HERA incl. $\sigma_{NC,CC}$ & a new PDF fit, HERAPDF2.0

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On behalf of
the H1 & ZEUS
collaborations

Outline

1) Introduction

2) Full HERA data combination
   H1+ZEUS, HERA-1 & –2 inclusive NC* and CC** cross sections ($\sigma_{NC,CC}$)
   → a major legacy of HERA

3) HERAPDF 2.0

4) Summary

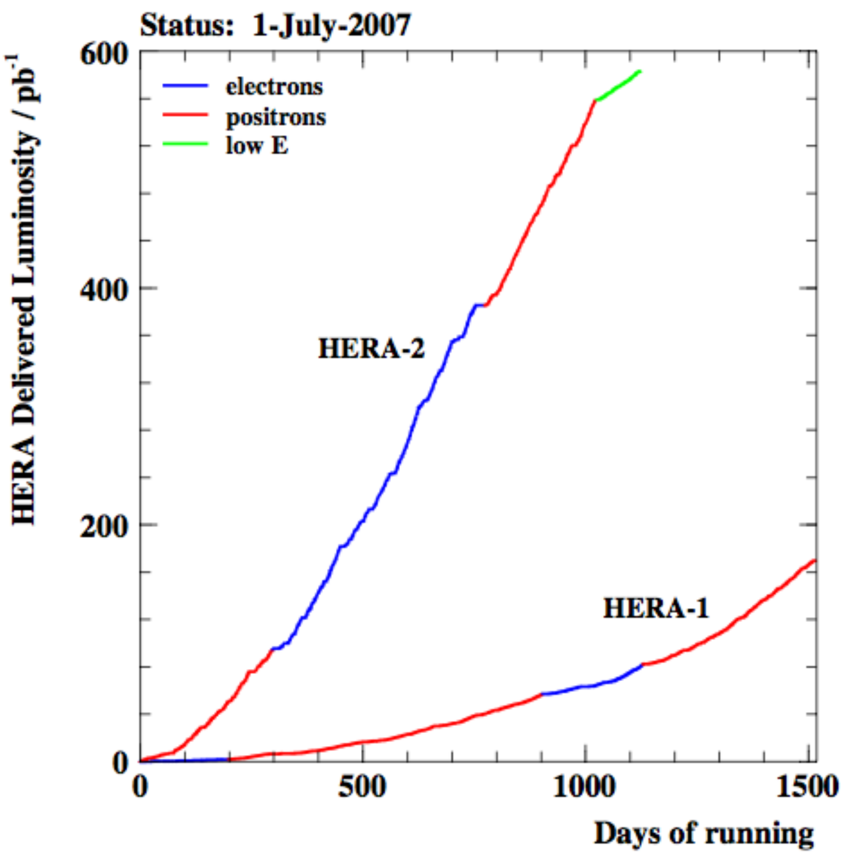
Freshly made public:
arXiv:1506.06042
- 160 pages
- 83 figures
- 16 tables

* NC: Neutral Current
** CC: Charged Current

Introduction

ep collider, HERA, used to be the largest electron microscope

Both NC and CC inclusive cross sections were precisely measured



HERA-1 (1992-2000):

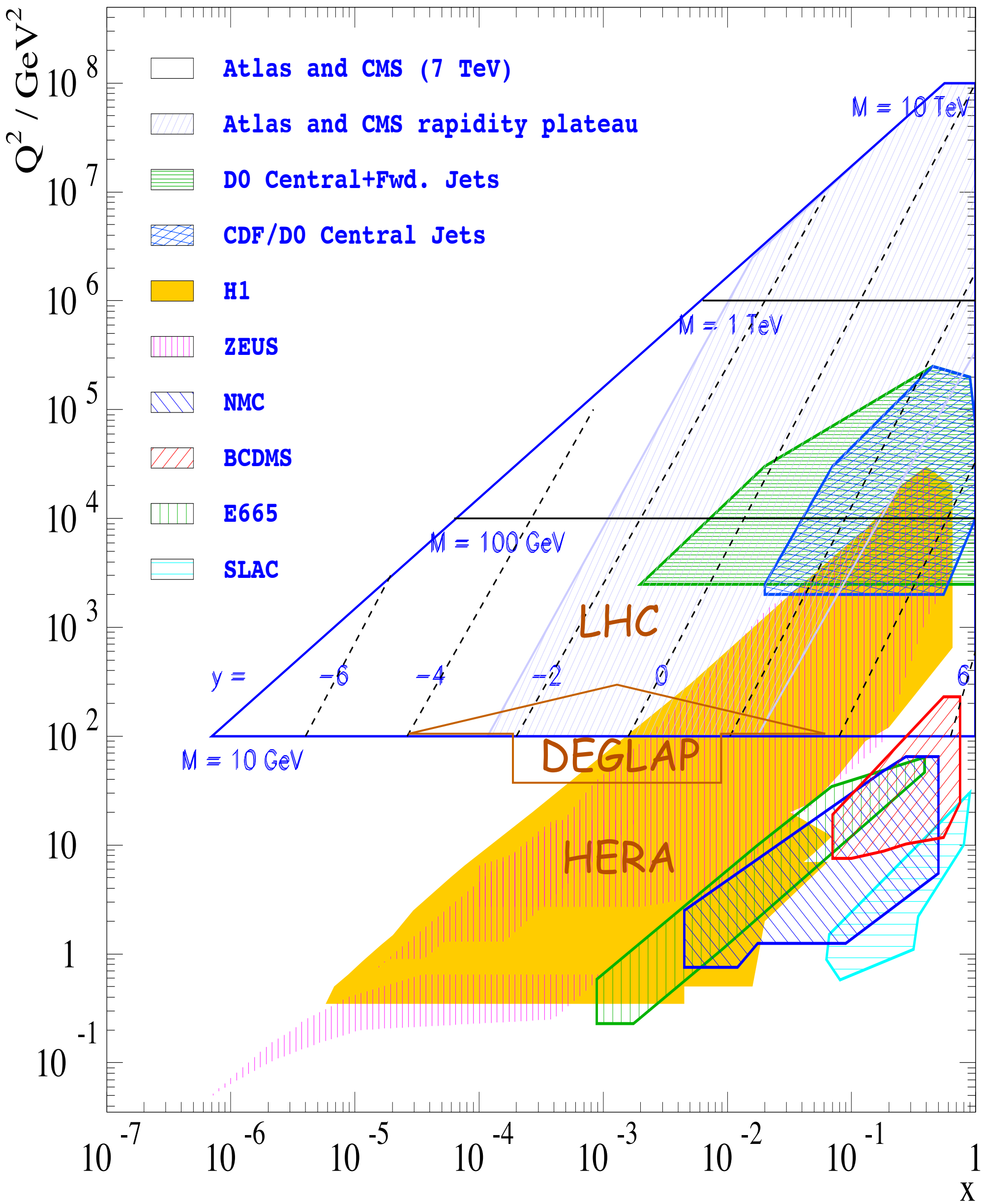
Combined HERA-1 data primary input for all modern PDF sets:

- CTEQ
- MRST
- NNPDFs
- HERAPDF1.0
- ……

HERA-2 (2003-2007):

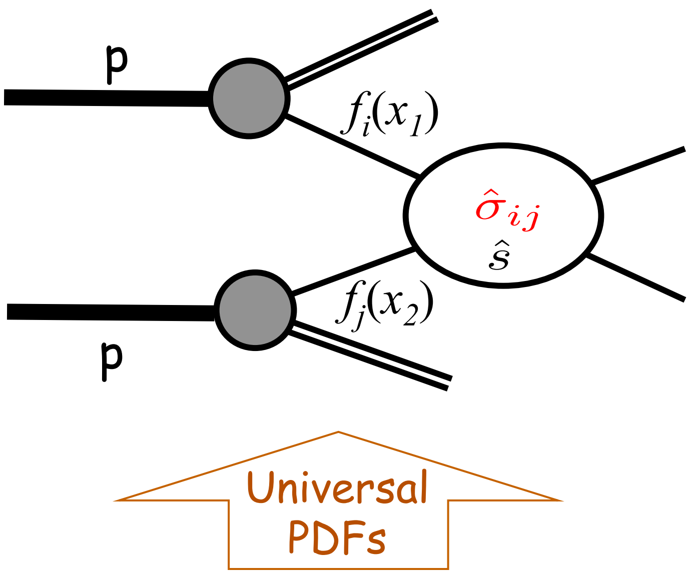
- Increased lumi (x10 e-, x2 e+)
- Long. polarized e beam
- Full combination HERA-1 & -2

Introduction



LHC: needs precise input PDFs

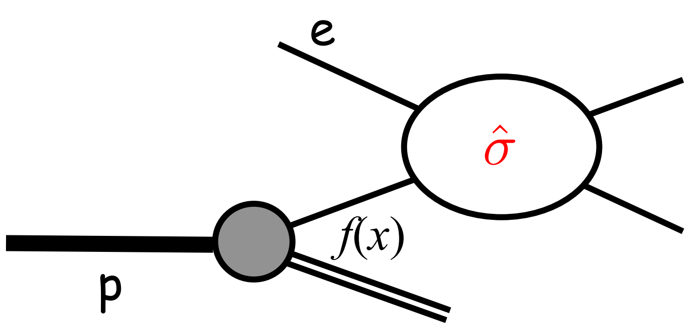
→ Essential for reliable predictions



HERA: factorization theorem:

PDFs f(x) + hard scattering $\hat{\sigma}$

→ PDFs determination



Full HERA Data Combination

HERA-1 combination → HERAPDF 1.0

HERA-1 + preliminary HERA-2 combination → HERAPDF 1.5

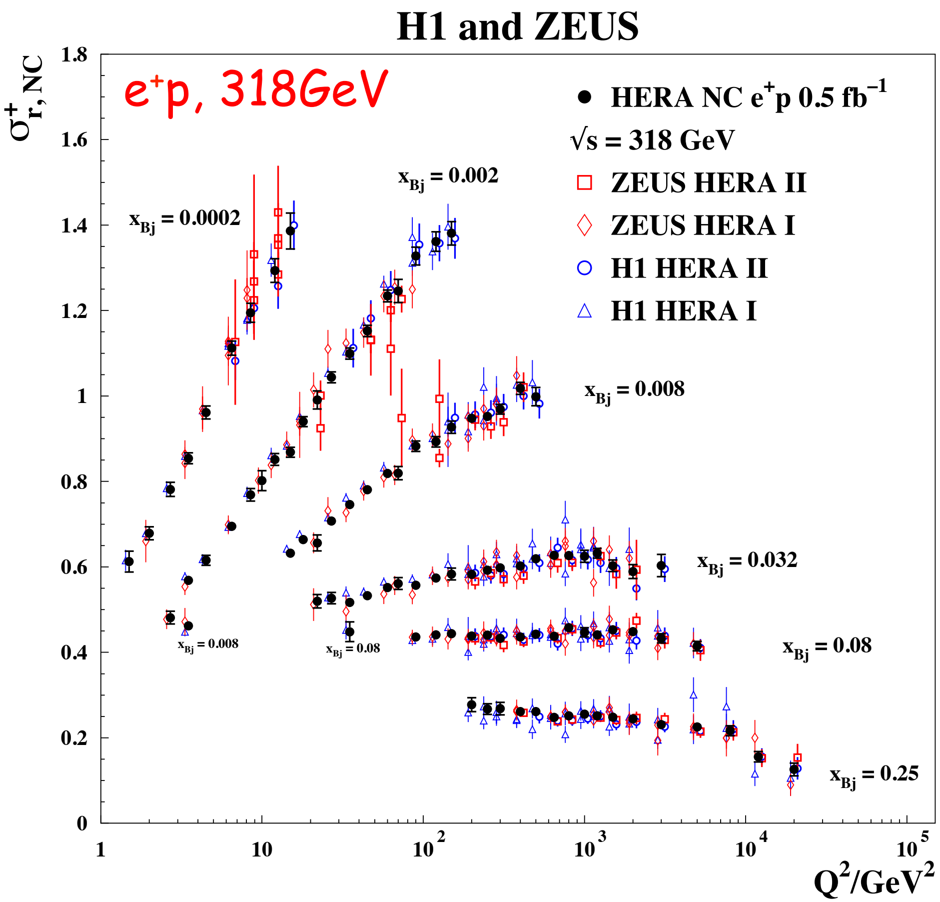
Full HERA-1 & -2 data combination → HERAPDF 2.0

- >20 publications
- 2927 data points combined into 1307

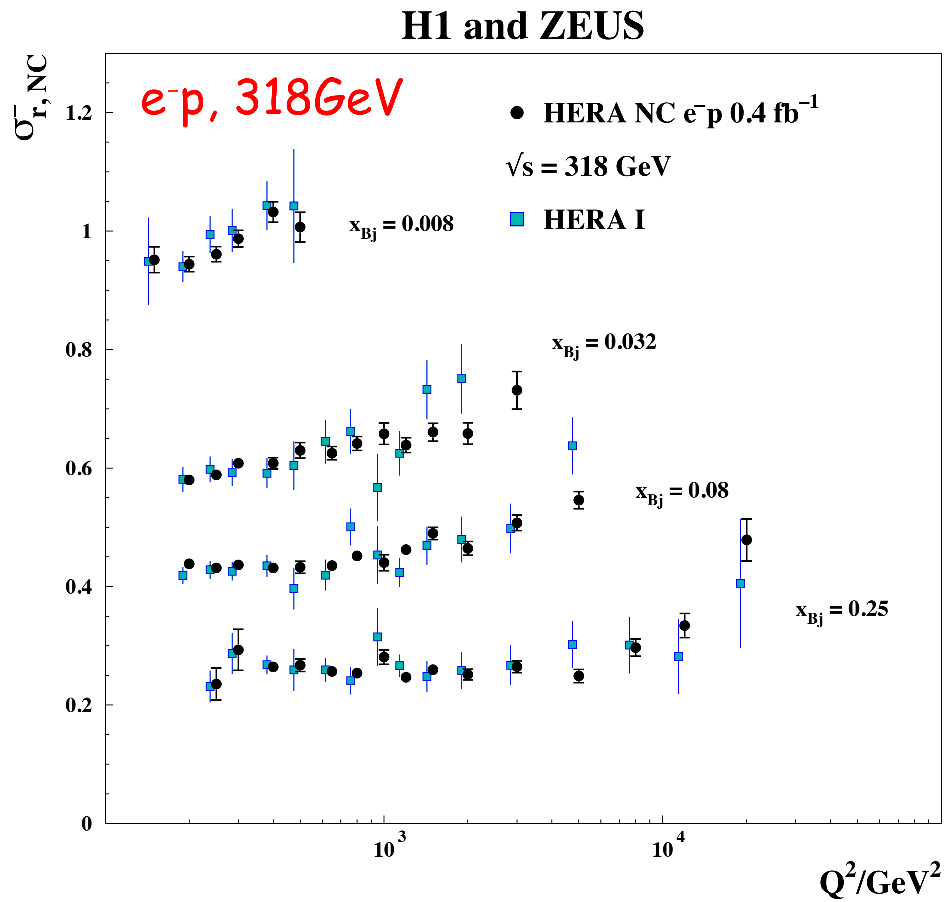
Data Set		x_{Bj} Grid from	to	Q^2[GeV^2] Grid from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
HERA I $E_p = 820$ GeV and $E_p = 920$ GeV data sets								
H1 svx-mb [2]	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2 [2]	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	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 [2] high/low Q^2	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

Combined NC Data vs. Individual & HERA-1

Combined vs. individual ones
(shown for a subset)



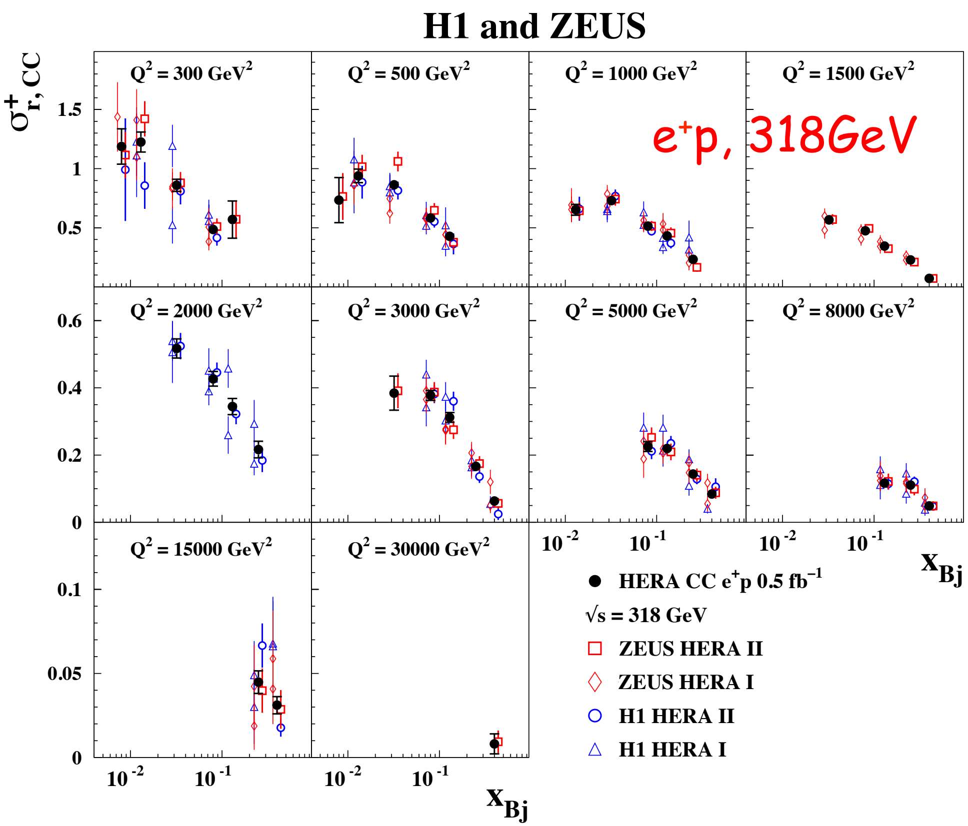
Combined vs. HERA-1 combination
(shown for high Q^2 data)

