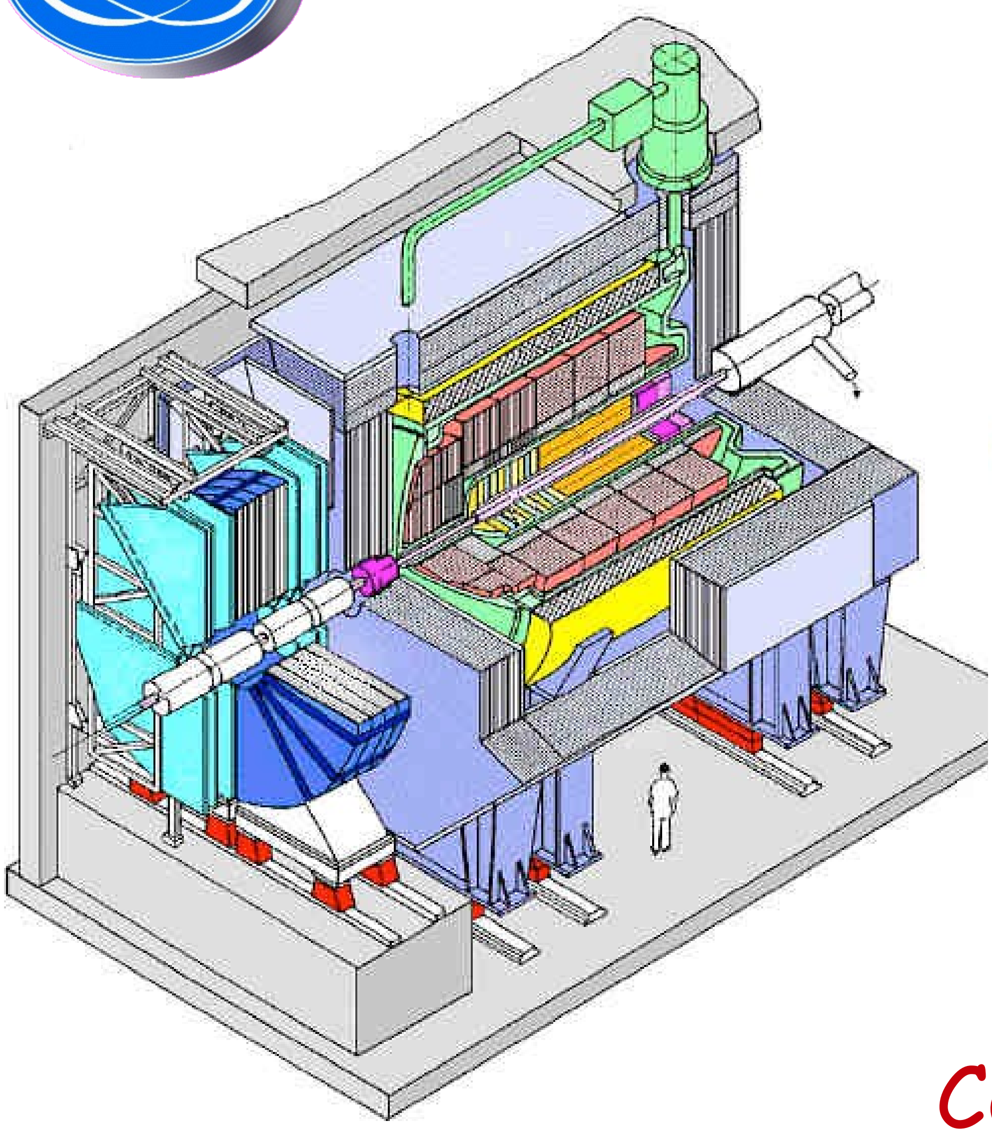
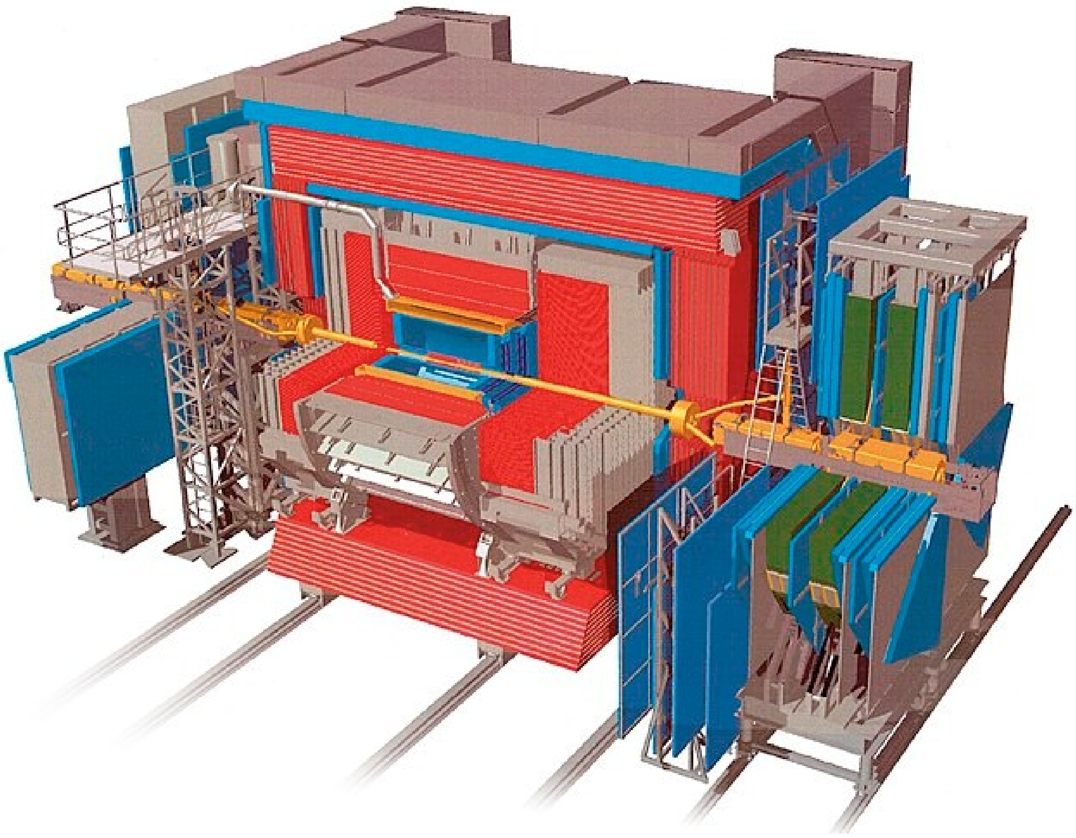




Competition:
H1 and Zeus at HERA

K. Wichmann

Complementarity: H1 and Zeus at HERA

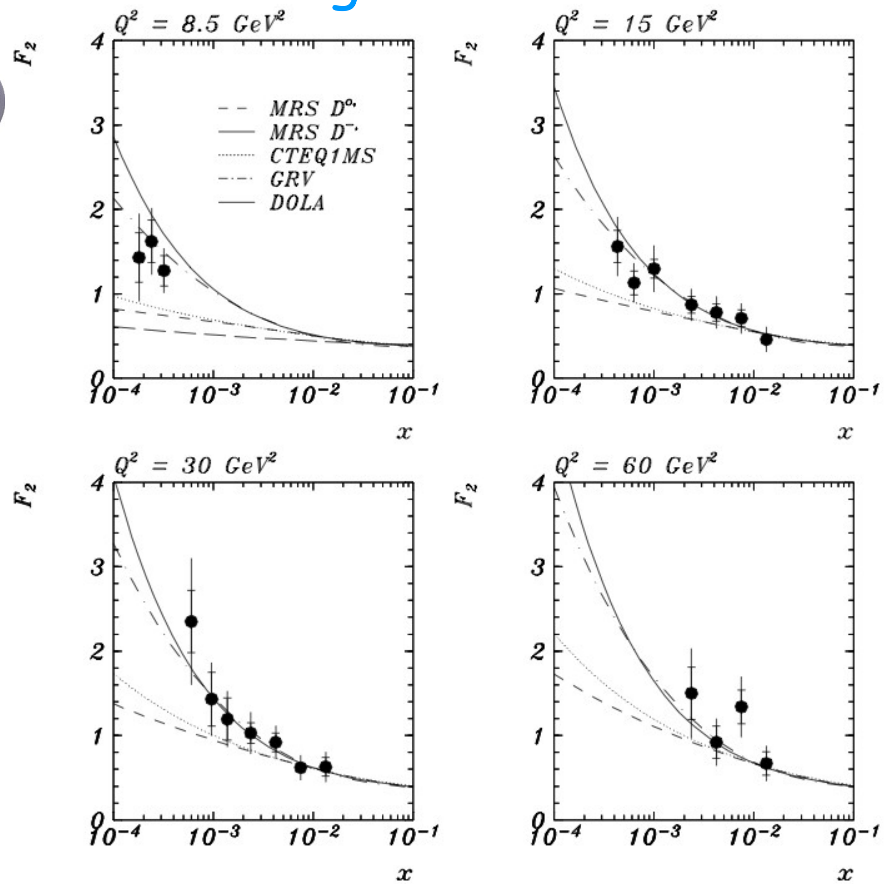
K. Wichmann

Complementarity – the obvious: cross checks

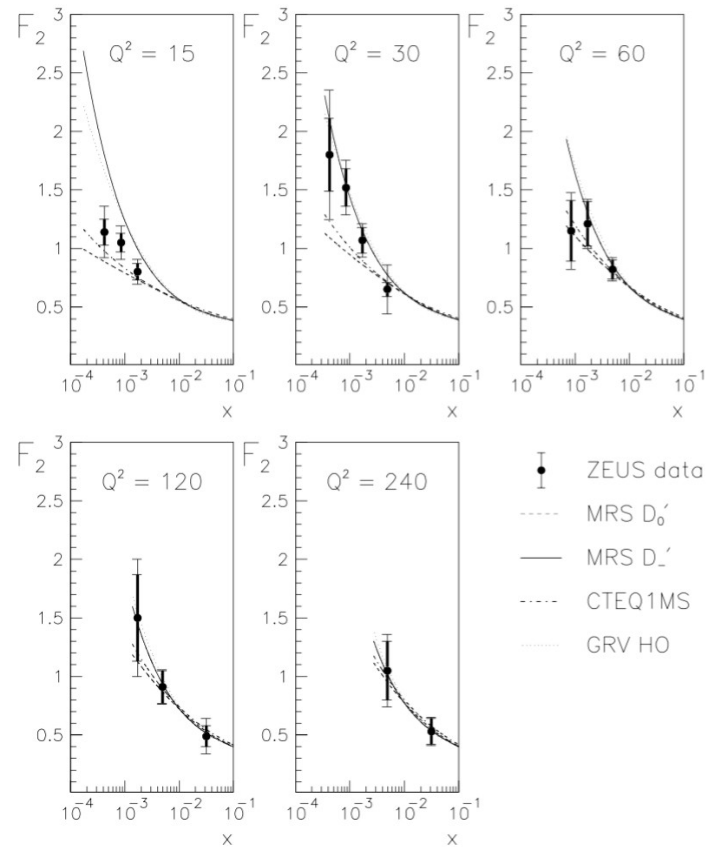
Expected:

First F_2 measurements @ HERA: 1993

August 25th



August 13th

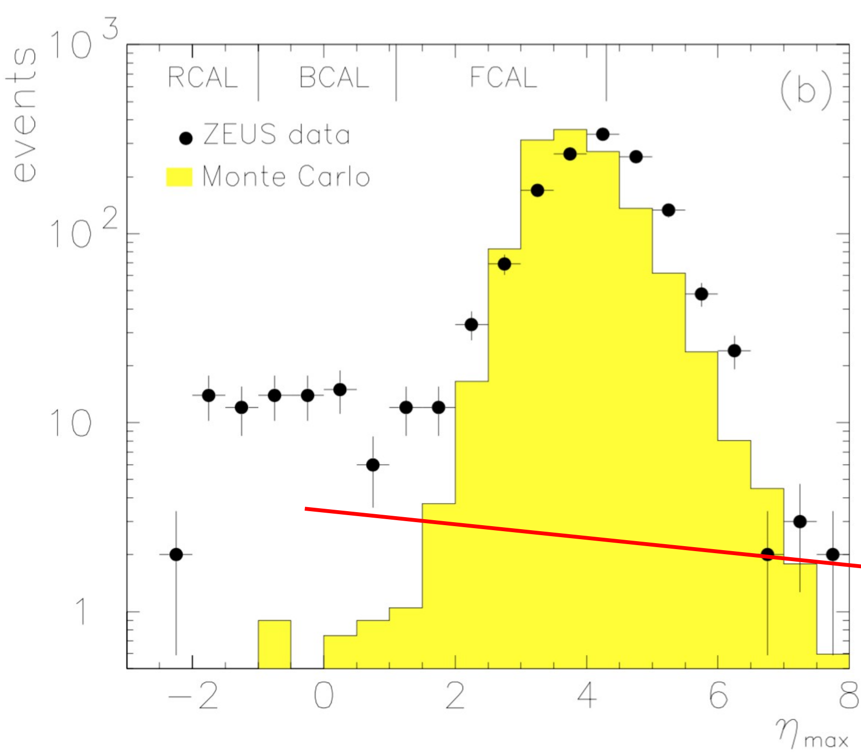


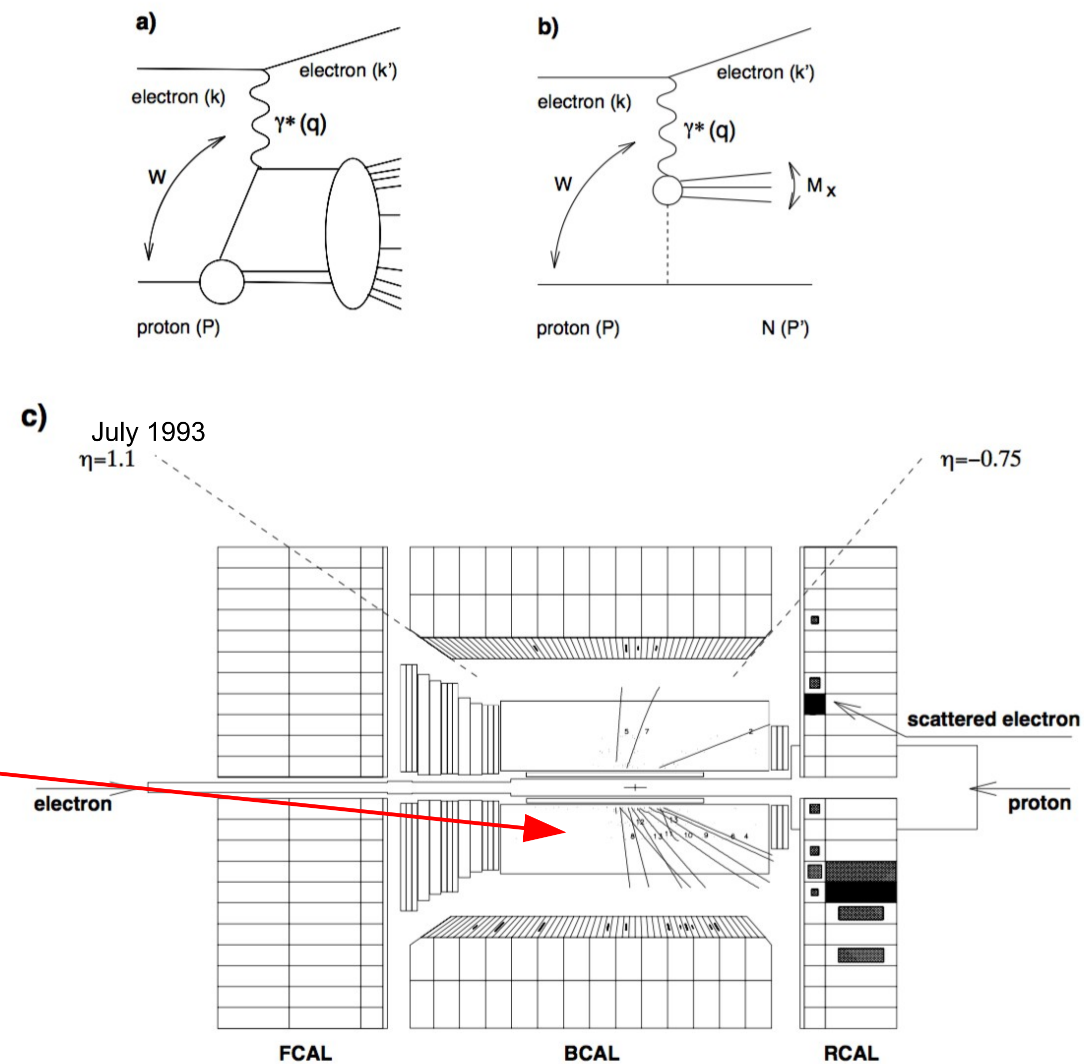
The F_2 structure function increases rapidly as x decreases.

it is exciting to see F_2 rise at small x.

