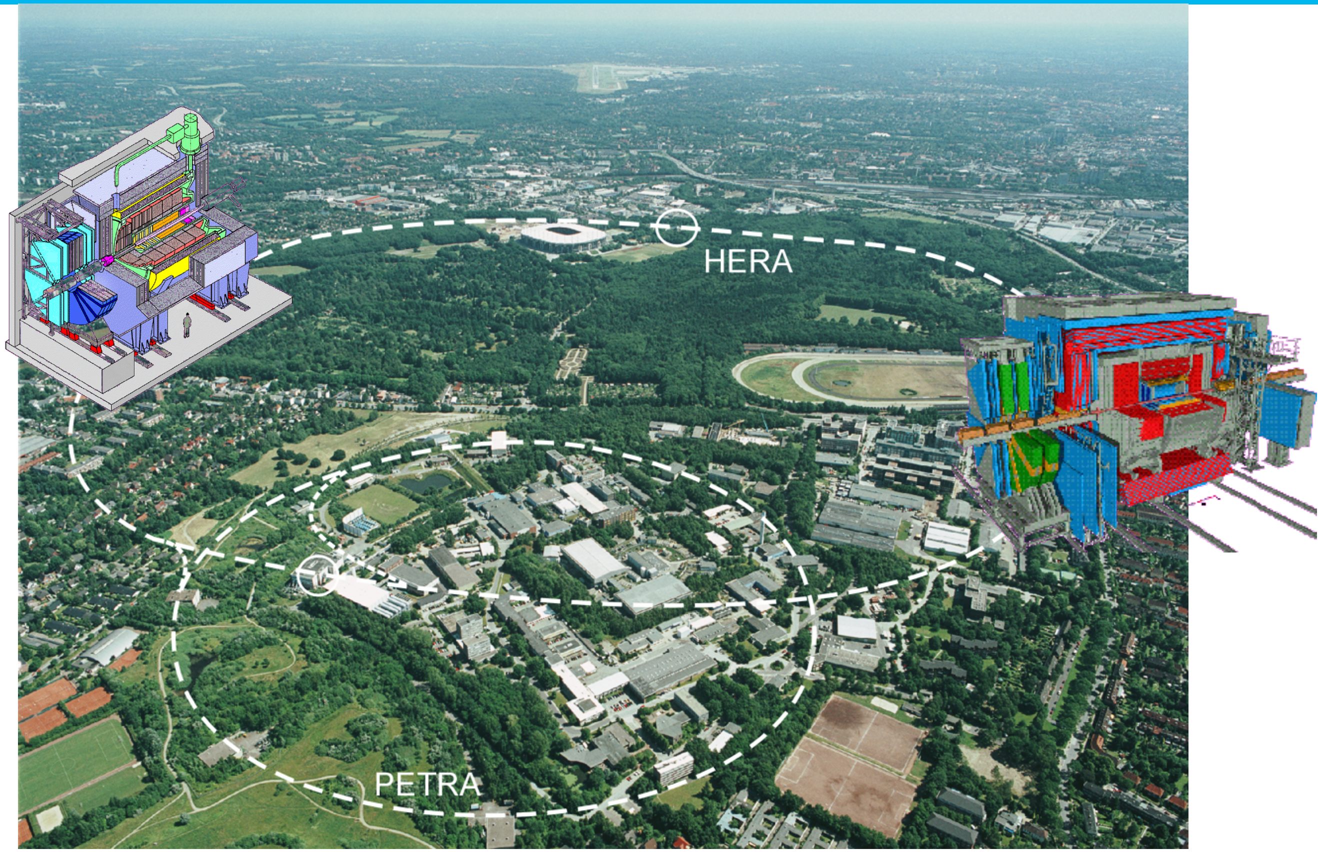
Combination of Measurements of Inclusive Deep Inelastic ep Scattering Cross Sections and QCD Analysis of HERA Data



PHOTON 2015
Novosibirsk

Uwe Schneekloth, DESY

on behalf of the
H1 and ZEUS Collaborations

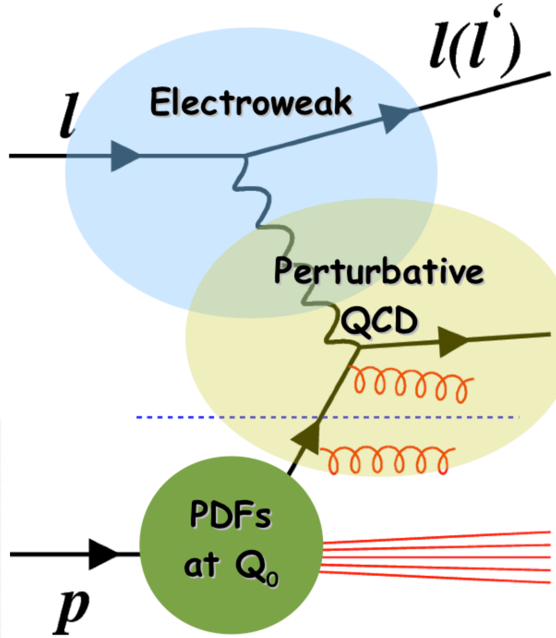
HELMHOLTZ ASSOCIATION

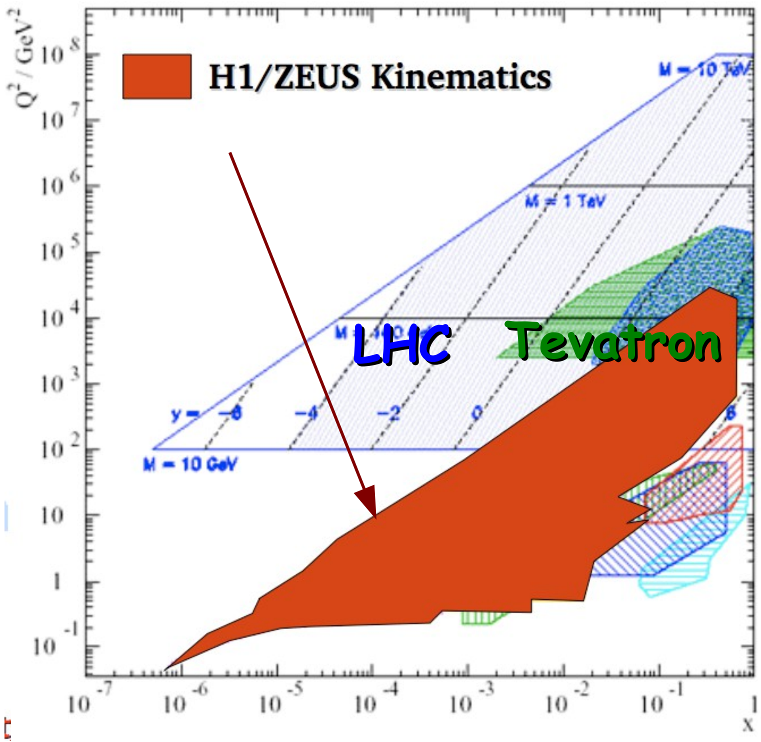
DESY

Outline

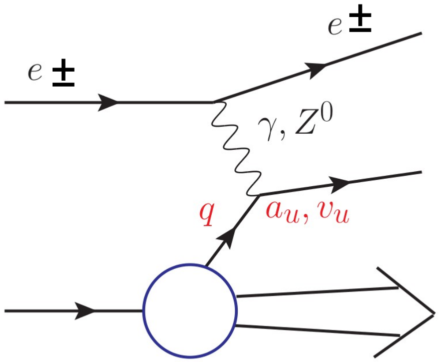
Deep Inelastic Scattering at HERA

- Introduction and Motivation
- Inclusive data sets/measurements
- Combination of inclusive cross sections
- QCD analysis
- HERA parton distribution functions
- Electroweak effects
- Conclusions





Deep Inelastic Scattering at HERA

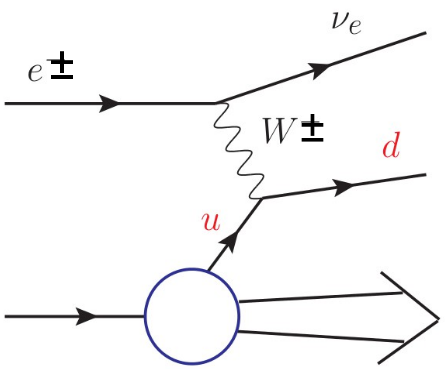


Neutral current

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_- xF_3 - y^2F_L\right] \qquad Y_\pm = 1 \pm (1-y)^2$$

$$F_2 \propto \sum_i e_i^2(xq_i + x\bar{q}_i) \qquad xF_3 \propto \sum_i e_i^2(xq_i - x\bar{q}_i) \qquad F_L \propto \alpha_s \times g$$

