HERAPDF

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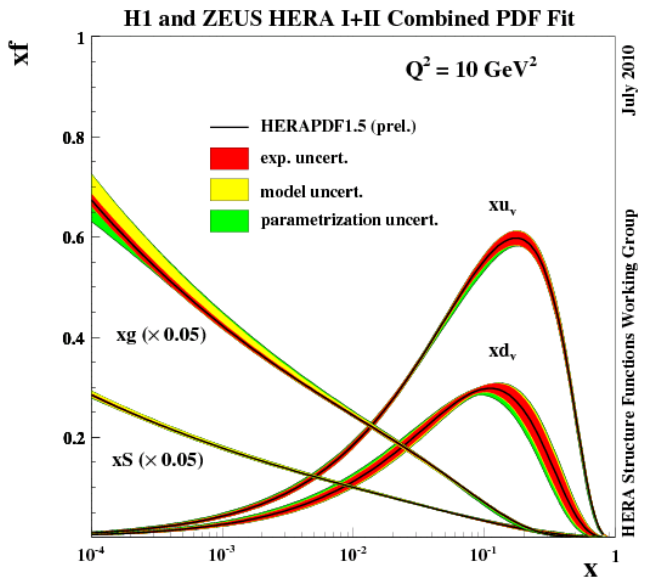
α_s-Workshop at MP, Munich

9th -11th February

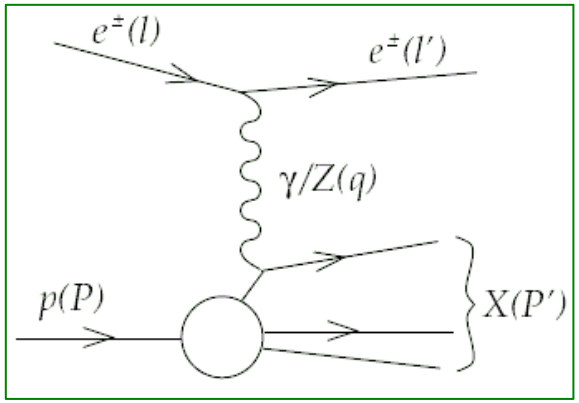
Outline

- Deep Inelastic Scattering at HERA
- HERAPDF analysis framework
- HERAPDF1.0 and HERAPDF1.5
- New Developments



Deep Inelastic Scattering (DIS)

Neutral Current (NC)



Boson virtuality

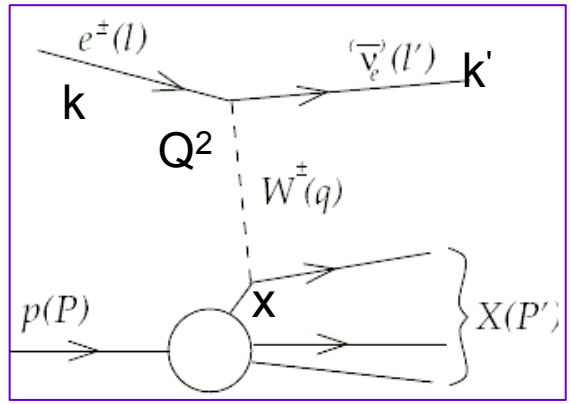
$$Q^2 = -q^2 = (k - k')^2$$

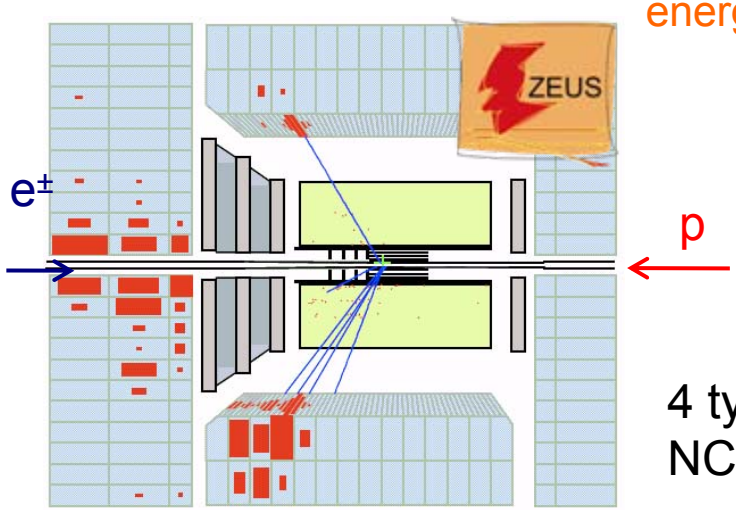
Bjorken x $\quad x = \dfrac{Q^2}{2(Pq)}$

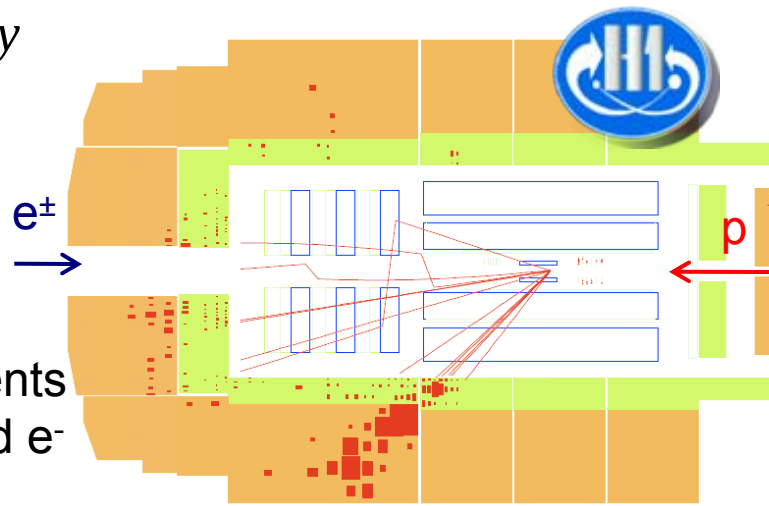
Inelasticity $\quad y = \dfrac{(Pq)}{(Pk)}$

Centre-of-mass energy $\quad s = (k+P)^2 = \dfrac{Q^2}{xy}$

Charged Current (CC)







4 types of measurements
NC, CC each in e^+ and e^-

Neutral Current Cross Section

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\mp} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}\right]$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

$$\kappa = \frac{1}{4\sin^2\theta_w\cos^2\theta_w}\frac{Q^2}{Q^2+M_Z^2}$$

Generalized structure functions:

$$\tilde{F}_2^{\pm} = F_2^{\gamma} + \kappa(-v_e \pm P_e a_e)F_2^{\gamma Z} + \kappa^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e)F_2^{Z}$$

$$x\tilde{F}_3^{\pm} = \kappa(-a_e \mp P_e v_e)xF_3^{\gamma Z} + \kappa^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^{Z}$$

$$\left[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}\right] = \sum_q \left[e_q^2, 2e_q v_q, v_q^2 + a_q^2\right] x(q+\bar{q})$$

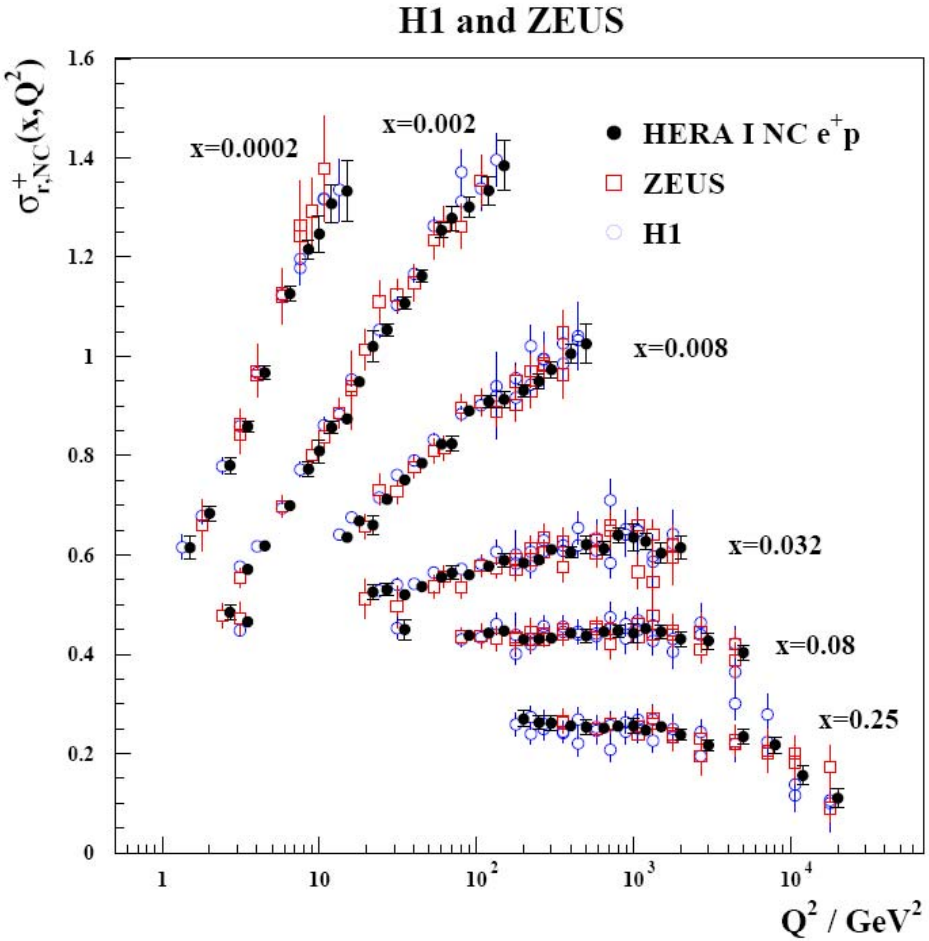
Sum of quarks and anti-quarks

$$\left[xF_3^{\gamma Z}, xF_3^{Z}\right] = \sum_q \left[e_q a_q, v_q a_q\right] 2x(q-\bar{q})$$

Valence quarks

Example NC cross sections

$$\sigma_r^{e^\pm p \to e^\pm X} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$



- Precise measurements from two experiments
- For $Q^2 \le 100$ GeV^2
  $\delta_{stat} \le 1\%, \delta_{sys} \le 3\%$
  for $Q^2 \ge 1000$ GeV^2
  $\delta_{stat} > \delta_{sys}$

- Combine dataset from both experiments:
  Key assumption
  H1 and ZEUS measure the same cross section at the same x,Q^2,y
- Model independent combination by minimizing a χ^2 →

Charged Current Cross Section

$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

CC reduced cross section

e^+/e^- sensitive to different quark densities:

$$\tilde{\sigma}_{CC}^{e^+p} = x\left[\bar{u} + \bar{c}\right] + (1-y)^2 x\left[d + s\right]$$

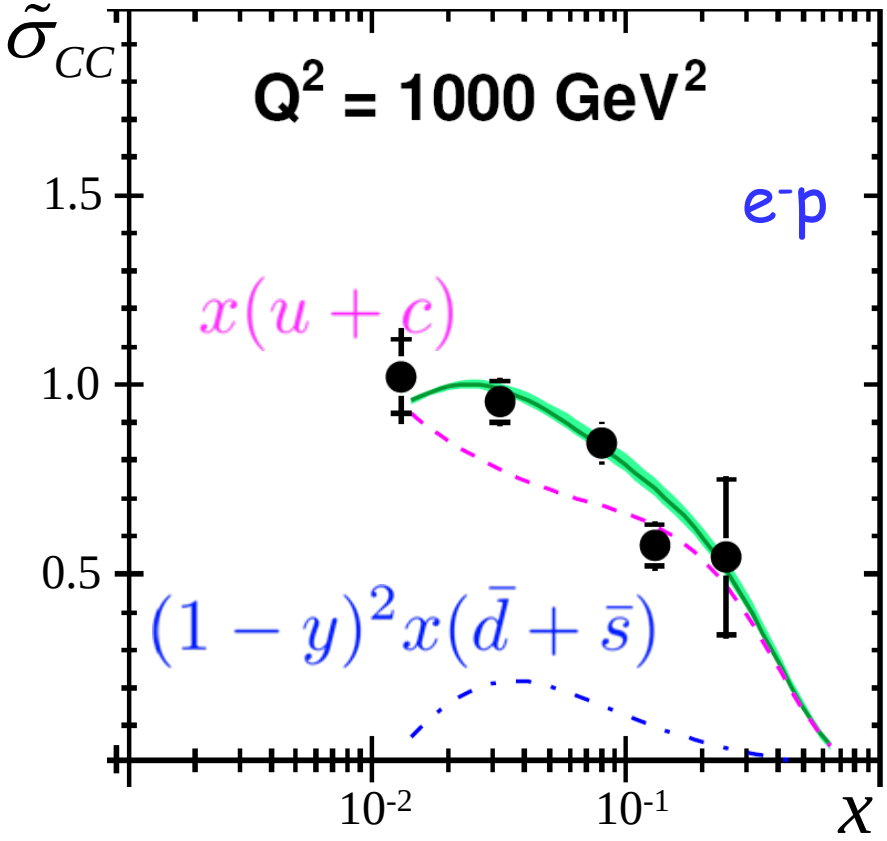
$$\tilde{\sigma}_{CC}^{e^-p} = x\left[u + c\right] + (1-y)^2 x\left[\bar{d} + \bar{s}\right]$$

CC gives sensitivity to different combinations of quarks as NC.

