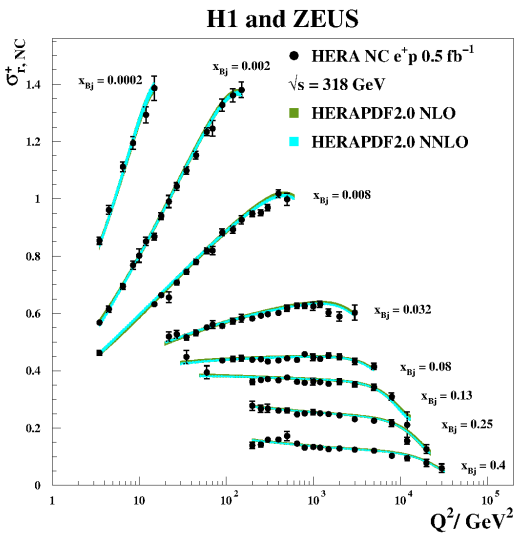
PDF and α_s measurements at HERA

XII Quark Confinement and the Hadron Spectrum

from 29 August 2016 to 3 September 2016
Europe/Athens timezone



HCHS2016
Thessaloniki, Greece

Stefan Schmitt, DESY
For the HERA collaborations
H1 and ZEUS

Outline

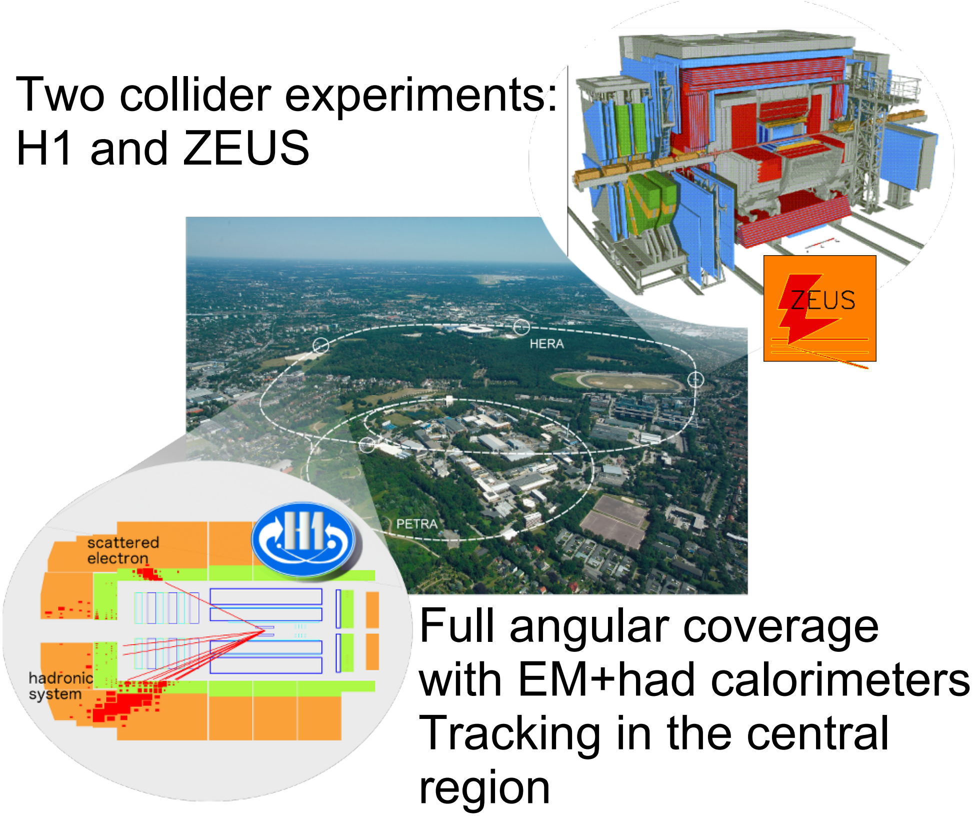
- The HERA collider
- Deep-inelastic scattering
- Data combination
- The combined HERA data
- The HERAPDF2.0 fit
- Jet production and α_s

The HERA collider

- World's only ep collider 1992-2007
- 920 x 27.6 GeV ($\sqrt{s}$=320 GeV)
- Two collider experiments, H1 and ZEUS
- Integrated Luminosity:

  ~2×0.5 fb^{-1}
- $e^{+}p$ and $e^{-}p$ data

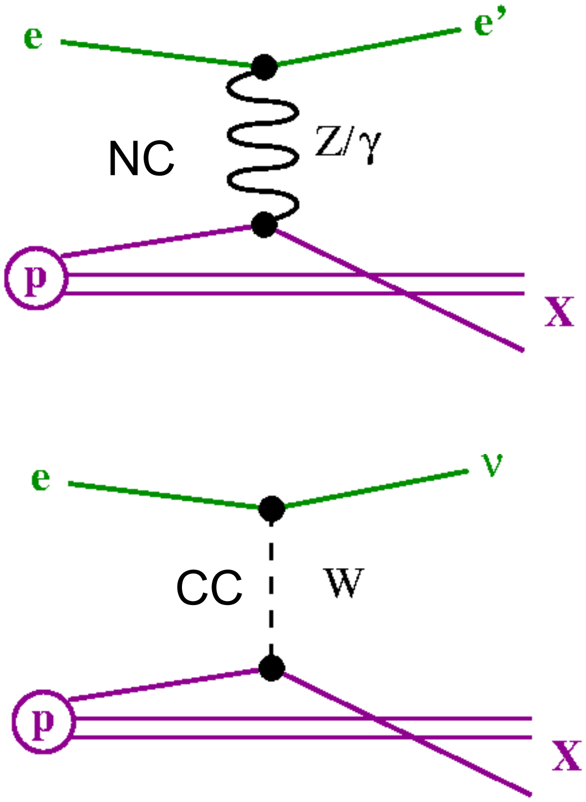
Two collider experiments: H1 and ZEUS



Full angular coverage with EM+had calorimeters
Tracking in the central region

Deep-inelastic scattering

- Inclusive processes
  - Neutral current (NC)
  - Charged current (CC)
- Momentum transfer Q^2
- Inelasticity y
- Bjorken-x



exchanged 4-momentum:

$$q = e - e' = X - p$$

Kinematic variables

$$Q^2 = -q^2$$

$$y = \frac{p\,q}{p\,e}$$

$$x = \frac{Q^2}{sy}$$

Deep-inelastic scattering

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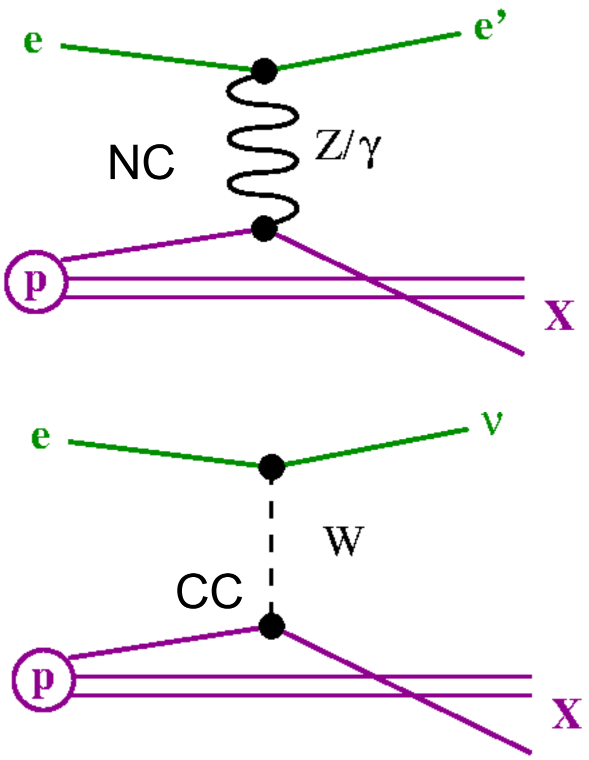


"Reduced" cross section: Double-differential cross section divided by couplings and kinematic factors
→ structure functions

NC reduced cross section

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

CC reduced cross section

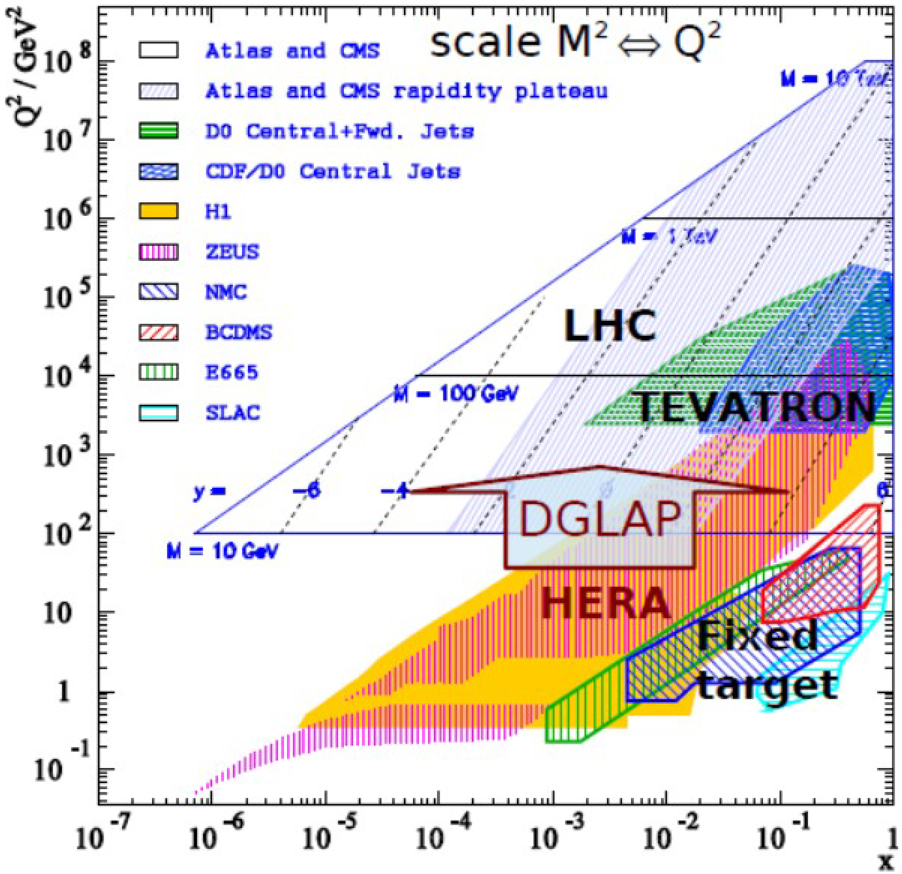
$$\sigma^{\pm}_{r,WC} = Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm} - y^2 W_L^{\pm}$$

helicity factors

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

Parton densities

- Structure functions are related to parton densities
- The precision measurements from HERA are the backbone of proton parton density determinations
- Parton densities are essential for predictions at hadron colliders



HERA datasets collected over 15 years

- Two experiments H1 and ZEUS
- 41 datasets with over 2900 individual cross section measurements
- Measurements in e^-p, e^+p; NC, CC; low and high Q^2
- Four centre-of-mass energies: 225, 251, 300, 318 GeV

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	Ref.
HERA I E_p = 820 GeV and E_p = 920 GeV data sets										
H1 svx-mb [2]	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319	13,17,18	[3]
H1 low Q^2 [2]	96-00	0.0002	0.1	12	150	22	e^+p	301, 319	13,17,18	[4]
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	19	[5]
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	14	[5]
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	19	[6]
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	14	[6]
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	13	[7]
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319	19	[7]
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	14	[7]
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300	13	[11]
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300	13, 19	[12]
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300	13	[13]
ZEUS NC [2] high/low Q^2	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300	21	[14]
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300	14	[15]
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318	20	[16]
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318	14	[17]
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318	20	[18]
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318	14	[19]
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	[8][1]
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	15000	182	e^+p	319	14	[8][1]
H1 NC $^{1.5p}$	03-07	0.0008	0.65	60	50000	151.7	e^-p	319	13, 19	[8][1]
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	30000	151.7	e^-p	319	14	[8][1]
H1 NC med Q^2 $^{*y.5}$	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319	13	[10]
H1 NC low Q^2 $^{*y.5}$	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319	13	[10]
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318	13,14,20	[22]
ZEUS CC $^{1.5p}$	06-07	0.0078	0.42	280	30000	132	e^+p	318	14	[23]
ZEUS NC $^{1.5}$	05-06	0.005	0.65	200	30000	169.9	e^-p	318	20	[20]
ZEUS CC $^{1.5}$	04-06	0.015	0.65	280	30000	175	e^-p	318	14	[21]
ZEUS NC nominal ^{*y}	06-07	0.000092	0.008343	7	110	44.5	e^+p	318	13	[24]
ZEUS NC satellite ^{*y}	06-07	0.000071	0.008343	5	110	44.5	e^+p	318	13	[24]
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	[9]
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252	13	[10]
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251	13	[24]
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251	13	[24]
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	[9]
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225	13	[10]
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225	13	[24]
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225	13	[24]