quark distributions — valence quarks — gluon



Charged current

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

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

Kinematic variables

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

Virtuality of exchanged boson

$$s = (k+p)^2 = \frac{Q^2}{xy}$$

center of mass energy

$$x = \frac{Q^2}{2p\cdot q}$$

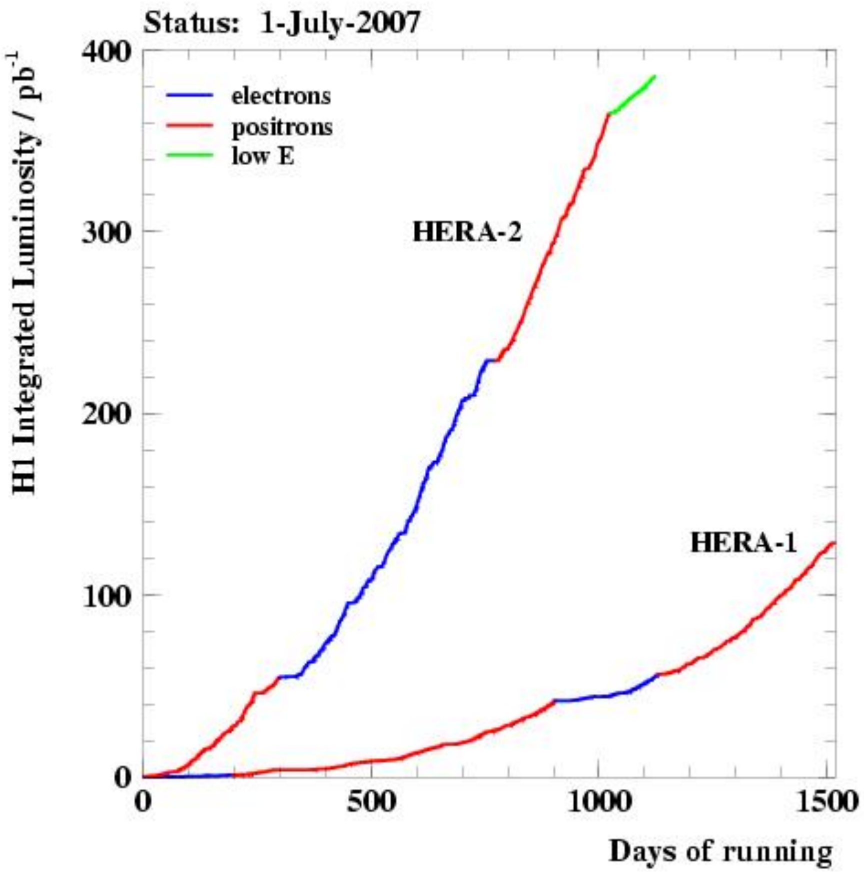
Bjorken scaling parameter

$$y = \frac{p\cdot q}{p\cdot k}$$

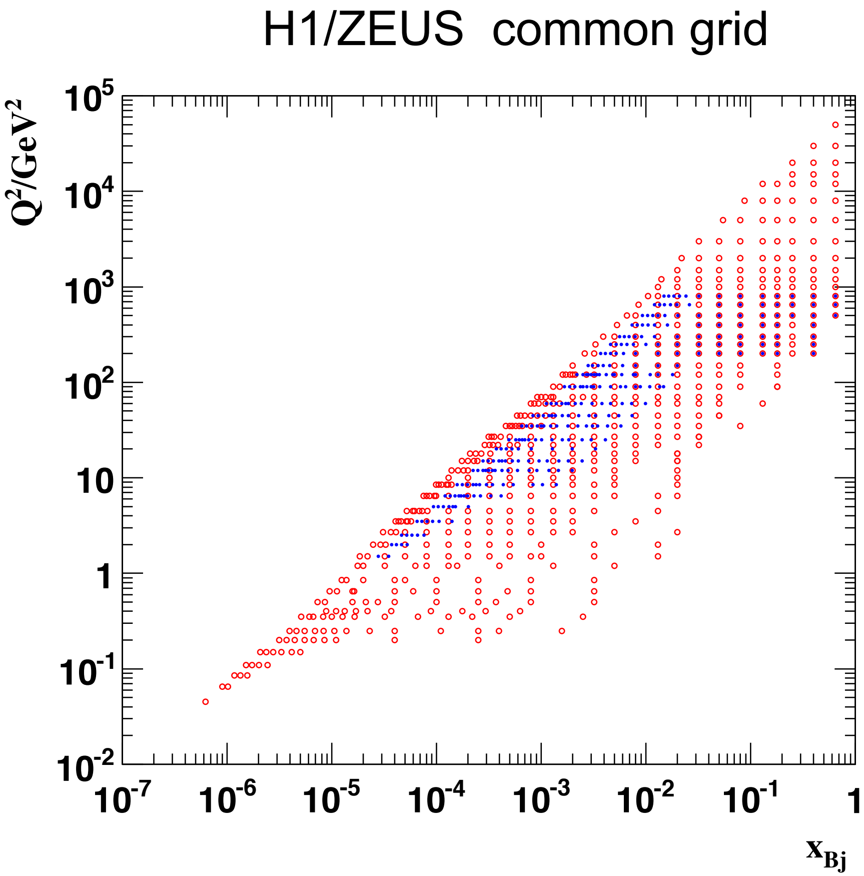
inelasticity

Final Inclusive HERA Data Combination

- H1 and ZEUS published all HERA inclusive DIS measurements (22 papers 1997-2014)
- Have now combined these measurements
  - In principle, detectors similar. Different technical solutions and different reconstructions techniques result in different systematic errors and contribute to reduction of systematic uncertainties.
- In total 41 final data sets including special runs:
  - Different proton beam energies (820, 920, 575 and 460 GeV)
  - Shifted vertex and satellite bunches
  - Special detectors at small angles
  - Effective electron beam energy reduced to due initial state radiation
  - Integrated luminosity ~500 pb^{-1} per experiment
  - Equally split between e^+ and e^- beams



Averaging Cross Sections Procedure



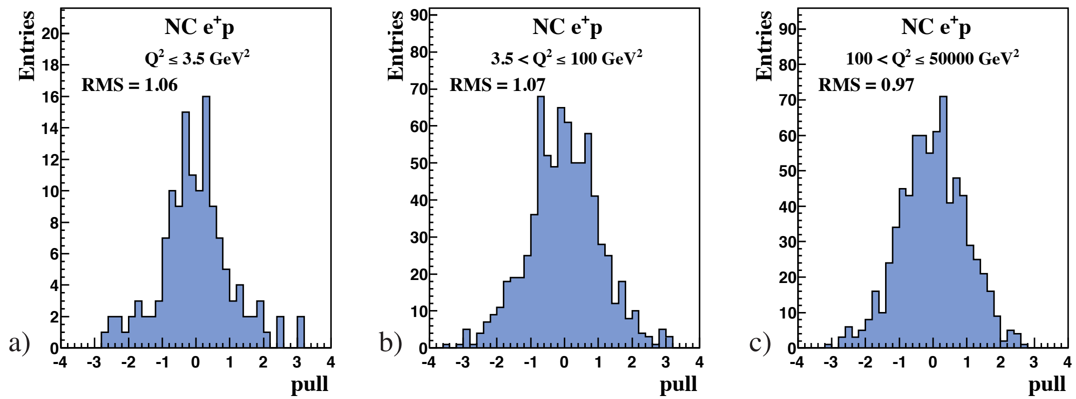
- Averaging performed using HERAverger tool based on X^2 minimization method, including correlated errors.
- Good data consistency X^2/dof = 1687/1620

Two separate common $Q^2 - x_{BJ}$ grids

- Inclusive grid for 820 and 920 GeV
- Fine-x_{Bj} grid for 460 and 575 GeV
- Data translated to common points using HERAFitter tool

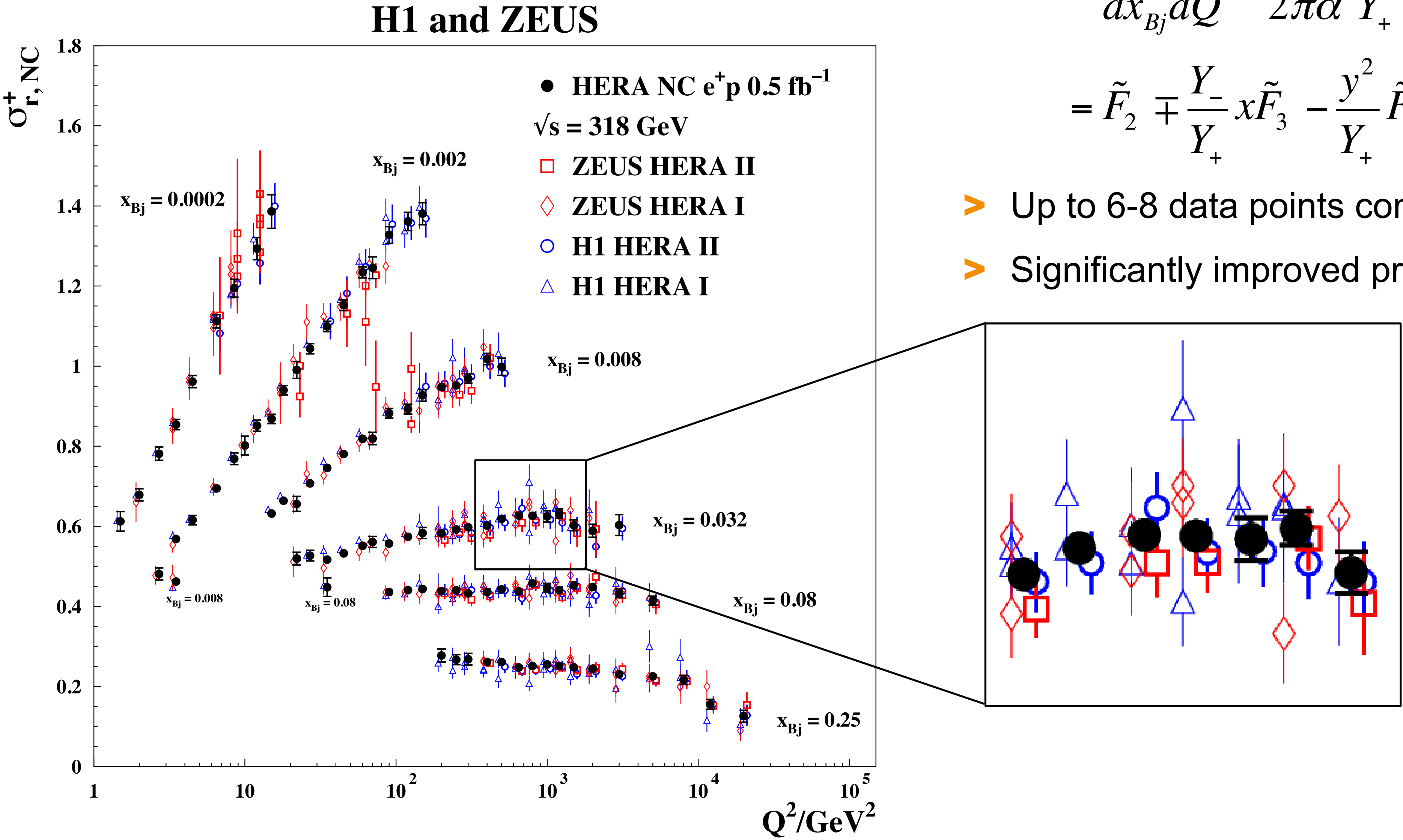
Total of 2927 data points combined to 1307

- $0.045 < Q^2 < 50000$ GeV^2
- $6x10^{-7} < x_{Bj} < 0.65$
- Six orders of magnitude in both Q^2 and x_{Bj}



Cross Sections Results

Reduced NC e⁺p cross section



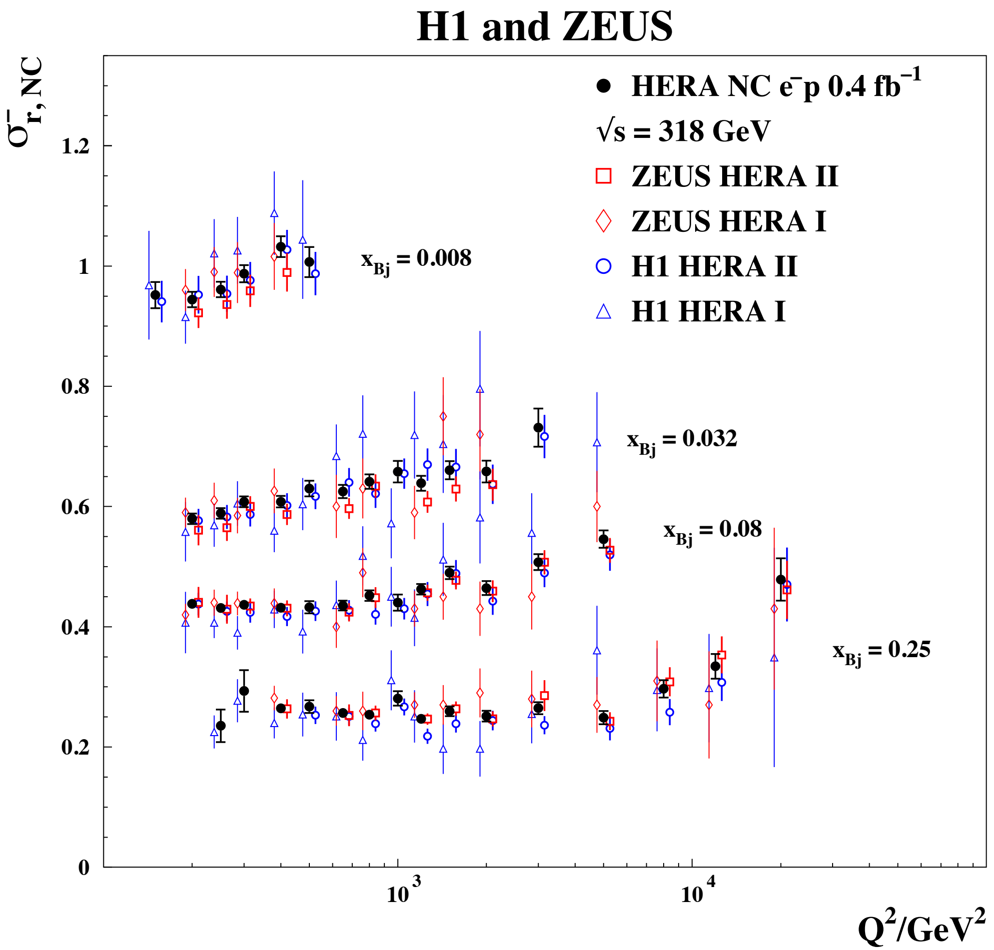
$$\sigma^{\pm}_{r,NC} = \frac{d^2\sigma^{e\pm p}_{NC}}{dx_{Bj}dQ^2} \cdot \frac{Q^4 x_{Bj}}{2\pi\alpha^2 Y_+}$$

