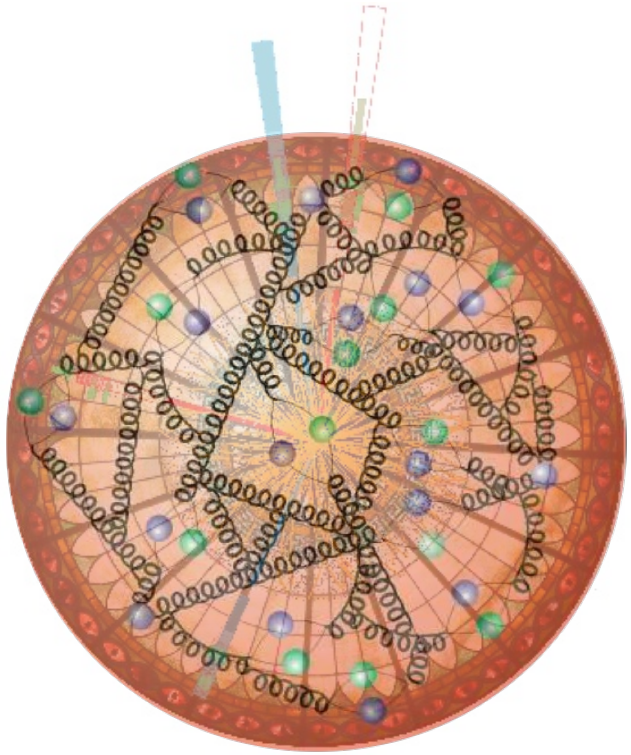
DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

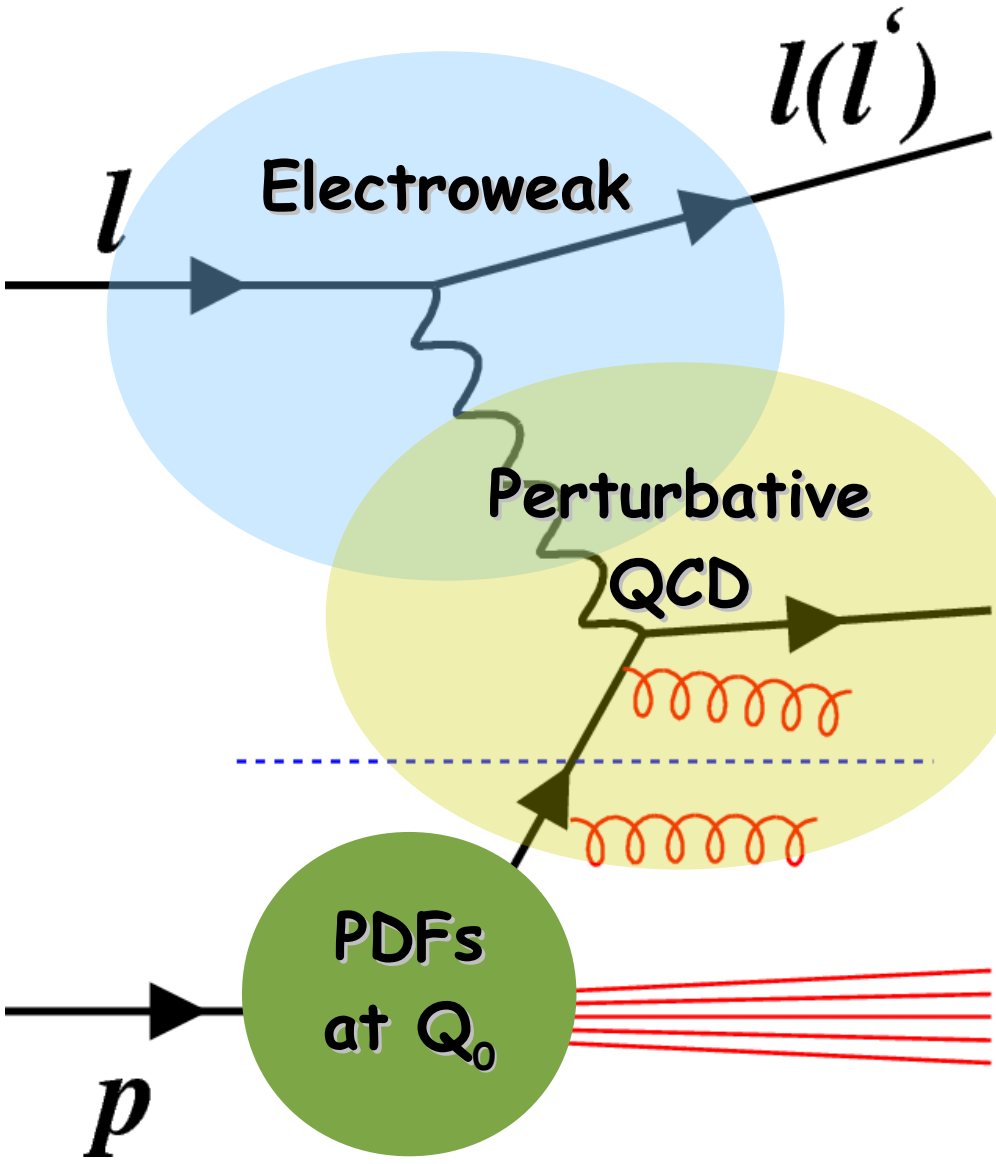
Dallas, Texas
April 27 – May 1, 2015



Combined Measurement of Inclusive ep Scattering Cross Sections at HERA

K. Wichmann on behalf of H1 and ZEUS Collaborations

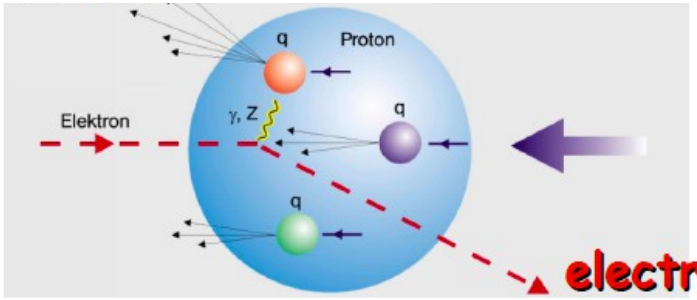
Deep Inelastic Scattering @ HERA



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

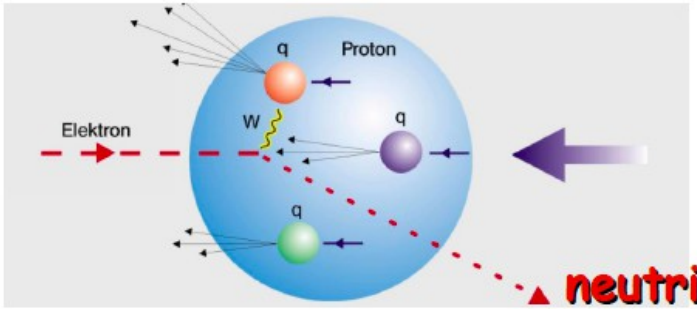
- Fix Electroweak & pQCD
  ! Determine PDFs

Combined inclusive DIS



Neutral Current (NC)

γ, Z^0 exchange



Charged Current (CC)

$W^{\pm}$ exchange

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

$$x_{Bj} = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

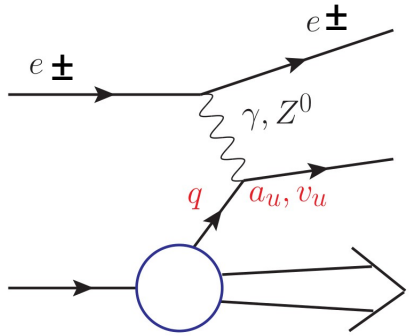
$$s = (p + k)^2 \qquad Q^2 = x_{Bj} \cdot y \cdot s$$

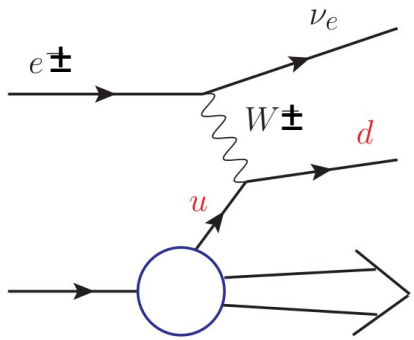
H1 and ZEUS published all HERA inclusive DIS measurements – 1 fb^{-1}

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 GeV
    - 4 high y data E_p = 920 GeV
    - 4 high y data E_p = 575 GeV
    - 4 high y data E_p = 460 GeV





- Data 1994-2007: over 10 years of data taking!
- 22 papers between 1997-2014: almost 20 years of data analysis!

Total of 2927 data points combined to 1307

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].

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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].

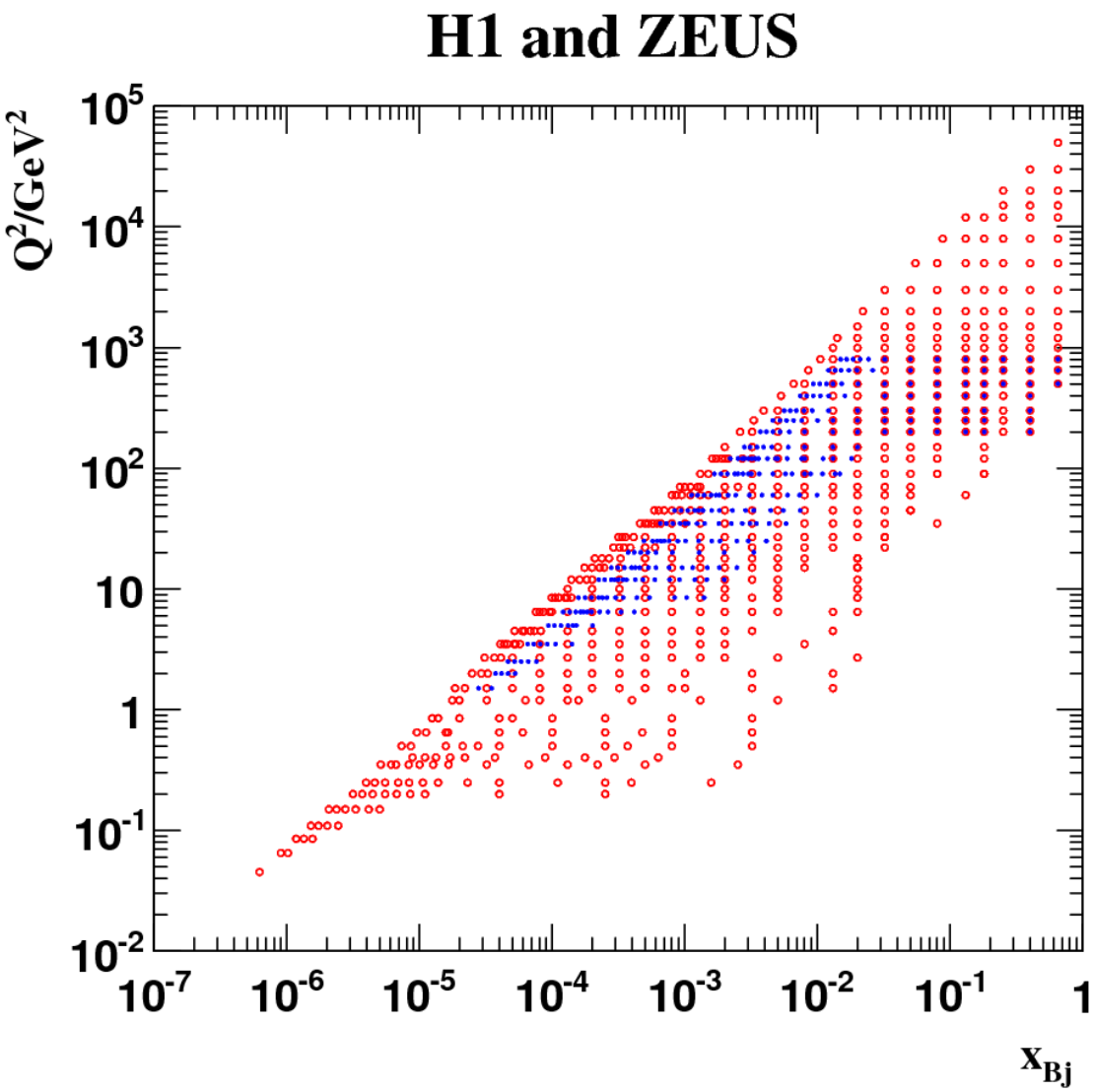
H. Abramowicz *et al.* [ZEUS Collaboration], Phys. Rev. D **87**, 052014 (2013), [arXiv:1208.6138].