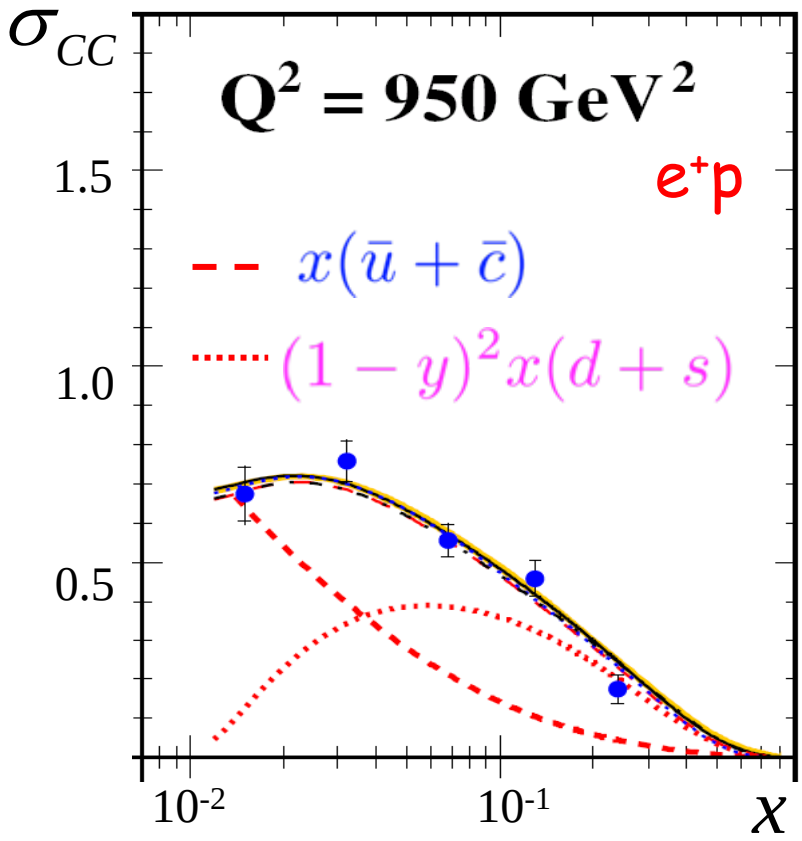
Quark Antiquark Decomposition

Data of the entire HERA II data sets (LH and RH, corrected to P_e=0)

H1 Preliminary



ZEUS



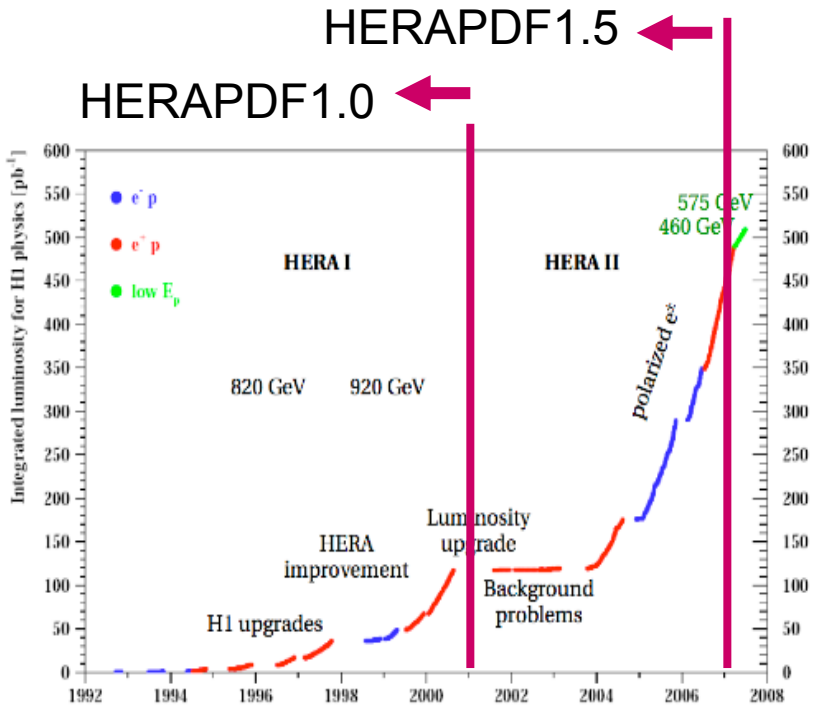
Datasets in HERAPDF

NC and CC Inclusive Data

- Combined HERA I inclusive data [JHEP01(2010) 109]:
  - HERAPDF1.0
  - In other PDF sets: NNPDF2.0, CT10, ABKM
- Combined HERA I + high Q2 HERA II Data [prelim]
  - Accurate measurements in high Q2 region sensitive to the valence distributions
  - HERAPDF1.5

Additional Datasets

- Low Energy Data HERA II [prelim]
  - Accurate measurements in Q2≥2.5GeV2, sensitive to structure function FL
- Combined Charm F2 data [prelim]
- HERA Jet Data [published data] fits [work in progress]



HERAPDF Analysis Framework

- QCD Fit settings:
  - NLO (and NNLO) DGLAP evolution equations
  - TR-VFNS (as for MSTW08)
    - Other schemes were investigated as well: RT (optimal), ACOT (full and χ), FFNS
  - PDF parametrised at the starting scale Q_0^2:

$$\mathbf{G},\ \mathbf{u_{val}},\ \mathbf{d_{val}},\ \overline{\mathbf{U}} = \overline{\mathbf{u}}(+\overline{\mathbf{c}}),\ \overline{\mathbf{D}} = \overline{\mathbf{d}} + \overline{\mathbf{s}}(+\overline{\mathbf{b}})$$

$xf(x,Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2)$

  - Fermion number and momentum sum rules are applied
  - The optimum number of parameters chosen by saturation of the χ^2
    - central fit with 10 free parameters
    - χ^2/dof=574/582

Scheme	TRVFNS
Evolution	QCDNUM
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

Sources of HERAPDF uncertainties

- **Experimental:**
  - Consistent data sets → use $\Delta\chi^2=1$
- **Model:**
  - Following variations have been considered

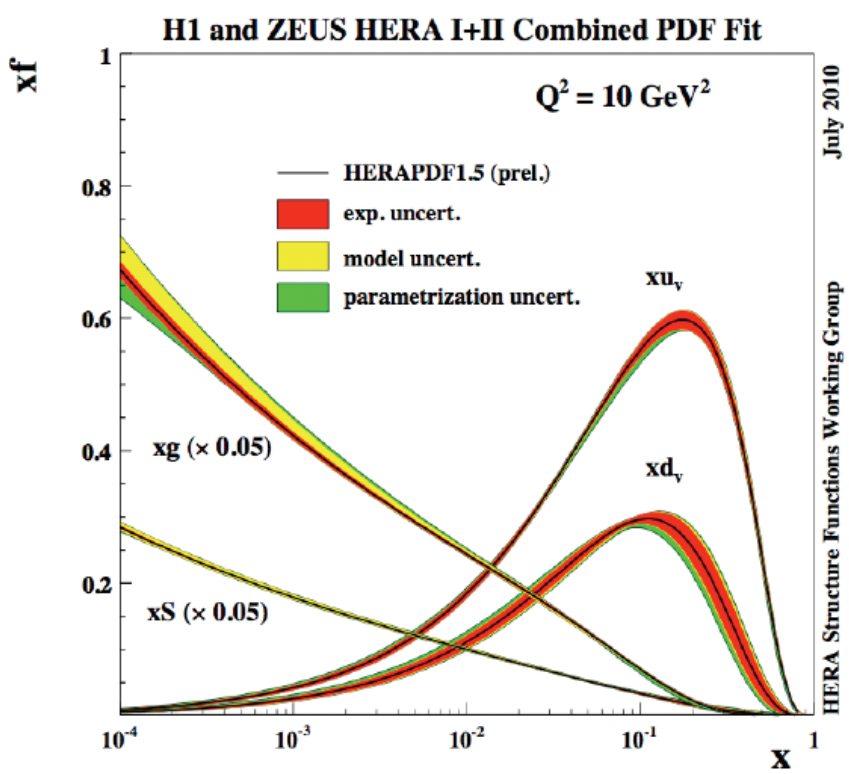
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0

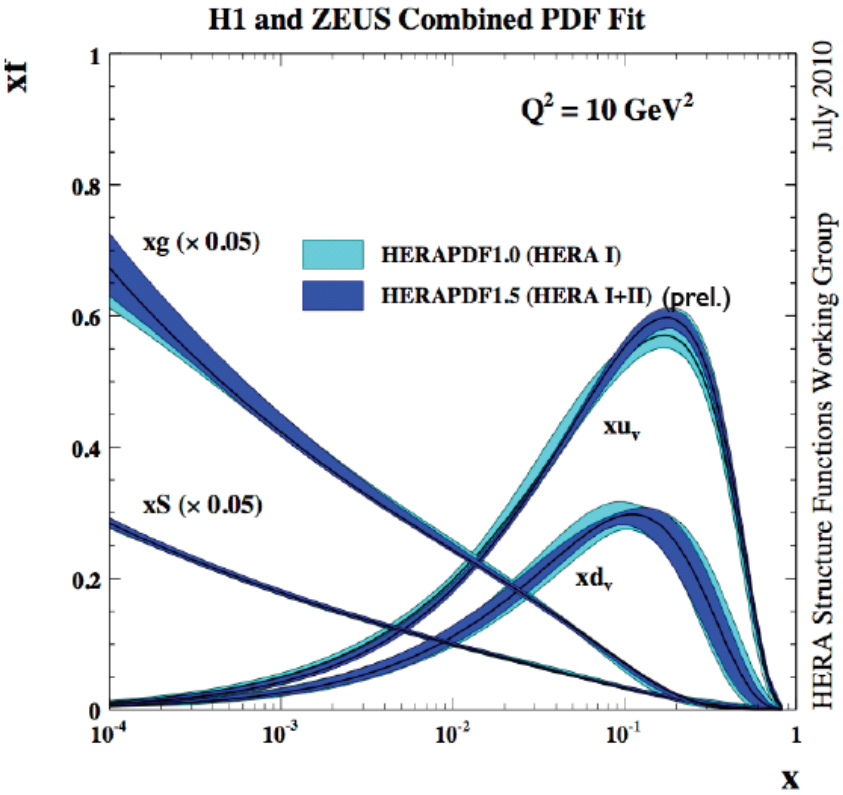
- **Parametrisation:**
  - An envelope is formed from PDF fits using variants of param. form at Q_0^2
    - Scanning of 11 parameter space
    - Q_0^2 variation and negative gluon parametrisation
    - Relaxing assumptions used for central fit

In addition variation of α_s is available: 0.1176 (central), 0.1156 (low), 0.1196 (high)

