The final H1+ZEUS combined inclusive data and HERAPDF2.0

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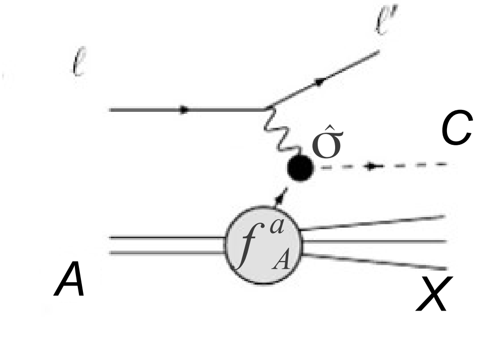
Volodymyr Myronenko
DESY

on behalf of
H1 and ZEUS collaborations

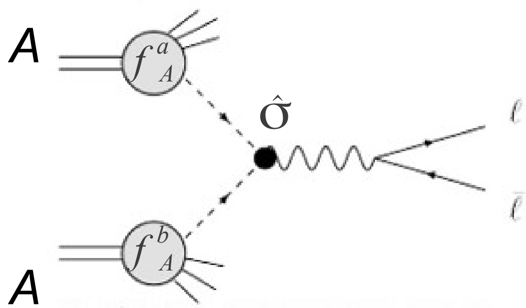
Rencontres de Moriond
La Thuile, Italy 2016

PDFs for the precision measurements

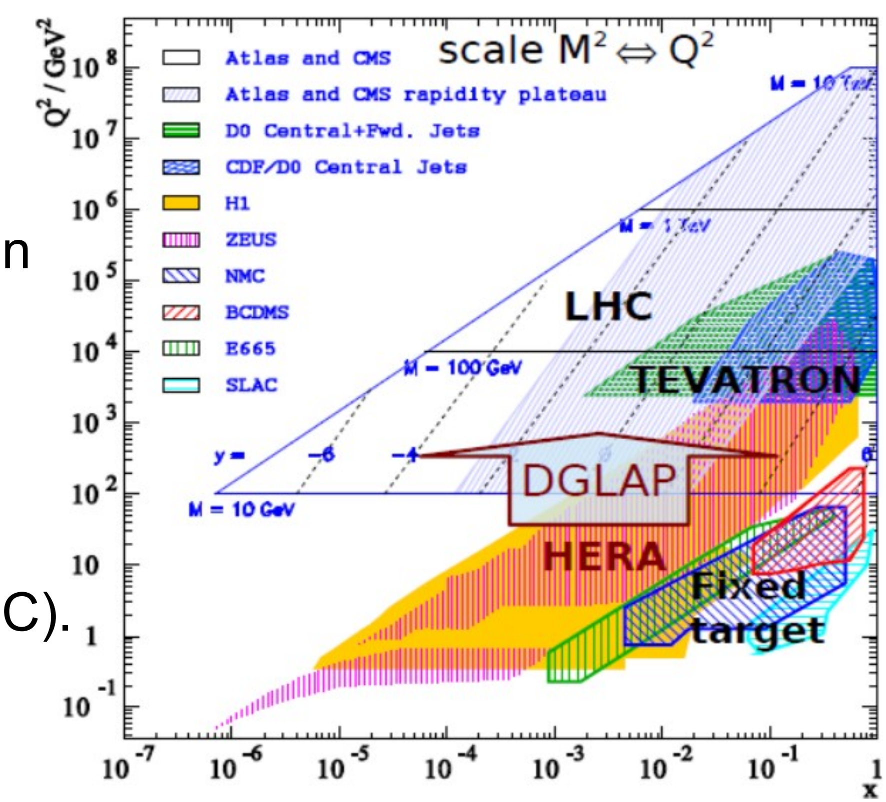


- **Factorisation theorem: PDFs + hard-scattering cross section**

$$\sigma^{i}_{A\to C}(q,p)=\sum_a\int_x^1 d\xi\, f^a_A(\xi,\mu)\,\hat{\sigma}^{i}_{a\to C}(q,\xi p,\mu,\alpha_s)$$



- PDFs are **universal** => essential for precision measurements.



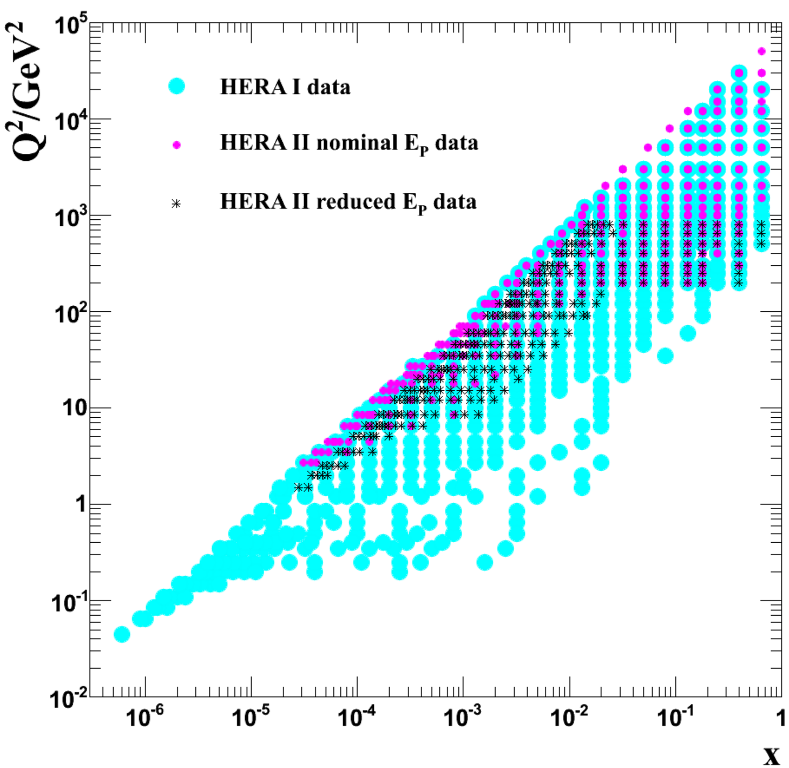
- HERA data is a core of every PDF determination
  - Covers wide kinematic range
  - Probes linear combination of quarks.
  - Sensitive to the quark flavor decomposition (CC).
  - Information on the gluon content of proton

Full HERA data combination

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0



Data Set		x_{Bj} Grid from	x_{Bj} 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 [1.5p]	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC [1.5p]	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC [1.5p]	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC [1.5p]	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2 [*y.5]	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2 [*y.5]	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 [1.5p]	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC [1.5]	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC [1.5]	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal [*y]	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite [*y]	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!

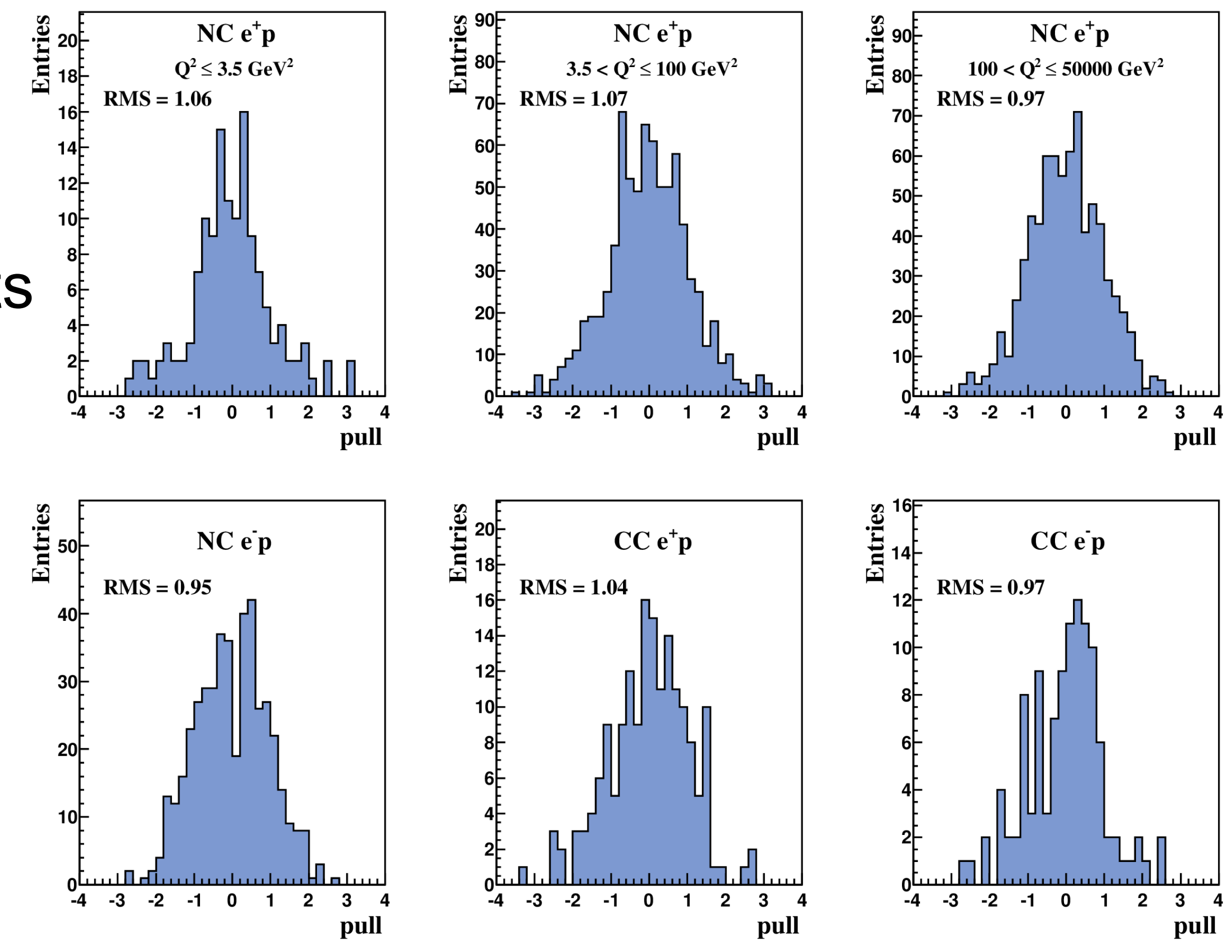
Combining measurements

2927 original measurements

1307 averaged measurements

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

H1 and ZEUS



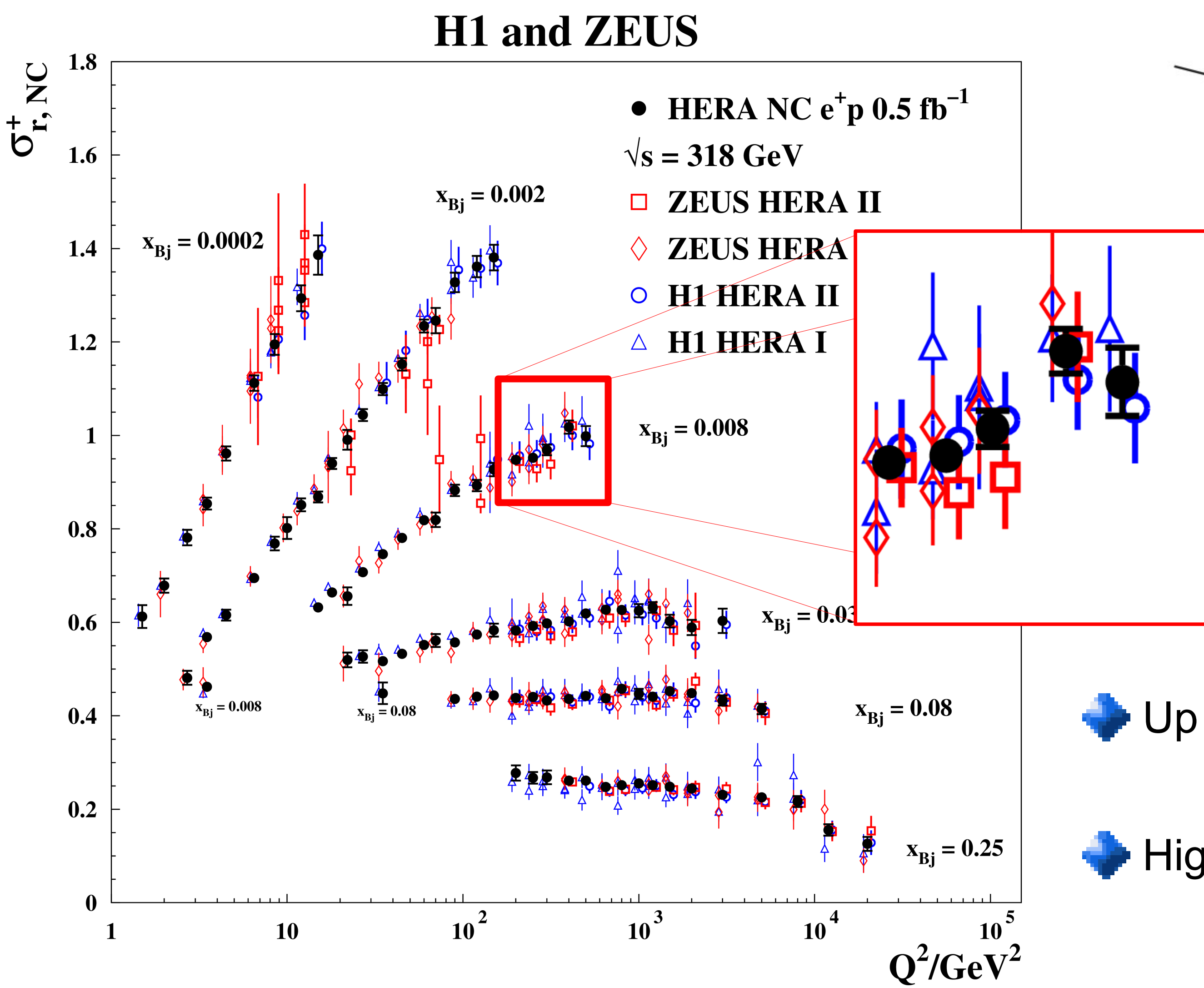
Consistant data sets: total χ^2/ndf = 1685/1620.