Unexpected: diffraction at HERA

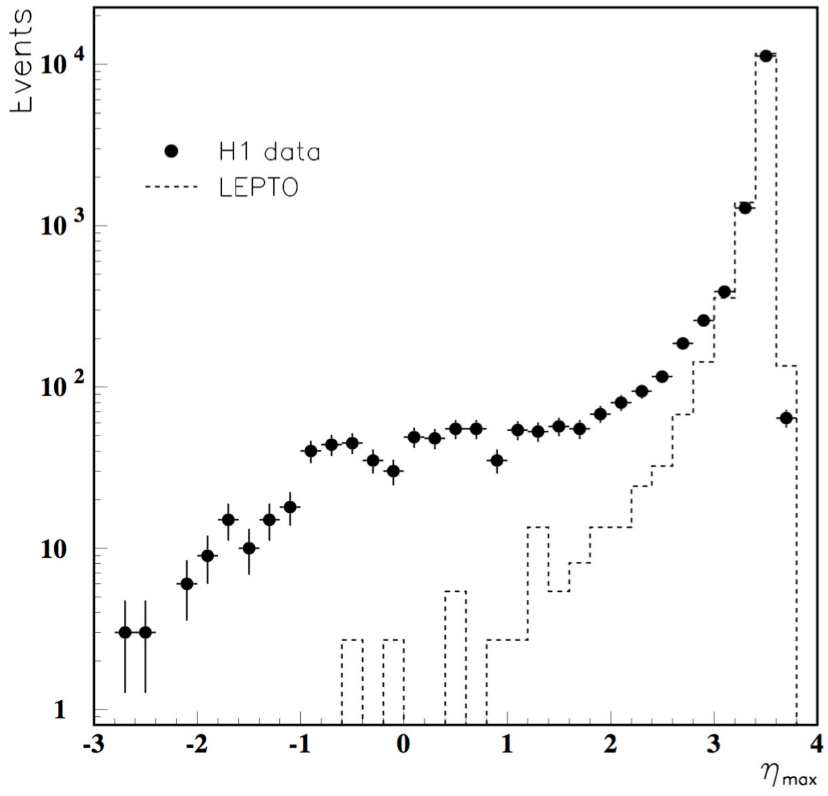
July 1993

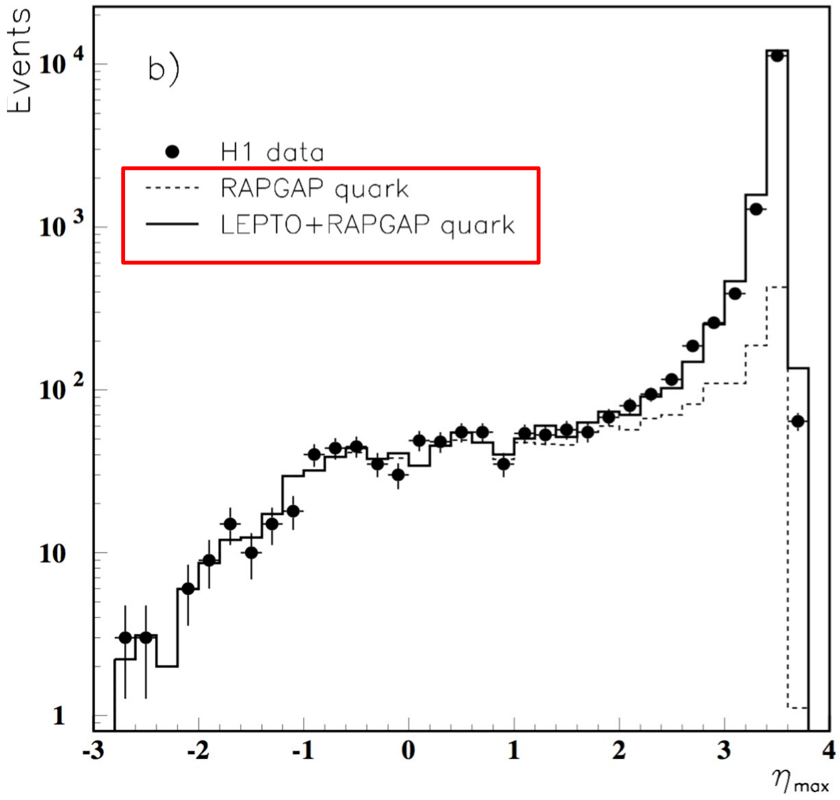




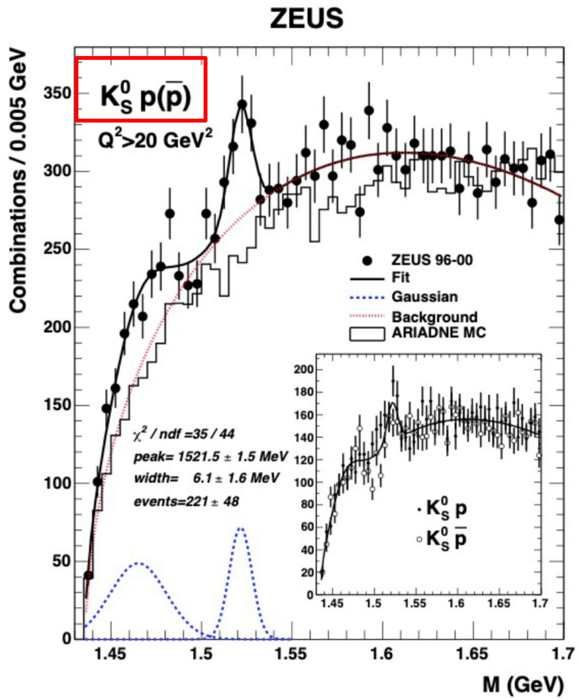
Unexpected: diffraction at HERA

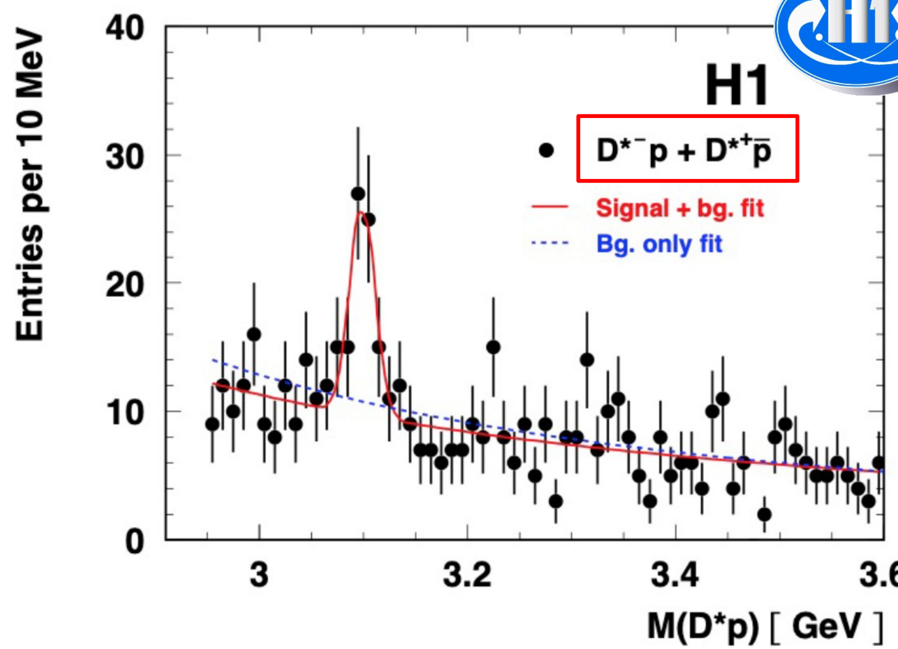
July 1994



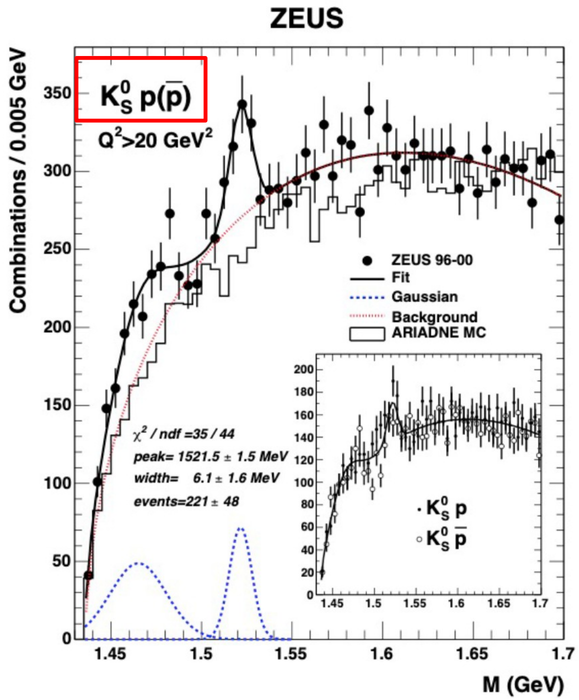


Unconfirmed: HERA Pentaquark frenzy 2004/5

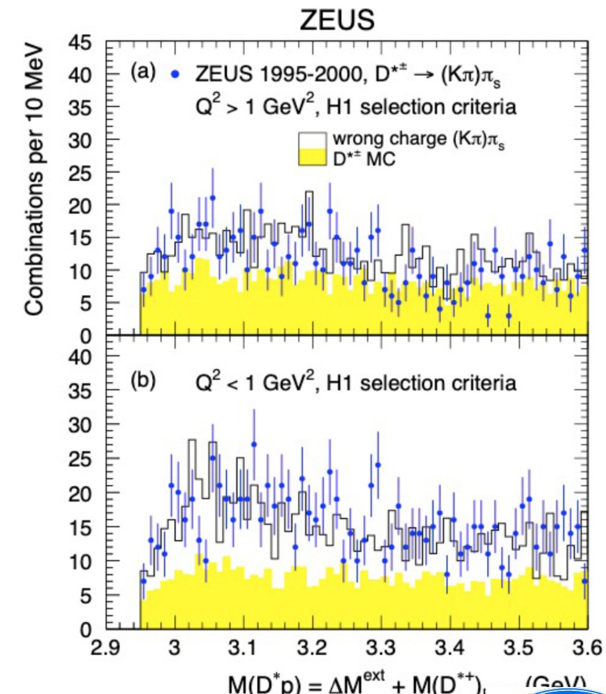


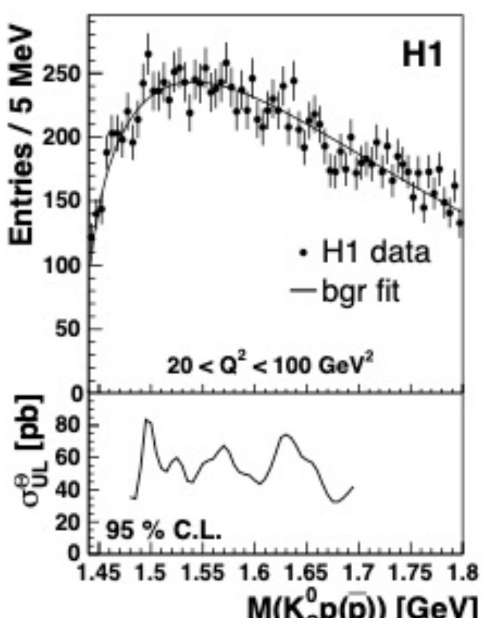


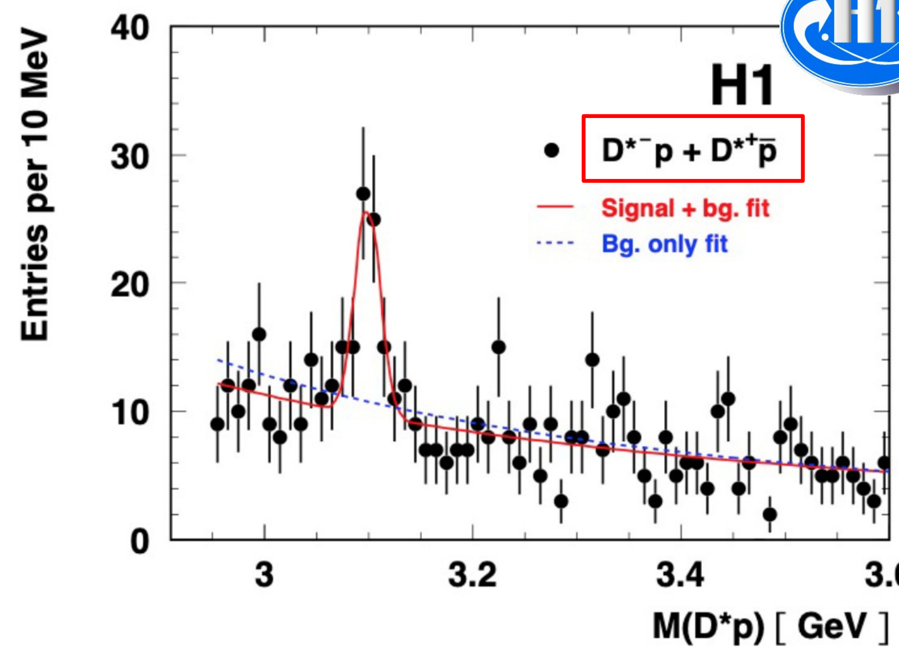
Unconfirmed: HERA Pentaquark frenzy 2004/5



Pentaquark signals not confirmed. Also not in HERAII data







Complementarity - the detectors

H1 and ZEUS detectors complementary

→ by chance ...

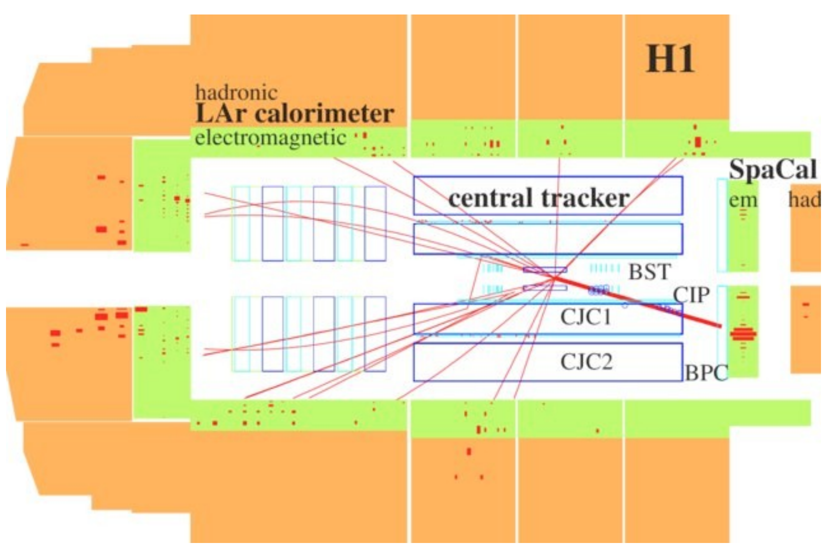
EIC has a chance to do it on purpose :)

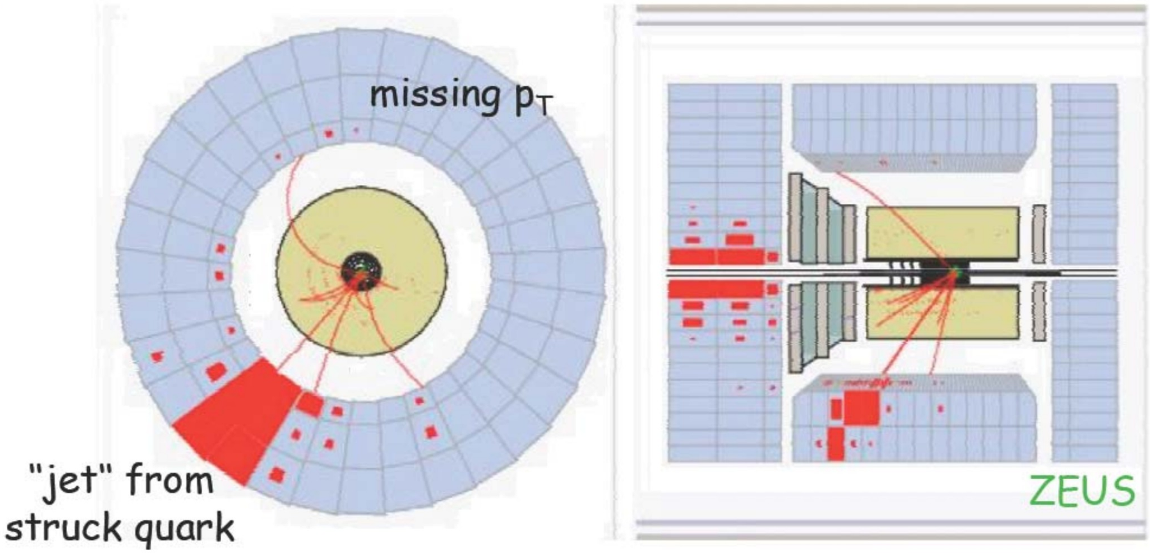
Detectors strengths

- Both detectors → almost fully hermetic multipurpose HEP detectors
- Design differences turned out to give complementarity – by chance

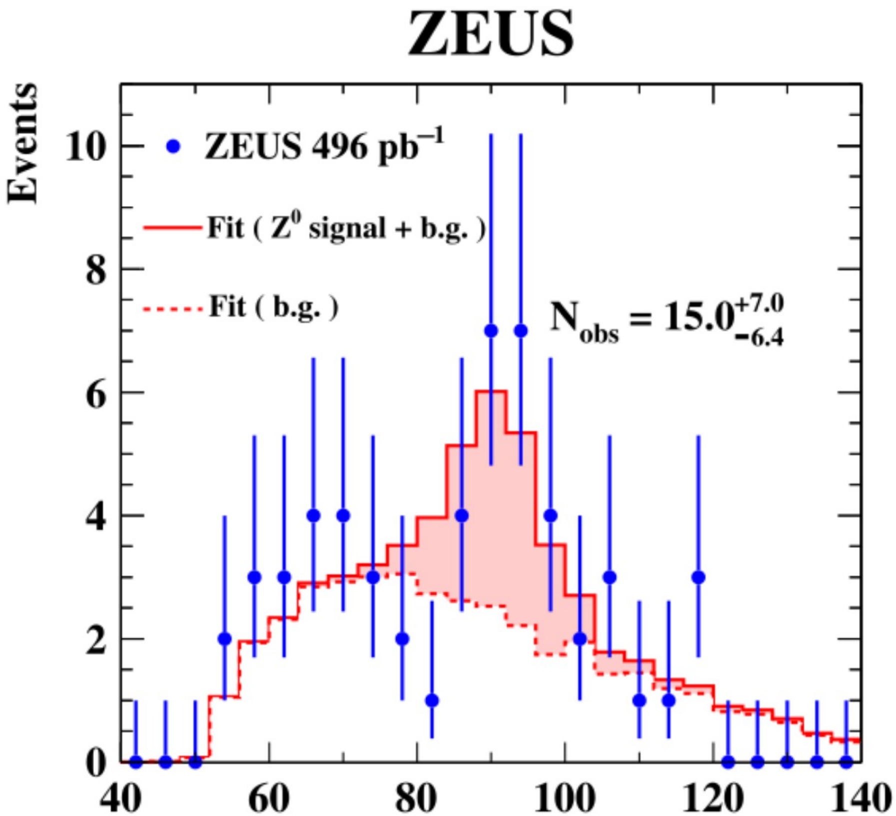
- H1 better at electron reconstruction due to EM calorimeter and detector design
- At HERAII → only forward detectors for diffraction