Data combination

- The 2927 measurements are averaged to about 1307 combined cross sections
- Point-to-point correlated systematic uncertainties

  → “cross-calibration” effects
- Up to 6 measurements contribute to a single point

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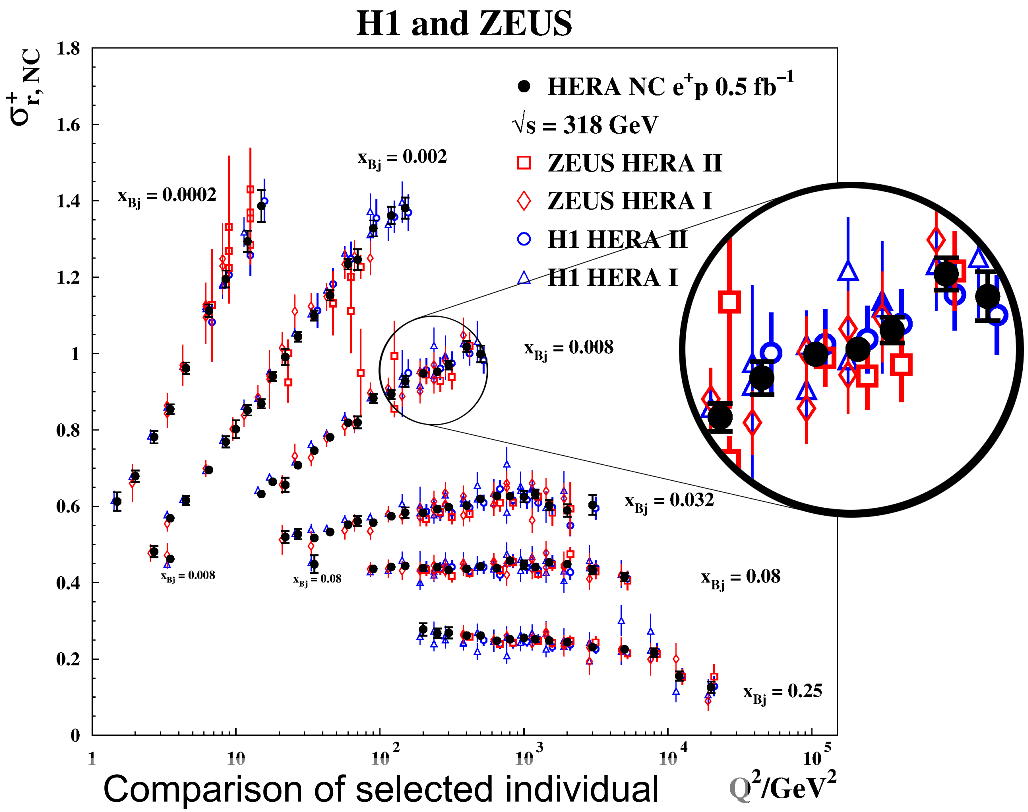

Comparison of selected individual measutements and their combination

Data combination

- The 2927 measurements are averaged to about 1307 combined cross sections
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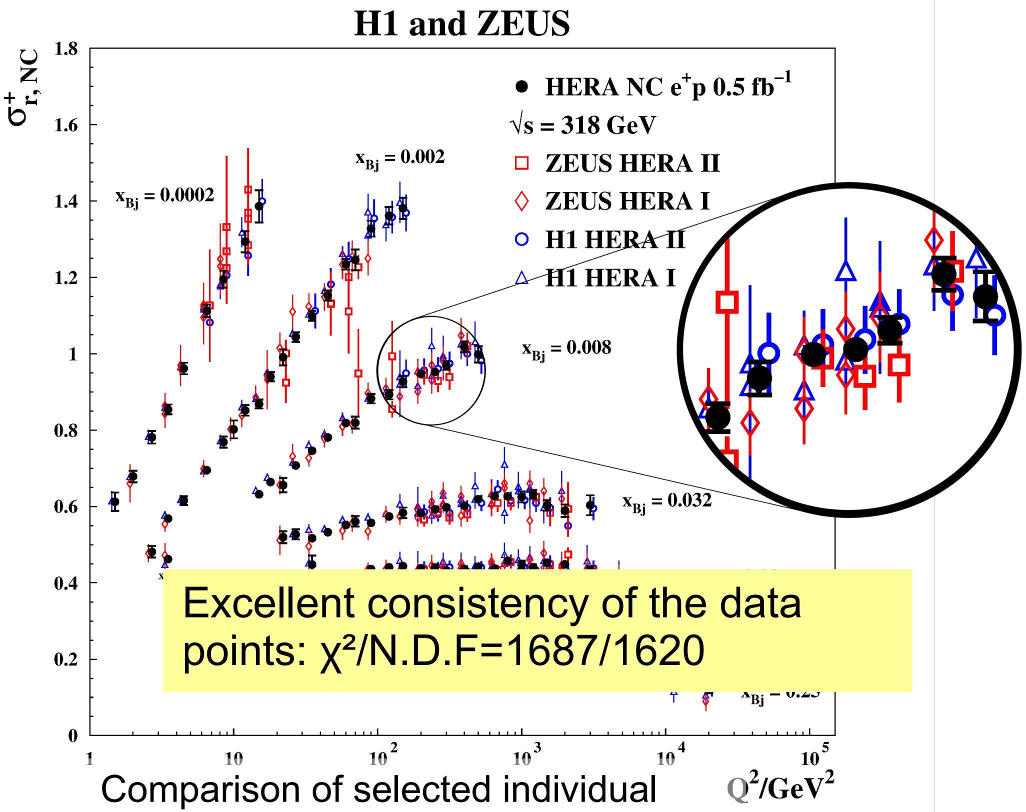
EPJ C75 (2015) 12, 85



