 1:
  - 1996 - 2000
- HERA 2 (longitudinal $e^{\pm}$ polarisation)
  - 2004 - 2007





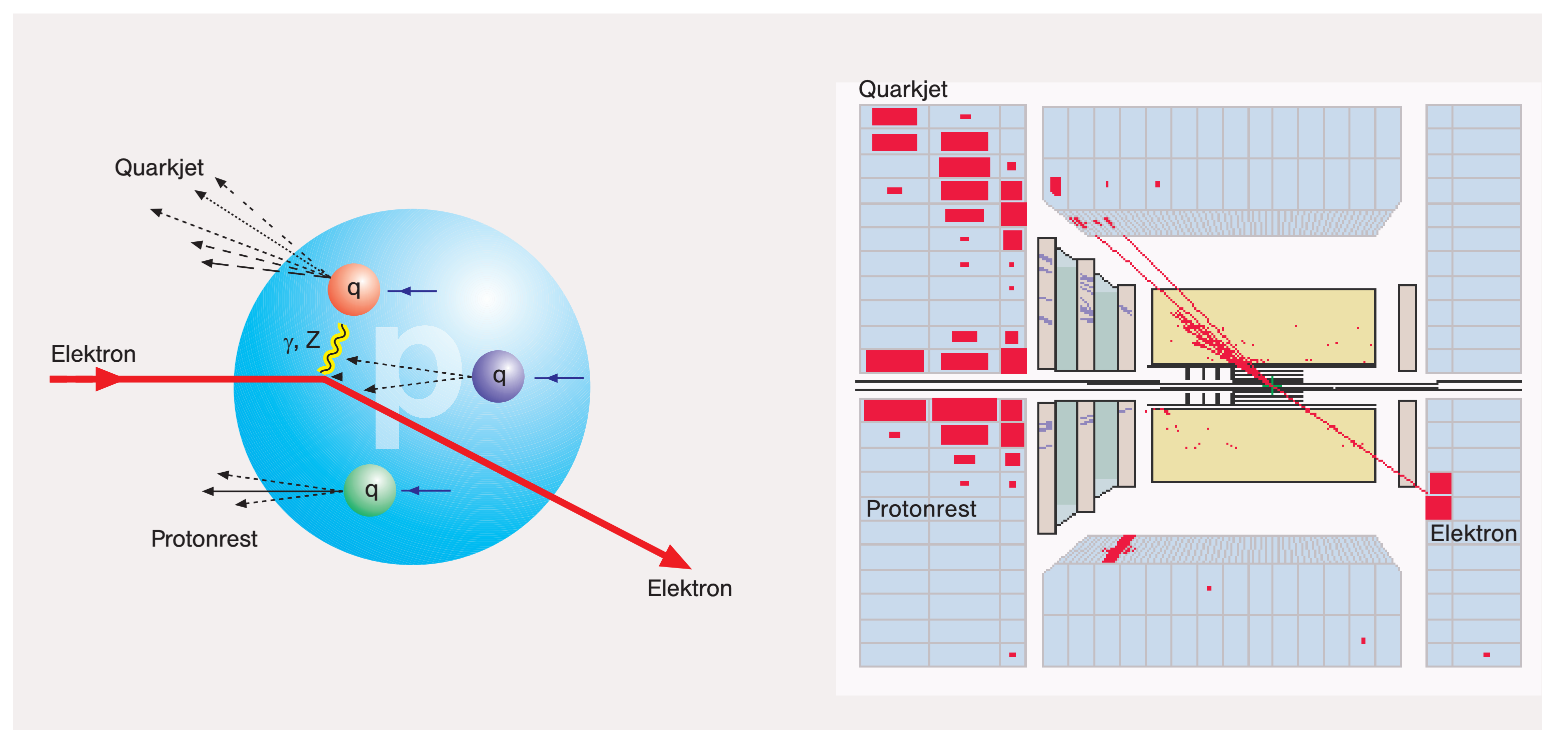
DIS events and kinematics

- Characterise events:
  - Q^2 $Q^2 = s\,x\,y$
  - Bjorken x, $(0 < x < 1)$
  - Inelasticity y, $(0 < y < 1)$

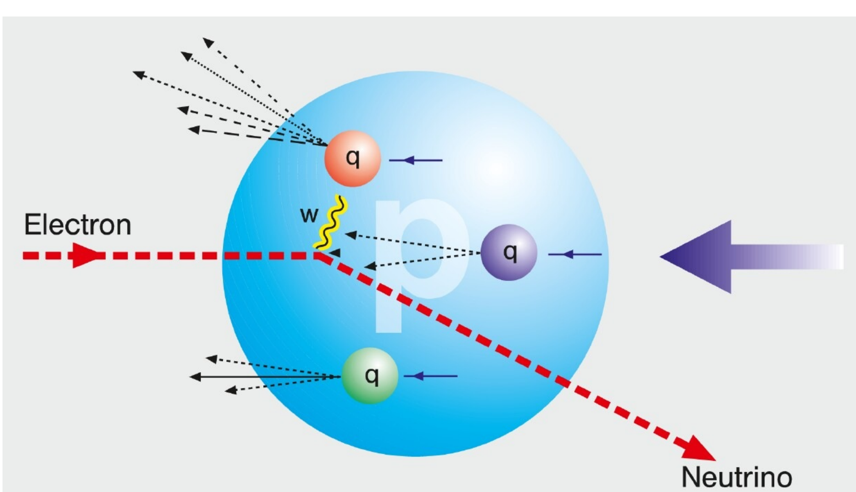
DIS ⇒ scattered e in detector

$Q^2 \gtrsim 1\ \mathrm{GeV}^2$

NC - scattered e



CC - scattered ν



Basic equations

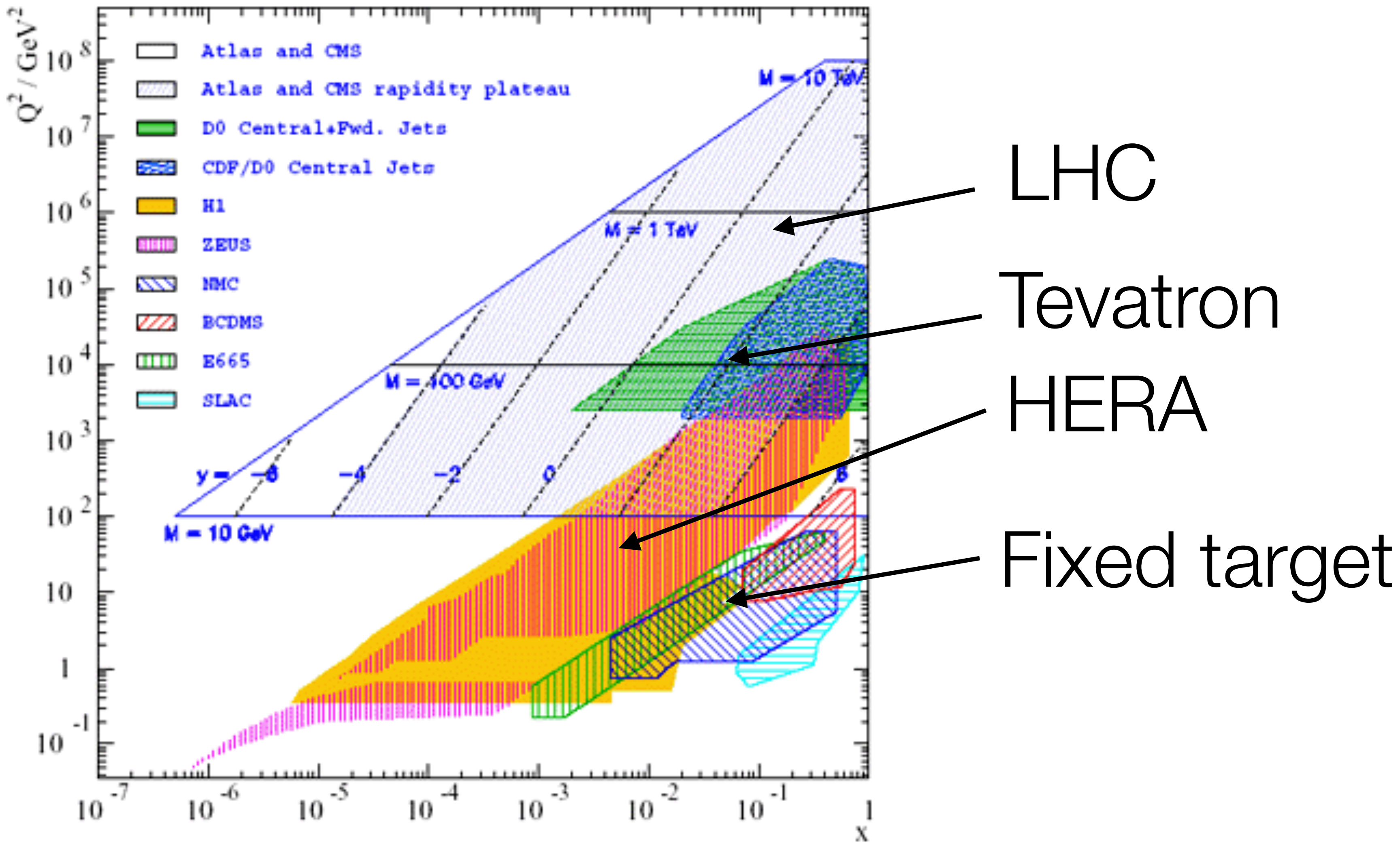
- $e^{\pm}p$ cross-section and structure functions $\quad Y_{\pm} = 1 \pm (1-y)^2$

$$\frac{\mathrm{d}^2\sigma(e^{\pm}p)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) \mp Y_- xF_3(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

- (Unpolarised) reduced cross-sections often used:

$$\sigma_{\mathrm{r}}(\mathrm{or}\ \tilde{\sigma}) = \frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2}\cdot\frac{xQ^4}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)$$

Kinematic regions



Parameterise structure functions as a function of *x*

Use DGLAP equations to evolve from HERA to LHC

Evolution depends on order: LO, NLO, NNLO

F_L

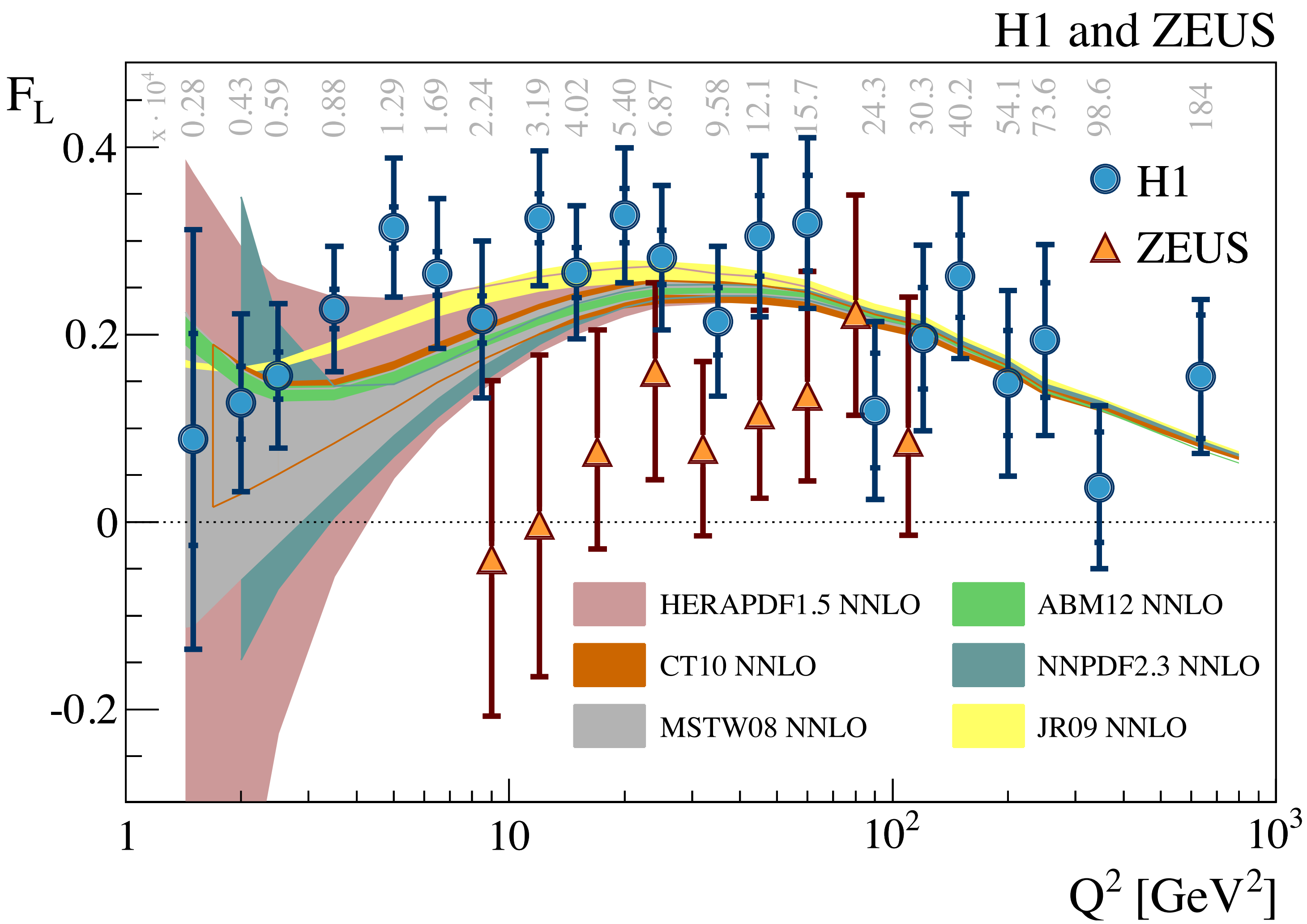
- F_L proportional to cross-section of long. polarised photons
    - 0 at lowest order!
- F_L term in cross-section multiplied by y^2
    - Go to high y
    - Make use of $Q^2 = s\,x\,y$
        - For given Q^2 and x, vary $s(y)$ to decouple F_2 and F_L
- HERA ran with E_p = 460 and 575 GeV in 2007 in order to vary s

$$\tilde{\sigma} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

F_L

- ZEUS: include high-precision HERA 1 data (with shifted vertex to improve low Q^2 measurement)