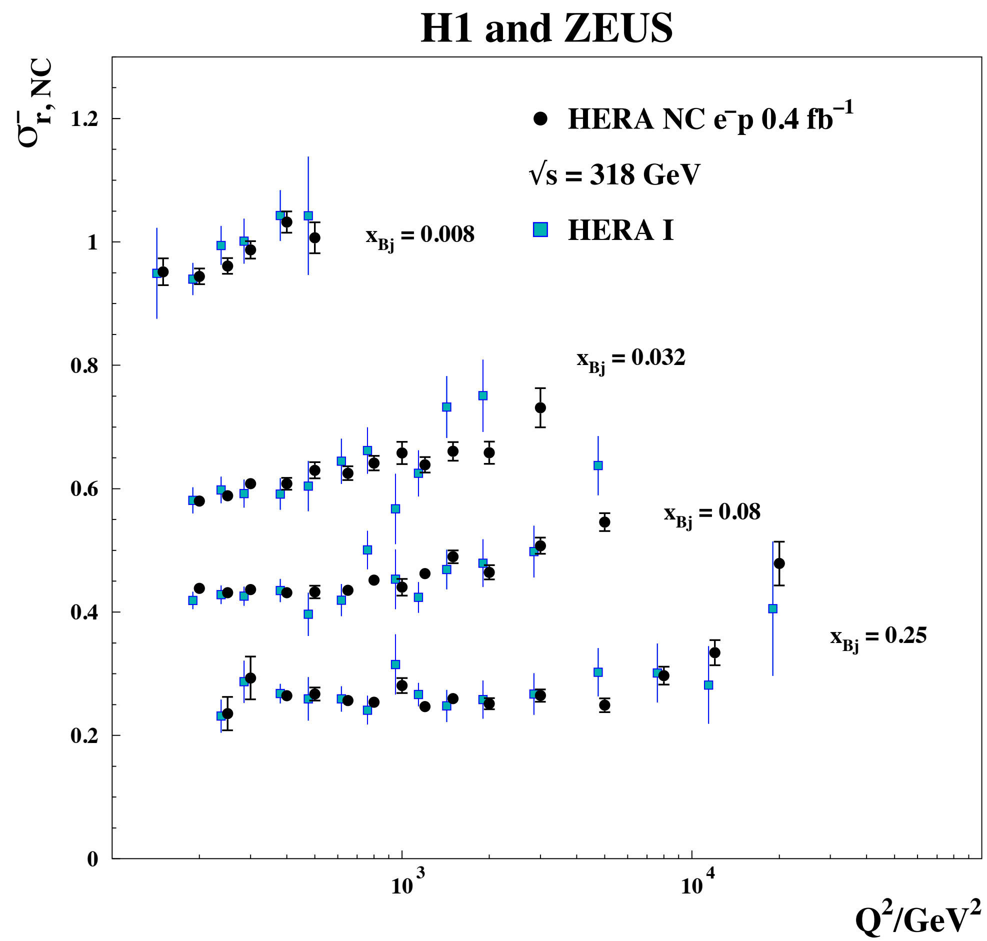
$$= \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

- Up to 6-8 data points combined to 1
- Significantly improved precision

Cross Sections Results: Improved Precision

Reduced NC e⁻p cross section

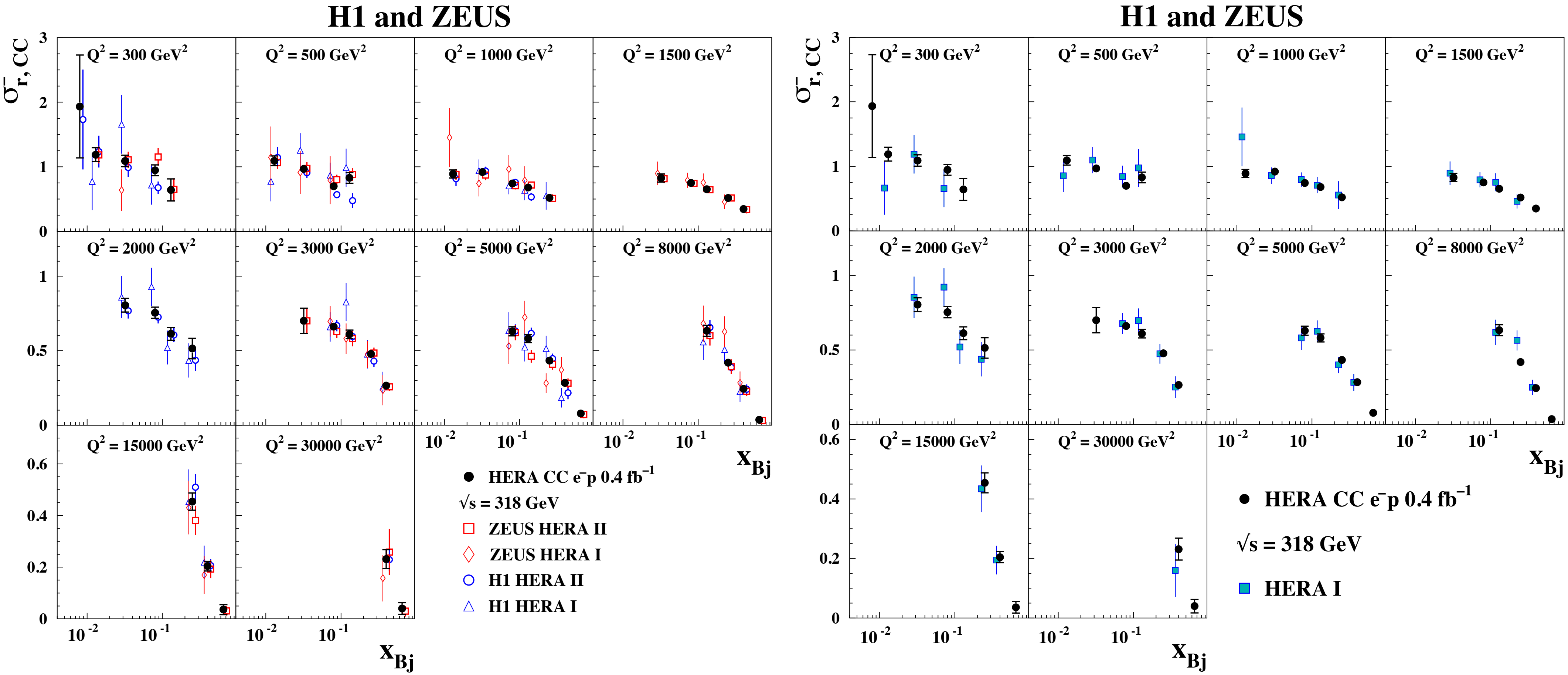




- NC e^+p cross section highest precision:
  total uncertainties < 1.5% for 3 < Q^2 < 500 GeV^2, < 3% up to 3000 GeV^2
- Largest improvement for NC e^-p due to 10x luminosity
- Consistent with previous HERA I results, with improved uncertainties

Cross Sections Results: Improved Precision

Reduced CC e^-p cross section

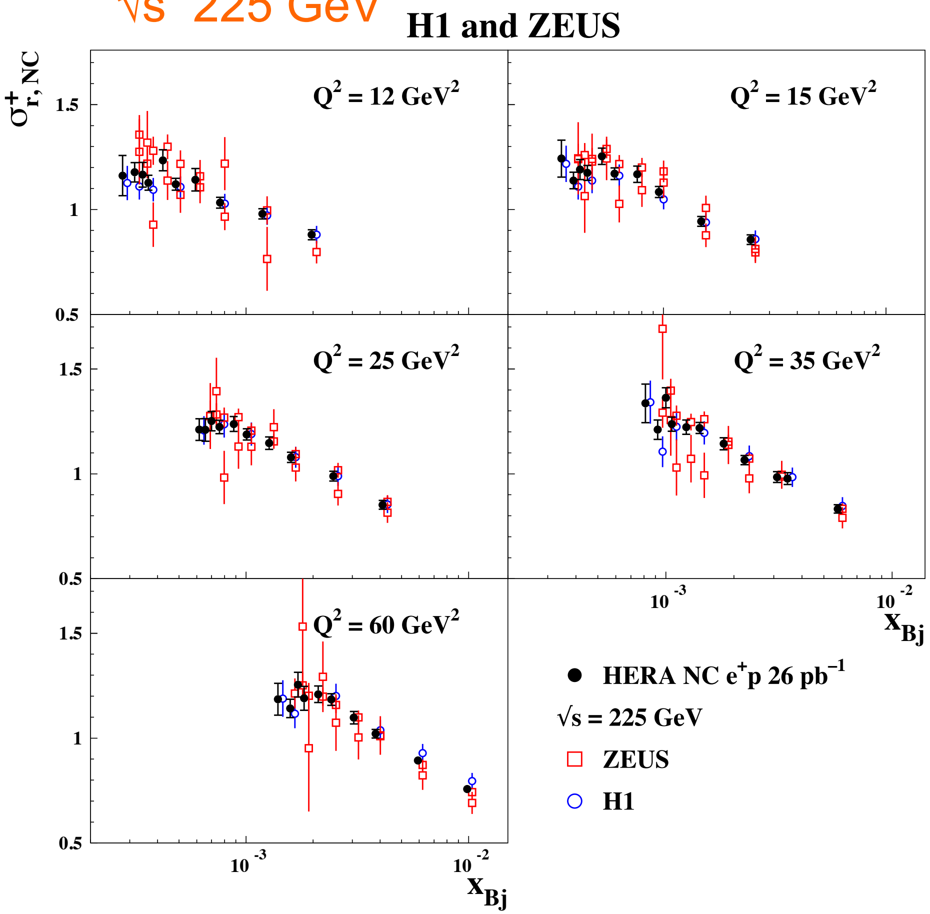


- Significantly reduced statistical error
- Kinematic range extended
- Reduced systematic uncertainties due to cross calibration techniques