- ZEUS better at hadron calorimetry → compensating uranium calorimeter → the only so far and one of the best calorimeters ever built

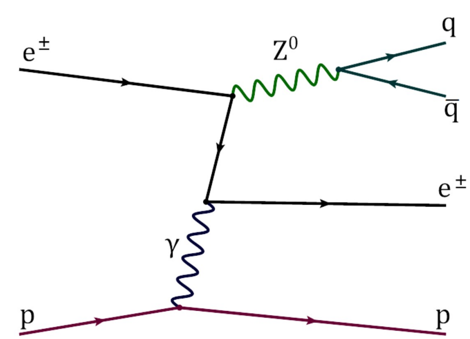


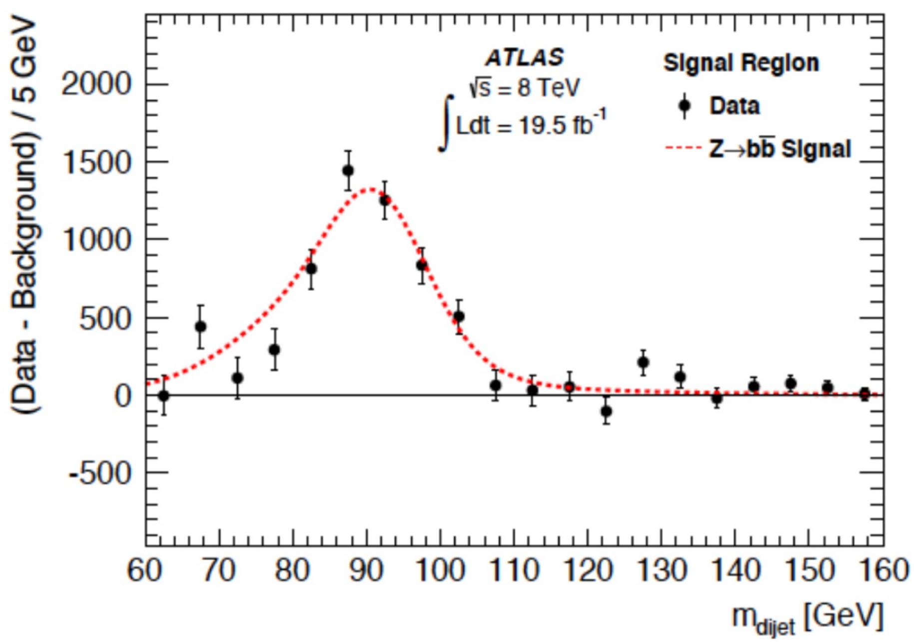


Real Z^0 @ ZEUS

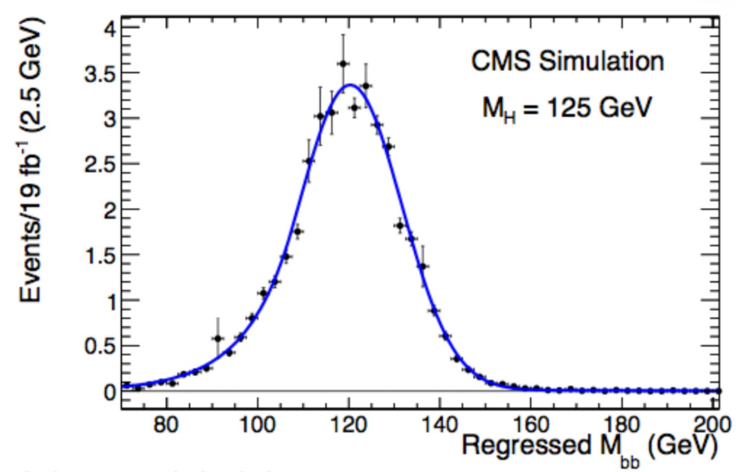


- ZEUS calorimeter allowed measurement of smallest HERA cross section in hadronic decays of real Z^0

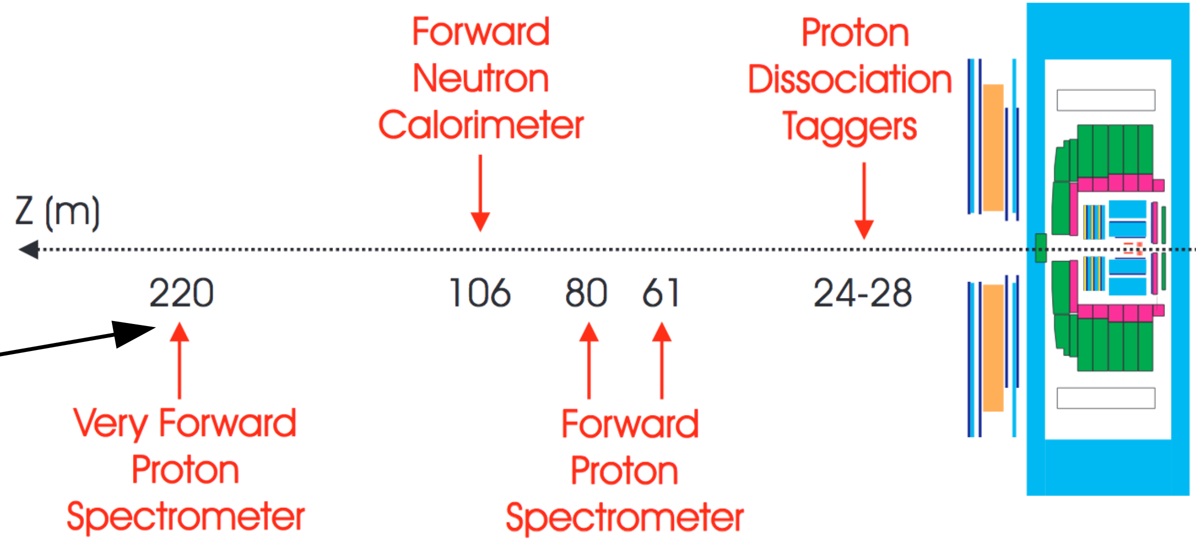


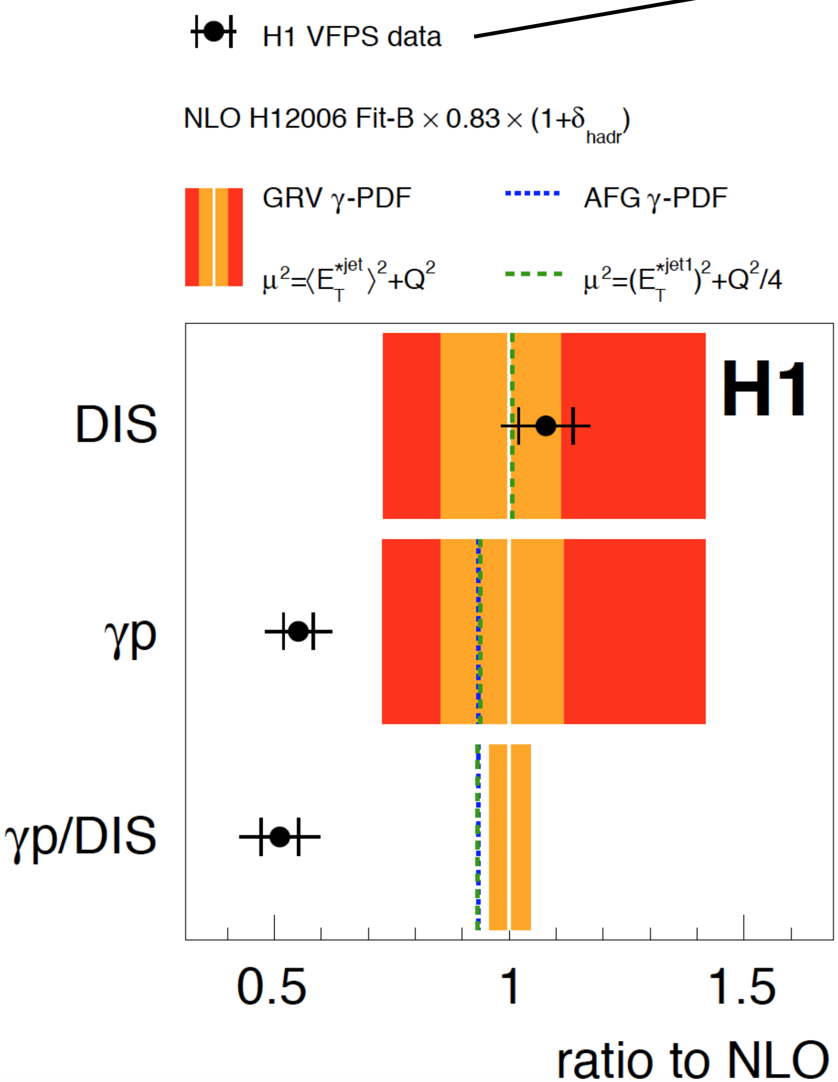


- ZEUS calorimeter resolution factor of two better than ATLAS or CMS in similar events



Diffraction @ HERAII





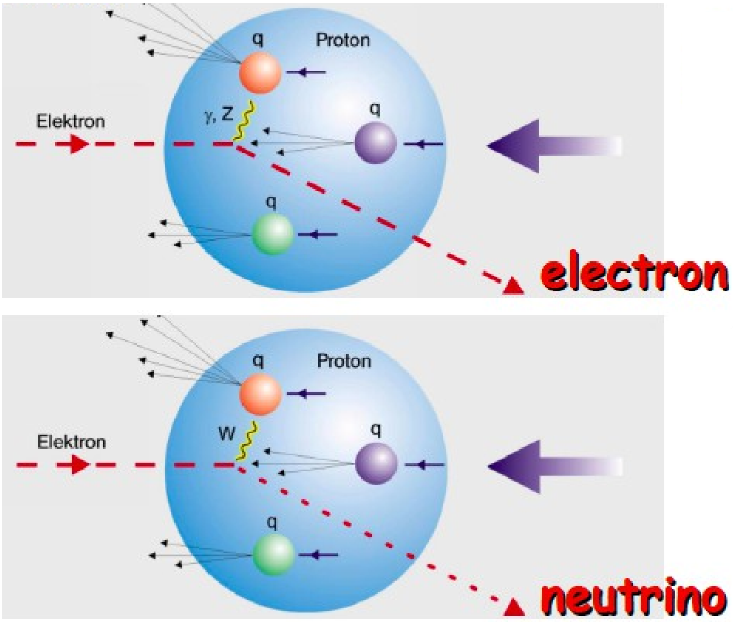
Diffractive dijet production with leading proton at H1

- Measurements in DIS and photoproduction for various variables
- Comparison to NLO calculation with assumed factorisation in diffraction
- Observation of diffractive factorisation breaking in photoproduction → confirming previous H1 measurements using other techniques of identifying diffraction

Complementarity – the matured: cross-calibration and combination

Combination of 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].

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].

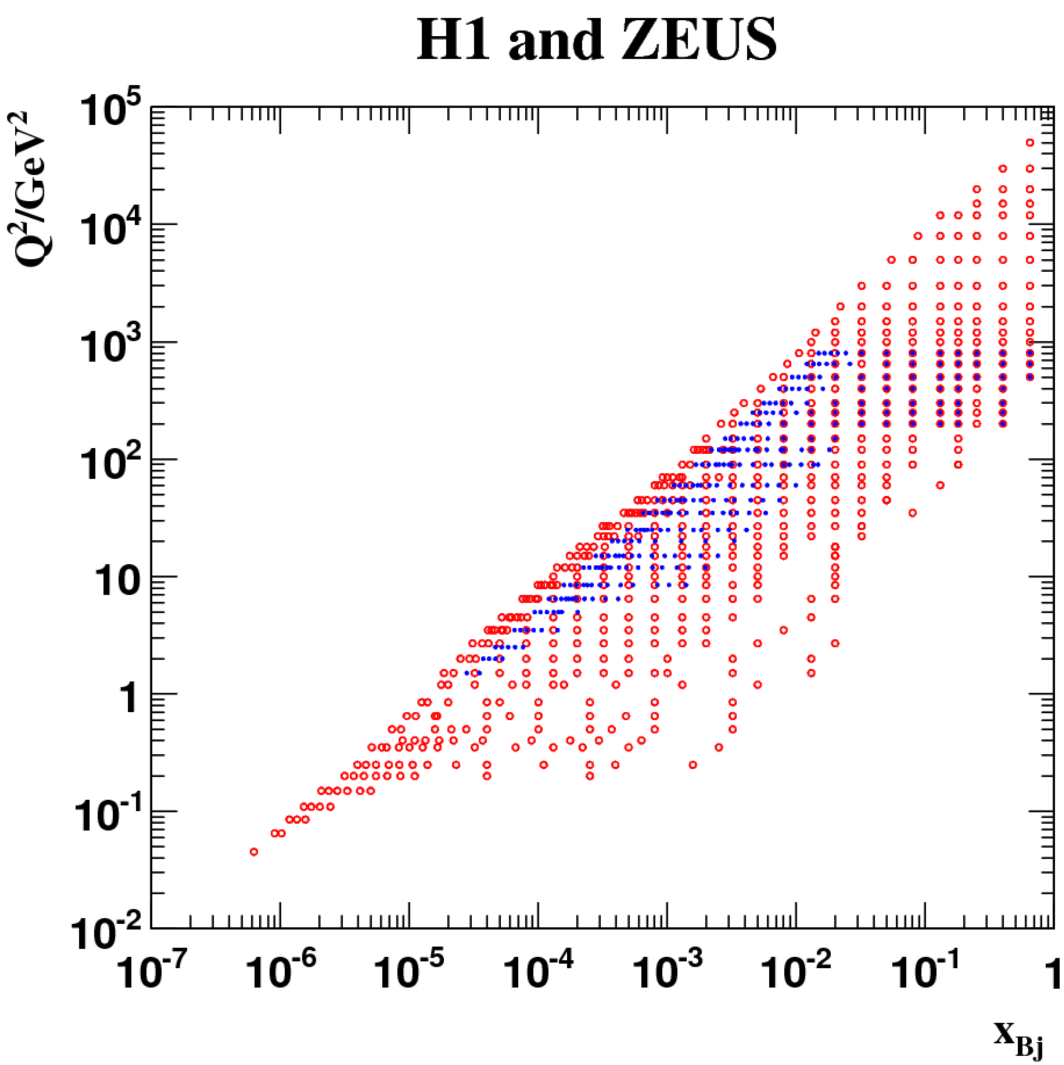
H. Abramowicz *et al.* [ZEUS Collaboration], Phys. Rev. D **90**, 072002 (2014), [arXiv:1404.6376].

DESY-15-039

ArXive: 1506.06042

EPJC 75 (2015) 580

Q^2-x_{Bj} common grids



<u>Two separate grids</u>

○ 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
  - $6\times10^{-07} < x_{Bj} < 0.65$

Averaging procedure

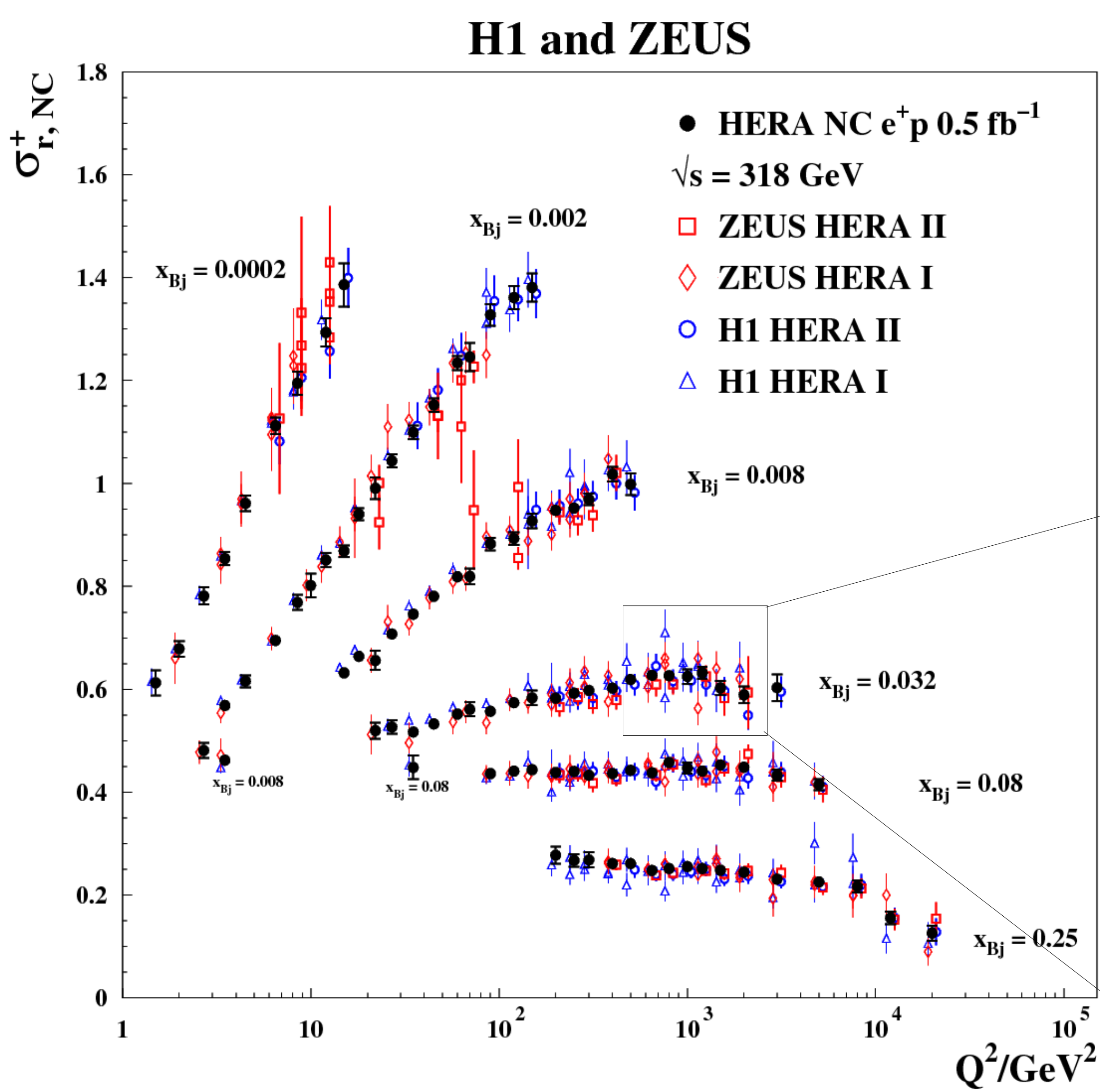
- Combination done using HERAverager: wiki-zeuthen.desy.de/HERAverager

