

HERA crown jewels: inclusive cross sections



arXiv.org > hep-ex > arXiv:1506.06042

High Energy Physics – Experiment

Combination of Measurements of Inclusive Deep Inelastic $e^\pm p$ Scattering Cross Sections and QCD Analysis of HERA Data

H1, ZEUS Collaborations

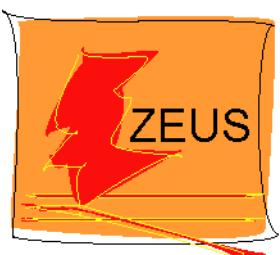
(Submitted on 19 Jun 2015)

DESY-15-039, accepted by EPJC

K. Wichmann on behalf of H1 and ZEUS Collaborations



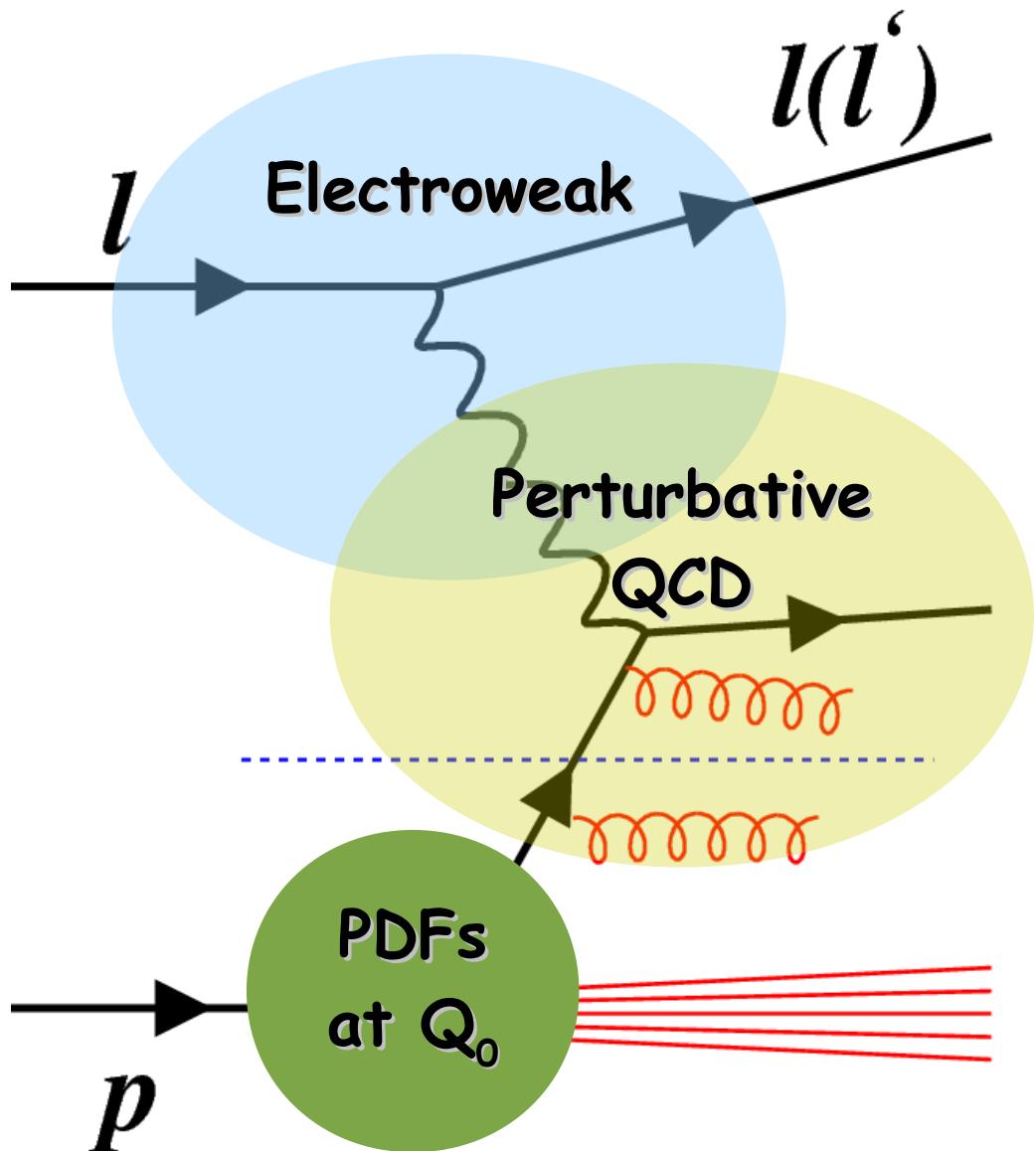
HERA accelerator



Two colliding experiments



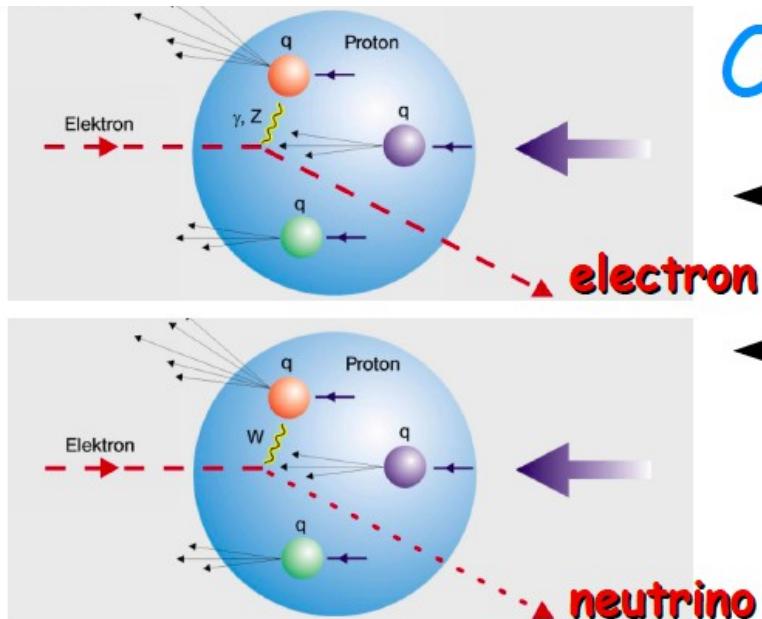
Deep Inelastic Scattering @ HERA



- Fix pQCD & PDFs
! Test Electroweak
- Fix Electroweak
! Test pQCD & PDFs

- Fix Electroweak & pQCD
! Determine PDFs

See talk of V. Radescu



Combined inclusive DIS

Neutral Current (NC)

γ, Z^0 exchange

Charged Current (CC)

W^\pm exchange

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

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

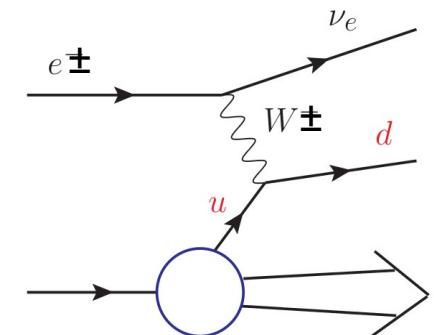
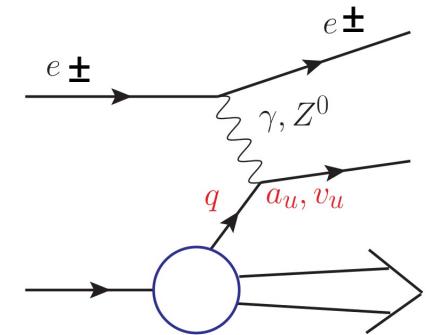
$$s = (p + k)^2 \quad Q^2 = x \cdot y \cdot s$$

H1 and ZEUS published all HERA inclusive DIS measurements - 1 fb⁻¹

Now we combine these measurements

Inclusive DIS data samples

- 41 final data sets with HERA inclusive measurements
- NCep and CCep
 - 21 HERA I data samples
 - 20 HERA II data samples, including:
 - 8 inclusive HERA II $E_p = 920 \text{ GeV}$
 - 4 high y data $E_p = 920 \text{ GeV}$
 - 4 high y data $E_p = 575 \text{ GeV}$
 - 4 high y data $E_p = 460 \text{ GeV}$
- Data 1994-2007: over 10 years of data taking!
- 22 papers between 1997-2015: almost 20 years of data analysis!

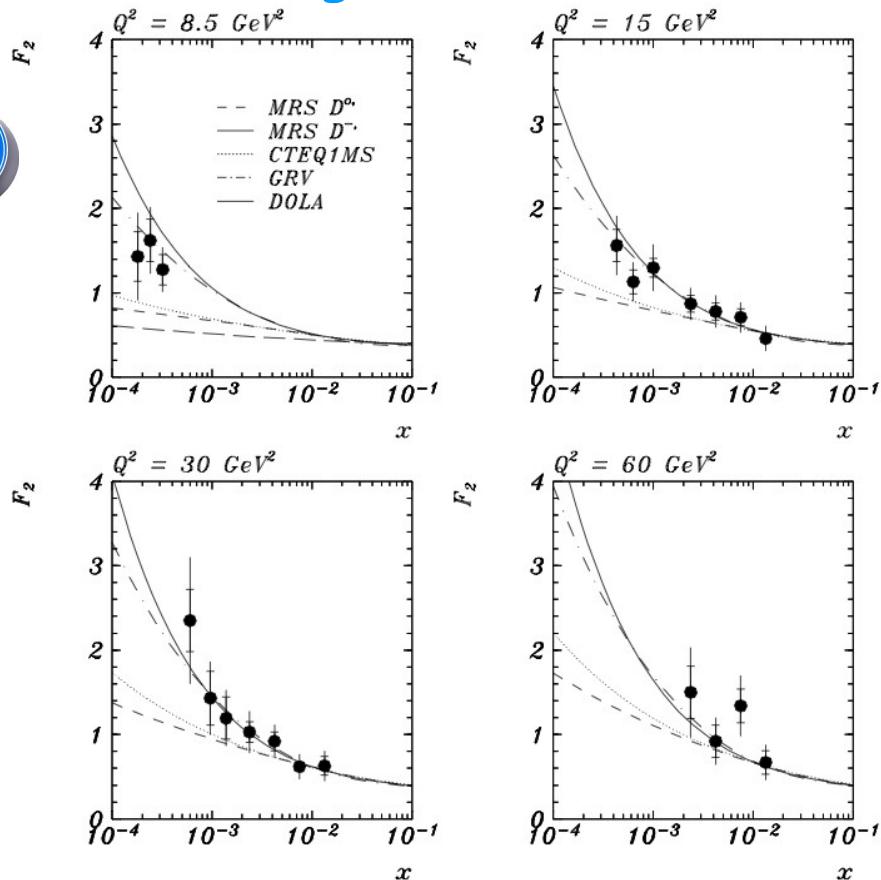


Total of 2927 data points combined to 1307

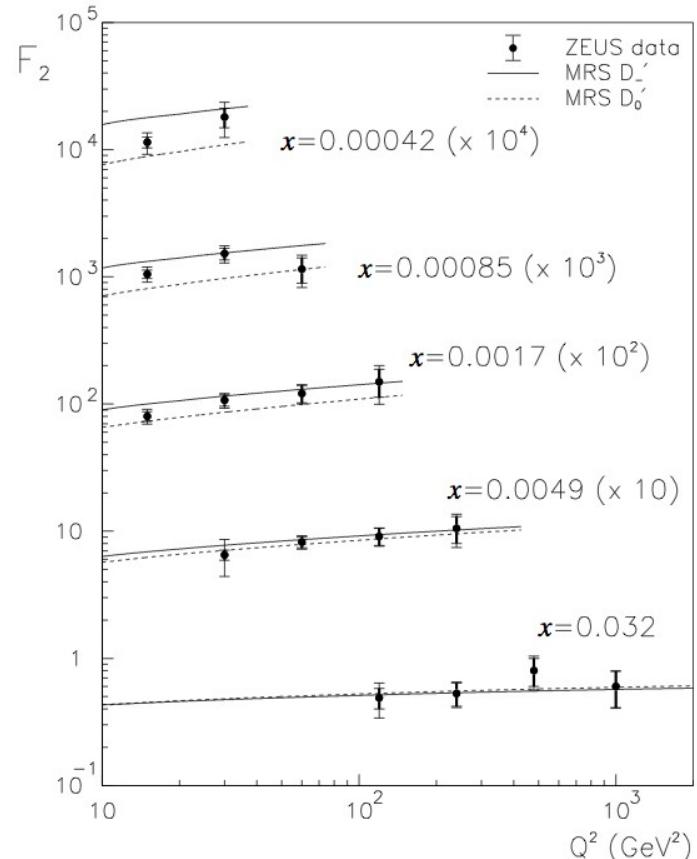
First F_2 measurements @ HERA: 1993

$\sim 20 \text{ nb}^{-1} \rightarrow 1 \text{ fb}^{-1}$

August 25th



August 13th



The F_2 structure function increases rapidly as x decreases.
it is exciting to see F_2 rise at small x .