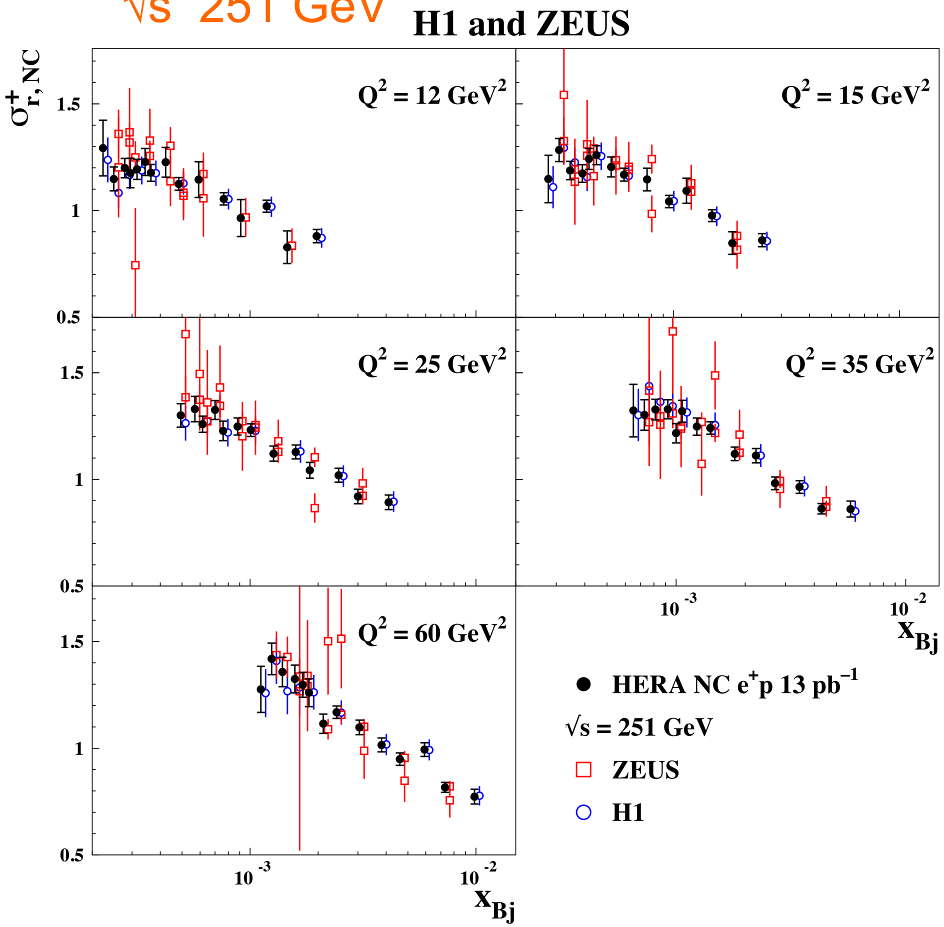
Cross Sections: New Kinematic Range

Reduced NC e^+p cross section

$\sqrt{s}$ 225 GeV



$\sqrt{s}$ 251 GeV

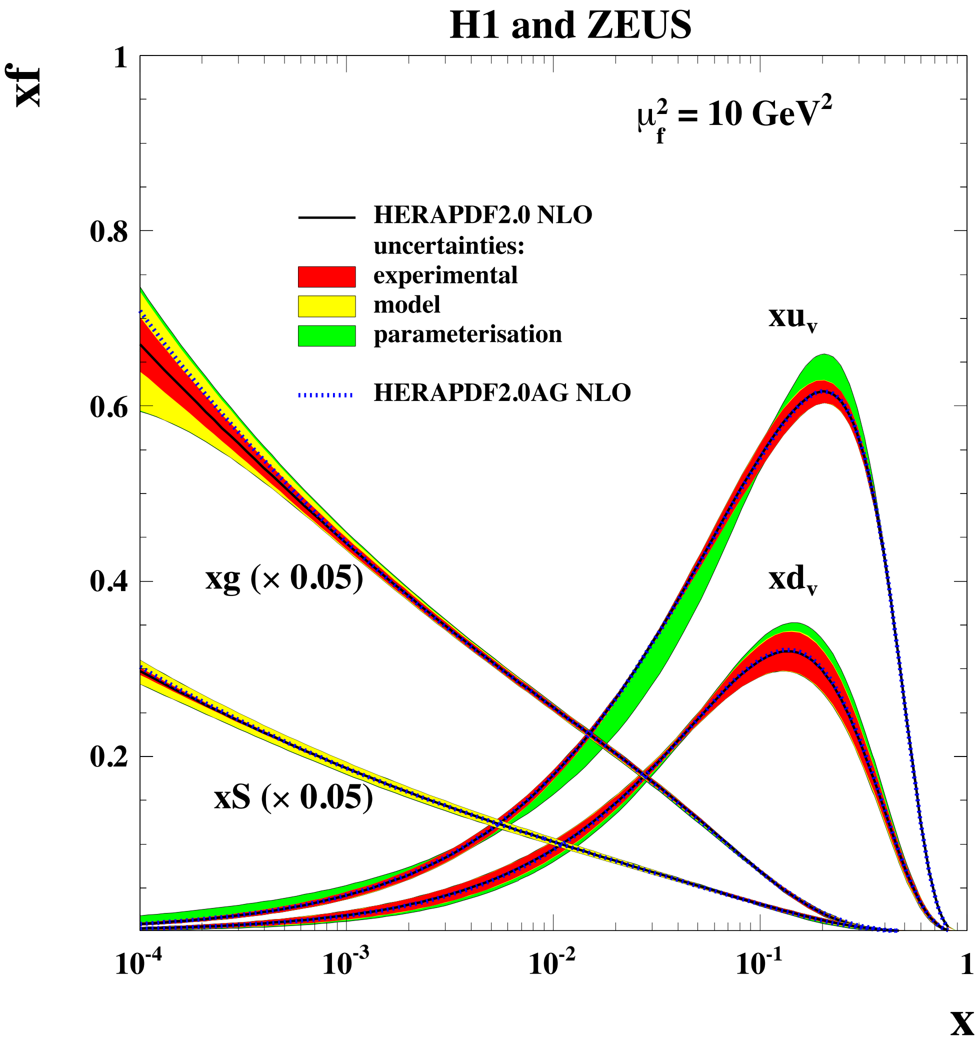


- Kinematic range extended by lowering proton beam energy

QCD Analysis - Parton Distribution Functions

- pQCD predictions fitted to all HERA data to determine HERAPDF2.0
- Predictions obtained by solving DGLAP evolution equations at LO, NLO and NNLO in $\overline{\text{MS}}$ scheme
- Data include 4 different processes: NC and CC for e^+p and e^-p, at 4 p beam energies
  - Can extract xd_v, xu_v, $x\bar{U}$ and $x\bar{D}$ PDFs and xg from scaling violation
- Single consistent data set with small systematic uncertainties
- No heavy-target corrections needed
- Same framework as for HERAPDF1.0
  - $Q^2 > 3.5$ GeV^2 safe kinematic region. W (cm energy at γp vertex) > 15 GeV -> large x_{Bj} higher twist correction neglected
  - $3.5 < Q^2 < 50000$ GeV^2, $0.651\ 10^{-4} < x_{Bj} < 0.65$
  - Included all experimental, model and parametrization uncertainties

HERAPDF2.0 – Error Estimation



Full systematic correlated error treatment

> Experimental uncertainties:

- Used Hessian method with full second-derivative matrix

> Model uncertainties

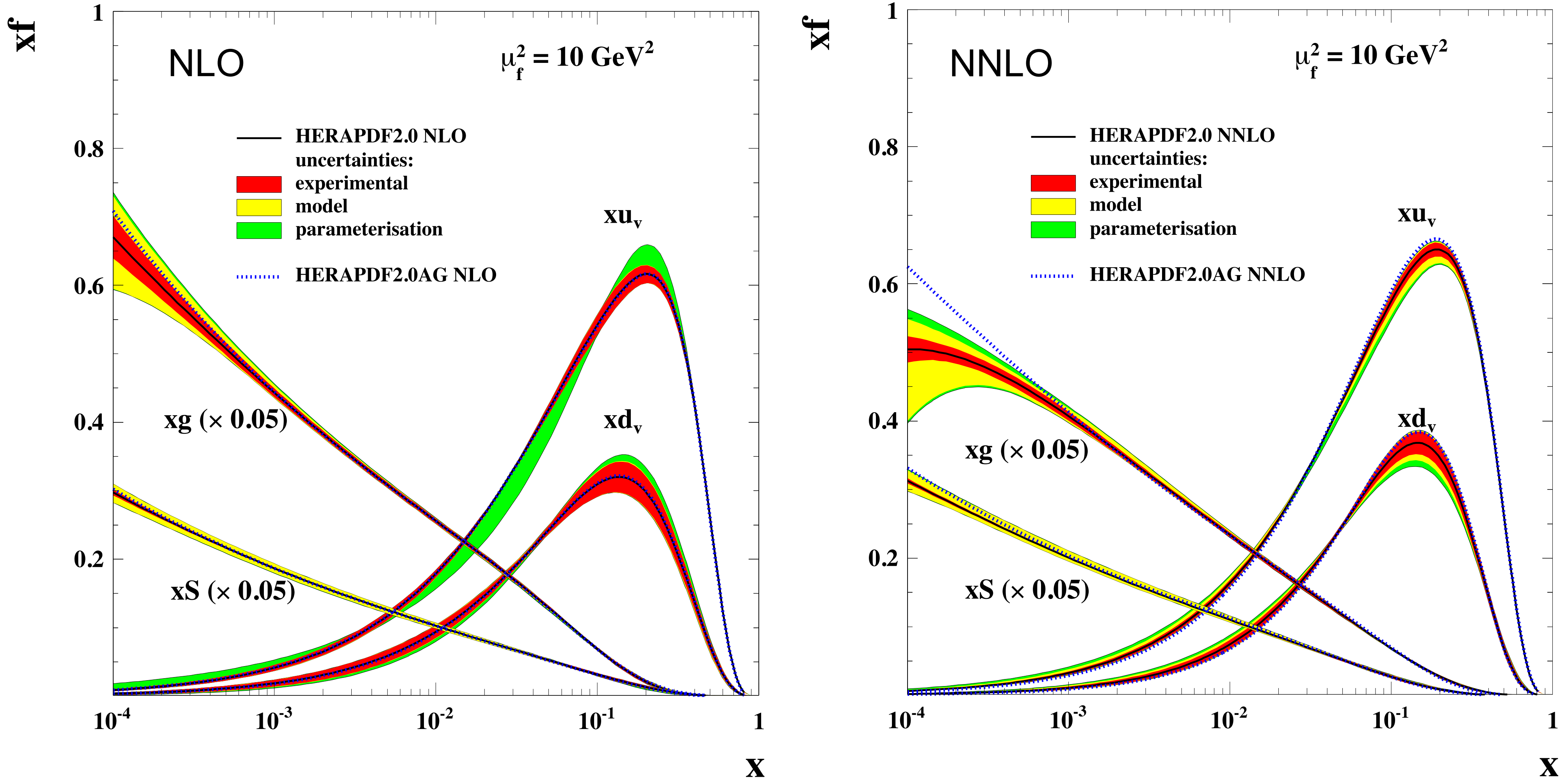
- Varying model assumptions, including Q^2_{min}, c and b masses, strange sea fraction

> Parametrization uncertainties:

- Varying parametrization assumptions, including additional parameters and starting scale in DGLAP equation

