Proton Structure from HERA

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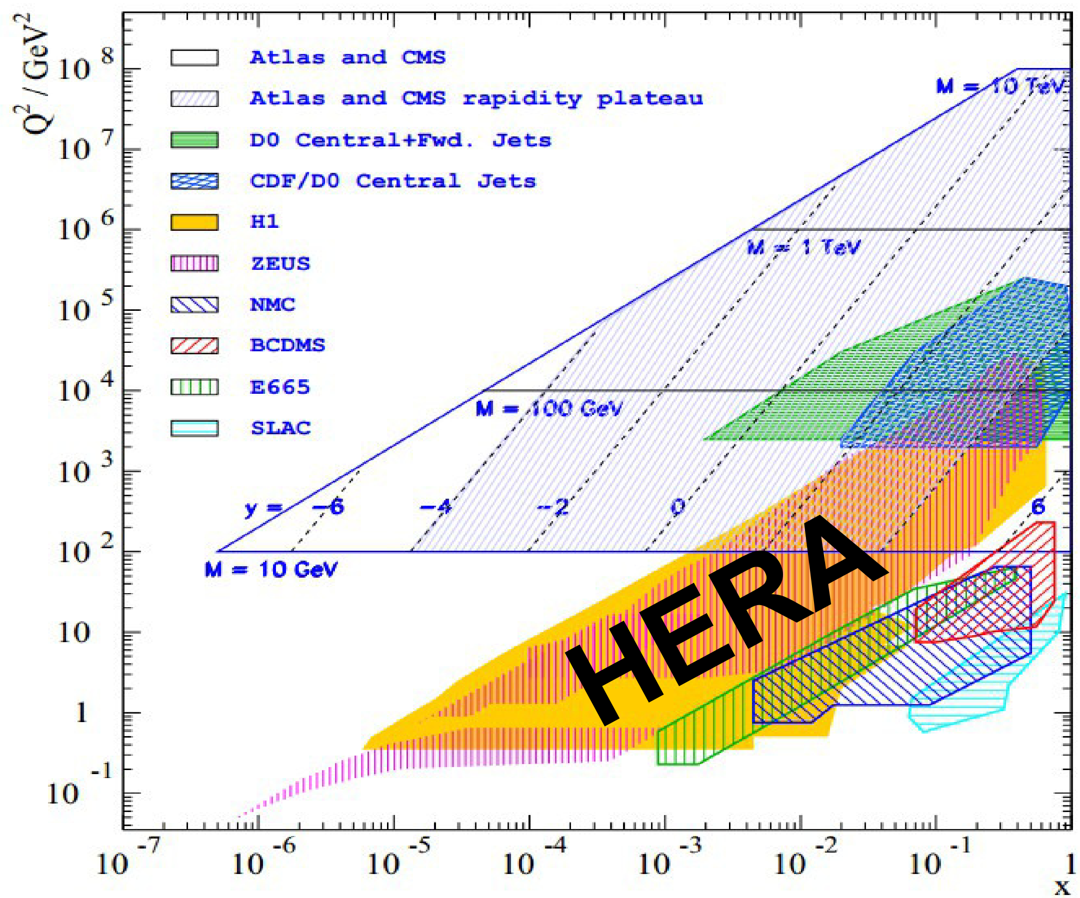
DESY
(on behalf of H1 and ZEUS collaborations)

ISMD conference
Bologna, Italy 2014

HERA collider

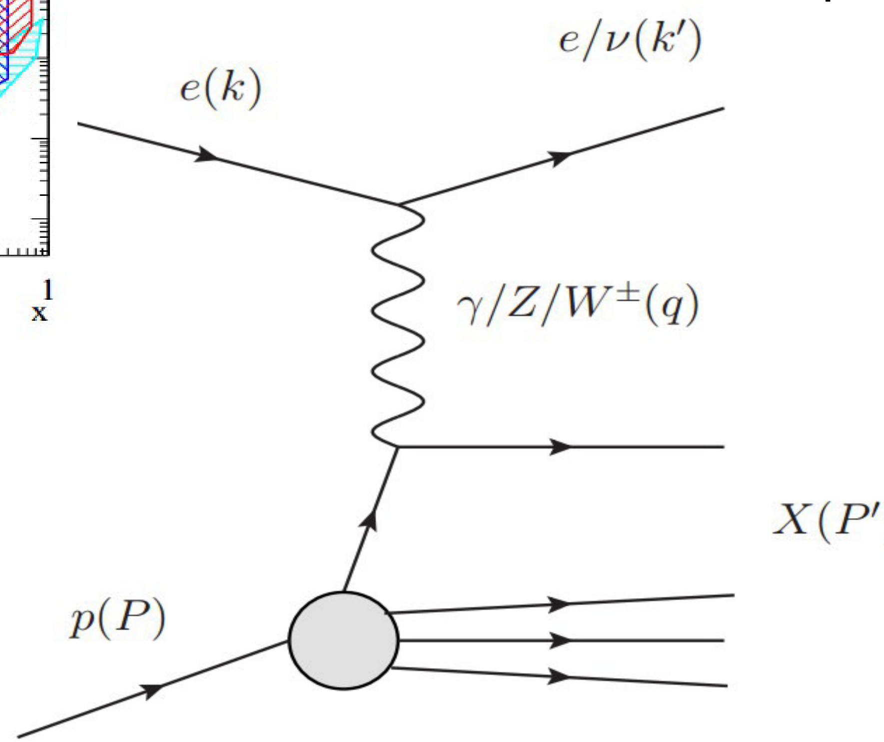


$$E_P = 920\,(460, 575)\,GeV$$
$$E_e = 27.5\,GeV$$

$$\sqrt{s} = 318\,(225, 252)\,GeV$$

Experimental achievements:

~ $0.5 fb^{-1}$ DIS data from each experiment



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

$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

$$s = (p + k)^2 \qquad Q^2 = xys$$

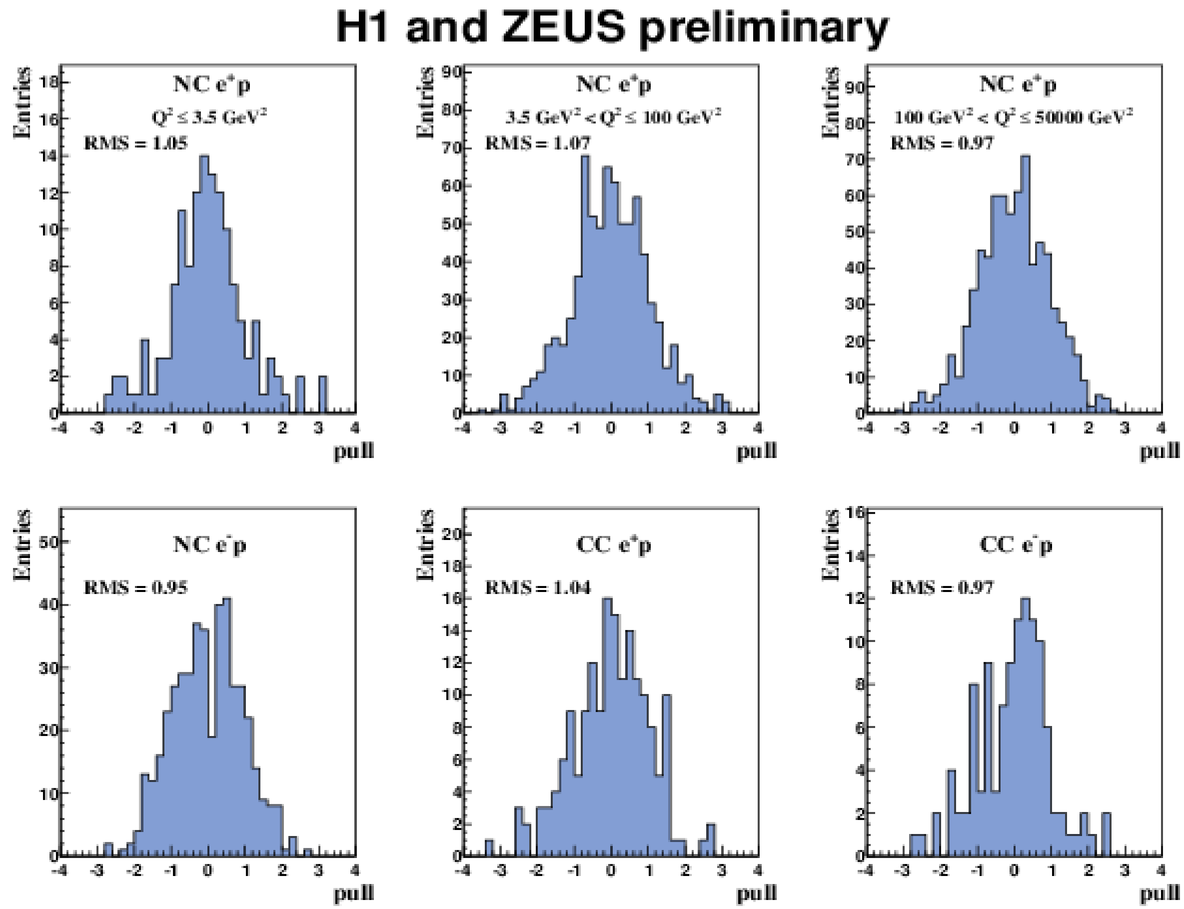
Combining measurements

- All inclusive DIS results are final and published!

2927 original measurements

1307 averaged measurements

$$p^{i,k} = \frac{\mu^{i,k} - \mu^{i,ave}\left(1 - \sum_j \gamma_j^{i,k} b_{j,ave}\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_{i,ave}^2}}$$



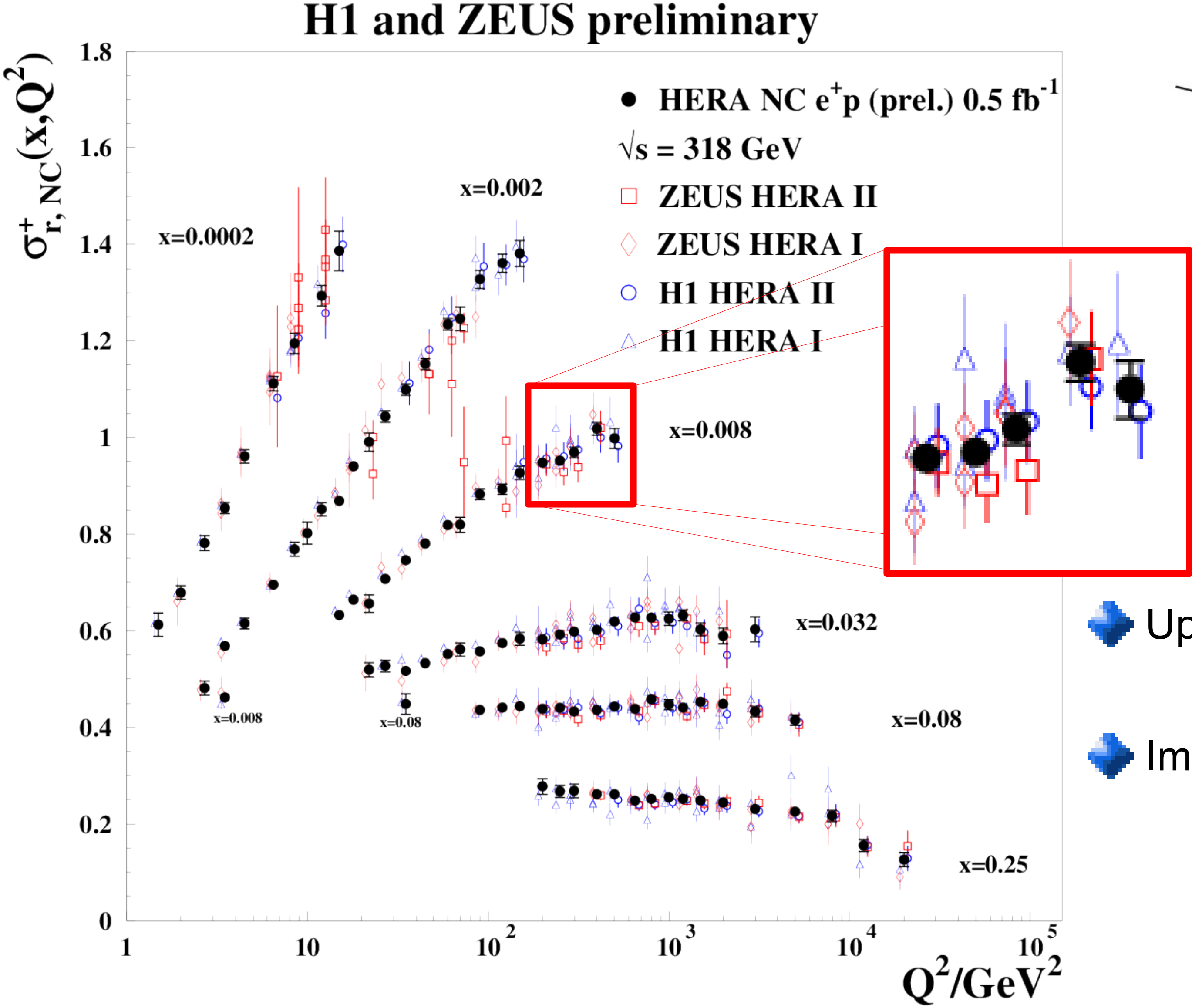
Consistant data sets: total χ^2/ndf = 1685/1620.

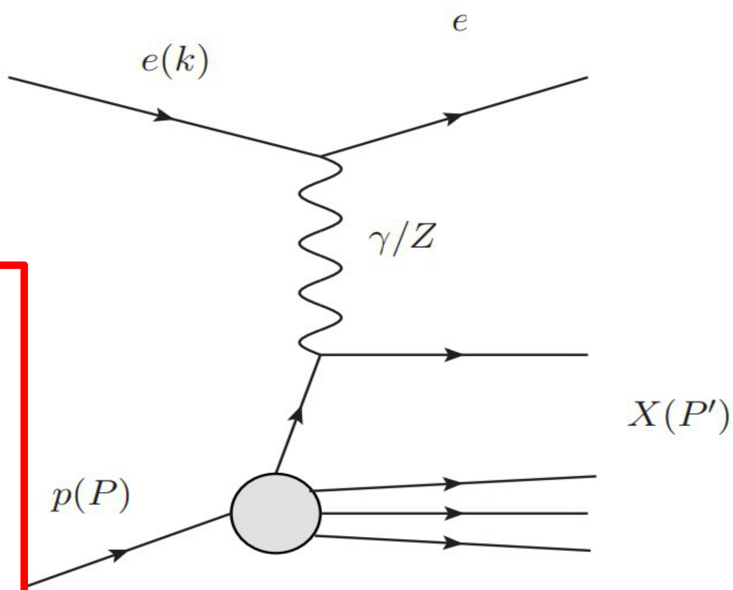
- Correlations of systematic uncertainties considered.
- Procedural uncertainties ~ 1%.

Combined reduced cross-sections

$$\sigma^{\pm}_{r,NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x \tilde{F}_3 - \frac{y^2}{Y_+} \tilde{F}_L$$

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



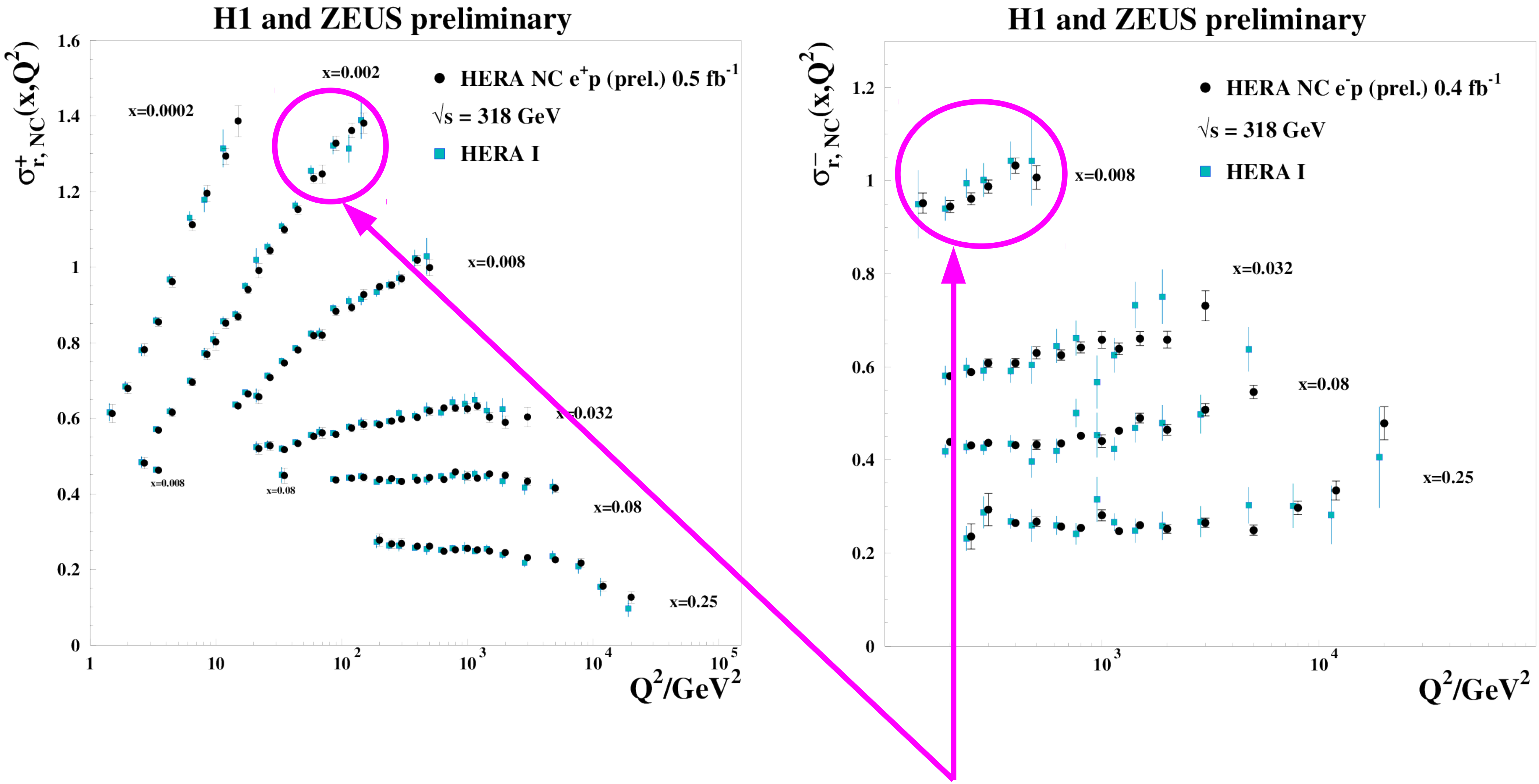


- Up to ~6 points averaged together.
- Impressive precision.