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

- **162** correlated systematic sources taken into account
  → treated in combination as nuisance parameters: scaled by fit
- Output
  - 7 data samples for $e^{\pm}p$, NC and CC, 3 CMEs
  - Statistical and uncorrelated systematic uncertainties
  - 162 correlated statistical uncertainties

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

Combined data accuracy reaches ~1%

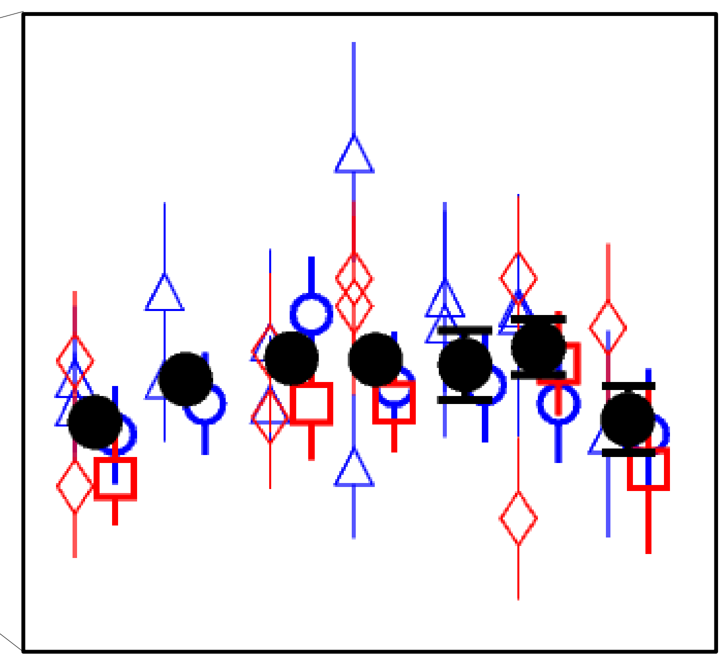


<u>Improvement well beyond statistical factor of sqrt(2)</u>

→ cross-calibration of systematic uncertainties

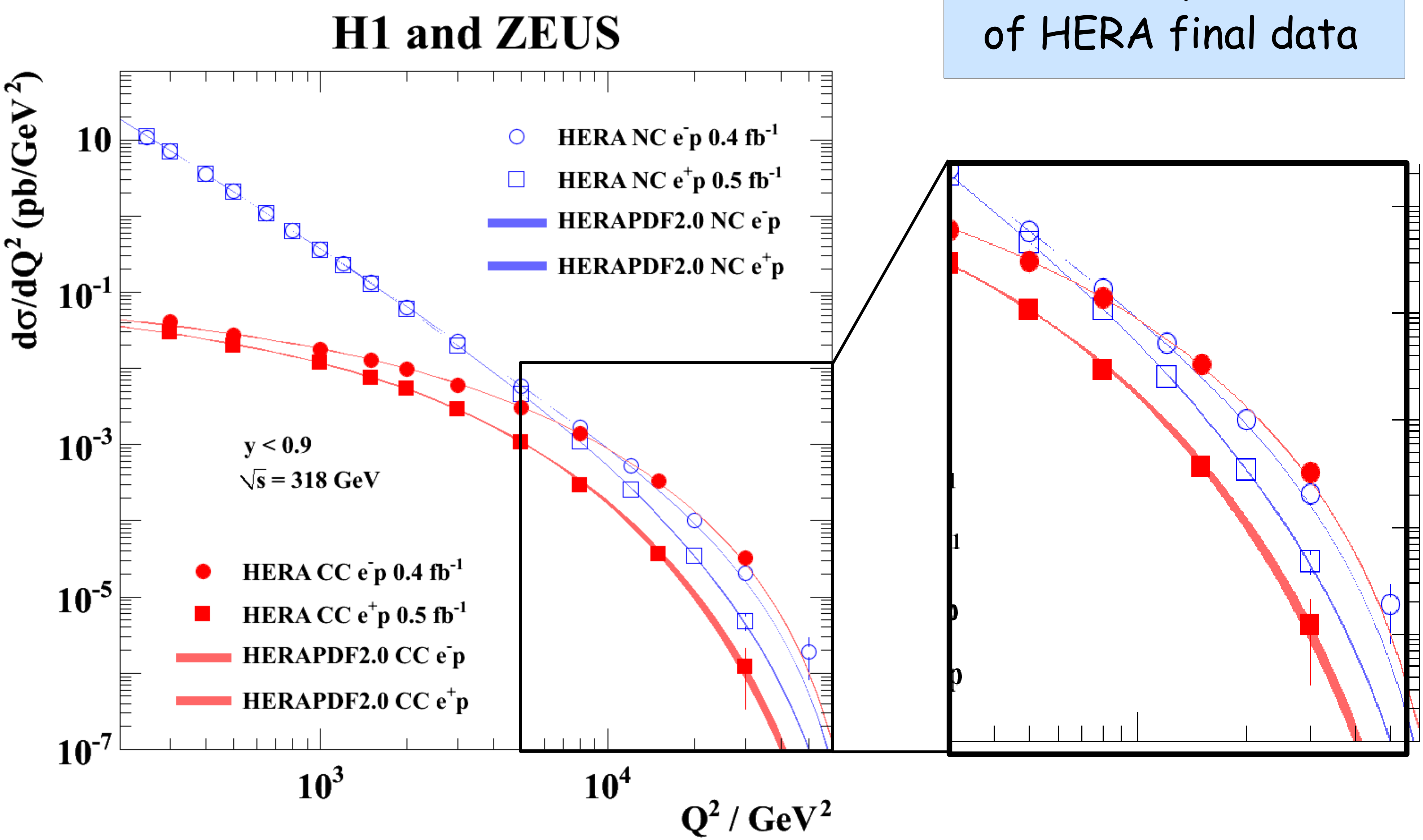
→ different dominant H1 and ZEUS systematics

