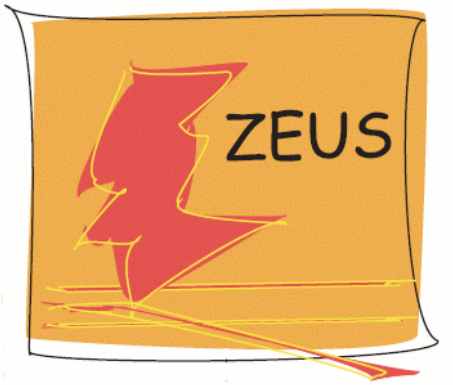
HERA inclusive data combination and PDF Fit

LHCP conference, Columbia University NYC, 5th June 2014

Olaf Behnke (DESY) on behalf of

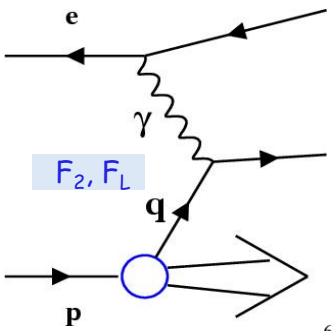


DOCUMENTATION

Combination: H1prelim-14-041/ZEUS-prel-14-005
PDF fit: H1prelim-14-042/ZEUS-prel-14-007
www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

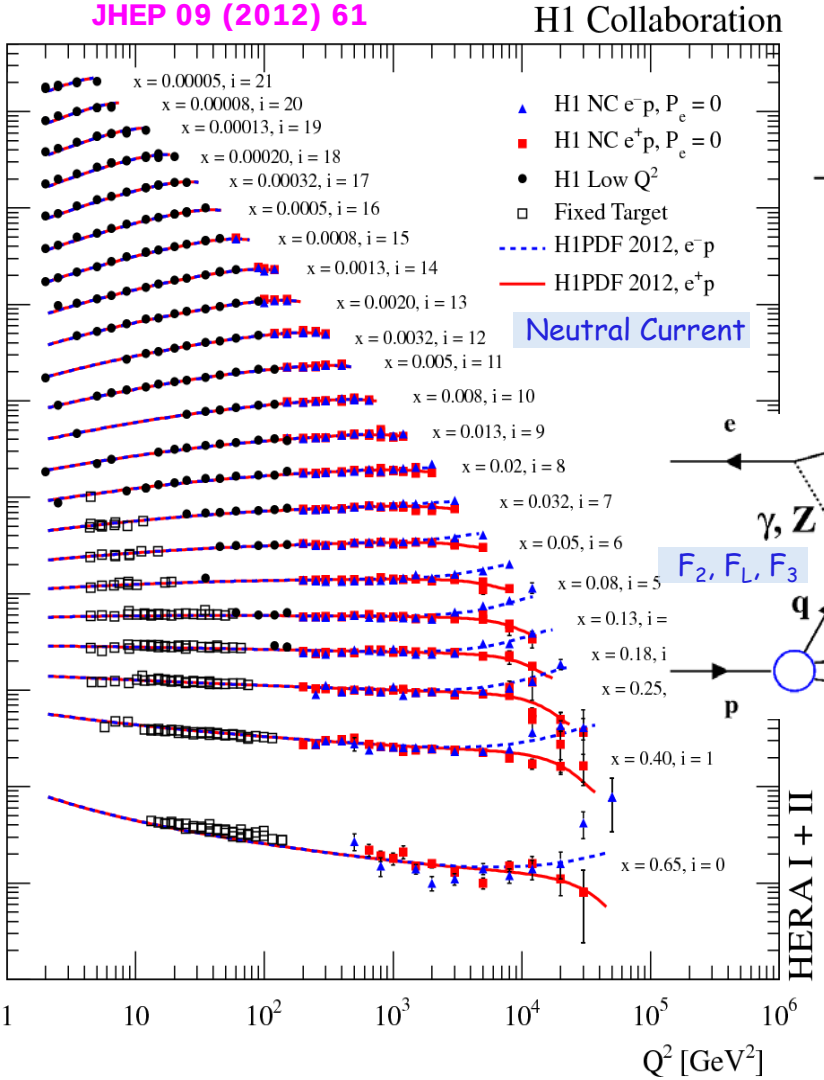
HERA

Proton structure

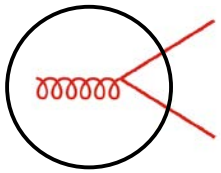


F_2, F_L

JHEP 09 (2012) 61

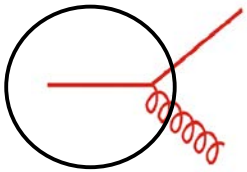


Neutral Current



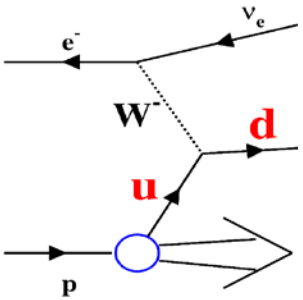
Scaling violations
~ $g(x,Q^2)$

F_2, F_L, F_3

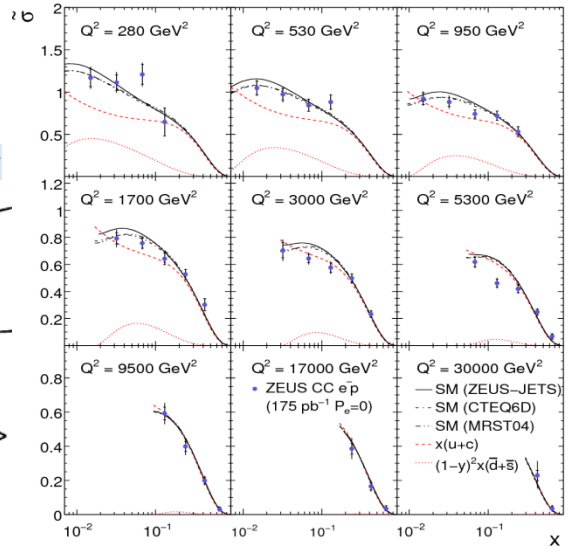


Bremsstrahlung
of valence
quarks

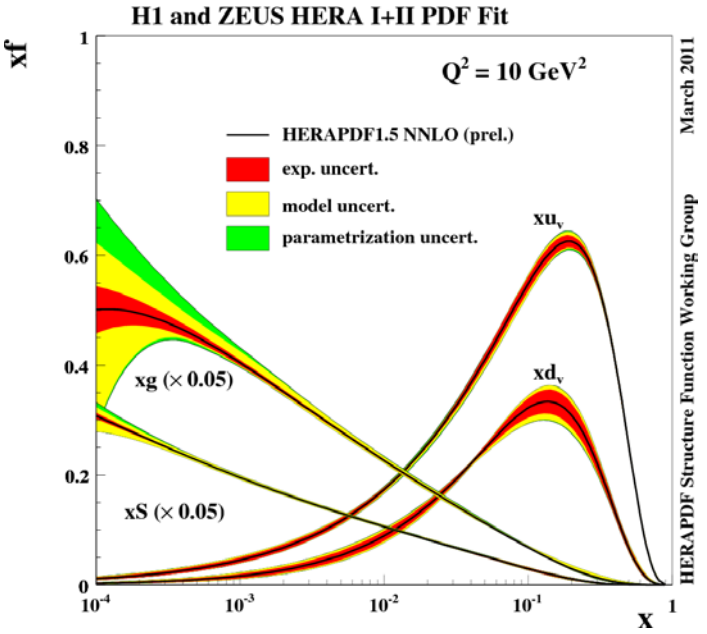
Charged Current



EPJC 61(2009) 223 ZEUS



Using all info in an NLO
QCD fit (DGLAP evolution) :



Time development of H1ZEUS inclusive data combination

. . .

H1ZEUS combination (2009)

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid 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 I

HERAPDF1.0

JHEP 1 (2010) 1

H1ZEUS combination (2010)

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid 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										
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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	30000	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]
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]

Preliminary Results

HERA I

HERAPDF1.5

H1prelim-10-141(2)

ZEUS-prel-10-017(8)

Partial HERA II

H1ZEUS combination (2014)

Data Set		x Grid from	x Grid to	Q^2/GeV^2 Grid from	Q^2/GeV^2 Grid 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]

HERA I

HERAPDF2.0 (prel.)

H1prelim-14-041(2)
ZEUS-prel-14-005(7)

Complete HERA II including Ep=460,575 GeV data

Data combination method

- Use HERAaverager program
  (wiki-zeuthen.desy.de/HERAverager)

χ^2 contribution from specific data set

Combined value

Relative systematic uncertainty

Shift of syst. parameter

measured value

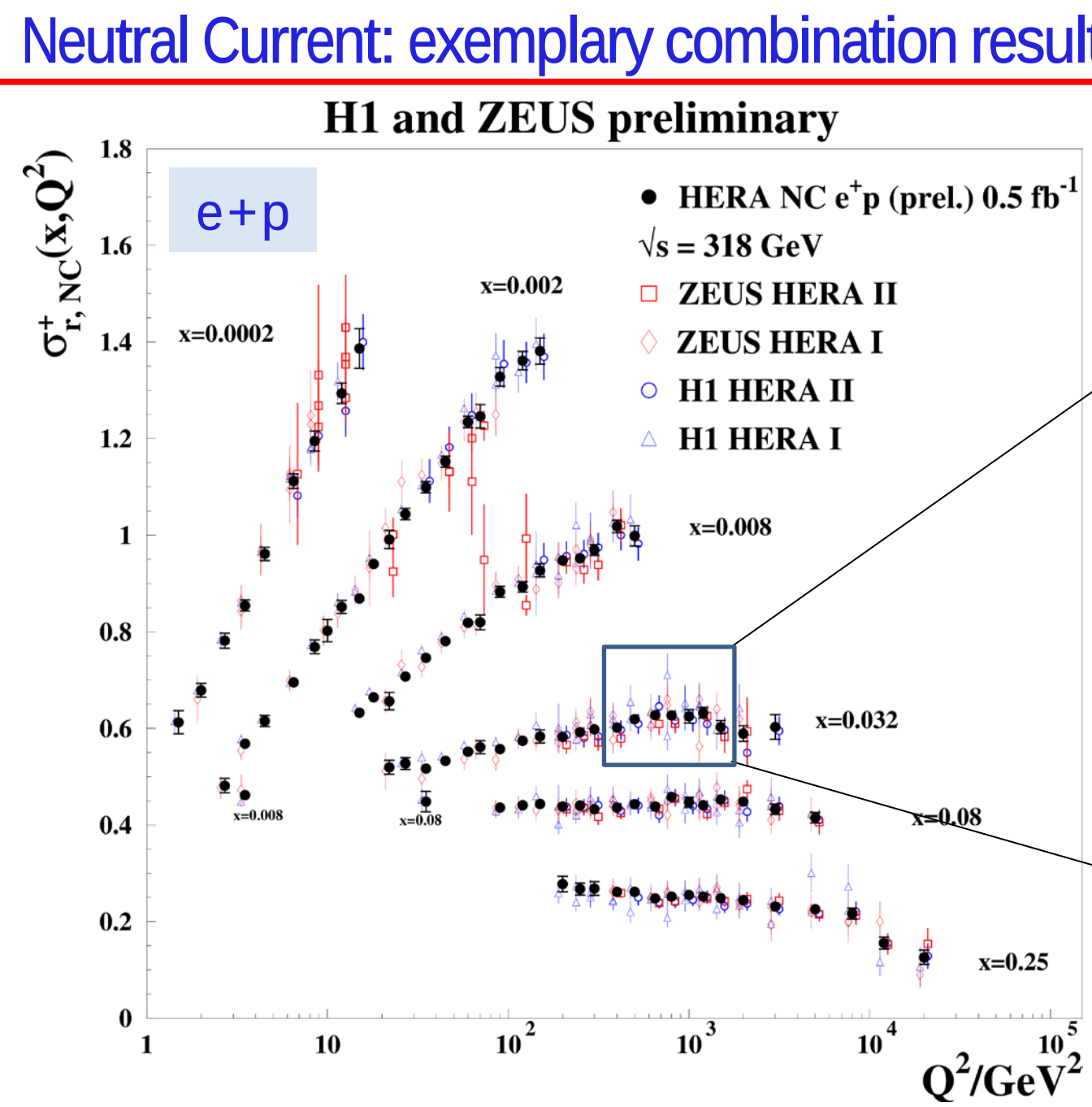
$$\chi^2_{\text{exp},ds}(\boldsymbol{m},\boldsymbol{b}) = \sum_{i,ds} + \sum_{j,b} = \sum_{i} \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\text{stat}}\,\mu^i\left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\text{uncor}}\, m^i\right)^2} + \sum_j b_j^2$$

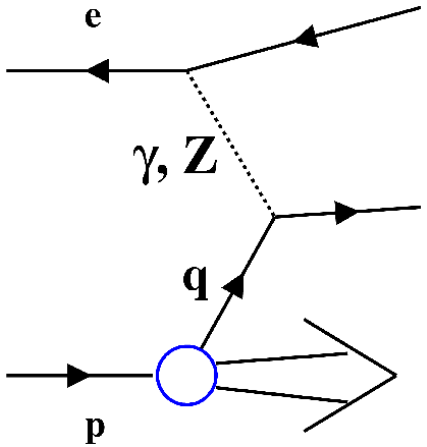
Sum over data points

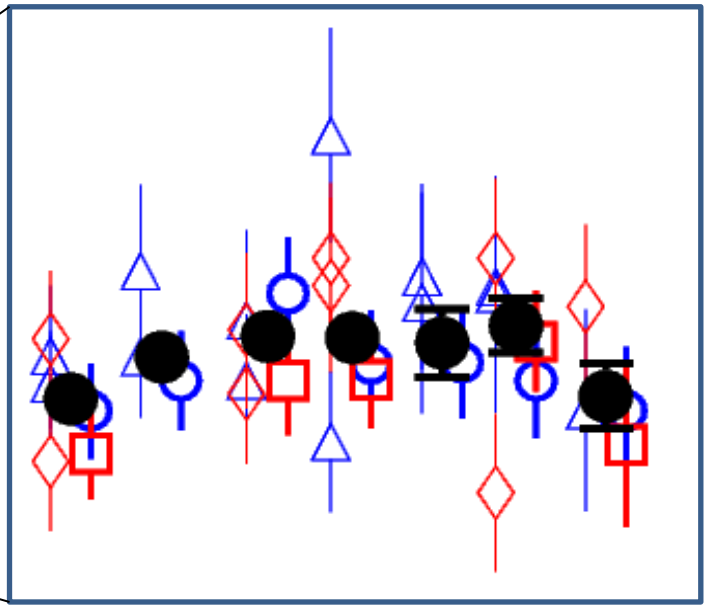
Sum over correlated systematics sources

- Statistical uncertainties assumed to scale ~$\sqrt{}$[expected #events] ≡ Pearsonχ^2
- All correlated systematic sources treated as multiplicative

Neutral Current: exemplary combination results

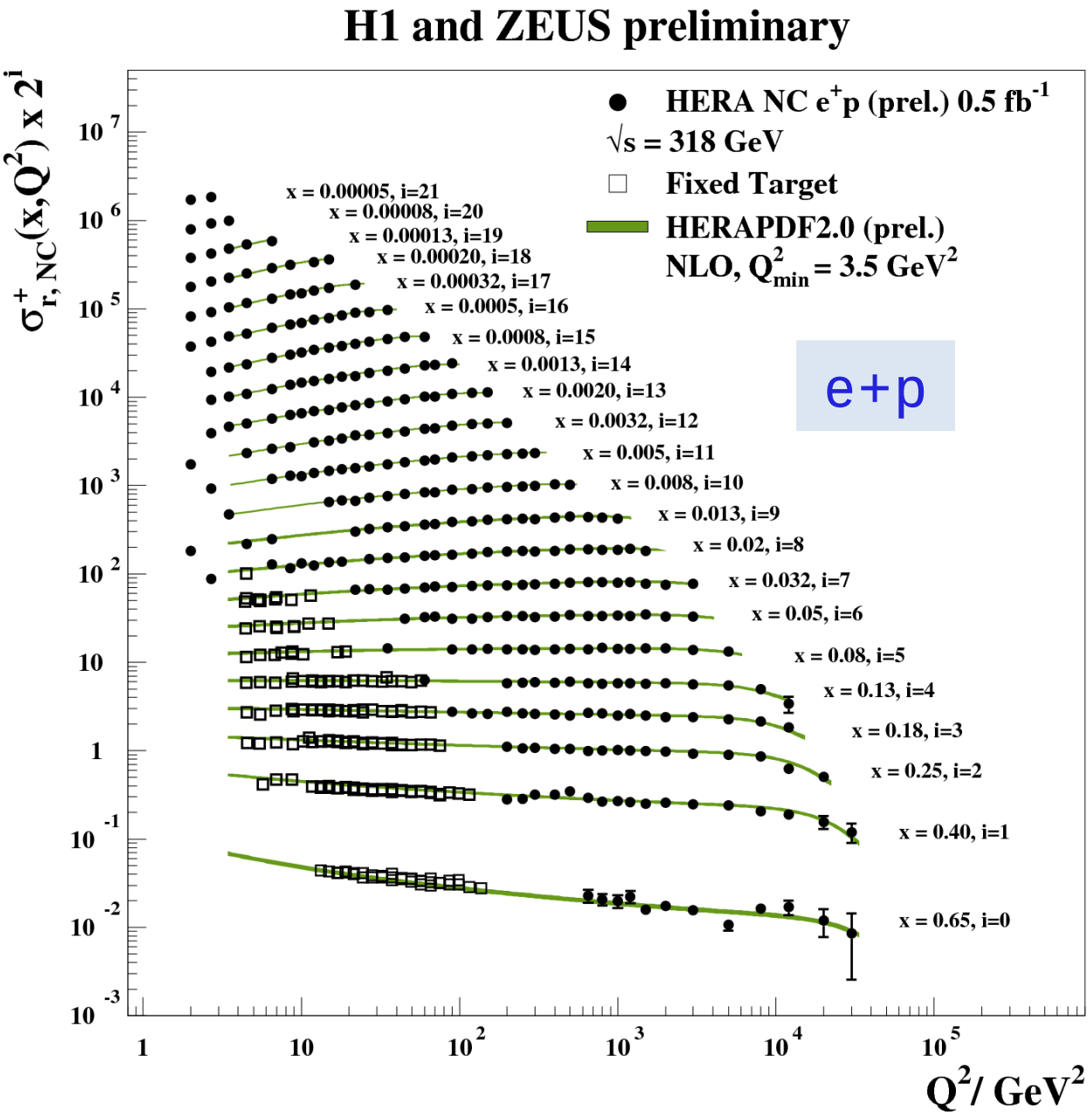






→ consistent data
→ large error reductions

Neutral Current: **perturbative** region $Q^2>2$ GeV^2



➔ Showing **all** combined points

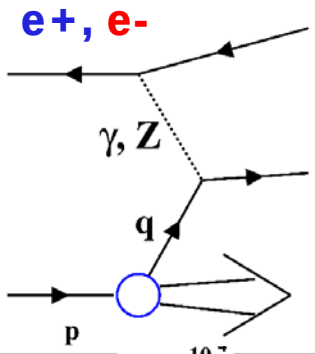
➔ Comprehensive map of scaling violations

➔ Smallest uncertainties

~1% for $20 < Q^2 < 100$ GeV^2

Neutral Current:

