Precision QCD measurements at HERA

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for the H1 and ZEUS collaborations

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Deep-inelastic scattering

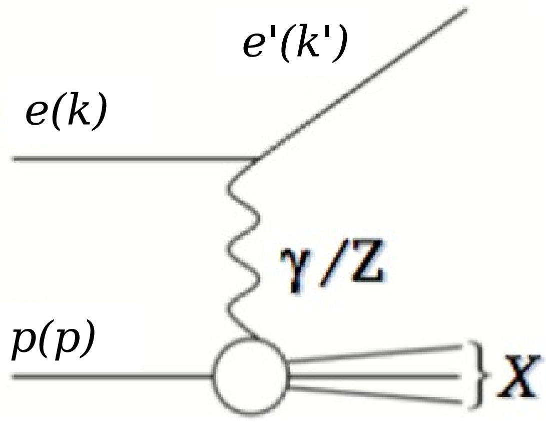
Kinematic variables
- virtuality of exchanged boson

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

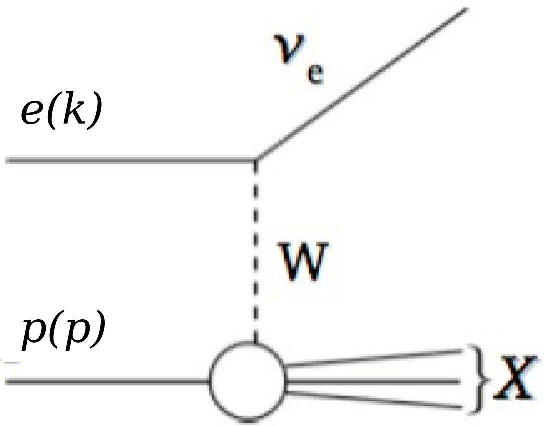
- Bjorken scaling variable

$$x = \frac{Q^2}{2\,p\cdot q}$$

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$



Factorization in ep collisions

$$\sigma_{ep\rightarrow eX} = f_{p\rightarrow i} \otimes \hat{\sigma}_{ei\rightarrow eX}$$

$xf_{p\rightarrow i}$ = quark/gluon momentum density in proton:
Parton density functions (PDFs)

PDFs are not observables – only structure functions are

Measuring these cross sections allows indirect access to the universal PDFs, which are also valid for pp collisions

Structure functions

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x} \left[\frac{1}{Q^2}\right]^2 \left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{4\pi x} \left[\frac{M_W^2}{M_W^2+Q^2}\right]^2 \left[Y_+ \tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

DIS cross sections are expressed in terms of structure functions

Dominant contribution from F_2 structure function

$$\tilde{F}_2 \propto \sum (xq_i + x\bar{q}_i)$$

Relevant at high $Q^2 \sim M_Z^2$

$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

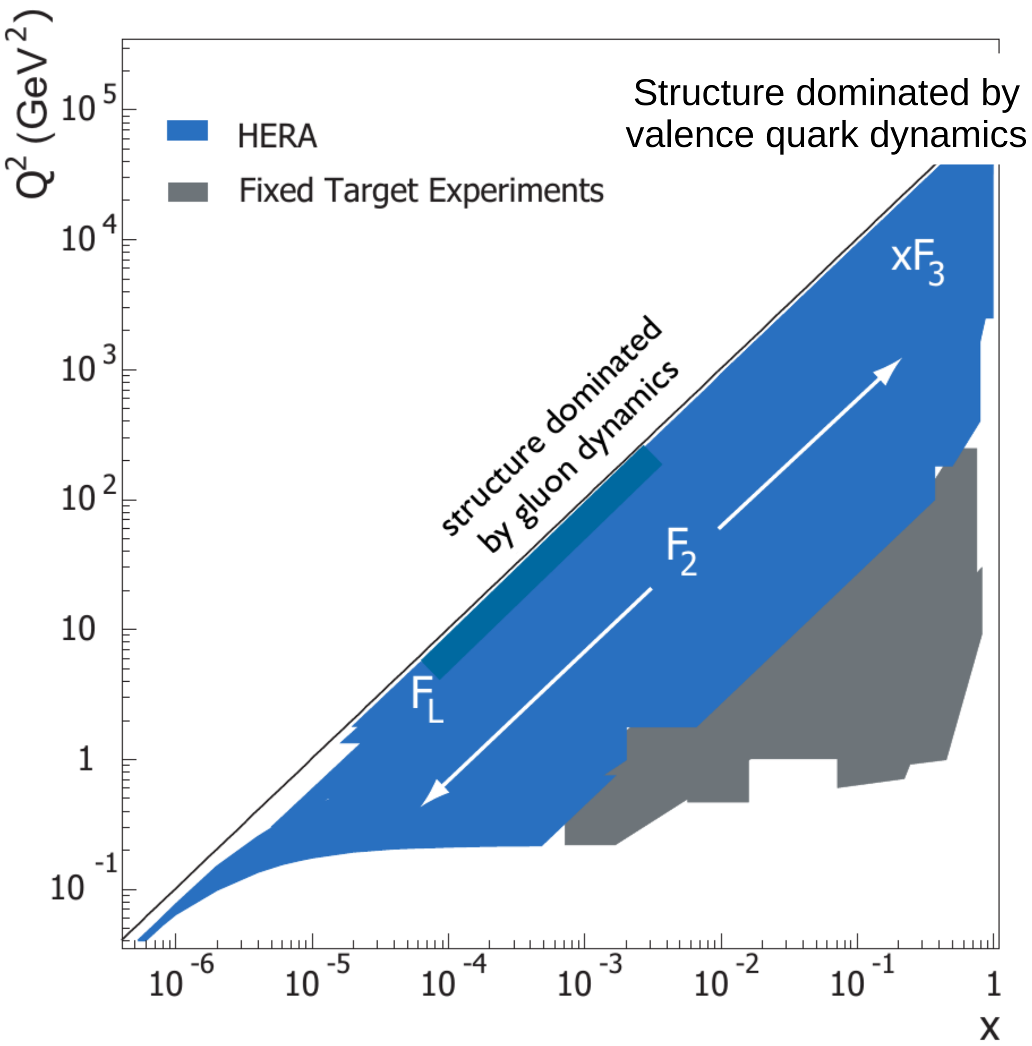
Sensitive at low Q^2 and high y

$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$

Measured cross sections are reduced cross sections

Measurement is a direct determination of the structure functions

HERA kinematic plane



HERA data cover a wide kinematic region of x,Q^2

NC measurements

- F_2 dominates most of Q^2 reach
- xF_3 contributes to EW regime
- F_L contributes only at highest y

CC measurements

- W_2 and xW_3 contribute equally
- W_L only at high y

LHC: largest mass states at large x

For central production $x_1=x_2$

$M = x^*\sqrt{s}$

i.e. M > 1TeV probes x > 0.1

High-x predictions rely on

- data (DIS / fixed target)
- sum rules
- behaviour of PDFs as x $\rightarrow$ 1

HERA operation

HERA-I operation 1993-2000

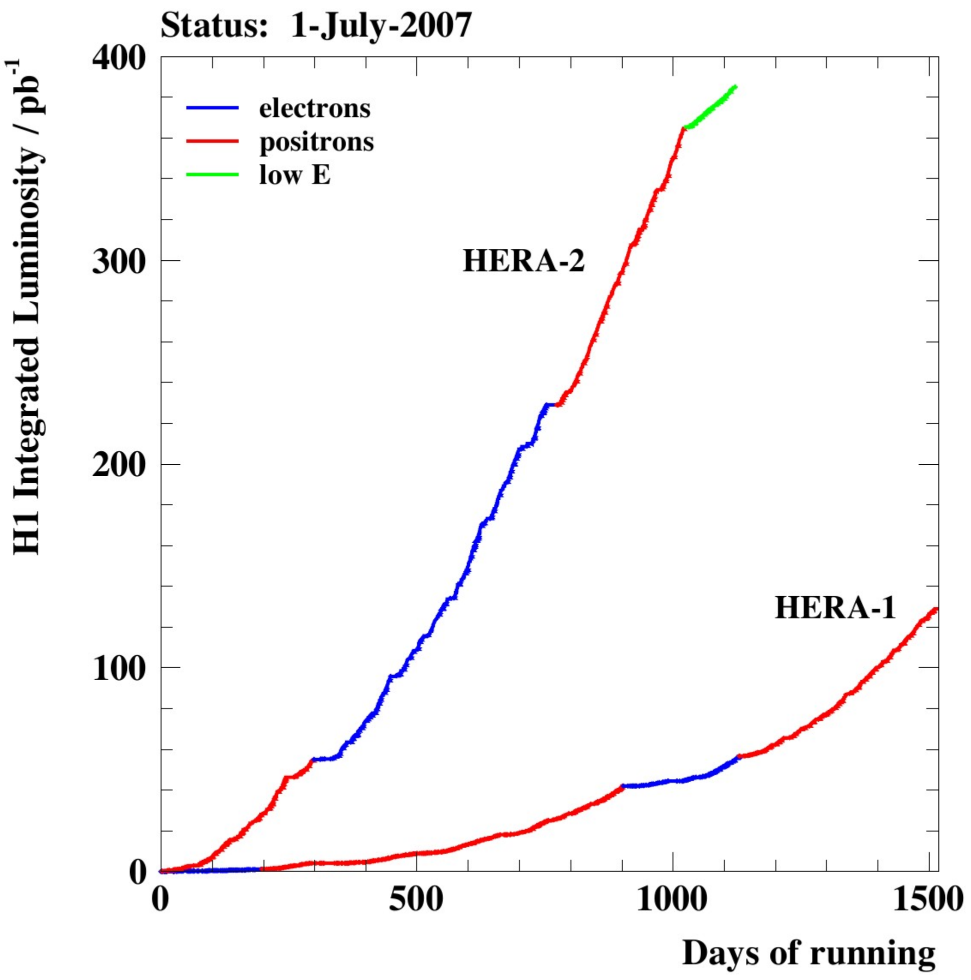
- E_e = 27.6 GeV
- E_p = 820 / 920 GeV
- $\sqrt{s}$ = 301 & 318 GeV
- int. Lumi. ~ 110 pb^{-1} per experiment

HERA-II operation 2003-2007

- E_e = 27.6 GeV
- E_p = 920 GeV
- $\sqrt{s}$ = 318 GeV
- int. Lumi. ~ 330 pb^{-1} per experiment
- Longitudinally polarised leptons

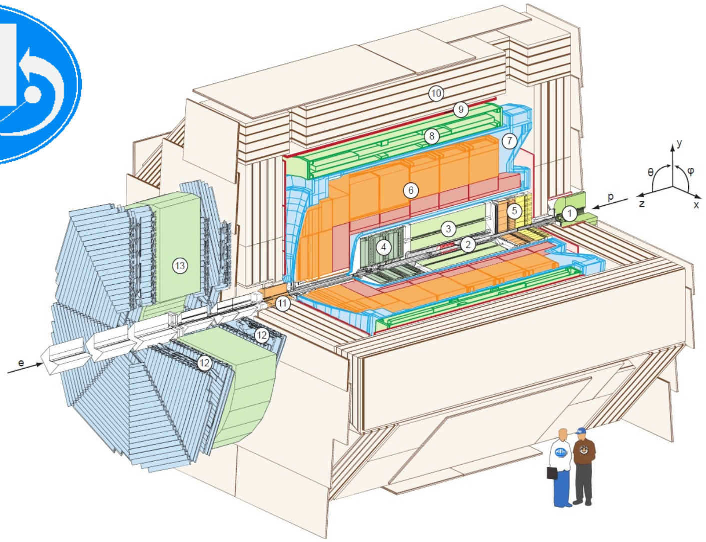
Low-Energy Run 2007

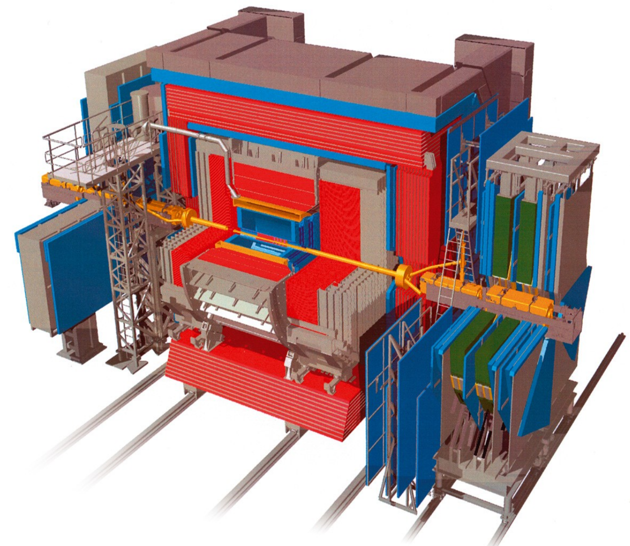
- E_e = 27.6 GeV
- E_p = 575 & 460 GeV
- $\sqrt{s}$ = 225 & 251 GeV
- Dedicated F_L measurement



H1 and ZEUS

Two multi-purpose collider experiments: H1 and ZEUS





High statistics

- Luminosity: approx. 0.5 fb^{-1} per experiment

Excellent control over experimental uncertainties

- Overconstrained system in DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Trigger and normalization uncertainties: 1-2 %
- Luminosity: 1.8 – 2.5%

HERA structure function data

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]

H1 & ZEUS have published all datasets
- HERA-I
- HERA-II at high Q^2
- HERA-II at reduced centre-of-mass energies

Data combination
- 41 datasets are combined
  - NC & CC cross sections
  - e^+p & e^-p scattering
  - 4 values of $\sqrt{s}$
- 2927 input data points
- 1307 combined points
- data points are swum to common (x,Q^2)-grid points:

$$\sigma(x_{grid}, Q^2_{grid}) = \frac{\sigma_{model}(x_{grid}, Q^2_{grid})}{\sigma_{model}(x_{meas}, Q^2_{meas})} \cdot \sigma_{meas}(x_{meas}, Q^2_{meas})$$

The usage of different reconstruction techniques and the differences in the strengths of the detector components of the two experiments lead to a substantial reduction of the systematic uncertainties of the combined cross sections.

EPJ C75 (2015) 12, 580

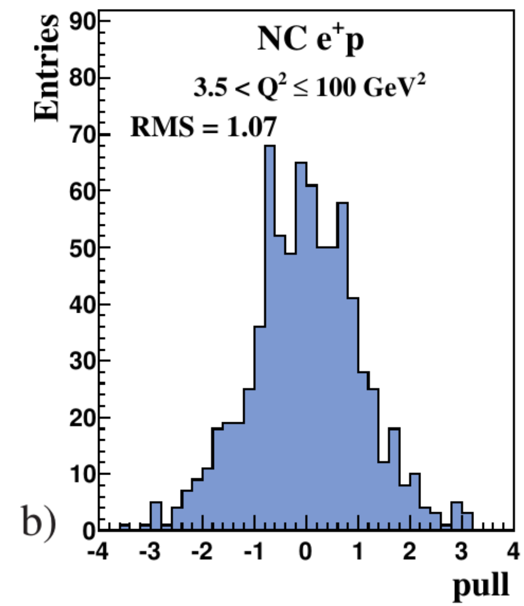
H1 & ZEUS data combination

Combination of all H1 and ZEUS datasets

- 2927 data points → 1307 combined points
- *HERAAverager* package used
- Correlations of systematic uncertainties fully considered
- Minimisation procedure based on χ^2 definition

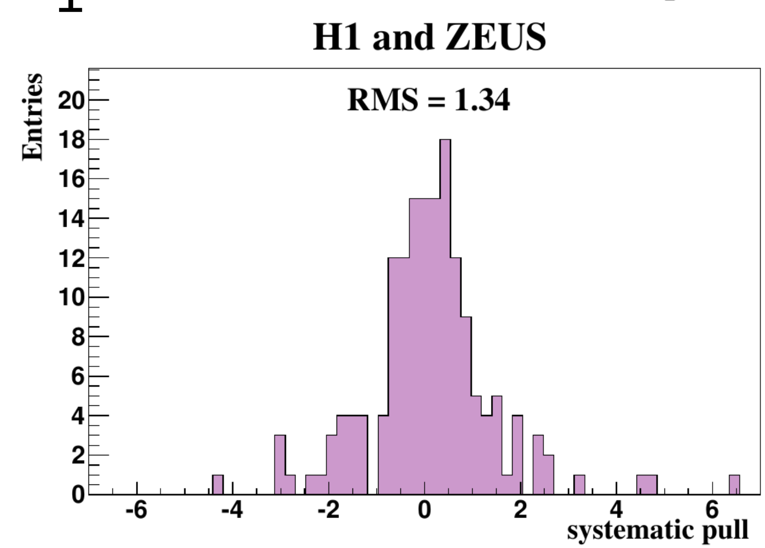
$$\chi^2_{\mathrm{exp},ds}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\mathrm{stat}}\,\mu^i\left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\mathrm{uncor}}\, m^i\right)^2} + \sum_j b_j^2$$

$$p^{i,k} = \frac{\mu^{i,k} - \mu^{i,ave}\left(1 - \sum_j \gamma^{i,k}_j b_{j,ave}\right)}{\sqrt{\Delta^2_{i,k} - \Delta^2_{i,ave}}}$$



Combination results

- χ^2 of combination: 1687 for 1620 degrees of freedom
- Pull values well distributed around zero with RMS ~ 1
- Great confirmation of consistency of datasets !