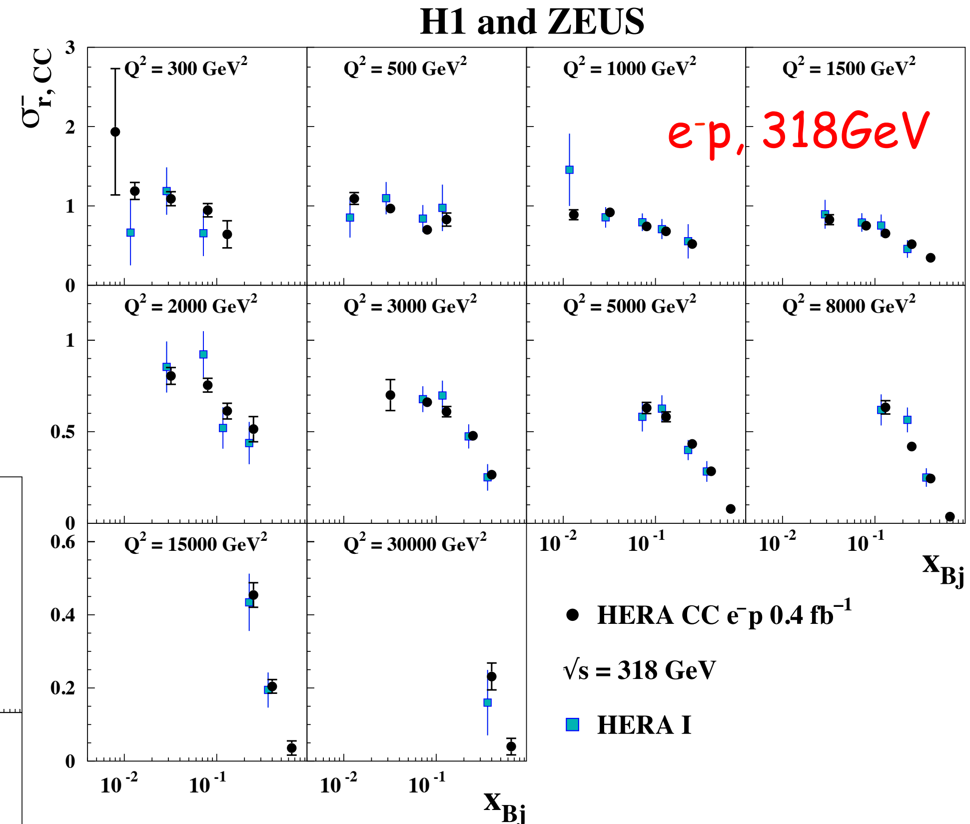


The improved precision is mainly statistical at high x and Q^2 and systematic at small x & Q^2

Combined CC Data vs. Individual & HERA-1

Combined vs. individual ones

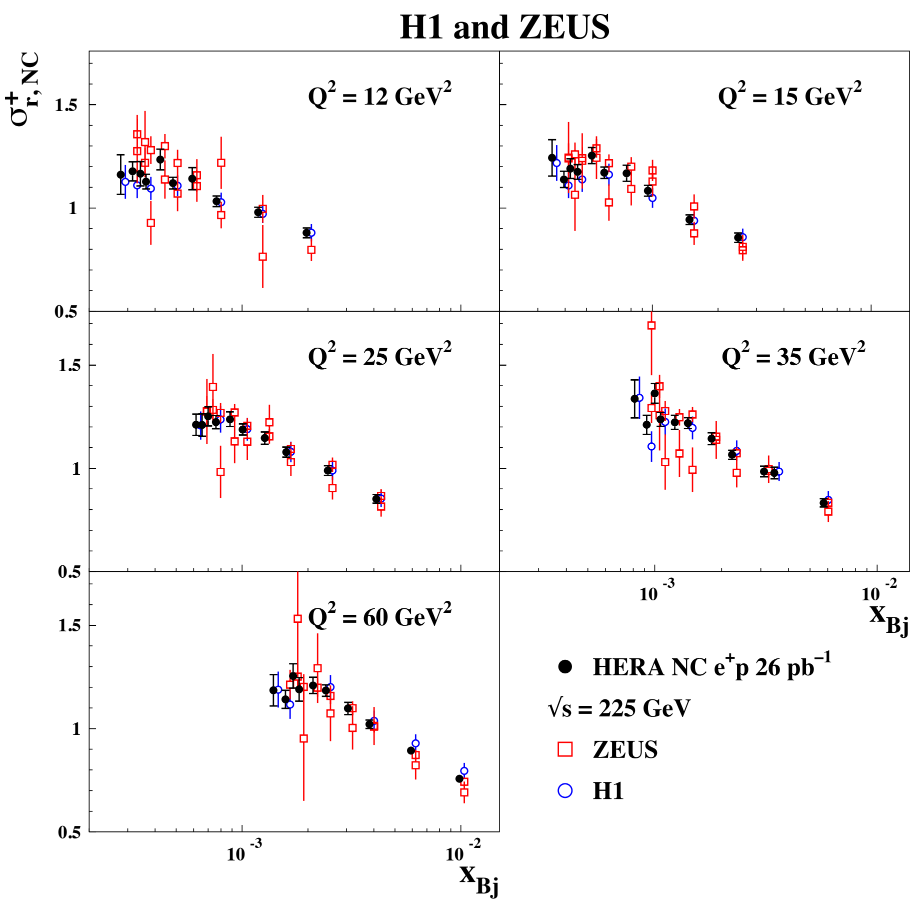




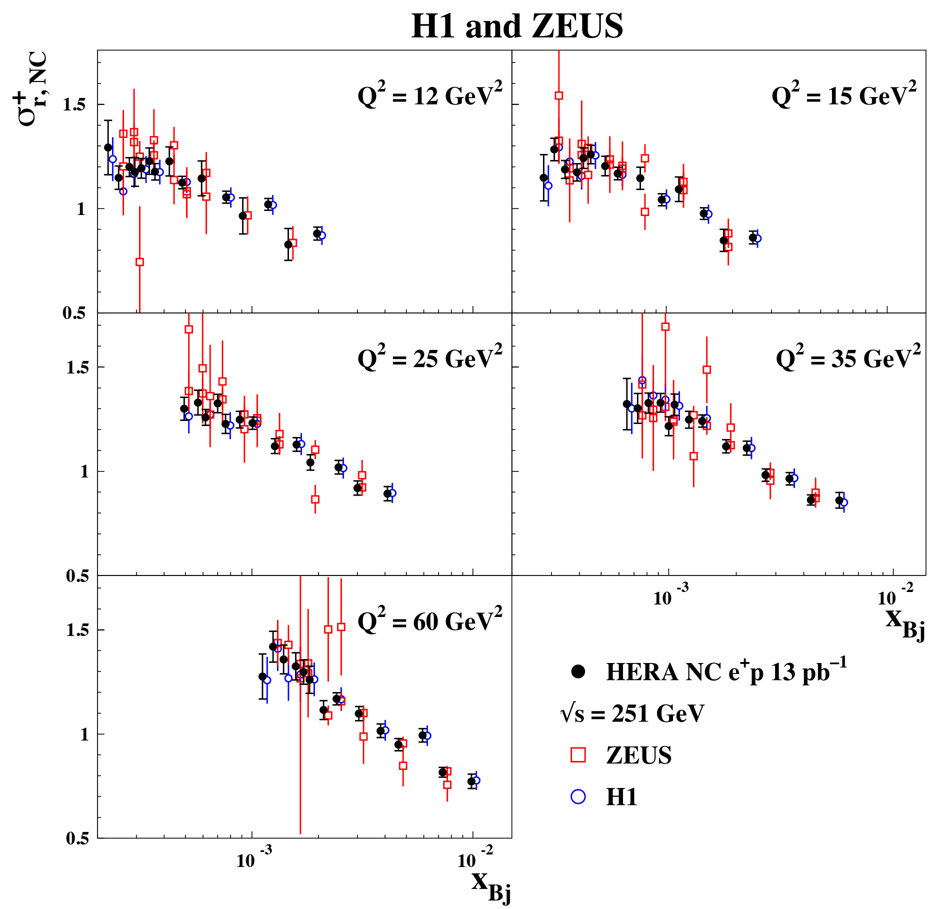
Combined vs. HERA-1 combination

Combined NC Data at Low Q^2 & E_p Energies

Combined vs. individual ones
($\sqrt{s}$=225GeV)



Combined vs. individual ones
($\sqrt{s}$=251GeV)



HERAPDF 2.0

- Input data: Combined HERA inclusive DIS NC & CC cross sections
- Fitting program: HERAFitter (www.herafitter.org)
- PDFs parameterized at μ^2_{f0}=1.9GeV^2

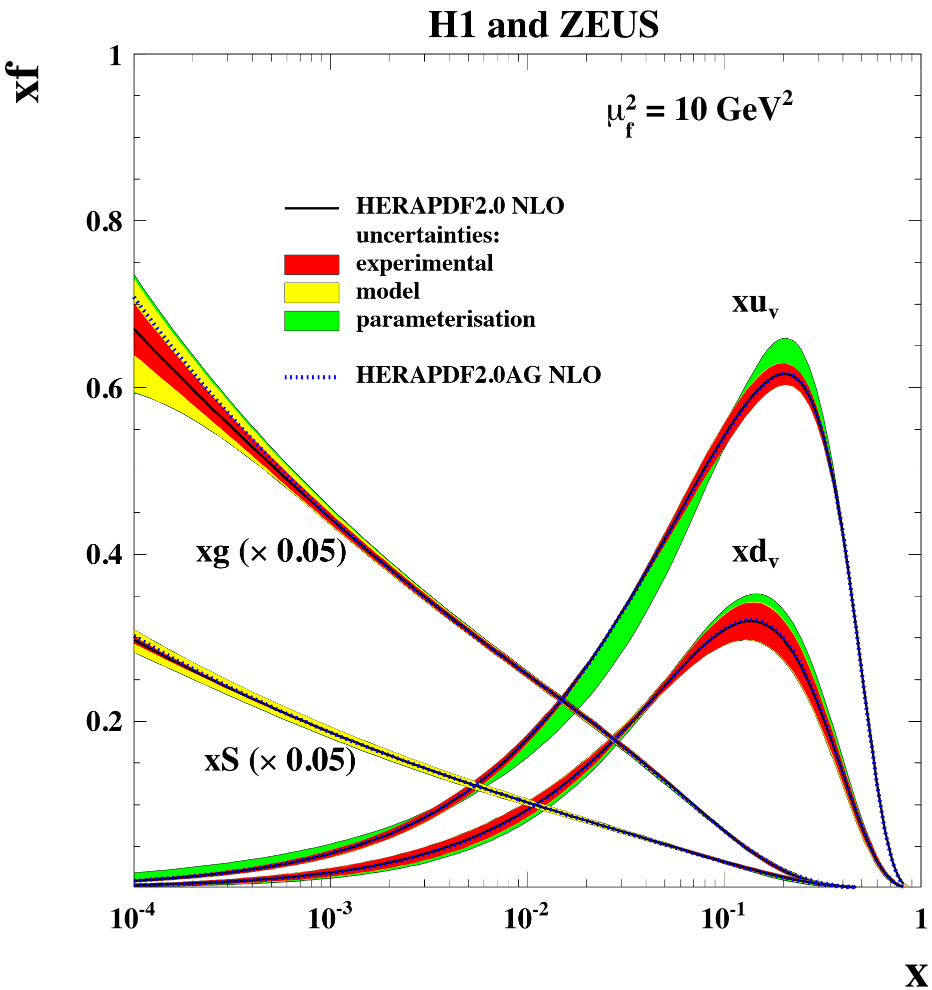
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

