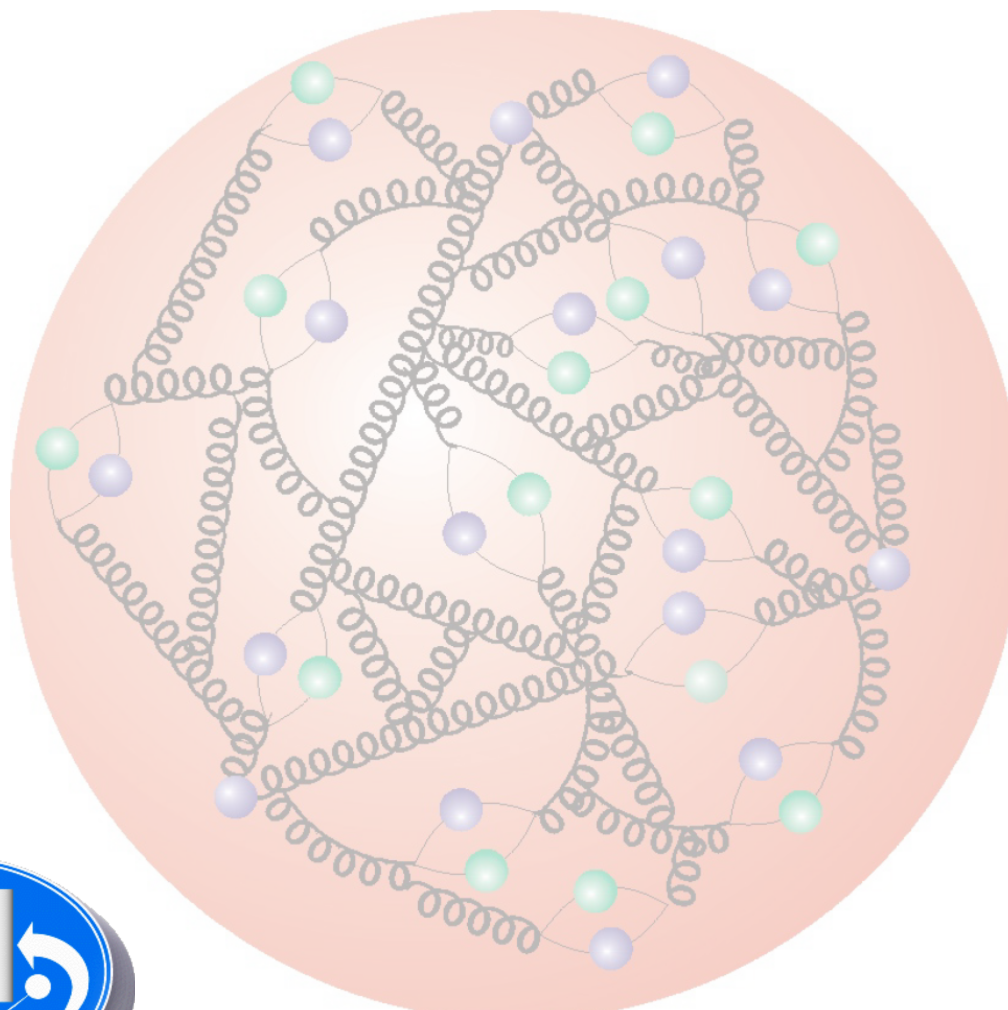
Proton Structure Measurements from HERA



- Deep Inelastic Scattering
- H1 , ZEUS & HERA ep Collider
- Data Combination
- QCD Analyses & HERAPDF2.0
- Conclusions

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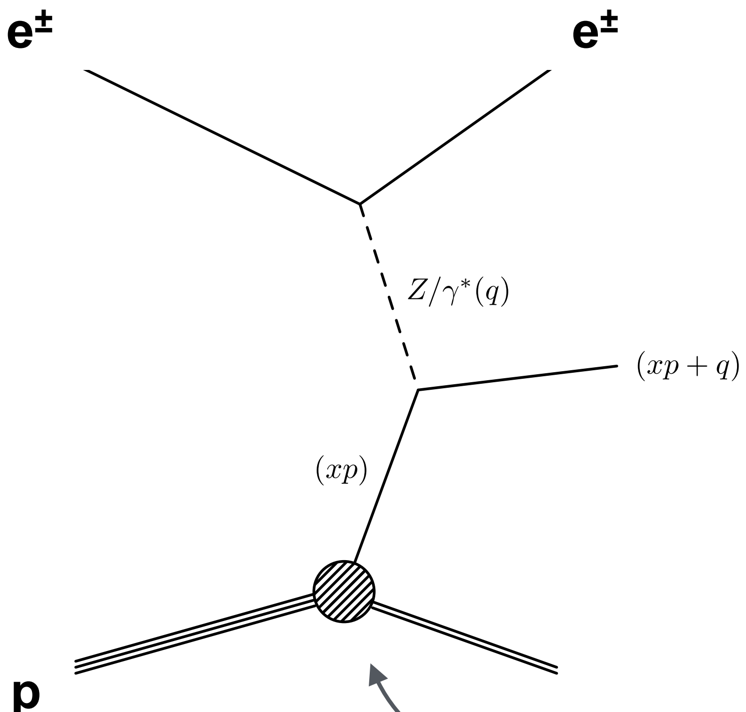
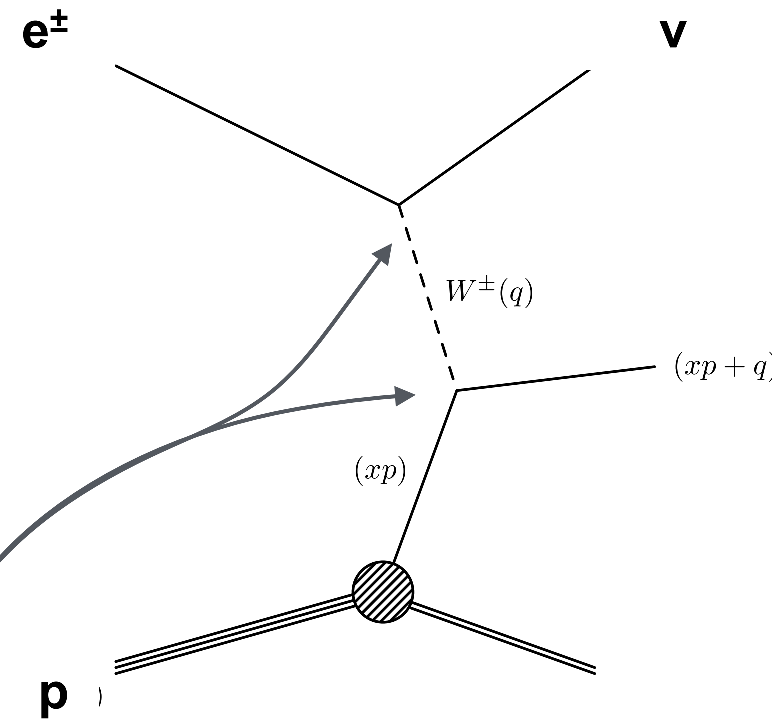
Neutral current scattering



Charged current scattering



Factorisation in ep collisions: $\sigma_{ep\to eX} = f_{p\to i} \otimes \hat{\sigma}_{ei\to eX}$

$xf_{p\to i}$ = quark / gluon momentum density in proton: parton density function (PDFs)

Use factorisation in pp collisions at LHC: $\sigma_{pp\to X} = f_{p\to i} \otimes \hat{\sigma}_{i,j\to X} \otimes f_{p\to j}$

Signature
Isolated electron/positron
pT balanced with hadronic system X

Signature
No detected lepton (neutrino)
pT imbalanced for hadronic system X

PDFs are not observables - only structure functions are
Measuring these cross sections allows indirect access to the universal PDFs $xf_{p\to i}$

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x} \left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{4\,\pi\,x} \left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \left[Y_+\,\tilde{W}_2^{\pm} \mp Y_-\,x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

$$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$$

Dominant contribution

$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

Only sensitive at high $Q^2 \sim M_Z^2$

$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$

Only sensitive at low Q^2 and high y

similarly for pure weak CC analogues:

$W_2^{\pm}$, $xW_3^{\pm}$ and $W_L^{\pm}$

The NC reduced cross section defined as:

$$\tilde{\sigma}^{\pm}_{NC} = \frac{Q^2 x}{2\alpha\pi^2}\frac{1}{Y_+}\frac{d^2\sigma^{\pm}}{dxdQ^2}$$

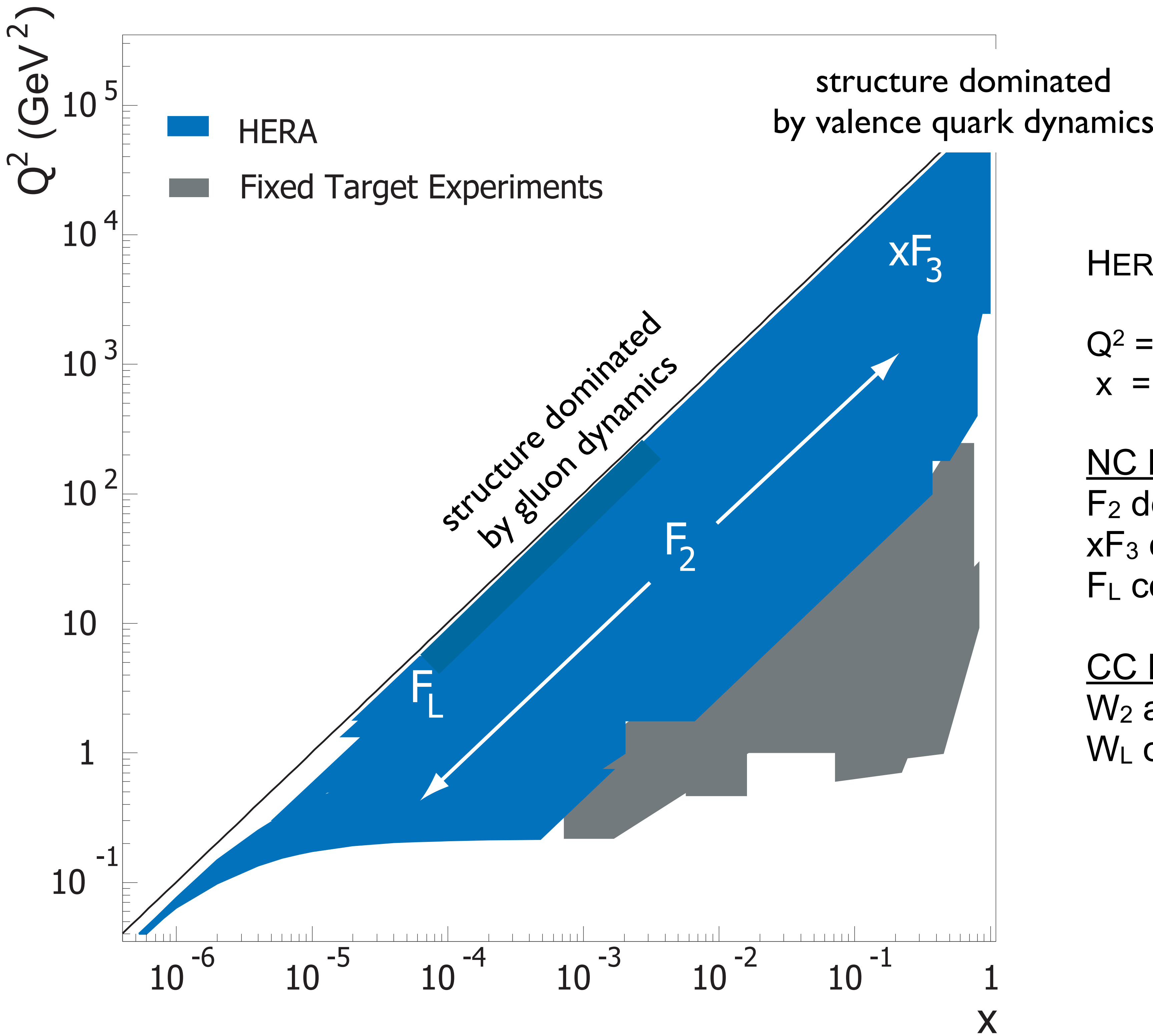
$$\tilde{\sigma}^{\pm}_{NC} \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

The CC reduced cross section defined as:

$$\sigma^{\pm}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{d\sigma^{\pm}_{CC}}{dxdQ^2}$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{1}{2}\left[Y_+\,W_2^{\pm} \mp Y_-\,xW_3^{\pm} - y^2W_L^{\pm}\right]$$

HERA Kinematic Plane



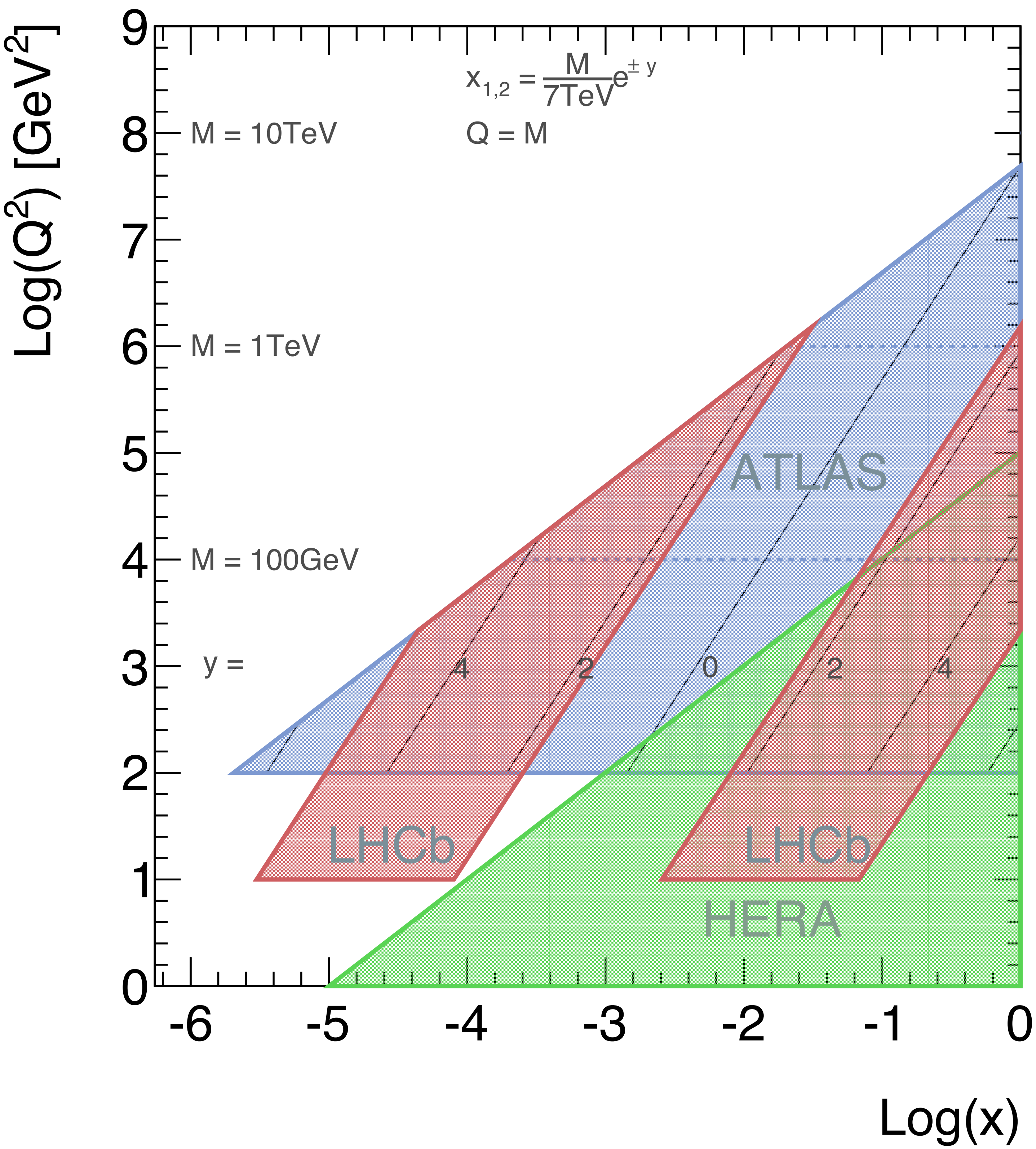
HERA data cover wide region of x, Q^2

Q^2 = boson virtuality
x = fractional momentum of struck quark

<u>NC Measurements</u>
F_2 dominates most of Q^2 reach
xF_3 contributes in EW regime
F_L contributes only at highest y

<u>CC Measurements</u>
W_2 and xW_3 contribute equally
W_L only at high y

LHC Kinematic Plane (7 TeV)