Procedural uncertainties

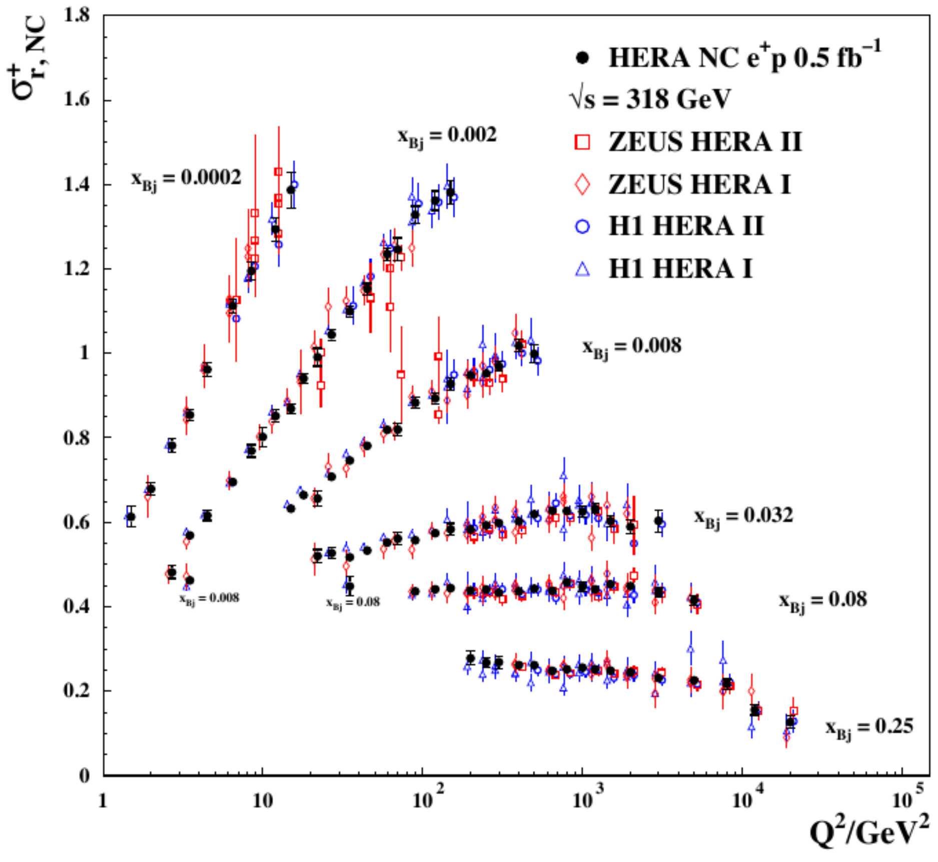
- Multiplicative vs. additive nature
- Correlation in photoproduction background
- Large pulls in corr. syst. uncert.

Combined NC DIS cross sections

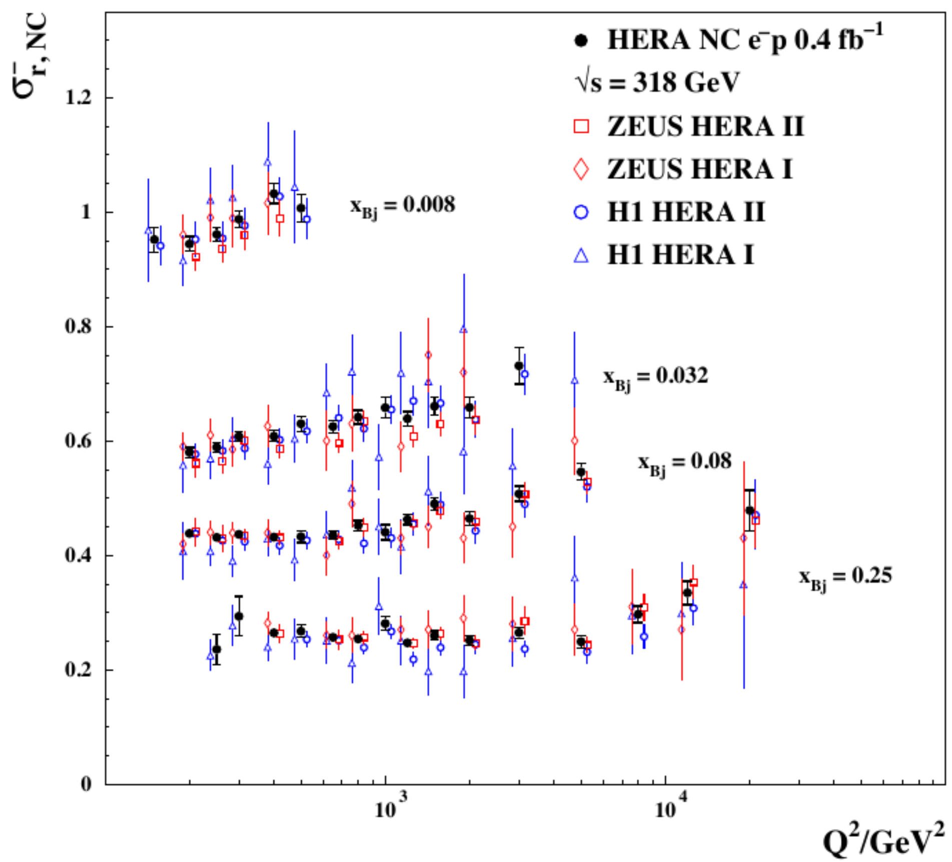
Combined HERA data based on approx. 1fb^{-1}

- Only 6 and 4 selected x-bins shown here for $\sqrt{s}$ = 318 GeV
- High precision reached over large kinematic range: Better than 1.3% for Q^2 < 400 GeV^2

e^+p



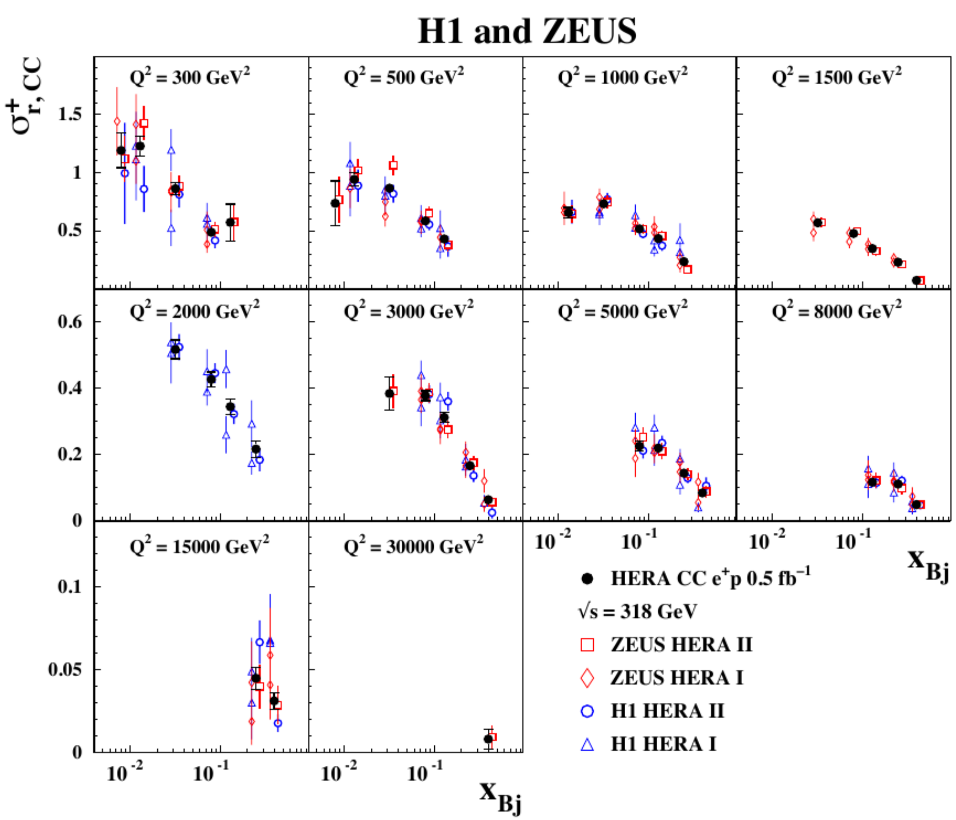
e^-p

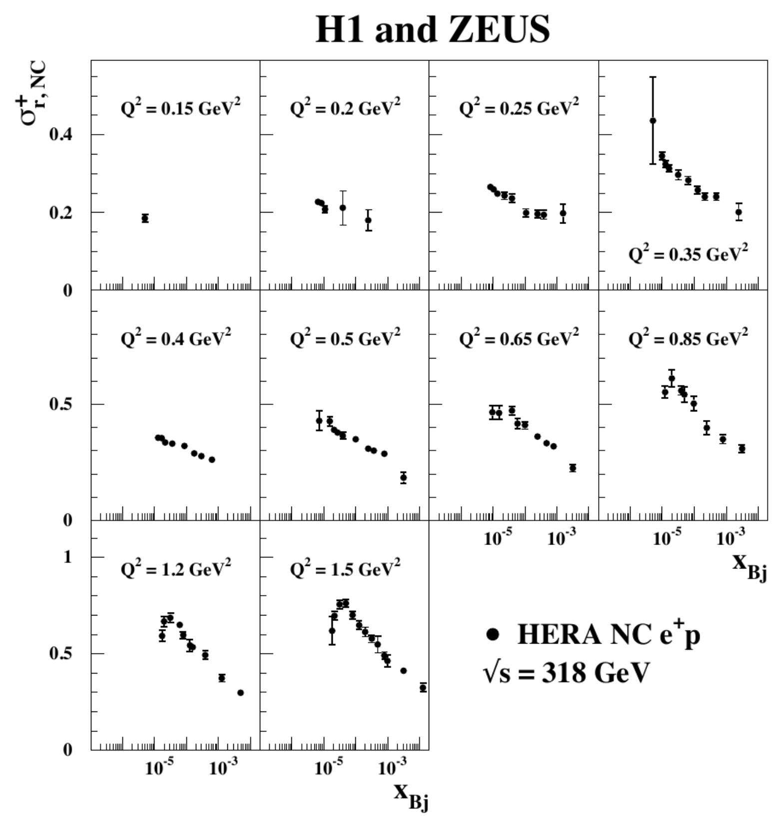


CC DIS and low-Q^2 cross sections

Combined charged current DIS cross sections for √s = 318 GeV

- Large improvement in statistical limitations of individual datasets





Further kinematic regions

- Great improvements also for √s = 225, 251 and 301 GeV
- Very low-Q^2 and low-x data for √s = 301 and 318 GeV
  - $Q^2 > 0.045$ GeV^2 and $x_{Bj} > 6\text{x}10^{-7}$
  - Interesting for dipole and saturation models

PDF extraction from data: HERAPDF2.0

HERAPDF approach

- Final combined $e^{\pm}p$ NC and CC data are very precise, so to allow the extraction of the parton densities
- DGLAP Analysis based only on HERA data
- PDFs parameterised at arbitrary starting scale $Q^2_0 = 1.9$ GeV^2

$$\begin{array}{ll} xg & xg \\ xu_v & xU = xu + xc \\ xd_v & xD = xd + xs \\ x\bar{U} & x\bar{U} = x\bar{u} + x\bar{c} \\ x\bar{D} & x\bar{D} = x\bar{d} + x\bar{s} \end{array} \longrightarrow \begin{array}{rcl} xg(x) & = & A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\ xu_v(x) & = & A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right), \\ xd_v(x) & = & A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\ x\bar{U}(x) & = & A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1 + D_{\bar{U}}x\right), \\ x\bar{D}(x) & = & A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}. \end{array}$$

fixed or constrained by sum-rules

parameters set equal but free

Minimise χ^2 function with respect to PDF parameters

- Perturbative QCD evolution allows PDFs to be determined at any other scale Q^2
- Calculate theory cross section at given x,Q^2 of measurement
- Usage of momentum/counting sumrules help to constrain parameter space

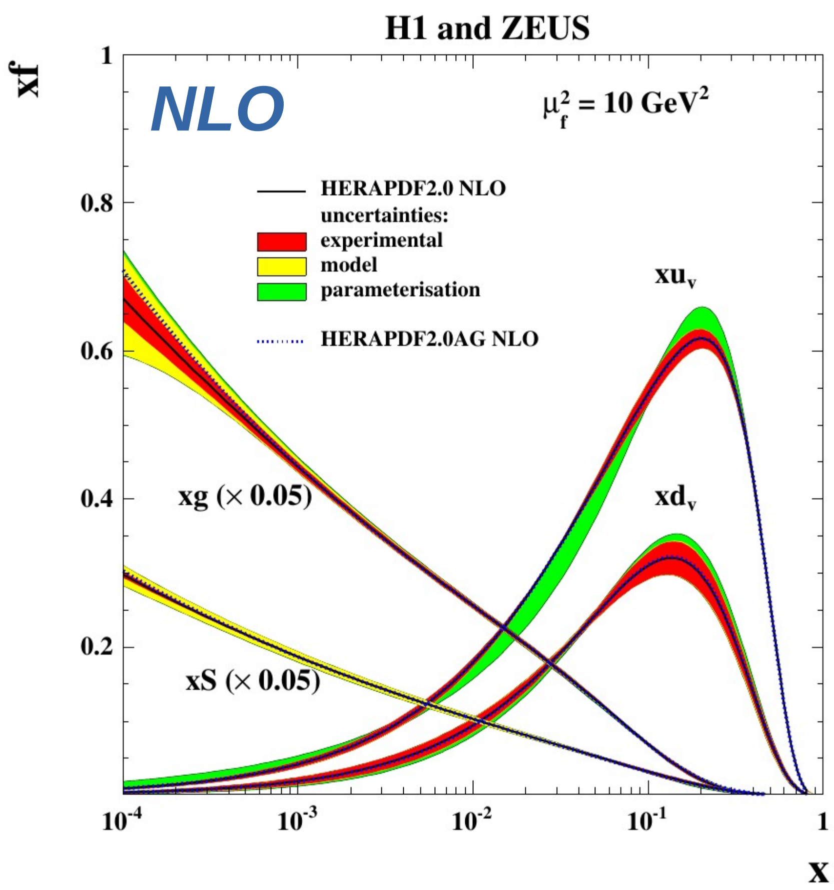
The use of a single consistent data sample allows a more rigorous treatment of the experimental uncertainties

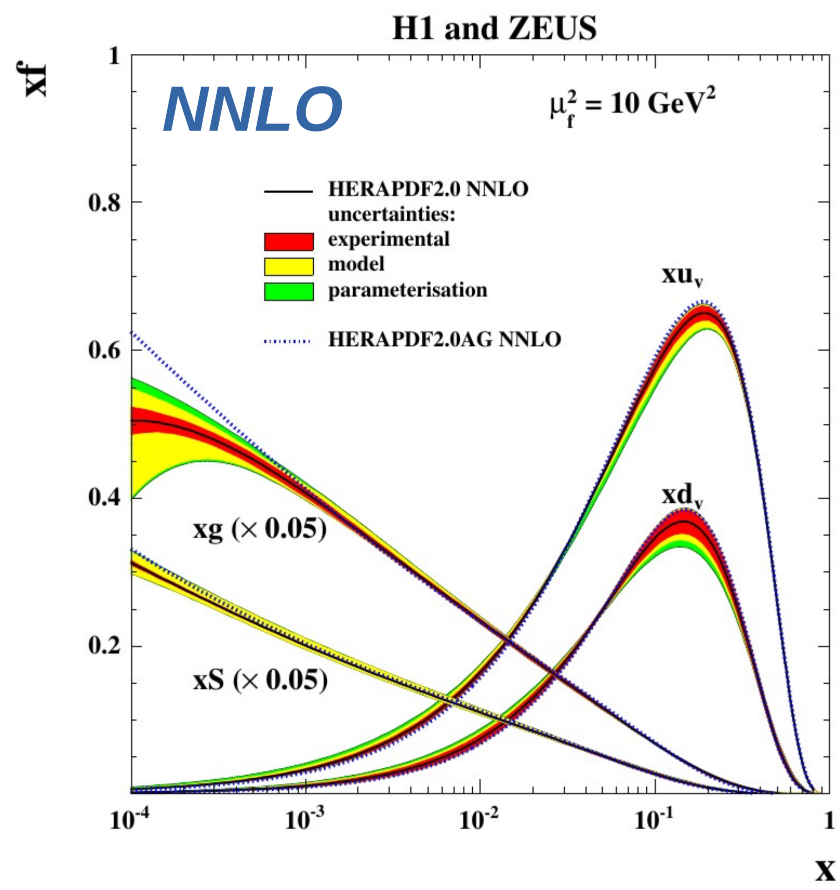
- No fixed target data, therefore no need for heavy-target/deuterium corrections