→ effectively use H1 electrons with ZEUS hadrons

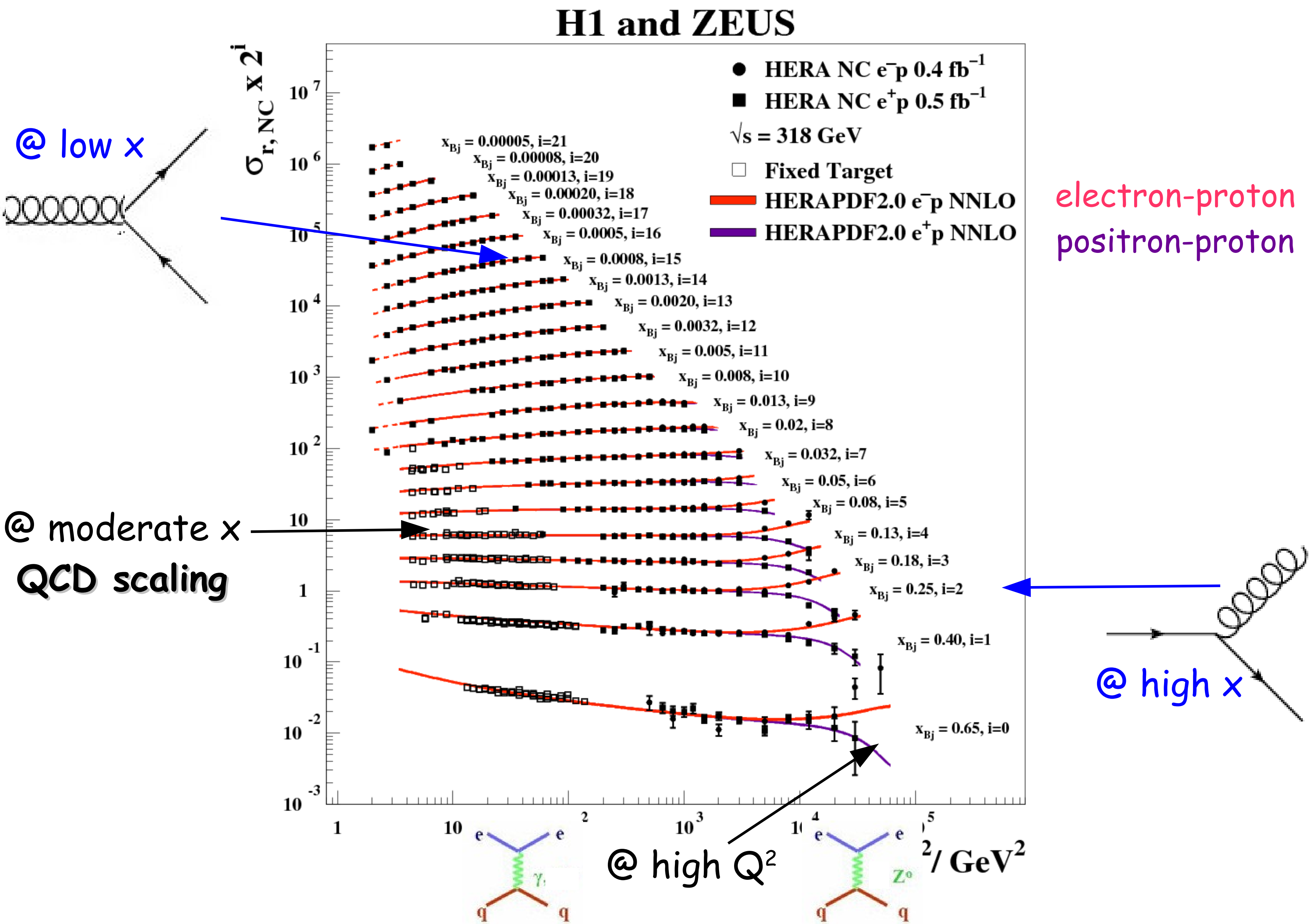


K. Wichmann, Workshop on 2nd detector for EIC, 17.05.2023

Electroweak unification

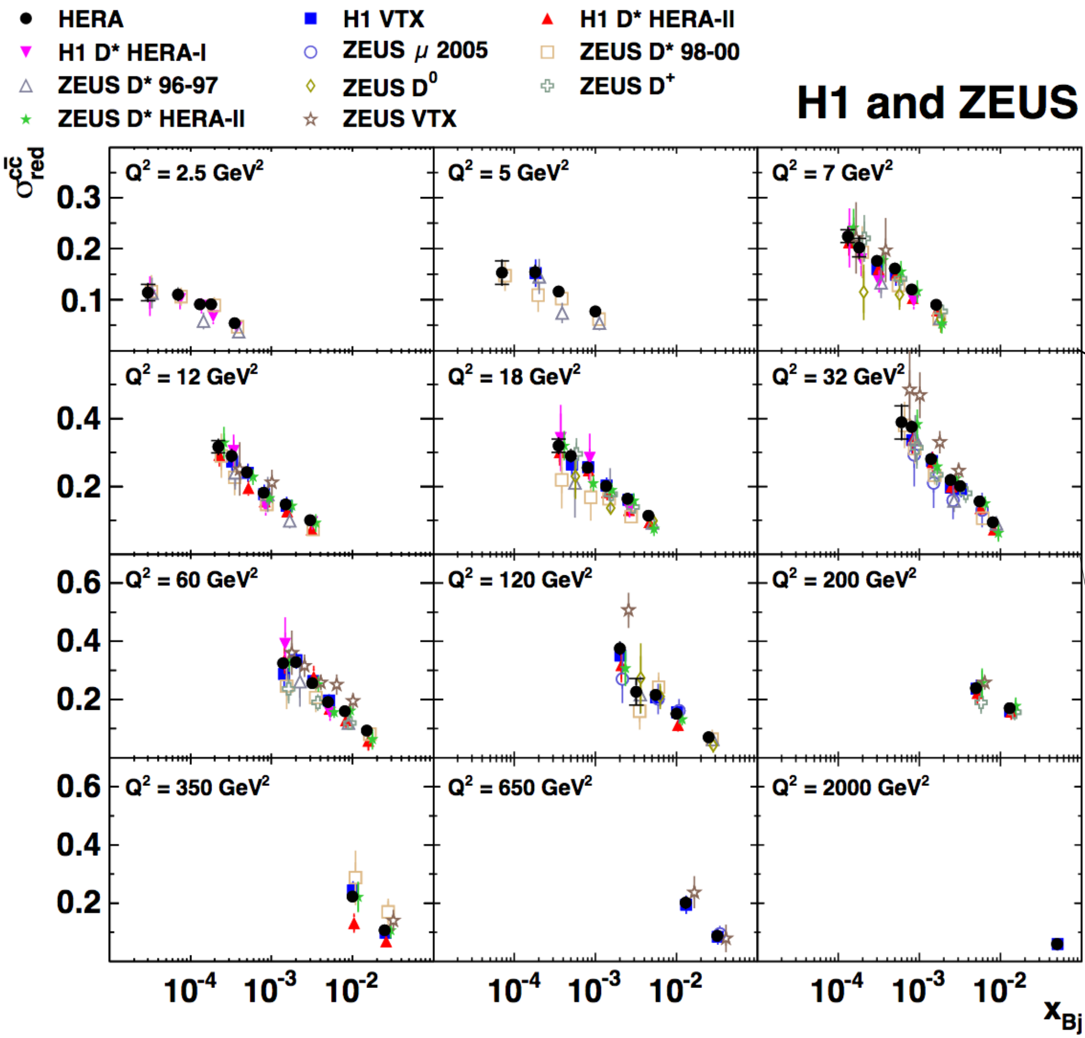


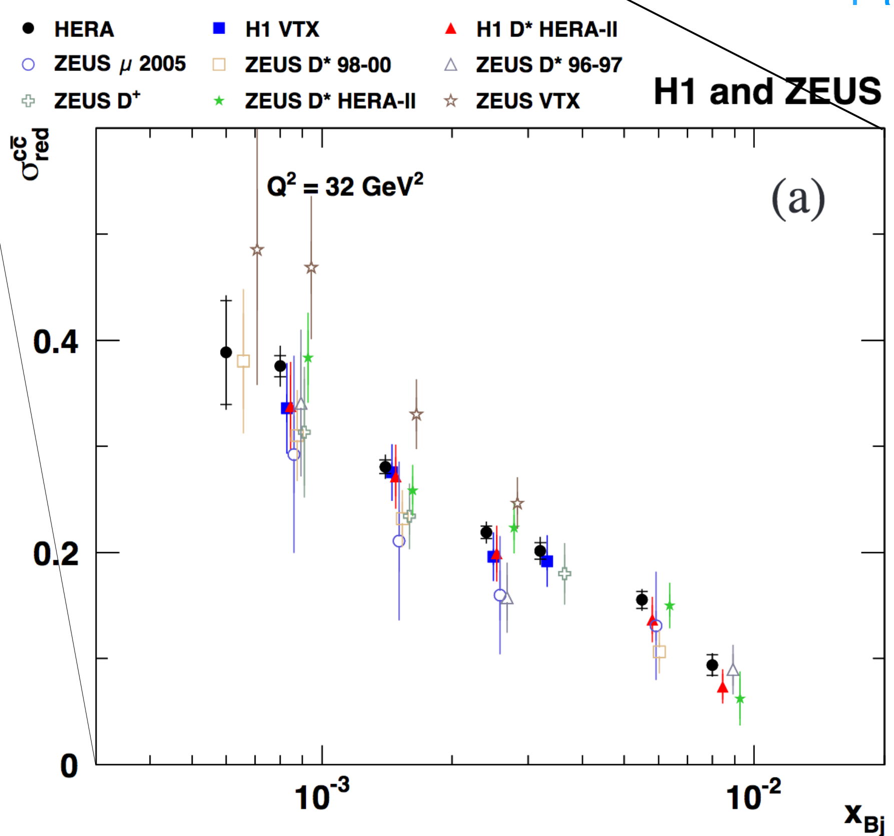
Fantastic precision of HERA final data



Text book plots of fundamental properties of particle interactions

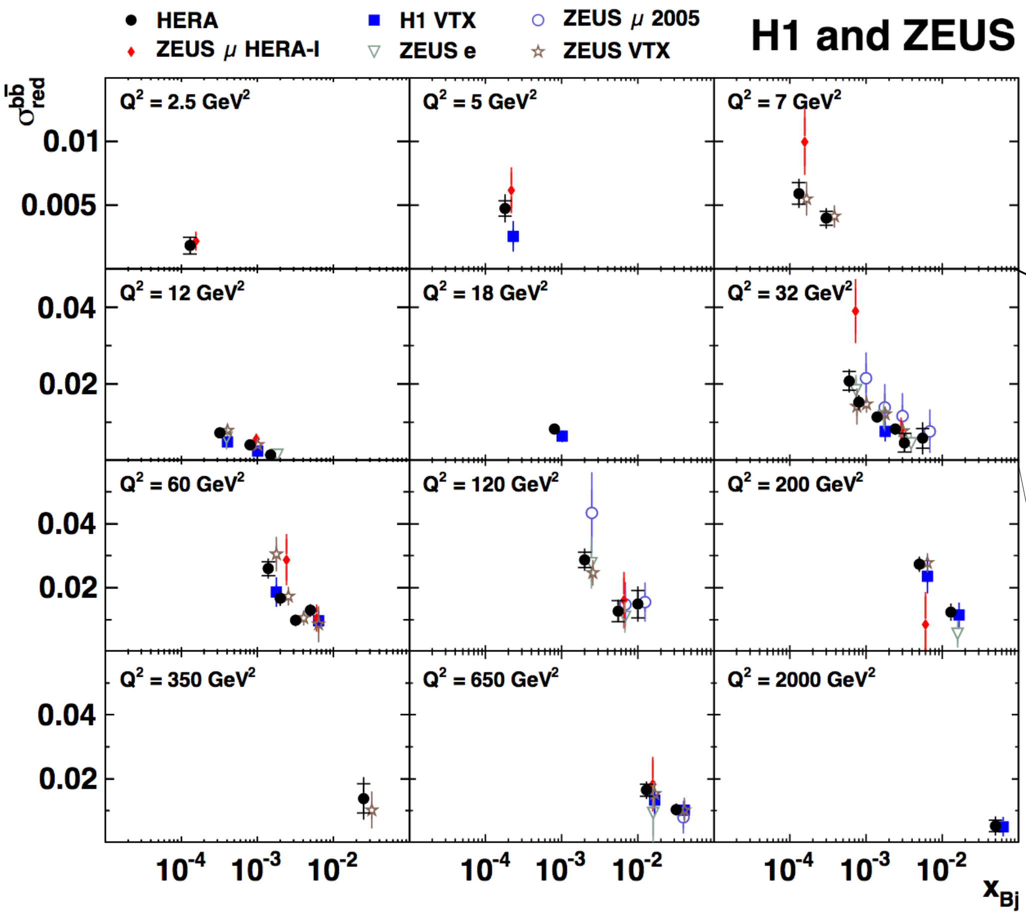
Combination of charm production

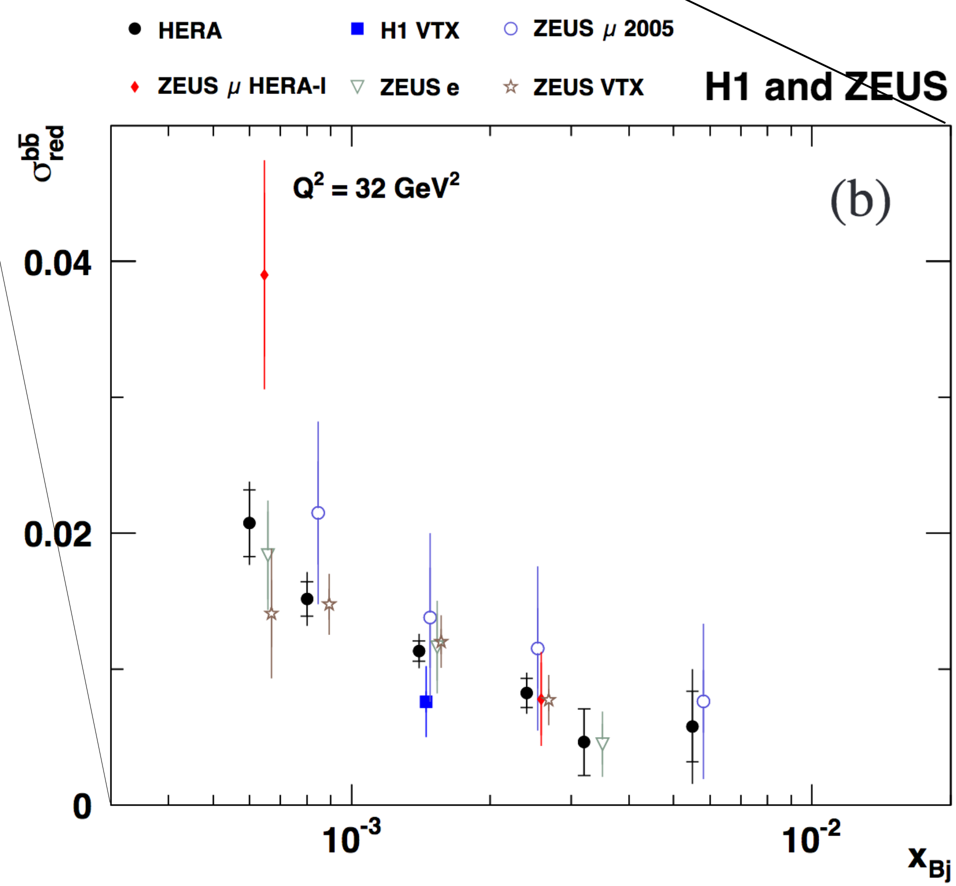




K. Wichmann, Workshop

Combination of beauty production





Beauty and charm in PDF fits

- Beauty and charm masses → model parameters in PDF fits
  → their uncertainties improved by combination
  → does it matter?

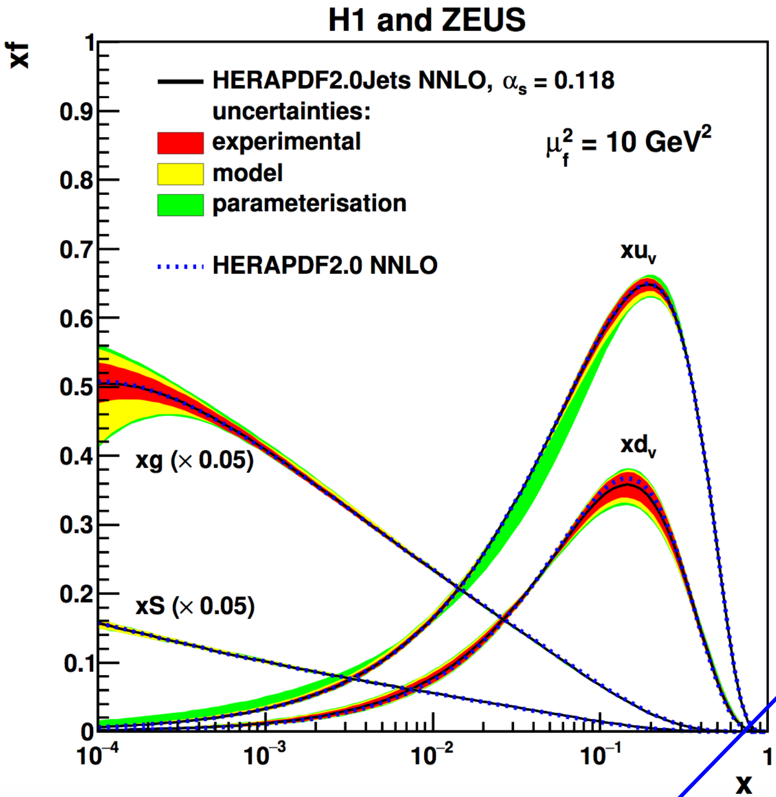
Pre-combination: HERAPDF2 NNLO

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

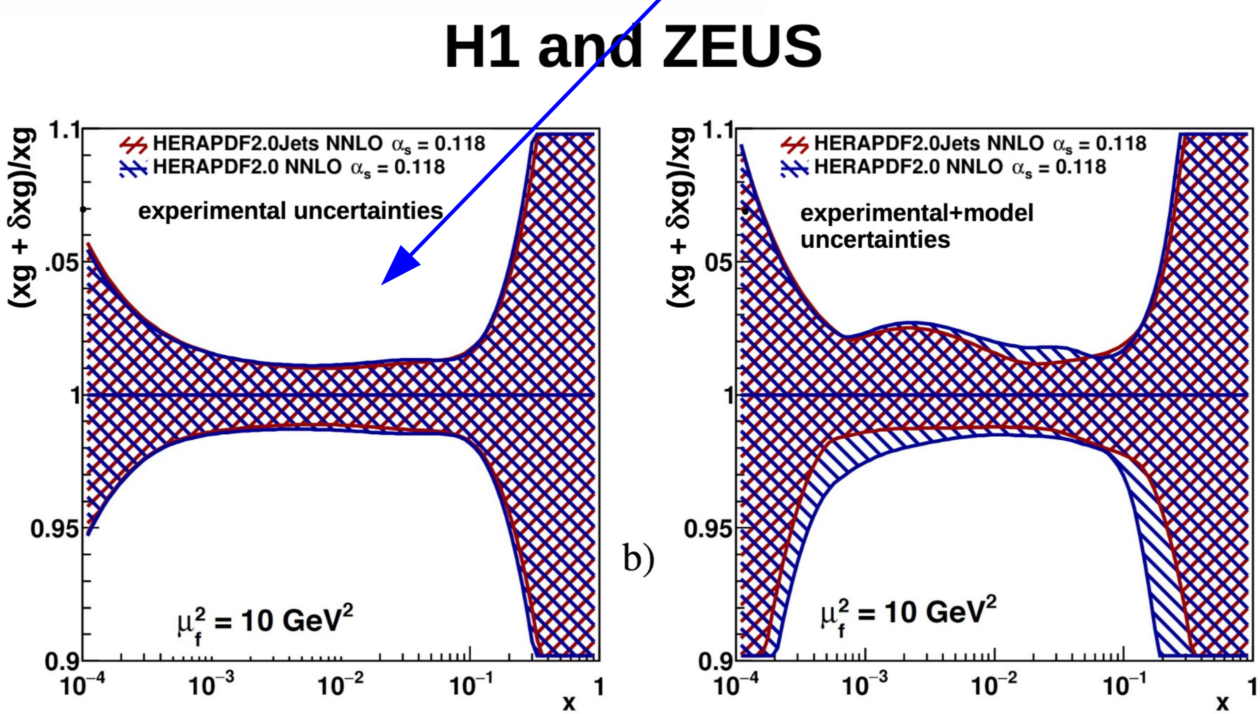
Post-combination: HERAPDF2Jets NNLO

Parameter	Central value	Downwards variation	Upwards variation
$Q^2_{\rm min}$ [GeV^2]	3.5	2.5	5.0
f_s	0.4	0.3	0.5
M_c [GeV]	1.41	1.37*	1.45
M_b [GeV]	4.20	4.10	4.30
μ^2_{f0} [GeV^2]	1.9	1.6	2.2*

Comparing HERAPDF2 NNLO and HERAPDF2Jets NNLO



- PDFs shapes very similar for pre- and post-combination HF masses
- Gluon experimental uncertainties hardly changed



- Model uncertainties improved thanks to procedure update and smaller parameters uncertainties
  → combination!
- It's not much but every inch matters

Message to take away

Complementarity of detectors

- In my opinion a second detector is a must

→ H1 and ZEUS did it by chance

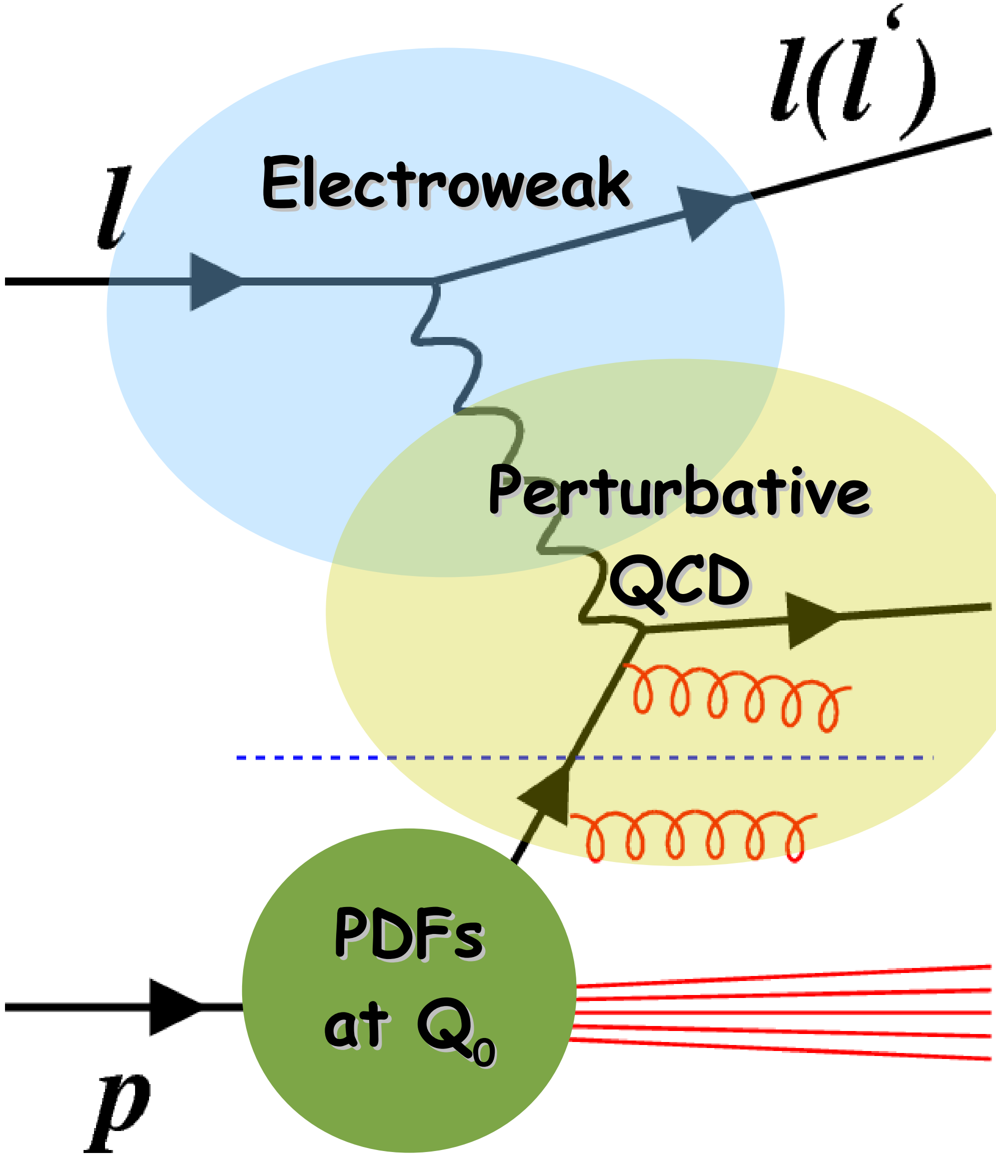
→ EIC has a chance to do it on purpose!

Additional slides

HERA accelerator

Two colliding experiments

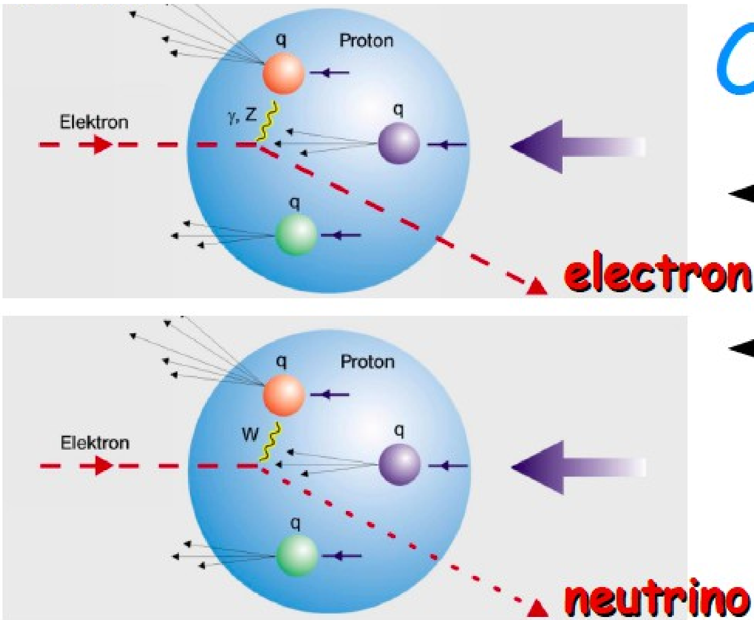
Deep Inelastic Scattering @ HERA



- 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

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

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

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

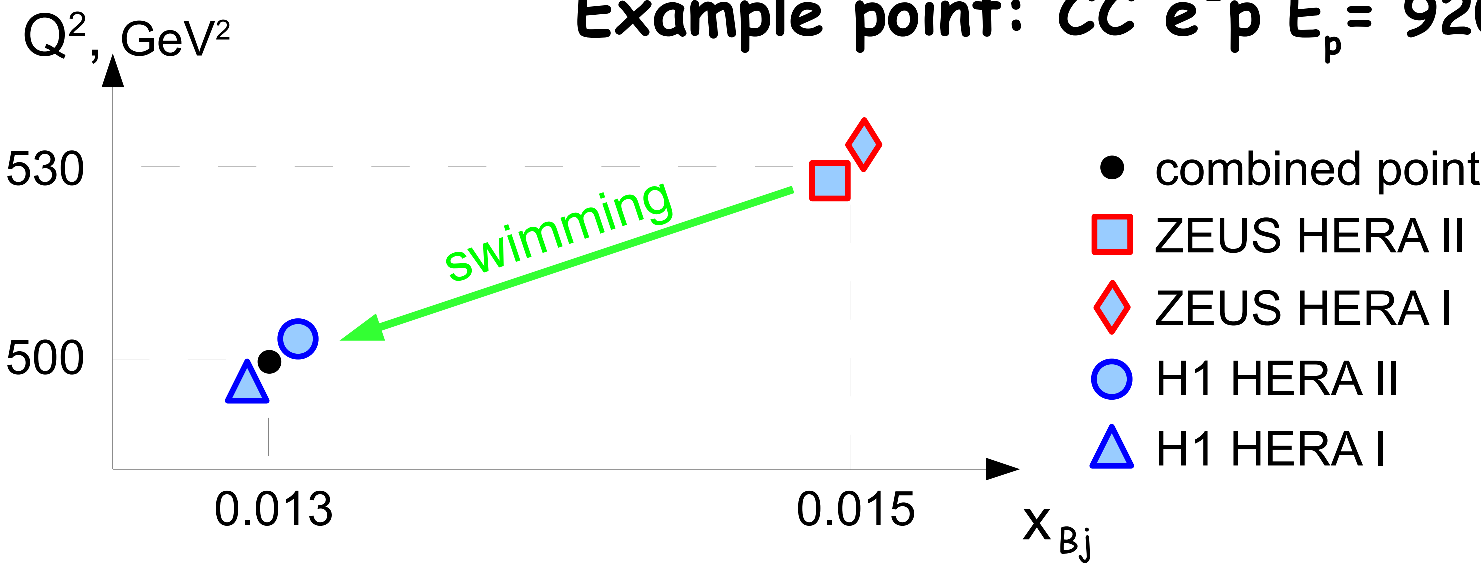
H1 and ZEUS published all HERA inclusive DIS measurements – 1 fb^{-1}