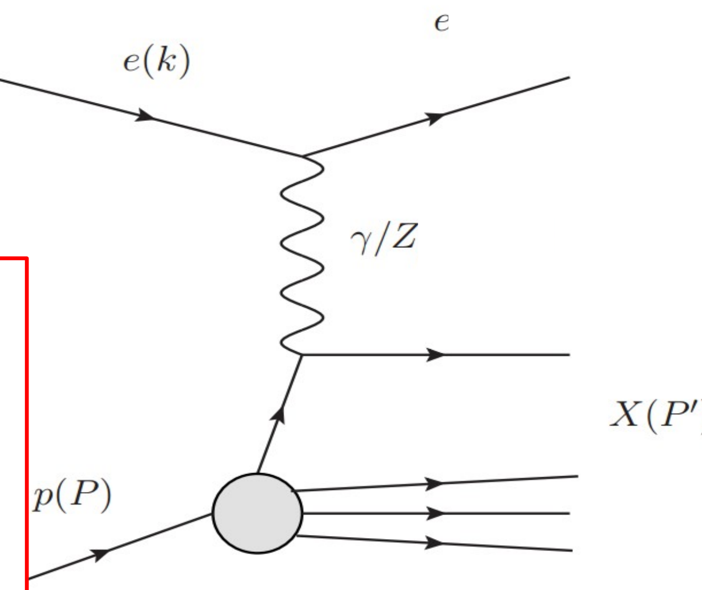
- Correlations of systematic uncertainties considered.
- Procedural uncertainties ~ 1%.

Combined reduced cross-sections

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

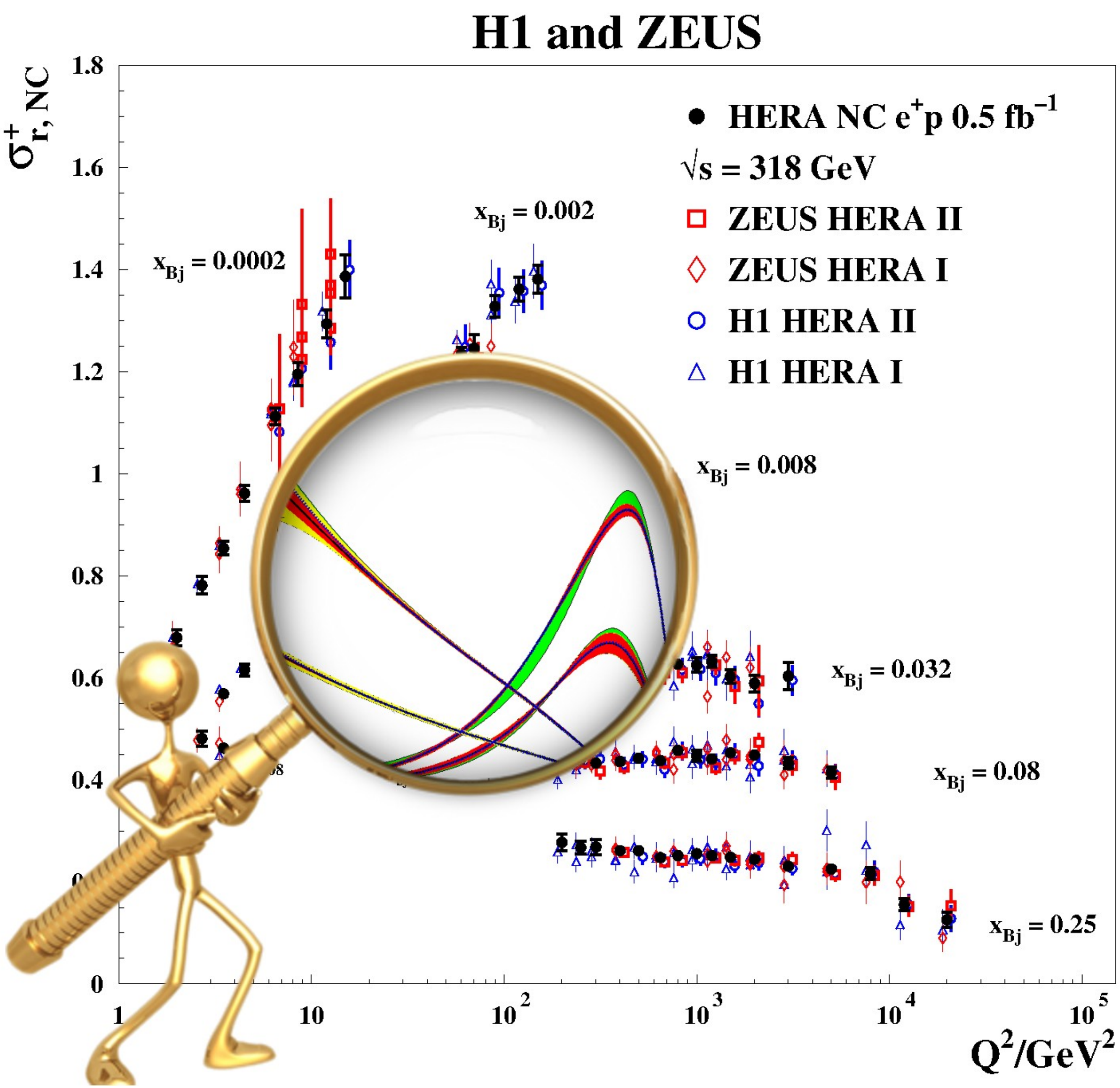
$$Y_\pm = 1 \pm (1-y)^2$$





- Up to ~6 measurements averaged.
- High precision achieved.

Extraction of PDFs from inclusive data



HERAPDF2.0: settings for QCD fit

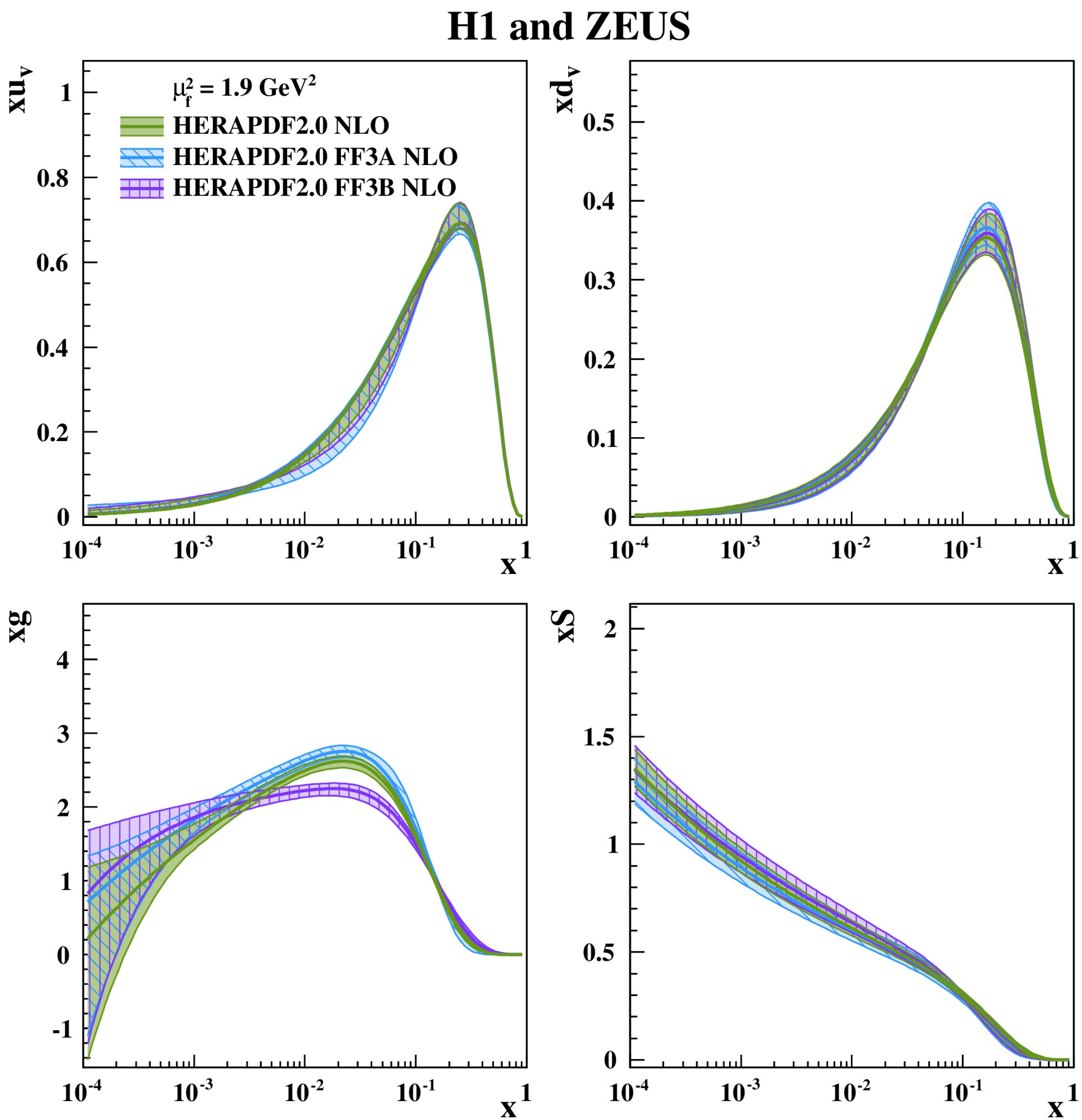
- The fit is performed using the HERA data only.
- QCD fits are performed using HERAFitter package
  www.herafitter.org
- PDFs (14p) are parametrised at $Q_0^2 = 1.9\ \mathrm{GeV}^2$

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

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

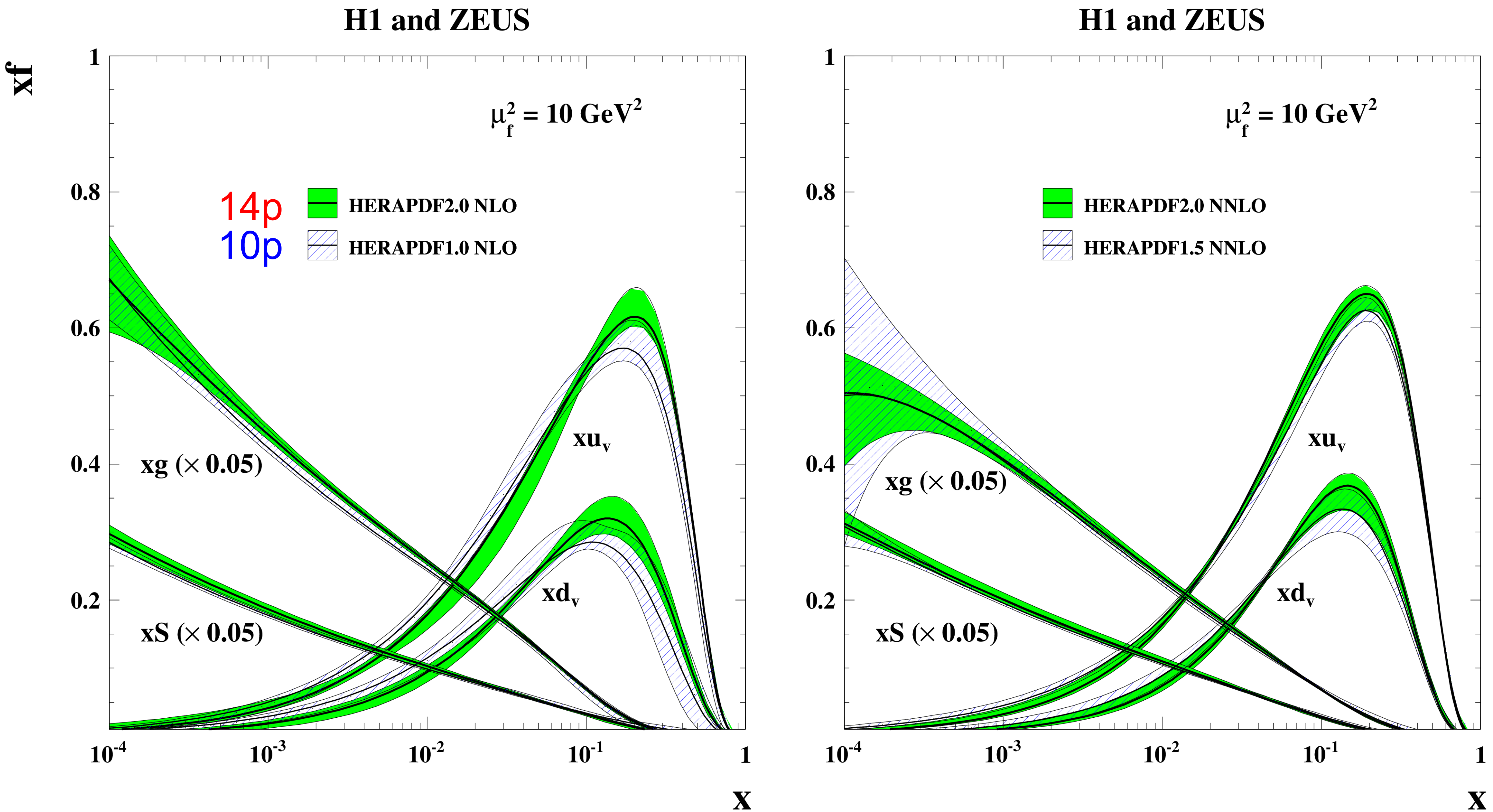
- PDF evolution is performed using DGLAP equations
- Heavy flavour coefficients are obtained within GM VFNS (RT OPT)

