ICFP 2012

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The HERA Proton

Shiraz Habib

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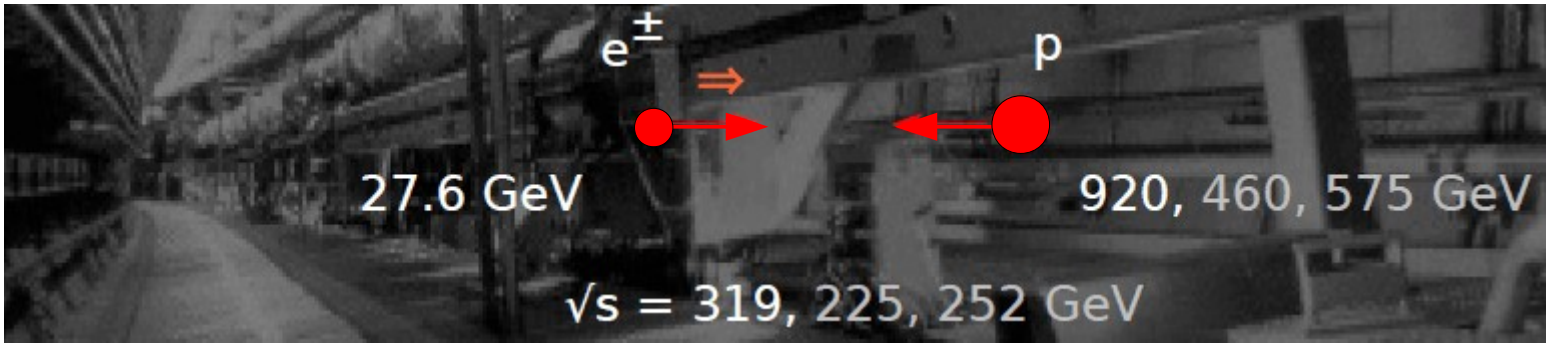
HERA **H1 & ZEUS** **Method** **Results** **Outlook**

HERA

Electron scattering offers a great tool to study the structure of the proton



$$\mathscr{L}_{P_e}\ [\text{pb}^{-1}_{\%}]$$

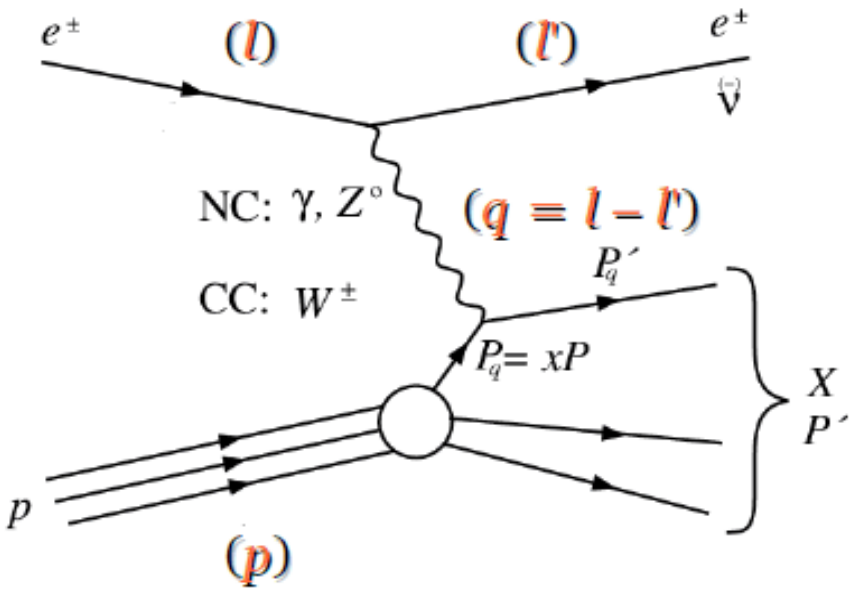
e^- :	15_{0} , 104_{-26} , 47_{+36}
e^+ :	100_{0} , 81_{-37} , 101_{+33}

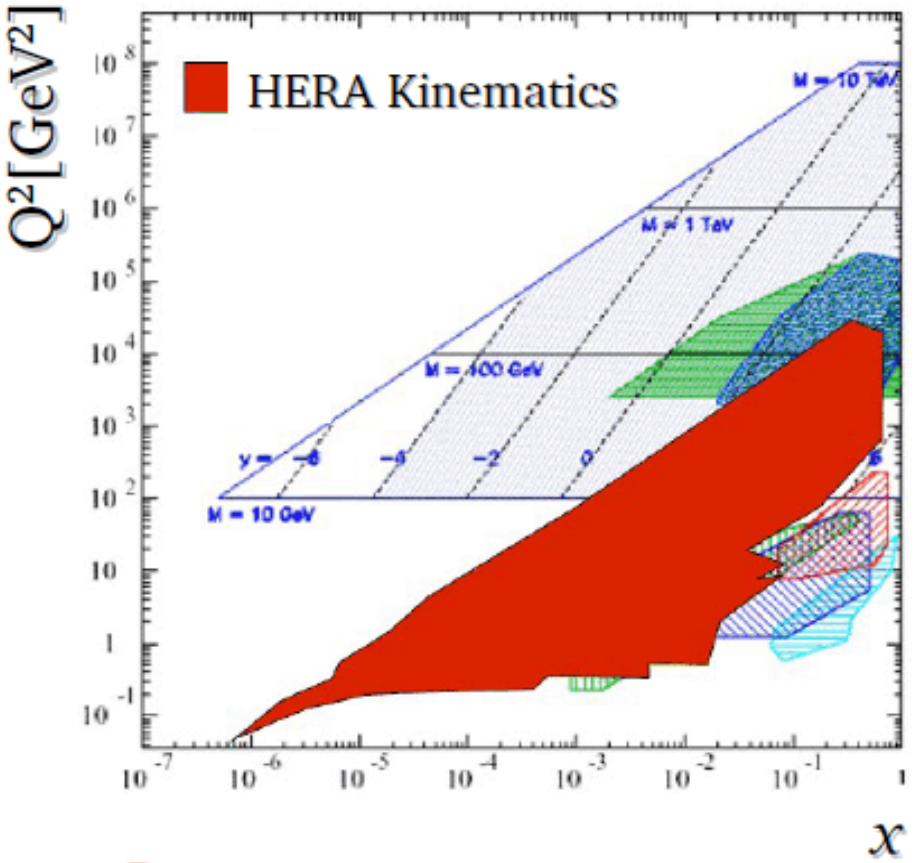
per colliding beam experiment

$$= 1\ \text{fb}^{-1}_{\text{HERA}}$$

HERA

Neutral / Charged Current DIS:
$ep \rightarrow e'X$ / $ep \rightarrow \nu X$





Kinematics

Momentum Transfer : $Q^2 = -q^2$

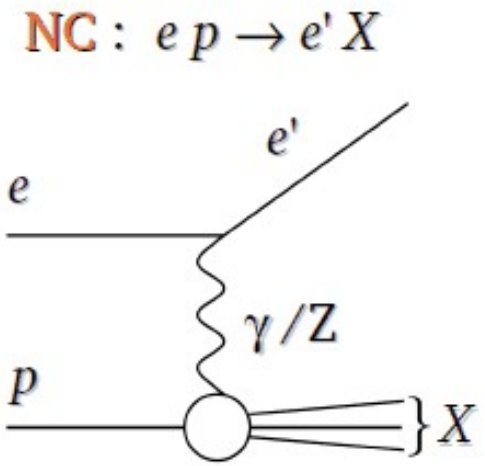
Bjorken x : $x = Q^2/(2p\cdot q)$

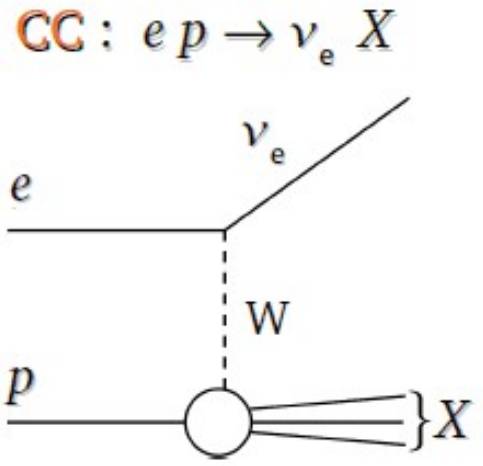
Inelasticity : $y = (p\cdot q)/(p\cdot l)$

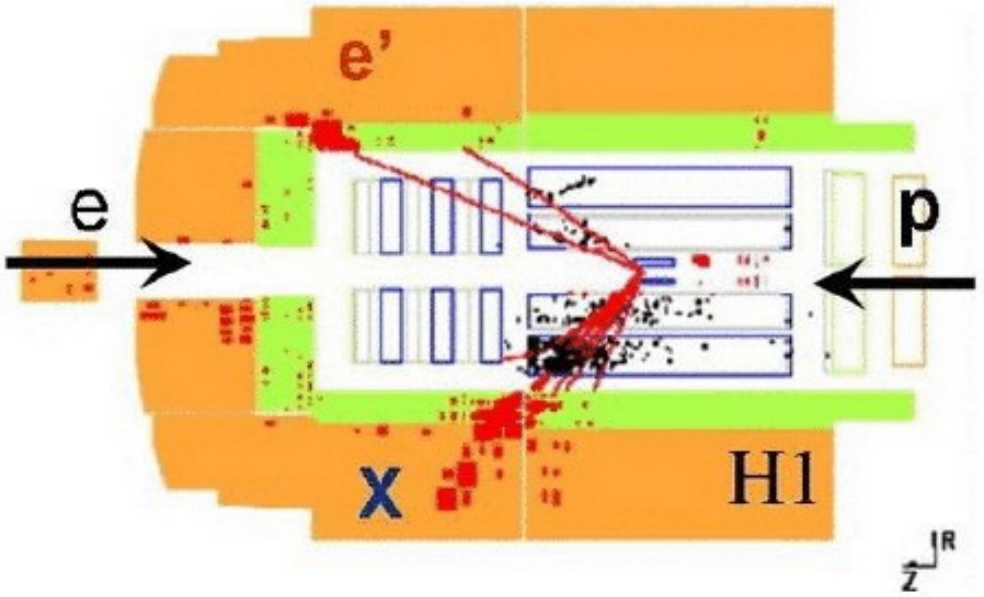
Range :
6 orders of magnitude in x and Q^2