HERAPDF1.5 vs. HERAPDF1.0

- xg, xu_v, xd_v, xSea (xSea=$x\overline{U}+x\overline{D}$) at the scale Q_0^2=10 GeV^2

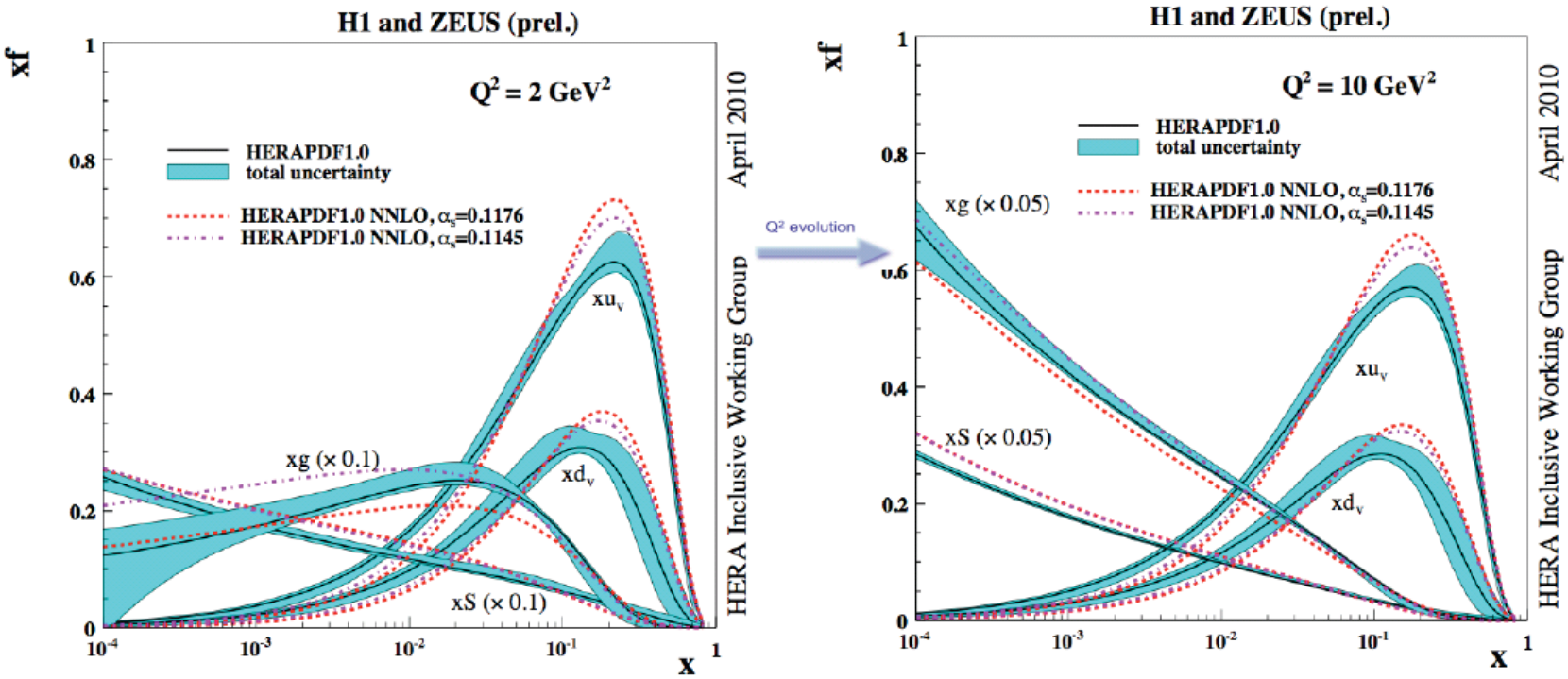




- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

HERAPDF1.0 at NNLO

- Fits performed to HERA I data (as used for HERAPDF1.0) at NNLO using RT-VFNS:
  - $\alpha_S(Mz)$ at NNLO = 0.1176 and $\alpha_S(Mz)$ at NNLO = 0.1145



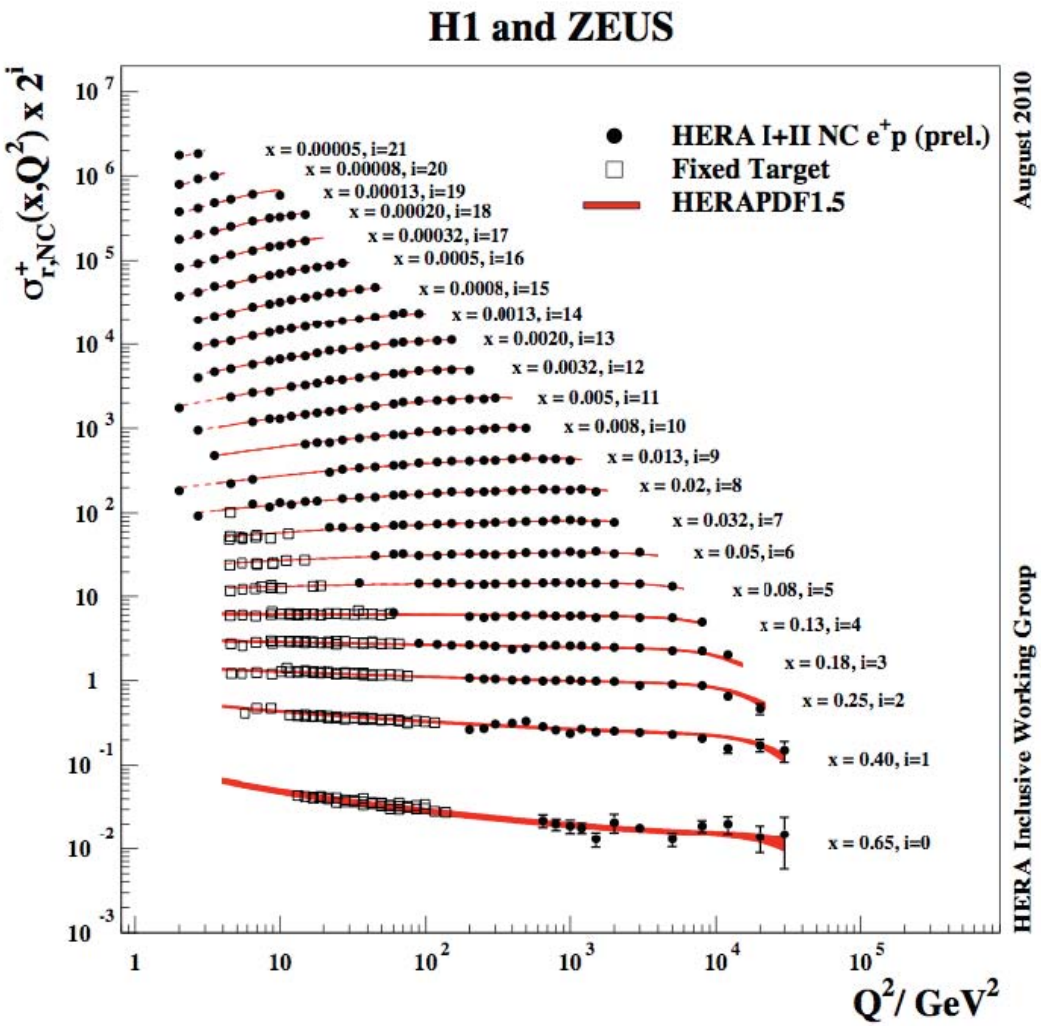
- Using the same settings as for NLO, the NNLO fit does not yell better results for this scheme.

scheme	NNLO $\alpha_S(Mz)$=0.1145	NNLO $\alpha_S(Mz)$=0.1176	NLO $\alpha_S(Mz)$=0.1176
All χ^2/dof	623.7/582	638.3/582	574.4/582

LHAPDF Grid Files are available at H1-ZEUS website: https://www.desy.de/h1zeus/combined_results/index.php

HERAPDF1.5 vs. DIS data

- Plots show the extended kinematic range of the HERA I(and II) data as compared to the fixed target measurements:
  - Data points include experimental errors
  - Fit line includes total error
- HERAPDF1.0 and HERAPDF1.5 fits describe our data well!
- Extrapolation of the HERAPDF1.0 and HERAPDF1.5 fits agree well with fixed target data:
  - SLAC and BCDMS