LHC: largest mass states at large x

For central production $x=x_1=x_2$

$M=x\sqrt{s}$

i.e. M > 1 TeV probes x>0.1

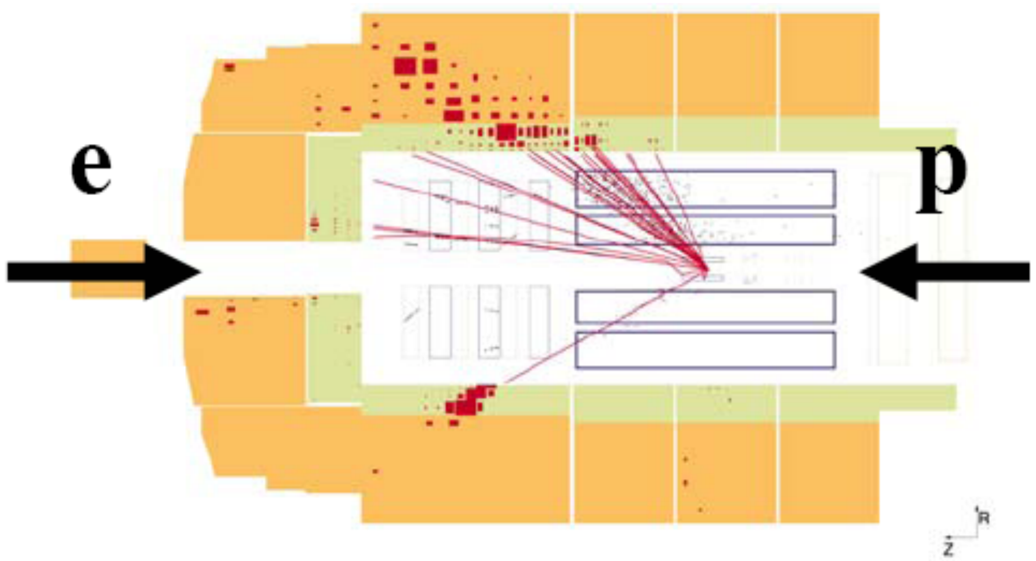
Searches for high mass states require precision knowledge at high x

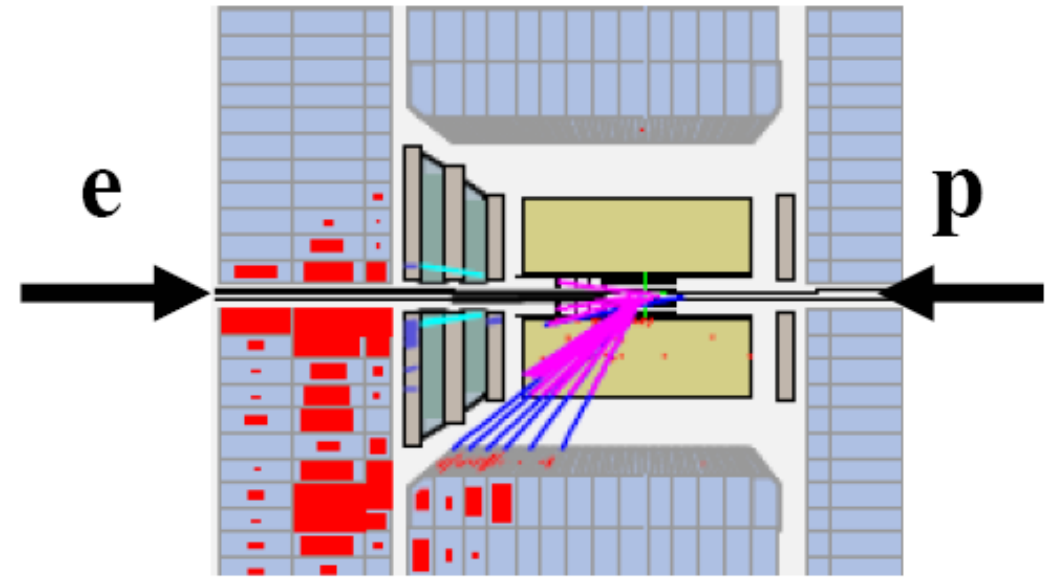
Z′ / quantum gravity / susy searches...

DGLAP evolution allows predictions to be made

High x predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as $x\rightarrow 1$





Neutral current event selection:

High P_T isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways:
energy/angle of hadrons & scattered lepton
provides excellent tools for sys cross checks

Removal of scattered lepton provides a
high stats “pseudo-charged current sample”
Excellent tool to cross check CC analysis

Final selection: ~10^5 events per sample at high Q^2
~10^7 events for $10 < Q^2 < 100$ GeV^2

Charged current event selection:

Large missing transverse momentum (neutrino)

Suppress huge photo-production background

Topological finders to remove cosmic muons

Kinematics reconstructed from hadrons

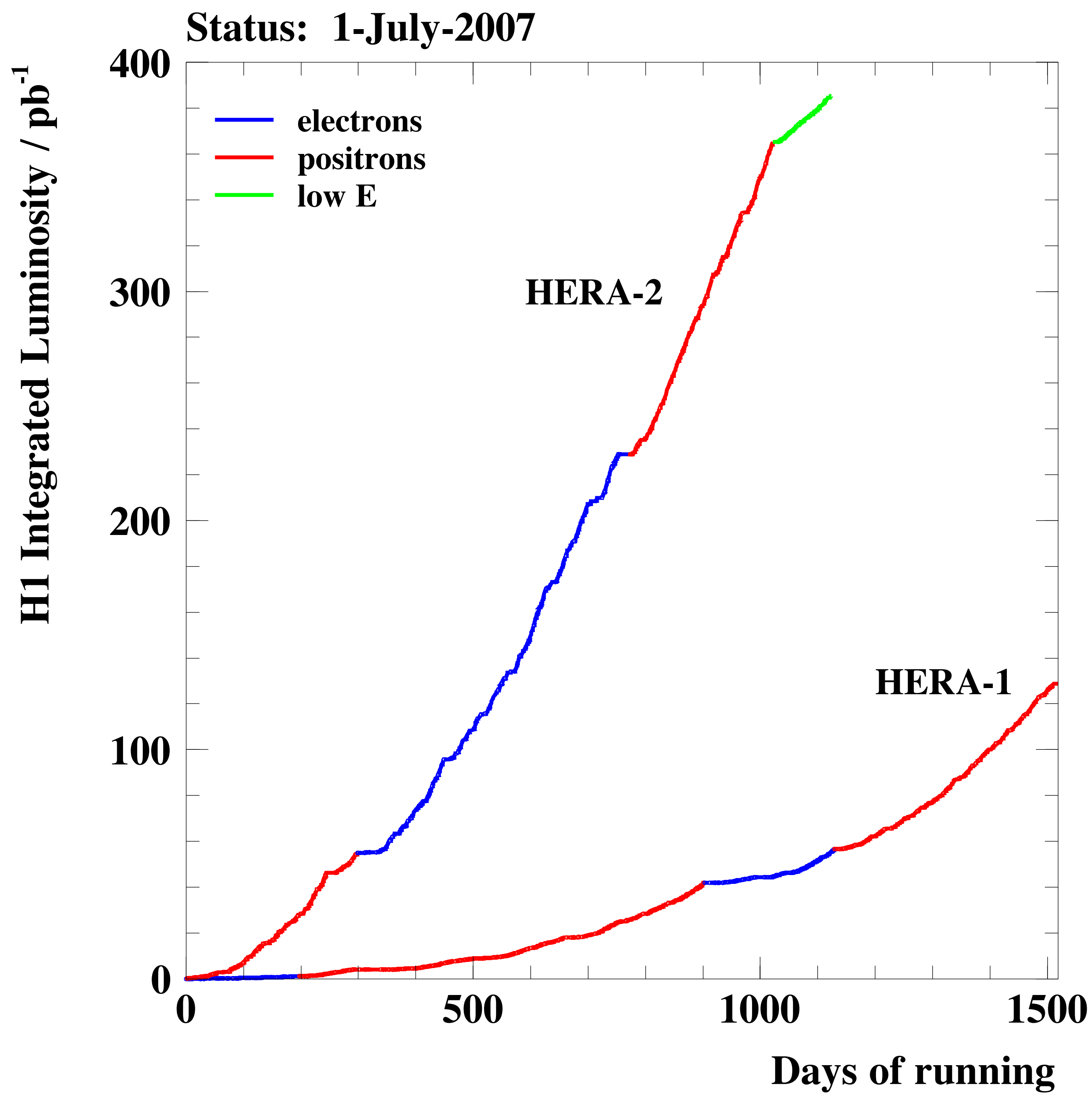
Final selection: ~10^3 events per sample

HERA Operation

<u>HERA-I operation 1993-2000</u>
Ee = 27.6 GeV
Ep = 820 / 920 GeV
$\sqrt{s}$=301 GeV & $\sqrt{s}$=318 GeV
$\int\mathcal{L}$ ~ 110 pb^{-1} per experiment

<u>HERA-II operation 2003-2007</u>
Ee = 27.6 GeV
Ep = 920 GeV
$\sqrt{s}$=318 GeV
$\int\mathcal{L}$ ~ 330 pb^{-1} per experiment
Longitudinally polarised leptons

<u>Low Energy Run 2007</u>
Ee = 27.6 GeV
Ep = 575 & 460 GeV
$\sqrt{s}$=225 GeV & $\sqrt{s}$=251 GeV
Dedicated F_L measurement



Summary of HERA-I datasets
Combined in HERAPDF1.0

Available since 2009

Data Set		x Range		Q^2 Range GeV^2		$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	e^+p	301-319
H1 low Q^2	96-00	2×10^{-4}	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	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	e^+p	301
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	e^+p	301
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	e^+p	301
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	e^+p	301
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	301
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	319
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	319
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	319
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	319

High Q^2 NC and CC data limited to
100 pb^{-1} e^+p
16 pb^{-1} e^-p

HERA Structure Function Data

Up till now HERA-II datasets only partially published

ZEUS CC e^-p	175 pb^{-1}	EPJ C 61 (2009)
ZEUS CC e^+p	132 pb^{-1}	EPJ C 70 (2010)
ZEUS NC e^-p	170 pb^{-1}	EPJ C 62 (2009)
ZEUS NC e^+p	135 pb^{-1}	ZEUS-prel-11-003
H1 CC e^-p	149 pb^{-1}	H1prelim-09-043
H1 CC e^+p	180 pb^{-1}	H1prelim-09-043
H1 NC e^-p	149 pb^{-1}	H1prelim-09-042
H1 NC e^+p	180 pb^{-1}	H1prelim-09-042

HERA-II datasets
Combined in HERAPDF1.5
(except ZEUS NC e^+p)

breakdown of HERA-II data samples

	R	L
e^-p	$\mathcal{L} = 47.3\,\mathrm{pb}^{-1}$ $P_e = (+36.0 \pm 1.0)\%$	$\mathcal{L} = 104.4\,\mathrm{pb}^{-1}$ $P_e = (-25.8 \pm 0.7)\%$
e^+p	$\mathcal{L} = 101.3\,\mathrm{pb}^{-1}$ $P_e = (+32.5 \pm 0.7)\%$	$\mathcal{L} = 80.7\,\mathrm{pb}^{-1}$ $P_e = (-37.0 \pm 0.7)\%$

ZEUS CC e^-p	175 pb^{-1}	EPJ C 61 (2009)
ZEUS CC e^+p	132 pb^{-1}	EPJ C 70 (2010)
ZEUS NC e^-p	170 pb^{-1}	EPJ C 62 (2009)
ZEUS NC e^+p	135 pb^{-1}	PRD 87 (2013) 052014
H1 CC e^-p	149 pb^{-1}	JHEP 09 (2012) 061
H1 CC e^+p	180 pb^{-1}	
H1 NC e^-p	149 pb^{-1}	
H1 NC e^+p	180 pb^{-1}	

Complete the analyses of HERA high Q^2 inclusive structure function data

New published data increase $\int\mathcal{L}$ by
~ factor 3 for e^+p
~ factor 10 for e^-p
much improved systematic uncertainties

→ HERAPDF2.0

HERA Structure Function Data

Data Set		x Grid from	to	Q^2/GeV^2 Grid from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x,Q^2 from equations	Ref.
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	11,15,16	[2]
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319	11,15,16	[3]
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	17	[4]
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	12	[4]
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	17	[5]
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	12	[5]
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	11	[6]
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319	17	[6]
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	12	[6]
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300	11	[10]
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300	11, 17	[11]
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300	11	[12]
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300	19	[13]
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300	12	[14]
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318	18	[15]
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318	12	[16]
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318	18	[17]
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318	12	[18]
HERA II E_p = 920 GeV data sets										
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319	11, 17	[7][1]
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319	12	[7][1]
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319	11, 17	[7][1]
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319	12	[7][1]
H1 NC med Q^2 *y.5	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319	11	[9]
H1 NC low Q^2 *y.5	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319	11	[9]
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318	11,12,18	[21]
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318	12	[22]
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318	18	[19]
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318	12	[20]
ZEUS NC nominal *y	06-07	0.000092	0.008343	7	110	44.5	e^+p	318	11	[23]
ZEUS NC satellite *y	06-07	0.000071	0.008343	5	110	44.5	e^+p	318	11	[23]
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	11, 17	[8]
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252	11	[9]
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251	11	[23]
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251	11	[23]
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	11, 17	[8]
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225	11	[9]
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225	11	[23]
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225	11	[23]

H1 & ZEUS have now published all datasets

- HERA-II measurements at high $\int\mathcal{L}$
- reduced $\sqrt{s}$ data

41 data sets to be combined:

- NC & CC cross sections
- e^+p and e^-p scattering
- 4 different $\sqrt{s}$ values

2927 data points in total → 1307

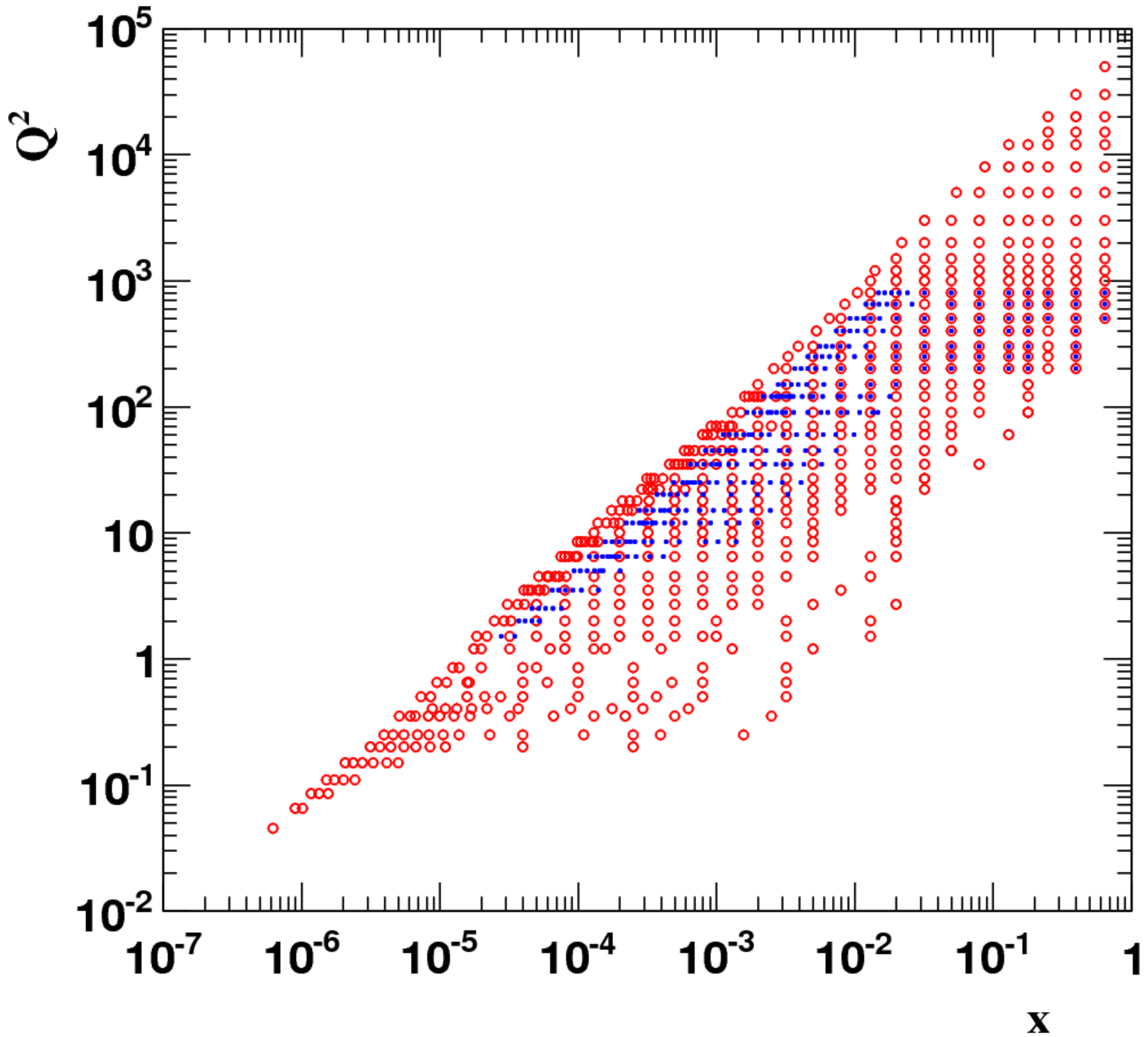
In some cases 6 measurements combined

$0.045 < Q^2 < 50{,}000$ GeV^2

$6\times10^{-7} < x < 0.65$

arXiv:1506.06042

H1 & ZEUS Data Combination

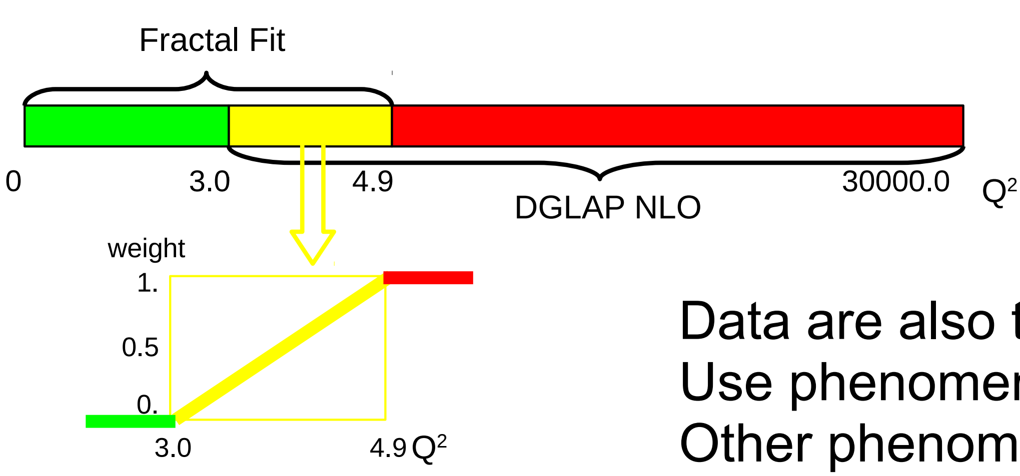


Data are combined onto a common x,Q^2 grid
Two grids used:
- inclusive measurements √s=318 GeV
- fine x grid for √s=251 & 225 GeV