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

- PDFs evolution: DGLAP equation at NLO, NNLO
- Heavy flavor scheme: GM VFNS* (RT OPT**)

* GM VFNS: General Mass Variable Flavor Number Scheme
** RT OPT: Robert Thorne OPTimal scheme: PRD86 (2012) 074017, arXiv:1201.6180

HERAPDF2.0 Uncertainties



Similar version exists for NNLO with smaller error bands

- ❑ Experimental uncertainties
  - taking into corr. account
  - HESSIAN method (x-checked with MC method)
- ❑ Model uncertainties

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
$\alpha_s(M_Z^2)$	0.118	–	–
μ^2_{f0} [GeV^2]	1.9	1.6	2.2

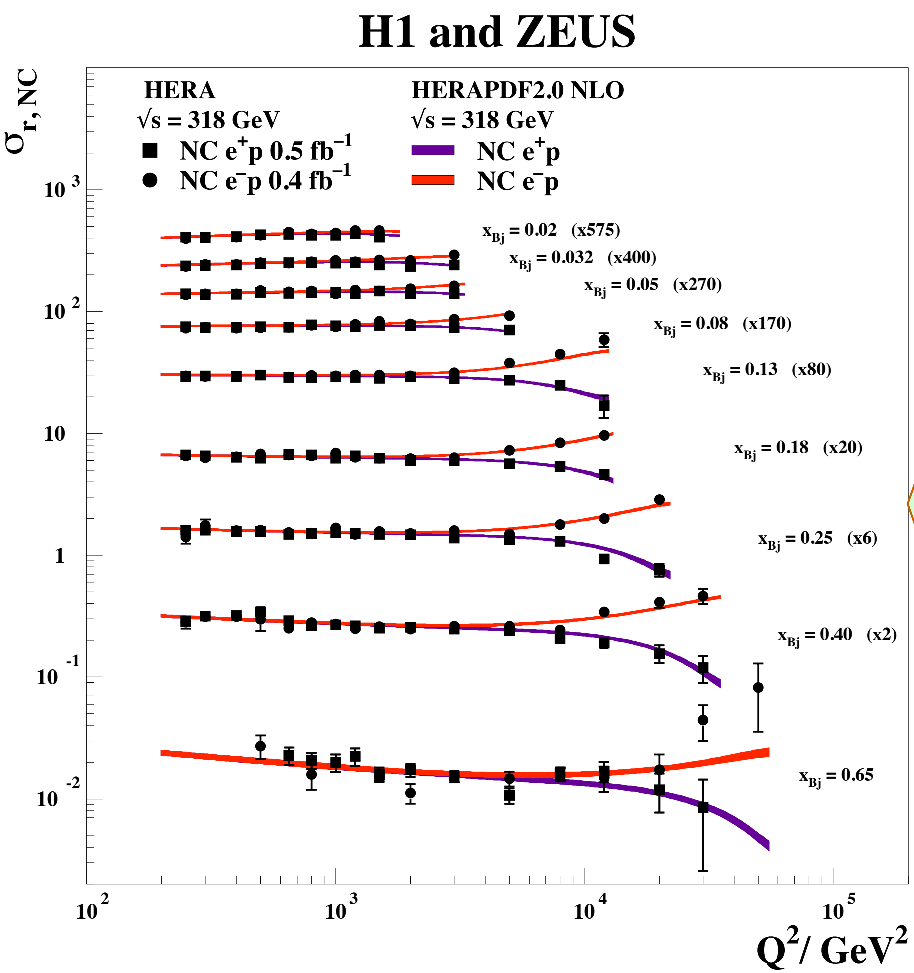
The addition of D & E parameters

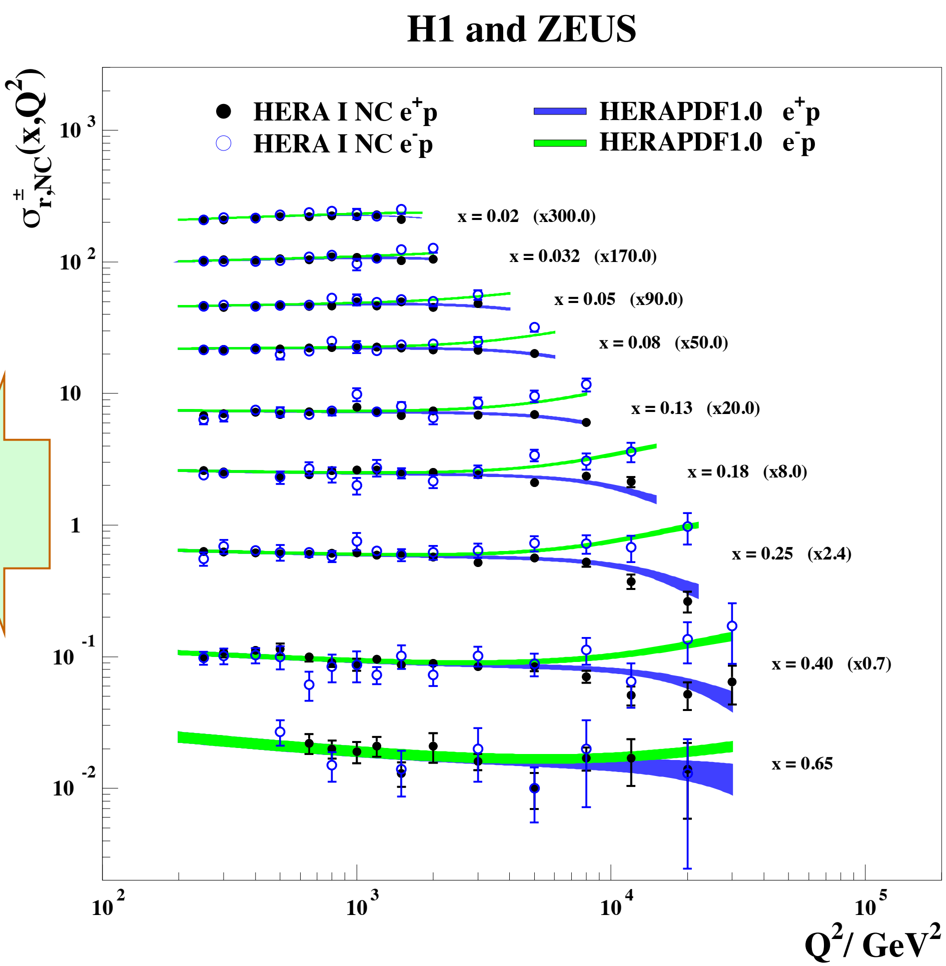
- ❑ Parameterization uncertainties

Other HERAPDF Fits & Comparison

- HERAPDF2.0 vs HERAPDF1.0
- HERAPDF2.0HiQ2:
  Use Q^2_{min}>10GeV^2 instead of Q^2_{min}>3.5GeV^2
- HERAPDF2.0 NLO vs NNLO
- HERAPDF2.0AG:
  Alternative Gluon PDF form (w/o negative term)
- HERAPDF2.0FF:
  Fixed Flavor schemes FF3A, FF3B (in addition to RTOPT, FONLL, ACOT)
- HERAPDF2.0Jets:
  Include also H1, ZEUS jet data & combined charm data