Sensitivity to the Gluon and α_s via Scaling violations

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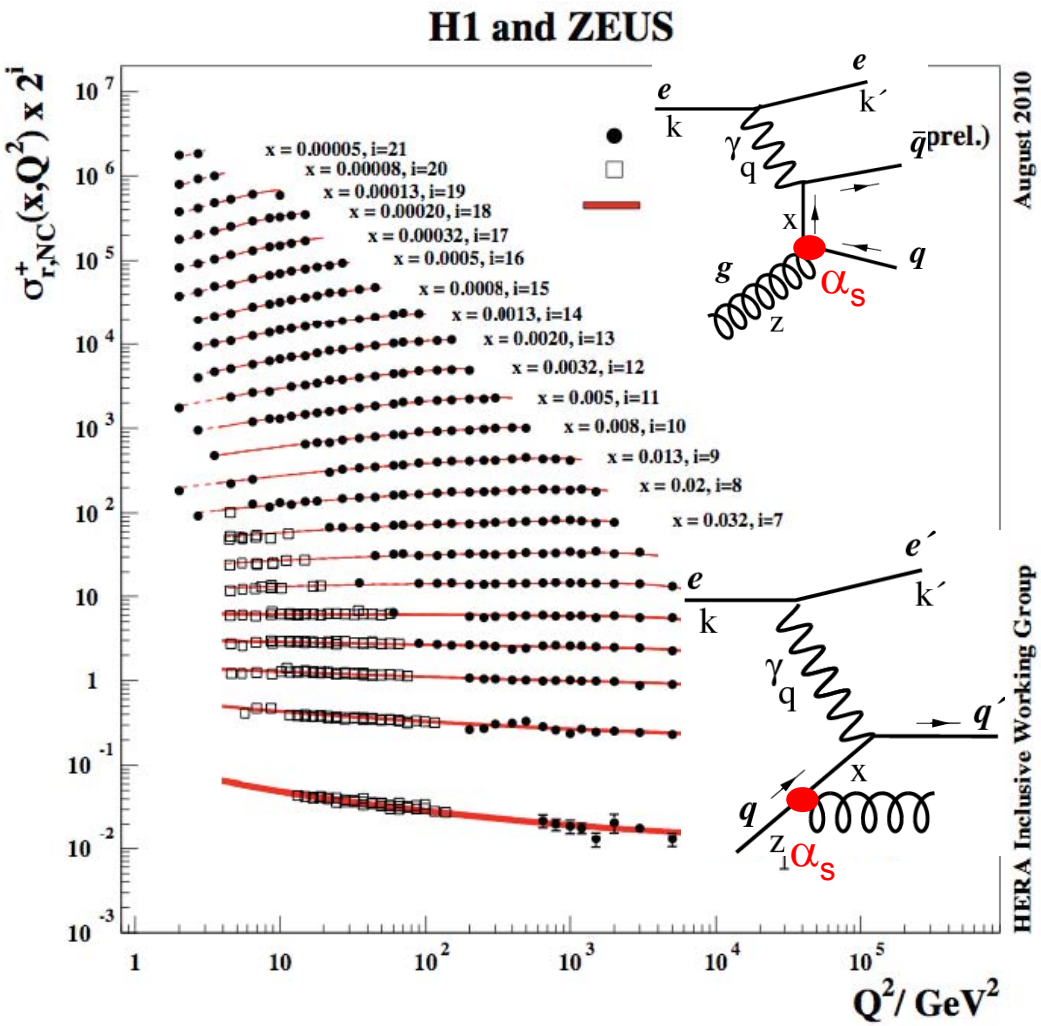
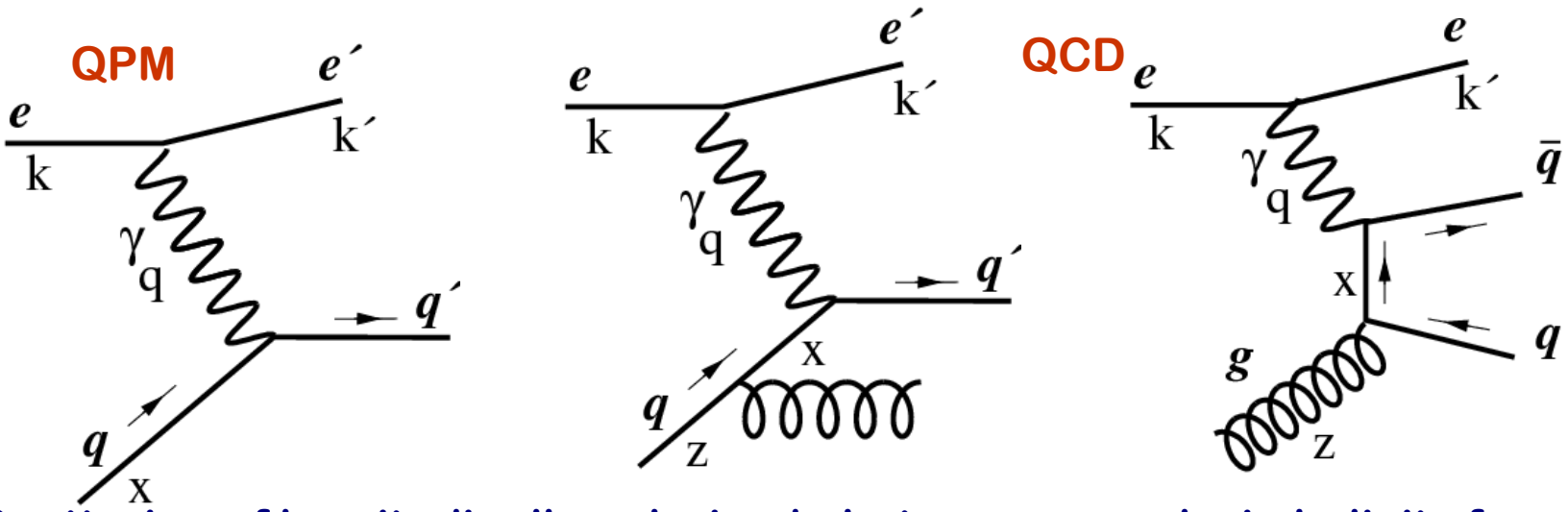
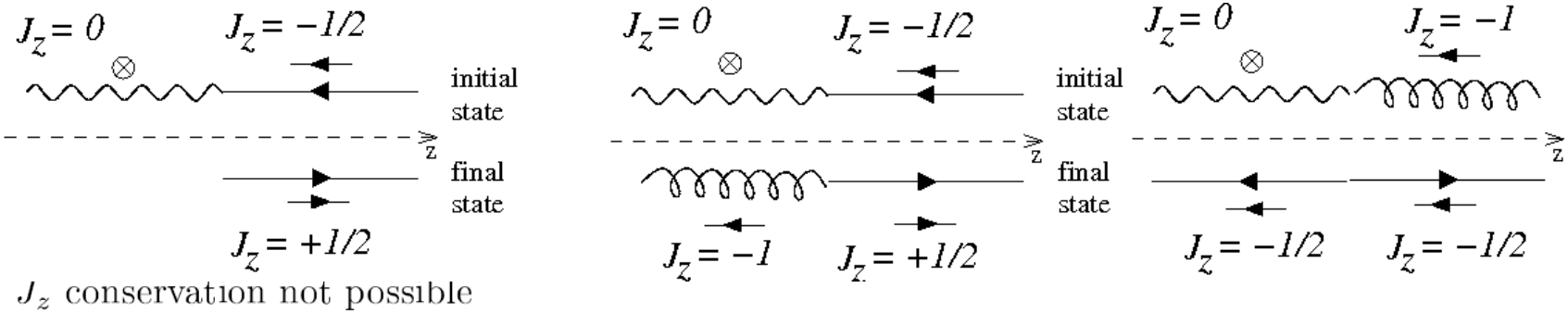


Longitudinal Structure Function F_L



Scattering of longitudinally polarized photons on quarks in helicity frame

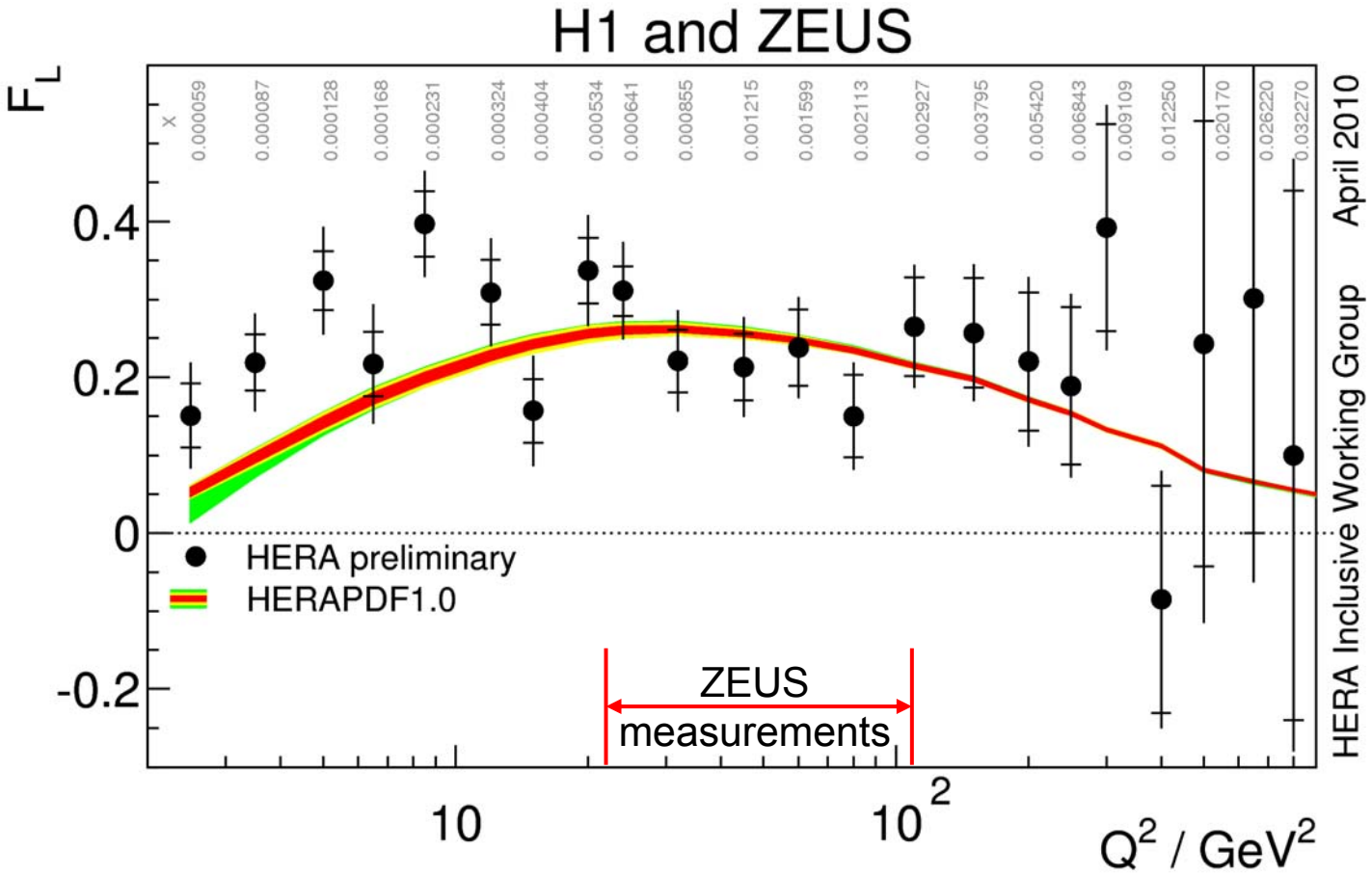


$$F_L \propto \sigma_L = 0$$

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} \sum_q z e_q^2 (q + \bar{q}) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) \cdot zg \right]$$

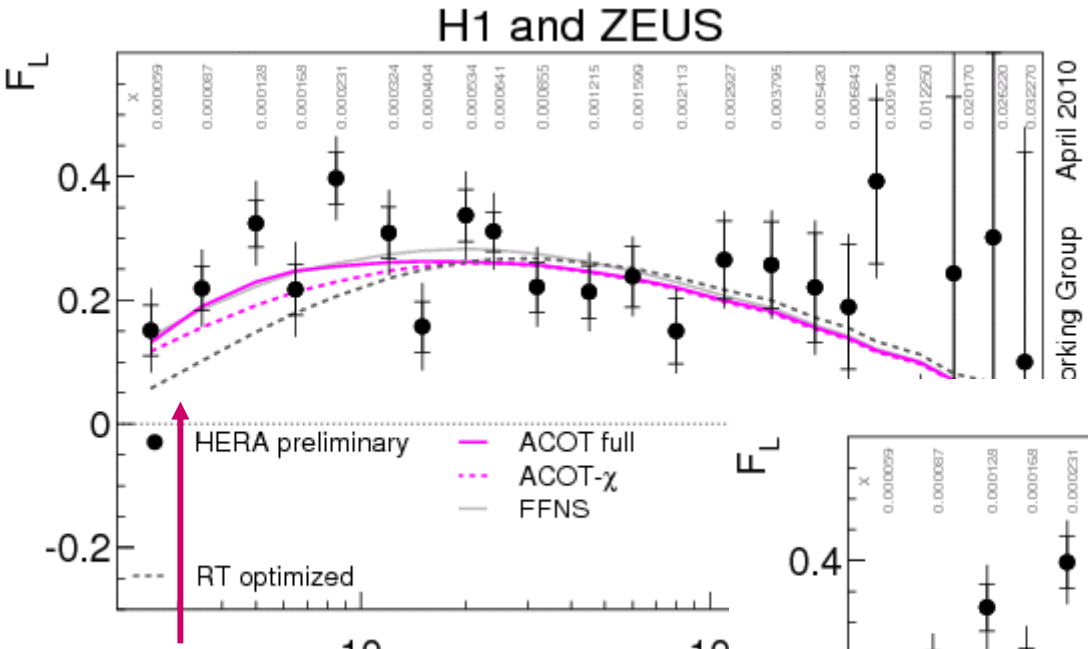
access to gluon density

H1 + ZEUS Combined F_L



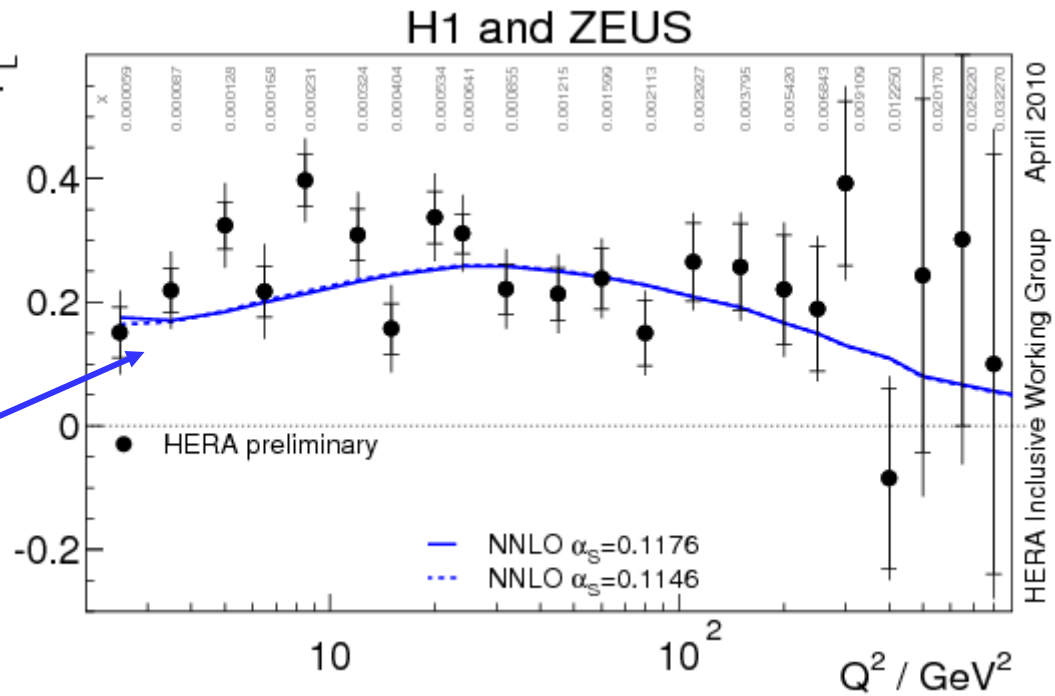
Good agreement between data and predictions for $Q^2>10$ GeV^2.
F_L at low Q^2 above prediction using HERAPDF1.0