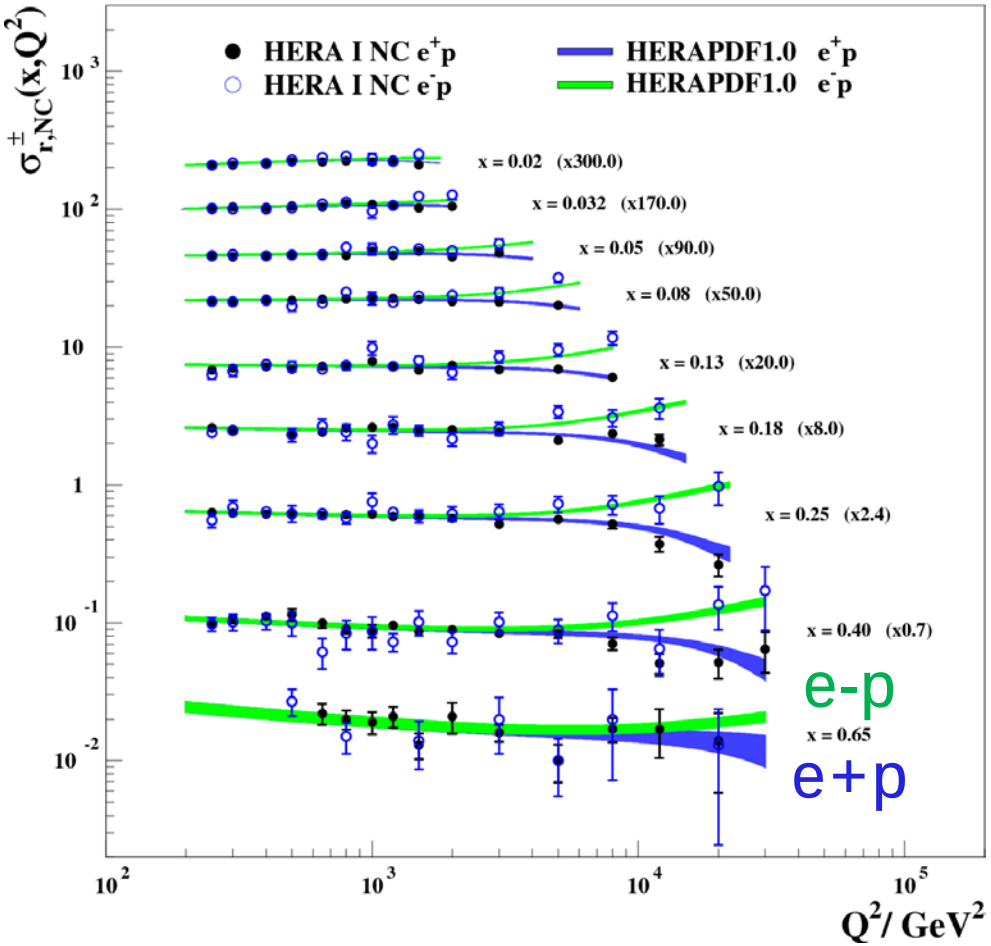
compare e^+p with e^-p

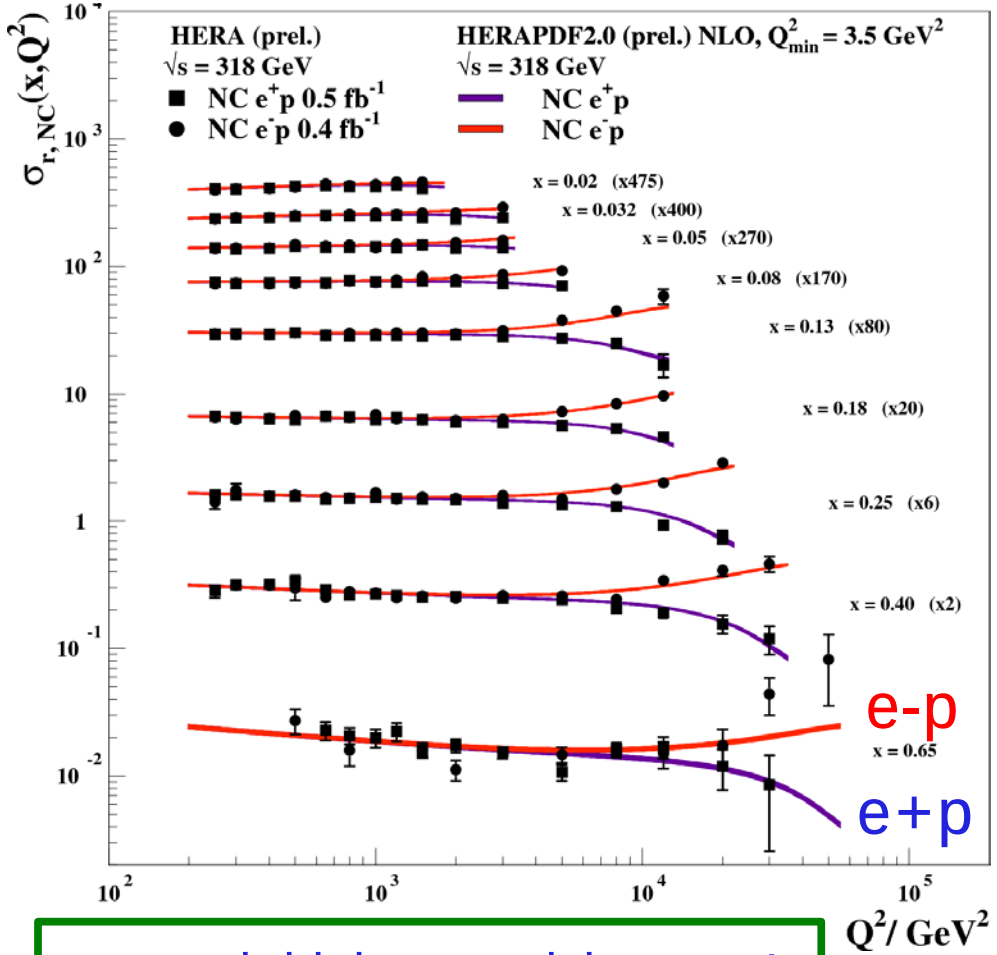


➔ See clear γz interference effects

HERAPDF1.0 = **HERA I**

HERAPDF2.0 = **ALL IN**

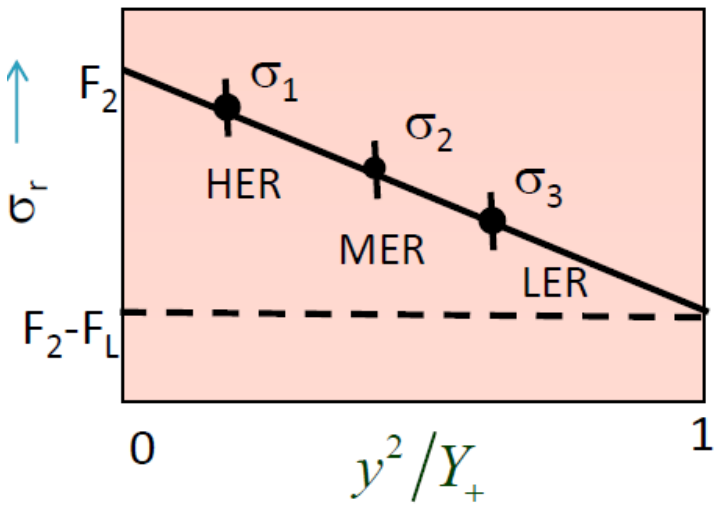


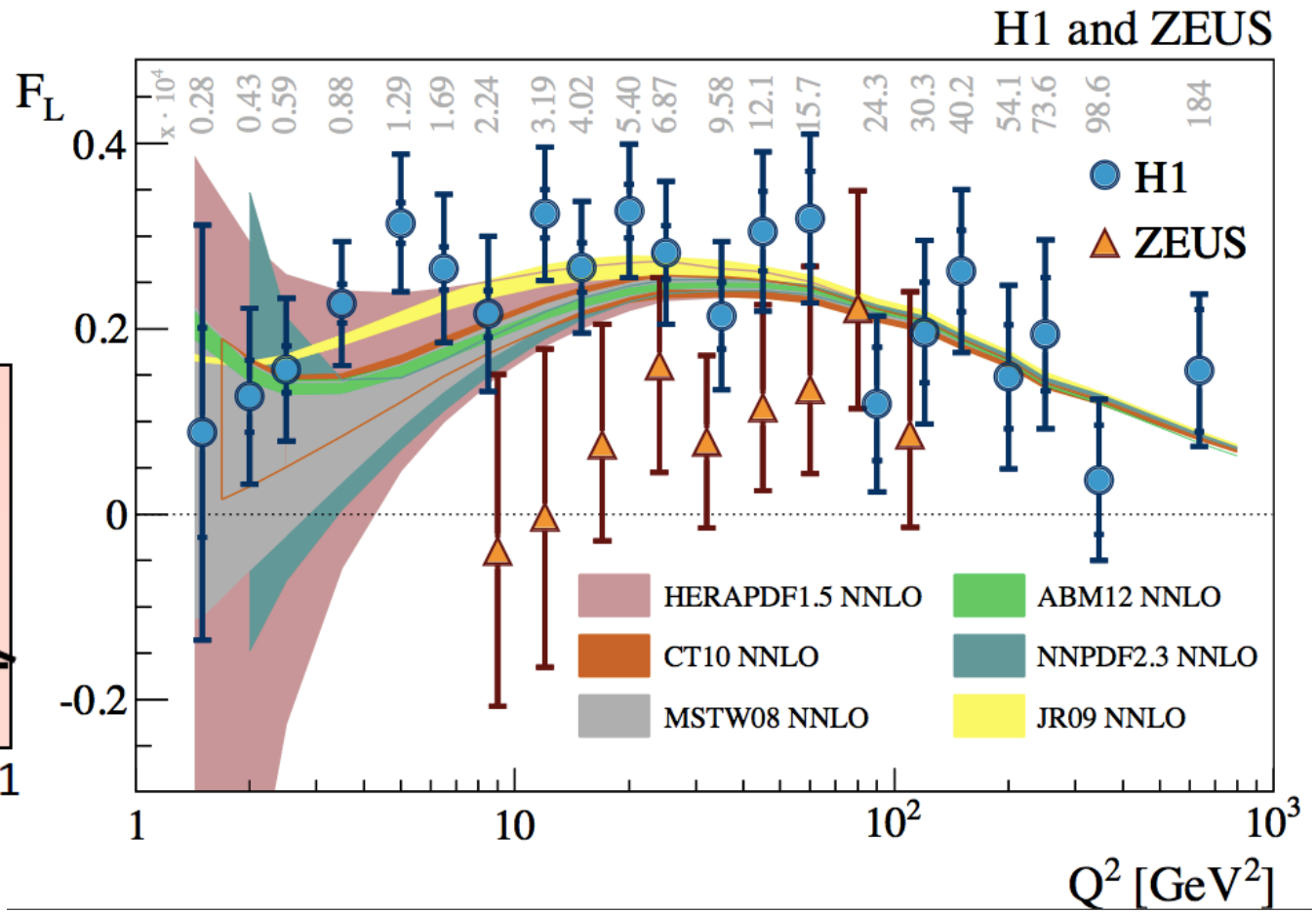


➔ much higher precision now!

Final F_L results from H1 ((EPJ C 74 (2014) 2814 EPJC C71 (2011) 1579) and ZEUS (DESY 14-053)

HER: Ep=920 GeV
MER: Ep=575 GeV
LER: Ep=460 GeV

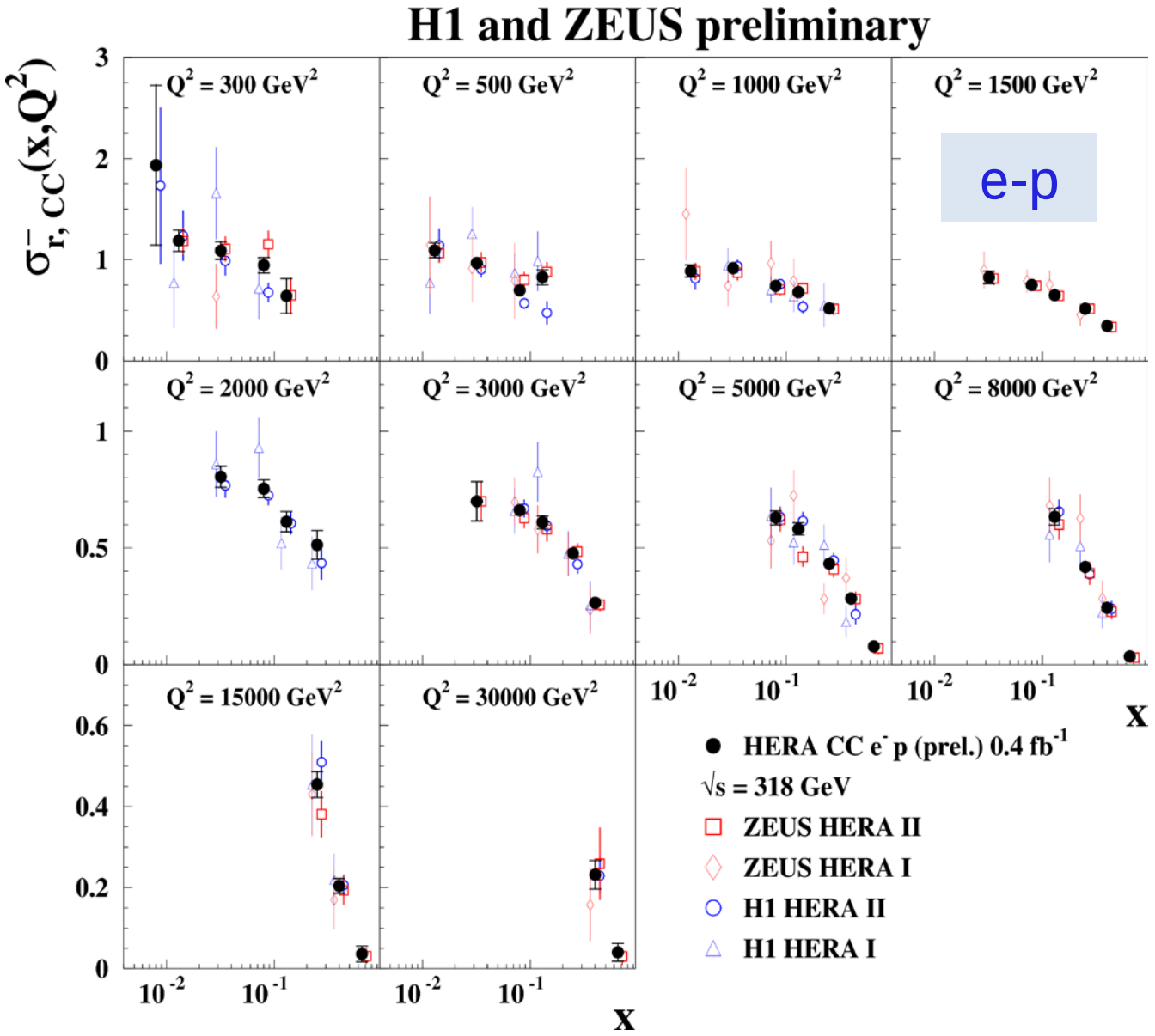


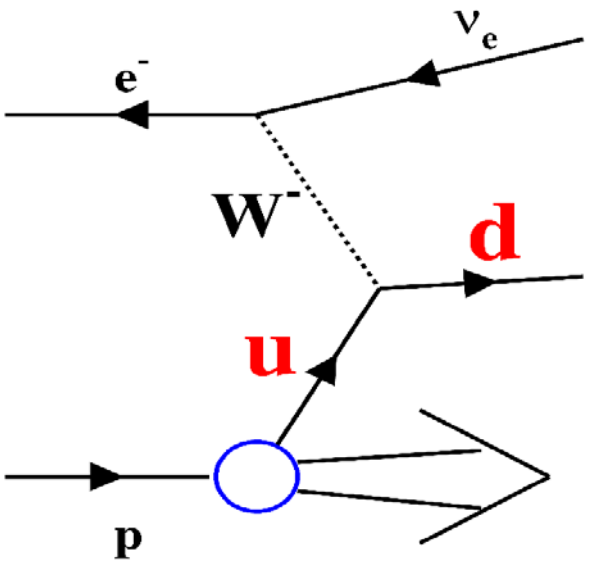


➔ Overall (using all data points) H1/ZEUS consistency within ~1-2 σ

➔ Reduced cross sections ***have already been combined*** (separately for HER, MER and LER), see appendix

Charged Current: exemplary combination results





➔ Consistent data
➔ Large error reductions

Second part of talk:

QCD analysis = PDF fit
to the new HERA combined data

HERAPDF2.0 PDF Fit - settings

- PDFs **parametrised** at starting scale $Q_0^2 = 1.9$ GeV^2:

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

- **Constraints**: fix $C'_g = 25$, QCD sum rules,

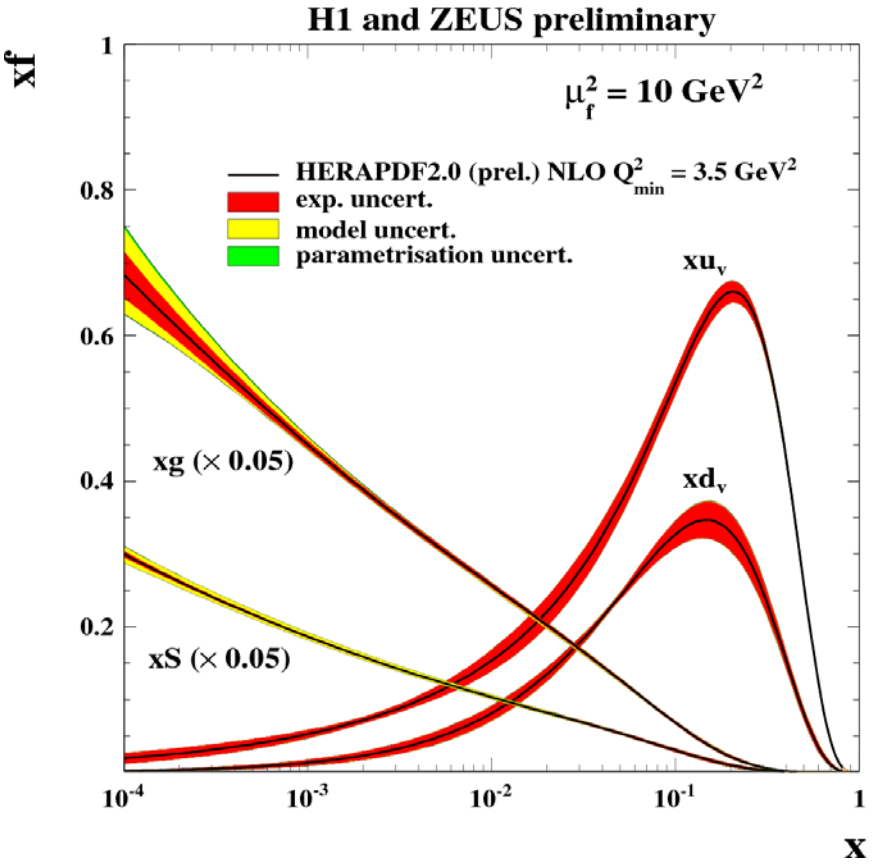
$x\bar{u} \to x\bar{d}$ as $x \to 0$, $x\bar{s} = f_s x\bar{D}$ $\longrightarrow$ **15 free parameters**