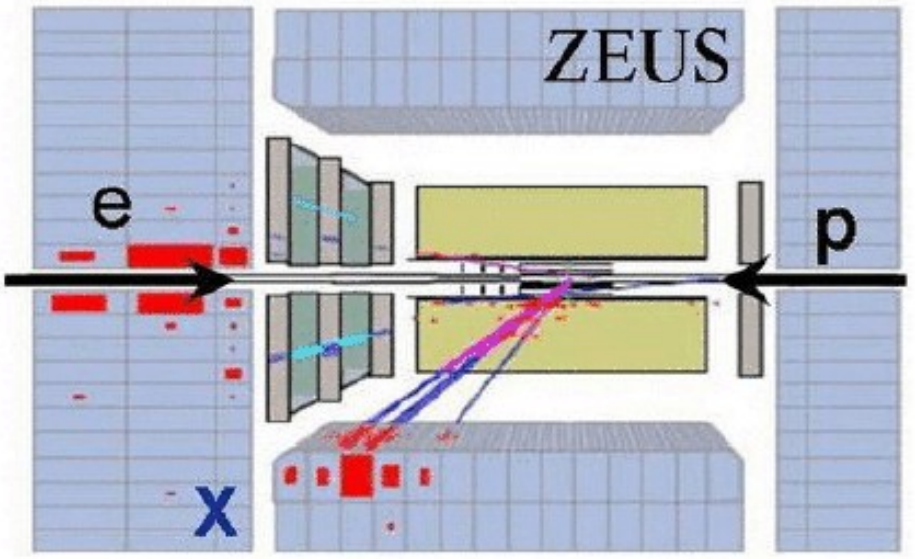
H1 and ZEUS

ep collisions observed by the **H1** and **ZEUS** experiments

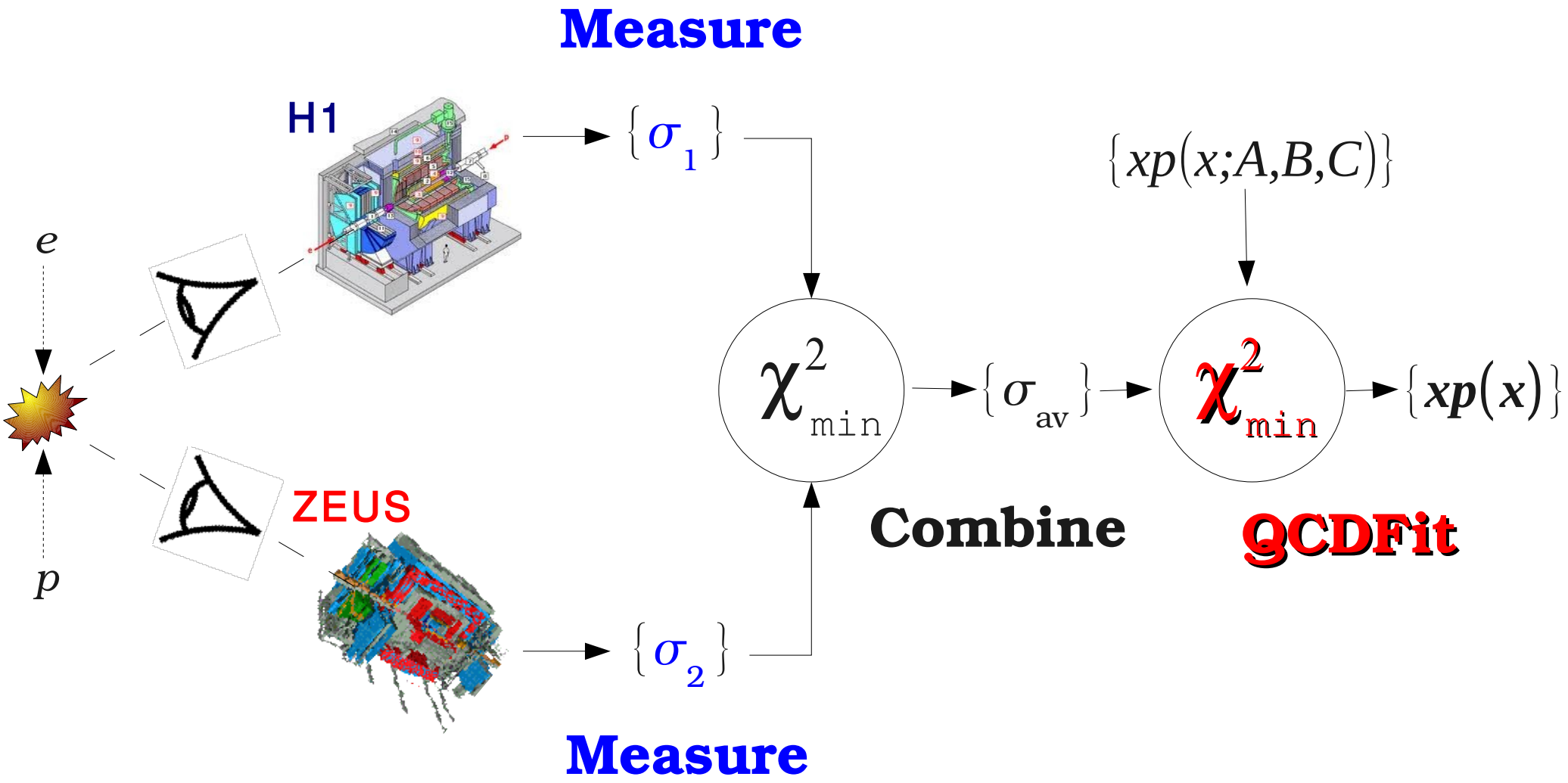








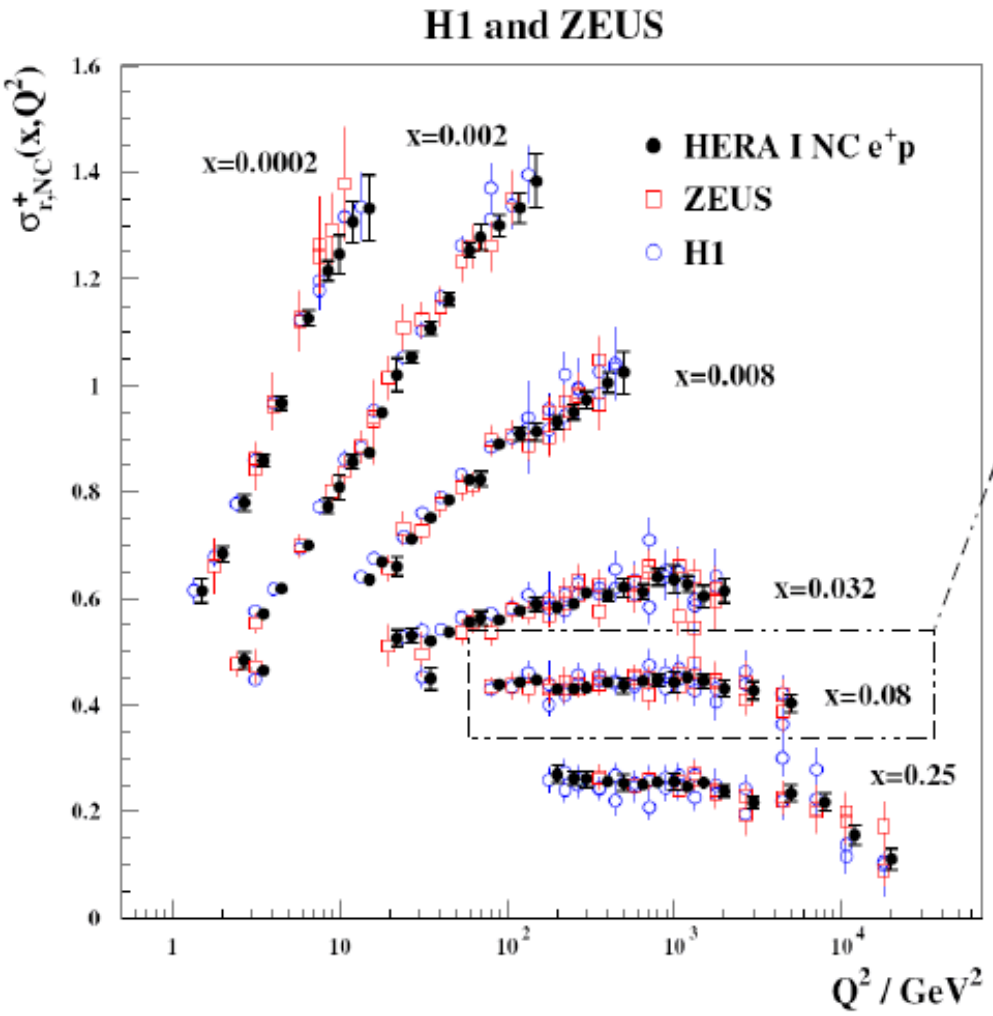
Method: Measuring, Combining and QCD Fitting

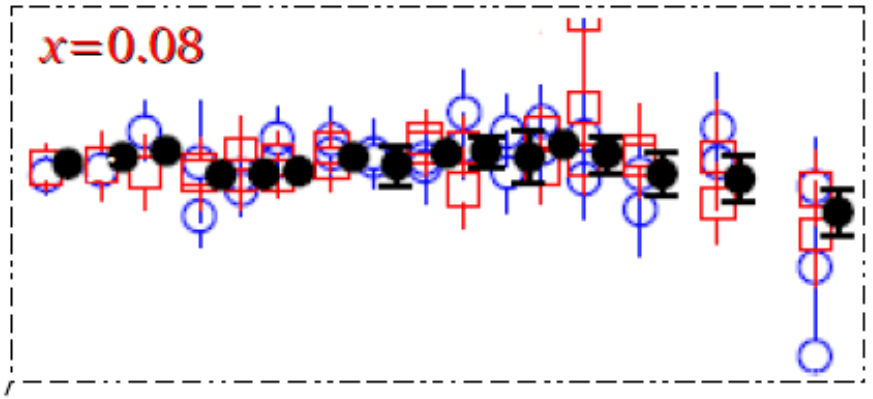


Results: HERA Inclusive **Combined** Cross Sections [1]

H1 and ZEUS published inclusive cross sections [NC,CC $e^{\pm}p$] are combined.