HERAPDF2.0 vs HERAPDF1.0

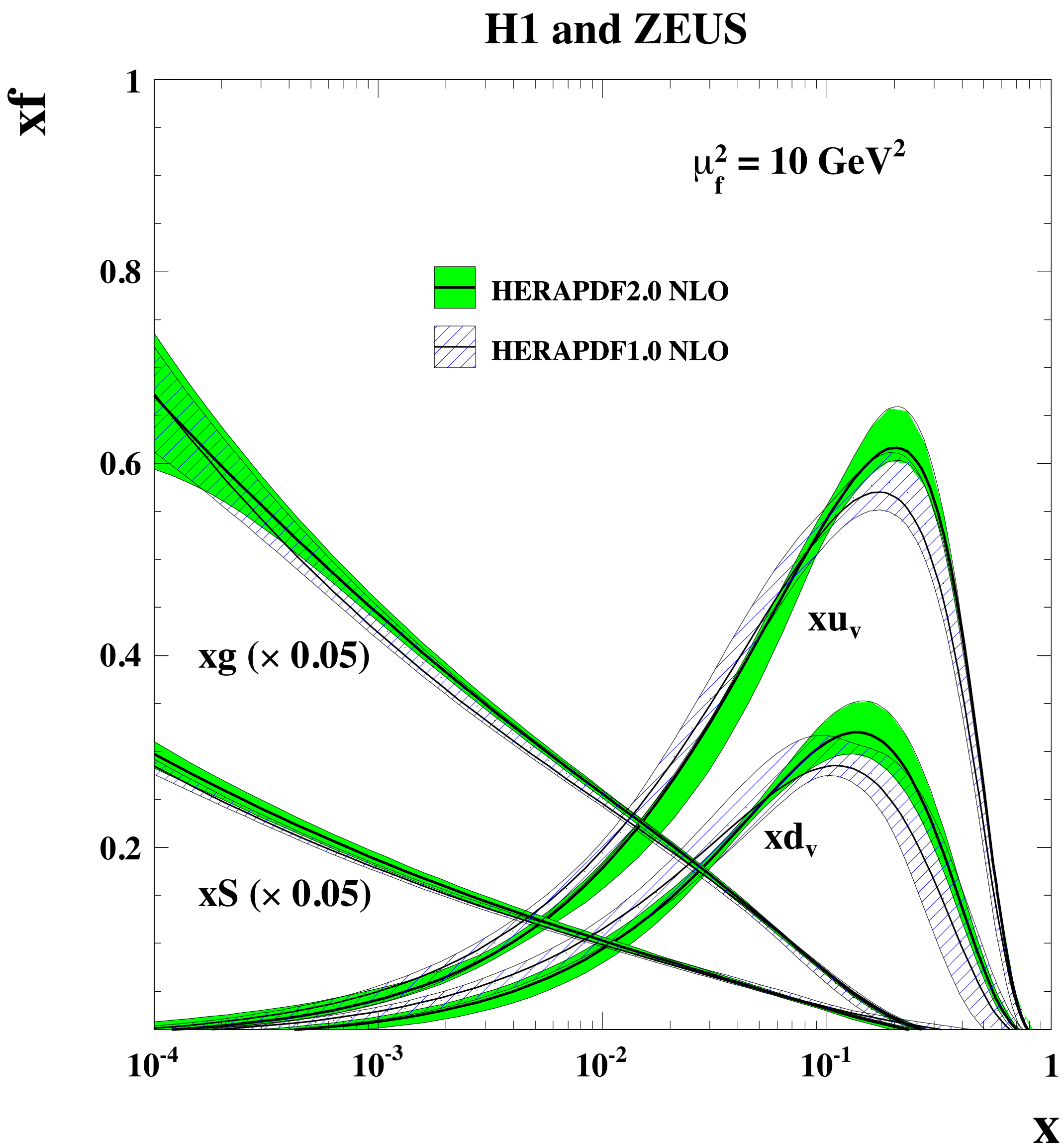




Predictions based on HERAPDF 1.0/2.0 describe well the data

Uncertainties of both data and PDFs have improved

HERAPDF2.0 vs HERAPDF1.0



Much more high-x data

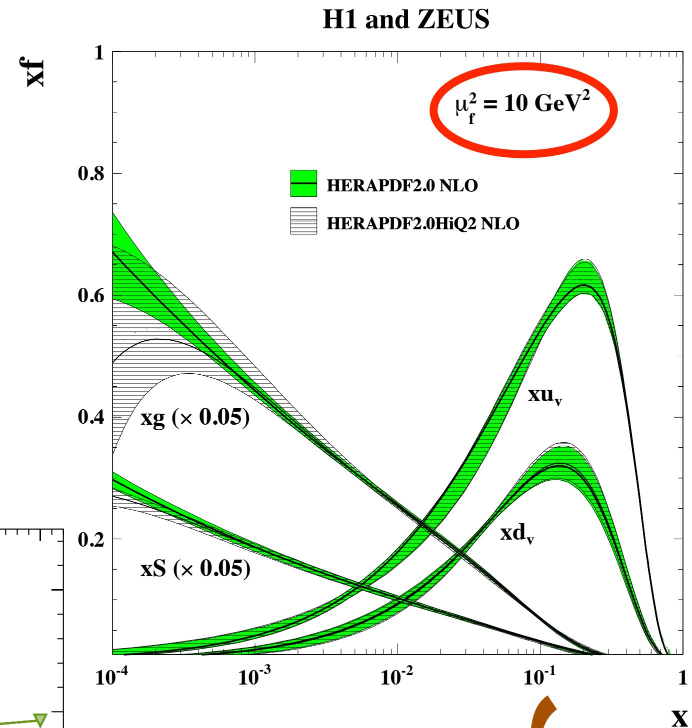
Substantially better precision at high-x

HERAPDF2.0 vs. HERAPDF2.0HiQ2

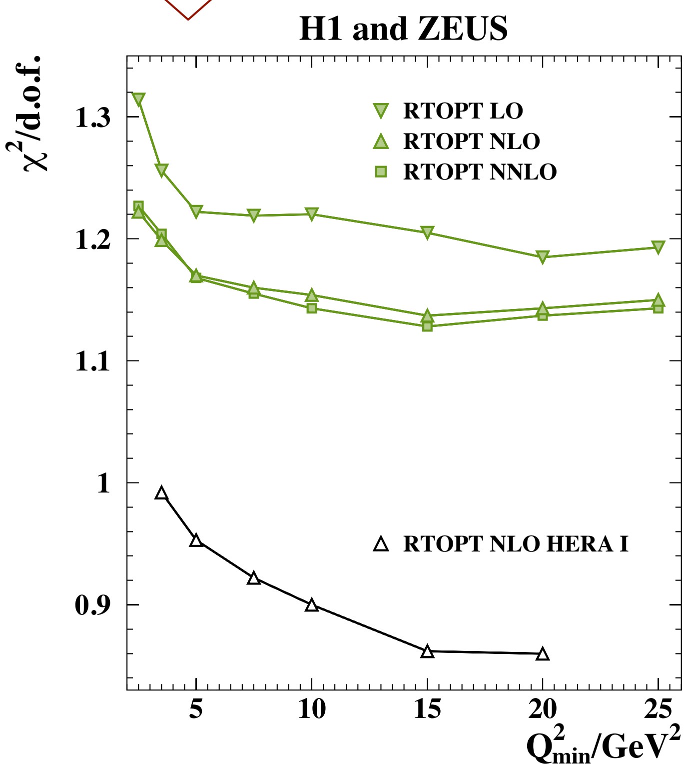
Improved χ^2 from 3.5 to ~10GeV^2

NLO better than LO

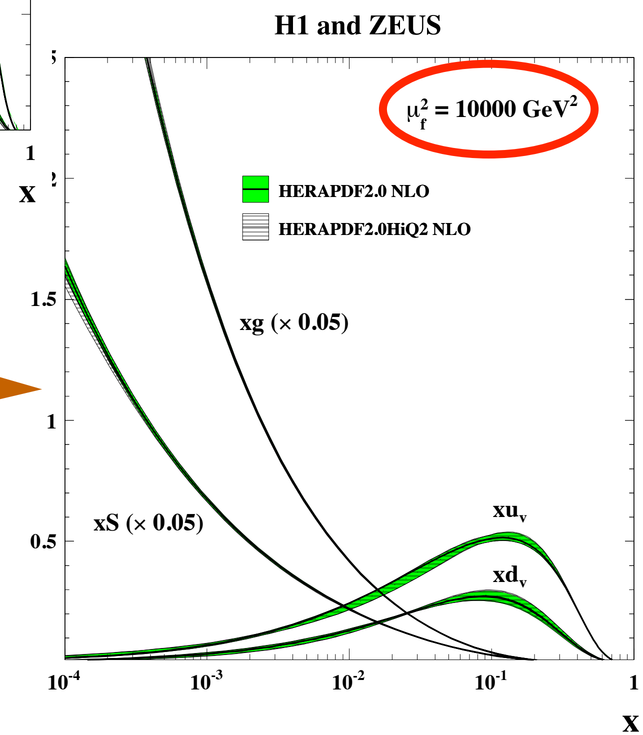
But NNLO~NLO



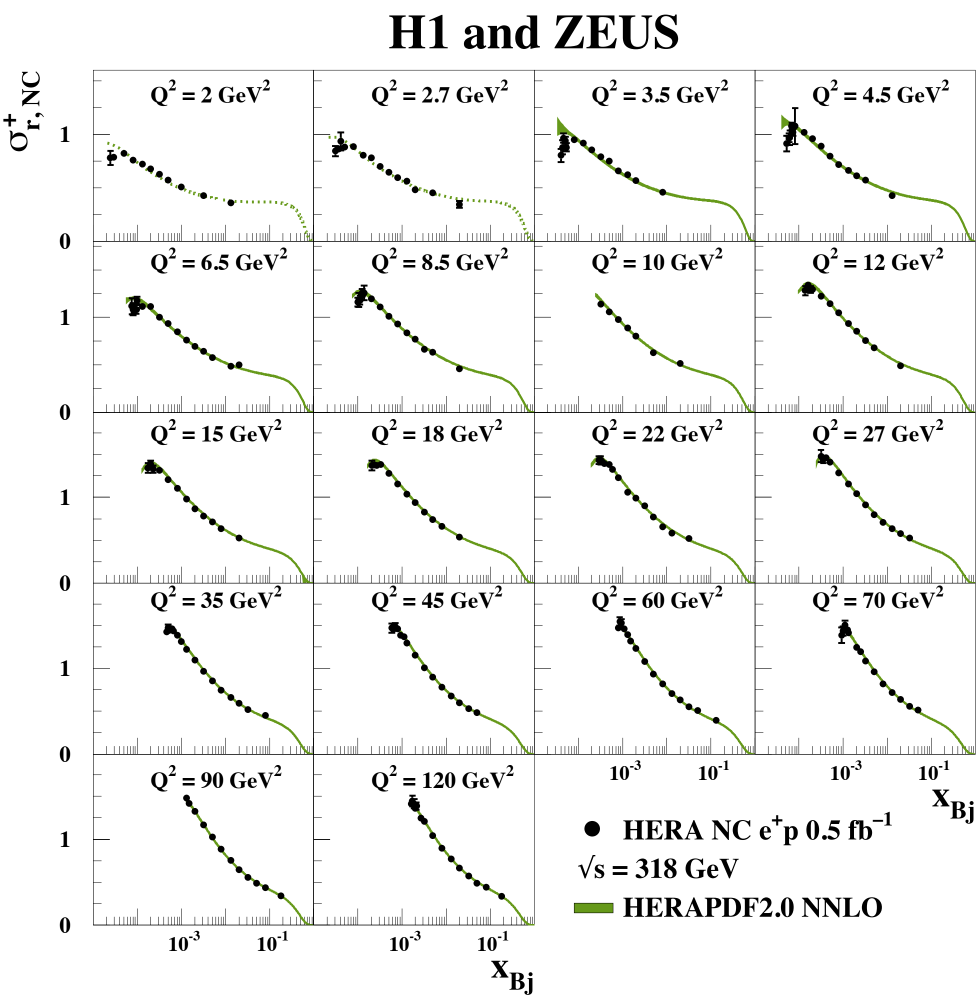
Without low Q^2 data, the gluon at low x is less constrained