- **Evolve** PDFs in Q^2 with DGLAP at (N)NLO ***QCDNUM program***

- **Heavy quarks** (charm and beauty):

  use ***Thorne-Roberts*** variable flavour number scheme

Sources of HERAPDF uncertainties



Experimental

- use $\Delta\chi^2=1$ criterion

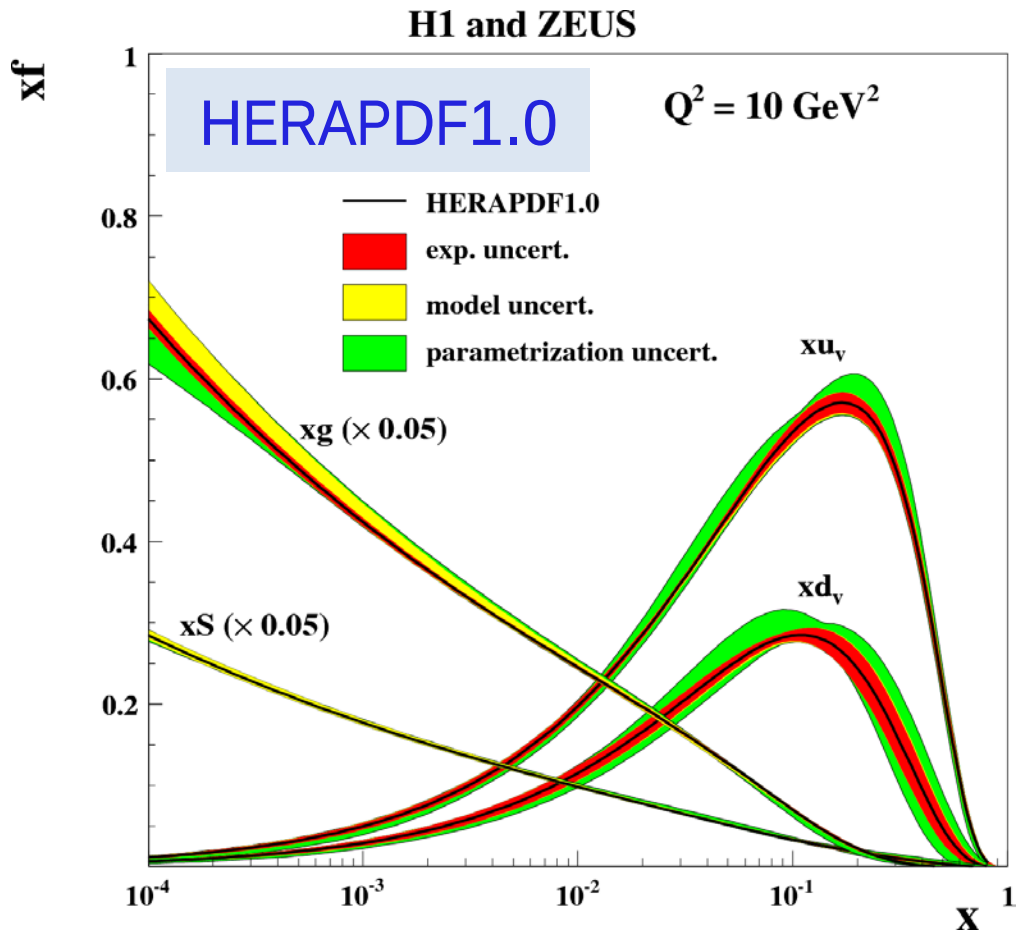
Model:

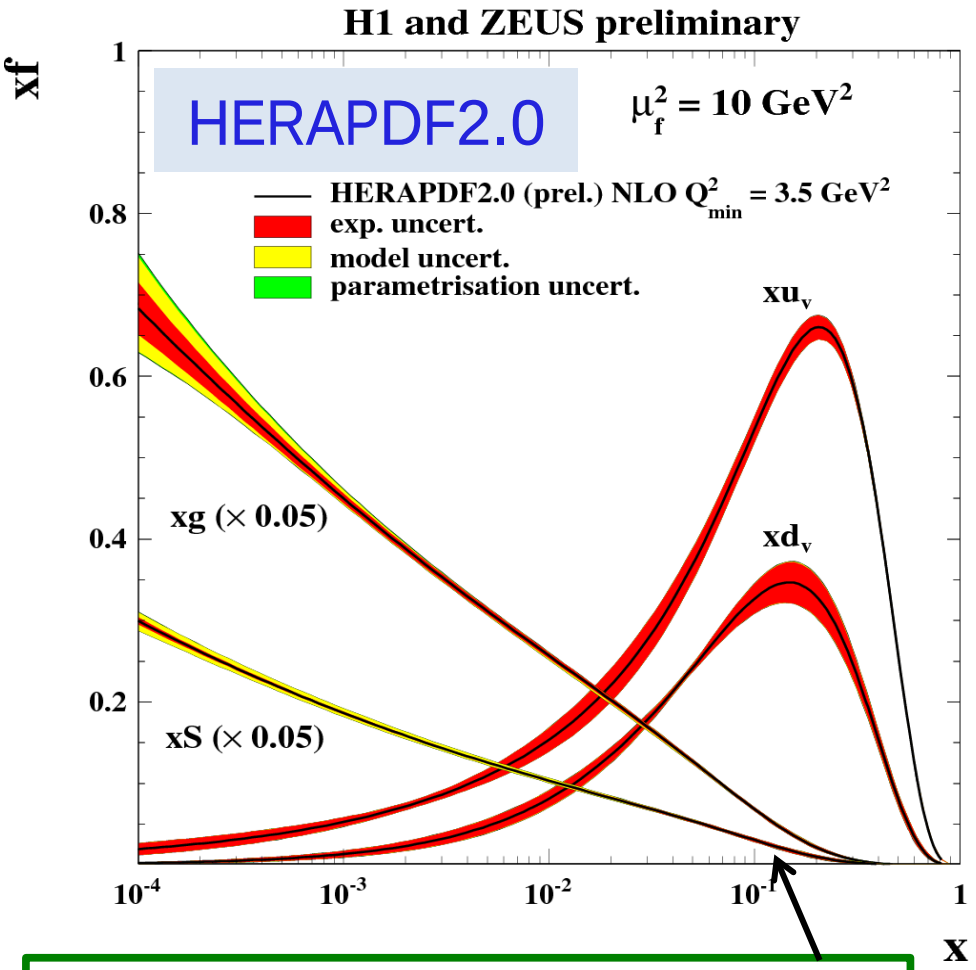
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q_0^2 [GeV^2]	1.9	1.6	2.2

Parametrisation

- Form envelope from variants:
  - Try out extra D or E parameters $(1 + Dx + Ex^2)$
  - Q_0^2 variation → dominant effect

HERAPDF1.0 and 2.0 *at NLO* with Q^2_{min}=3.5 GeV^2

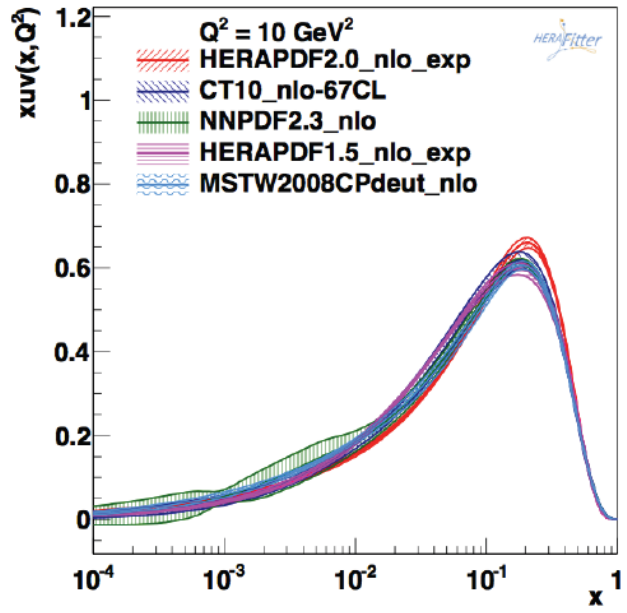


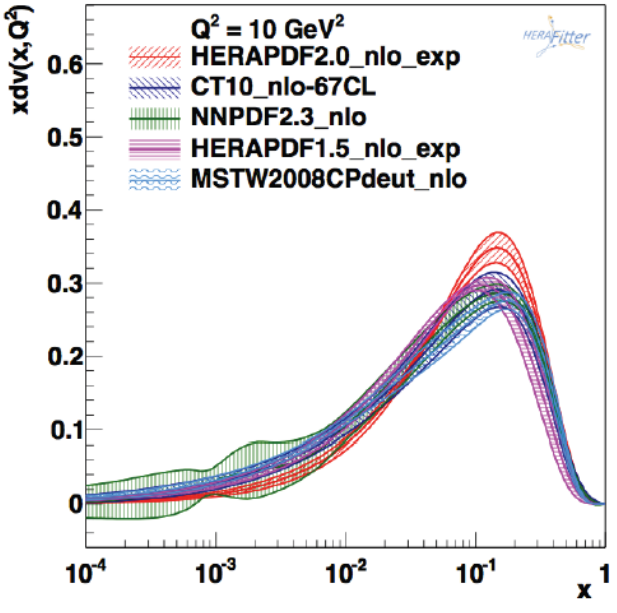


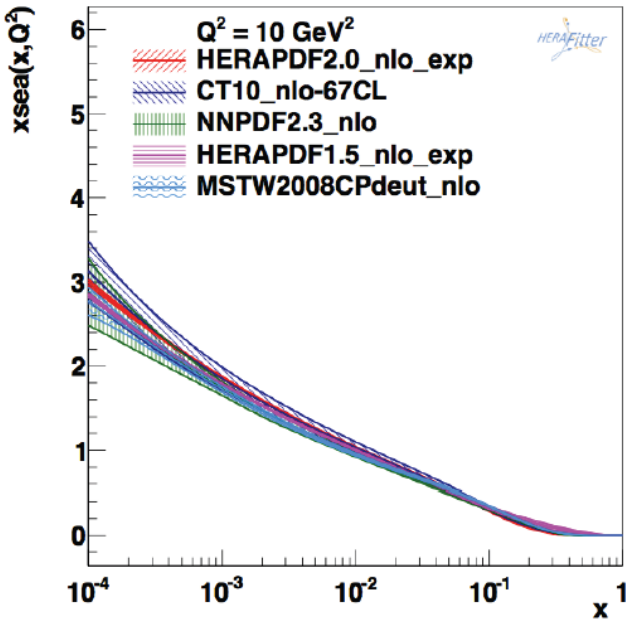
➔ HERAPDF2.0: softer sea & overall reduced uncertainties

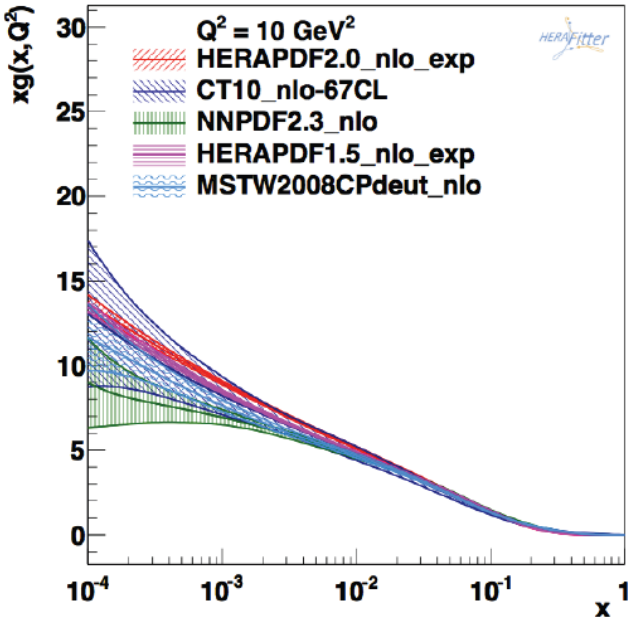
➔ ***NNLO version in appendix***

Comparison to other (global) PDFs



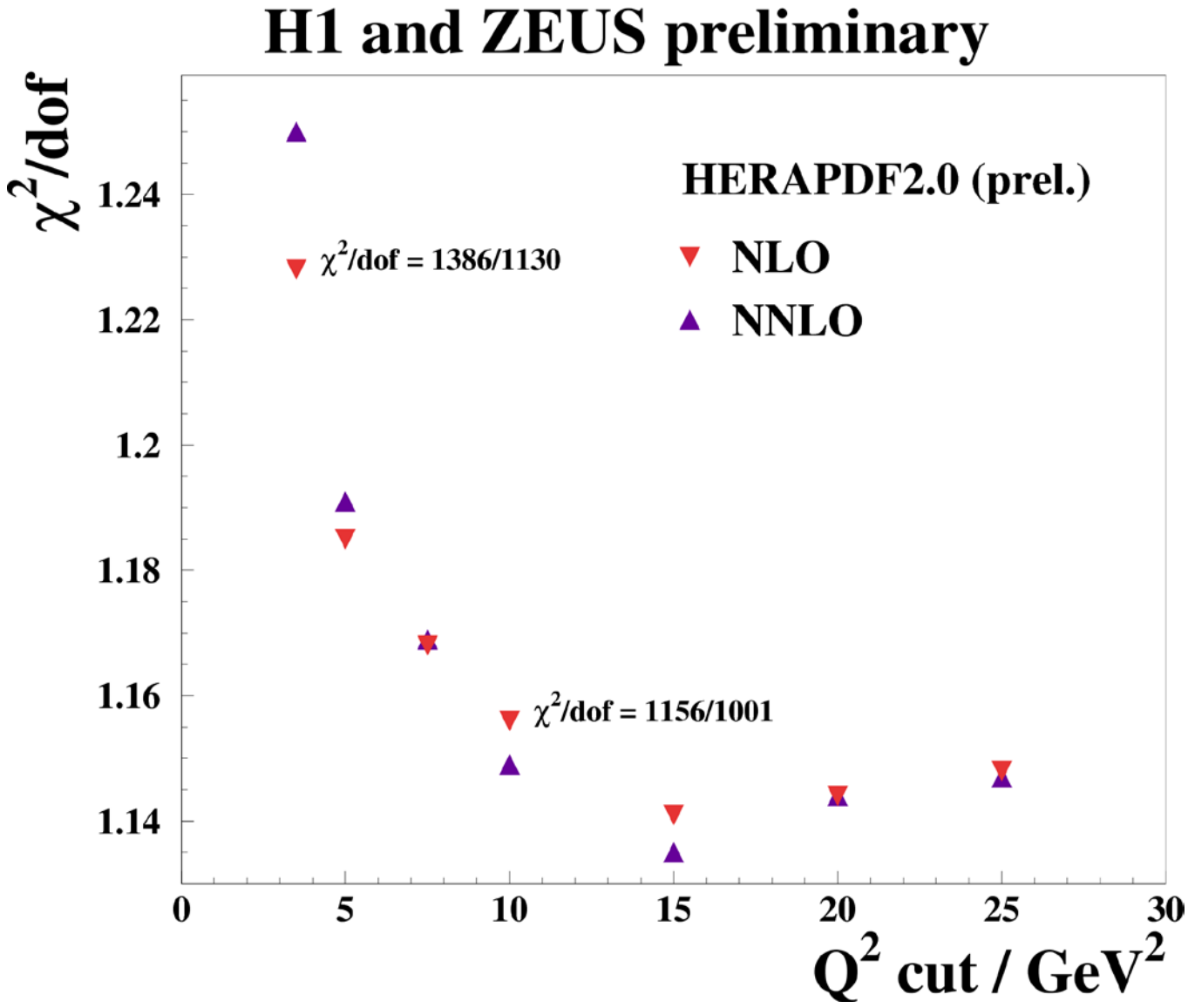






NOTE: HERAPDF sets are shown only with Exp uncert only!

HERAPDF2.0: χ^2 goodness of fit to HERA data



vs Q^2_{min} cut

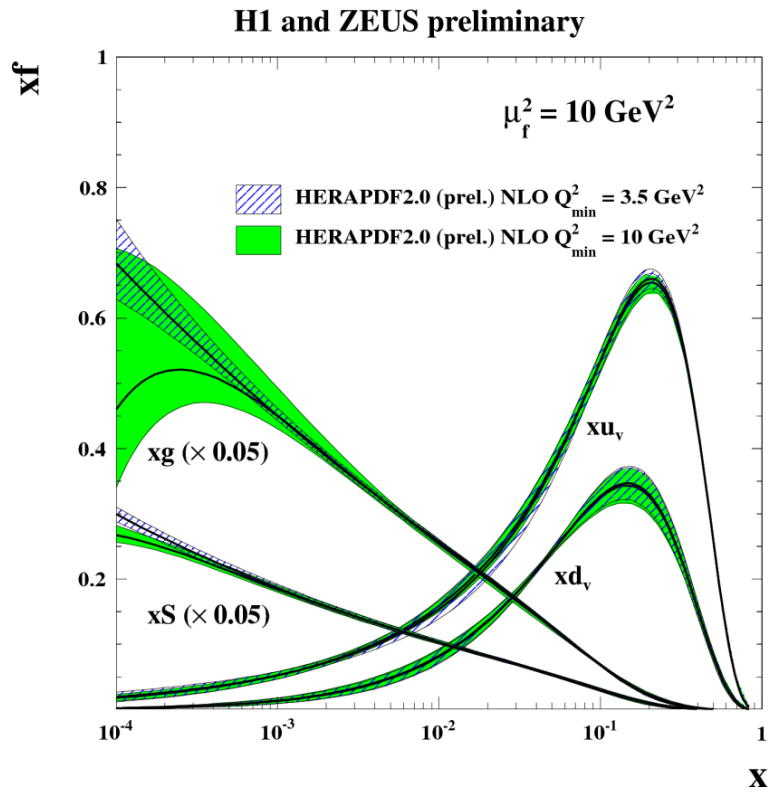
➔ Similar fit-quality for NNLO and NLO

➔ **also** provide PDF sets with Q^2_{min}=10 GeV^2

Summary

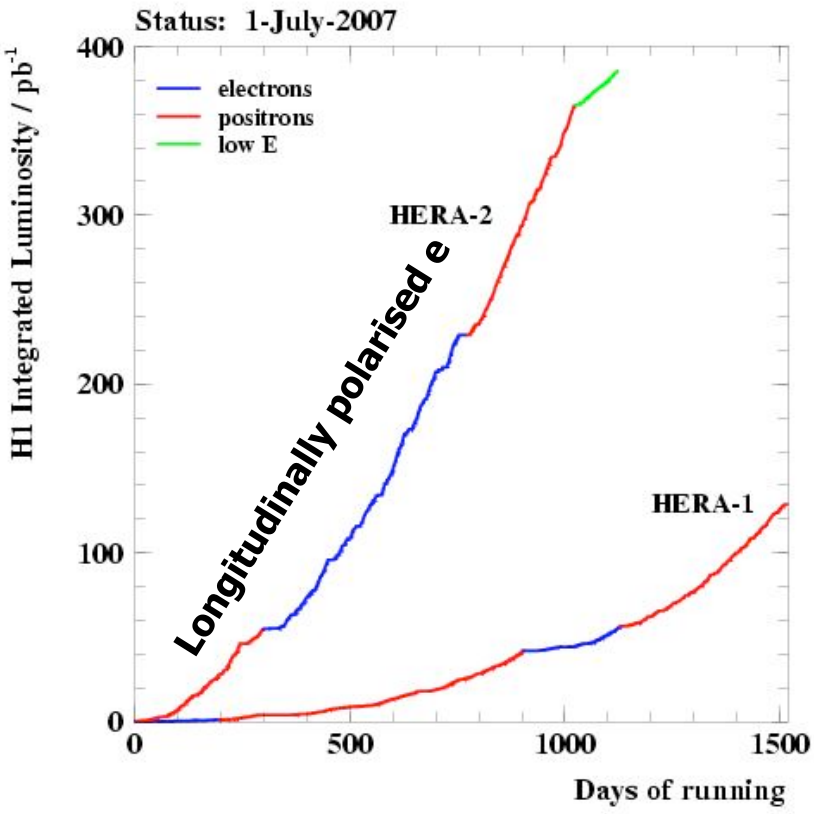
- **HERA data combination:**
  - of all final inclusive deep inelastic cross section measurements by H1 and ZEUS
  - obtained results, based on 1 fb-1 luminosity, have high precision (smallest uncertainties of ~1% at $20<Q^2<100$ GeV^2)