HERAPDF2.0 and variants



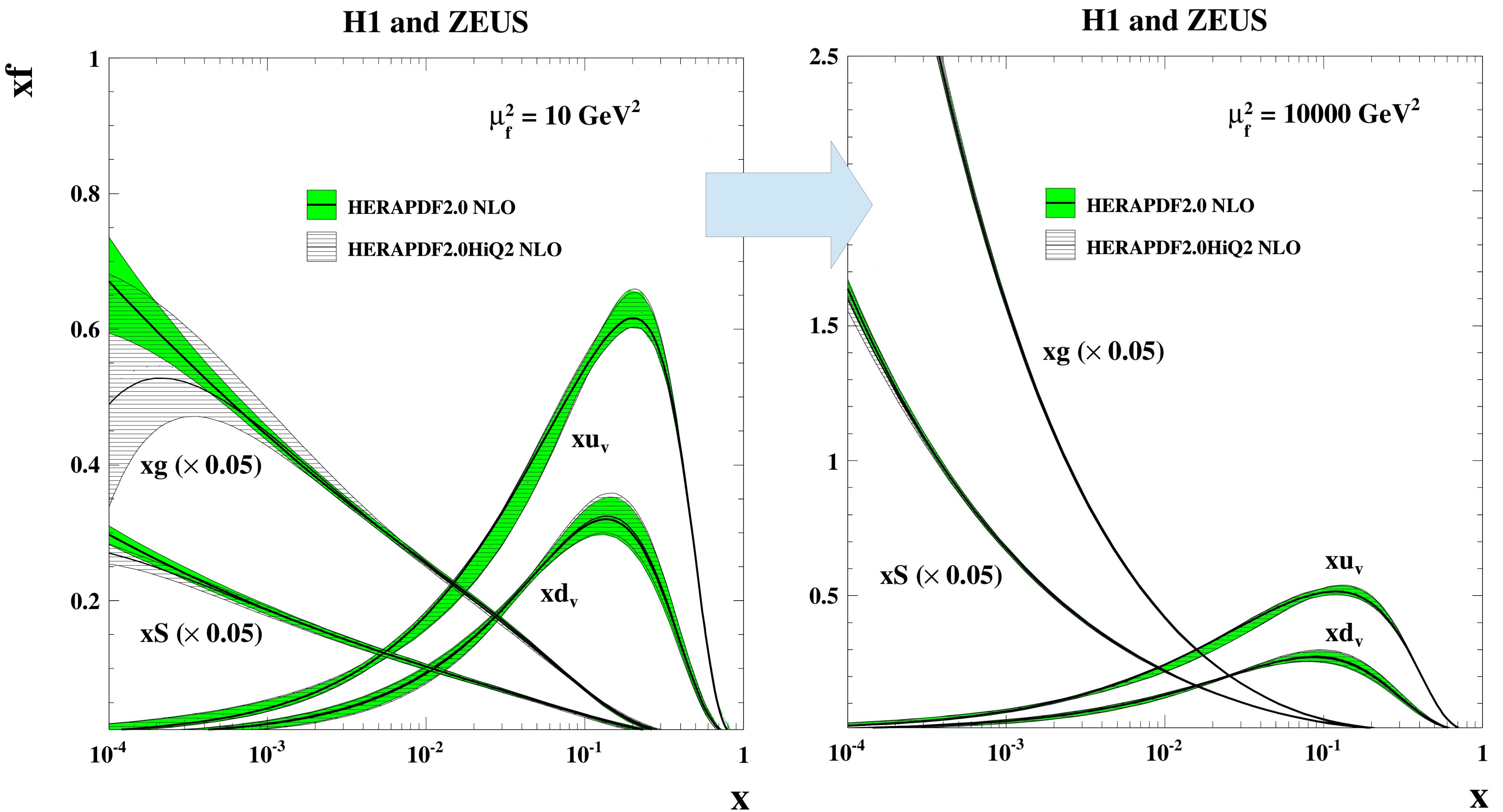
- Data above:
  - Q^2_{min} = 3.5 GeV^2
  - Q^2_{min} = 10 GeV^2
- Orders of calculation:
  - LO
  - NLO
  - NNLO
- HF schemes:
  - GM VFNS (RTOPT)
  - FF3A / FF3B
- Various α_S as input
- Various gluon parmetrisations.

HERAPDF1.0 vs HERAPDF2.0



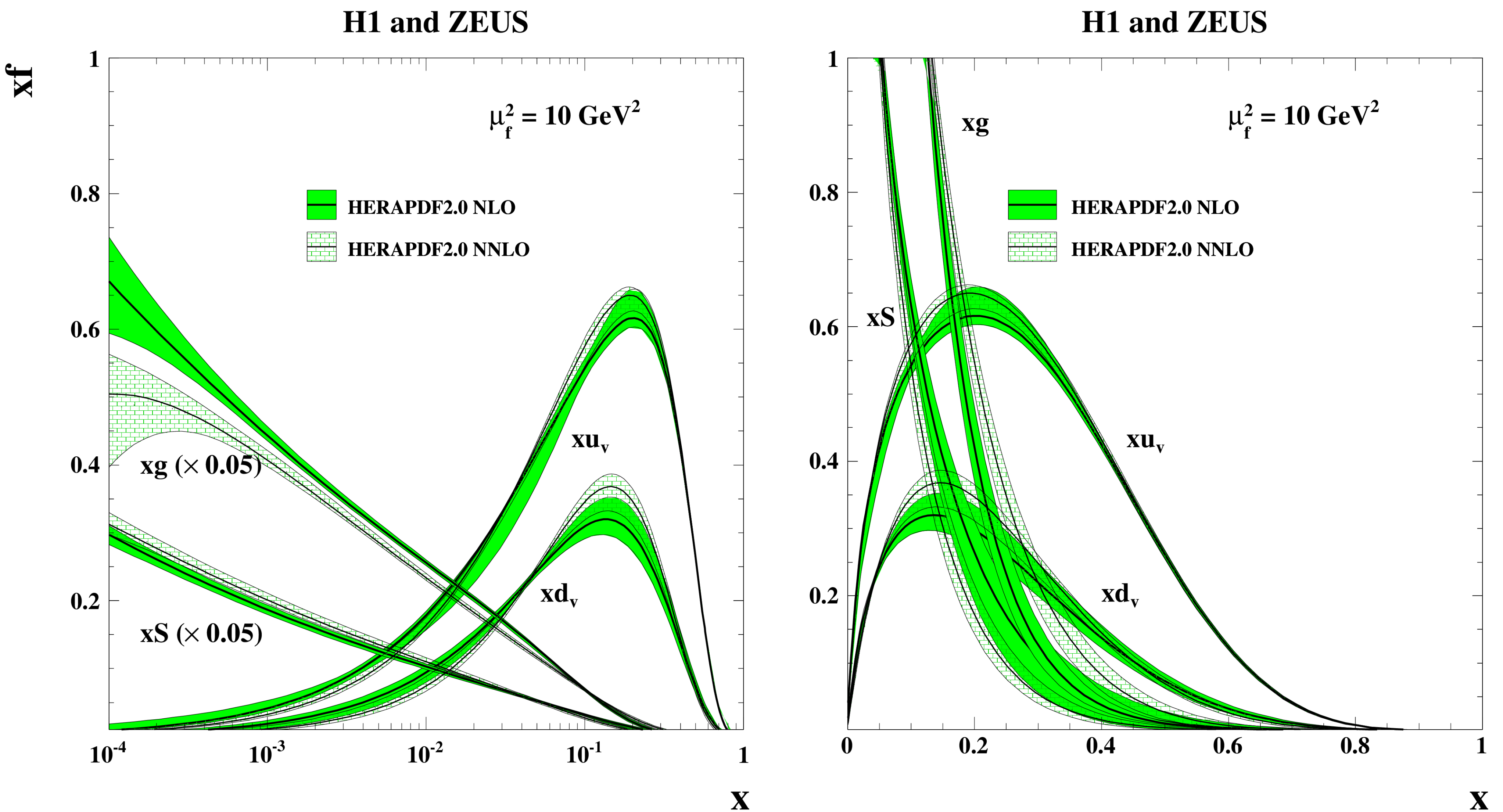
- Valence are more peaked and precise at HERAPDF2.0 (new data).
- Smaller uncertainties at high x.

HERAPDF2.0 vs HERAPDF2.0HiQ2



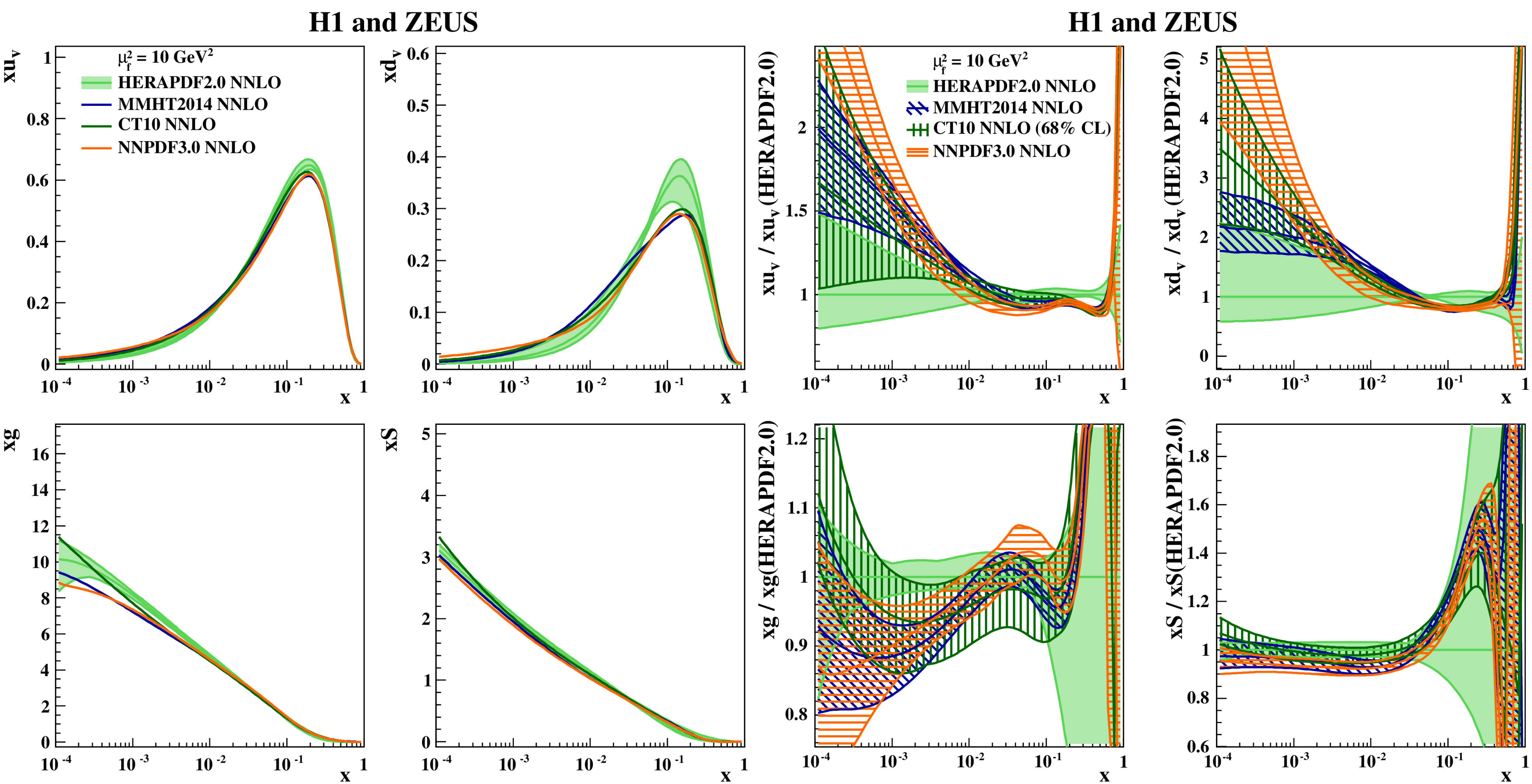
- Larger uncertainty for HERAPDF2.0HiQ2 gluon at low x.
- PDFs very alike at higher scales => similar predictions at LHC domain.