HERAPDF2.0 at NLO and NNLO

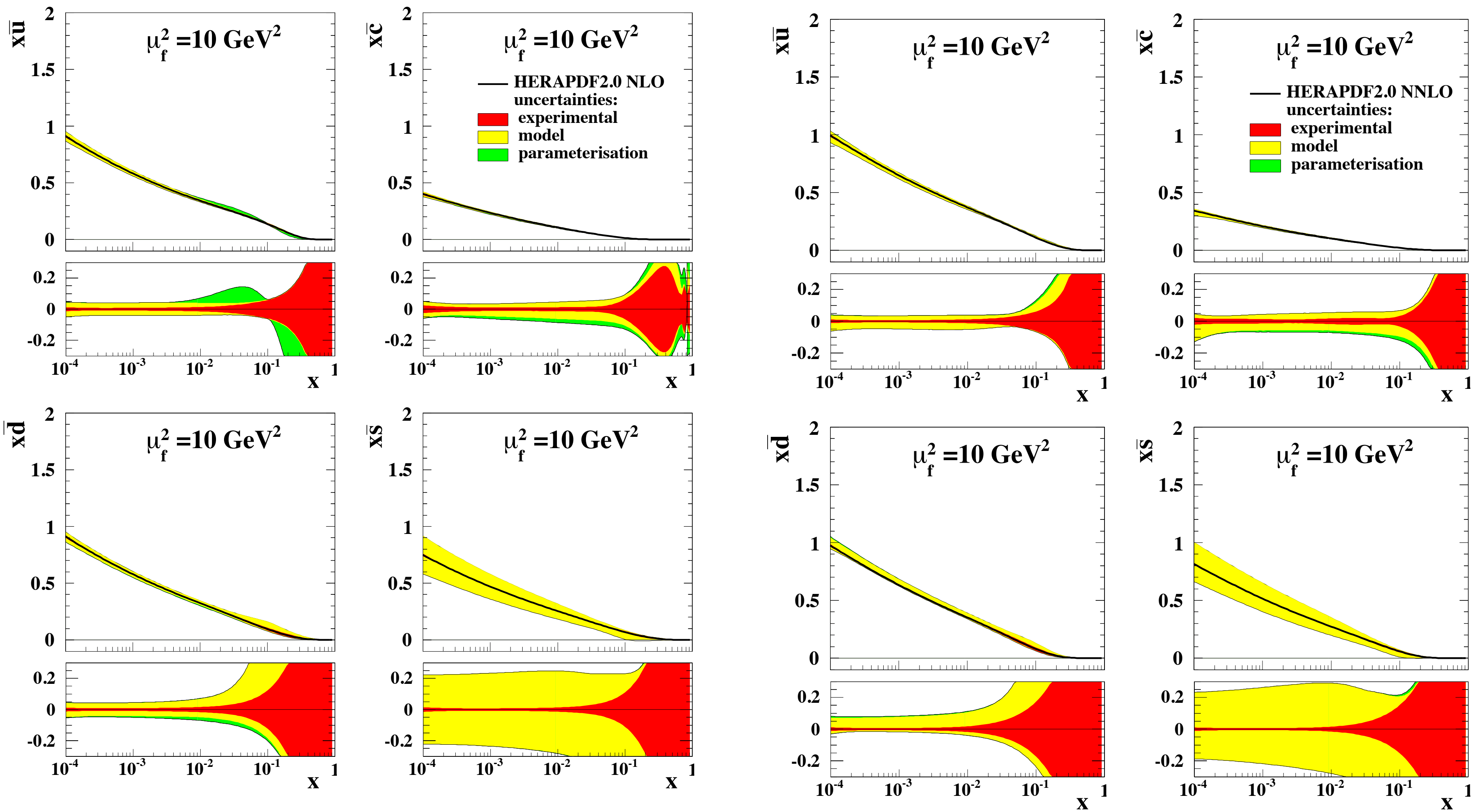
Valence (xu_v, xd_v), sea $(xS = 2x(\bar{U} + \bar{D}))$ and gluon (xg) distributions



- PDFs in variable-flavor-number-scheme (VNFS) at various orders
- Variant with alternative gluon parametrization

HERAPDF2.0 at NLO and NNLO

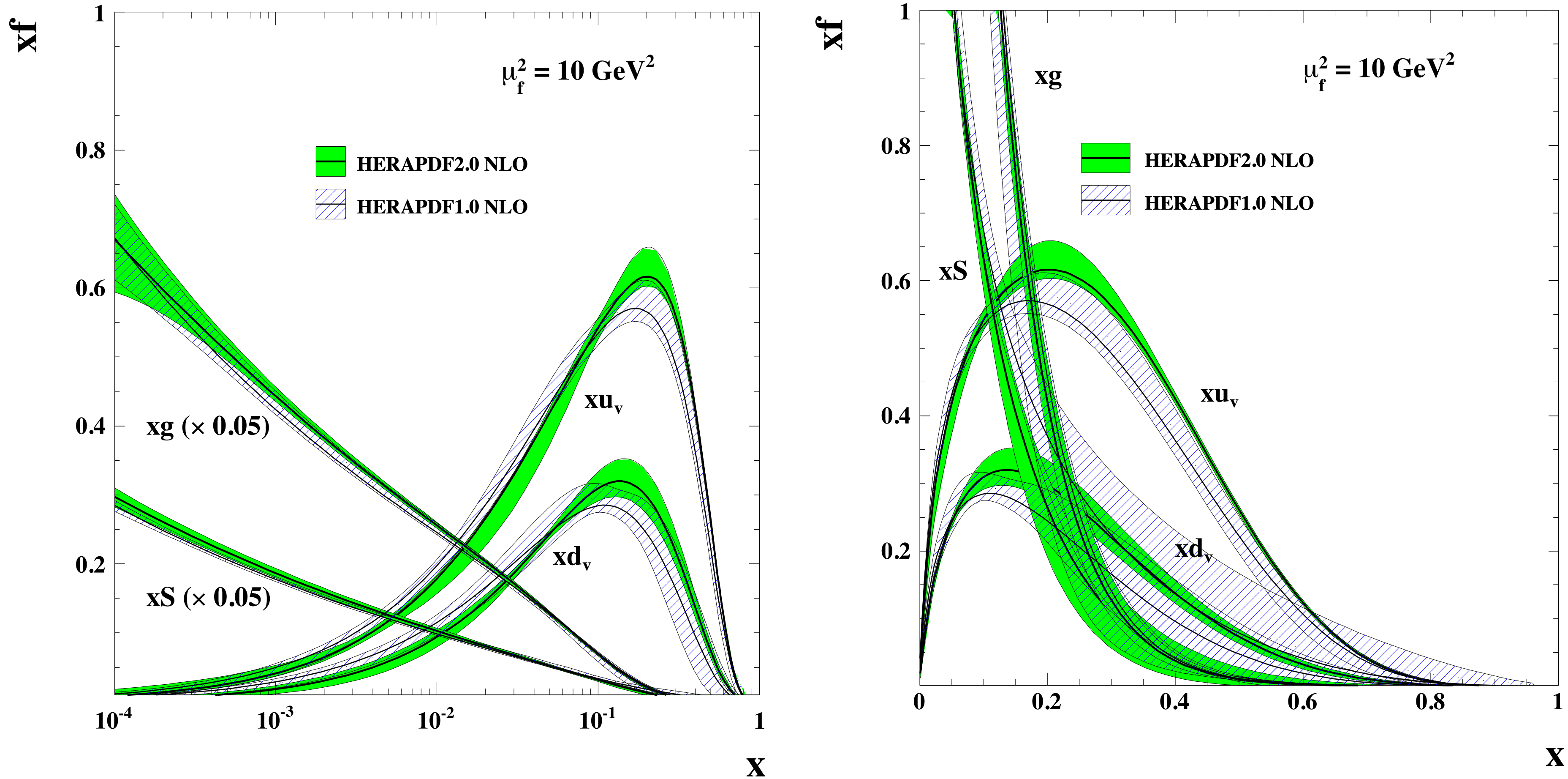
NLO Flavor breakdown of sea distributions NNLO



> NLO and NNLO very similar
> Uncertainties dominated by model uncertainties

HERAPDF1.0 / 2.0 – HERA I / II

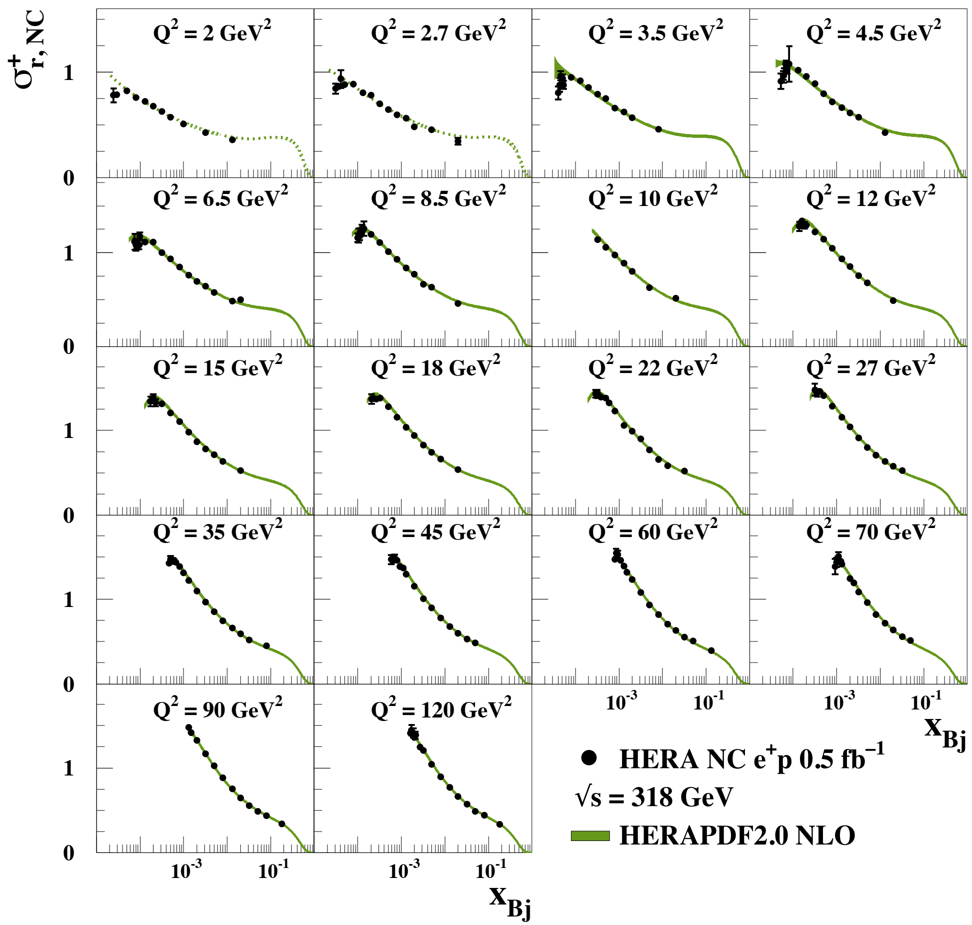
Valence (xu_v, xd_v), sea $(xS = 2x(\bar{U}+\bar{D}))$ and gluon (xg) distributions

