PDFs and hard QCD at HERA

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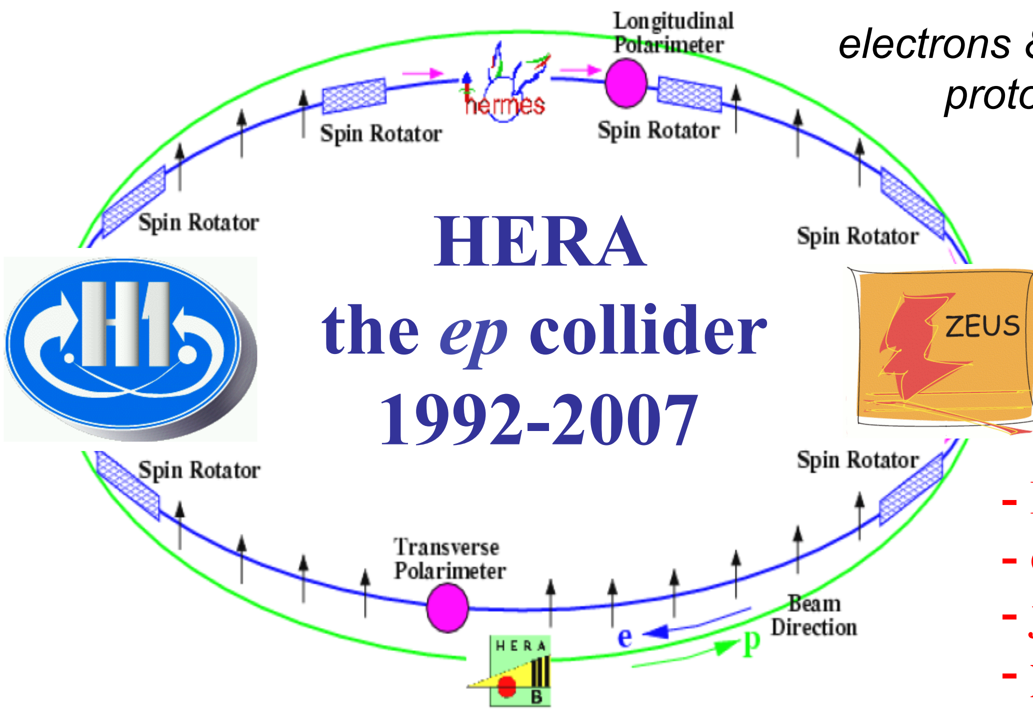
on behalf of the H1 and ZEUS Collaborations



electrons & positrons of E_e=27.5 GeV collided with protons of E_p = 920, 820, 575 and 460 GeV. Two multi-purpose collider experiments H1 & ZEUS collected in total 1 fb^{-1}.

- **Combination of all inclusive NC&CC data from H1&ZEUS at HERA**
- F_2, $xF_3^{\gamma Z}$, $(F_2^{\gamma Z}, F_L, \sigma_{CC}^{tot}, ...)$
- **HERAPDF 2.0 PDF set and its variants**
- **charm production and combination of D***
- **jet production and α_s; multi-jets at low Q^2**
- **prompt photon & jet production in DIS**

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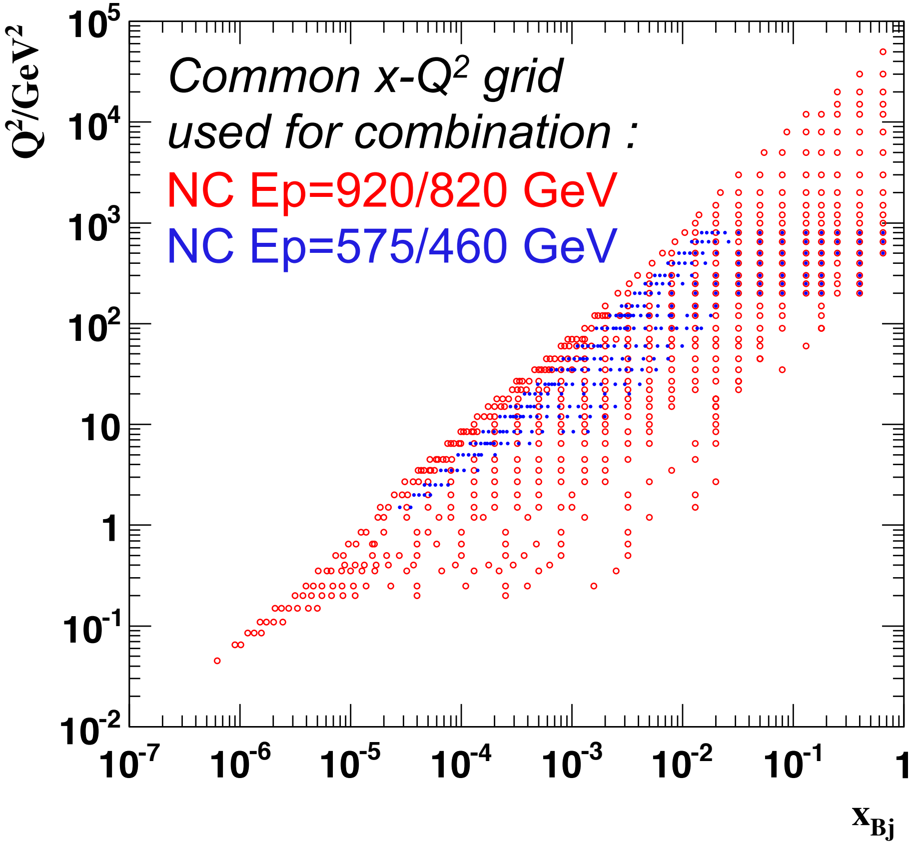
NC and CC inclusive data sets at HERA

41 NC and CC data sets from H1 and ZEUS corresponding to 1 fb^{-1}
$0.045 \leq Q^2 \leq 50000$ GeV^2, $6\ 10^{-7} \leq x \leq 0.65$

H1 and ZEUS



21 data sets from HERA I
NC & CC at E_p=920 and 820 GeV
and 20 data sets from HERA II (2003-2007)
12 NC & CC sets at E_p= 920 GeV
4 NC sets at E_p= 575 GeV
4 NC sets at E_p= 460 GeV

These data are collected over 15 years with changing beams and detectors conditions and different focus.
It is important to handle them properly, e.g. in view of possible correlations

→ combine them into one coherent data set as it was done for HERA I before
(JHEP 1001:109, 2010 and HERAPDF 1.0)

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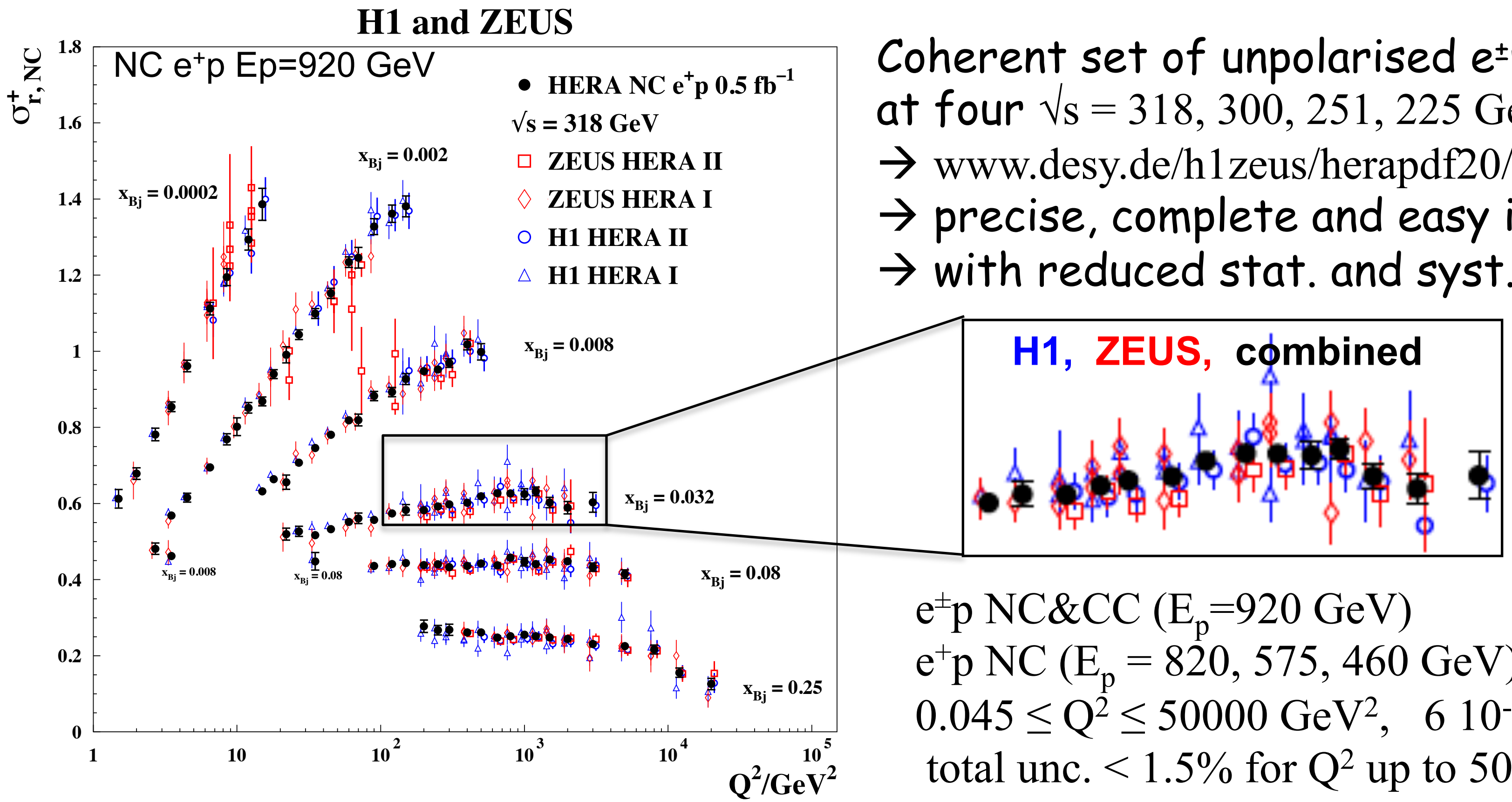
Averaging of all NC and CC data at HERA