- **1402** measurements with **110** correlated sources of uncertainty combined to **741** cross sections.
- χ^2 / dof = 636.5 / 656 ⇐ H1 and ZEUS Agree!





Systematic Uncertainty:

- $\delta_{\text{H1 LAR}} \rightarrow 0.45\ \delta_{\text{H1 LAR}}$
- $\delta_{\text{ZEUS BG}} \rightarrow 0.35\ \delta_{\text{ZEUS BG}}$

Overall Precision:

- 2% for $3<Q^2<500$ GeV^2
- 1% for $2<Q^2<100$ GeV^2

Results: **HERAPDF1.0** QCD Fit [1]

Data

The HERA Inclusive Combined Cross Sections allow the extraction of the valence, sea quark and gluon (scaling violation)

Model

PDF Evolution	:	Parameterize at $Q^2 = 1.9\ \text{GeV}^2$ and use DGLAP @ NLO to evolve to general Q^2
m_c	:	1.4 GeV
m_b	:	4.75 GeV
$\alpha_s(M_Z)$	:	0.1176
Min. Q^2 of Data	:	$3.5\ \text{GeV}^2$
Heavy Quark Coefficient Functions	:	GMVFNS Robert Thorne VFNS 2008

Parameterization, *xf(x)*

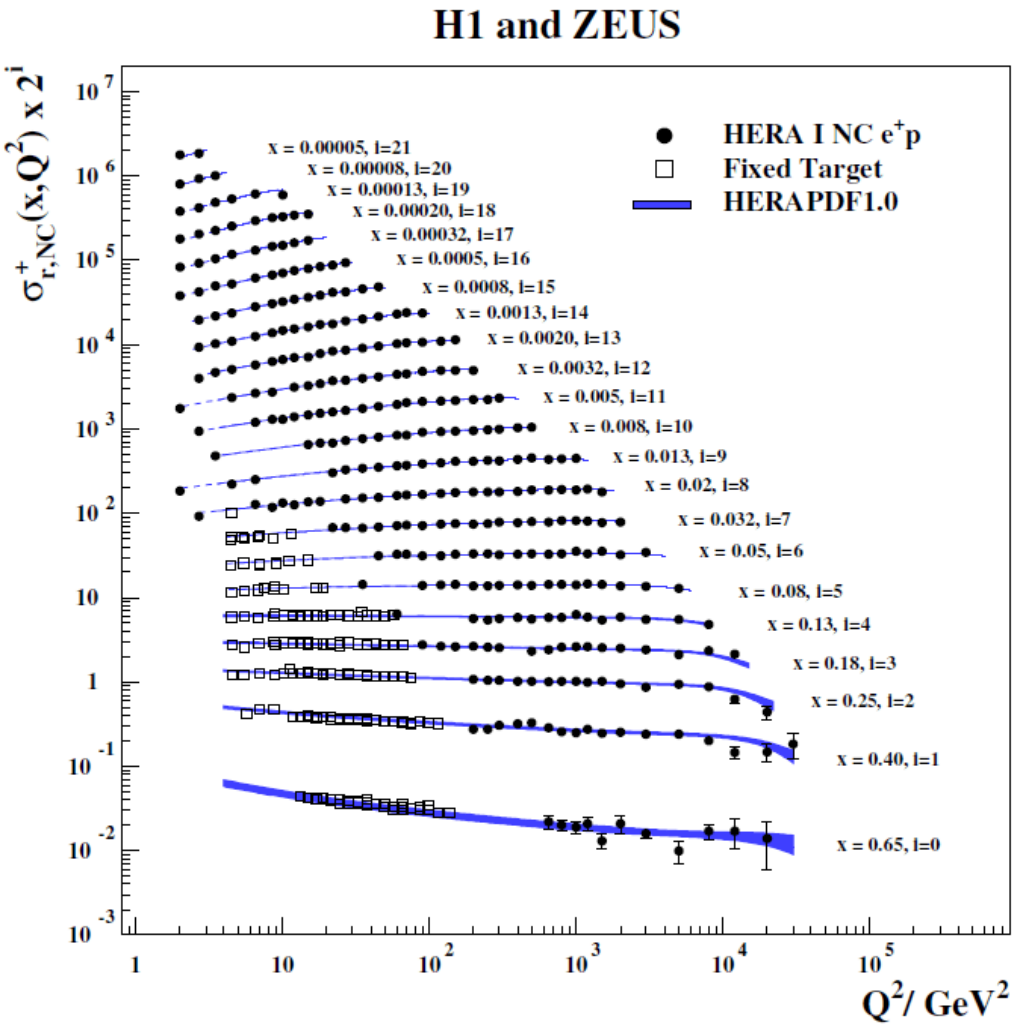
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.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

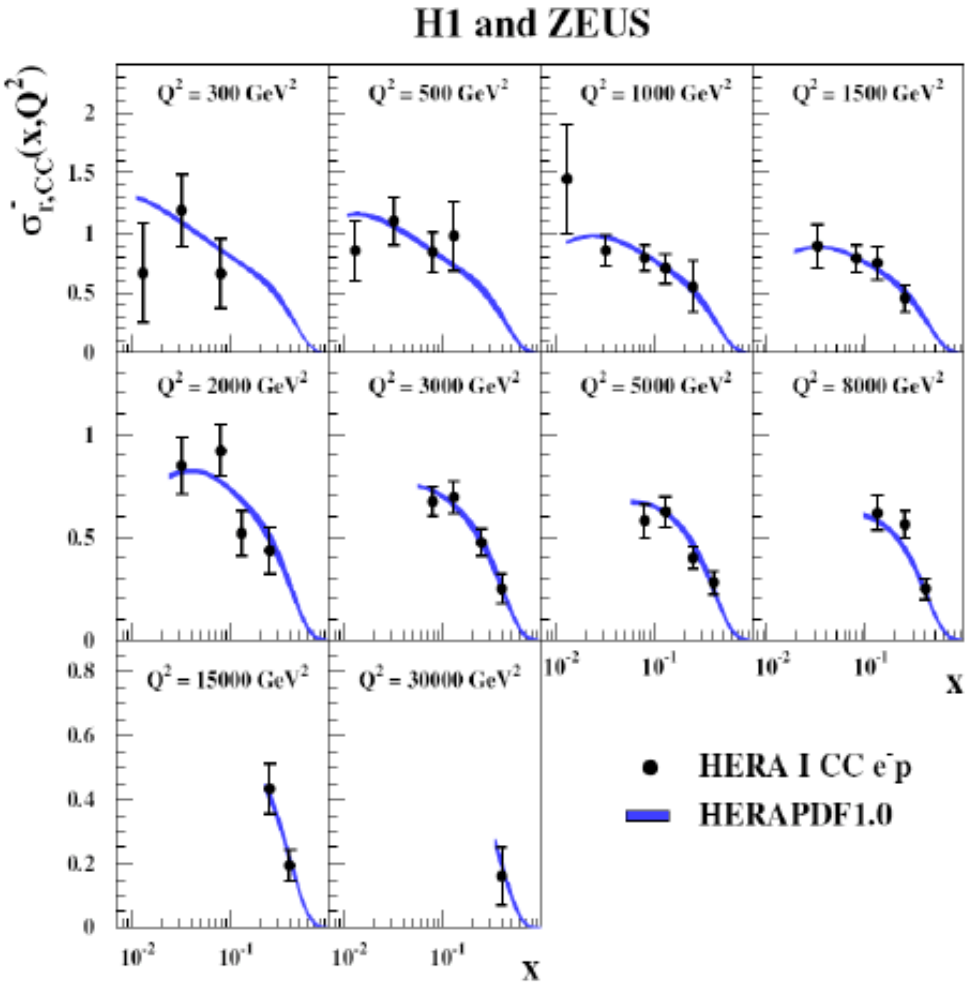
Additional Contraints:

- Quark Number Sum Rules
- Momentum Sum Rule
- $B_{\bar{U}} = B_{\bar{D}}$ & $A_{\bar{U}} = A_{\bar{D}}(1\text{-}f_s)$
  $\bar{u} \to \bar{d}$ as $x \to 0$
- $B_{u_v} = B_{d_v}$

Results: HERAPDF1.0 QCD Fit [1]

