An investigation of the HERA combined data at low Q^2

Submitted to PRD [arXiv:1604.02299]

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Low x meeting
Károly Róbert College,
Gyöngyös, Hungary 2016

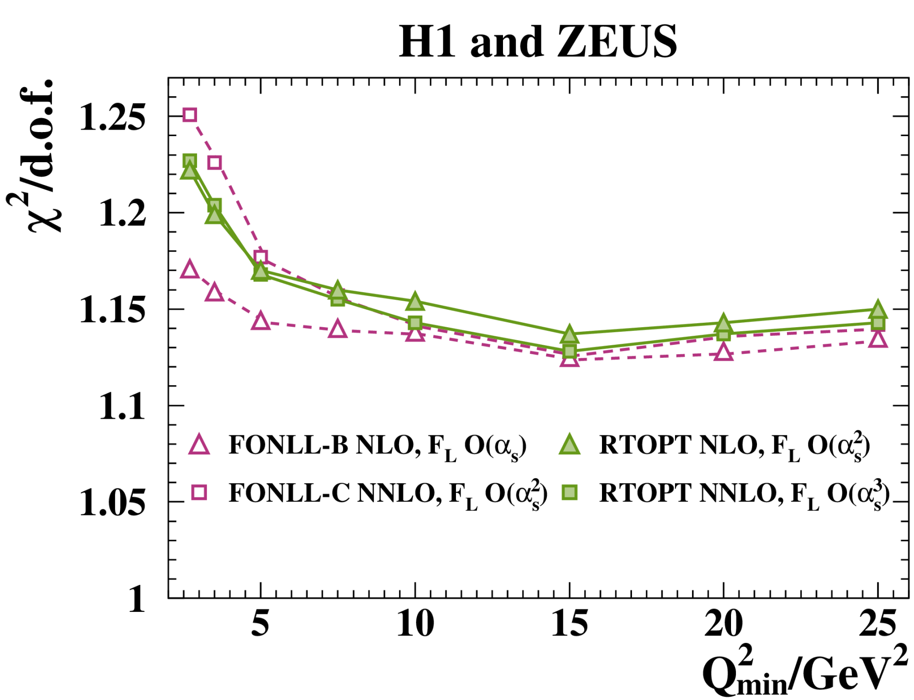
Low Q^2 data in HERAPDF2.0

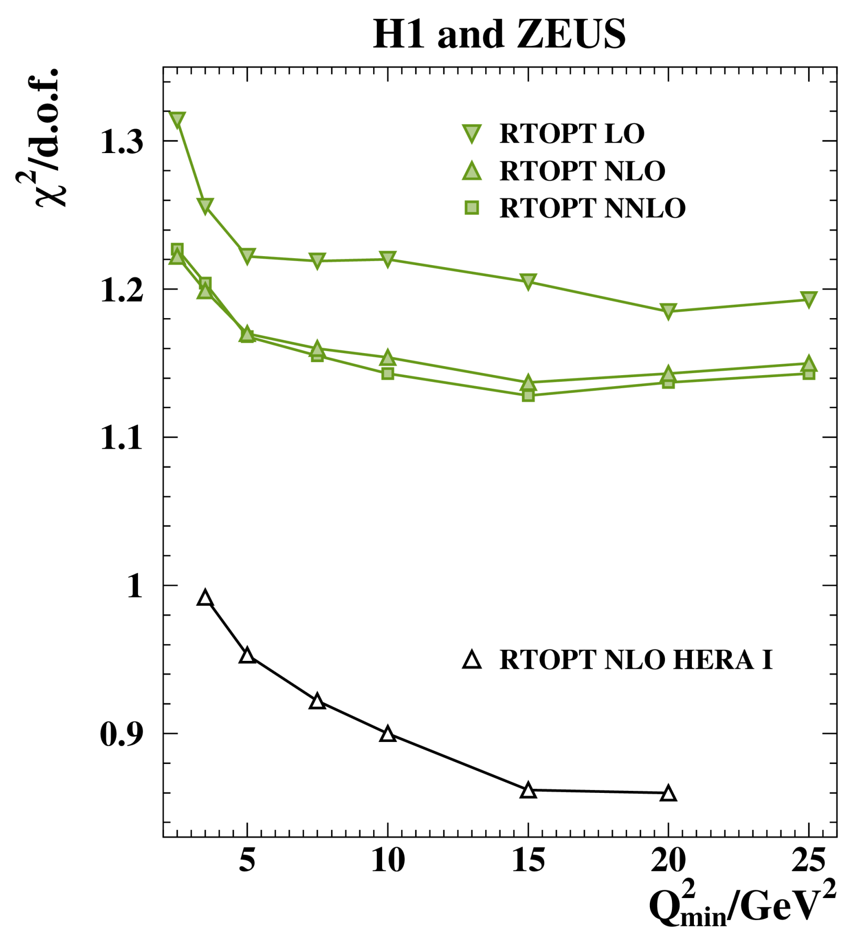
Eur.Phys.J.C75 (2015) 12, 580 [arxiv:1506.06042]

- DGLAP data description gets worse at low scales.
- The case is observed for various orders of calculation & HF schemes.
- Q^2_{min} = 3.5 GeV^2
  HERAPDF2.0

NLO $\frac{\chi^2}{ndf} = \frac{1356}{1131} \approx 1.20$

NNLO $\frac{\chi^2}{ndf} = \frac{1363}{1131} \approx 1.21$





Low Q^2 data in HERAPDF2.0

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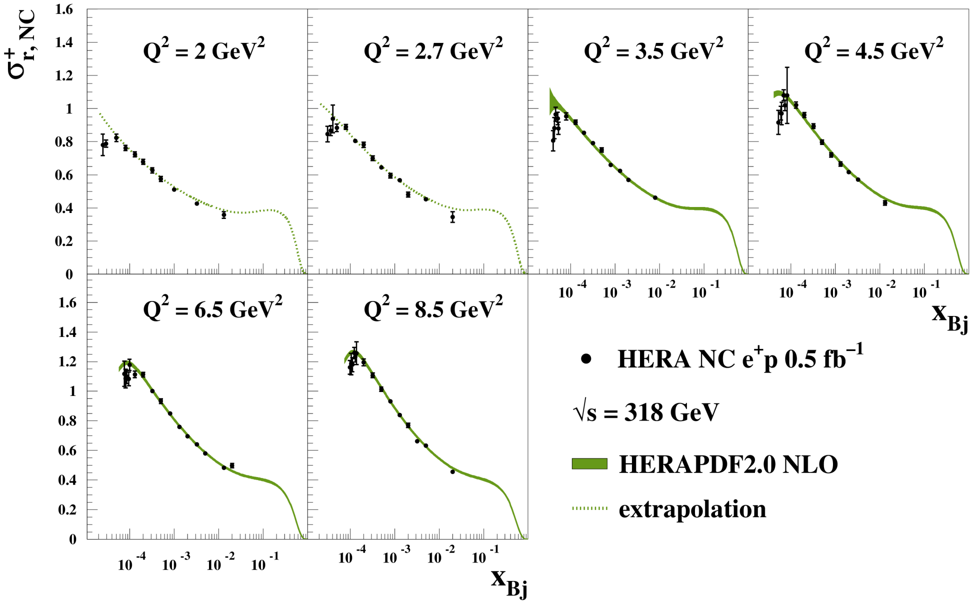
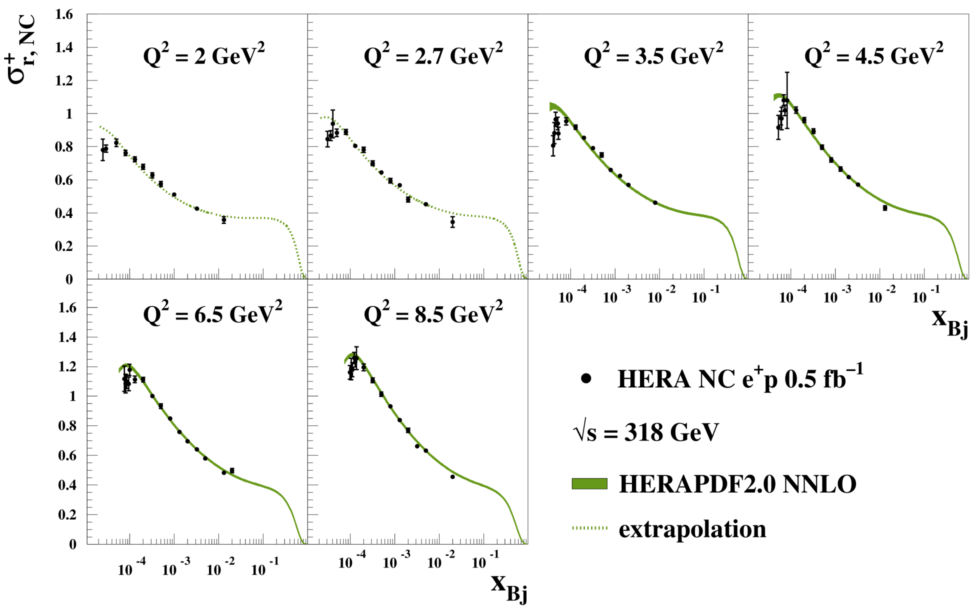


- Data between Q^2 = 3.5 GeV^2 and Q^2 = 15 GeV^2 create one third of the excess χ^2/d.o.f.
- Two thirds originate from the data with Q^2 > 150 GeV^2 (fluctuations)