2927 cross sections are combined to 1307 points with 169 correlated systematic errors and χ^2/d.o.f. = 1685/1620



Coherent set of unpolarised $e^{\pm}p$ NC&CC at four $\sqrt{s}$ = 318, 300, 251, 225 GeV:

→ www.desy.de/h1zeus/herapdf20/

→ precise, complete and easy in use

→ with reduced stat. and syst. errors

$e^{\pm}p$ NC&CC (E_p=920 GeV)

$e^{+}p$ NC (E_p = 820, 575, 460 GeV)

$0.045 \le Q^2 \le 50000$ GeV^2, $6\ 10^{-7} \le x_{Bj} \le 0.65$

total unc. < 1.5% for Q^2 up to 500 GeV^2

→ up to 6 measurements are combined into one averaged point

→ correlated shifts are propogated to all points (even measured by single experim.)

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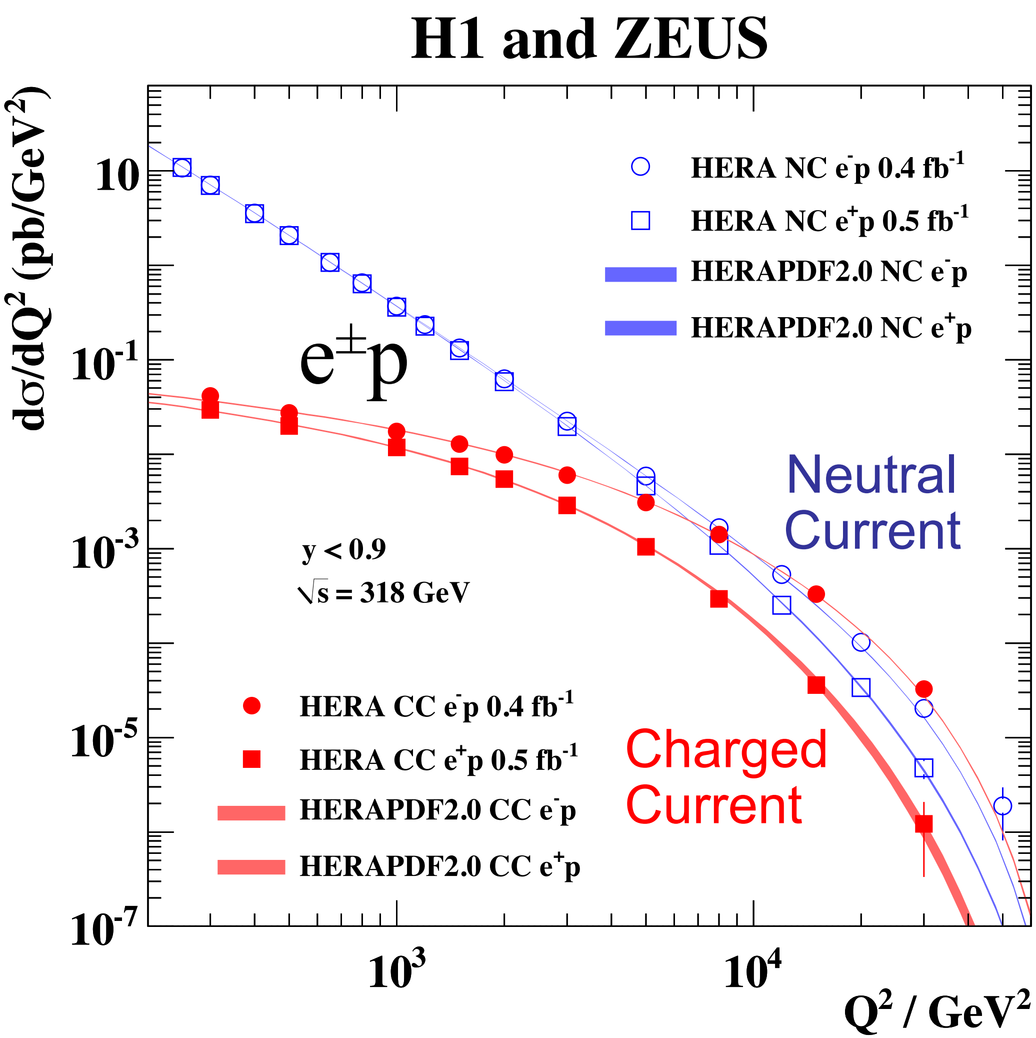
Combined NC and CC $e^{\pm}p$ data



- single differential cross sections are obtained by integration over x of the combined NC and CC $e^{\pm}p$ data at $\sqrt{s}$=318 GeV and y<0.9
- e^+p NC and e^-p NC are the same in the γ-exchange domain at low Q^2 and start to differ at high Q^2 due to γZ interference.
- CC is two orders of magnitude smaller than NC at Q^2=200 GeV^2 and about the same at Q^2 around M_Z^2, M_W^2, demonstrating **electroweak unification.**
- remaining differences in CC are related to u, d content of the proton and to helicity factors.