HERAPDF2.0 NLO and NNLO

Fits performed in LO, NLO and NNLO

- NLO: χ^2/ndf = 1357 / 1131
- NNLO: χ^2/ndf = 1363 / 1131





Differences between NLO and NNLO fit

- gluon ceases to raise at low-x
- sea at low-x somewhat steeper w.r.t. NLO

HERAPDF2.0 uncertainties

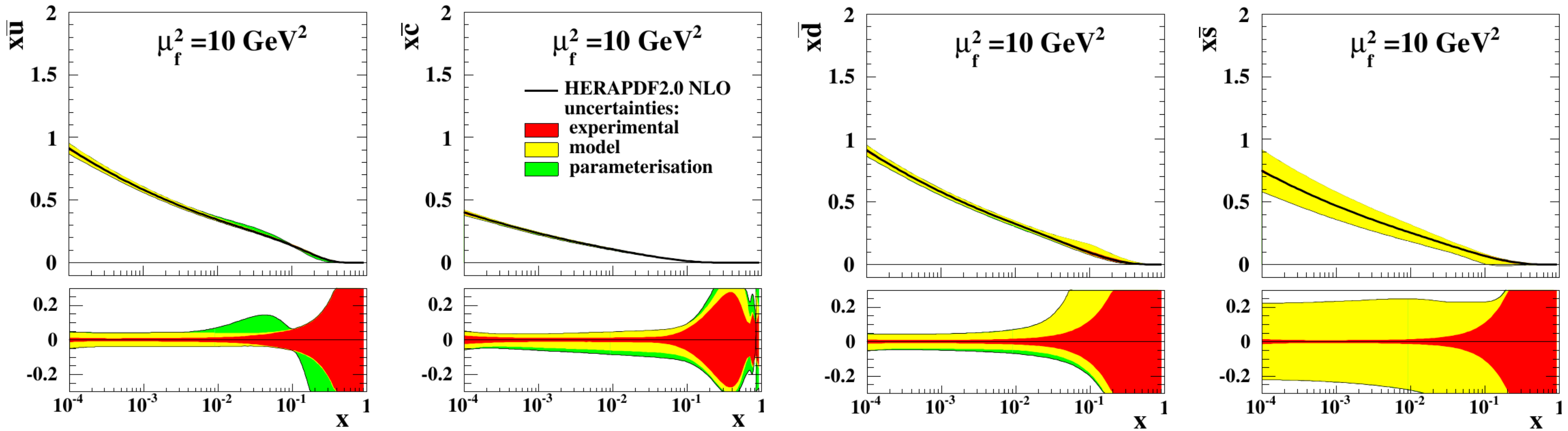
Experimental Uncertainties
Hessian method uses 14 eigenvector pairs
Standard definition $\Delta\chi^2=1$ for 68% CL error bands

Model Assumptions
Variation of charm and bottom quark masses M_c , M_b
Variation of Q^2 minimum cut used on input data Q^2_{min}
Variation of strange quark fraction f_s

Parameterisation Uncertainties
Variation of Q_0^2
Variation of fit using additional 15th parameter

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{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
$\alpha_s(M_Z^2)$	0.118	–	–
μ_{f_0} [GeV]	1.9	1.6	2.2

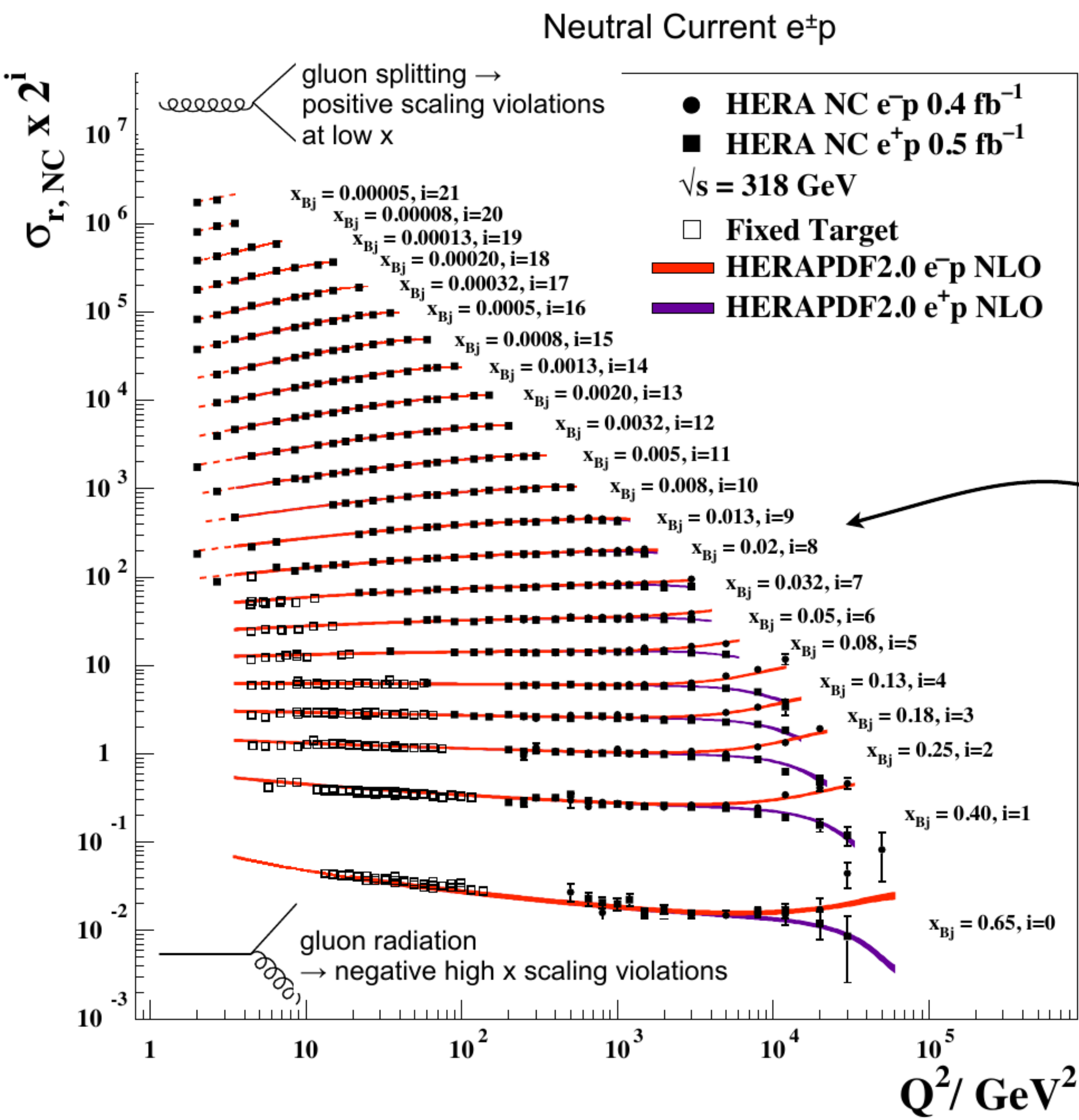
$\alpha_s(M_Z)$ fixed but series of PDFs provided for large range: 0.110 to 0.130



Flavor breakdown of sea distribution

EPJ C75 (2015) 12, 580

NC cross sections & HERAPDF2.0



Precision 1.3% for $Q^2 < 400$ GeV^2
⇒ factor 2 reduction in error wrt HERA-I

Statistics limited at higher Q^2 and high x

Extended reach at high x compared to H1 preliminary data

This x region is the ‘sweet spot’
High precision with long Q^2 lever arm
x-range relevant for Higgs production

Combination of high Q^2 data HERA-1 and HERA-II

Larger HERA-II luminosity
→ improved precision at high x / Q^2

HERAPDF2.0 provides good description

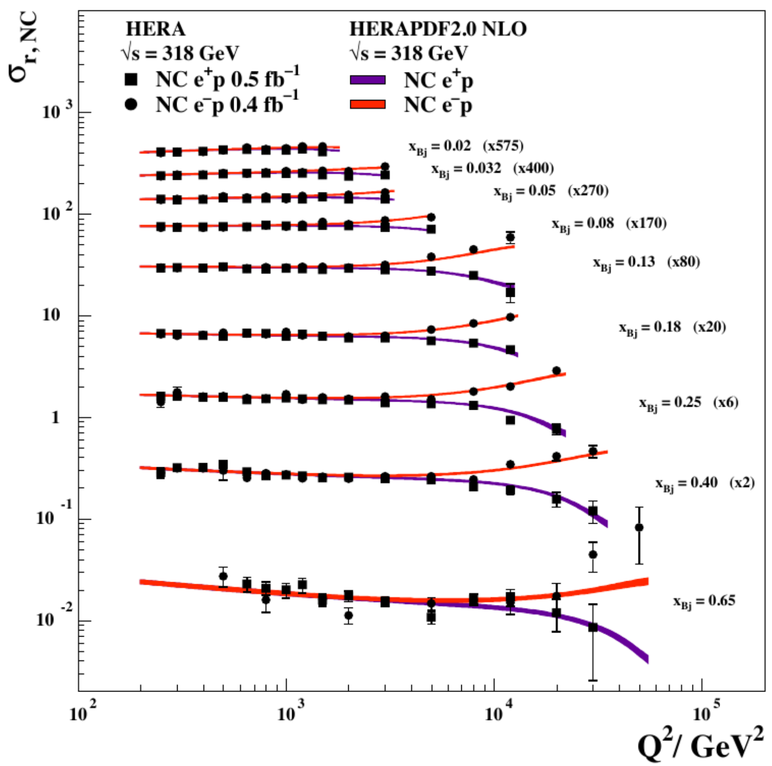
EPJ C75 (2015) 12, 580

High Q^2 NC & CC Cross Sections

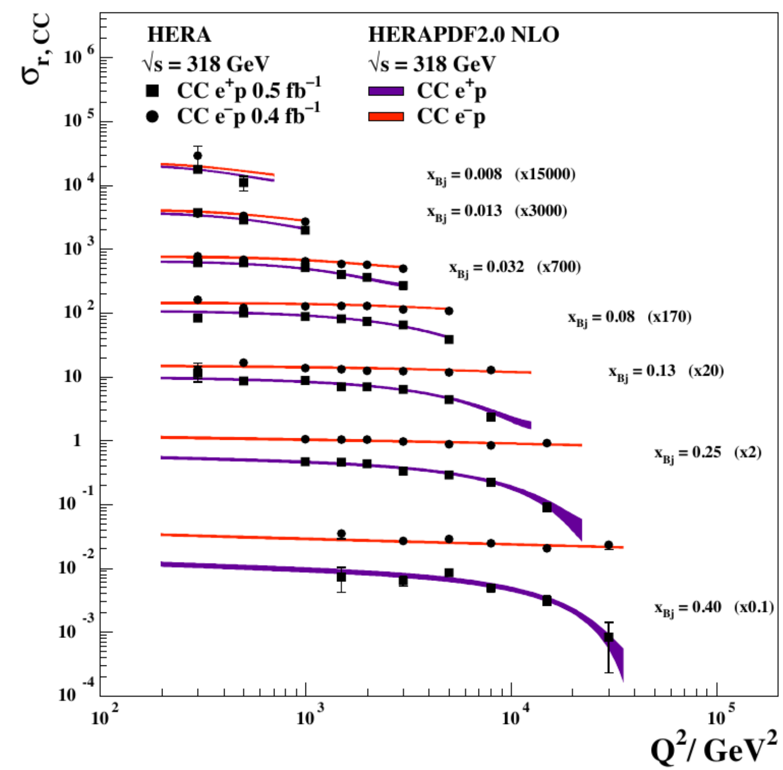
High Q^2, high-x cross sections

- Difference in NC at high-x for e^+ and e^- due to xF_3 and Z-boson exchange
- CC e^+p suppressed at high-x due to $(1-y)^2$ helicity suppression of quarks
- CC e^-p unaffected as helicity suppression applies to anti-quarks

Neutral Current $e^{\pm}p$



Charged Current $e^{\pm}p$



HERAPDF2.0 describes high-x data well for both NC and CC channels

EPJ C75 (2015) 12, 580

χ^2 and Q^2_{min} study and heavy flavors

Minimum value of Q^2 for data to ensure that pQCD is applicable

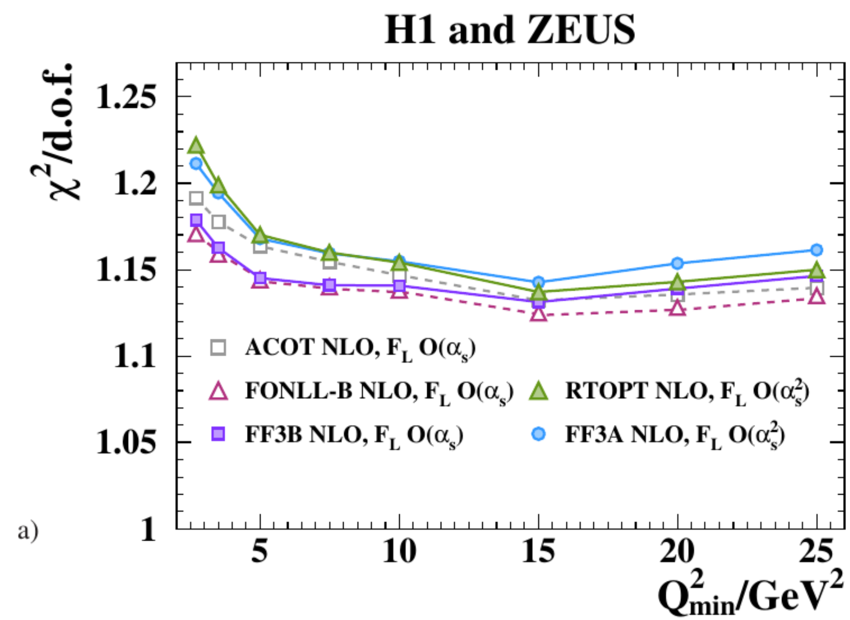
- HERAPDF2.0: Q^2_{min} = 3.5 GeV^2
- Consider variation of this cut:
  χ^2 decreases with increase of Q^2

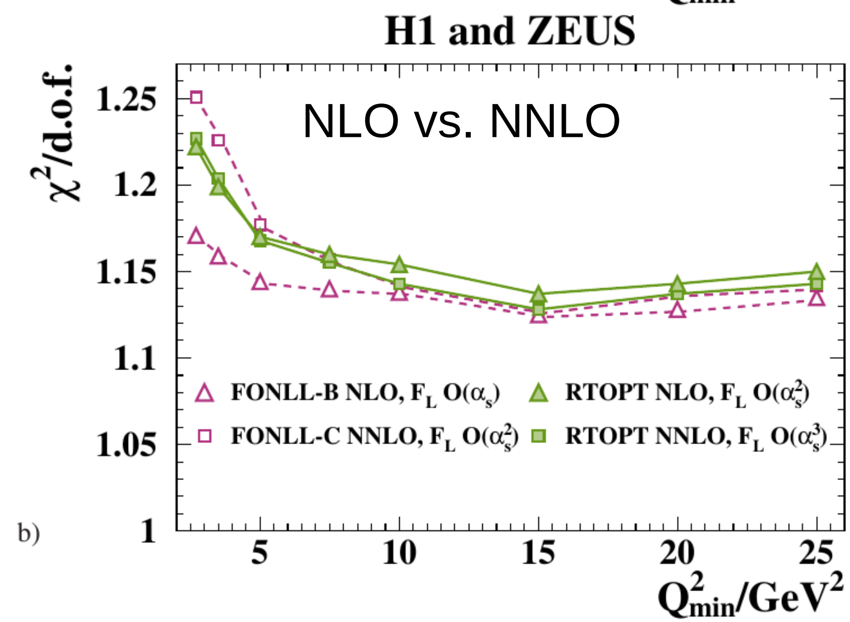
- NLO and NNLO behave similarly
- Low-Q^2 cuts also removes low-x region:
  Region where non-pert. effects, ln(1/x)-resummation, saturation become important

- Fits for Q^2_{min} = 10 GeV^2 also released as PDF tables

Heavy flavor scheme

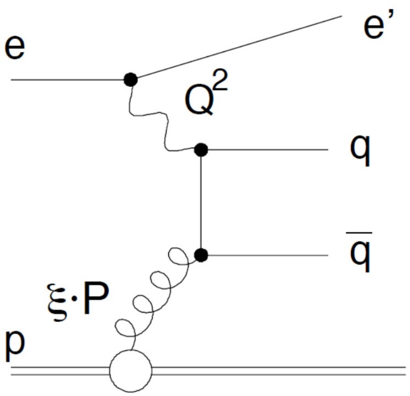
- Treating F_L to $O(\alpha_S)$ (the same order as F_2) yields better χ^2 than treating F_L to $O(\alpha_S^2)$
- RT-Opt NNLO is marginally worse than NLO
- FONLL NNLO is worse than NLO