Variants of Predictions for F_L

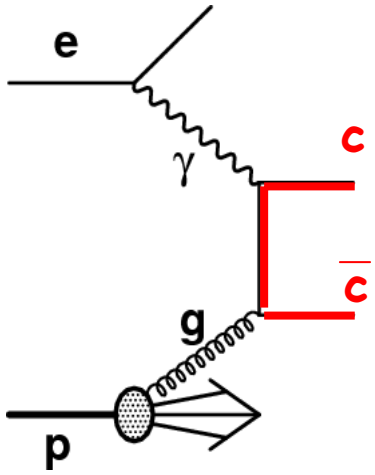


Variation of heavy flavour treatment

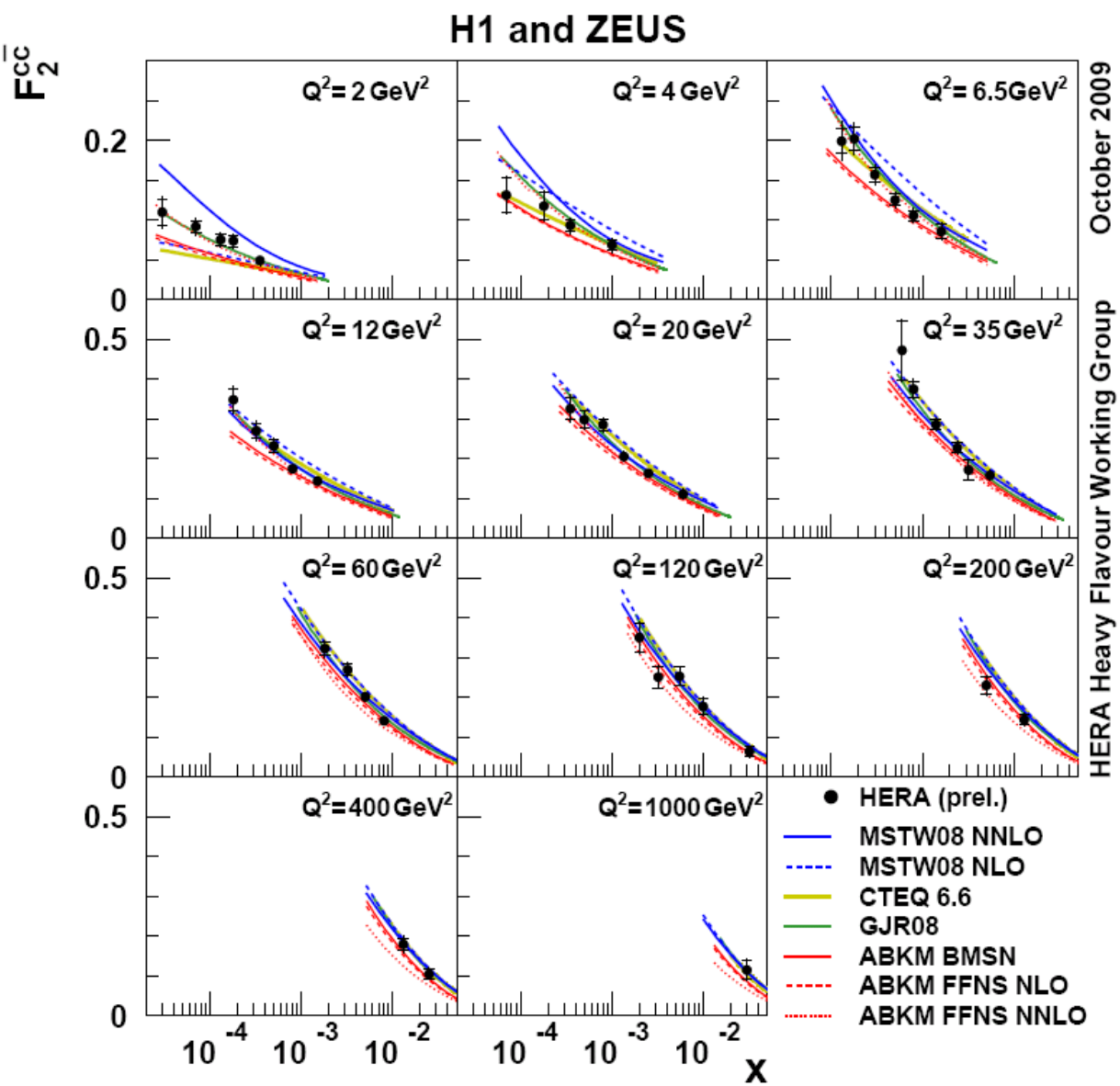
Higher Order calculation



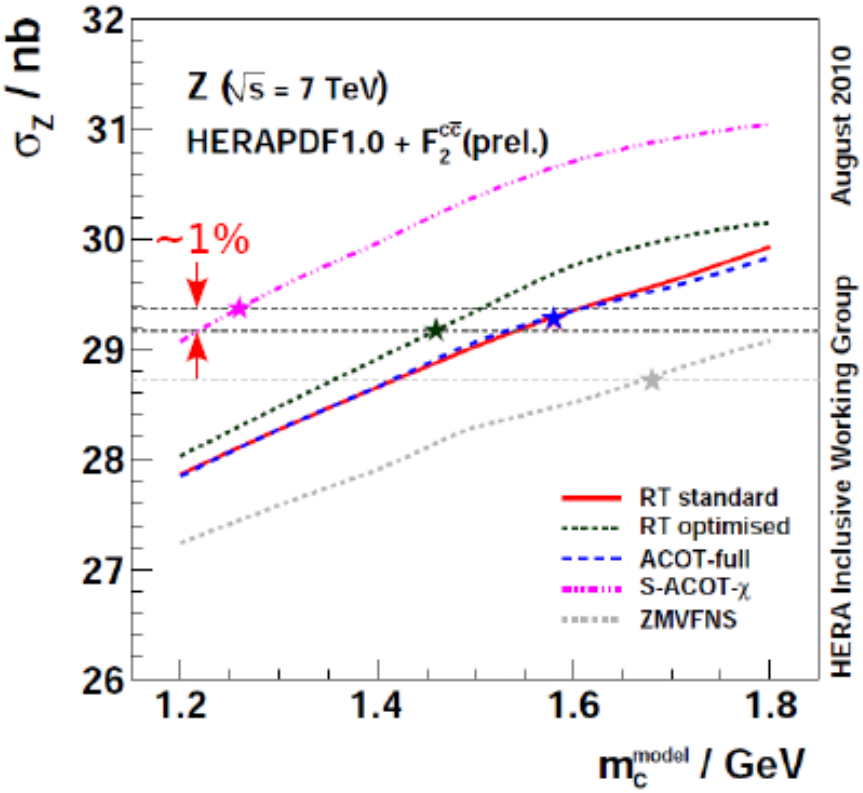
Combined $F_2^{c\bar{c}}$ vs. various Theories



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



Z cross sections at LHC



(★ indicate σ with PDFs at m_c^{model}(opt))

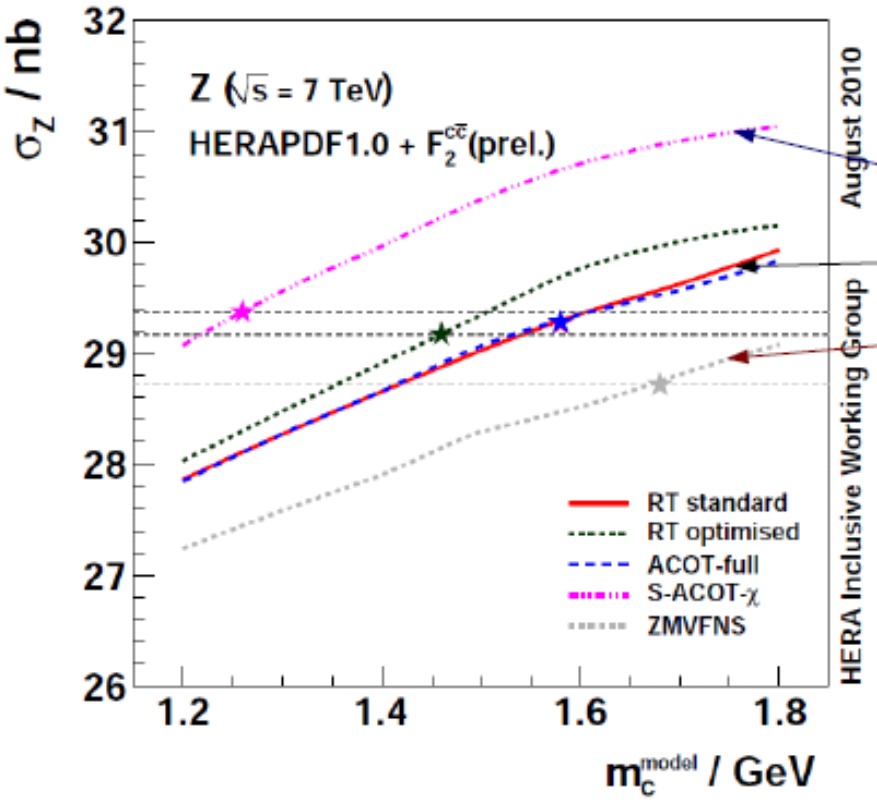
- cross section predictions for each scheme vary ~7% for $1.2 < m_c^{model} < 1.8$ GeV

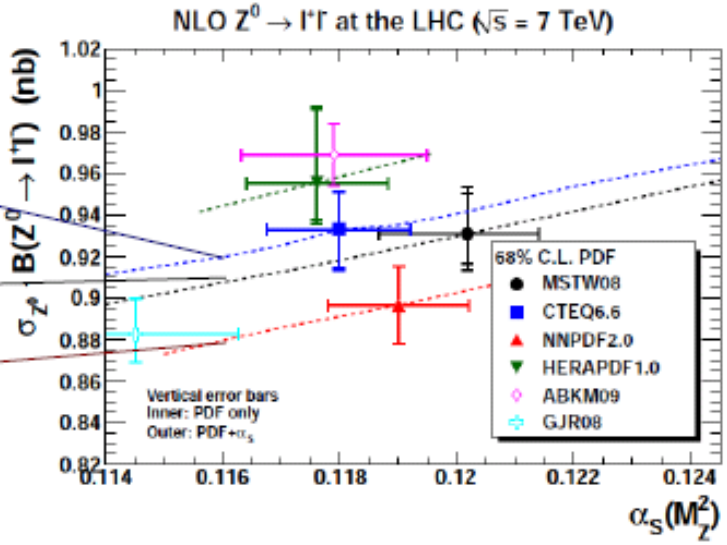
- predictions for all schemes vary ~7% for given m_c^{model}

BUT:

- predictions for m_c^{model} (opt) has much smaller spread: <1% (~2% with ZMVFNS)