ZEUS-prel-14-005

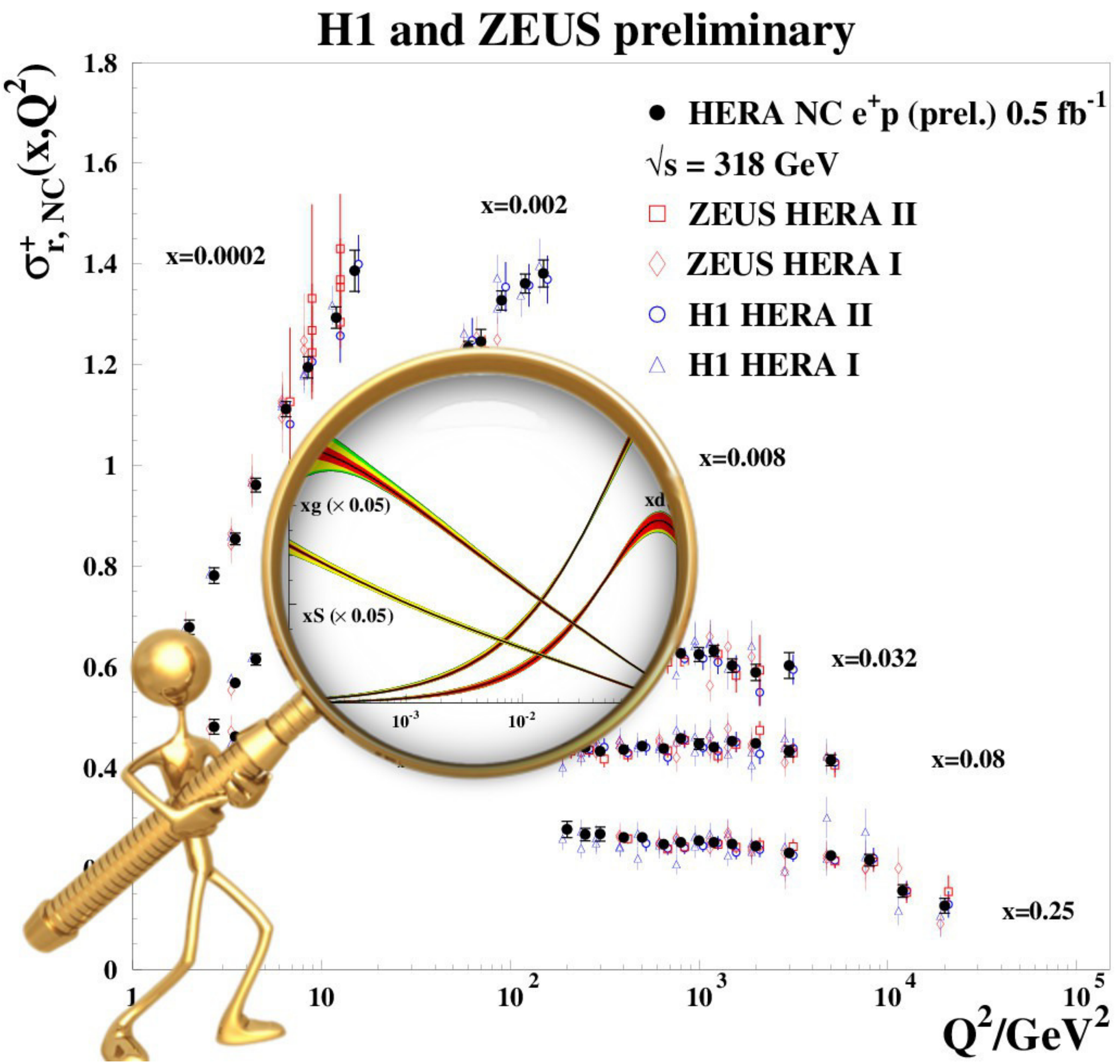
H1prelim-14-041

Comparison to HERA I



Significant reduction of the uncertainties!
(increase of statistics, coherent treatment of correlations)

Extraction of PDFs from inclusive data



HERAPDF2.0: settings for QCD fit

- QCD fits are performed using HERAFitter package
  www.herafitter.org

(See talk by R. Sadykov)

- PDFs (15p) are parametrised at $Q_0^2 = 1.9$ GeV^2

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

$$xg(x), xu_v(x), xd_v(x), x\bar{U}(x), x\bar{D}(x)$$

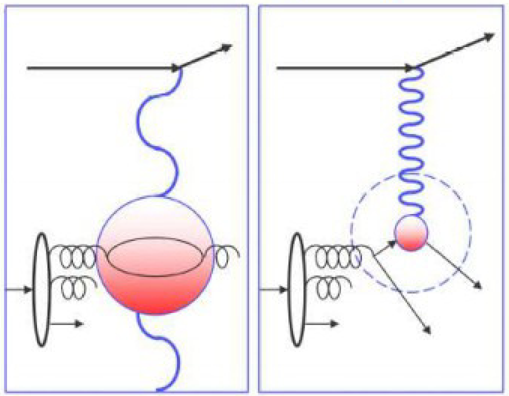
- PDF evolution is performed using DGLAP equations

- Heavy flavour coefficients are obtained within GM VFNS (RT)

HERAPDF2.0: NC $e^{\pm}p$

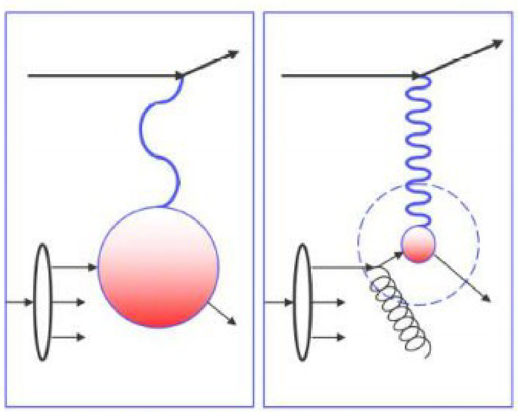
- Clearly seen EW and scaling violation effects

Small x: Gluons, sea quarks

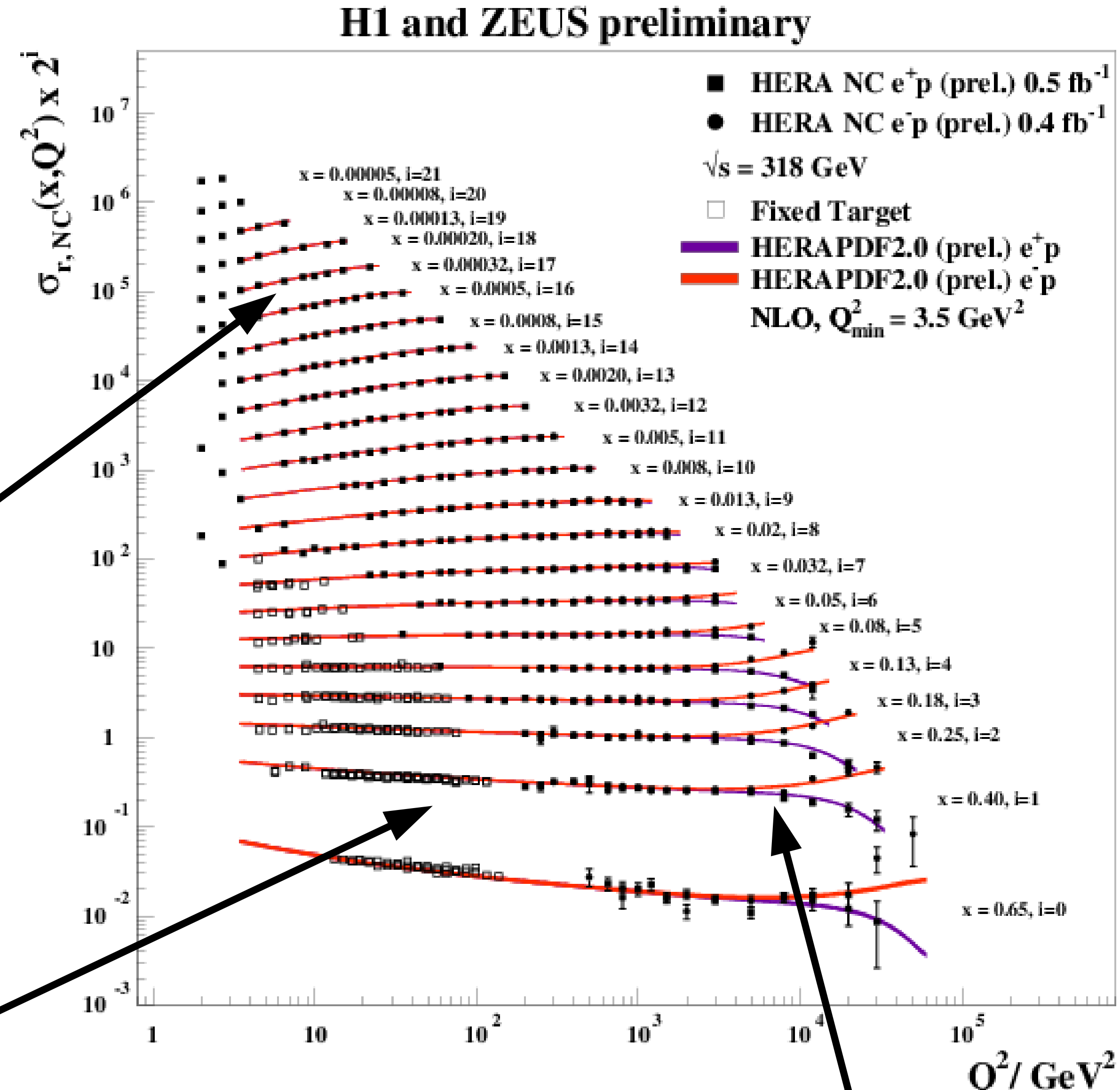


$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x

Large x: valence quarks



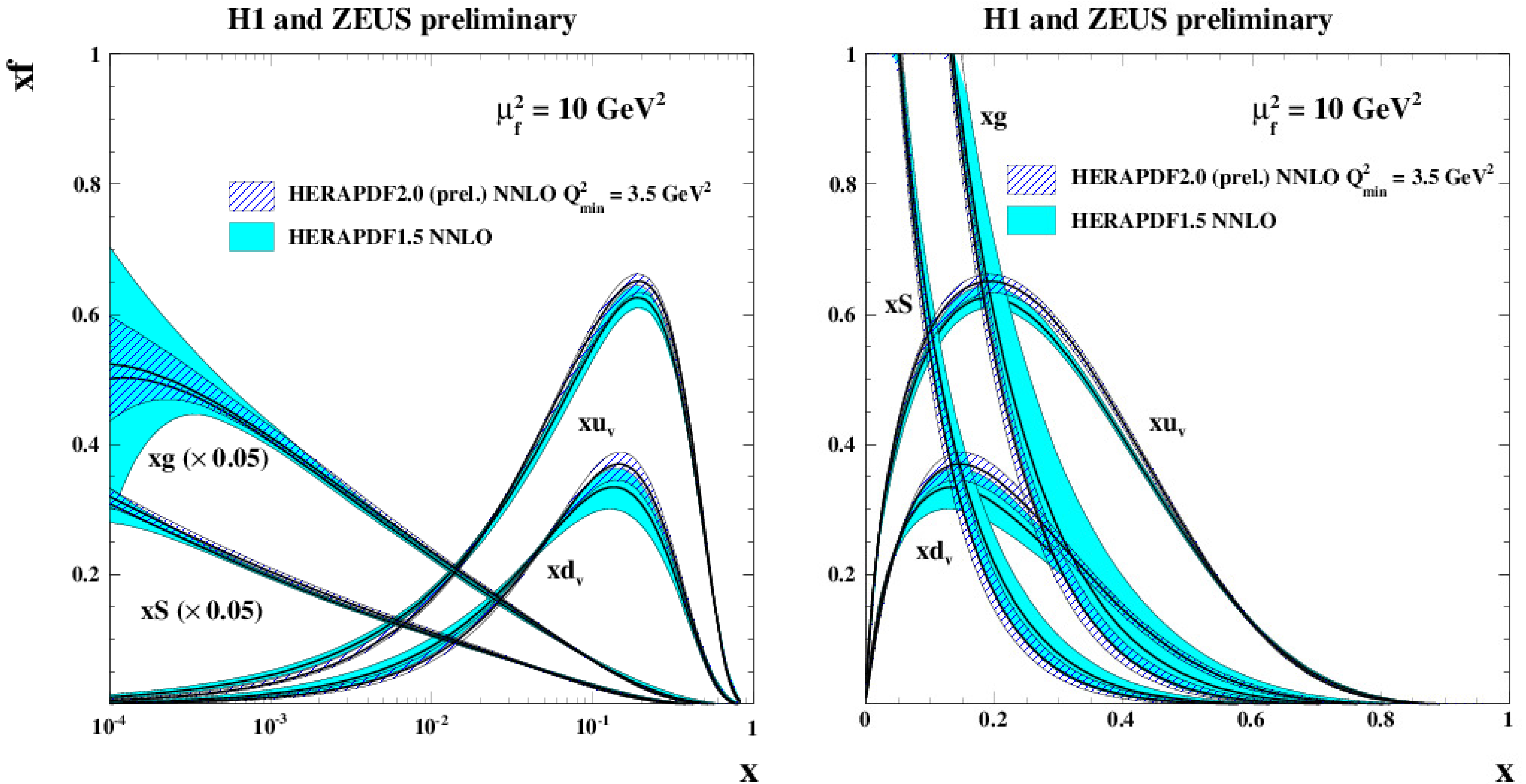
$Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x



$$\sigma^{\pm}_{r,NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+}\frac{d^2\sigma^{e^{\pm}p}_{NC}}{dxdQ^2} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

H1prelim-14-042 *ZEUS-prel-14-007*

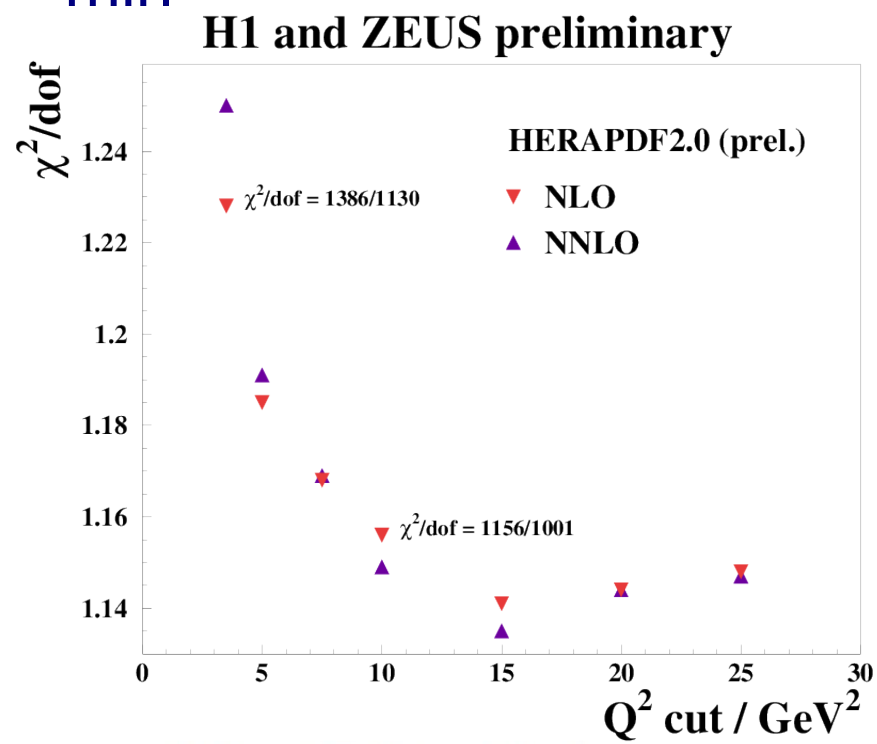
HERAPDF1.5 vs HERAPDF2.0

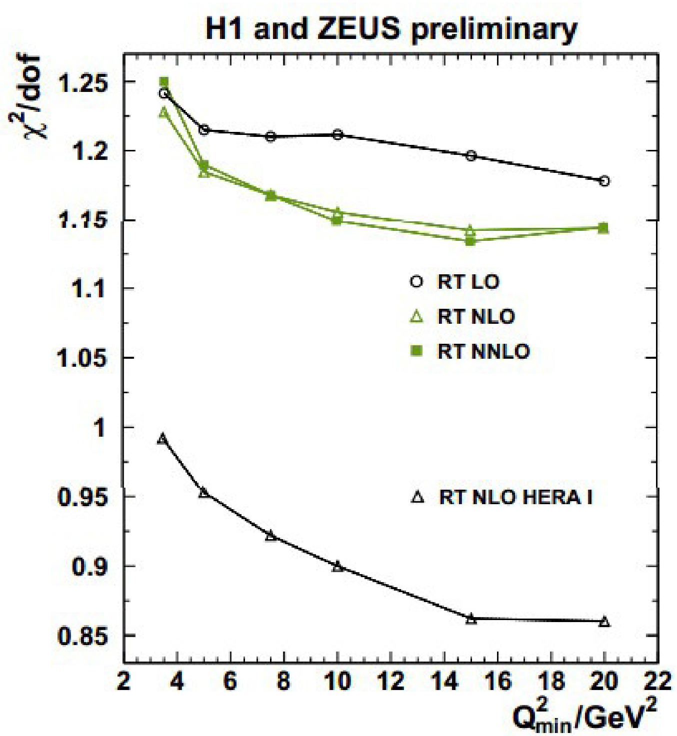


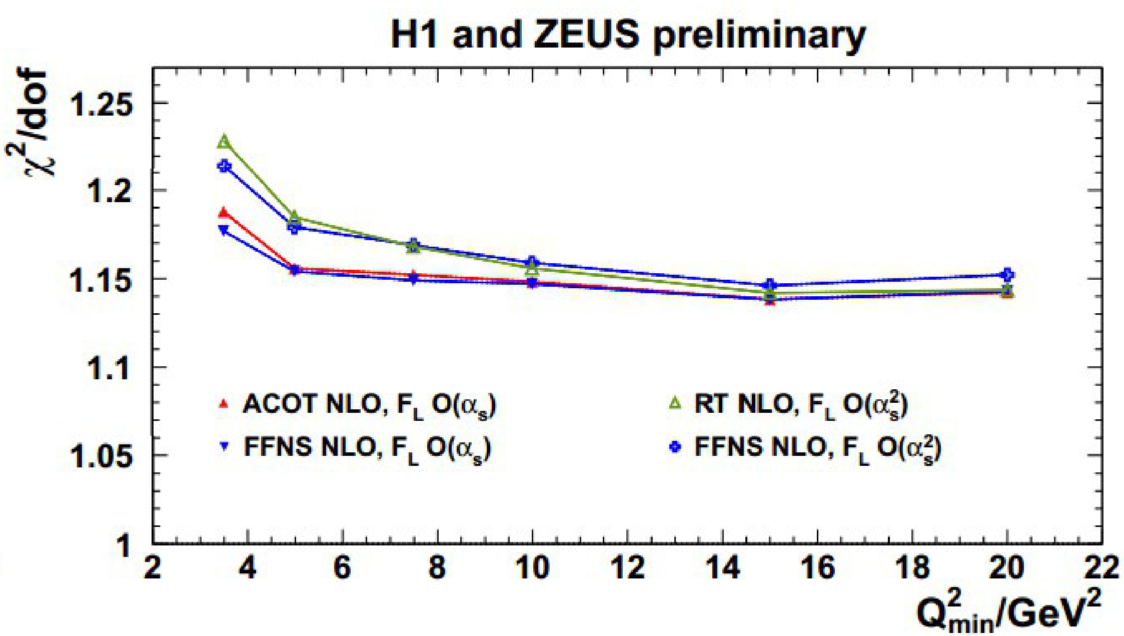
- Valence distributions look alike, HERAPDF2.0 are a bit more peaked.
- Low x gluon uncertainty is larger for HERAPDF1.5.