2927 data points → 1307 combined measurements

Data are translated to nearest x,Q^2 grid point
Iterative process using NLO QCD fit to data
Use uncombined data in first iteration
Then combined data in later iterations
No changes after 3 iterations

$$\sigma(x_{grid}, Q^2_{grid}) = \frac{\sigma_{model}(x_{grid}, Q^2_{grid})}{\sigma_{model}(x_{meas}, Q^2_{meas})} \cdot \sigma_{meas}(x_{meas}, Q^2_{meas})$$



Data are also translated outside of region of DGLAP fit validity $Q^2 < 3.0$ GeV^2
Use phenomenological "fractal" model and interpolate to DGLAP region
Other phenomenological fits tested → negligible differences

i data points
j systematic error sources

Correlated uncertainties treated multiplicative: size proportional to central averaged value
True for normalisation uncertainties
Perhaps not true for other uncertainties

$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1-\sum_j \gamma^i_j b_j)]^2}{\delta^2_{i,stat}\mu^i m^i(1-\sum_j \gamma^i_j b_j) + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2$$

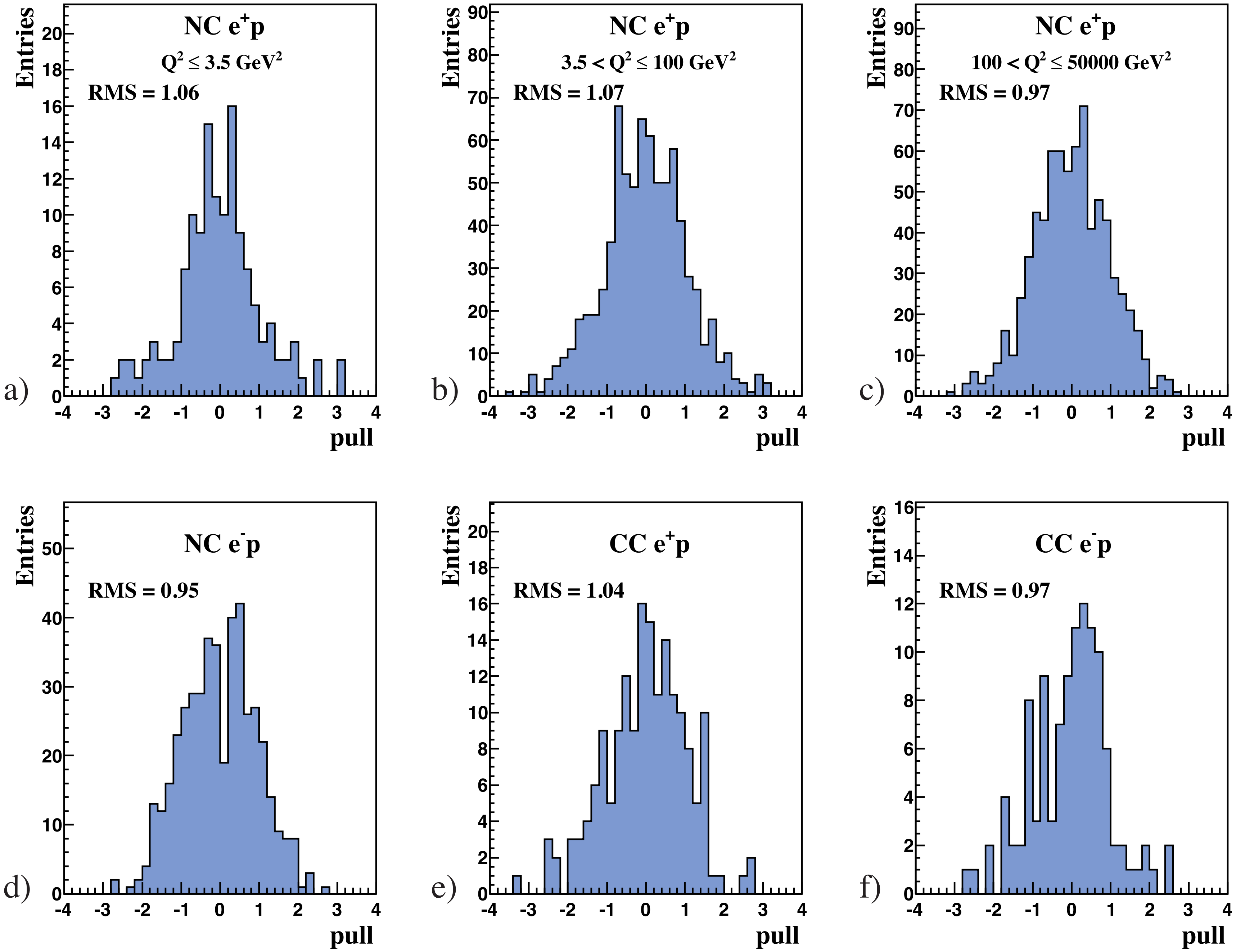
μ^i = measurement
m^i = averaged value
γ^i_j = correlated relative (%) sys uncertainty on point i from error source j
b_j = systematic error source strength
nuisance parameter left free in fit but constrained
no extra degrees of freedom due to additional constraint

For HERAPDF2.0 number of correlated error sources j = 169
These include:
- b/g uncertainty
- luminosity uncertainty
- EM calibration scale
- had calibration scale
- etc.…

Are correlated point-to-point within a single measurement
Reported in detail in individual publications from experiments
May also be correlated across measurements
May also be correlated between H1 & ZEUS (e.g. had scale & photo-production b/g)

Extra procedural uncertainty included:
difference between using
additive vs multiplicative
correlated uncertainties (except normalisation)
⇒ extra ~0.5% uncertainty

H1 & ZEUS Data Combination



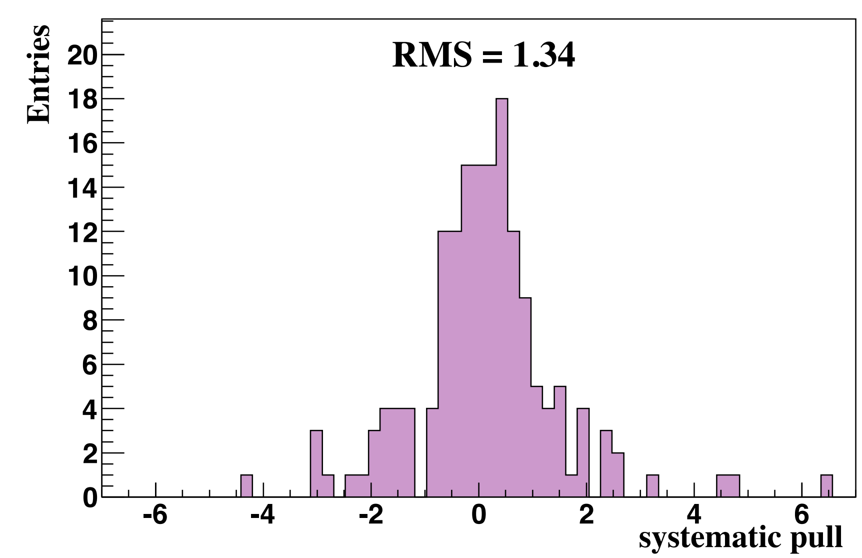
Overall χ^2/ndf = 1685 / 1620 = 1.04

Pulls defined for each measurement difference between measured & average values after applying sys shifts b_j in units of uncorrelated uncertainty

Pulls of the data points should be distributed as a unit Gaussian

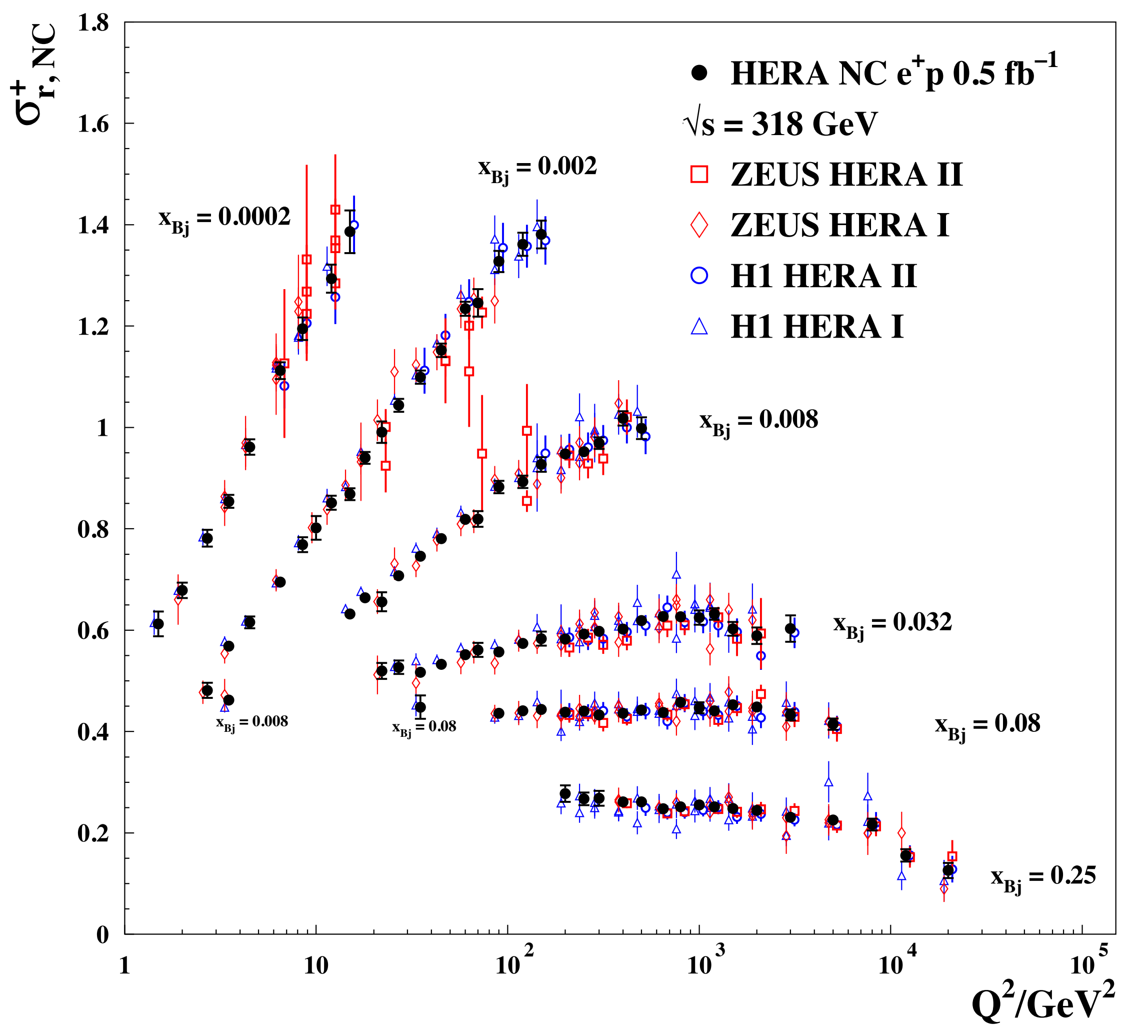
Each measurement channel shows pull centred on zero & unit width