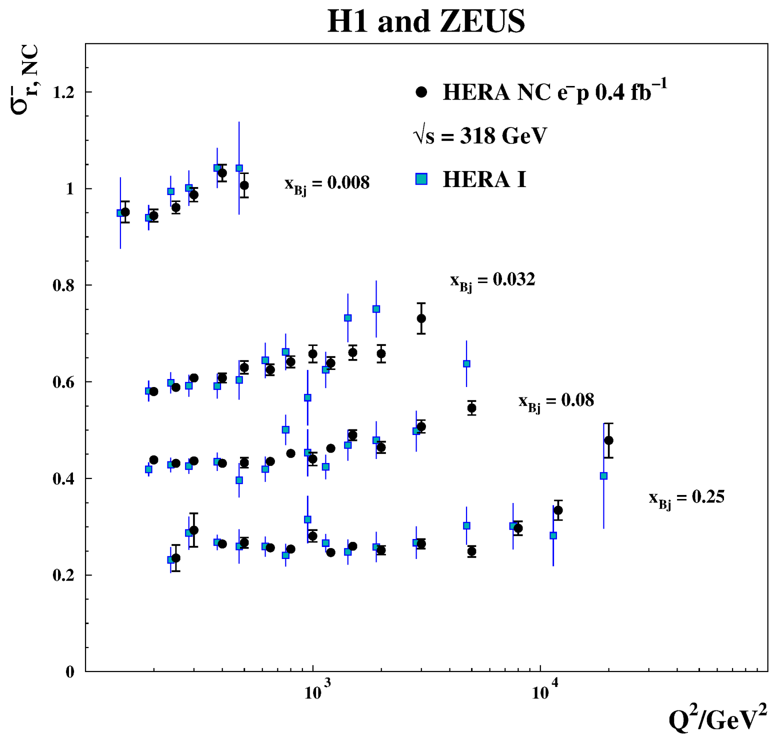
Excellent consistency of the data points: χ^2/N.D.F=1687/1620

Comparison of selected individual measutements and their combination

Combined Neutral Current dataset

- Four e^+p datasets at different centre-of-mass energies
- One e^-p dataset
- Main improvements wrt HERA-I data:
  - Reach to lower sqrt(s)
  - Much improved e^-p dataset
  - Precision <1.5% over a wide range

	Q² [GeV²]	x
e+p, sqrt(s)=225 GeV	1.5 .. 800	0.348×10^{-4} .. 0.65
e+p, sqrt(s)=251 GeV	1.5 .. 800	0.279×10^{-4} .. 0.65
e+p, sqrt(s)=300 GeV	0.045 .. 30000	0.621×10^{-6} .. 0.4
e+p, sqrt(s)=318 GeV	0.15 .. 30000	0.502×10^{-5} .. 0.65
e–p, sqrt(s)=318 GeV	60 .. 50000	0.8×10^{-3} .. 0.65

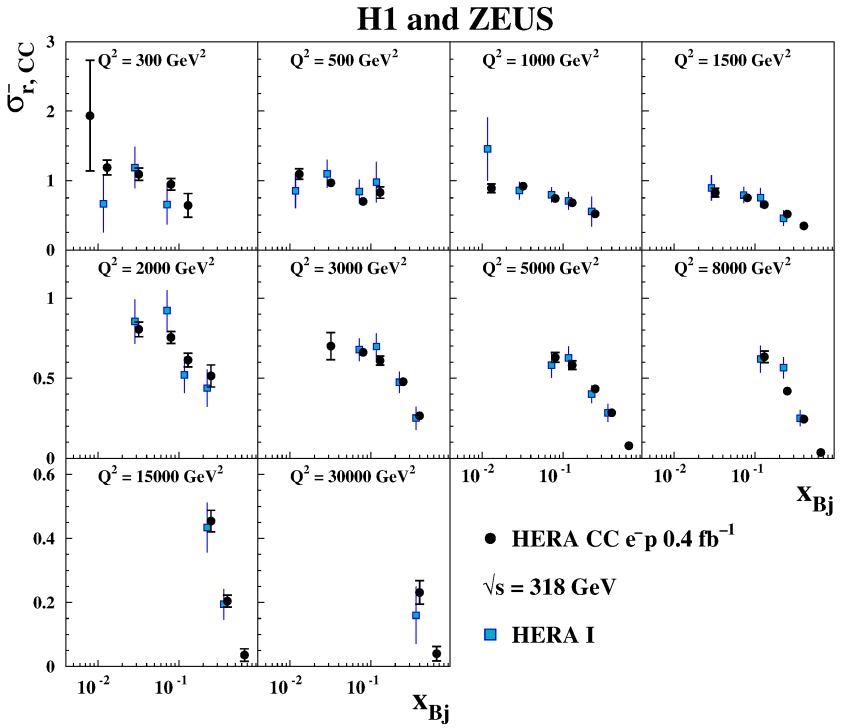


e^-p (NC): selected x, compare HERA-I with new combination

Combined Charged Current dataset

- Two dataset: e^+p and e^-p
- Much improved precision, as compared to HERA-I combination
- Most striking improvement: e^-p (luminosity increase ×15)