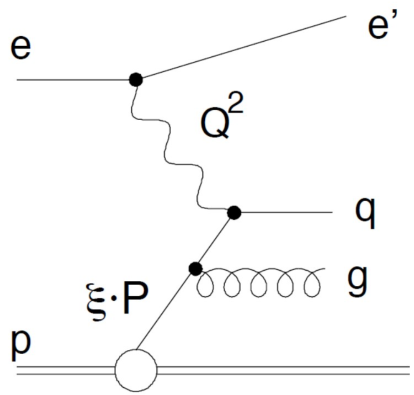


Jet production in DIS

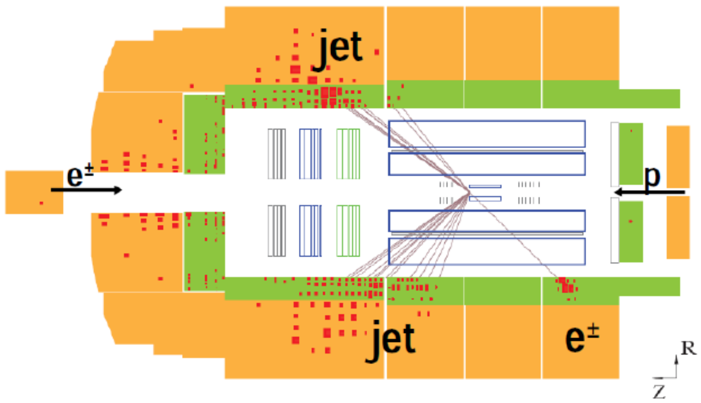
Jet production in leading-order pQCD



boson-gluon fusion



QCD Compton scattering



Jet measurements are perfomed in Breit-frame

virtual boson collides head on with a parton from the proton

Inclusive jets

Count each jet of an event

Dijet and trijet

Count events with two/three jet event structure

Observable: average transverse momentum of two/three jets

Normalised jets

Normalise all jet data w.r.t. inclusive NC DIS cross section

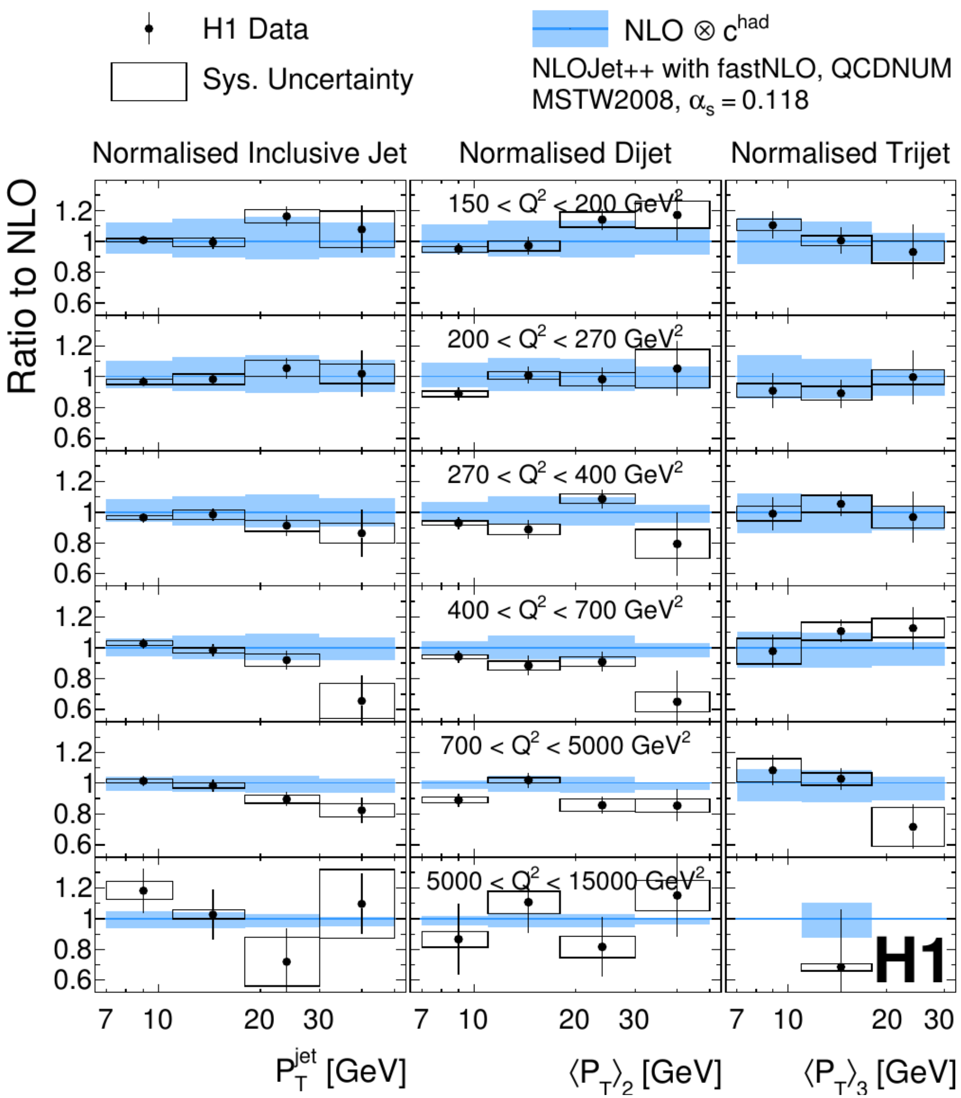
Jet production in DIS

Normalised and non-normalised jet data

- Data well described by NLO theory (nlojet++)
- Data in general with smaller uncertainties than NLO from scale variations
- Differences between different PDF sets typically small

Data used to extract strong coupling constant

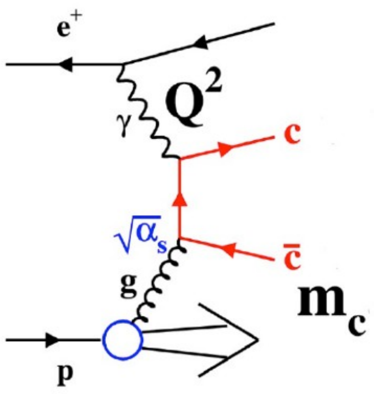
- χ^2 minimisation of α_s in coefficient function
- Dependencies of the PDF on α_s considered as uncertainties

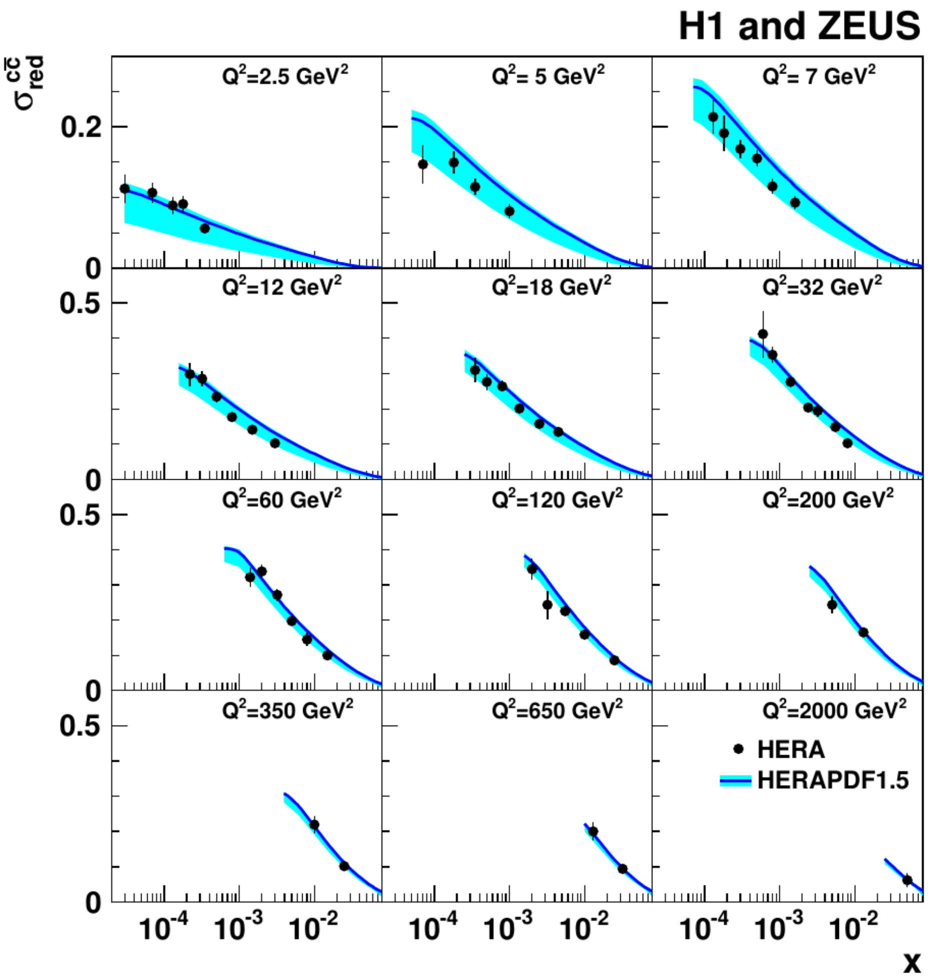


$$\alpha_s(M_Z)|_{k_T} = 0.1165\ (8)_{\rm exp}\ (5)_{\rm PDF}\ (7)_{\rm PDFset}\ (3)_{{\rm PDF}(\alpha_s)}\ (8)_{\rm had}\ (36)_{\mu_r}\ (5)_{\mu_f}$$
$$= 0.1165\ (8)_{\rm exp}\ (38)_{\rm pdf,theo}\ .$$

Eur. Phys. J. C73 (2013) 2311

Charm production in DIS





Charm production at HERA

- Charm is produced in virtual photon-gluon fusion
- Charm production directly sensitive to the gluon density xg(x)

Combined charm cross sections

- Whealth of HERA charm data combined into common charm cross sections

$$\frac{\mathrm{d}^2\sigma^{c\bar{c}}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2(Q^2)}{xQ^4}([1+(1-y)^2]F_2^{c\bar{c}}(x,Q^2) - y^2 F_L^{c\bar{c}}(x,Q^2))$$

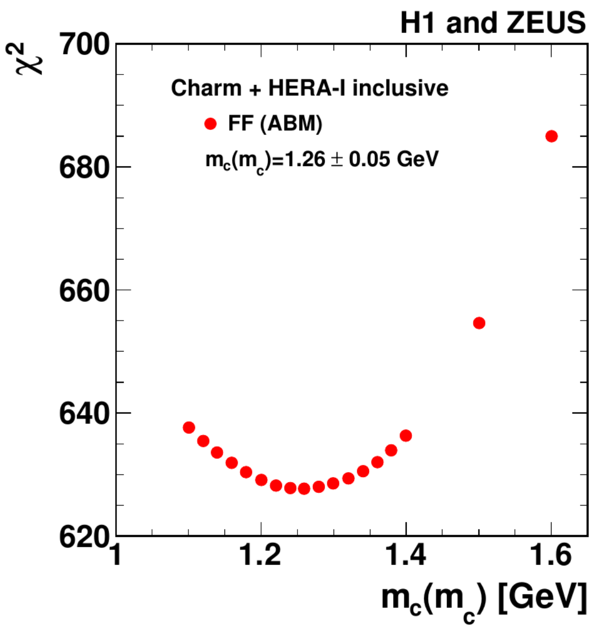
Eur. Phys. J. C73 (2013) 2311
H1prelim-14-071, ZEUS-prel-14-006

Extraction of charm mass running

Extraction of charm mass

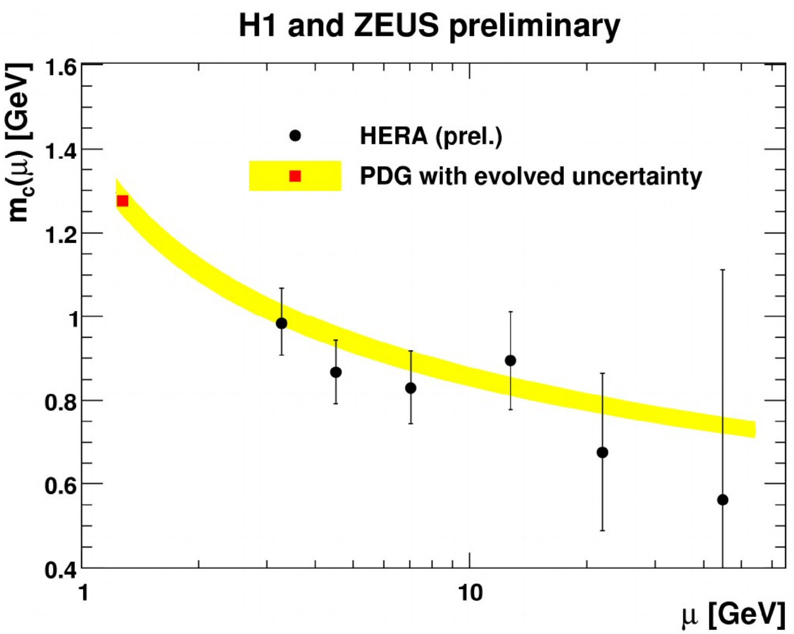
- Simultaneous fit of combined charm data + inclusive HERA-I DIS data
- Different heavy-flavor schemes explored
- FFNS ABM scheme defines charm mass in MSbar scheme

$$m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{par} \pm 0.02_{\alpha s}\,\mathrm{GeV}$$



Charm mass running

- extract $m_c(m_c)$ separately for 6 kinematic ranges in $\mu^2 = Q^2 + 4m_c^2$
- use appropriate PDF set for each mass (from inclusive DIS data only)
- fit charm data + HERA-I incl. data
- Translate back to $m_c(\mu)$ using LO formula consistent with NLO MS QCD fit (OpenQCDrad, Alekhin et al.)

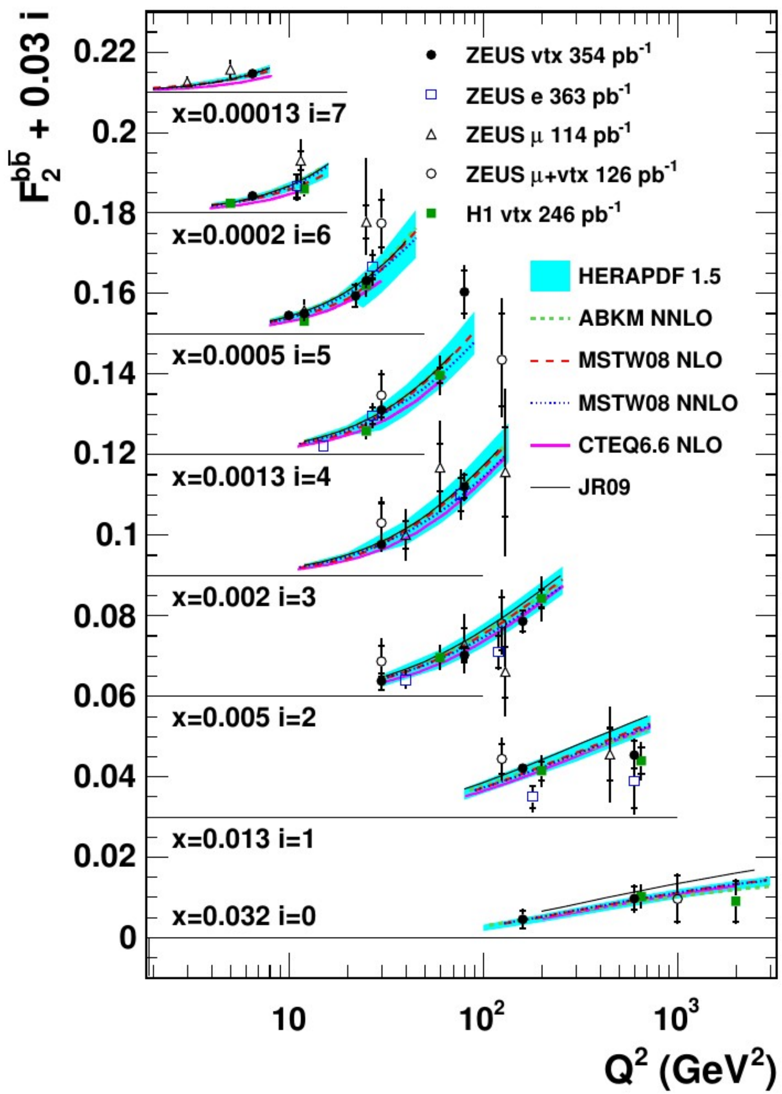


JHEP 09 (2014) 127
EPJ C65 (2010) 89

Determination of beauty mass

Beauty cross sections

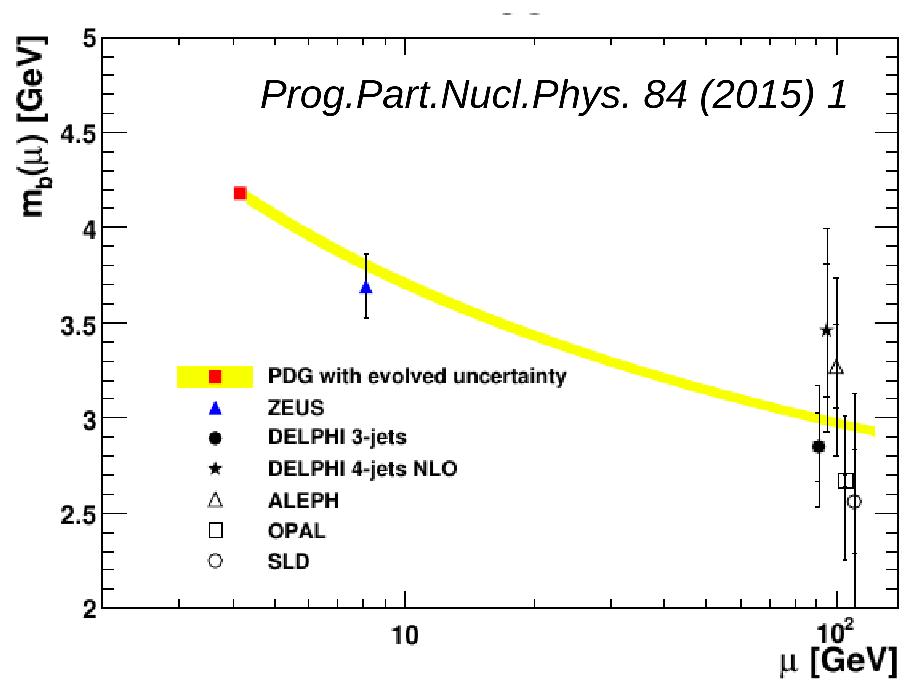
- Measured of HF jets using secondary vertices + lifetime tag
- Good description of data by massive NLO QCD predictions