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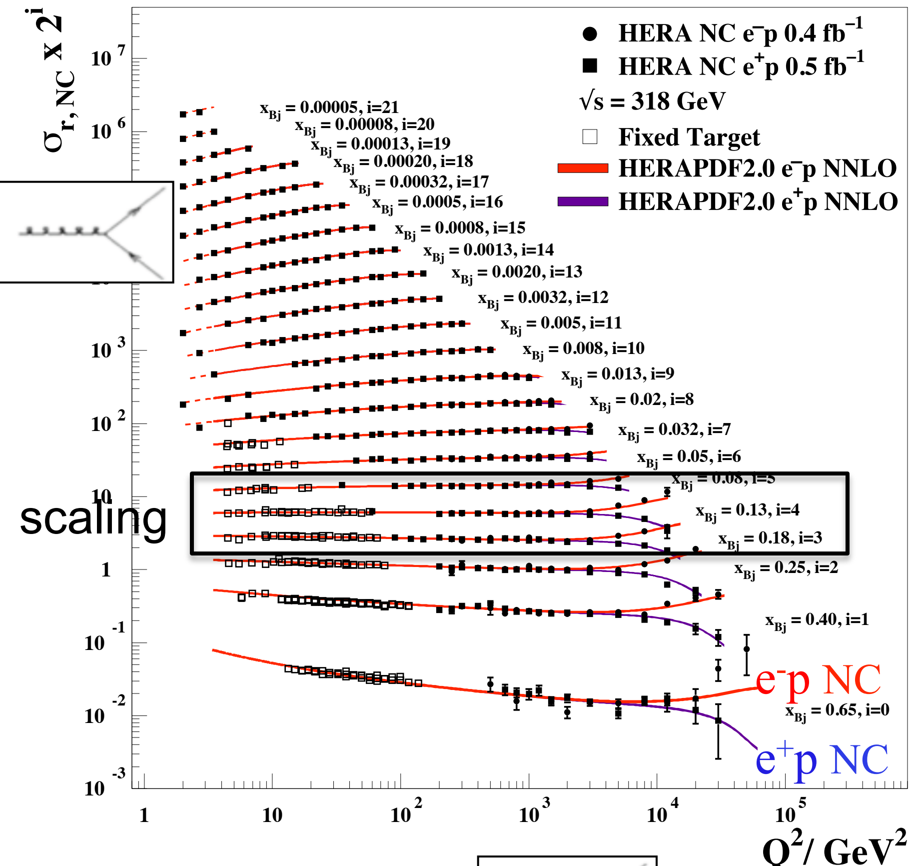
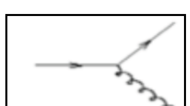
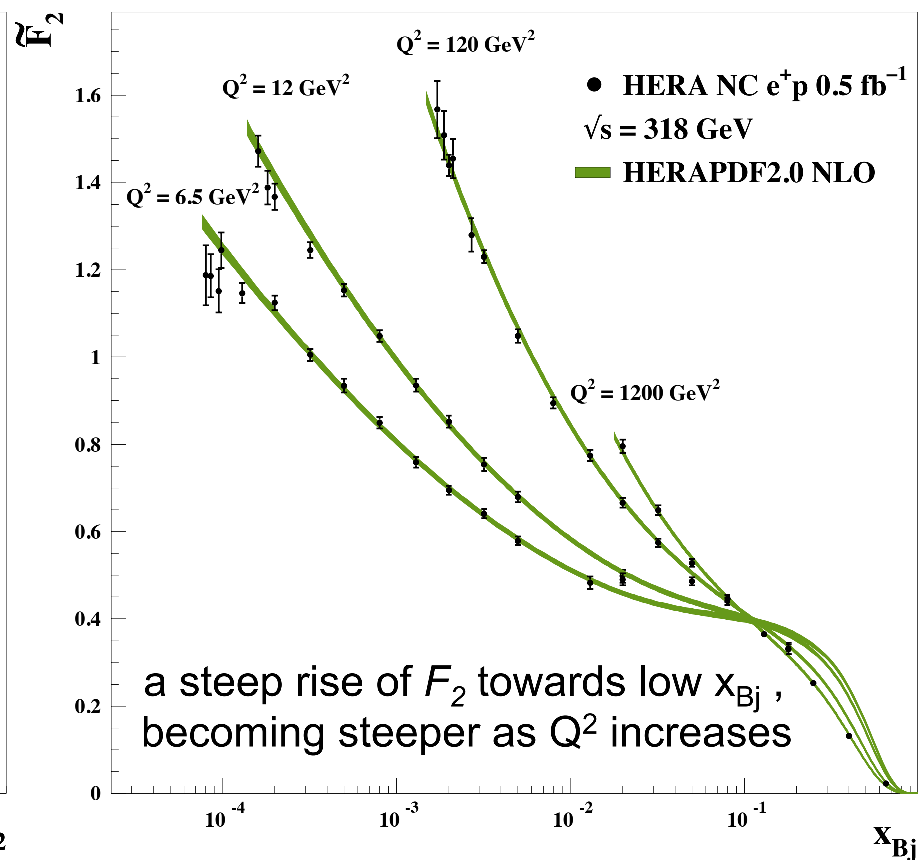
Proton structure function F_2

$$\sigma^{\pm}_{r,\mathrm{NC}} \equiv \frac{d^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{dx\,dQ^2}\,\frac{xQ^4}{2\pi\alpha^2}\,\frac{1}{Y_+} \equiv \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3 \qquad Y_{\pm}=1\pm(1-y)^2$$







F_2 scaling (independence of Q^2) at moderate x and scaling violations at high x_{Bj} and low x_{Bj} due to gluon emission and gluon splitting

ICHEP 2016
Chicago, 5.08.2016

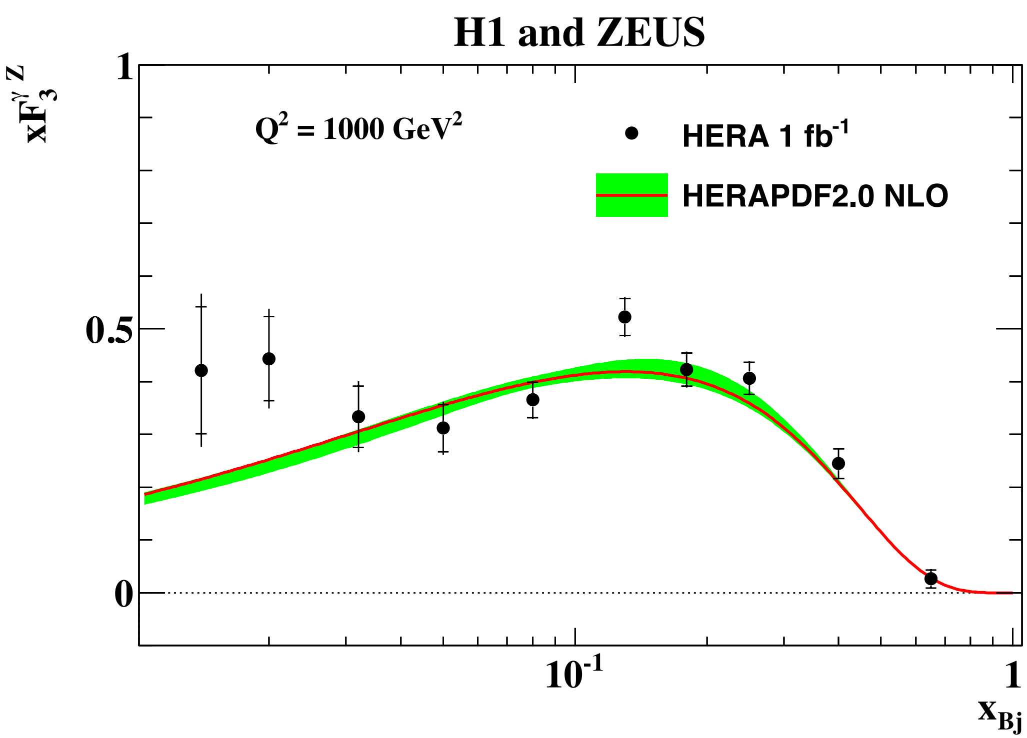
$e^{\pm}p$ NC: lepton charge dependence and xF_3

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}(\sigma^-_{r,\mathrm{NC}} - \sigma^+_{r,\mathrm{NC}})$$

charge asymmetry of $e^{\pm}p$ NC cross sections is mostly due to γZ interference

$$xF_3^{\gamma Z} = -x\tilde{F}_3\,(Q^2 + M_Z^2)/(a_e k\, Q^2)$$

$$\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)$$



transform the $xF_3^{\gamma Z}(x,Q^2)$ measurements to $Q^2 = 1000\ \mathrm{GeV}^2$ and average them to get $xF_3^{\gamma Z}(x)$ at $Q^2 = 1000\ \mathrm{GeV}^2$

→ related to valence quark: $F_3^{\gamma Z} \approx (2u_v + d_v)/3$

→ integration over the measured range $0.016 < x_{Bj}\ 0.725$ gives 1.165+0.042-0.053 for data and 1.314±0.057(stat)±0.057(syst) using HERAPDF2.0