- **HERAPDF2.0 (prel.) PDF fit:**
  - High precision PDFs at NLO or NNLO
  - Two versions: fitting data with $Q^2_{min}>3.5$ or >10 GeV^2



Backup slides

The HERA ep collider (1992-2007)



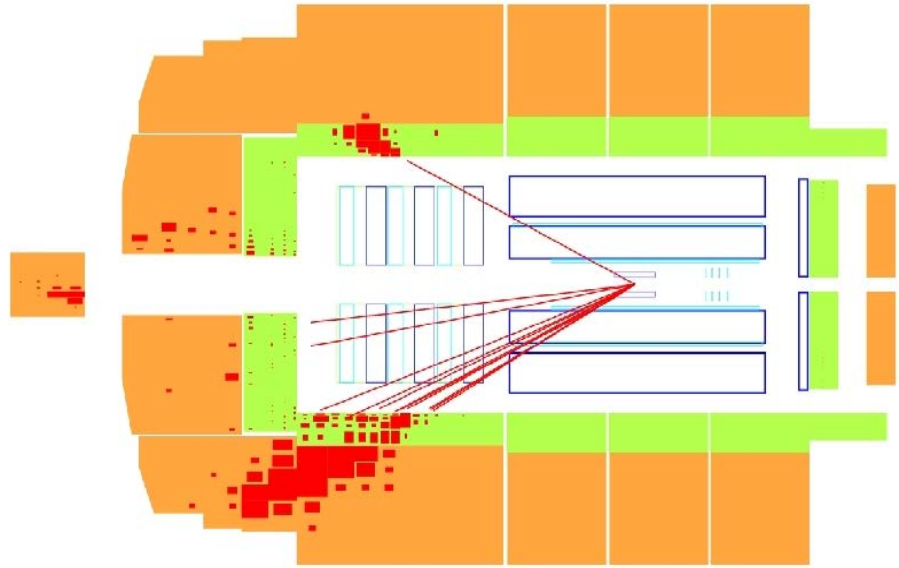
HERA:

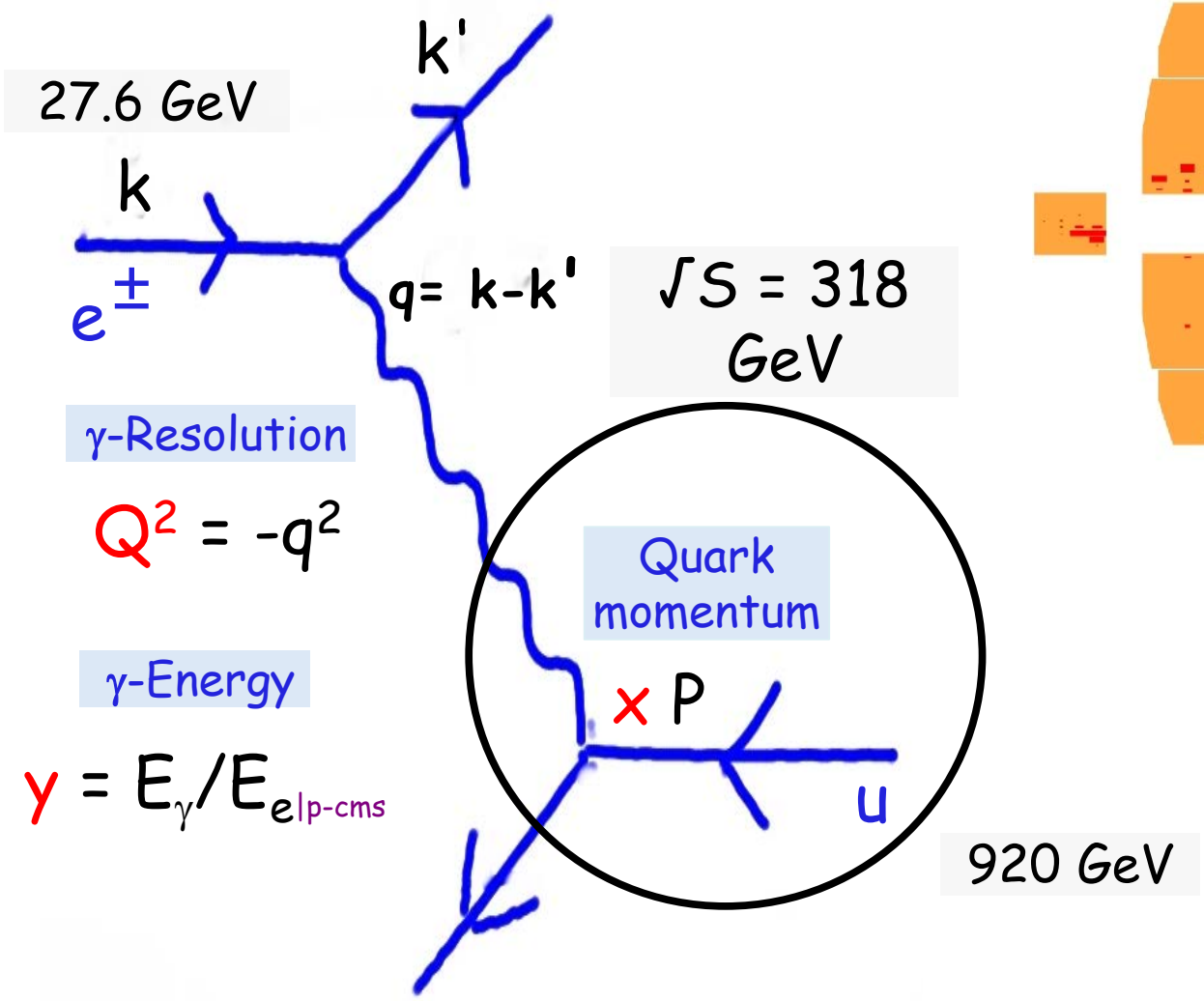
p (920 GeV) $e^{\pm}$(27.6 GeV)

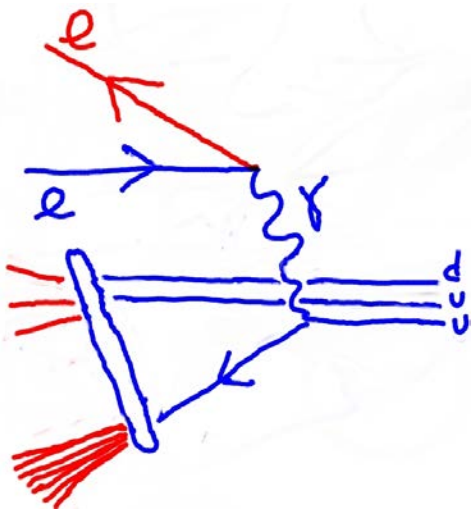
~0.5 fb^{-1} per experiment

Deep inelastic scattering at HERA

NC event in H1 detector:

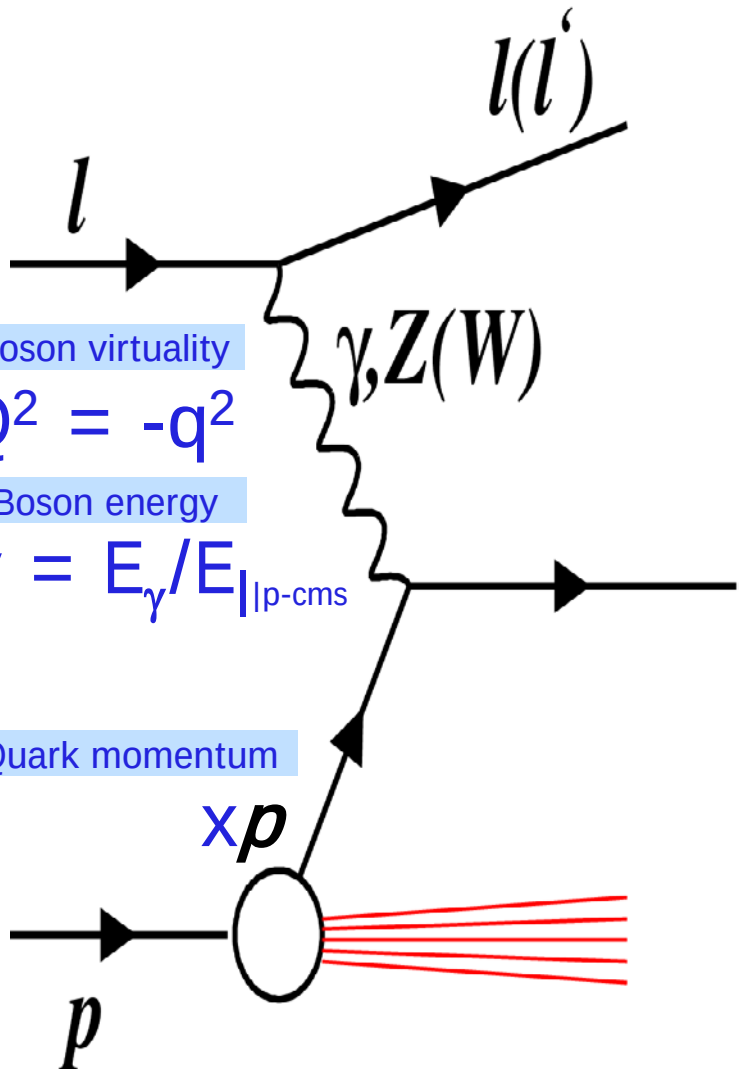






Relation: $Q^2 = Sxy$

Probing p Structure in Deep Inelastic scattering at HERA



Boson virtuality

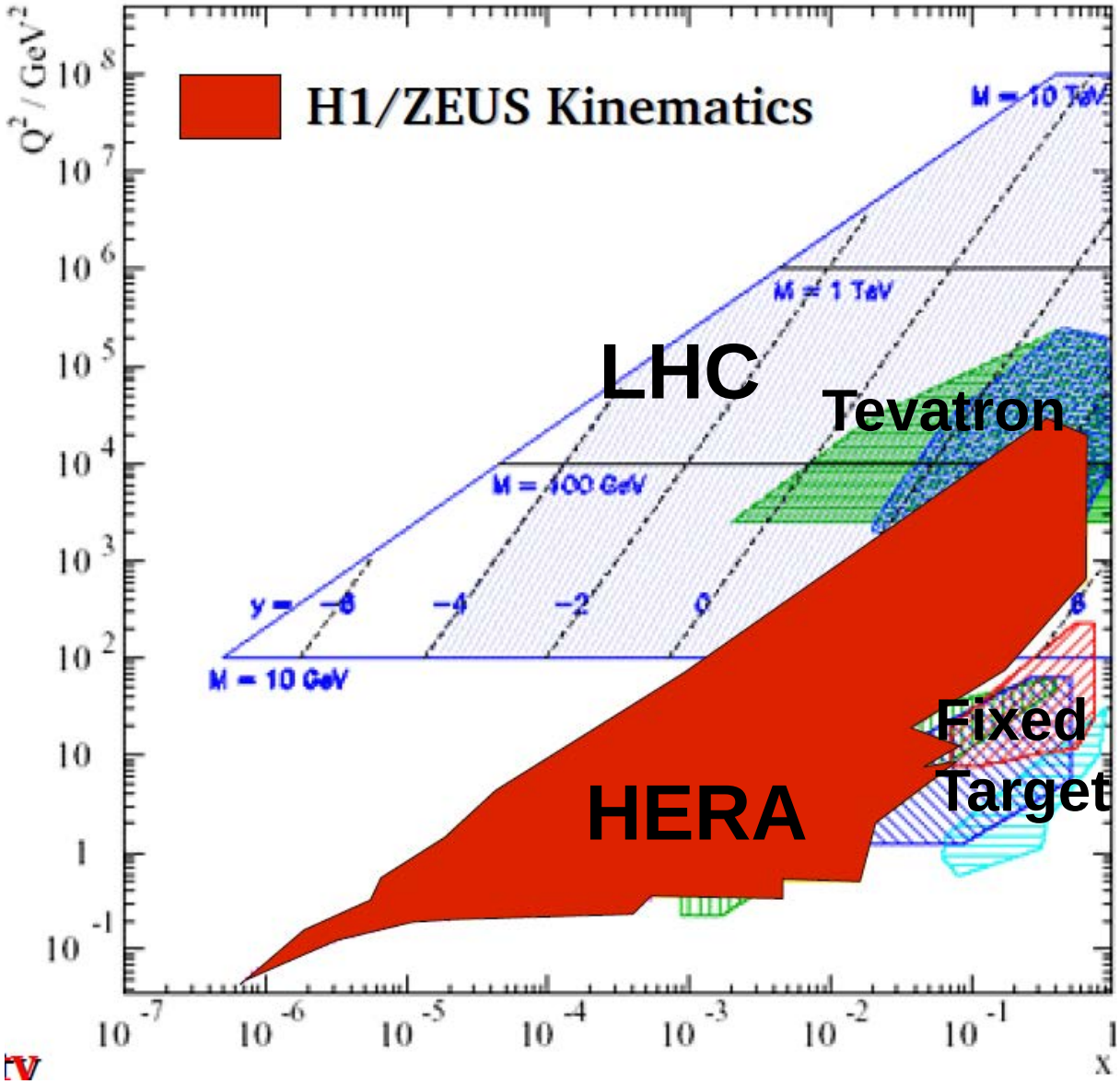
$Q^2 = -q^2$

Boson energy

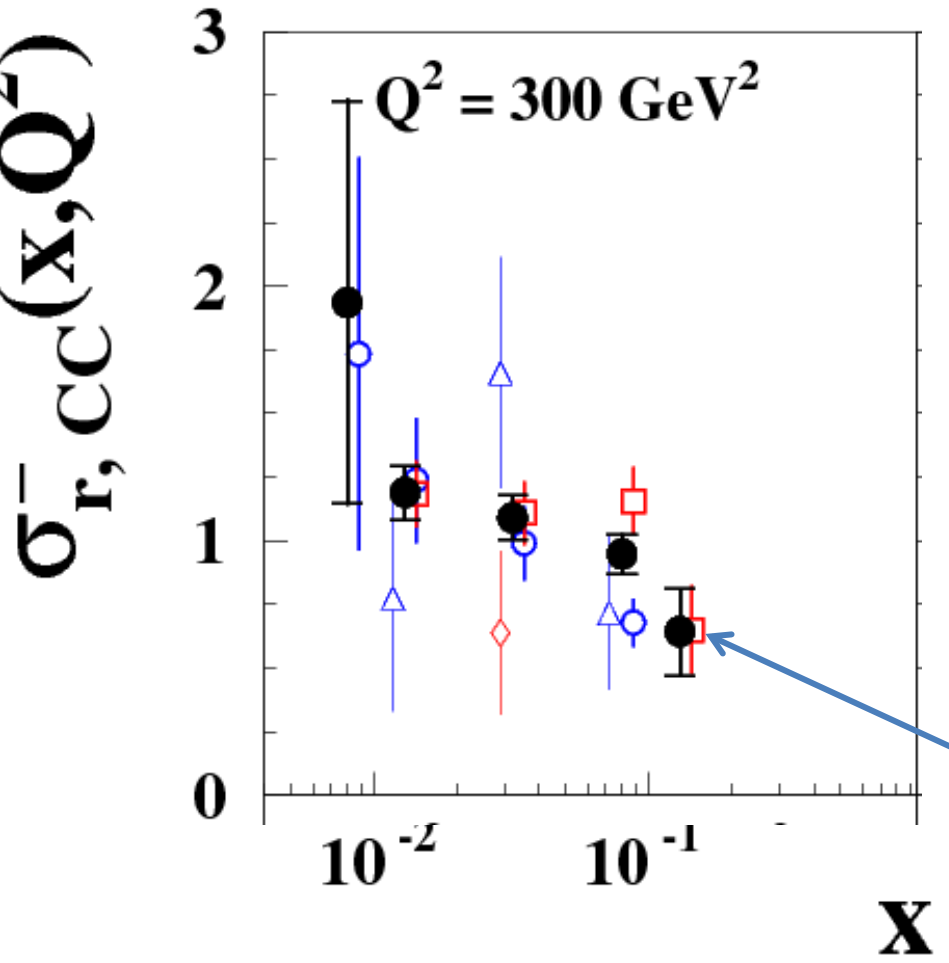
$y = E_\gamma/E_{l|p\text{-cms}}$

Quark momentum

Constraint: $Q^2 = sxy$



Data combination - example



● HERA CC e^- p (prel.) 0.4 fb^{-1}

$\sqrt{s} = 318$ GeV

□ ZEUS HERA II

◇ ZEUS HERA I

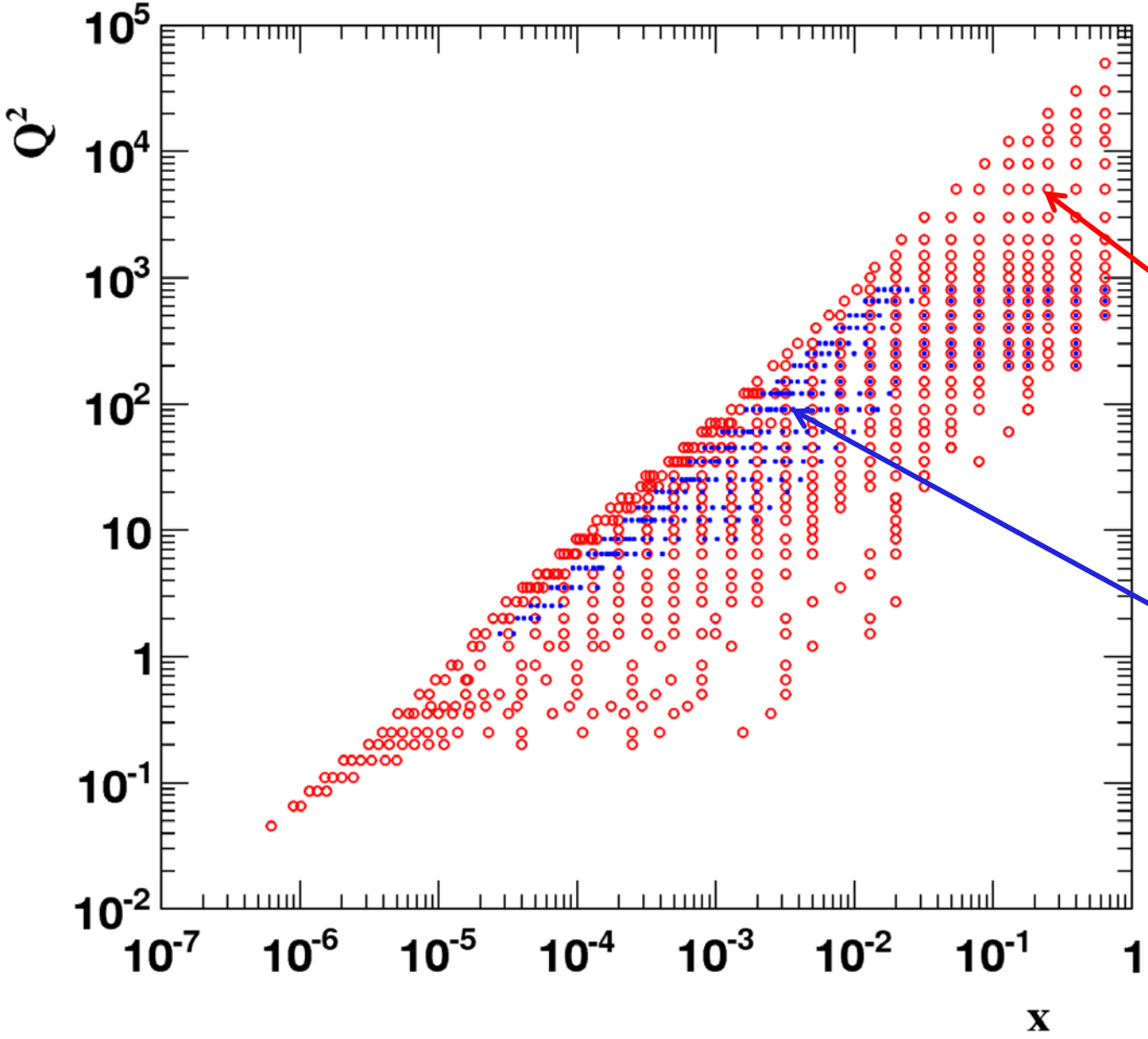
○ H1 HERA II

△ H1 HERA I

For **'LONELY SINGLE'** data points apply only final systematic shifts

➔ Combine nearby data at common Q^2,x points (grids of points)
⇒ requires sometimes some *swimming* (details in appendix)