Extraction of b-quark mass

- QCD fit (FFNS) of HERA-I incl. data + ZEUS beauty data
- m_b as free parameter

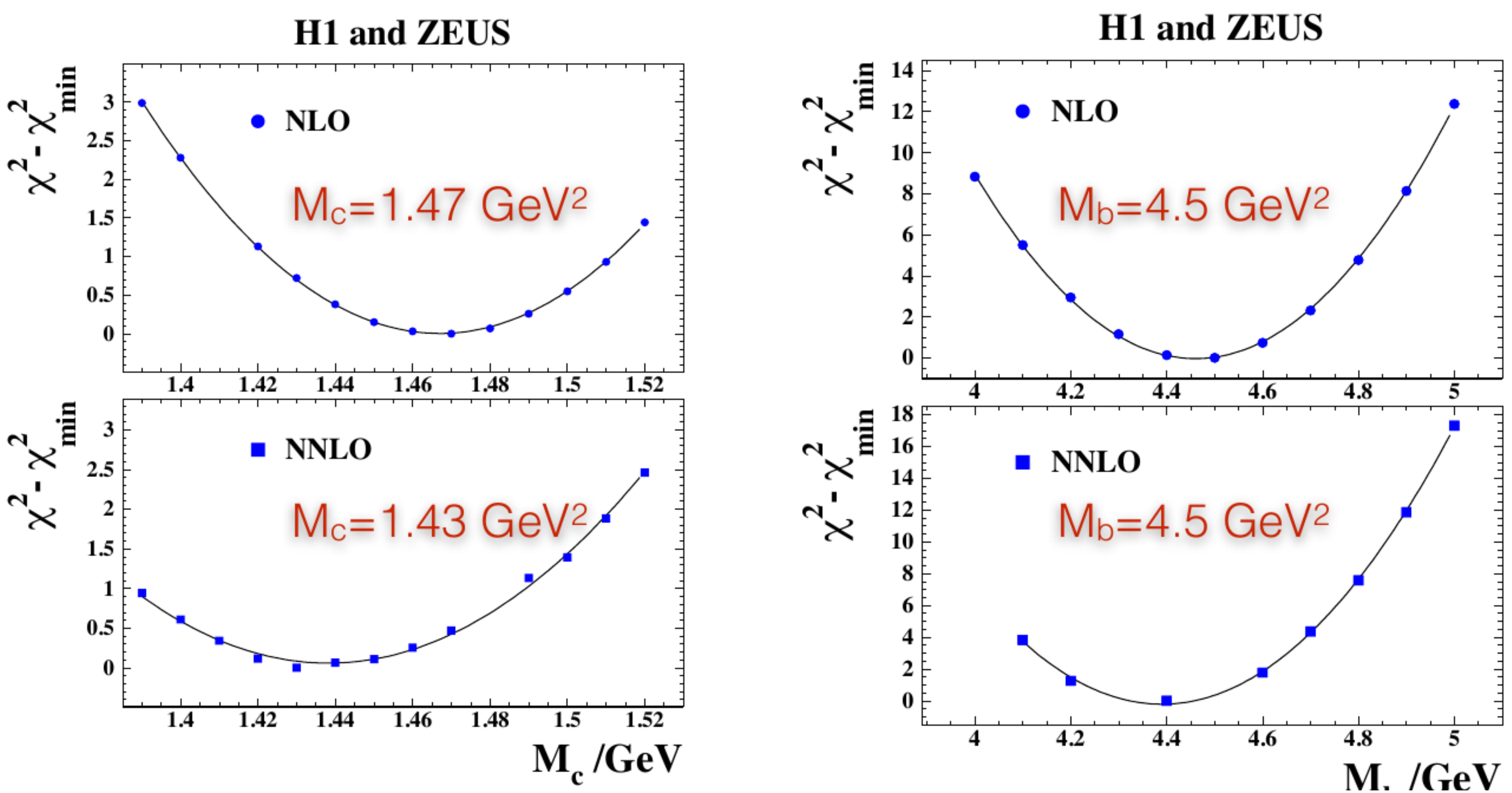
$$m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})^{+0.01}_{-0.07}\,(\text{mod.})^{+0.05}_{-0.00}\,(\text{param.})\,^{+0.08}_{-0.05}\,(\text{theo.})\ \text{GeV}$$



Charm and jet data in HERAPDF2.0

Charm and bottom data used in HERAPDF2.0 QCD analysis

- Charm and bottom data used to determine best quark-mass parameters
- Values of charm and bottom masses used DGLAP fits determined as χ^2 scan of NLO and NNLO fits

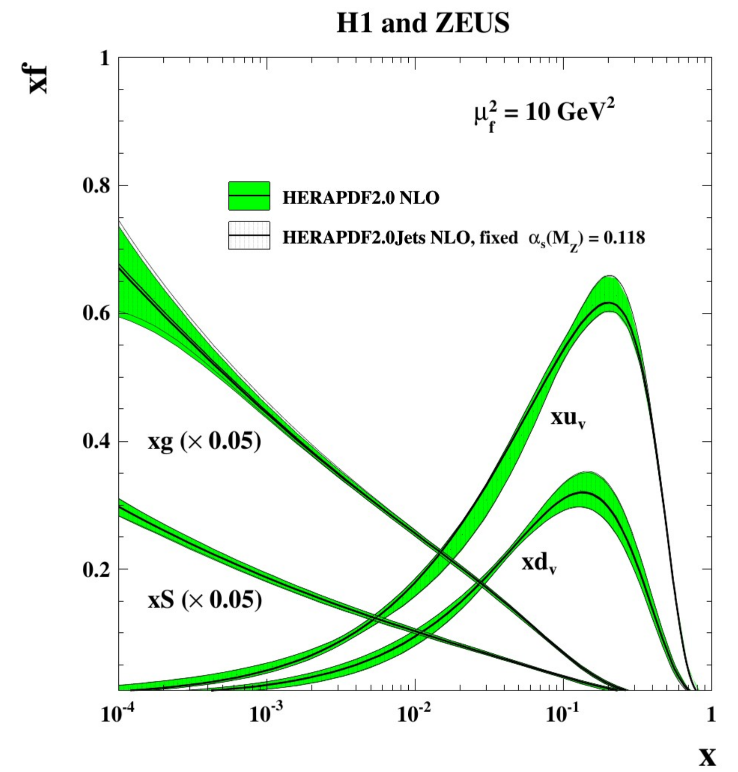


Charm and jet data in HERAPDF2.0

Additional datasets in QCD analysis

- Combined charm cross sections
- H1 norm. multijets at high Q^2 (HERA-II)
- H1 multijets at low Q^2 (HERA-I)
- H1 incl. jets at high Q^2 (HERA-I)
- ZEUS dijets at high Q^2 (HERA-II)
- ZEUS incl. jets at high Q^2 (HERA-I)

- Jet predictions available in NLO (nlojet++)
- Jet data significantly helps to disentangle gluon-α_s correlation

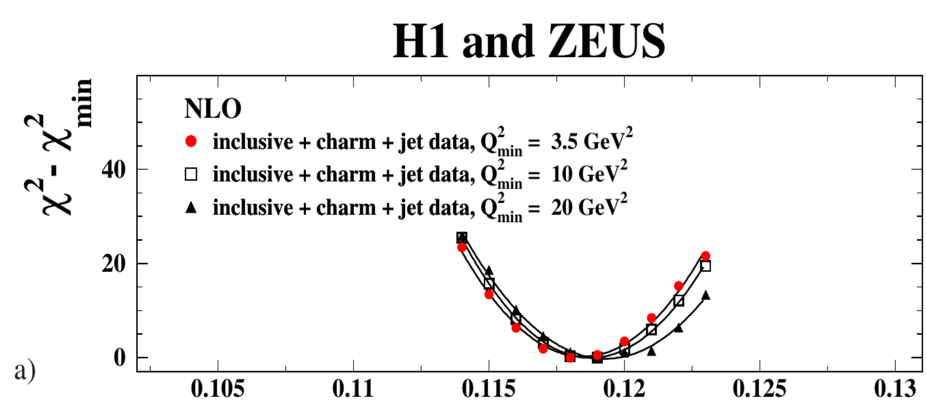


Determination of strong coupling

- α_s is additional free parameter in PDF fit
- Jet data constrain α_s

$$\alpha_s(m_Z) = 0.1183 \pm 0.0009_{exp} \pm 0.0005_{mod} \pm 0.0012_{had} \pm 0.004_{scale}$$

- Value mostly constrained by H1 norm. multijet data



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PL B 705 (2011) 52

Usage of HERA 'combined' data

HERA combined data

- Limit on effective quark radius
- Consider finite radius through form-factor

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1-\frac{R_e^2}{6}Q^2\right)^2\left(1-\frac{R_q^2}{6}Q^2\right)^2$$

- Fit PDFs and 'quark radius'
- 95% C.L. on quark radius

$$-(0.47\cdot 10^{-16}\,\mathrm{cm})^2 < R_q^2 < (0.43\cdot 10^{-16}\,\mathrm{cm})^2$$

Data improves previous limit by ZEUS and <u>H1</u> which has also previously constrained

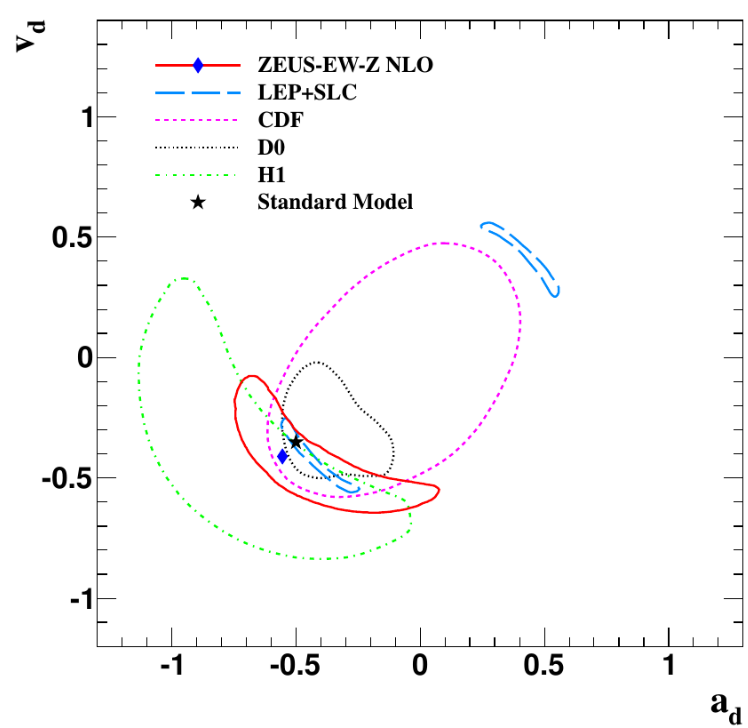
- Limits on compositeness scale of contact interactions (3.6 – 7.2 TeV)
- Limits on low-scale quantum gravity gravitons
- Limits on Leptoquark exchange and s-quarks

H1 and ZEUS data + ZEUS polarized HERA-II data

- Study Couplings of u- and d-quarks to Z-boson
- Use in additional ZEUS polarized data

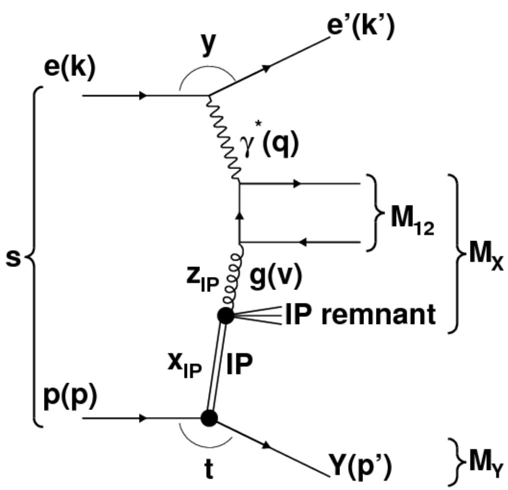
$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z ,$$

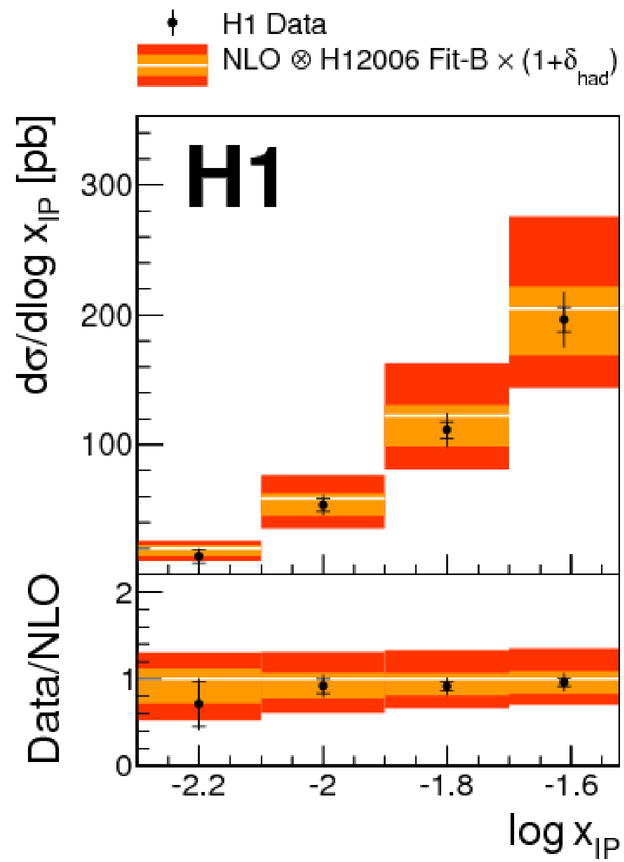
- Simultaneous fit of PDFs and axial and vector-'quark couplings'
- Values consistent with SM expectations
- Sensitivity on u-quark higher than d-quark



Dijets in diffractive DIS (LRG)

(Inclusive) dijets in diffractive DIS





- Diffractive events identified by 'large rapidity gap' (LRG)
- $4 < Q^2 < 100$ GeV2, $p_T^{\mathrm{jet1(2)}} > 5.5\ (4.0)$ GeV
- Theory: nlojet++ & H1DPDF2006 FitB
- Data used to extract strong coupling constant
  -> Fit supports concept of pQCD calculations for diff. dijets
  -> Exp. precision overshoots theoretical one

$$\begin{aligned}\alpha_s(M_Z) &= 0.119 \pm 0.004\,(\mathrm{exp}) \pm 0.002\,(\mathrm{had}) \pm 0.005\,(\mathrm{DPDF}) \pm 0.010\,(\mu_r) \pm 0.004\,(\mu_f) \\ &= 0.119 \pm 0.004\,(\mathrm{exp}) \pm 0.012\,(\mathrm{DPDF, theo})\end{aligned}$$

Diffr. Dijets in Photoprod. and DIS (VFPS)

History

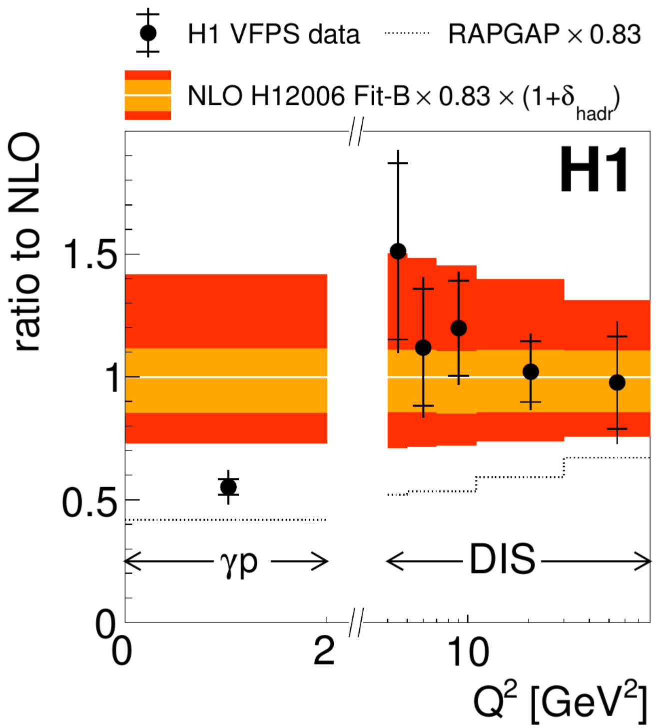
- 'Factorisation breaking' observed in diffractive events at Tevatron
- Photoproduction provides similar testing ground
- Fact. breaking observed by H1 but not by ZEUS

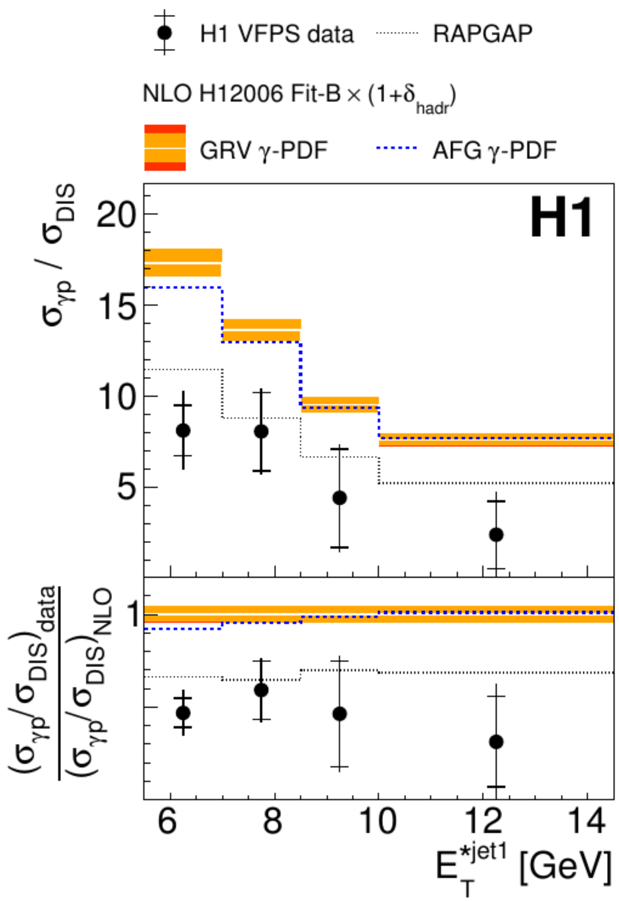
Here: Simultaneous measurement of dijets in diffr. DIS and PHP