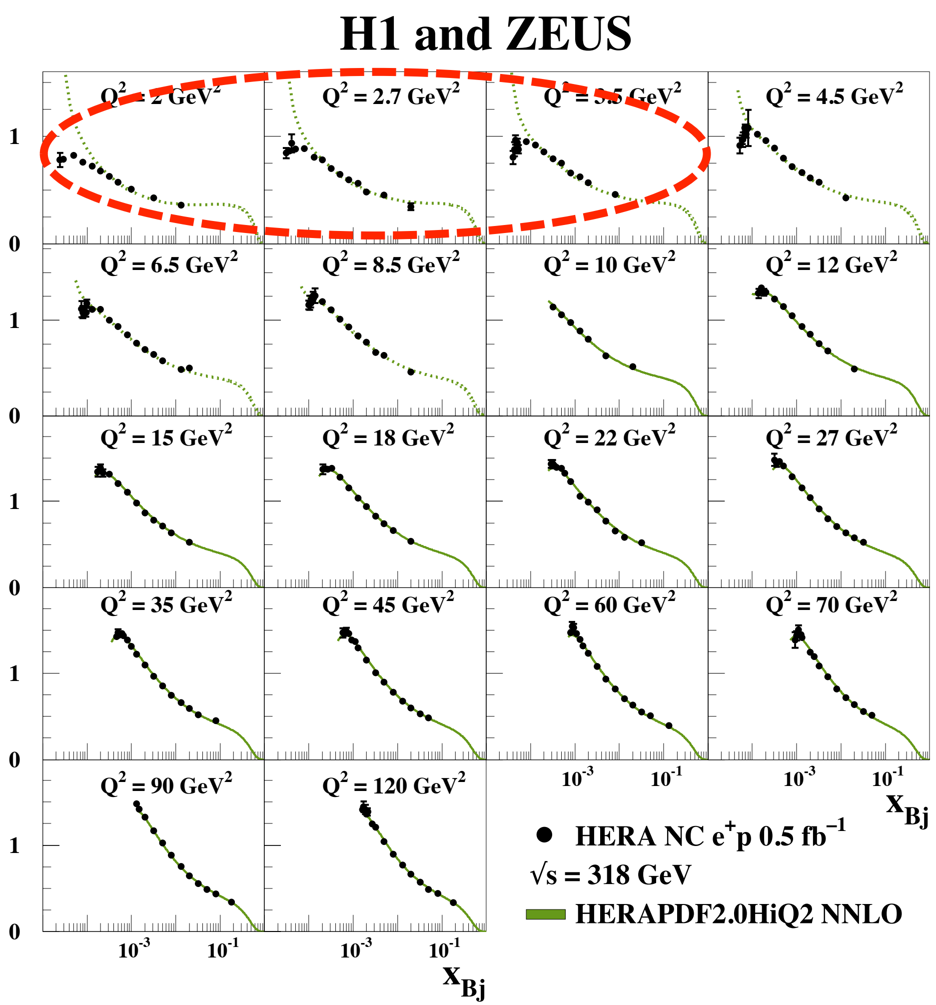


Uncertainties & difference shrink at large Q^2 (LHC kinematic region)



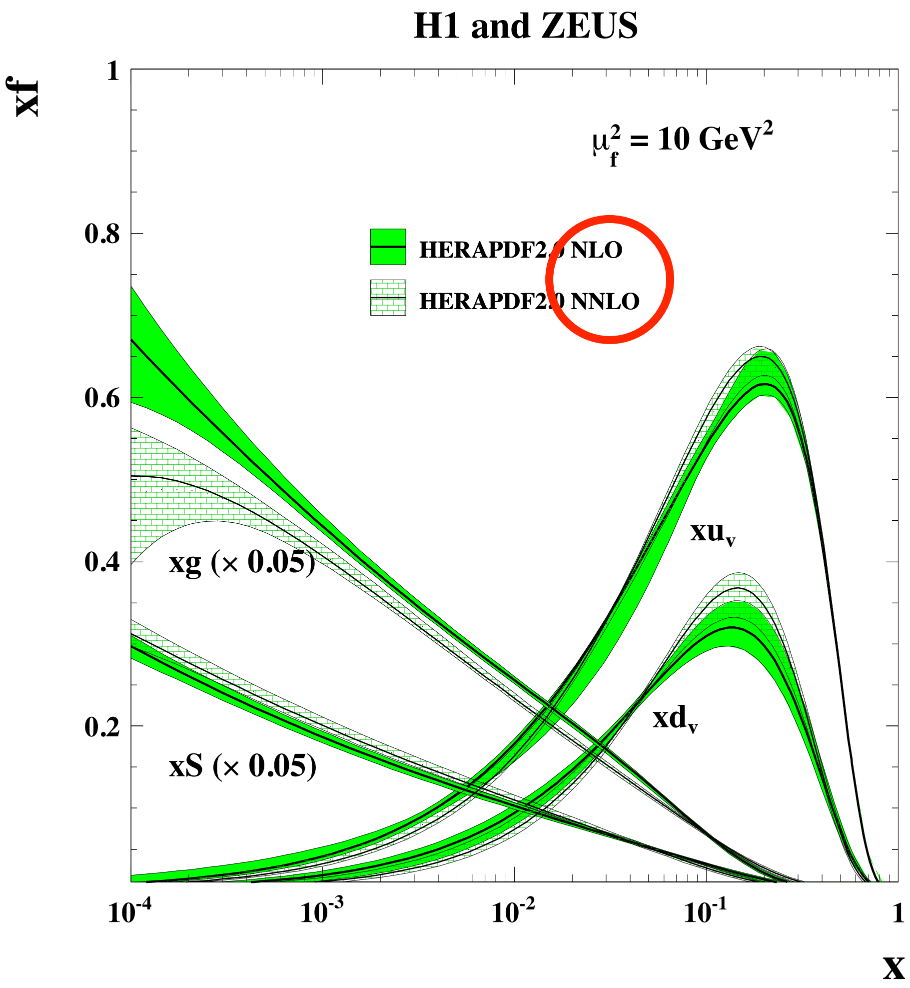
HERAPDF2.0 vs. HERAPDF2.0HiQ2

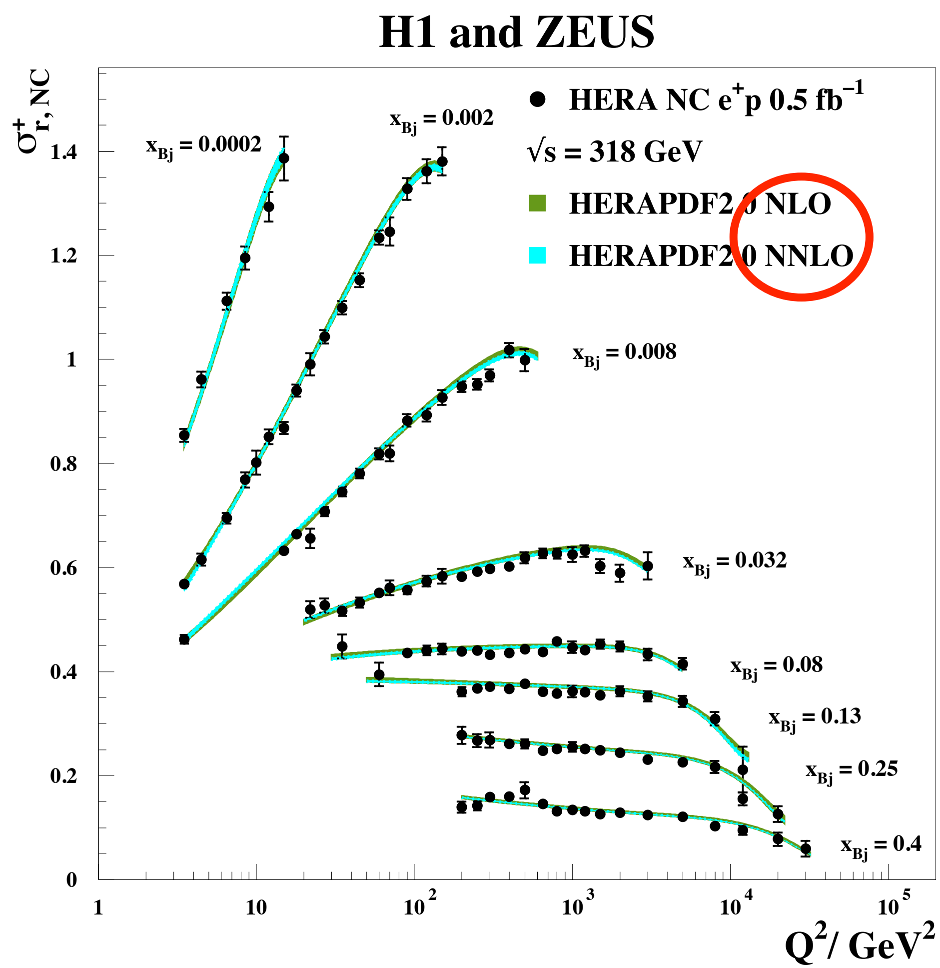




χ^2/n_{dof} improves from 1.2 to 1.15 for Q^2_{min}>10GeV² fit but the extrapolation to lower Q² does not describe the data