- H1: reanalyse and extend to lowest possible E'_e



Reasonable precision
~10% per point

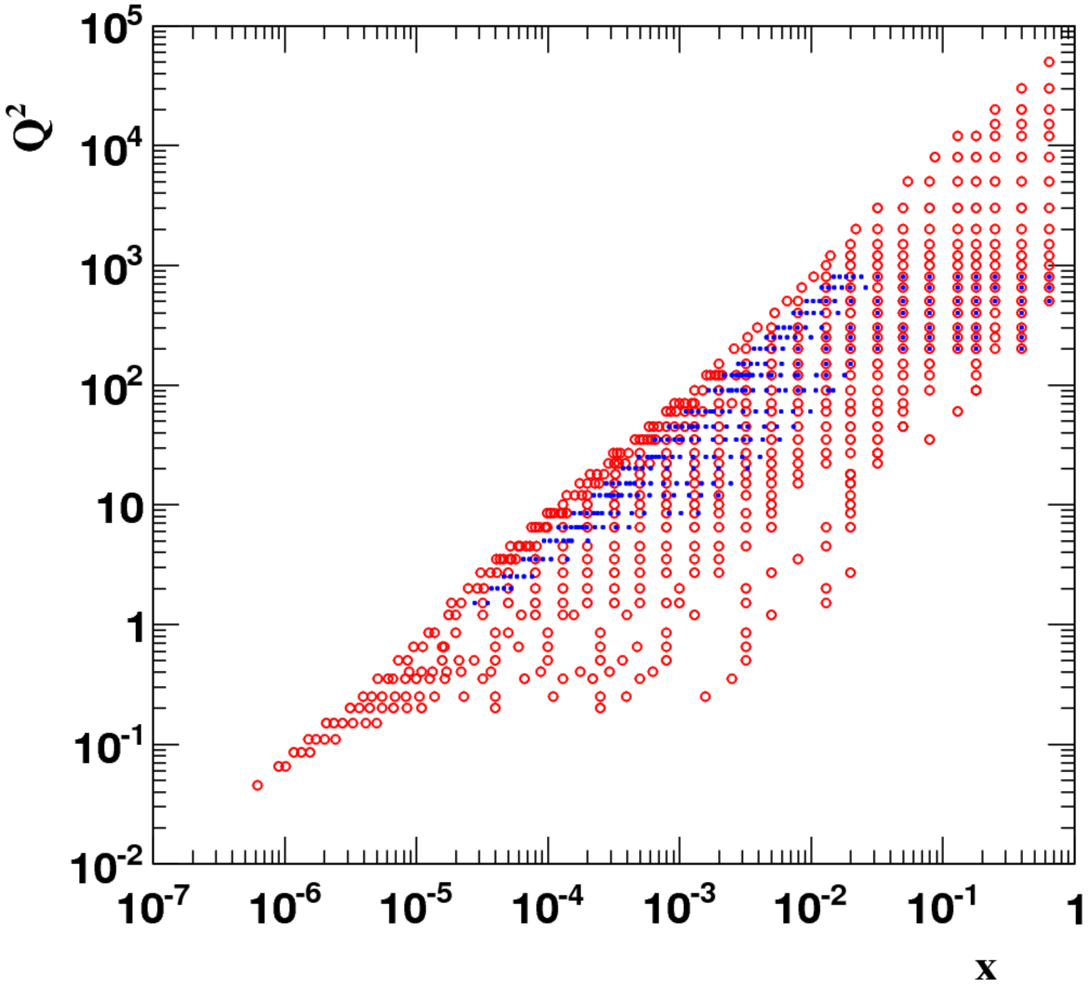
Limited int. lumi.:
11.8 pb^{-1} at $\sqrt{s}$ = 225 GeV
5.4 pb^{-1} at $\sqrt{s}$ = 252 GeV

DESY-13-211, EPJ. C 74 (2014) 2814

DESY-14-053, arXiv:1404.6376

Combined cross-sections

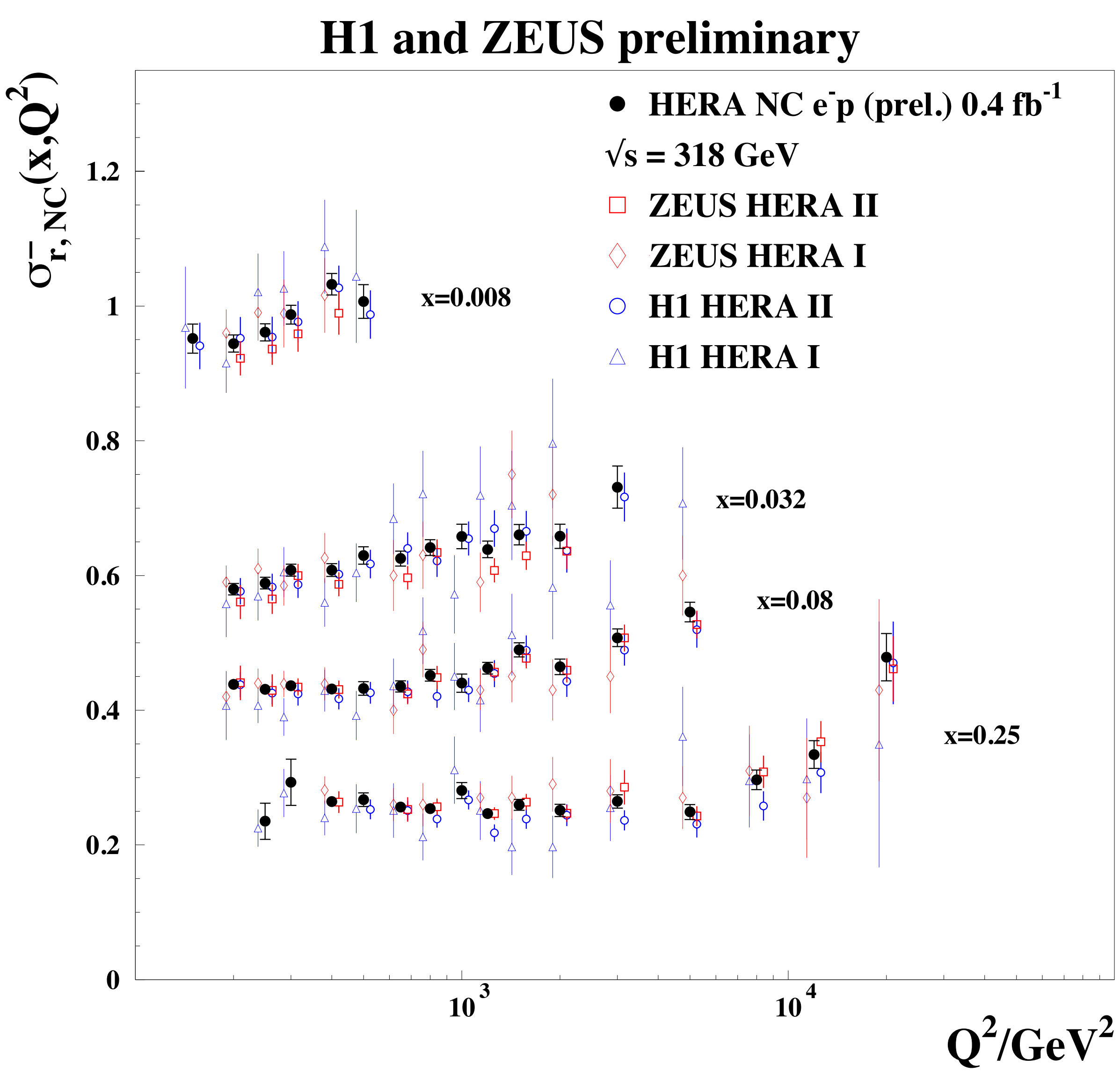
- Complete set of H1 and ZEUS NC and CC measurements
  - HERA 1 and HERA 2 data combined
  - Also includes latest F_L and high x measurements
  - 1307 data points!
- Correlated syst. uncertainties properly taken into account

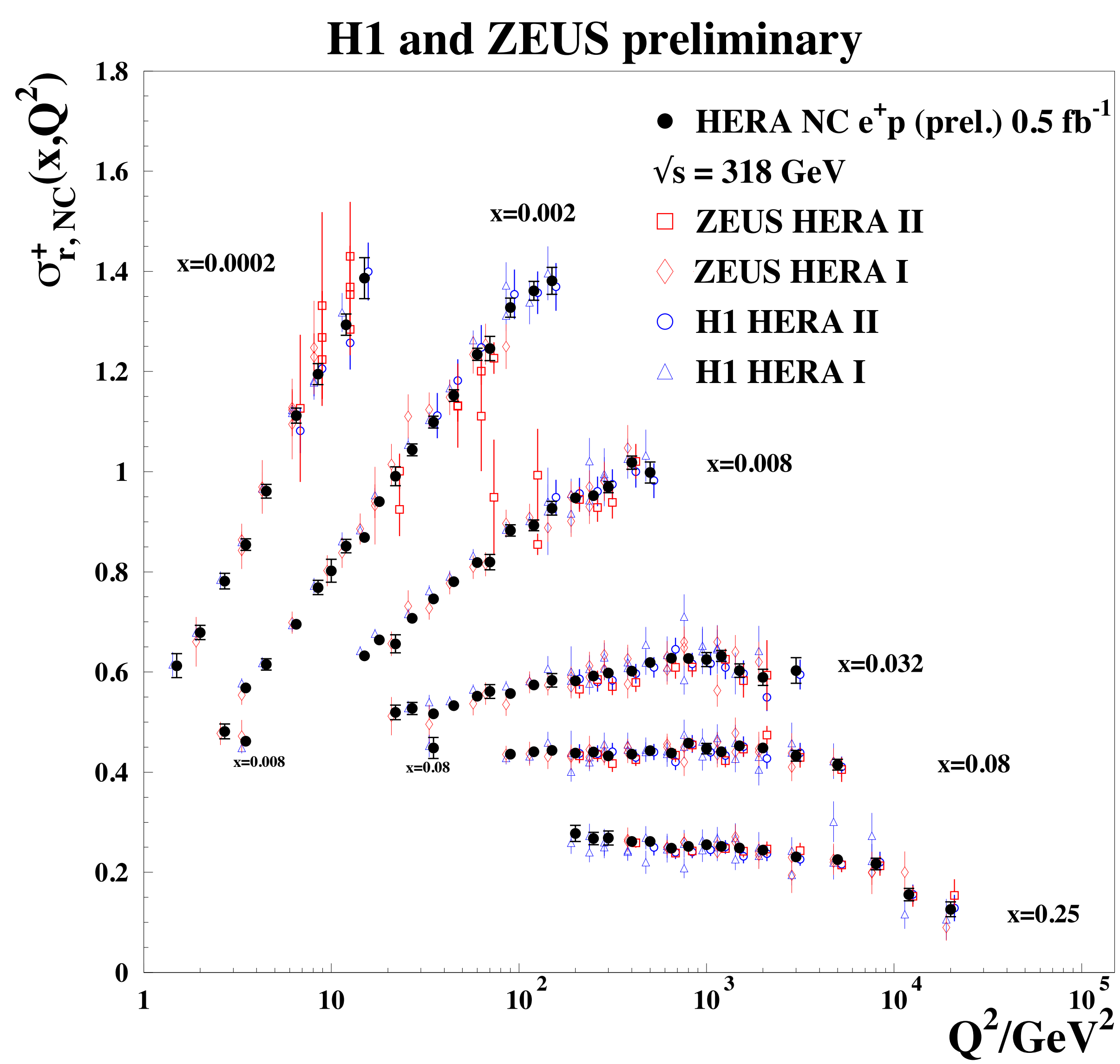


Good χ^2: 1685/1620 d.o.f.