Z cross sections at LHC



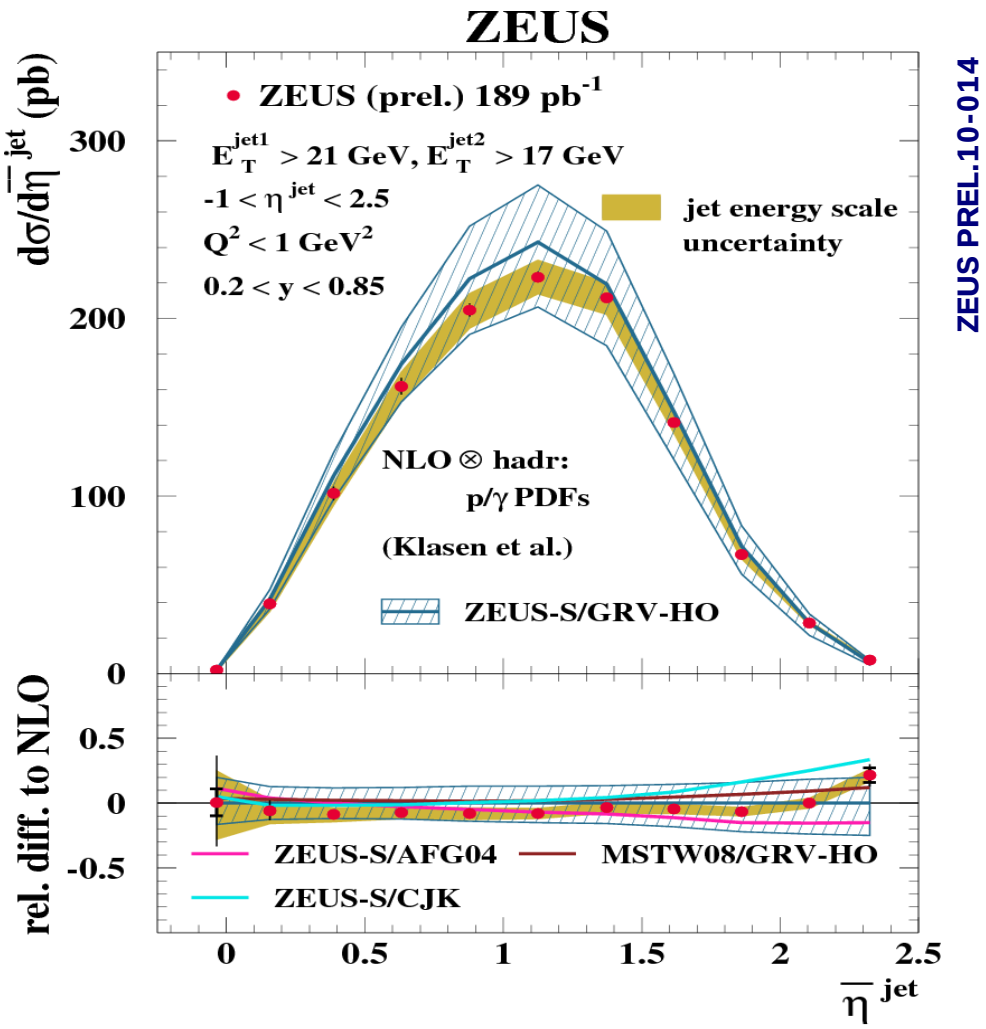


- comparison of Z cross sections as a function of $\alpha_S(M_Z^2)$
  G.Watt, PDF4LHC 26.03.2010

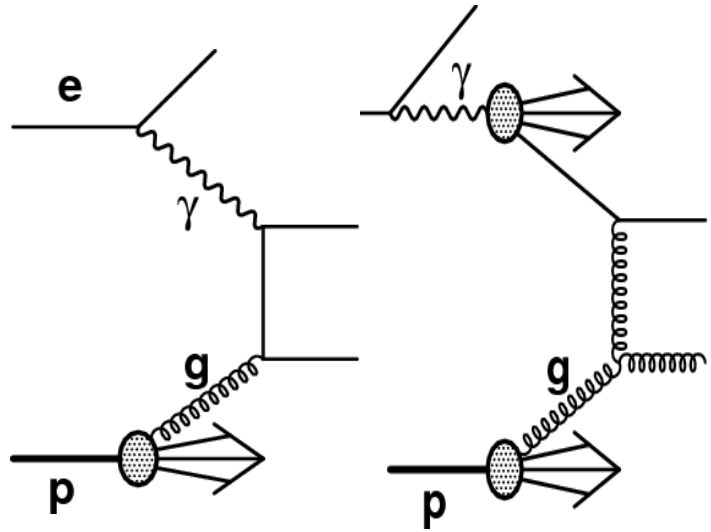
→ could explain part of existing differences between PDFs

(★ indicate σ with PDFs at m_c^{model}(opt))

Jet data example:
Dijet in Photoproduction



ZEUS PREL.10-014



➔ Highly sensitive to
- Proton PDF (gluon density)
- Resolved photon PDF

Summary

- HERA delivered a wealth of *ep* DIS data
- H1 and ZEUS measurements reach their ultimate precision
- Flavour separated sets of PDFs extracted
- Work in progress:
  Use Jet data, low energy and F2charm to simultaneously extract as and gluon

Backup

More material on

- PDF parameterization
- FL extraction
- F2charm
- LHC W cross sections

PDF Determination in HERAPDF1.0

DGLAP at NLO → QCD predictions

PDFs parametrised (at starting scale Q^2_0) using standard parametrisation form:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

A: overall normalisation

B: small x behavior

C: $x \to 1$ shape

The optimal number of parameters chosen by saturation of the χ^2
- central fit with 10 free parameters

xg, xu_v, xd_v, $x\bar{U}$, $x\bar{D}$
where $x\bar{U}=x\bar{u}$ and $x\bar{D}=x\bar{d}+x\bar{s}$ at the starting scale ($x\bar{s}=f_s x\bar{D}$ with $f_s=0.31$)

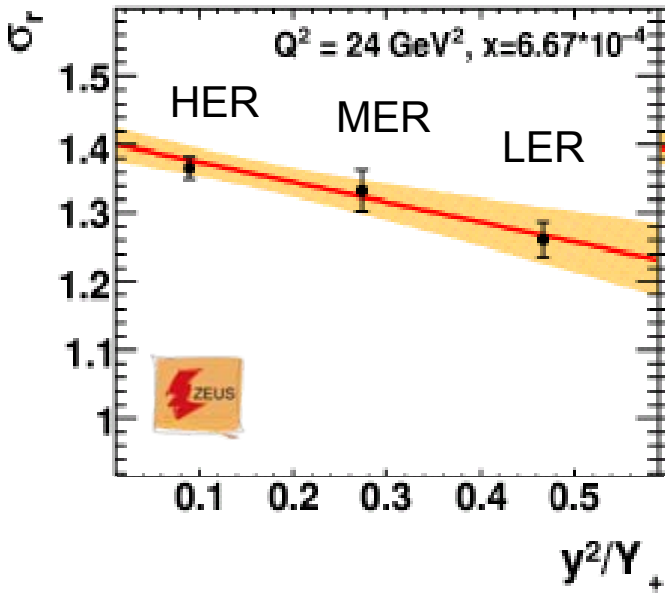
A_g, A_{uv}, A_{dv} are fixed by sum rules

extra constrains for small x behavior of d- and u-type quarks:
$B_{uv}=B_{dv}$, $B_{\bar{U}}=B_{\bar{D}}$, $A_{\bar{U}}=A_{\bar{D}}(1-f_s)$ for $\bar{u}=\bar{d}$ as $x \to 0$

Measurement of FL

Measure cross sections $\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{Y_+} F_L\left(x,Q^2\right)$

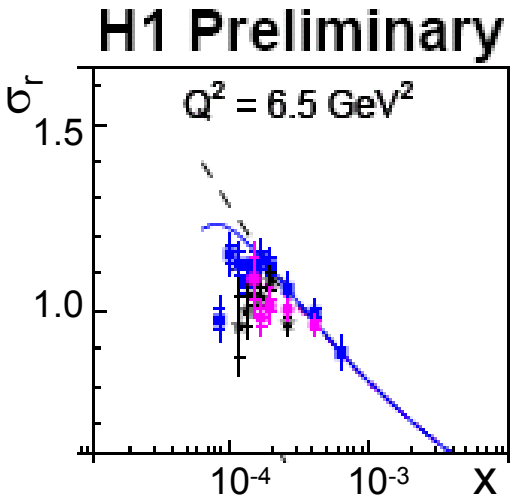
at same *x* and Q^2 but different $y = Q^2/x \cdot s$ → vary s

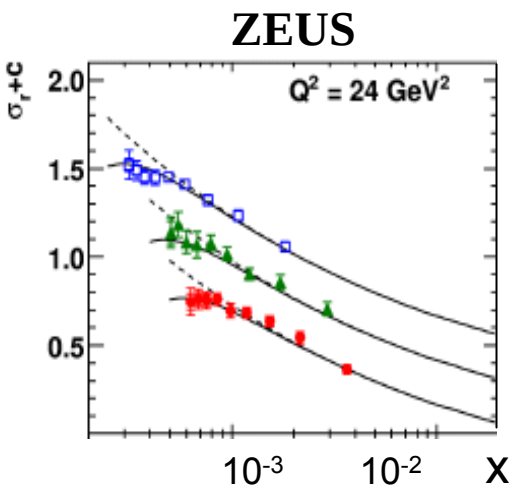


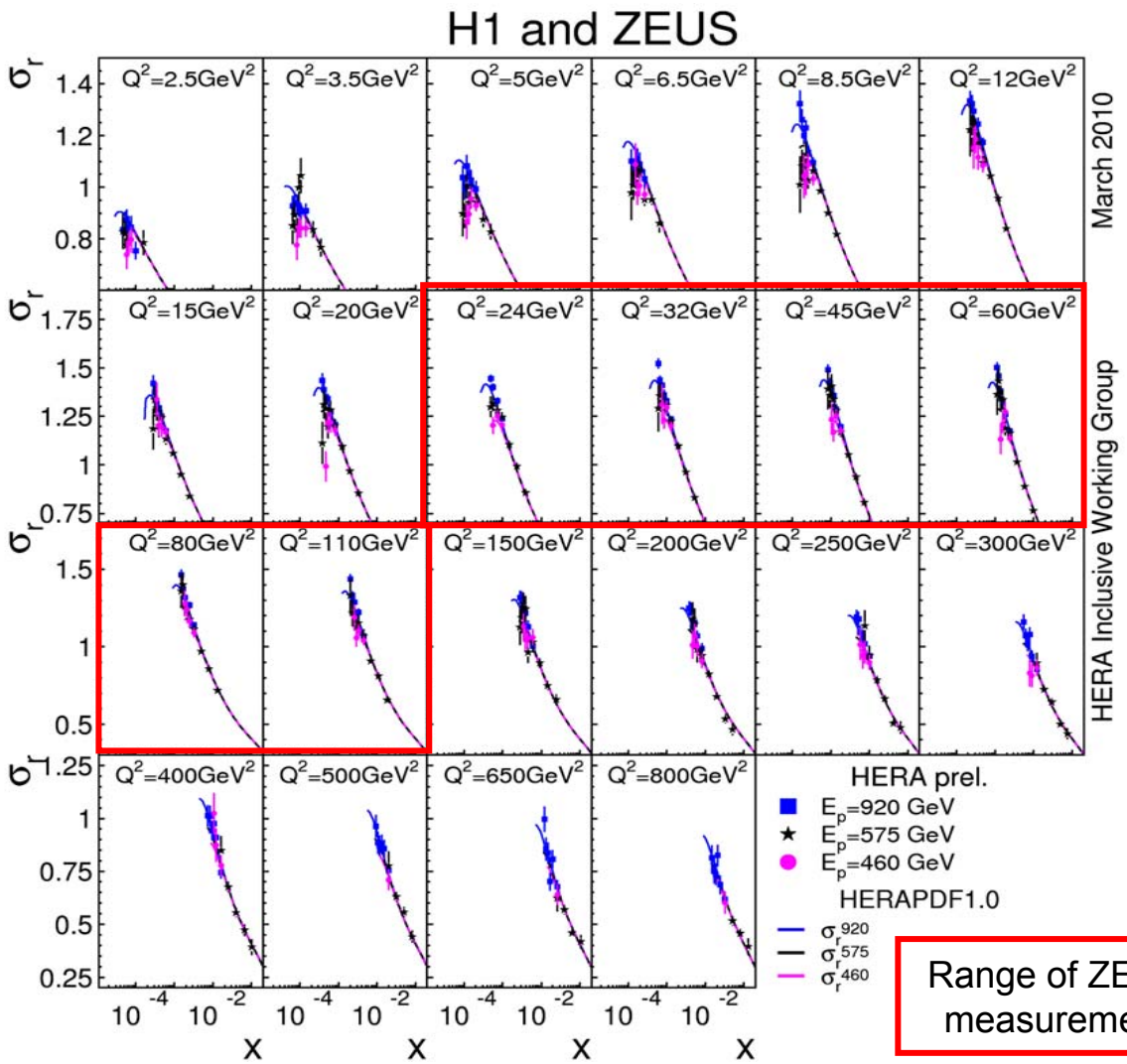
- Change proton beam energy to change cms energy
  - E_p = 920 GeV, High Energy Run (HER)
  - E_p = 575 GeV, Medium Energy Run (MER):
  - E_p = 460 GeV, Low Energy Run
- Large lever arm in y^2/Y_+
- Measure at high *y* in LER