pulls of the systematic sources b_j

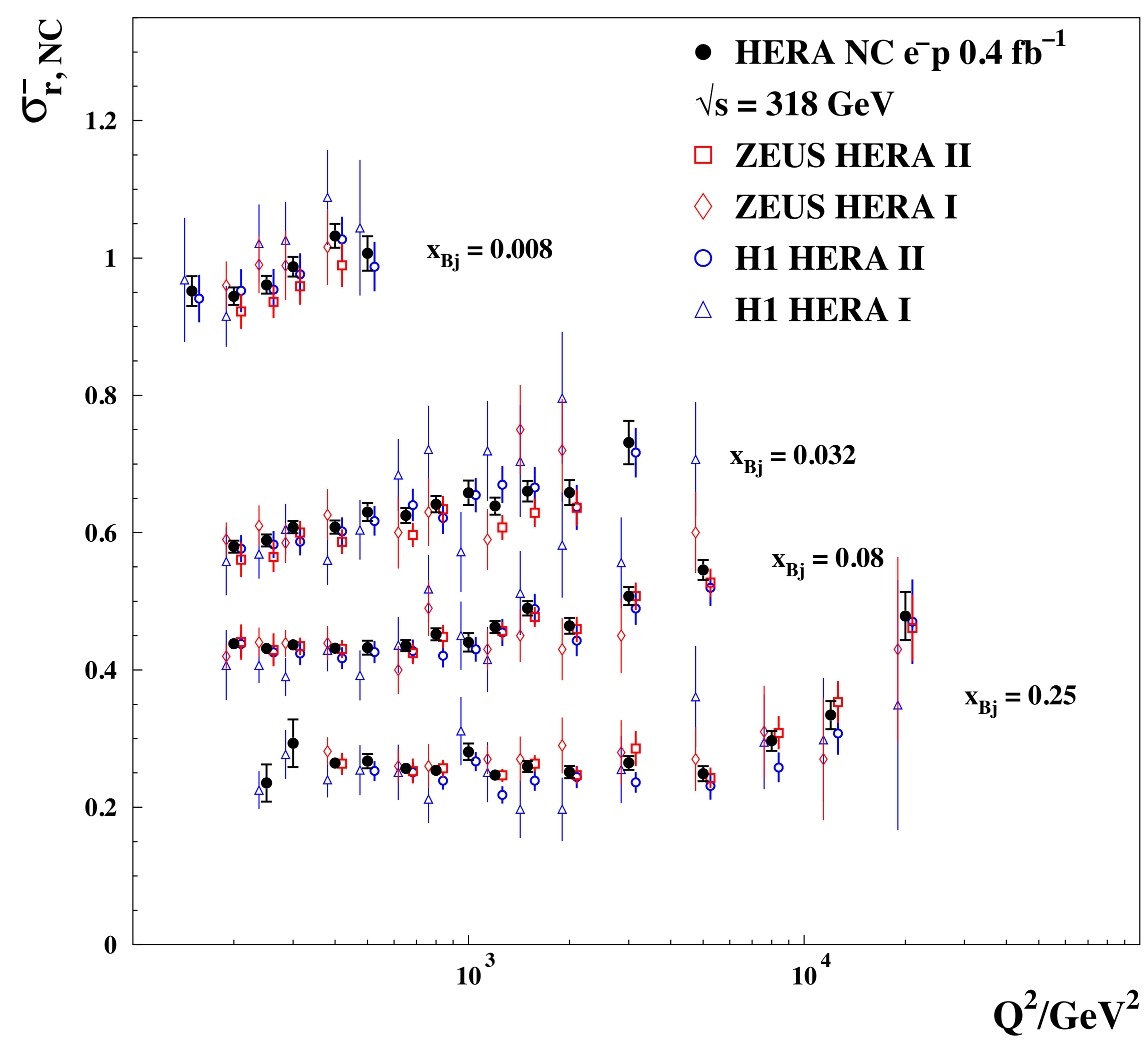


Combined NC Cross Sections

e⁺p



e⁻p

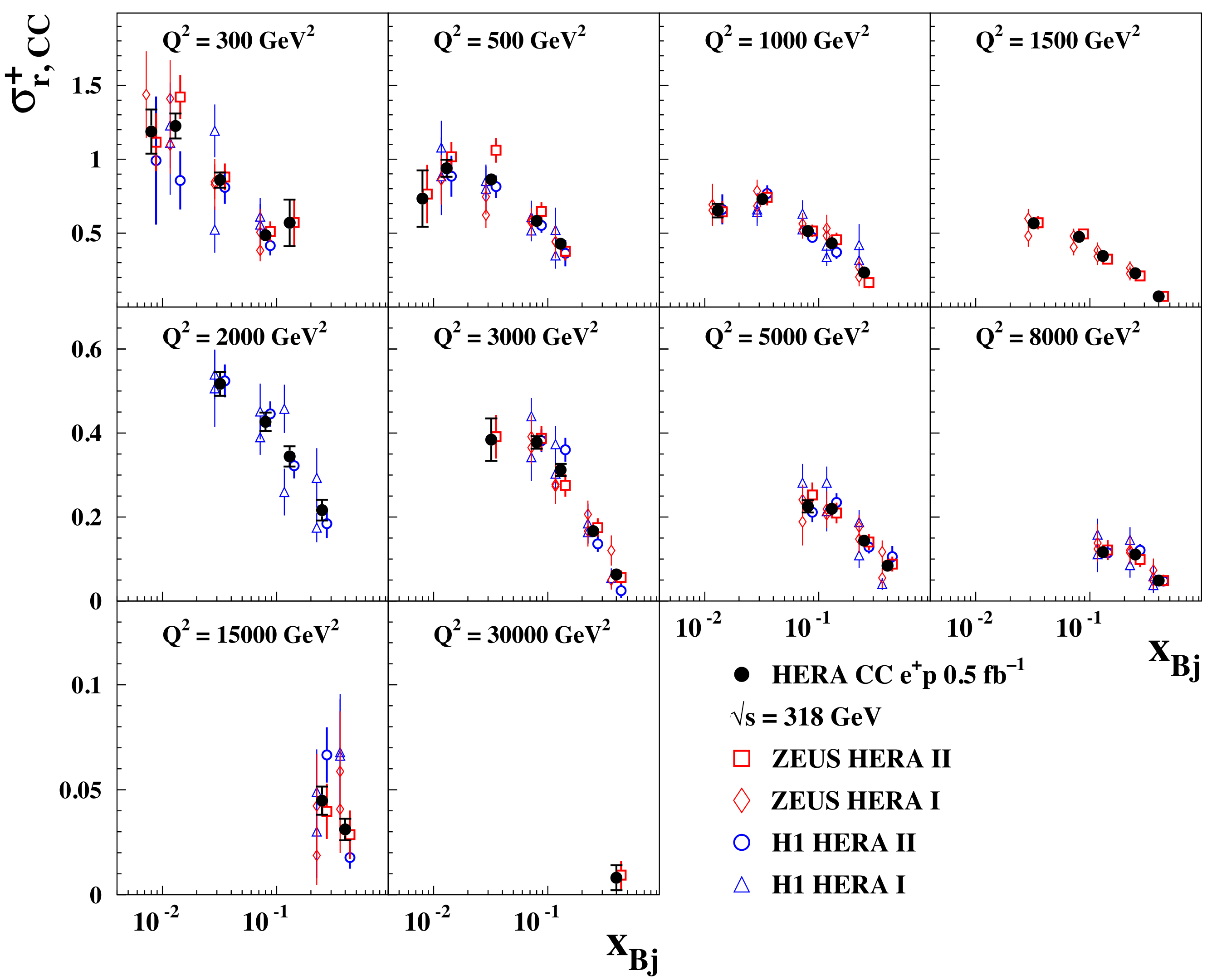


only 6 x bins shown here
factor 10 more data than HERA-I data sets
NC e⁺p data systematically limited

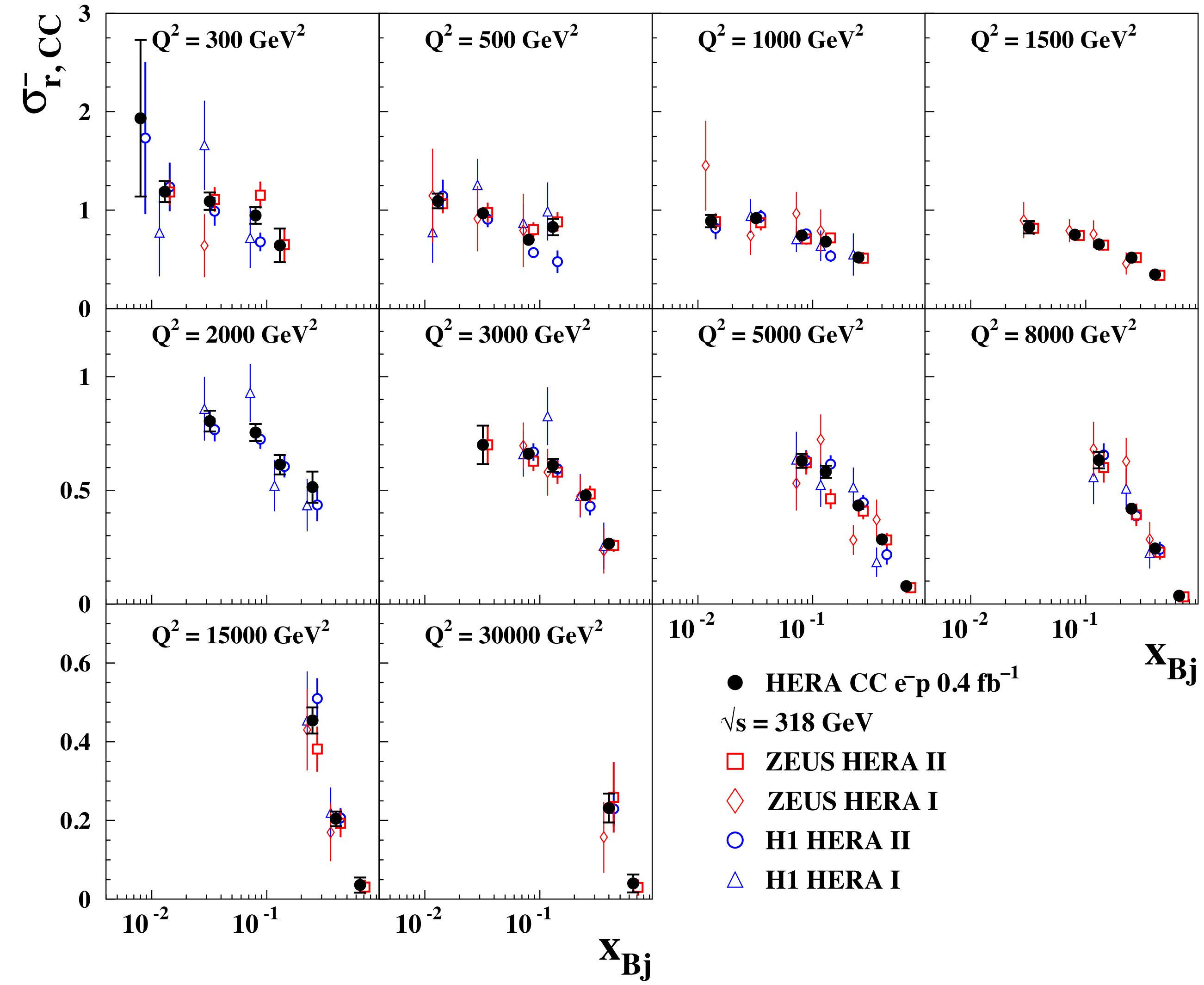
χ^2 / ndf = 1687 / 1620
high precision reached over large kinematic range better than 1.3% $Q^2 < 400$ GeV^2

Combined CC Cross Sections

e+p



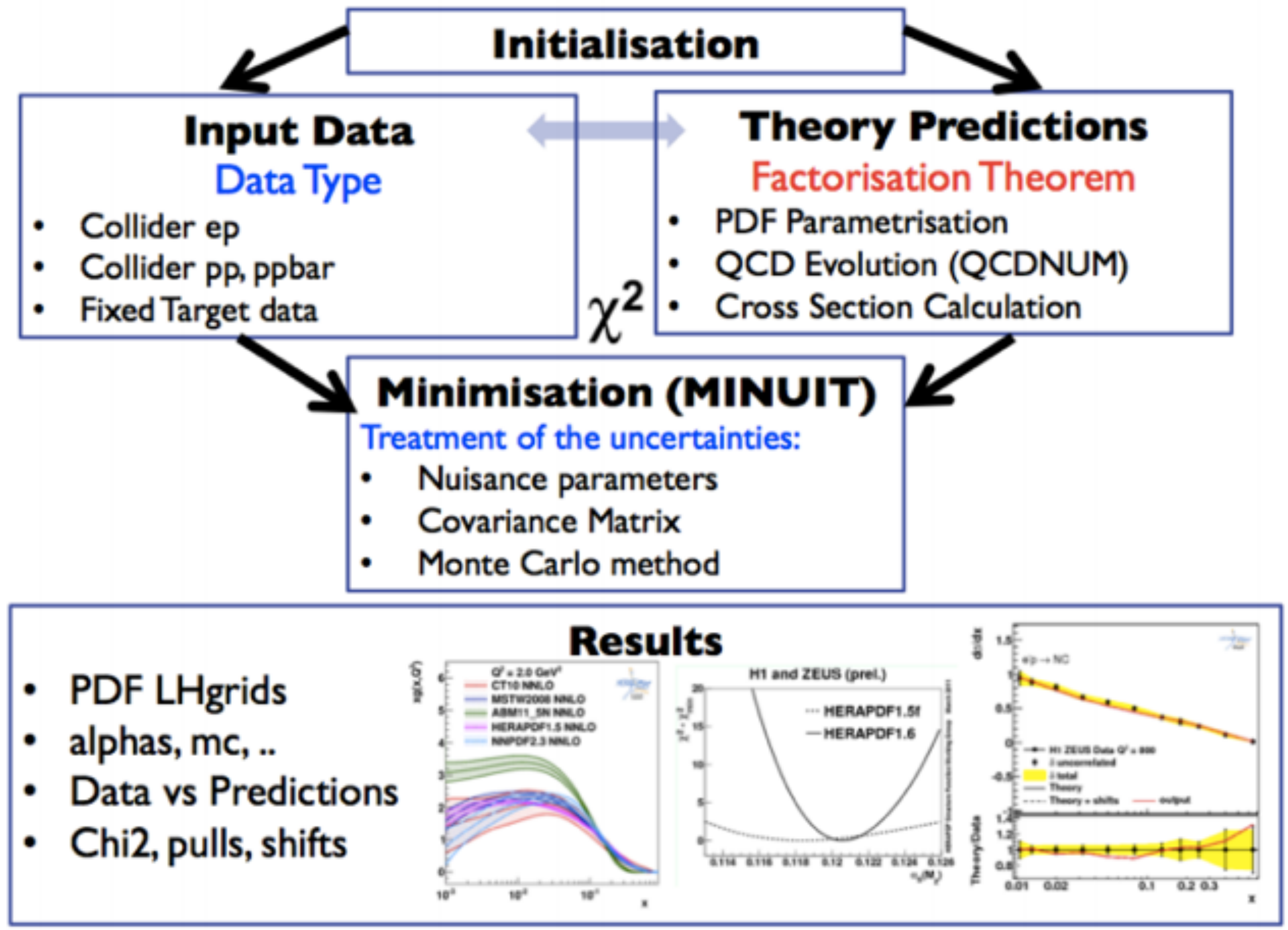
e−p



Large improvement in statistical limitations of individual data sets from H1 & ZEUS

PDF Extractions from Data

- Parameterise PDFs at arbitrary starting scale Q_0^2
- Perturbative QCD evolution equations allows PDFs to be determined at any other scale Q^2
- Calculate theory cross section at given x,Q^2 of measurement
- Compare data & theory via χ^2 function
- Minimise χ^2 function with respect to PDF parameters ~ 2000 iterations



<u>HERAPDF1.0 & 1.5</u>
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
NNLO HERAPDF 1.5 with 14p

<u>HERAPDF2.0</u>
Include additional NC and CC HERA-II combined data
Complete MSbar NLO and NNLO fit
NLO & NNLO fits require15 parameters

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1 + Dx + Ex^2)$$

xg	xg	
xu_v	$xU = xu + xc$	
xd_v	$xD = xd + xs$	→
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$	
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$	

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

HERAPDF1.0 & NLO HERAPDF1.5

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

HERAPDF2.0

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

Apply momentum/counting sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

$B_{\bar{U}} = B_{\bar{D}}$

$Sea = 2(\bar{U} + \bar{D})$

$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$

ensures $x\bar{u} \to x\bar{d}$ as $x \to 0$

$Q_0^2 = 1.9$

$Q^2_{\min} = 3.5$ or $10\ GeV^2$

$\alpha_s(M_z^2) = 0.118$

$2 \cdot 10^{-4} \le x \le 0.65$

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

fixed or constrained by sum-rules

parameters set equal but free

NC structure functions

$$F_2 = \frac{4}{9}\left(xU + x\bar{U}\right) + \frac{1}{9}\left(xD + x\bar{D}\right)$$

$$xF_3 \sim xu_v + xd_v$$

CC structure functions

$$W_2^- = x(U + \overline{D}), \qquad W_2^+ = x(\overline{U} + D)$$

$$xW_3^- = x(U - \overline{D}), \qquad xW_3^+ = x(D - \overline{U})$$

Additional parameters:
heavy quark masses M_c and M_b are optimised
f_s = 0.4 ⇒ compromise value between unsuppressed (f_s = 0.5) and ‘default’ strange sea from dimuon data

$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1-\sum_j \gamma^i_j b_j)]^2}{\delta^2_{i,stat}\mu^i m^i(1-\sum_j \gamma^i_j b_j) + (\delta_{i,unc}m^i)^2} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,unc}m_i^2 + \delta^2_{i,stat}\mu^i m^i}{\delta^2_{i,unc}\mu_i^2 + \delta^2_{i,stat}\mu_i^2}$$

modified χ^2 definition includes ln term to account for likelihood transition to χ^2 after error scaling

HERAPDF 2.0 Uncertainties

Experimental Uncertainties
Hessian method uses 14 eigenvector pairs
Standard definition $\Delta\chi^2$=1 for 68% CL error bands

Model Assumptions
Variation of charm and bottom quark masses M_c , M_b
Variation of Q^2 minimum cut used on input data Q^2_{min}
Variation of strange quark fraction f_s

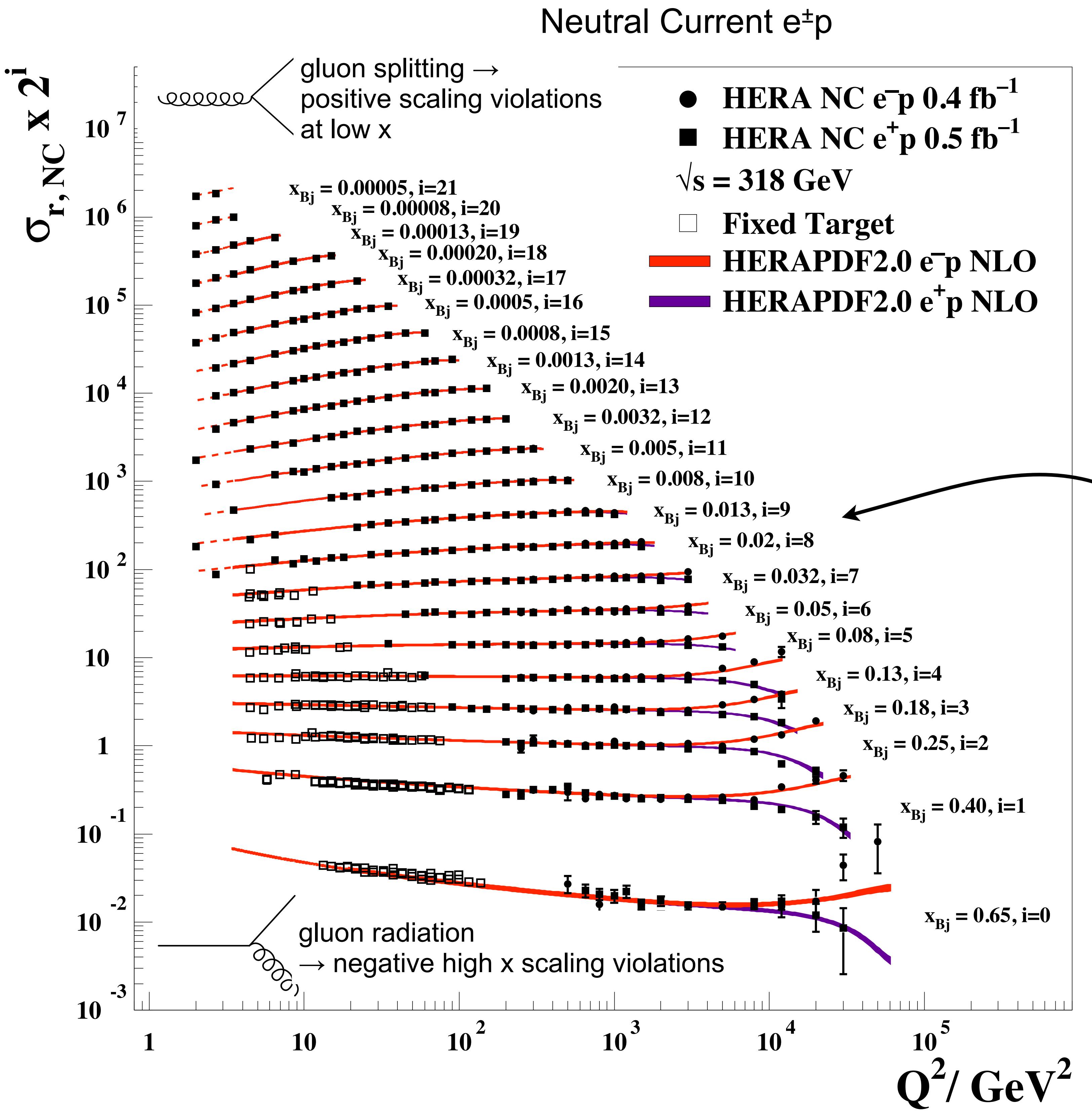
Parameterisation Uncertainties
Variation of Q_0^2
Variation of fit using additional 15th parameter