HERAPDF2.0 NLO vs NNLO

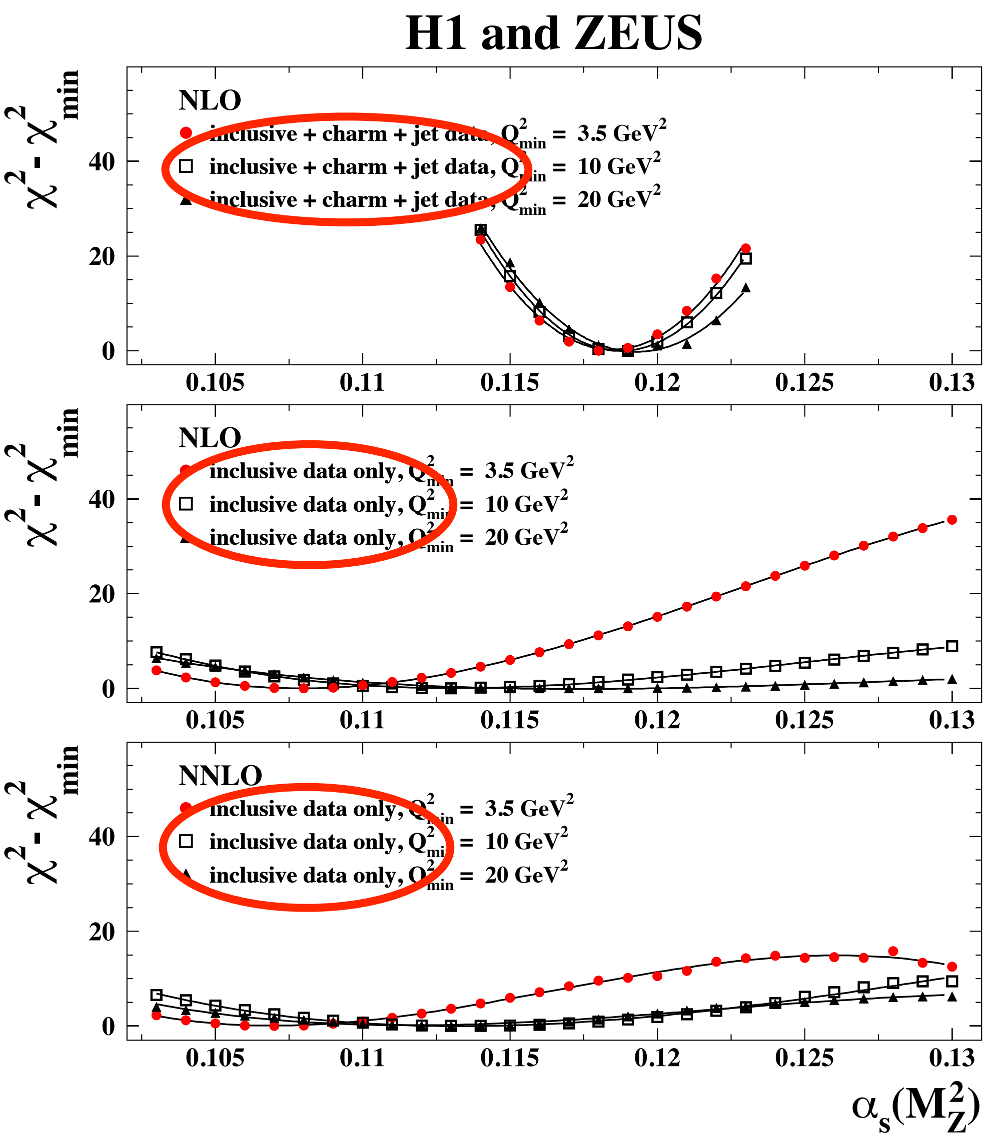




The main difference is on xg(x) due to different NLO/NNLO evolutions

Both NLO/NNLO predictions describe the data (selected sample for clarity)

HERAPDF2.0 vs. HERAPDF2.0Jets



Including jet (& charm) data provide additional constraint on gluon

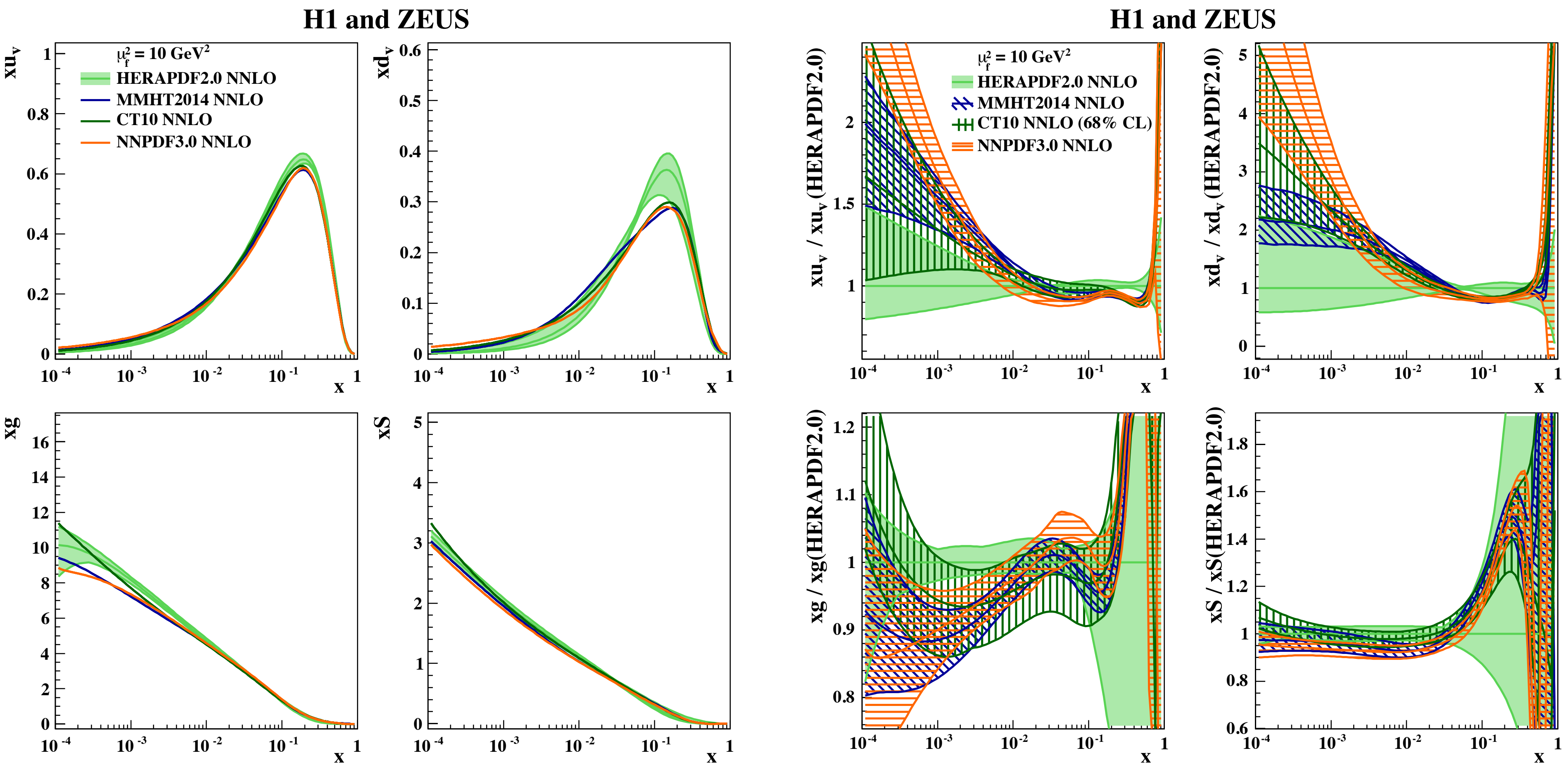
Inclusive + charm + jet
➔ A precise α_s determination

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009_{\text{exp}} \pm 0.0005_{\text{model/par.}} \pm 0.0012_{\text{had.}} \,{}^{+0.0037}_{-0.0030}\,{}_{\text{scale}}$$

The result agrees well with world average value

& is competitive w.r.t. other determinations

HERAPDF2.0 vs. Other PDFs



In general, good agreement within the uncertainty bands

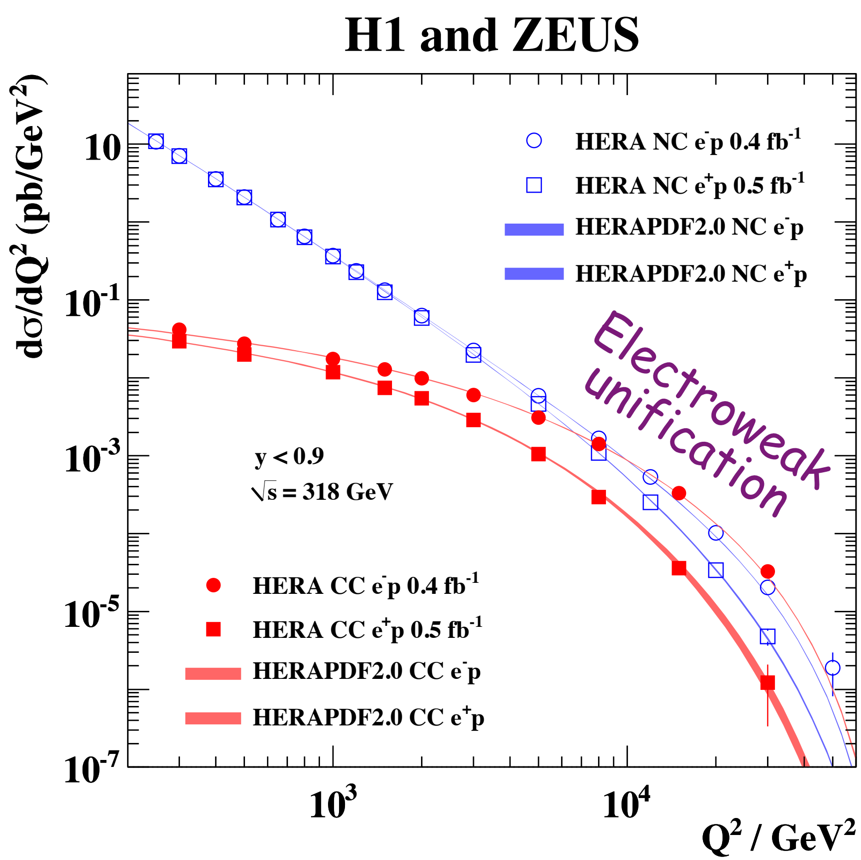
Valence quarks u and d are both harder at large x than the other PDFs