HERAPDF2.0: Q^2_{min} dependence

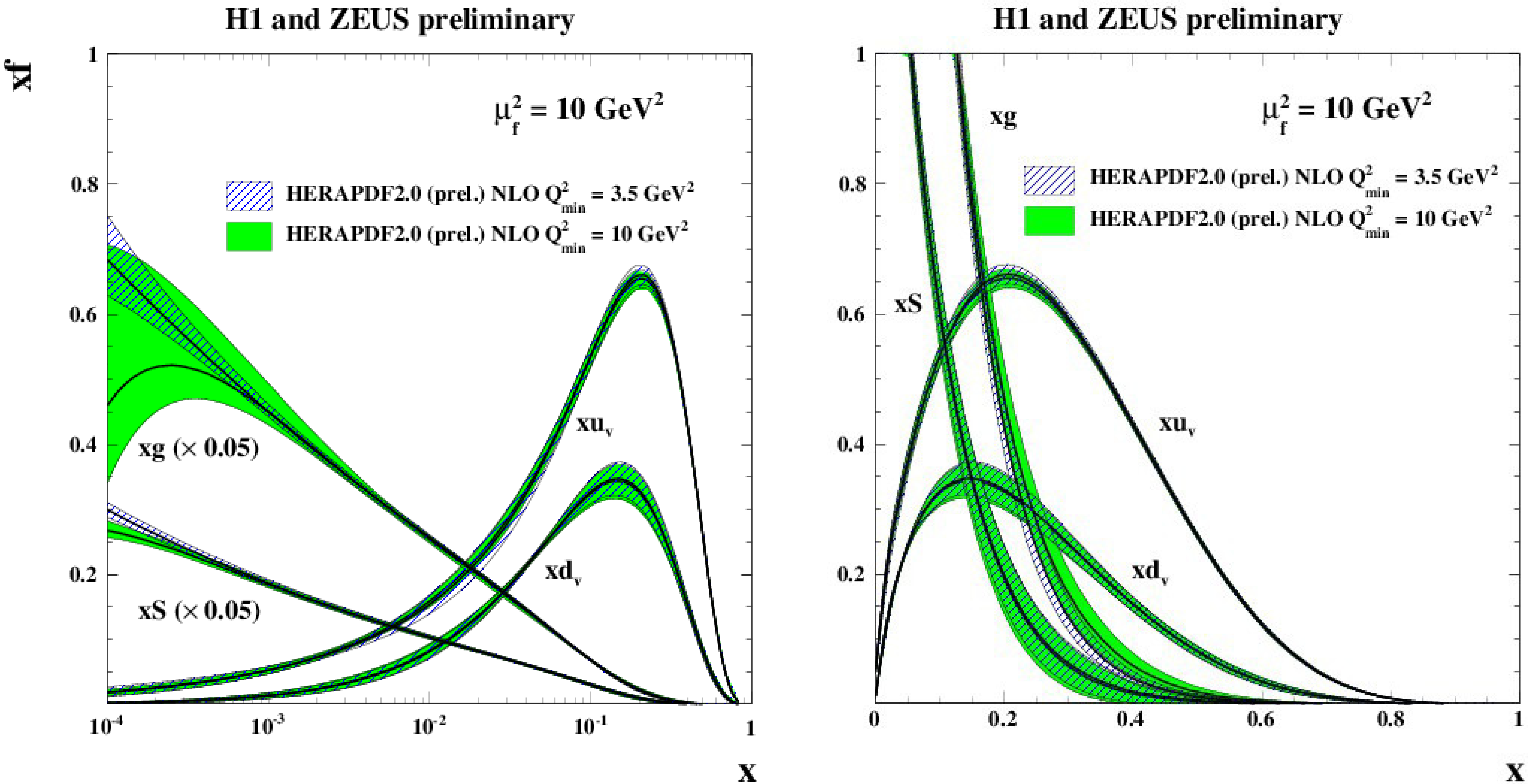
- $Q^2_{min} = 3.5$ GeV^2
  - NLO $\frac{\chi^2}{ndf} = \frac{1386}{1130}$
  - NNLO $\frac{\chi^2}{ndf} = \frac{1414}{1130}$
- $Q^2_{min} = 10$ GeV^2
  - NLO $\frac{\chi^2}{ndf} = \frac{1156}{1001}$
  - NNLO $\frac{\chi^2}{ndf} = \frac{1150}{1001}$
- Small tension between low and high Q^2 data.





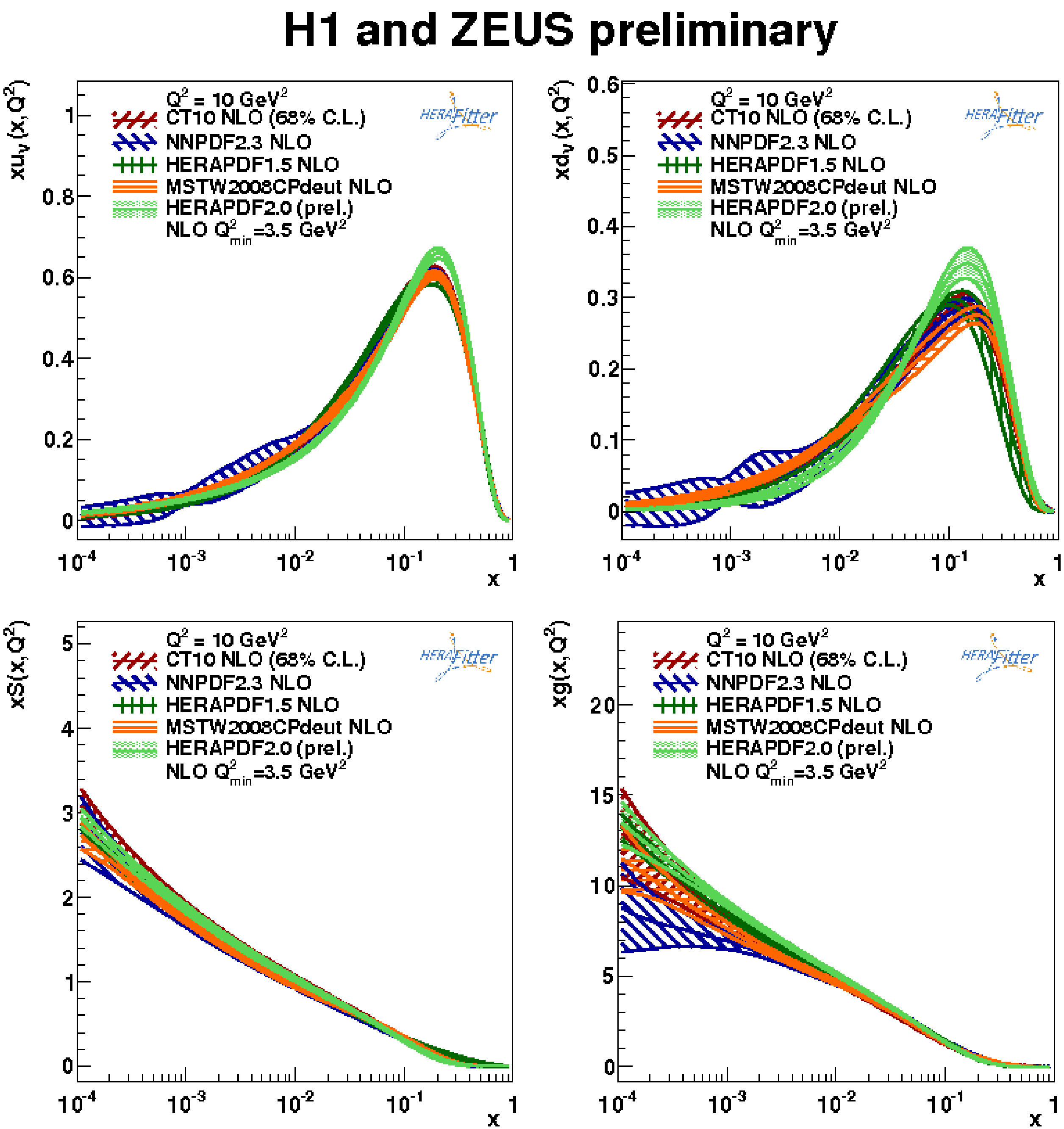


HERAPDF2.0: NLO fits



- Valence distributions look similar.
- High x gluons are a bit shifted.
- For Q^2_{min} = 10 GeV^2 gluon uncertainty is significantly larger at low x.

HERAPDF2.0: NLO fits

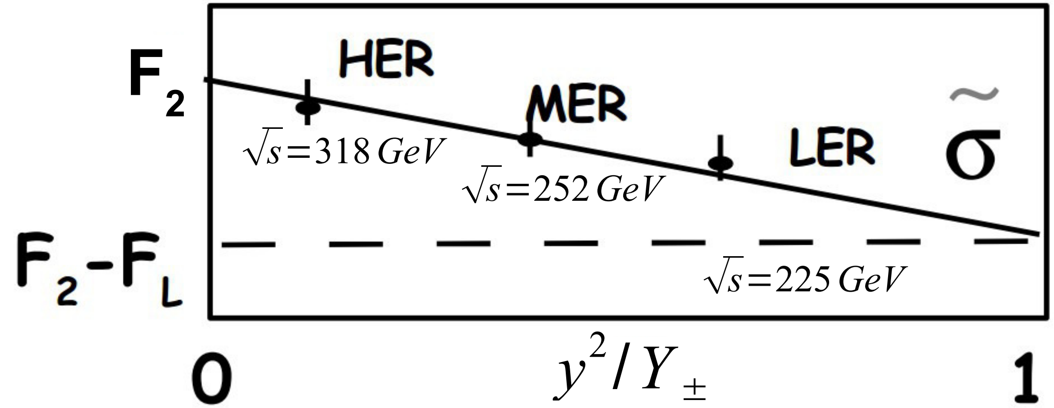


- Noticeable reduction of uncertainty
  - New data added
  - Coherent treatment of correlations of systematic uncertainties

Longitudinal structure function F_L

Reduced NC cross section: $\sigma^{\pm}_{r,NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L$

$Y_\pm = 1 \pm (1-y)^2$ $\qquad Q^2 = xys$



- $F_2(x, Q^2)$ total quark content

$$F_2(x,Q^2) = \sum_i e^2_{q_i} x (q_i + \bar{q}_i)$$

- $F_L(x, Q^2)$ longitudinal structure function (QPM)

$$F_L(x,Q^2) = F_2 - 2xF_1 = 0$$

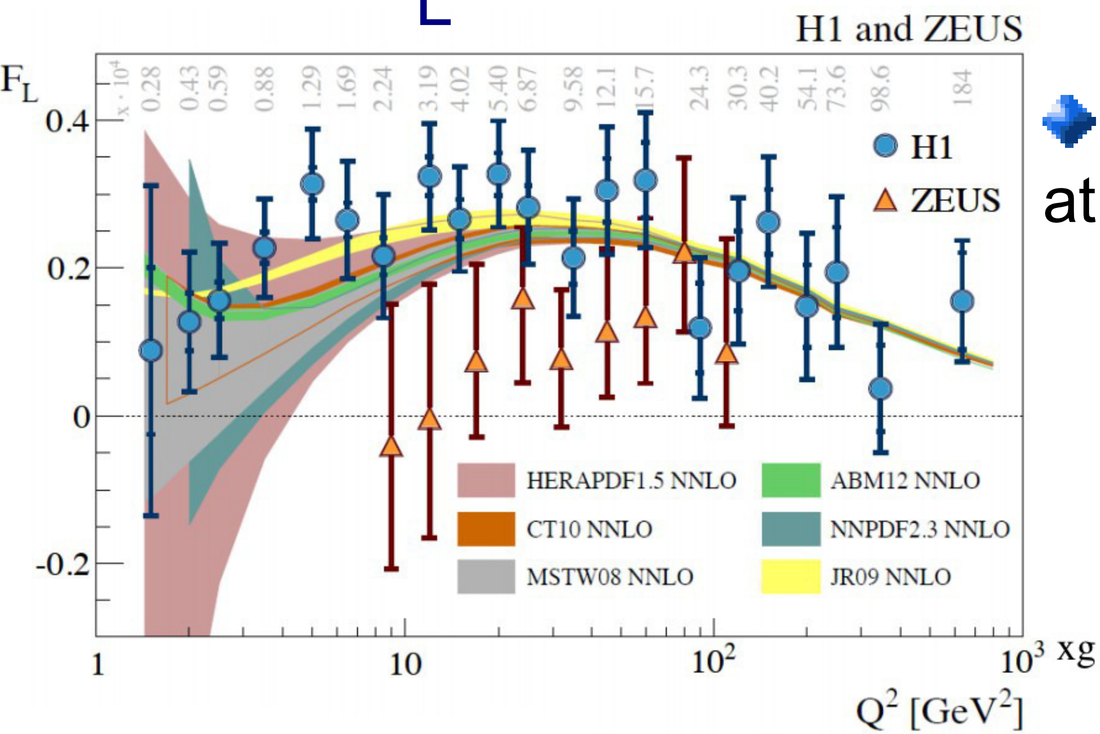
Callan-Gross relation

- $F_L(x, Q^2)$ longitudinal structure function (QCD)

$$F_L(x,Q^2) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) xg\right]$$

  - F_L is directly sensitive to the gluon density
  - To disentangle F_2 and F_L: fix x and Q^2, vary y

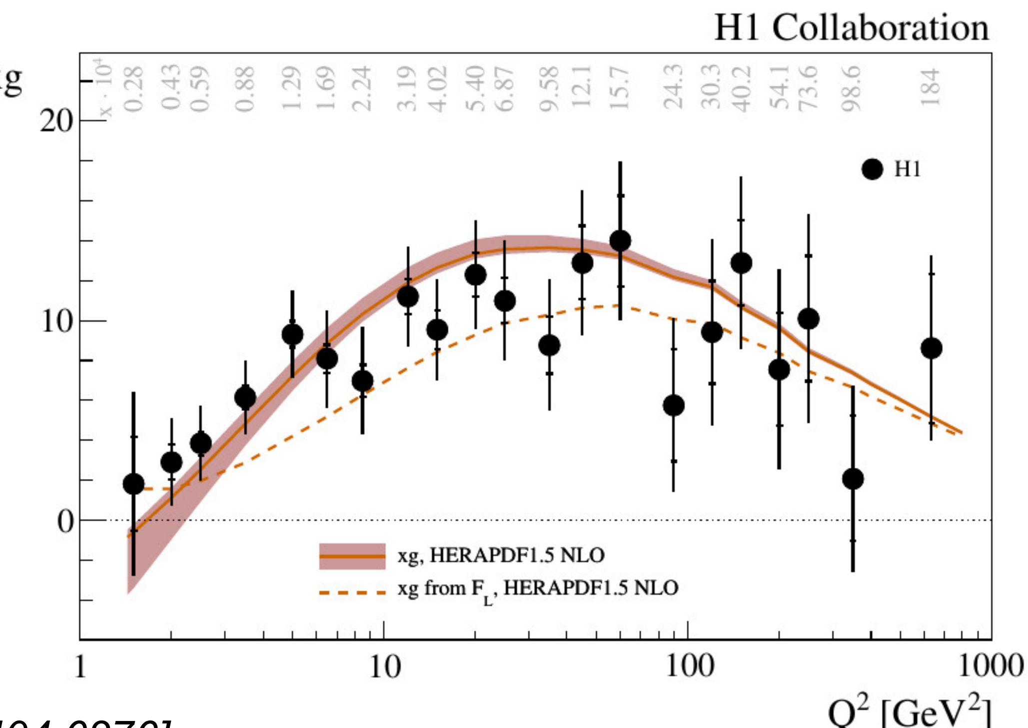
F_L structure function & xg(x)



- Average F_L measurements over x at each Q^2 to reduce stat. uncertainty.
  - Probability of agreement is about 20%.
  - Good agreement between the NNLO predictions and the measurements.

- Direct probe of gluon distribution from the F_L data.

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$



DESY-14-053, submitted to Phys. Lett. B [arXiv:1404.6376]

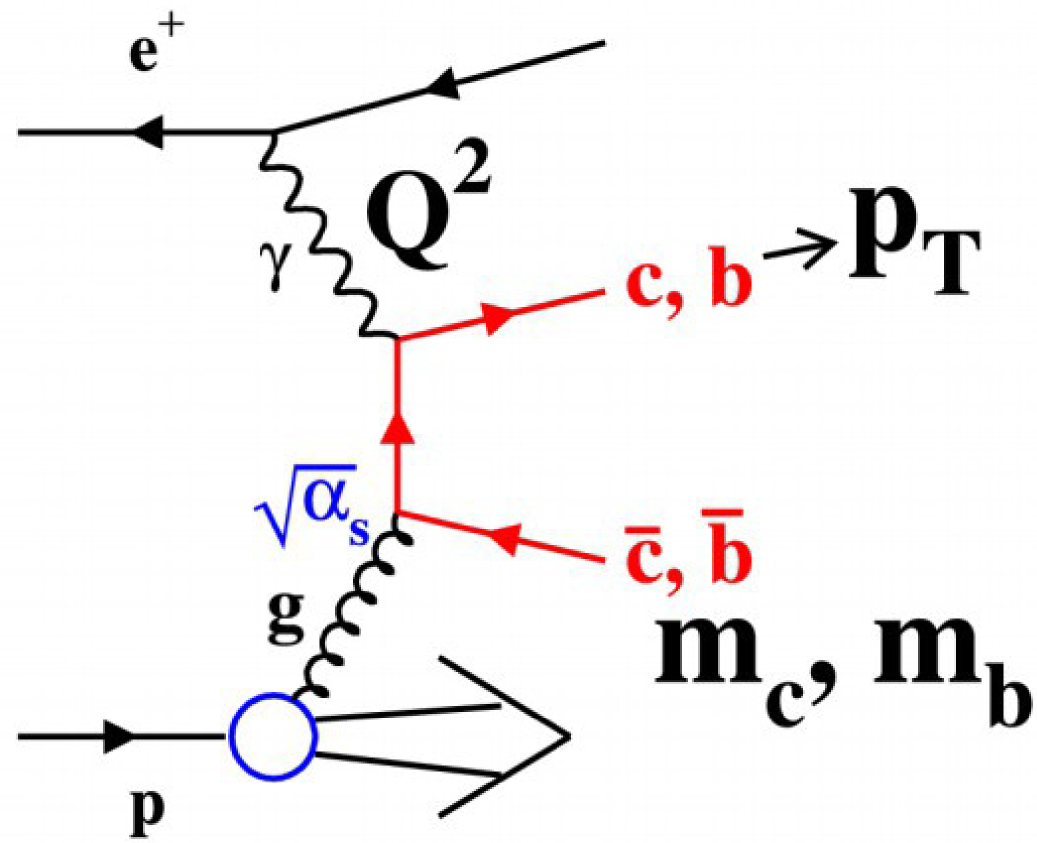
Eur. Phys. J. C 74 (2014) 2814 [arXiv:1312.4821]

F_2^{cc} & F_2^{bb} structure functions

$$\sigma_r^{q\bar{q}} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma_{NC}^{q\bar{q}}}{dx dQ^2} = F_2^{q\bar{q}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{q\bar{q}}(x, Q^2)$$

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

$$Q^2 \ll M_Z^2$$



- $F_2(x, Q^2)$ – dominant contribution

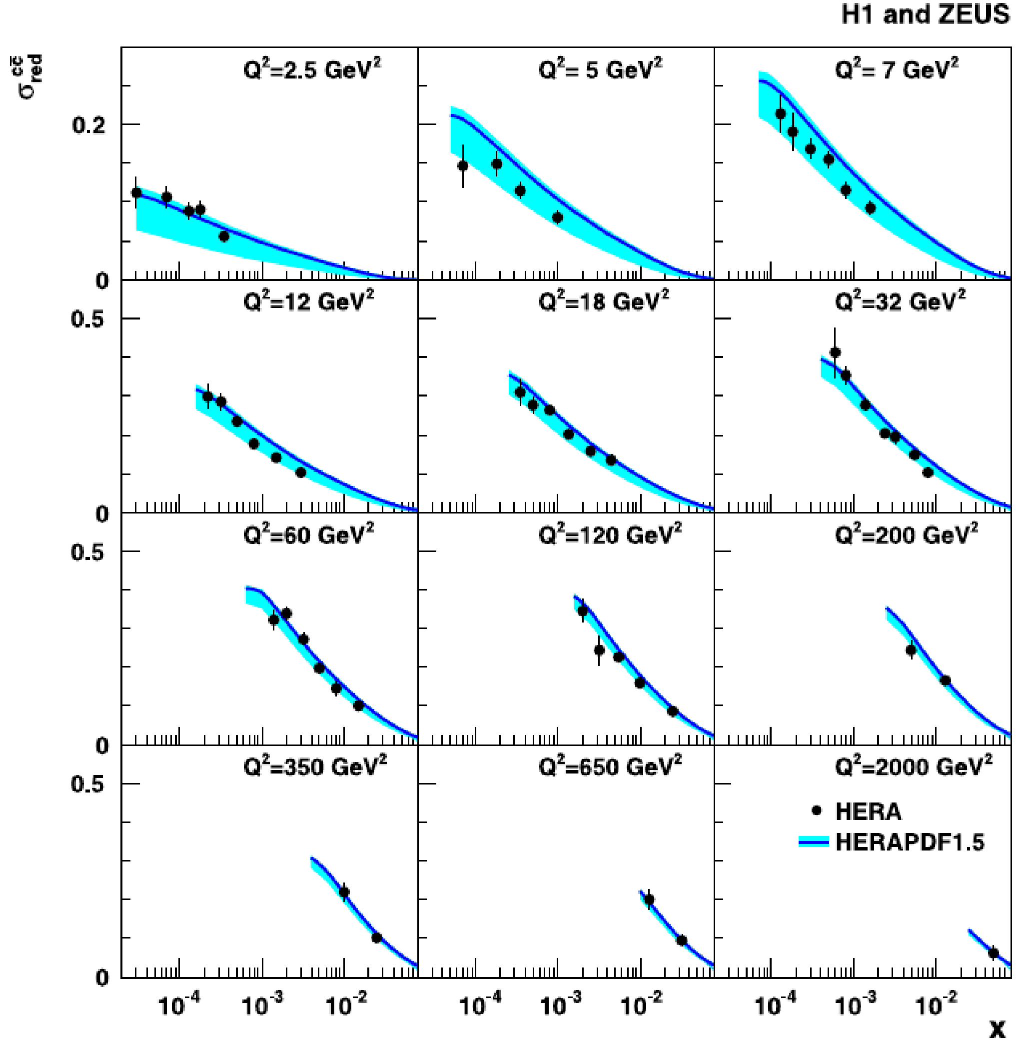
$$F_2(x, Q^2) = \sum_i e_{q_i}^2 x(q_i + \bar{q}_i)$$

