HERA results on proton structure and hard QCD

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on behalf of the H1 and ZEUS Collaborations

New Trends in High-Energy Physics

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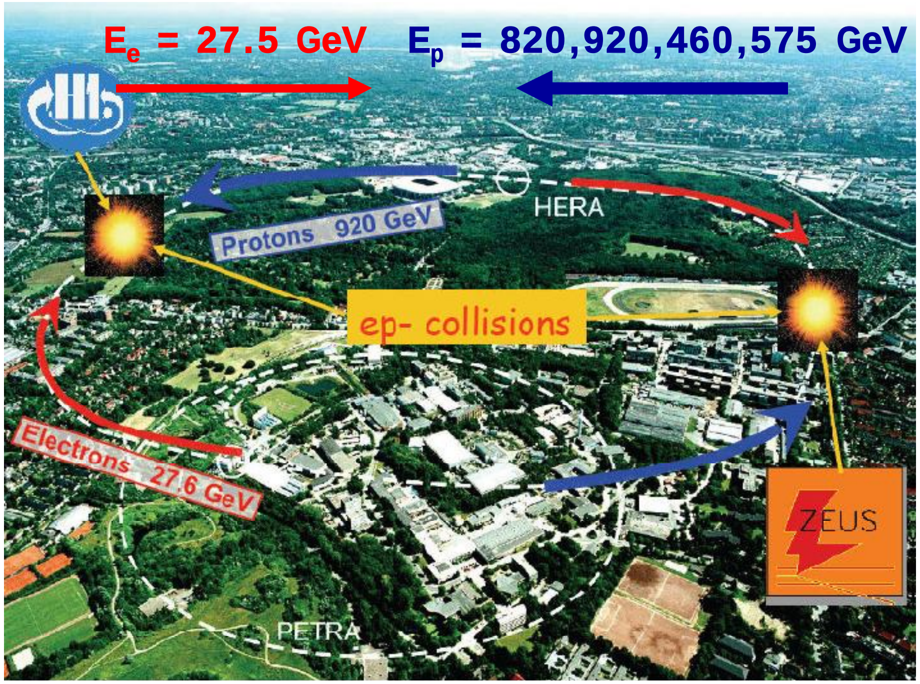


HERA (DESY, Hamburg): 1992 - 2007

- Total lumi H1, ZEUS: 0.5 fb^{-1} each

  HERA-I 1992-2000 ~120 pb^{-1}

  HERA-II 2003-2007 ~380 pb^{-1}

- Beams and energies

  $E_{e+/e-}$ = 27.6 GeV

  E_p = 820, 920 GeV (HERA-I)

  E_p = 920 GeV (HERA-II)

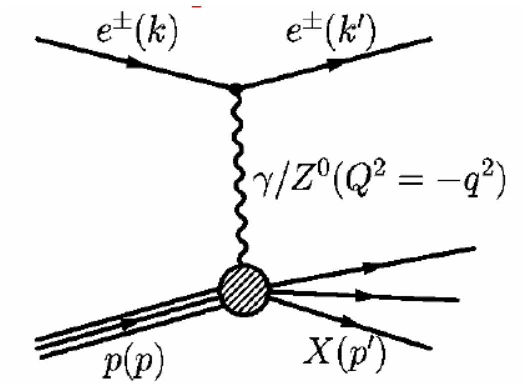
  E_p = 460, 575 GeV (Since April 2007 until the end of June)

Outline

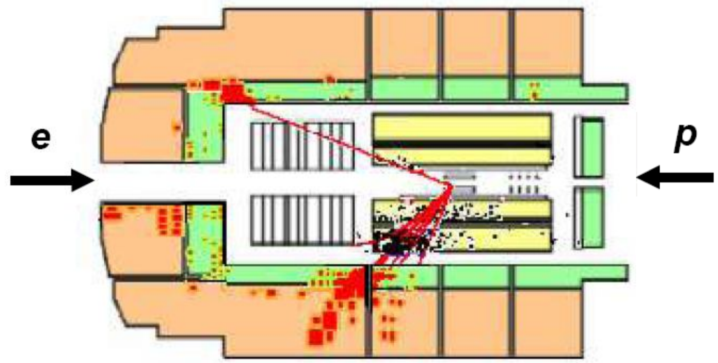
- Combination of all inclusive NC and CC data from H1 and ZEUS experiments
- Last QCD fit from the combined data: HERAPDF2.0
- Combined EW and QCD fit of inclusive NC and CC data
- (Multi)jets at low Q^2 and α_s
- Prompt photon and jet production in DIS