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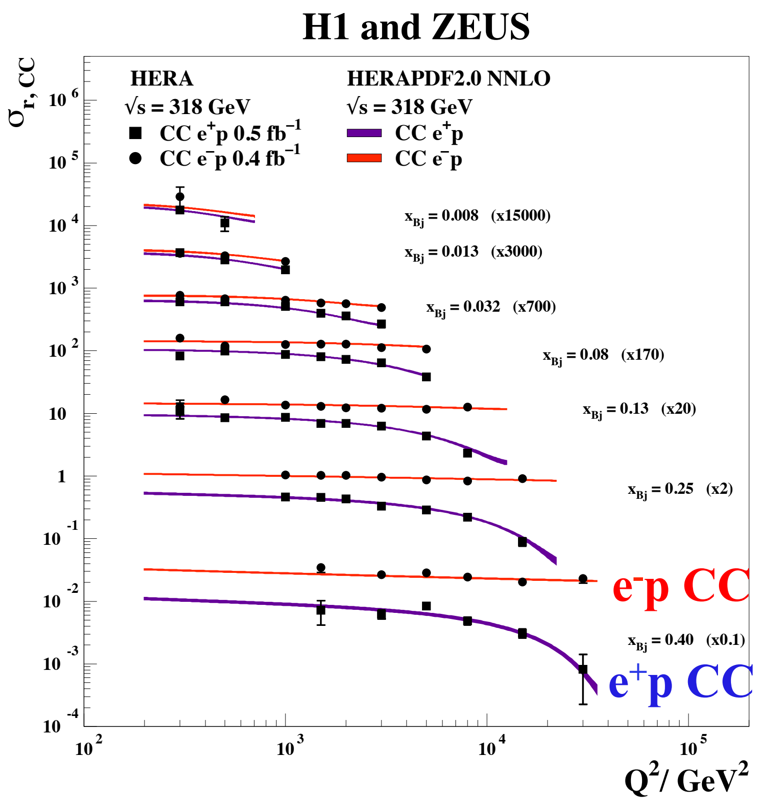
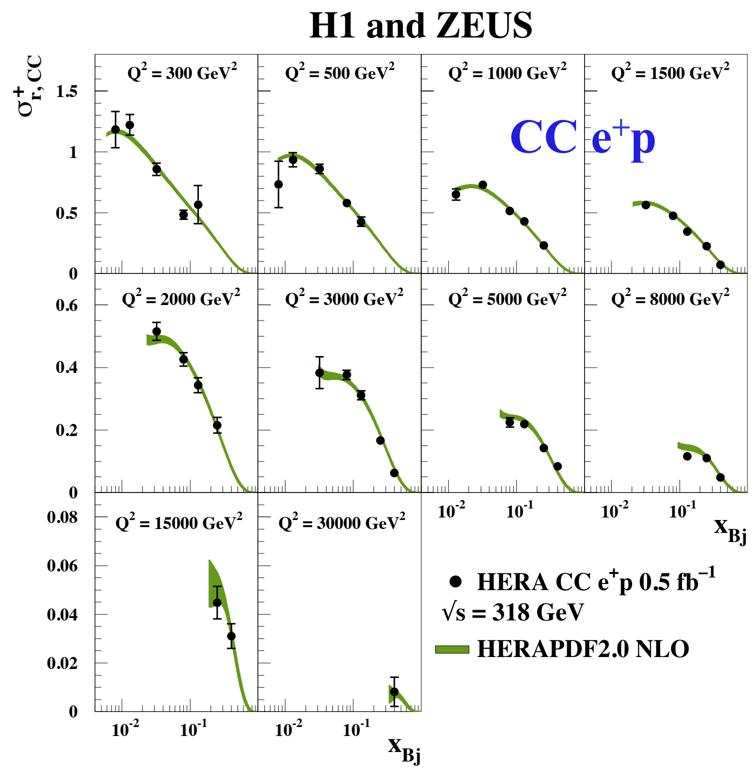
$e^{\pm}p$ CC probe u/d composition of proton

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

$$\sigma^{+}_{r,\mathrm{CC}} \sim (x\bar{u}+x\bar{c}) + (1-y)^2(xd+xs)$$
$$\sigma^{-}_{r,\mathrm{CC}} \sim (xu+xc) + (1-y)^2(x\bar{d}+x\bar{s})$$





e^+p CC at high x is related to d-quark (Q^2 dependence is due to helicity factor $(1-y)^2$)

e^-p CC is dominated by u-quark and depends weakly on Q^2 at given x

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HERAPDF2.0 QCD Fit

The combined $e^{\pm}p$ NC/CC HERA data set is the only input

- no nuclear, heavy target or HT corrections; consistency of data, $\Delta\chi^2 = 1$ criterion
- parametrisation of PDFs at starting scale Q_o^2=1.9 GeV^2 with 14 free parameters

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \qquad x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\left(1+D_{\bar{U}}x\right),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \qquad x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

- **QCD evolution of PDFs using DGLAP equations at NLO and NNLO**
- **Thorne-Roberts general mass variable-flavor-number scheme RTOPT (as used in MMHT)**
- **default Q^2_{min}=3.5 GeV^2, f_s=0.40 ($x\bar{s} = f_s\, x\bar{D}$ at Q_o^2)**
- **M_c and M_b values are optimized using HERA charm and beauty production data**
- **$\alpha_s(M^2_Z)$=0.118 is consistent with HERA jet data**

→ **available at www.desy.de/h1zeus/herapdf20/ and on LHAPDF:**

HERAPDF2.0 at NLO and NNLO
also with a scan of $\alpha_s(M^2_Z)$ from 0.110 to 0.130 in steps of 0.001

additional PDF sets :
- HERAPDF2.0HiQ2 at NLO and NNLO - Q^2_{min}=10 GeV^2
- HERAPDF2.0AG at LO, NLO and NNLO - alternative gluon parameterisation (strictly positive)
- HERAPDF2.0FF3A and FF3B - fixed flavor number schemes at NLO

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Uncertainties of HERAPDF2.0

Three types of PDF uncertainties are considered:

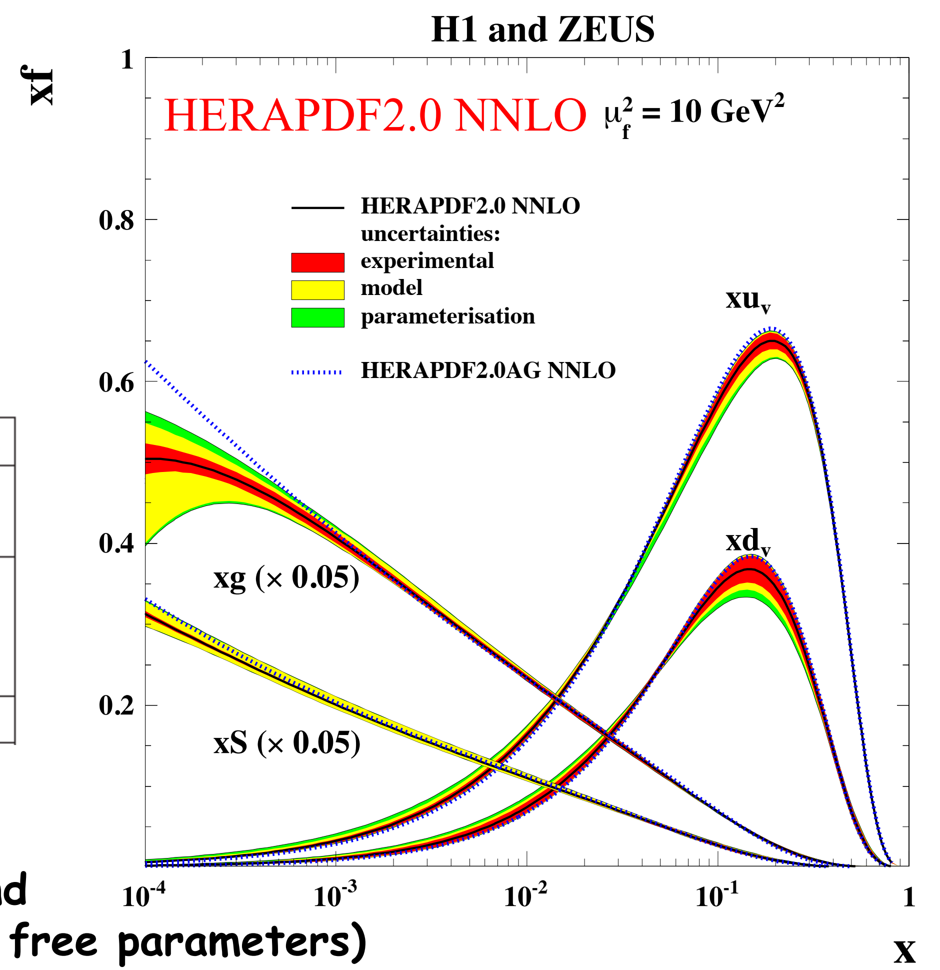
Experimental uncertainty band

- **Hessian method with $\Delta\chi^2$ = 1**
verifyed by MC method - replicas of data

Model uncertainty band

- **variation of model assumptions**

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



Parameterisation uncertainty band

- **variation of the starting scale Q_o^2 and**
- **form of parameterisation (number of free parameters)**