Now we combine these measurements

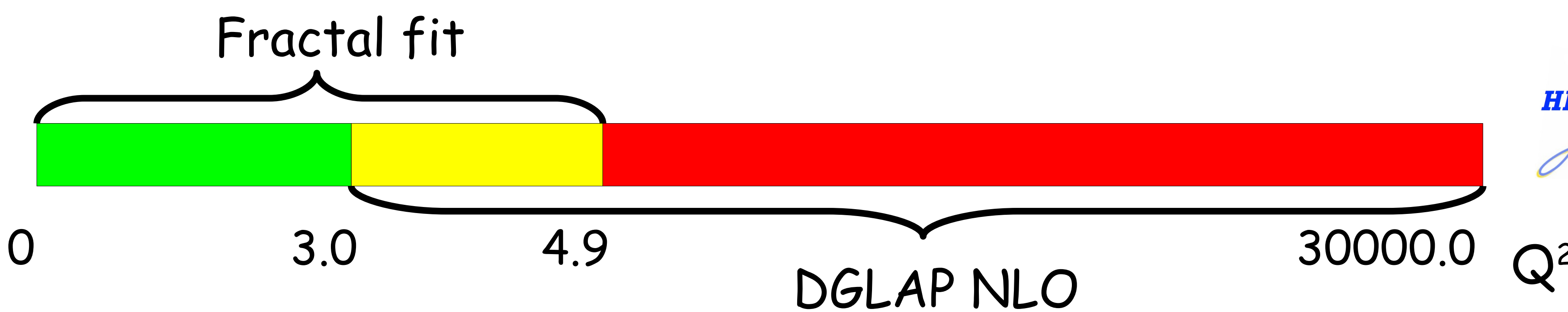
Data Set		x_{Bj} Grid from	x_{Bj} Grid to	Q^2[GeV^2] Grid from	Q^2[GeV^2] Grid to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV	x_{Bj}, Q^2 from equations
HERA I $E_p = 820$ GeV and $E_p = 920$ GeV data sets									
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319	13,17,18
H1 low Q^2	96-00	0.0002	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

Swimming procedure

Example point: CC e^-p E_p= 920 GeV

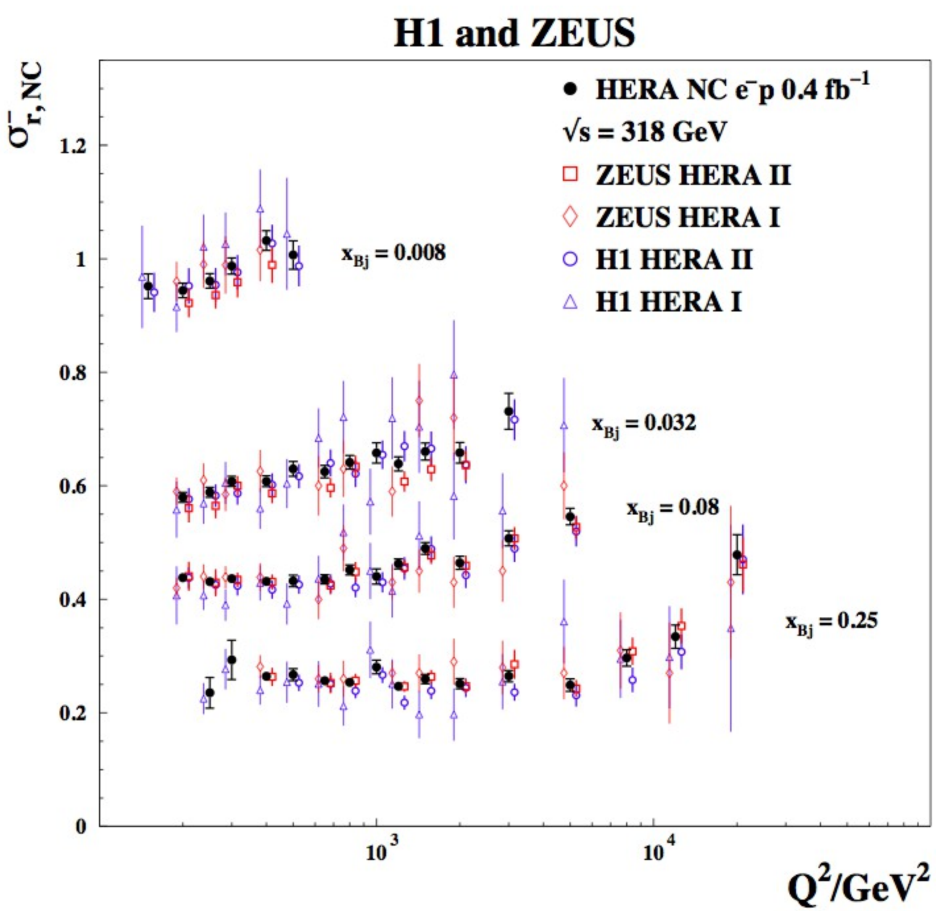


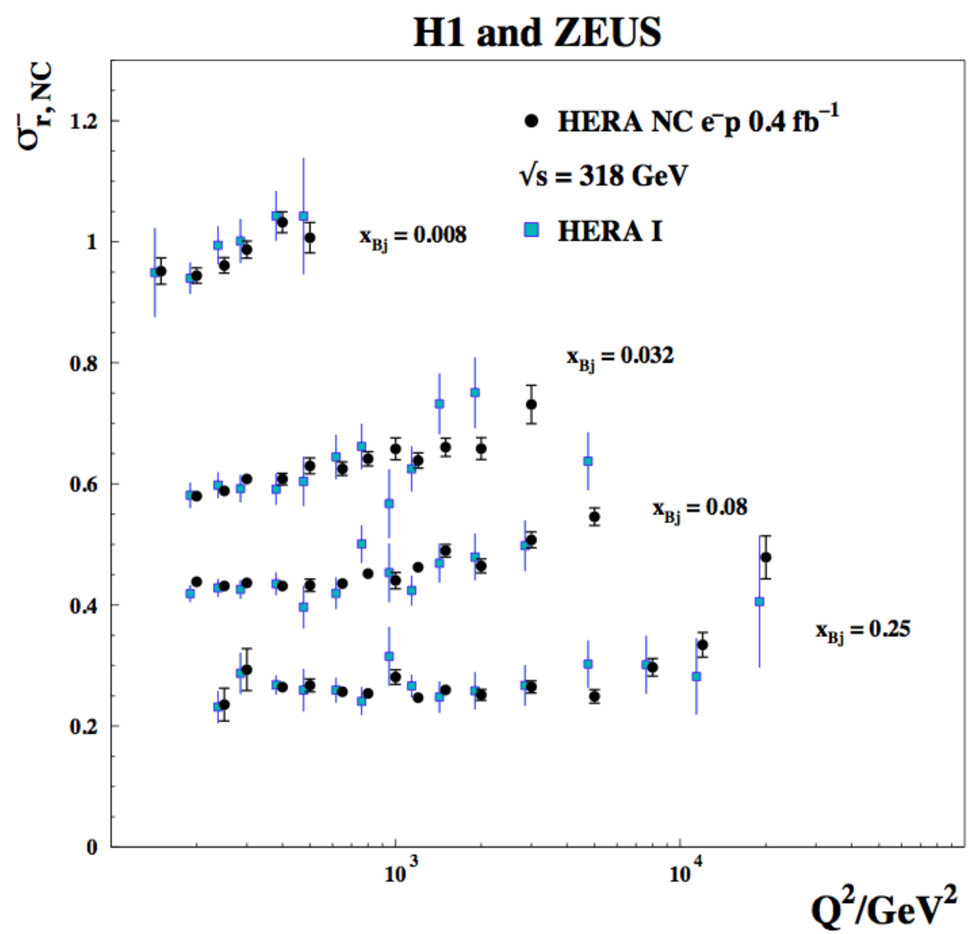
- Swimming done iteratively using our own data
  - 1st iteration uncombined HERAI+II data, later - combined data



- Swimming factors are usually at level of few %

Improved precision

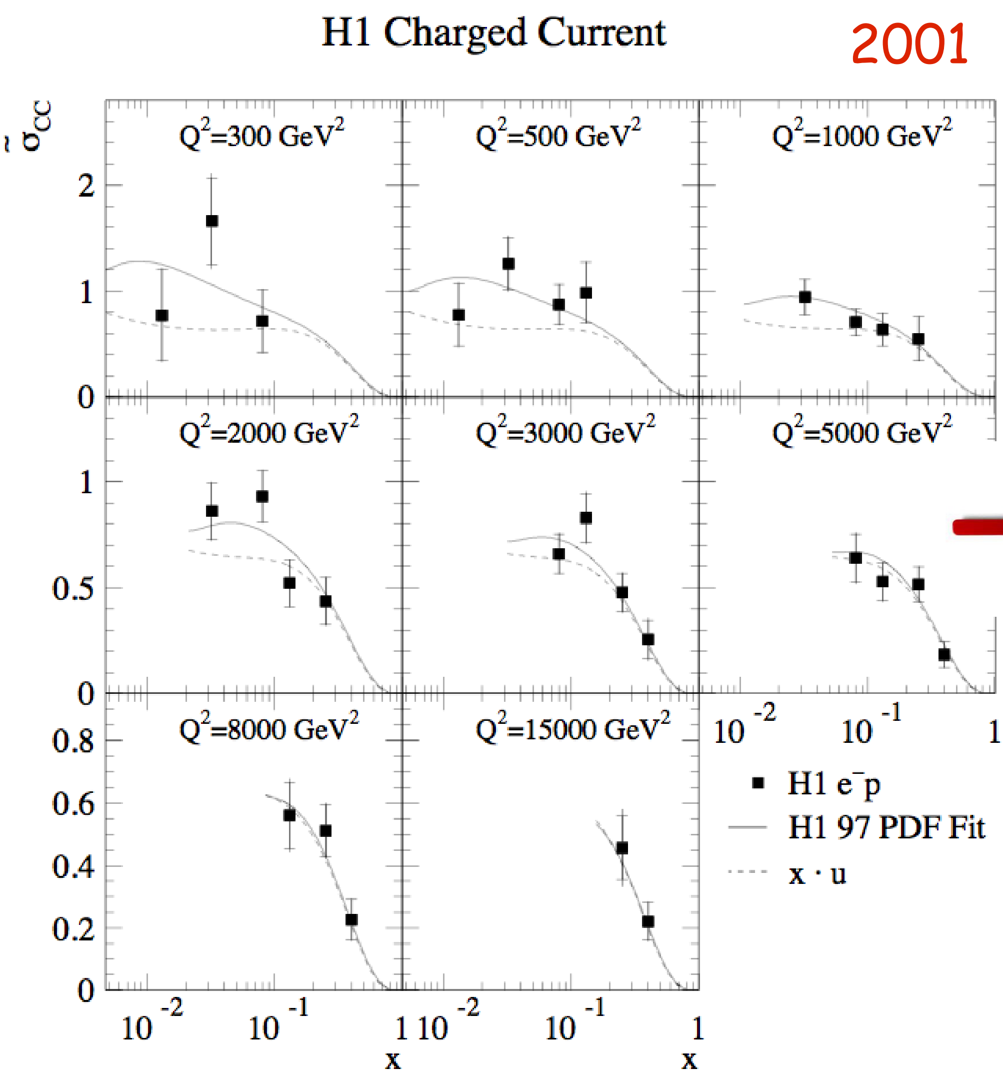


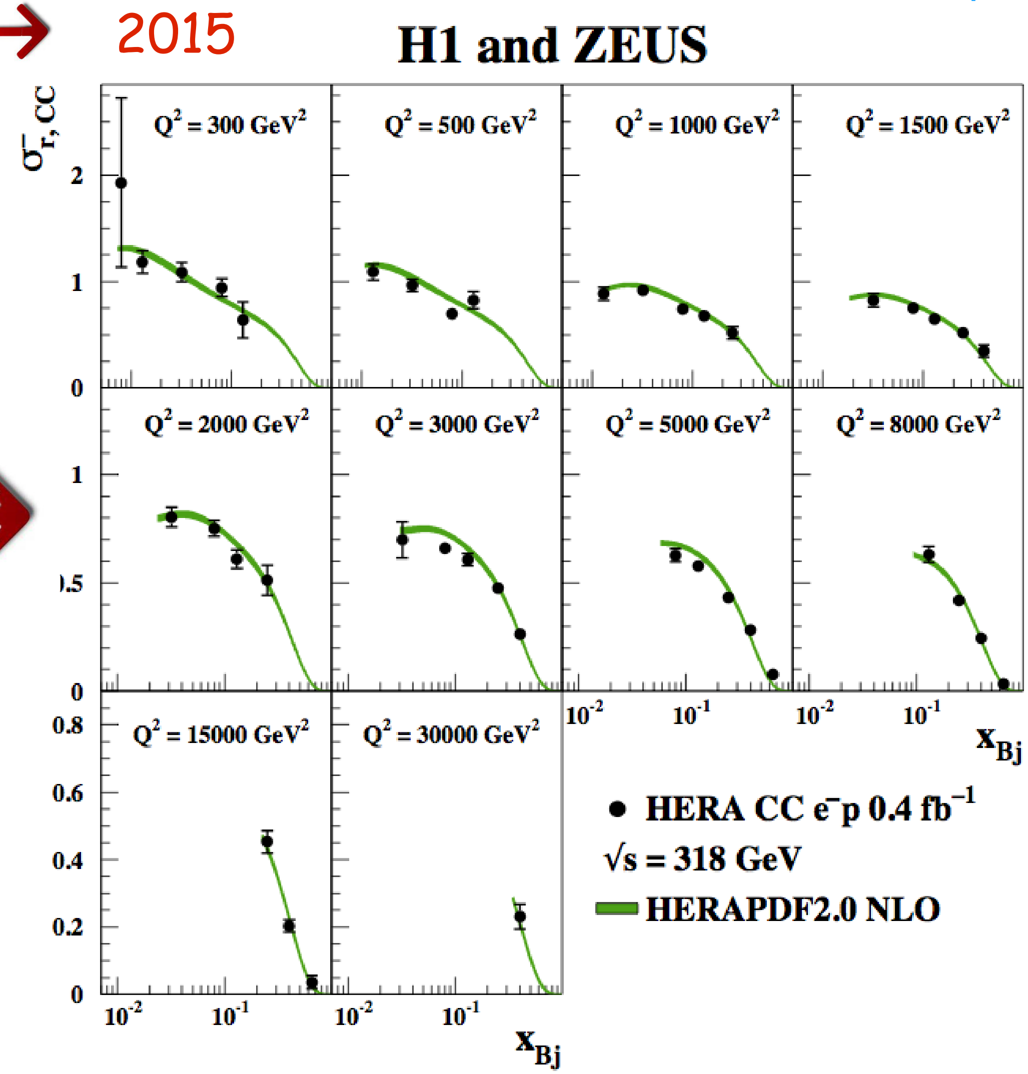


- Largest and most accurate data sample is for the NC e^+p process
- The combined data accuracy reaches ~ 1%
- Largest improvement for NC e^-p – 10 times more luminosity
- Consistent with HERA-I + improved uncertainties