Common Q^2,x grids

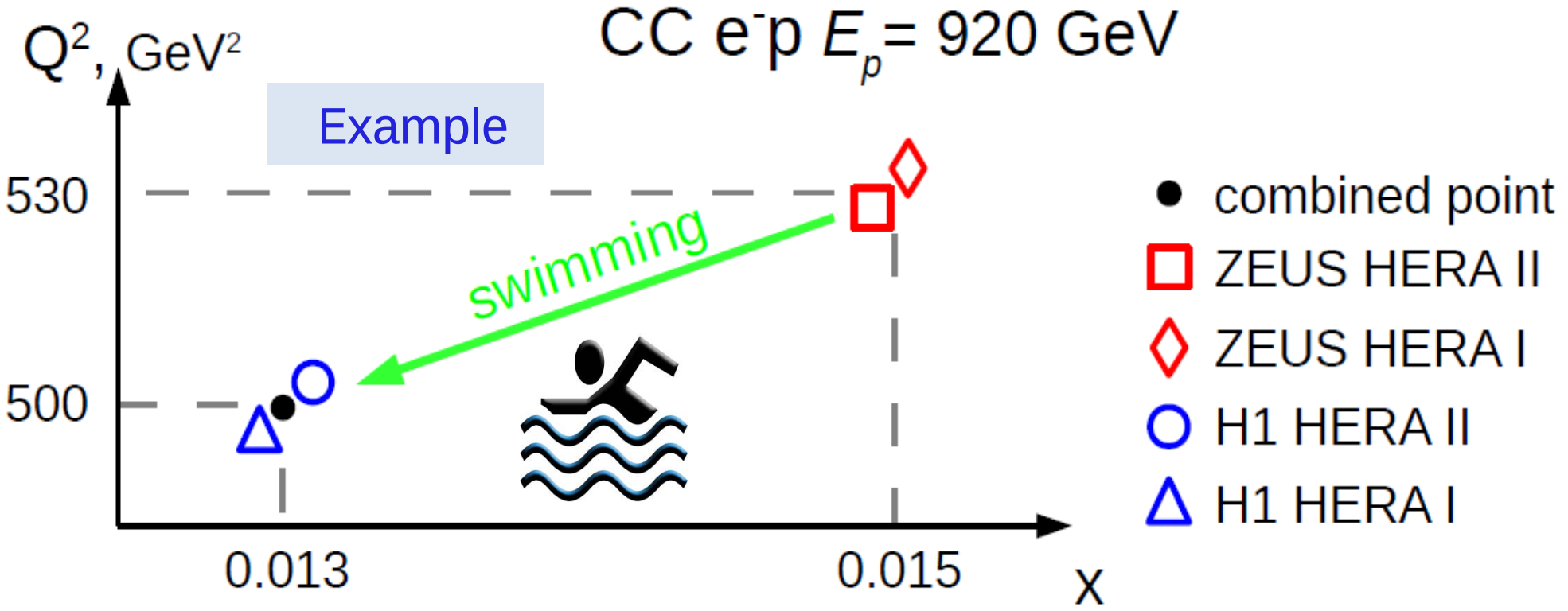


Two separate grids:

- Grid for E_p=920 & 820 GeV data sets

- Finer x Grid for E_p=460 & 575 GeV data sets

Swim data to common grid points



- Use QCD fit to all the inclusive HERA data for swimming correction
- for $Q^2>3$ GeV^2: QCD fit with **DGLAP**; for $Q^2<4.9$ GeV^2 fit **fractal model**, interpolate between the two corrections for $3<Q^2<4.9$ GeV^2
- Iterative procedure (Fit first to uncombined data and later to combined data)

Systematic uncertainties

- Note: the proper classification of systematic uncertainties into **uncorrelated or correlated** (between bins, samples or the two experiments) **is a most important combination issue**

- There are in total 162 sources of correlated uncertainties spread over the various H1 and ZEUS data sets (examples: hadronic & electromagnetic energy scales)

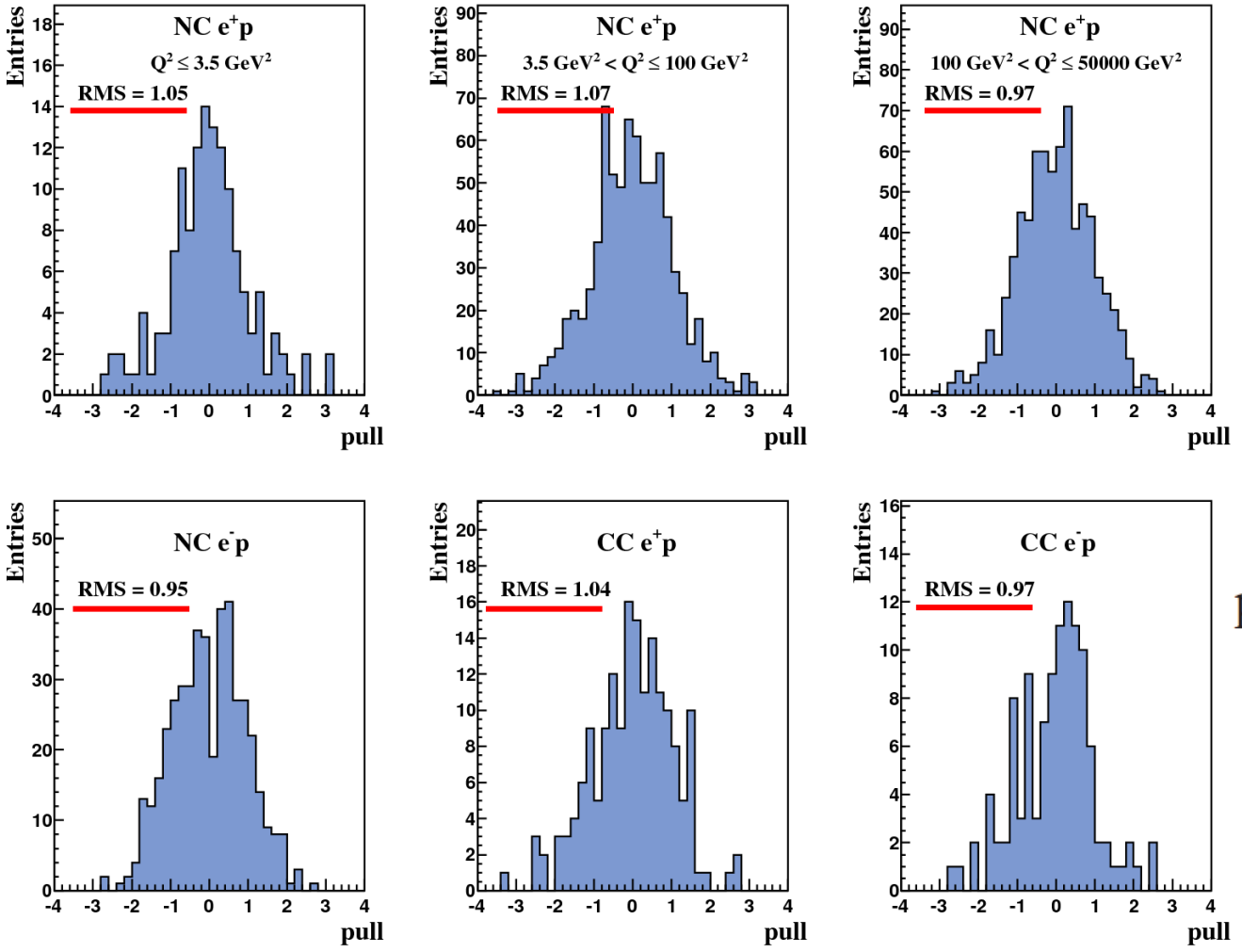
Add extra procedural uncertainties:

- Treat errors in χ^2 as additive (instead of multiplicative)
- Consider possible correlations beteen data sets/experiments:
  - *Hadronic energy scale*
  - *Photoproduction background*

First look at combination results - consistency

- 2927 data points combined to 1307*: total $\chi^2/ndf = 1685/1620$*
- Shifts for 162 correlated systematics usually small (max. ~2.4 σ)

H1 and ZEUS preliminary

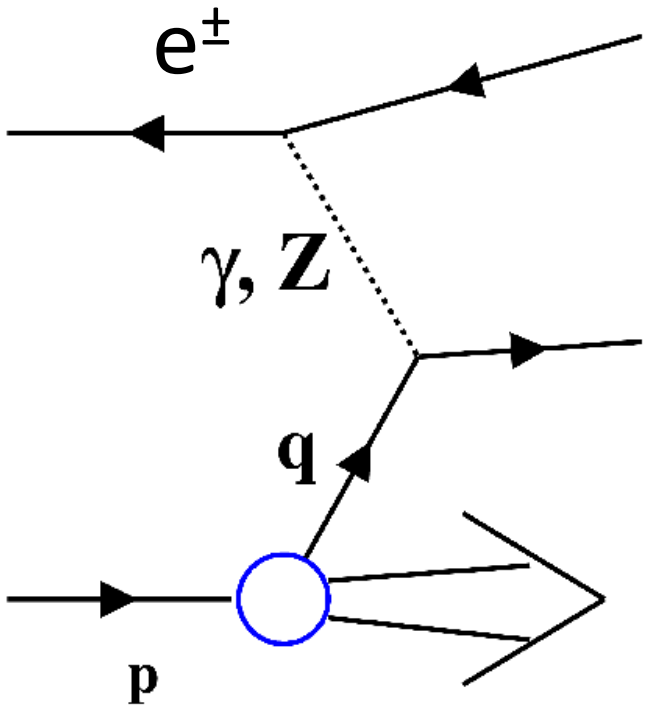


Pulls for data points:

$$p^{i,k} = \frac{\mu^{i,k} - \mu^{i,\mathrm{ave}}\left(1 - \sum_j \gamma_j^{i,k} b_{j,\mathrm{ave}}\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_{i,\mathrm{ave}}^2}}$$

➔ consistent data

Results for Neutral currents

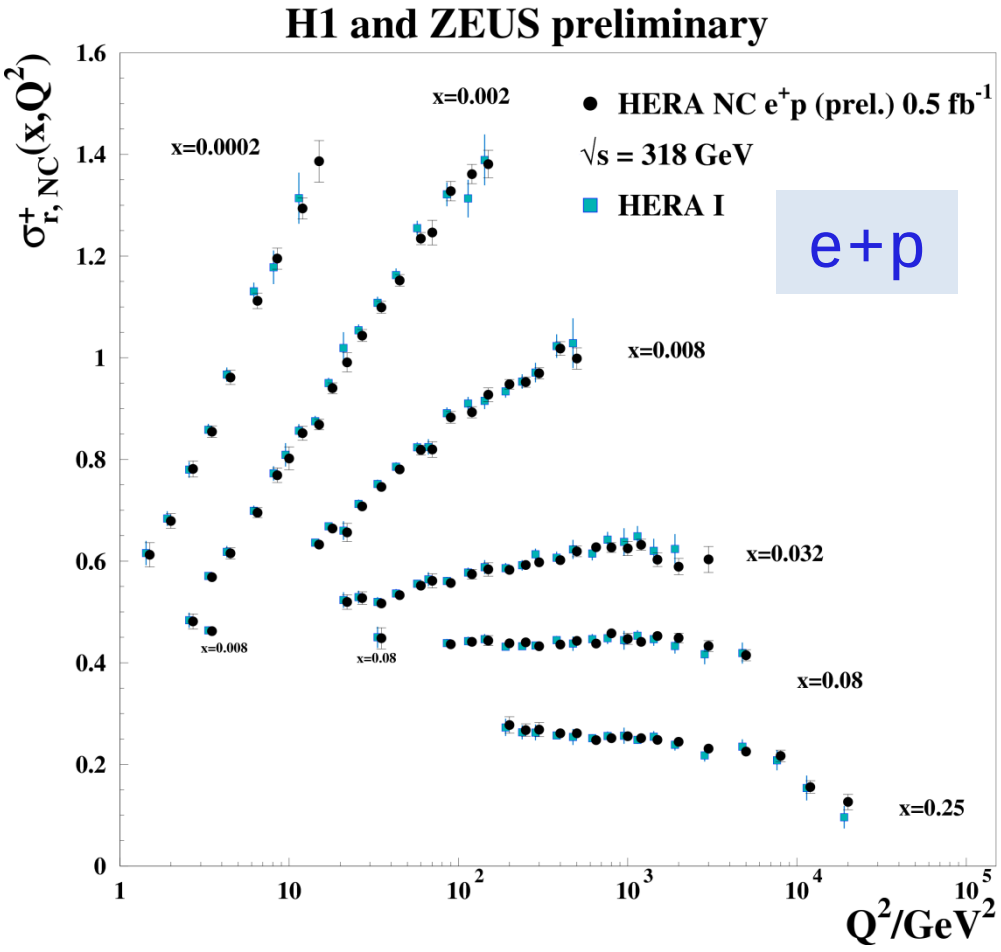


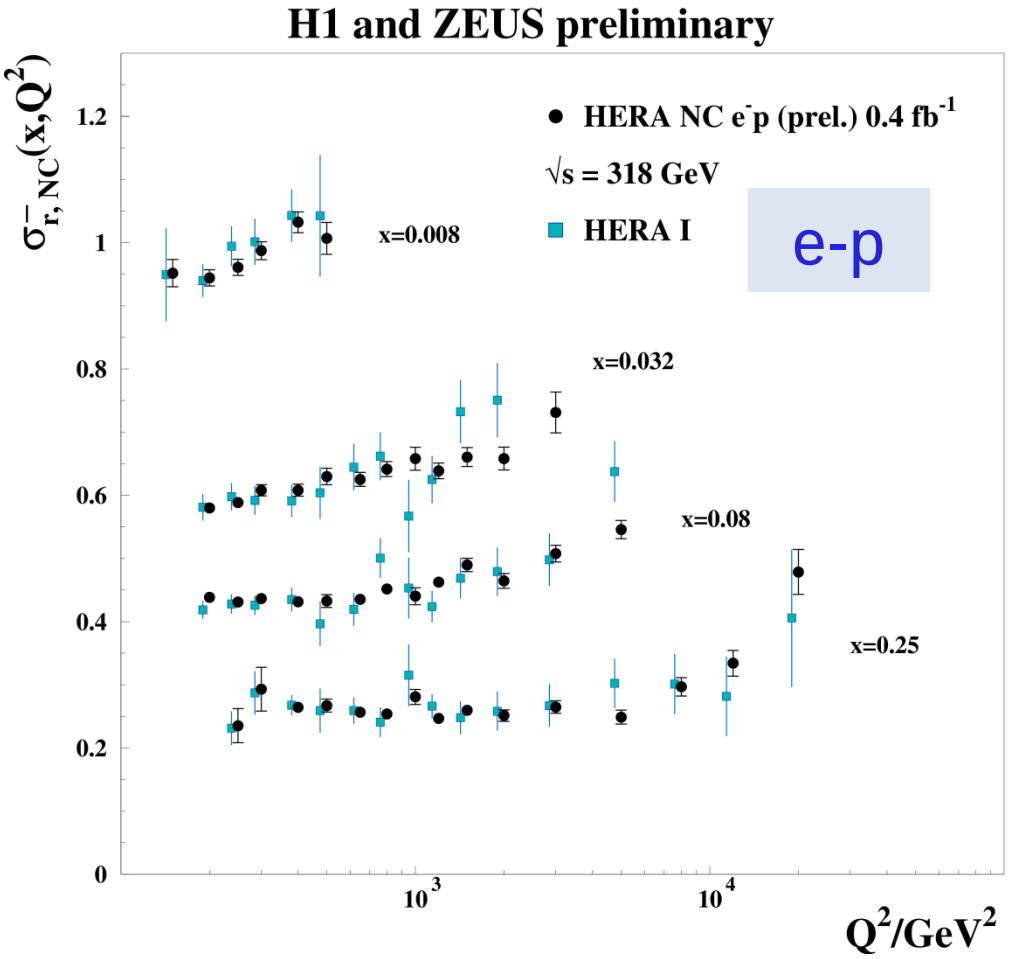
- Combined are the reduced cross sections:

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

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

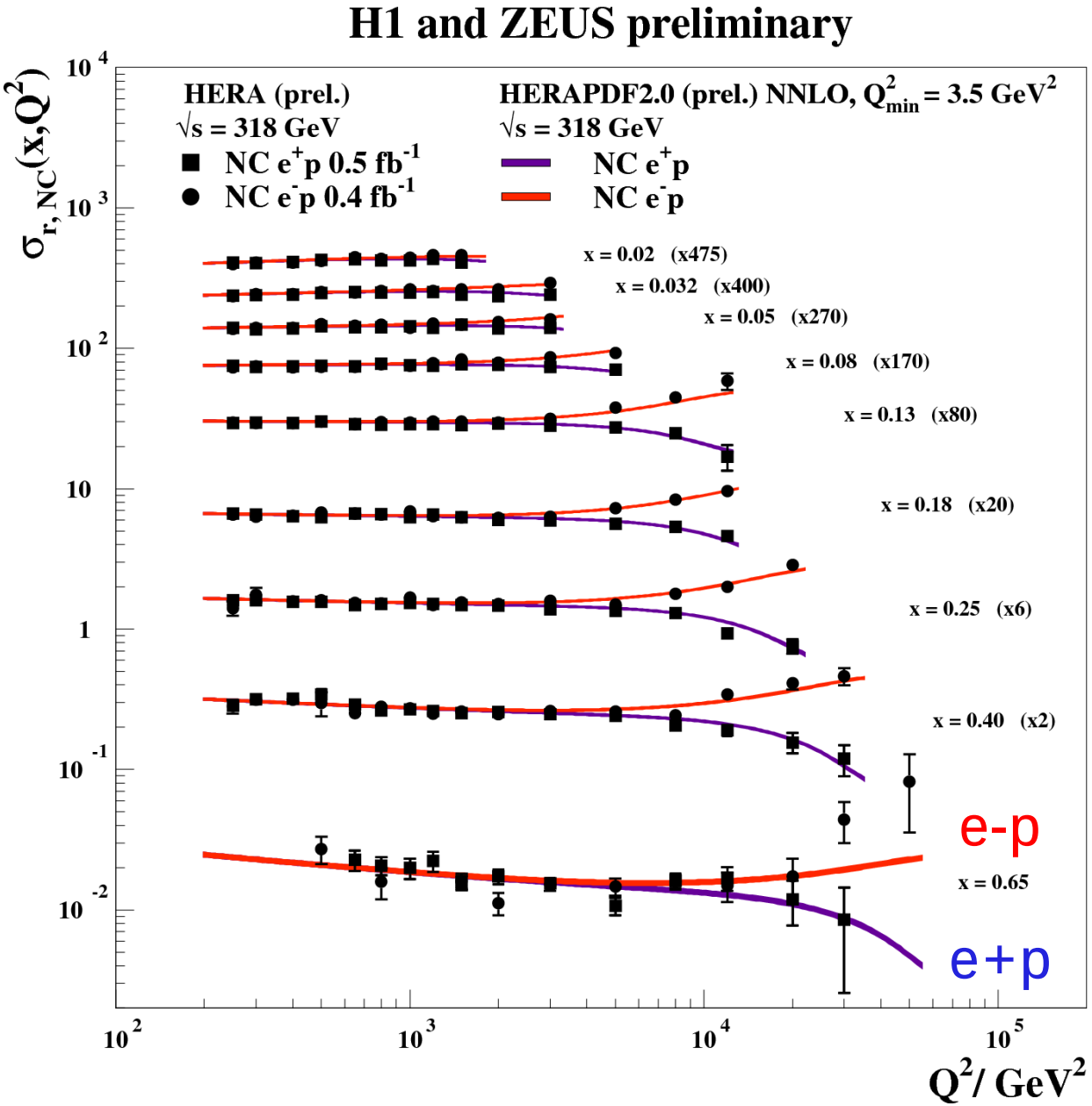
Neutral Current: new combination vs HERA I

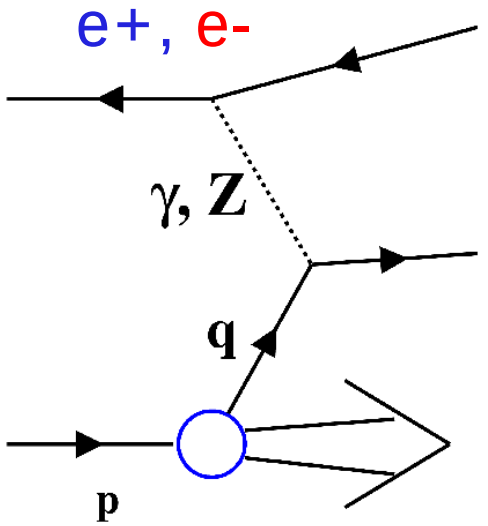




➔ e+p: Sizable error reductions (up to 3x lumi increase)
➔ e- p: Large error reductions (10x lumi increase)

Neutral Current: compare e^+p with e^-p

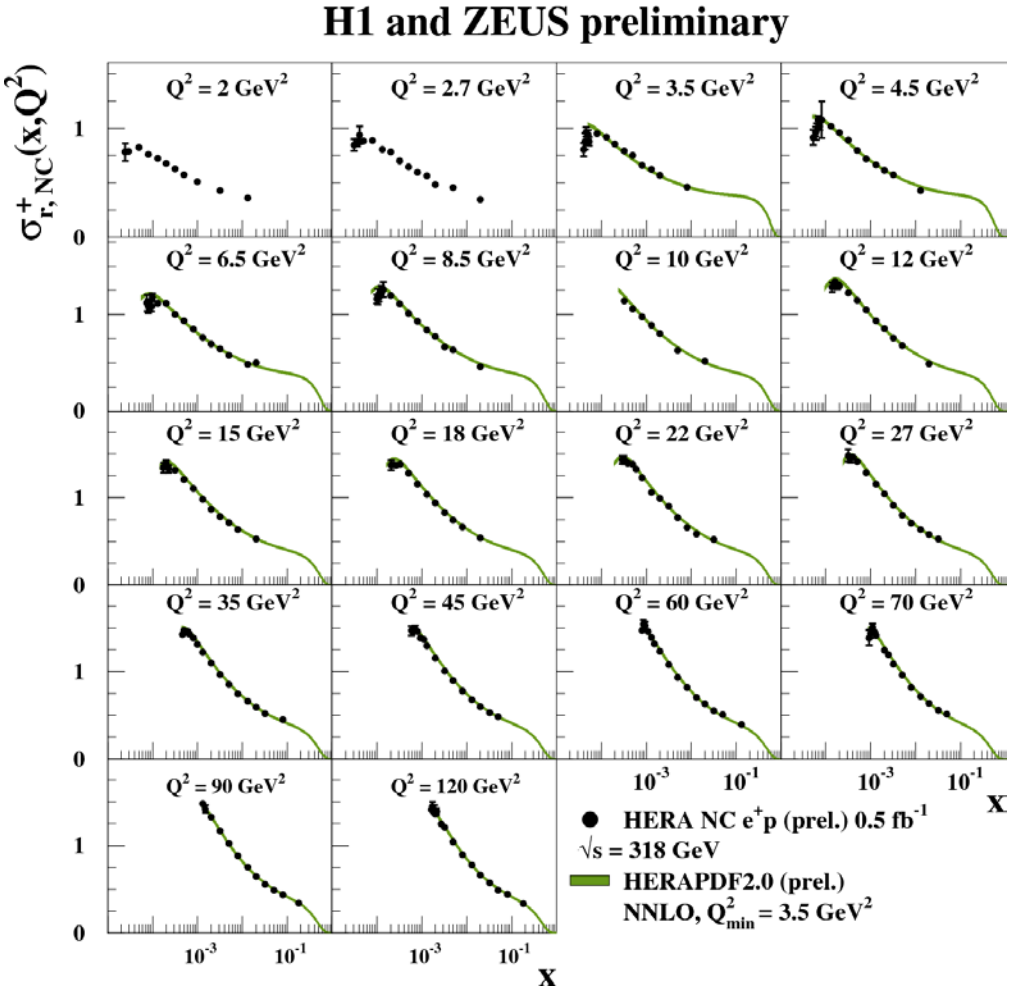


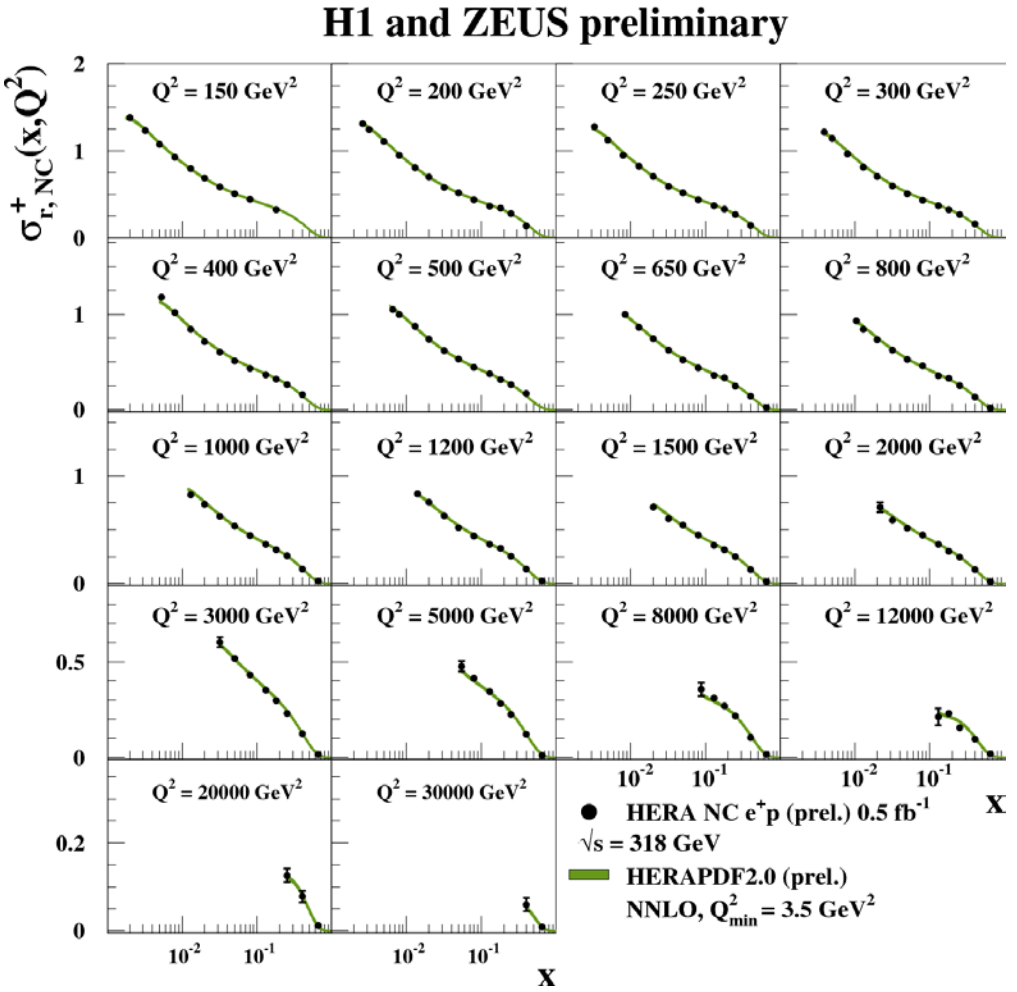


➔ See clear γz interference effects

Neutral Current: **perturbative** region $Q^2>2$ GeV^2

Other view on e+p data: as function of x for fixed values of Q^2

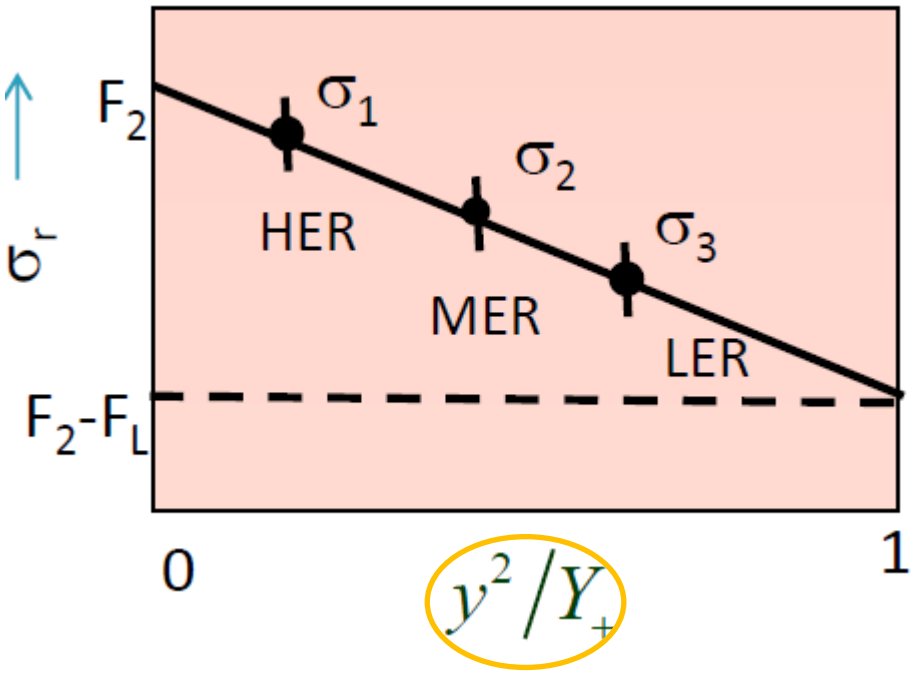




➔ ~map of $q+\bar{q}$ densities

HERA low **Ep** data and F_L

- Bulk of HERA data: Ep=920 GeV (HER)
- Ep=460 GeV (LER) and Ep=575 (MER) data taken in 2007

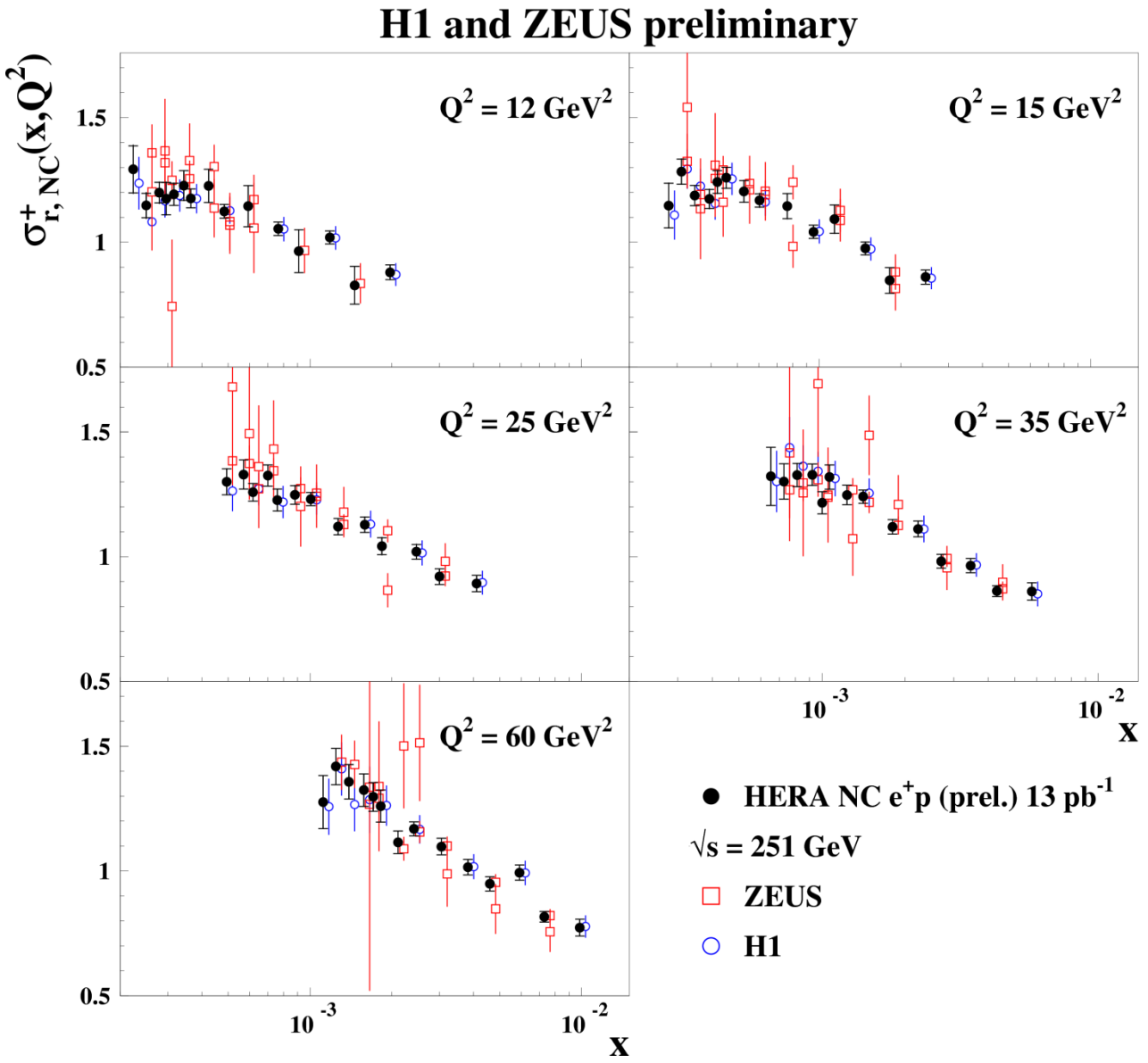


$$\sigma_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L$$

Straight line fit:
F_2 = Intercept
F_L = Negative slope

- Recently both H1 (EPJ C 74 (2014) 2814 EPJC C71 (2011) 1579) and ZEUS (DESY 14-053) published their final results on LER/MER data and on F_L, extending the Q^2 phasespace
- Cross section data were already combined,  see next slide

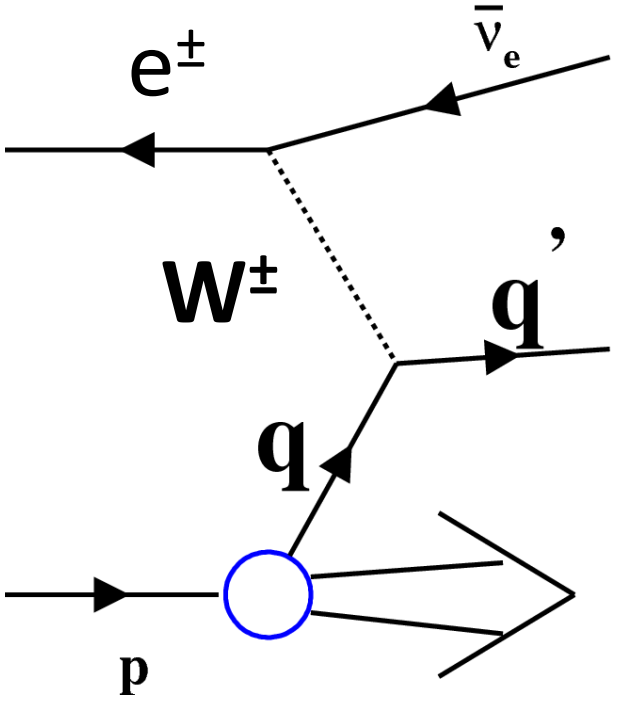
Neutral current: combination of Ep=460 GeV data