- $F_L(x, Q^2)$ – exchange of longitudinally polarised photons

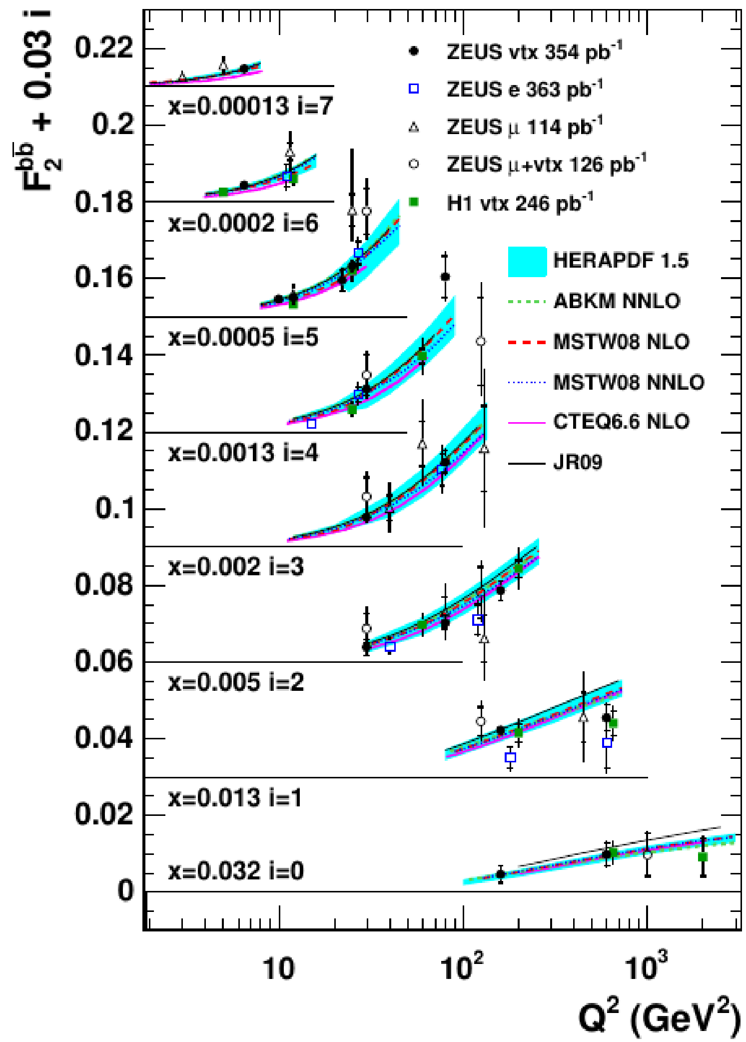
- Small contribution: up to 1-2% only at high y

F_2^{cc} & F_2^{bb} structure functions

Eur. Phys. J. C73 (2013) 2311



[arXiv:1405.6915 hep-ph]

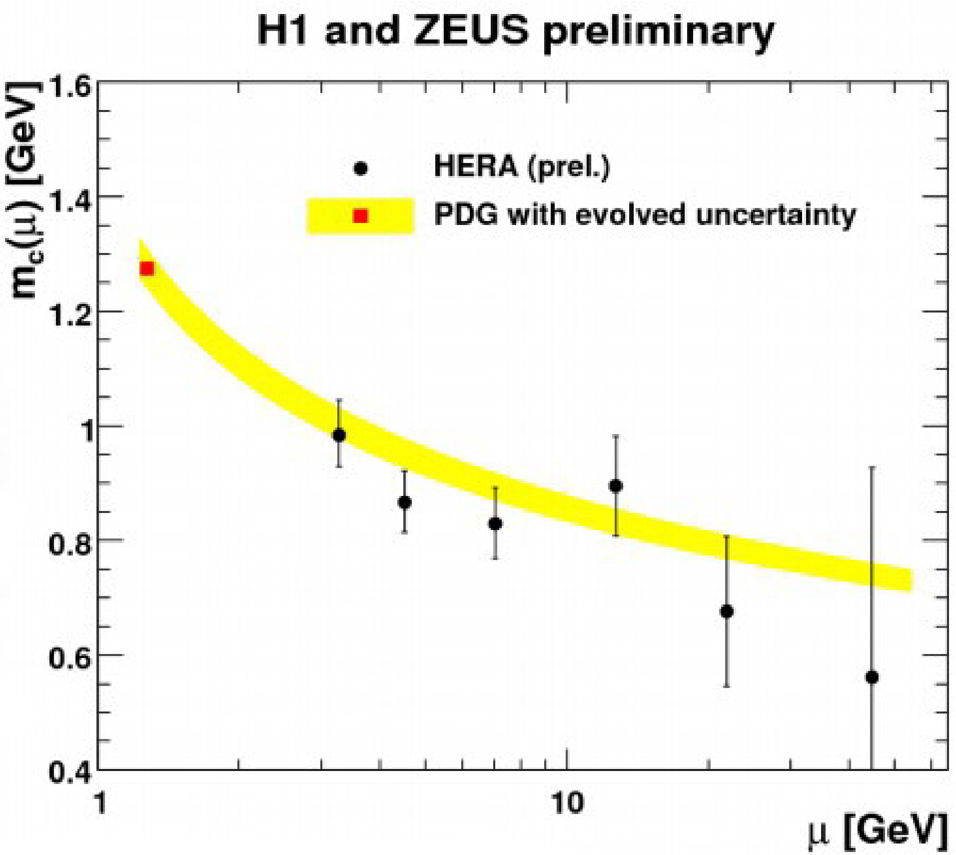


- Measurements performed in wide range of Q^2.
- Reasonable agreement of measurements with various predictions.

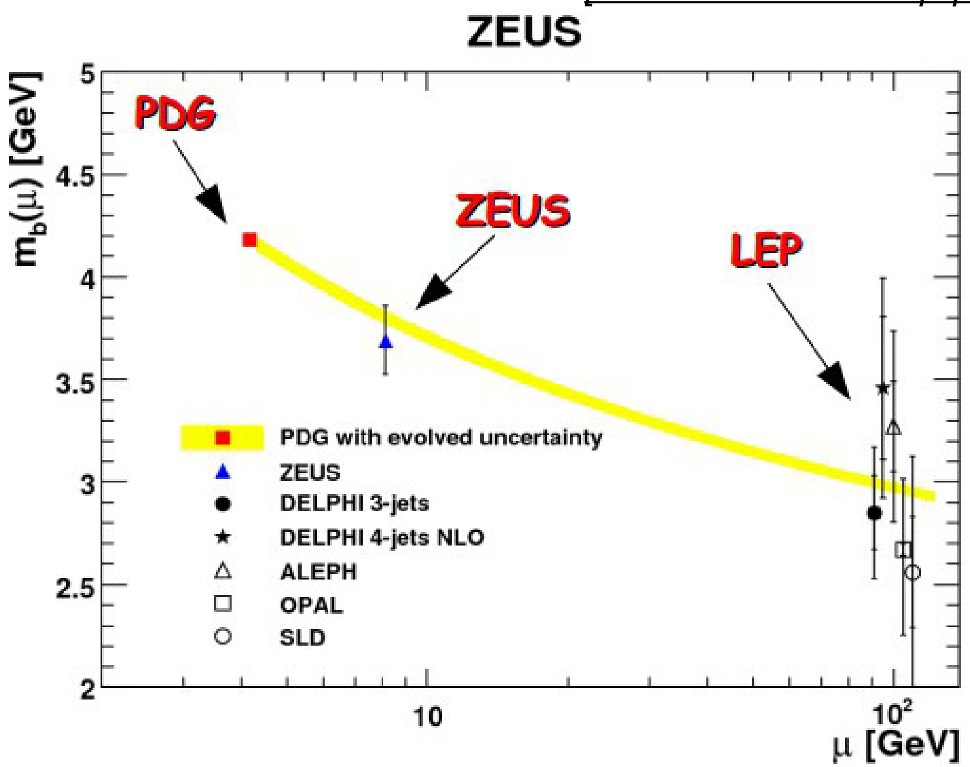
m_c and m_b extraction

- Running masses extracted using QCD fit to HERA I Inclusive + charm (beauty).
- FFNS by ABM is used. Masses are defined in $\overline{MS}$ scheme.

ZEUS-prel-14-006



[arXiv:1405.6915 hep-ph]

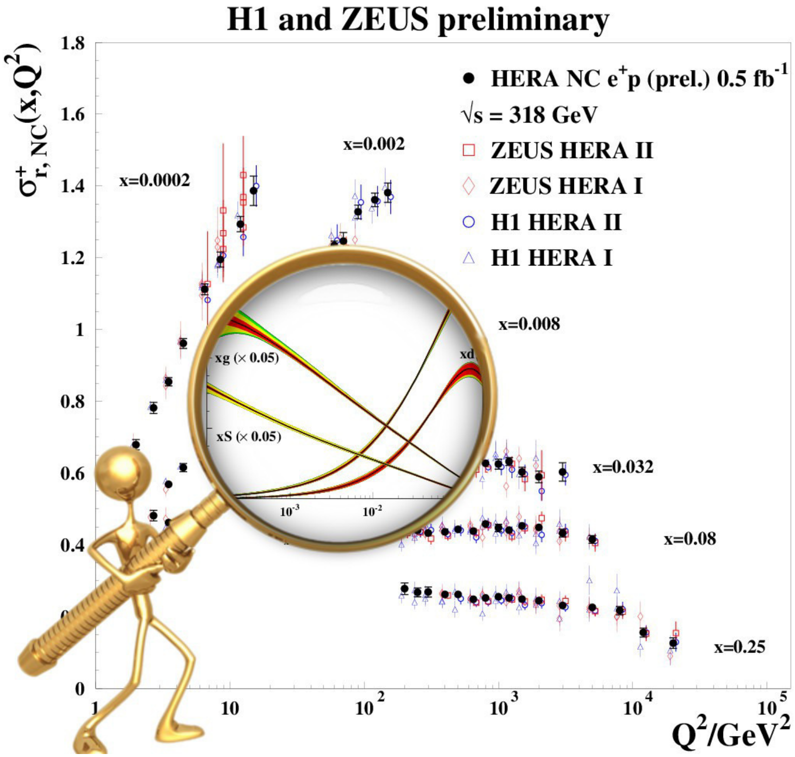


$$m_b(m_b) = 4.07 \pm 0.14 (exp.)^{+0.01}_{-0.07} (mod.)^{+0.05}_{-0.00} (param.)^{+0.08}_{-0.05} (\alpha_S)$$

$$m_c(m_c) = 1.26 \pm 0.05 (exp.) \pm 0.03 (mod.) \pm 0.02 (param.) \pm 0.02 (\alpha_S)$$

Eur. Phys. J. C73 (2013) 2311

Summary



- Combination of full HERA I+II inclusive data performed.

  H1prelim-14-041 *ZEUS-prel-14-005*

- HERAPDF2.0 fits are performed at NLO and NNLO using combined HERA data.

  H1prelim-14-042 *ZEUS-prel-14-007*

- New measurement of NC DIS cross section at different center-of-mass energies by H1 and ZEUS.

  DESY-14-053, submitted to Phys. Lett. B [arXiv:1404.6376]

  Eur. Phys. J. C 74 (2014) 2814 [arXiv:1312.4821]

- Inclusive F_2^{bb} and F_2^{cc} measurements finalised. $m_c(m_c)$ and $m_b(m_b)$ were extracted.

  Eur. Phys. J. C73 (2013) 2311
  [arXiv:1405.6915 hep-ph]

- Running of $m_c(\mu)$ was studied.

  ZEUS-prel-14-006

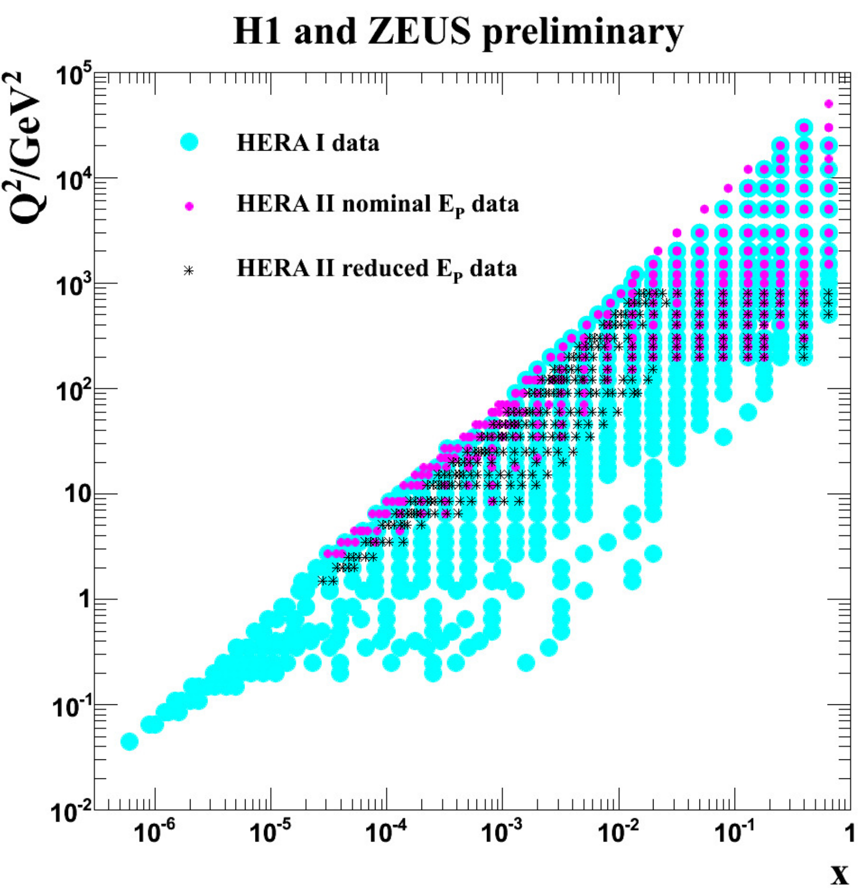
Backup

HERA data collection

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0



Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
HERA I E_p = 820 GeV and E_p = 920 GeV data sets								
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318
HERA II E_p = 920 GeV data sets								
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite	06-07	0.000071	0.008343	5	110	44.5	e^+p	318
HERA II E_p = 575 GeV data sets								
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251
HERA II E_p = 460 GeV data sets								
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225

Full HERA I data

HERA II data HER

HERA II data LER

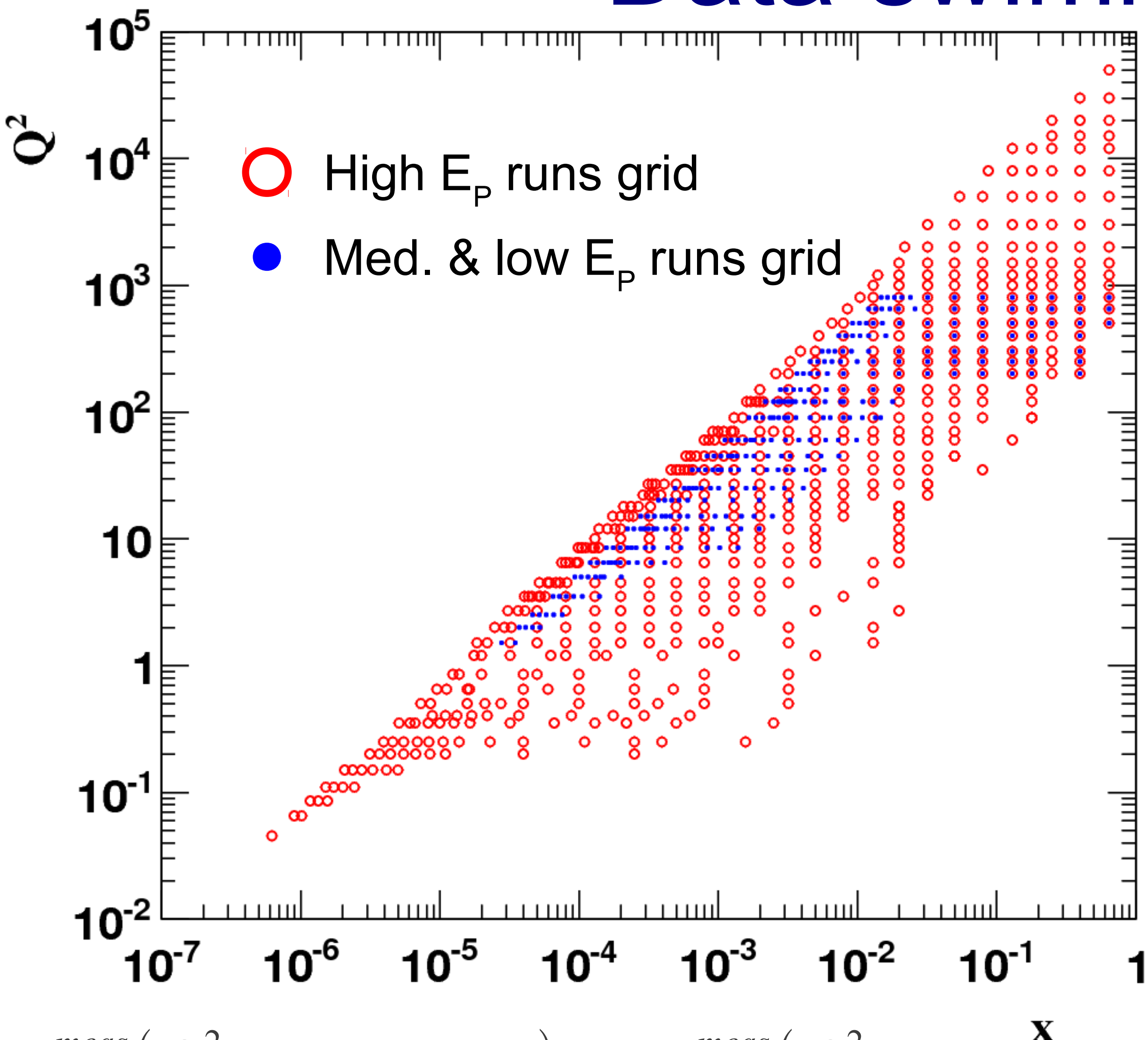
- All inclusive DIS results are final and published!

Combination challenge

- Translating/Swimming various measurements to common points of kinematic phase space.
- Averaging measurements

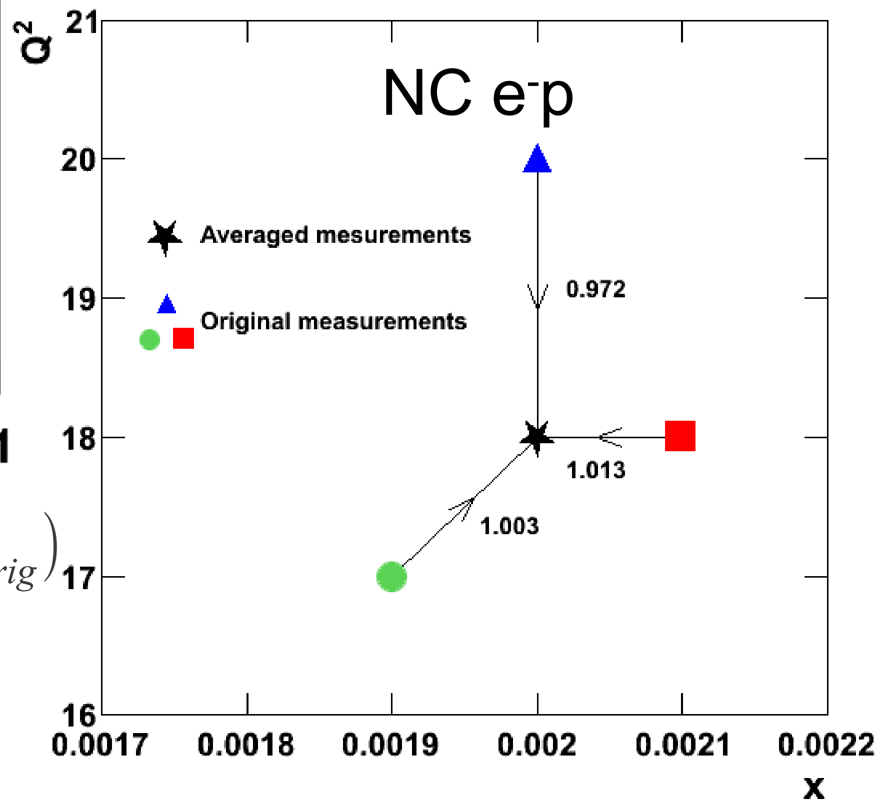
  (account for correlations of systematic uncertainties).
- Estimate procedural uncertainties.