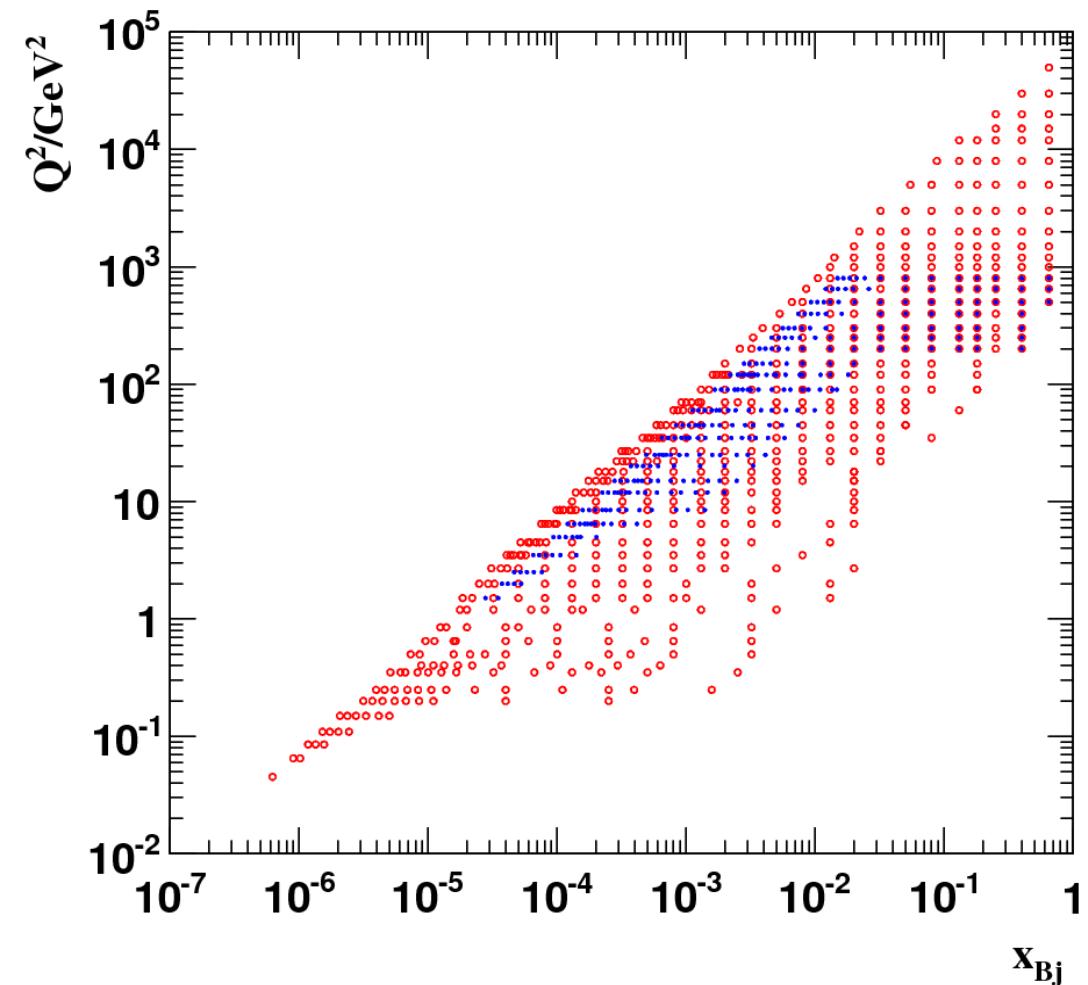
Full publication list

- F. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **63**, 625 (2009), [arXiv:0904.0929].
- F. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **64**, 562 (2009), [arXiv:0904.3513].
- C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. C **13**, 609 (2000), [hep-ex/9908059].
- C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. C **19**, 269 (2001), [hep-ex/0012052].
- C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. C **30**, 1 (2003), [hep-ex/0304003].
- F. Aaron *et al.* [H1 Collaboration], JHEP **1209**, 061 (2012), [arXiv:1206.7007].
- V. Andreev *et al.* [H1 Collaboration], Eur. Phys. J. C **73**, 2814 (2013), [arXiv:1312.4821].
- F. Aaron *et al.* [H1 Collaboration], Eur. Phys. J. C **71**, 1579 (2011), [arXiv:1012.4355].
- J. Breitweg *et al.* [ZEUS Collaboration], Phys. Lett. B **407**, 432 (1997), [hep-ex/9707025].
- J. Breitweg *et al.* [ZEUS Collaboration], Phys. Lett. B **487**, 53 (2000), [hep-ex/0005018].
- J. Breitweg *et al.* [ZEUS Collaboration], Eur. Phys. J. C **7**, 609 (1999), [hep-ex/9809005].
- S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **21**, 443 (2001), [hep-ex/0105090].
- J. Breitweg *et al.* [ZEUS Collaboration], Eur. Phys. J. C **12**, 411 (2000), [Erratum-ibid. C **27**, 305 (2003), [hep-ex/9907010].
- S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **28**, 175 (2003), [hep-ex/0208040].
- S. Chekanov *et al.* [ZEUS Collaboration], Phys. Lett. B **539**, 197 (2002), [Erratum-ibid. B **552**, 308 (2003)], [hep-ex/0205091].
- S. Chekanov *et al.* [ZEUS Collaboration], Phys. Rev. D **70**, 052001 (2004), [hep-ex/0401003].
- S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **32**, 1 (2003), [hep-ex/0307043].
- S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **62**, 625 (2009), [arXiv:0901.2385].
- S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **61**, 223 (2009), [arXiv:0812.4620].
- H. Abramowicz *et al.* [ZEUS Collaboration], Phys. Rev. D **87**, 052014 (2013), [arXiv:1208.6138].
- H. Abramowicz *et al.* [ZEUS Collaboration], Eur. Phys. J. C **70**, 945 (2010), [arXiv:1008.3493].
- H. Abramowicz *et al.* [ZEUS Collaboration], Phys. Rev. D **90**, 072002 (2014), [arXiv:1404.6376].

DESY-15-039
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Q^2 - x_{Bj} common grids

H1 and ZEUS

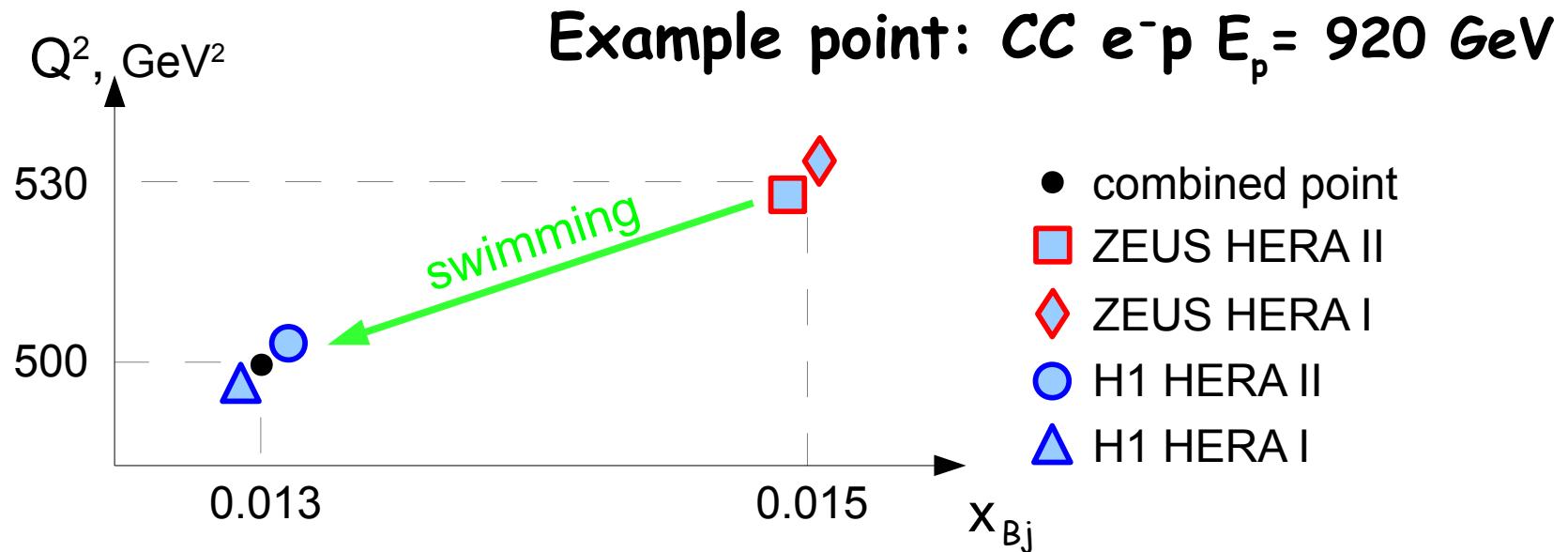


Two separate grids

- inclusive grid, for $E_p = 920 \text{ GeV}$ and $E_p = 820 \text{ GeV}$ data sets
- fine- x_{Bj} grid, for $E_p = 575 \text{ GeV}$ and $E_p = 460 \text{ GeV}$ data sets

- 1307 grid points
 - $0.045 < Q^2 < 50000 \text{ GeV}^2$
 - $6 \times 10^{-7} < x_{Bj} < 0.65$

Swimming procedure



- Swimming done iteratively using our own data &
- 1st iteration uncombined HERA I+II data, later - combined data



herafitter.org
arXiv:1503.05221

Fractal fit



- Swimming factors are usually at level of few %

Averaging procedure

- Combination done using HERAverager: wiki-zeuthen.desy.de/HERAverager

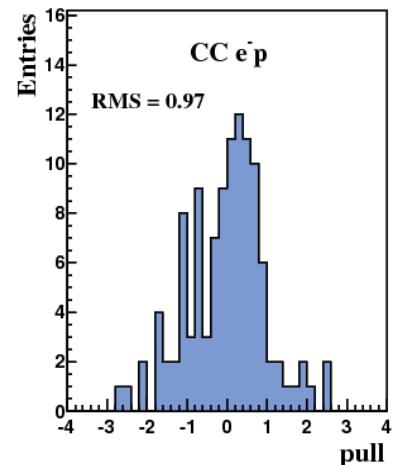
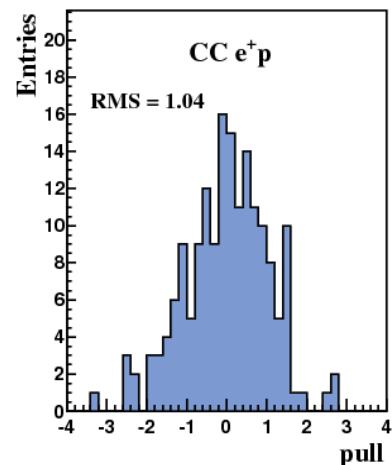
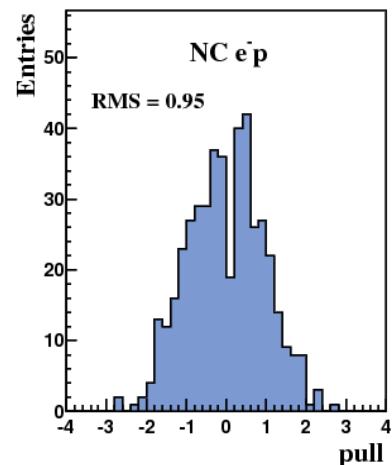
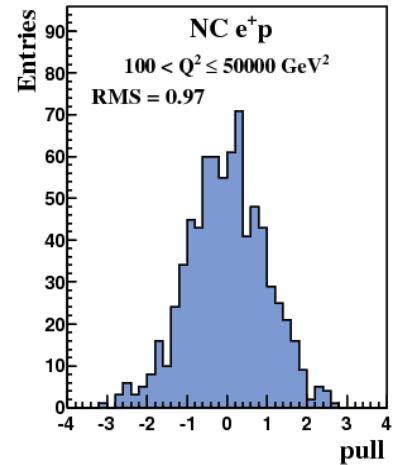
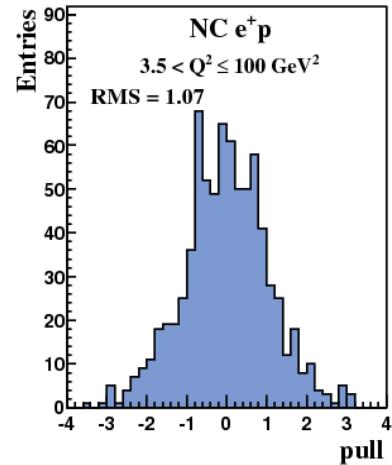
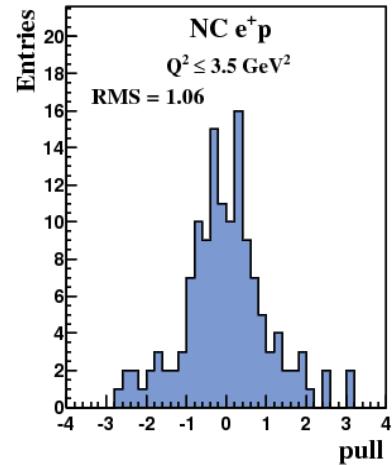
$$\chi^2_{\text{exp},ds}(\mathbf{m}, \mathbf{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma_j^{i,ds} m^i b_j - \mu^{i,ds} \right]^2}{\delta_{i,ds,\text{stat}}^2 \mu^{i,ds} \left(m^i - \sum_j \gamma_j^{i,ds} m^i b_j \right) + \left(\delta_{i,ds,\text{uncor}} m^i \right)^2} + \sum_j b_j^2$$

- 162 correlated systematic sources taken into account
- Results
 - 7 data samples for $e^\pm p$, NC and CC, 3 CMEs
 - Available at <https://www.desy.de/h1zeus/inclusive/herapdf20/>
 - Statistical and uncorrelated systematic uncertainties
 - 162 correlated statistical uncertainties
 - 7 procedural uncertainties calculated → see additional material