➔ Consistent data

Similar results for Ep = 575 GeV data

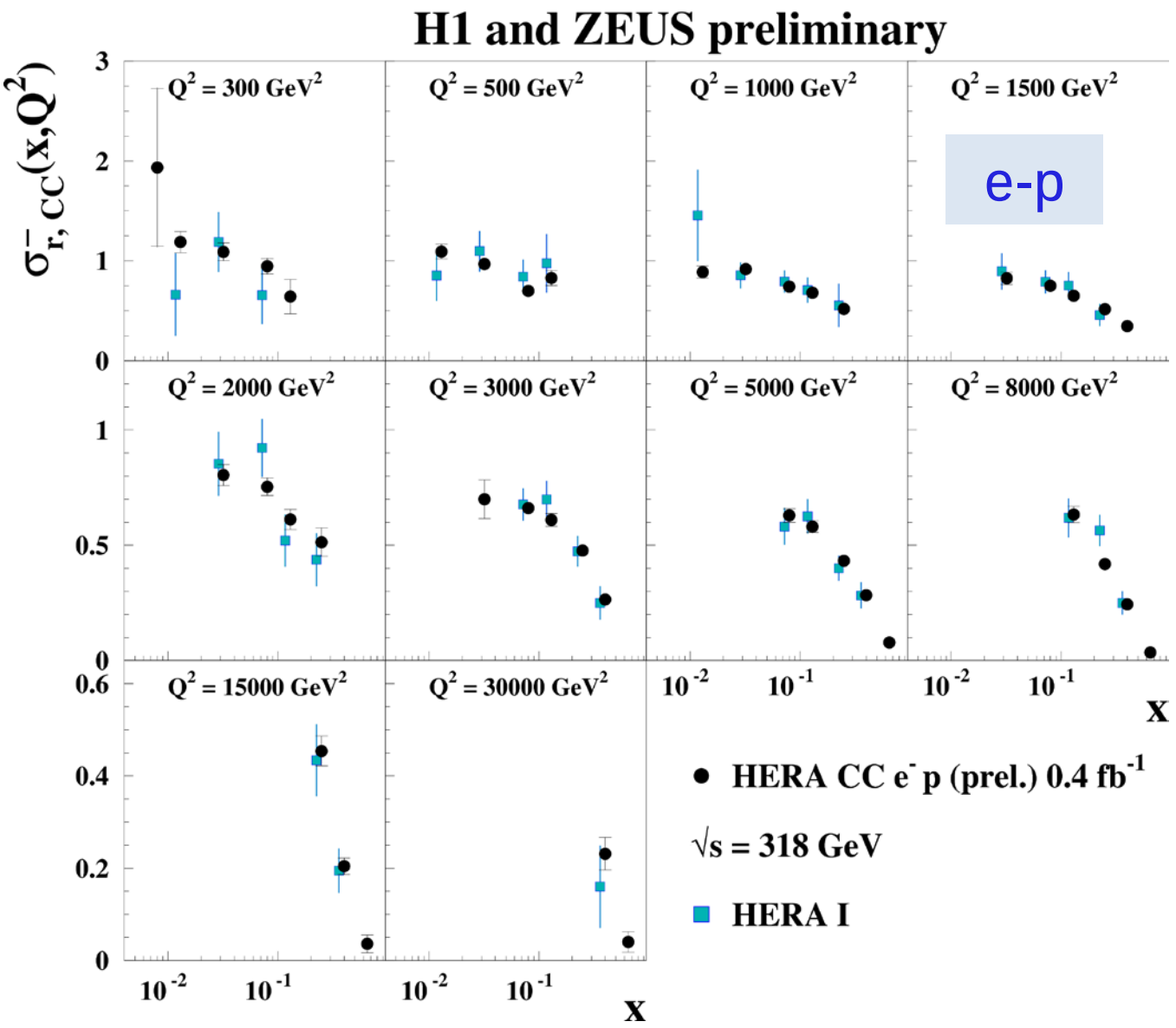
Results for Charged currents



- Combined are the reduced cross sections:

$$\sigma^{\pm}_{r,\mathrm{CC}} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{CC}}}{\mathrm{d}x\mathrm{d}Q^2}$$

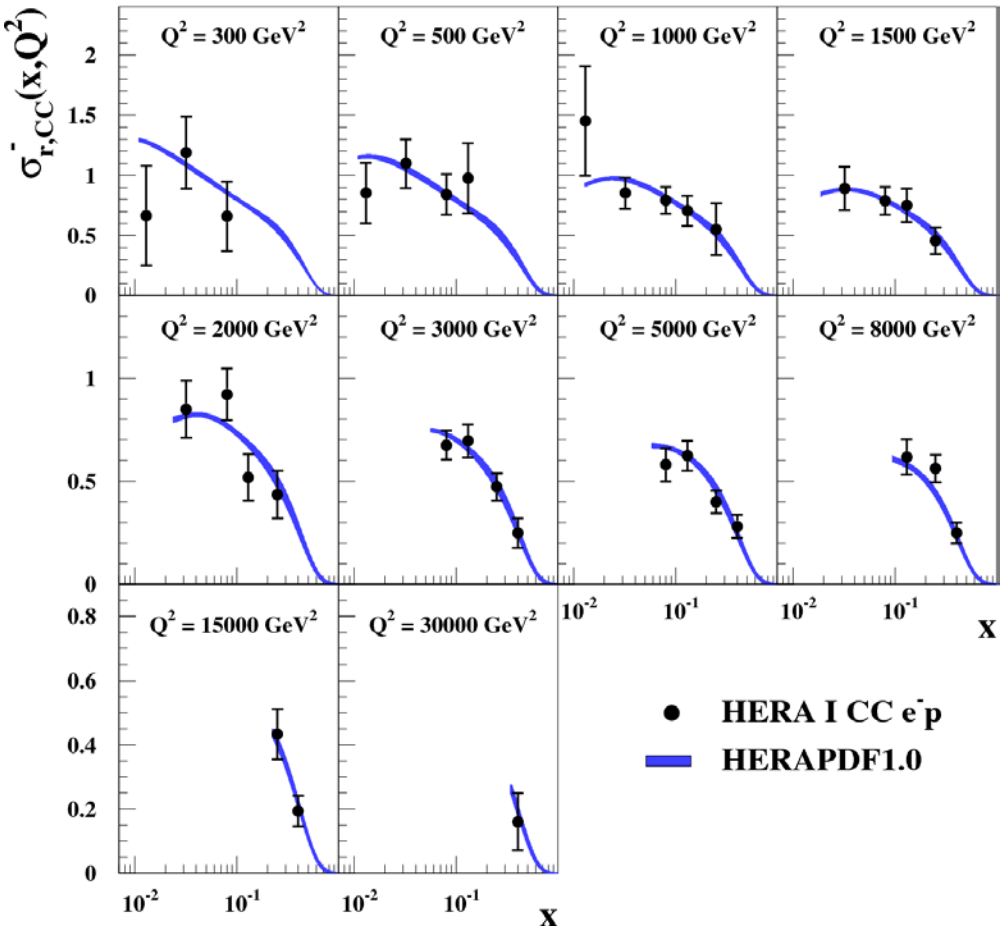
Charged Current: new combination vs HERA I



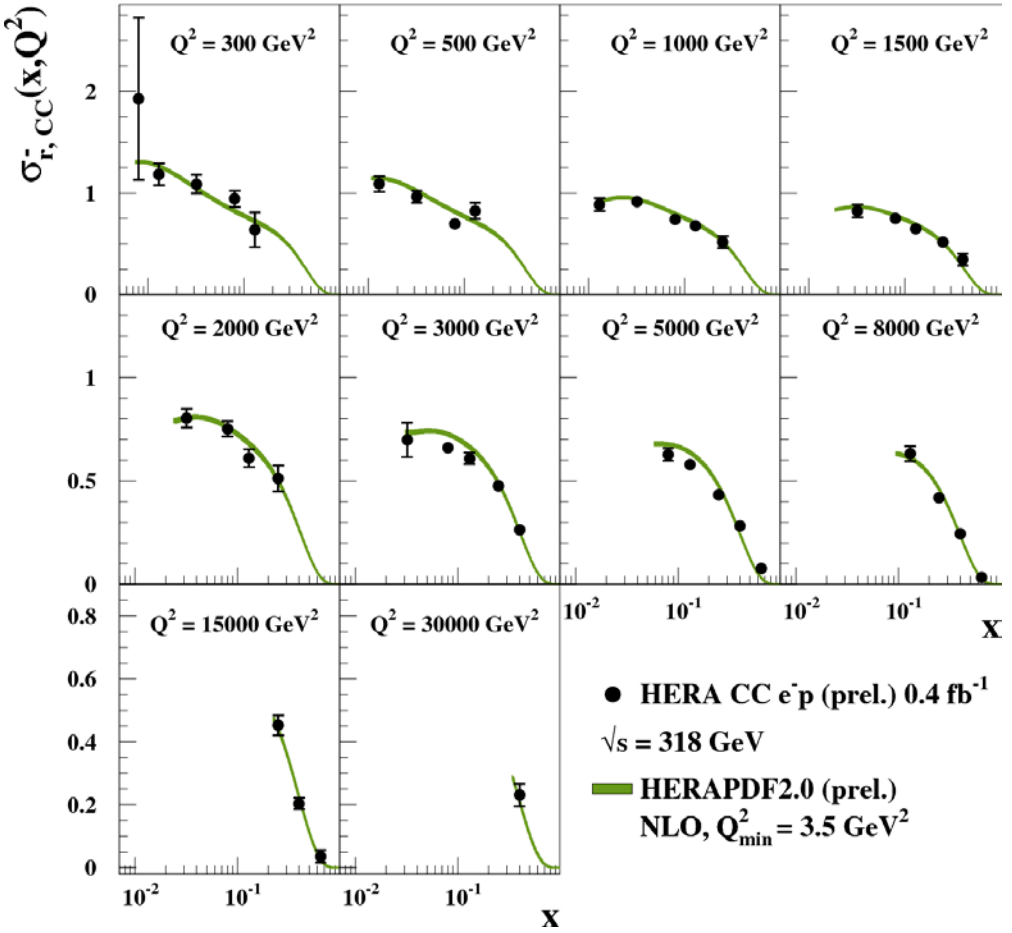
➔ Large error reductions

Charged Current: old and new combination

HERAPDF1.0 = **HERA I**

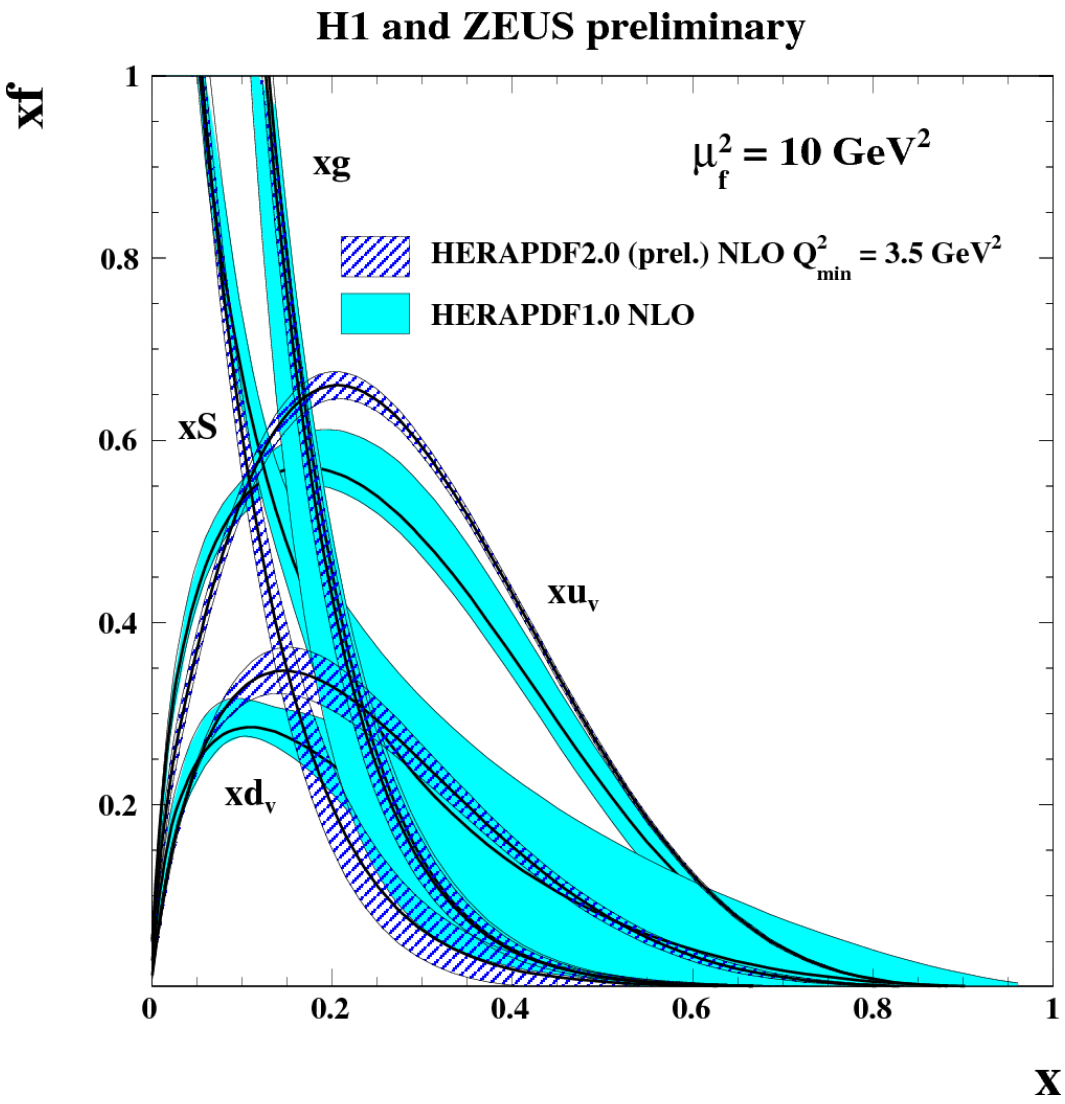


HERAPDF2.0 = **ALL IN**



➔ much improved precision and *new* data points

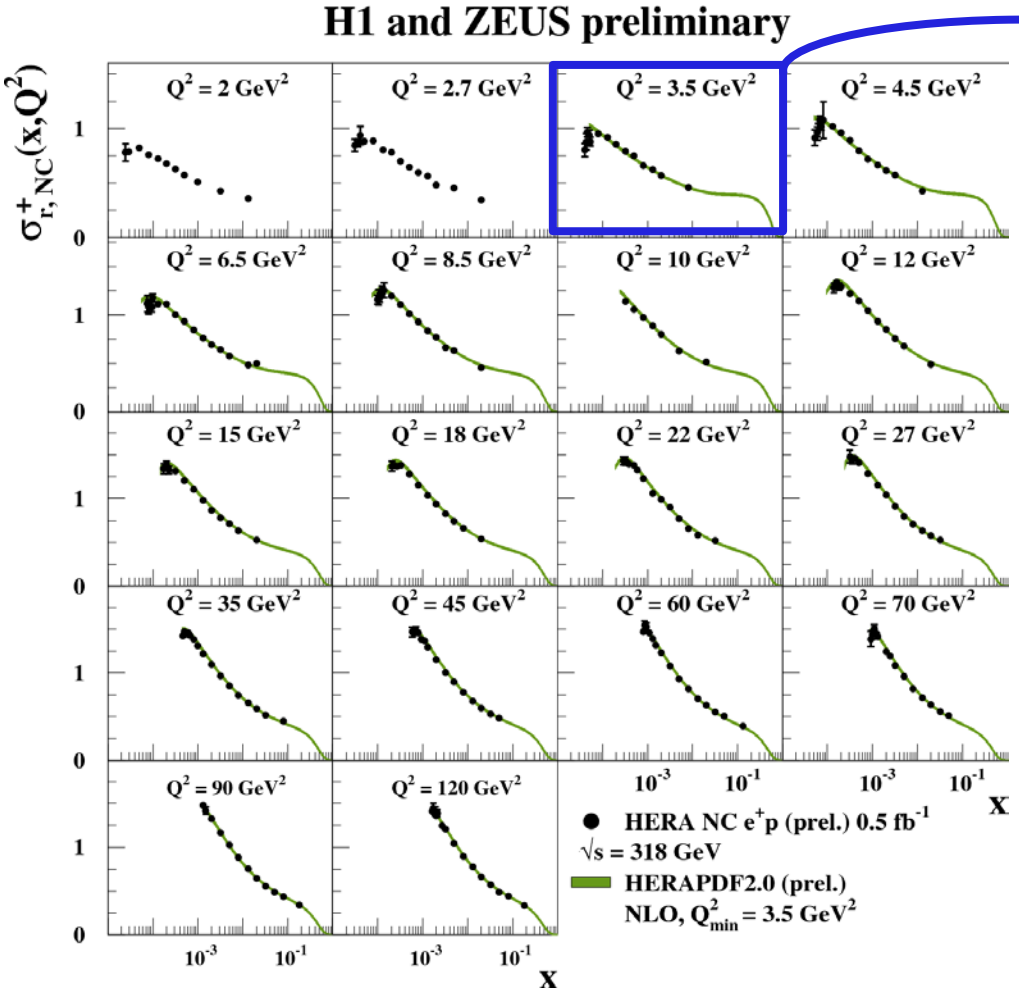
HERAPDF1.0 and 2.0 *at NLO* with Q^2_{min}=3.5 GeV^2

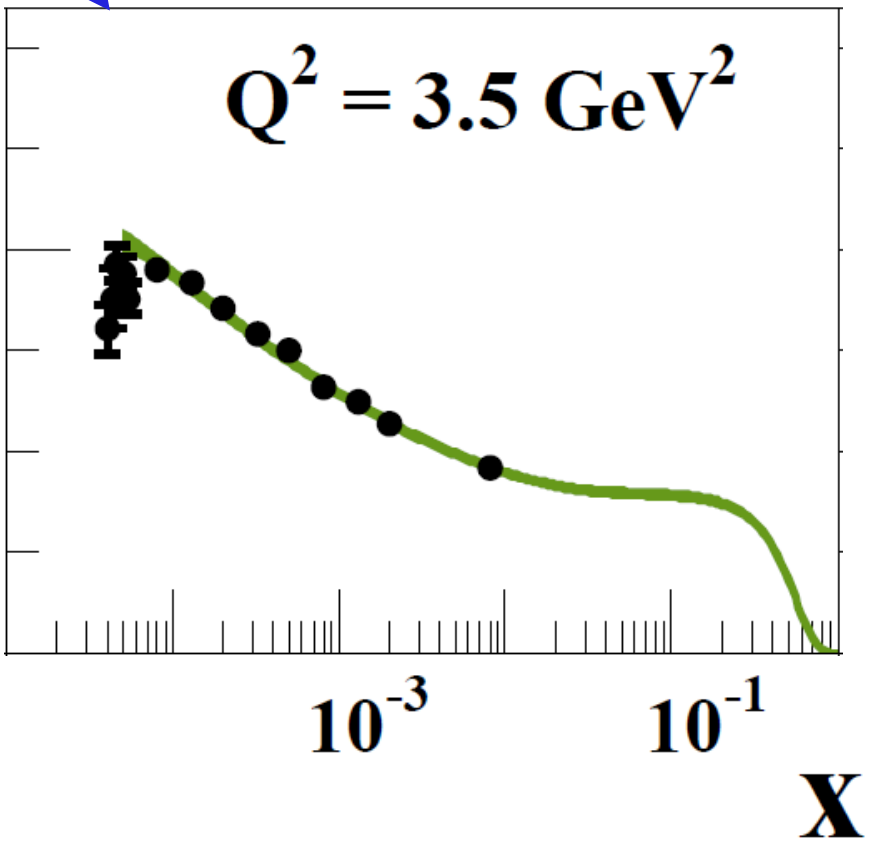


Linear x scale

➔ HERAPDF2.0: softer sea & overall reduced uncertainties

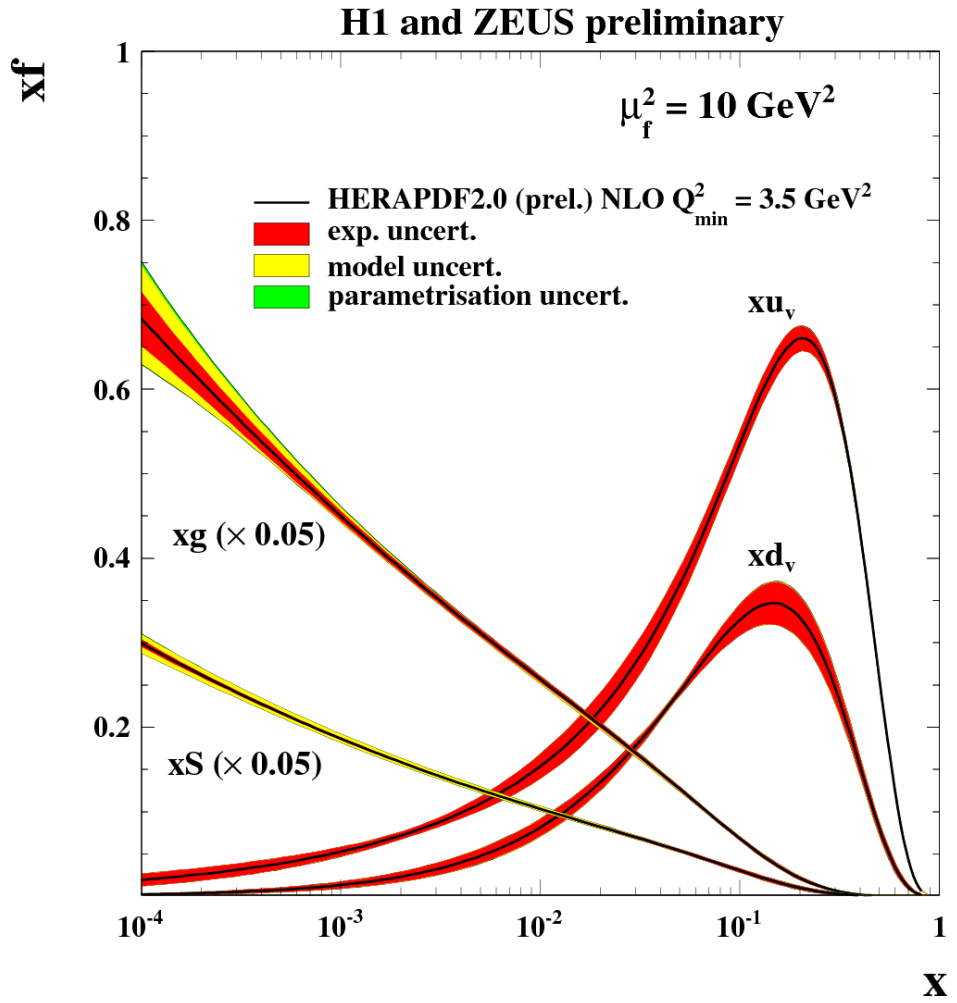
e+p Neutral Current data vs HERAPDF2.0 NLO