- Use VFPS 220m from interaction point
- Calculate double-ratios: PHP/DIS

Single differential cross sections

- DIS data well described by NLO
- PHP NLO overshoots data
- New data with complementary method consistent with previous H1 results
- 'Suppression' shows no dependence as function of x_γ or E_T^{jet1}





Study diffractive models

Exclusive dijets in diffractive DIS

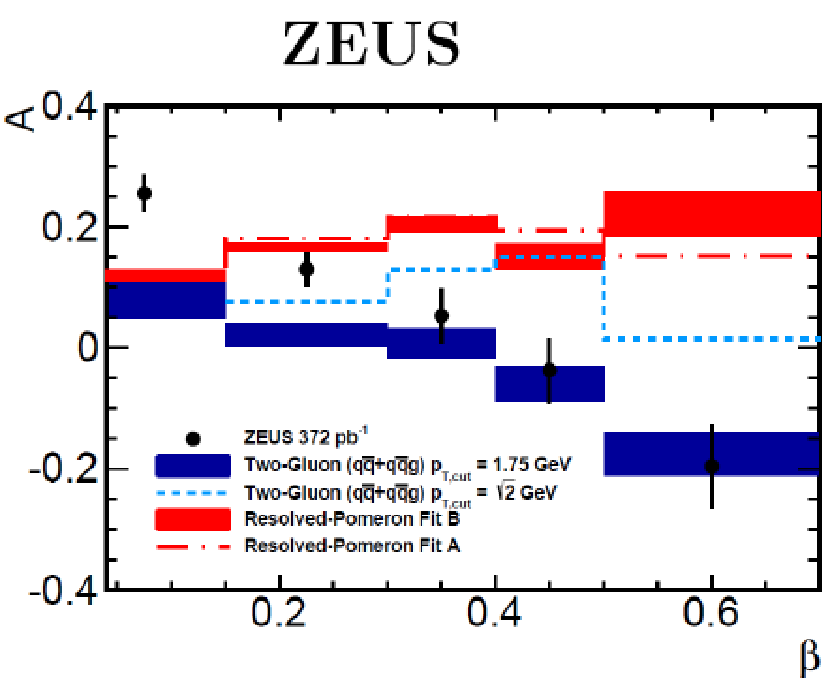
- Study (normalised) angle between jet-plane and lepton-plane

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \propto 1 + A\cos 2\phi$$

- Sensitive to nature of diffr. exchange: Resolved pomeron vs. two-gluon exchange model

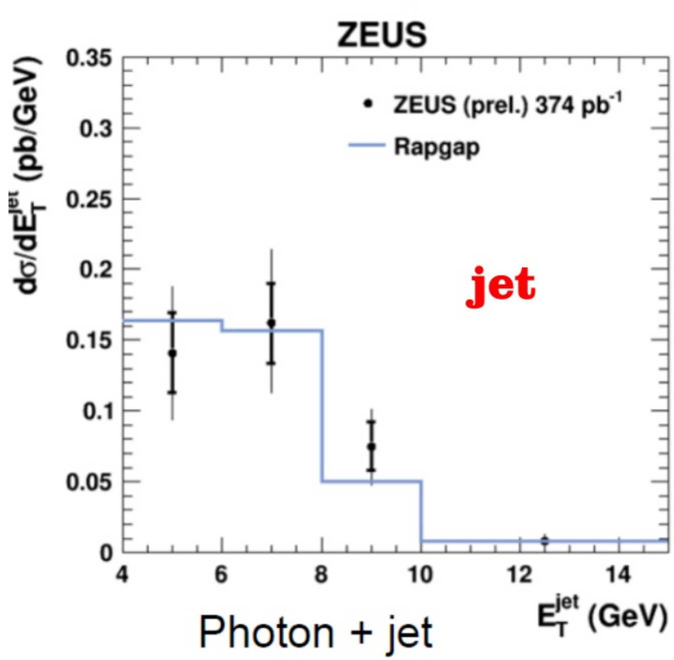
$$\beta = x_{\mathrm{Bj}}/x_{IP}$$

- Two-gluon model is more successful in describing data than resolved Pomeron model



Diffractive prompt isolated photons

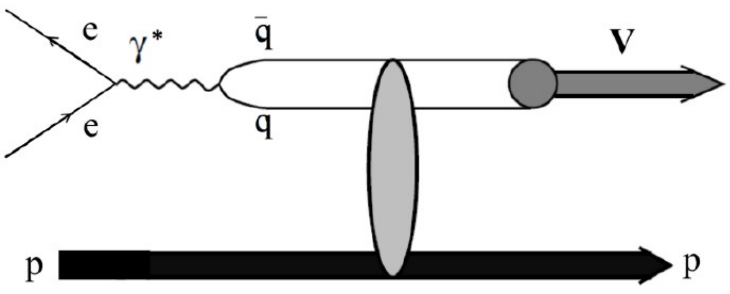
- Analysis extends prompt photon analysis in non-diff. PHP
  - Reminder: NLO and k_T-factorization predictions give good descriptions
- Prompt photon variables well described by Rapgap & H1PDF2006-FitB
- Problems at $z_{IP} \rightarrow 1$, where H1PDF2006-FitB was not fitted

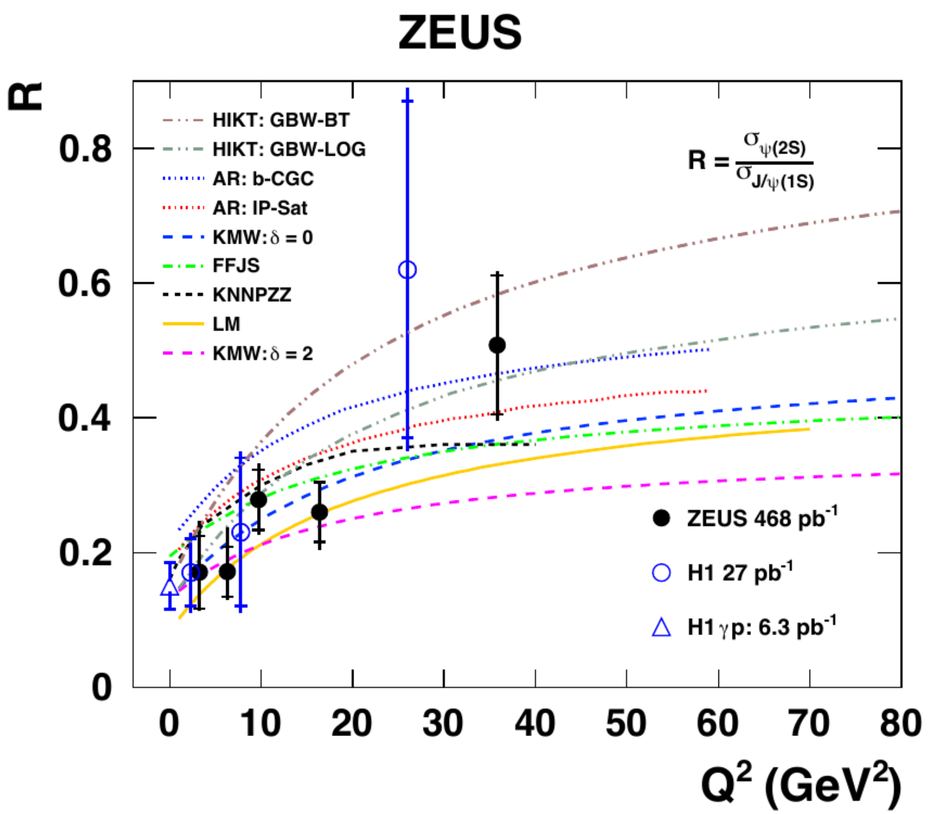


Exclusive vector-meson production

Exclusive electroproduction of vector meson

- Measure ratio of ψ(2s) over J/ψ(1s) as function of Q^2





- Identify VM in $\mu^+\mu^-$ decay channels
  - $30 < W < 210$ GeV, $|t| < 1\text{GeV}^2$
- Compare against various models for
  - Generating cc-dipole in photon
  - cc-dipole scattering amplitude
  - Probability to form vector charmonium

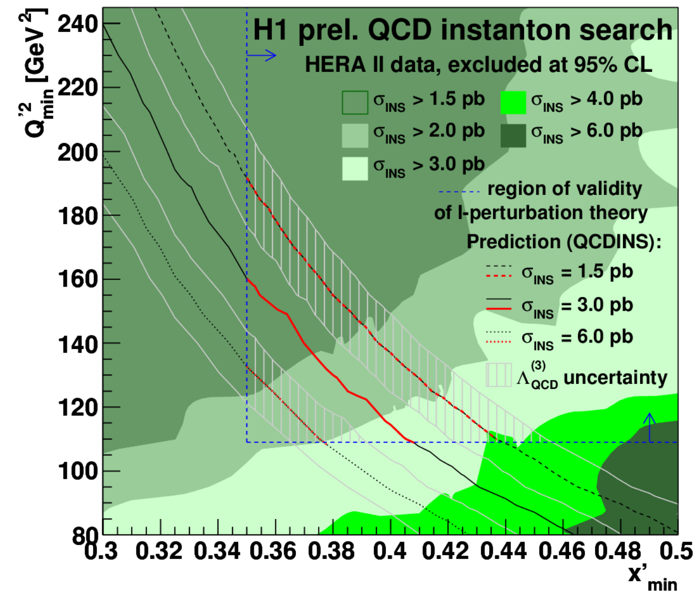
All models perform reasonably well

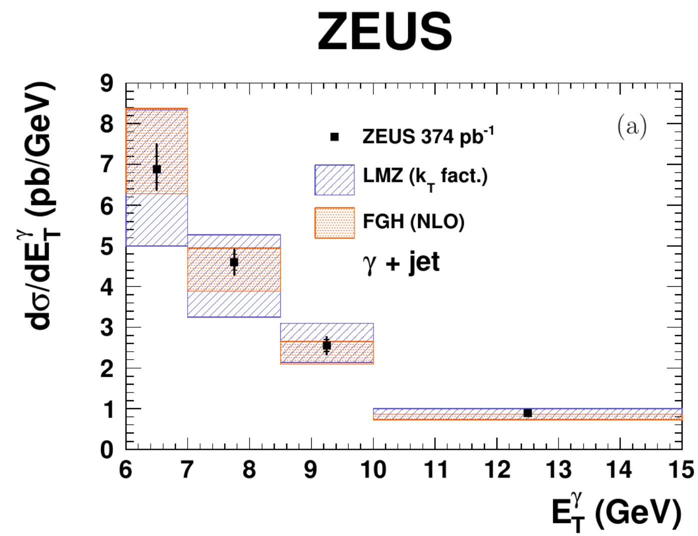
- Ratio tend to be constant vs. W and |t|
- Spread indicate large theory uncertainty

Wealth of more QCD related measurements

New measurements, old measurements, and maybe forgotten ones...

- Search for QCD instantons
  to be published by H1
- Isolated photons in photoproduction
  PLB 730 C (2014) 293 & JHEP 08 (2014) 03
- Exclusive ρ^0 Meson Photoproduction with a Leading Neutron at HERA
  Eur.Phys.J.C76 (2016) 1
- Elastic and Proton-Dissociative Photoproduction of J/psi Mesons at HERA
  Eur.Phys.J.C73 (2013) 2466
- Event shapes
  Nucl. Phys. B 767 (2007) 1, EPJ C46 (2006) 343
- Numberous D* measurements
  JHEP 1509 (2015) 149, ...
- Carged particle production spectra
  Eur.Phys.J.C73 (2013) 2406
- ....





Conclusion

HERA inclusive DIS cross sections finalized

- One consistent dataset of all HERA structure function data
- HERAPDF2.0 as HERA-only PDF
- Baseline data for future PDF fits

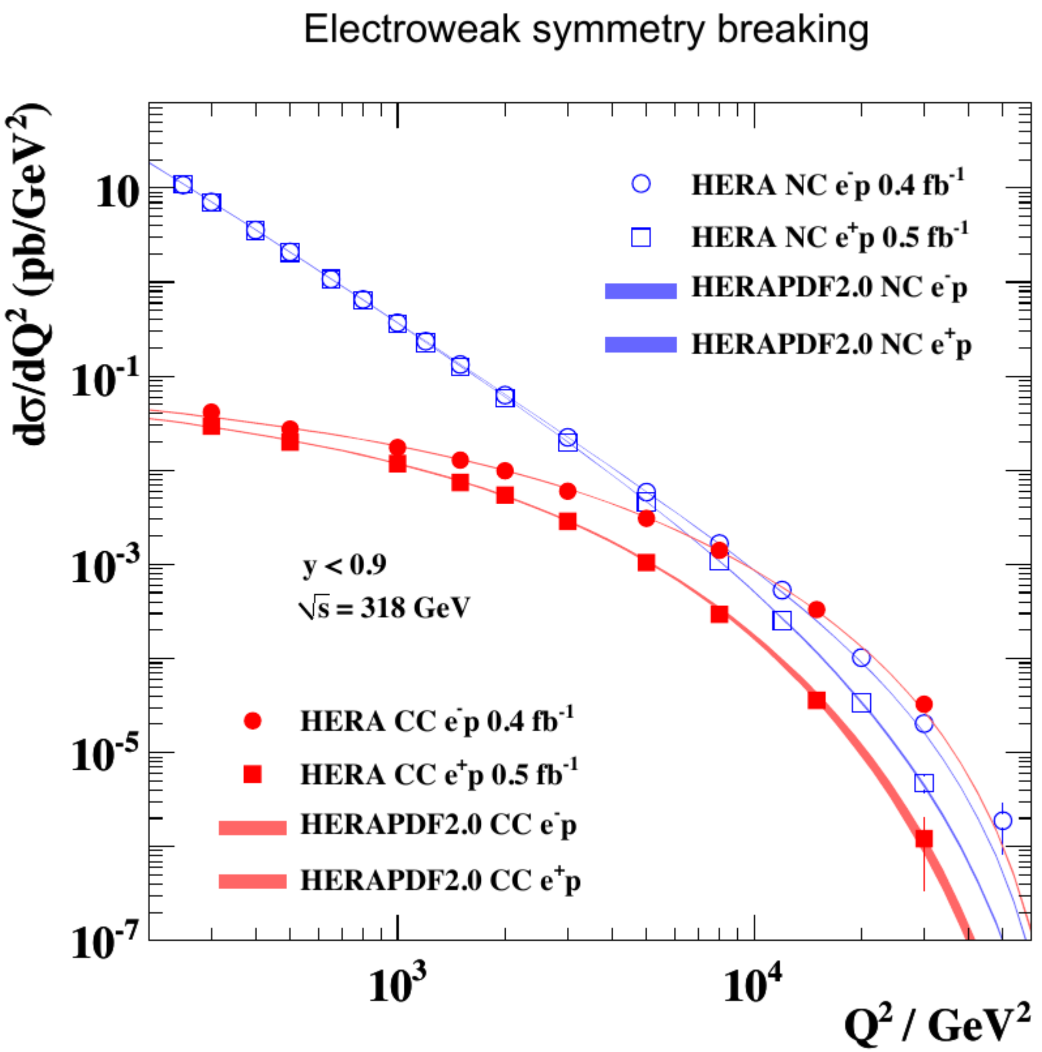
Wealth of precision QCD measurements
Many topics not covered in this short talk

- Jet and photon cross sections
- Various searches and limits
- Strong diffractive DIS programme
- Many exclusive final states measured with full HERA-II statistics
- low-x and soft physics

HERA experiments still active

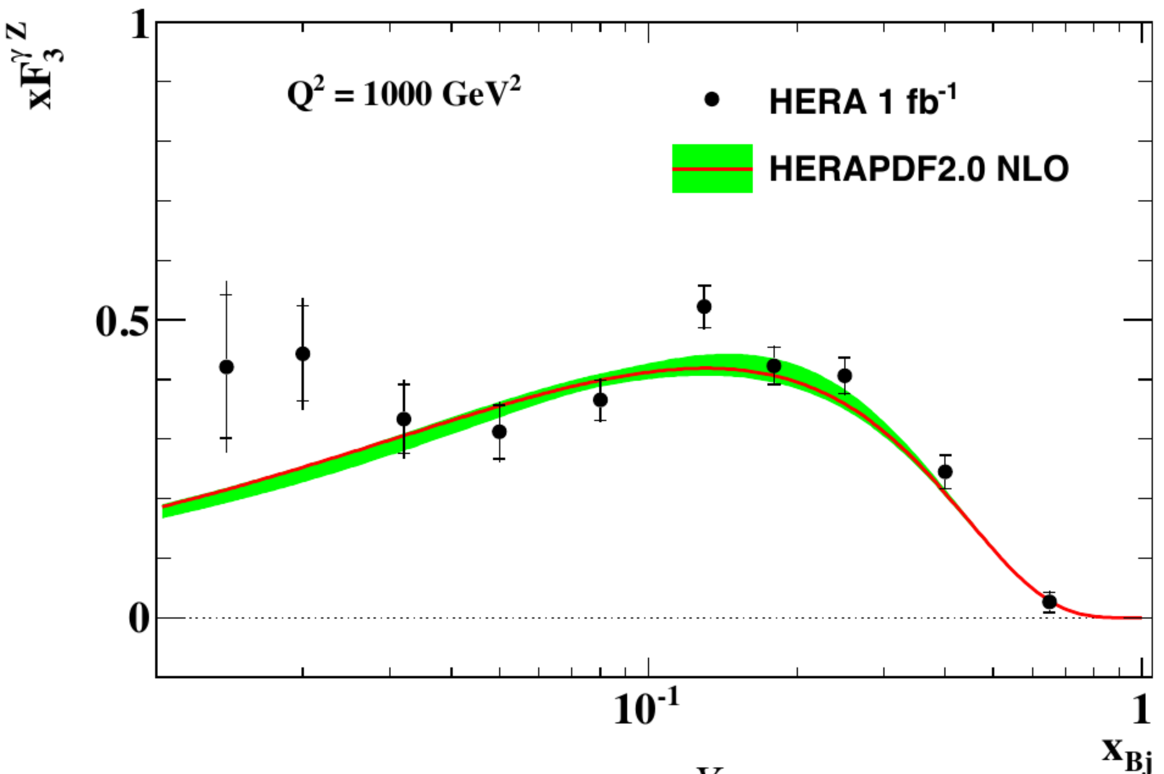
- Improved/new measurements can still be expected this year