Averaging results

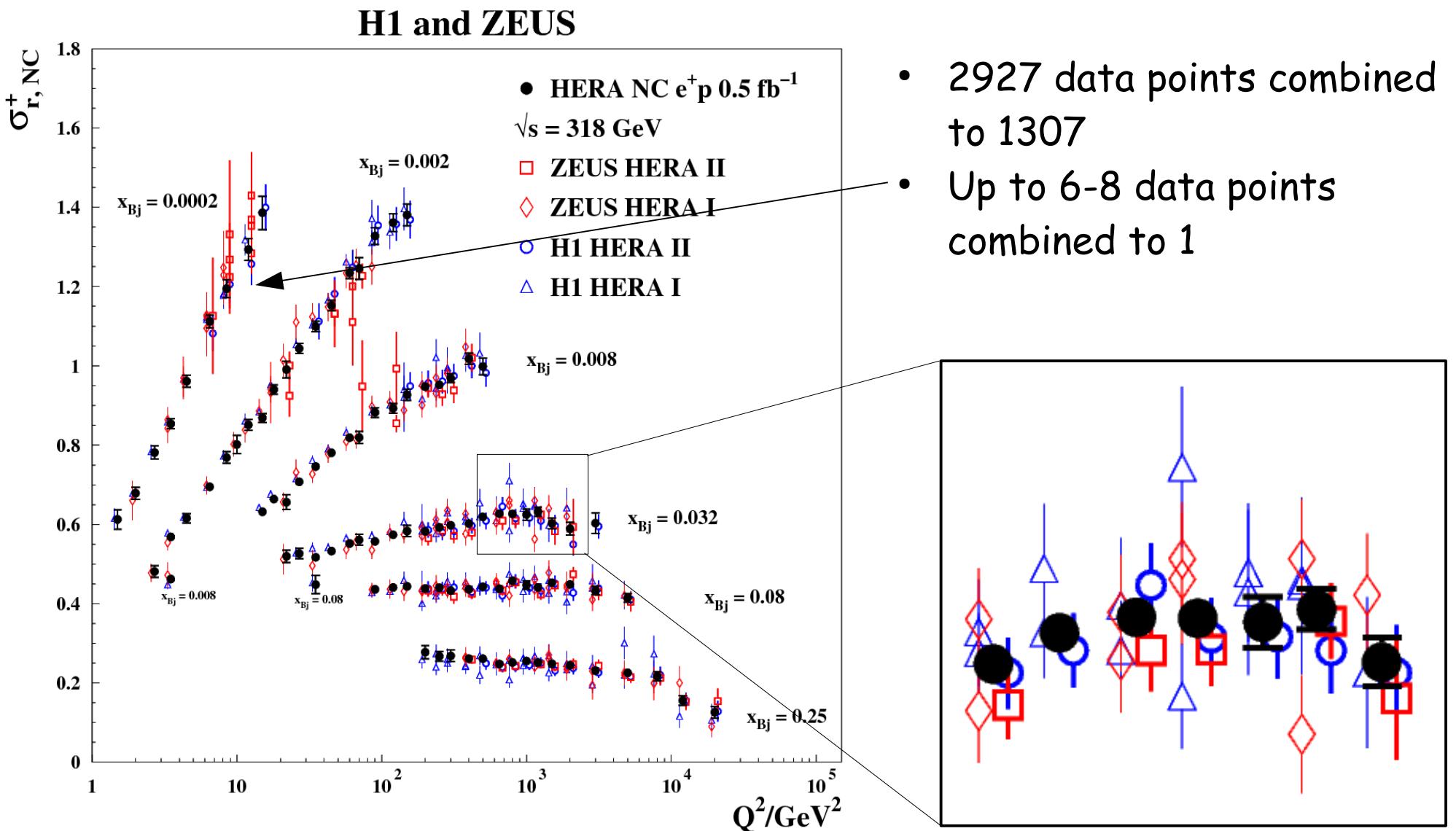
$$p^{i,k} = \frac{\mu^{i,k} - \mu^i \left(1 - \sum_j \gamma_j^{i,k} b'_j\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_i^2}}$$

H1 and ZEUS



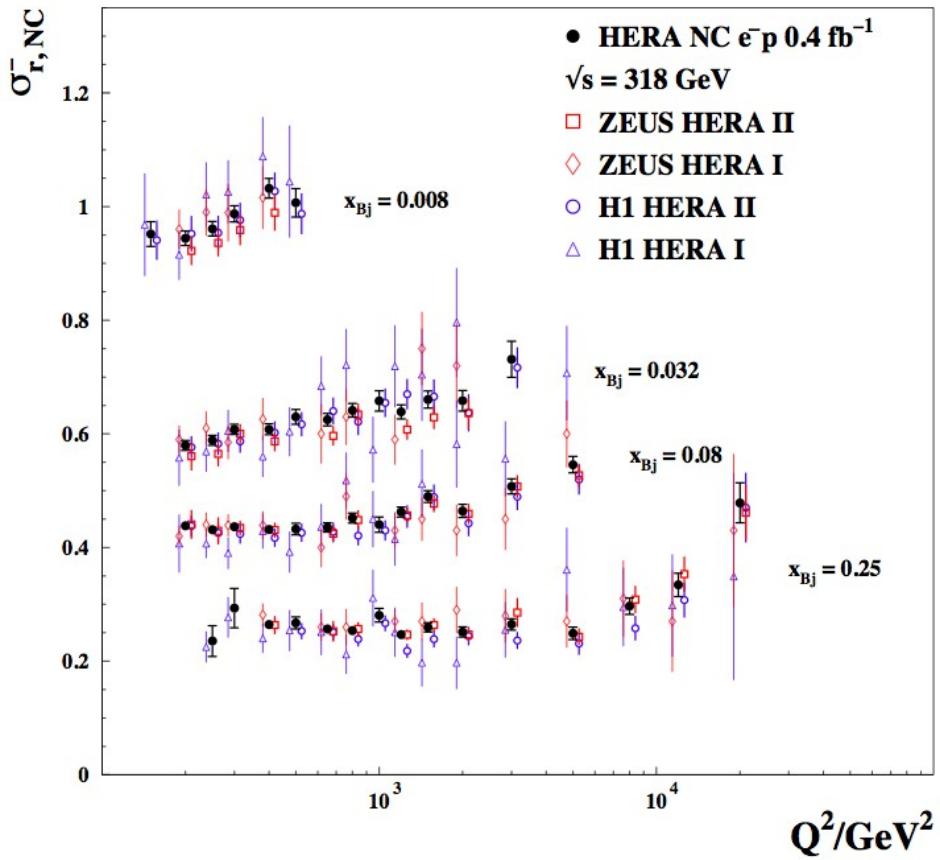
Good data consistency: $\chi^2/\text{dof} = 1687/1620$

Impressive amount of data points combined

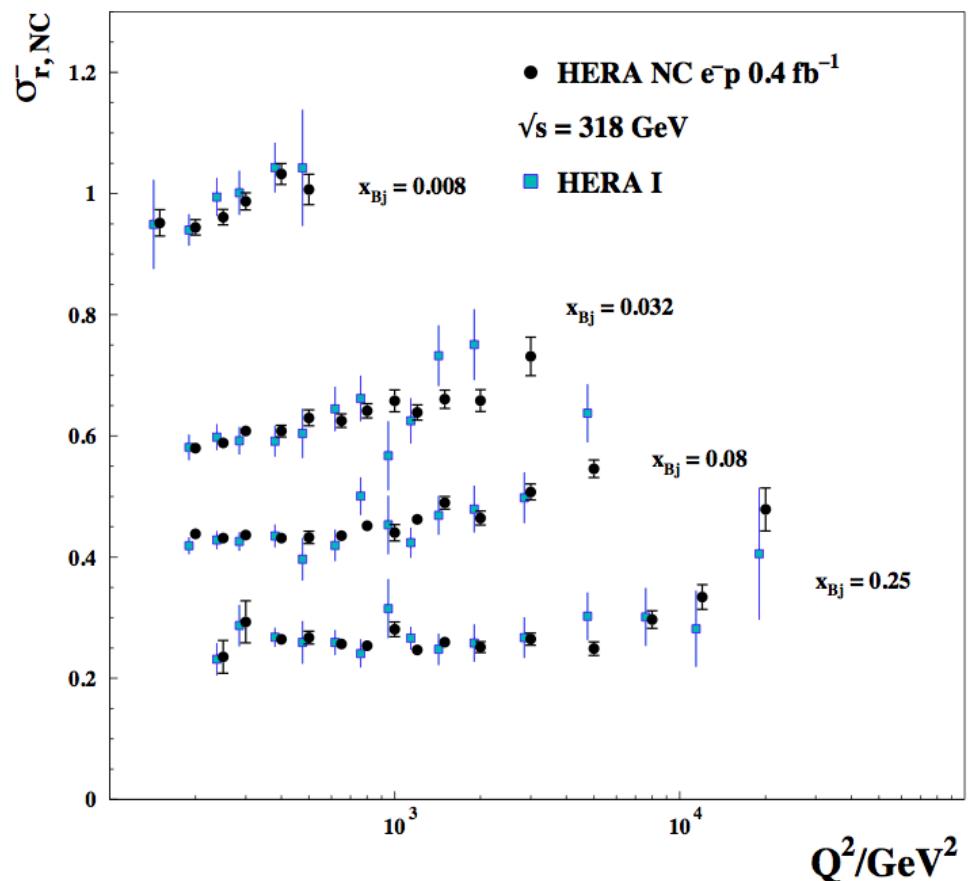


Improved precision

H1 and ZEUS

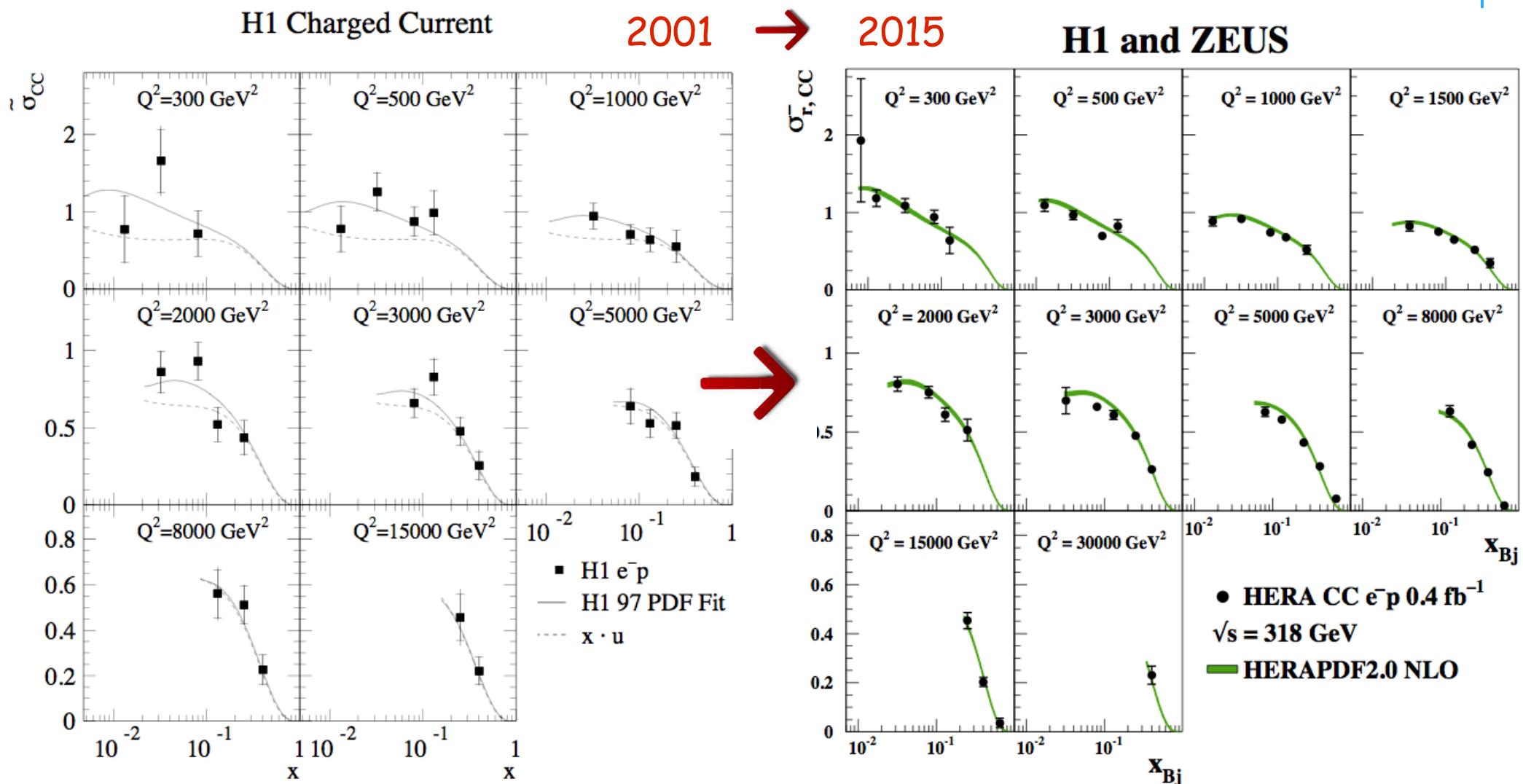


H1 and ZEUS



- Largest and most accurate data sample is for the NC e^+p process
 - The combined data accuracy reaches $\sim 1\%$
- Largest improvement for NC e^-p - 10 times more luminosity
- Consistent with HERA-I + improved uncertainties