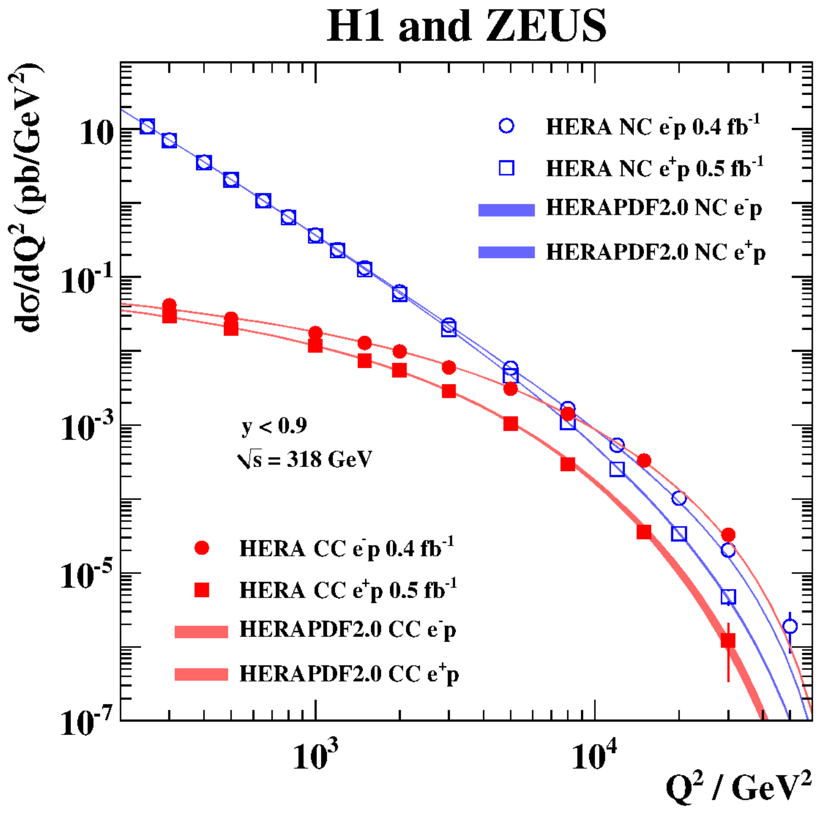
	Q² [GeV²]	x
e+p, sqrt(s)=318 GeV	300 .. 30000	0.8×10^{-2} .. 0.4
e–p, sqrt(s)=318 GeV	300 .. 30000	0.8×10^{-2} .. 0.4



e^-p (CC): compare HERA-I with new combination

Electroweak unification at high Q^2

- Single-differential cross sections: integrated over $y<0.9$
- At high $Q^2 \sim m_W^2$: NC and CC cross sections are similar in size, visualizes electroweak unification
- Low Q^2 NC: photon propagator $\sim 1/Q^4$
- High Q^2 NC: difference e^+p and e^-p due to γ/Z interference



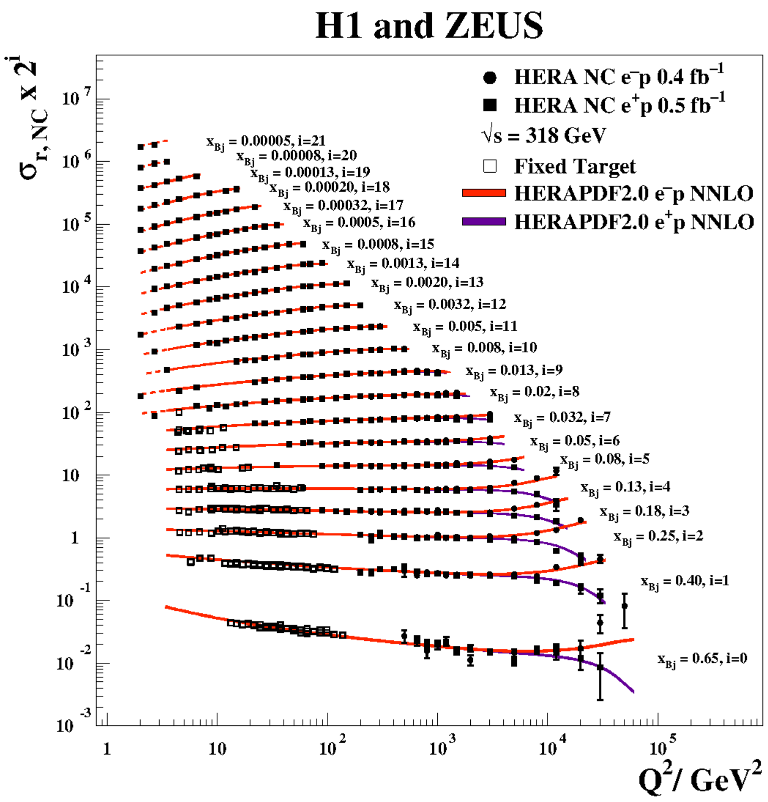
Scaling violations and DGLAP

- Measurements over a wide range in Q² and x: precision measurement of scaling violations
  - cross section rises with Q² at low x but drops at high x
- Electroweak effects (structure function xF_3) visible at high Q²

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

helicity factors

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



HERAPDF fits based on DGLAP

- Parametrize parton densities at starting scale Q_0
- Evolve PDFs to other scales using DGLAP equations
- Three types of uncertainties
  - Experimental
  - Parametrization
  - Model

HERAPDF parametrization:

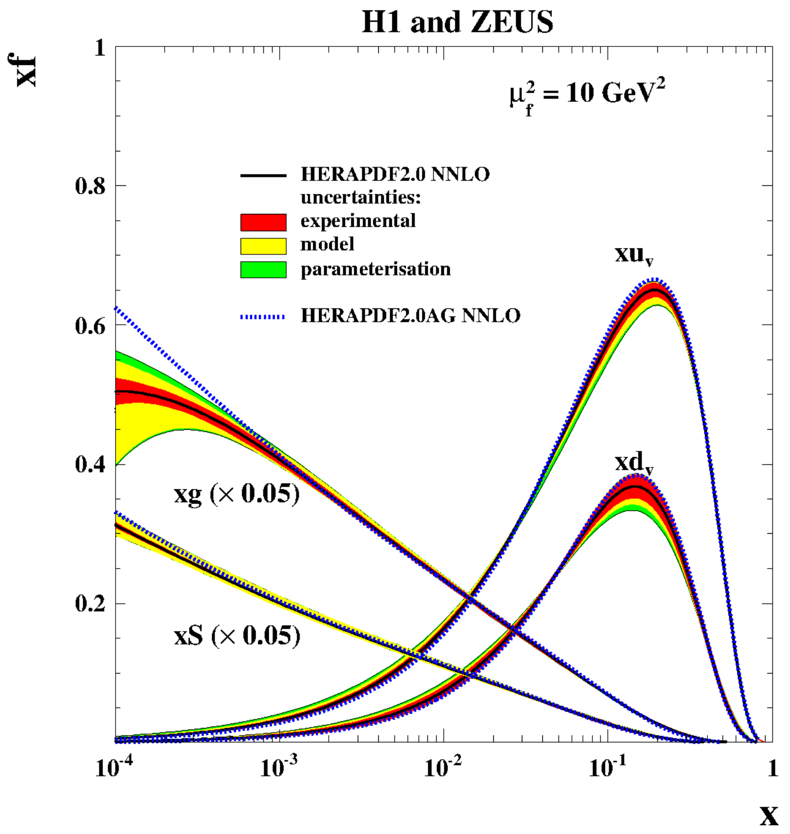
$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right), \\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