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].

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

Q^2-x_{Bj} common grids

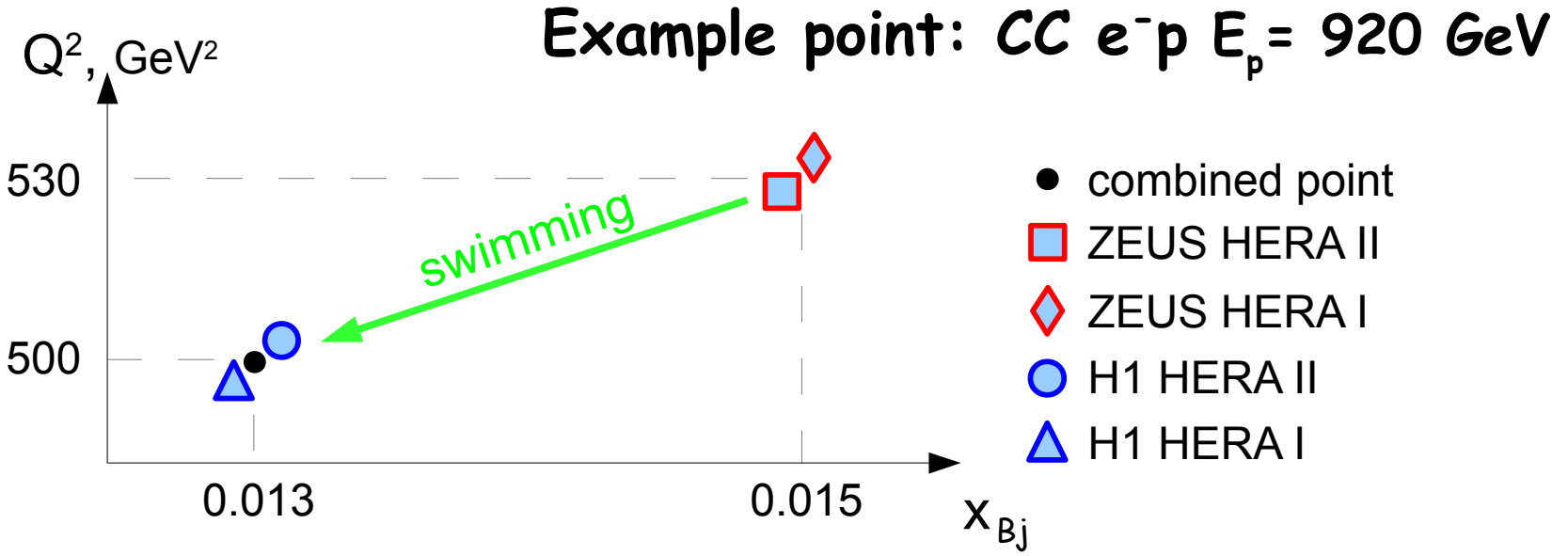


Two separate grids

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

- 1307 grid points
  - $0.045 < Q^2 < 50000$ GeV^2
  - $6\times10^{-07} < x_{Bj} < 0.65$

Swimming procedure



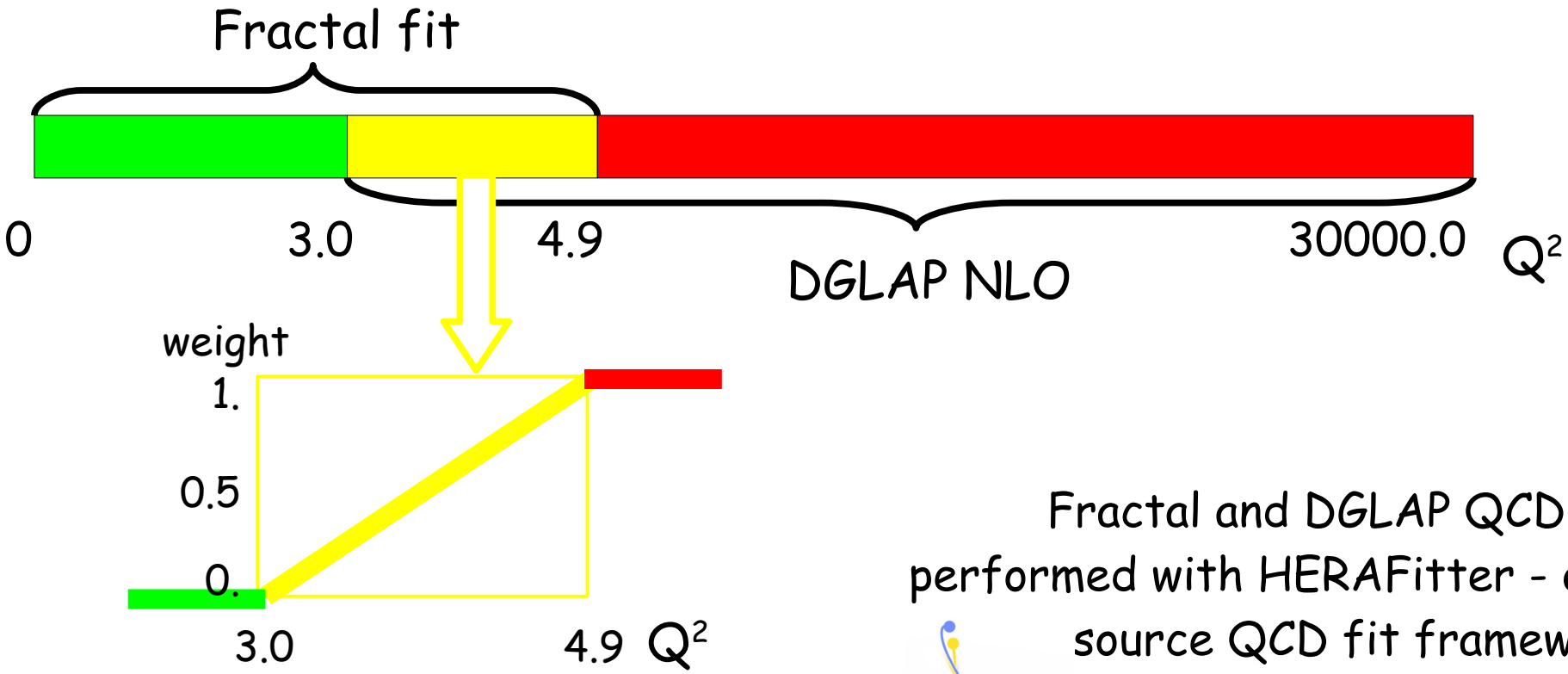
- Swimming factors

$$\sigma^{e\mp p}_{meas}\left(x_{grid},Q^2_{grid}\right)=\frac{\sigma^{e\mp p}_{model}\left(x_{grid},Q^2_{grid}\right)}{\sigma^{e\mp p}_{model}\left(x_{meas},Q^2_{meas}\right)}\cdot\sigma^{e\mp p}_{meas}\left(x_{meas},Q^2_{meas}\right)$$

- We need model for swimming
- Swimming factors are usually at level of few %

Swimming procedure

- Swimming done iteratively using our own data
  - 1st iteration uncombined HERAI+II data, later - combined data
  - Convergence after 3 iterations



Averaging of scale factors performed as a function of Q^2

Fractal and DGLAP QCD fits performed with HERAFitter - open source QCD fit framework: www.herafitter.org

Averaging procedure

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

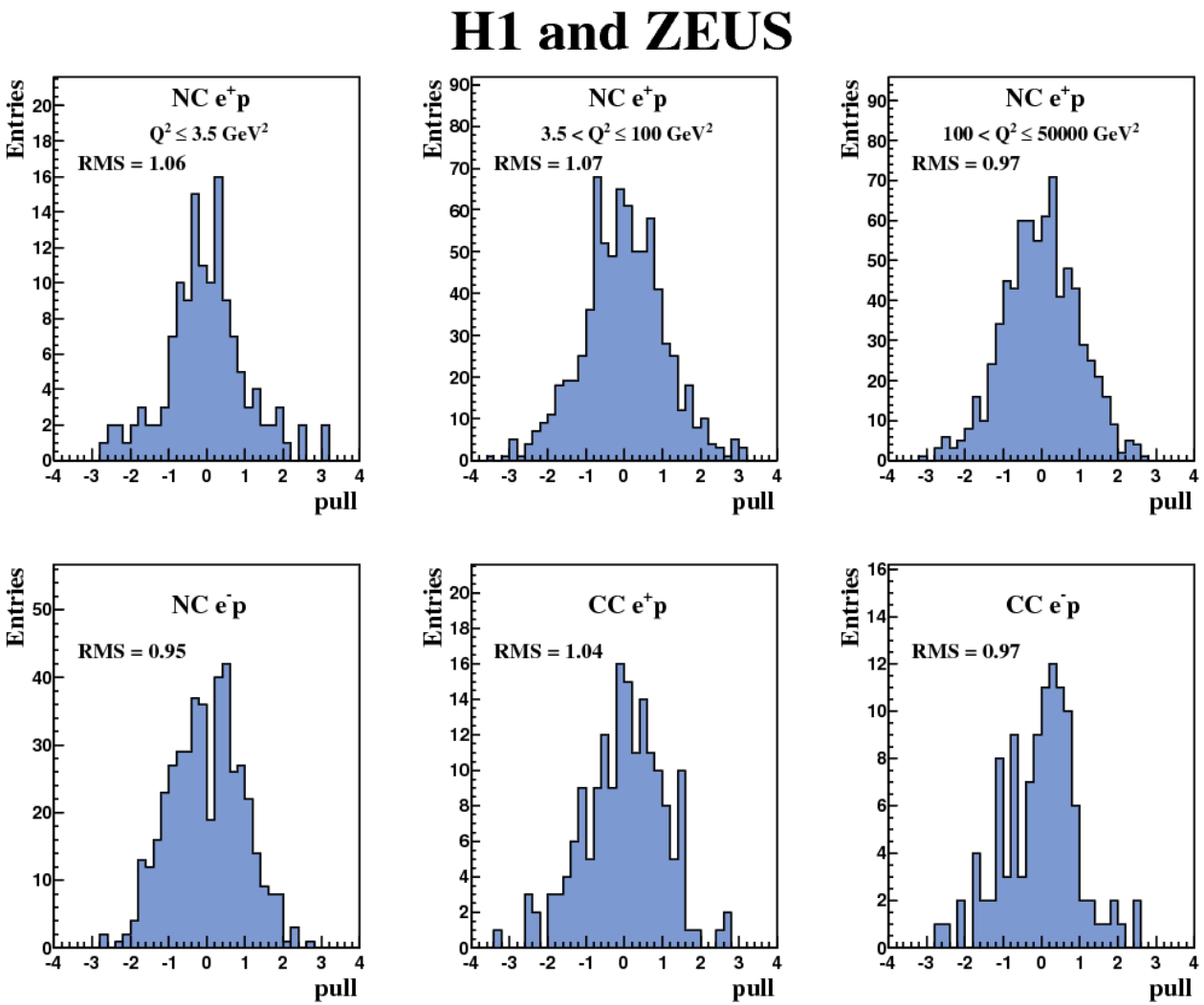
$$\chi^2_{\mathrm{exp},ds}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma_j^{i,ds} m^i b_j - \mu^{i,ds}\right]^2}{\delta^2_{i,ds,\mathrm{stat}}\,\mu^{i,ds}\left(m^i - \sum_j \gamma_j^{i,ds} m^i b_j\right) + \left(\delta_{i,ds,\mathrm{uncor}}\, m^i\right)^2} + \sum_j b_j^2$$