Improving previous results

2001 → 2015



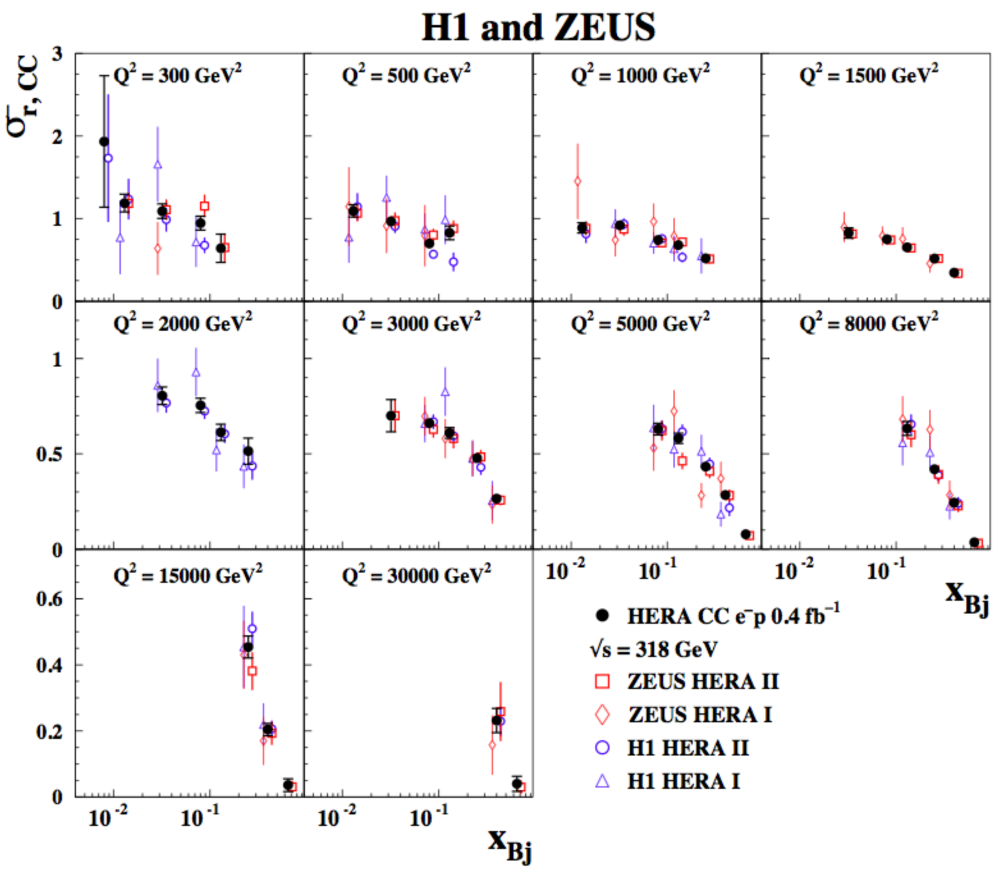


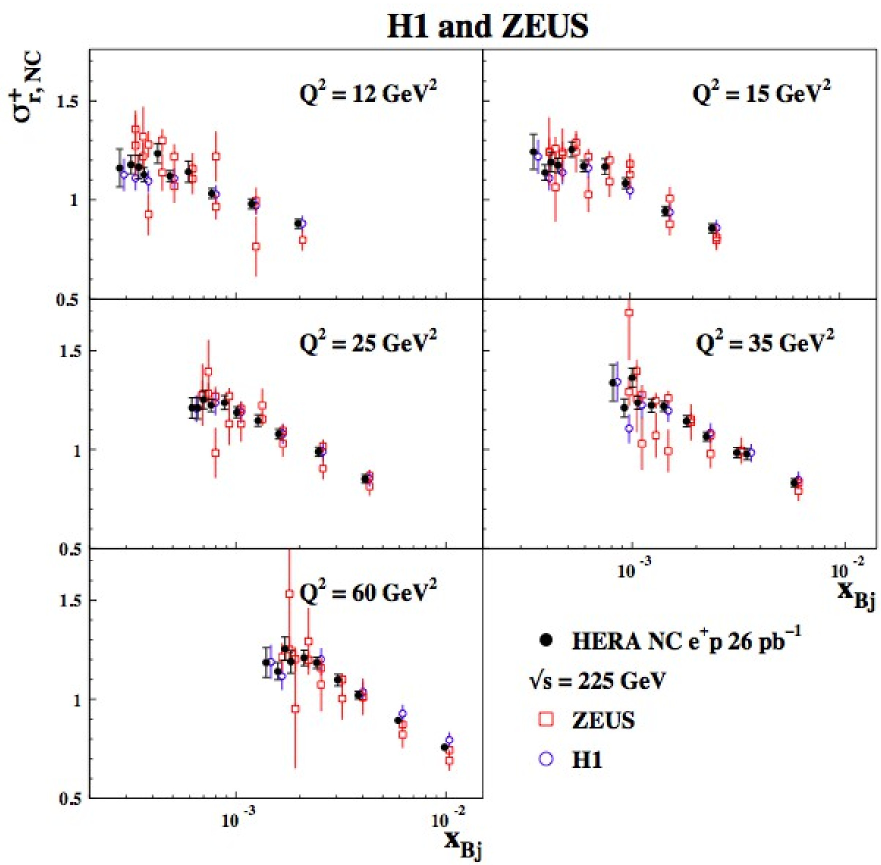
- increases statistical significance
- reduces systematic uncertainties via cross calibration techniques

Great gain in precision

New kinematic ranges explored

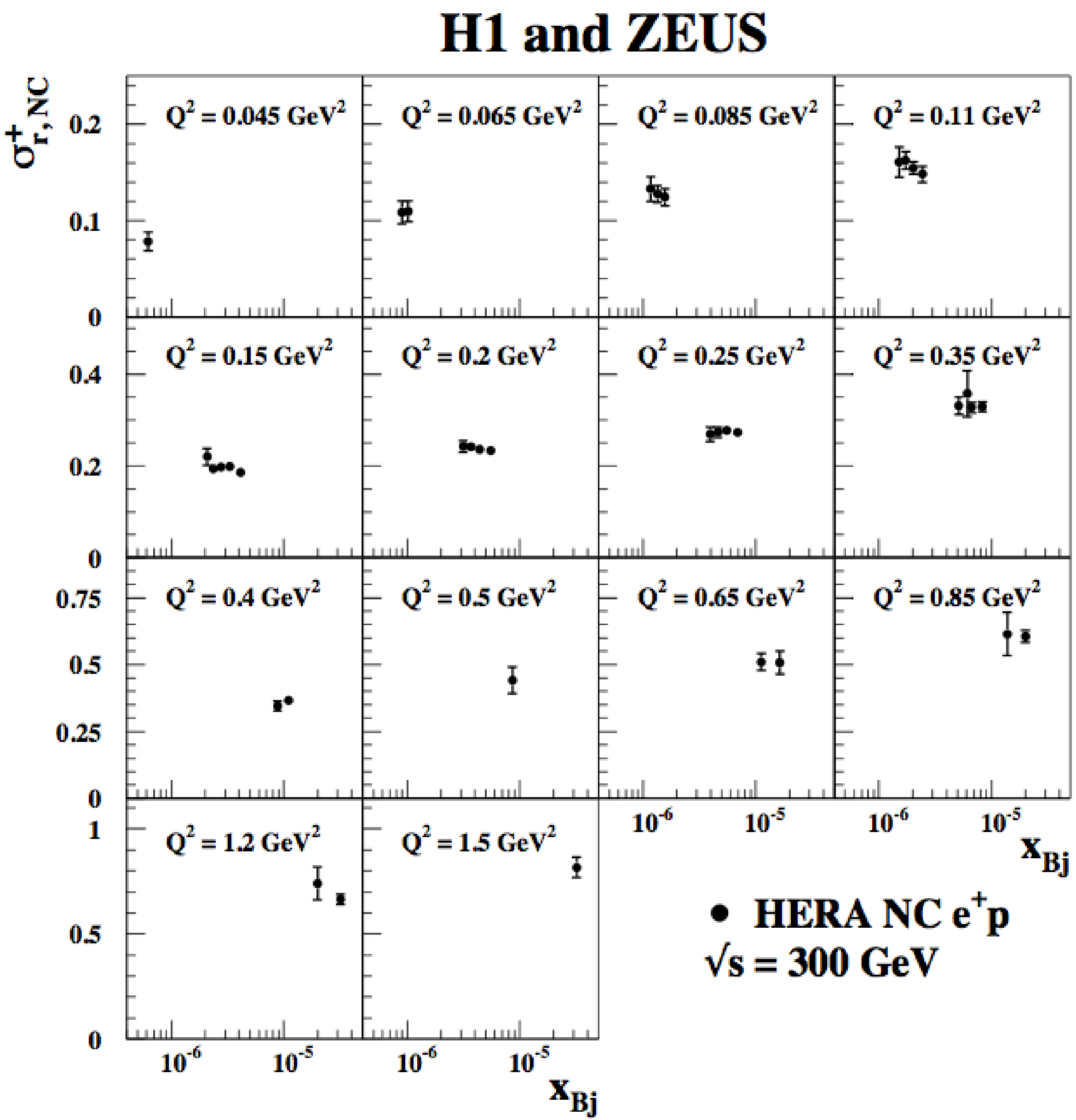
- Kinematic range extended for existing data samples
- Low energies added: CME = 225 GeV and 251 GeV





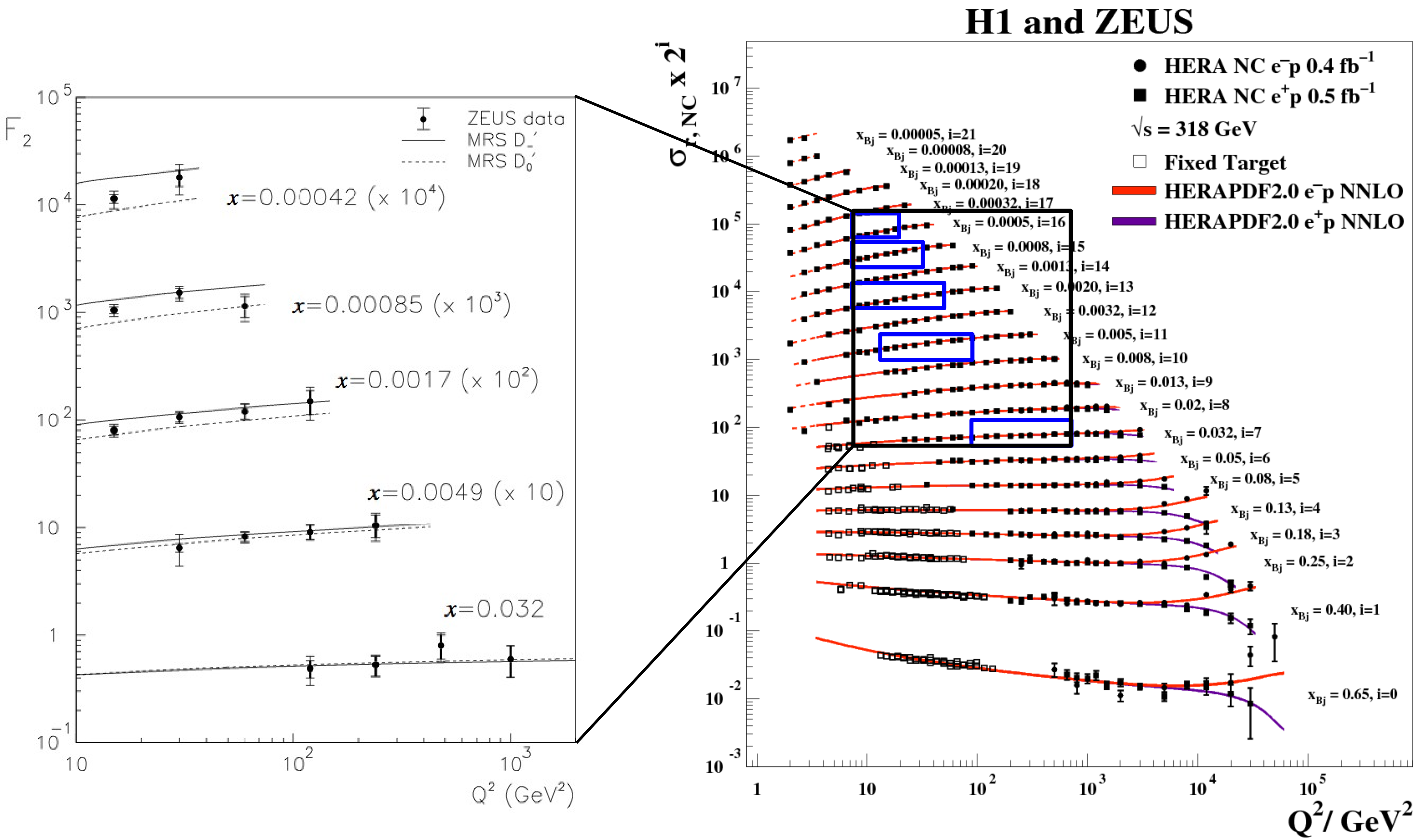
K. Wichmann, Workshop on 2nd detector for EIC, 17.05.2023

Low Q^2 combined data



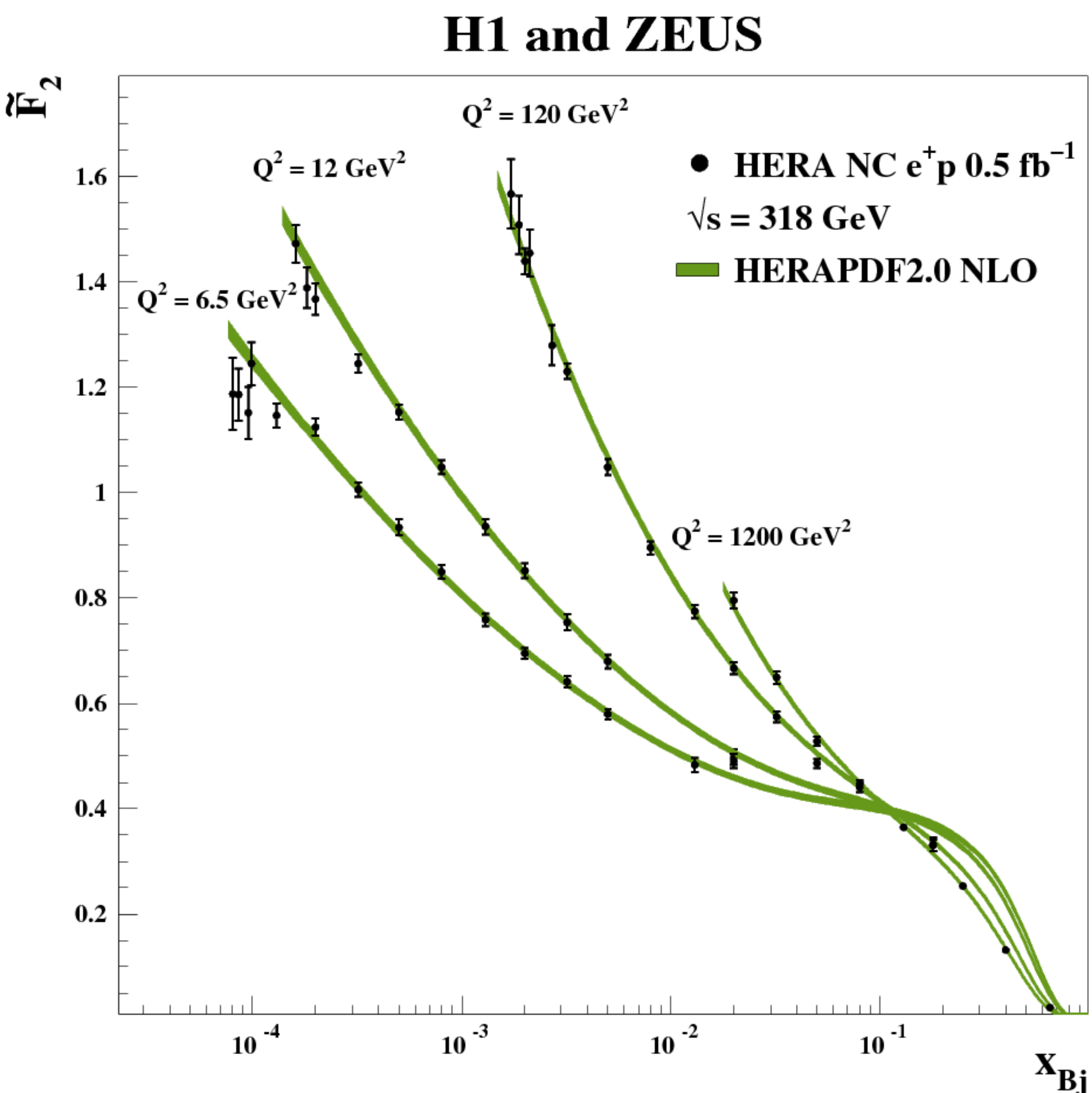
- Combined inclusive cross sections for low Q^2
- Available for two CMEs
  - 300 GeV
  - 318 GeV
- Interesting for
  - dipole/saturation models
  - studying higher twists

First → Final



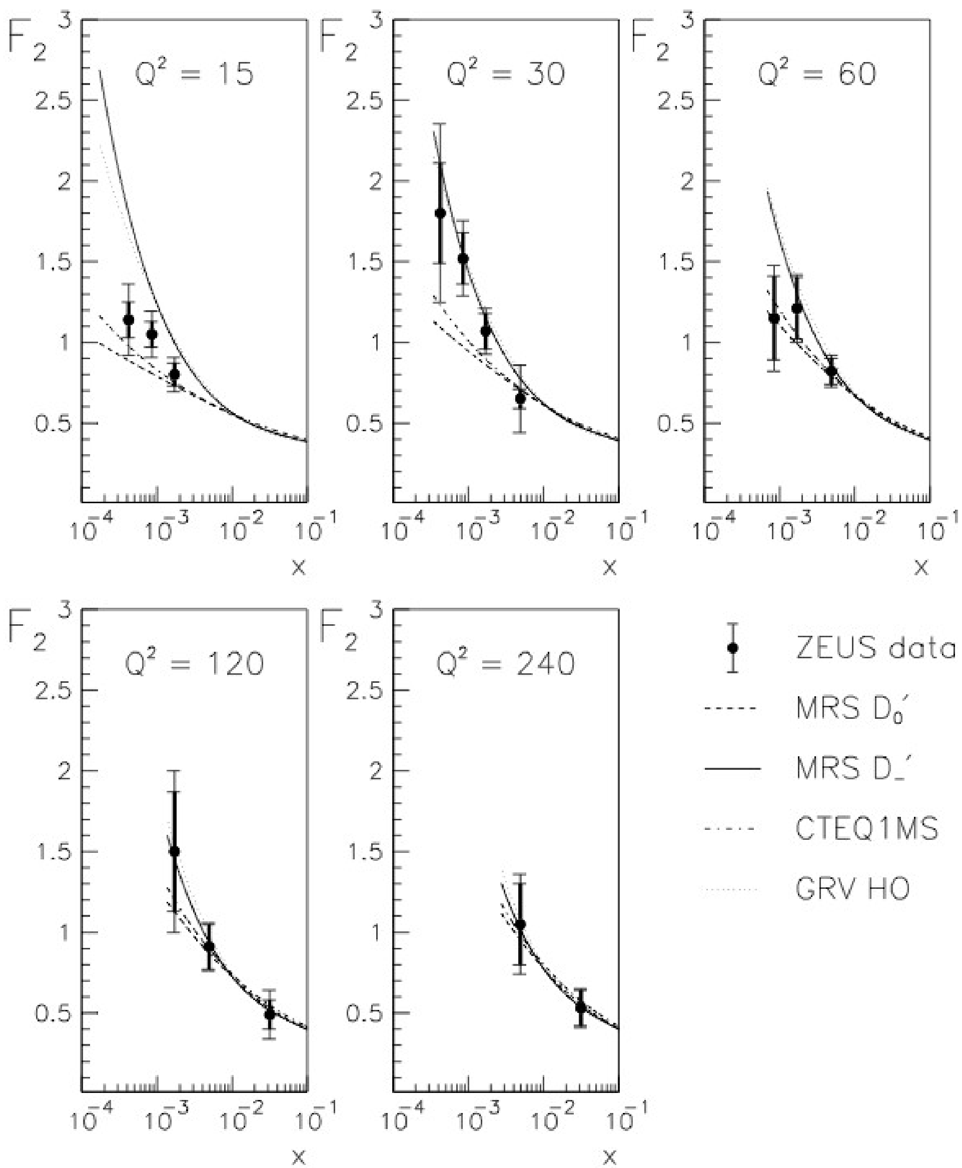
F2
ZEUS data
MRS D−′
MRS D0′
x=0.00042 (x 10⁴)
x=0.00085 (x 10³)
x=0.0017 (x 10²)
x=0.0049 (x 10)
x=0.032
Q² (GeV²)
H1 and ZEUS
σr,NC x 2^i
HERA NC e⁻p 0.4 fb⁻¹
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
Fixed Target
HERAPDF2.0 e⁻p NNLO
HERAPDF2.0 e⁺p NNLO
xBj = 0.00005, i=21
xBj = 0.00008, i=20
xBj = 0.00013, i=19
xBj = 0.00020, i=18
xBj = 0.00032, i=17
xBj = 0.0005, i=16
xBj = 0.0008, i=15
xBj = 0.0013, i=14
xBj = 0.0020, i=13
xBj = 0.0032, i=12
xBj = 0.005, i=11
xBj = 0.008, i=10
xBj = 0.013, i=9
xBj = 0.02, i=8
xBj = 0.032, i=7
xBj = 0.05, i=6
xBj = 0.08, i=5
xBj = 0.13, i=4
xBj = 0.18, i=3
xBj = 0.25, i=2
xBj = 0.40, i=1
xBj = 0.65, i=0
Q²/ GeV²