Data swimming



Most of measurements stay at original Q^2, x and y

Only ~ 1/3 of measurements are swum



$$\sigma^{meas}(Q^2_{grid}, x_{grid}, y_{grid}) \equiv \alpha\, \sigma^{meas}(Q^2_{orig}, x_{orig}, y_{orig})$$

$$\alpha = \frac{\sigma^{theor}(Q^2_{grid}, x_{grid}, y_{grid})}{\sigma^{theor}(Q^2_{orig}, x_{orig}, y_{orig})}$$

Data swimming

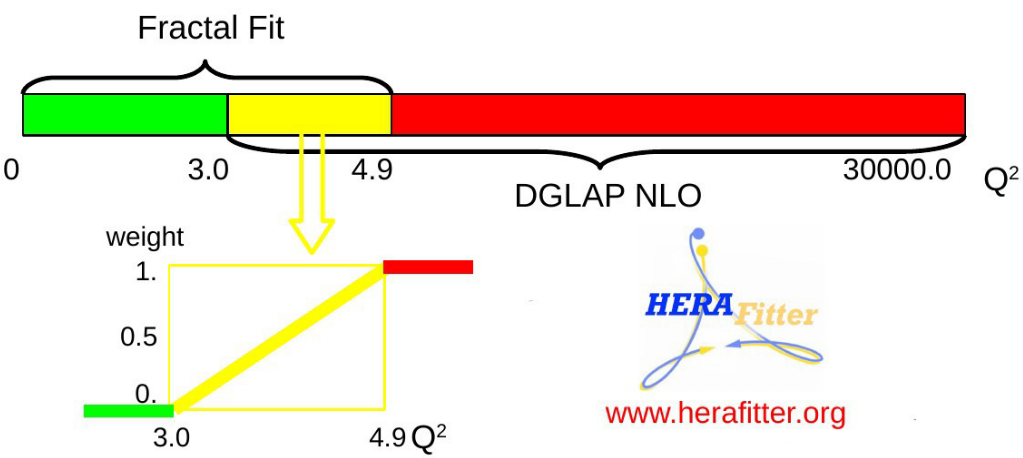
Swimming factors α are obtained from the QCD fit to the uncombined data. HERAFitter used www.herafitter.com

Most of measurements stay at original Q^2, x and y

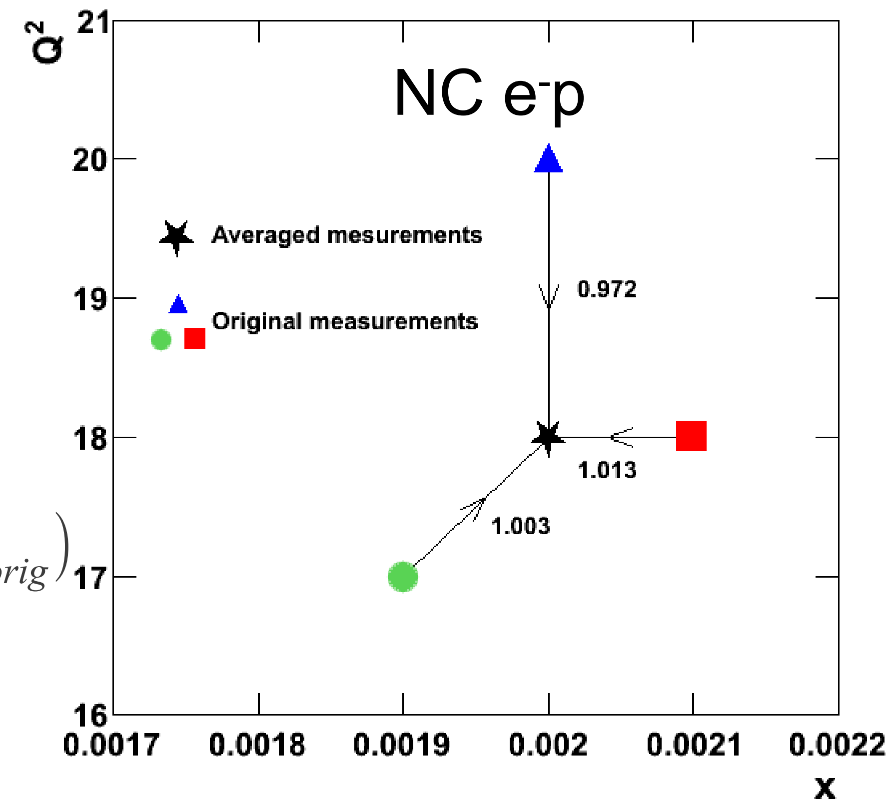
Only ~ 1/3 of measurements are swum

$Q^2 > 3$ GeV^2 DGLAP formalism is used.

$Q^2 < 4.9$ GeV^2 Fractal model is used.



www.herafitter.org



$$\sigma^{meas}(Q^2_{grid}, x_{grid}, y_{grid}) \equiv \alpha\, \sigma^{meas}(Q^2_{orig}, x_{orig}, y_{orig})$$

$$\alpha = \frac{\sigma^{theor}(Q^2_{grid}, x_{grid}, y_{grid})}{\sigma^{theor}(Q^2_{orig}, x_{orig}, y_{orig})}$$

Averaging measurements

Averaging was performed using HERAverager package

https://wiki-zeuthen.desy.de/HERAverager

Multiplicative treatment of systematic uncertainties

Contribution to χ^2 from a data set

Original measurements

$$\chi^2_{\exp,ds}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,stat}\,\mu^i\left(m^i - \sum_j \gamma^i_j m^i b^i_j\right) + \left(\delta_{i,uncor}\, m^i\right)^2} + \sum_j b_j^2$$

Vector of averaged values

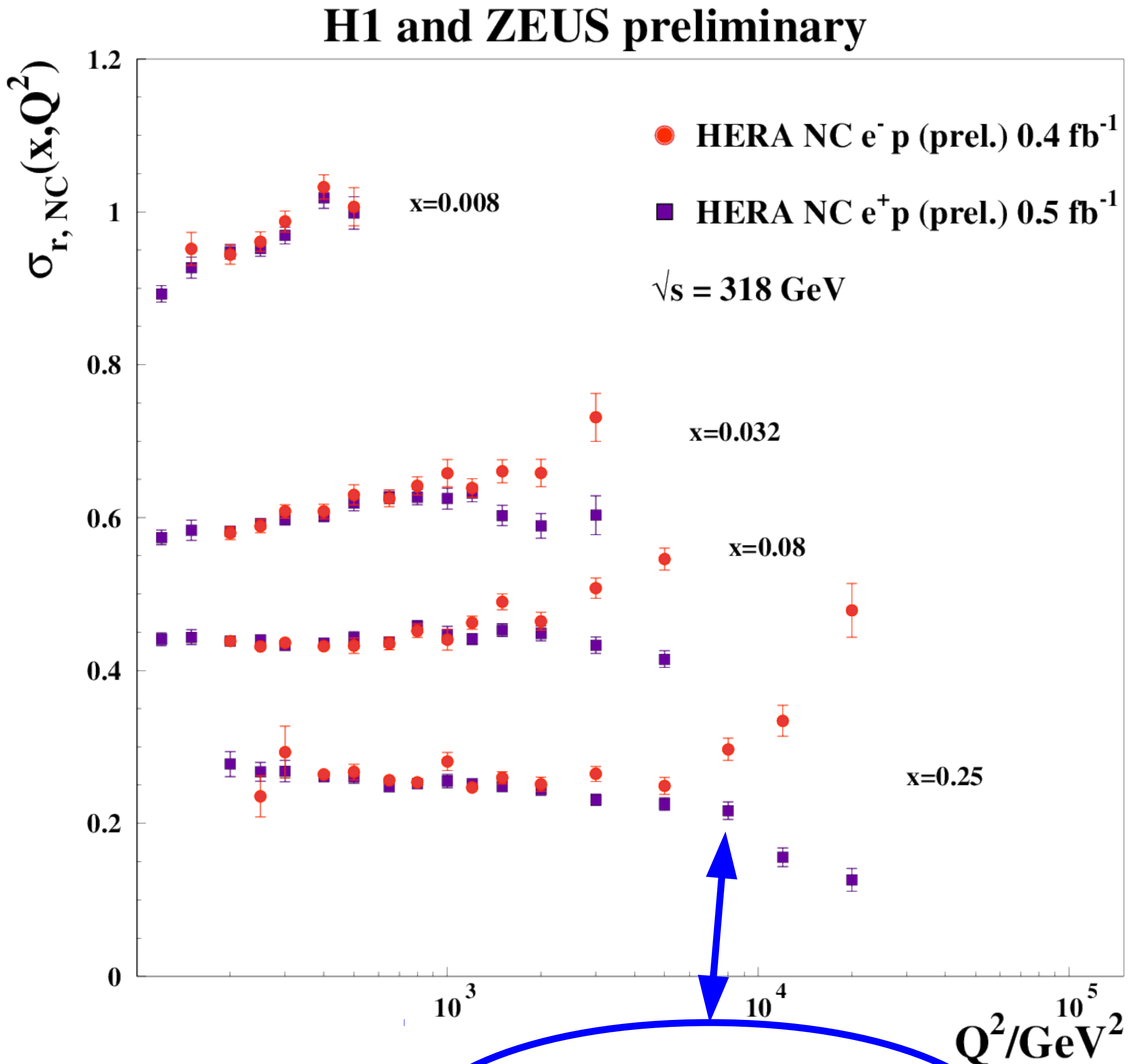
Vector of systematic uncert. shifts

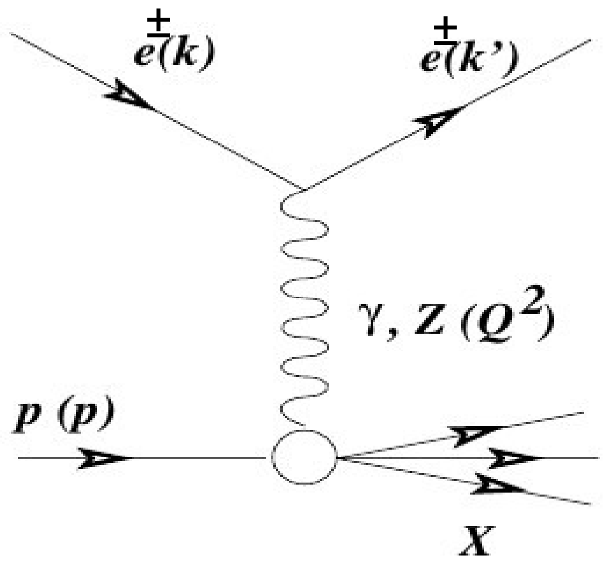
Correlated systematic uncert.

Procedural uncertainties

- Multiplicative versus additive
  - All correlated systematic uncertainties treated as multiplicative for nominal result
  - Correlated systematic uncertainties except normalization uncertainties treated as additive in this check
- Hadronic energy scale procedural uncertainty (HAD) and PhP background procedural uncertainty
  - Hadronic energy scale and PhP BG uncertainties cross-correlated between H1 and ZEUS for HERAI (as in HERAI paper)
  - HERAII
    - ZEUS uncertainties NOT correlated to HERAI and NOT to H1
    - H1 uncertainties correlated to HERAI
- **Procedural uncertainties included in QCD fits as correlated uncertainties**

Electroweak effects



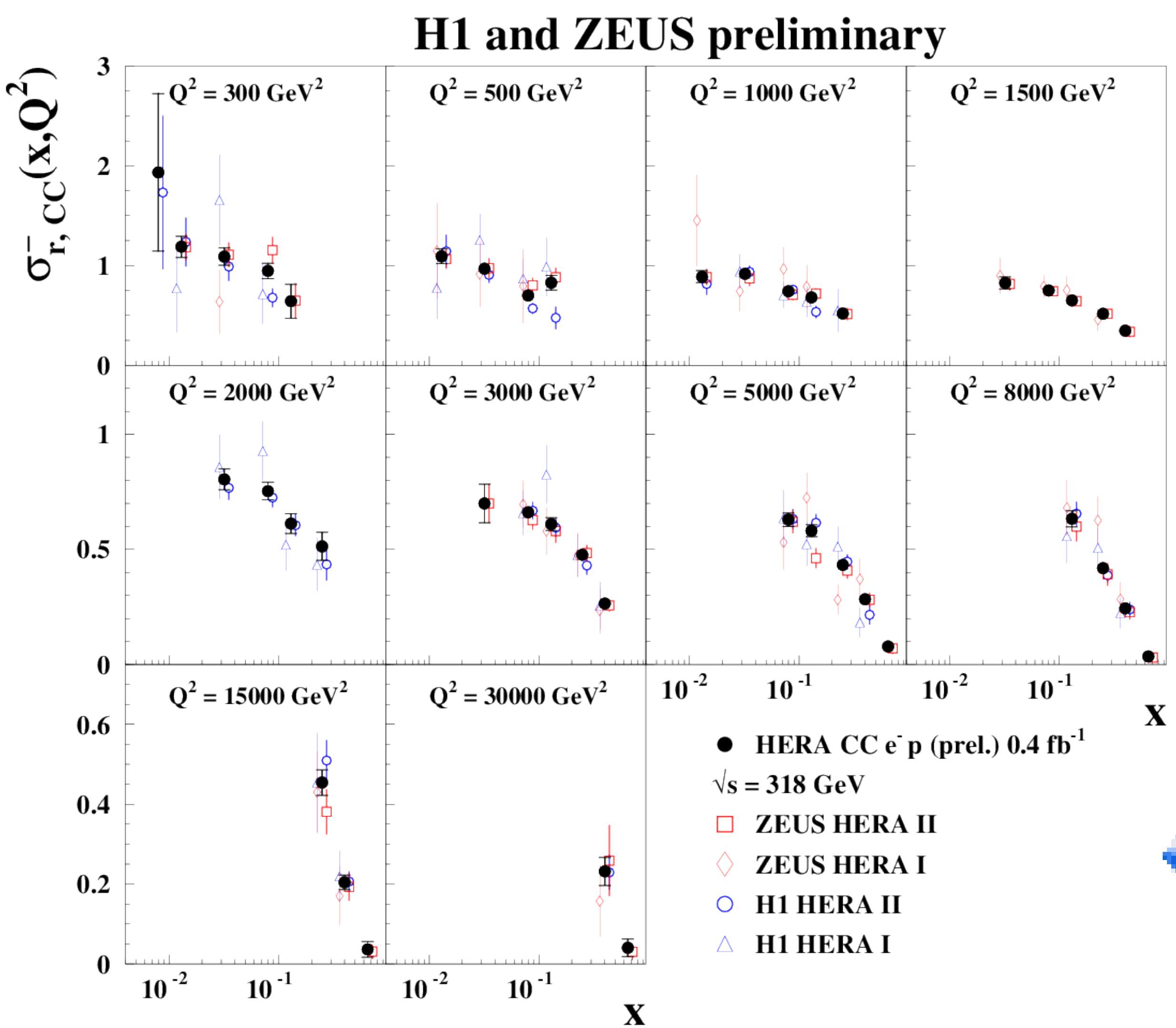


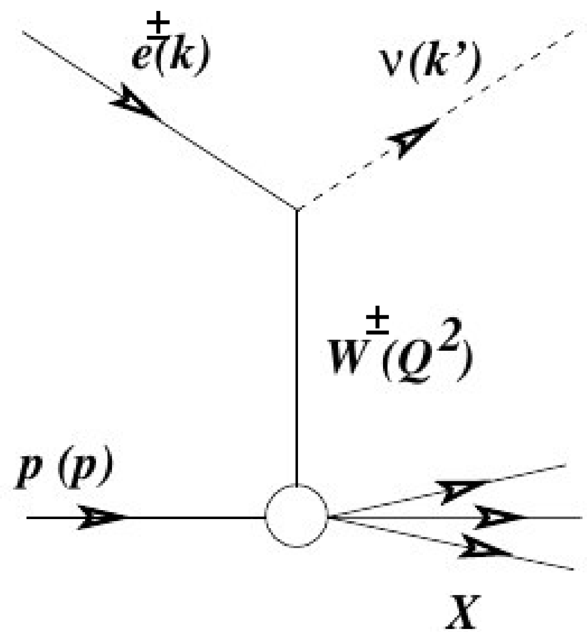
- γZ^0 interference term effect is clearly seen.

$$x\tilde{F}_3 = -a_e \frac{\kappa Q^2}{Q^2 + M_{Z^0}^2} xF_3^{\gamma Z^0} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2 + M_{Z^0}^2}\right)^2 F_3^{Z^0}$$

Combined reduced cross-sections

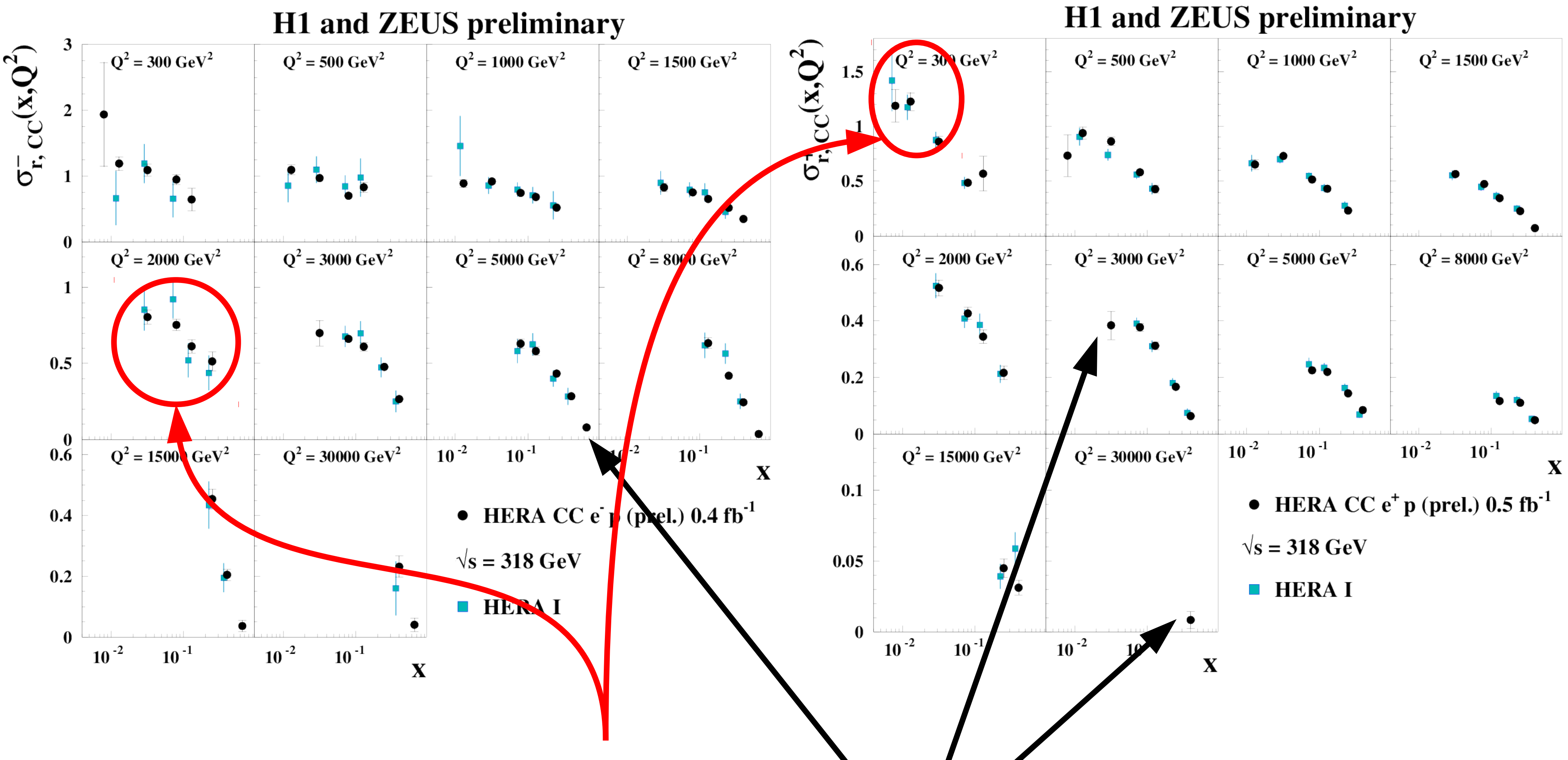
$$\sigma^{\pm}_{r,CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{d^2\sigma^{e^\pm p}_{CC}}{dxdQ^2} = \frac{Y_+}{2}W_2^{\pm} \mp \frac{Y_-}{2}xW_3^{\pm} - \frac{y^2}{2}W_L^{\pm}$$





- Very good precision.