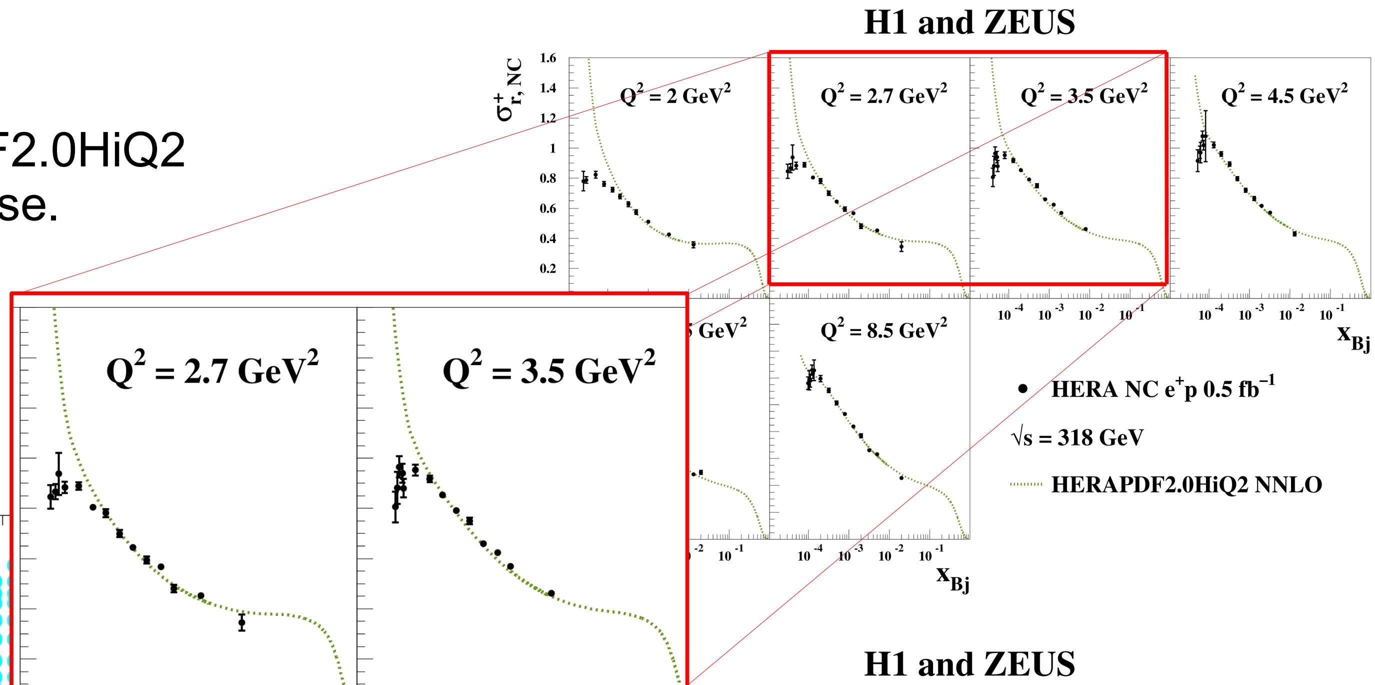


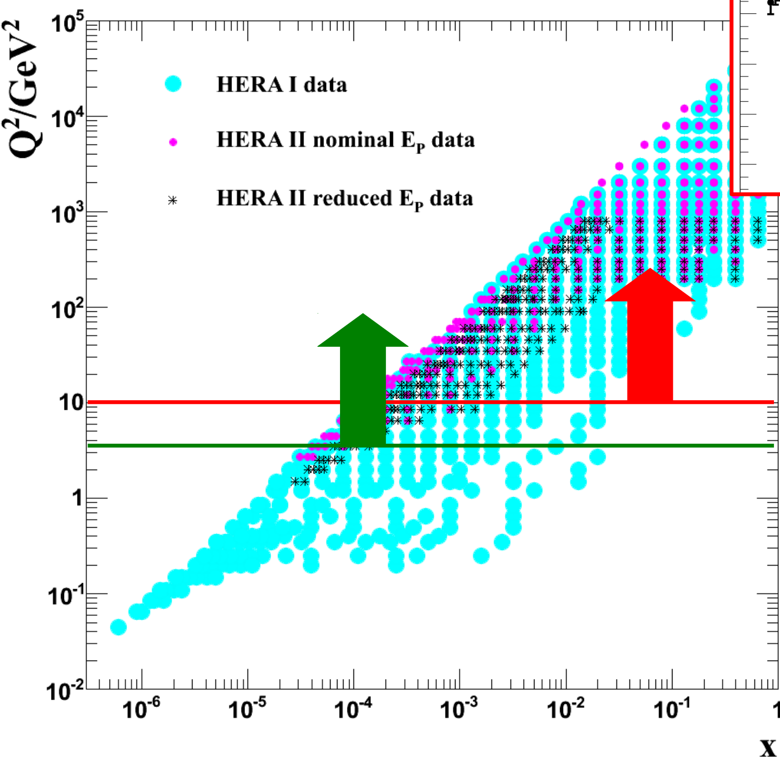
Is cutting harder an option?!

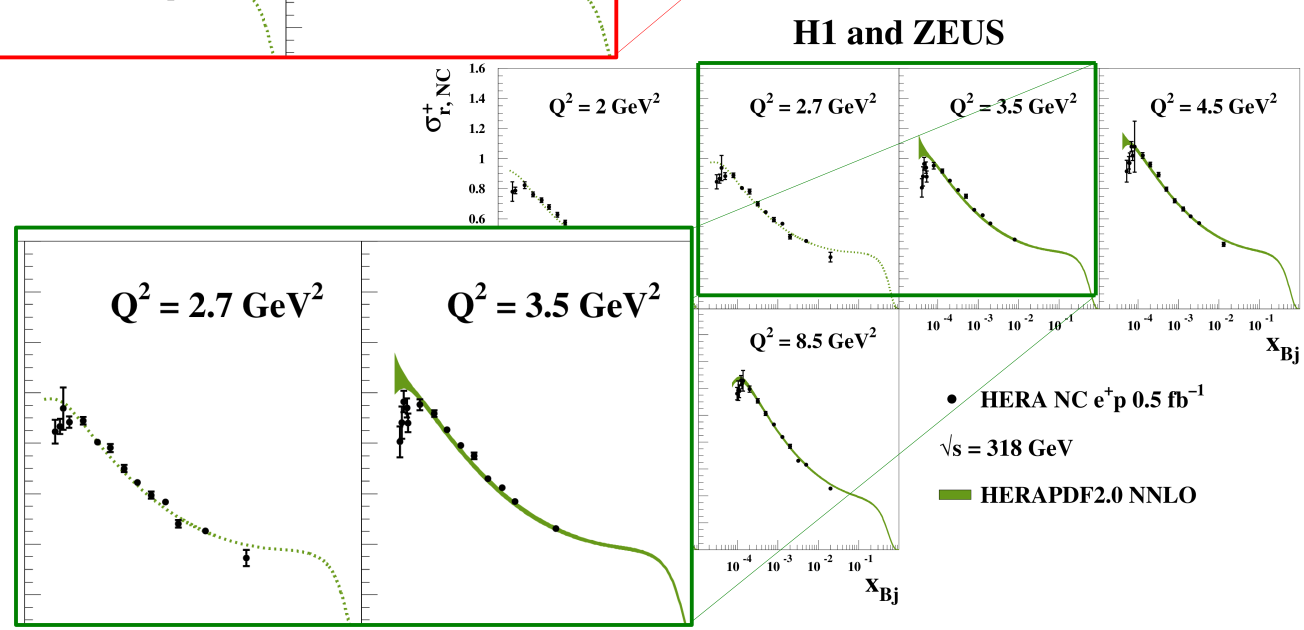
Low Q^2 data in HERAPDF2.0

- Cut on low Q^2 implies cut on low x
- Predictions from HERAPDF2.0HiQ2 describe low Q^2 data even worse.
- Although high scale predictions do not change!

Eur.Phys.J.C75 (2015) 12, 580 [arxiv:1506.06042]





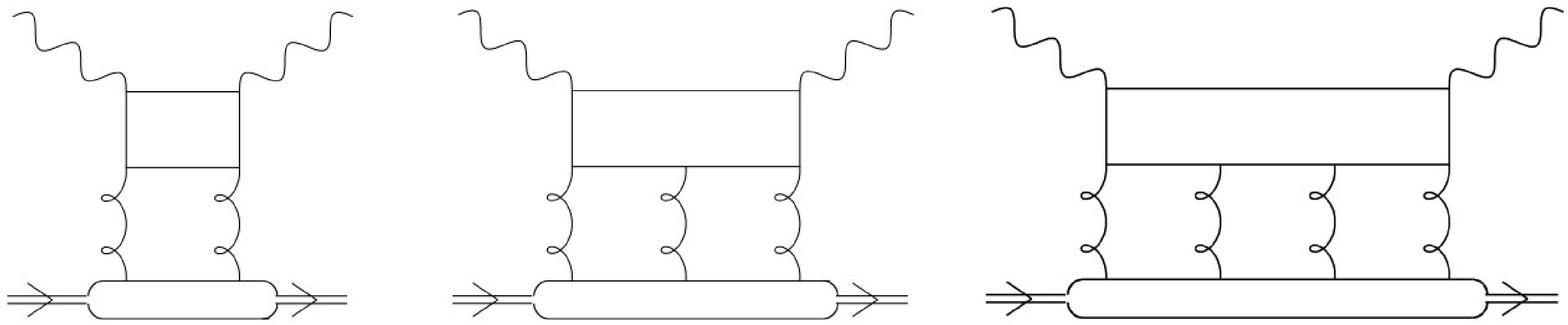


Higher-twist correction

- The problem <u>might</u> be in absence of higher twist consideration in evolution equations

May be visualized as gluon leaders with recombining gluons

Eur. Phys. J. C 71, 121 (2000), [hep-ph/0003042v4]



$$\sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_{+.}} F_L$$

Cross section — a linear combination of structure functions

- Introduce simple correction factors to each of structure functions

$$F_2^{HT} = F_2^{DGLAP}\left(1 + \frac{A_2^{HT}}{Q^2}\right)$$

$$F_L^{HT} = F_L^{DGLAP}\left(1 + \frac{A_L^{HT}}{Q^2}\right)$$

- Higher twist terms expected to contribute to F_L

$$F_L \frac{4\pi^2\alpha}{Q^2(1-x)} = \sigma_L$$

- ...and cancel in F_2

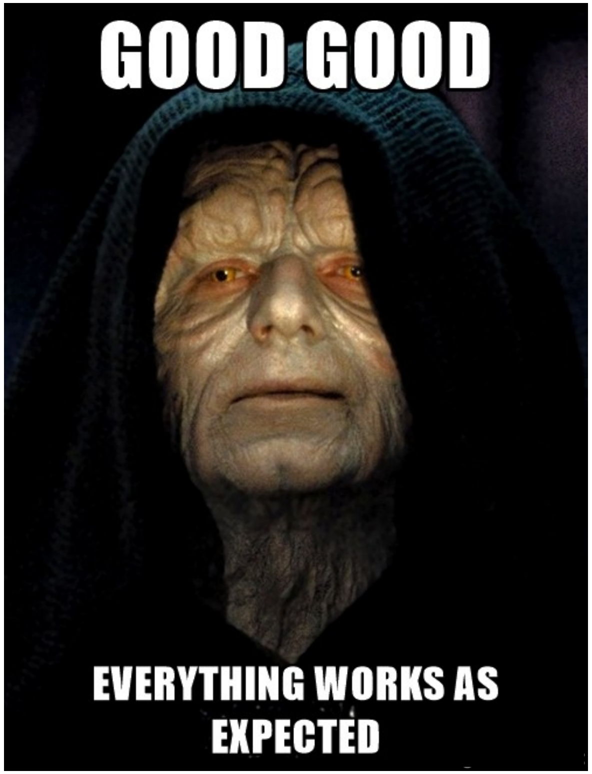
$$F_2 \frac{4\pi^2\alpha}{Q^2(1-x)} = \sigma_T + \sigma_L$$

Higher-twist correction effect

HERAPDF2.0

NLO $\frac{\chi^2}{ndf}=\frac{1356}{1131}\approx 1.20$

NNLO $\frac{\chi^2}{ndf}=\frac{1363}{1131}\approx 1.21$



- Introducing $F_2^{HT}=F_2^{DGLAP}\left(1+\frac{A_2^{HT}}{Q^2}\right)$ gives almost no effect:

HHT@F_2

NLO $\frac{\chi^2}{ndf}=\frac{1354}{1130}\approx 1.20$

NNLO $\frac{\chi^2}{ndf}=\frac{1357}{1130}\approx 1.20$

A_2^{HT} = 0.14 ± 0.10 GeV^2

A_2^{HT} = 0.12 ± 0.07 GeV^2

corr. factors consistent with 0

- Introducing $F_L^{HT}=F_L^{DGLAP}\left(1+\frac{A_L^{HT}}{Q^2}\right)$ helps a lot more:

HHT@F_L

NLO $\frac{\chi^2}{ndf}=\frac{1329}{1130}\approx 1.18$

NNLO $\frac{\chi^2}{ndf}=\frac{1316}{1130}\approx 1.16$

$\Delta\chi^2=27$

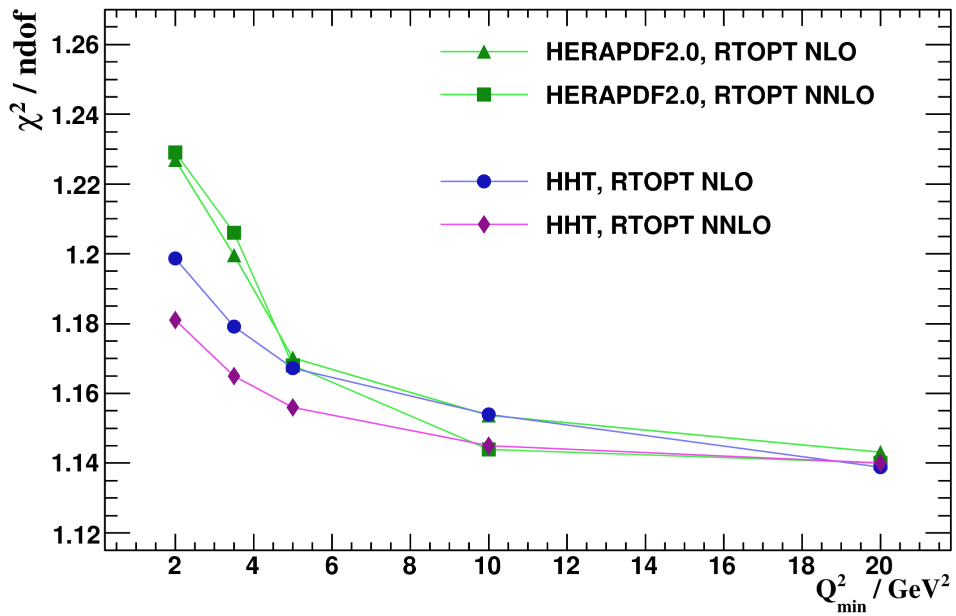
$\Delta\chi^2=47$

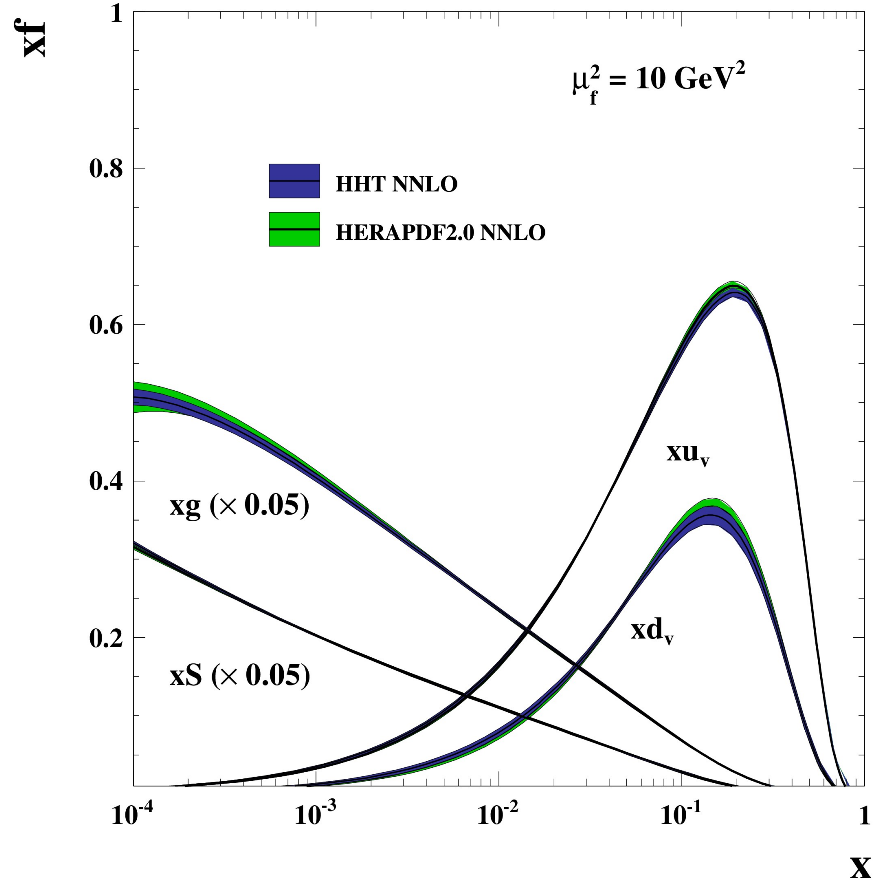
A_L^{HT} = 4.2 ± 0.7 GeV^2

A_L^{HT} = 5.5 ± 0.6 GeV^2

Higher-twist correction effect

- Q^2_{min} dependence flattens significantly





- and PDFs almost do not change!

HHT@F_L

NLO $\frac{\chi^2}{ndf}=\frac{1329}{1130}\approx 1.18$

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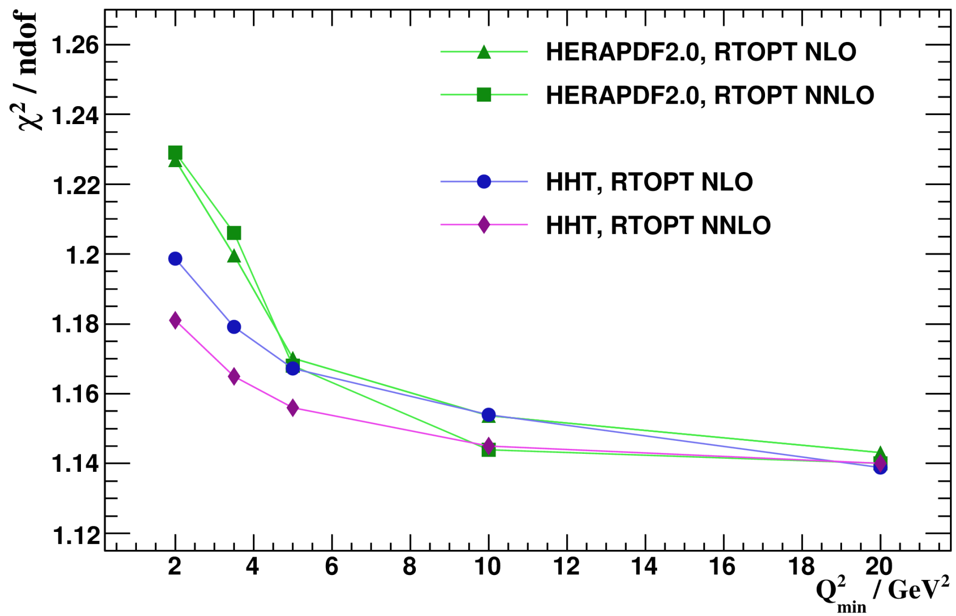
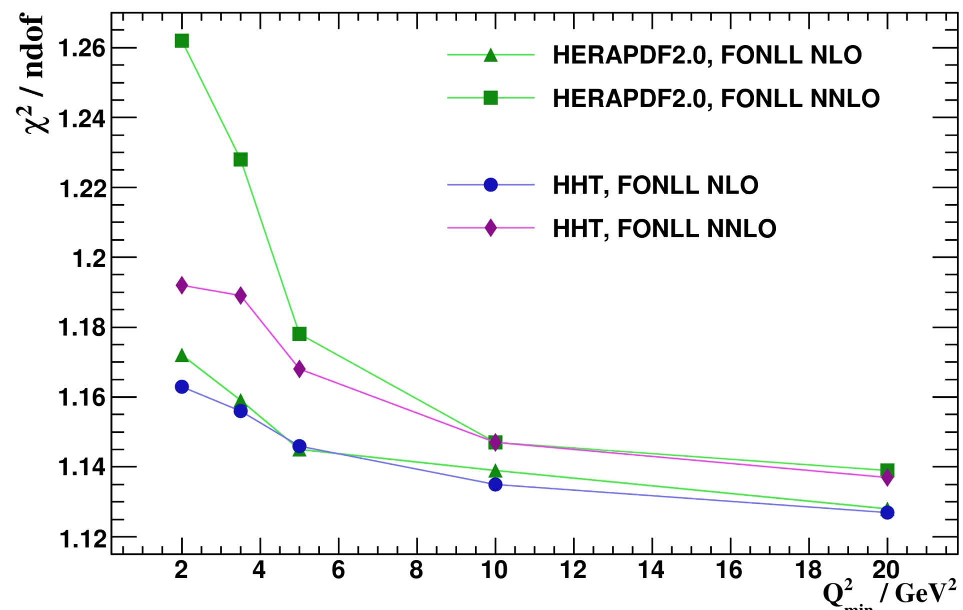


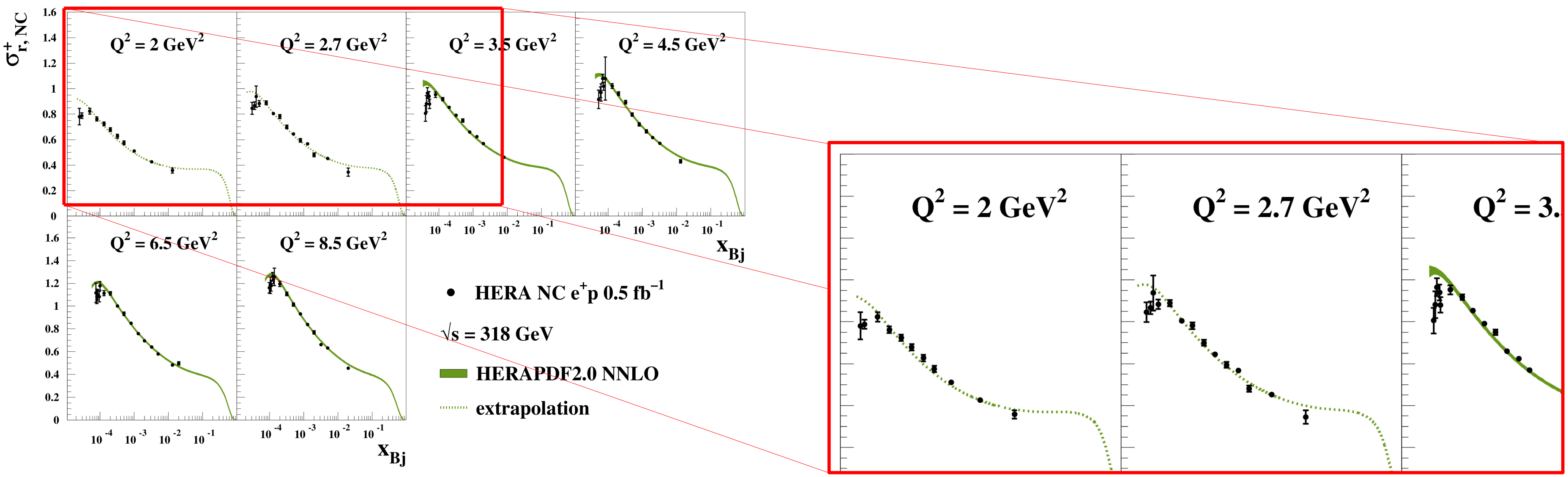
- and it also does within various HF schemes!

FONLL scheme:

- Not much of a gain @NLO (F_L^{FONLL} $O(\alpha_S)$)
- Substantial improvement @NNLO (F_L^{FONLL} $O(\alpha_S^2)$)

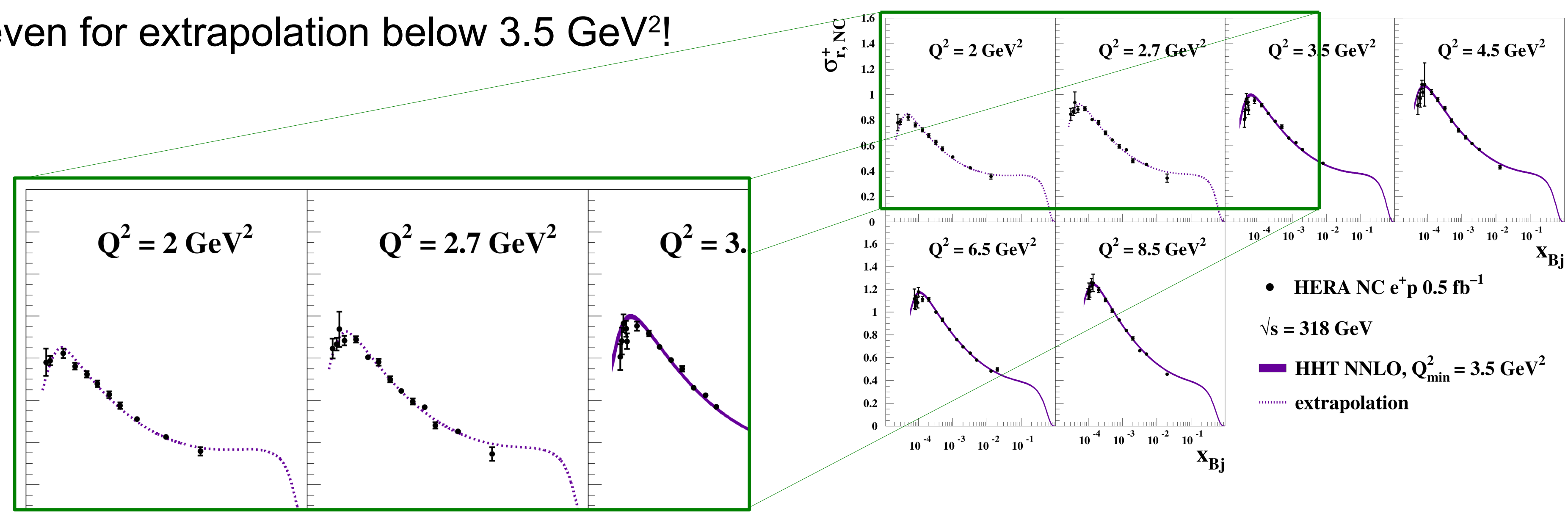


HHT: data description



- Low Q^2 description improves remarkably

- ...even for extrapolation below 3.5 GeV^2!



HHT: data description

What about the fitting data over Q^2_{min} = 2 GeV² then?