Improving previous results

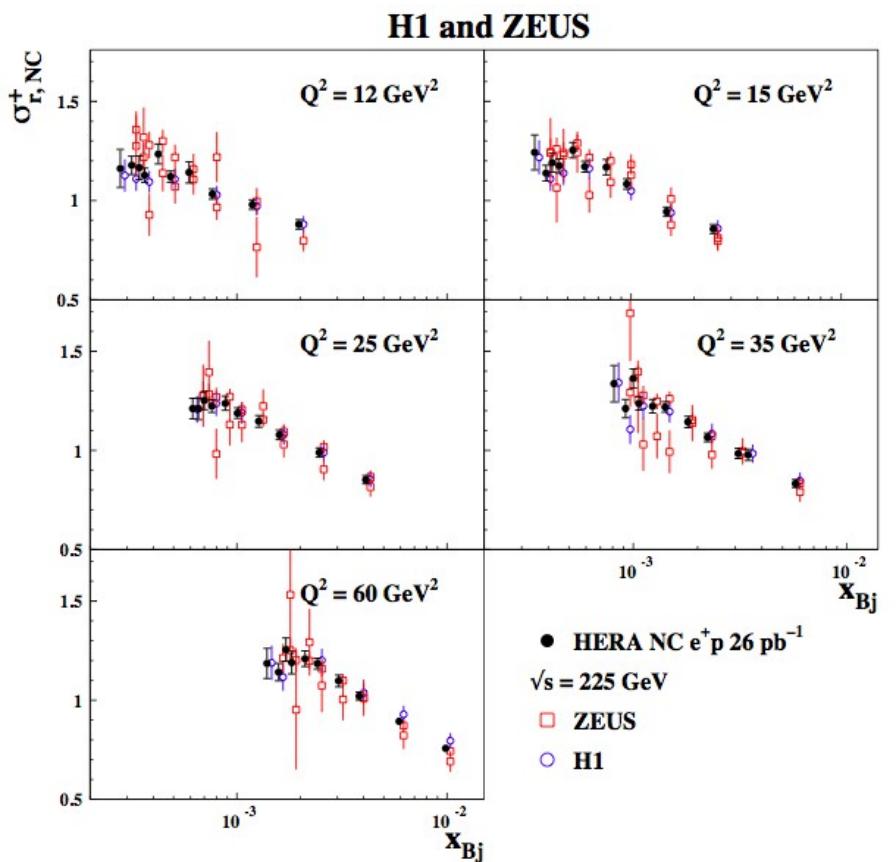
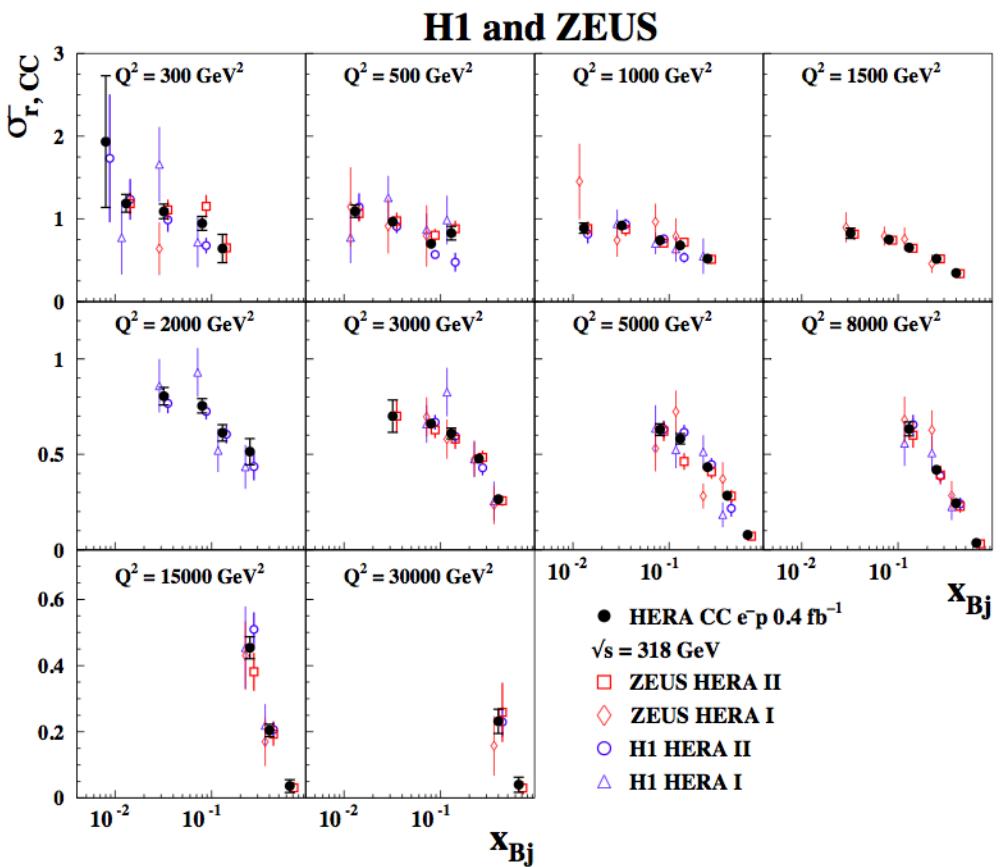


- increases statistical significance
- reduces systematic uncertainties via cross calibration techniques

Great gain in precision

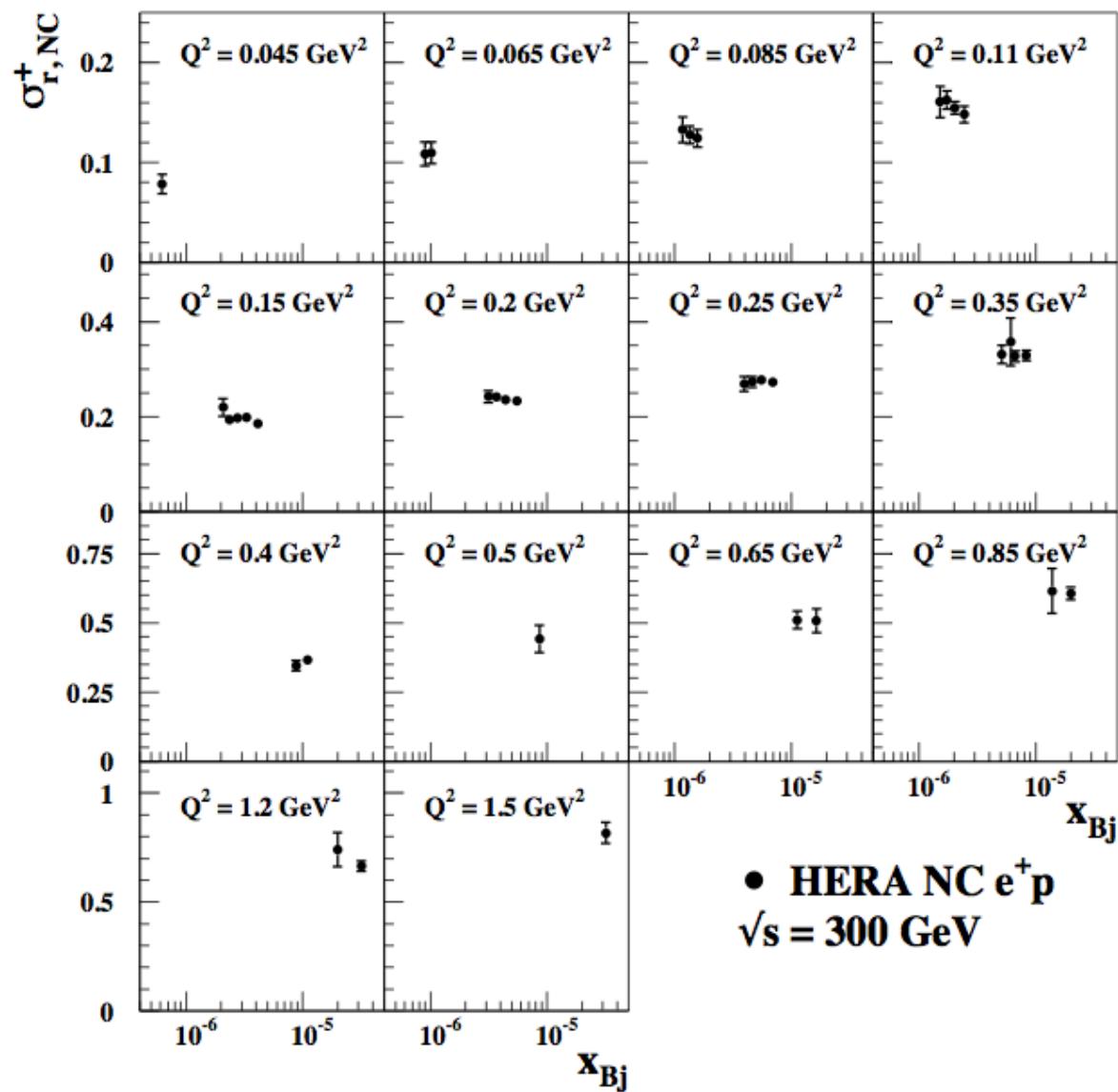
New kinematic ranges explored

- Kinematic range extended for existing data samples
- Low energies added: $CME = 225$ GeV and 251 GeV



Low Q^2 combined data

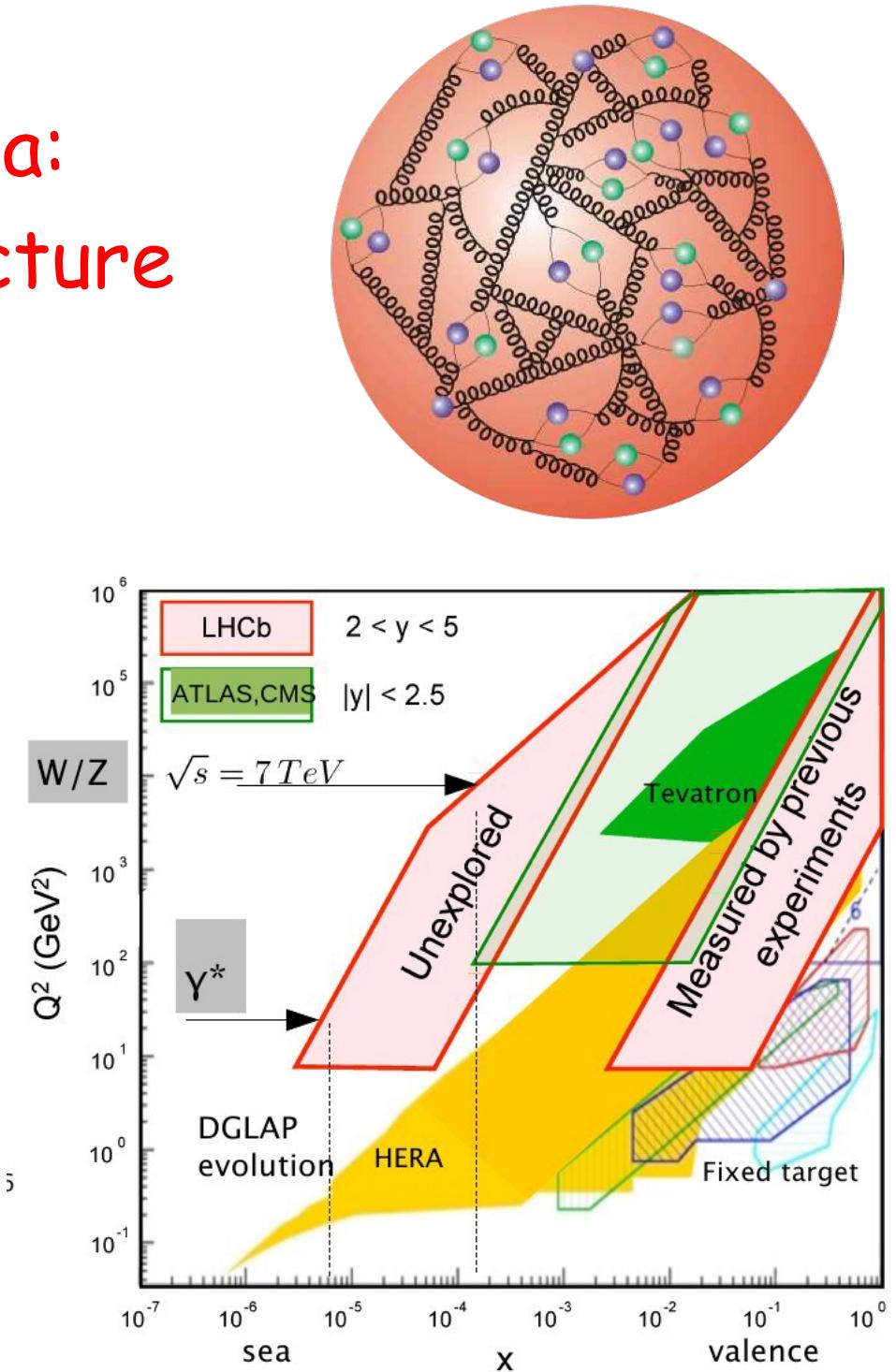
H1 and ZEUS



- Combined inclusive cross sections for low Q^2
- Available for two CMEs
 - 300 GeV
 - 318 GeV
- Interesting for
 - dipole/saturation models
 - studying higher twists

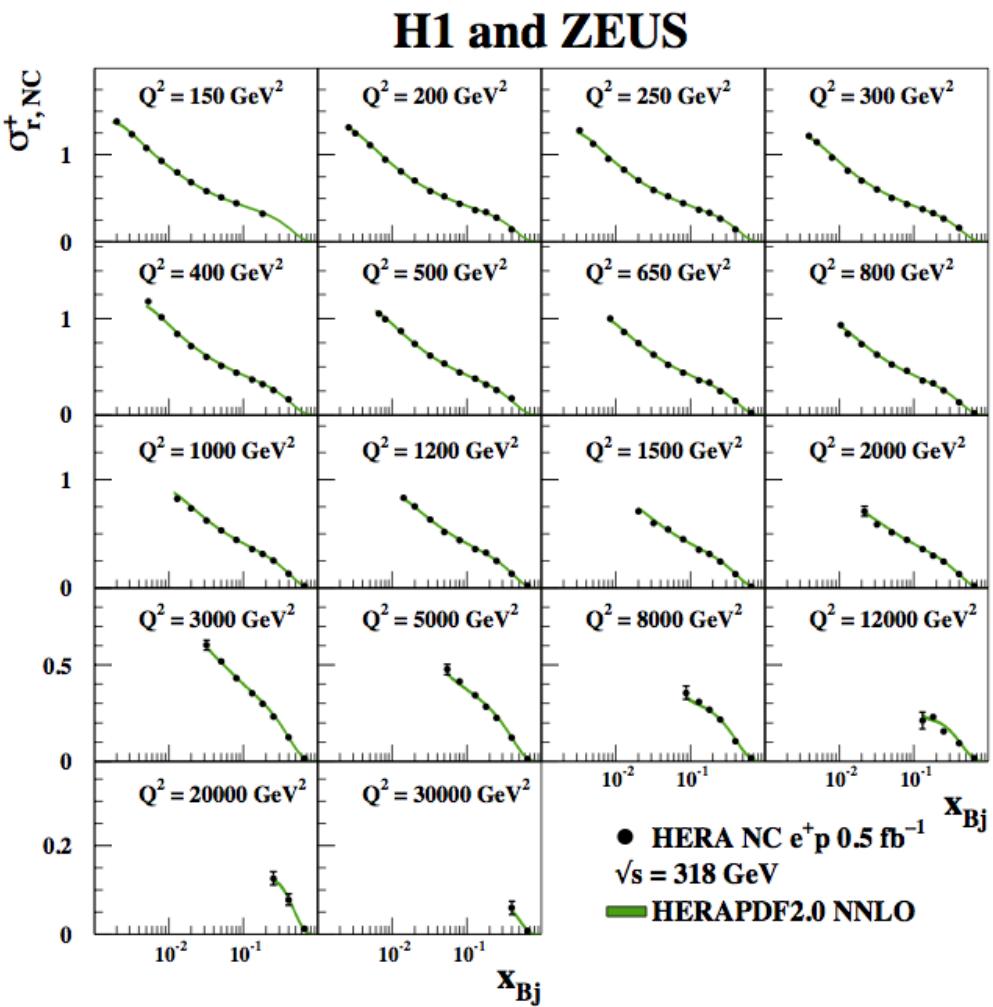
High Q^2 combined data: insight into proton structure