Inclusive Deep Inelastic Scattering (DIS)

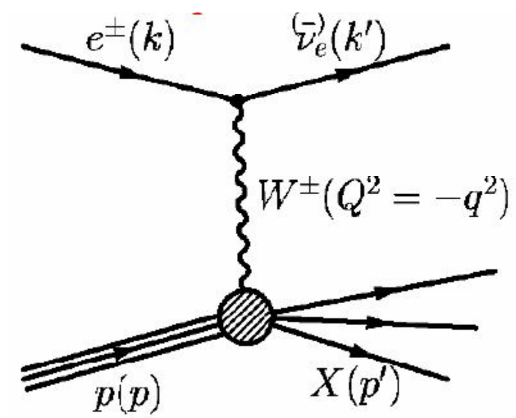
Neutral **C**urrent (**NC**)



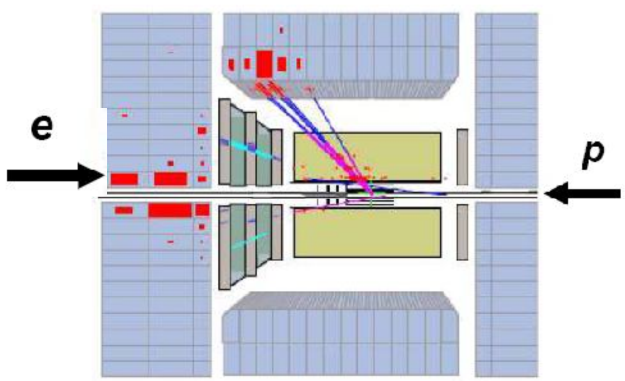
H1 NC event display



Charged **C**urrent (**CC**)



ZEUS CC event display



Virtuality of exchanged boson:

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

Fraction of proton momentum carried by struck quark

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

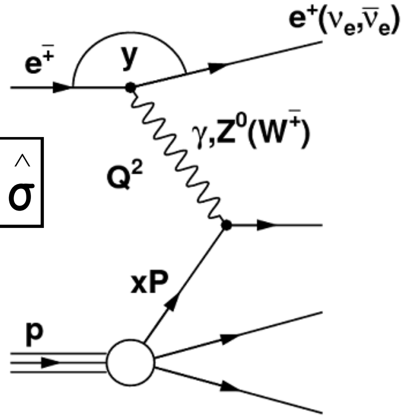
Fraction of energy transferred from incoming lepton in proton rest frame

$$y = \frac{p \cdot q}{p \cdot k}$$

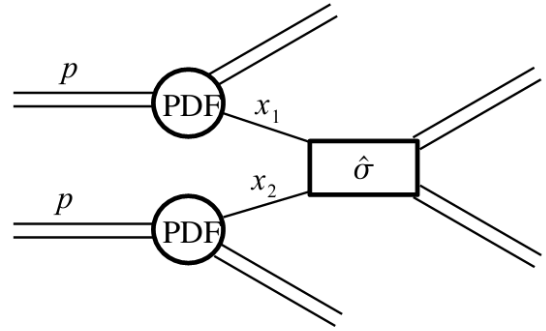
HERA Parton Density Functions (PDFs)

HERA:

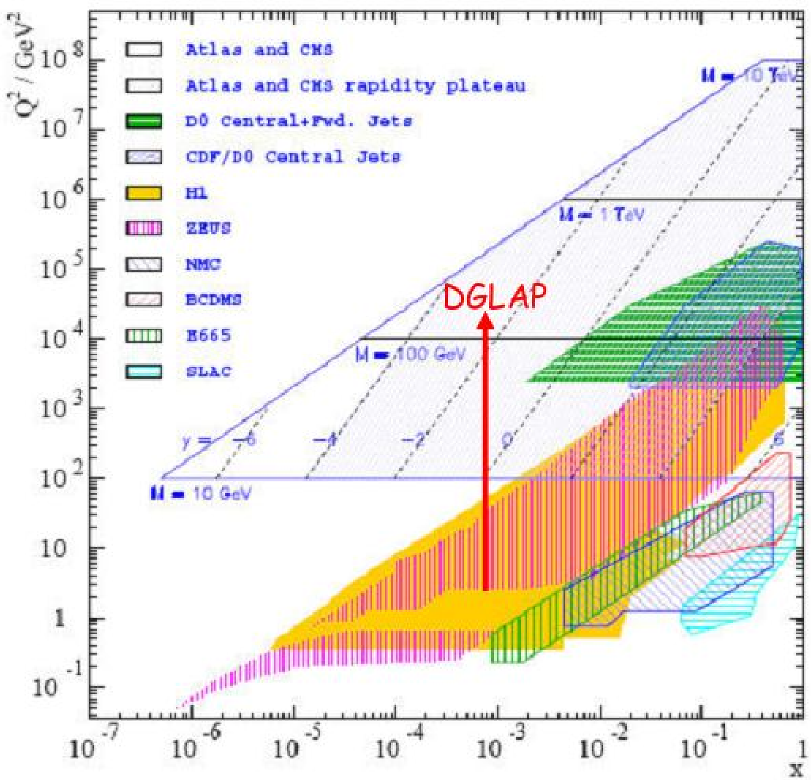
$\sigma \propto \mathrm{PDF}(x) \times \hat{\sigma}$