Q^2_{min} = 3.5 GeV²

NLO $\frac{\chi^2}{ndf} = \frac{1329}{1130} \approx 1.18$

NNLO $\frac{\chi^2}{ndf} = \frac{1316}{1130} \approx 1.16$

A_L^{HT} = 4.2 ± 0.7 GeV²

A_L^{HT} = 5.5 ± 0.6 GeV²

Q^2_{min} = 2 GeV²

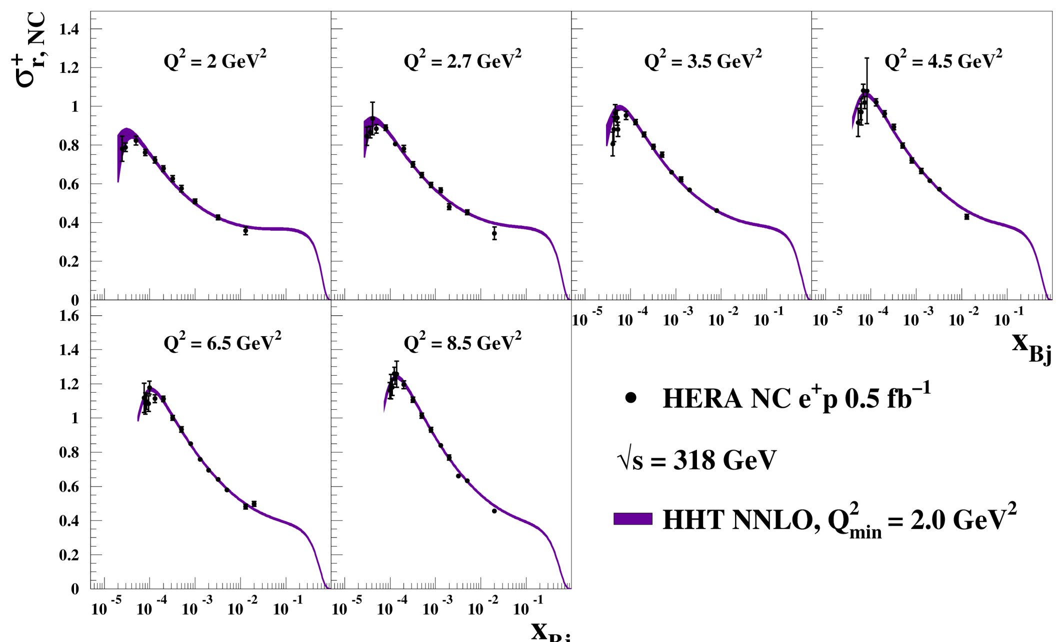
NLO $\frac{\chi^2}{ndf} = \frac{1398}{1170} \approx 1.19$

NNLO $\frac{\chi^2}{ndf} = \frac{1381}{1170} \approx 1.18$

A_L^{HT} = 4.0 ± 0.6 GeV²

A_L^{HT} = 5.2 ± 0.7 GeV²

- Excellent data description!
- Although χ^2/dof is somewhat higher



HHT: data description

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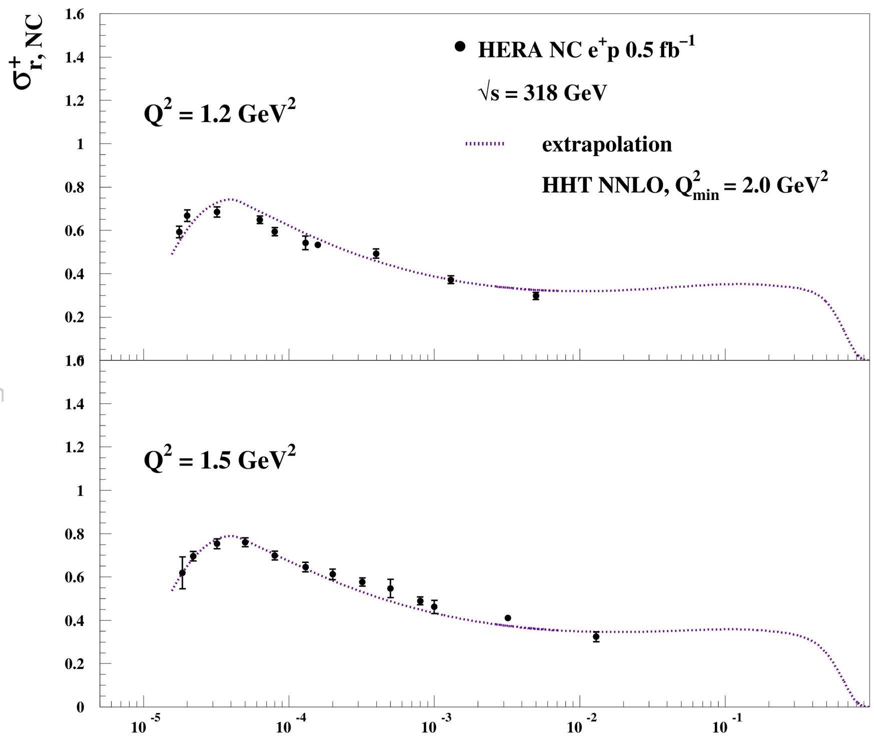
A_L^{HT} = 4.2 ± 0.7 GeV²

A_L^{HT} = 5.5 ± 0.6 GeV²

) ± 0.6 GeV²

2 ± 0.7 GeV²

Q^2_{min}



- Excellent data description!

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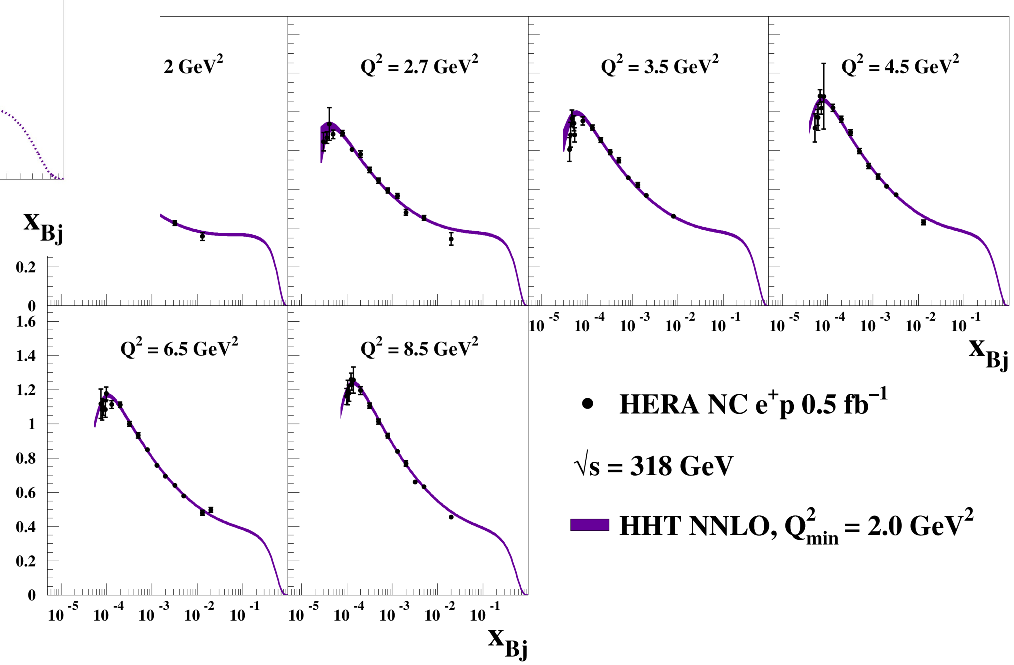


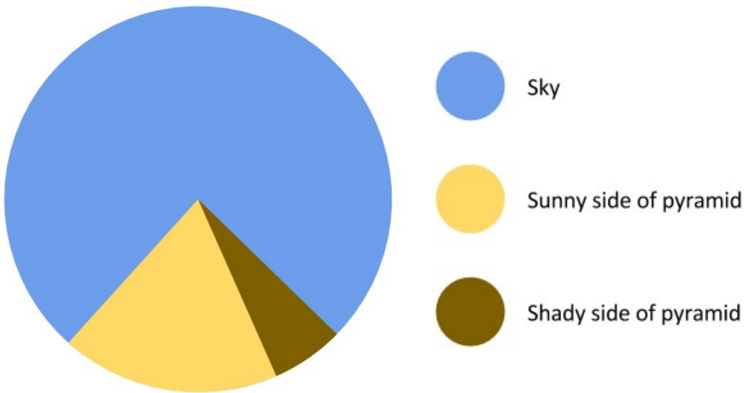
HHT: prediction components

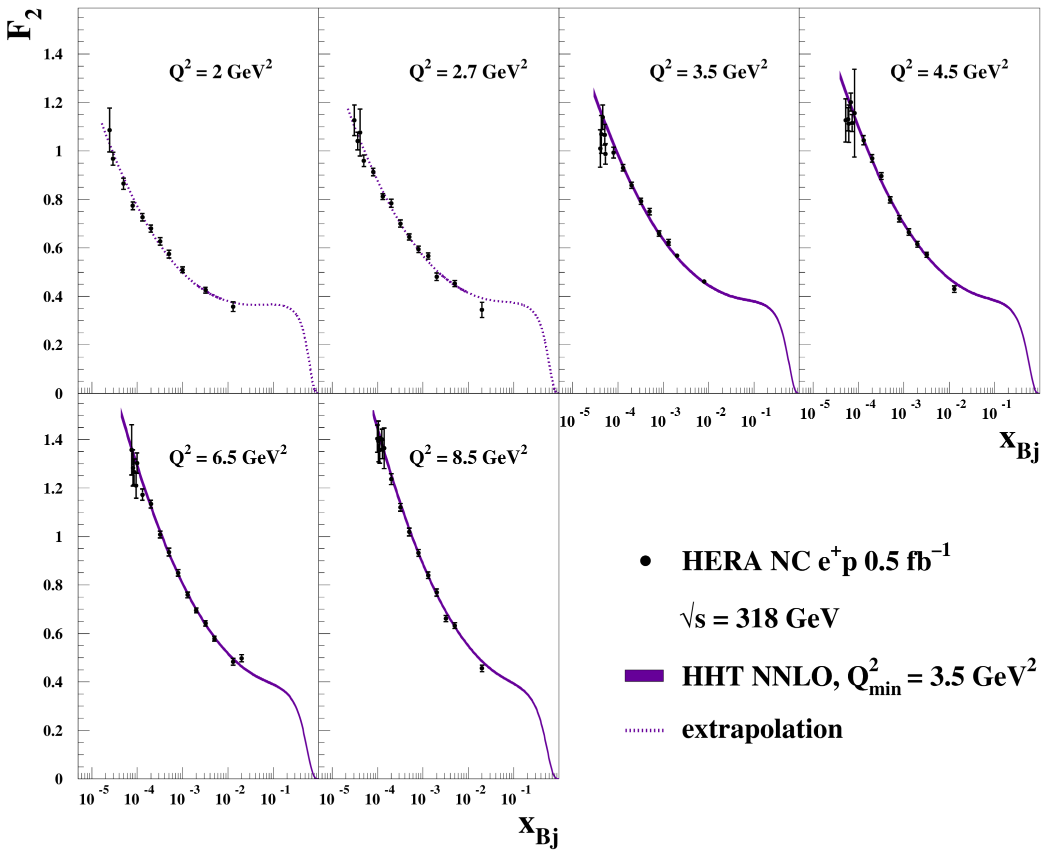
- σ predictions do great job! What are the constituents of this?

$$\sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L$$

+HHT

$$\sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L \left(1 + \frac{A_L^{HT}}{Q^2}\right)$$





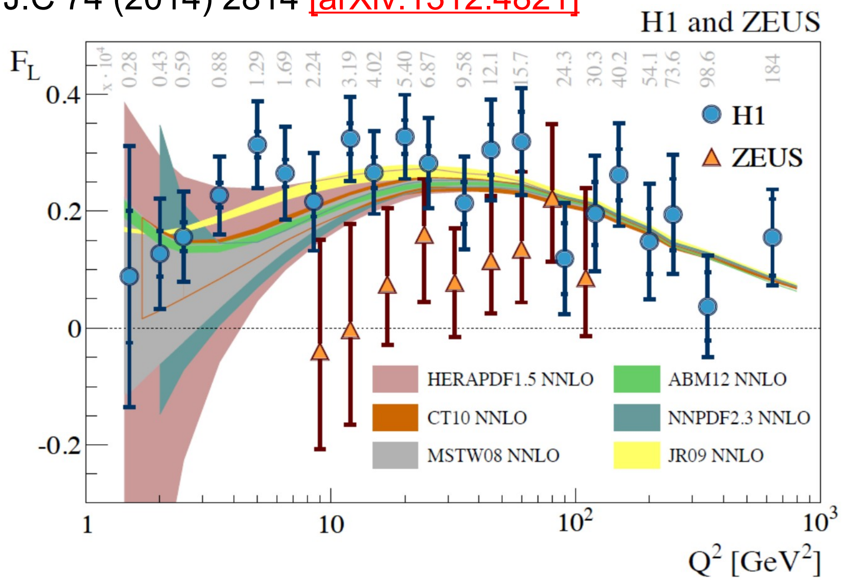
- F_2 looks reasonable as well
- Prediction describes extracted F_2 well.