Variation	Standard Value	Lower Limit	Upper Limit
$Q^2_{\rm min}$ [GeV^2]	3.5	2.5	5.0
$Q^2_{\rm min}$ [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_{f_0} [GeV]	1.9	1.6	2.2

$\alpha_s(M_Z^2)$ is fixed but series of PDFs provided scanning large range in value: 0.110 to 0.130

Experimental uncertainties also checked using RMS spread of 400 replica fits

NC Cross Sections



Precision 1.3% for $Q^2 < 400$ GeV^2
⇒ factor 2 reduction in error wrt HERA-I

Statistics limited at higher Q^2 and high x

Extended reach at high x compared to H1 preliminary data

This x region is the 'sweet spot'
High precision with long Q^2 lever arm
x-range relevant for Higgs production

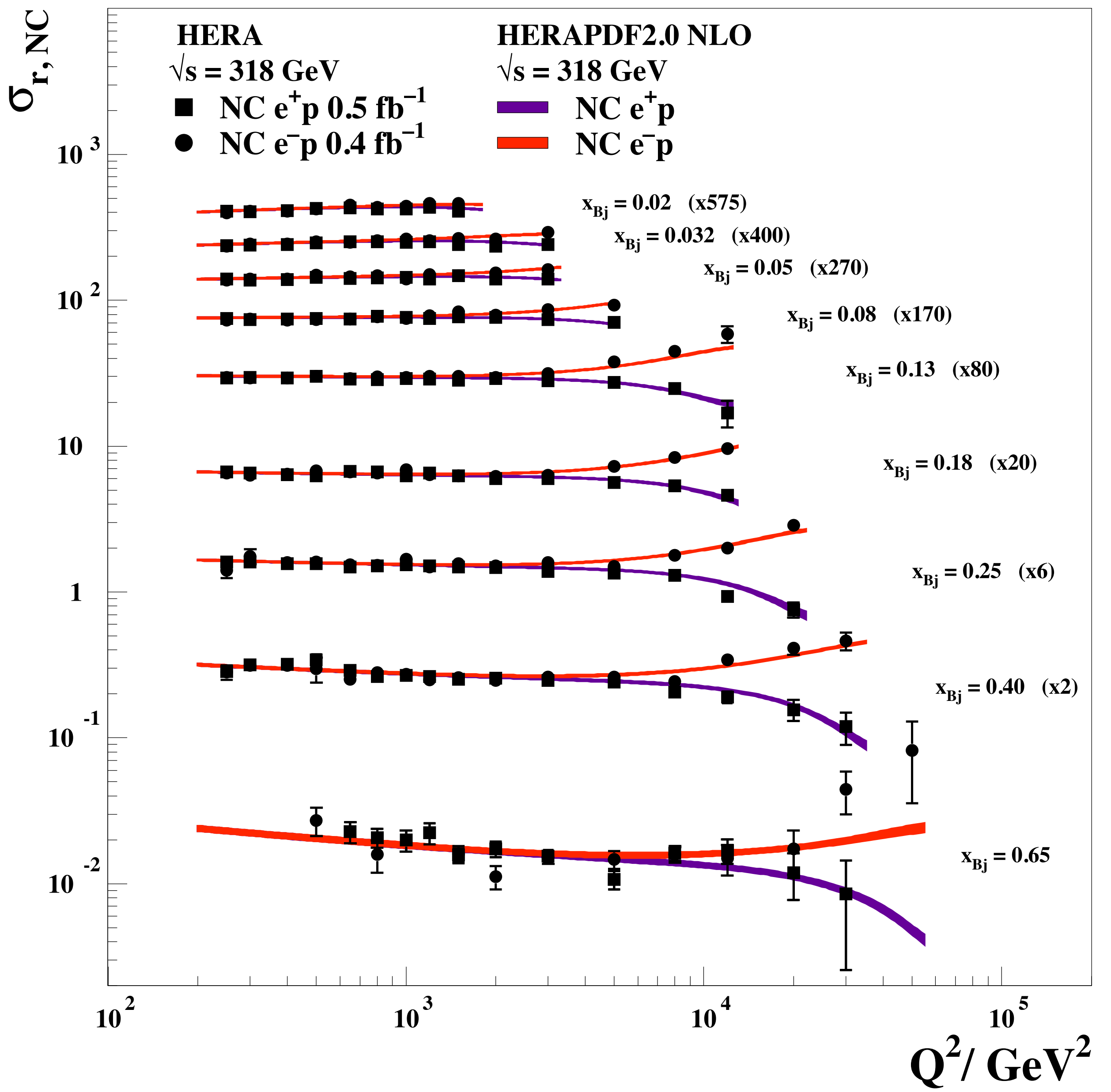
Combination of high Q^2 data HERA-1 and HERA-II

Larger HERA-II luminosity
→ improved precision at high x / Q^2

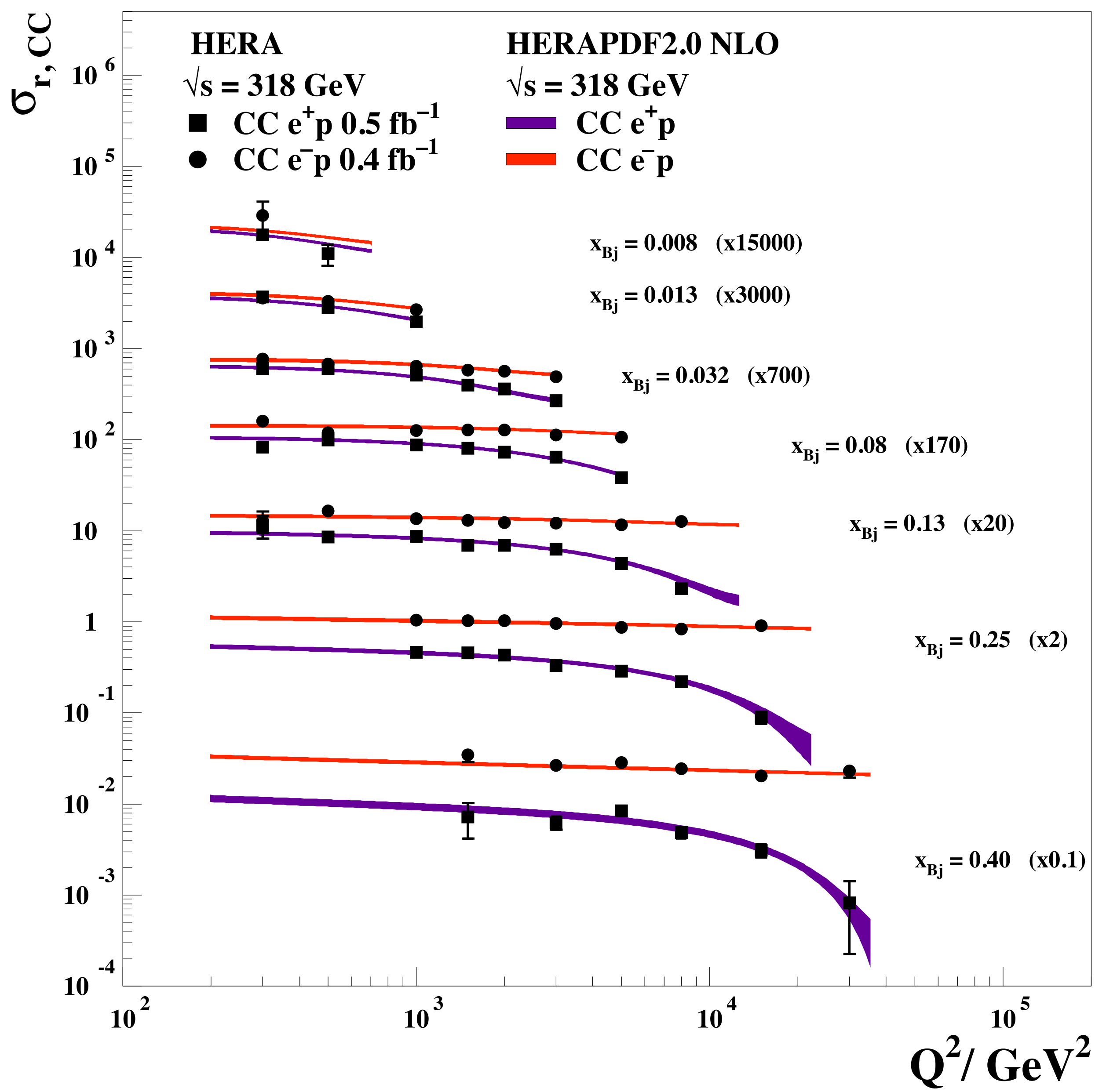
HERAPDF2.0 provides good description

High Q² NC & CC Cross Sections

Neutral Current e±p

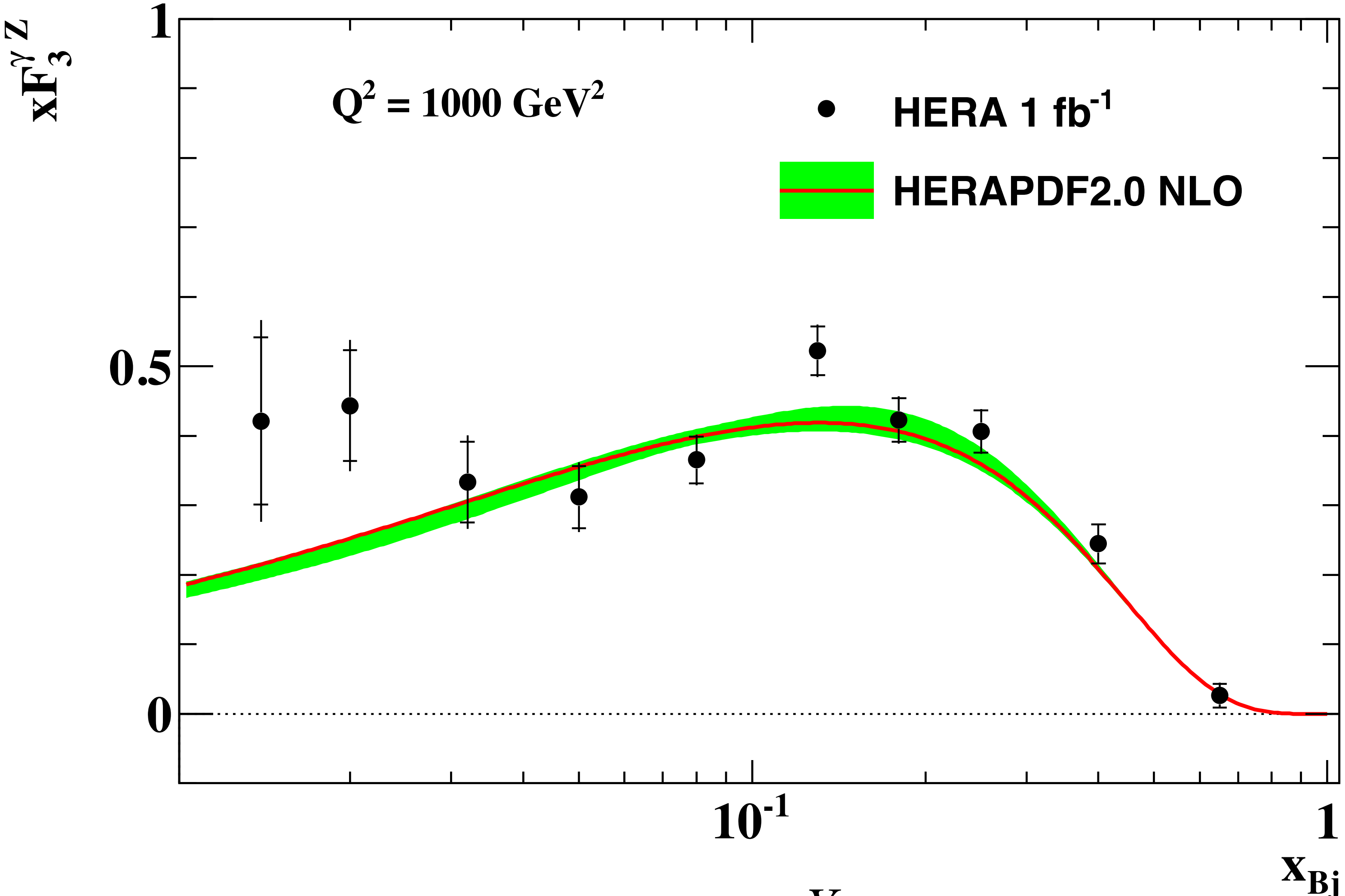


Charged Current e±p



- Difference in NC at high x for e^+ and e^- is due to xF_3 and Z boson exchange → valence quarks
- CC e^+p suppressed at high x due to $(1-y)^2$ helicity suppression of quarks at high y,Q^2 & fixed x
- CC e^-p unaffected as helicity suppression applies to anti-quarks
- HERAPDF2.0 describes high x data well for both NC and CC channels

Valence quarks and xF_3



At high Q^2 xF_3 arises due to Z^0 effects
enhanced e^- cross section wrt e^+
Difference is xF_3
Sensitive to valence PDFs

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}) \approx a_e \chi_Z x F_3^{\gamma Z}$$

$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

Measure integral of $xF_3^{\gamma Z}$ - validate sumrule:

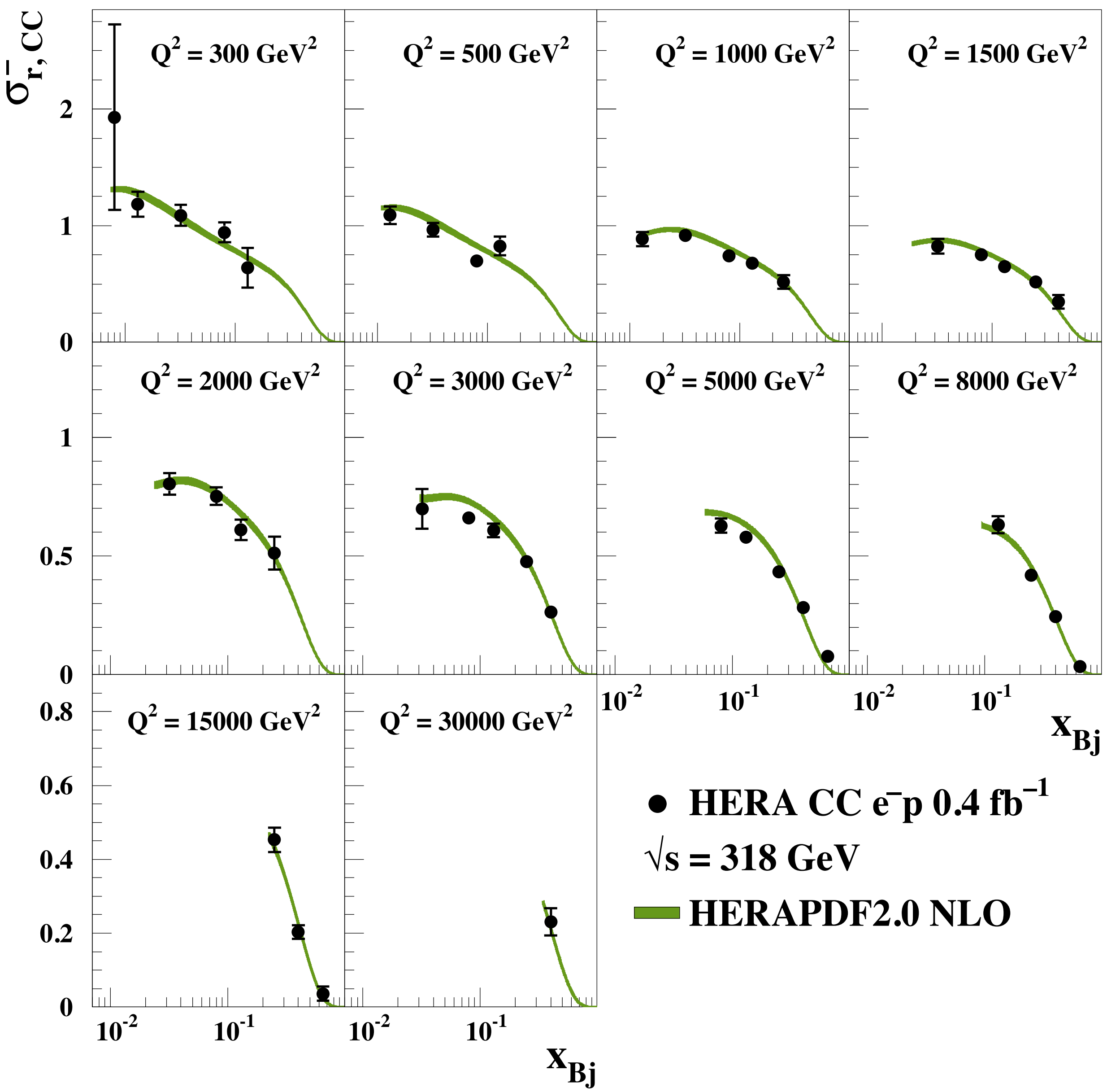
$$\int_{0.016}^{0.725} \mathrm{d}x\ F_3^{\gamma Z}(x, Q^2 = 1\,500\,\mathrm{GeV}^2) = 1.314 \pm 0.057(\mathrm{stat}) \pm 0.057(\mathrm{syst})$$