LHC:



$\sigma \propto \mathrm{PDF}(x_1) \times \mathrm{PDF}(x_2) \times \hat{\sigma}$



- Proton structure described by precise PDFs needed for making accurate predictions for any process involving protons

- **DGLAP QCD** evolution provides Q^2 dependence of the PDFs, x dependence must come from data. HERA covers the most important region for the LHC

NC and CC cross sections

Neutral current cross section

$\tilde{\sigma}_{NC}(x, Q^2)$ - NC reduced cross-section

$$\frac{d^2\sigma_{NC}(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+\left[F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right] \qquad Y_\pm = 1 \pm (1-y)^2$$

Contribution from **valence and sea quarks** (→ F_2)

Directly related to **gluon** in pQCD $F_L \sim \alpha_s \cdot xg(x,Q^2)$ (**sizeable only at high y**) (→ F_L)

Contribution from **valence quarks** at high Q^2 (→ xF_3)

Charged current cross section

$$\frac{d^2\sigma_{cc}^{e^\pm p}}{dx\,dQ^2} = \frac{G_F^2 M_W^4}{2\pi x(Q^2 + M_W^2)^2}\sigma_{cc}^{\pm}$$

$$\sigma_{cc}^{e^+p} \sim (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$

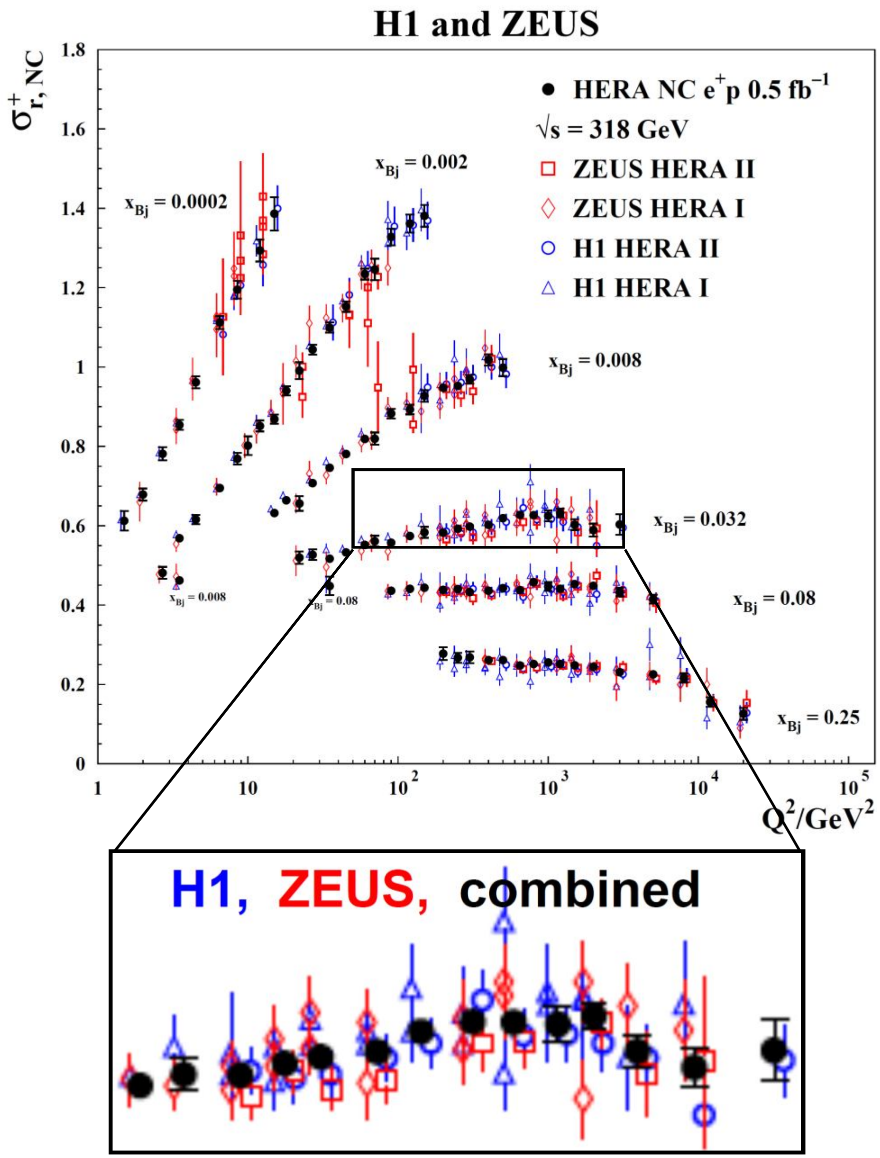
$$\sigma_{cc}^{e^-p} \sim (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s})$$