$$F_2^{extr} = F_2^{pred} \frac{\sigma_r^{meas}}{\sigma_r^{pred}}$$

<u>How about F_L?..</u>

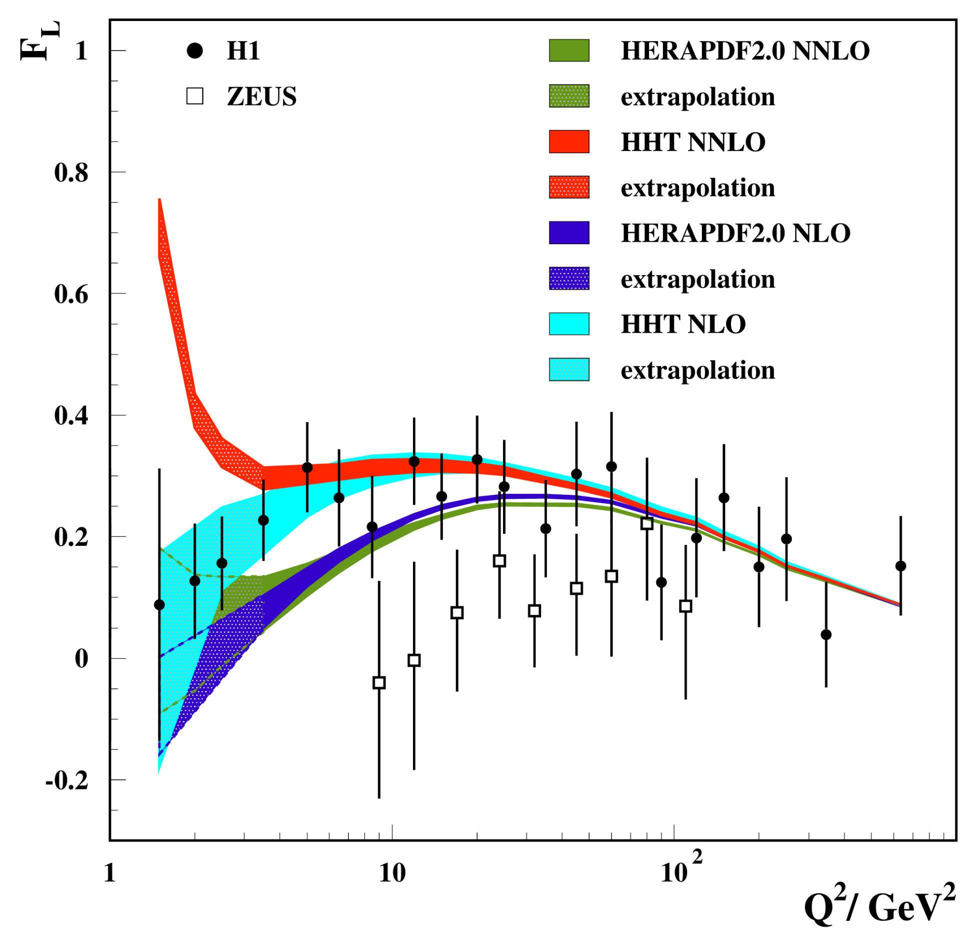
HHT: F_L structure function

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



Previous studies:

- Large uncertainties
- Predictions indicate very similar behavior



Current study:

- Way smaller uncertainties
- F_L from HHT is larger both @ NLO and NNLO
- F_L@NNLO shows a dramatic upturn at low Q^2

HHT: F_L structure function

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

- F_L wants to be larger
- F_L is directly related to gluon PDF

...can try to drop negative gluon term in xg parametrization

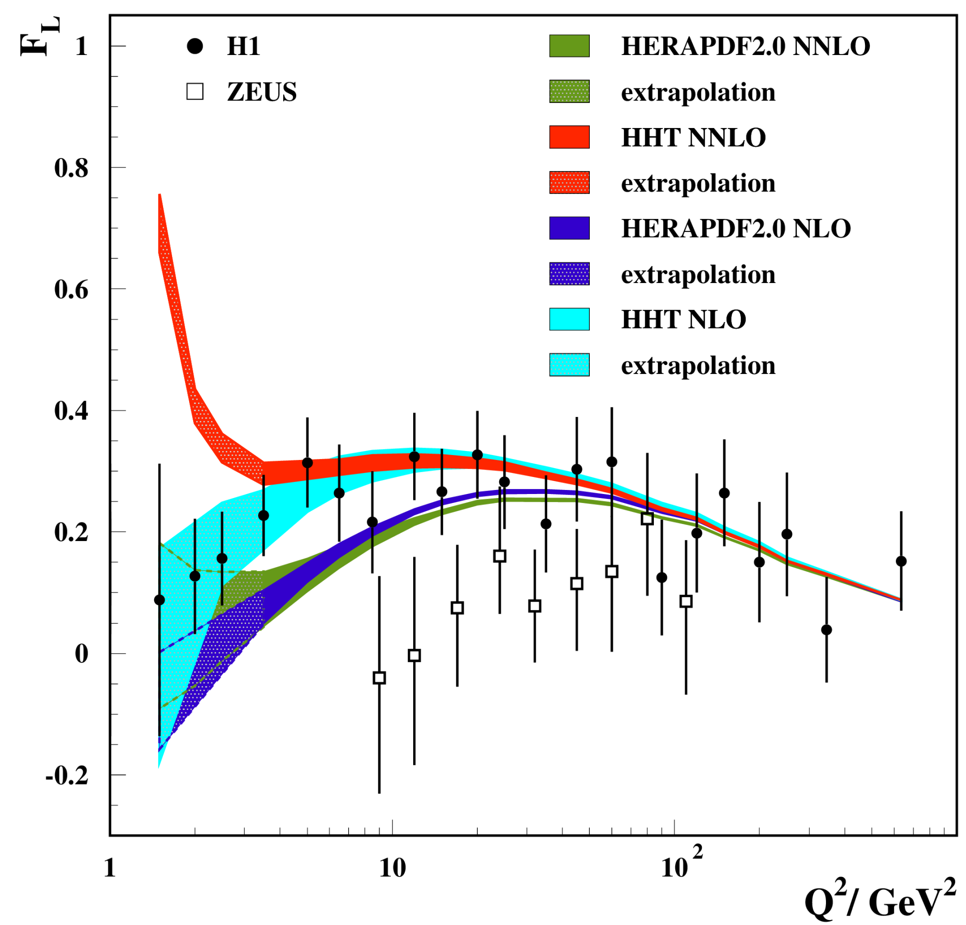
$$xg(x) = A_g x_g^B (1-x)_g^C \cancel{- A_g' x_g^{B'} (1-x)_g^{C'}}$$

HHT@NNLO $\frac{\chi^2}{ndf} = \frac{1316}{1130} \approx 1.16$

HHT_{AG}@NNLO $\frac{\chi^2}{ndf} = \frac{1350}{1132} \approx 1.20$

$\mathrm{HERAPDF2.0}_{AG}$@NNLO $\frac{\chi^2}{ndf} = \frac{1385}{1132} \approx 1.22$

- Negative gluon term is definitely needed!



HHT: prediction components

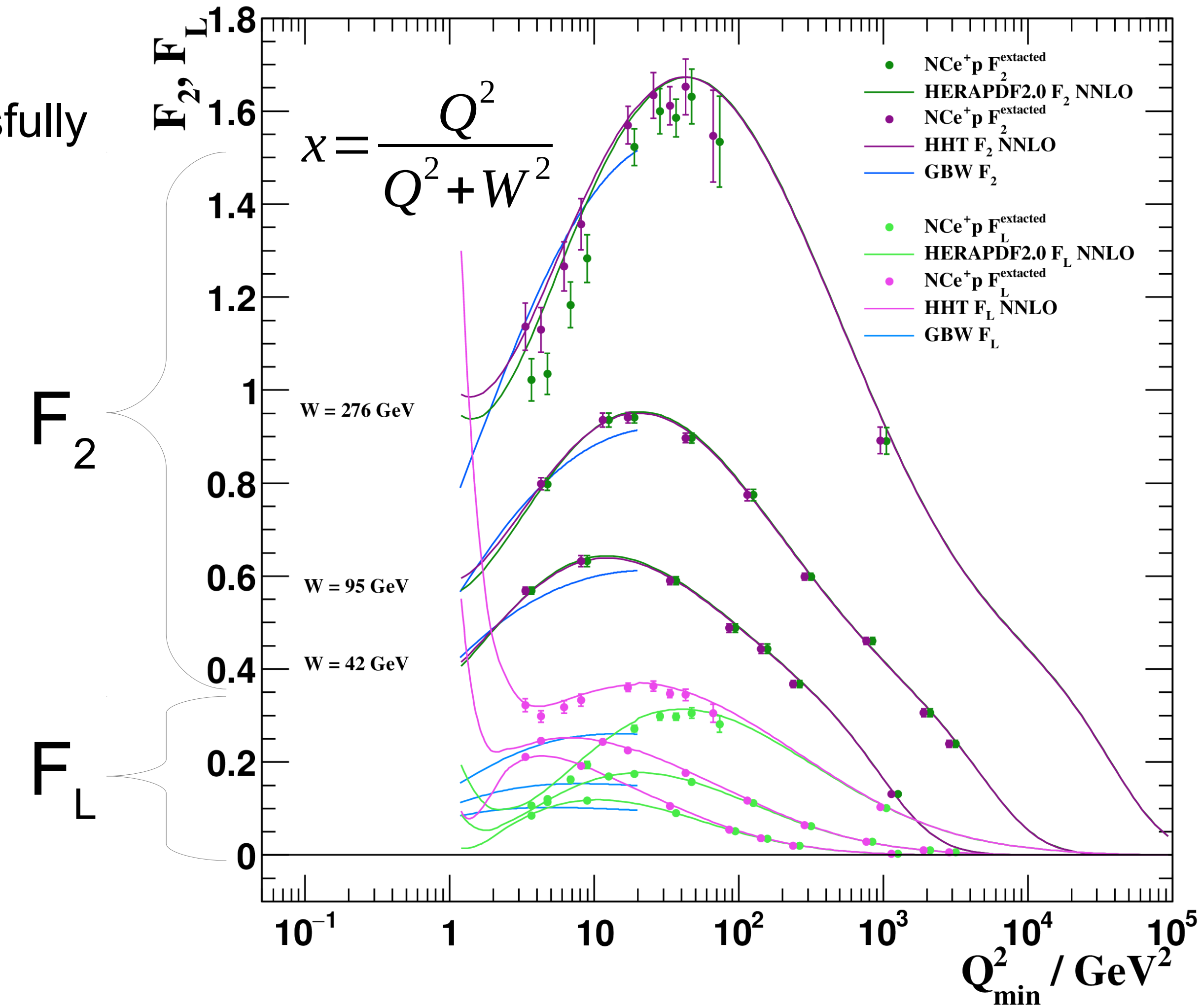
Another perspective: data at constant W and various Q^2:

- Discrepancies observed at low x => should appear at high W

- HHT describes F_2^{extr} more successfully

$$F_{2/L}^{extr} = F_{2/L}^{pred} \frac{\sigma_r^{meas}}{\sigma_r^{pred}}$$

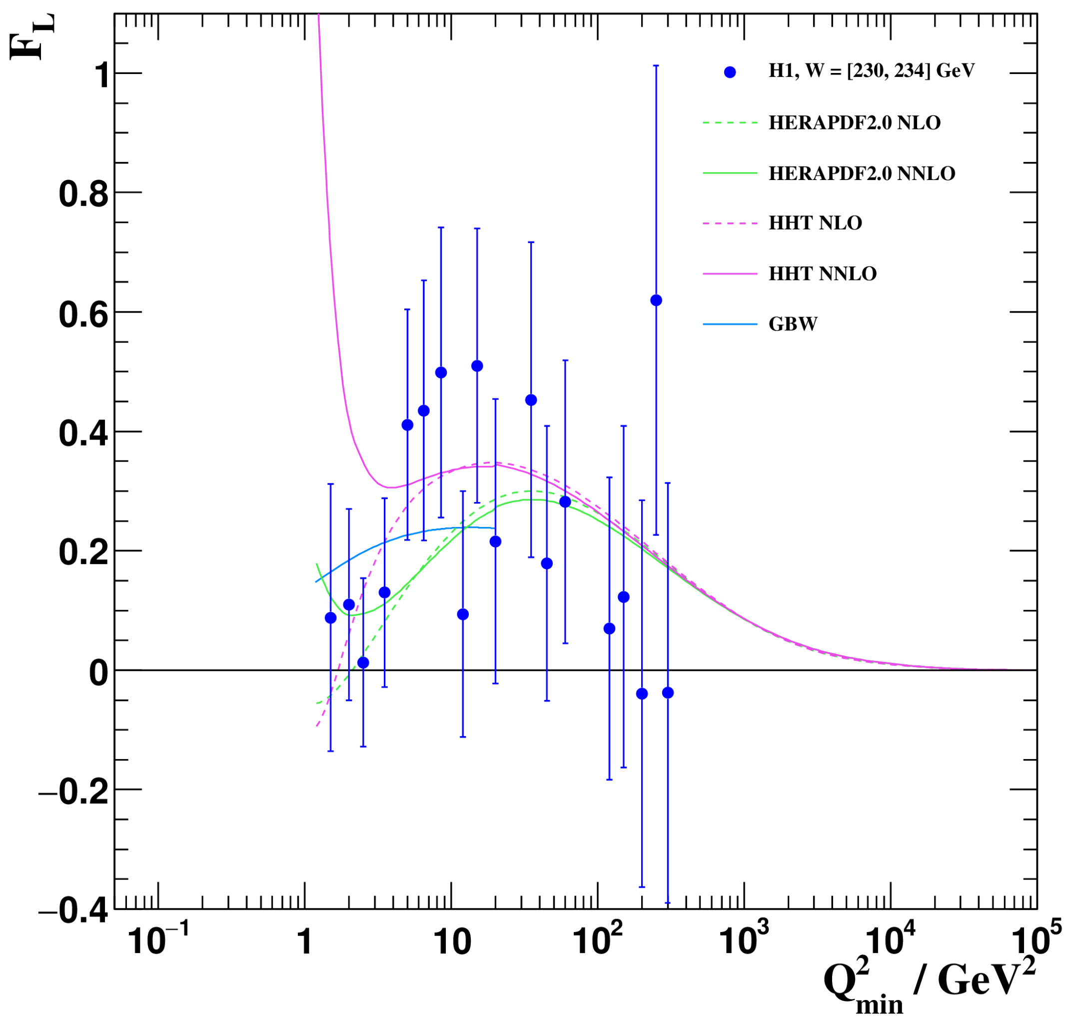
- Also Golec-Biernat, Wusthoff dipole model is shown:
  - GBW agrees well with HHT at region of applicability.
  - GBW and HHT start to disagree when either excedes its relevant region



HHT: F_L structure function

- $F_L^{extr} = F_L^{pred} \dfrac{\sigma_r^{meas}}{\sigma_r^{pred}}$ is highly model dependent

- Direct measurements of F_L exist:



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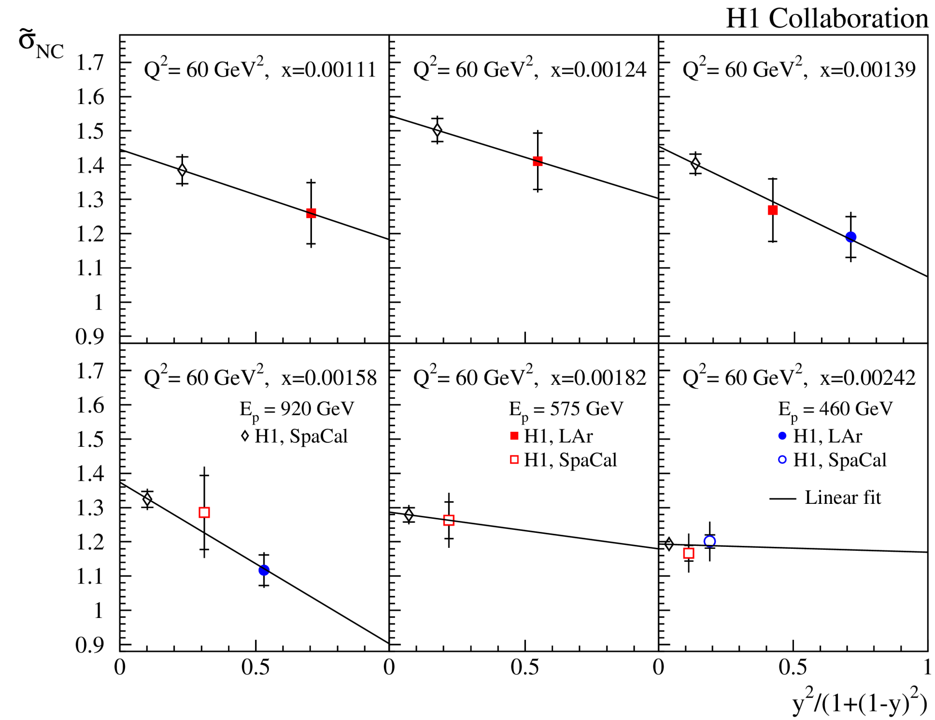
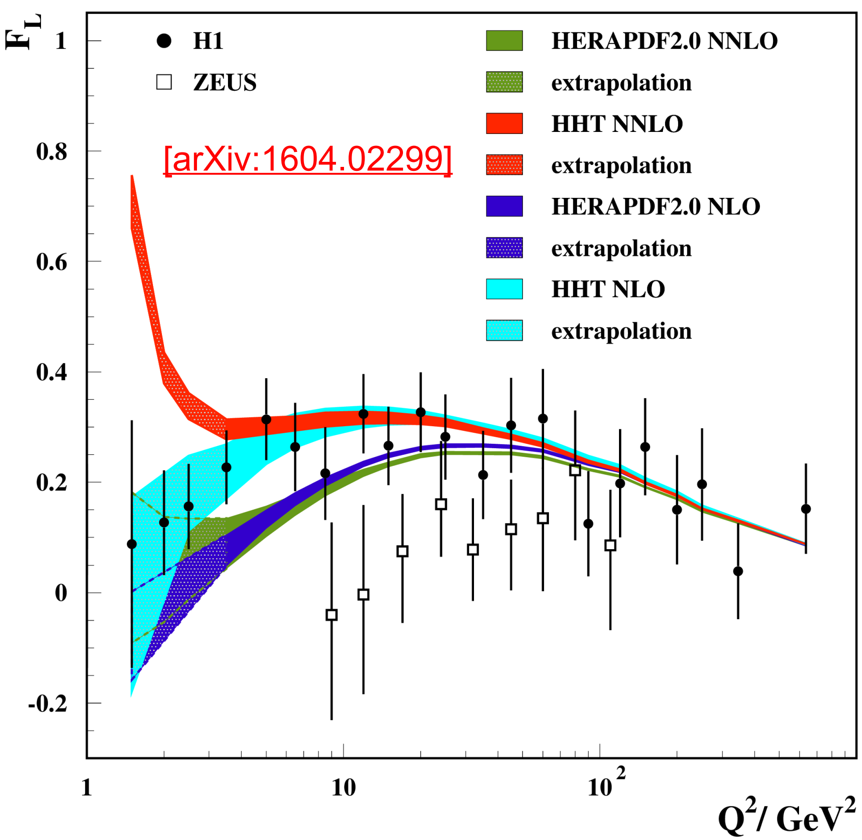


- Model independent data does not show any upturn at low Q^2

- More investigations required for proper F_L predictions

Summary

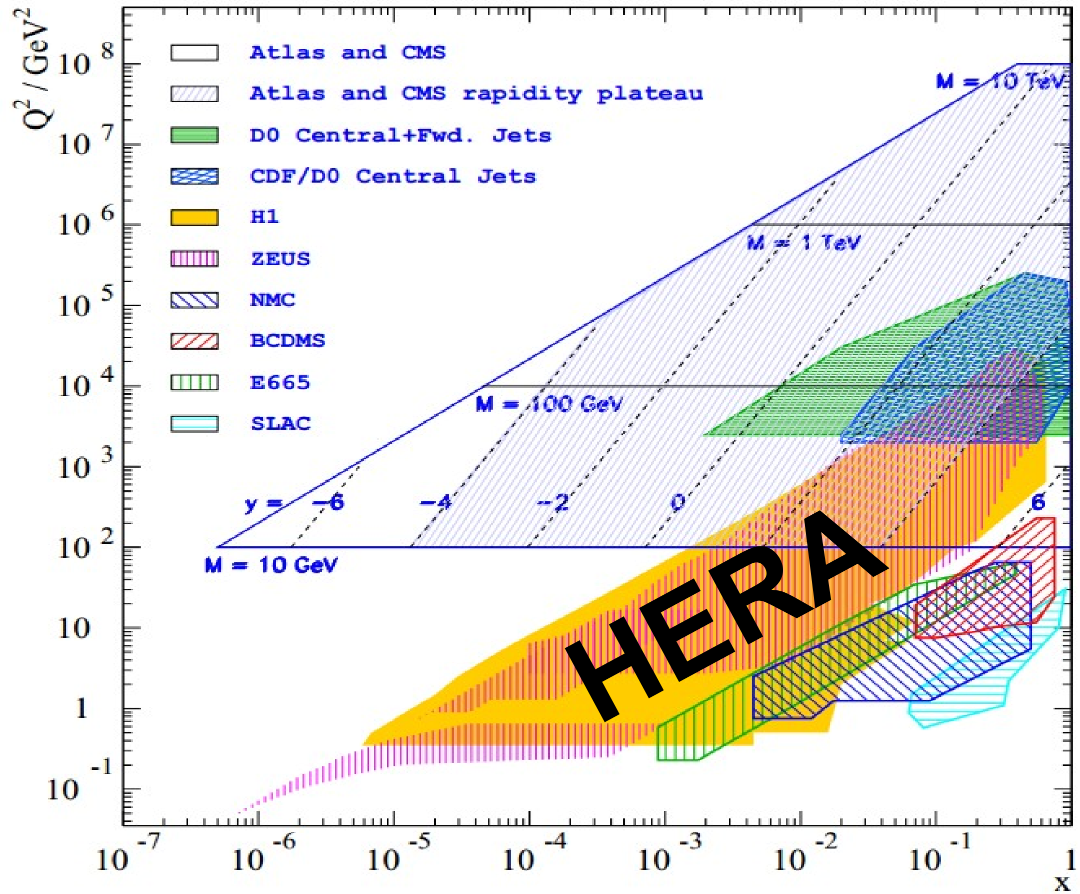
- HHT successfully describe inclusive ep cross sections data down to $Q^2 \sim 2\ \mathrm{GeV}^2$
- Addition of HT corrections flattens $\chi^2(Q^2)$ dependence substantially
- HT correction does not change PDFs much
- F_L from HHT demonstrates unphysical upturn at low scales
- The HHT approach might be too simplistic therefore requires more studies.



Backup

not necessarily useful...