- Extended measurement to high y region
  $y = 1-E'_e/E_e(1-\cos\theta)$ →high *y* means low E'_e

Combined low E_p Cross Sections

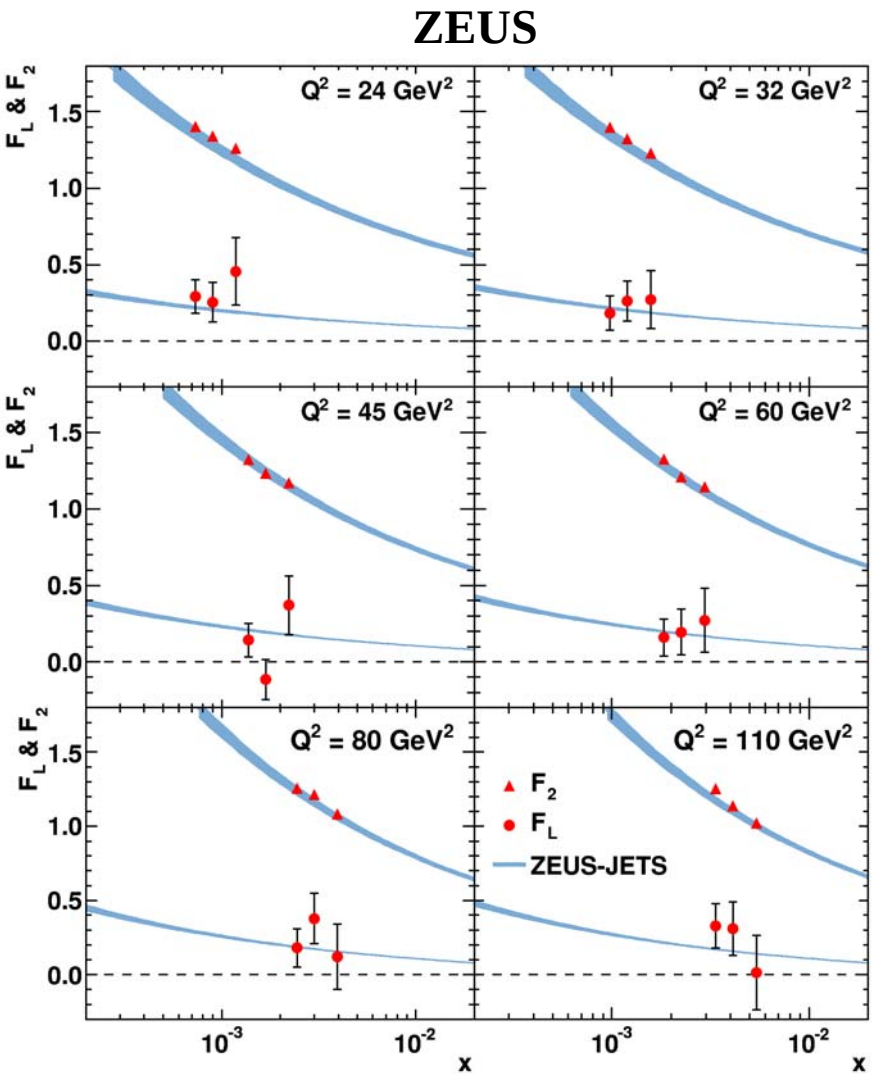






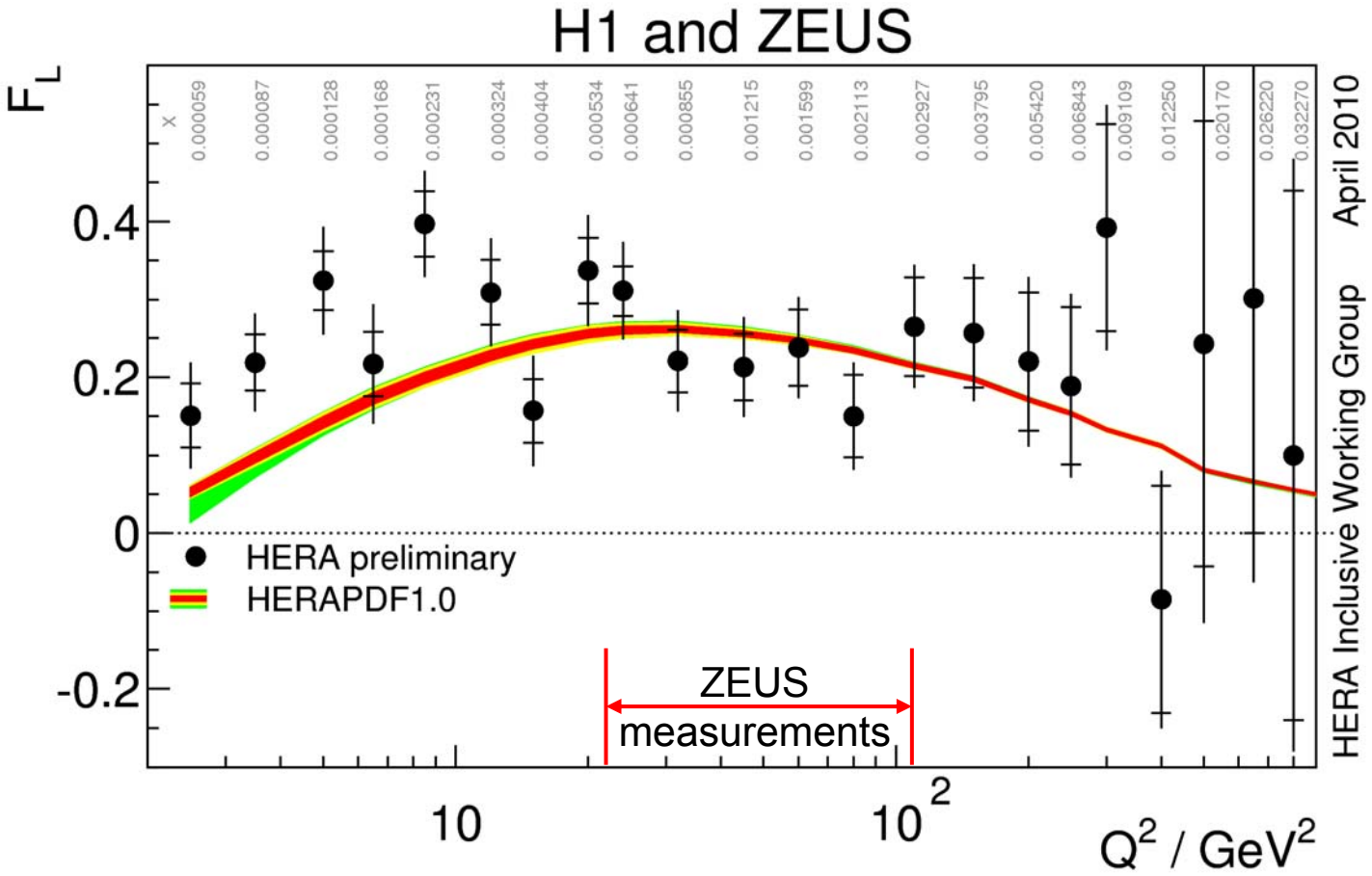
Range of ZEUS measurement

Extracted F_L and F_2



- First F_2 measurement without assumptions on F_L
- Data support a non-zero F_L
- Predictions for F_2 and F_L are consistent with data

H1 + ZEUS Combined F_L



Good agreement between data and predictions for $Q^2>10$ GeV^2.
F_L at low Q^2 above prediction using HERAPDF1.0

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

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

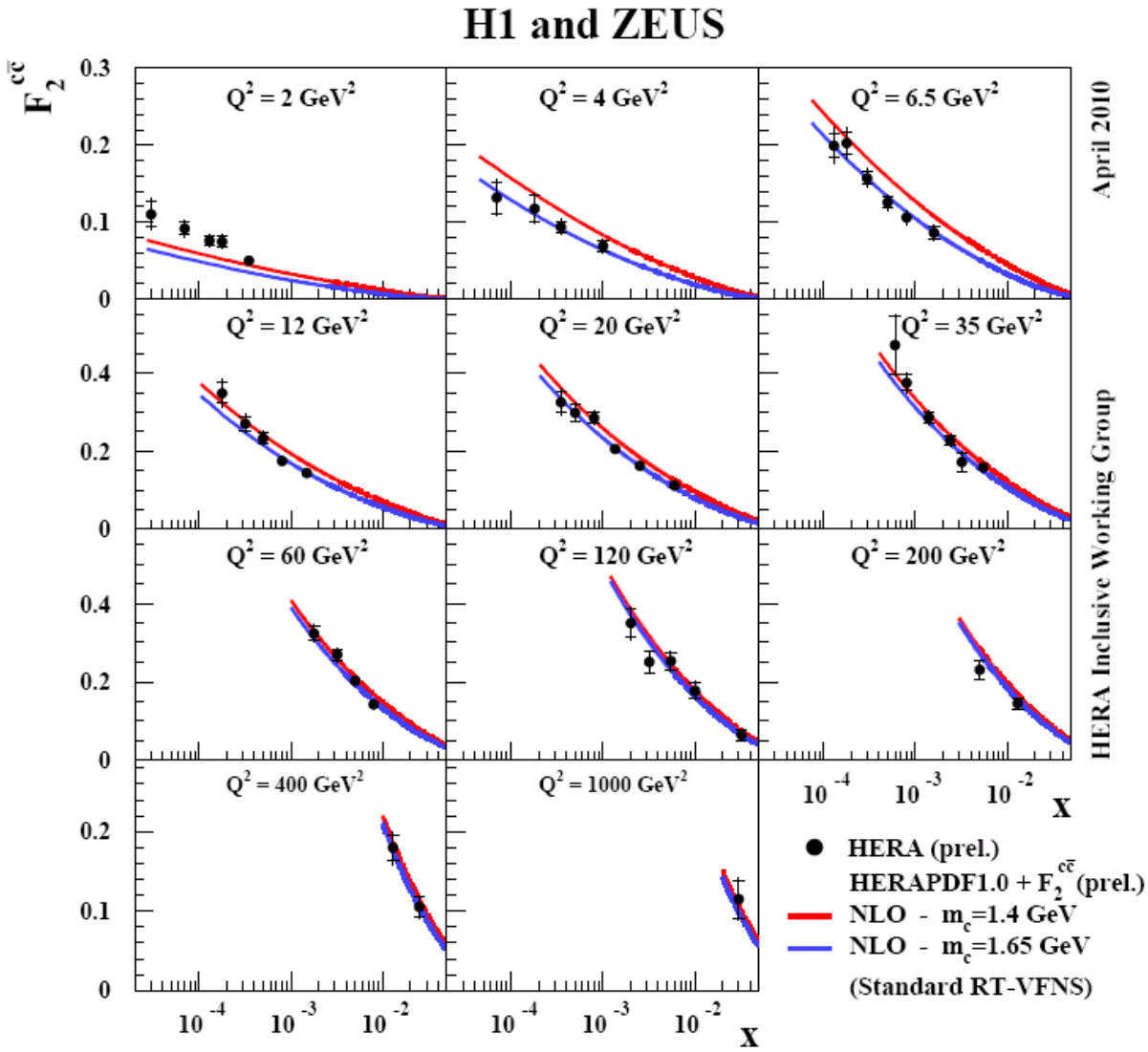
  $Q^2 > 3.5$ GeV^2 ($Q^2 = 2$ GeV^2 bin excluded)