- Inclusive measurements from HERA are core of every parton density extraction
 → HERA inclusive data - exclusively! - used as input to global QCD fit HERAPDF2.0
 - Dedicated talk of V. Radescu



Neutral Current

$$\frac{d^2\sigma_{NC}^\pm}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[Y_+ F_2 \mp Y_- x F_3 - y^2 F_L \right]$$



Proton structure functions

$$F_2 = x \sum e_q^2 [q(x) + \bar{q}(x)]$$

- Sensitive to quarks

$$xF_3 = x \sum 2e_q a_q [q(x) - \bar{q}(x)]$$

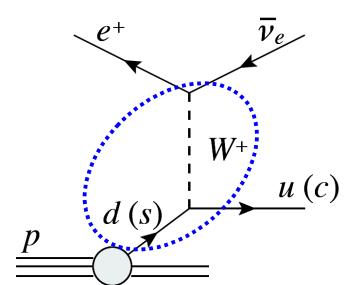
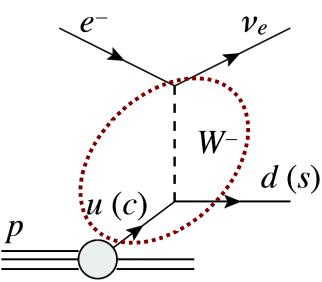
- Sensitive to valence distributions

$$F_L \sim \alpha_s \times g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

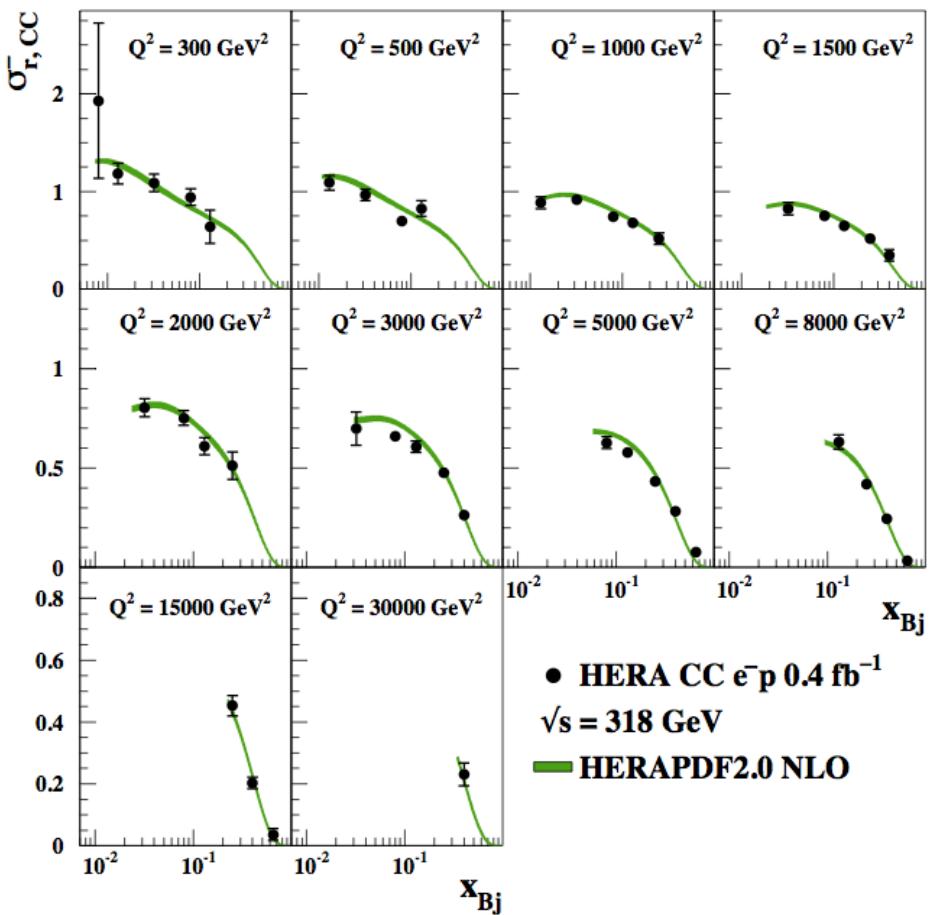
Charge Current: flavor decomposition



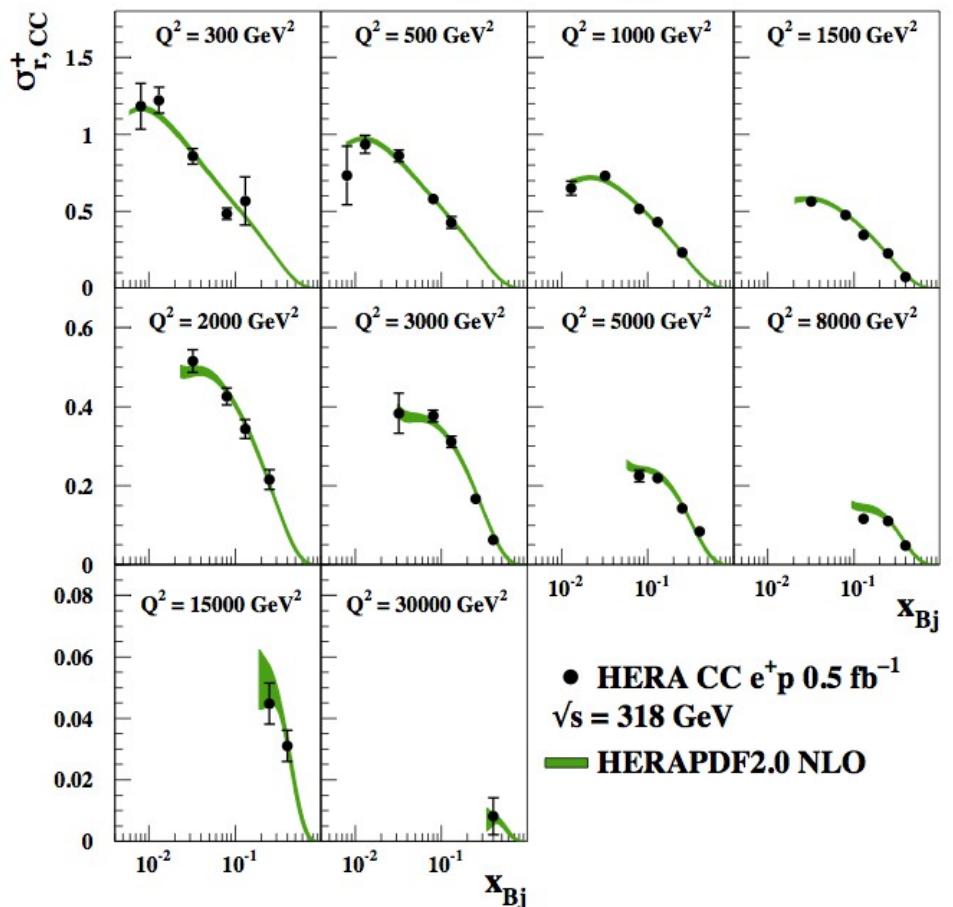
$$\sigma_{CC}^- \sim x[u + c] + x(1 - y)^2[\bar{d} + \bar{s}]$$