As expected: low-x rise of F_2

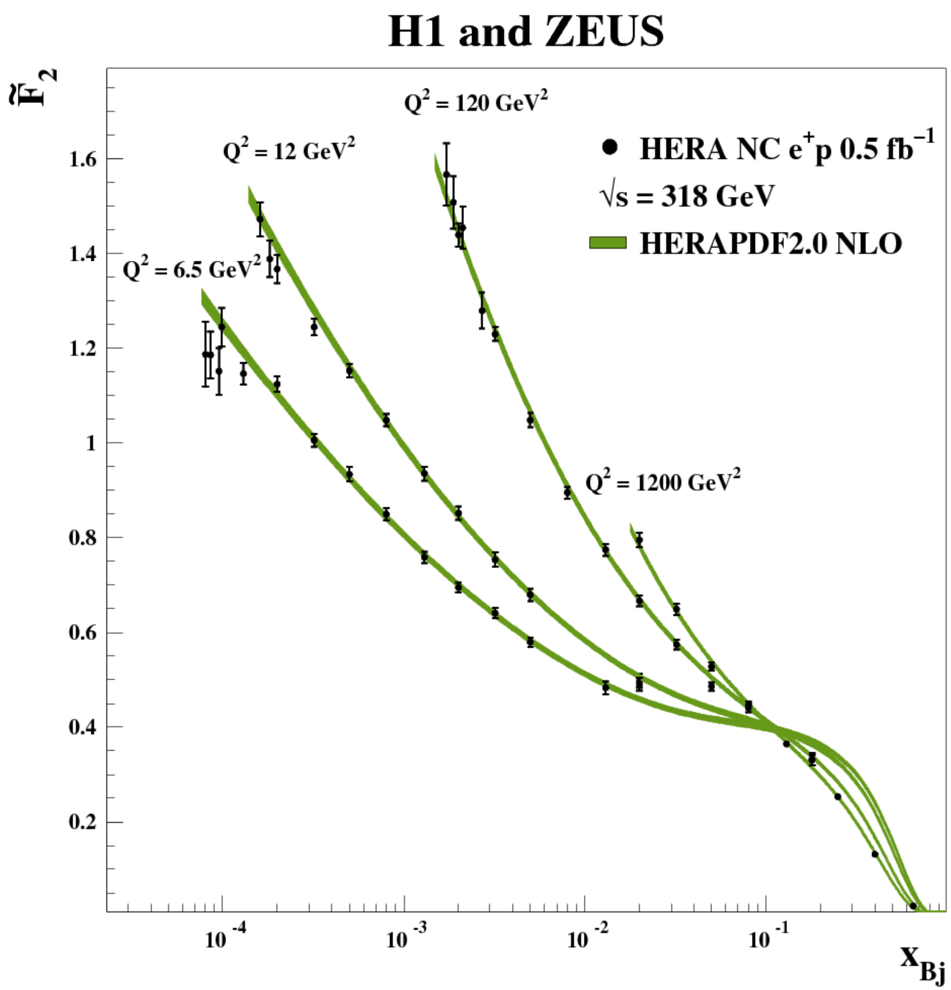


K. Wichmann, Workshop on 2nd detector for EIC, 17.05.2023

1993 → 2015



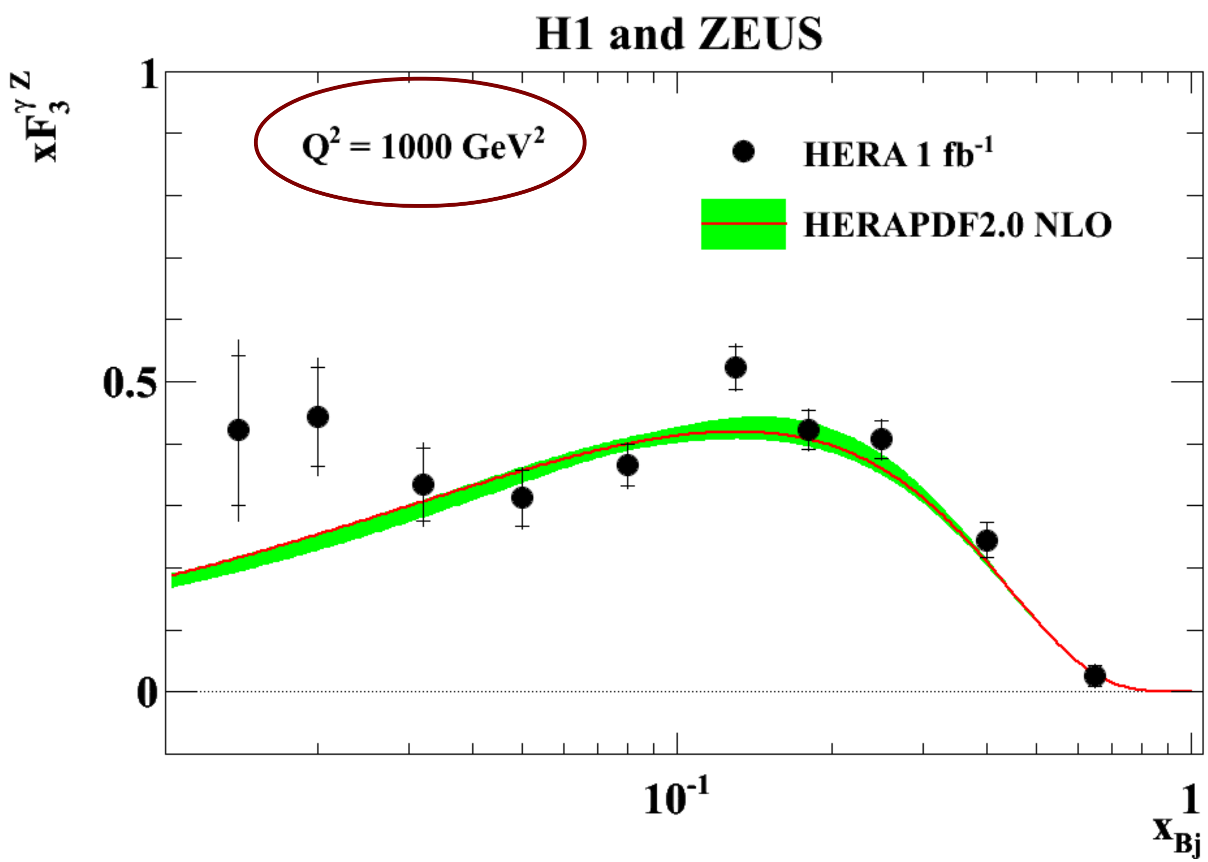
Q² = 15
Q² = 30
Q² = 60
Q² = 120
Q² = 240
F2
x
ZEUS data
MRS D0′
MRS D_′
CTEQ1MS
GRV HO



H1 and ZEUS
F̃2
xBj
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

$xF_3^{\gamma Z}$ 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 GeV^2 and averaged
- Good agreements with predictions



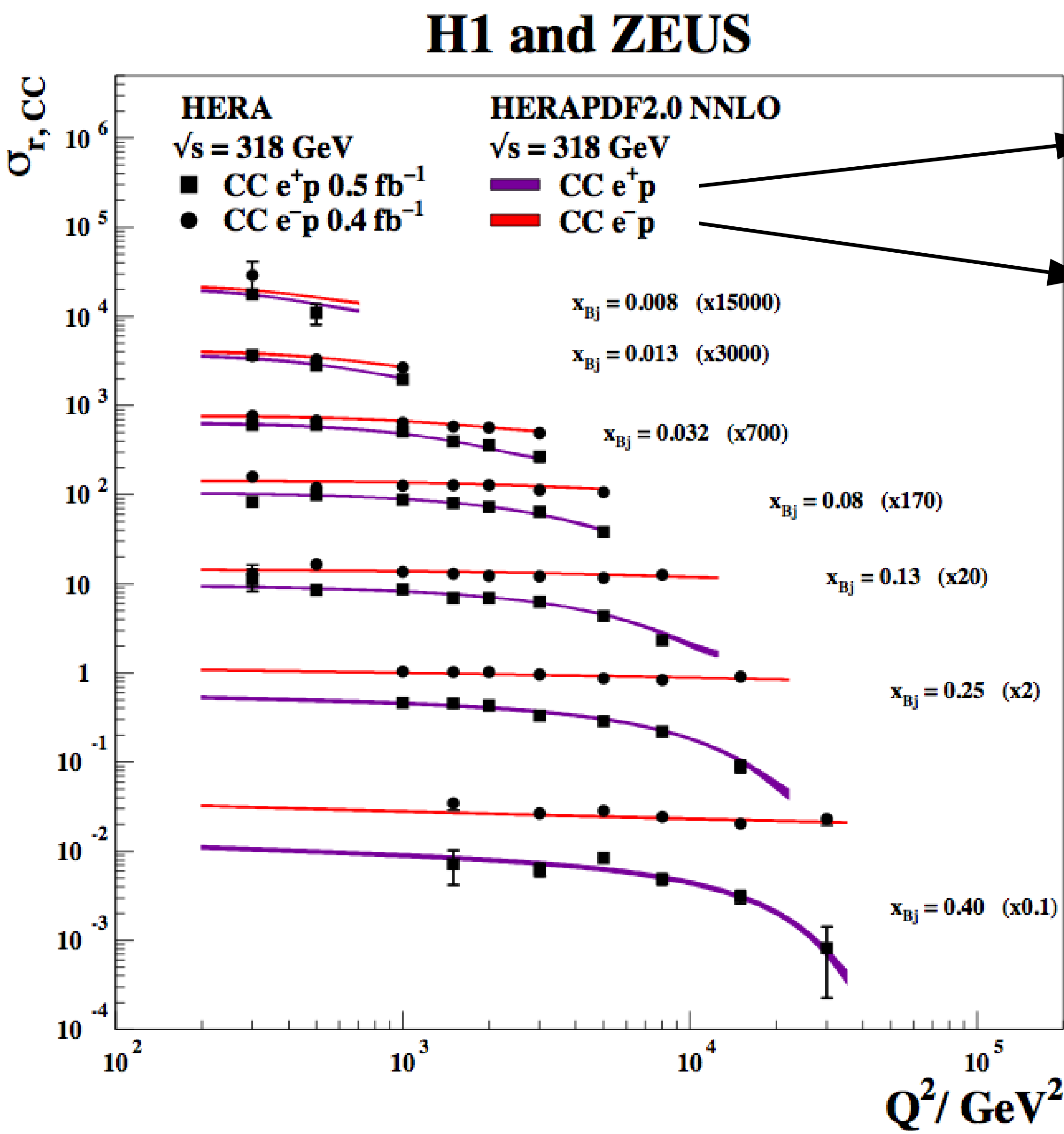
- Integrated over x:

$0.016 < x_{Bj} < 0.725$ 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

CC: helicity effects



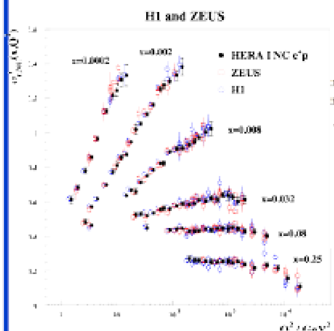
$$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$

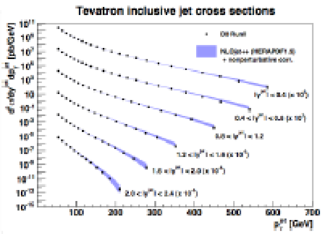
$$\sigma^{-}_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

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

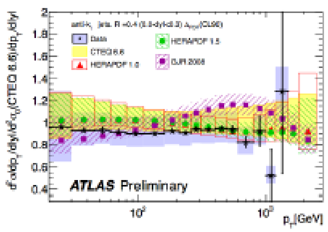
https://www.herafitter.org

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



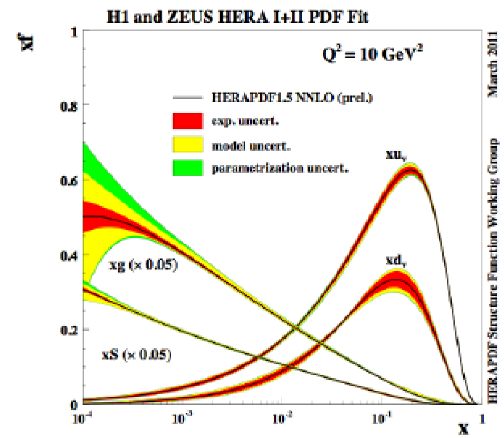
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

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

$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

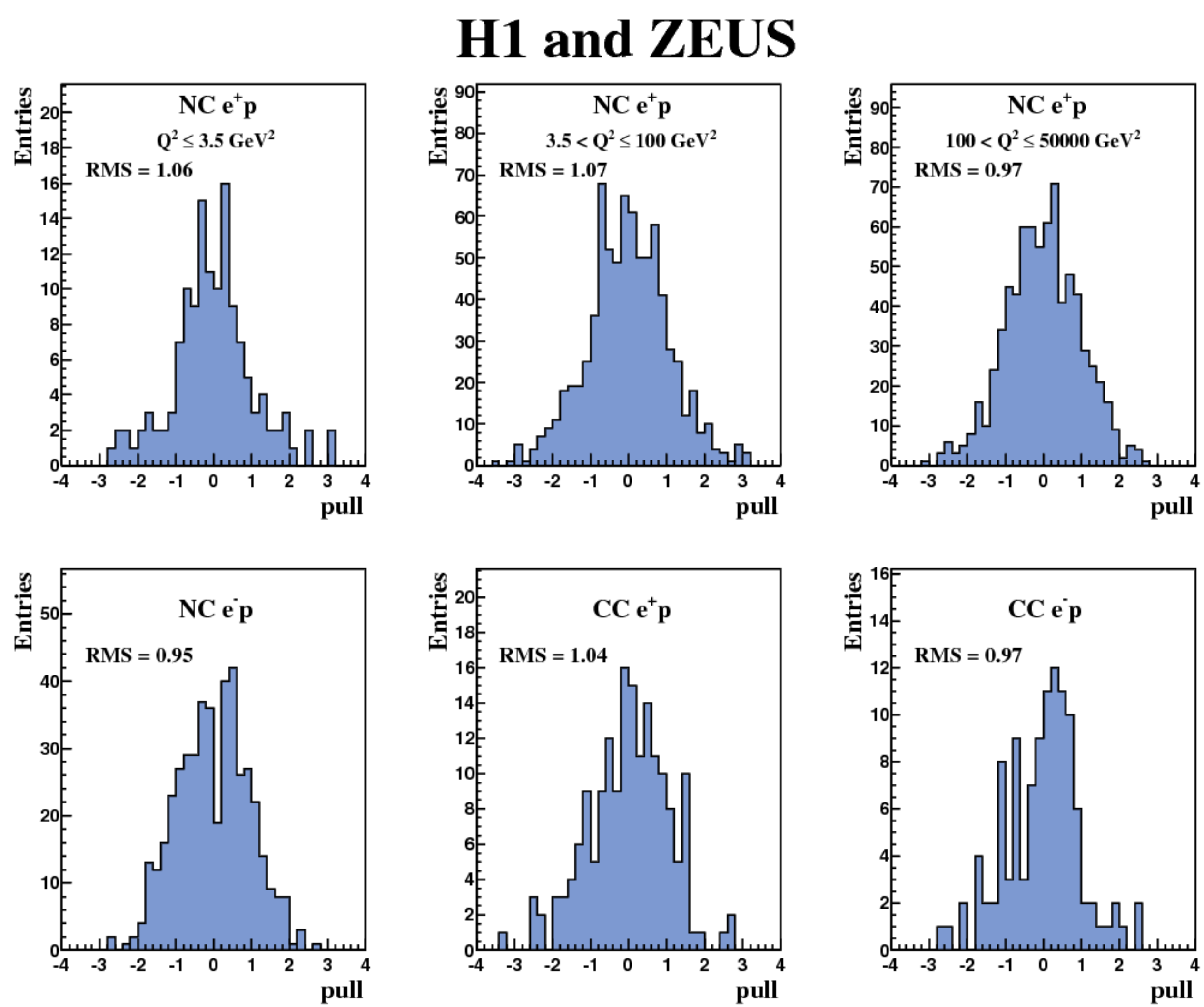
Benchmarking

Comparison of schemes

Averaging results

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

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



Procedural uncertainties

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

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

- **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 combinatio