Electroweak symmetry breaking



- H1 / ZEUS completed their final SF measurements
- New HERA-II data provide tighter constraints at high x / Q^2
- These data provide some of the most stringent constraints on PDFs
- Stress-test of QCD over 4 orders of mag. in Q^2
- DGLAP evolution works very well
- HERA data provide a self-consistent data set for complete flavour decomposition of the proton
- Final combination of HERA data completed
- HERAPDF2.0 QCD fit at NLO & NNLO

Valence quarks and xF3



At high Q^2 xF_3 arises due to Z^0 effects
enhanced e^- cross section wrt e^+
Difference is xF_3
Sensitive to valence PDFs

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\tilde{\sigma}_{NC}^- - \tilde{\sigma}_{NC}^+) \approx a_e \chi_Z x F_3^{\gamma Z}$$

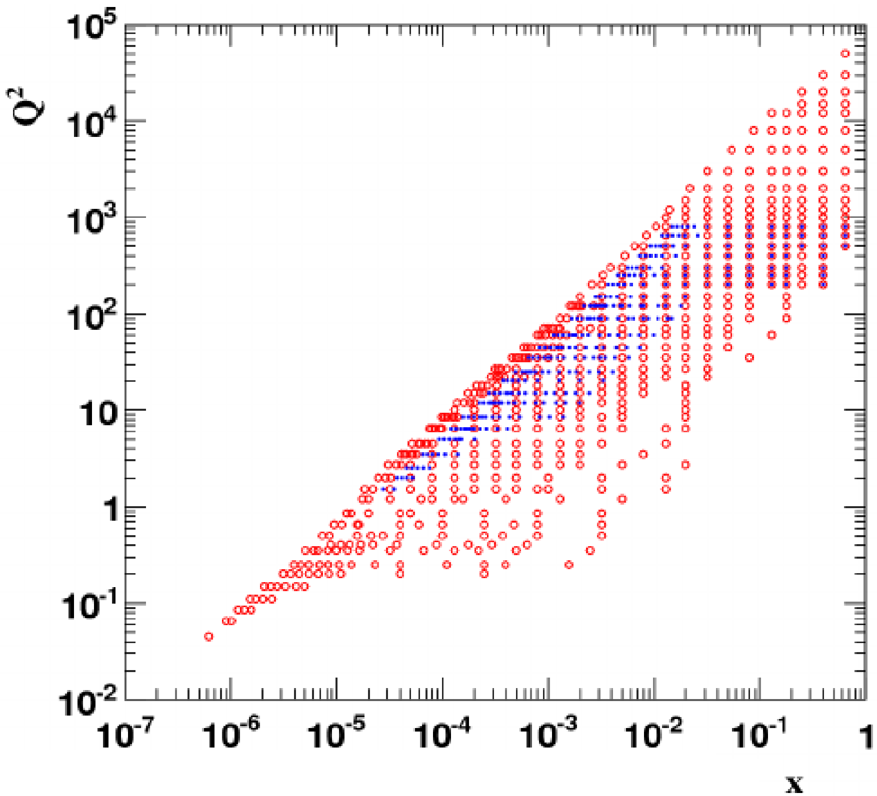
$$x\tilde{F}_3 \propto \sum (xq_i - x\bar{q}_i)$$

Measure integral of $xF_3^{\gamma Z}$ - validate sumrule:

$$\int_{0.016}^{0.725} \mathrm{d}x\ F_3^{\gamma Z}(x, Q^2 = 1\,500\,\mathrm{GeV}^2) = 1.314 \pm 0.057(\mathrm{stat}) \pm 0.057(\mathrm{syst})$$

LO integral predicted to be $5/3 + \mathcal{O}(\alpha_S/\pi)$

'Swimming' of data points

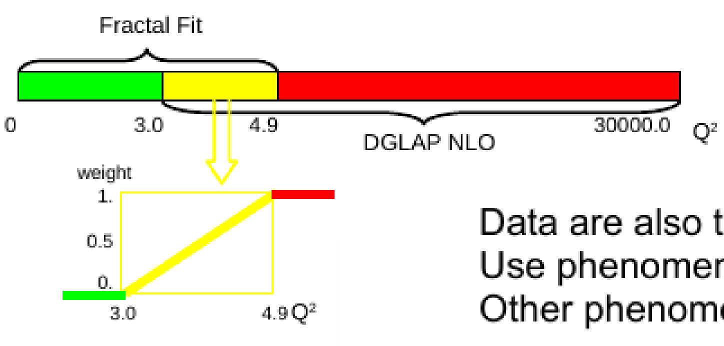


Data are combined onto a common x,Q^2 grid
Two grids used:
- inclusive measurements $\sqrt{s}$=318 GeV
- fine x grid for $\sqrt{s}$=251 & 225 GeV

2927 data points → 1307 combined measurements

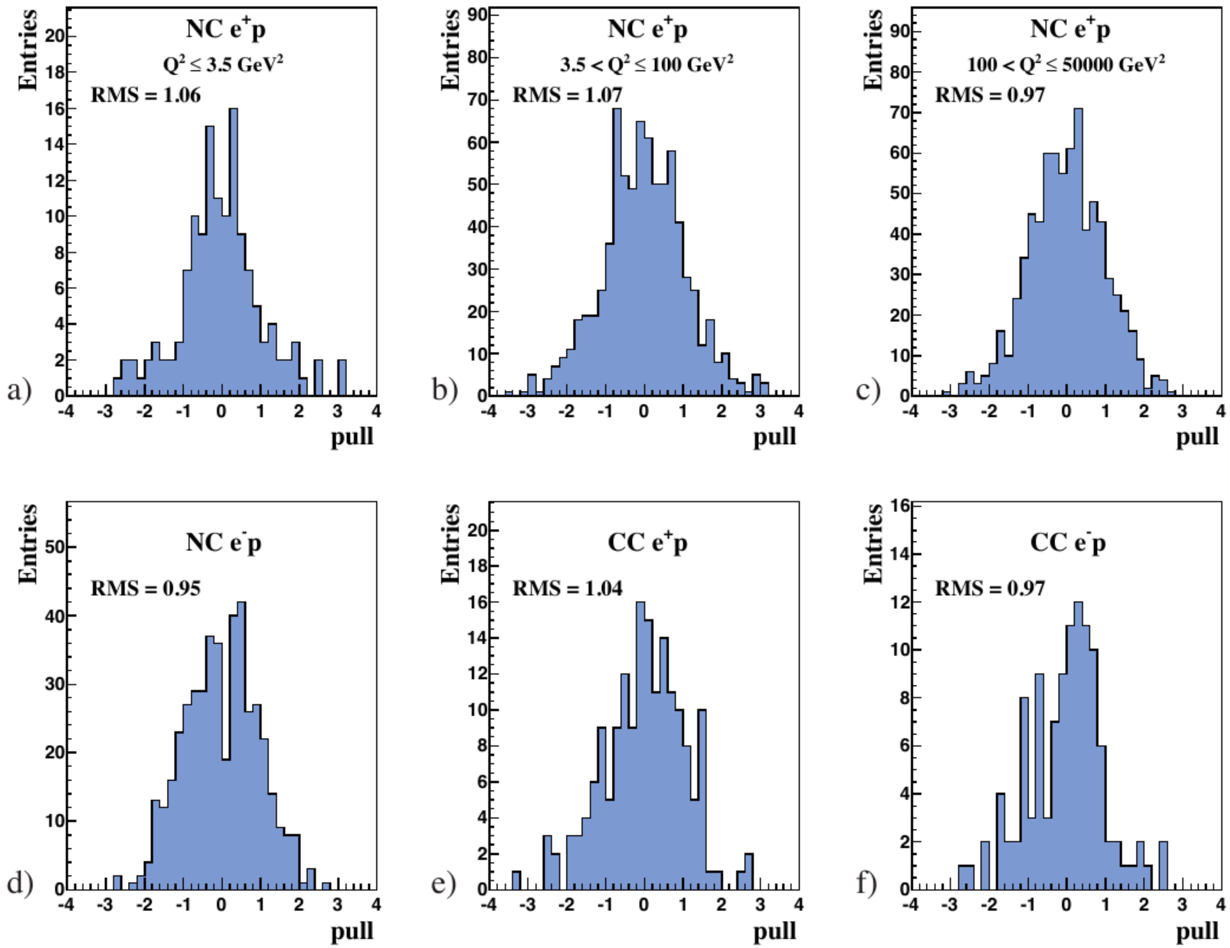
Data are translated to nearest x,Q^2 grid point
Iterative process using NLO QCD fit to data
Use uncombined data in first iteration
Then combined data in later iterations
No changes after 3 iterations

$$\sigma(x_{grid}, Q^2_{grid}) = \frac{\sigma_{model}(x_{grid}, Q^2_{grid})}{\sigma_{model}(x_{meas}, Q^2_{meas})} \cdot \sigma_{meas}(x_{meas}, Q^2_{meas})$$



Data are also translated outside of region of DGLAP fit validity $Q^2 < 3.0$ GeV^2
Use phenomenological “fractal” model and interpolate to DGLAP region
Other phenomenological fits tested → negligible differences

H1 & ZEUS data combination II



Overall χ^2/ndf = 1685 / 1620 = 1.04

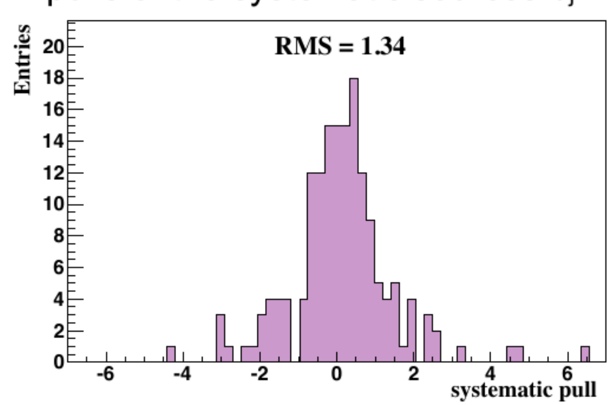
Pulls defined for each measurement difference between measured & average values after applying sys shifts b_j in units of uncorrelated uncertainty

Pulls of the data points should be distributed as a unit Gaussian

Each measurement channel shows pull centred on zero & unit width

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

pulls of the systematic sources b_j



PDF extraction from data: HERAPDF2.0

<u>HERAPDF1.0 & 1.5</u>
Combine NC and CC HERA-I data from H1 & ZEUS
Complete MSbar NLO fit
NLO: standard parameterisation with10 parameters
NNLO HERAPDF 1.5 with 14p

<u>HERAPDF2.0</u>
Include additional NC and CC HERA-II combined data
Complete MSbar NLO and NNLO fit
NLO & NNLO fits require15 parameters

$$xf(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C \cdot (1 + Dx + Ex^2)$$

xg	xg
xu_v	$xU = xu + xc$
xd_v	$xD = xd + xs$
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$

$\longrightarrow$

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

HERAPDF1.0 & NLO HERAPDF1.5

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

HERAPDF2.0

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

Apply momentum/counting sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

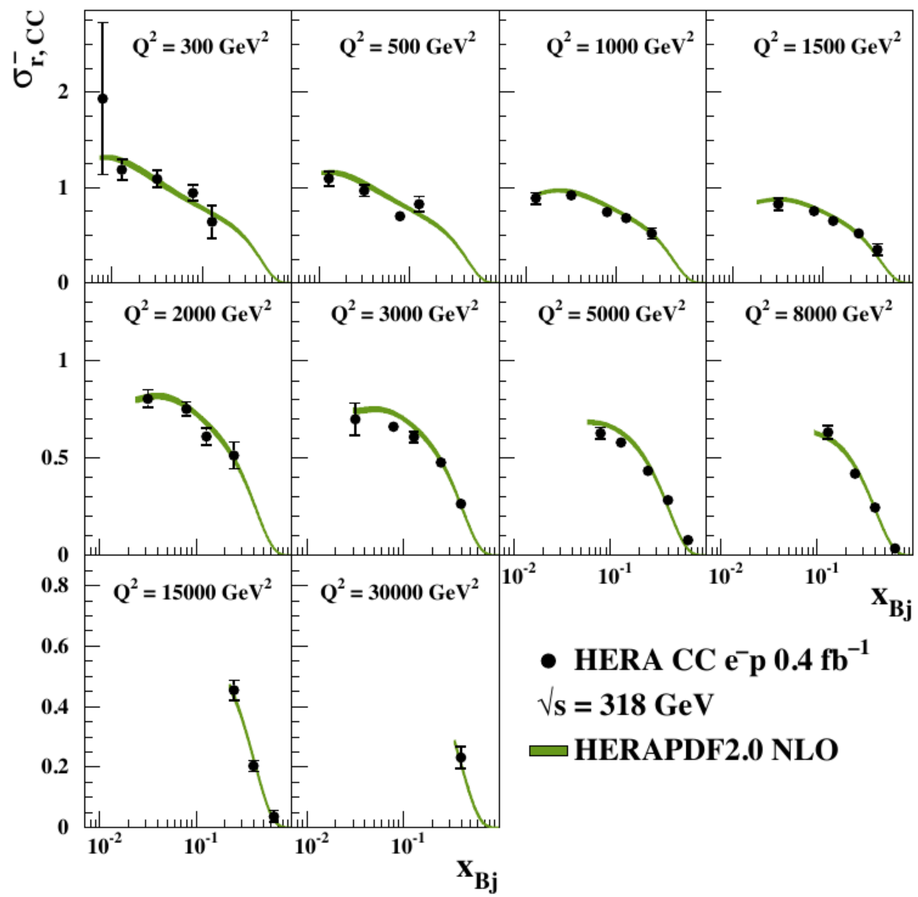
$B_{\bar{U}} = B_{\bar{D}}$
$Sea = 2(\bar{U} + \bar{D})$
$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$
ensures $x\bar{u} \to x\bar{d}$ as $x \to 0$

$Q_0^2 = 1.9$
$Q^2_{\min} = 3.5$ or $10\ GeV^2$
$\alpha_s(M_z^2) = 0.118$
$2 \cdot 10^{-4} \le x \le 0.65$

High Q^2 charged current cross sections

Electron scattering

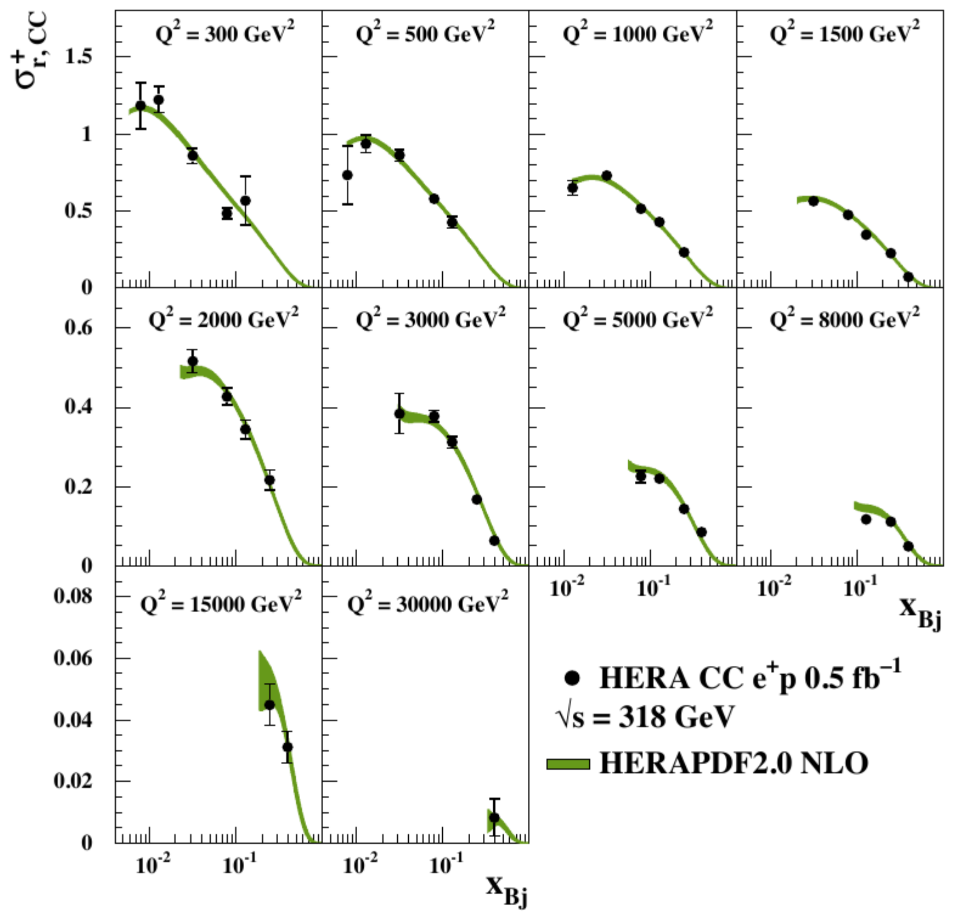
$$\frac{d^2\sigma^-_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \left[(u+c)+(1-y)^2(\bar{d}+\bar{s})\right]$$