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

H1 and ZEUS



H1 and ZEUS

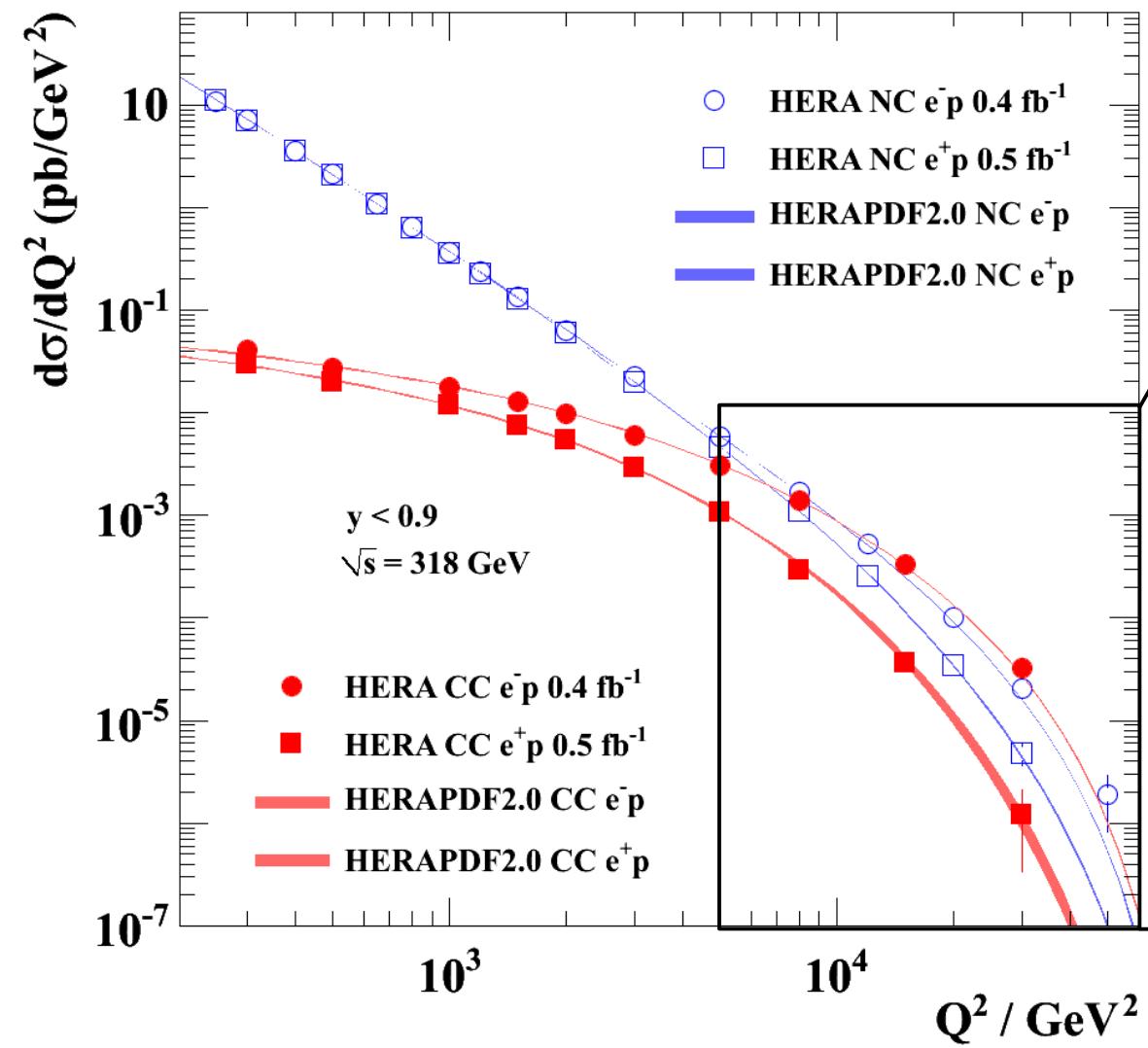




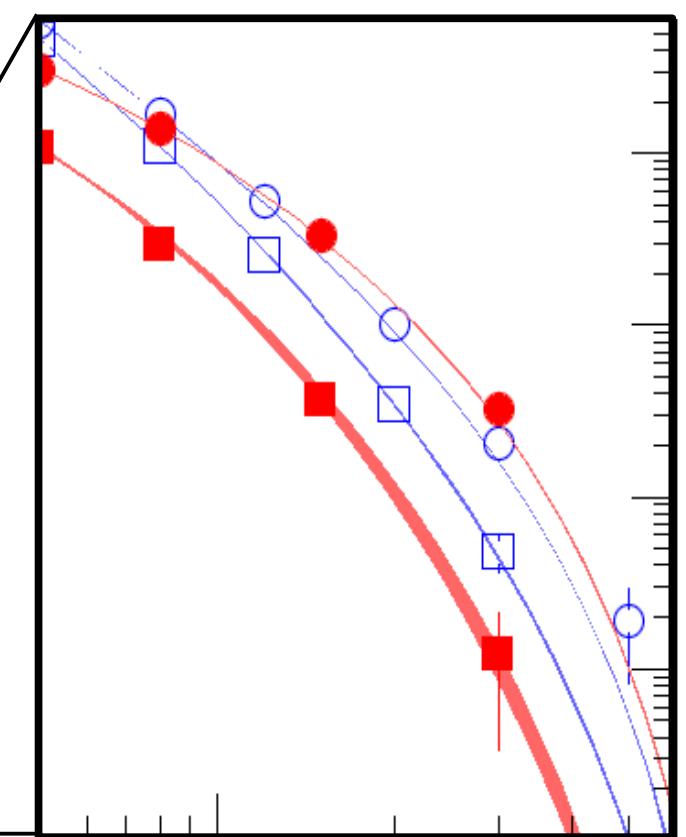
MORTAL KOMBAT
HERA LEGACY

Electroweak unification

H1 and ZEUS

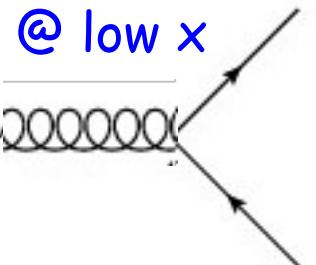


Fantastic precision
of HERA final data



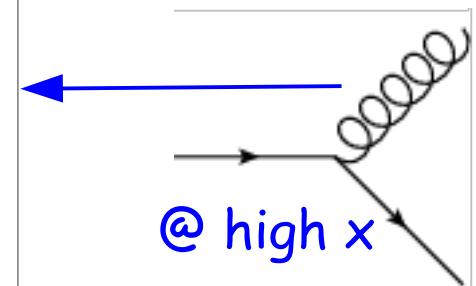
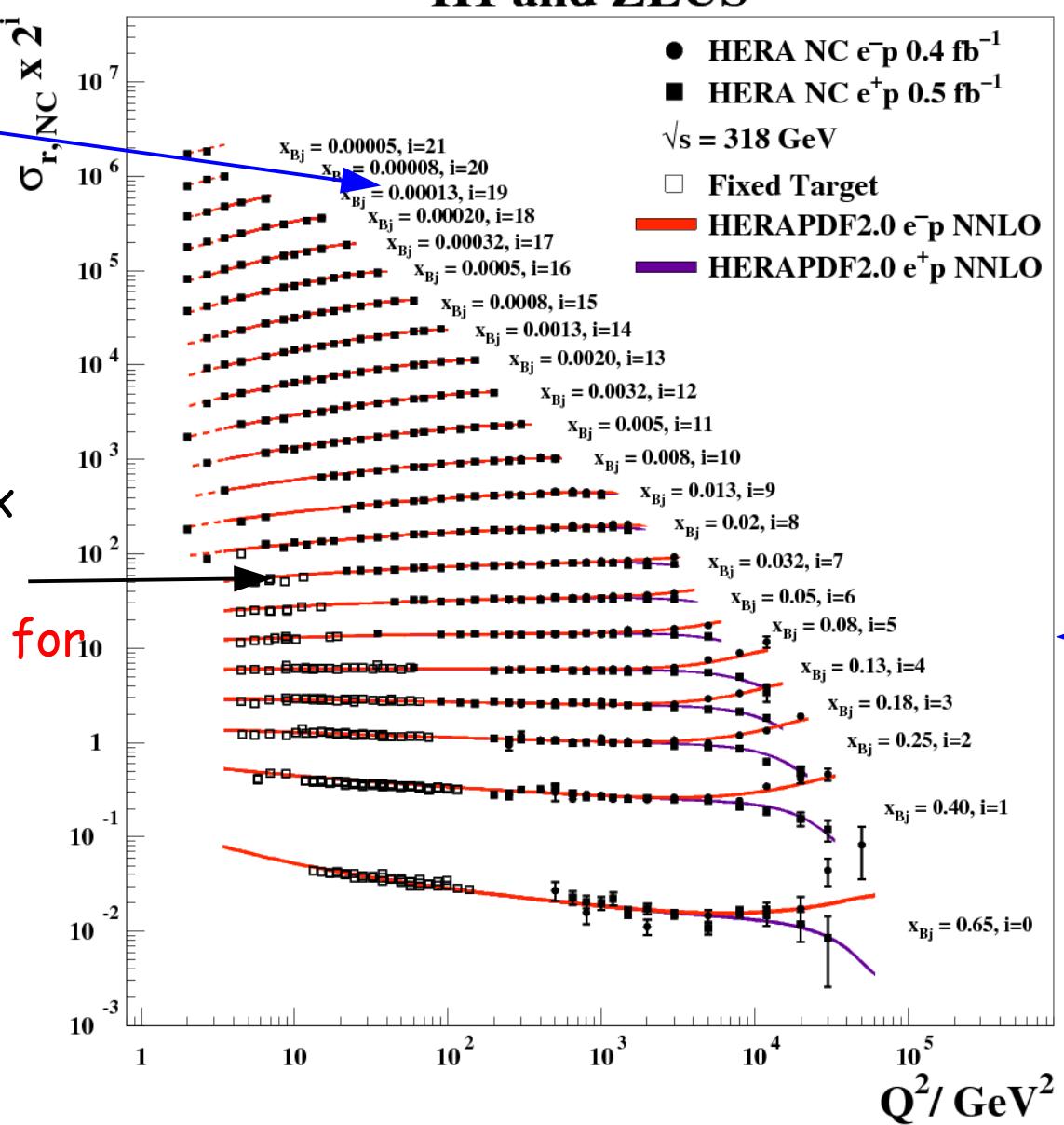
QCD scaling and scaling violation

H1 and ZEUS



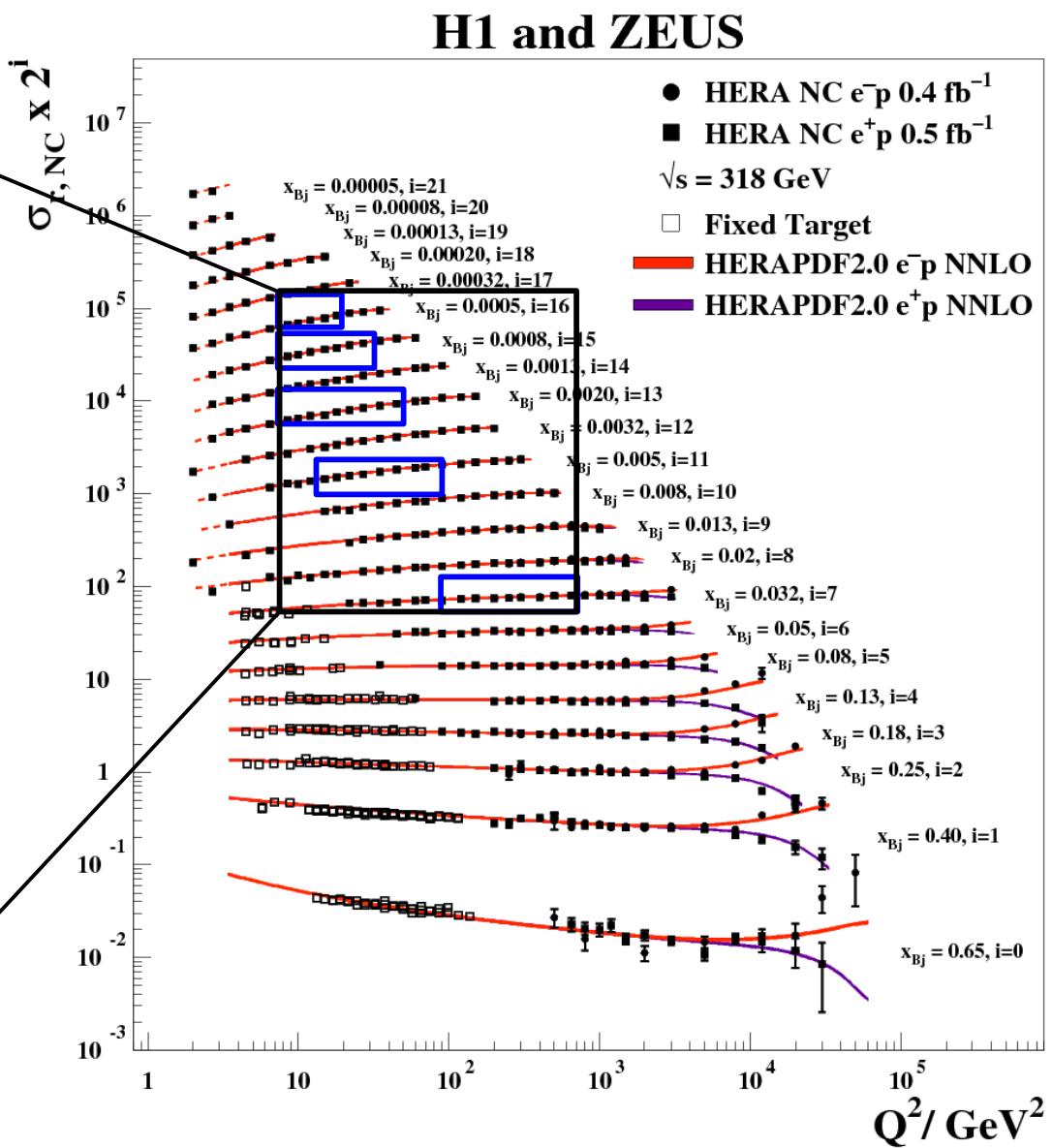
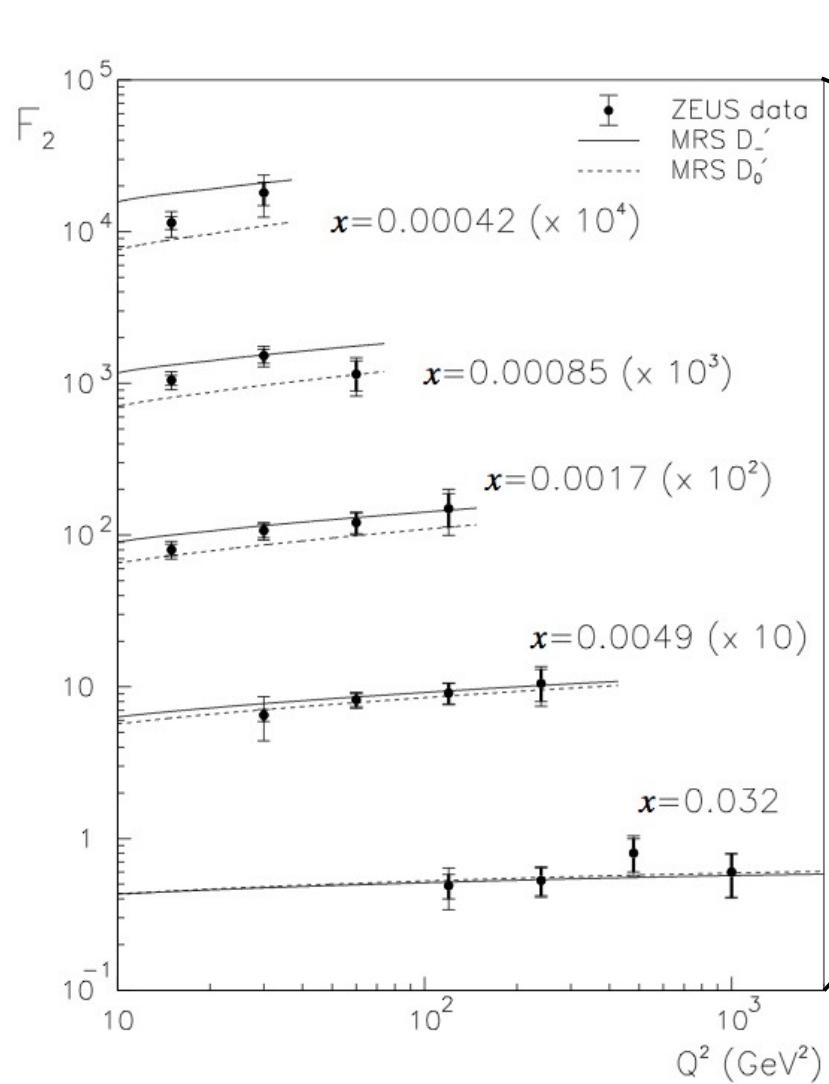
@ low x
QCD scaling