H1prelim-14-041, ZEUS-prel-14-005

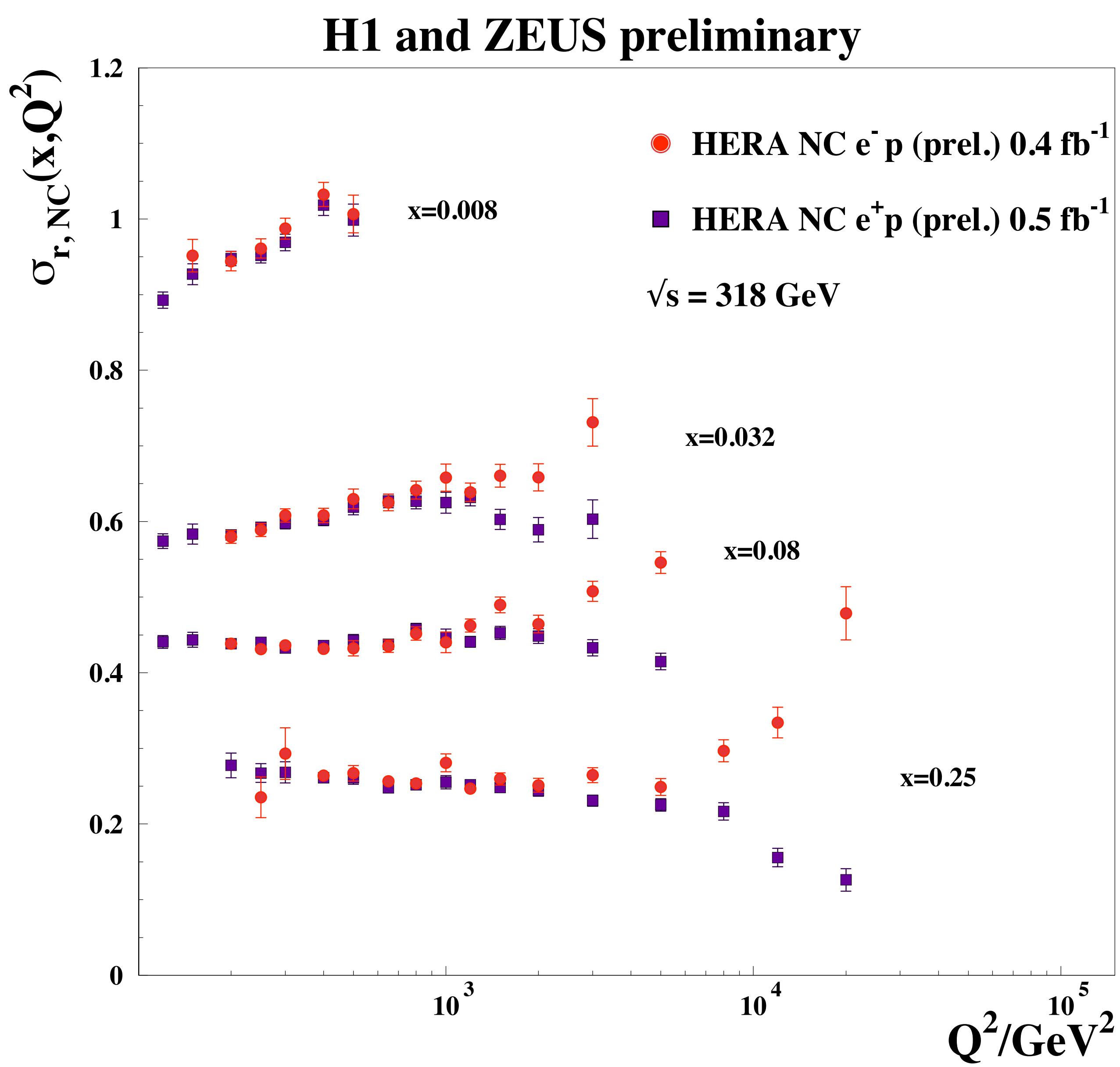
Combined cross-sections

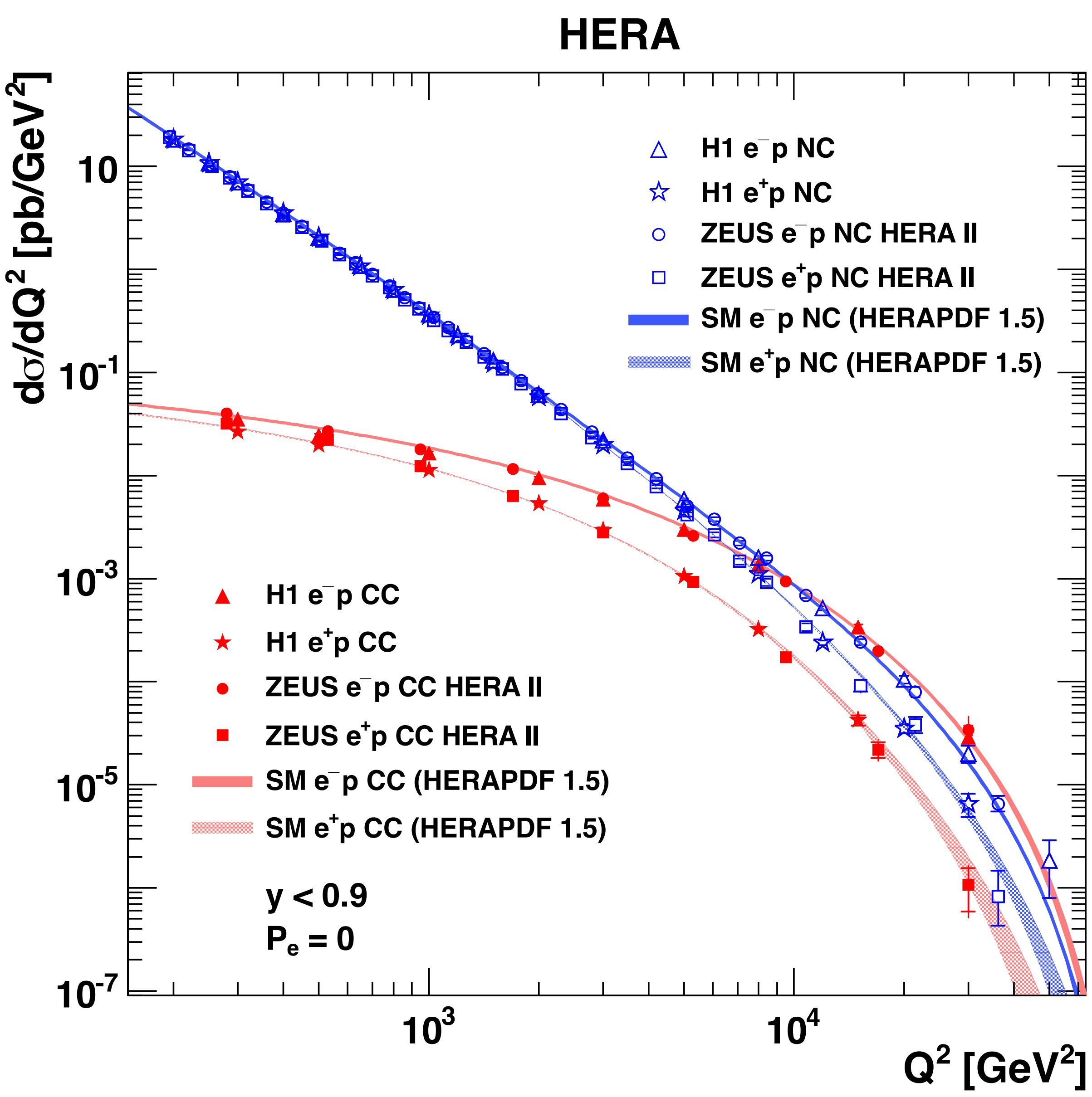




H1prelim-14-041, ZEUS-prel-14-005

Electroweak effects





H1prelim-14-041, ZEUS-prel-14-005

HERAPDF 2.0

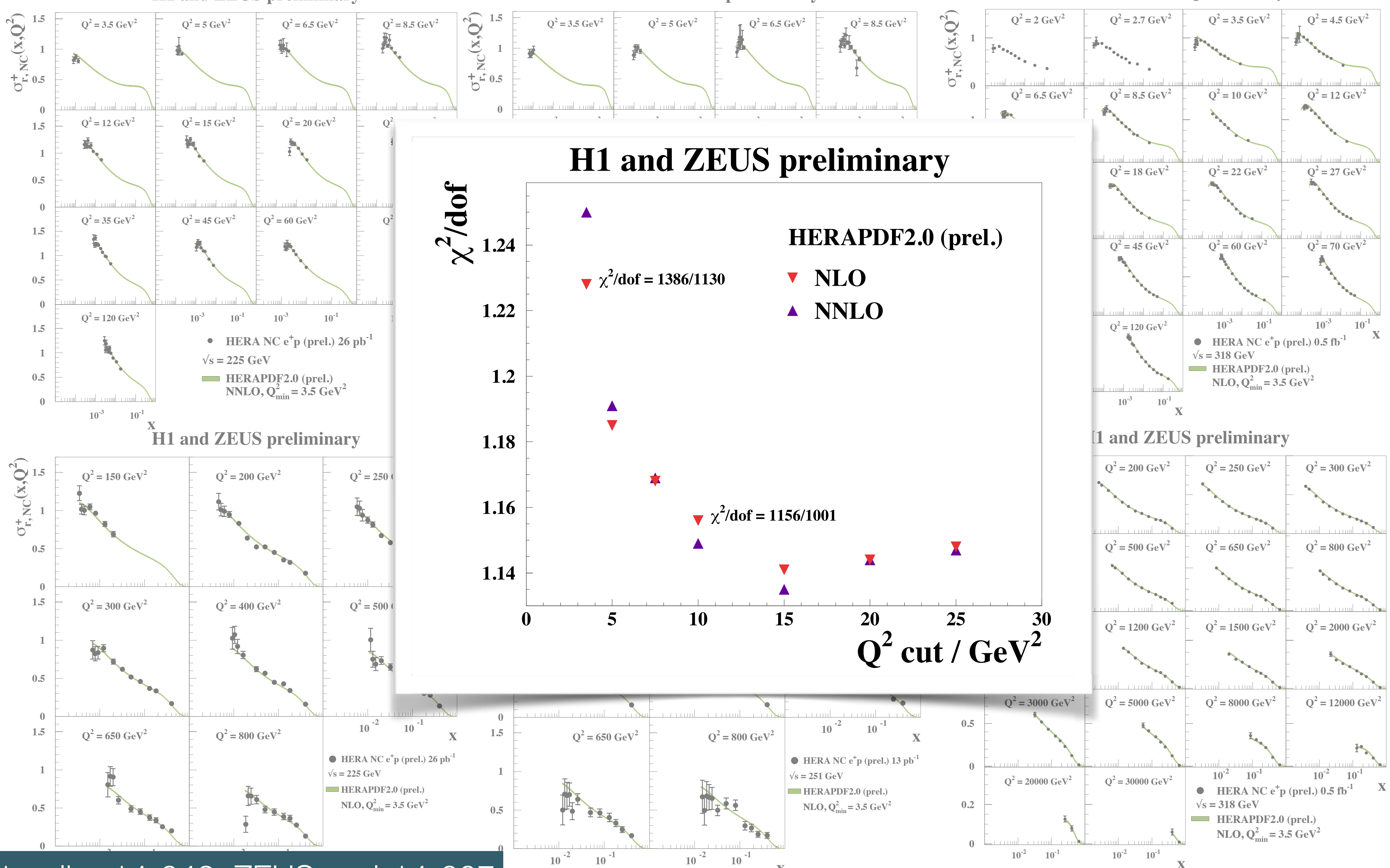
- Use ZEUS + H1 combined cross-sections (only) to extract PDFs:
  - Low Q^2 data constrain sea and gluon
  - High Q^2 NC and CC data constrain valence quarks
- Main tool used is HERAFitter (see next talk)
- Up-to-date theory treatment (especially of heavy flavour) included
- NLO + NNLO PDFs determined

HERAPDF 2.0 (NC data)

√s = 225 GeV

√s = 251 GeV

√s = 318 GeV



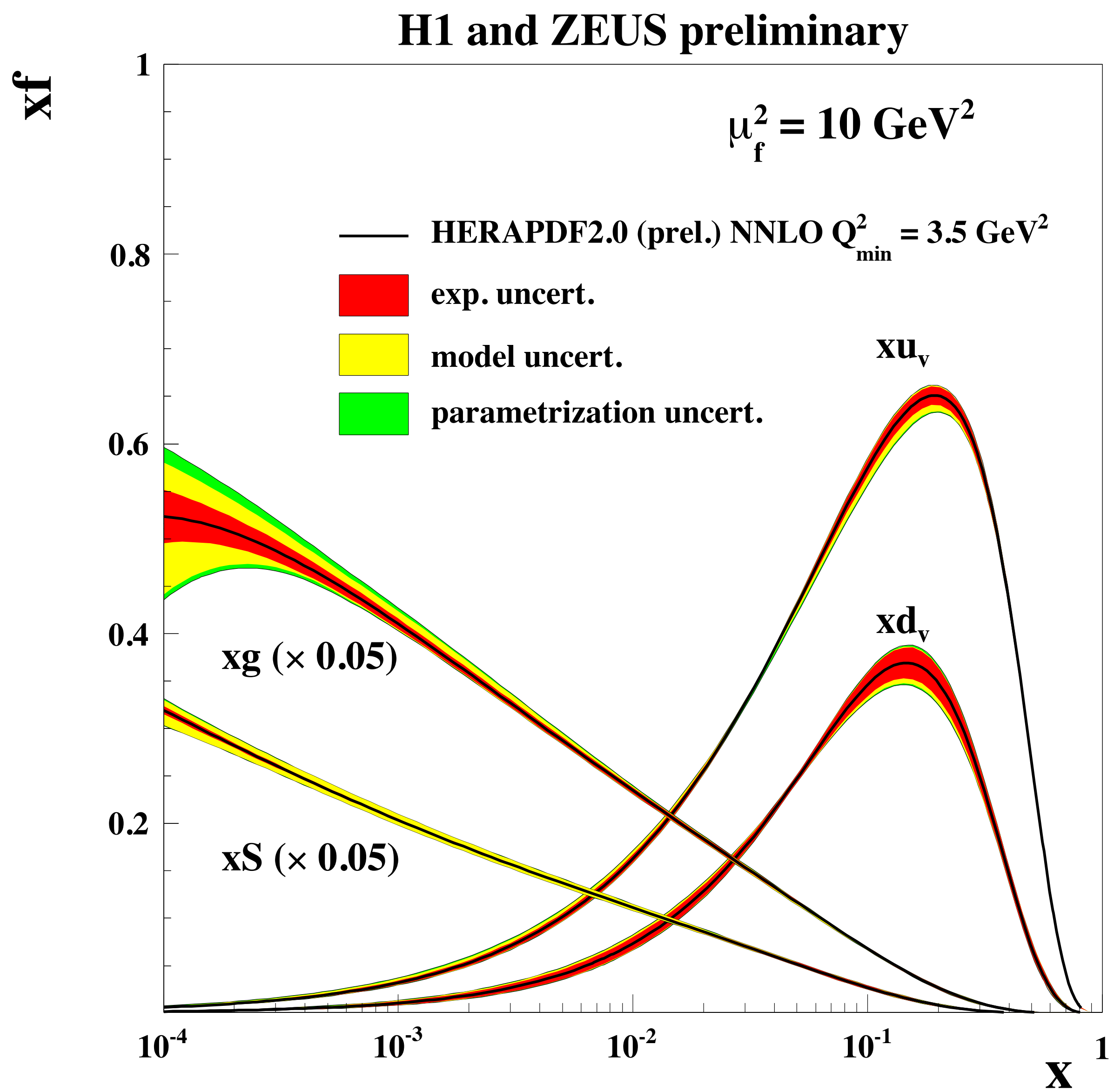
Low Q^2

High Q^2

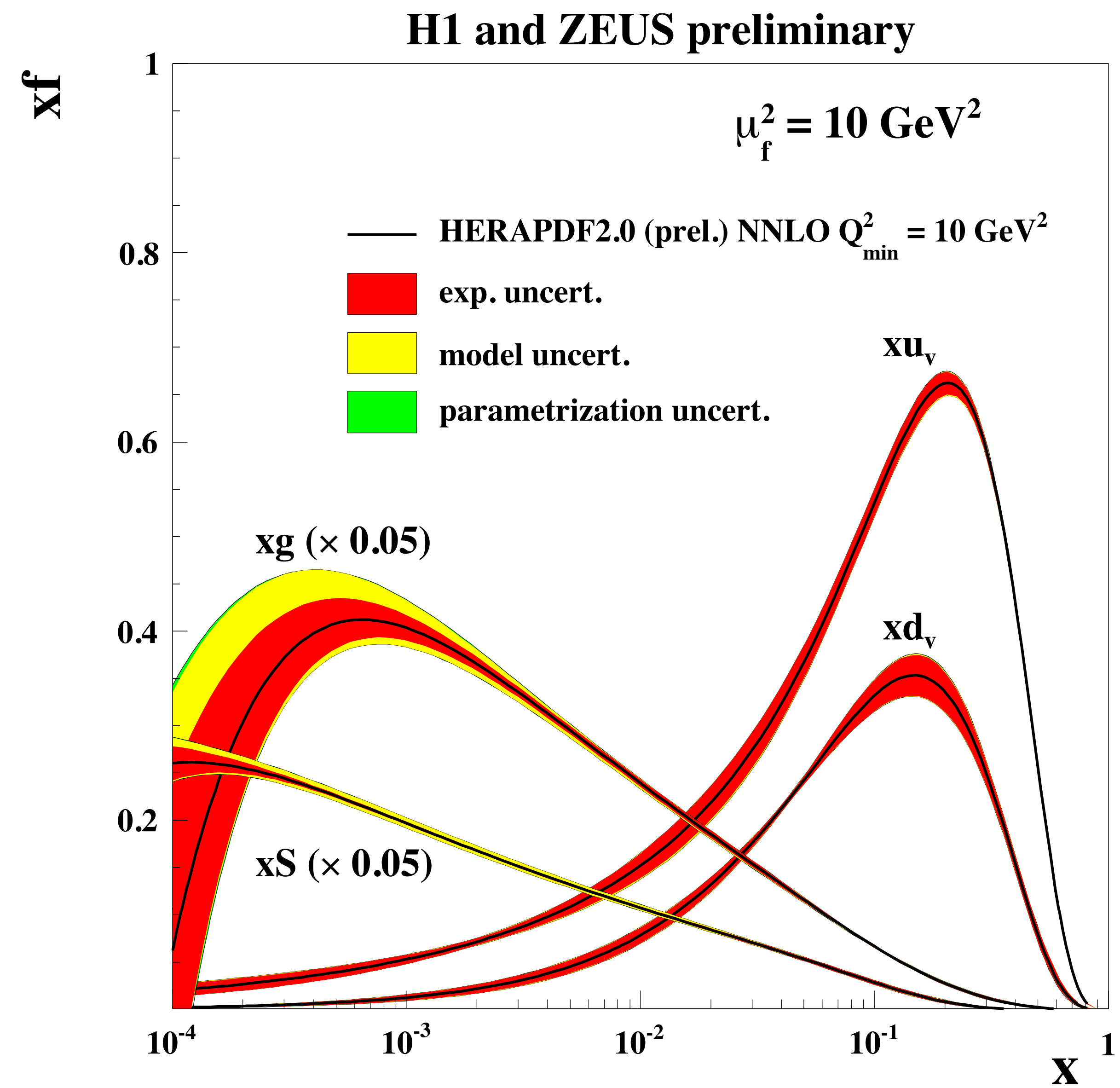
H1prelim-14-042, ZEUS-prel-14-007

HERAPDF 2.0 NNLO (2 of many plots!)