Sensitivity to the flavour of the valence distributions at high x

- Direct measure of structure functions (various linear combinations of PDFs)
- HERA can disentangle proton PDFs with few assumptions

Combined NC and CC ep data

Eur. Phys. J. C75 (2015) 580



- To get high precision measurements of PDFs **H1 and ZEUS results** are **combined** into one coherent data set

- 41 NC and CC data sets from H1 and ZEUS collected over 15 years (1 fb^{-1}) $0.045 \leq Q^2 \leq 50000$ GeV^2, $6 \cdot 10^{-7} \leq x \leq 0.65$
- $\sqrt{s}$ = 318, 300, 251, 225 GeV

- Close to 3000 cross sections are combined to about 1300 points with 169 correlated syst. errors and χ^2/d.o.f. = 1685/1620

  → Significant reduction of statistical and systematic errors

- Total uncertainty less than 1.5 % for $Q^2 \leq 500$ GeV^2

EW effects at high Q^2

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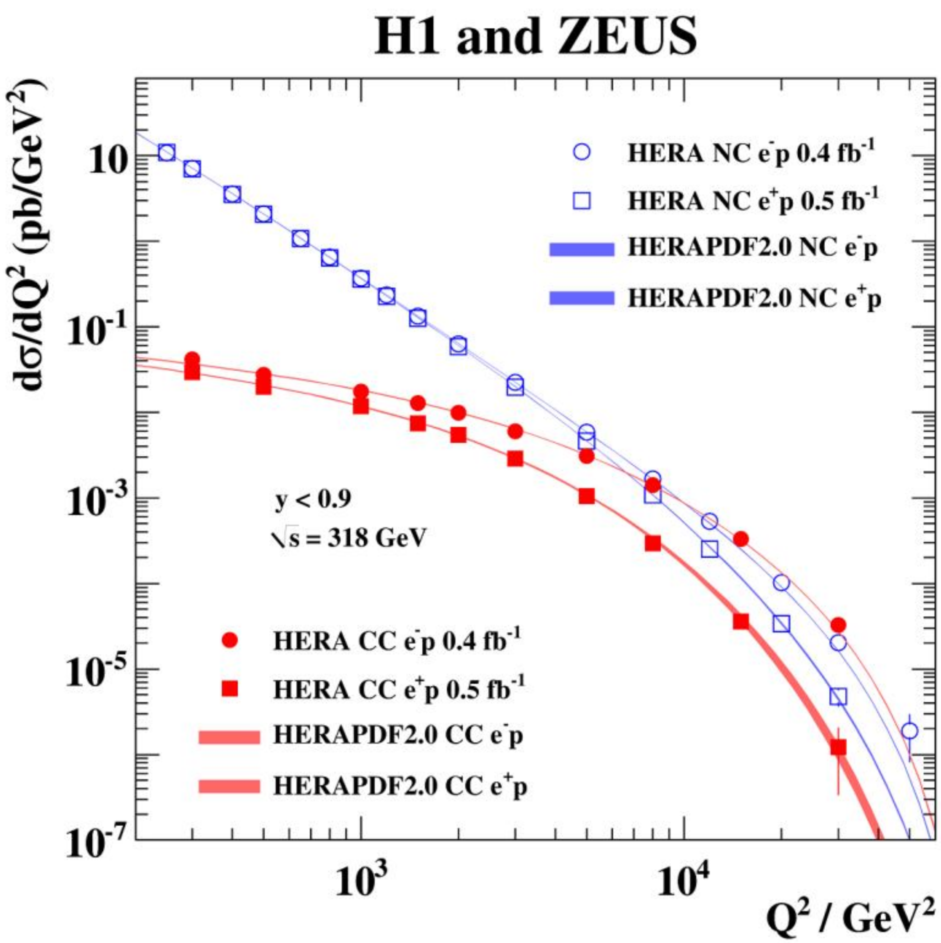