→ *valid in the x-range covered by the QCD fit to HERA data*

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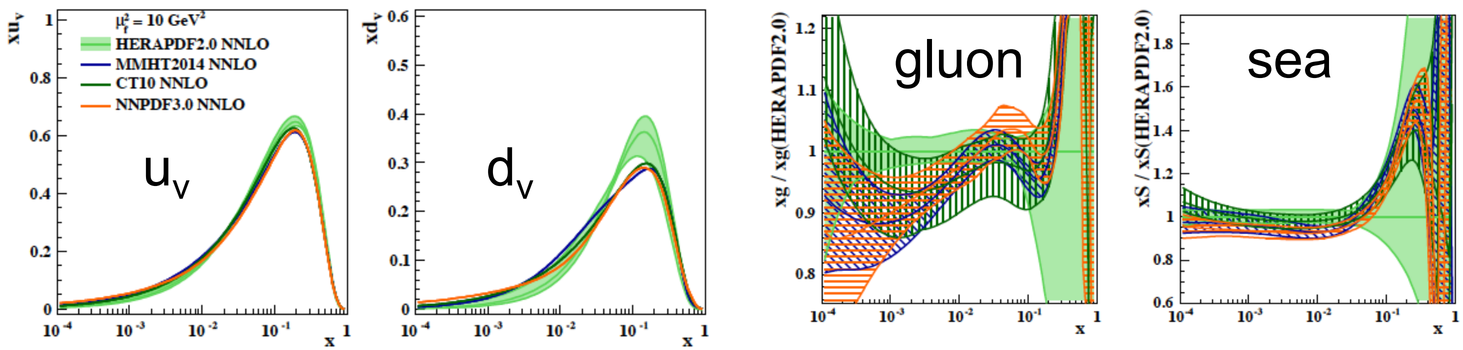
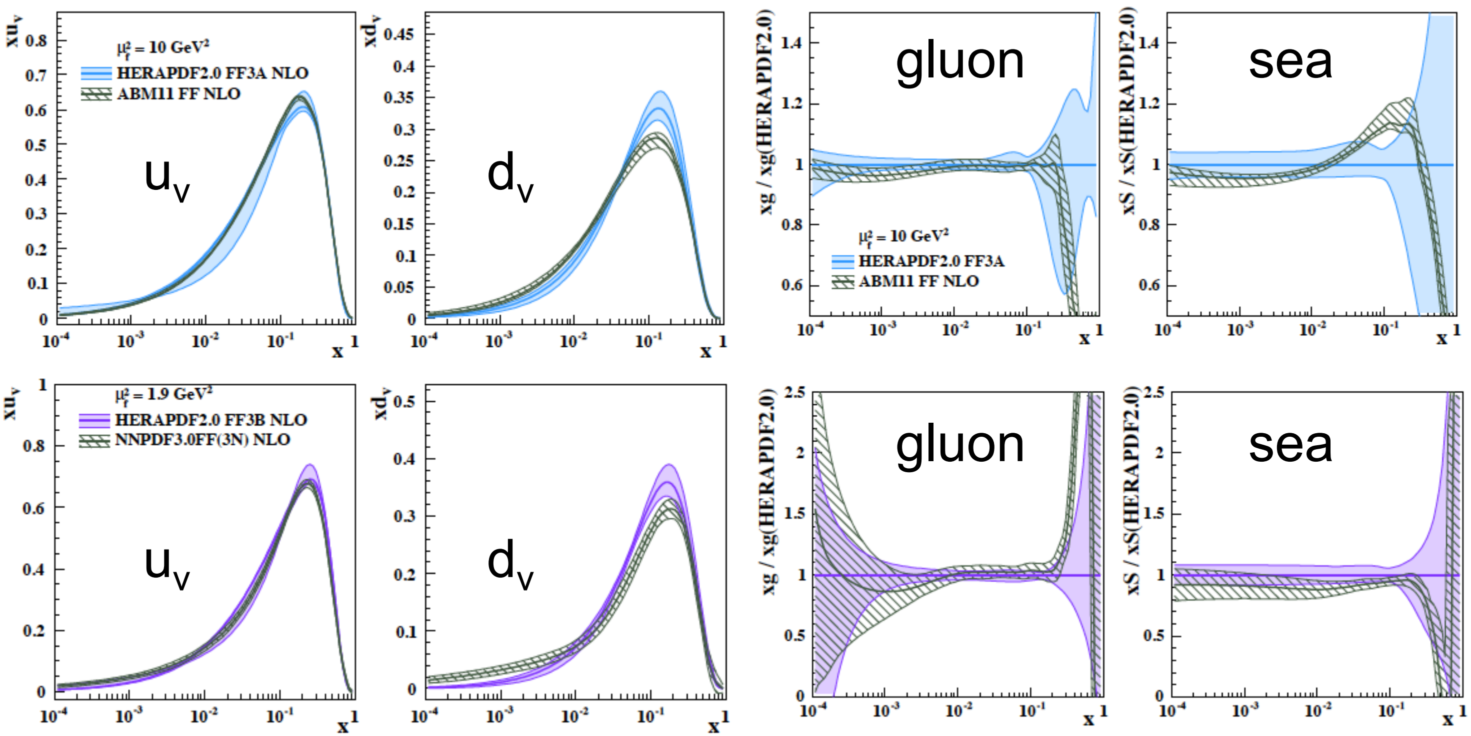
Comparison with modern PDFs from global fits

vs. PDFs using variable-flavor-number scheme: MMHT2014, CT10, NNPDF3.0



vs. PDFs using fixed-flavor-number scheme: ABM11 FF, NNPDF3.0FF(3N)



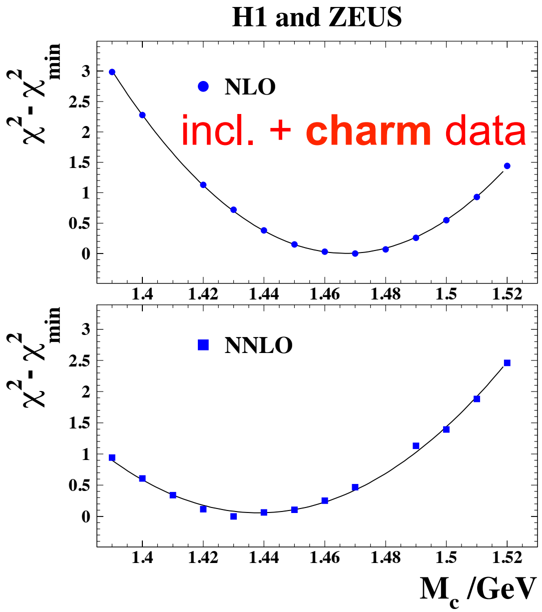
→ differences in valence quarks at high x: new HERA data

→ sea and gluon are consistent

Charm production in DIS

Charm mass parameter in HERAPDF2.0

M_c and M_b, charm and bottom mass parameters, are determined in χ^2 scans of the HERA charm and bottom data together with combined inclusive data

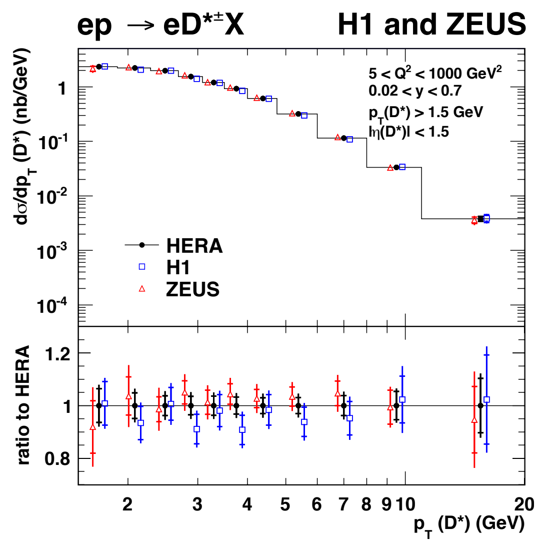


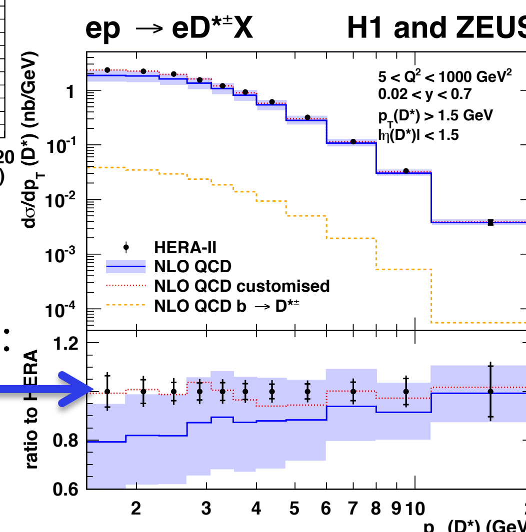
→ ***reduction of the M_c and M_b uncertainties in HERAPDF fits***