Q^2_{min} = 3.5 GeV^2



Q^2_{min} = 10 GeV^2



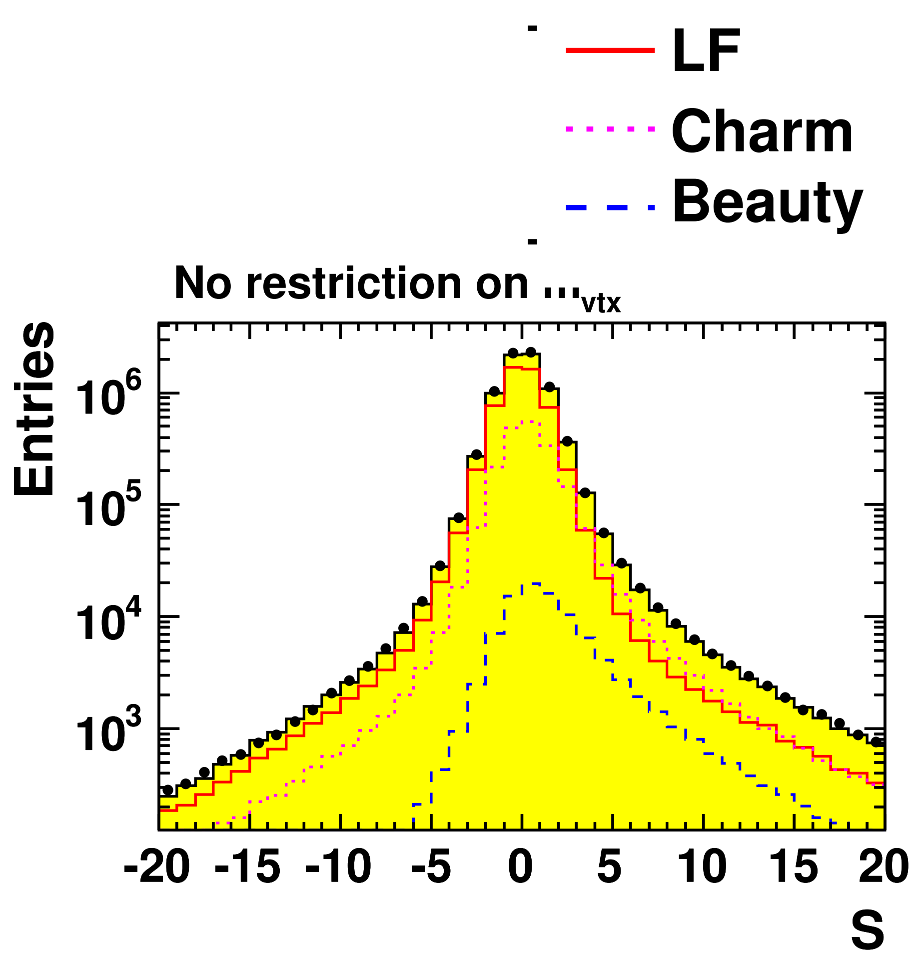
H1prelim-14-042, ZEUS-prel-14-007

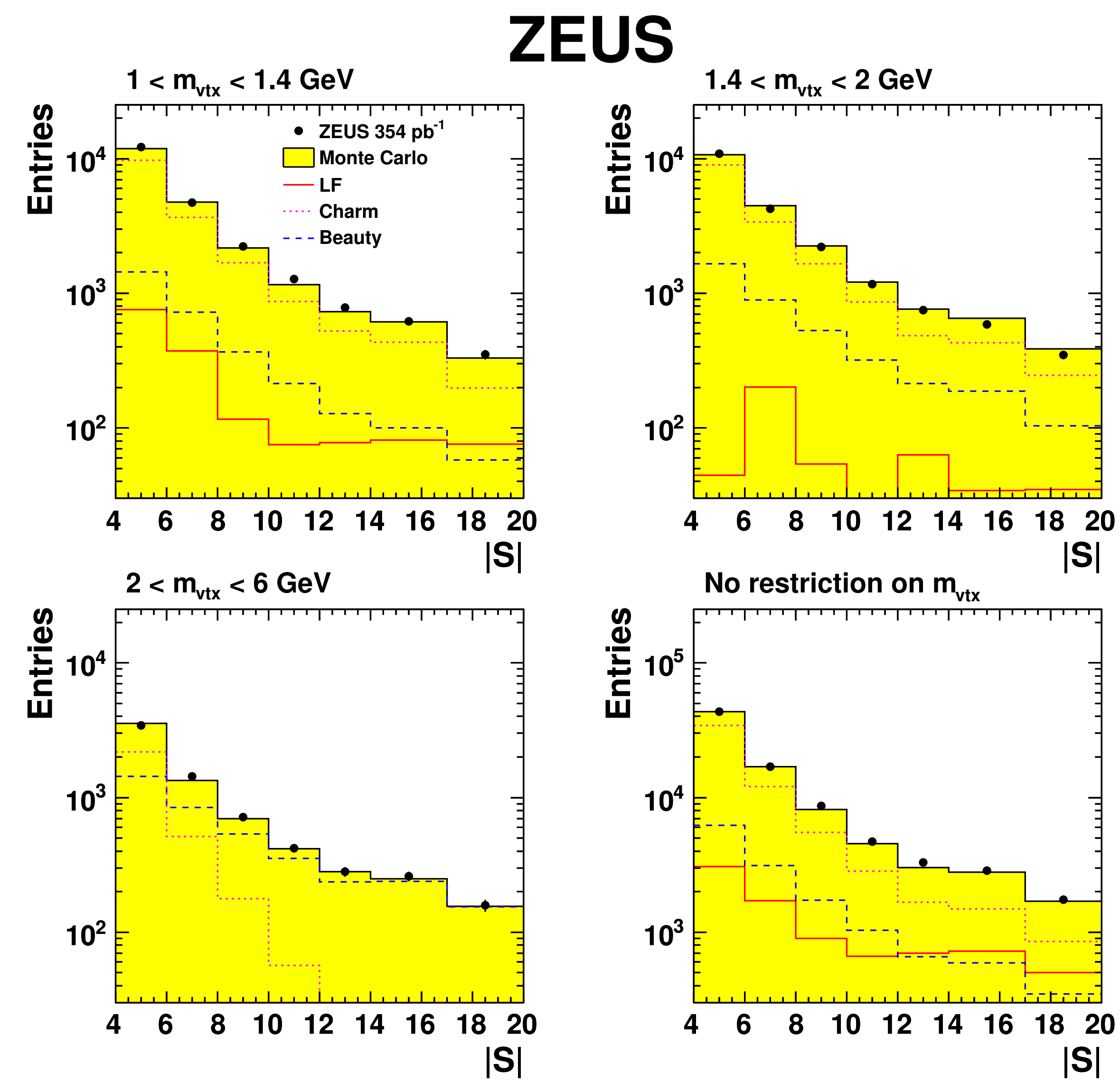
HERAPDF 2.0

- Preliminary version released (NLO + NNLO); LO to come
- Still studying:
  - Start from 3.5 or 10 GeV^2 for default fit
  - Gluon parametrisation?
  - Number of free parameters?
  - Heavy flavour scheme: RTOPT or ACOT

F_2^b and F_2^c

- ZEUS has finalised inclusive measurement of F_2^b and F_2^c
  - Uses secondary vertex decay-length significance and jet mass to separate *b*, *c*, and light flavour