Good χ^2 / dof = 574 / 582

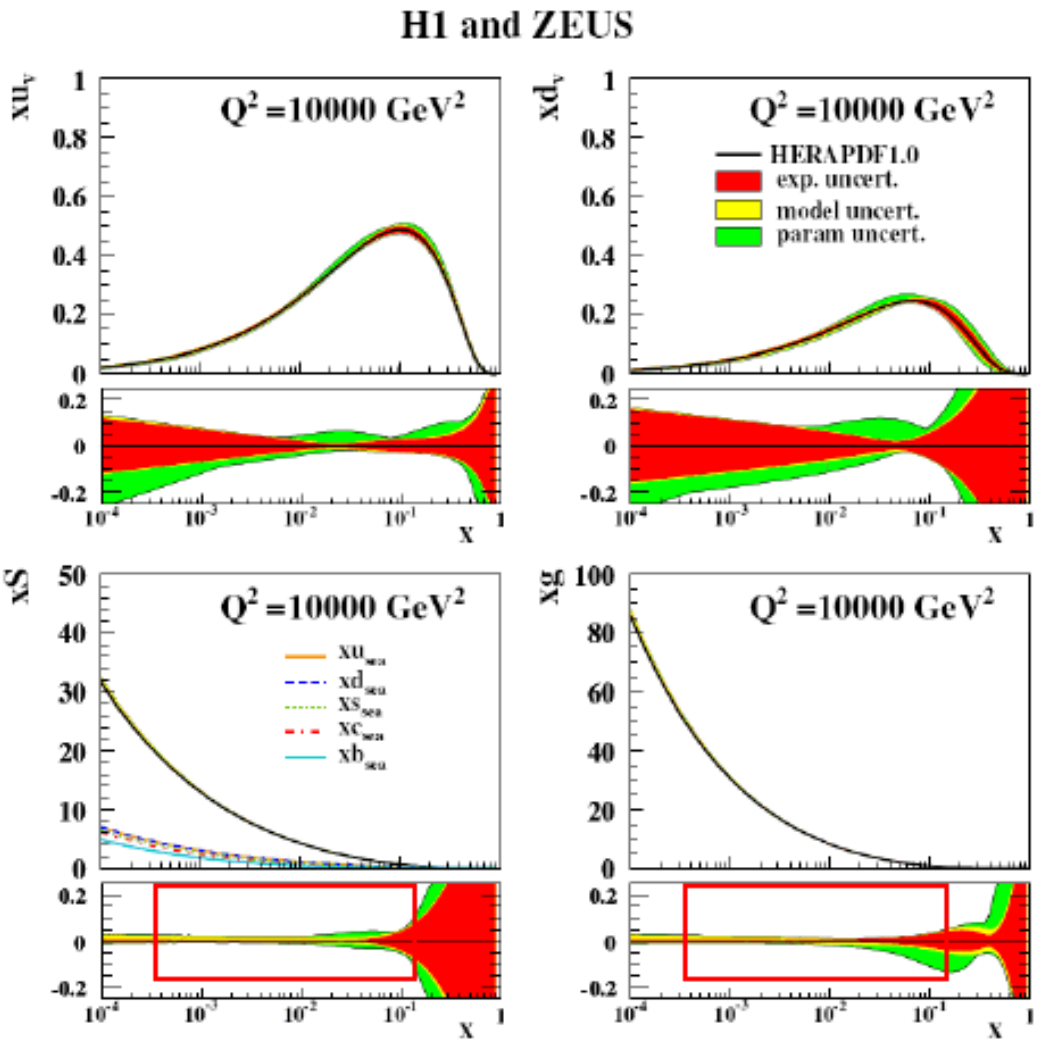




Combined NC data and CC e^-p data well described by HERAPDF1.0.

Results: **HERAPDF1.0** QCD Fit [1]

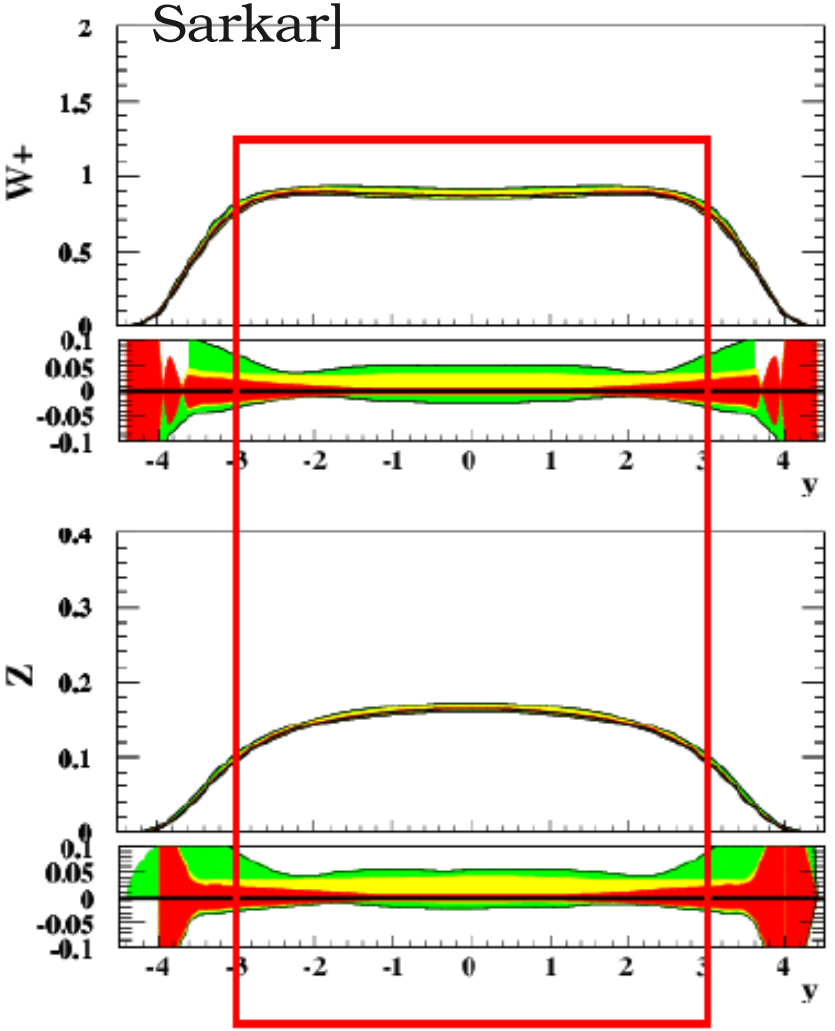
Q^2 = 10000 GeV^2 [scale relevant for W/Z production @ LHC]



Few % uncertainty for central region of LHC detector

Rapidity distribution LHC [7 TeV]

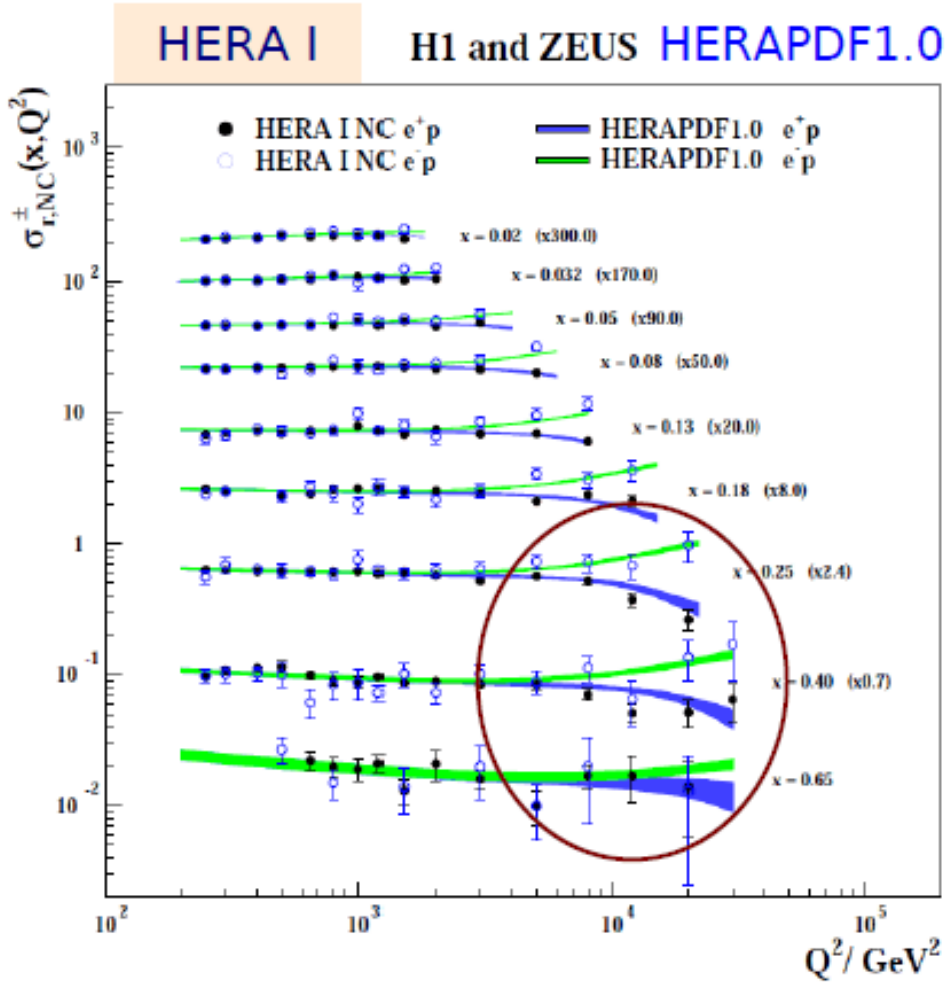
[Amanda Cooper-Sarkar]