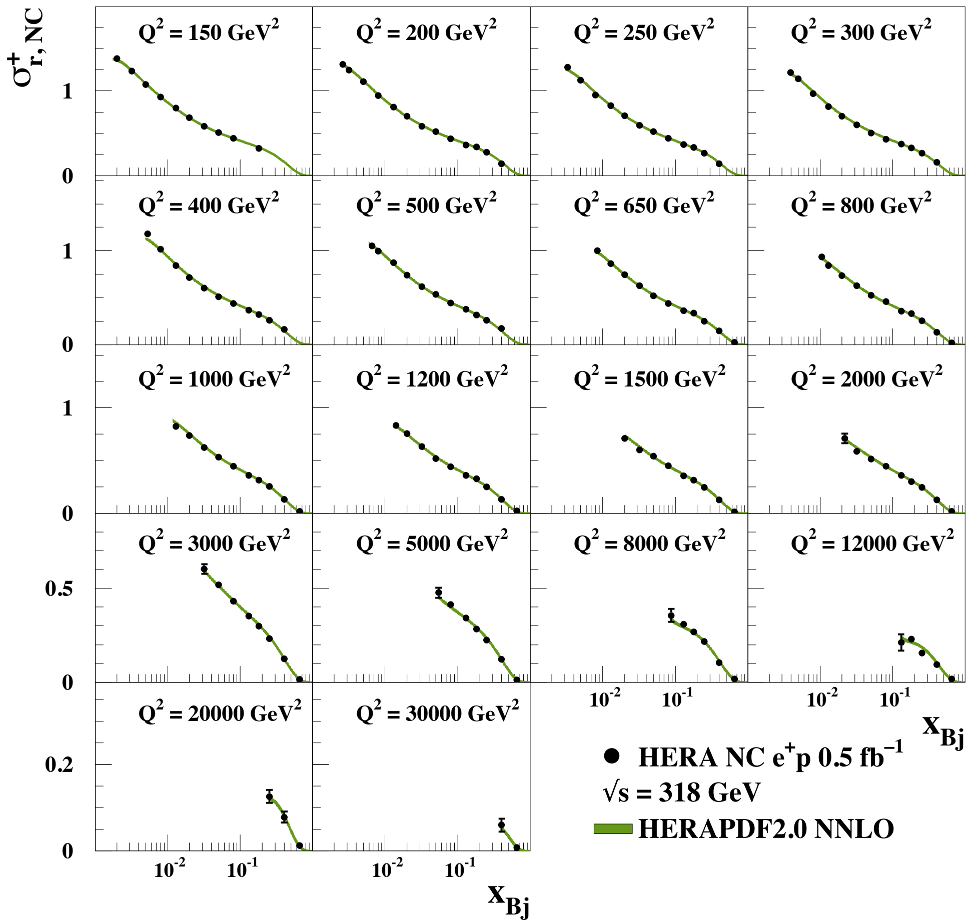


- Valence distributions more peaked at HERAPDF2.0
- High x sea is softer, gluon harder at HERAPDF2.0
- Significantly reduced uncertainties at high x

HERAPDF2.0 Comparison with Data

NC $e^{+}p$ cross section for $2 < Q^2 < 30000$ GeV^2

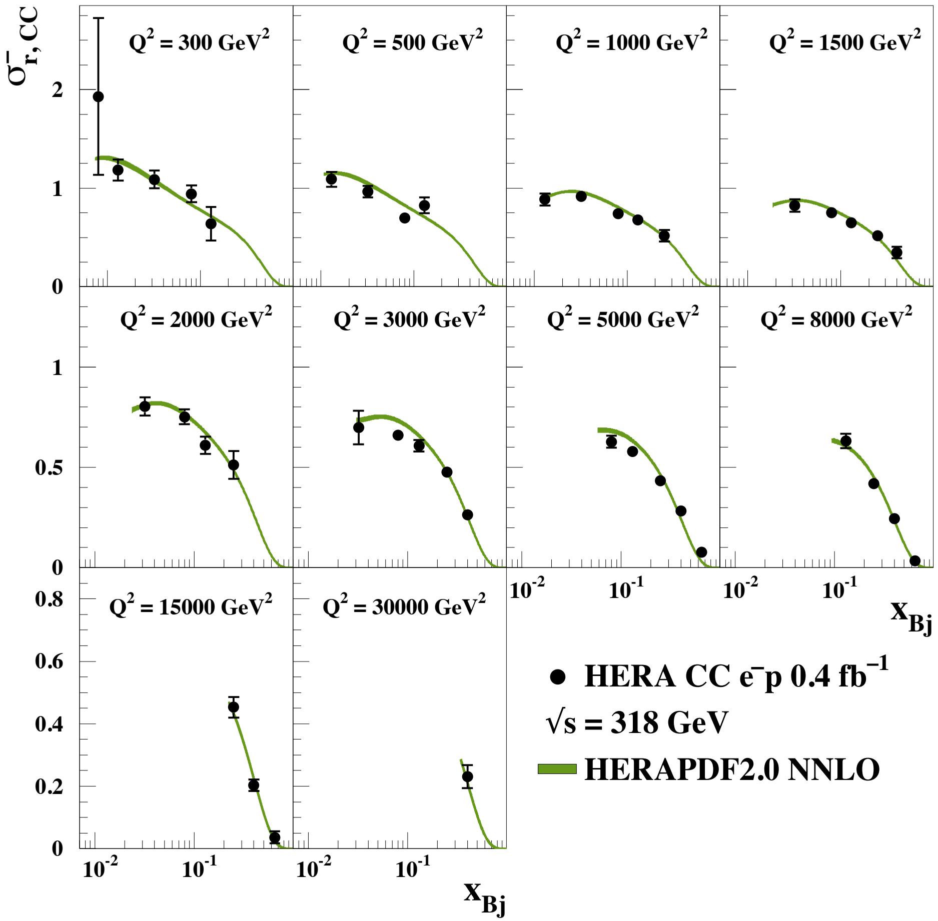




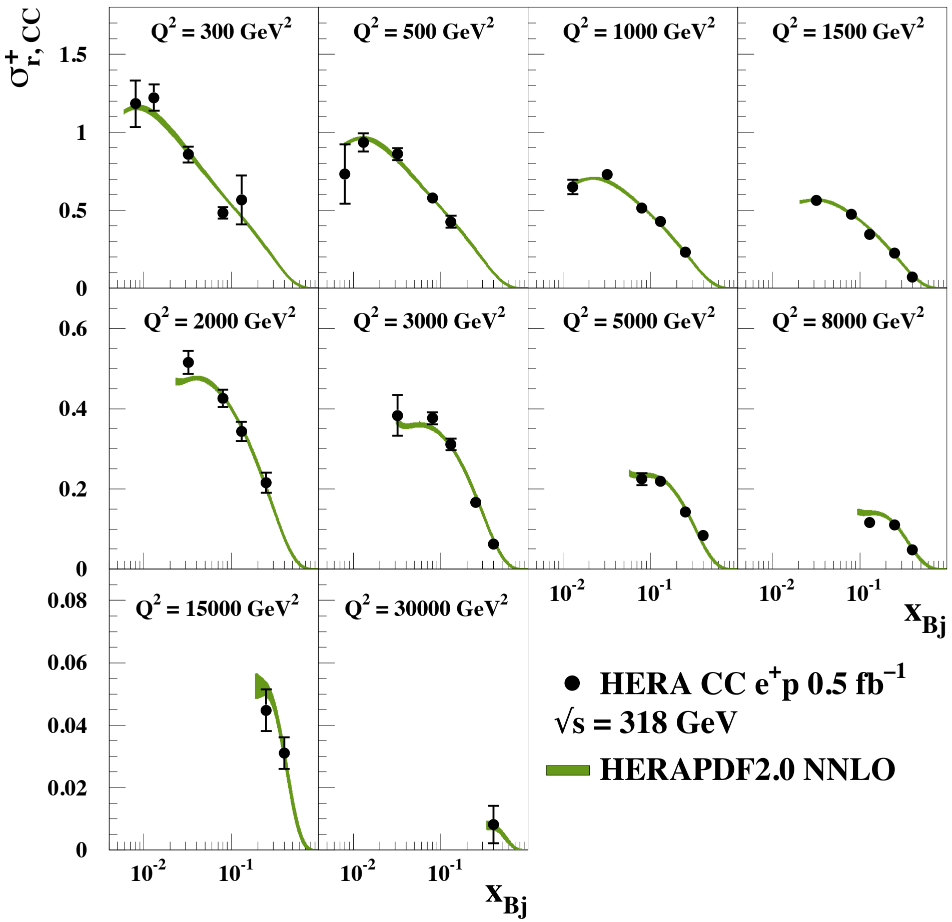
- Excellent agreement with data, except for turnover at low x_{Bj} and low Q^2 due to F_L
- NLO and NNLO fits very similar

HERAPDF2.0 Comparison with CC Data

$$\sigma_{CC}^{-} \sim x\left[u+c\right]+x(1-y)^2\left[\bar{d}+\bar{s}\right]$$



$$\sigma_{CC}^{+} \sim x\left[\bar{u}+\bar{c}\right]+x(1-y)^2\left[d+s\right]$$



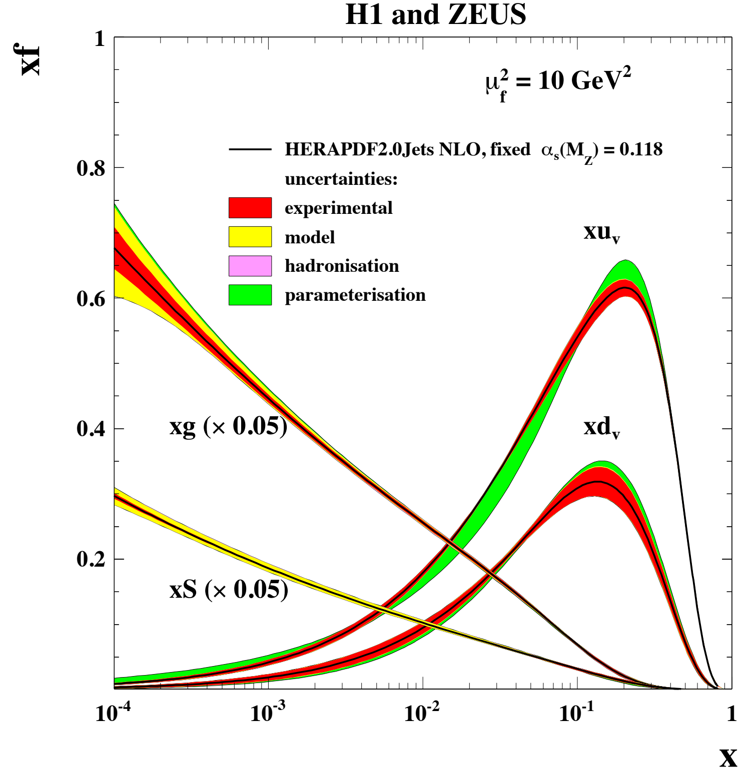
- Good agreement with data
- NLO and NNLO fits very similar