Comparison to HERA I



- Large uncertainty reduction.
- New points coming from HERA II only.

HERAPDF2.0: settings for QCD fit

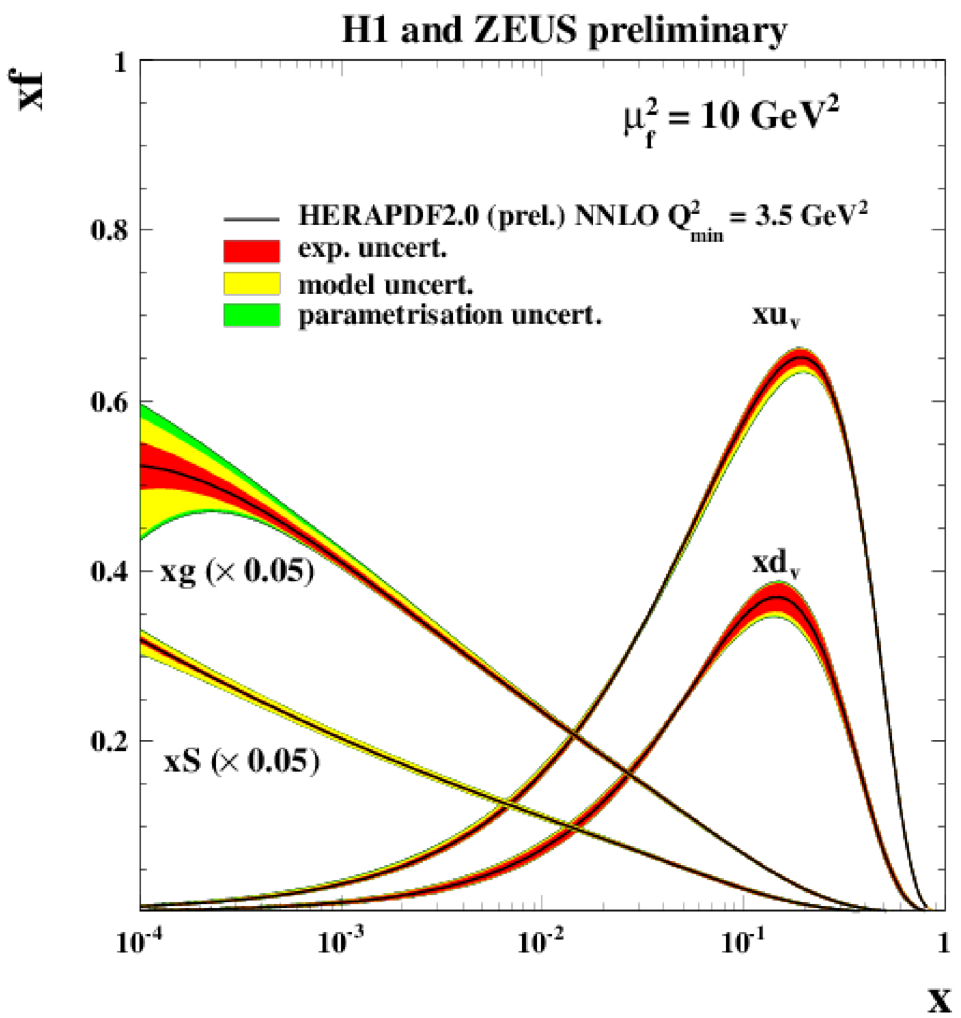
- QCD fits are performed using HERAFitter package
- PDFs (15p) are parametrised at $Q_0^2 = 1.9\ \mathrm{GeV}^2$

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

- A_{u_v}, A_{d_v}, A_g are constrained by QCD sum rules
- $x\bar{u} \xrightarrow{x\to 0} x\bar{d}$
- $A_{\bar{U}}, A_{\bar{D}}$ are constrained via $x\bar{s} = f_s x\bar{D}$
- PDF evolution is performed using DGLAP equations
- Heavy flavour coeffitients are obtained within GM VFNS (RT)

$$
\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,uncor}\, m_i^2 + \delta^2_{i,stat}\,\mu_i m_i\left(1 - \sum_j \gamma^i_j b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,uncor}\, m_i^2 + \delta^2_{i,stat}\,\mu_i m_i}{\delta^2_{i,uncor}\,\mu_i^2 + \delta^2_{i,stat}\,\mu_i^2}
$$

HERAPDF2.0: errors estimation



- **Experimental uncertainties:**
  - Hessian method used: full second-derivative matrix calculated
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

- **Model uncertainties:**

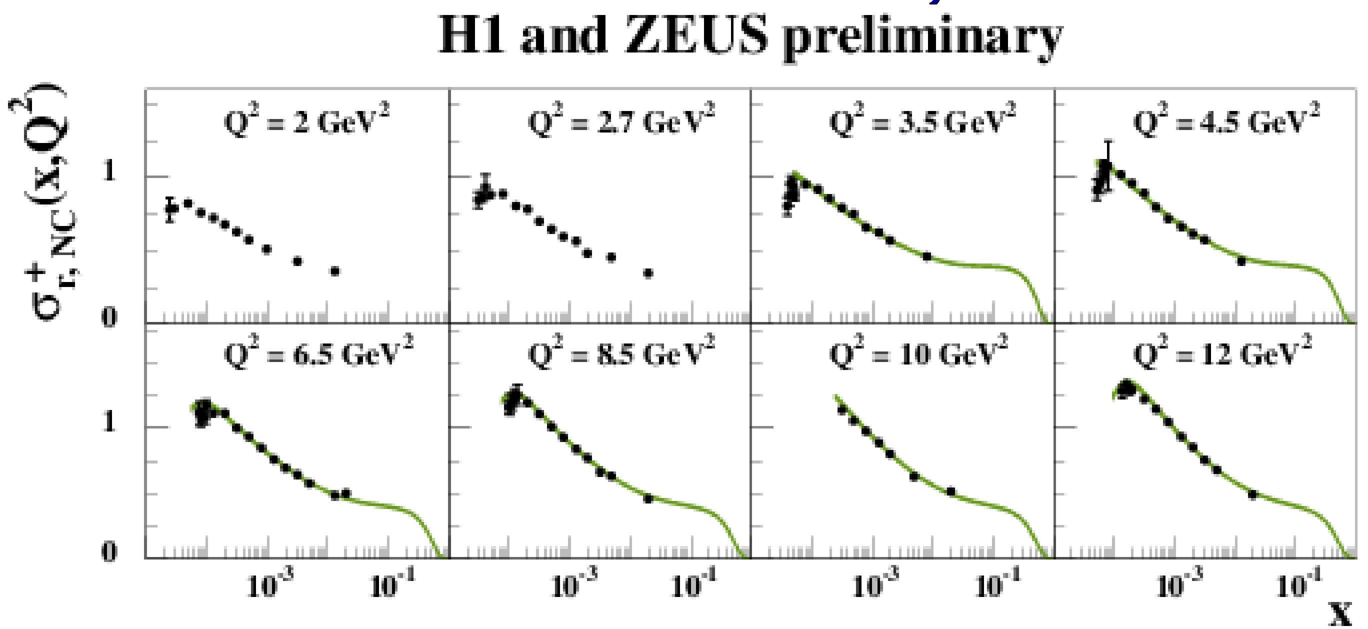
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2

- **Parametrisation uncertainties:**
  - Starting scale Q_0^2 variation.

HERAPDF2.0: NC low Q^2, x

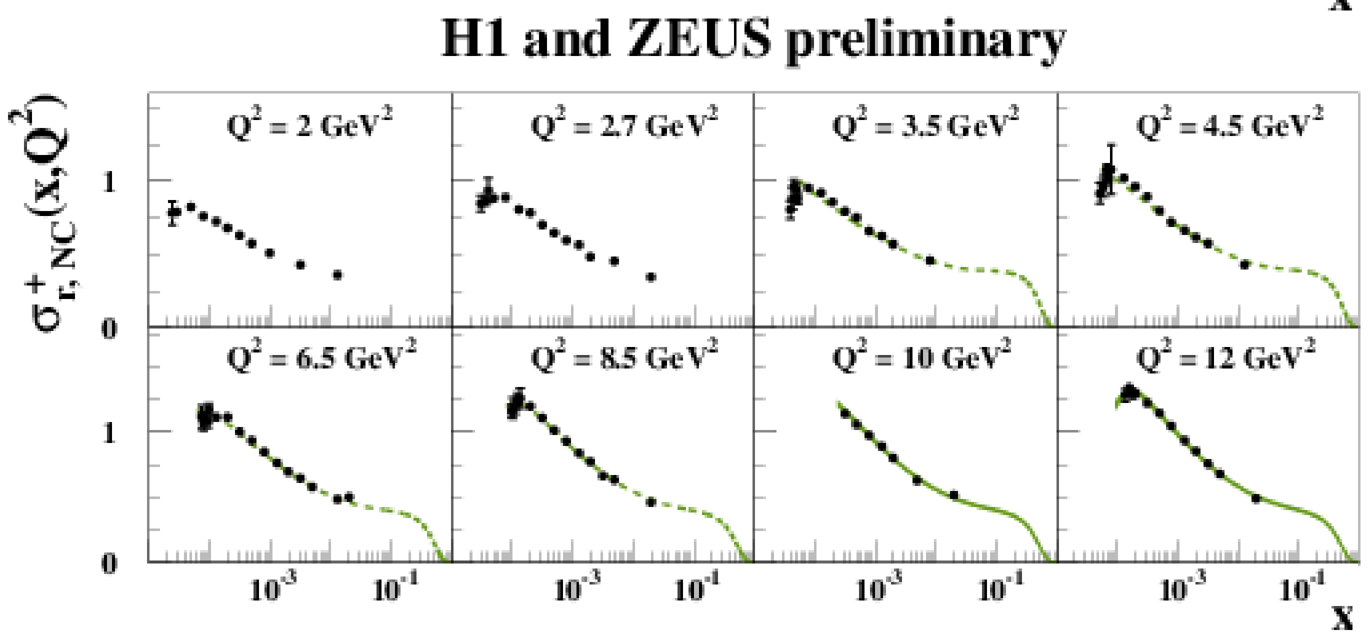
- Q^2_{min} = 3.5 GeV²

$$\frac{\chi^2}{ndf} = \frac{1386}{1130} \approx 1.226$$ NLO



- Q^2_{min} = 10 GeV²

$$\frac{\chi^2}{ndf} = \frac{1156}{1001} \approx 1.151$$ NLO

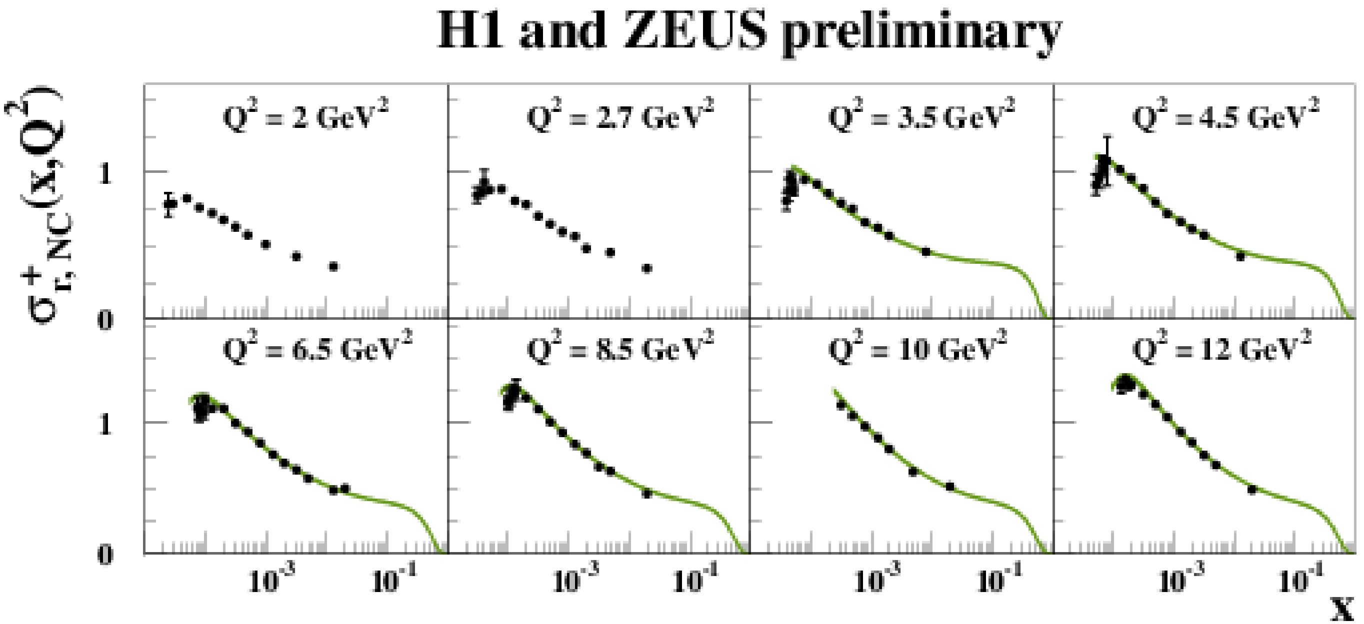


- NLO fit does not agree well with the low Q^2, x.