- **162** correlated systematic sources taken into account
  - treated as multiplicative
- Output
  - 7 data samples for $e^{\pm}p$, NC and CC, 3 CMEs
  - Statistical and uncorrelated systematic uncertainties
  - 162 correlated statistical uncertainties
  - 7 procedural uncertainties calculated → see additional material

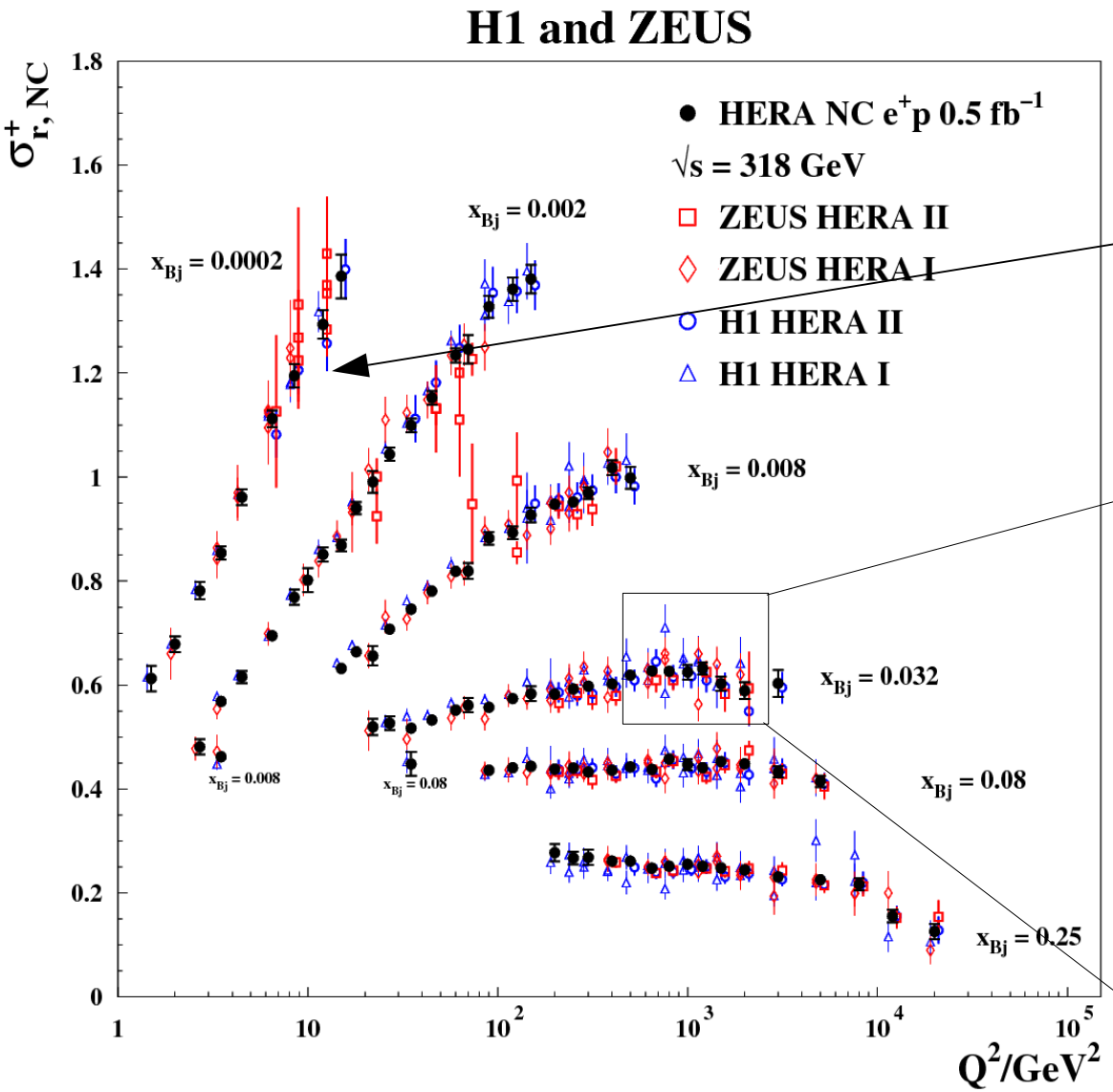
Averaging results

- Good data consistency: χ^2/dof = 1687/1620

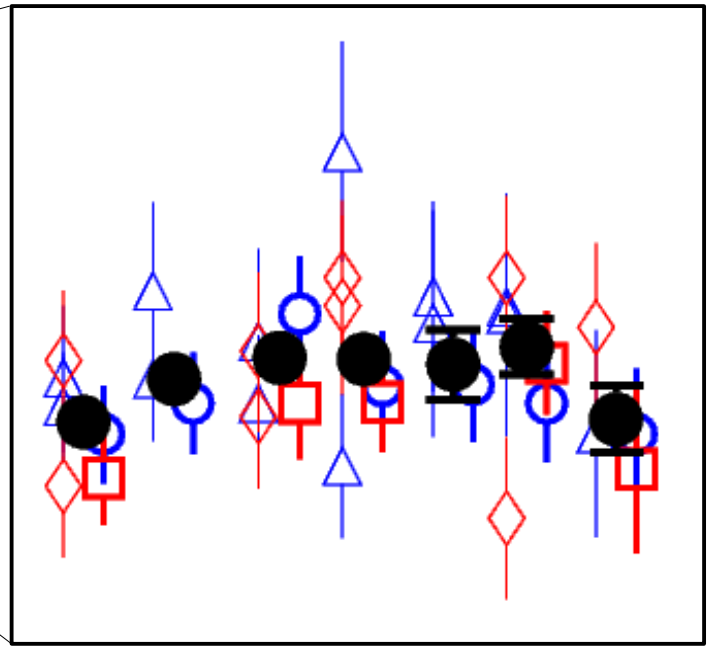
$$p^{i,k} = \frac{\mu^{i,k} - \mu^i \left(1 - \sum_j \gamma_j^{i,k} b'_j\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_i^2}}$$



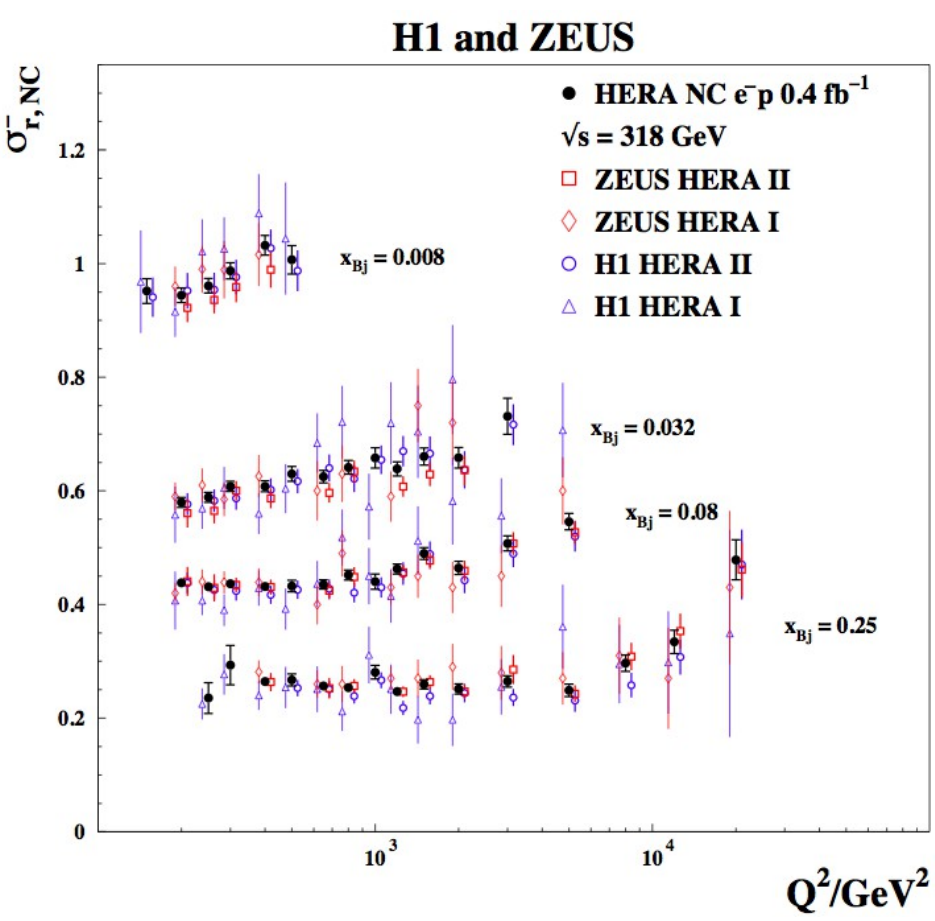
Impressive amount of data points combined