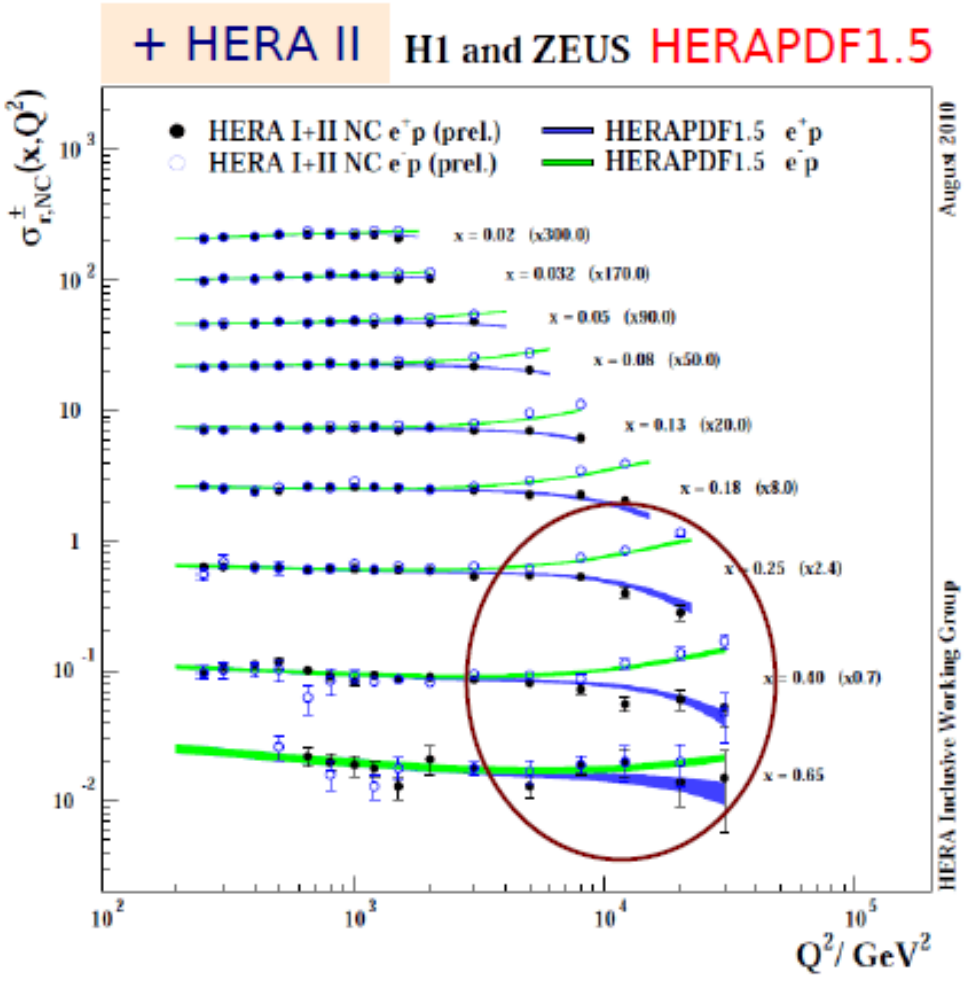


5% and better prediction

HERA II Results: HERAPDF1.5 QCD Fit [1b]

HERAPDF1.0: combined inclusive HERA I [NLO]
HERAPDF1.5: combined inclusive HERA I and HERA II data [NLO, NNLO]

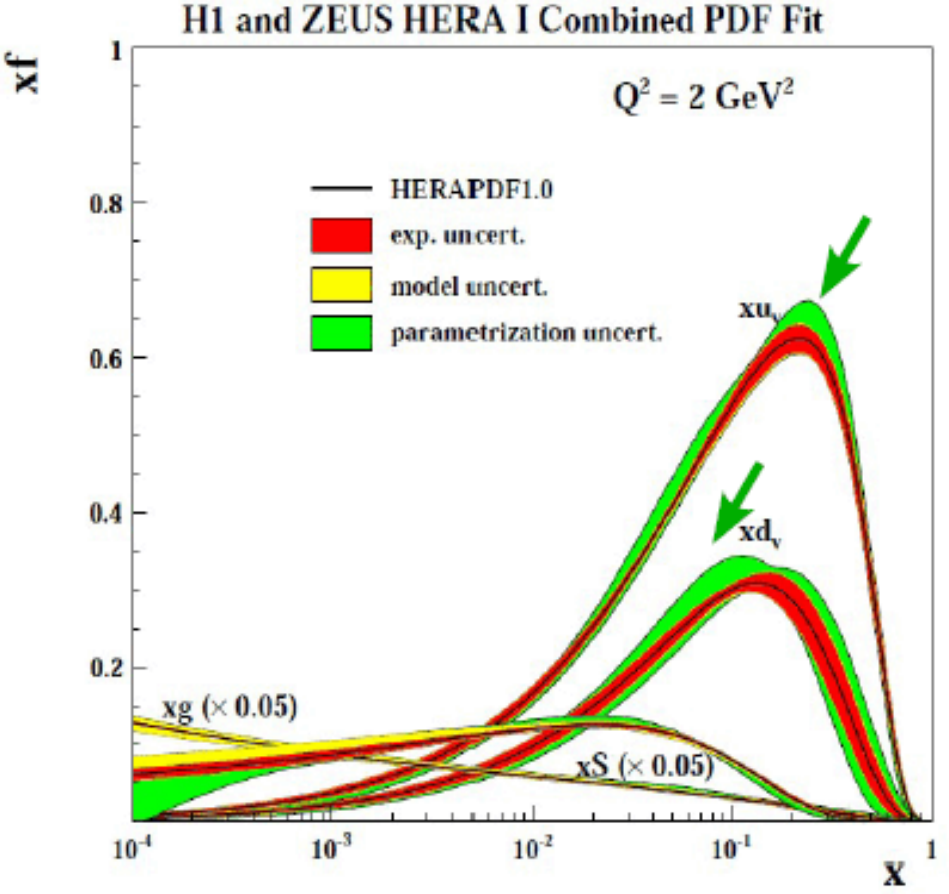




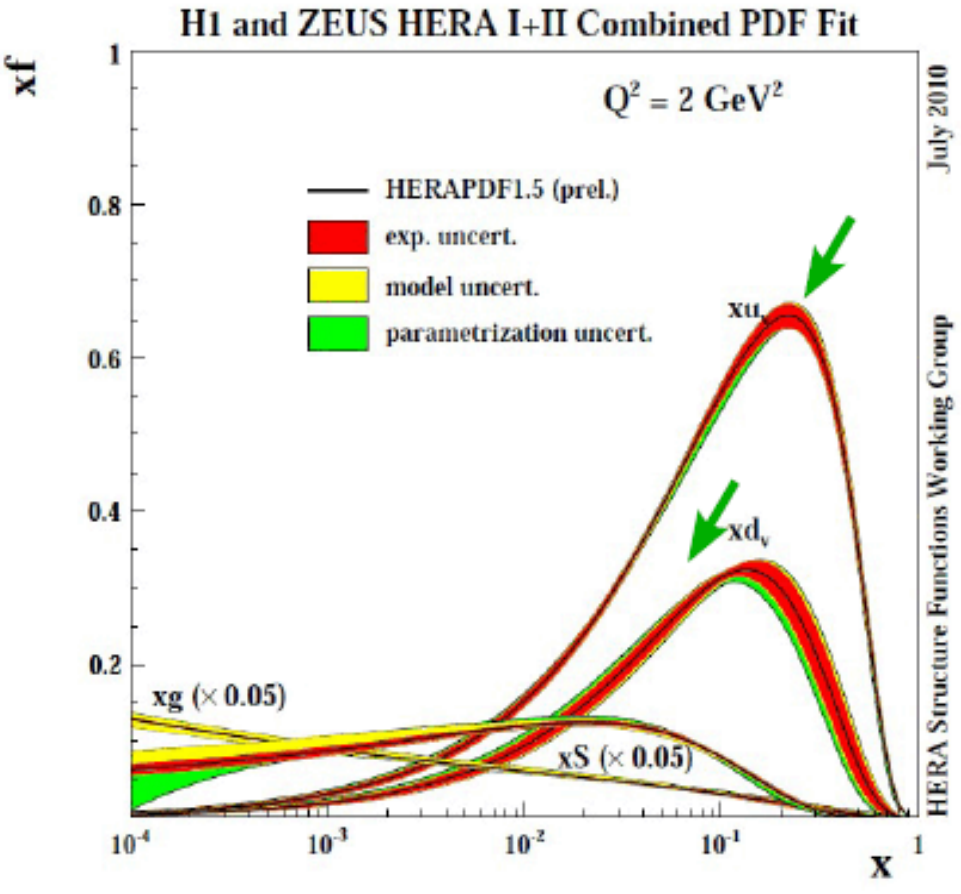
Improved data precision → Improved PDFs

HERA II Results: HERAPDF1.5 QCD Fit [1b]

HERAPDF1.0



HERAPDF1.5



Better constrained valence quarks

Reduced experimental and parametrisation uncertainties

HERA II Results: First $F_2^{\gamma Z}$ measurement [2–H1]

$F_2^{\gamma Z}$ structure function offers different sensitivities to the PDFs through couplings to Z^0.

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

NC Cross Section in terms of the Proton Structure Functions:

$$\frac{\mathrm{d}^2\sigma_{\mathrm{NC}}^{\pm}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2 - y^2\tilde{F}_L \mp Y_- x\tilde{F}_3)$$

Proton Structure Functions :
($q(x,Q^2)$, $g(x,Q^2)$)

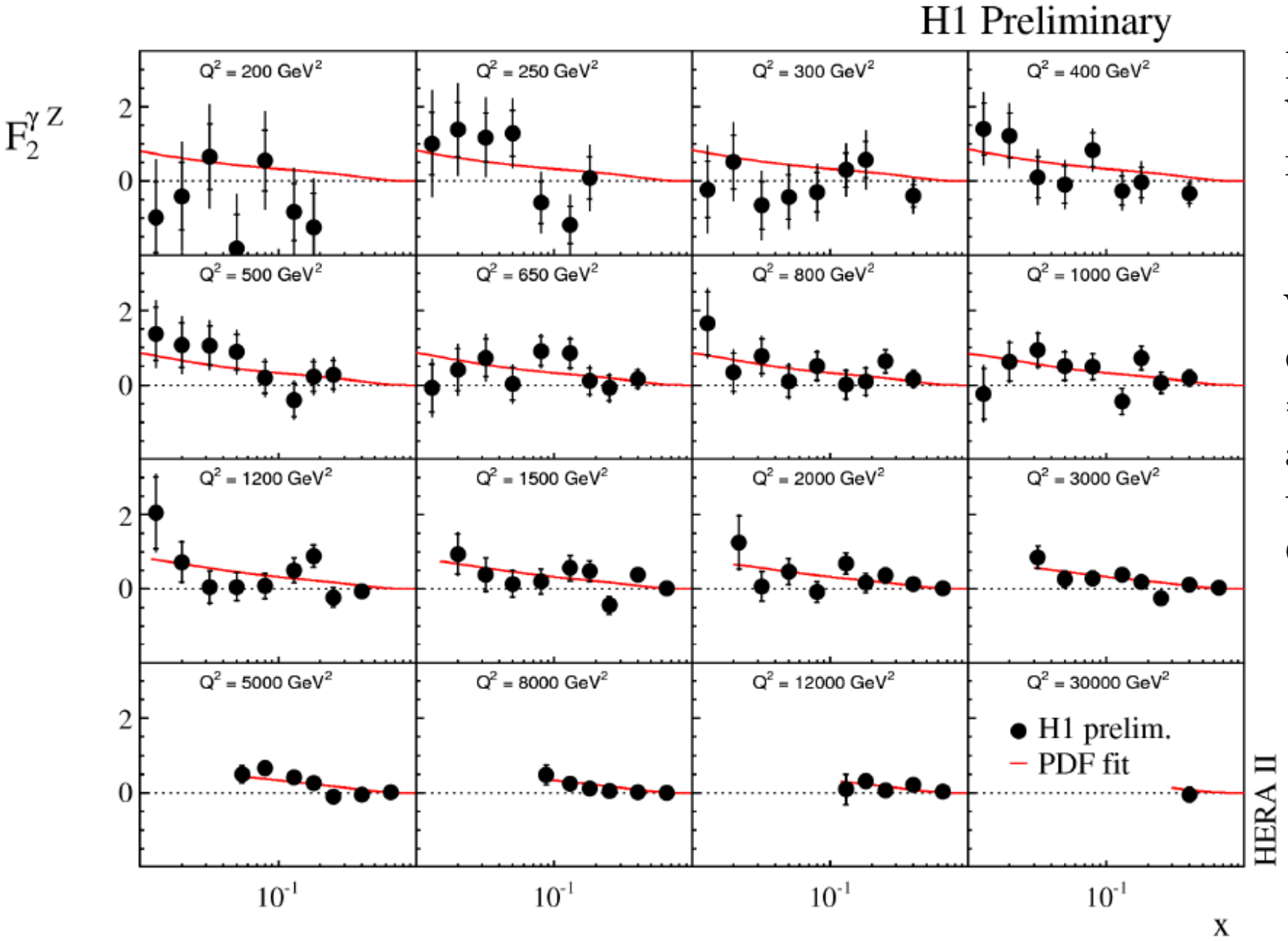
Measured at H1exploiting the polarization dependence of the $e^{\pm}p$ cross sections.