HERAPDF2.0: NLO vs NNLO fits



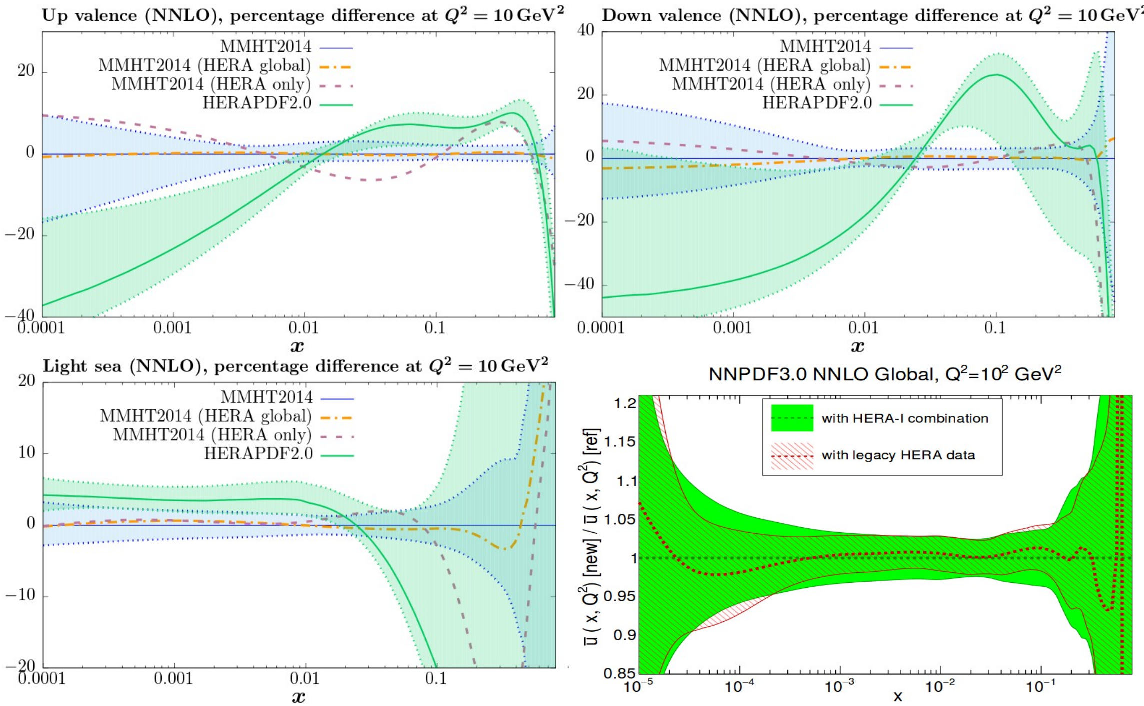
- Valence distributions look similar.
- Gluons are a bit shifted.

HERAPDF2.0 vs other PDFs

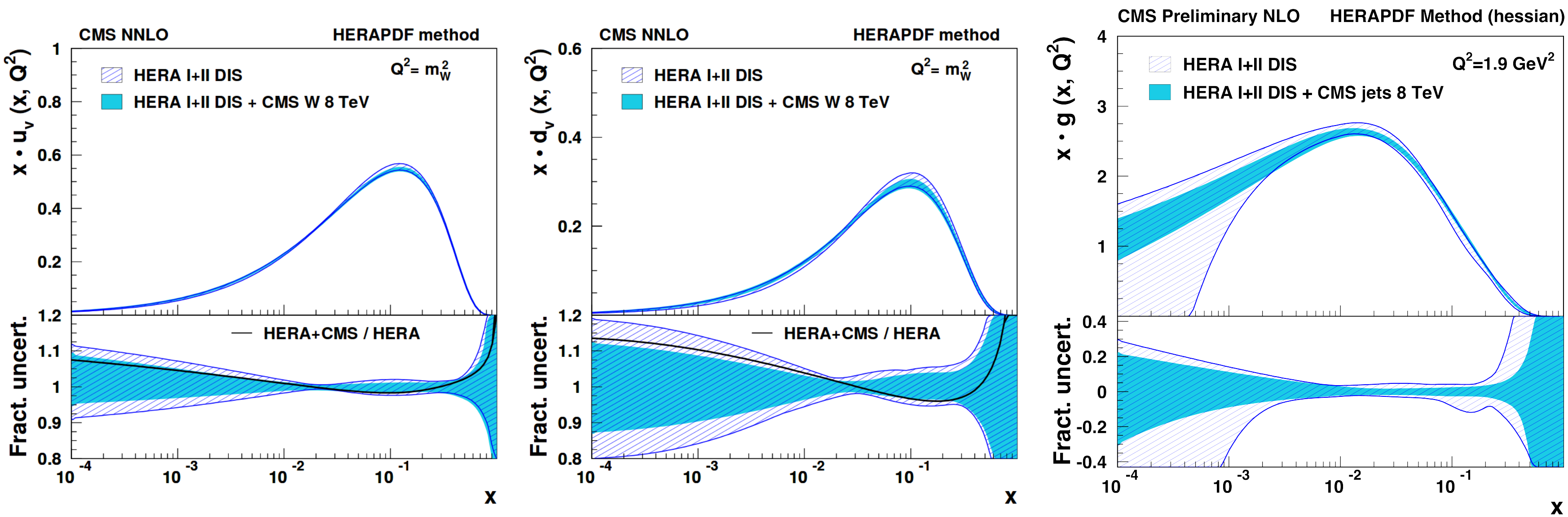


- The largest difference - xu_v at $x \approx 0.4$ (2.5σ).
- Various gluon behaviours at low x.

HERA data in global fits

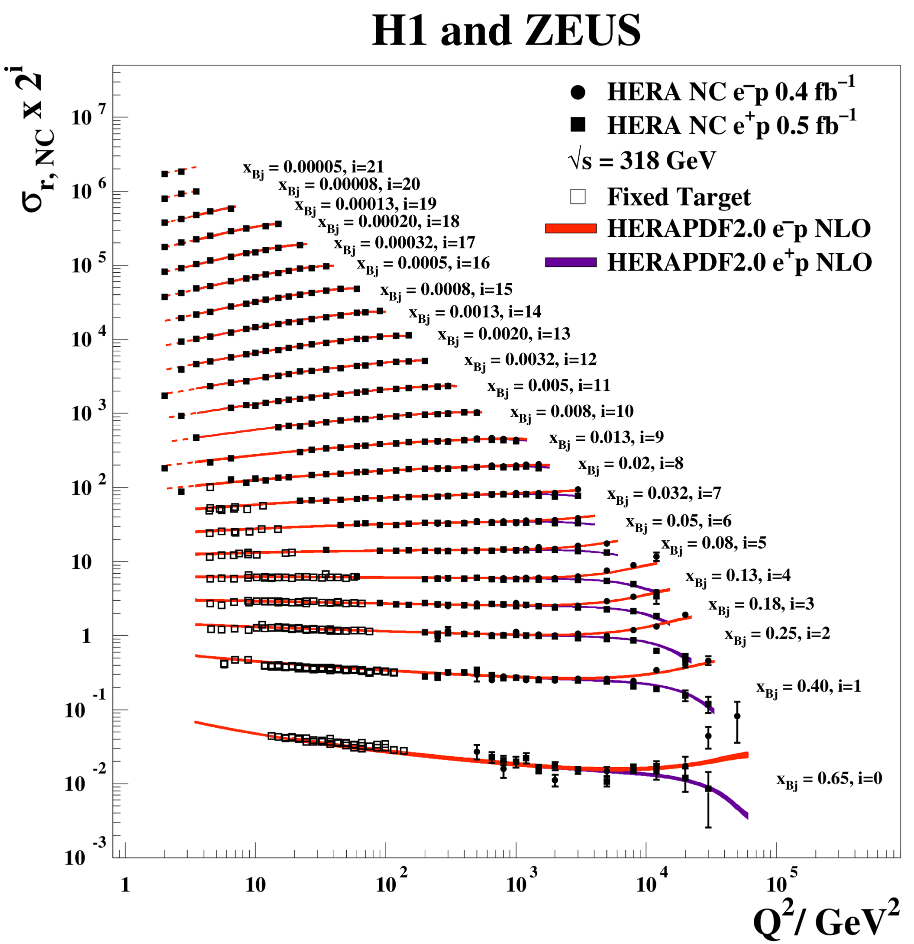


- Precision improvement of few percent at moderate x.
- No tensions within global fits from HERA data.



Summary

- Final combination of HERAI+II data is performed.
- Significant reduction of uncertainties is achieved.
- HERAPDF2.0 fits are performed using combined HERAI+II data.
- PDFs are publicly available in many variations.
- Adding new HERA II data improves PDFs precision.



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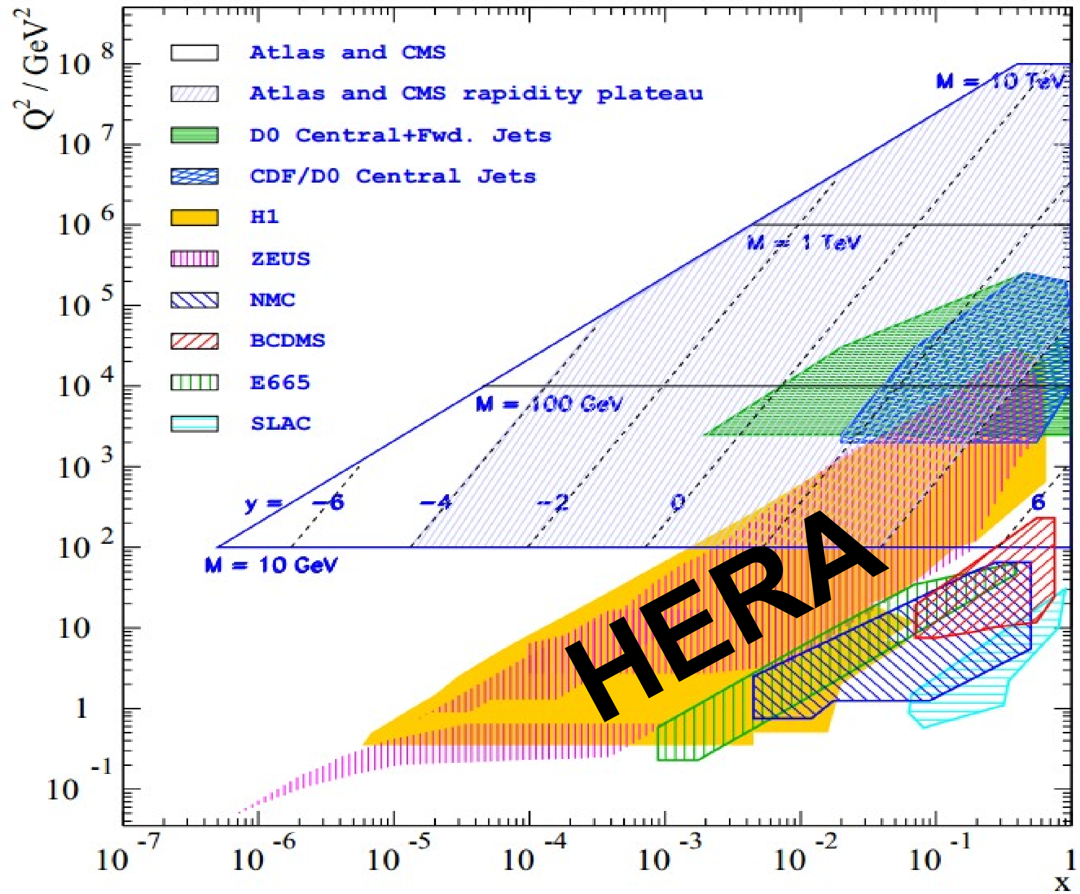
Backup

not necessarily useful...

HERA collider

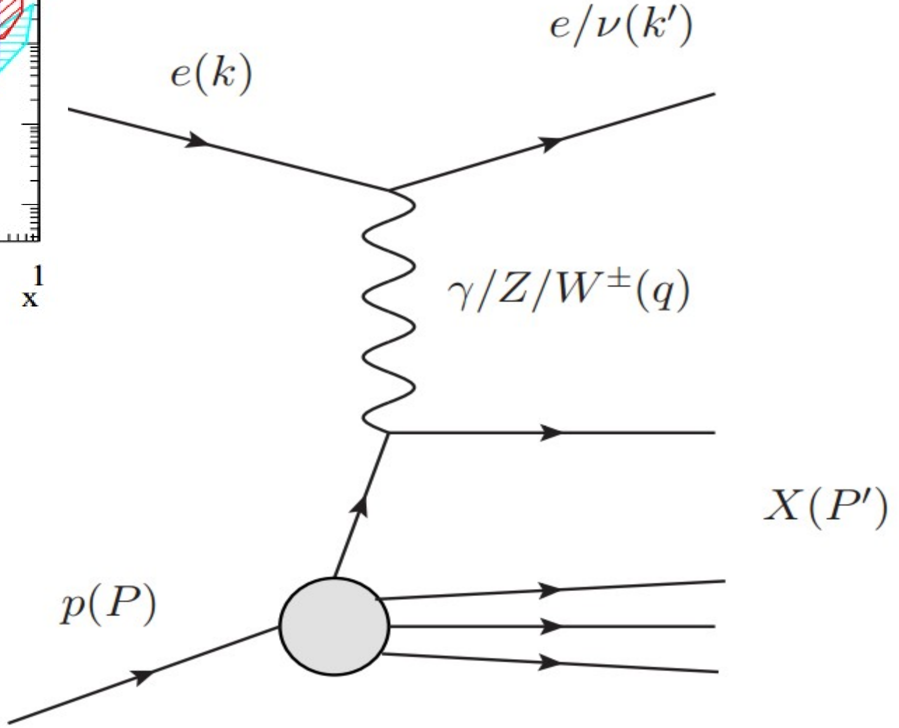


$$E_P = 920\,(460, 575)\,GeV$$
$$E_e = 27.5\,GeV$$

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

Experimental achievements:

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



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

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

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

HERAPDF2.0: settings for QCD fit

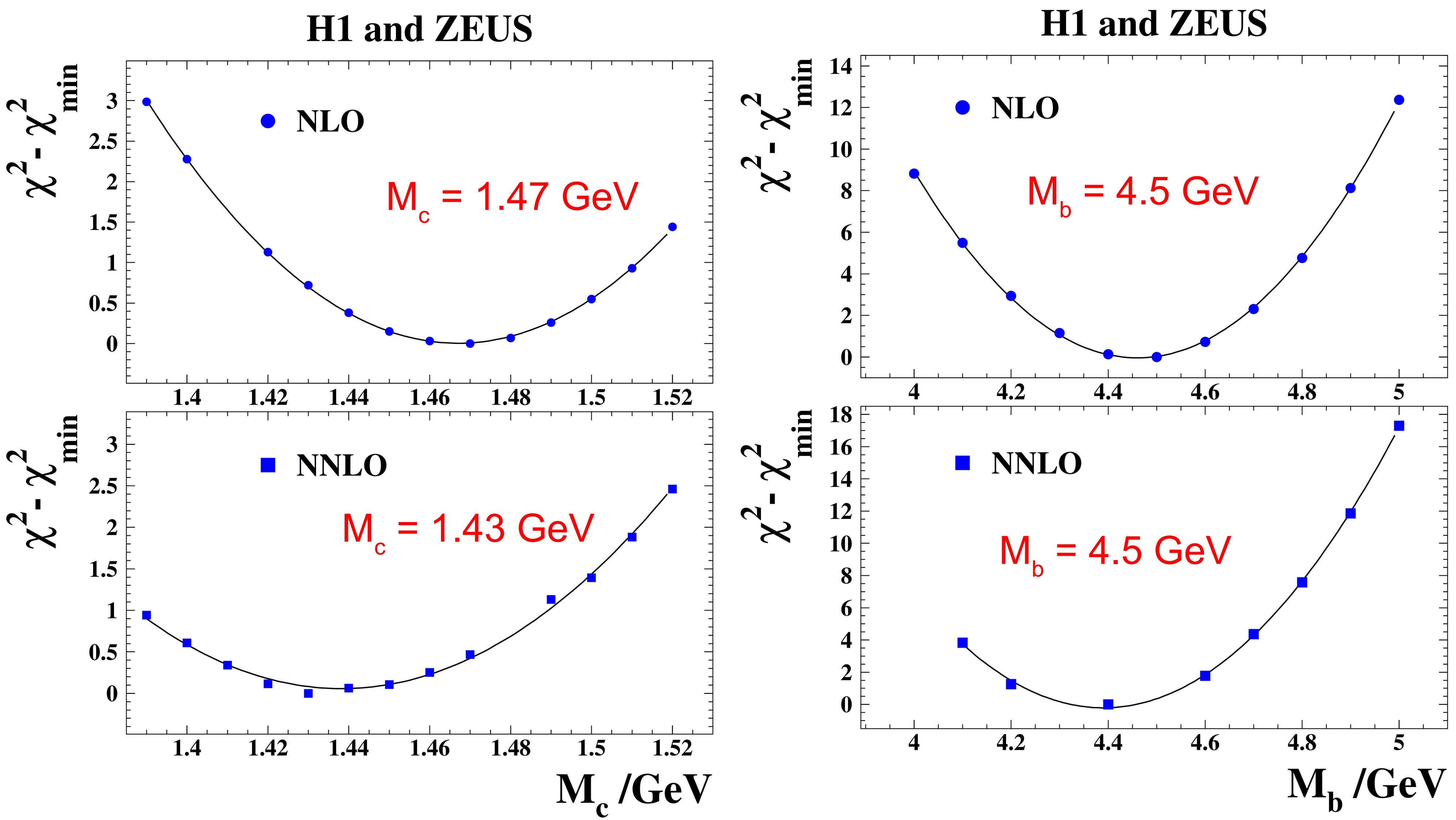
- QCD fits are performed using HERAFitter package
- PDFs (14p) are parametrised at $Q_0^2 = 1.9$ GeV^2

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

- 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 OPT)

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

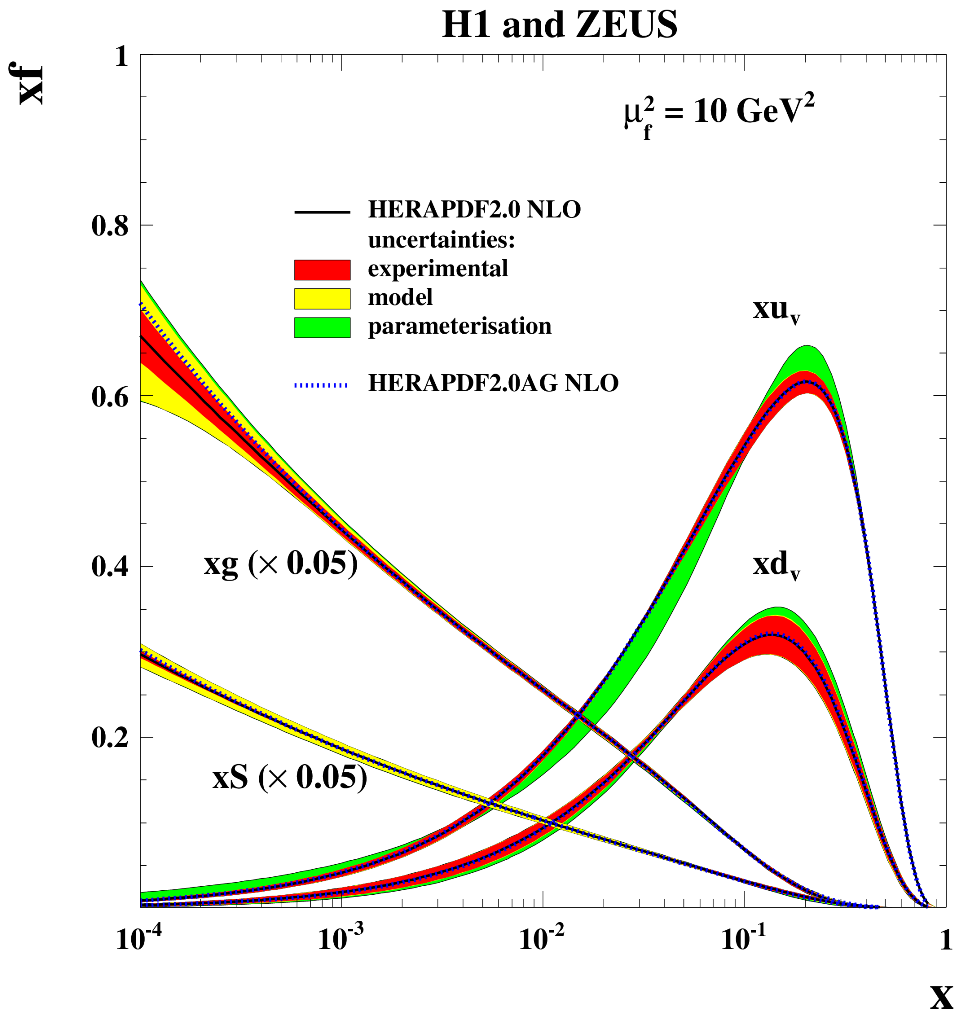
Charm and beauty mass parameters



- M_c / M_b determined from inclusive data + charm / beauty data.

Method from the HERA charm combination (Eur. Phys. J. C73 (2013) 2311)

HERAPDF2.0: errors estimation



- Full systematic correlation treatment.
- Experimental uncertainties:
  - Hessian method used: full second-derivative matrix calculated
  - Conventional $\Delta\chi^2 = 1$ => 68% CL
- Model uncertainties:
  - All variations are added in quadratures, separately positive and negative.

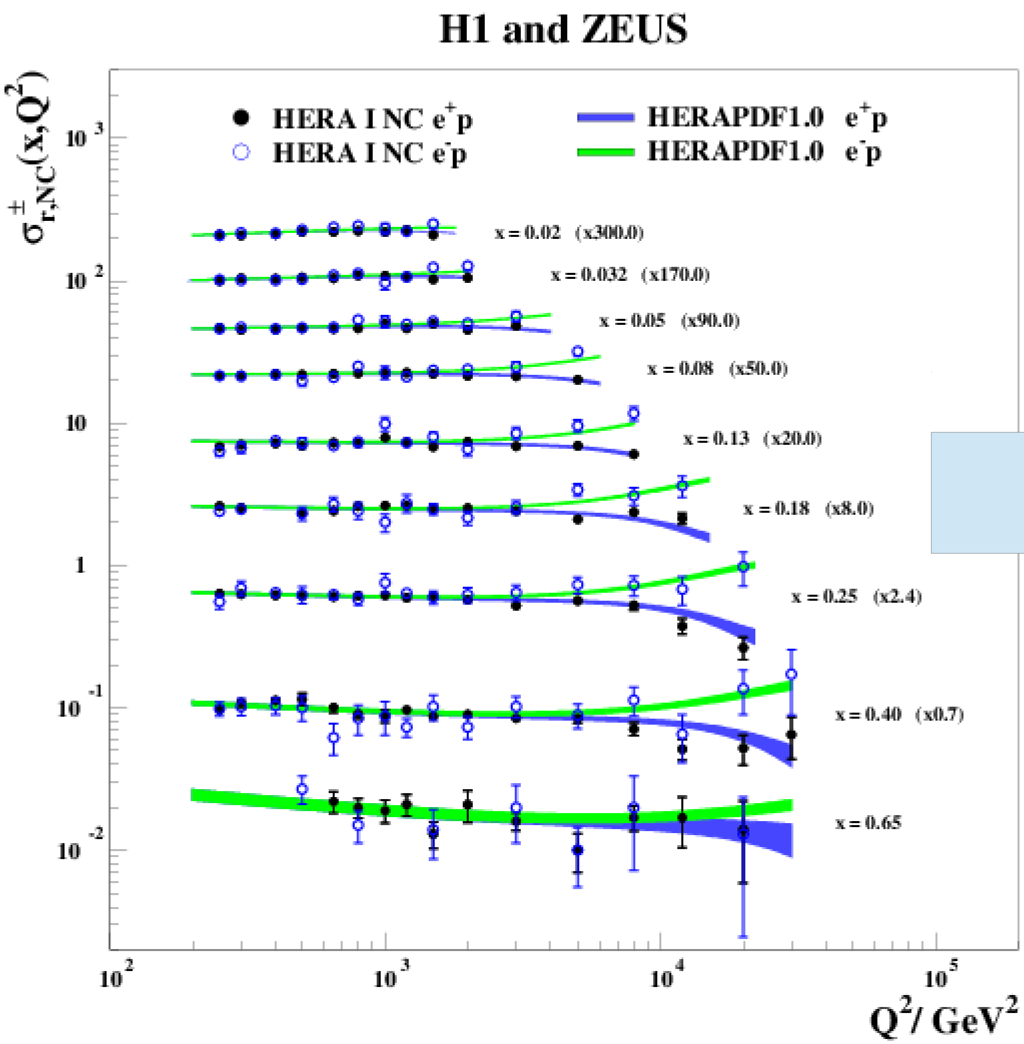
Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

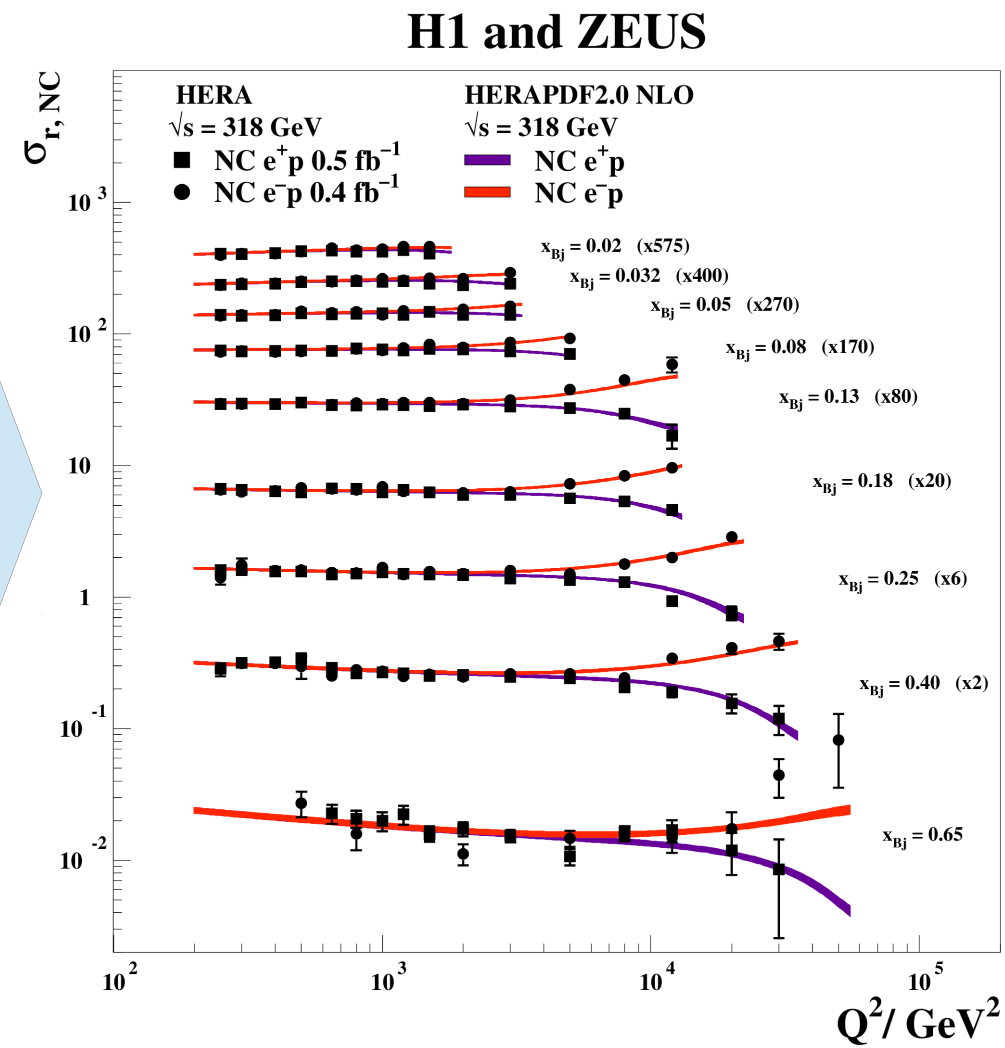
Adding D and E parameters to each PDF

- Parametrisation uncertainties:

- The largest deviation taken.