HERA collider

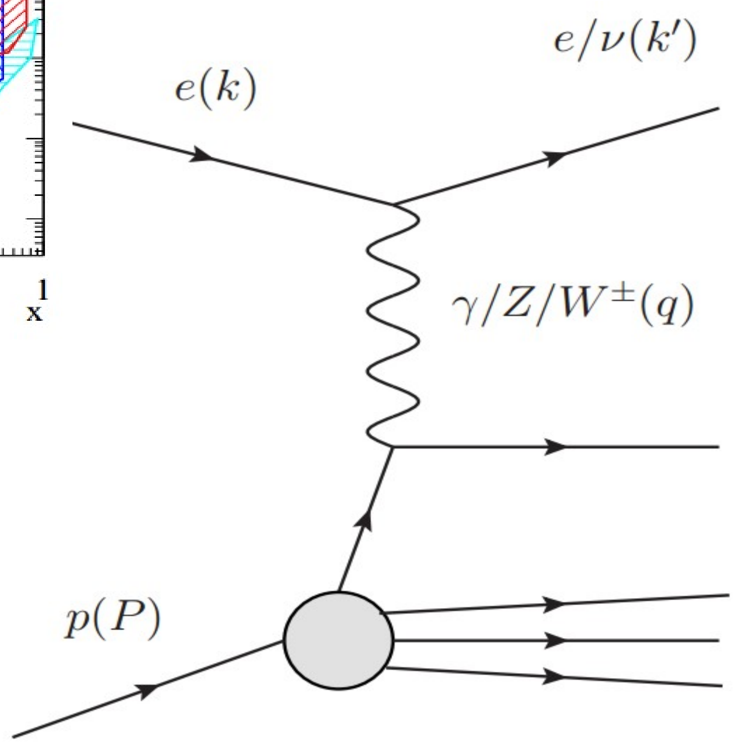


$$E_P = 920\,(460, 575)\,GeV$$
$$E_e = 27.5\,GeV$$

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

Experimental achievements:

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

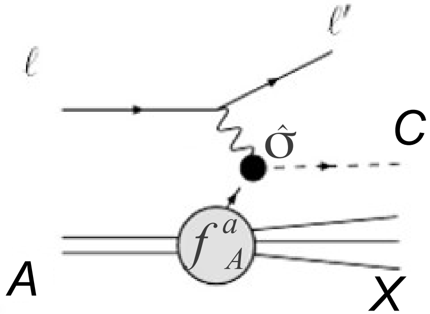


$$Q^2 = -q^2 = -(k - k')^2$$

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

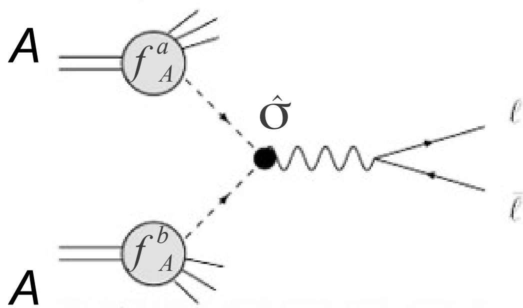
$$s = (p + k)^2 \qquad Q^2 = xys$$

PDFs for the precision measurements



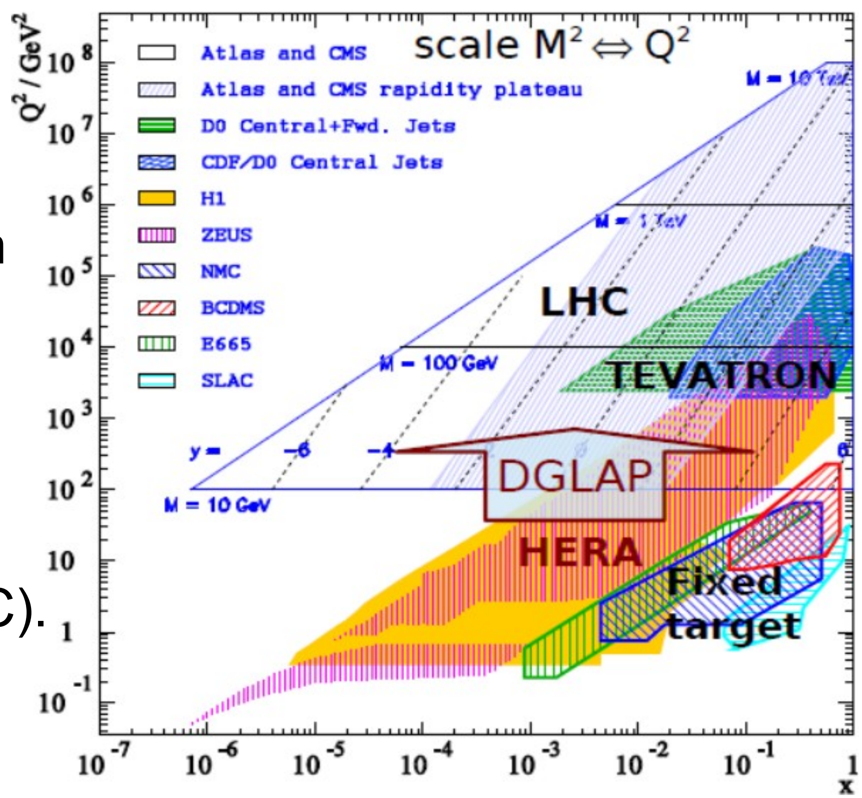
- **Factorisation theorem: PDFs + hard-scattering cross section**

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



- 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

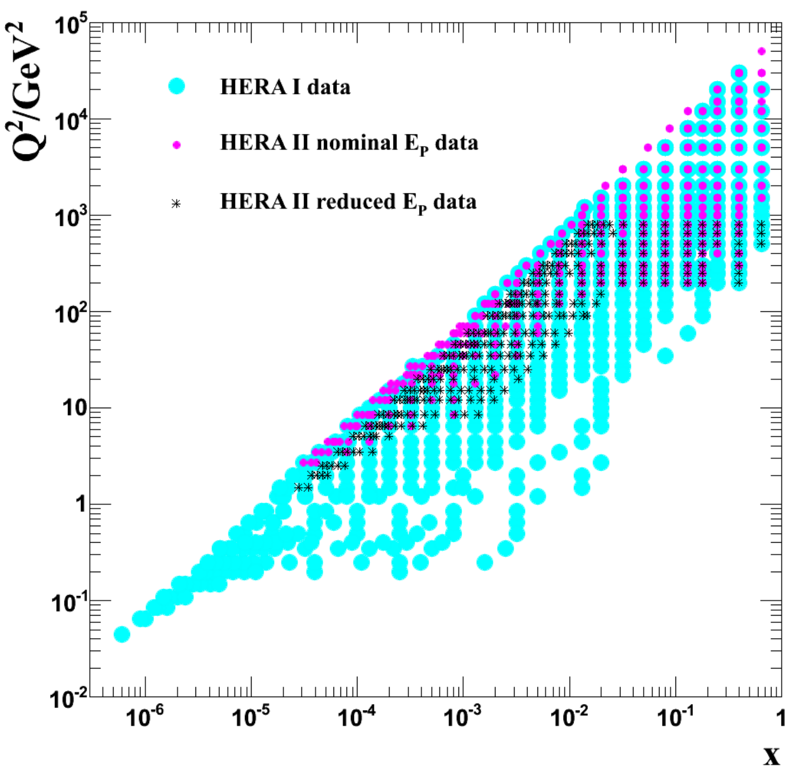


Full HERA data combination

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0



Data Set		x_{Bj} Grid from	to	Q^2[GeV^2] Grid from	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!

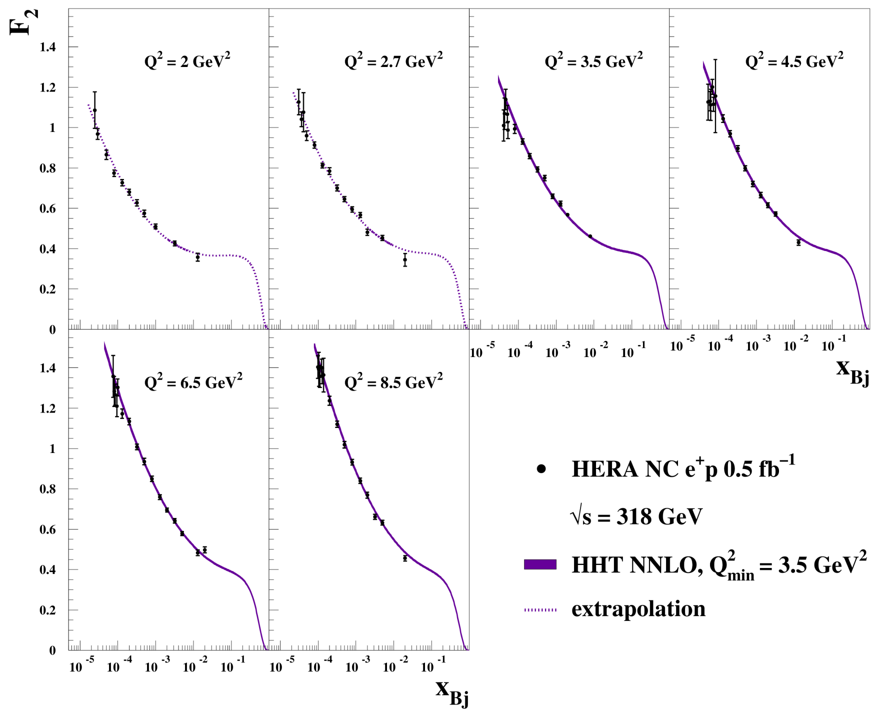
HERAPDF2.0: settings for QCD fit

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

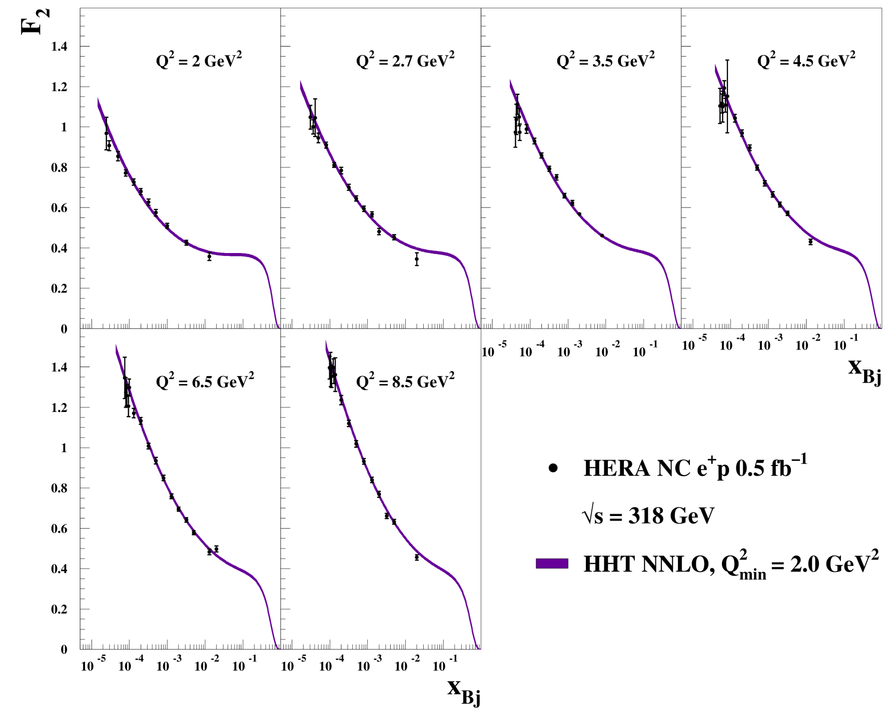
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},\\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right),\\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}},\\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right),\\
x\bar{D}(x)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

- 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)

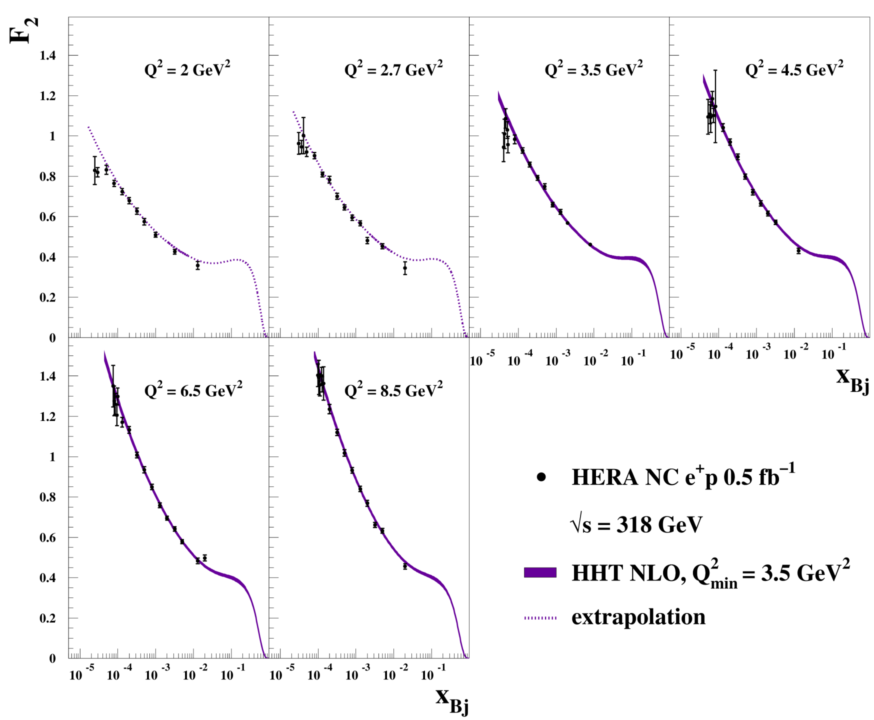
$$
\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1-\sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,uncor}\, m_i^2 + \delta^2_{i,stat}\, \mu_i m_i\left(1-\sum_j \gamma^i_j b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,uncor}\, m_i^2 + \delta^2_{i,stat}\, \mu_i m_i}{\delta^2_{i,uncor}\, \mu_i^2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