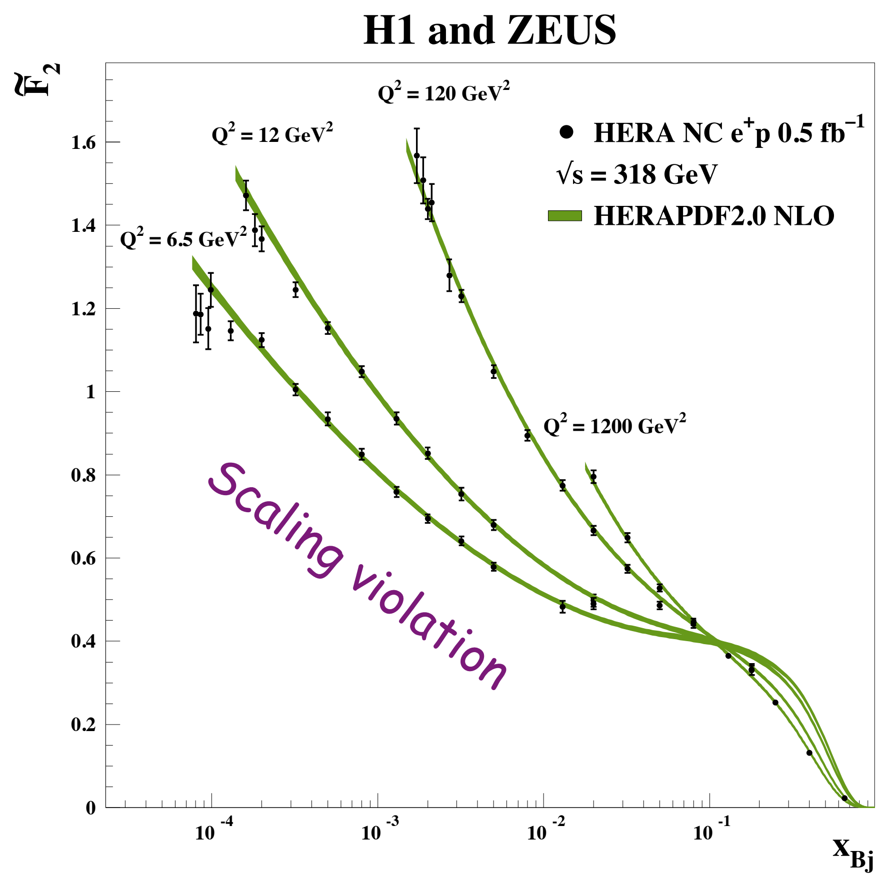
➔ Need more (LHC) data to constrain the low and high x

Summary

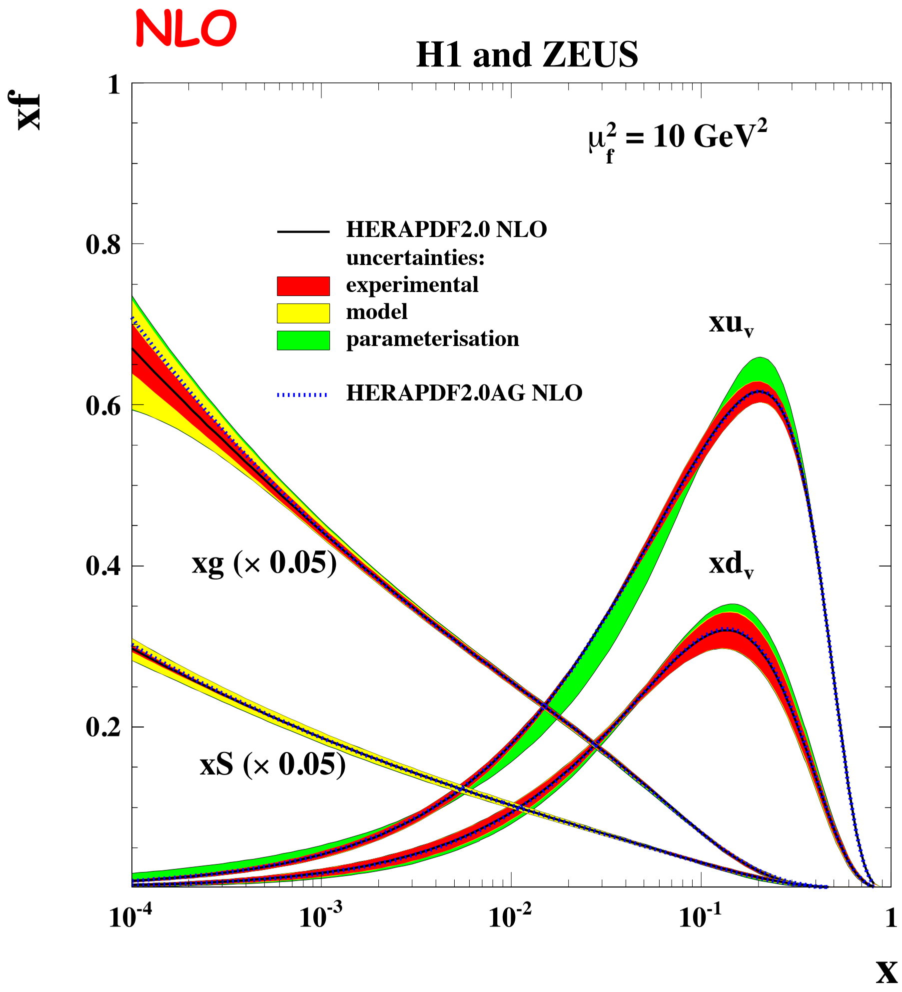
- Final combination of the inclusive NC and CC cross sections is ready
  the data cover wide kinematic range and show unprecedented precision
  → legacy of HERA

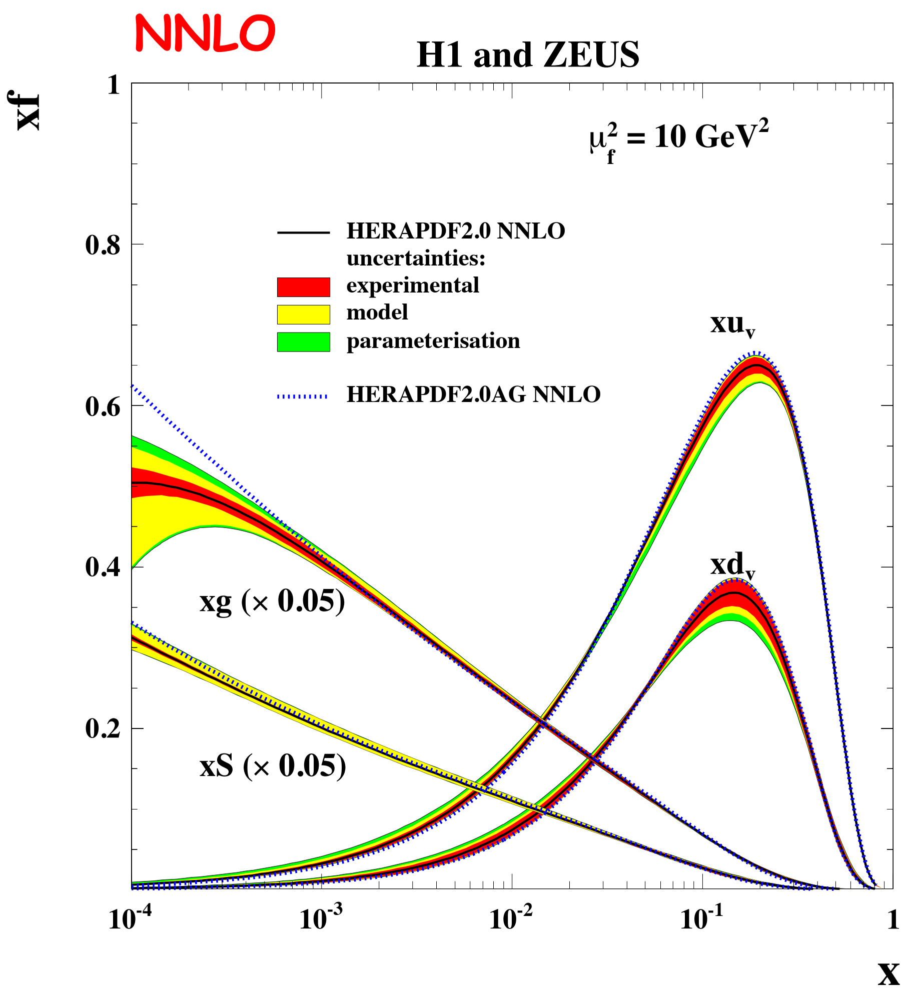
- New HERAPDF 2.0 provides improved PDF precision
  → Timely input for Run-II predictions @LHC





HERAPDF2.0 vs. HERAPDF2.0AG





HERAPDF2.0 vs. HERAPDF2.0FF

FF3A:
- 3 flavor running of α_s
- F_L at $O(\alpha^2_s)$
- Pole masses: m_c^{pole}, m_b^{pole}

FF3B:
- variable flavor running of α_s
- F_L at $O(\alpha_s)$
- MSbar masses: $m_c(m_c)$, $m_b(m_b)$