EW effects: HERAPDF 1.0 vs 2.0

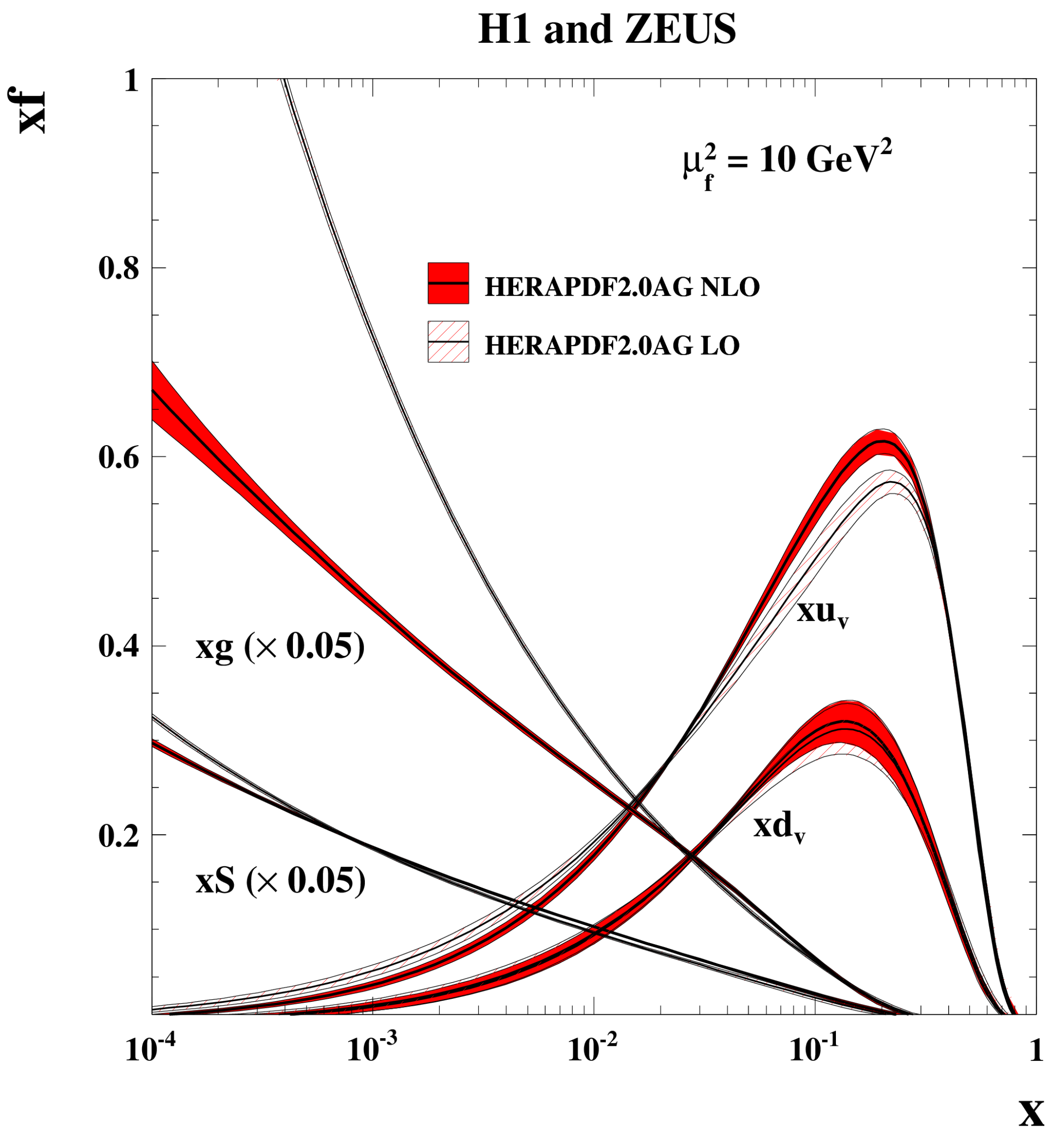




- Great precision!

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

HERAPDF2.0 at LO



- Parton densities @LO are presented.
- Essential for parton showers simulation in LO+PS Monte Carlo event generators

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

- Q^2_{min} = 3.5 GeV^2
  HERAPDF2.0

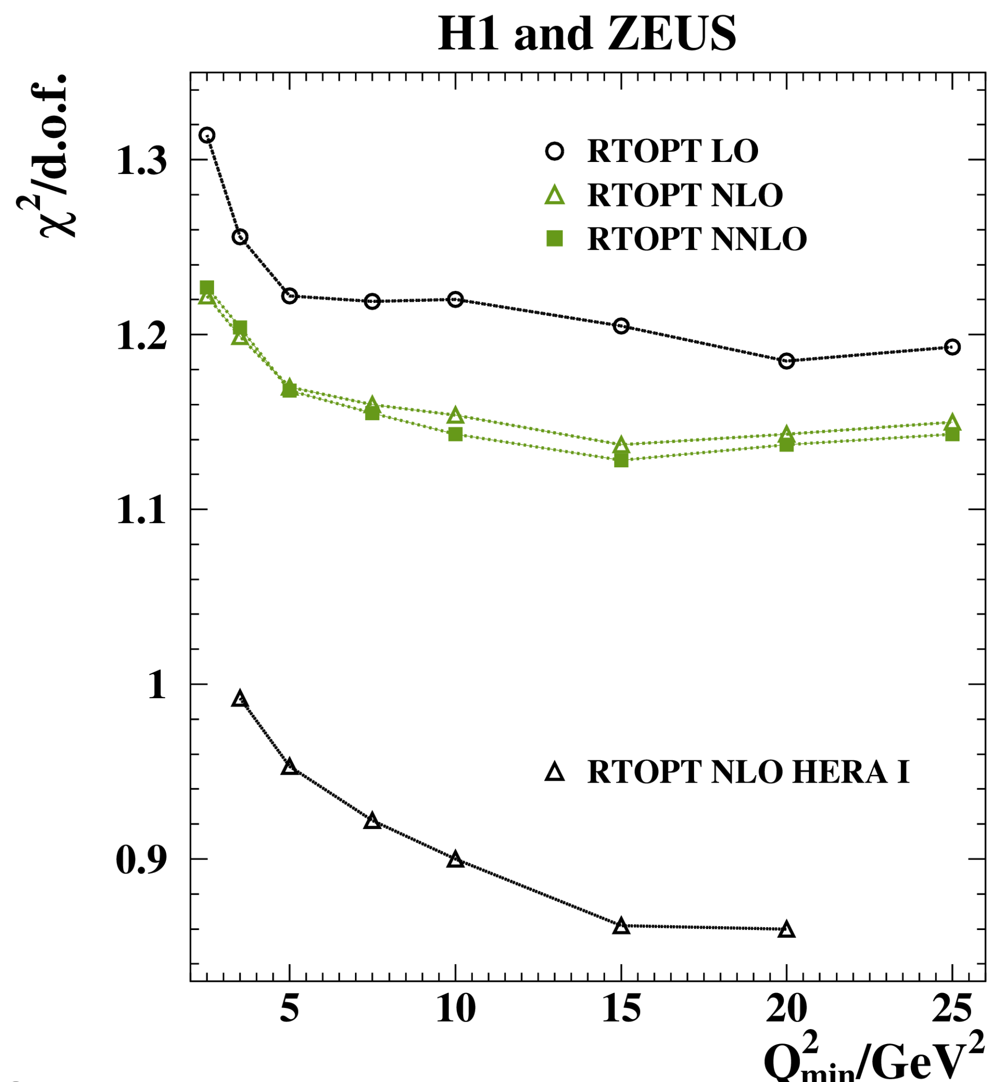
  NLO $\frac{\chi^2}{ndf} = \frac{1357}{1131}$

  NNLO $\frac{\chi^2}{ndf} = \frac{1363}{1131}$

- Q^2_{min} = 10 GeV^2
  HERAPDF2.0HiQ2

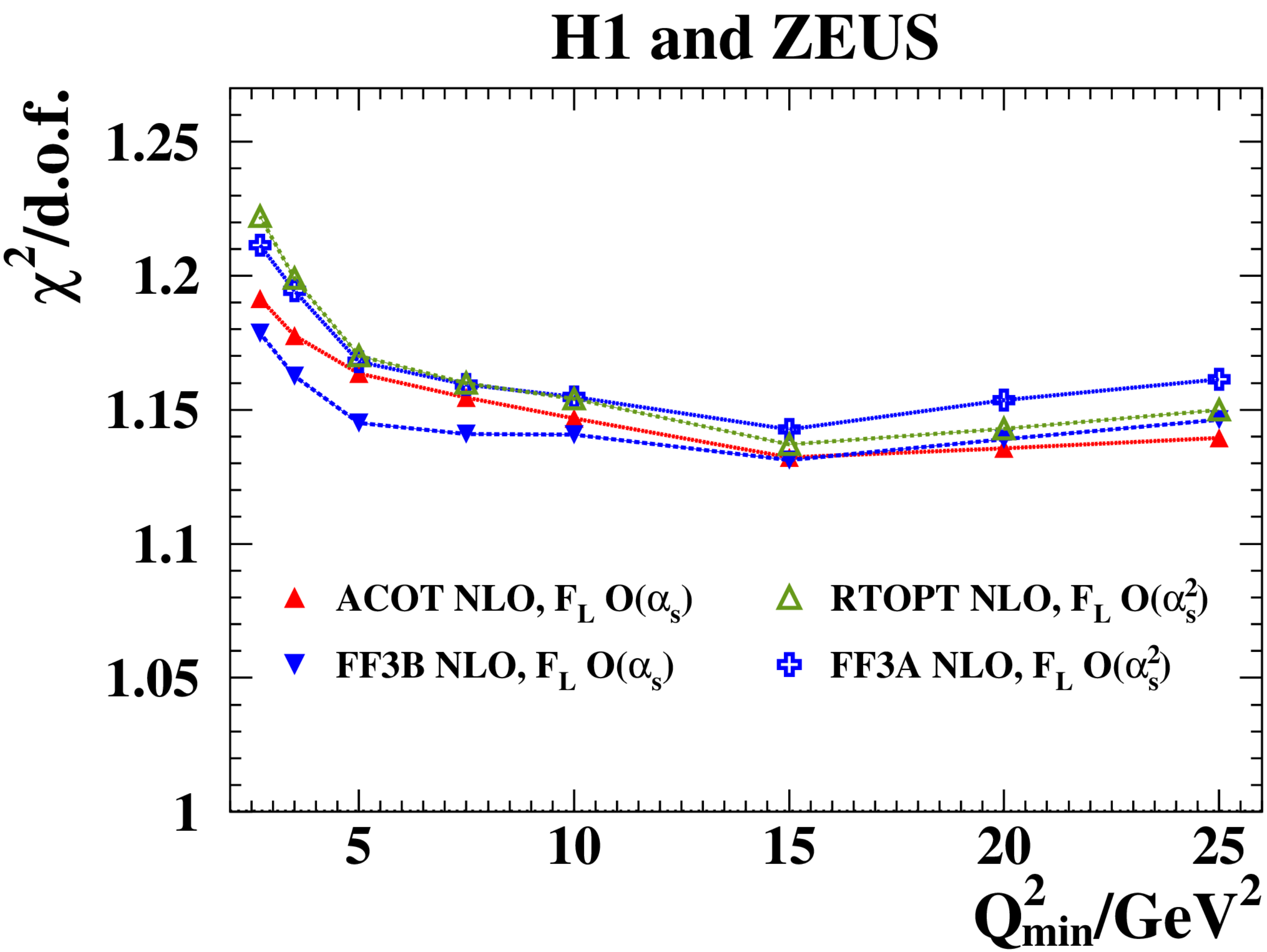
  NLO $\frac{\chi^2}{ndf} = \frac{1156}{1002}$

  NNLO $\frac{\chi^2}{ndf} = \frac{1146}{1002}$



- Small tension between low and high Q^2 data.