- CC is two orders of magnitude smaller than NC at low Q^2 due to γ-exchange contribution
- CC and NC about the same size demonstrating electroweak unification at Q^2 around M_Z^2, M_W^2
- e^+p NC and e^-p NC are the same at low Q^2, in the γ-exchange domain and differ at high Q^2 mainly due to γZ interference
- differences in e^+p CC and e^-p CC are related to u, d content of the proton and to helicity factors $(1-y)^2$

Scaling violations

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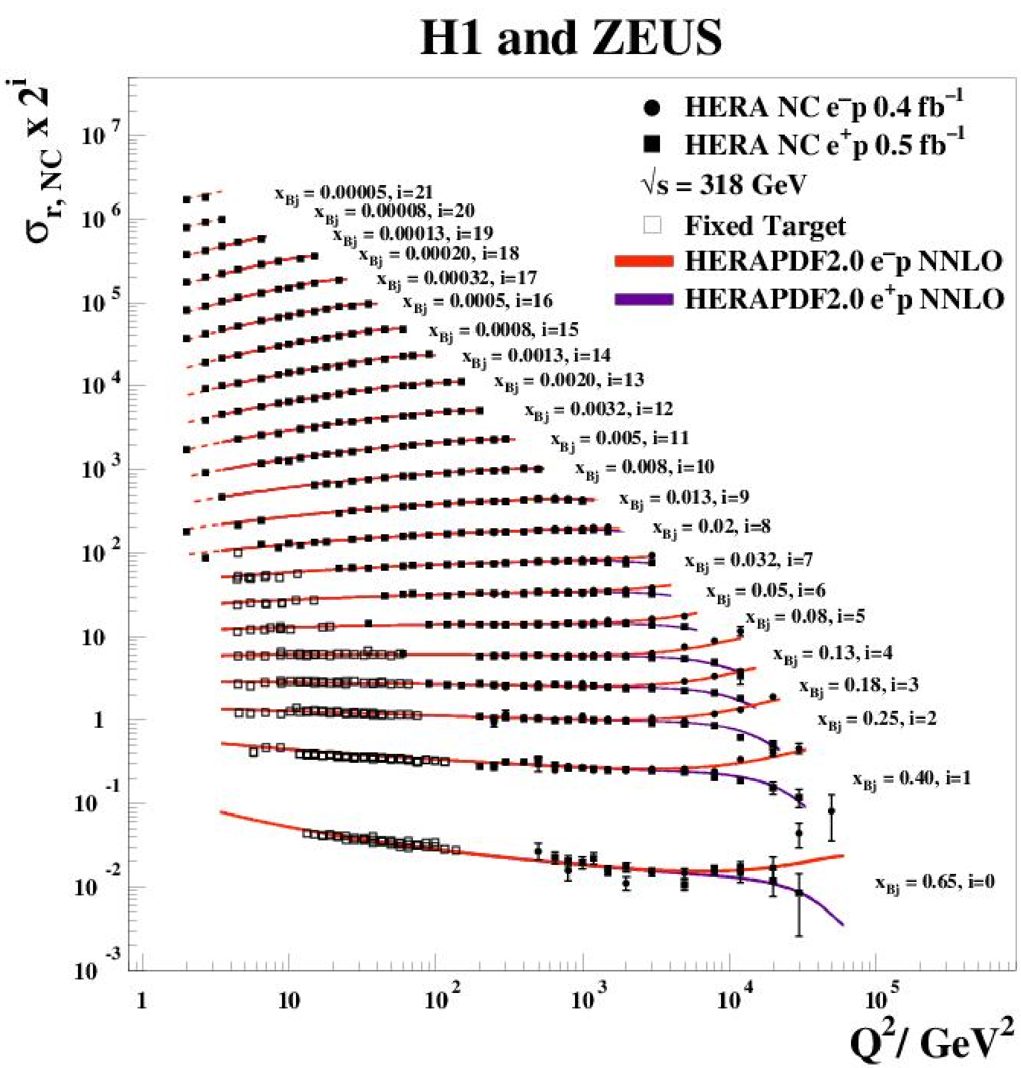

$$\sigma_{NC}(e^{\pm}p) = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y}{Y_+}xF_3$$