HERAPDF2.0: NC low Q^2, x

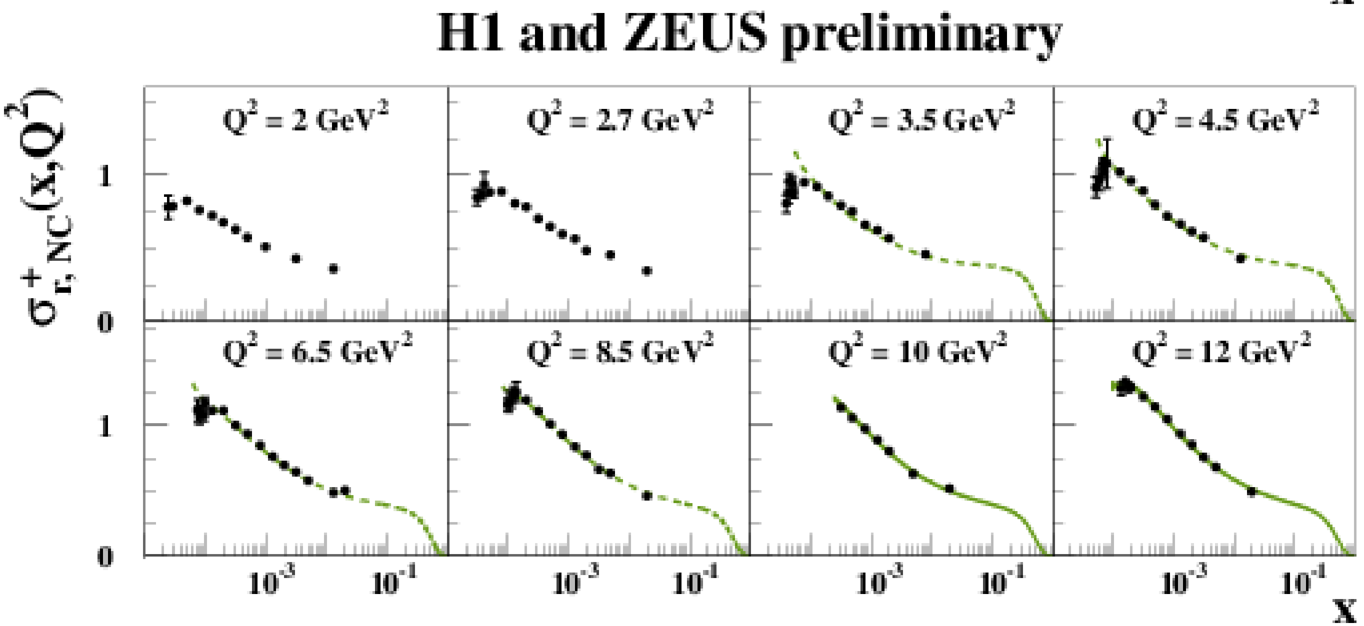
- Q^2_{min} = 3.5 GeV^2

$$\frac{\chi^2}{ndf} = \frac{1414}{1130} \approx 1.251$$ NNLO



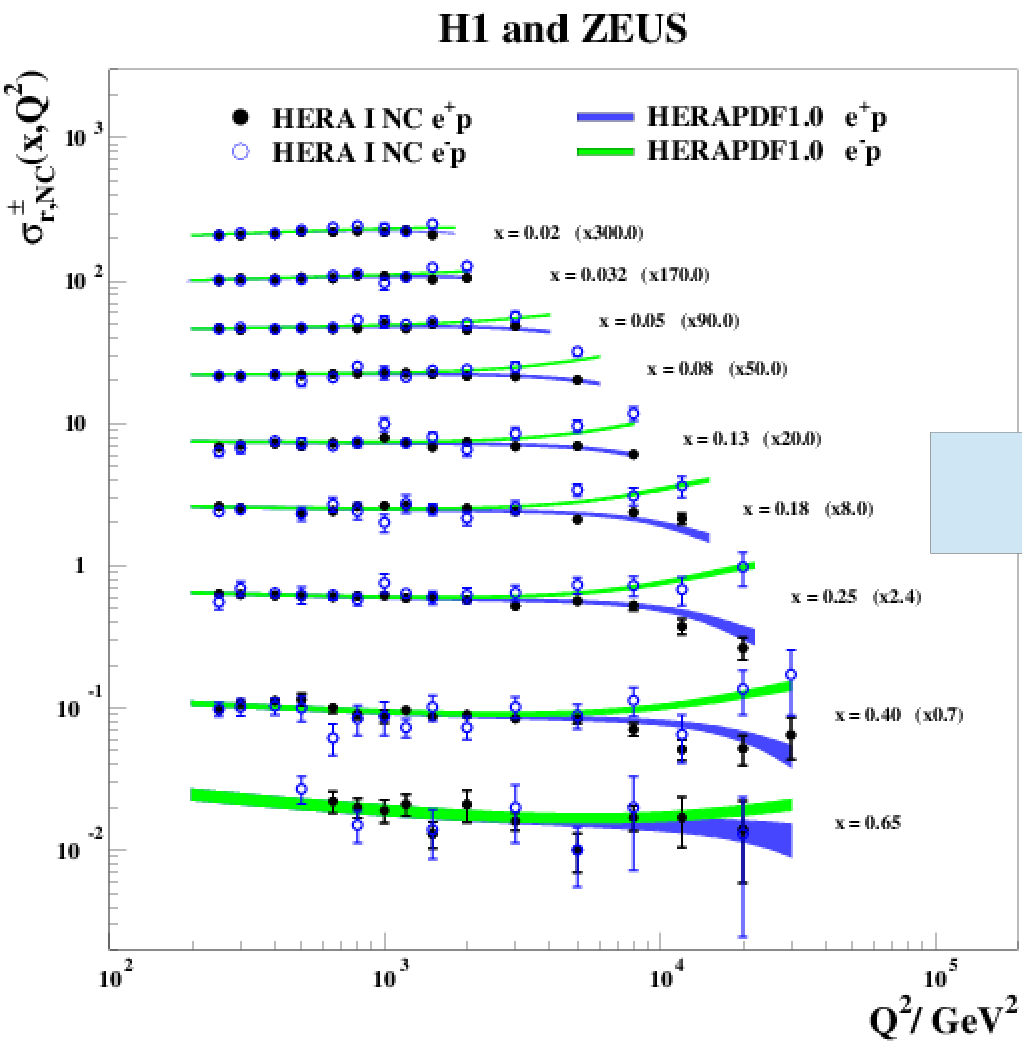
- Q^2_{min} = 10 GeV^2

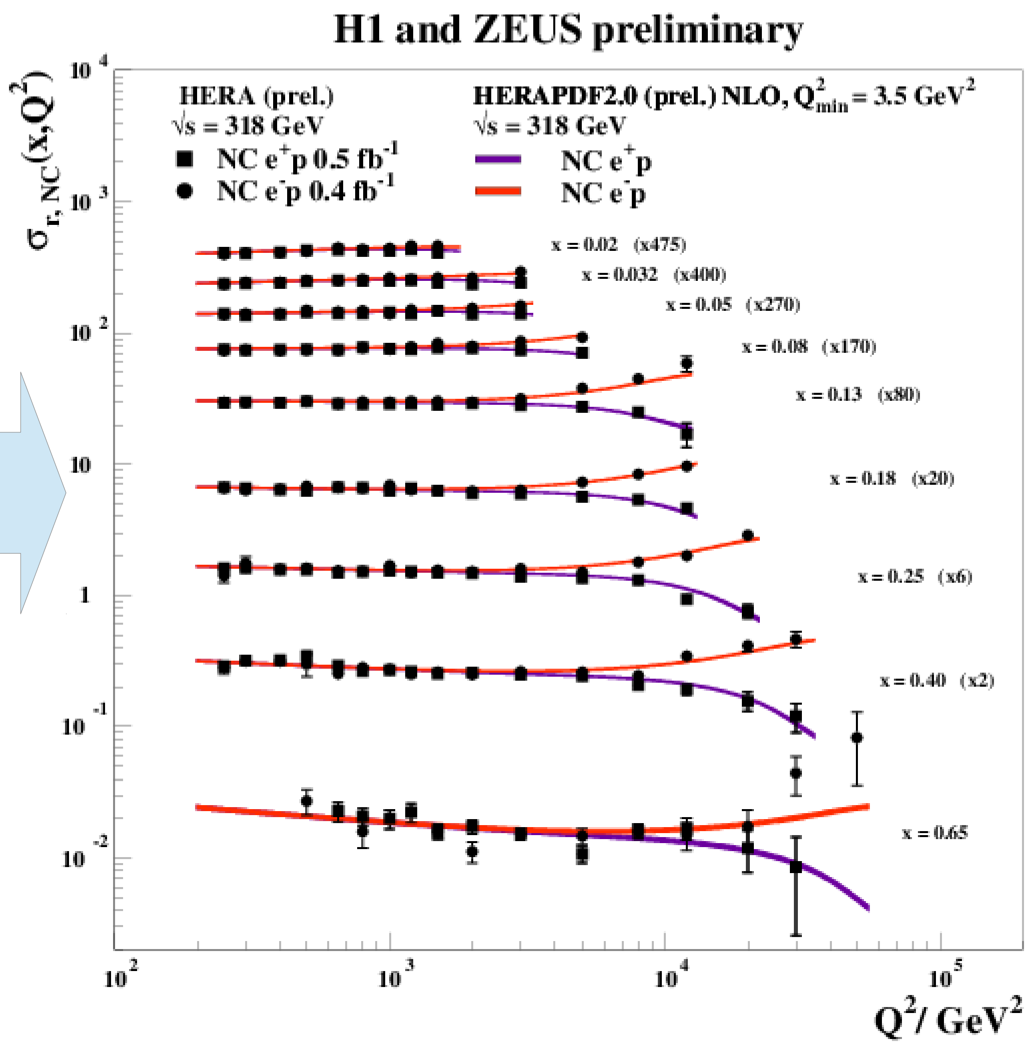
$$\frac{\chi^2}{ndf} = \frac{1150}{1001} \approx 1.148$$ NNLO



- NNLO fit also does not agree well.

EW effects: HERAPDF 1.0 vs 2.0

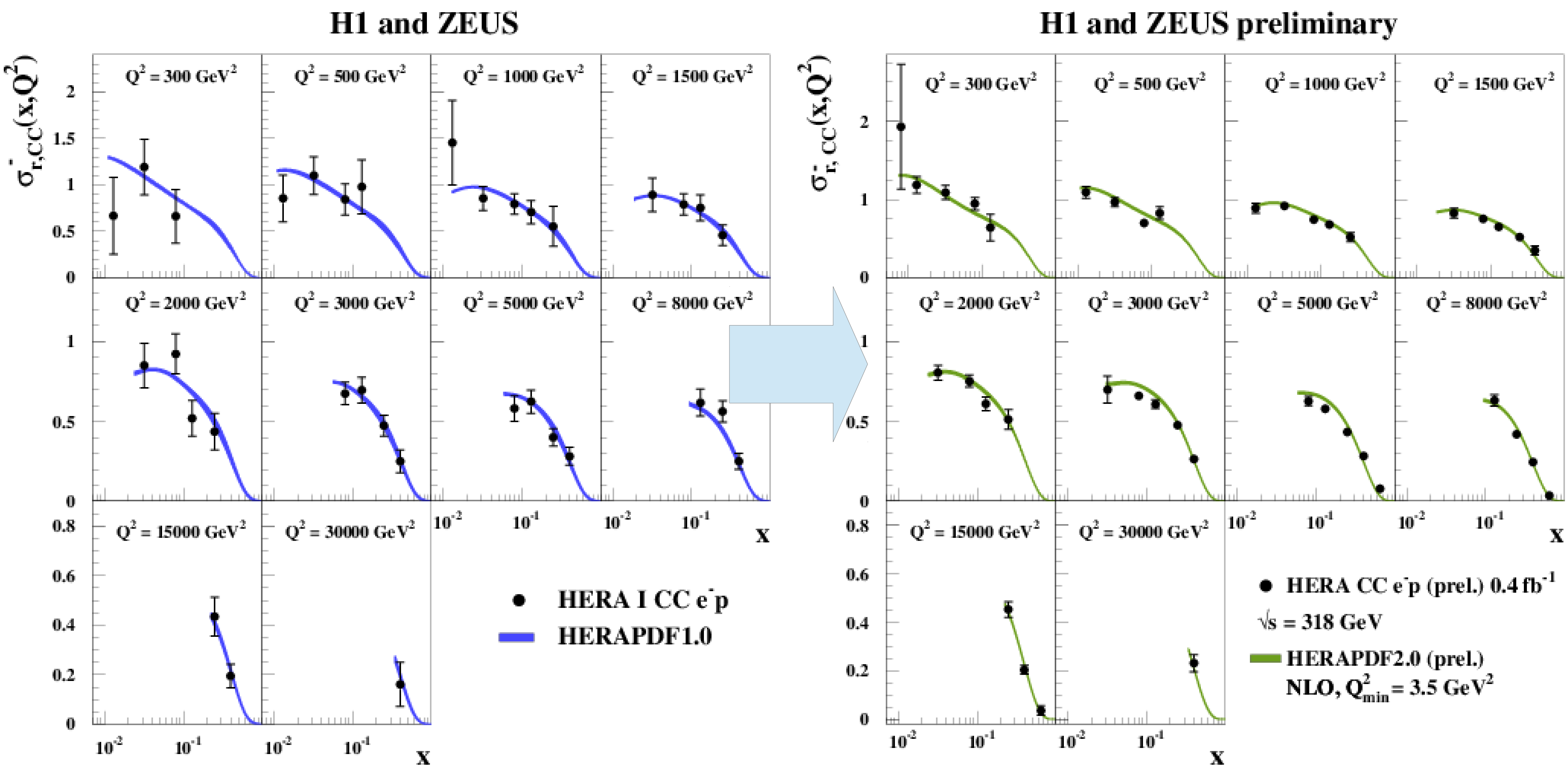




- Great precision!

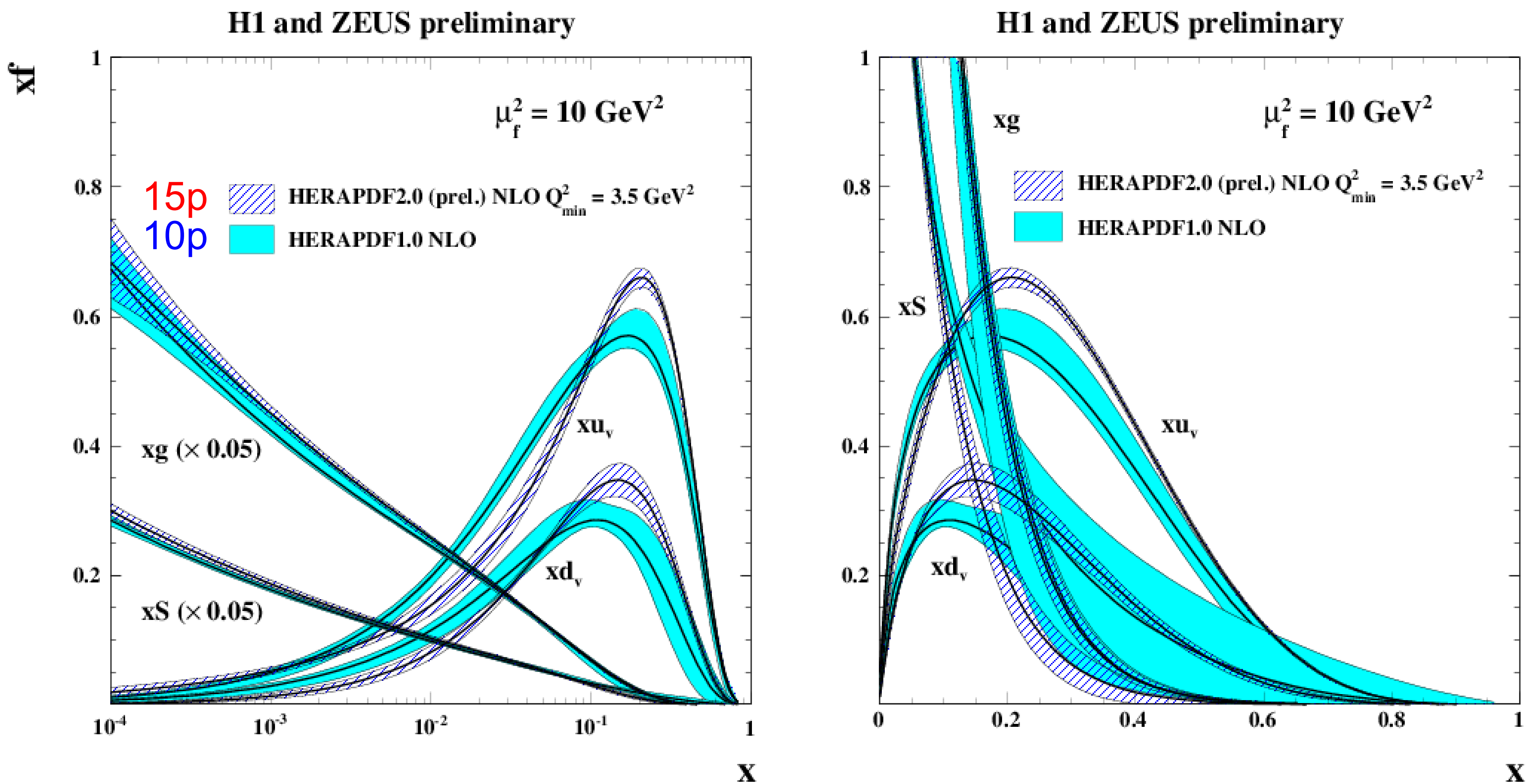
$$x\tilde{F}_3 = -a_e \frac{\kappa Q^2}{Q^2+M_{Z^0}^2} xF_3^{\gamma Z^0} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2+M_{Z^0}^2}\right)^2 F_3^{Z^0}$$

CC high Q^2, x: HERAPDF 1.0 vs 2.0



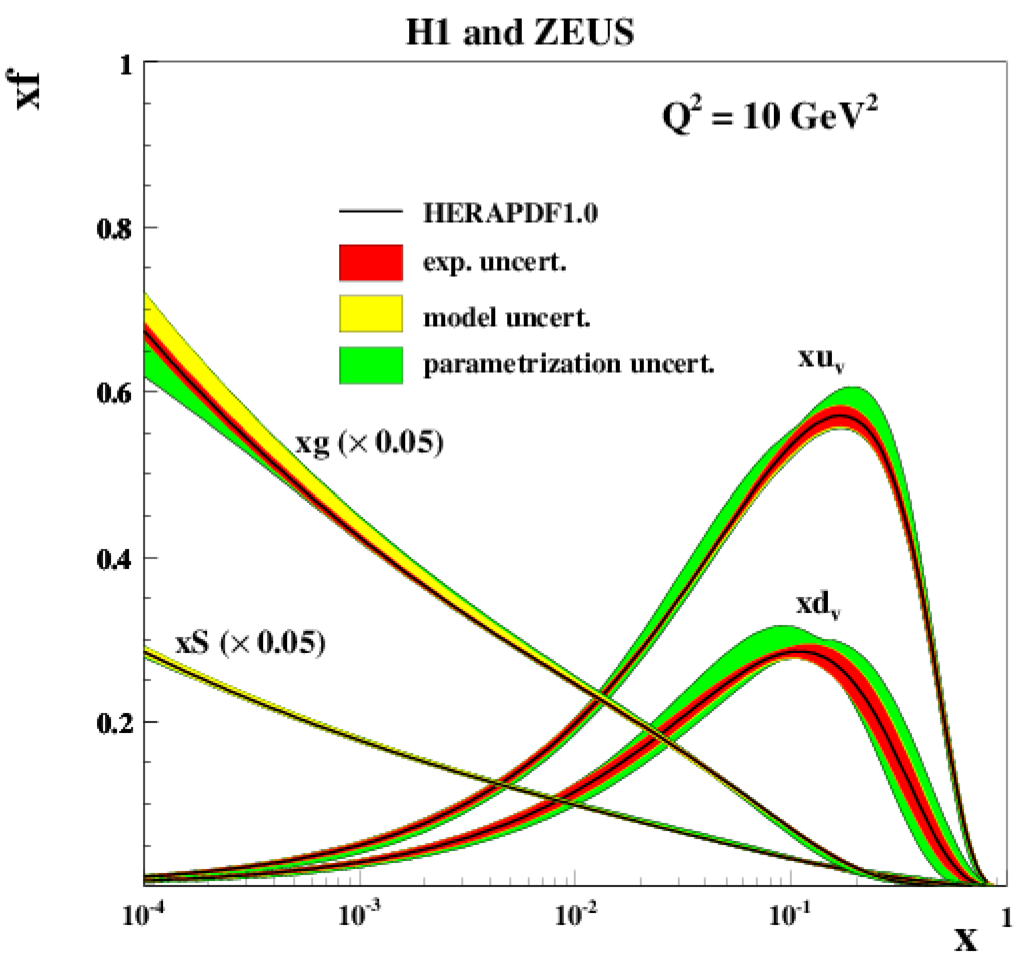
- Significantly more data since HERAPDF1.0.
- Improved precision!

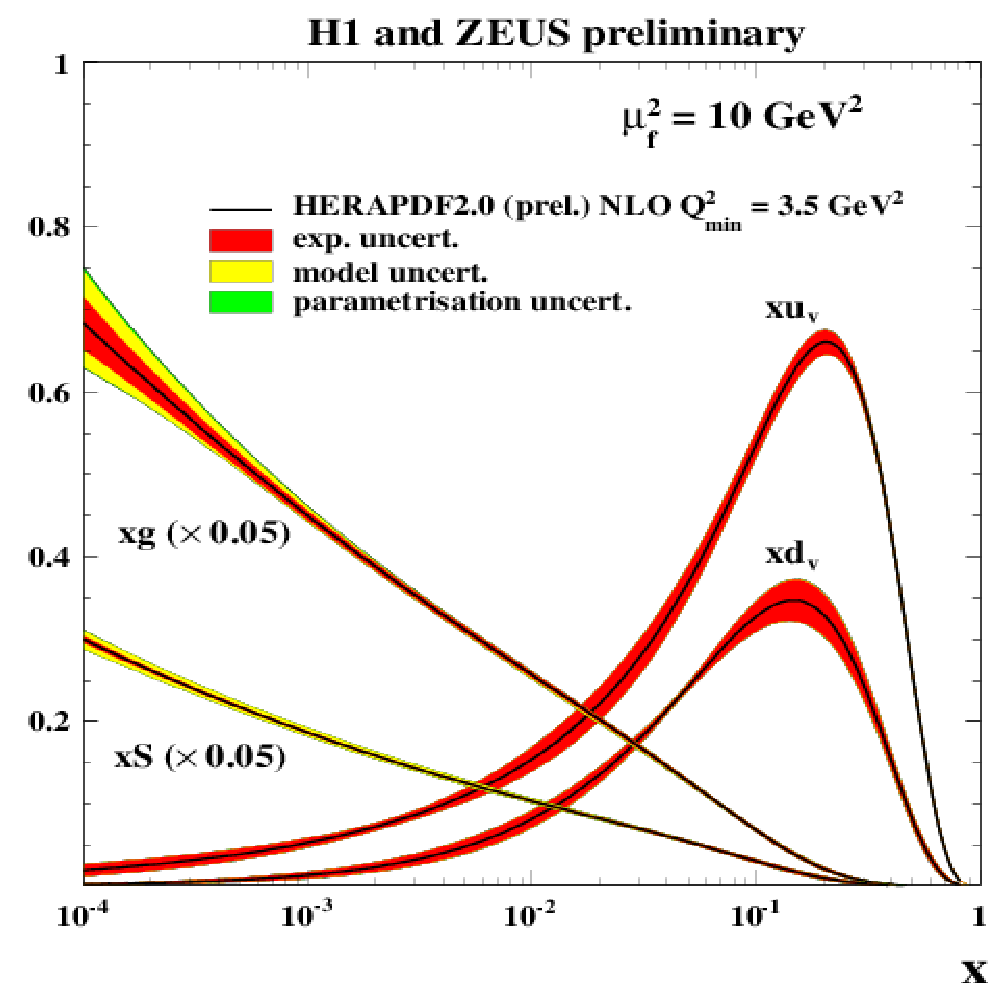
HERAPDF1.0 vs HERAPDF2.0



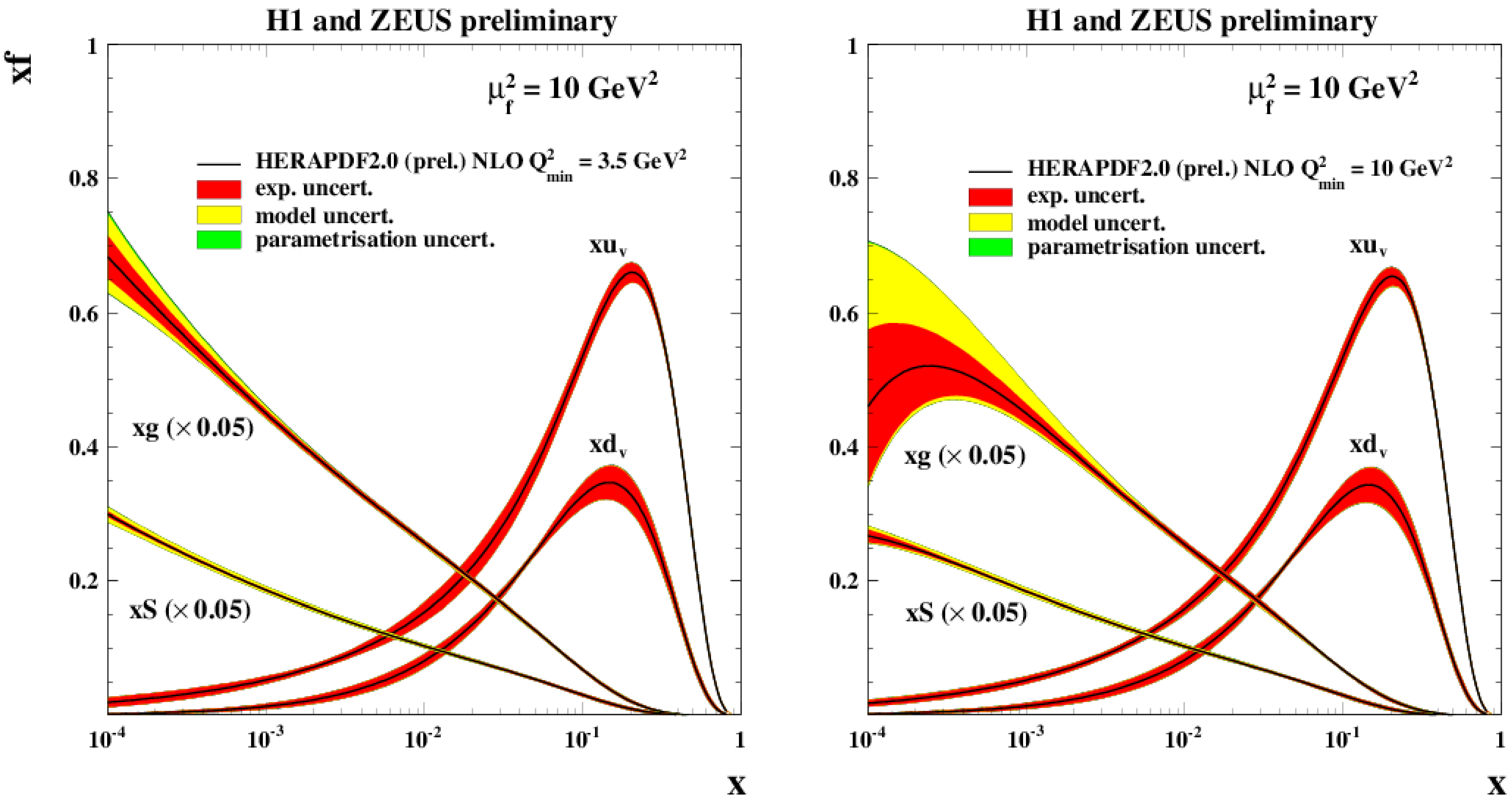
- Valence distributions are more peaked at HERAPDF2.0 (new data).
- High x sea is softer whereas gulon is harder at HERAPDF2.0.