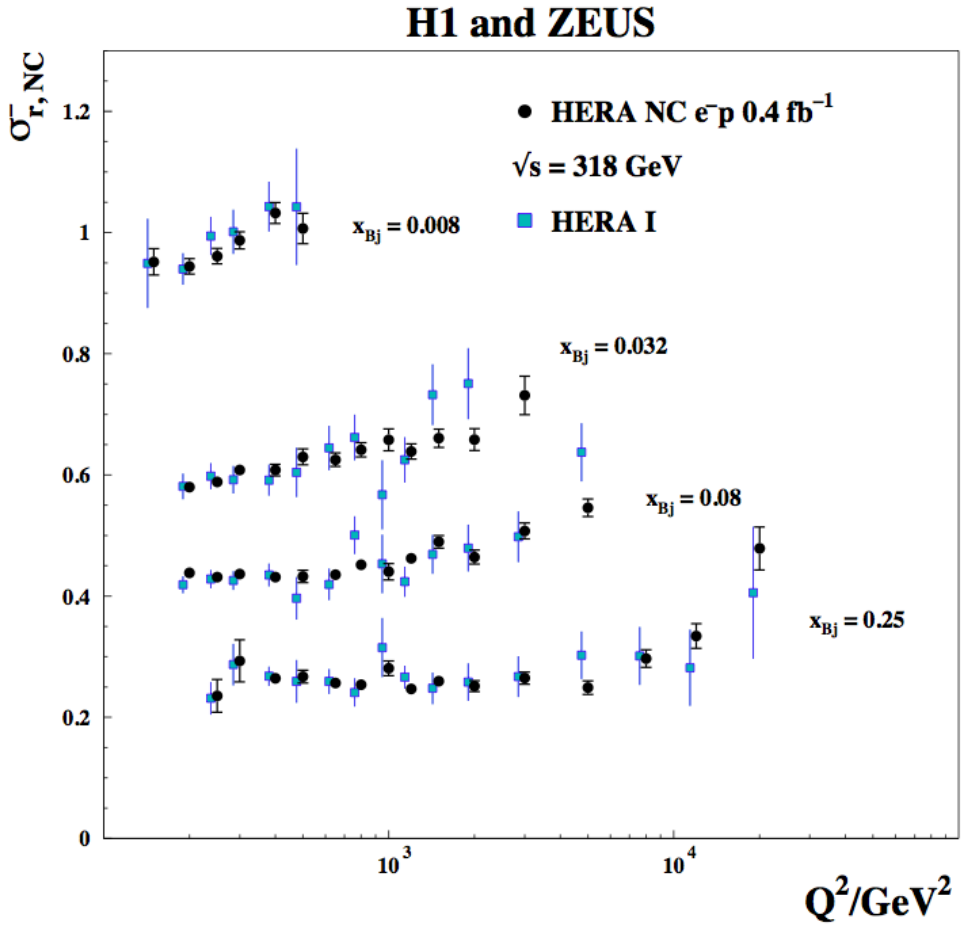


- 2927 data points combined to 1307
- Up to 6-8 data points combined to 1



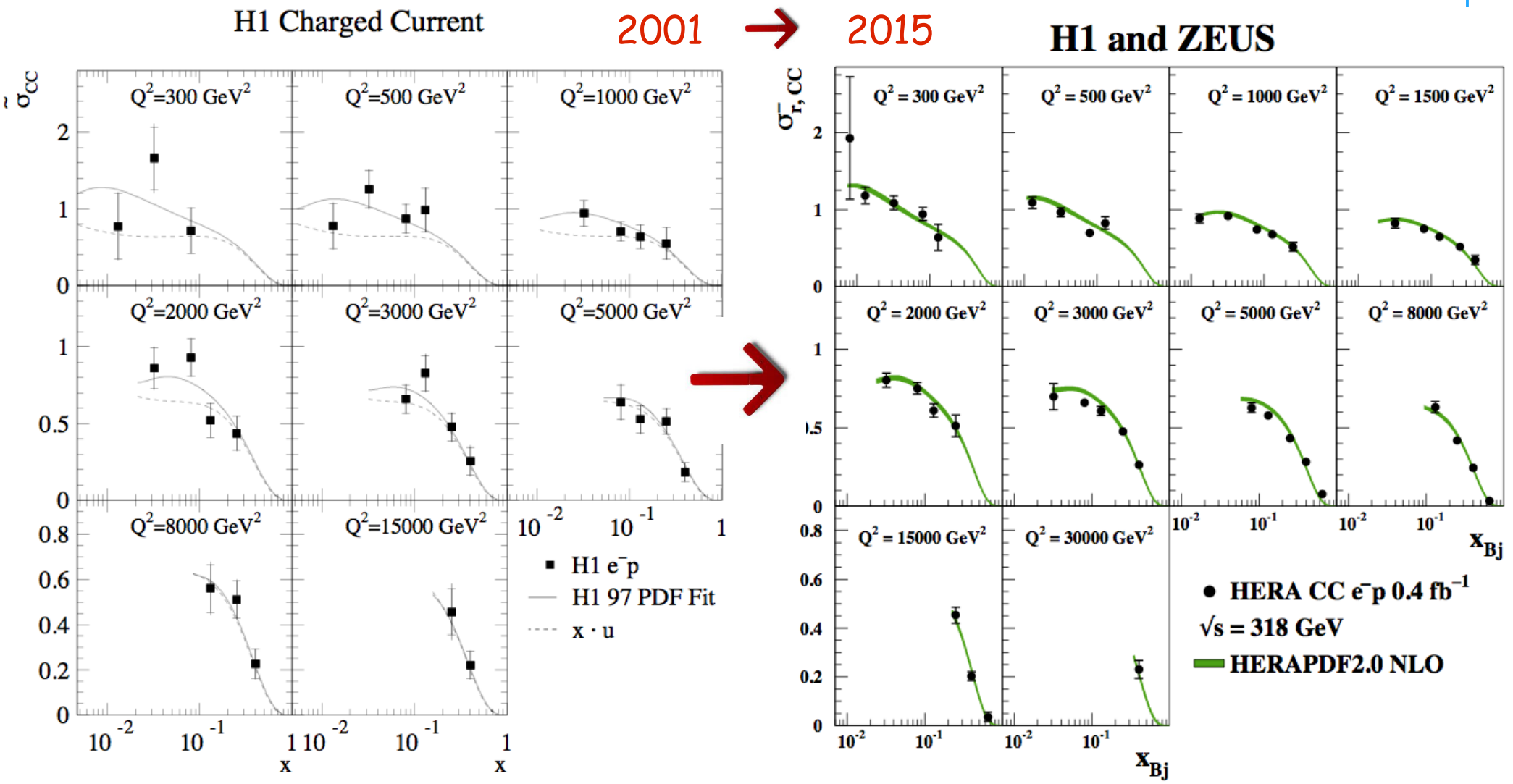
Improved precision





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

Improving previous results

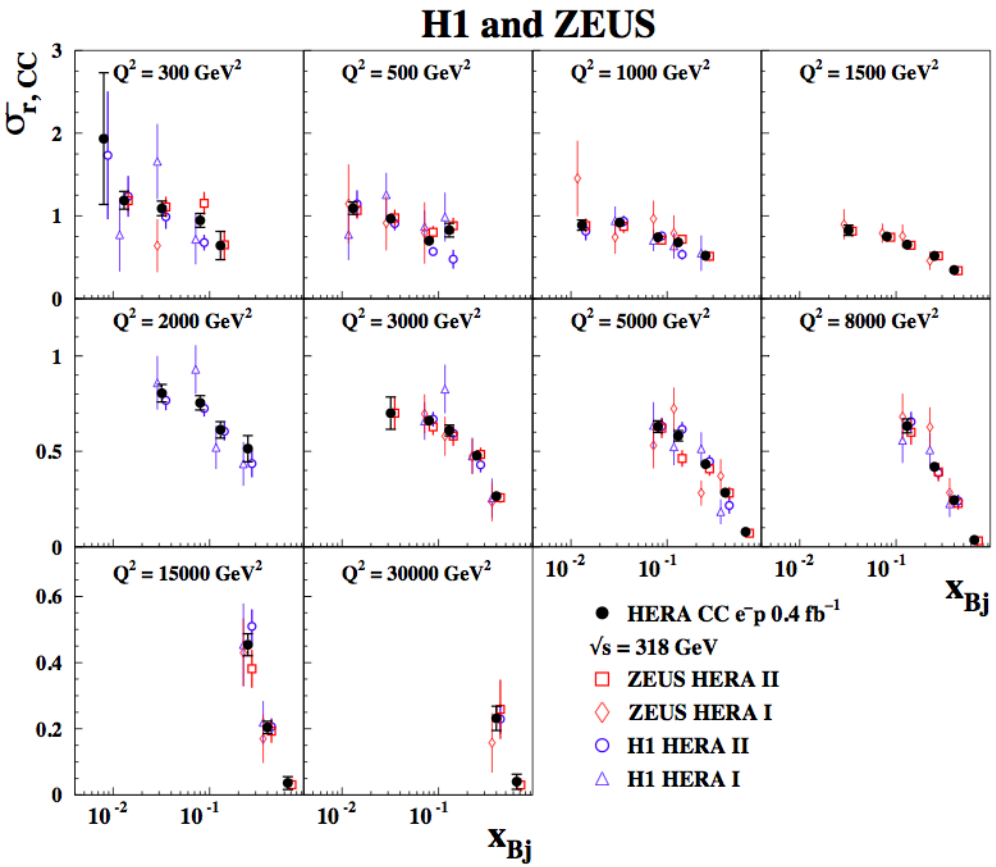


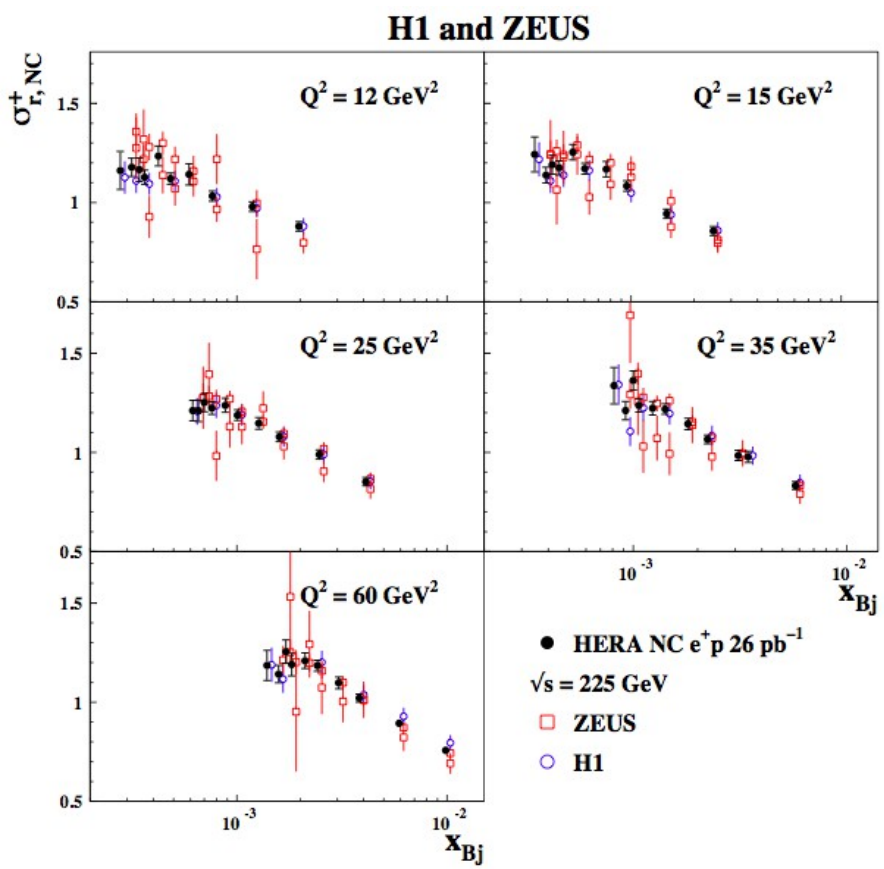
- increases statistical significance
- reduces systematic uncertainties via cross calibration techniques