LO integral predicted to be $5/3 + \mathcal{O}(\alpha_S/\pi)$

High Q² CC Cross Sections

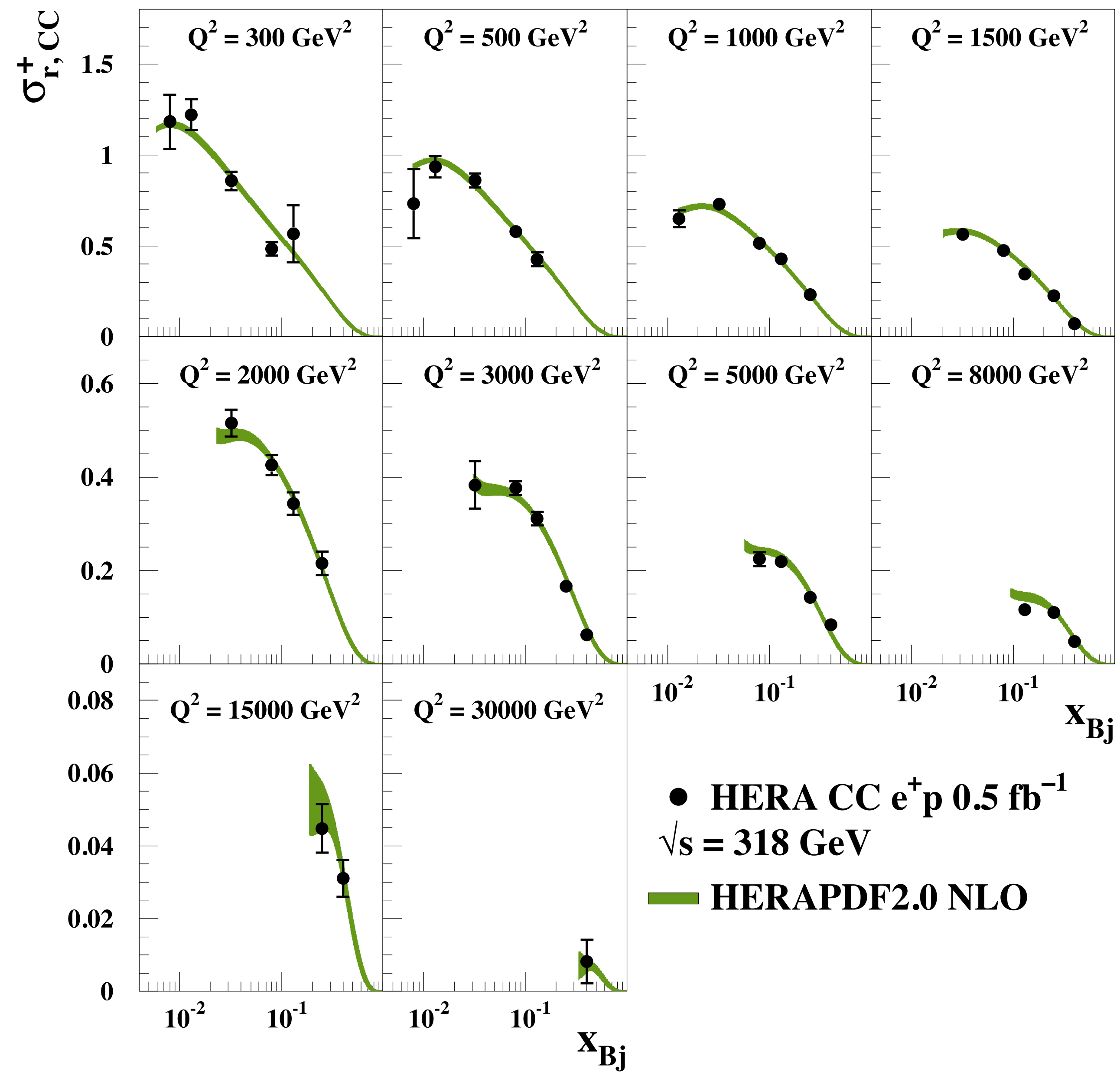
Electron scattering

$$\frac{d^2\sigma^-_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(u+c)+(1-y)^2(\bar{d}+\bar{s})\right]$$



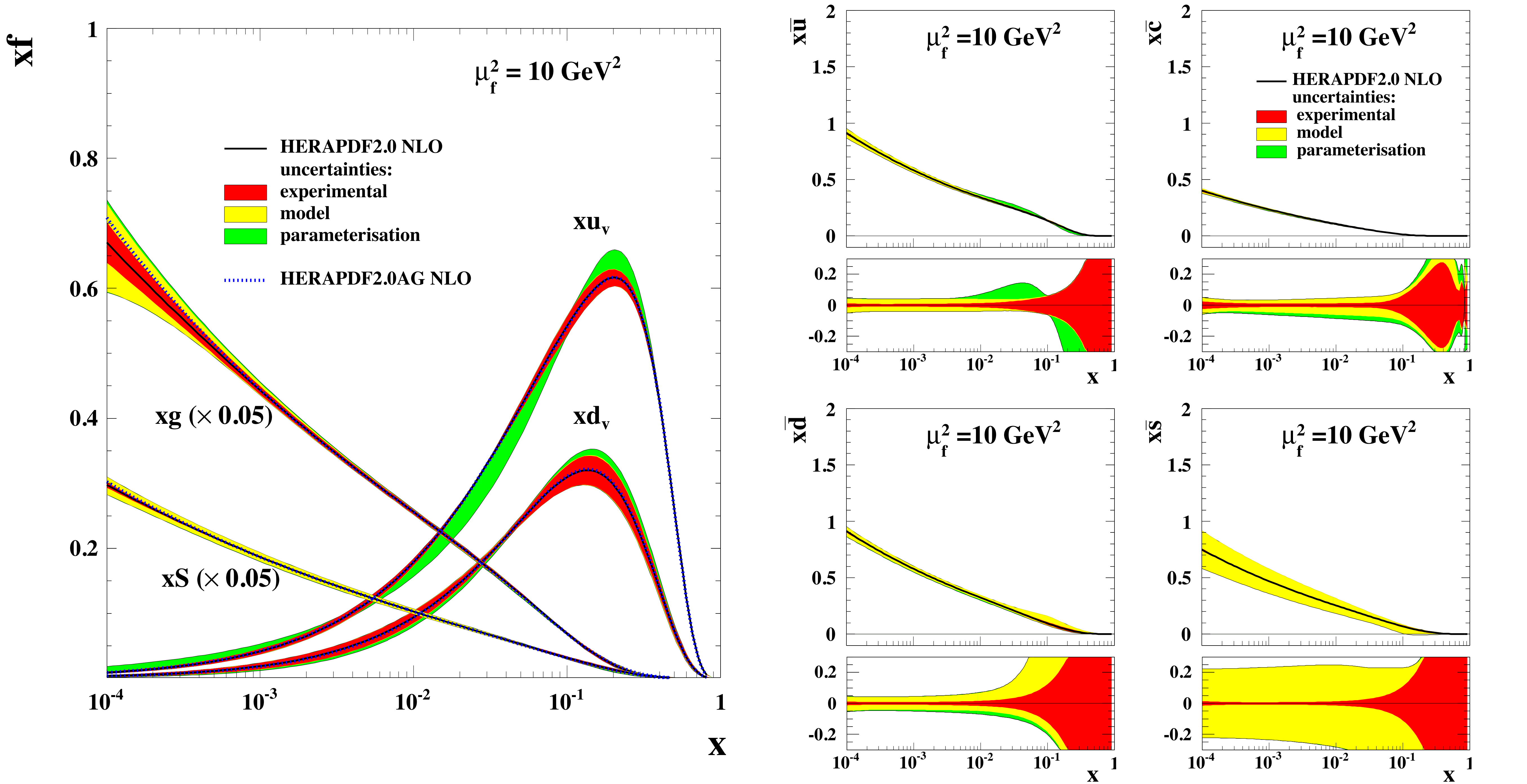
Positron scattering

$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[(\bar{u}+\bar{c})+(1-y)^2(d+s)\right]$$

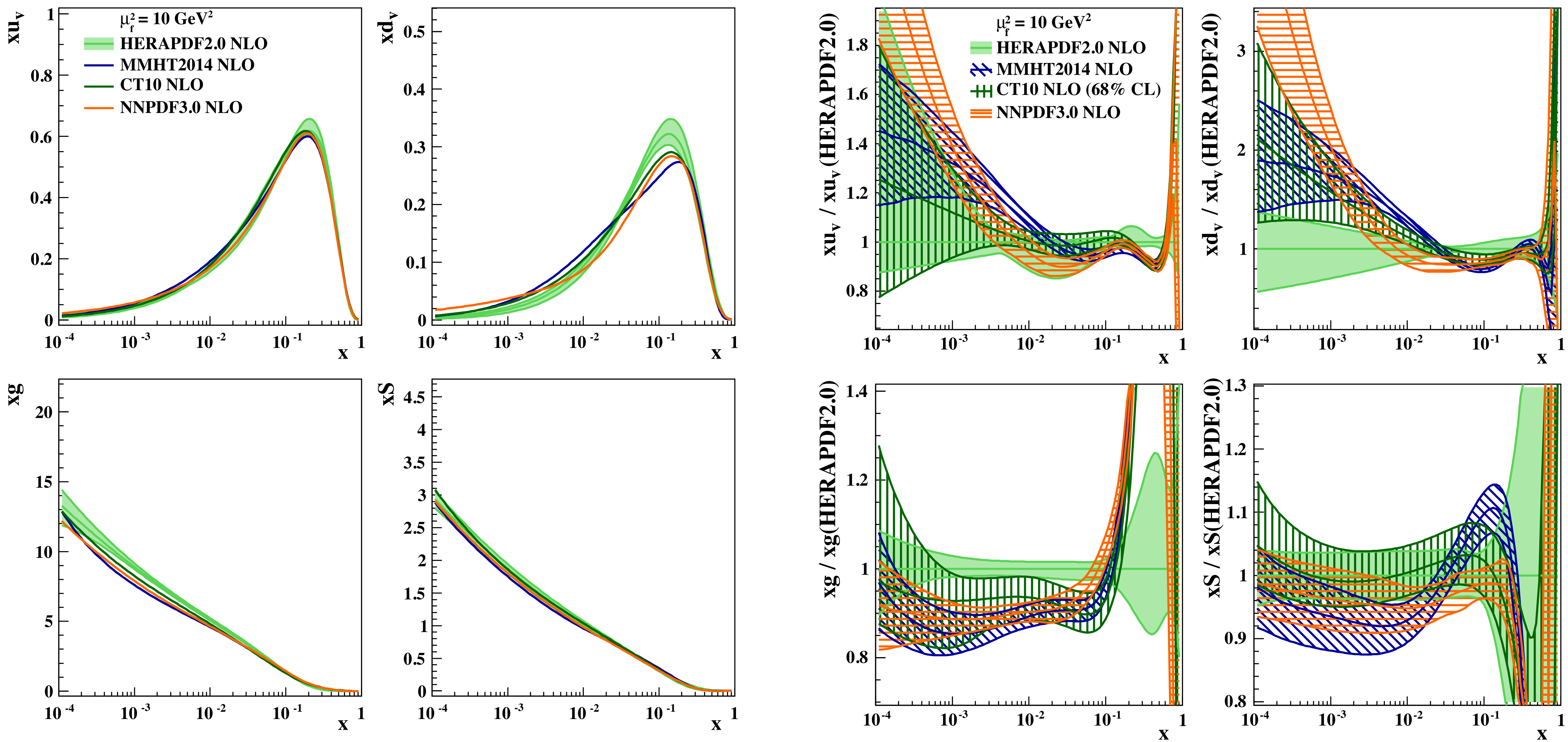


Combination of high Q² CC data (HERA-I+II)
Improvement of total uncertainty
Dominated by statistical errors
Provide important flavour decomposition information

CC e+ data provide strong d_v constraint at high x
Precision limited by statistics: typically 3-7%
HERA-I precision of 10-15% for e+p


xf
μ_f^2 = 10 GeV^2
HERAPDF2.0 NLO
uncertainties:
experimental
model
parameterisation
HERAPDF2.0AG NLO
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
x
$x\bar{u}$
$x\bar{c}$
$x\bar{d}$
$x\bar{s}$
μ_f^2 =10 GeV^2

HERAPDF 2.0 Comparison to Other PDFs



Comparison of HERAPDF2.0 vs MMHT14 , NNPDF3.0 , CT10 (others use only HERA-1 combined data)