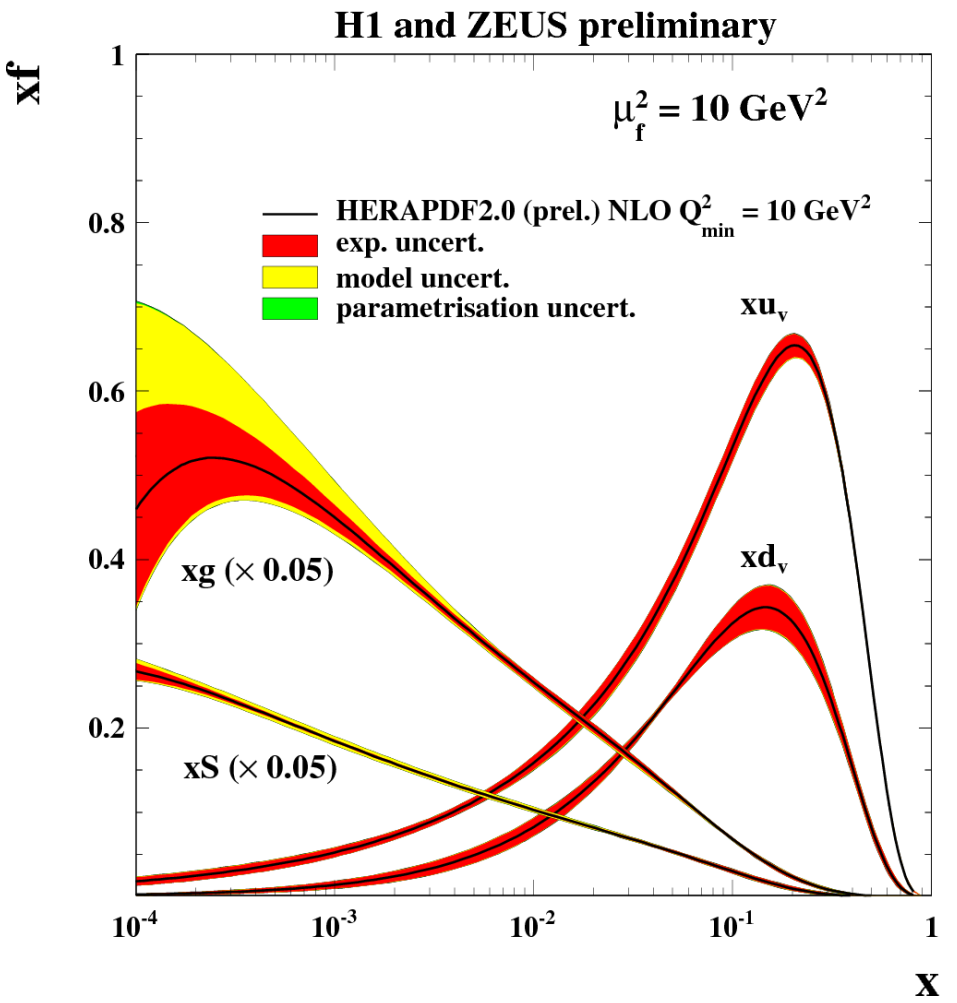




➔ in general good description by fit (for all fitted data sets!)
➔ At low Q^2<10 GeV^2 description gets (here) a bit worse
➔ Very similar picture at NNLO

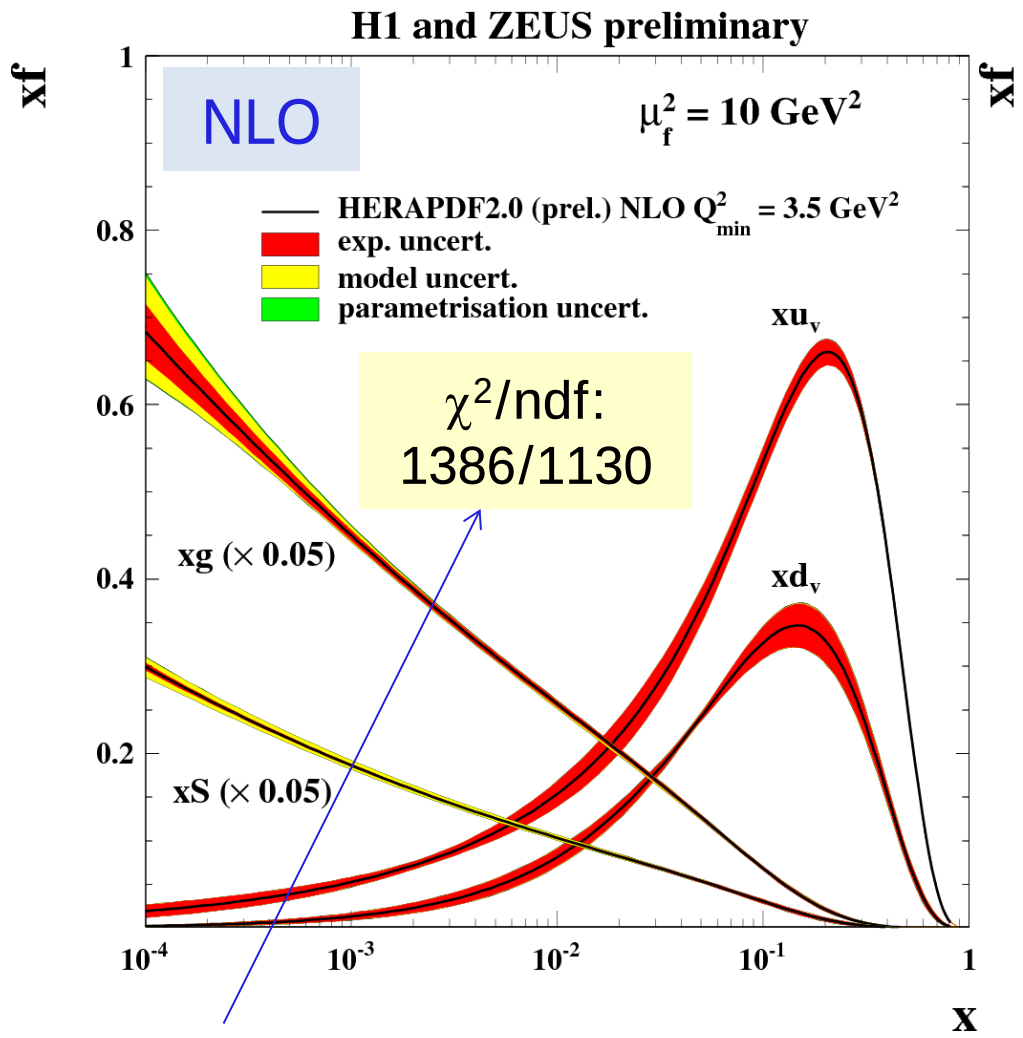
Comparison of PDFs with Q^2_{min} = 3.5 and 10 GeV^2

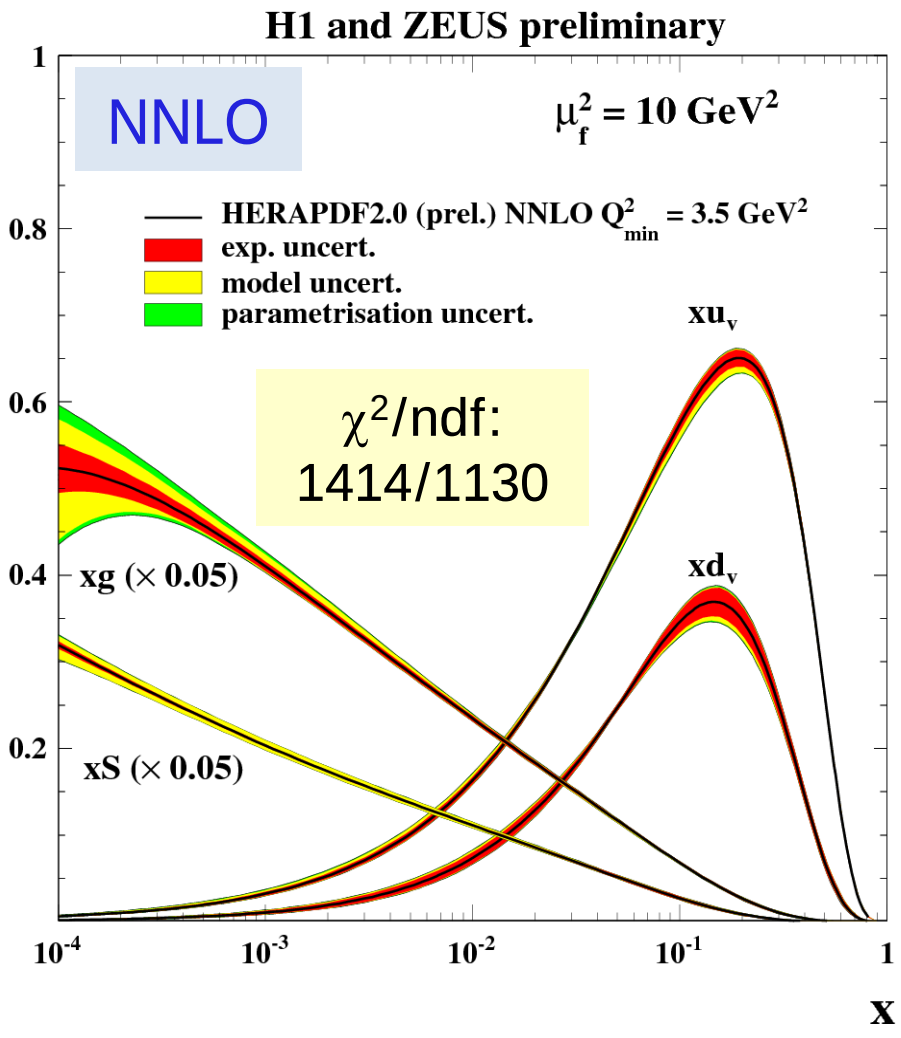




➔ Q^2_{min}=10 GeV^2 cut: ⇒ increases uncertainty of low-x gluon
⇒ leaves high-x region ~unaffected

HERAPDF2.0 NLO and NNLO *variants*

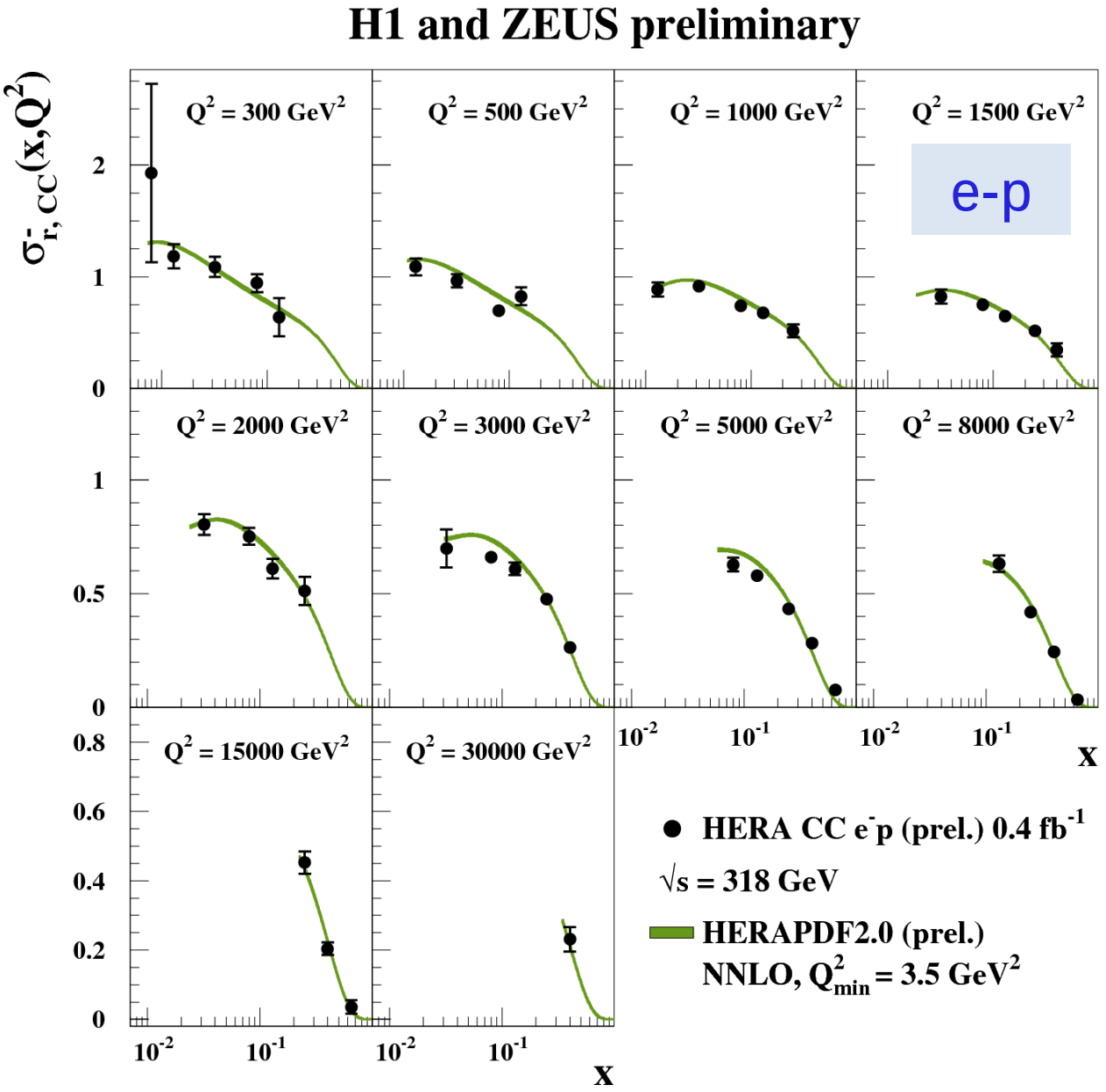




χ^2/ndf for describing the fitted HERA data

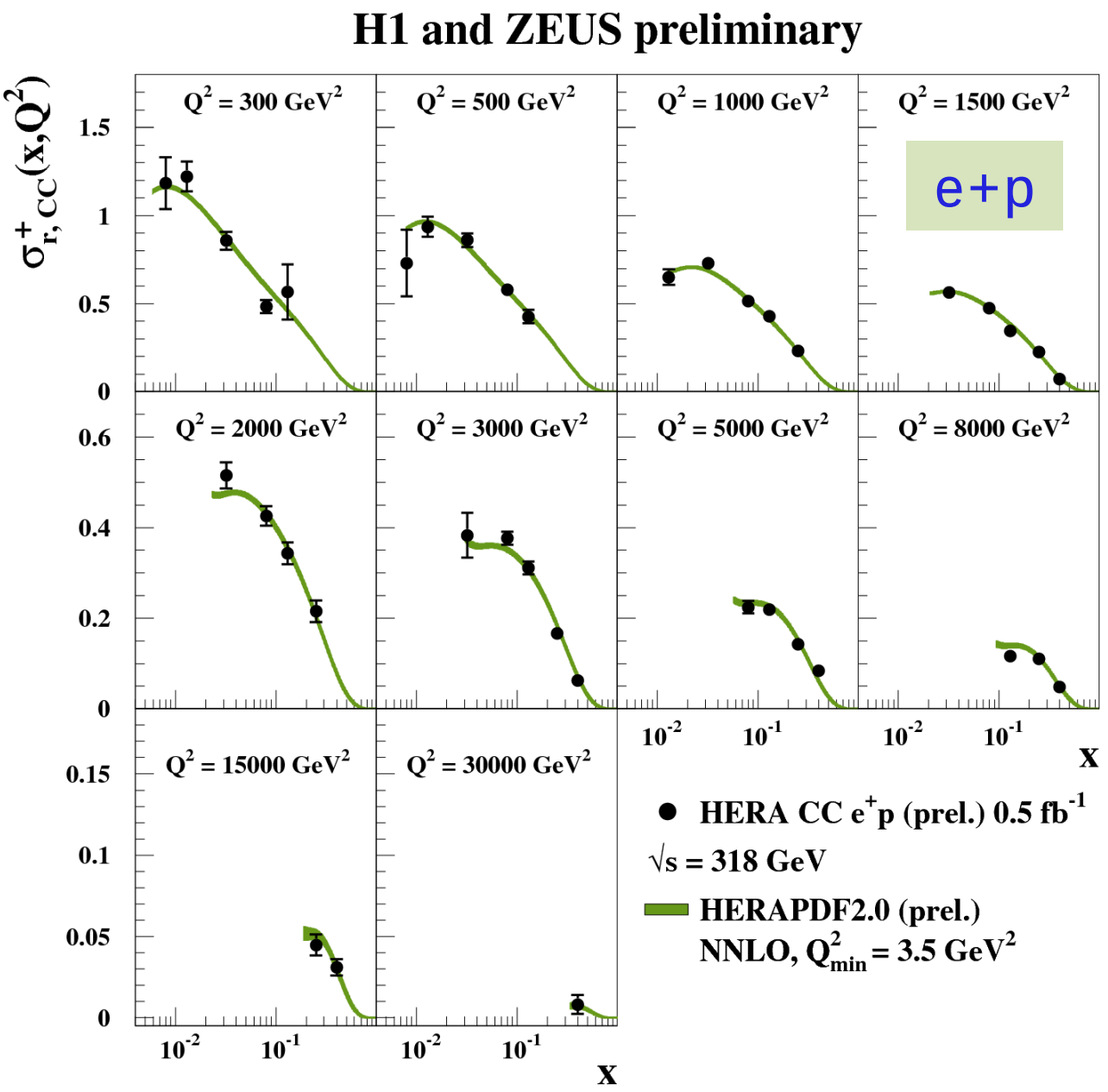
➔ Similar fit quality at NLO and NNLO

Charged Current: combined results vs HERAPDF2.0 NNLO



➔ Nice description

Charged Current: combined results vs HERAPDF2.0 NNLO



➔ Nice description