HERAPDF1.0 vs HERAPDF2.0

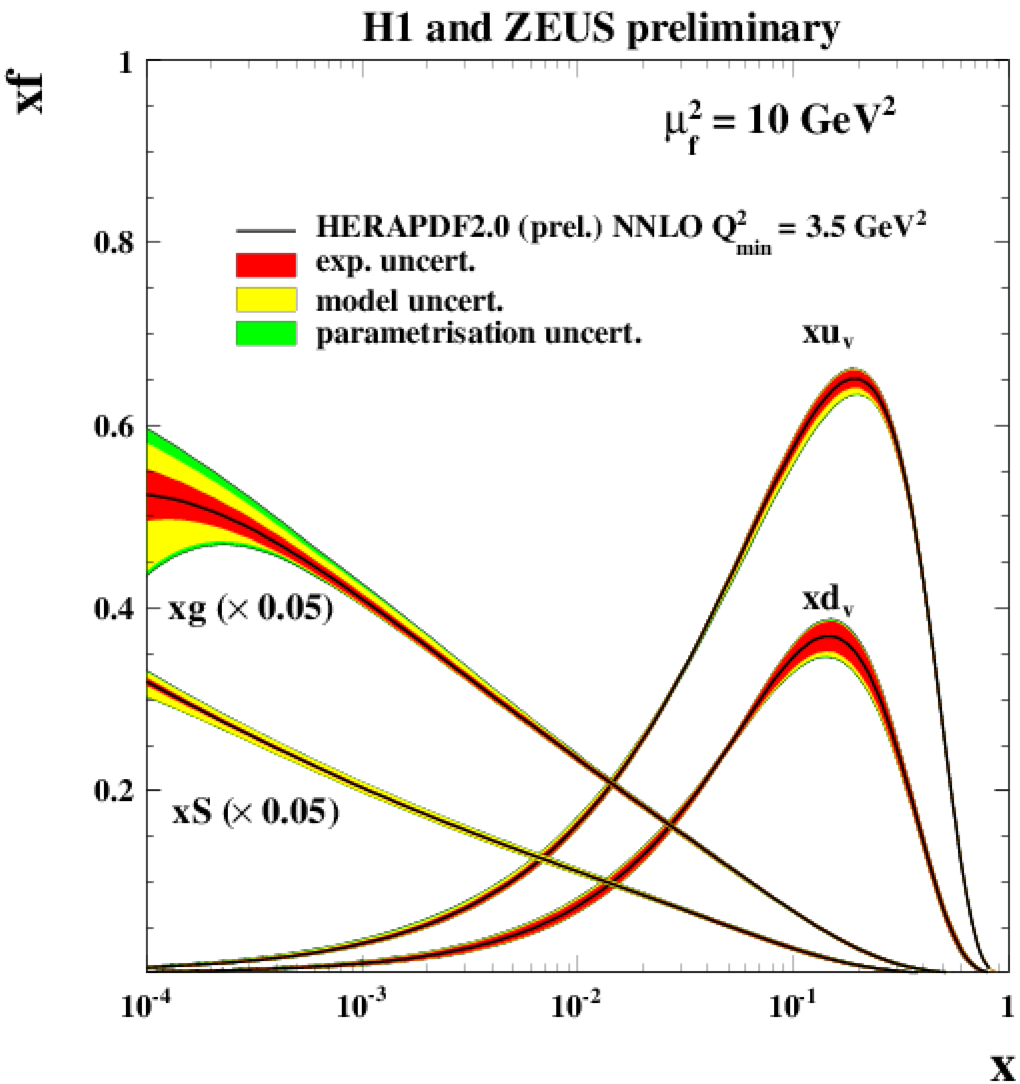


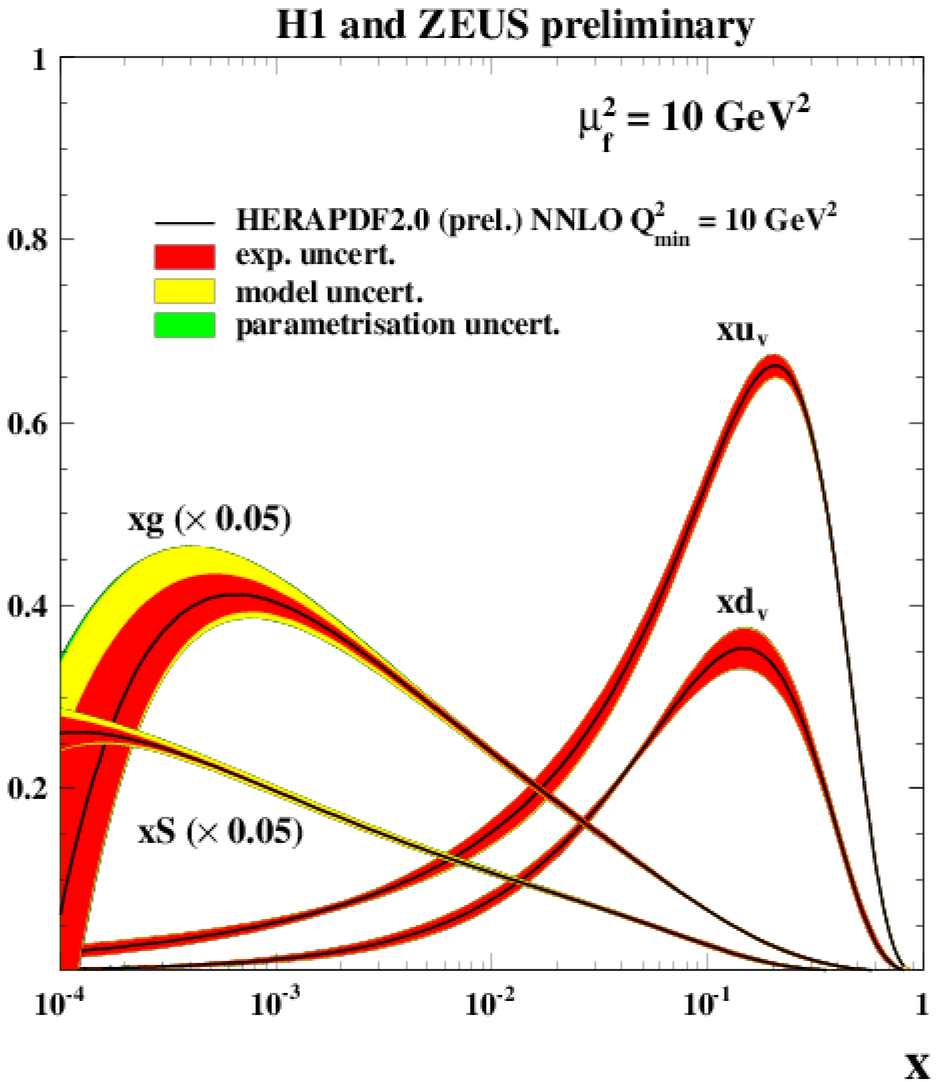


HERAPDF2.0: NLO fits

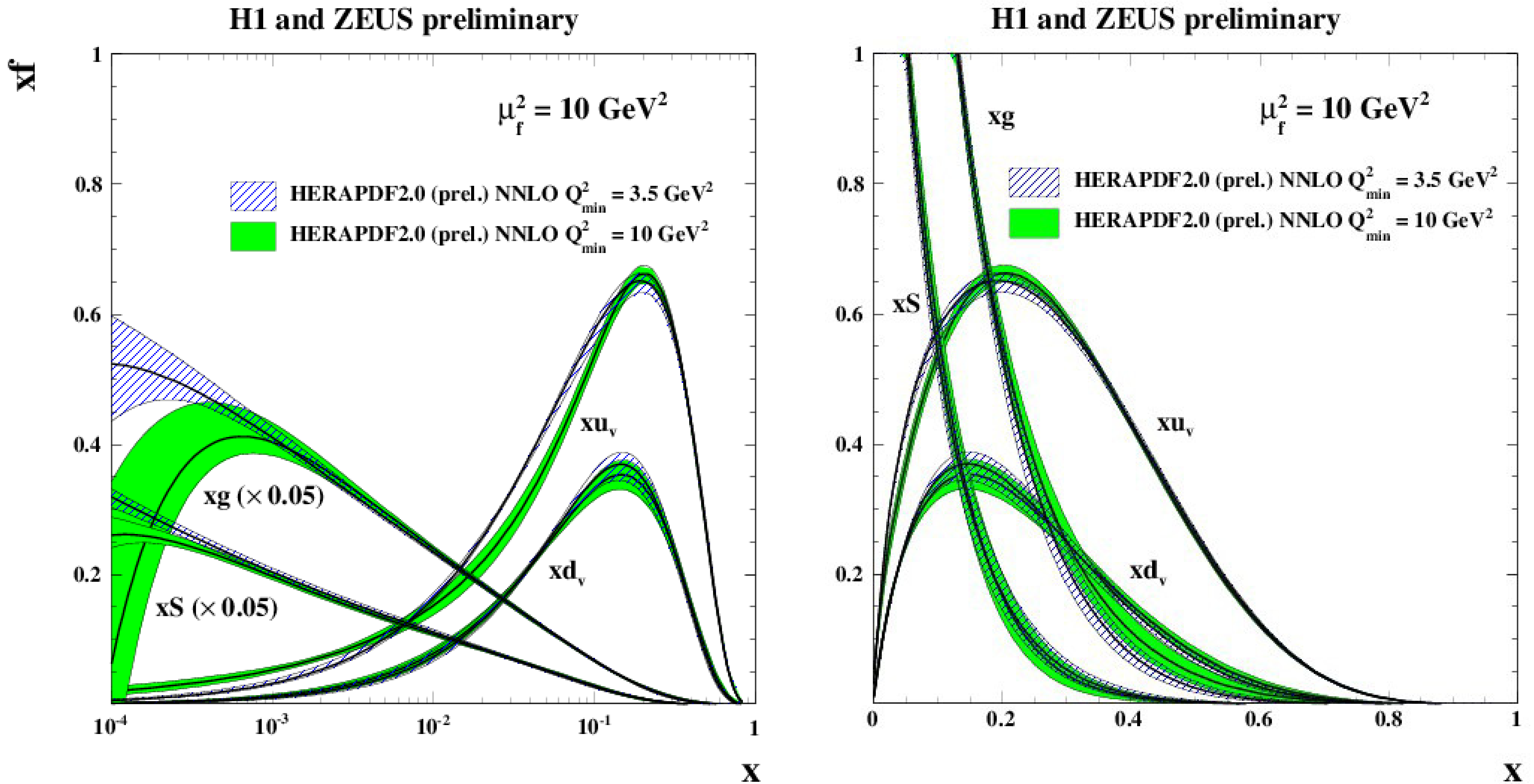


HERAPDF2.0: NNLO fits





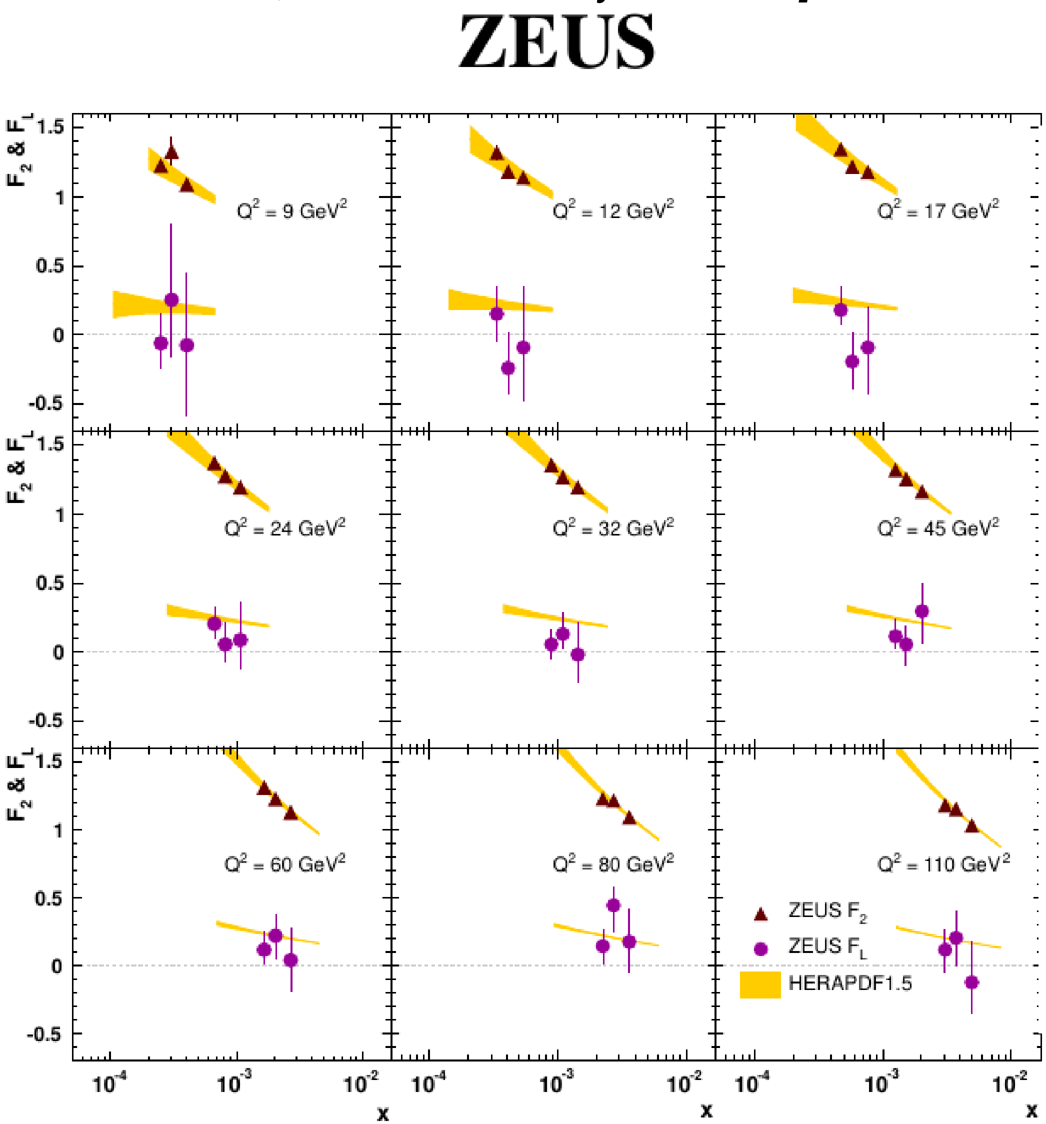
HERAPDF2.0: NNLO fits



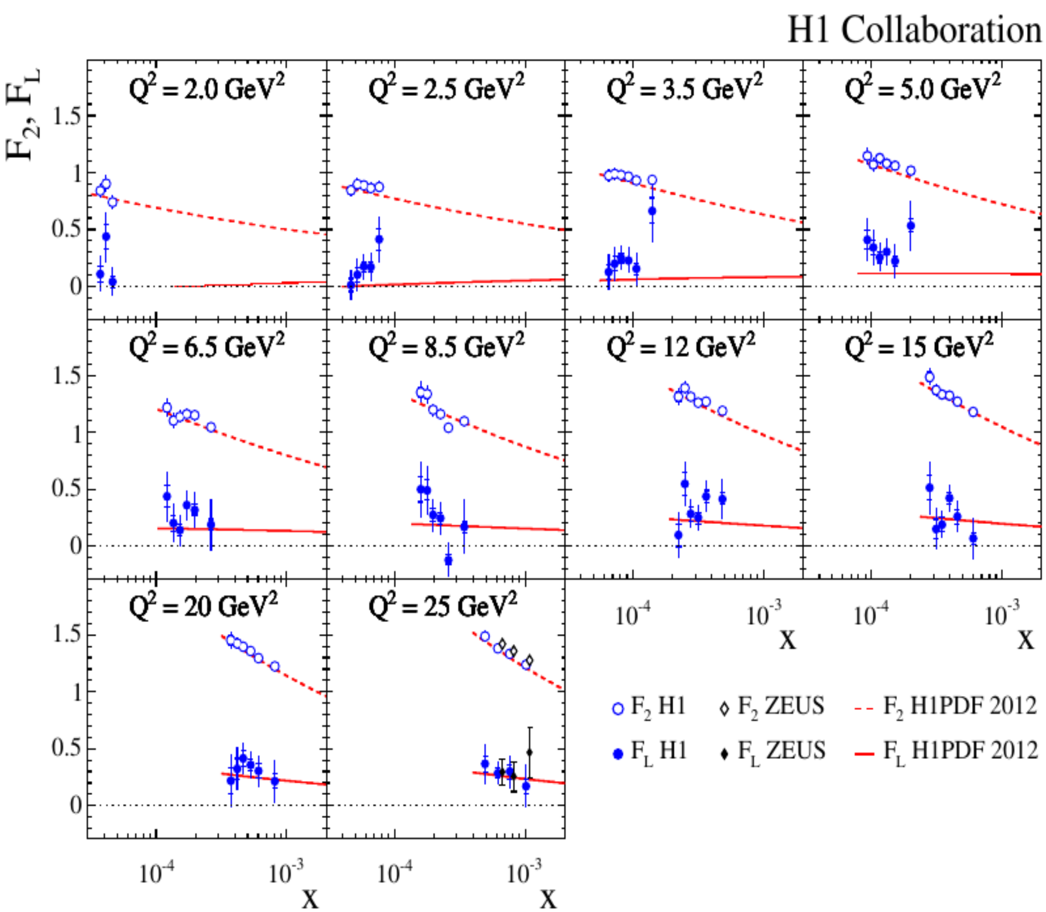
- For $Q^2_{min} = 10\ GeV^2$ gluon uncertainty is larger.
- Resemblance of fits at high x, but remarkable differences at low x.
- Different shapes for gluons and sea at $Q^2_{min} = 3.5\ GeV^2$ and $Q^2_{min} = 10\ GeV^2$.

Longitudinal structure function F_L

DESY-14-053, submitted to Phys. Lett. B [arXiv:1404.6376]



Eur. Phys. J. C 74 (2014) 2814 [arXiv:1312.4821]



- Good agreement between measurements and predictions.

Charm quark mass running measurement

From $m_c(m_c)$ it was translated back to $m_c(\mu)$ by 1-loop formula :

$$m_c(\mu) = m_c(m_c)\frac{\left(\frac{\alpha_s(\mu)}{\pi}\right)^{\frac{1}{\beta_0}}}{\left(\frac{\alpha_s(m_c)}{\pi}\right)^{\frac{1}{\beta_0}}}$$

Where β_0 for N_f=3 is $\frac{9}{4}$
$\mu = \sqrt{Q^2 + 4m_c^2}$,
Formula implementation cross-checked with RunDec [arXiv:hep-ph/0004189] code.
Q^2 was chosen to be log average between Q^2 of used bins