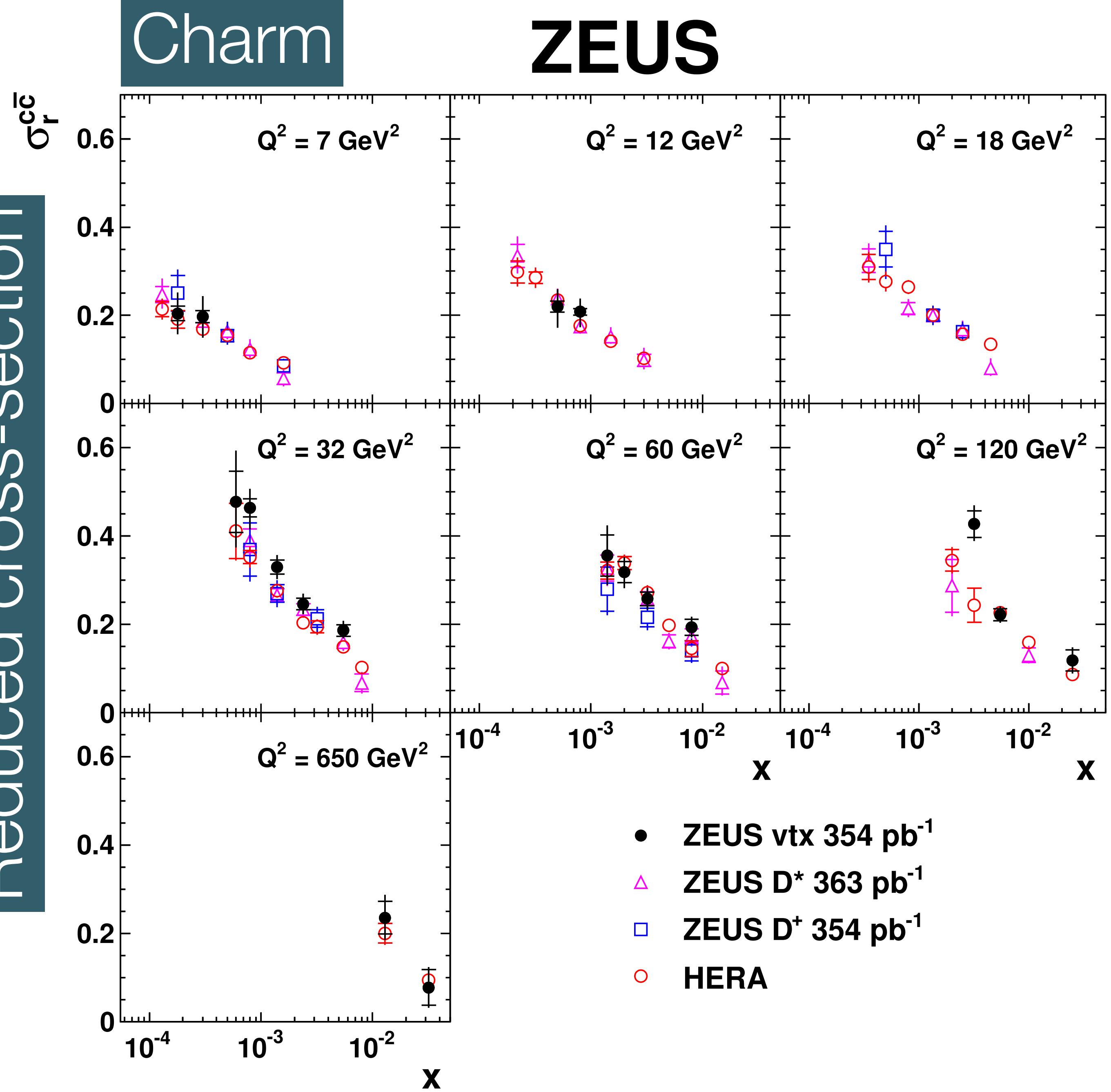


DESY-14-083, arXiv:1405.XXXX

Reduced cross-sections & F_2^b / F_2^c

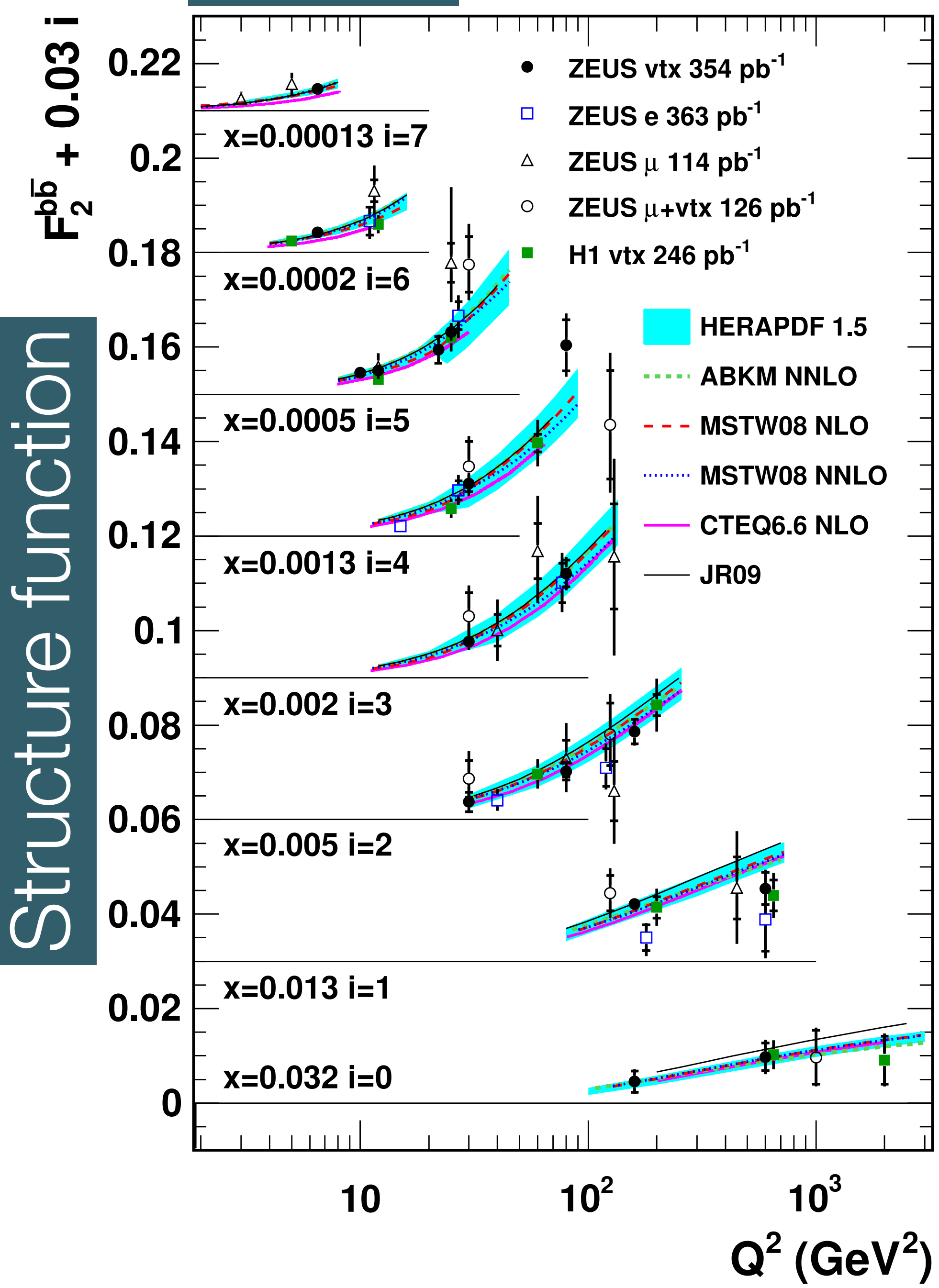
Charm

Reduced cross-section



Beauty

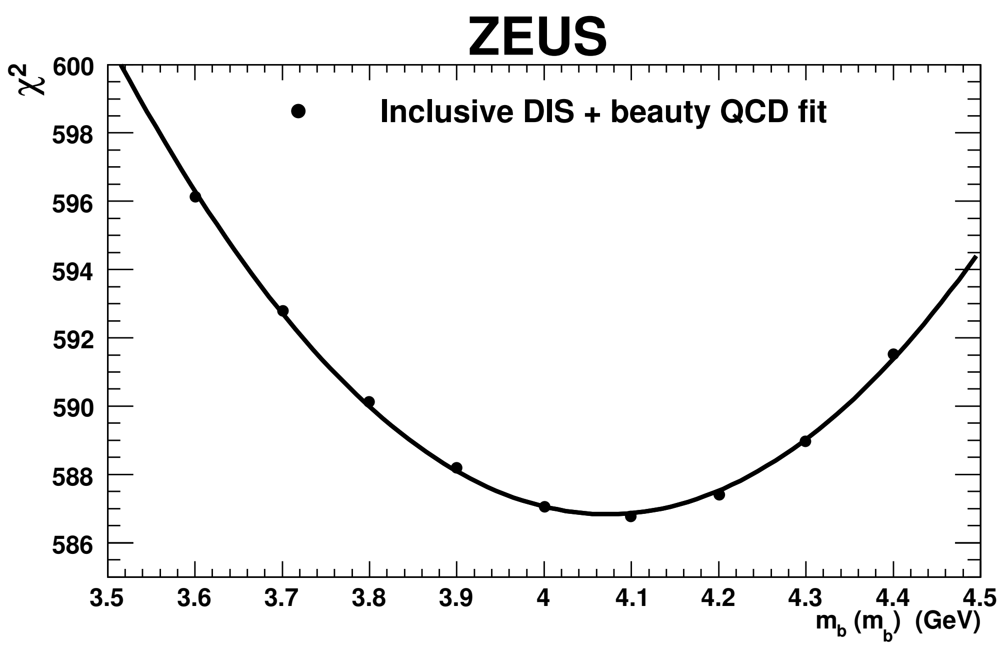
Structure function

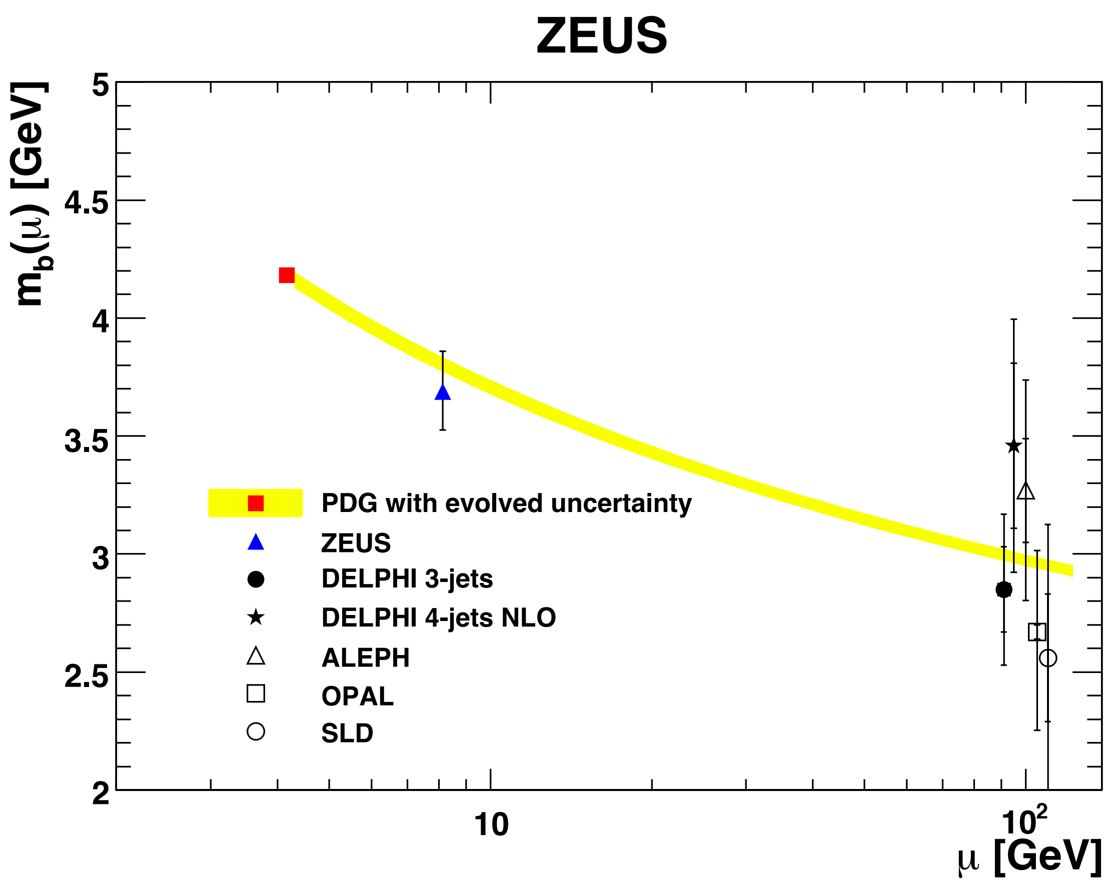


DESY-14-083, arXiv:1405.XXXX

Beauty-quark mass

- Use σ_r^b and HERA 1 cross-sections to extract m_b
- Similar method already used for m_c





$$m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})^{+0.01}_{-0.07}\,(\text{mod.})^{+0.05}_{-0.00}\,(\text{param.})\,^{+0.08}_{-0.05}\,(\text{theo.})\,\text{GeV}$$

DESY-14-083, arXiv:1405.083

Summary

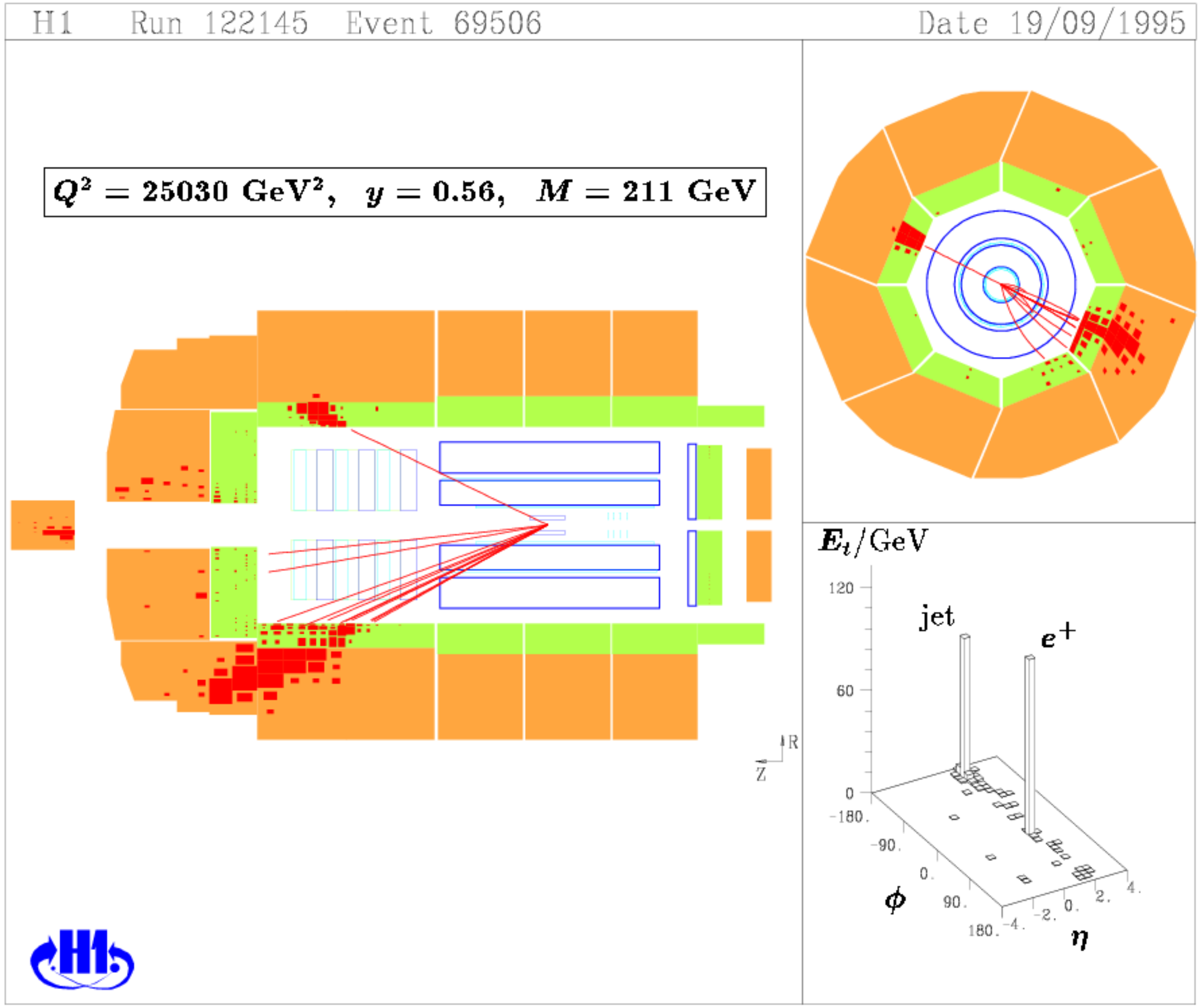
- ZEUS and H1 NC cross-sections combined
  - Much improved precision!
  - Updated measurements of F_L and cross-sections at high x
- HERAPDF 2.0 (prelim.) recently released
  - NLO and NNLO PDFs available; publication in preparation
- ZEUS inclusive F_2^b and F_2^c measurements finalised
  - Most precise F_2^b over wide kinematic range
  - Use σ_r^b data to extract $m_b(m_b)$ at hadron collider for 1st time

Backup

DIS events and kinematics

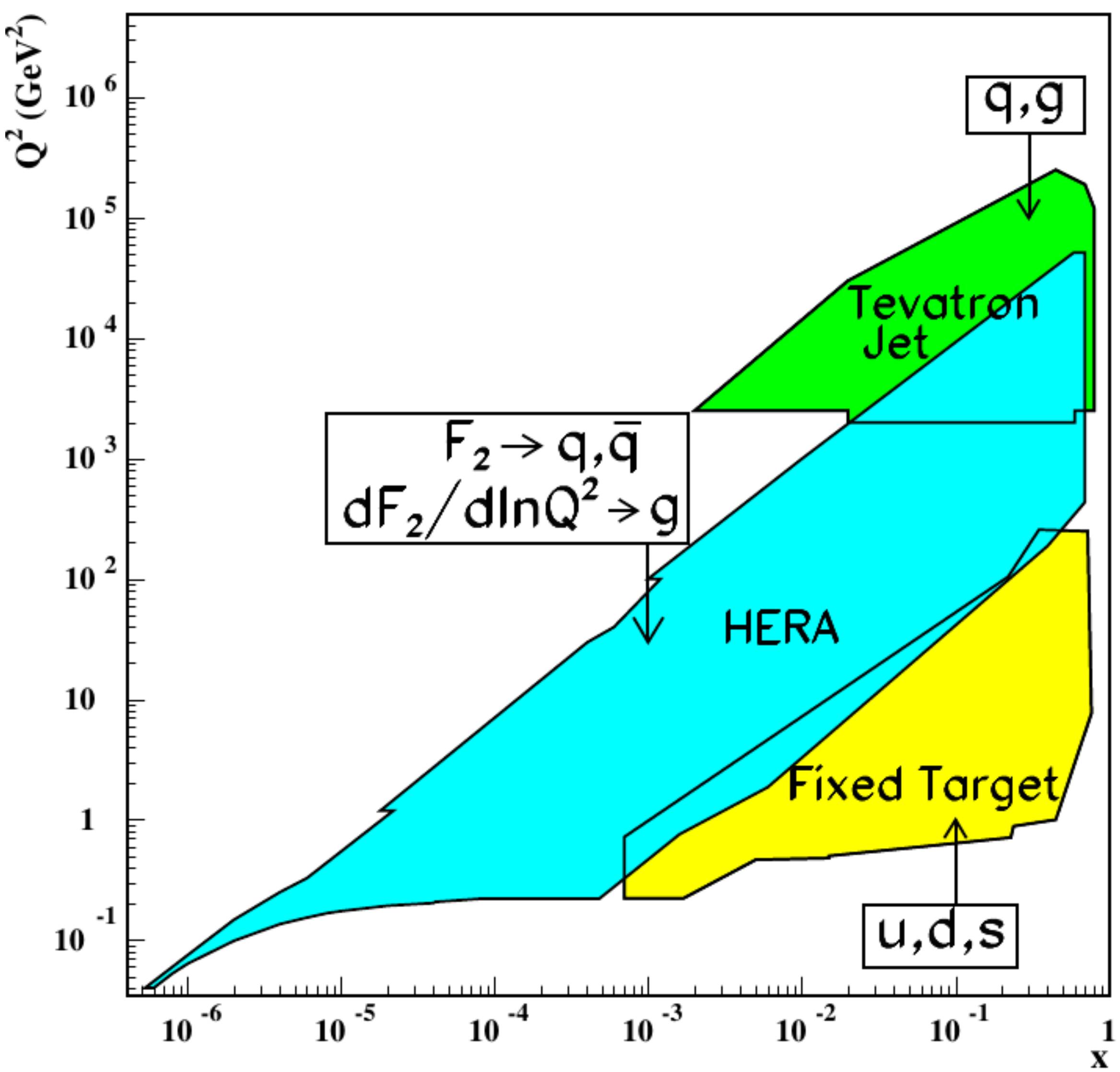
- Characterise events:
  - Q^2 $Q^2 = s\,x\,y$
  - Bjorken x, $(0 < x < 1)$
  - Inelasticity y, $(0 < y < 1)$