$$\frac{\sigma^{\pm}(P_L) - \sigma^{\pm}(P_R)}{P_L - P_R} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2 + M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$

Beam charge dependent term

Beam charge independent term

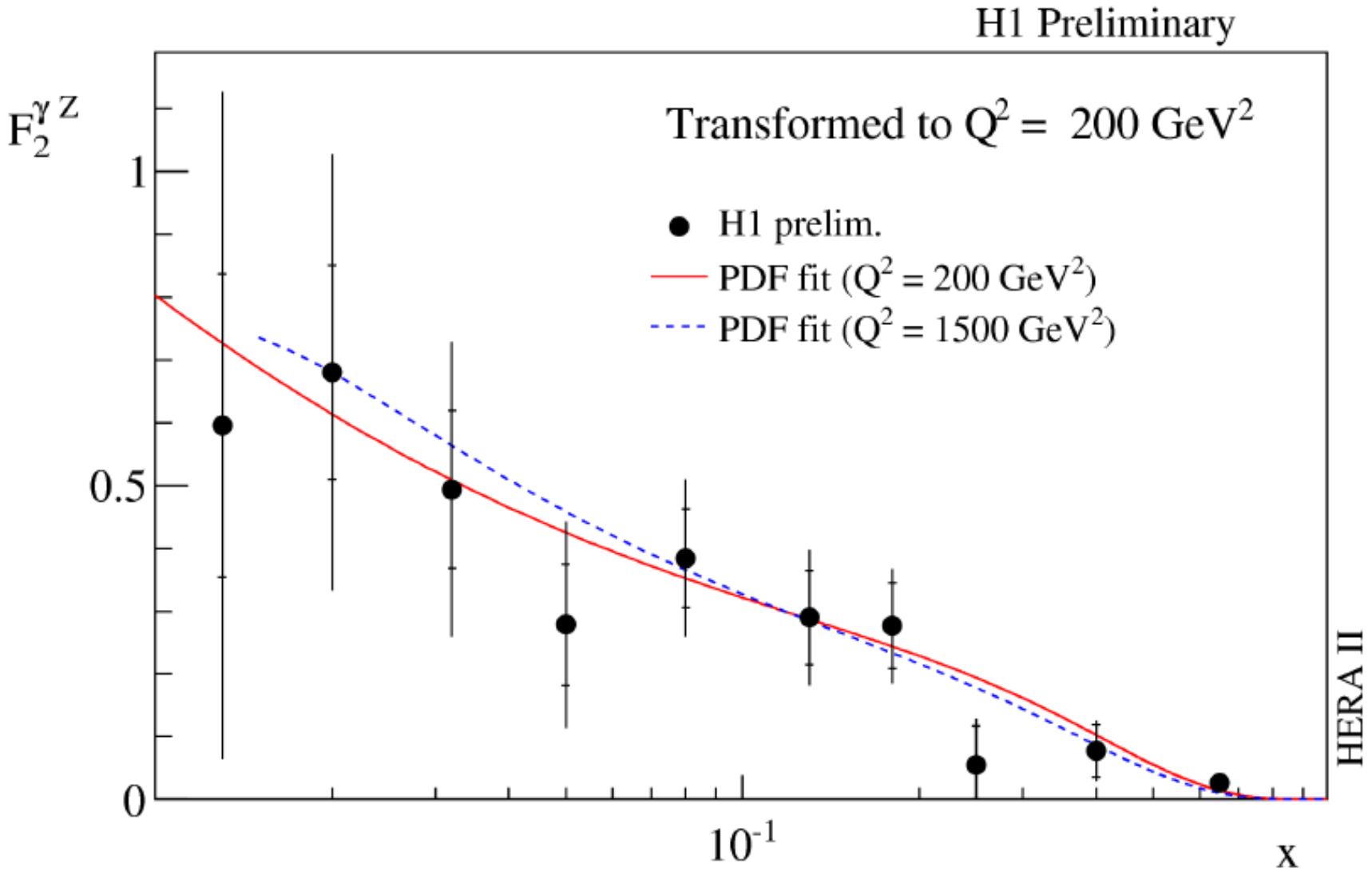
HERA II Results: First $F_2^{\gamma Z}$ measurement [2–H1]



Described by PDF fit

Weak Q^2 dependence ⇒ Transform and average to Q^2 = 200 GeV^2

HERA II Results: First $F_2^{\gamma Z}$ measurement [2–H1]

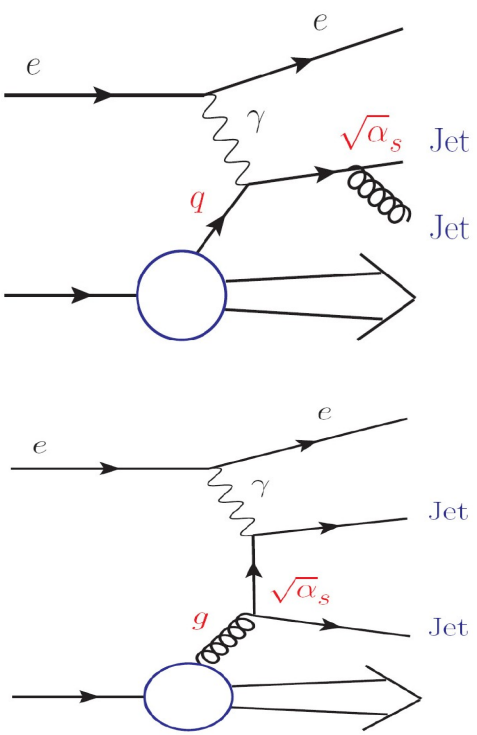


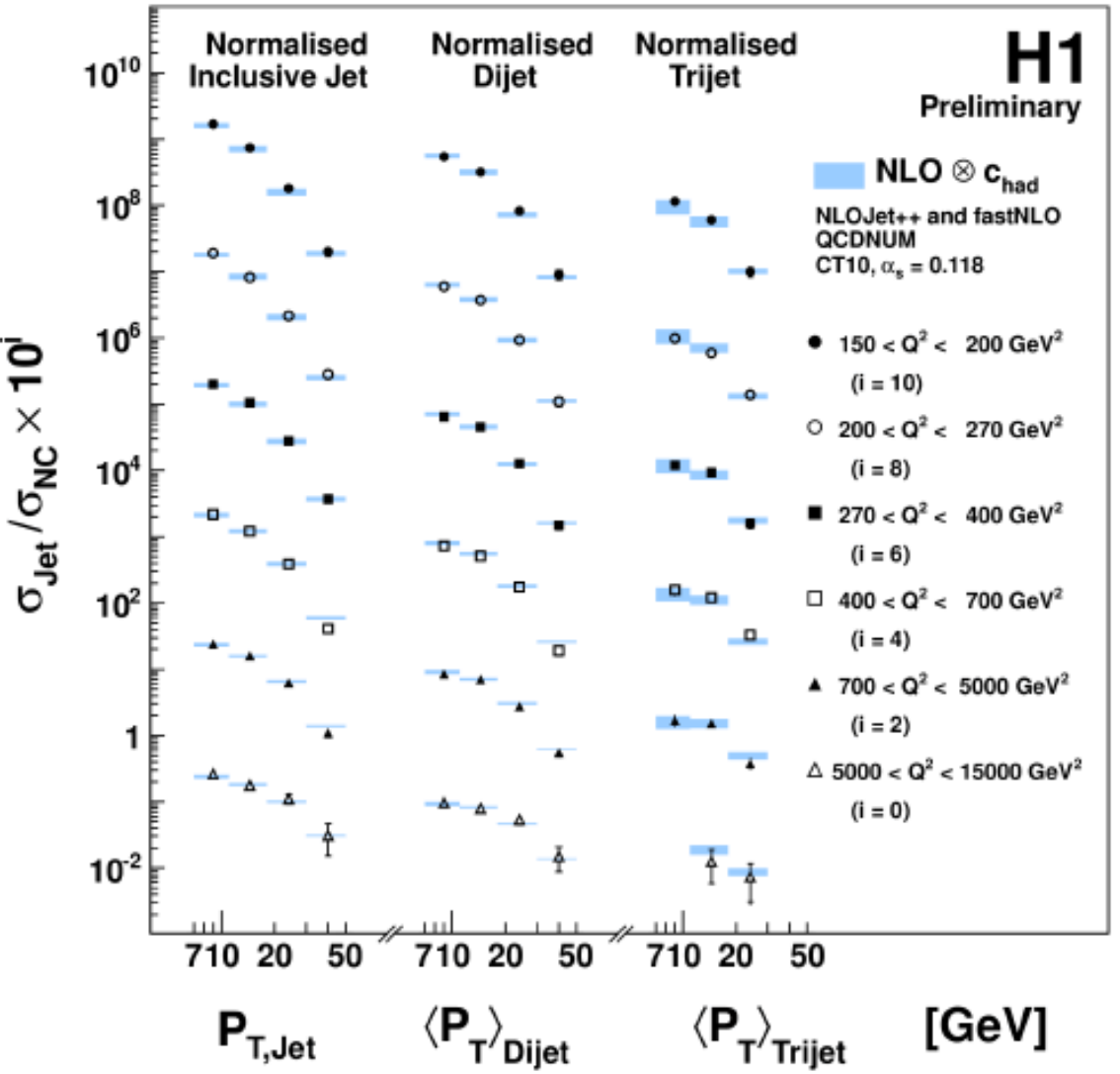
Described by PDF fit

HERA II Results: Including **Jet** Data [3–H1,4–ZEUS]

Jet data constrains the gluon and the PDFs at high x.