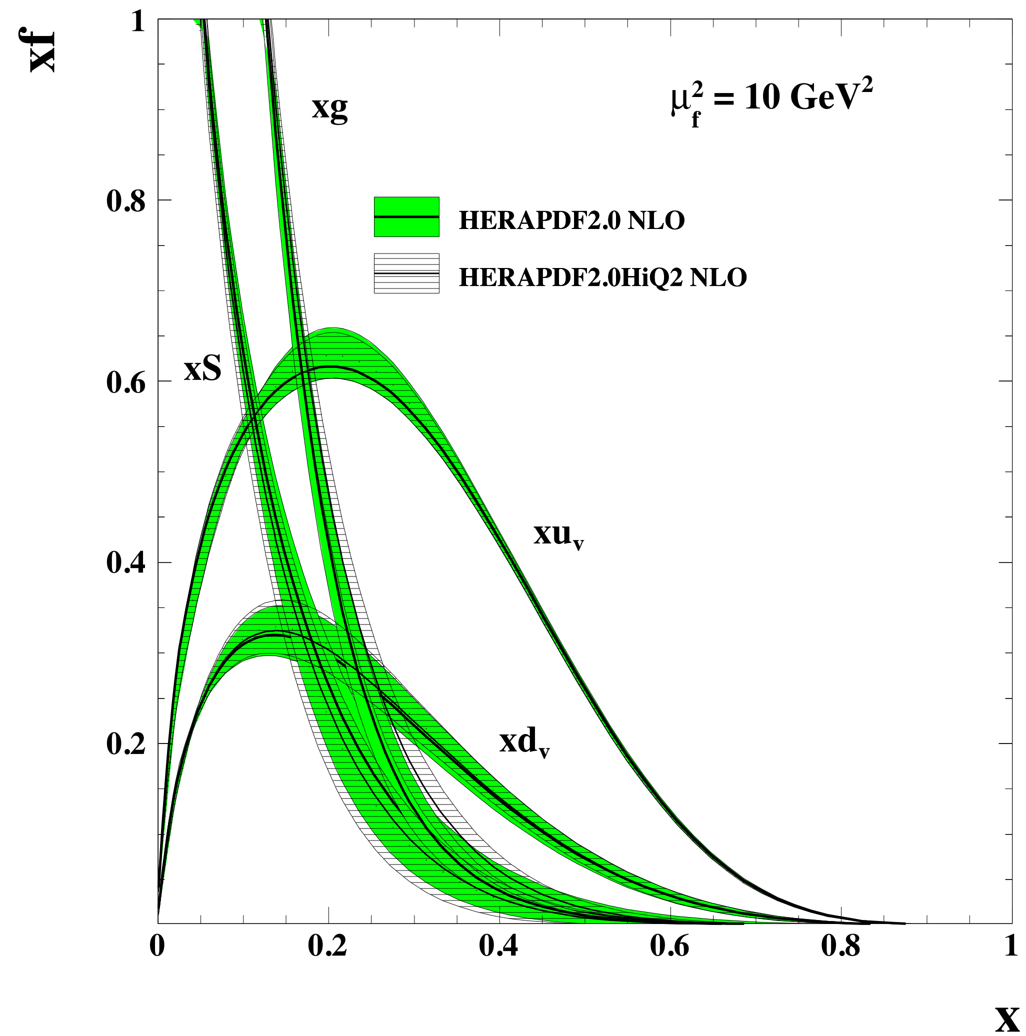
Differences at high x

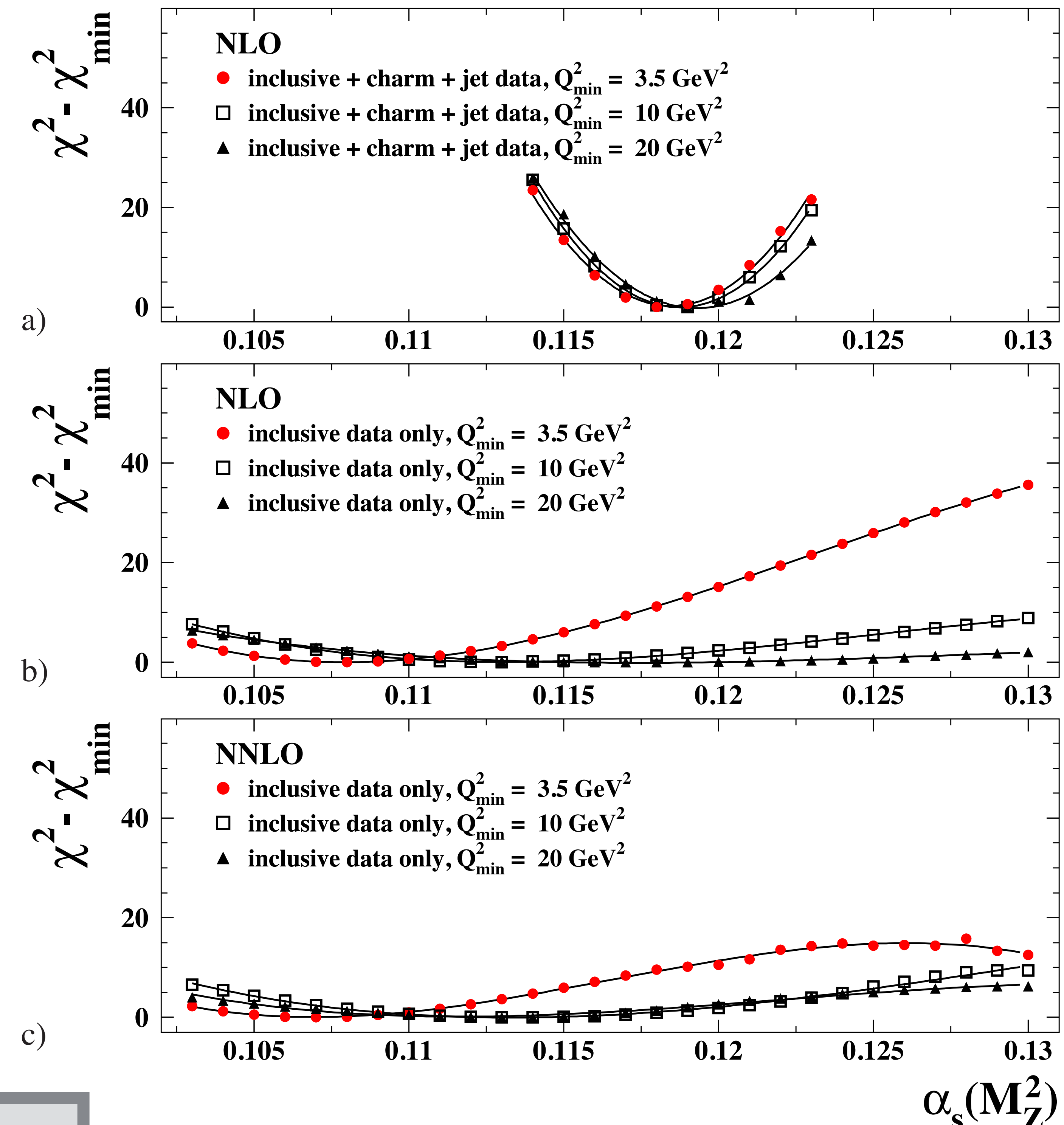
- New HERA combined data improve precision at high x, Q^2
- HERAPDF uses proton target data only → no nucleon / deuterium data
- Softer gluon at high x

HERAPDF 2.0 Jets

Inclusive jet + charm cross sections in ep collisions are sensitive to xg and α_s

Separate H1 & ZEUS measurements are added to HERAPDF2.0 → HERAPDF2.0-Jets



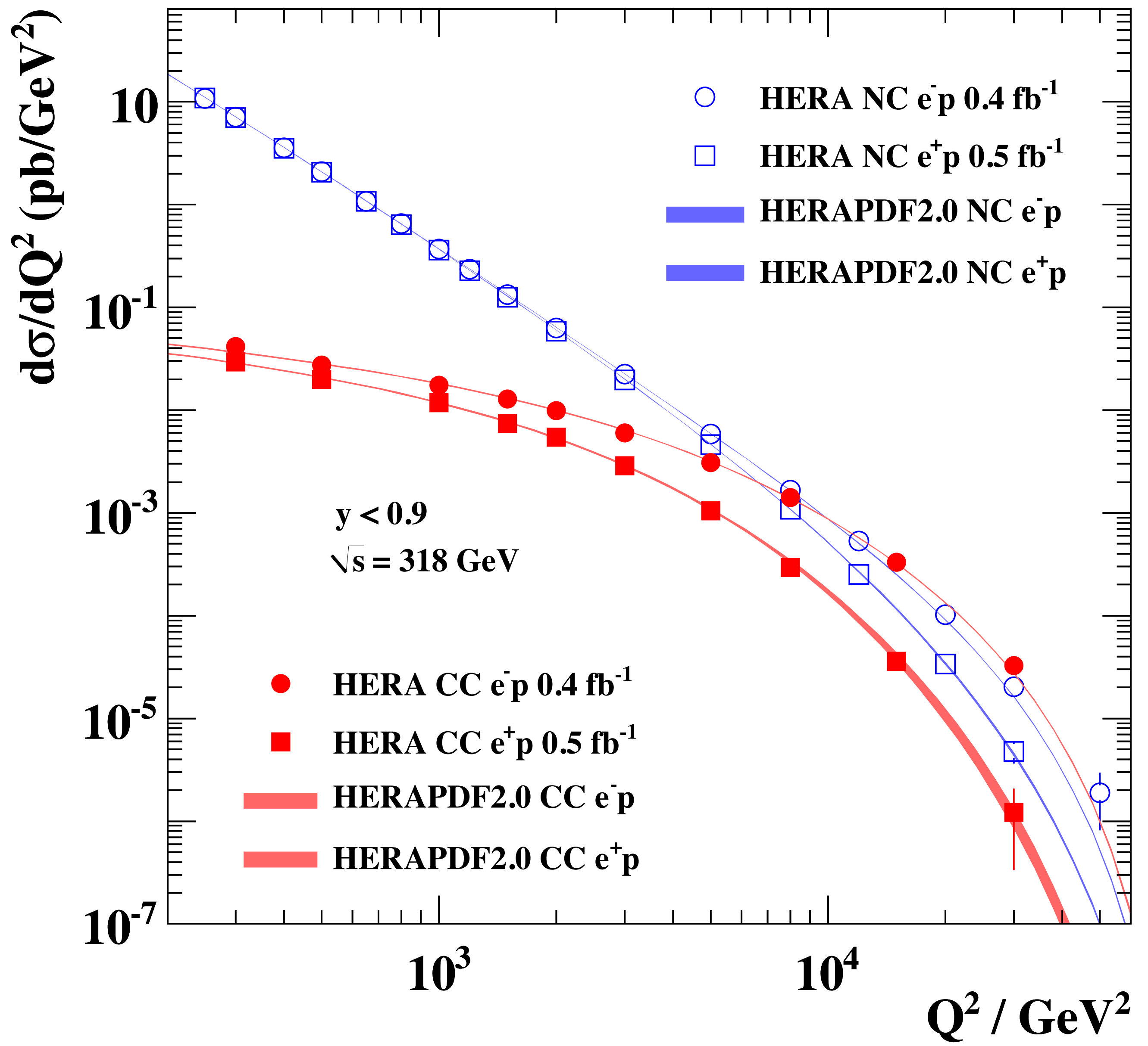


Value of α_s determined from DIS data:

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\mathrm{exp}) \pm 0.0005(\mathrm{model/parameterisation}) \pm 0.0012(\mathrm{hadronisation})\ ^{+0.0037}_{-0.0030}(\mathrm{scale})\ .$$

Consistent with world average
Competitive with other NLO determinations

Electroweak symmetry breaking



- H1 / ZEUS completed their final SF measurements
- New HERA-II data provide tighter constraints at high x / Q^2
- These data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in Q^2
- DGLAP evolution works very well
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- Final combination of HERA data completed
- HERAPDF2.0 QCD fit at NLO & NNLO

Backup

<u>HERAPDF1.0</u>
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
α_s = 0.1176 (fixed in fit)

desy-09-158

<u>HERAPDF1.5</u>
Include additional NC and CC HERA-II data
Complete MSbar NLO and NNLO fit
NLO: standard parameterisation with10 parameters
<u>HERAPDF1.5f</u>
NNLO: extended fit with 14 parameters

H1-10-142 / ZEUS-prel-10-018

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1+Dx+Ex^2)$$

$$xg,\quad xu_v,\quad xd_v,\quad x\bar{U},\quad x\bar{D} \longrightarrow xg,\quad xU = xu + xc,\quad xD = xd + xs,\quad x\bar{U} = x\bar{u} + x\bar{c},\quad x\bar{D} = x\bar{d} + x\bar{s} \longrightarrow$$

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

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

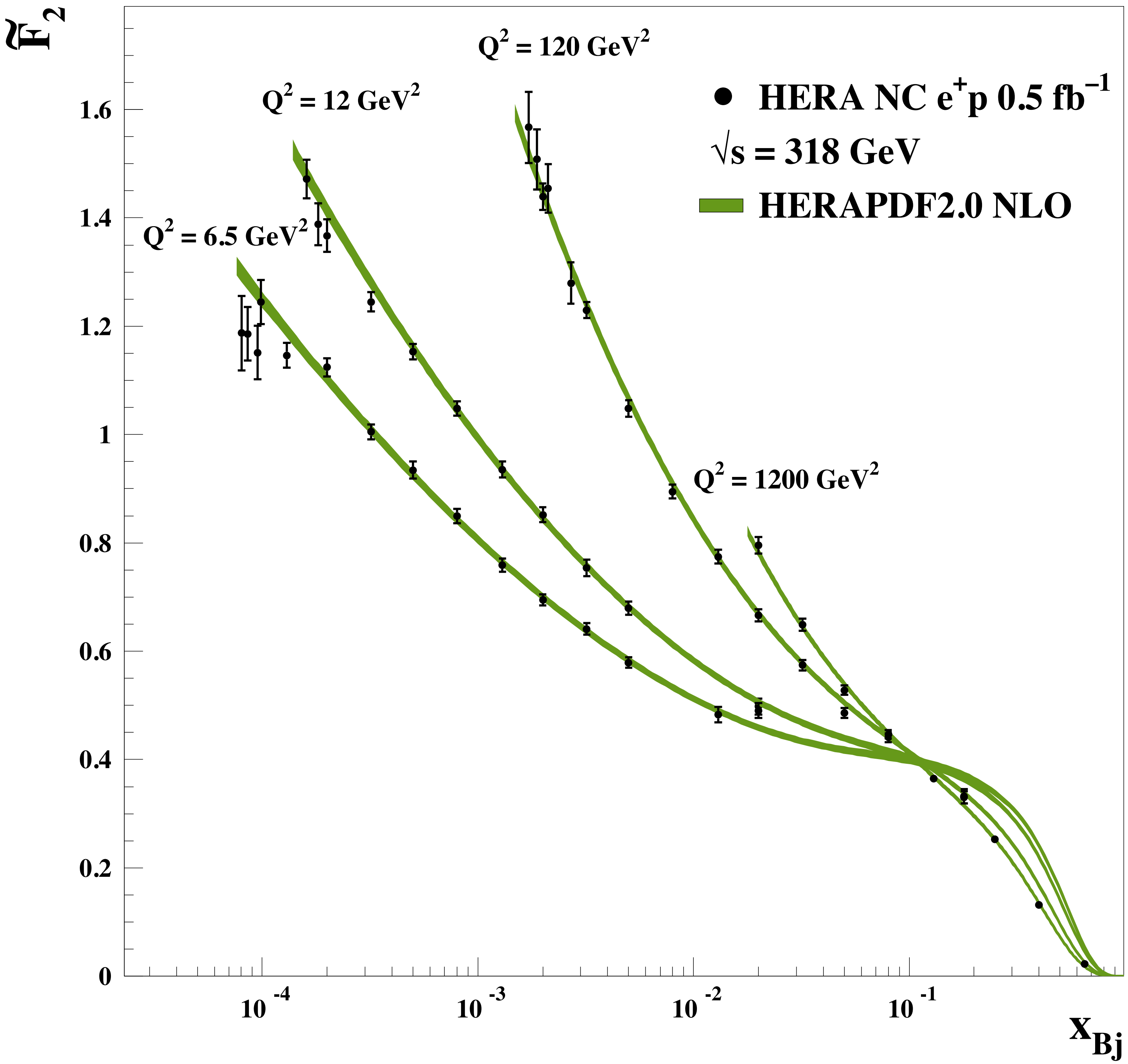
Apply momentum/counting sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

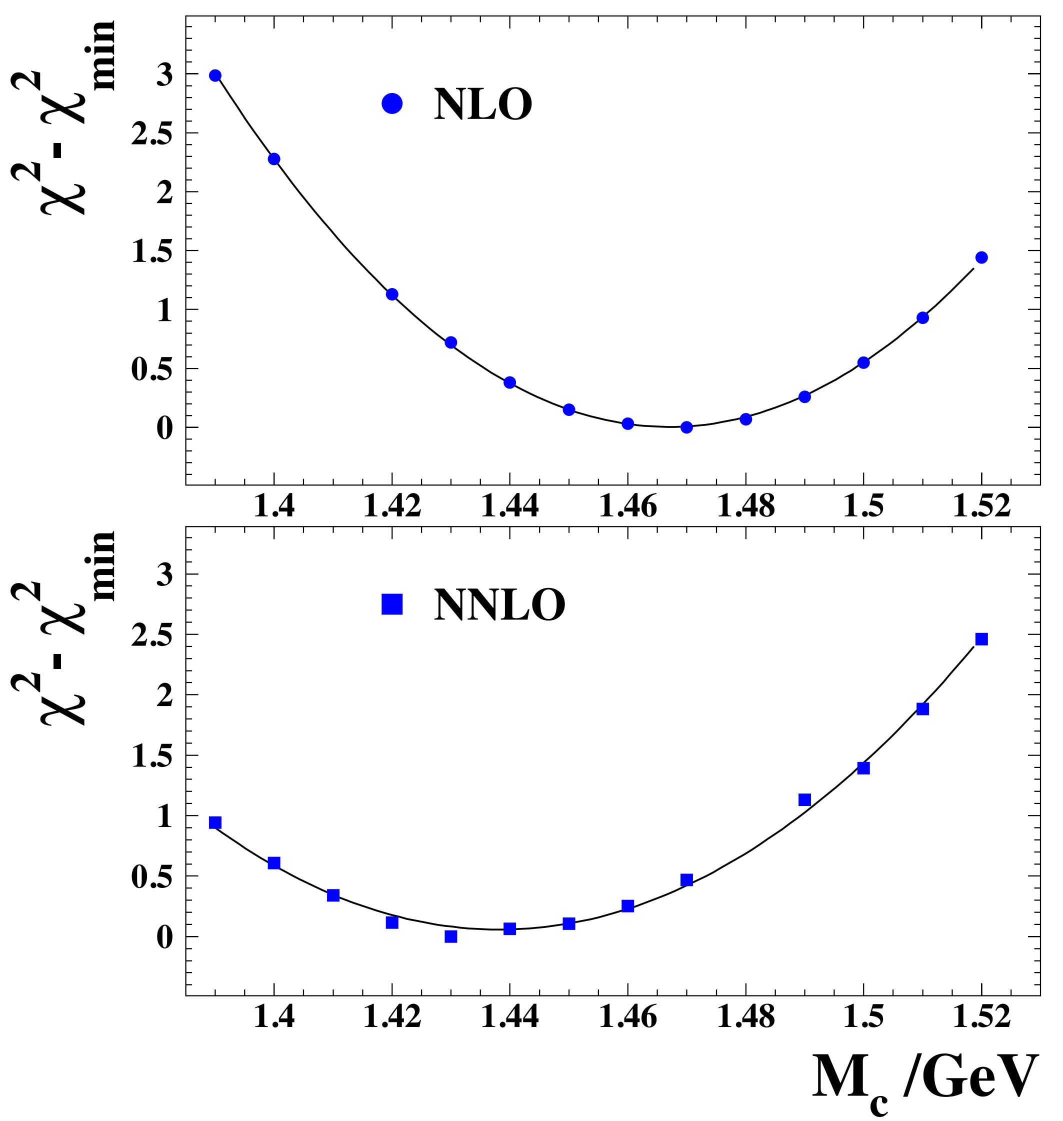
Parameter constraints:
$B_{uv} = B_{dv}$
$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