Great gain in precision

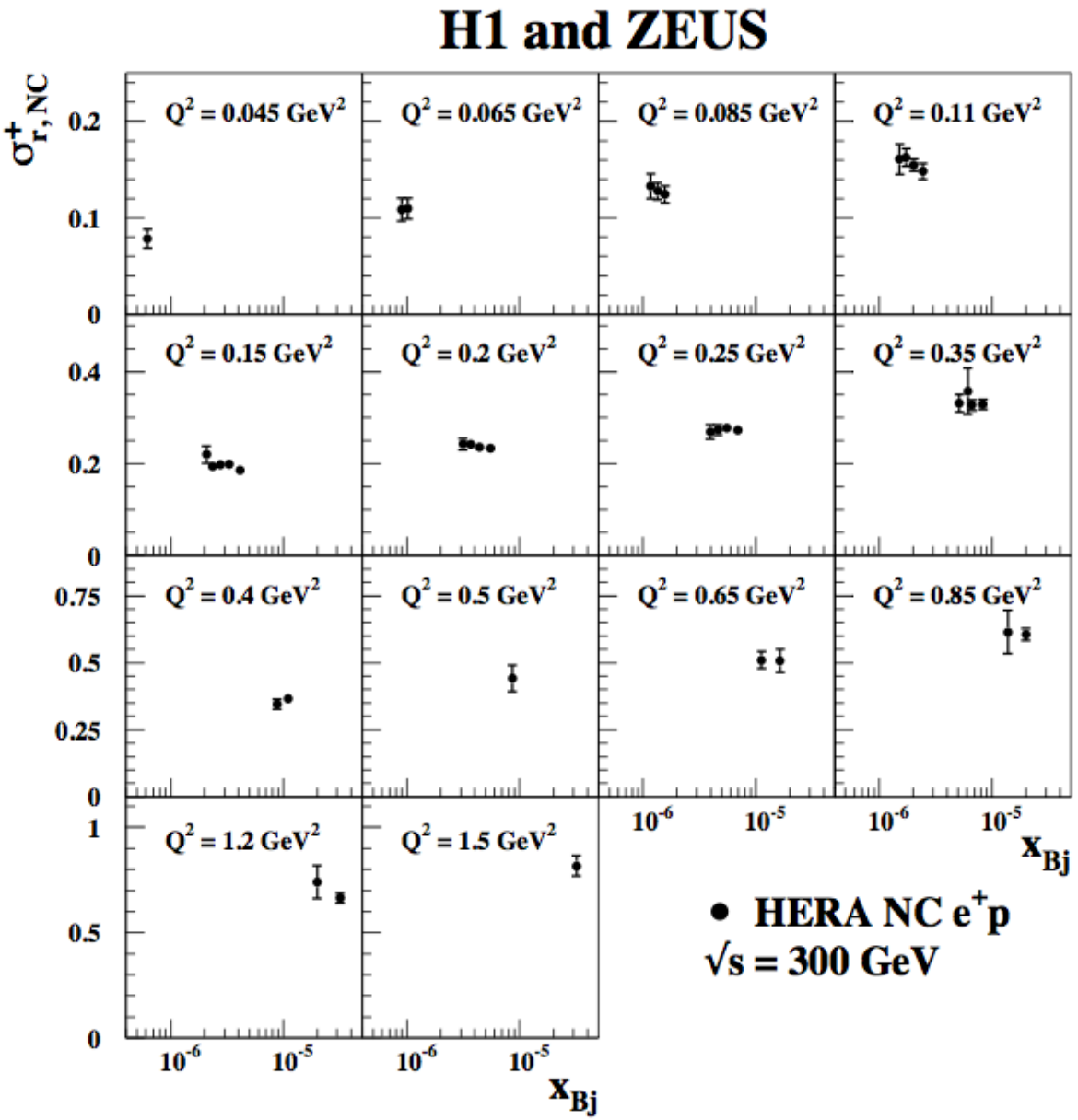
New kinematic ranges explored

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





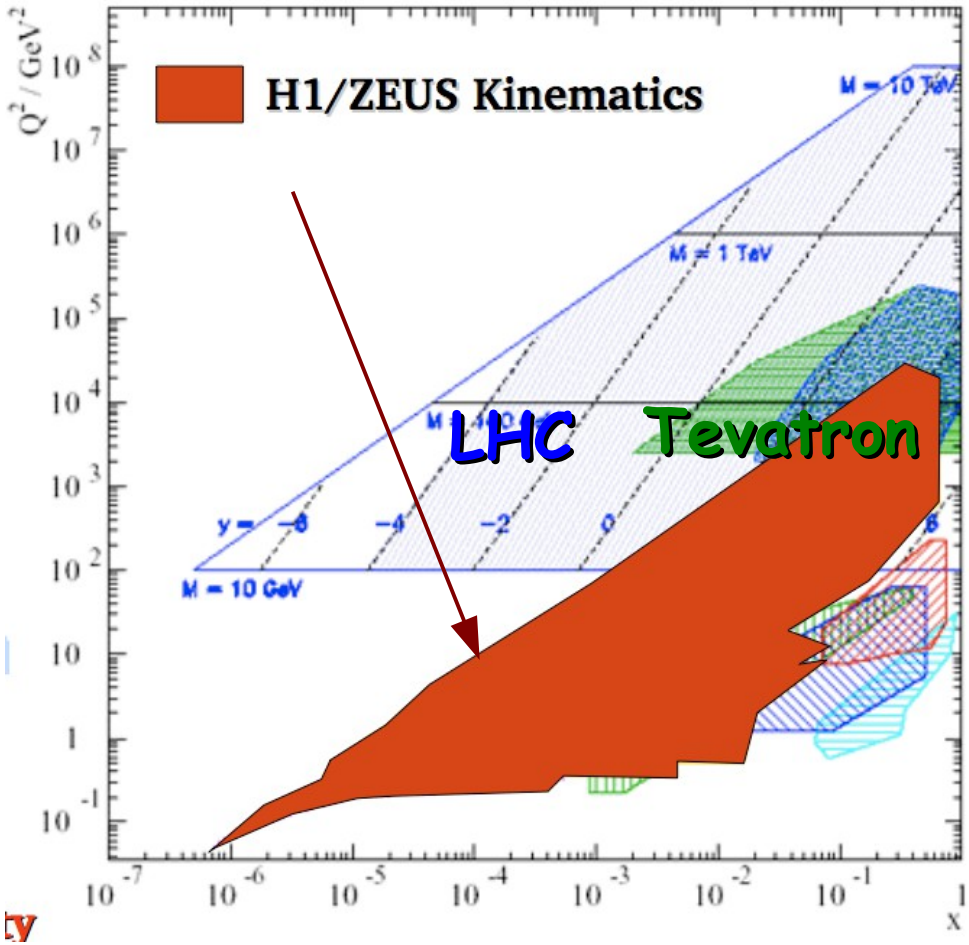
Low Q^2 combined data

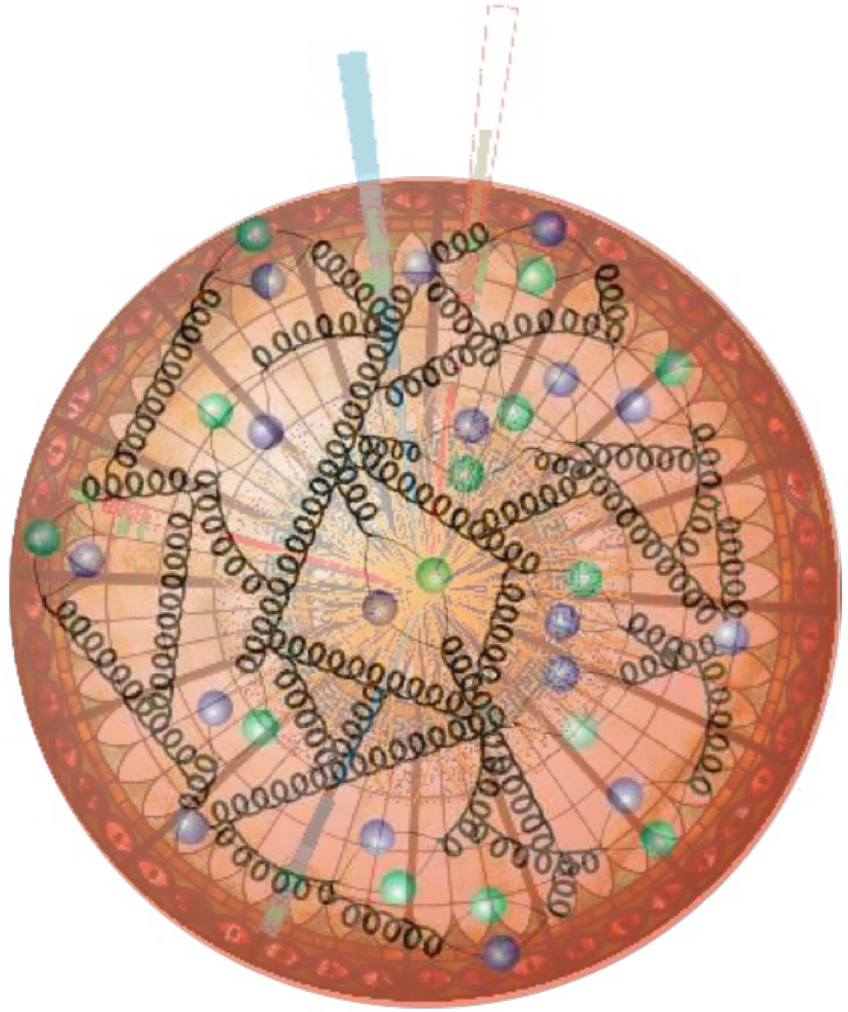


- Combined inclusive cross sections for low Q^2
- Available for two CMEs
  - 300 GeV
  - 318 GeV
- Interesting for
  - dipole/saturation models
  - studying higher twists

Proton structure

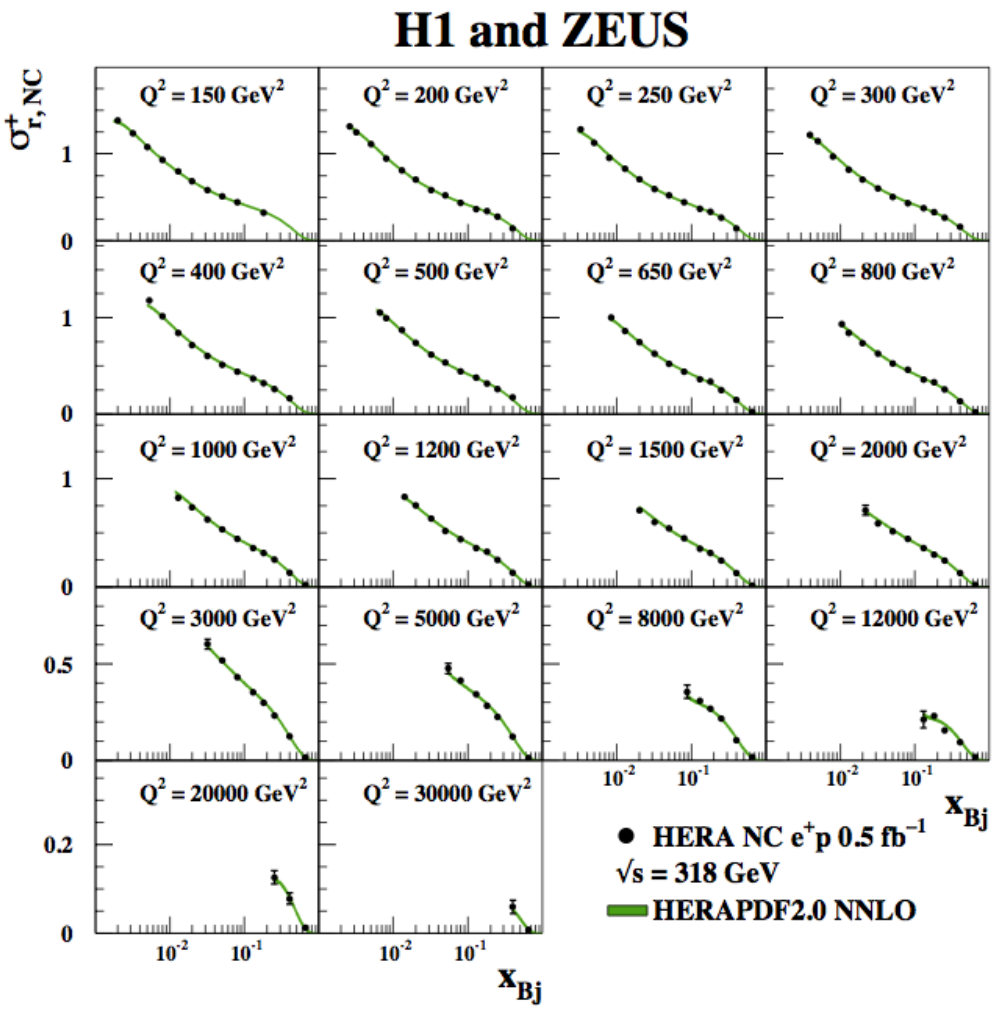
Inclusive measurements from HERA are core of every parton density extraction