Very high Q2 event

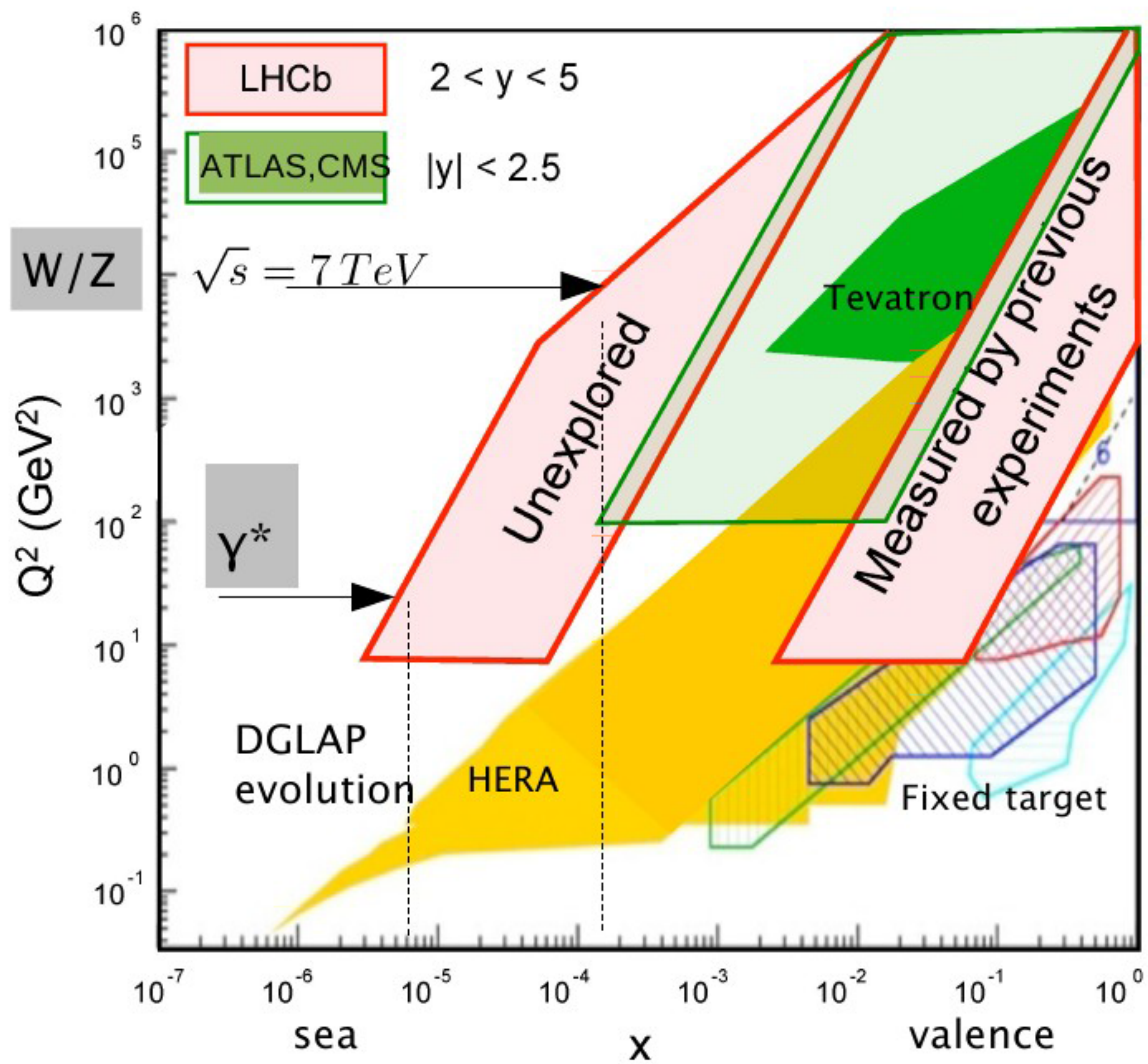


Kinematic regions

Before LHC



With LHC



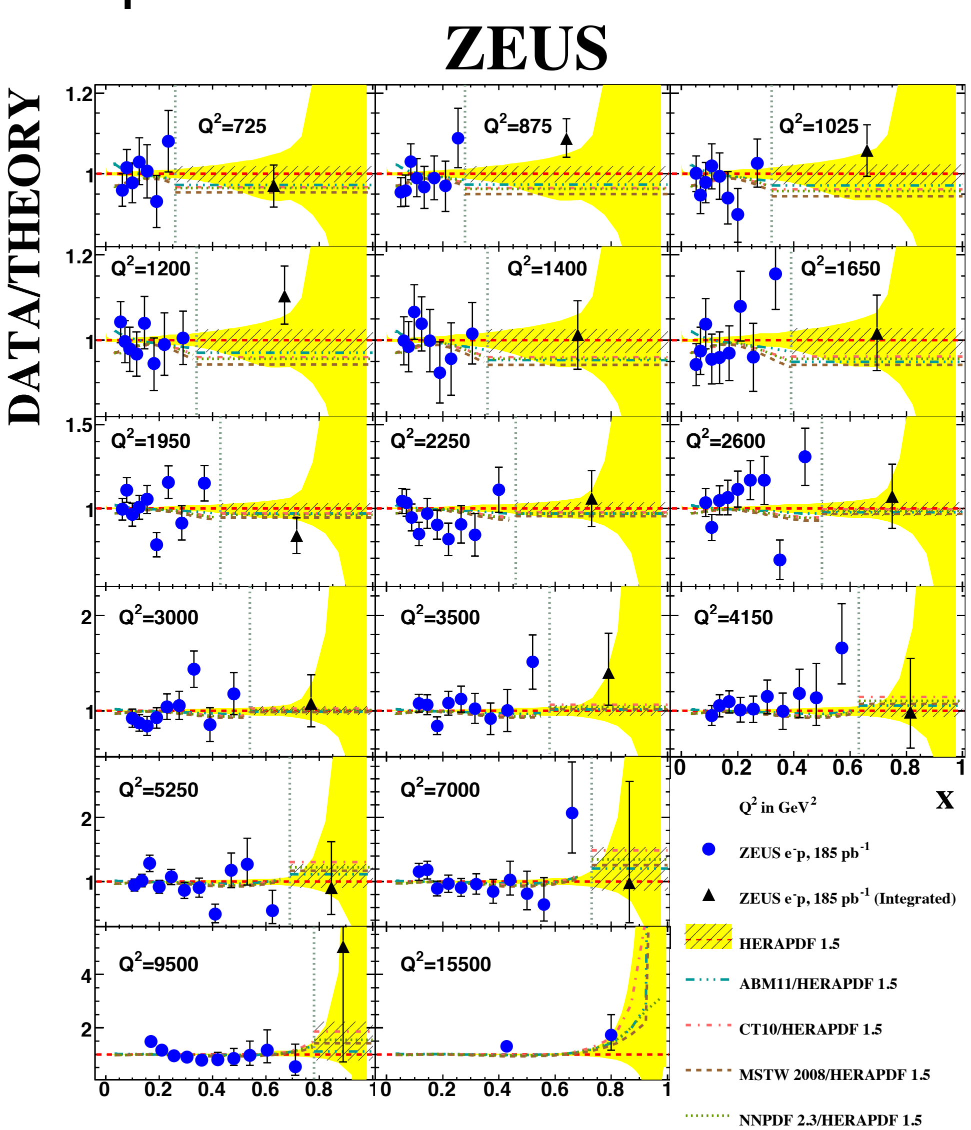
Use DGLAP equations to evolve from HERA to LHC

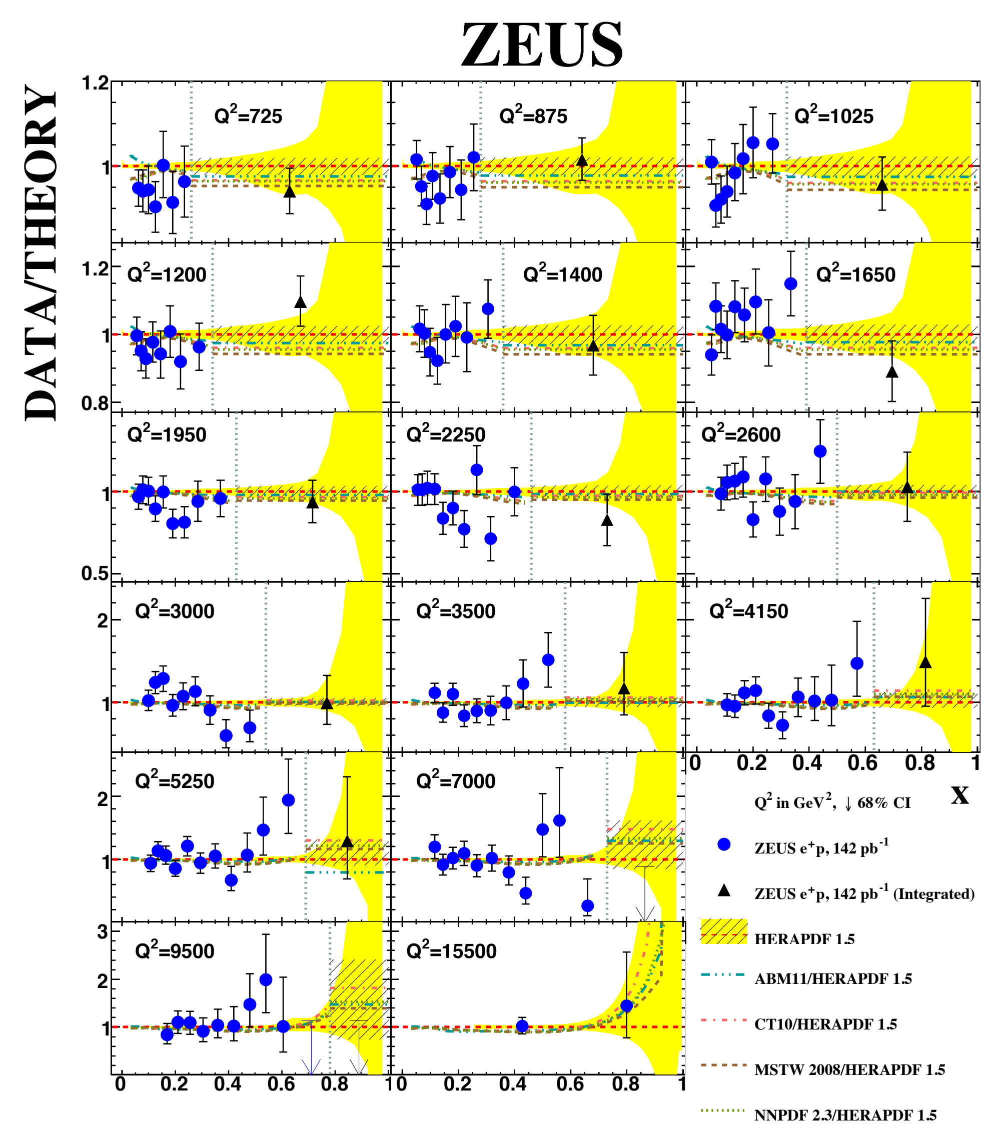
Typical NC event selection

- Electron or high E_T trigger
- Scattered electron with $E > 10$ GeV
- Cut on $\Sigma(E - p_Z) \approx 2E_e$ (calorimeter) for DIS events
- Cut on event vertex (tracker)

High-*x* cross-sections

- Extend analysis to $x \approx 1$ by using electron E_T or modified Jacquet-Blondel method to measure x





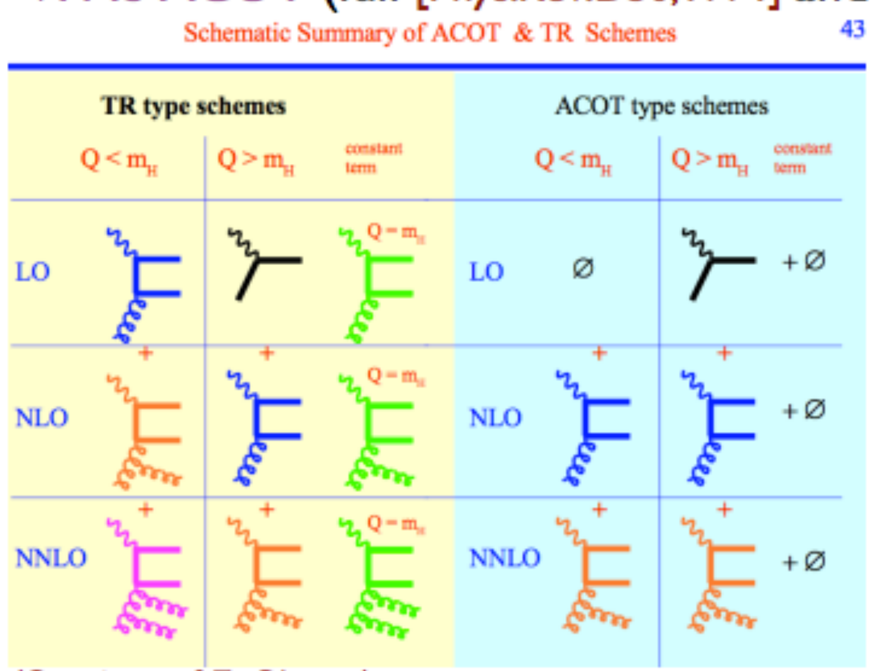
DESY-13-245, arXiv:1312.4438

GMVFNS schemes: RTOPT and ACOT etc.

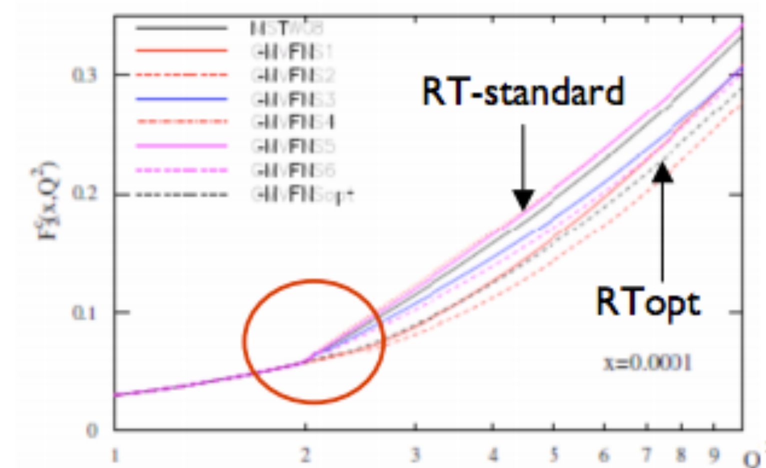
Various Heavy Flavour treatments at NLO

Low Q^2 region is sensitive to the treatment of charm quark production.

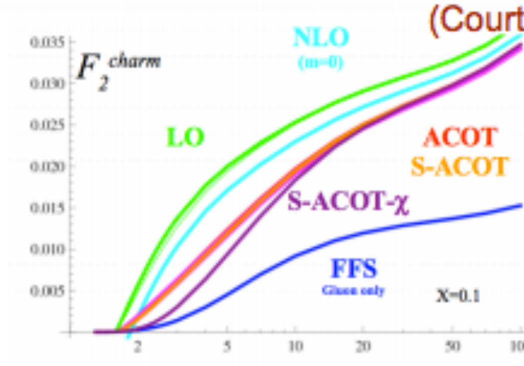
- Compare various schemes taking into account heavy quark production:
  - VFNS RT (standard [MSTW08] and optimal [R. Thorne's presentation])
  - VFNS ACOT (full [Phys.Rev.D50,1994] and χ [Phys.Rev.D62,2000])



(Courtesy of F. Olness)



(Courtesy of R. Thorne)



  - FFNS (from QCDNUM17v06 [M. Botje])
- We observe significant differences among these schemes → next slides.

HERAPDF PDF parametrisations

The resulting parametrisations are

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \quad (2)$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + D_{u_v}x + E_{u_v}x^2\right), \quad (3)$$

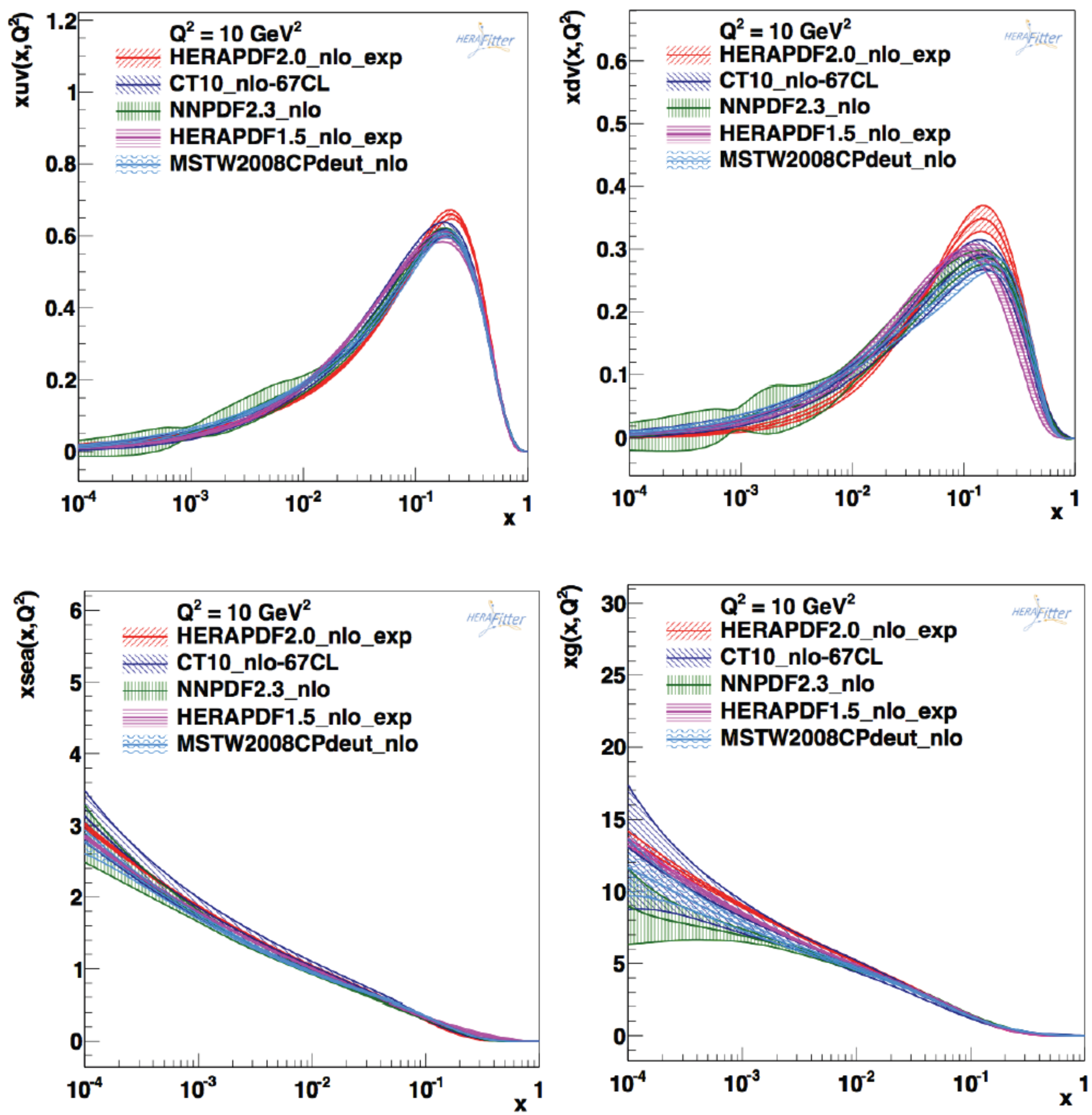
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \quad (4)$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}}x), \quad (5)$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}. \quad (6)$$

The normalisation parameters, A_g, A_{u_v}, A_{d_v}, are constrained by the quark number sum rules and momentum sum rule. The B parameters $B_{\bar{U}}$ and $B_{\bar{D}}$ are set equal, $B_{\bar{U}} = B_{\bar{D}}$, such that there is a single B parameter for the sea distributions. The strange quark distribution is expressed as x-independent fraction, f_s, of the d-type sea, $x\bar{s} = f_s x\bar{D}$ at Q_0^2. The central value $f_s = 0.4$ is chosen to be a compromise between the determination of a suppressed strange sea from neutrino-induced di-muon production [13,14] and a recent determination of an unsuppressed strange sea from the ATLAS collaboration [15]. The further constraint $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$, together with the requirement $B_{\bar{U}} = B_{\bar{D}}$, ensures that $x\bar{u} \to x\bar{d}$ as $x \to 0$.