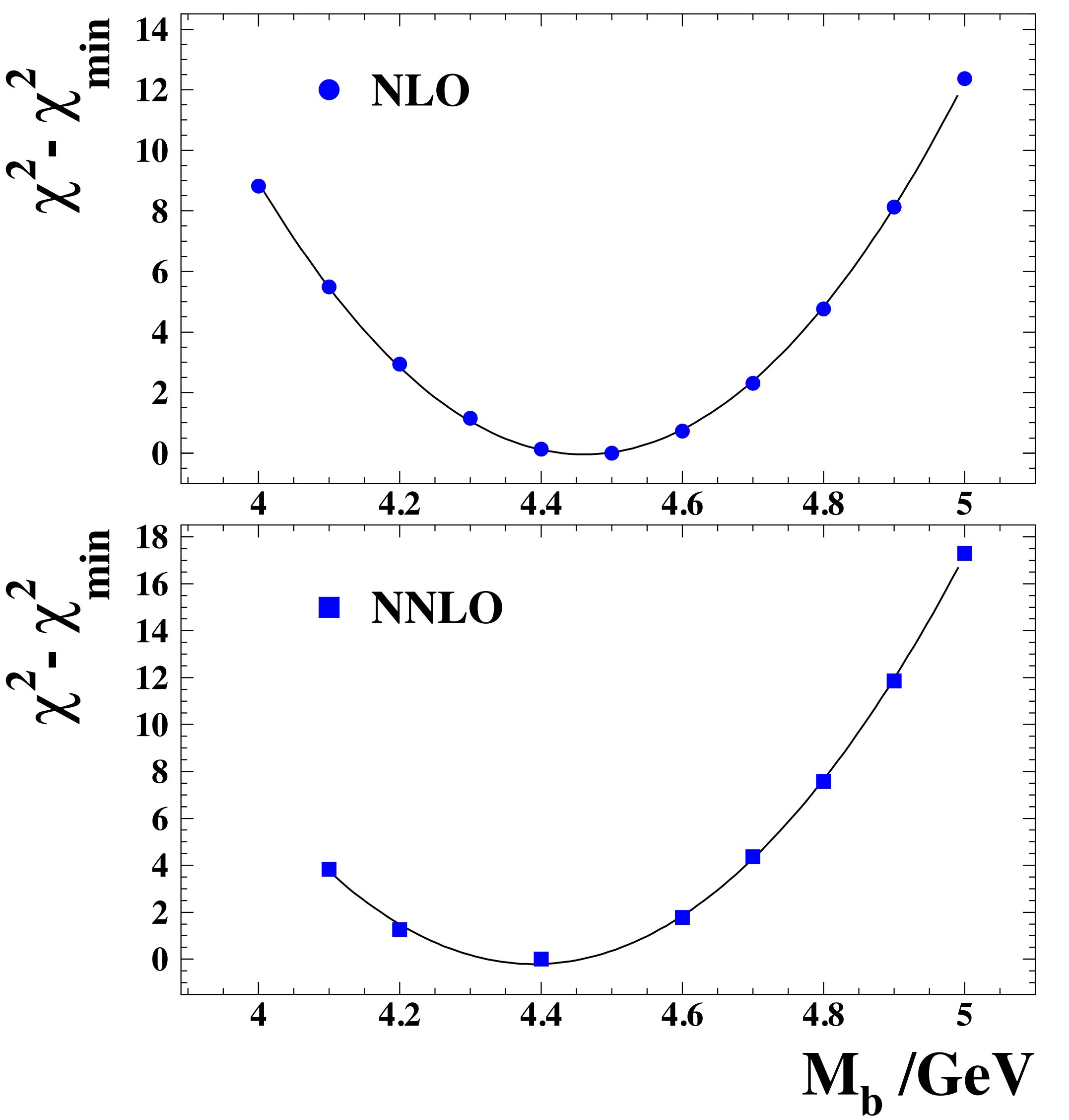
Q_0^2 = 1.9 GeV^2 (below m_c)
Q^2 > 3.5 GeV^2
2 x 10^{-4} < x < 0.65
Fits performed using RT-VFNS



F̃2
Q2 = 6.5 GeV2
Q2 = 12 GeV2
Q2 = 120 GeV2
Q2 = 1200 GeV2
HERA NC e+p 0.5 fb−1
√s = 318 GeV
HERAPDF2.0 NLO
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10 -4
10 -3
10 -2
10 -1
xBj

Optimisation of Heavy Quark Masses





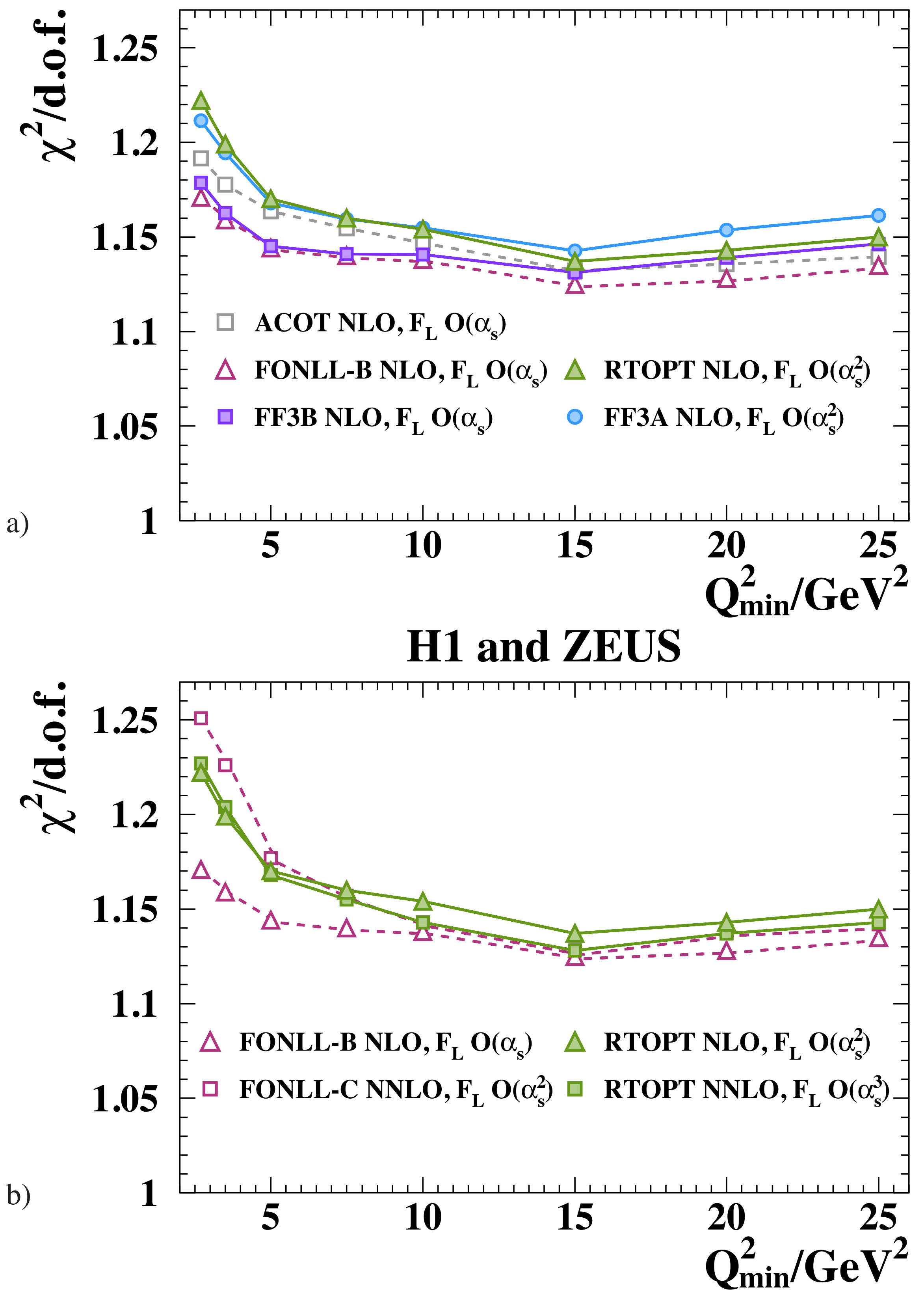
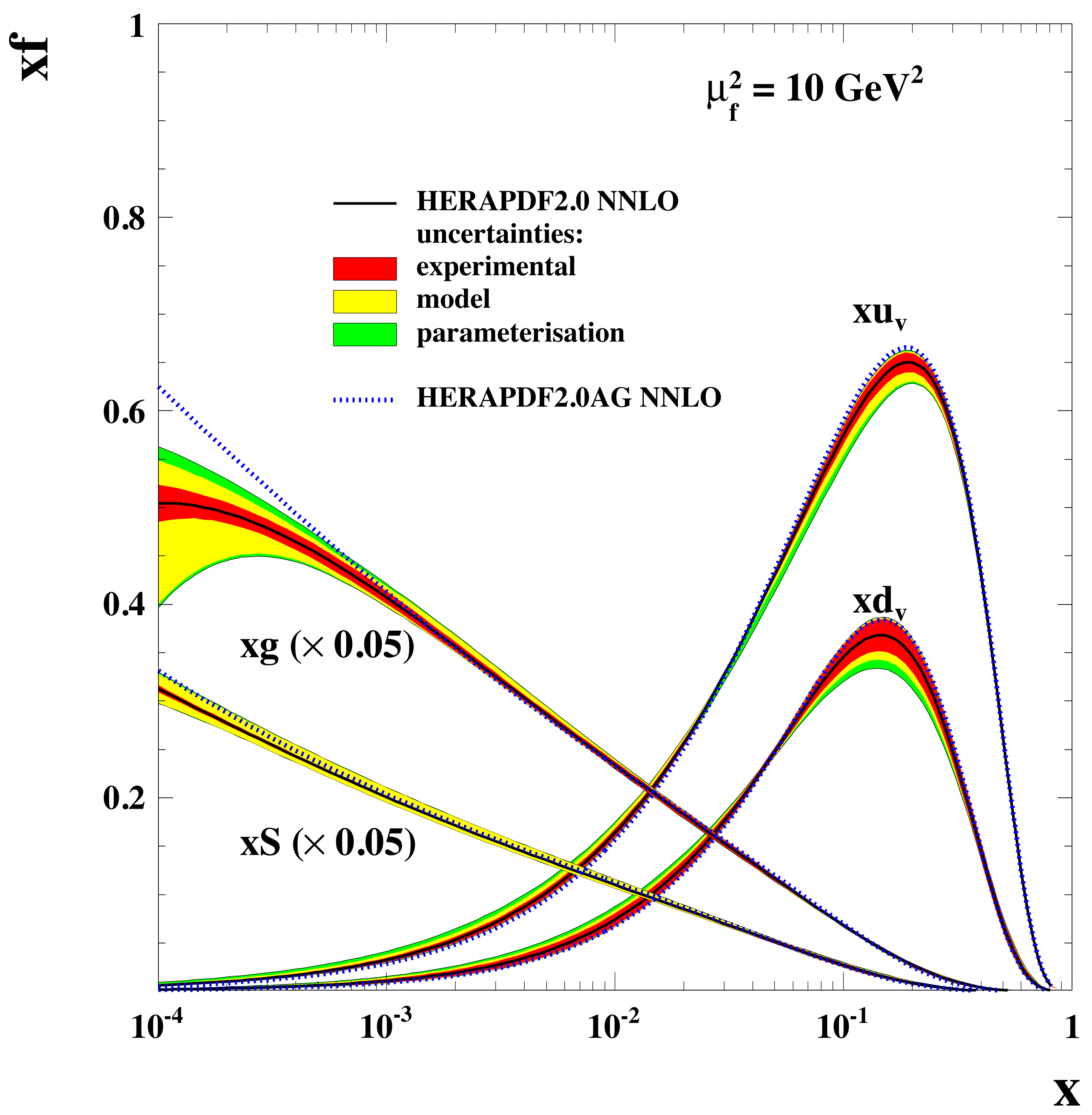
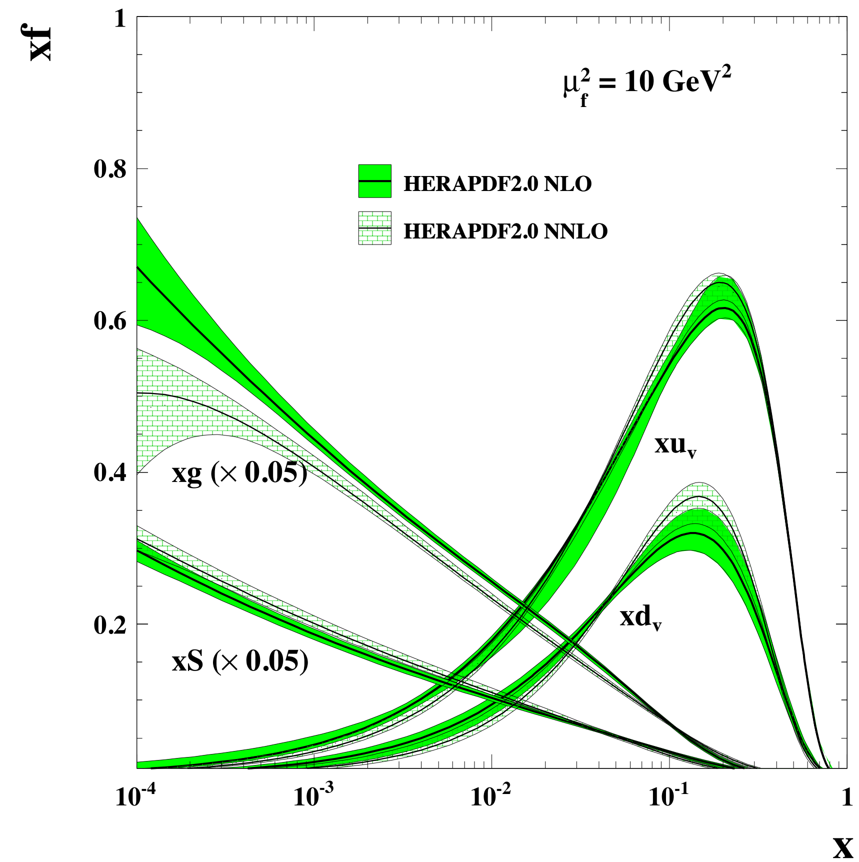
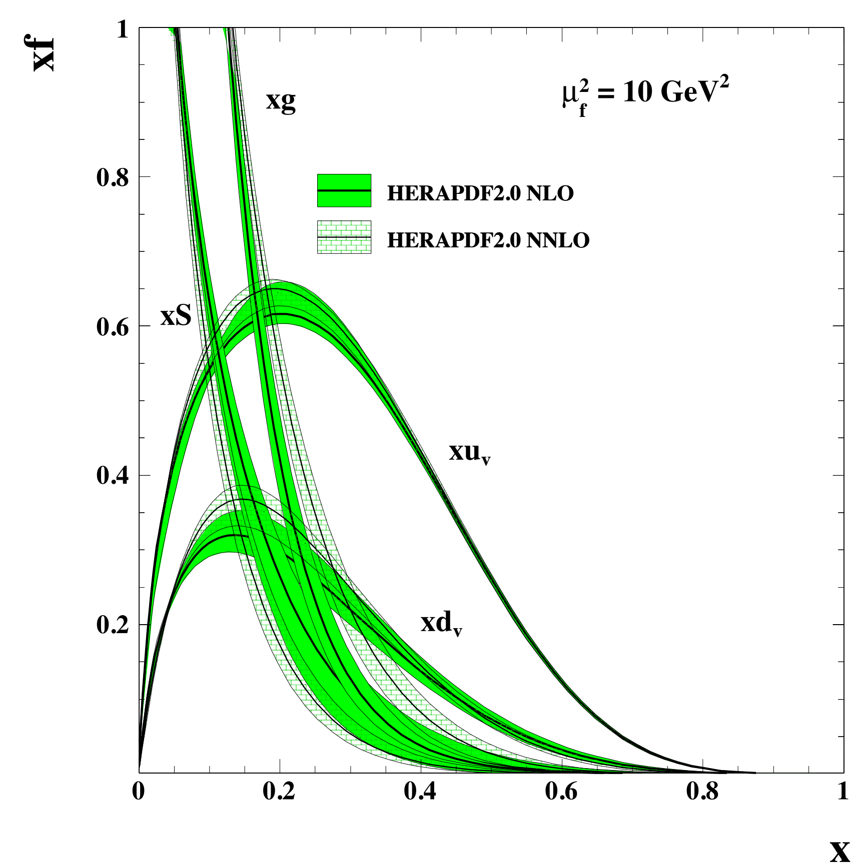


Figure 20: The dependence of χ^2/d.o.f. on Q^2_{min} for HERAPDF2.0 fits using a) the RTOPT [83], FONNL-B [90], ACOT [109] and fixed-flavour (FF) schemes at NLO and b) the RTOPT and FONNL-B/C [91] schemes at NLO and NNLO. The F_L contributions are calculated using matrix elements of the order of α_s indicated in the legend. The number of degrees of freedom drops from 1148 for $Q^2_{\mathrm{min}} = 2.7\,\mathrm{GeV}^2$ to 1131 for the nominal $Q^2_{\mathrm{min}} = 3.5\,\mathrm{GeV}^2$ and to 868 for $Q^2_{\mathrm{min}} = 25\,\mathrm{GeV}^2$.

HERAPDF 2.0 (NLO vs NNLO Fit)







HERAPDF 2.0 Variants

HERAPDF	Q^2_{min}[GeV^2]	χ^2	d.o.f.	χ^2/d.o.f
2.0 NLO	3.5	1357	1131	1.200
2.0HiQ2 NLO	10.0	1156	1002	1.154
2.0 NNLO	3.5	1363	1131	1.205
2.0HiQ2 NNLO	10.0	1146	1002	1.144
2.0 AG NLO	3.5	1359	1132	1.201
2.0HiQ2 AG NLO	10.0	1161	1003	1.158
2.0 AG NNLO	3.5	1385	1132	1.223
2.0HiQ2 AG NNLO	10.0	1175	1003	1.171
2.0 NLO FF3A	3.5	1351	1131	1.195
2.0 NLO FF3B	3.5	1315	1131	1.163
2.0Jets $\alpha_s(M_Z^2)$ fixed	3.5	1568	1340	1.170
2.0Jets $\alpha_s(M_Z^2)$ free	3.5	1568	1339	1.171

Table 11: The values of χ^2 per degree of freedom for HERAPDF2.0 and its variants.