Neutral Current

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$



Proton structure functions

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

- Sensitive to quarks

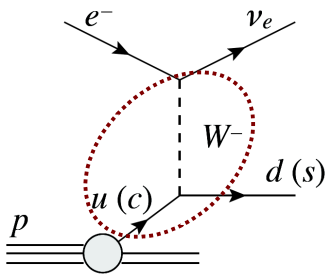
$$xF_3 = x\sum 2e_q a_q[q(x) - \bar{q}(x)]$$

- Sensitive to valence distributions

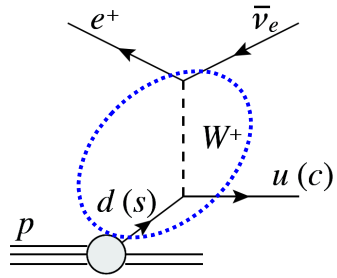
$$F_L \sim \alpha_S \, x \, g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

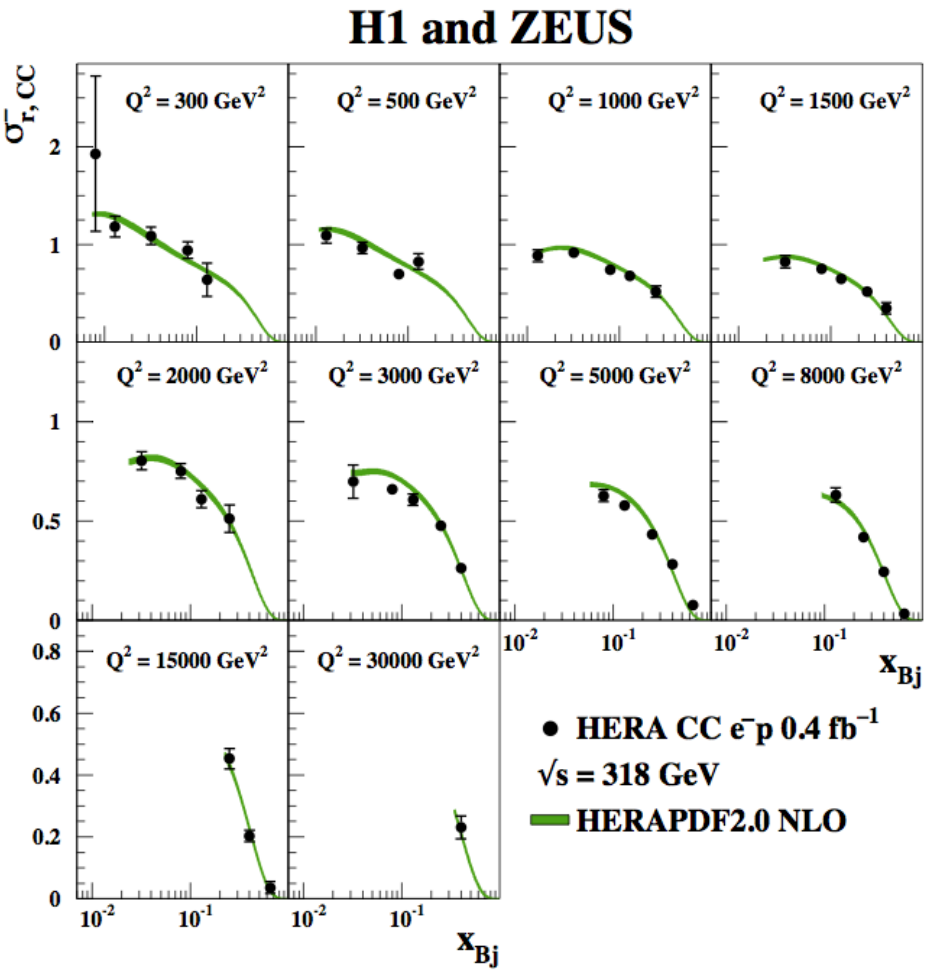


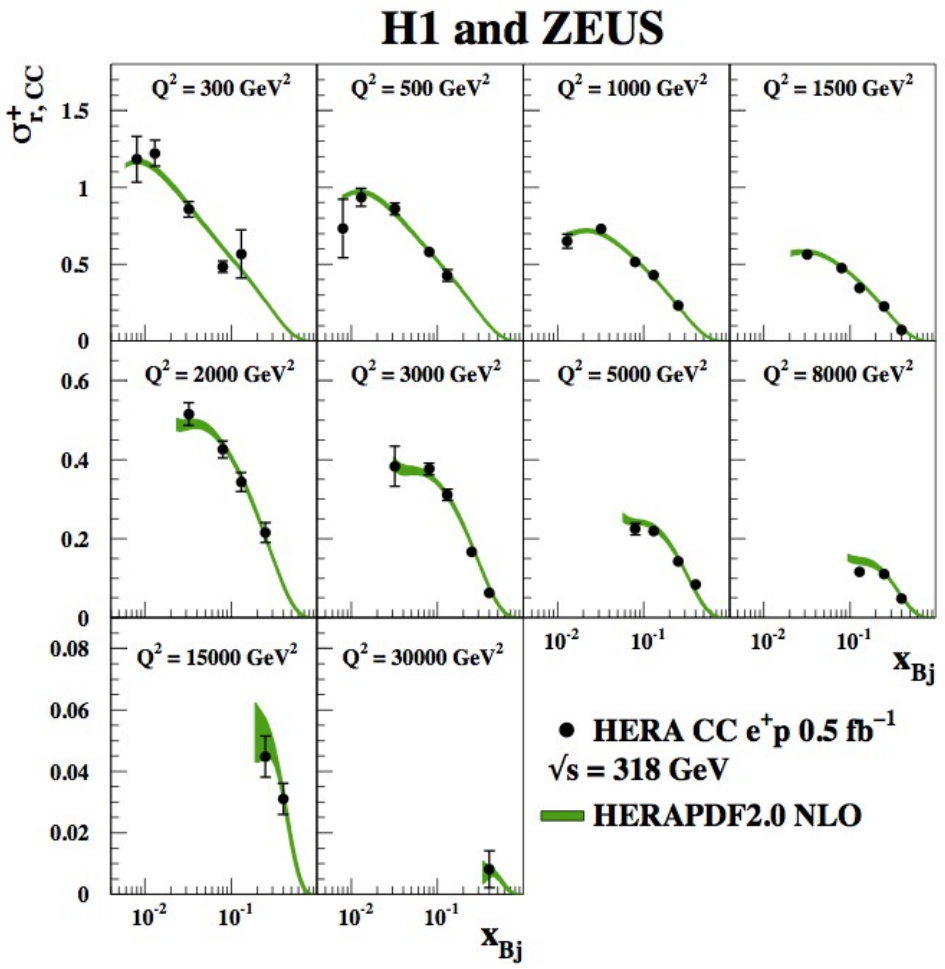
Charge Current: flavor decomposition



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

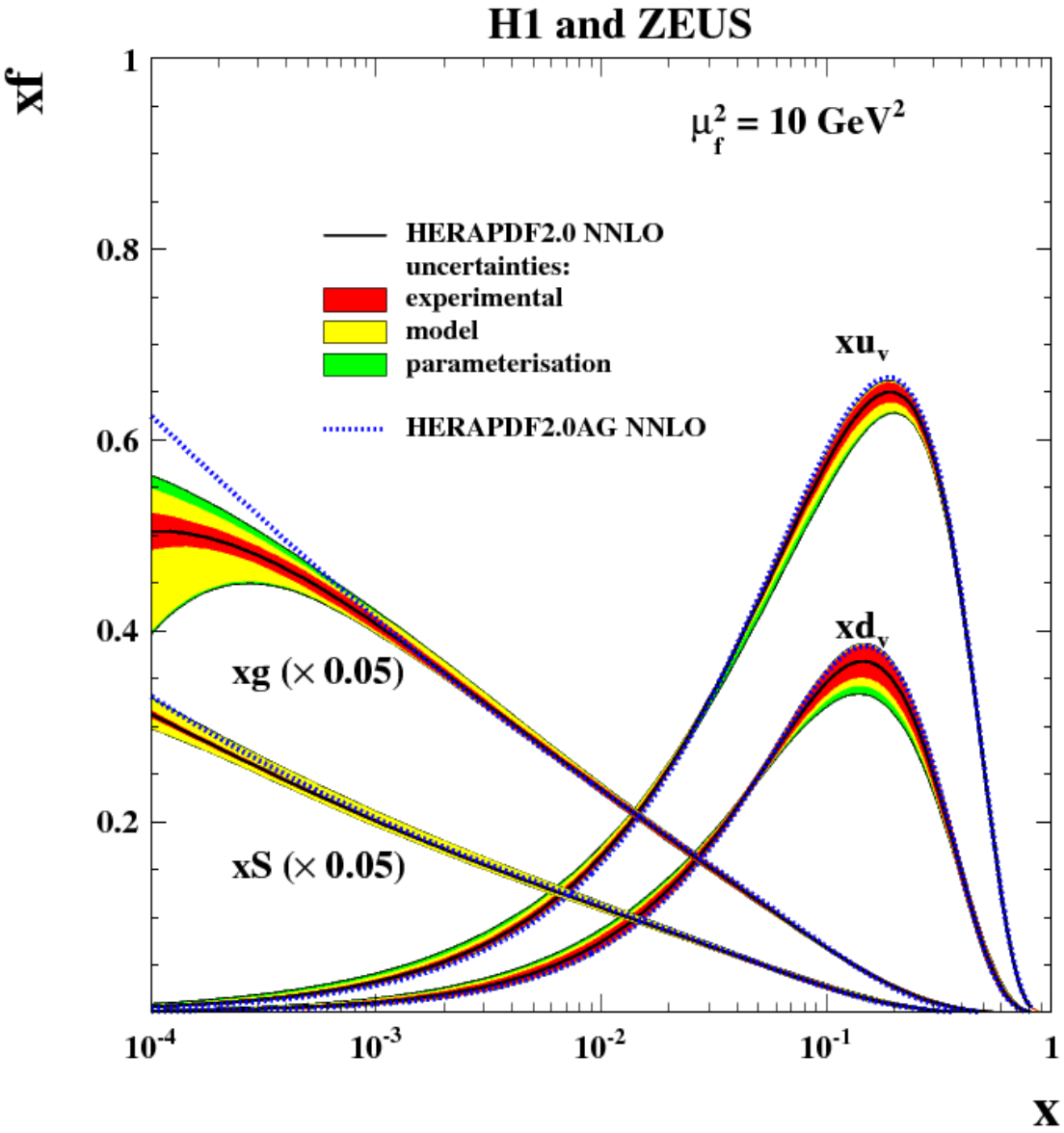
$$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1 - y)^2[d + s]$$