Parametrization uncertainties: vary Q_0, change number of parameters

Model uncertainties: heavy quark masses, strangeness fraction, etc

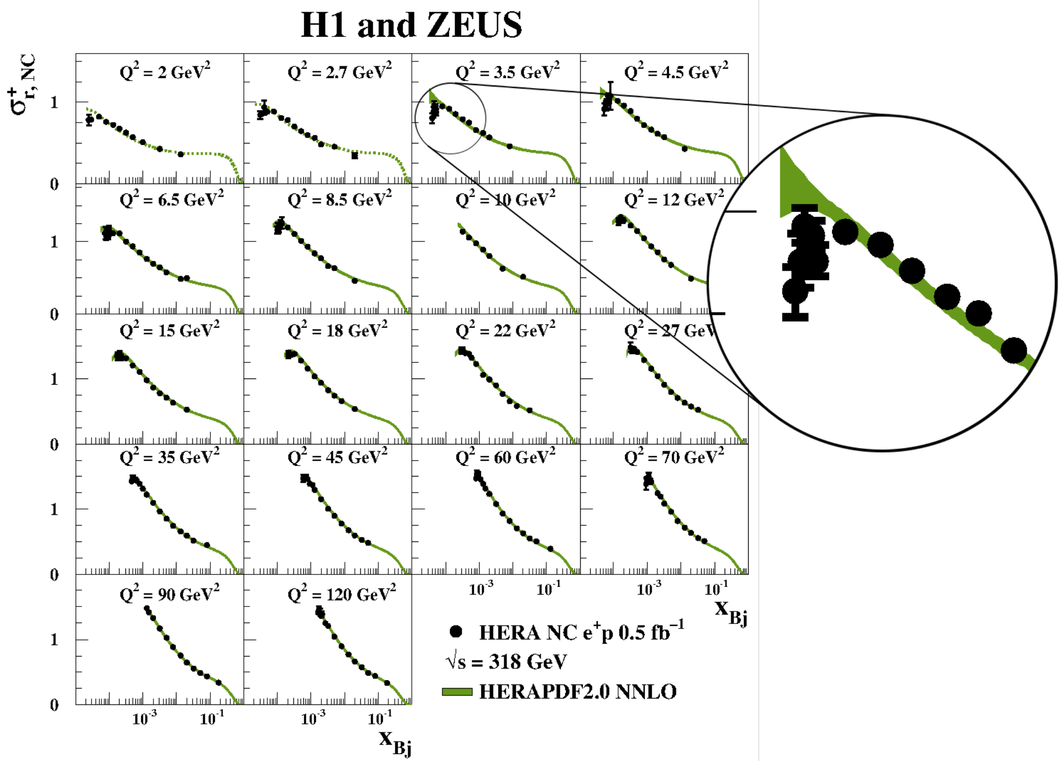
HERAPDF2.0

- HERAPDF2.0 PDFs: family of fits based on HERA data alone, at NLO and NNLO
- All fit variants are available in the LHAPDF library
- Shown here:
  - Default NNLO fit with uncertainty bands: “HERAPDF2.0 NNLO”
  - Variant with non-negative gluon “HERAPDF2.0AG NNLO”



HERAPDF2.0

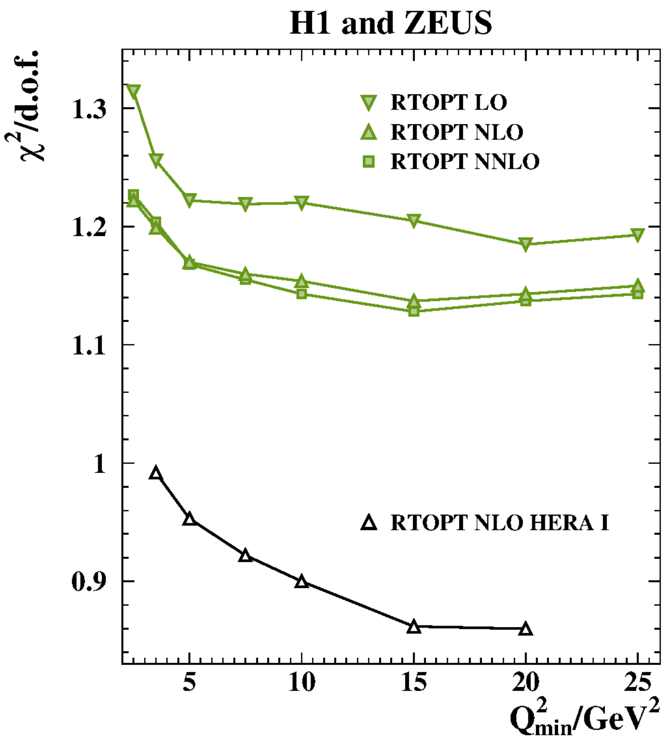
- HERAPDF2.0 PDFs: family of fits based on HERA data alone, at NLO and NNLO
- Overall good description of the data down to low Q²
- Some deviations in the region of low x at low Q²



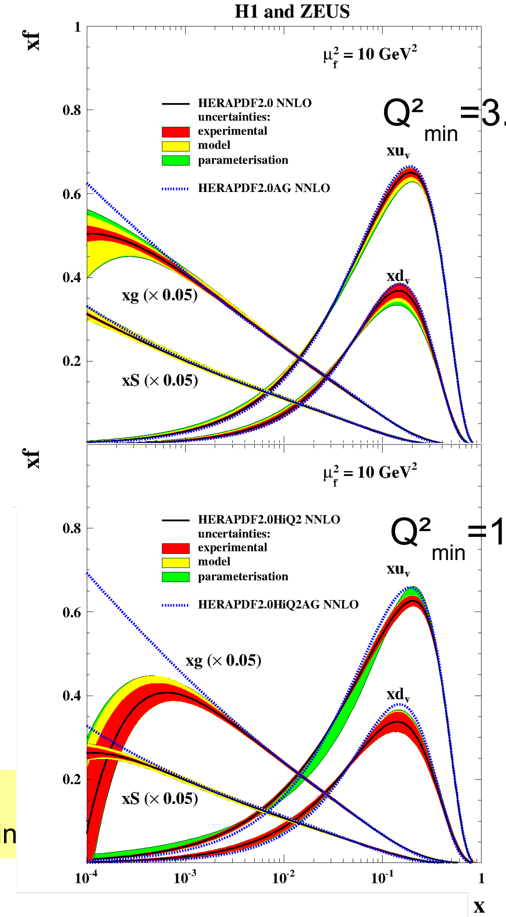
Dependence on Q^2_{min}

- Test theory against data using selection $Q^2 > Q^2_{min}$
- Fit quality and low-x gluon shape changes as Q^2_{min} is varied from 3.5−10 GeV²

  → something going on beyond DGLAP at low-x and/or low Q²?