Comparison of PDFs



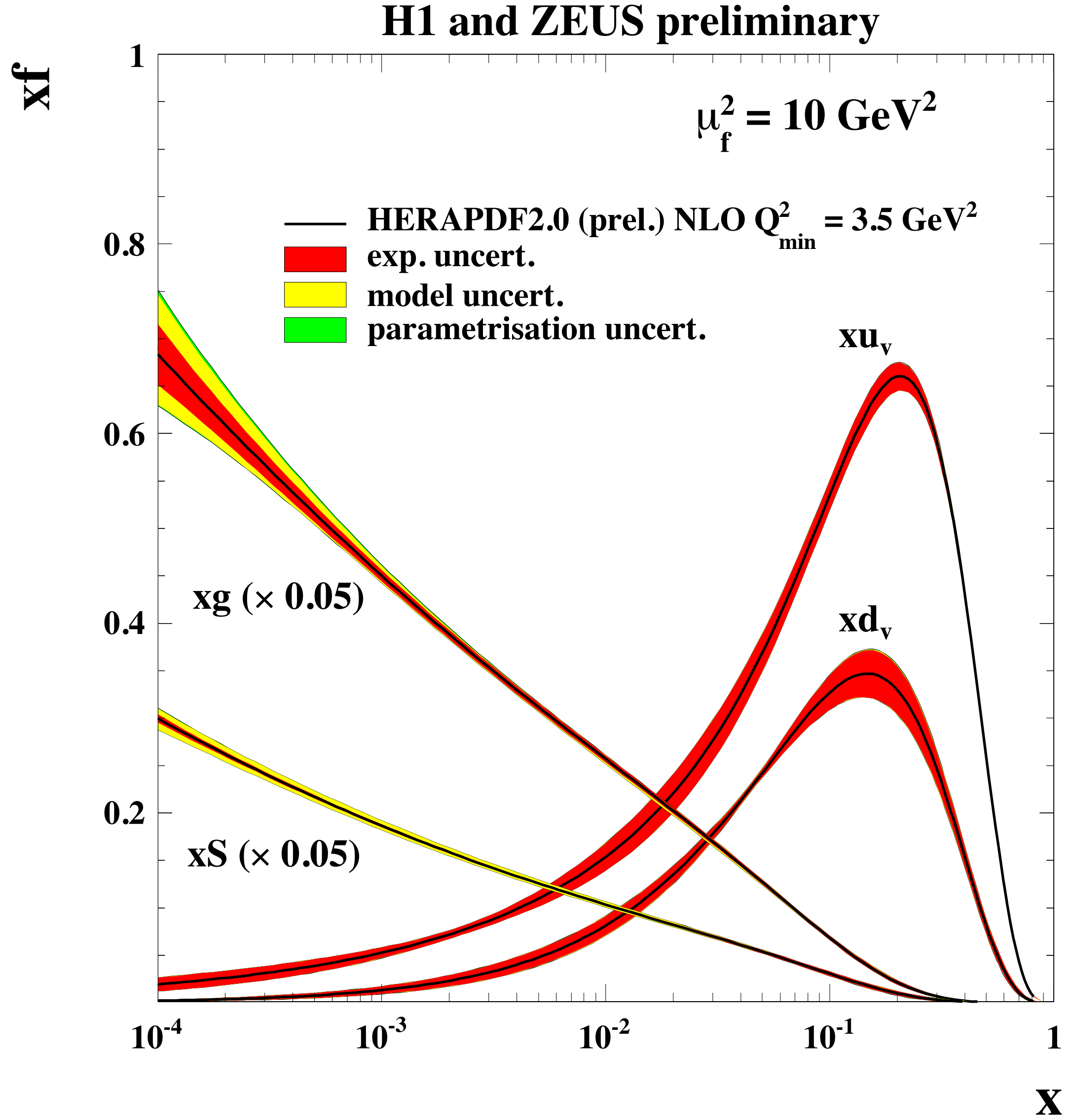
NOTE: HERAPDF sets are shown only with Exp uncert only!