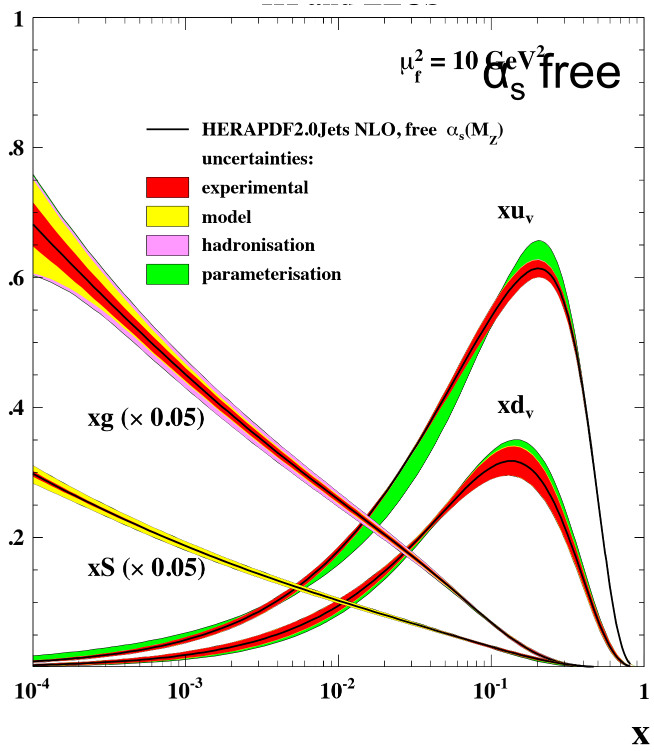
HERAPDF Variants

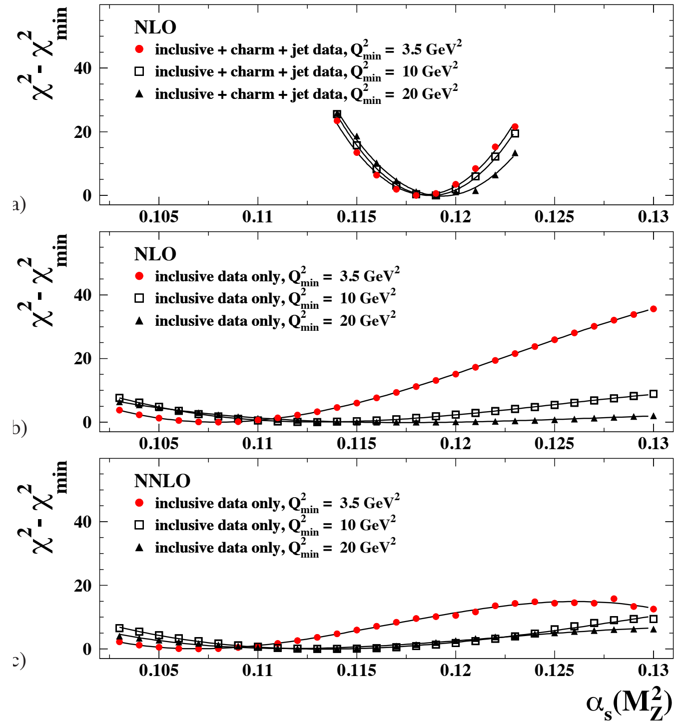
- HERAPDF2.0AG "alternative gluon parametrization":
  - HERAPDF2.0 fits HERA data better. However at NNLO, produces negative gluon distribution for $x < 10^{-4}$ (outside kinematic region of fit).
  - AG: gluon distribution forced to be positive
- HERAPDF2.0HiQ2:
  - $Q^2_{min} > 10\ GeV^2$ instead of $3.5\ GeV^2$
  - Fit lower than data at low x_{Bj} and low Q^2, DGLAP evolution not fully adequate
- HERAPDF2.0FF3A/B
  - Fixed-flavor (FF) scheme instead of variable-flavor-number-scheme (VNFS)
- HERAPDF2.0Jets
  - Adding inclusive + charm + jet data (7 data sets on incl. jet, dijet and trijet at low/high Q^2)
  - Excellent agreement with jet production data

HERAPDF2.0Jets - α_s

Added charm and jet data, NLO at μ_f = 10 GeV^2



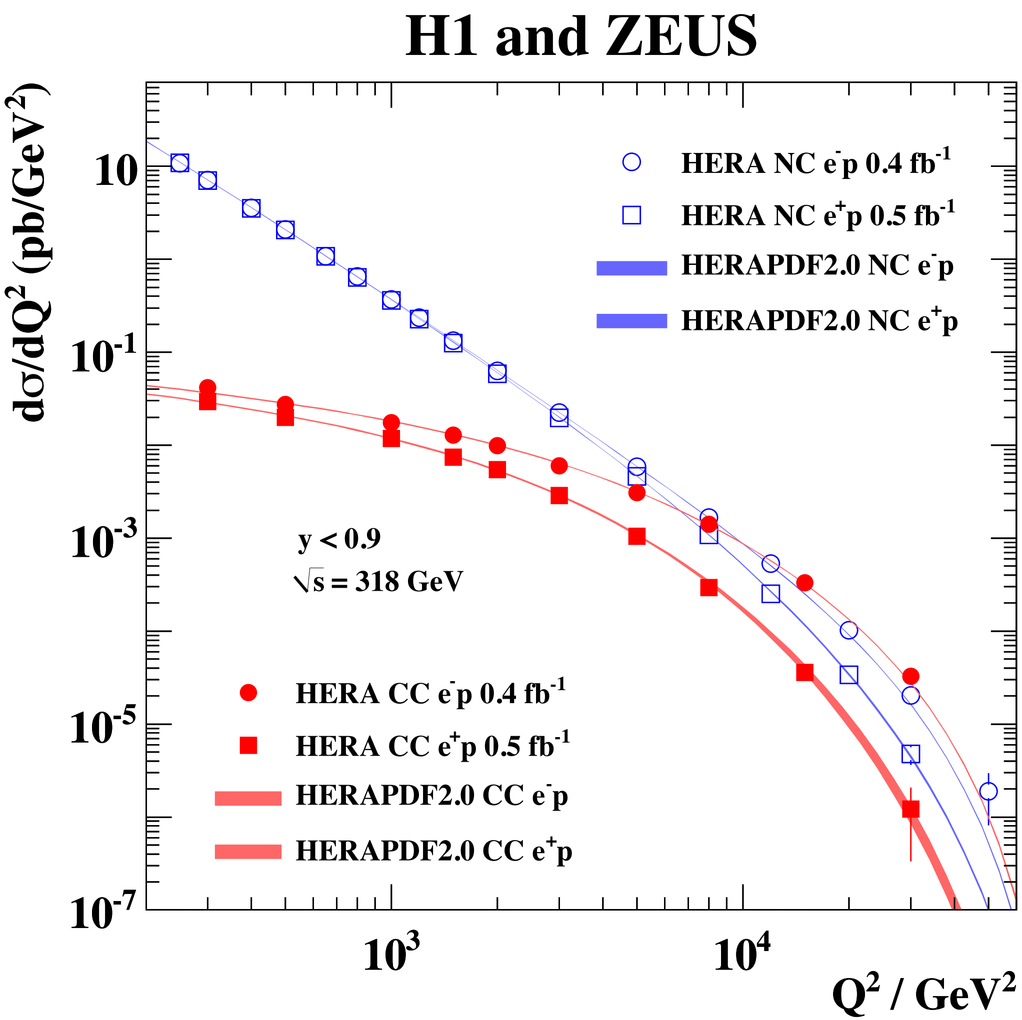




- Fits very similar in both cases. Confirms choice of α_s = 0.118 in fixed fit
- Full treatment of uncertainties in both cases
- Fit with free $\alpha_s(M_Z)$ results in

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

Electroweak Unification



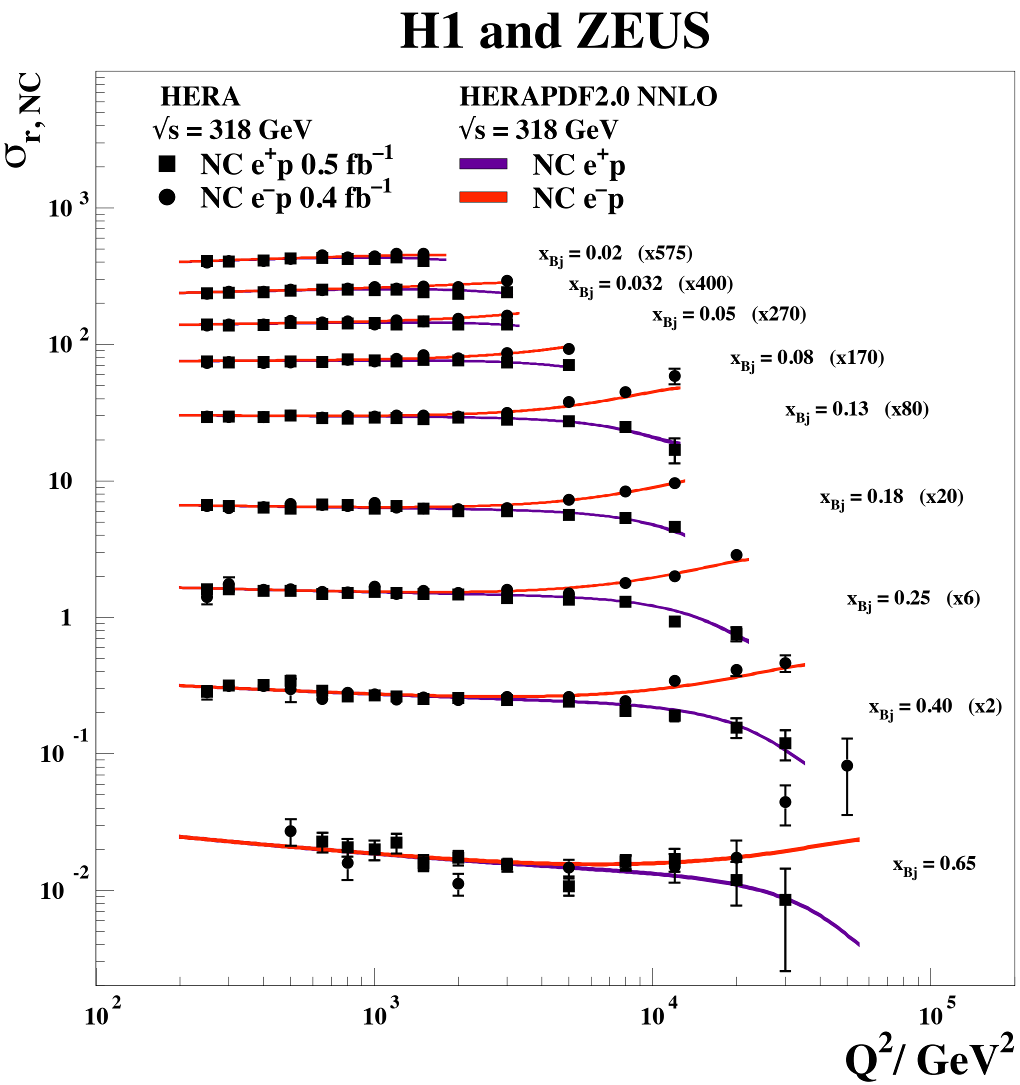
$d^2\sigma/dQ^2\,dx_{Bj}$ integrated over x_{Bj} using HERAPDF2.0 NLO

- Virtual photon exchange dominant for Q < 1000 GeV^2
- NC and CC cross sections similar for $Q^2 > 10000$ GeV^2 demonstrating electroweak unification

Impressive precision

QCD and Electroweak Effects

Reduced NC e^+p and e^-p cross sections

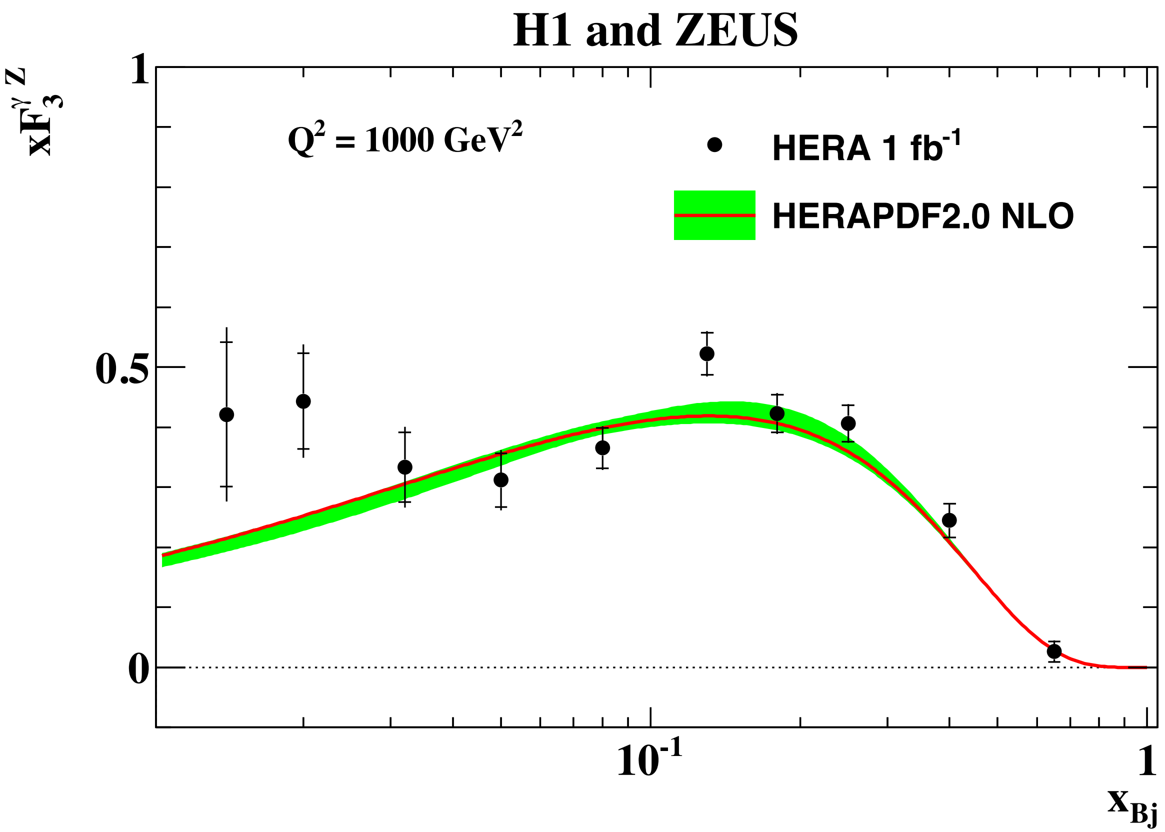


$$\sigma^{\pm}_{r,NC} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

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

At high Q^2 e^+p and e^-p cross sections differ due to γ-Z interference

Structure Function $xF_3^{\gamma Z}$



$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\sigma^-_{r,NC} - \sigma^+_{r,NC})$$