Fit χ²/NDF changes with Q^2_{min}



Q^2_{min}=3.5 GeV²

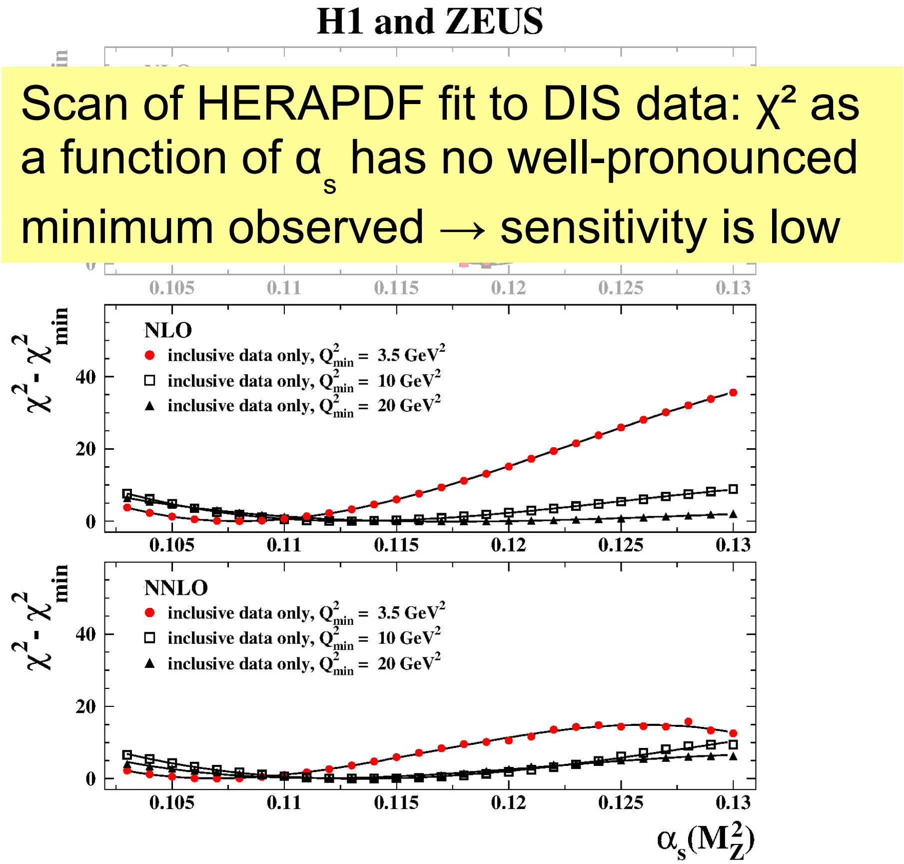
Q^2_{min}=10 GeV²

Sensitivity to the strong coupling

- Inclusive DIS data alone have only moderate sensitivity to α_s

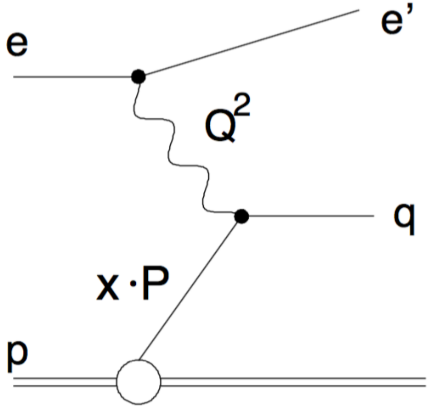
  Reason: normalization of gluon density and α_s are strongly correlated

- → include data on jet production in DIS

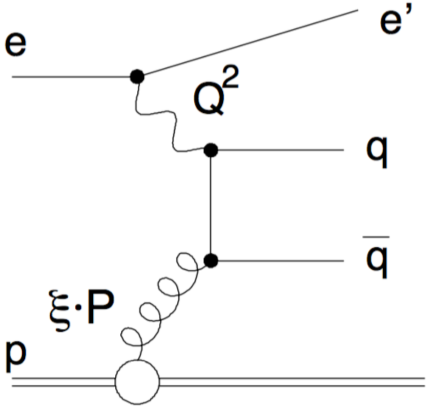


Jet production in DIS

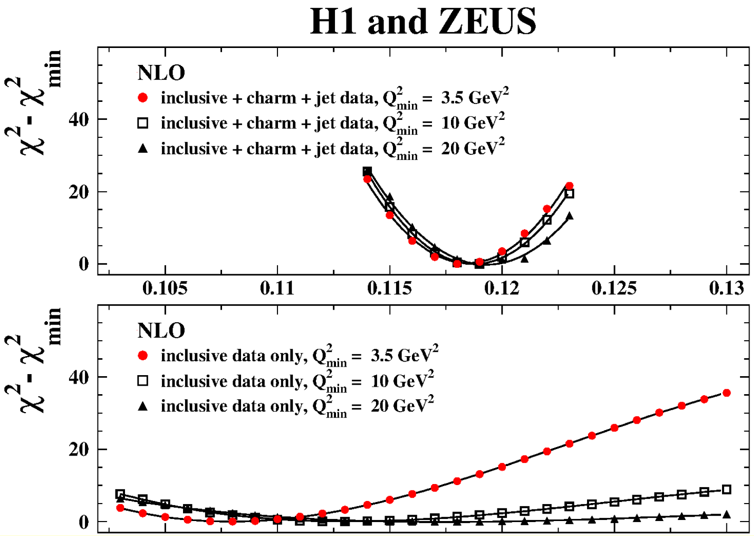
- Jet production is measured in Breit frame → jet production is directly sensitive to α_s