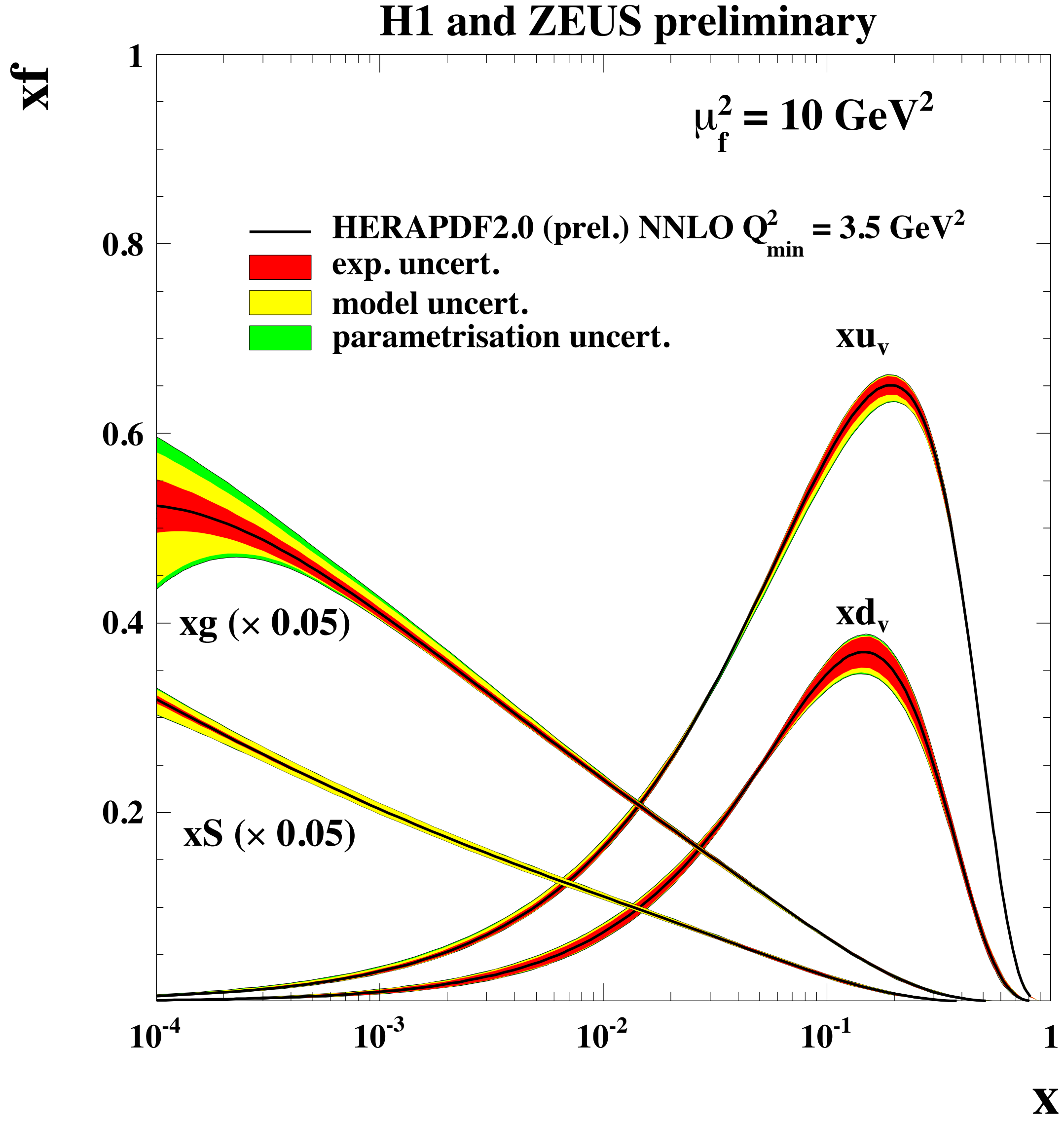
HERAPDF 2.0

Q^2_{min} = 3.5 GeV^2

NLO

NNLO



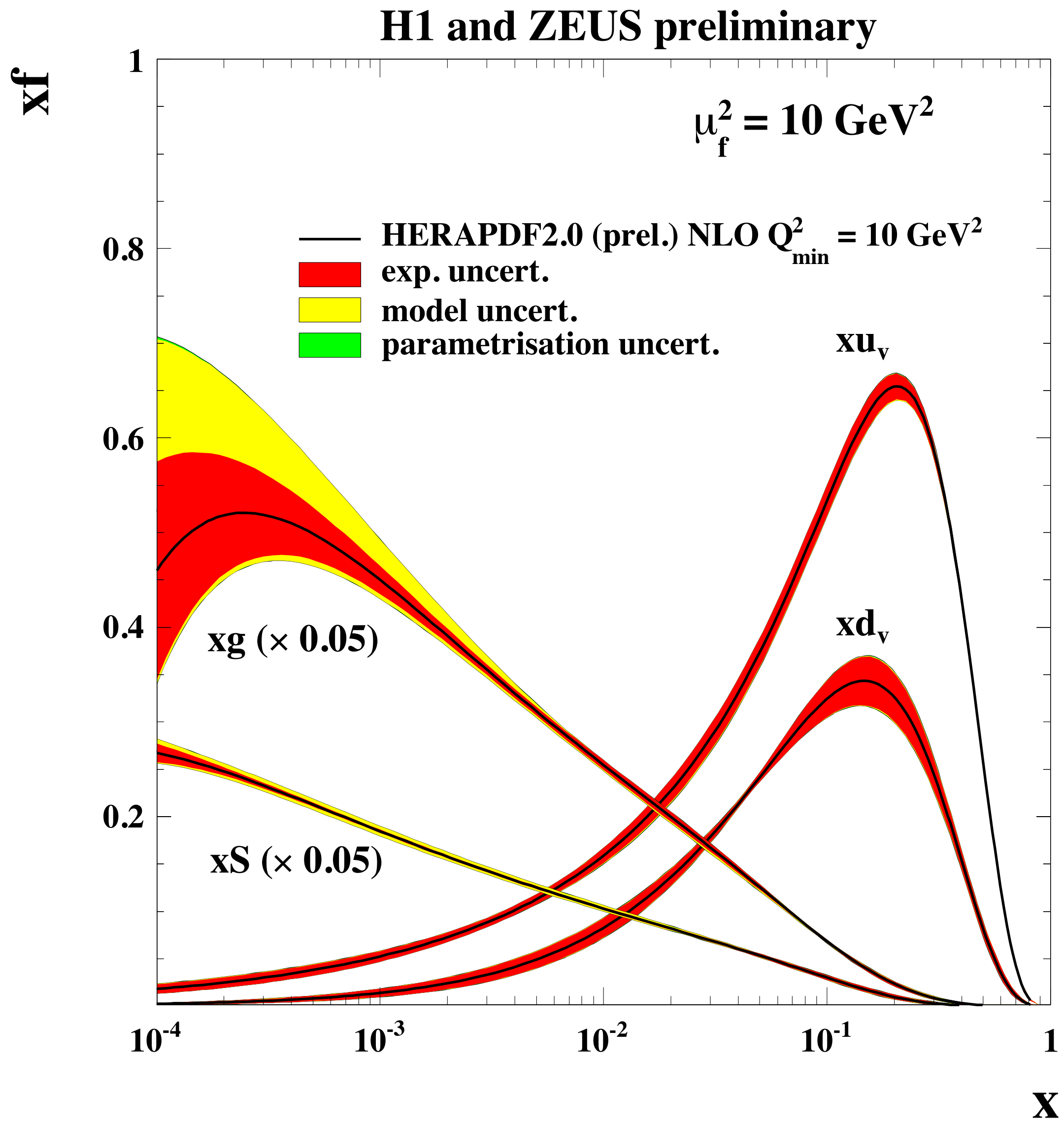


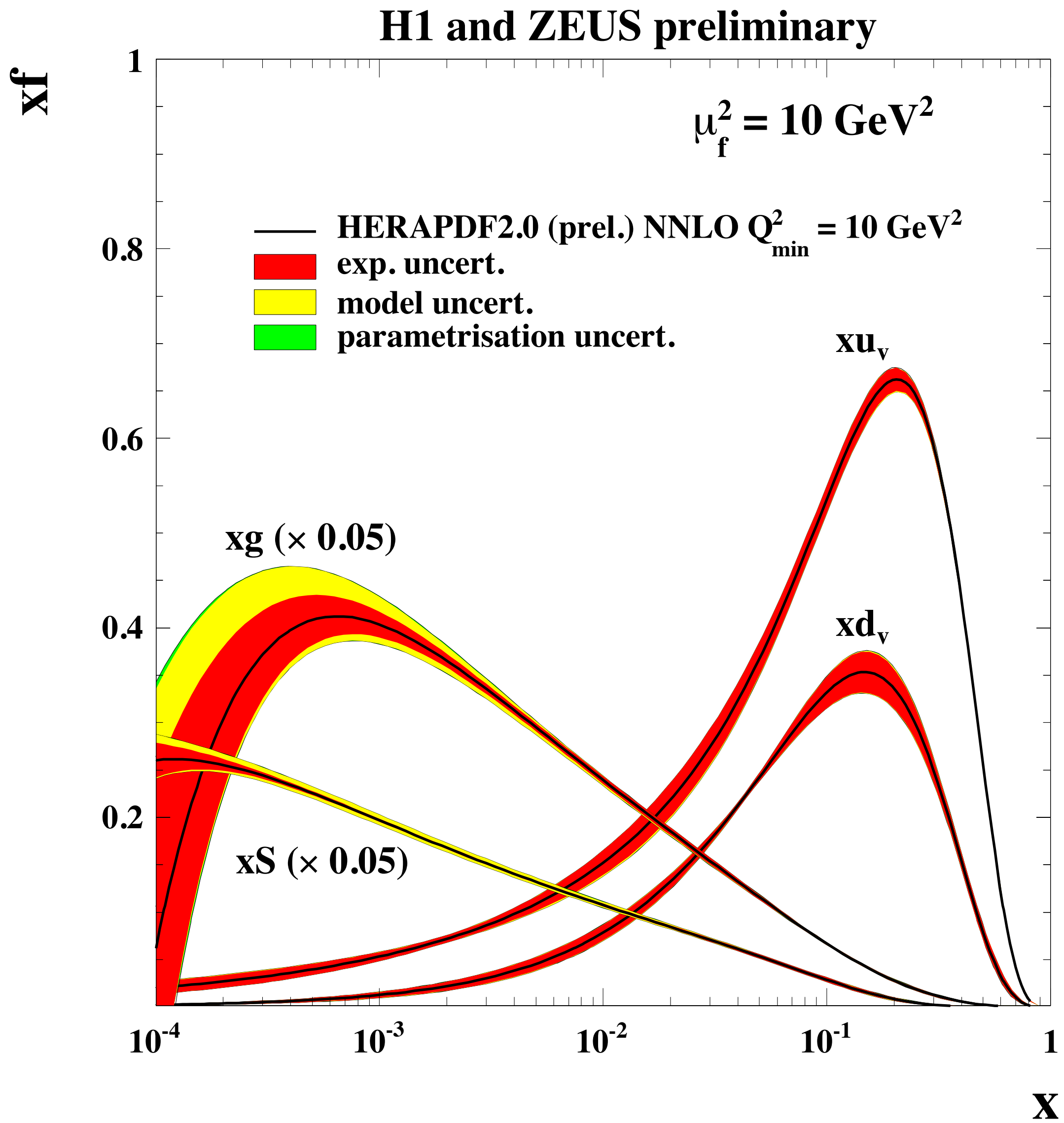
HERAPDF 2.0

Q^2_{min} = 10 GeV^2

NLO

NNLO



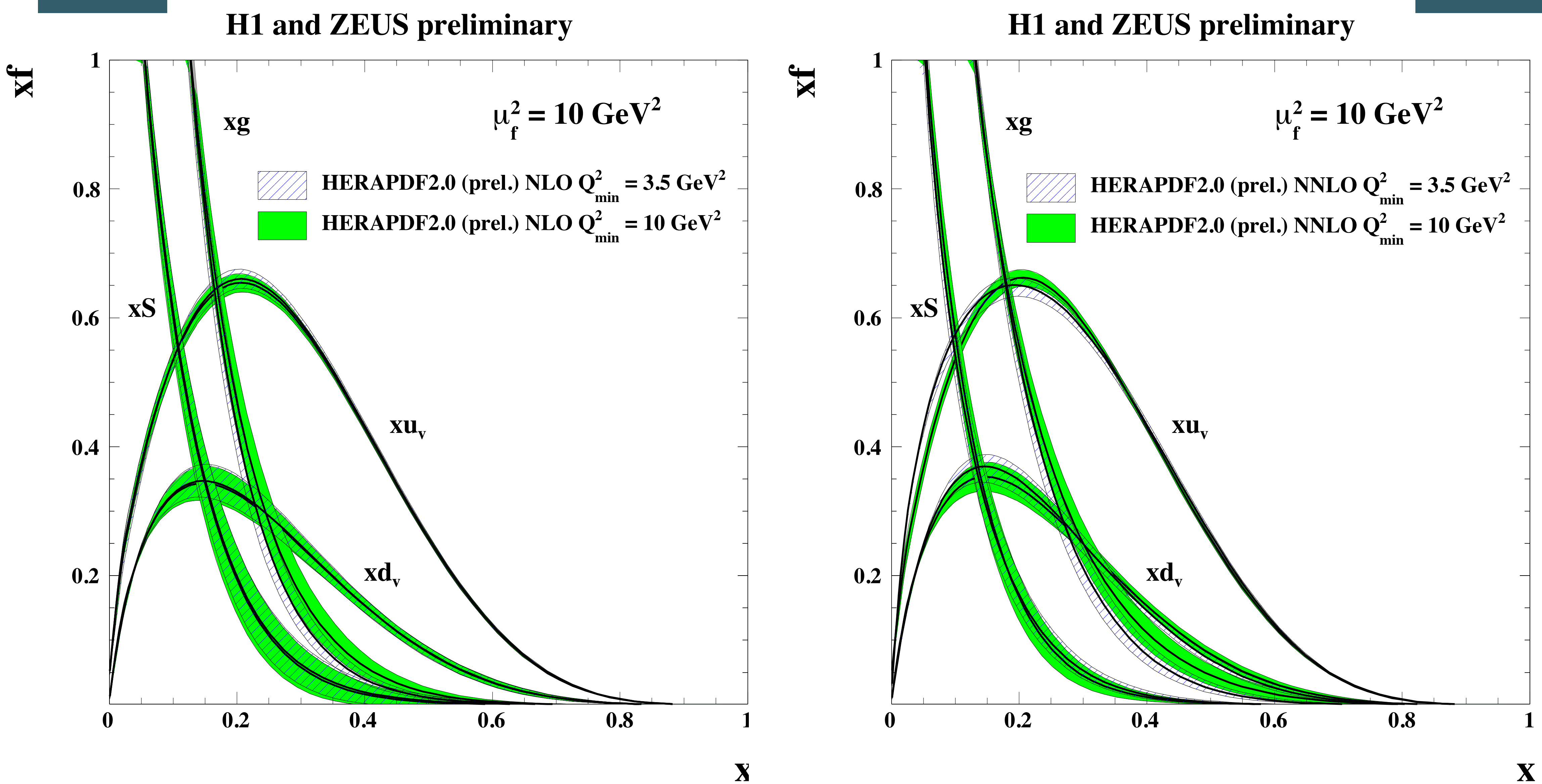


HERAPDF 2.0 (linear *x* scale)

Vary Q^2_{min}

NLO

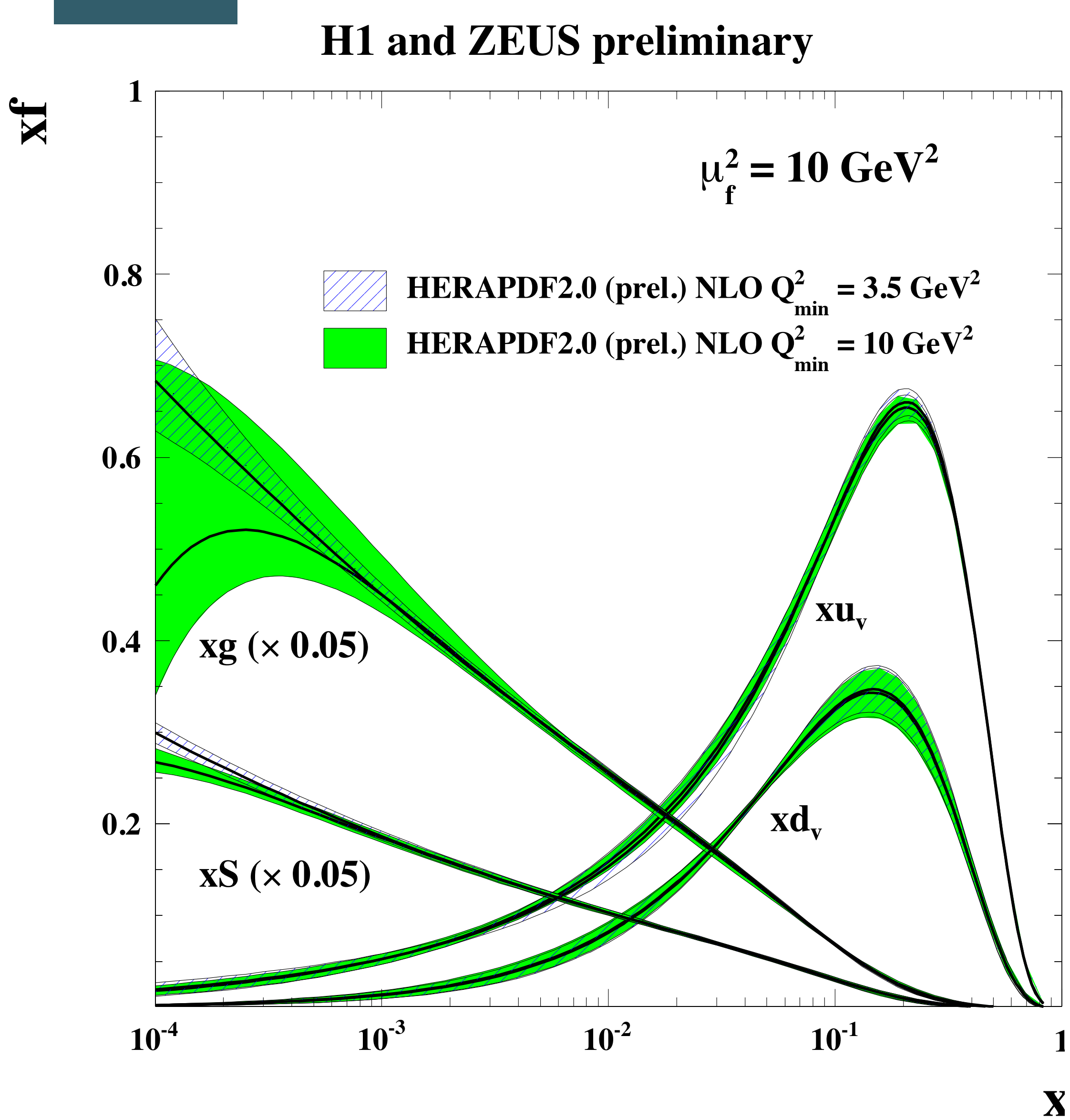
NNLO



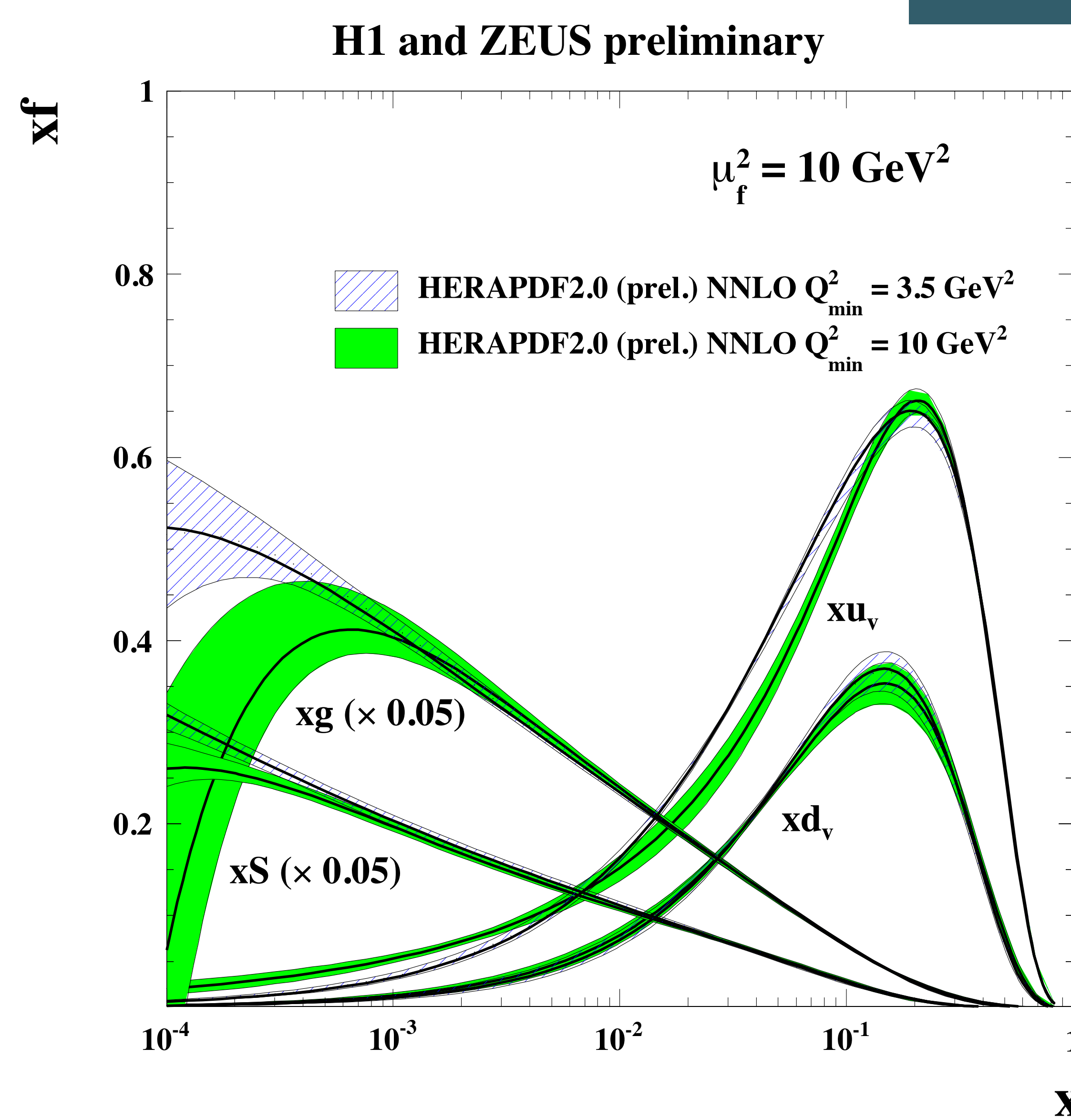
HERAPDF 2.0 (log *x* scale)

Vary Q^2_{min}

NLO



NNLO

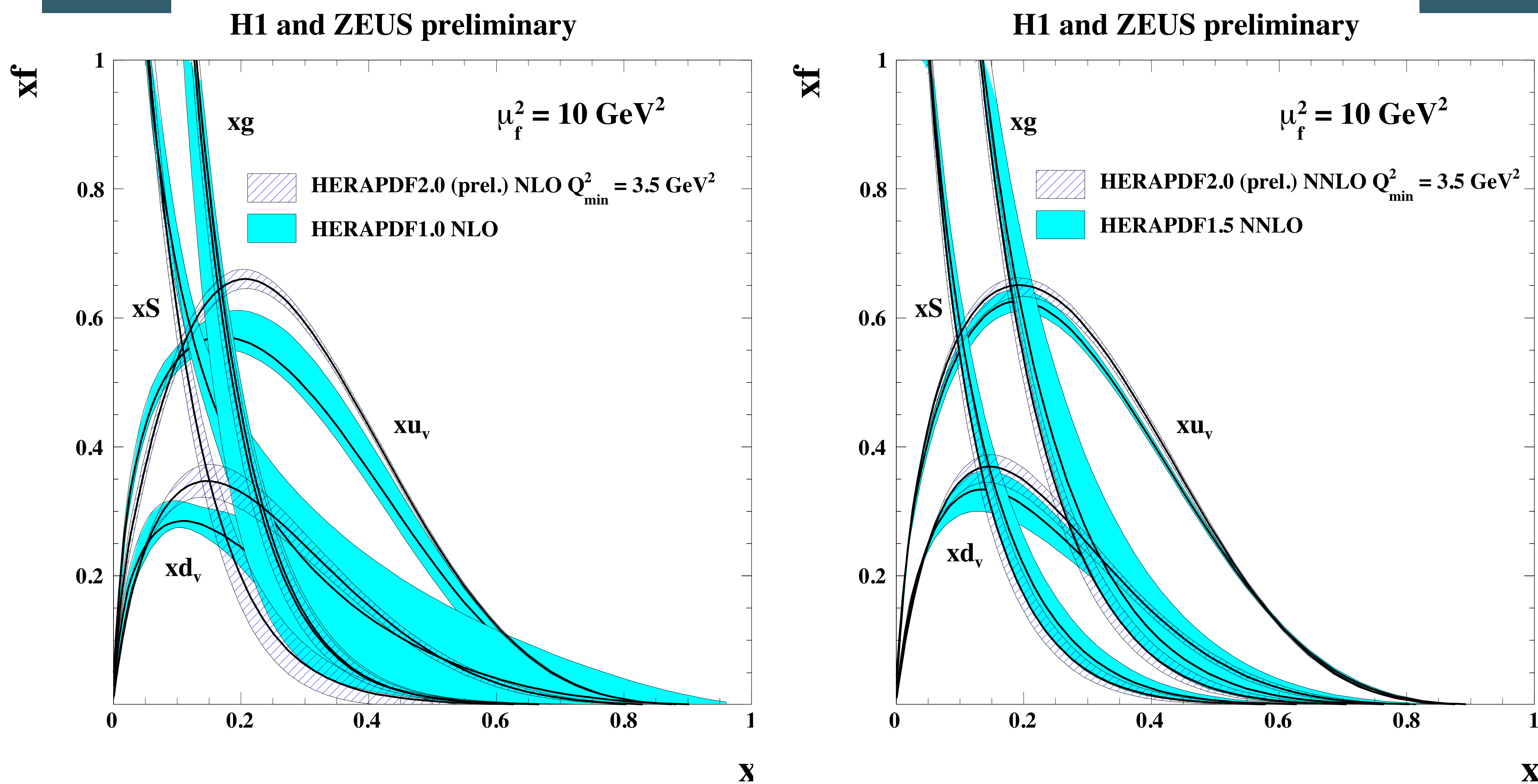


HERAPDF 1.0 & 1.5 vs. 2.0 (linear *x* scale)

Q^2_{min} = 3.5 GeV^2

NLO

NNLO



HERAPDF 1.0 & 1.5 vs. 2.0 (log *x* scale)

Q^2_{min} = 3.5 GeV^2

NLO

NNLO