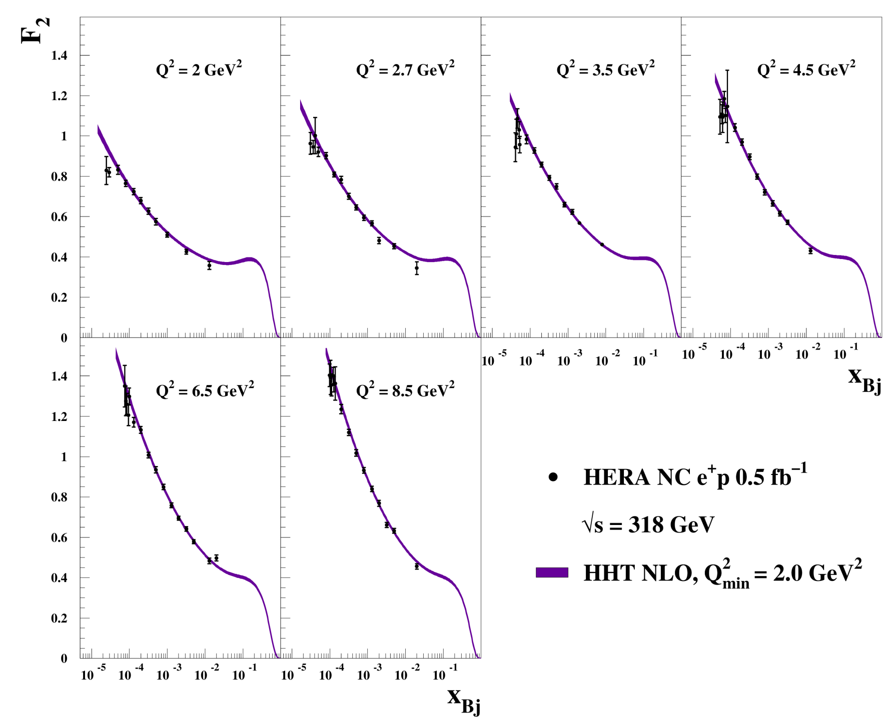
F2
Q2 = 2 GeV2
Q2 = 2.7 GeV2
Q2 = 3.5 GeV2
Q2 = 4.5 GeV2
Q2 = 6.5 GeV2
Q2 = 8.5 GeV2
xBj
HERA NC e+p 0.5 fb−1
√s = 318 GeV
HHT NNLO, Q2min = 3.5 GeV2
extrapolation



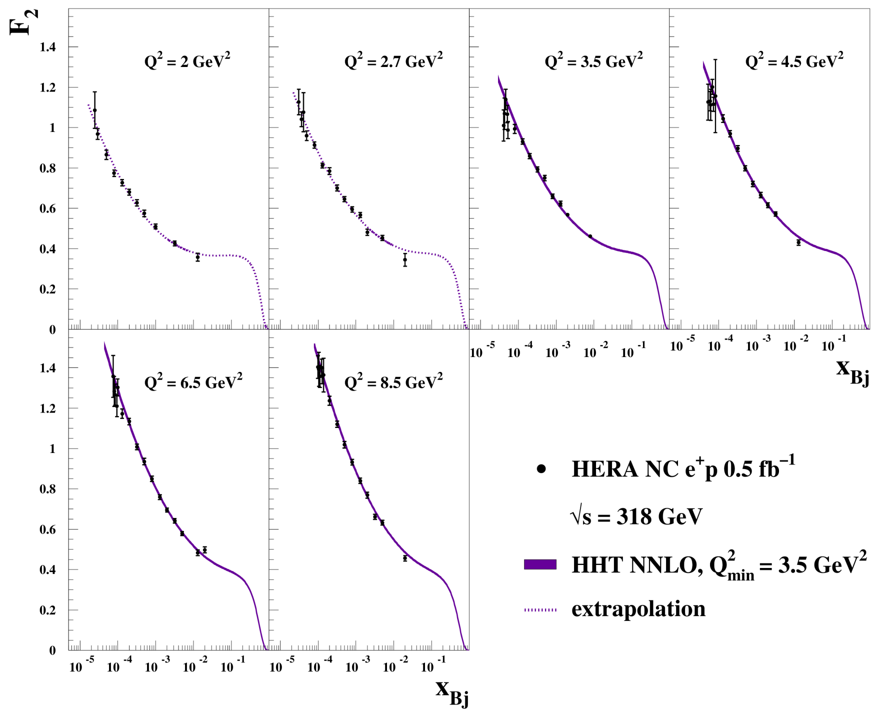
F2
Q2 = 2 GeV2
Q2 = 2.7 GeV2
Q2 = 3.5 GeV2
Q2 = 4.5 GeV2
Q2 = 6.5 GeV2
Q2 = 8.5 GeV2
xBj
HERA NC e+p 0.5 fb−1
√s = 318 GeV
HHT NNLO, Q2min = 2.0 GeV2

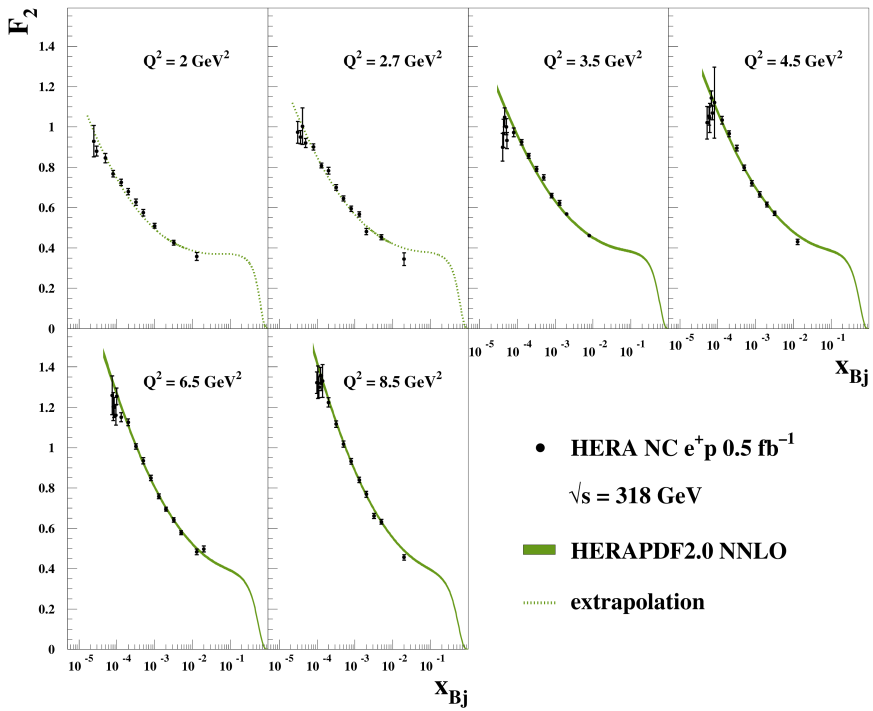


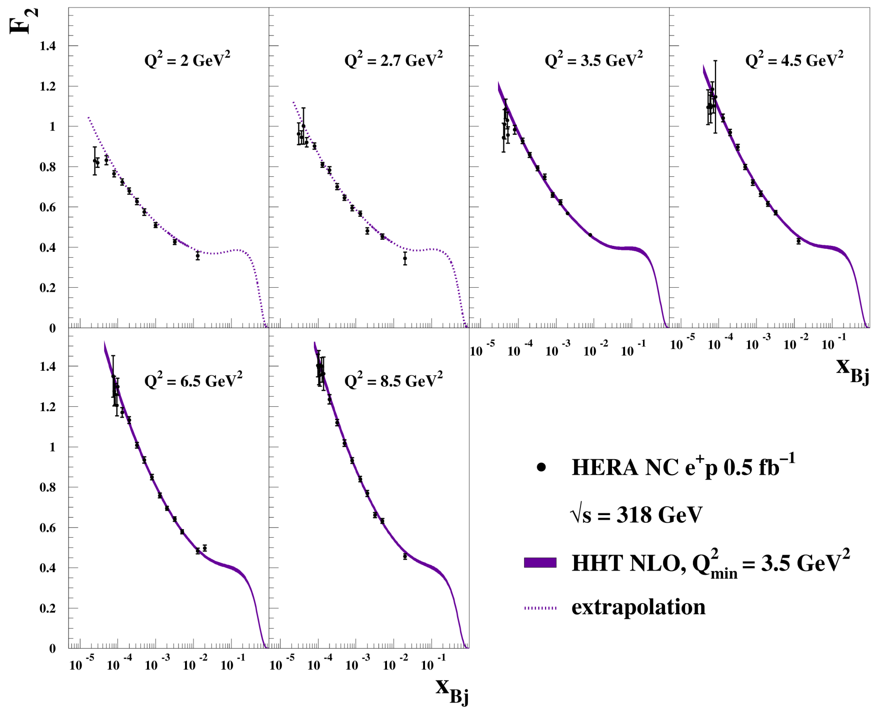
F2
Q2 = 2 GeV2
Q2 = 2.7 GeV2
Q2 = 3.5 GeV2
Q2 = 4.5 GeV2
Q2 = 6.5 GeV2
Q2 = 8.5 GeV2
xBj
HERA NC e+p 0.5 fb−1
√s = 318 GeV
HHT NLO, Q2min = 3.5 GeV2
extrapolation

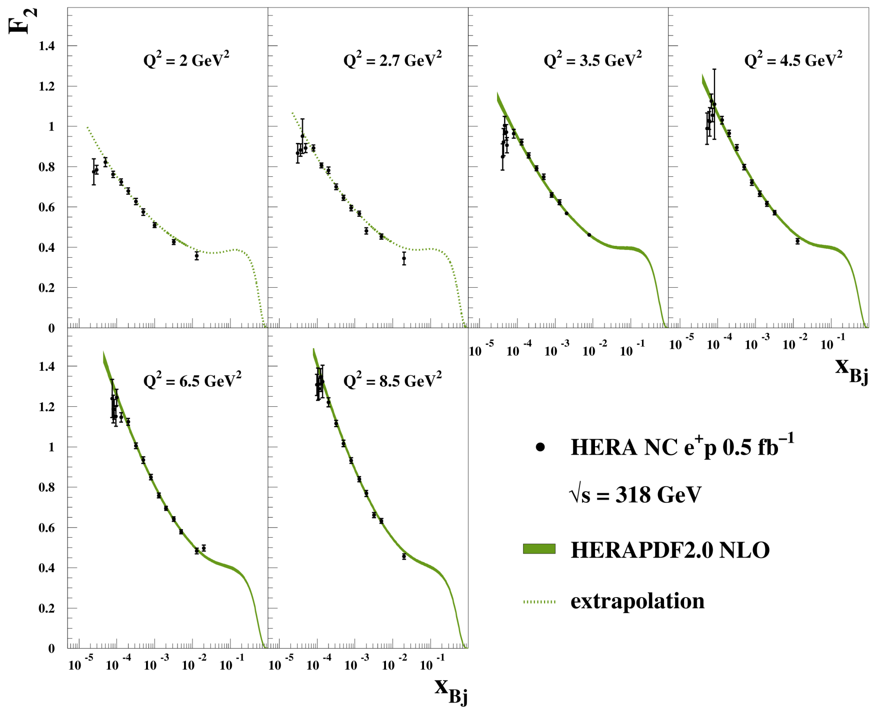


F2
Q2 = 2 GeV2
Q2 = 2.7 GeV2
Q2 = 3.5 GeV2
Q2 = 4.5 GeV2
Q2 = 6.5 GeV2
Q2 = 8.5 GeV2
xBj
HERA NC e+p 0.5 fb−1
√s = 318 GeV
HHT NLO, Q2min = 2.0 GeV2


F2
Q² = 2 GeV²
Q² = 2.7 GeV²
Q² = 3.5 GeV²
Q² = 4.5 GeV²
Q² = 6.5 GeV²
Q² = 8.5 GeV²
xBj
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
HHT NNLO, Q²min = 3.5 GeV²
extrapolation


F2
Q² = 2 GeV²
Q² = 2.7 GeV²
Q² = 3.5 GeV²
Q² = 4.5 GeV²
Q² = 6.5 GeV²
Q² = 8.5 GeV²
xBj
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
HERAPDF2.0 NNLO
extrapolation


F2
Q² = 2 GeV²
Q² = 2.7 GeV²
Q² = 3.5 GeV²
Q² = 4.5 GeV²
Q² = 6.5 GeV²
Q² = 8.5 GeV²
xBj
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
HHT NLO, Q²min = 3.5 GeV²
extrapolation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HERAPDF2.0 NLO
extrapolation