H1 measured the **DIS** Jet cross sections (sigle-, dijet and trijet) normalized to the NC inclusive measurement





- very good statistical precision
- low systematic uncertainty
- in good agreement with a prediction from NLO QCD

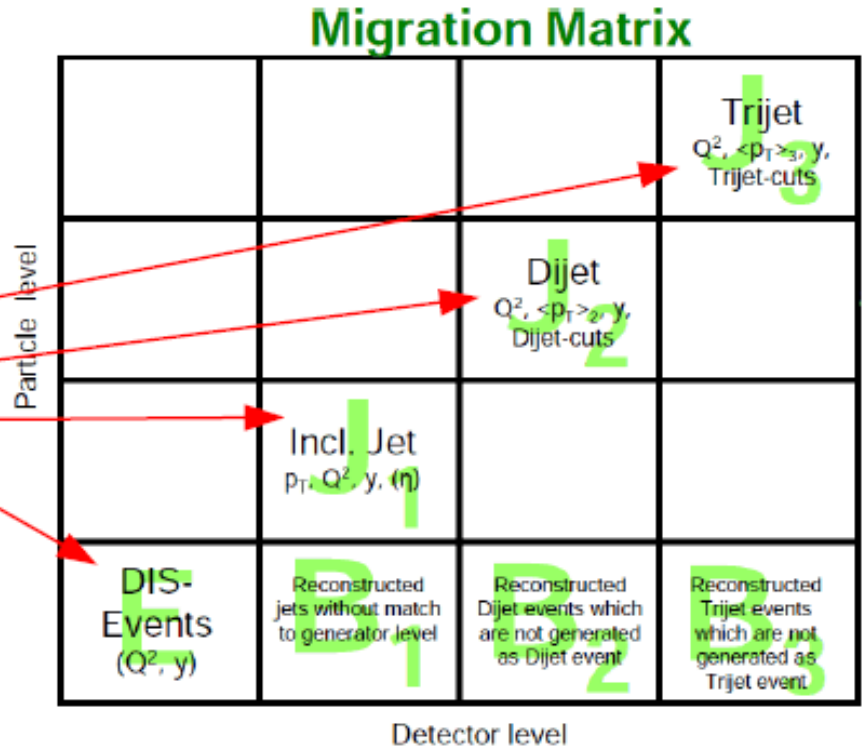
HERA II Results: Including **Jet** Data [3–H1,4–ZEUS]

Unfolding method employed to extract multi-jet cross sections in order to reduce model uncertainty

Simultaneous extraction of:

Trijet cross sections
Dijet cross sections
Inclusive jet cross sections
Inclusive DIS cross sections

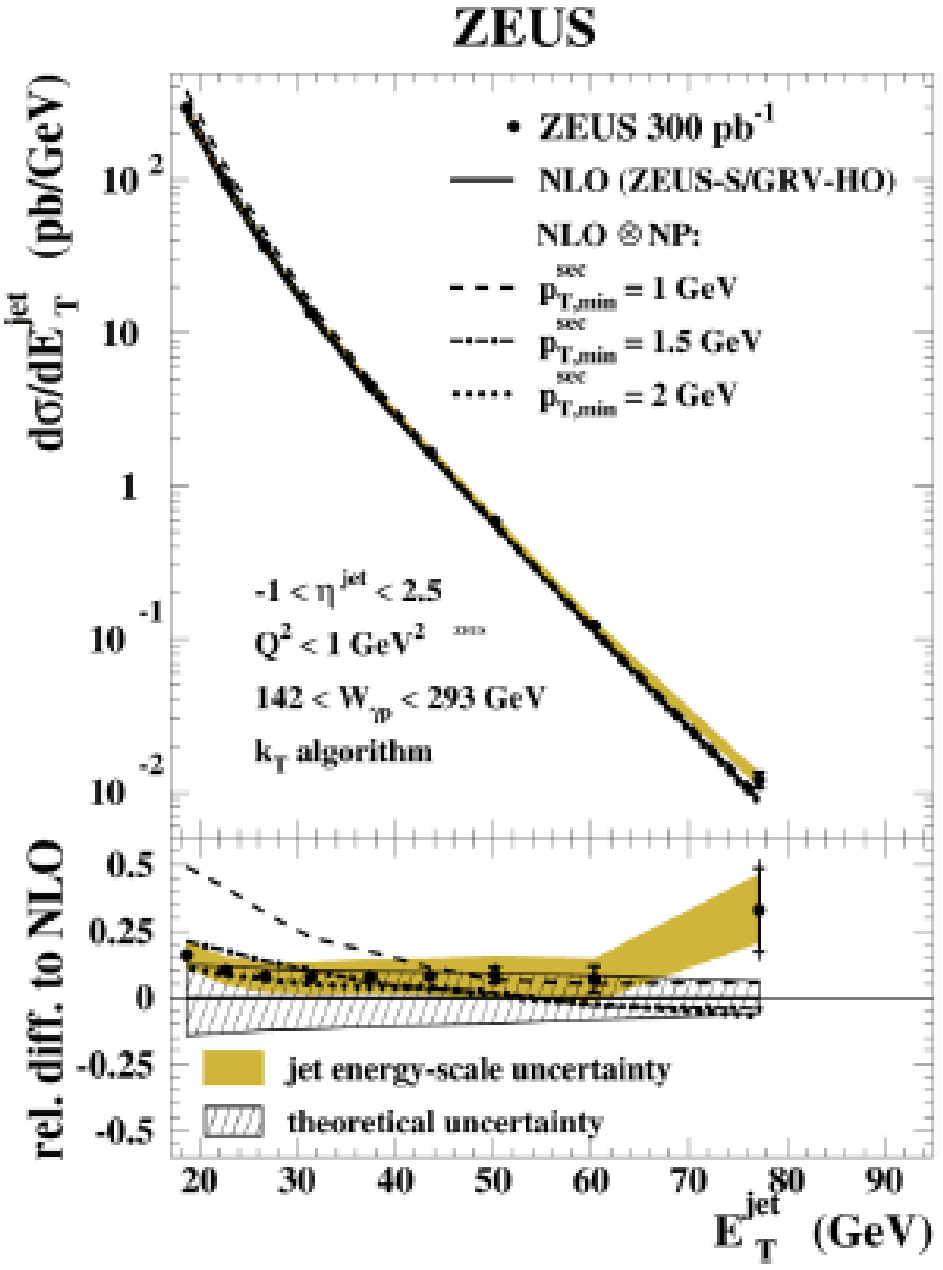
Full correlation matrix calculated (important for fits)



HERA II Results: Including **Jet** Data [3–H1,4–ZEUS]

Photoproduction

- Measurement of jet cross sections in γp using k_T, anti-k_T and SIScone jet algorithm.
- Stringent test of new algorithms

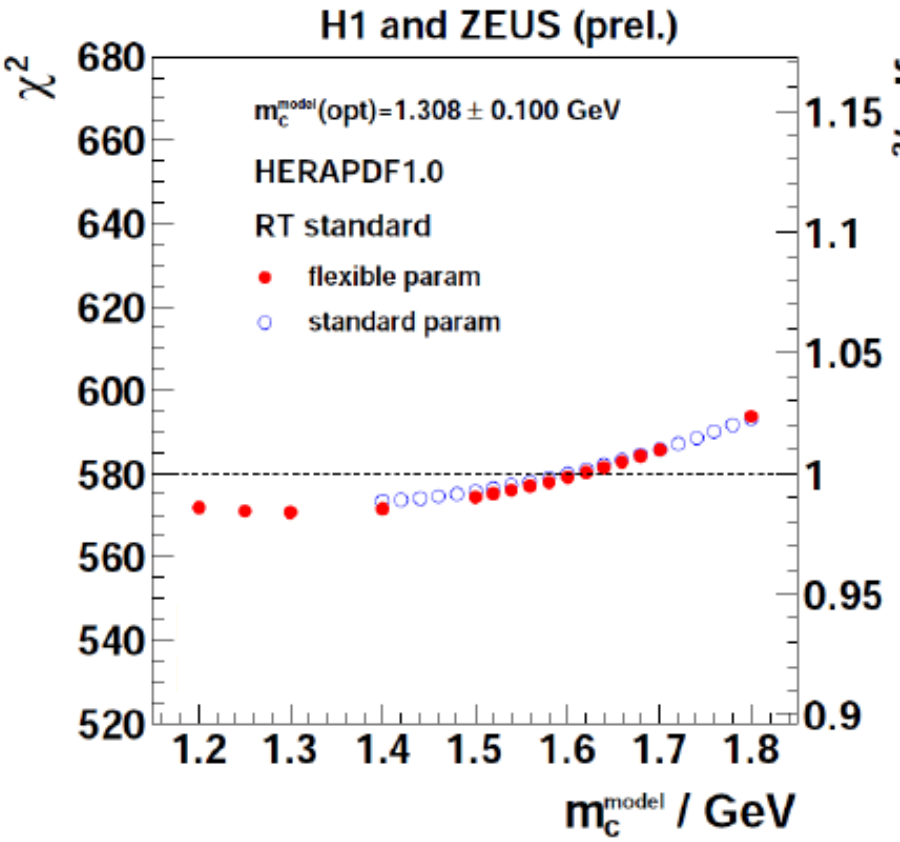


HERA II Results: Including **Charm** Data [5,6]