at HERA $\quad x\tilde{F}_3^{\gamma Z} \approx \frac{x}{3}(2u_v + d_v)$

- Sensitive at valence quark distributions
- Good agreement with prediction (translated to common scale of 1000 GeV^2)

Integrated over x

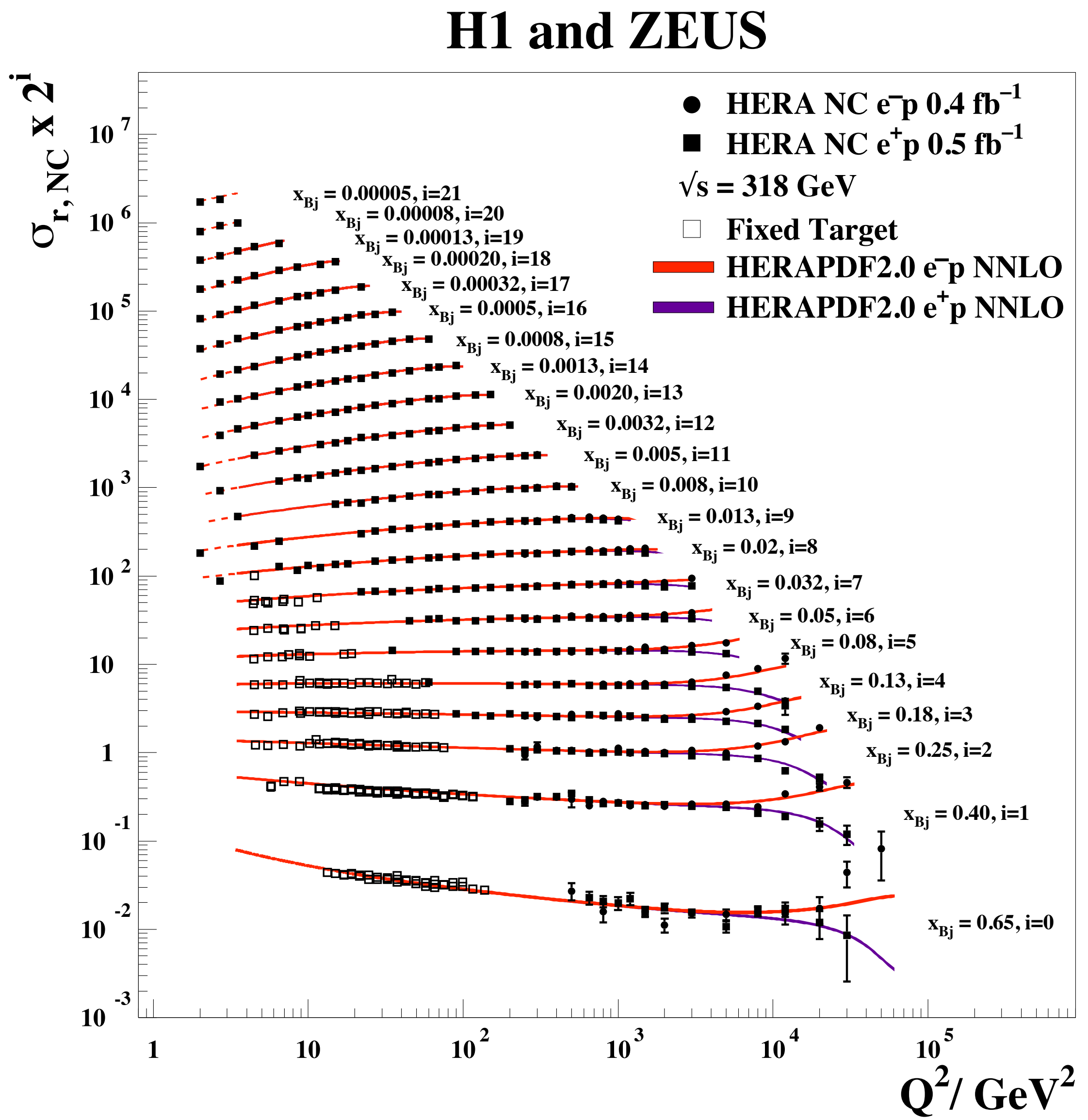
$0.016 < x_{Bj} < 0.725$ HERAPDF2.0: $1.165^{+0.042}_{-0.053}$ Data: $1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst})$

$0 < x_{Bj} < 1$ HERAPDF2.0: $1.588^{+0.078}_{-0.100}$ Data: $1.790 \pm 0.078(\text{stat}) \pm 0.078(\text{syst})$

QPM prediction: 5/3

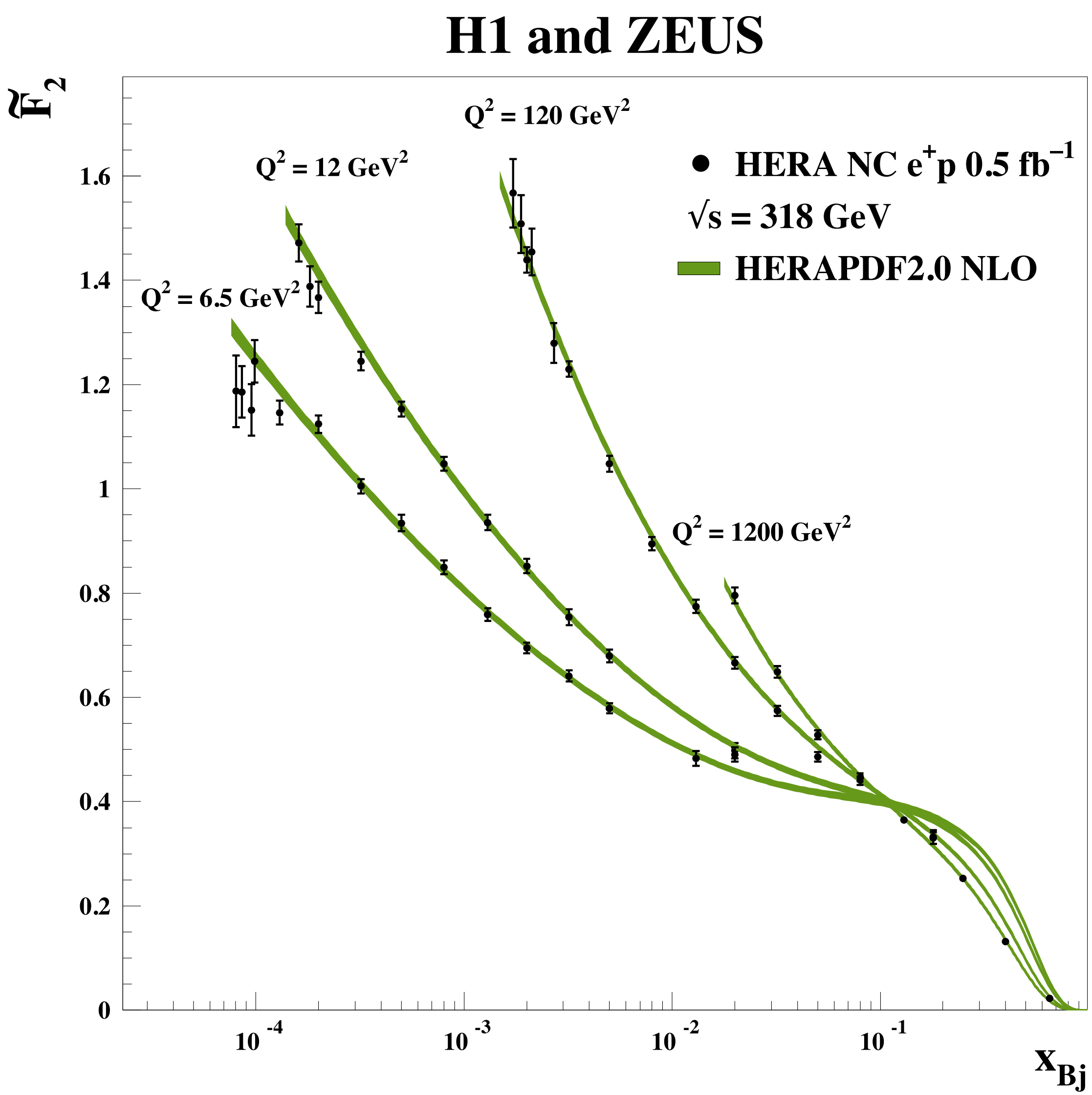
Scaling Violations

Reduced NC e⁻p and e⁺p cross sections



- Scaling violations clearly visible
  - Increasing gluon content of proton with decreasing x_{Bj}
- Well described by HERAPDF2.0 NLO and NNLO

Low - x Rise of F_2 Structure Function



For phase space with small $x\tilde{F}_3$ and $\tilde{F}_L$

$$\tilde{F}_2 = \sigma^{\pm}_{r,NC} \frac{\tilde{F}_2^{predicted}}{\sigma^{\pm\,predicted}_{r,NC}} = \sigma^{\pm}_{r,NC}(1 + C_F)$$

- Prediction computed using HERAPDF2.0 NLO
- Plot selected values with $|C_F| < 0.1$
- Steep rise of $\tilde{F}_2$, becomes steeper as Q^2 increases
  - Increasing gluon density
- Well described by HERAPDF2.0

Conclusions

- H1 and ZEUS measured inclusive $e^{\pm}p$ cross sections from 1994 to 2007
- Final combination of all inclusive data, total integrated luminosity ~1 fb^{-1}
- High precision cross sections spanning six orders of magnitude in both Q^2 and x_{Bj}
  - Most precise ever published for ep scattering in such large kinematic region
- QCD analysis performed to obtain parton density functions HERAPDF2.0 at LO, NLO and NNLO
  - Including several variants (fixed flavor scheme, high Q^2)
- Precise measurement of $\alpha_s(M_Z)$ done using QCD fit including jet- and charm cross sections measured by H1 and ZEUS
- Electroweak effects studied
- These precision DIS data are one of the legacies of HERA

- Only presented brief summary of very sophisticated analysis.
- Details presented at DIS, Dallas 2015 (4 talks), 150+ page paper to be submitted soon