M_c = 1.47 (1.43) GeV at NLO (NNLO)

Combination of all D* at HERA

in the visible phase space, including latest D* cross section measurements by ZEUS.
No need for extrapolation to the full phase space as in the former combination of available charm data obtained using different techniques:
D* and D± reconstruction, vertex fitting, leptons in the final state.
→ *single diff.: P_T, η, z, Q^2, y and double diff. Q^2-y*





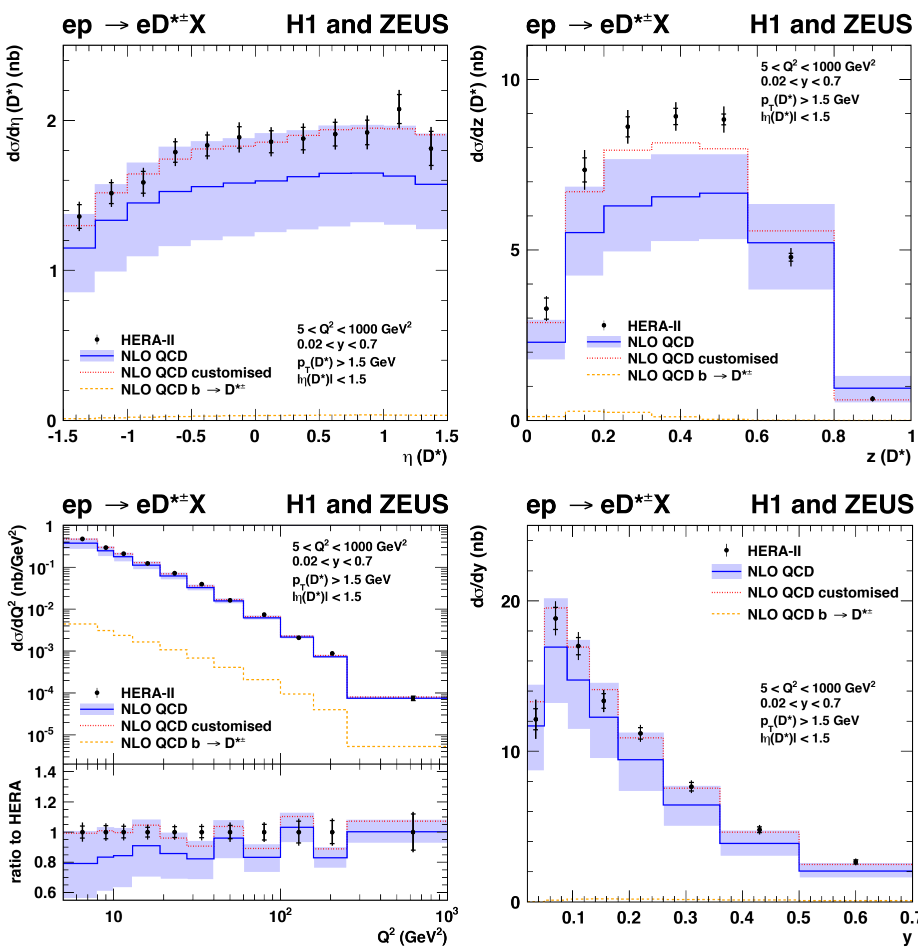
NLO QCD customised:
...+ **m_c = 1.4 GeV**

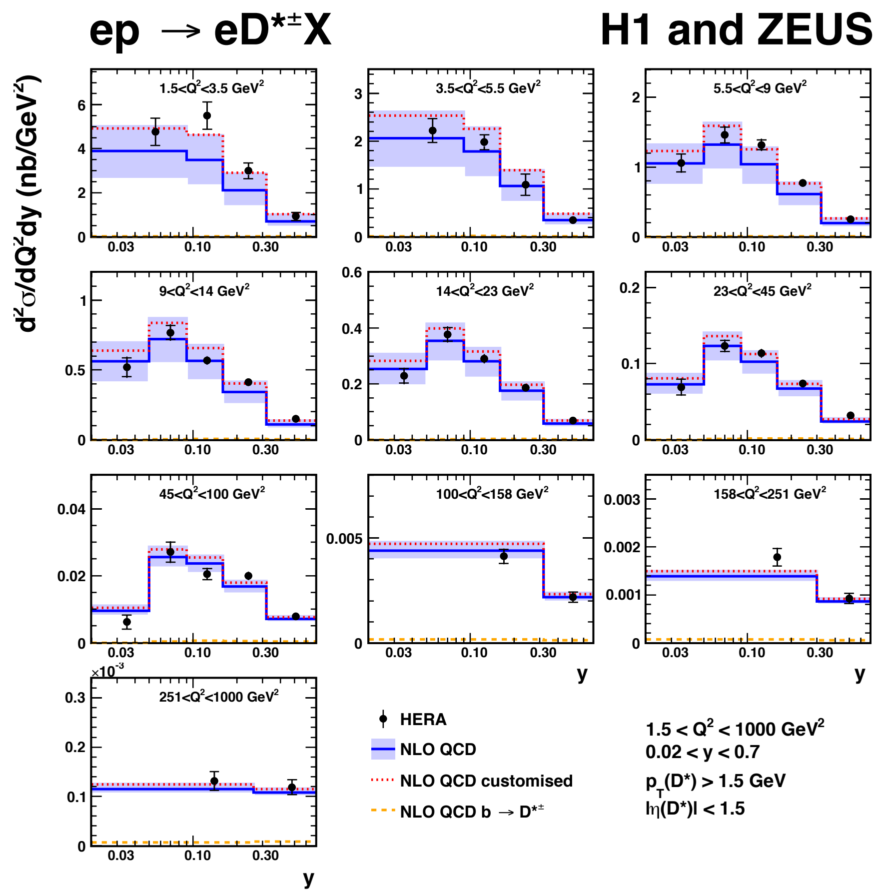
JHEP09(2015)149

Combined H1 & ZEUS visible D* cross sections

single differential: $d\sigma(D^*)/dP_T$, $d\sigma/d\eta$, $d\sigma/dz$, $d\sigma/dQ^2$, $d\sigma/dy$

double differential : $d^2\sigma/dQ^2dy$





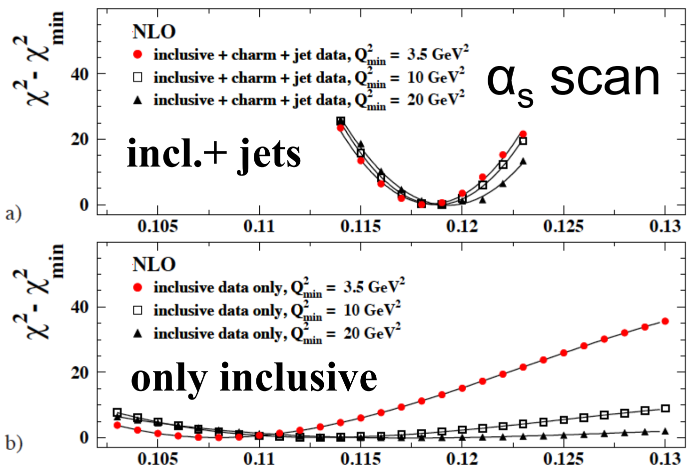
Jet production and the strong coupling constant

HERAPDF2.0Jets NLO

include also HERA combined charm and selected jet production data :

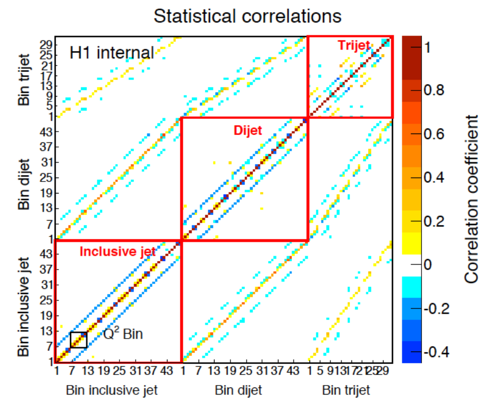
→ *α_s from a simultaneous fit with PDFs:*

$\alpha_s(M^2_Z)$ = 0.1183 ± 0.0009(exp) ± 0.0005(model) ± 0.0012(hadronisation) $^{+37}_{-30}$(scale)