Combination of high Q^2 CC data (HERA-I+II)
Improvement of total uncertainty
Dominated by statistical errors
Provide important flavour decomposition information

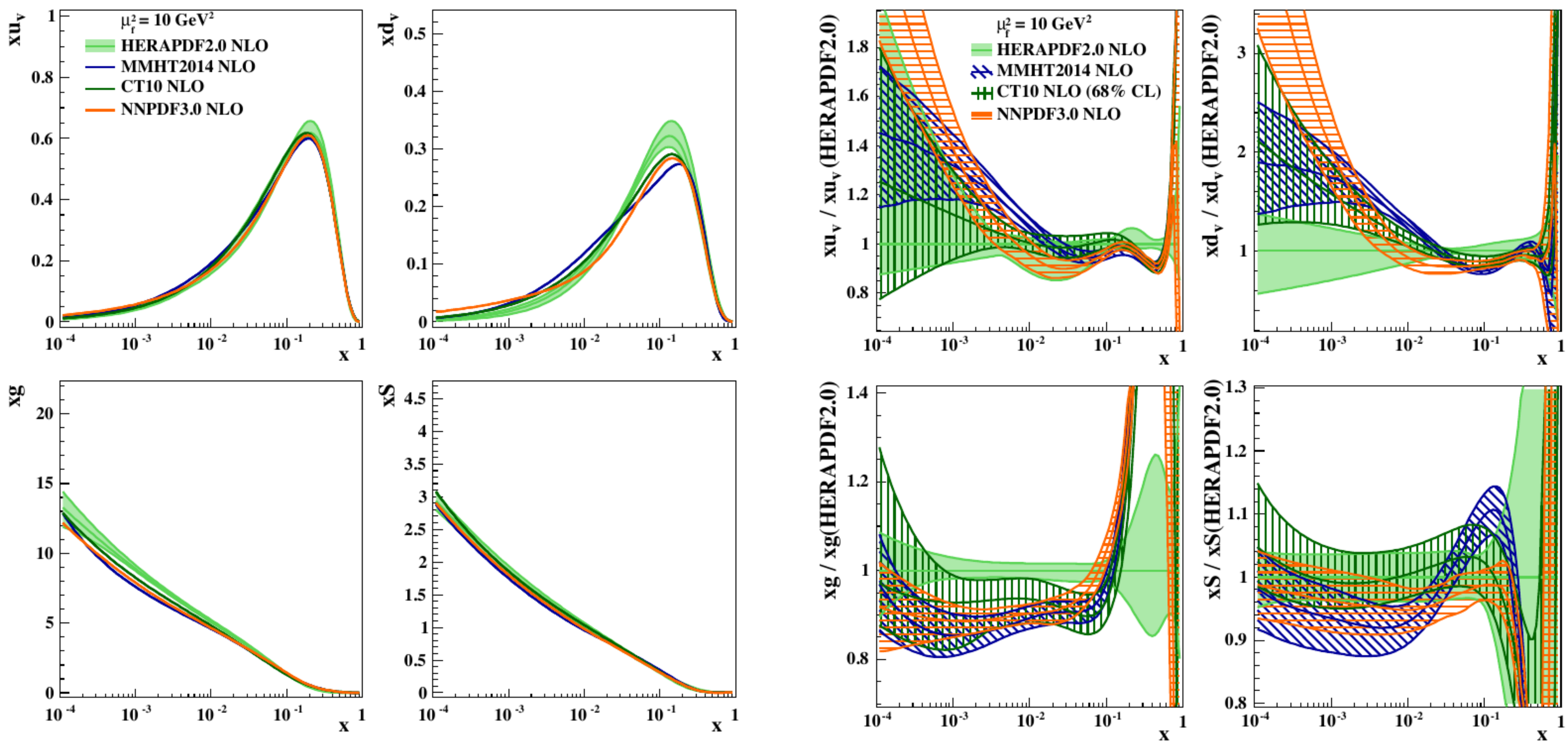
Positron scattering

$$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \left[(\bar{u}+\bar{c})+(1-y)^2(d+s)\right]$$



CC e+ data provide strong d_v constraint at high x
Precision limited by statistics: typically 3-7%
HERA-I precision of 10-15% for e+p

HERAPDF2.0 comparisions

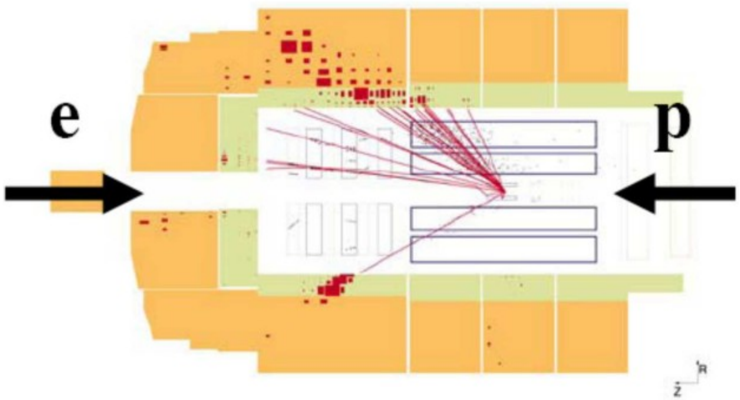


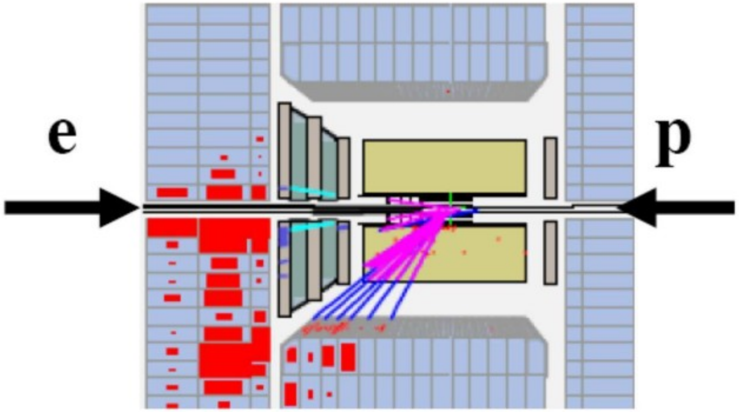
Comparison of HERAPDF2.0 vs MMHT14 , NNPDF3.0 , CT10 (others use only HERA-1 combined data)

Differences at high x

- New HERA combined data improve precision at high x, Q^2
- HERAPDF uses proton target data only → no nucleon / deuterium data
- Softer gluon at high x

NC and CC measurements





Neutral current event selection:

High P_T isolated scattered lepton
Suppress huge photo-production background by imposing longitudinal energy-momentum conservation

Kinematics may be reconstructed in many ways:
energy/angle of hadrons & scattered lepton
provides excellent tools for sys cross checks

Removal of scattered lepton provides a
high stats "pseudo-charged current sample"
Excellent tool to cross check CC analysis

Final selection: ~10^5 events per sample at high Q^2
~10^7 events for $10 < Q^2 < 100$ GeV^2

Charged current event selection:

Large missing transverse momentum (neutrino)

Suppress huge photo-production background

Topological finders to remove cosmic muons

Kinematics reconstructed from hadrons

Final selection: ~10^3 events per sample

slide by E. Rizvi

Heavy flavor schemes

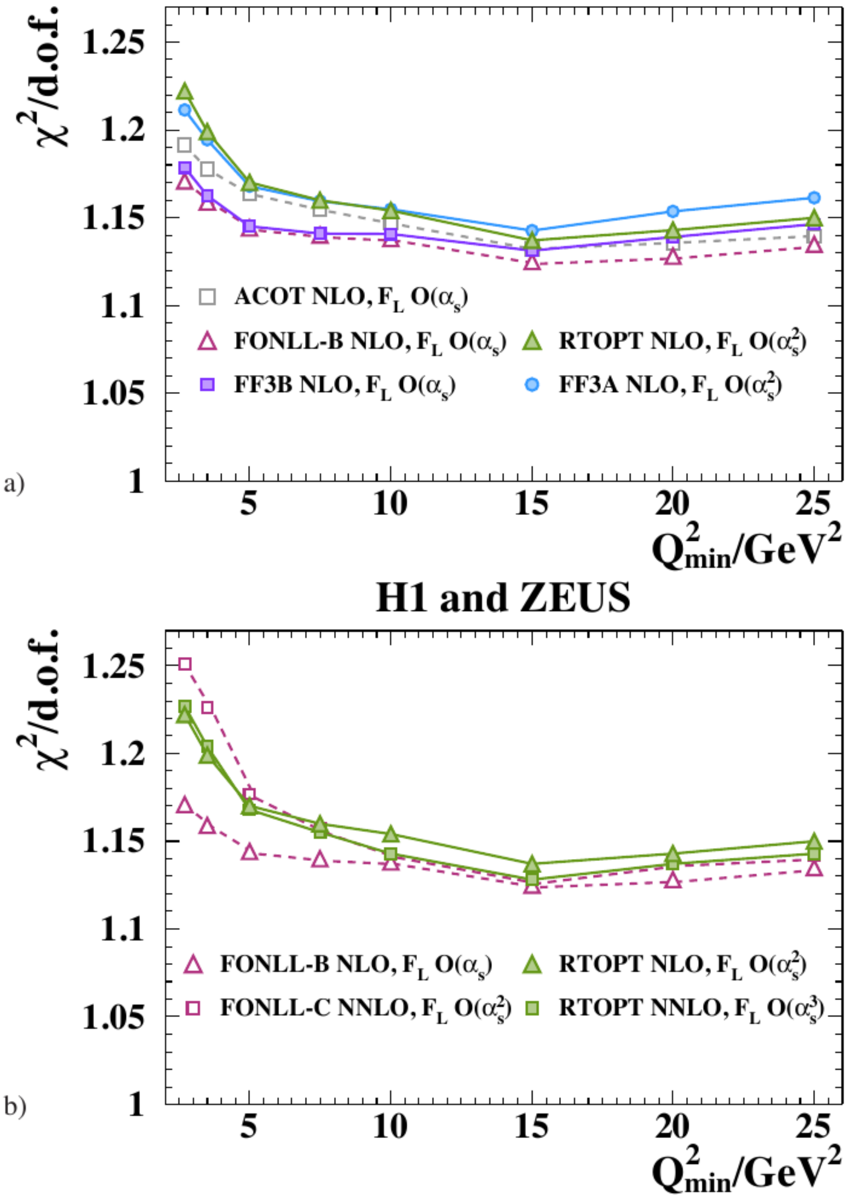
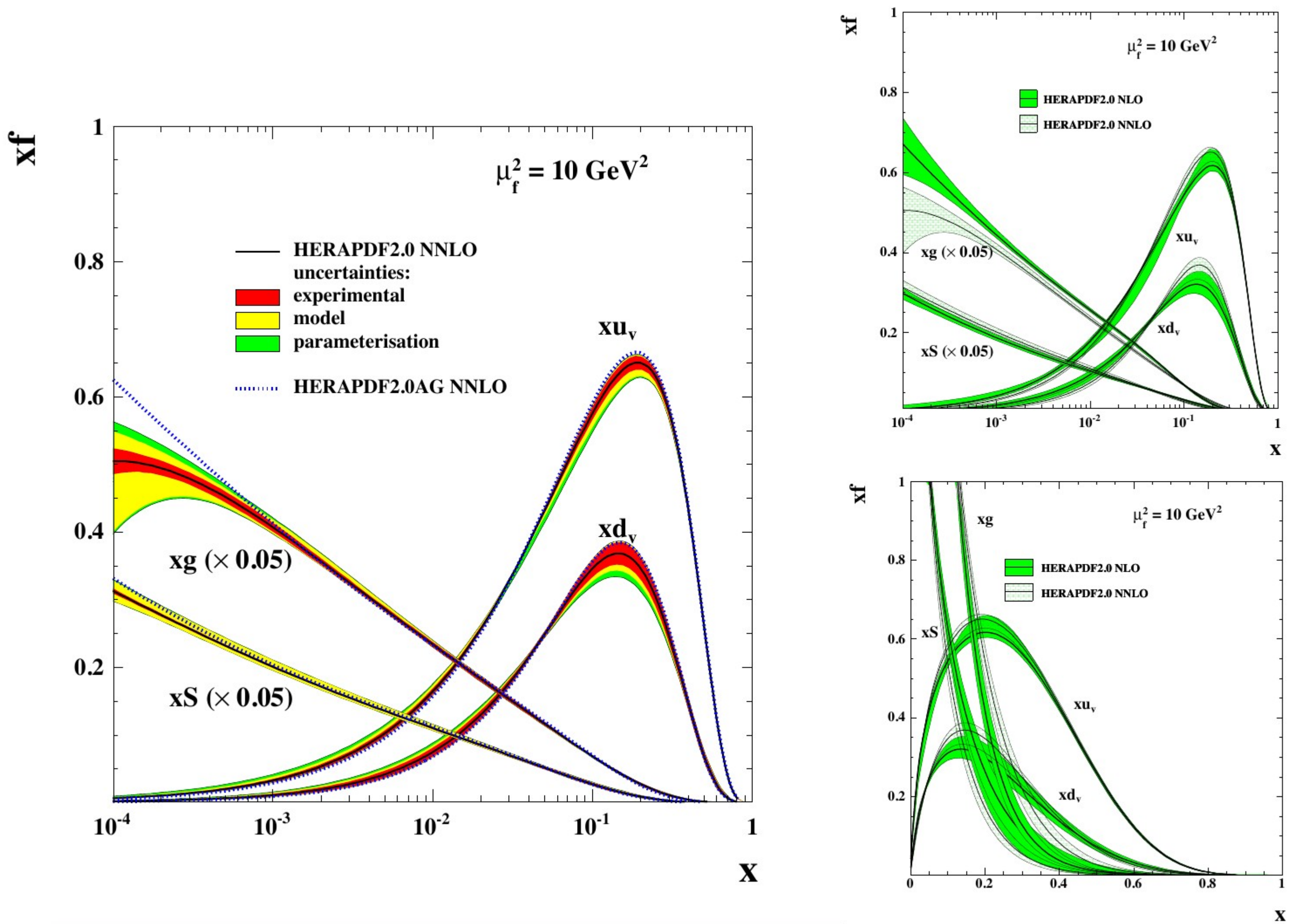


Figure 20: The dependence of χ^2/d.o.f. on $Q^2_{\rm min}$ for HERAPDF2.0 fits using a) the RTOPT [83], FONNL-B [90], ACOT [109] and fixed-flavour (FF) schemes at NLO and b) the RTOPT and FONNL-B/C [91] schemes at NLO and NNLO. The F_L contributions are calculated using matrix elements of the order of α_s indicated in the legend. The number of degrees of freedom drops from 1148 for $Q^2_{\rm min} = 2.7\,{\rm GeV}^2$ to 1131 for the nominal $Q^2_{\rm min} = 3.5\,{\rm GeV}^2$ and to 868 for $Q^2_{\rm min} = 25\,{\rm GeV}^2$.

HERAPDF2.0 NLO vs. NNLO



HERAPDF2.0 variants

The following variants of the HERAPDF2.0 PDFs have been released and will soon be available on LHAPDF (https://lhapdf.hepforge.org)

HERAPDF2.0 (NLO,NNLO, Q^2_{min}=3.5 GeV^2) "Default PDF set"

- Data: combined HERA NC and CC inclusive cross sections
- HF Scheme: ROPT
- $\alpha_s(M_Z^2)=0.118$
- Grid with different $\alpha_s(M_Z^2)$ values (in the range [0.110-0.130] in steps of 0.01) are also released

HERAPDF2.0HiQ2 (NLO,NNLO) "High-Q^2 version"

- as HERAPDF2.0 but with Q^2_{min}= 10 GeV^2

HERAPDF2.0AG (LO,NLO,NNLO, Q^2_{min}=3.5 GeV^2) "Alternative Gluon"

- Data: combined HERA NC and CC inclusive cross sections
- Use an alternative gluon parameterisation
- HF Scheme: ROPT
- $\alpha_s(M_Z^2)=0.130$ (LO) and $\alpha_s(M_Z^2)=0.118$ (NLO,NNLO)

HERAPDF2.0FF (NLO, Q^2_{min}=3.5 GeV^2) "FF Schemes"

- Data: combined HERA NC and CC inclusive cross sections
- HF Schemes: Use two alternative (**FF3A** and **FF3B**) Fixed-Flavour schemes
- $\alpha_s(M_Z^2)^{Nf=3}=0.106573$ equivalent to $\alpha_s(M_Z^2)^{Nf=5}=0.118$(FF3A) and $\alpha_s(M_Z^2)=0.118$ (FF3B)

HERAPDF2.0Jets (NLO, Q^2_{min}=3.5 GeV^2) "Charm and Jets"

- Data: combined HERA NC and CC inclusive cross sections and selected HERA charm and jet production measurements
- HF Schemes: ROPT
- free $\alpha_s(M_Z^2)$ or $\alpha_s(M_Z^2)=0.118$