HERAPDF2.0

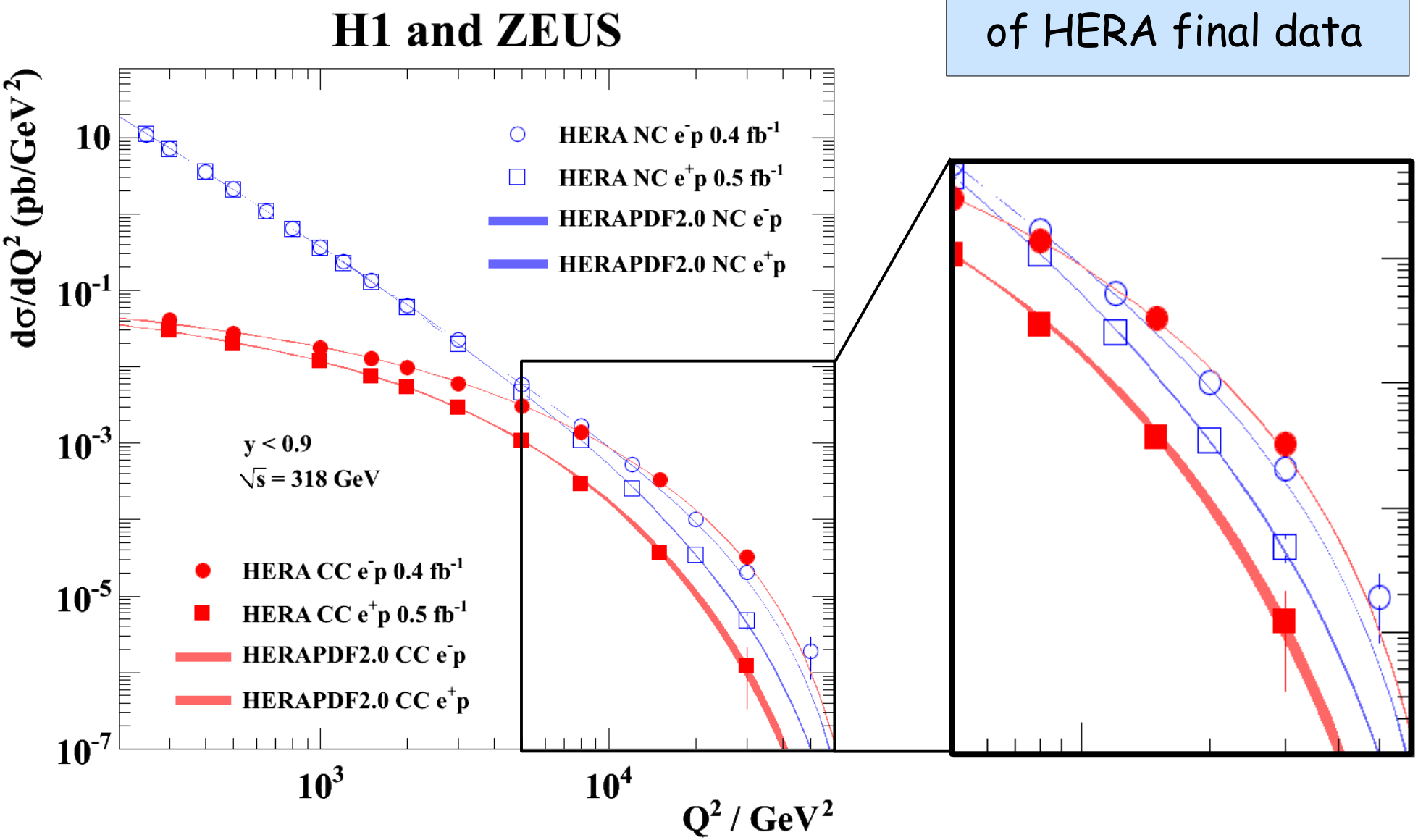
- HERAPDF2.0 used HERA data only → see talk of V. Myronenko



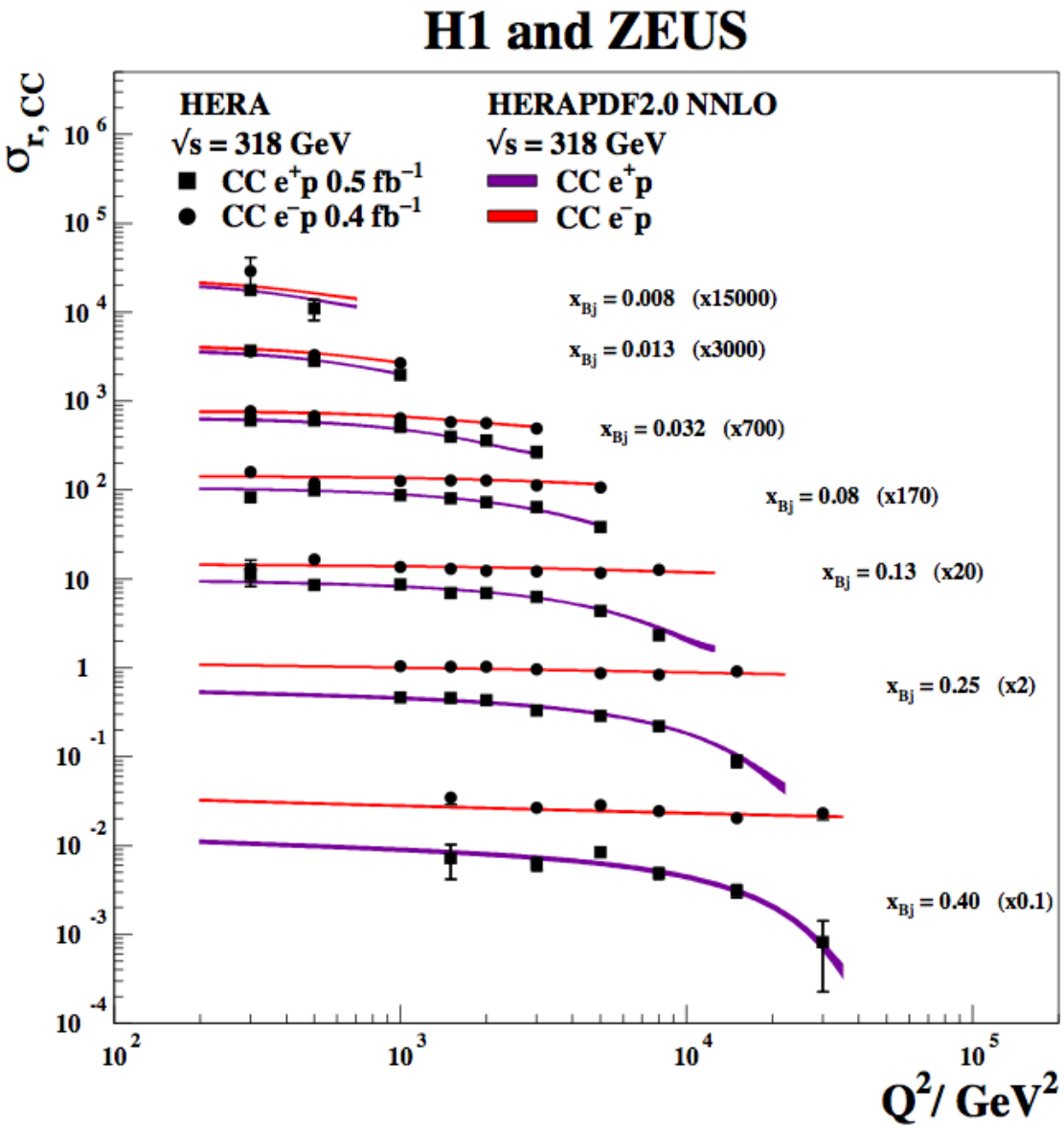

MORTAL KOMBAT
HERA LEGACY

Electroweak unification

Fantastic precision of HERA final data



CC: helicity effects

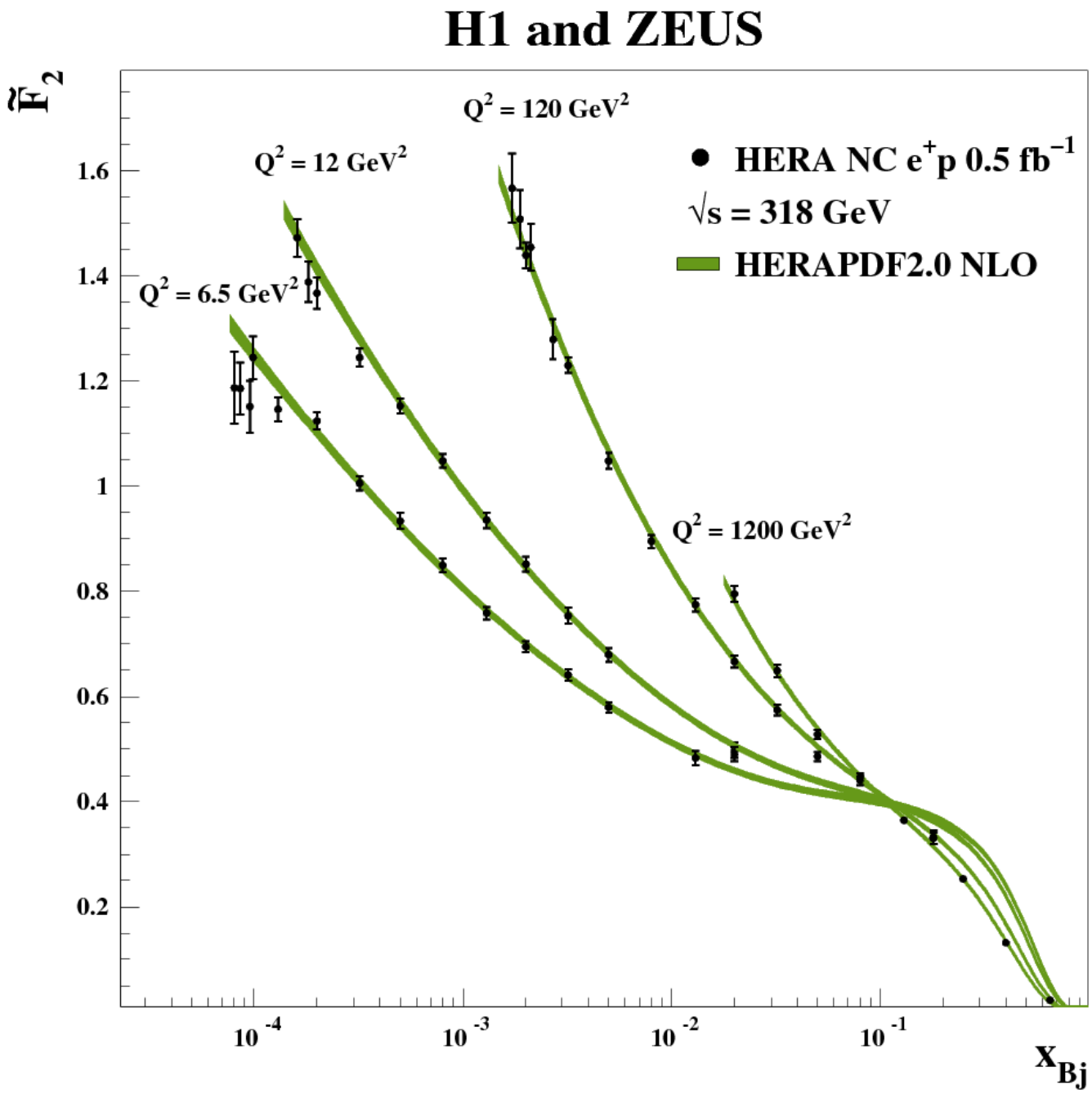


$$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$

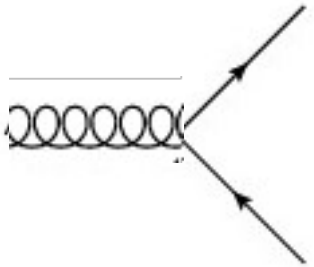
$$\sigma^{-}_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