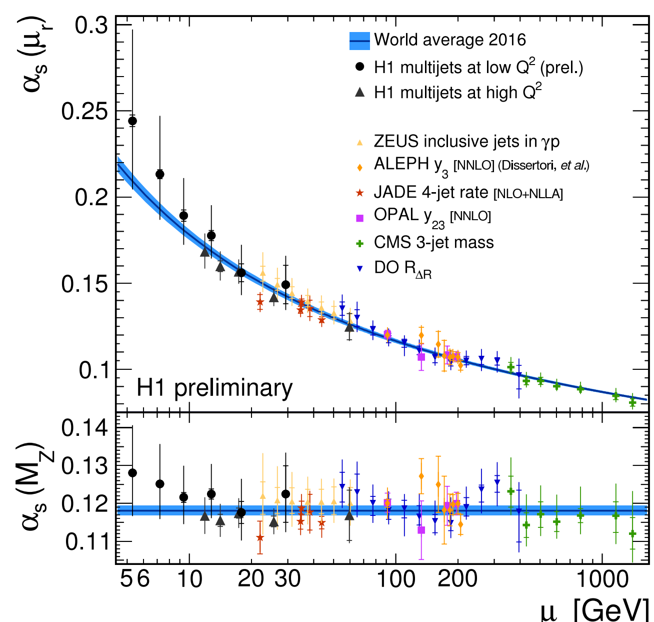


PDFs and the error bands are very close to HERAPDF2.0 obtained using inclusive data and M_c and M_b already optimized using charm and bottom HERA data and ***α_s****=0.118, consistent with the HERA multi-jet data. (slight increase of err. band is due to hadronisation).*

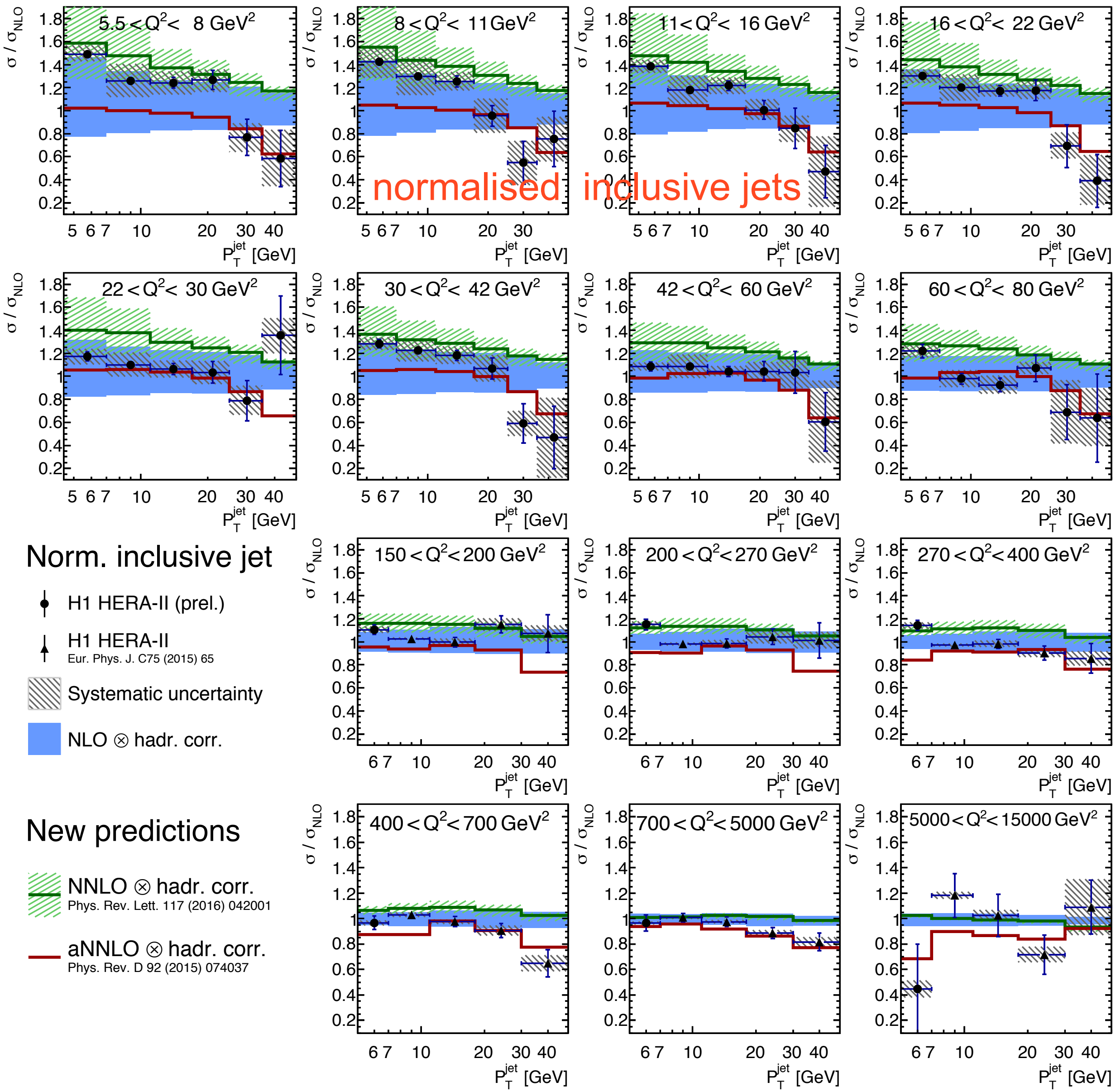
Multijet Production in ep DIS at low Q^2 by H1



Regularised unfolding of inclusive jets, dijets and trijets is used by H1 to obtain low Q^2 cross sections as it was done at high Q^2 in Eur.Phys.J.C75(2015)65



Multijet cross sections in DIS compared to NNLO



Inclusive jet, dijet and trijet *cross sections, absolute and normalised to NC (with partial cancellation of systematics) are measured in Q^2 and P_T^{jet} bins*

$5.5 < Q^2 < 80$ GeV^2 and

$4.5 < P_T^{jet} < 50$ GeV

For the first time normalised jet cross sections are compared to predictions at NNLO :

- full NNLO

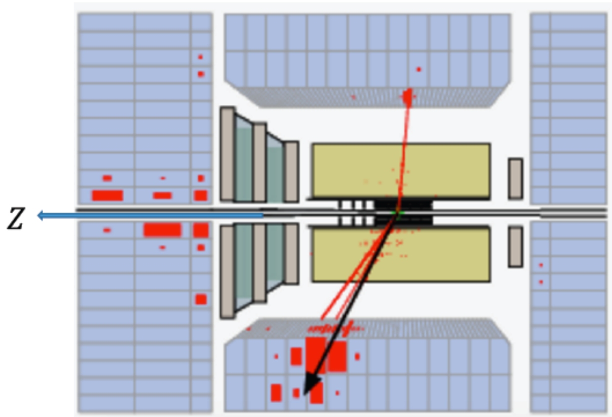
Phys.Rev.Lett.117(2016)042001

- approximate NNLO

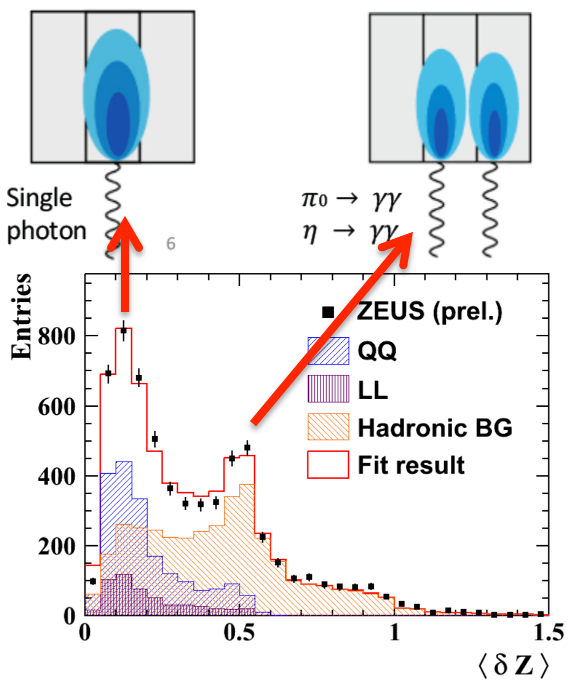
Phys.Rev. **D92** (2015) 074037

→ estimated experimental precision of $\alpha_s(M_Z)$ in fit to the H1 normalised jet cross sections at low and high Q^2 is 0.4%