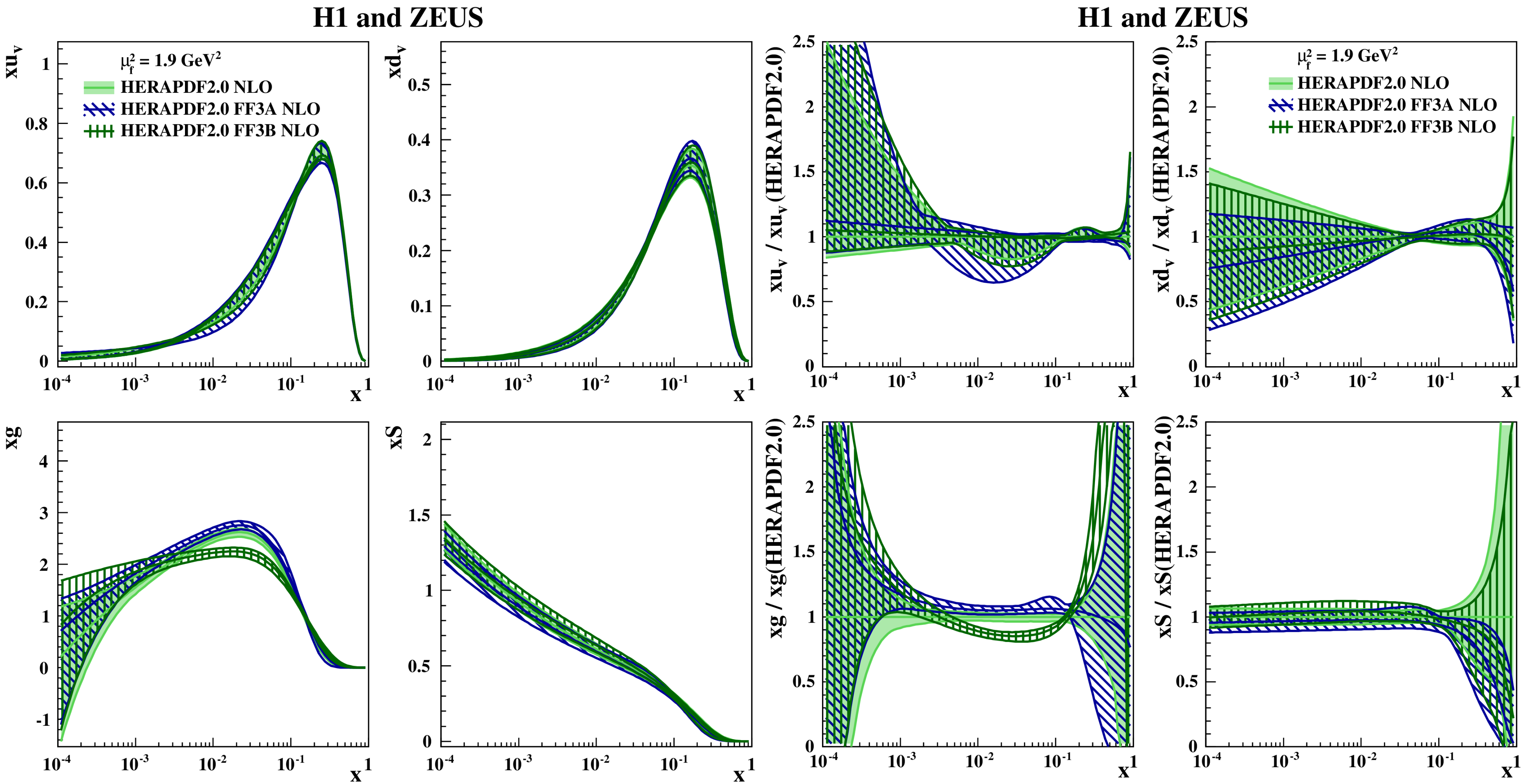
HERAPDF2.0: dependence on F_L order



- RTOPT ~ MMHT;
- ACOT ~ CT;
- FF3A ~ ABM;

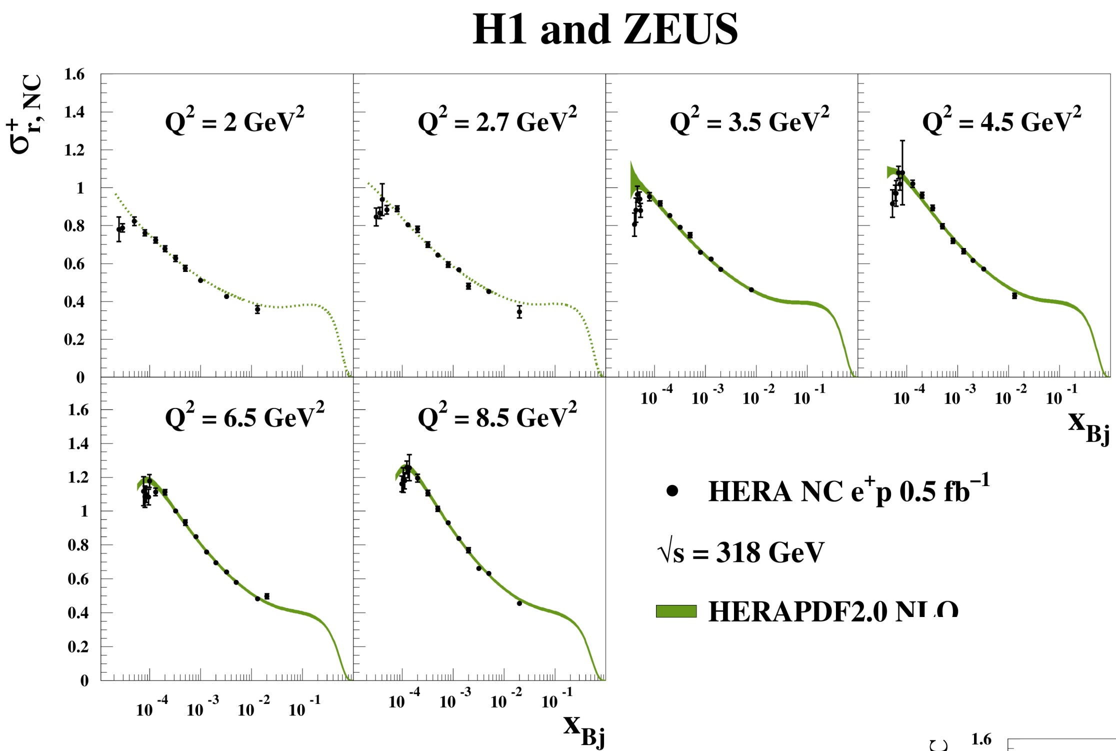
- Treating of F_L to the same order in α_S as F_2 gives better results at NLO.
- Almost independent of HF scheme.

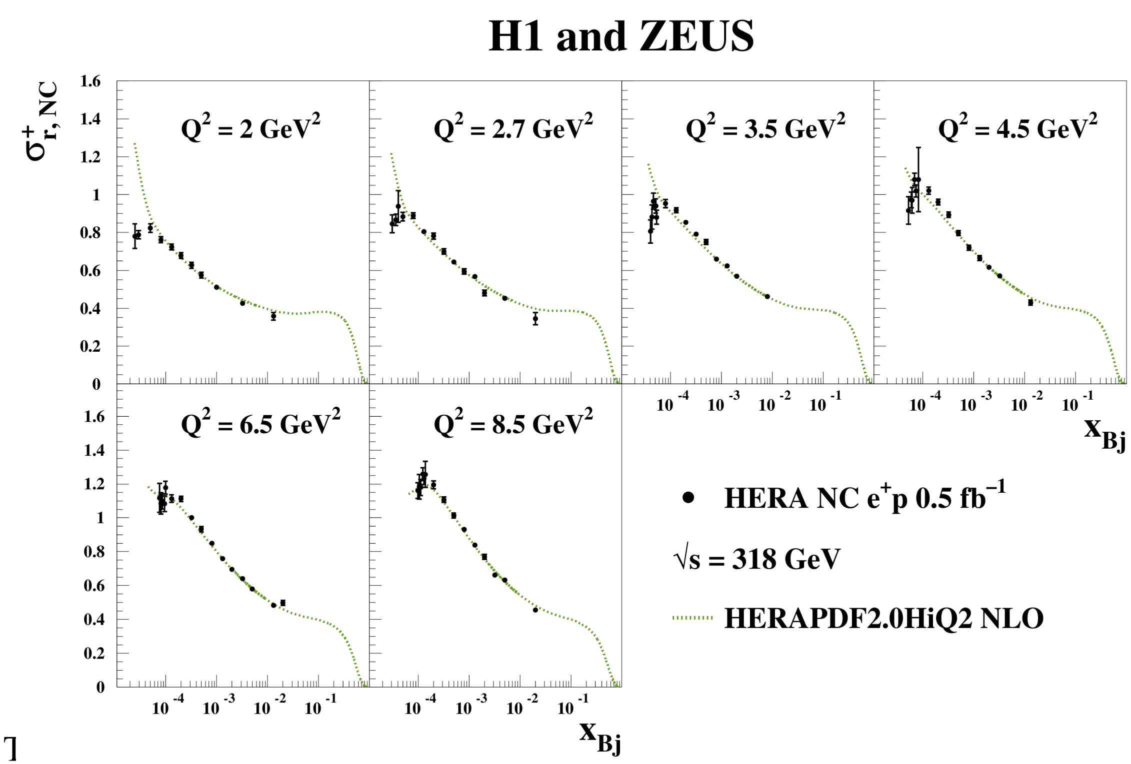
HERAPDF2.0 FF3A and FF3B



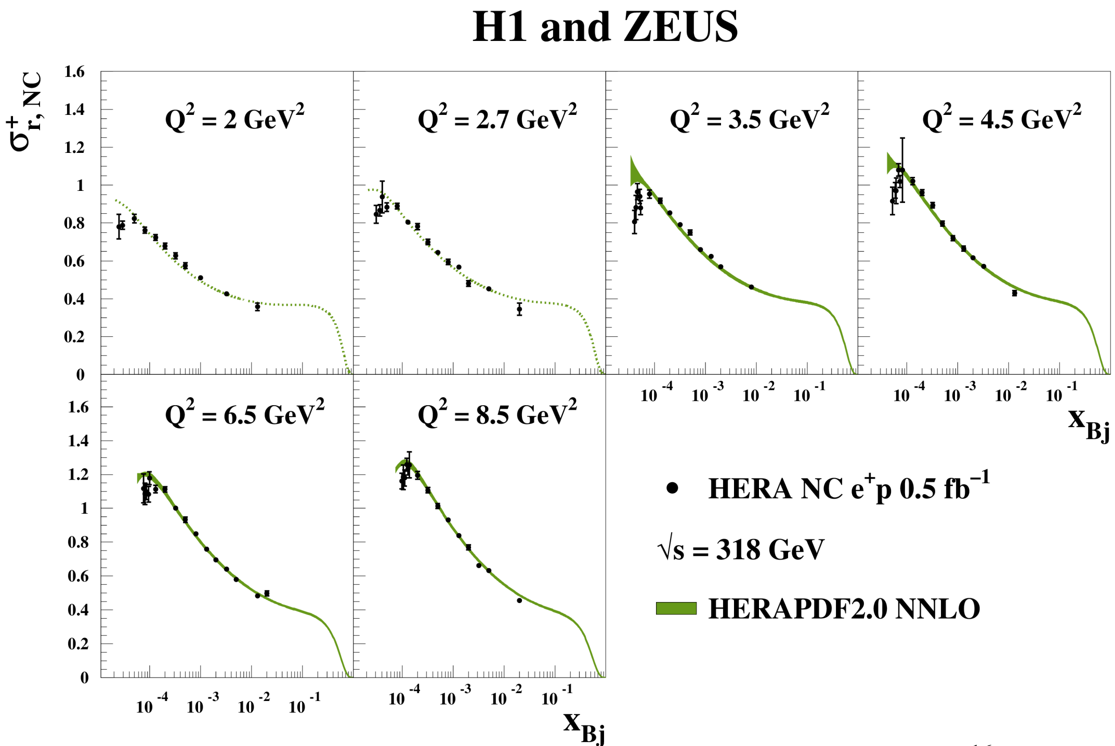
- Deferences in gluons between RTOPT and FF → different F_L orders in α_S.