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

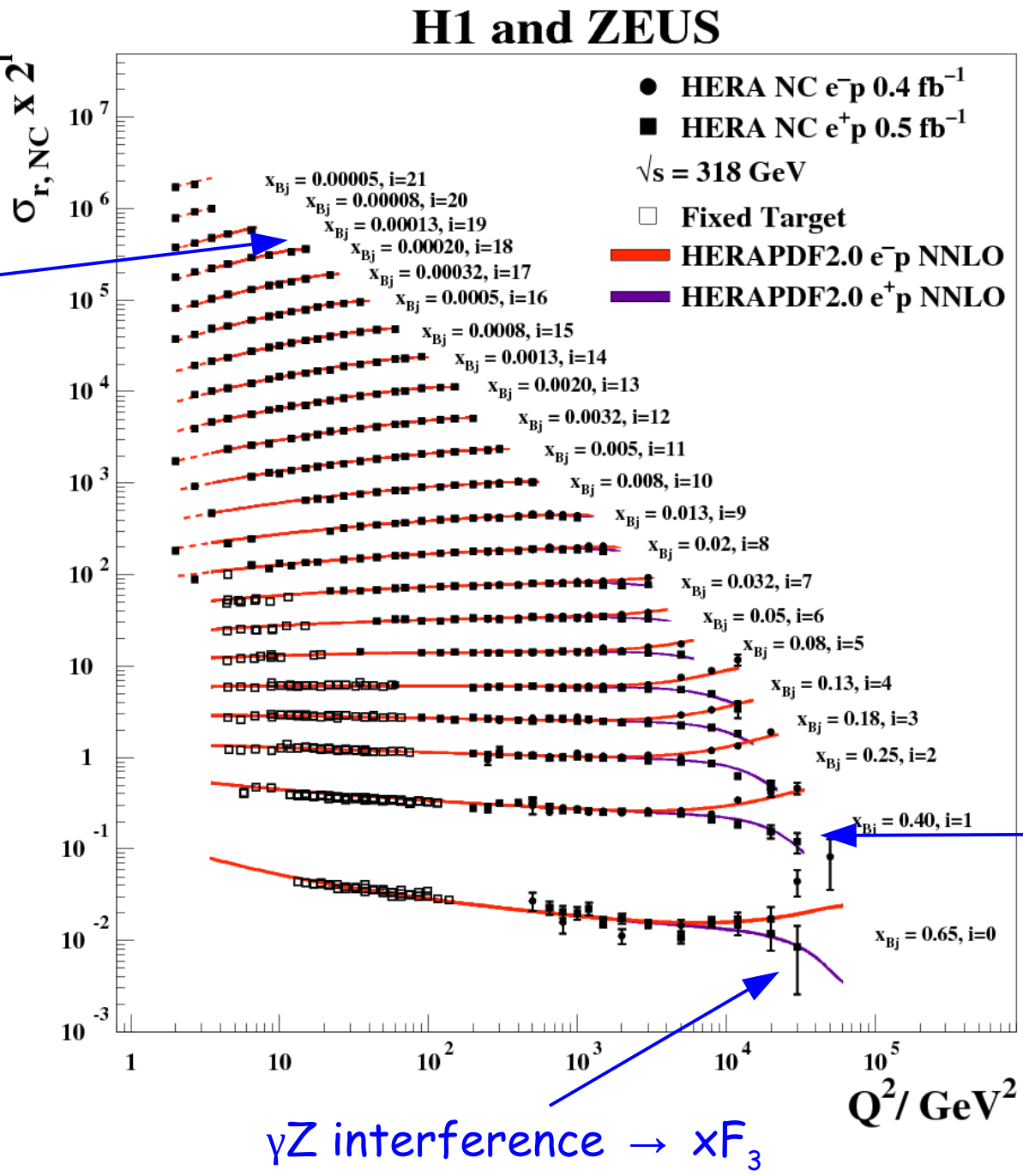
Low-x rise of F_2

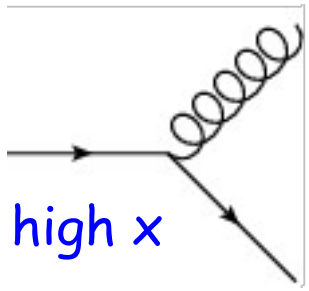


QCD and electroweak effects



@ low x





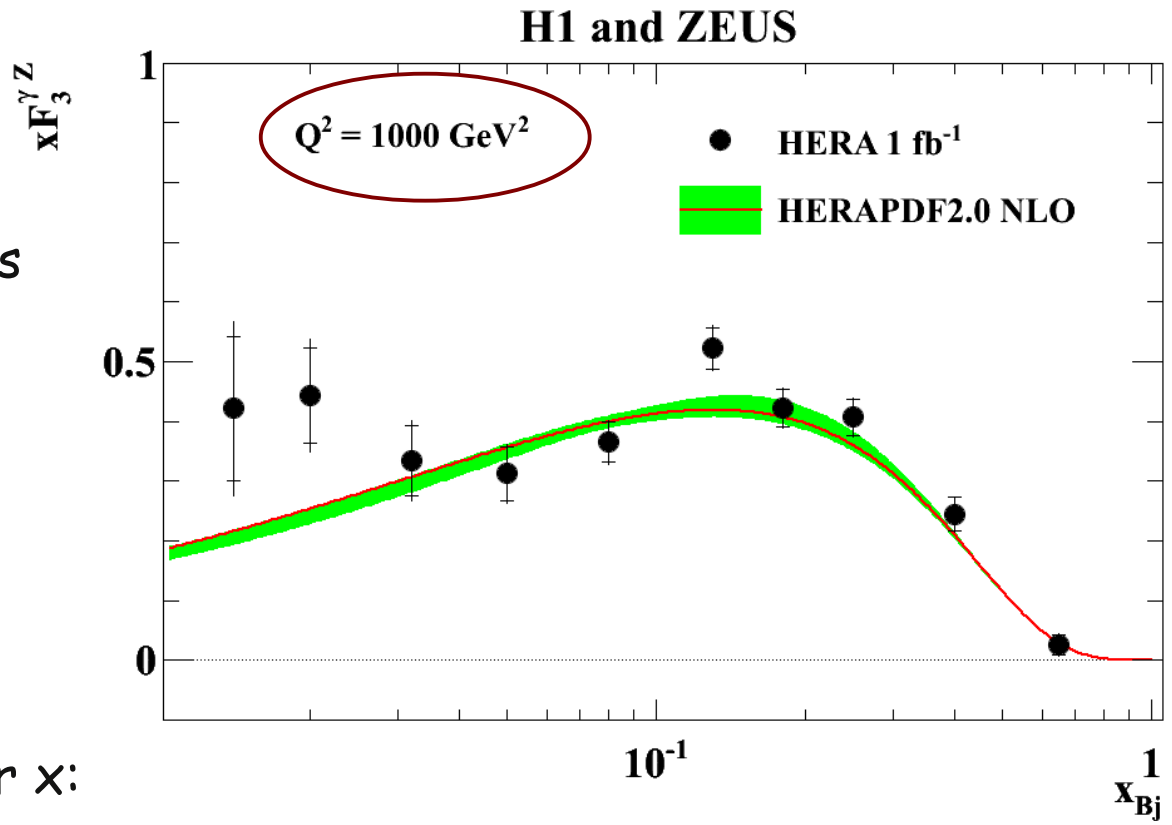
@ high x

γZ interference → xF_3

$xF_3^{\gamma Z}$ from combined data

- xF_3^{gZ} from subtracting the NC e^+p from the NC e^-p cross sections
- Function of x_{Bj} in bins of Q^2
- Weak Q^2 dependence → translated to Q^2 = 1000 GeV^2 and averaged

- Good agreements with predictions



- Integrated over x:

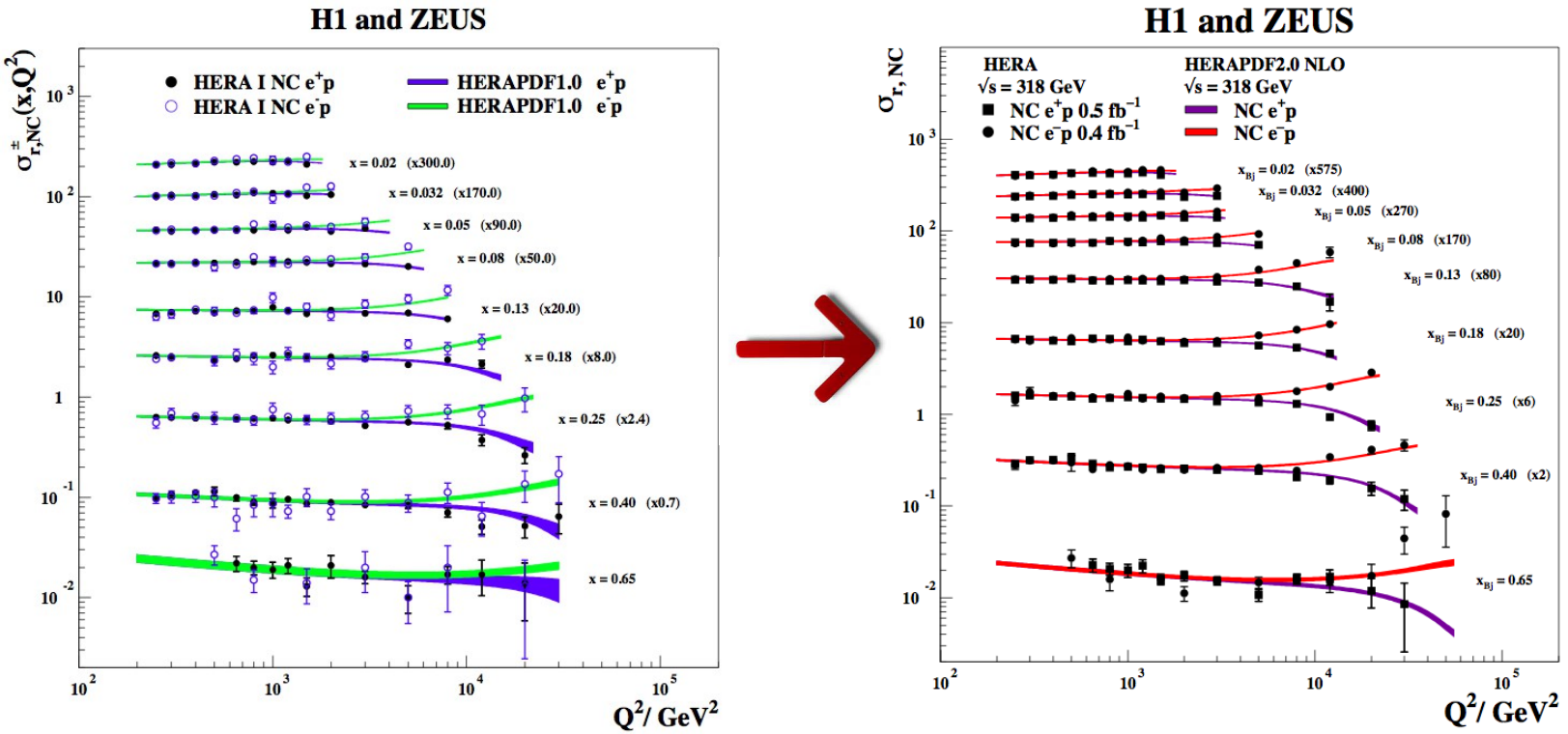
$0.016 < x_{Bj} < 0.725$ HERAPDF2.0 : $1.165^{+0.042}_{-0.053}$ Data : $1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst})$

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

QPM: 5/3

Summary

- HERA combined measurements of inclusive DIS final
- Combined HERA data set provides ultimate sample for inclusive neutral and charged current cross section studies in wide kinematic range.
  - HERAPDF2.0 PDF based on final combination
  - Low Q^2 data provide additional checks of the QCD calculations
- Plethora of beautiful physics seen in inclusive DIS measurements
  - HERA legacy of almost 25 years of activity



Additional slides

Procedural uncertainties

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

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

- **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 combinatior