Prompt photon accompanied by jets in ep DIS



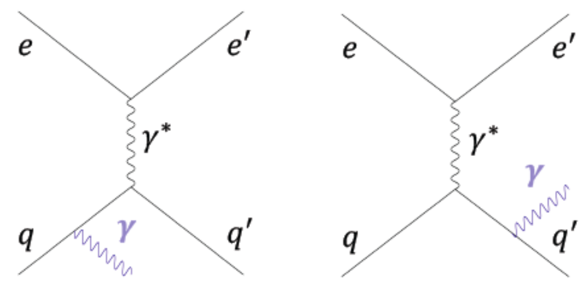
→ fine segmentation of BCAL in Z direction



ZEUS-prel-16-001

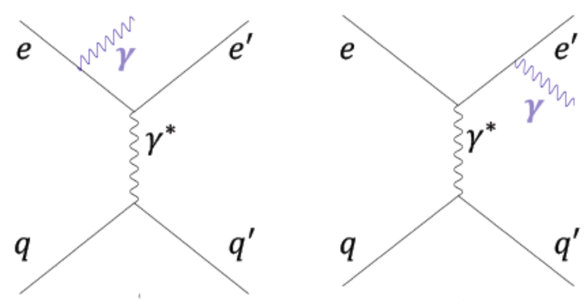
Prompt photons are produced
before quarks and gluons form hadrons

QQ - photons



γ is emitted from quark as part of hard process
→ hard process, similar to multi-jets

LL - photons



γ is radiated from incoming or outgoing lepton
→ theoretically well determined

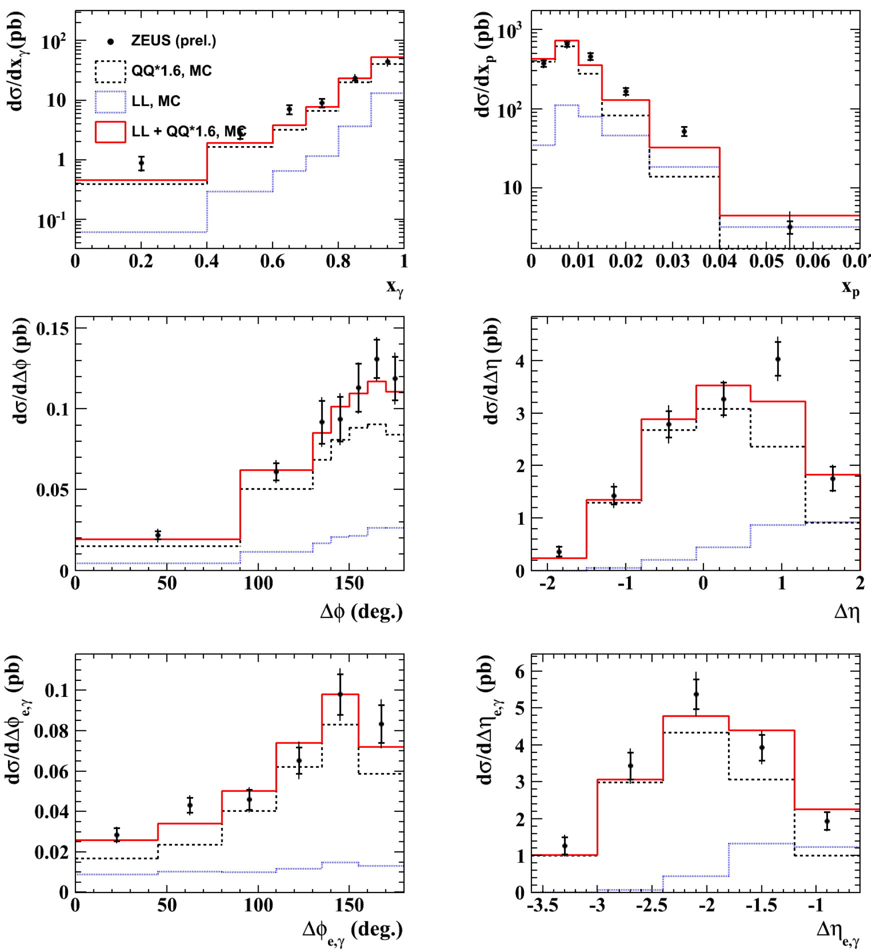
ZEUS-prel-16-001

Prompt photon cross section is measured as function of

- x_γ (x_p) - fractions of incoming photon (proton) energy taken by γ+jet (parton)
- $\Delta\phi_{e,\gamma}$, $\Delta\eta_{e,\gamma}$ - between γ and scattered electron
- $\Delta\phi$, $\Delta\eta$ - between γ and jet

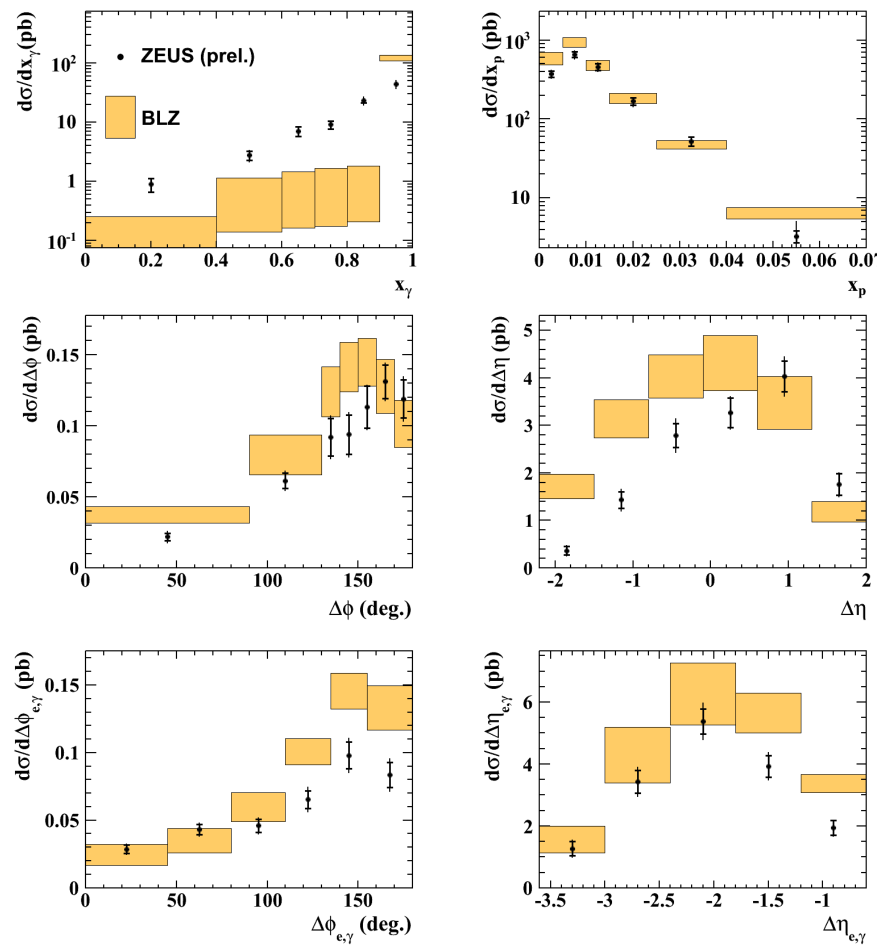
$10 < Q^2 < 350$ GeV^2
$4 < E_T^\gamma < 15$ GeV
$-0.7 < \eta^\gamma < 0.9$
$2.5 < E_T^{jet} < 35$ GeV
$-1.5 < \eta^{jet} < 1.8$

LL (Djangoh) + QQ (Pythya) scaled by 1.6



Comparison with BLZ model

Baranov-Lipatov-Zotov, Phys.Rev. D81, 094034 (2010)



Conclusions

H1 and ZEUS continue to deliver the HERA legacy results:

H1 and ZEUS completed the inclusive DIS program at HERA by combining all inclusive unpolarised measurements into one coherent data set of NC & CC e^+p & e^-p at $\sqrt{s}$ = 318, 300, 251 and 225 GeV.

The combined inclusive HERA data on NC and CC are used as a sole input to the QCD analysis resulting in the set of parton distribution functions HERAPDF2.0 (together with its variants).

All H1 and ZEUS D production cross section measurements in DIS are combined in the visible phase space in P_T, η, z, Q^2 and y.*

Inclusive jets, dijets, trijets cross sections (absolute and normalised to NC) are measured by H1 at low Q^2 and compared to predictions at NLO and NNLO → precise experimental input to α_s determinations

Prompt photons accompanied by jets are measured in DIS by ZEUS

Dijets and Trijets in DIS compared to NLO, NNLO