2015 Wolf prize for
J. Bjorken!

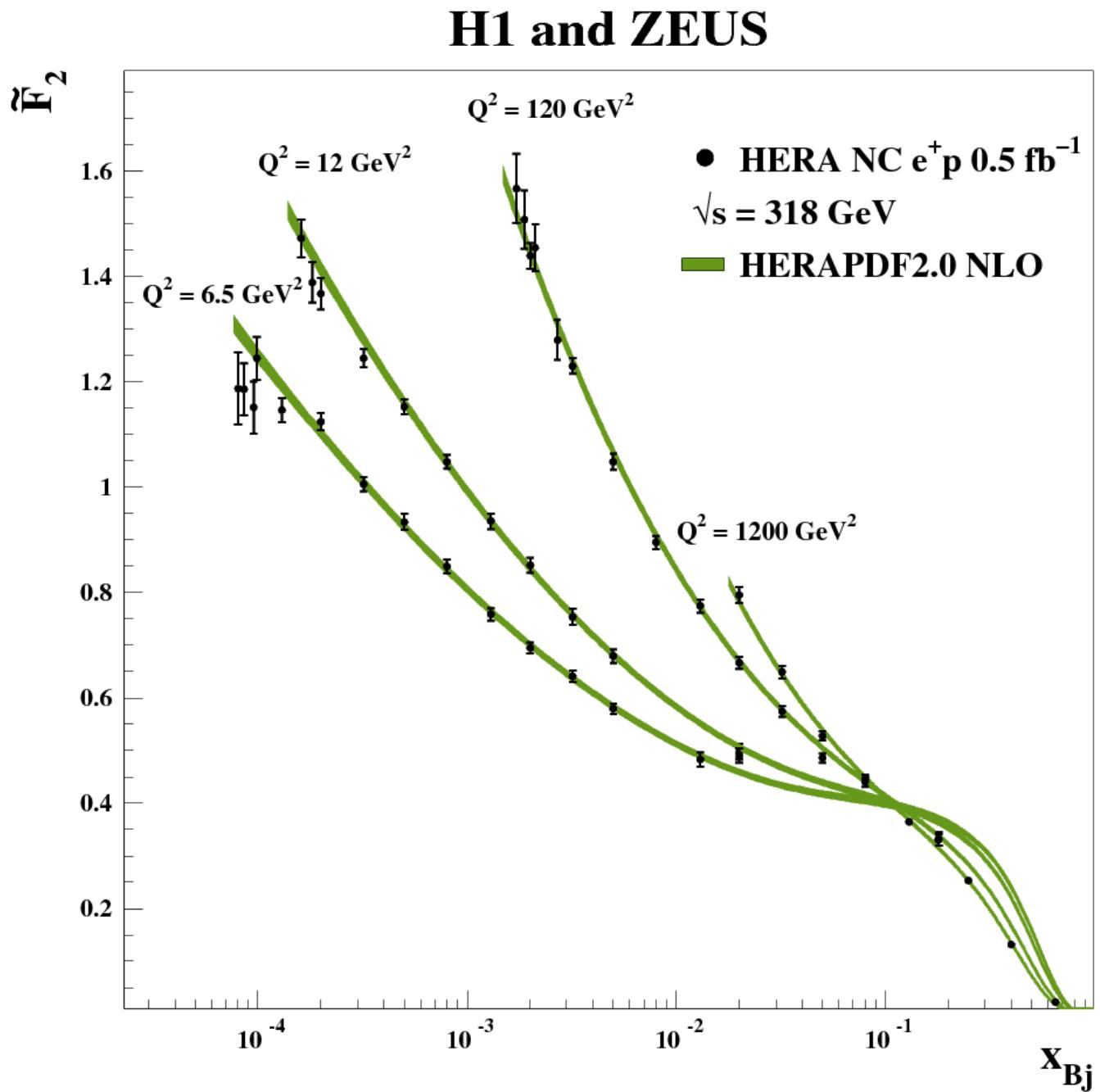


Text book plots of fundamental properties of particle interactions

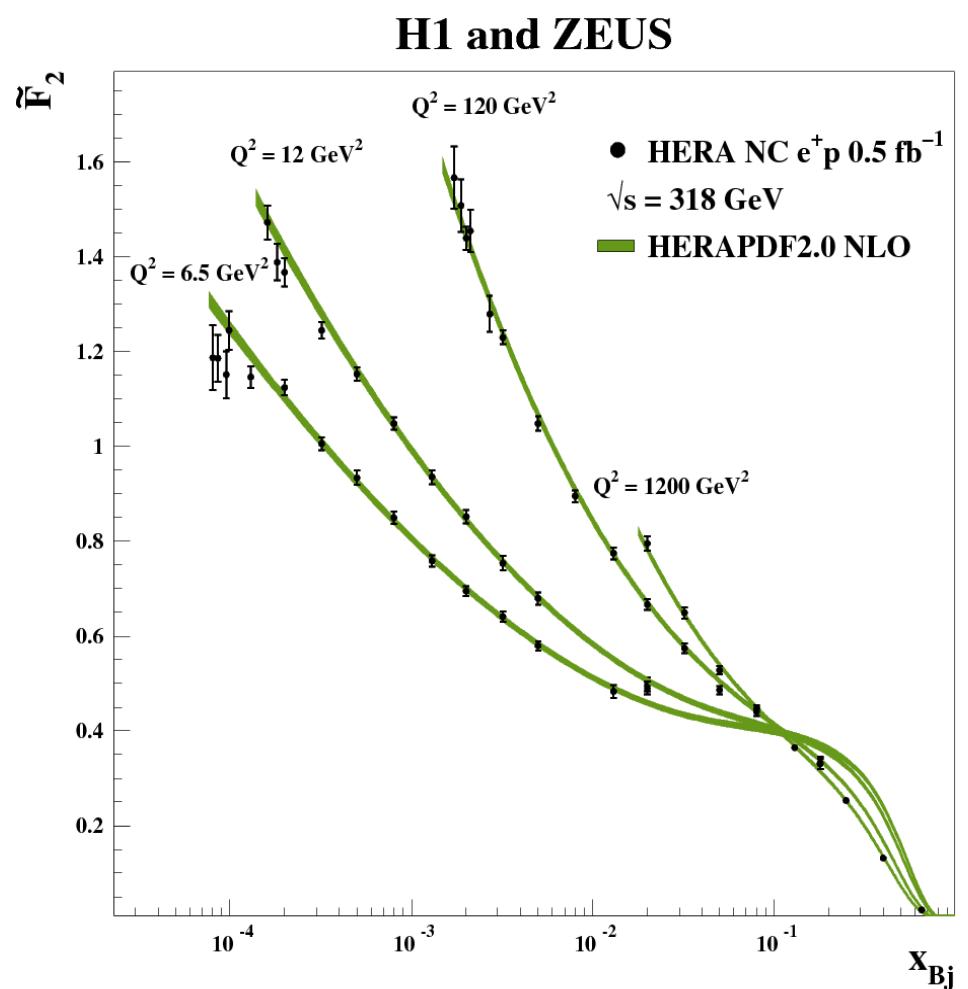
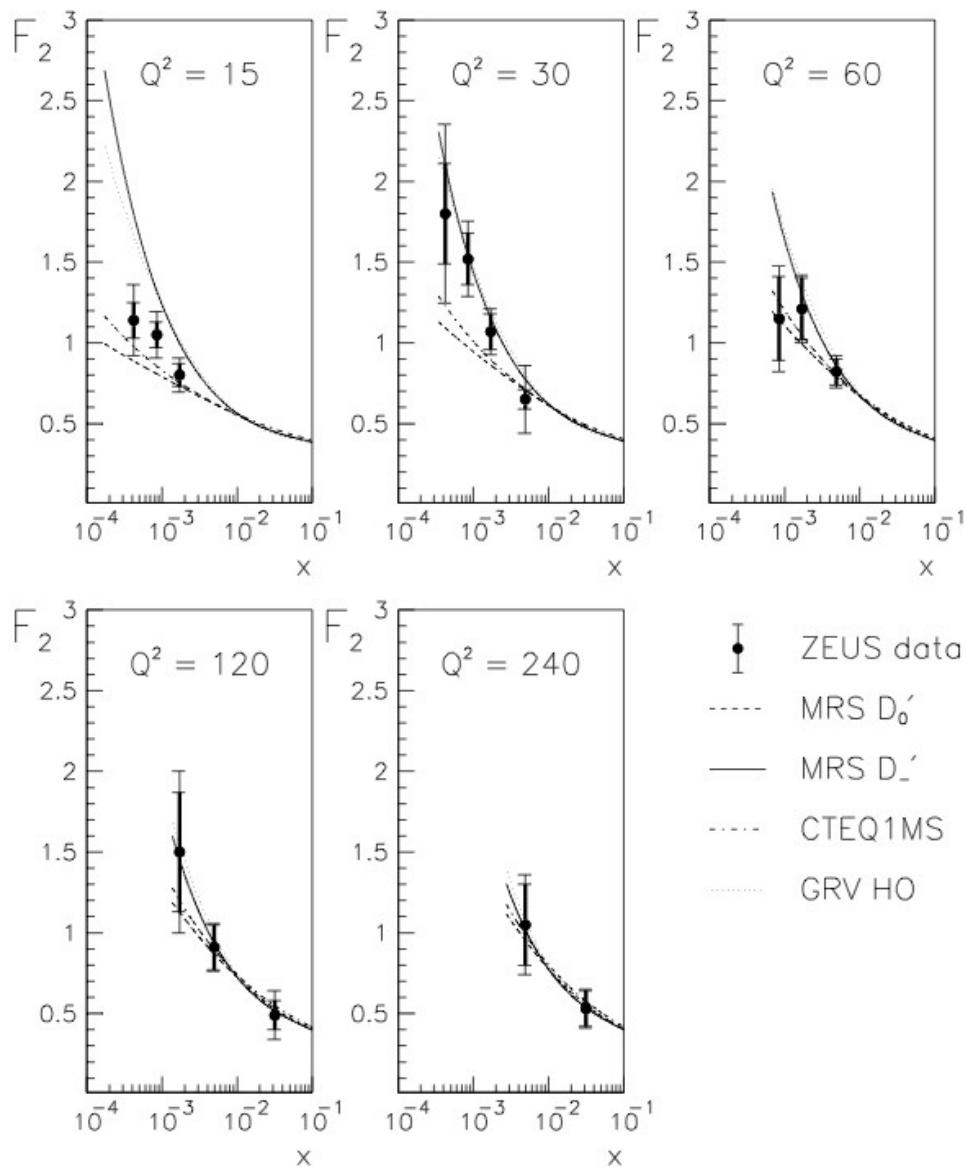
First → Final