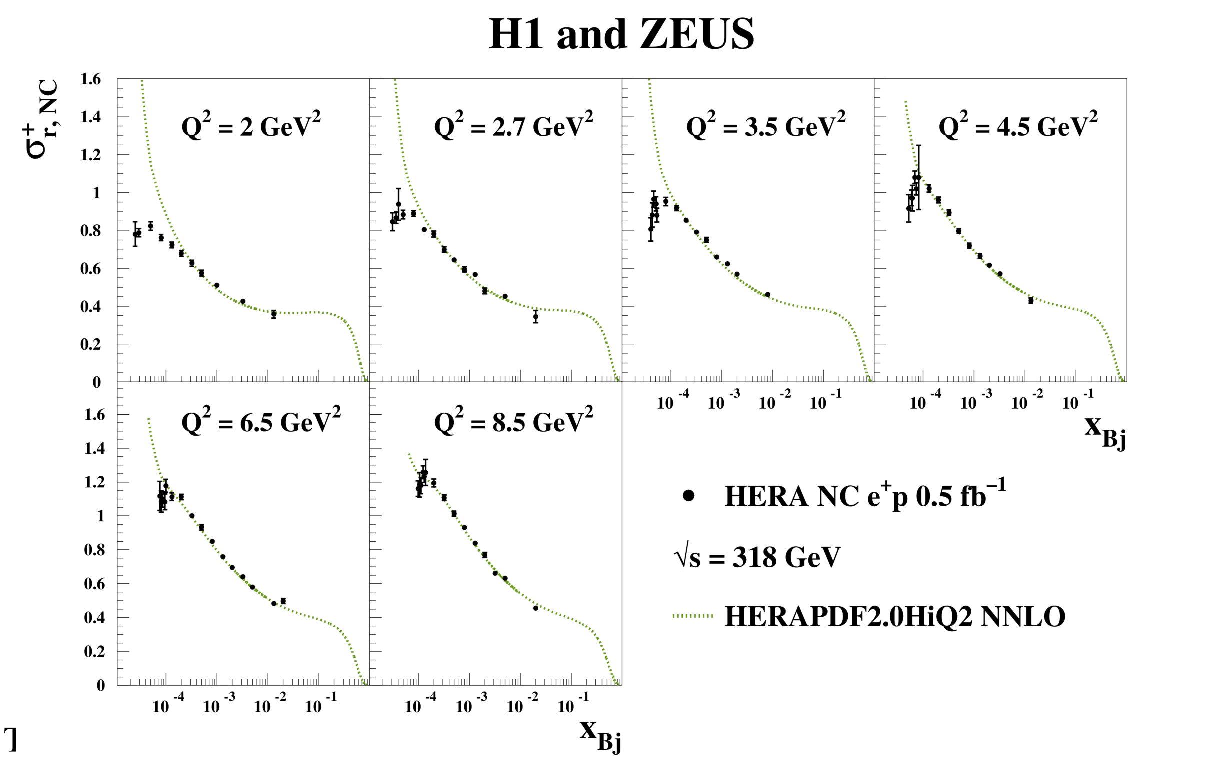
NLO: NC low Q^2, x





NNLO: NC low Q², x





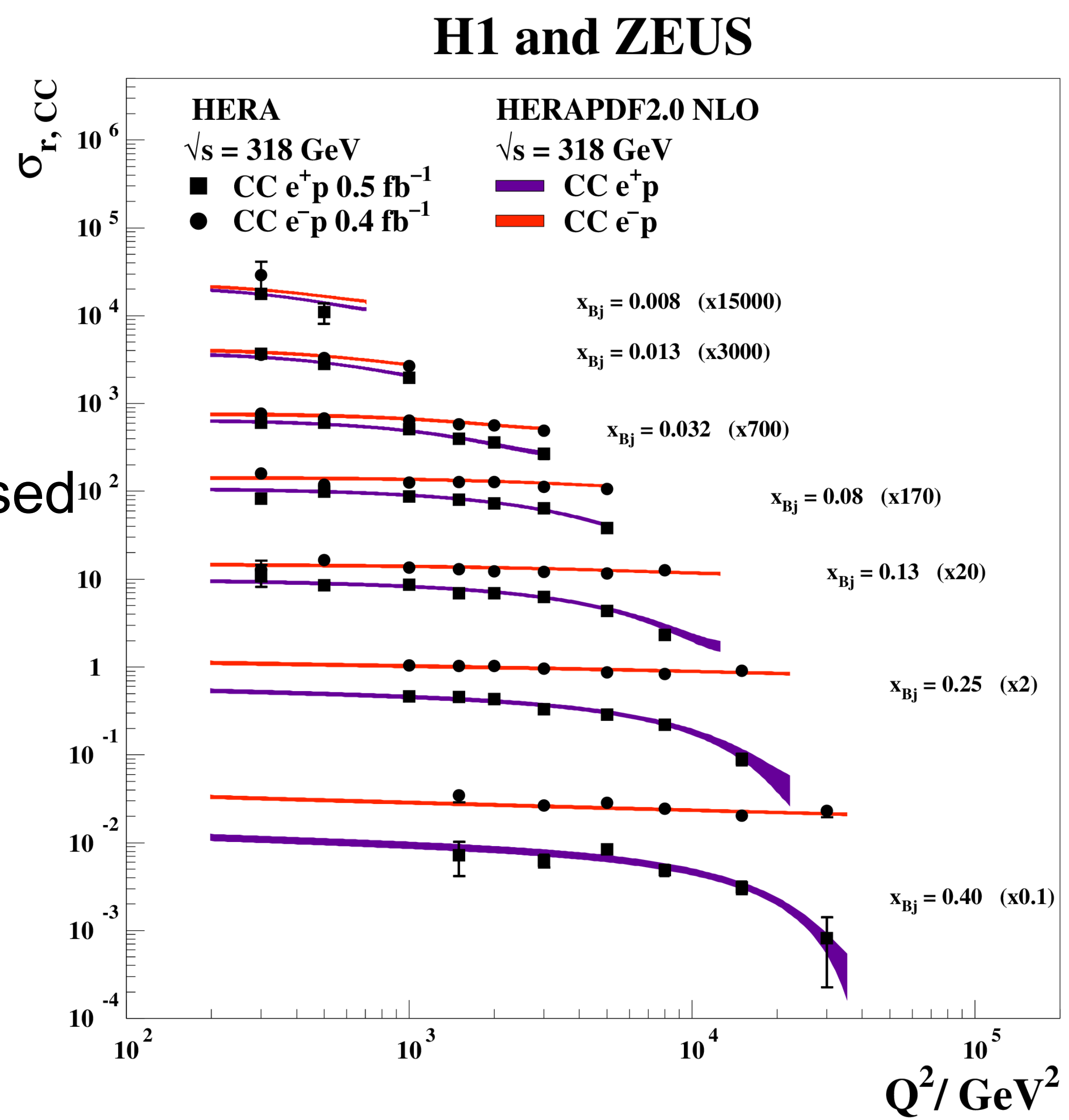
Helicity effects in CC interactions

$$\sigma^{+}_{r,CC} \approx x\,\bar{U} + (1-y)^2\, xD$$

$$\sigma^{-}_{r,CC} \approx x\,U + (1-y)^2\, x\,\bar{D}$$

- e^+p: d_v quarks are suppressed at high Q^2.

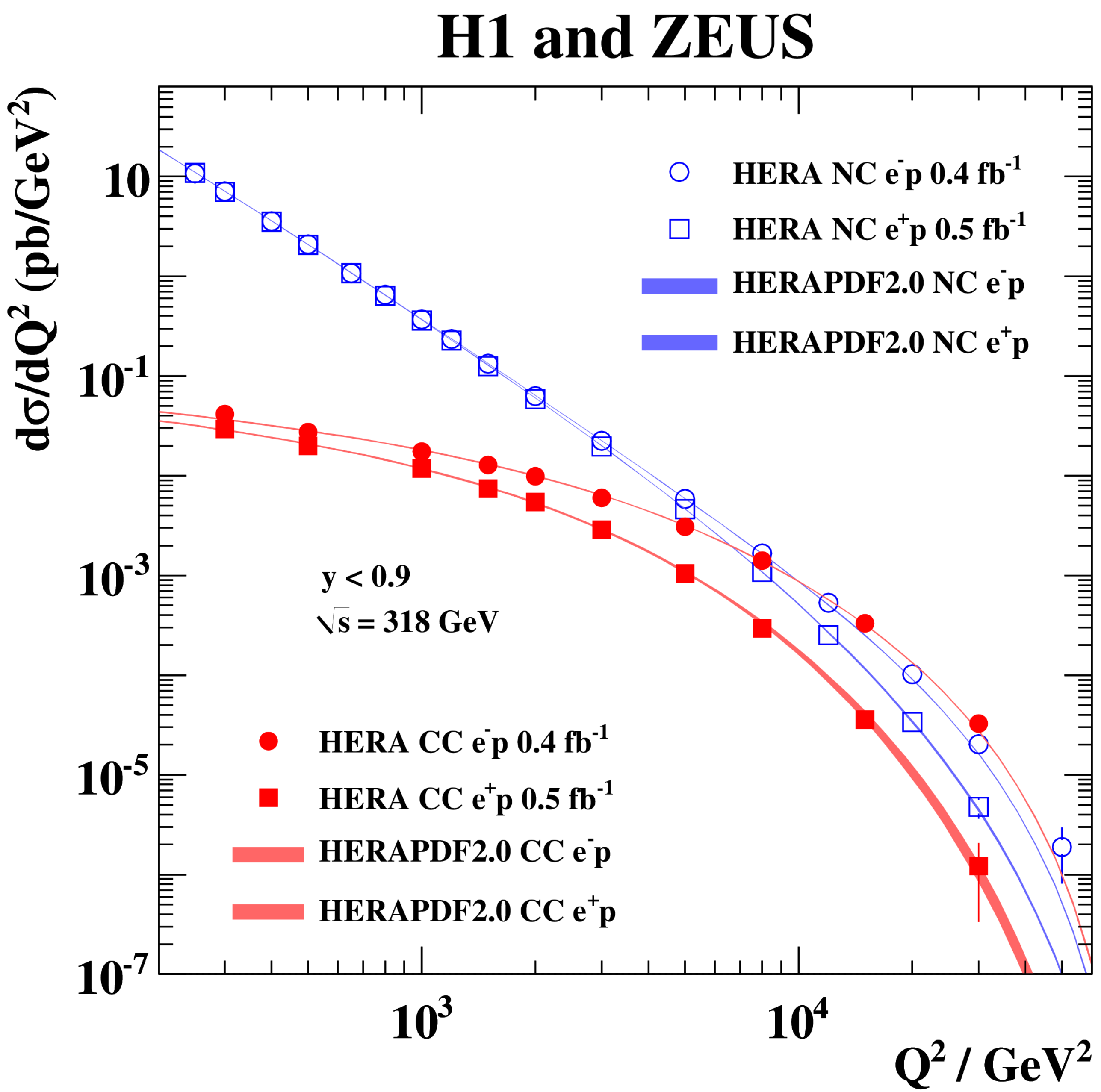
- e^-p: helicity factor applies only to sea quarks.



Electroweak unification

- Virtual photon exchange is dominant for low Q^2 NC reactions.

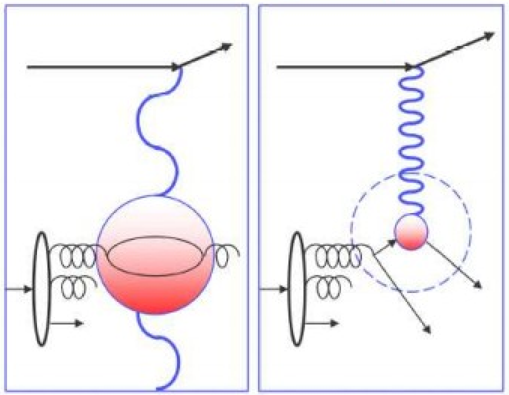
- At high scales CC and NC become similar in magnitude.



Scaling violation

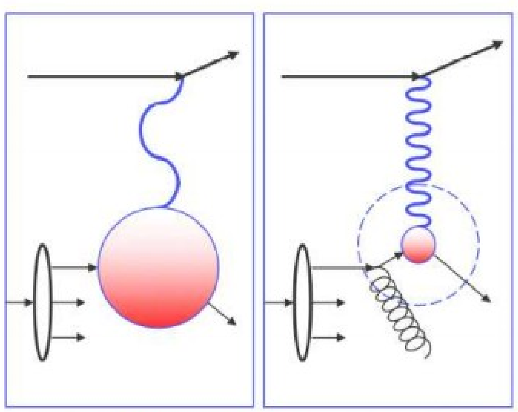
- NLO and NNLO predictions are similar

Small x: Gluons, sea quarks

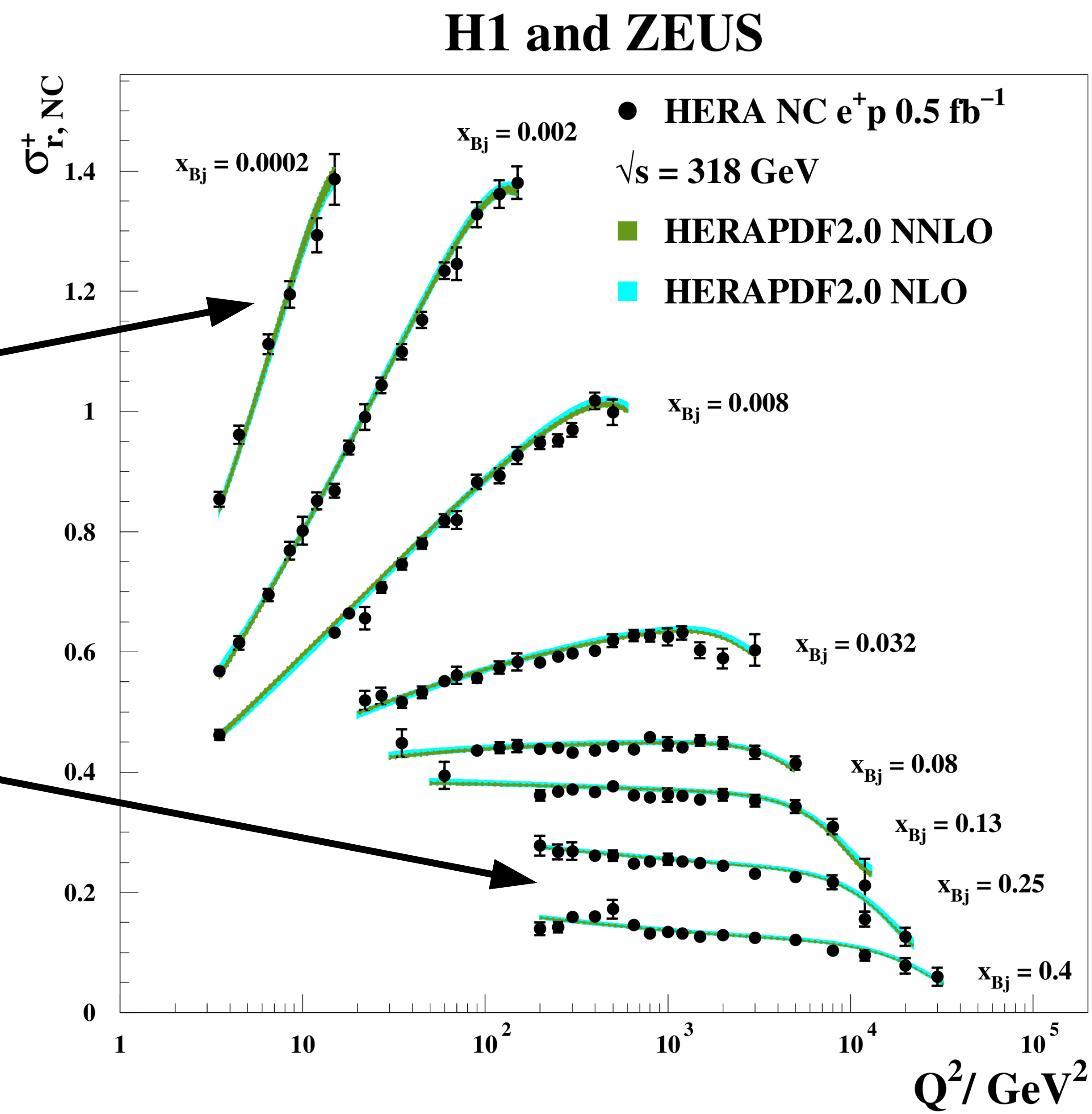


$Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x

Large x: valence quarks



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



FF3A and FF3B

- FF3A
  - Three flavour running of α_S;
  - F_L calculated to $O(\alpha_S^2)$;
  - Pole masses for charm and beauty.
- FF3B
  - Variable-flavour running of α_S;
  - F_L calculated to $O(\alpha_S)$;
  - MSbar running masses for charm and beauty.