  41 charm points

- RT GM-VFNS

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

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

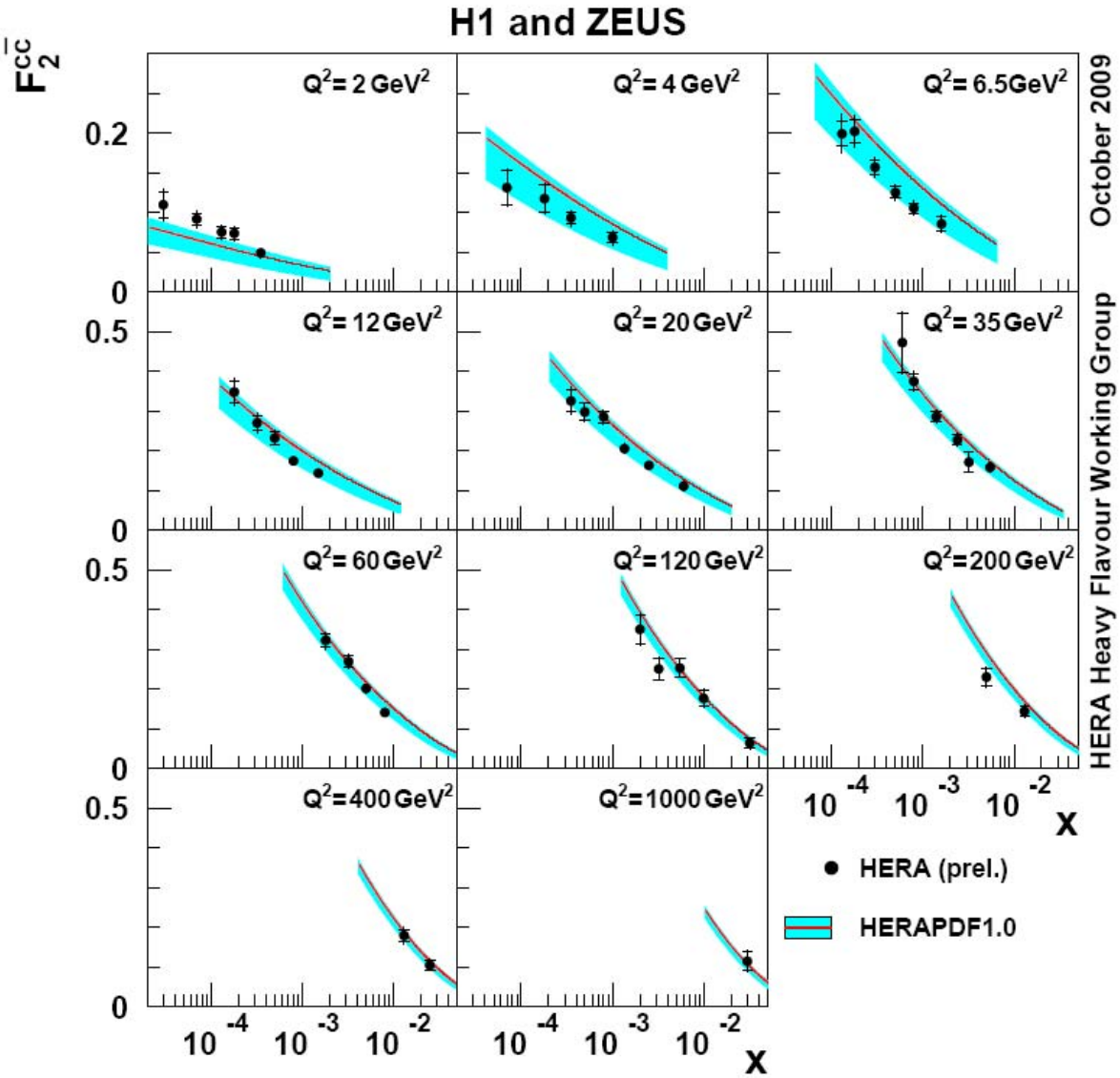


H1-ZEUS combined $F_2^{c\bar{c}}$ vs. HERAPDF1.0

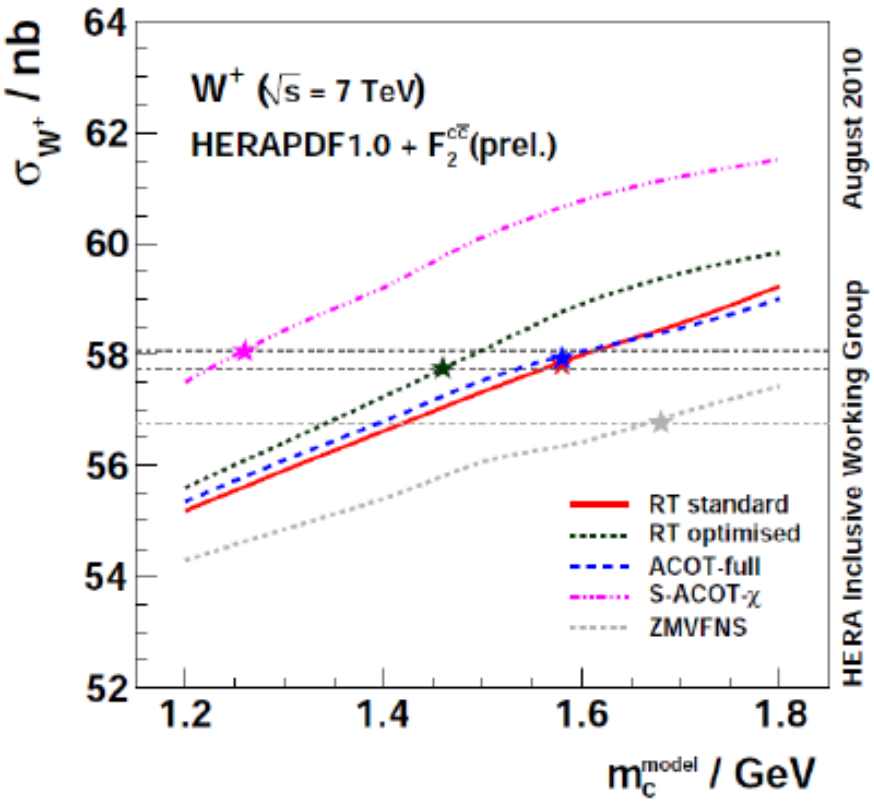
- HERAPDF 1.0 fit to inclusive HERA I data
- RT GM-VFNS (as MSTW08)
- Central curve: $m_c = 1.4$ GeV

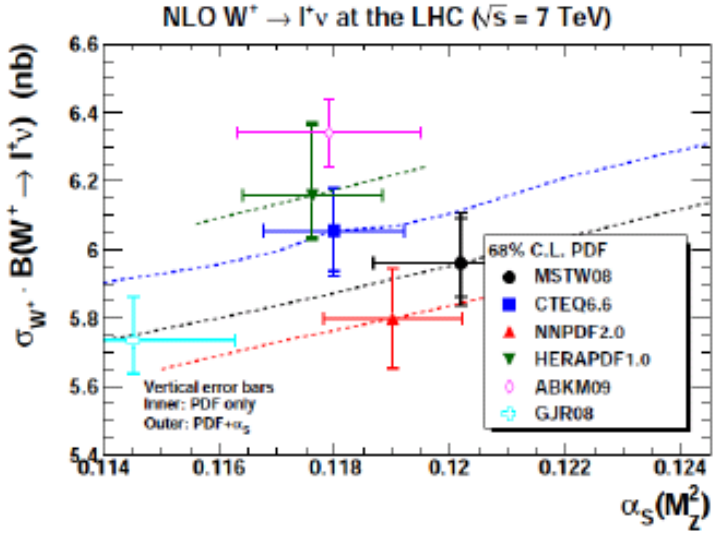
  band: $m_c = 1.3$GeV (upper) $m_c = 1.65$GeV (lower)

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



W^+ cross sections at LHC

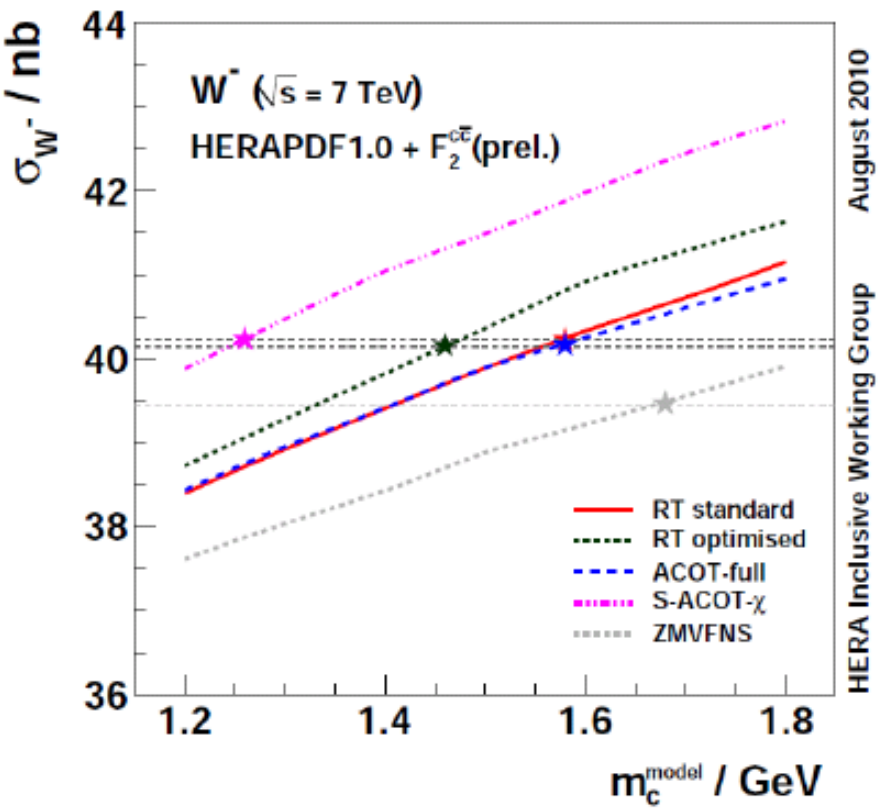


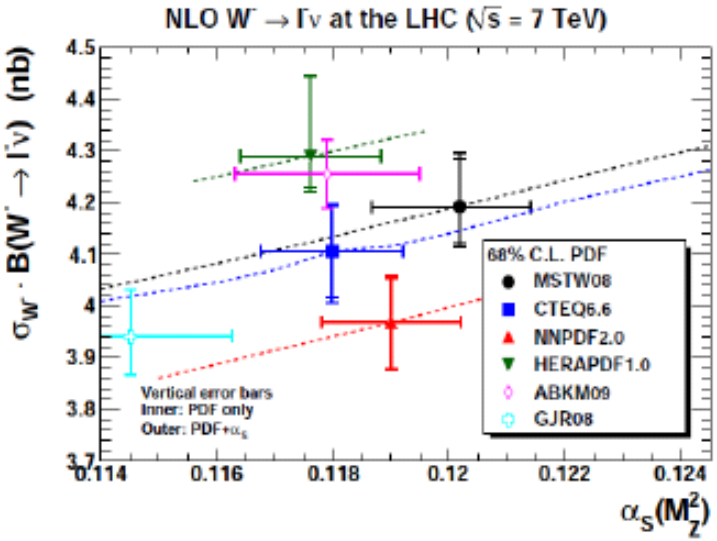


- comparison of W^+ cross sections as a function of $\alpha_S(M_Z^2)$
  G.Watt, PDF4LHC 26.03.2010

(★ indicate σ with PDFs at m_c^{model}(opt))

W^- cross section ay LHC





- comparison of W^- cross sections as a function of $\alpha_S(M_Z^2)$
G.Watt, PDF4LHC 26.03.2010

(★ indicate σ with PDFs at m_c^{model}(opt))