Charm is produced via $\gamma g \to c\bar{c}$: charm measurements constrains the gluon

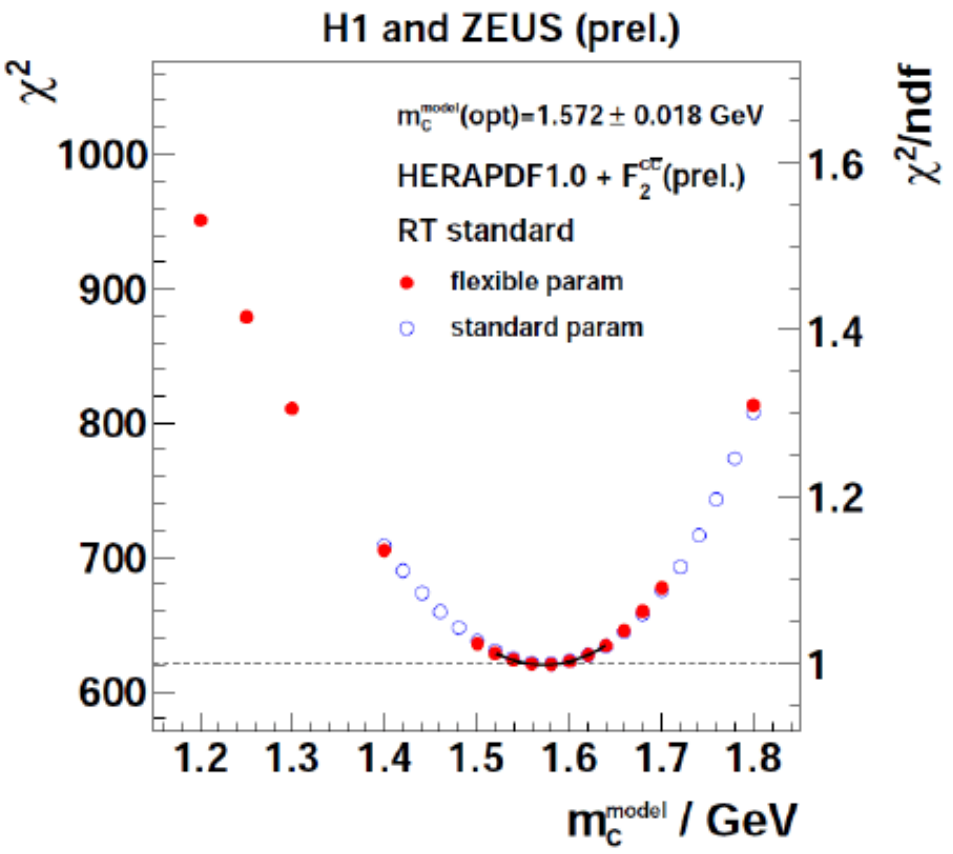
H1,ZEUS (D* , Displaced Tracks, Semi-leptonic decays) ⇒ Combined $F_2^{c\bar{c}}$

Inclusive Data Only



No sensitivity to charm mass

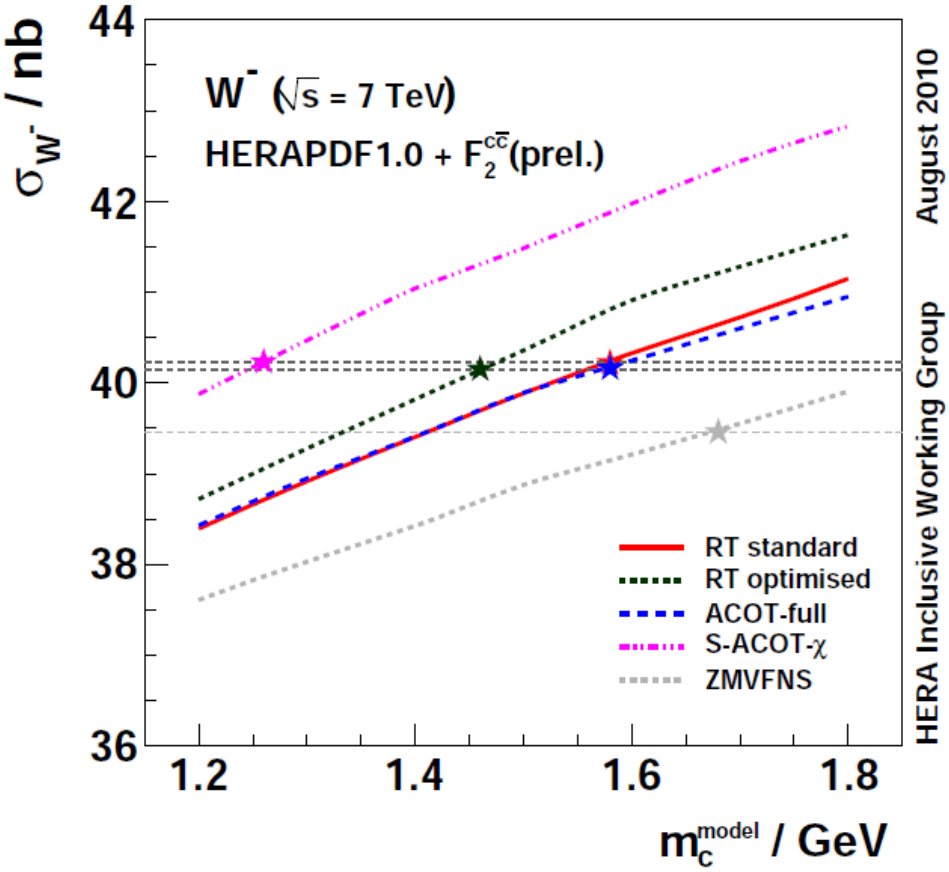
Inclusive + Charm Data

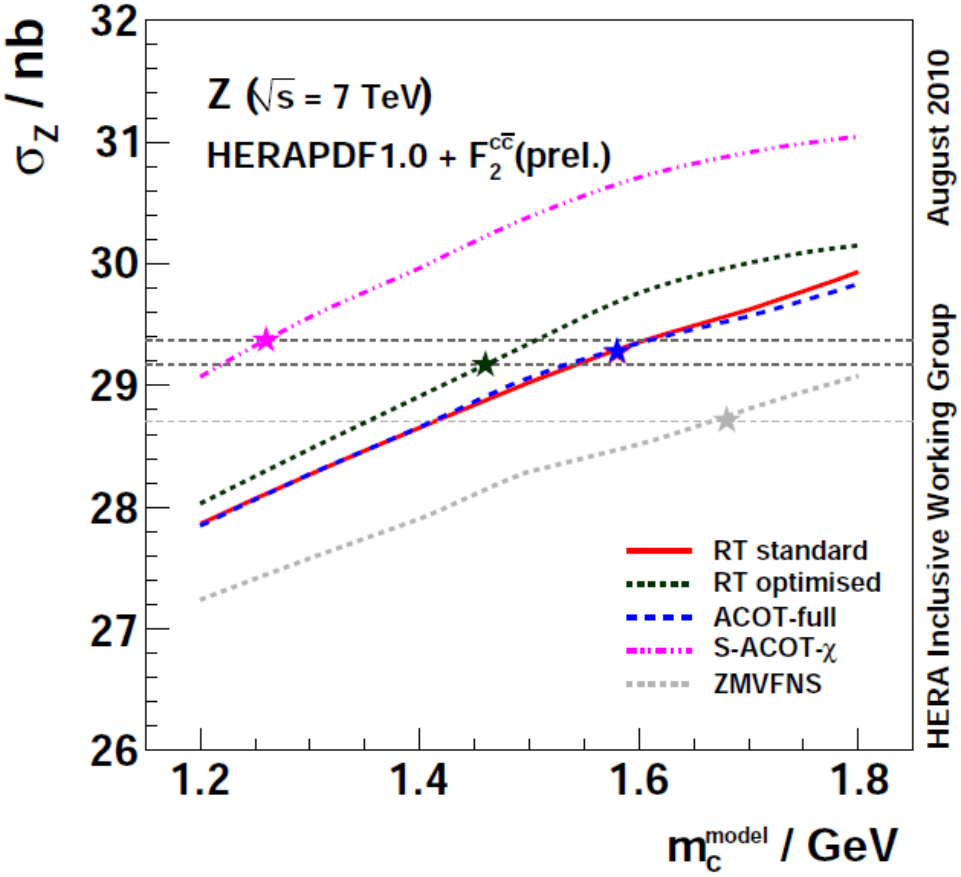


Clear sensitivity to charm mass

HERA II Results: Including **Charm** Data [5,6]

W and Z production at LHC





Agreement of cross sections is much better using each HF treatment's optimum charm mass than if they all agreed to use a common value.

Conclusion:

The measurers, combiners and fitters work together to provide one of the most complete and accurate pictures we have of the proton.

Outlook:

HERAPDF2.0

Thank You

References:

[1] DESY 09-158

[1b] H1prelim-10-141, ZEUS-prel-10-017,
H1prelim-10-142, ZEUS-prel-10-018,
H1prelim-11-042, ZEUS-prel-11-002

[2–H1] H1prelim-12-142

[3–H1] H1prelim-12-031

[4–ZEUS] DESY-12-045

[5] H1prelim-09-171, ZEUS-prel-09-015

[6] H1prelim-10-143, ZEUS-prel-10-019