As expected: low- x rise of F_2

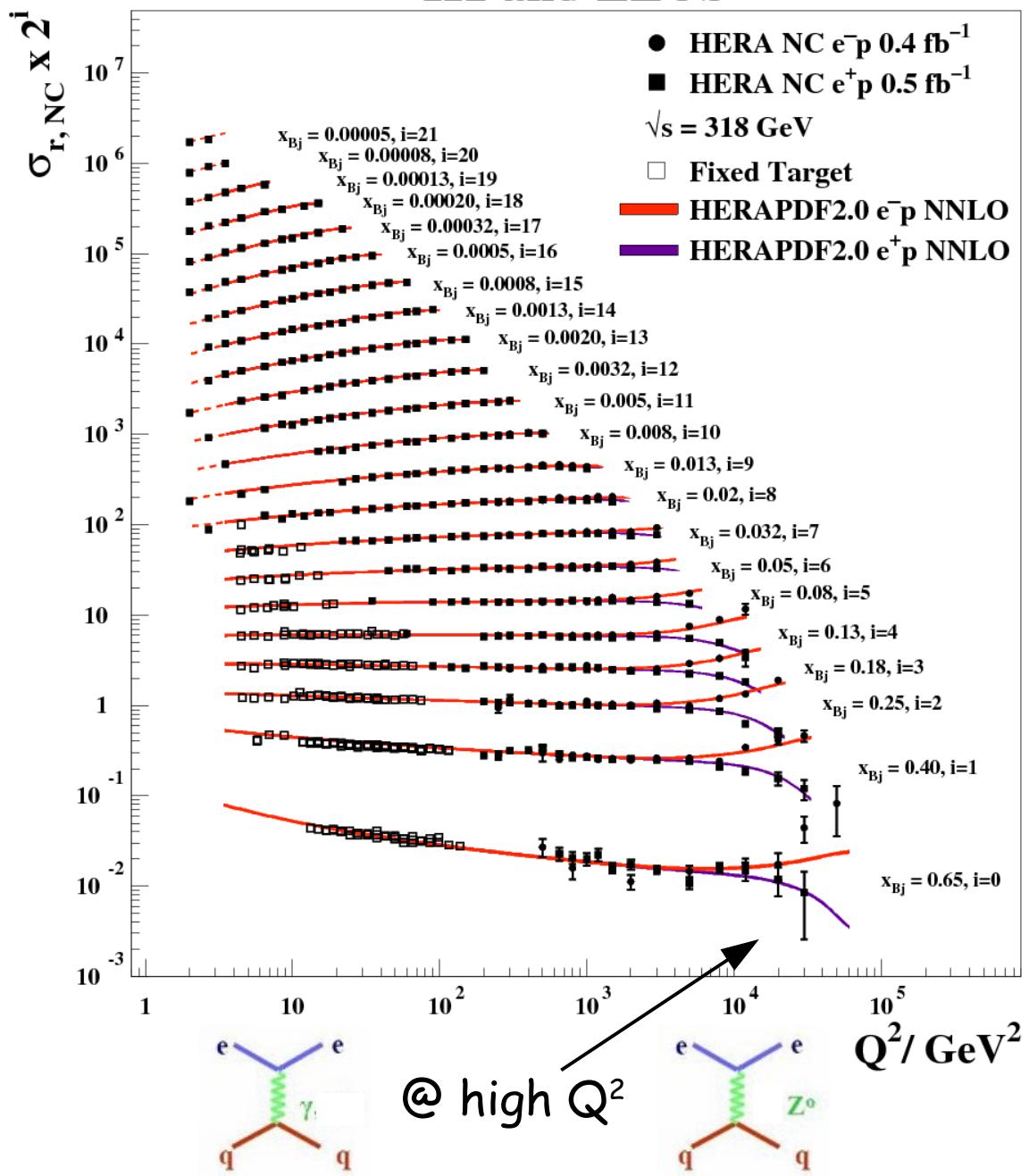


1993 → 2015



Electroweak effects

H1 and ZEUS

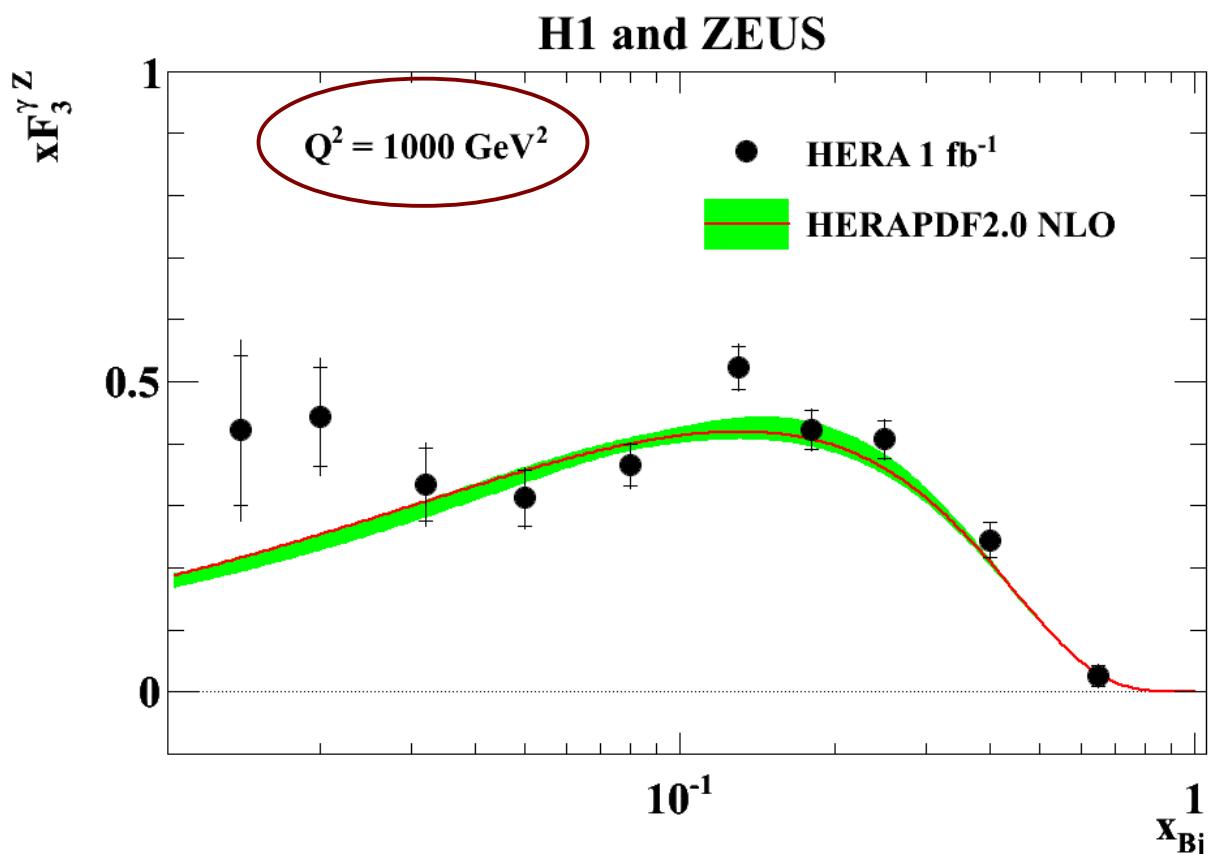


electron-proton
positron-proton

xF_3^{gZ} from combined data

- xF_3^{gZ} from subtracting the NC e^+p from the NC e^-p cross sections
- Weak Q^2 dependence → translated to $Q^2 = 1000 \text{ GeV}^2$ and averaged

- Good agreements with predictions
- Integrated over x :



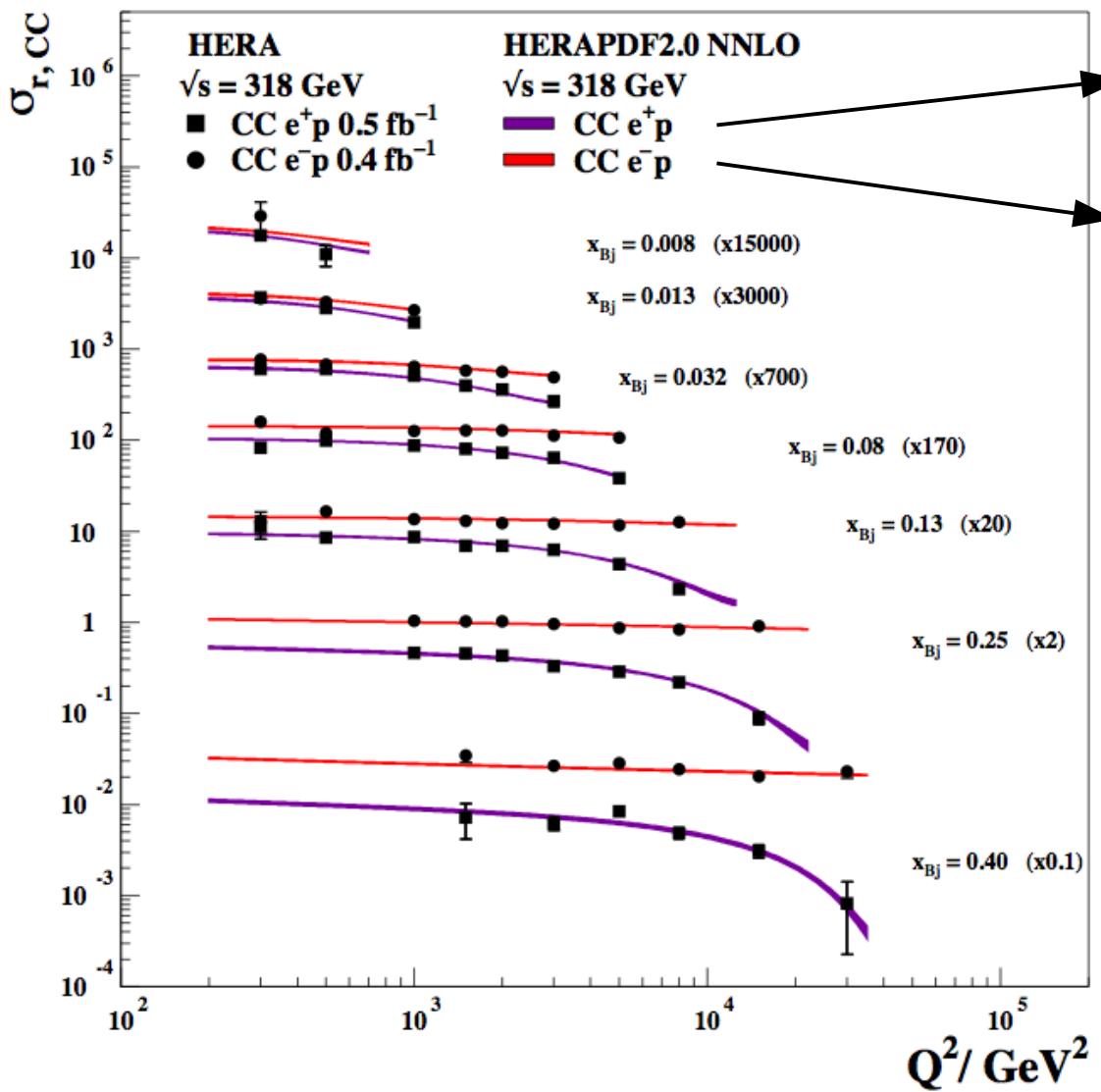
$$0.016 < x_{Bj} < 0.725 \quad \text{HERAPDF2.0 : } 1.165^{+0.042}_{-0.053}$$

$$0 < x_{Bj} < 1 \quad \left\{ \begin{array}{l} \text{HERAPDF2.0 : } 1.588^{+0.078}_{-0.100} \\ \text{QPM: } 5/3 \end{array} \right.$$

Data : $1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst})$
 Data : $1.790 \pm 0.078(\text{stat}) \pm 0.078(\text{syst})$

CC: helicity effects

H1 and ZEUS



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

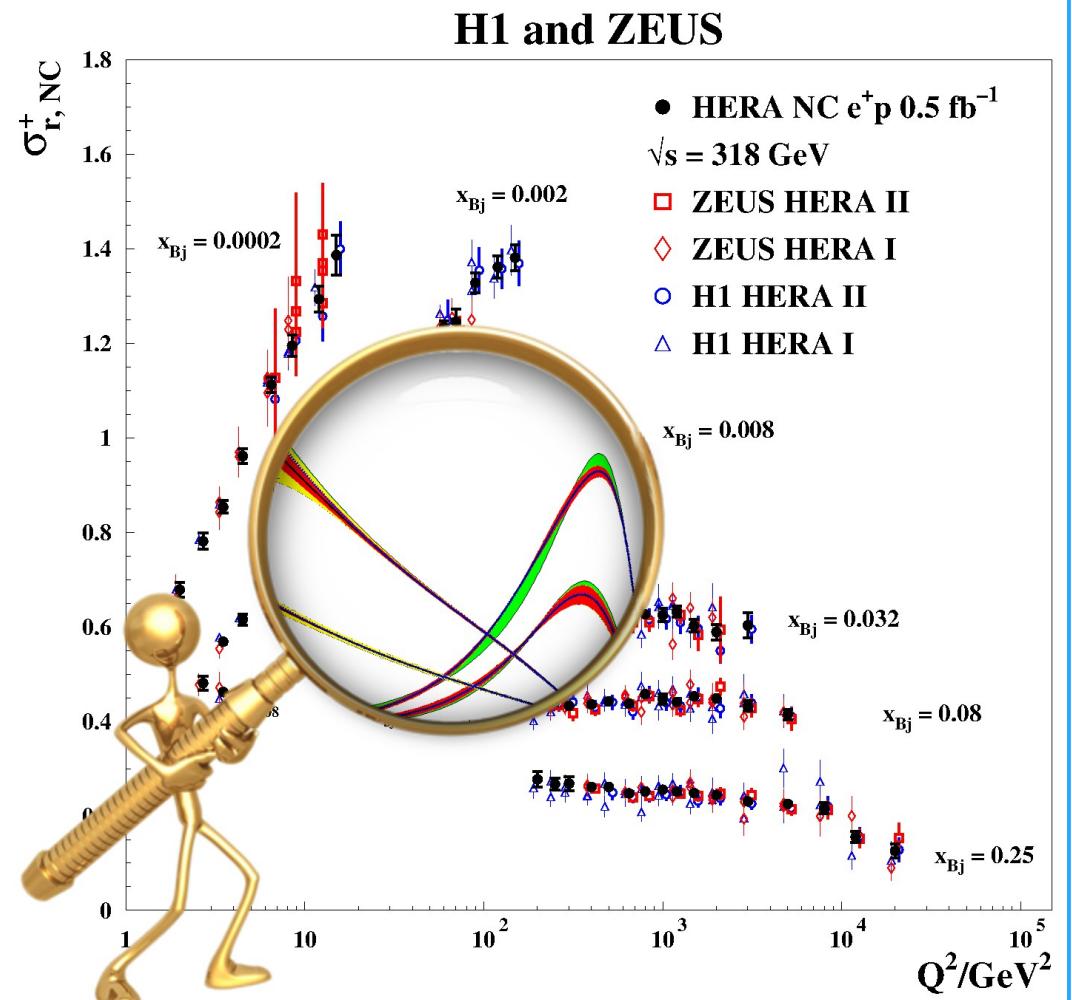
$$\sigma_{\text{CC}}^- \sim x[u + c] + x(1 - y)^2[\bar{d} + \bar{s}]$$

- $e^+ p$: d_V quarks are suppressed at high Q^2
- $e^- p$: helicity factor applies to sea quarks only

HERA Summary

- Combined HERA data set provides ultimate sample for inclusive NC and CC cross section studies in wide kinematic range
 - Low Q^2 data → additional checks of QCD calculations
- Plethora of beautiful physics in inclusive DIS measurements
- Core of every PDF extraction

HERA legacy of almost 25 years of activity

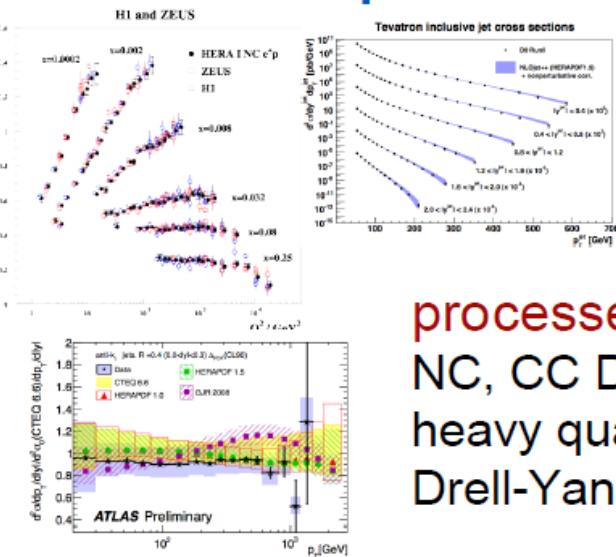




Additional slides

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

experimental input



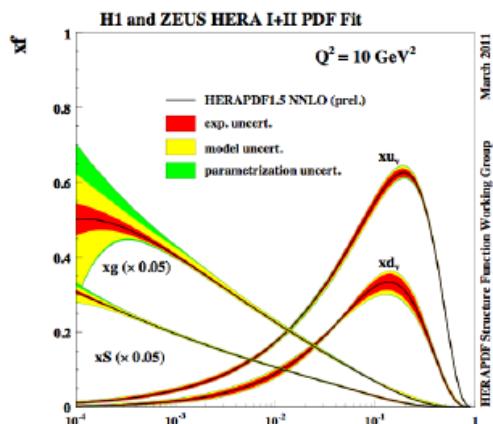
experiments:
HERA, Tevatron,
LHC, fixed target

processes:
NC, CC DIS, jets, diffraction,
heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes: MSTW, CTEQ, ABM
 Jets, W, Z production: fastNLO, Applgrid
 Top production NNLO (Hathor)
 QCD Evolution DGLAP (QCDNUM)
 k_T factorisation
 Alternative tools NNPDF reweighting
 Other models Dipole model
 + Different error treatment models
 + Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

$\alpha_s(M_Z), m_c, m_b, m_t, f_s, \dots$

Theory predictions

Benchmarking

Comparison of schemes

Procedural uncertainties

- Combination done using HERAverager: wiki-zeuthen.desy.de/HERAverager

$$\chi^2_{\text{exp},ds}(\mathbf{m}, \mathbf{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma_j^{i,ds} m^i b_j - \mu^{i,ds} \right]^2}{\delta_{i,ds,\text{stat}}^2 \mu^{i,ds} \left(m^i - \sum_j \gamma_j^{i,ds} m^i b_j \right) + \left(\delta_{i,ds,\text{uncor}} m^i \right)^2} + \sum_j b_j^2$$

- 162** correlated systematic sources taken into account
 - treated as multiplicative

- Procedural errors calculated
 - multiplicative vs additive
 - possible correlations between data sets
(H1/ZEUS, HERAI/HERAII)
 - photoproduction background
 - hadronic energy scale
 - connected with large pulls in combination