QPM event → no P_T in Breit frame → no jet



$O(\alpha_s)$ → two jets in Breit frame



Very good sensitivity to α_s when including jet data – but jet calculations are done at NLO only*

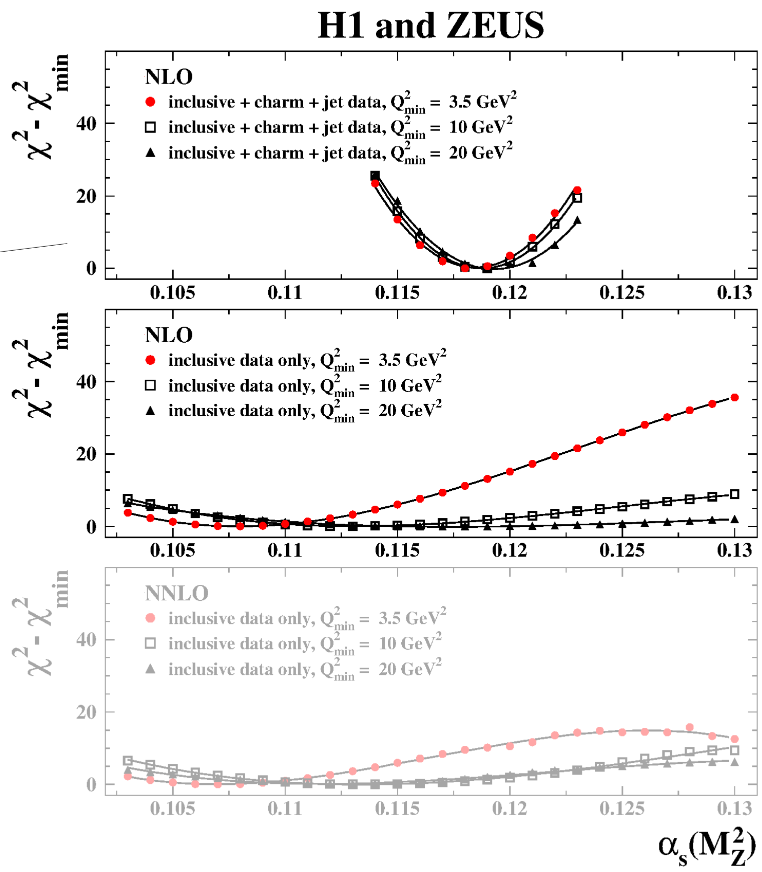
* recent NNLO calculations by Gehrmann et al. from 2016

Determination of α_s from DIS jets at NLO

- Combined fit of PDF and α_s at NLO

$$\alpha_s(m_Z) = 0.1183 \pm 0.0009\,(\text{exp}) \pm 0.0005\,(\text{model/param}) \pm 0.0012\,(\text{hadr}) {}^{+0.0037}_{-0.0030}\,(\text{scale})$$

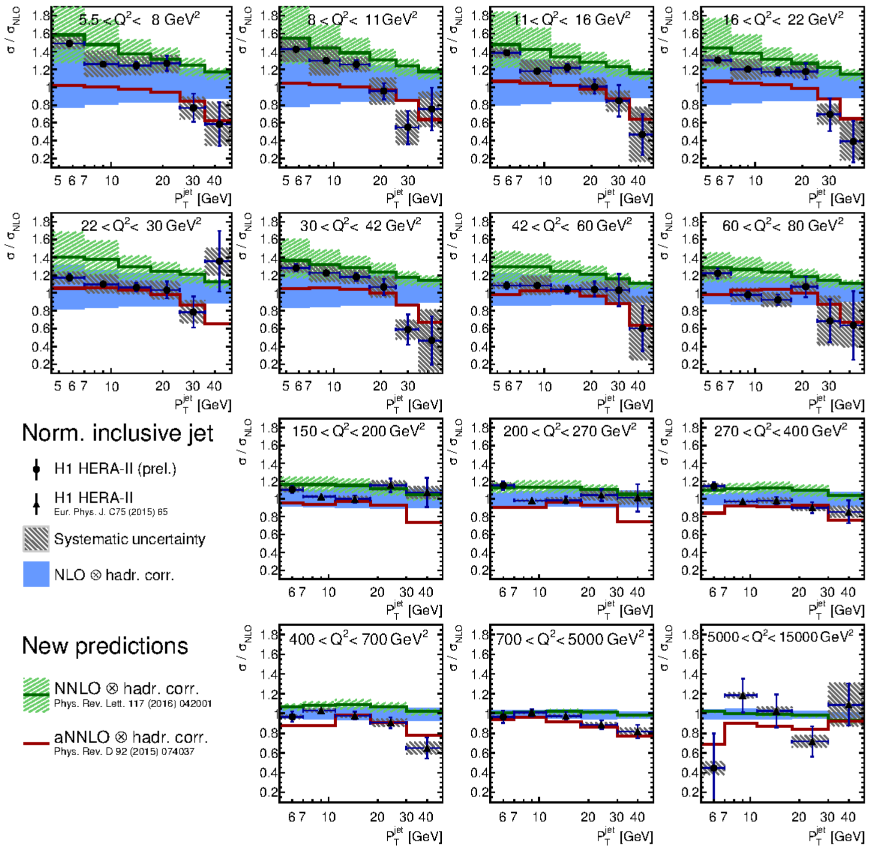
- Overall α_s uncertainty limited by scale uncertainties at NLO



New jet data and NNLO calculations

- New prelimnary H1 data at low Q²
- Together with H1 data at high Q² the most precise jet data in DIS
- New NNLO calculations → reduced scale uncertainties
- Precision determination of α_s from DIS jets seems possible in the near future

New H1 data, ratio to NLO:
NNLO describes shape better



Summary

- Recent publication of combined HERA inclusive cross section data: precision better than 1.5% for $Q^2<500$ GeV^2
- A unique dataset probing the proton structure over more than five orders of magnitude in Q^2 and x
- Parton densities HERPDF2.0 derived from HERA data alone
- Together with DIS jet data, the strong coupling can be measured
- Aim to reduce scale uncertainties on α_s from DIS jets in the near future using NNLO calculations