- F_2 scaling at moderate x
- precision measurement of scaling violations
  → cross section rises with Q^2 at low x but drops at high x
- scaling violations at low x due to gluon splitting and at high x due to gluon emission
- Electroweak effects pronounced at high Q^2 (xF_3 contribution)

QCD analysis

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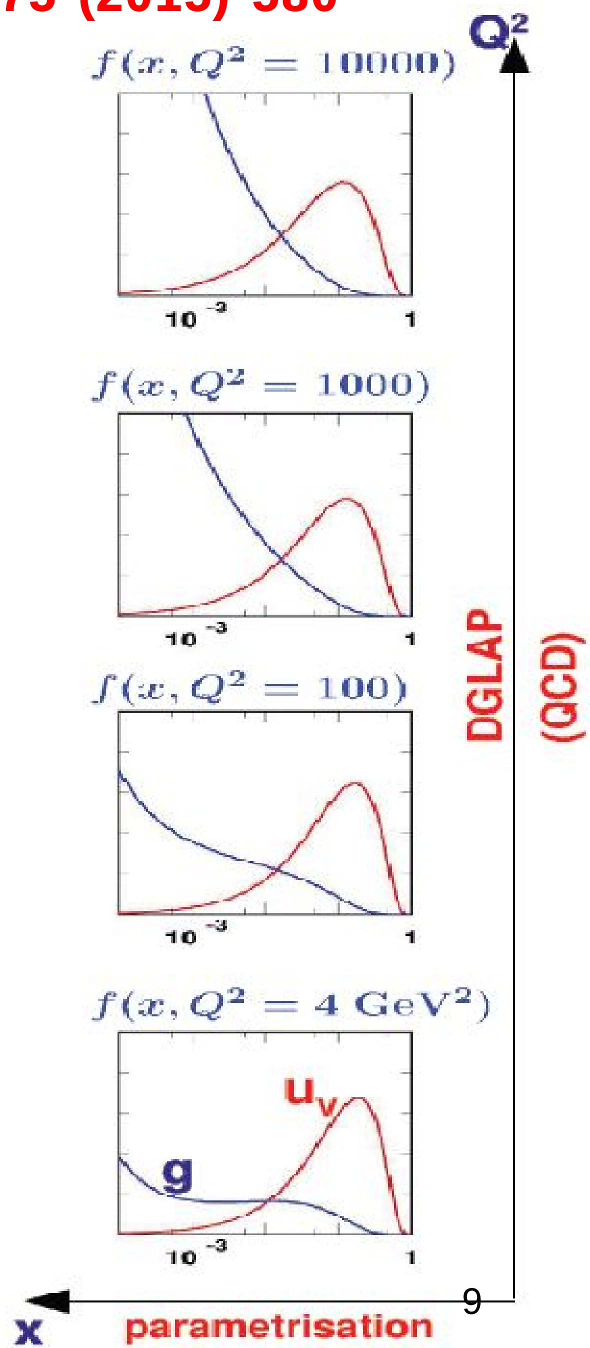
PDF determination

- ❑ Parametrise the parton density functions at low starting scale Q_0^2 = 1.9 GeV^2 by smooth analytic functions as $Ax^B(1-x)^c(1 + Dx + Ex^2 \dots)$
- ➢ Express the strange-quark distribution as an x-independent fraction, f_s= 0.4, of the d-type sea at Q_0^2 ($x\bar{s} = f_s x\bar{D} = f_s(x\bar{d}+x\bar{s})$)
- ➢ Use Thorne-Roberts general mass variable-flavor-number scheme RTOPT
- ➢ M_c and M_b values optimized using HERA HF data
- ➢ $\alpha_s(M_Z^2)$=0.118 is consistent with HERA jet data
- ❑ Evolve these functions using the DGLAP equations to higher Q^2 and calculate x-sections
- ❑ Compare the calculation to experimental data
- ❑ Minimisation of χ^2 adjusting the free parameters
- ❑ To safely remain in the kinematic region where pQCD is expected to be applicable, only cross sections for Q^2 starting from Q^2_{min}= 3.5 GeV^2 are used



HERAPDF2.0

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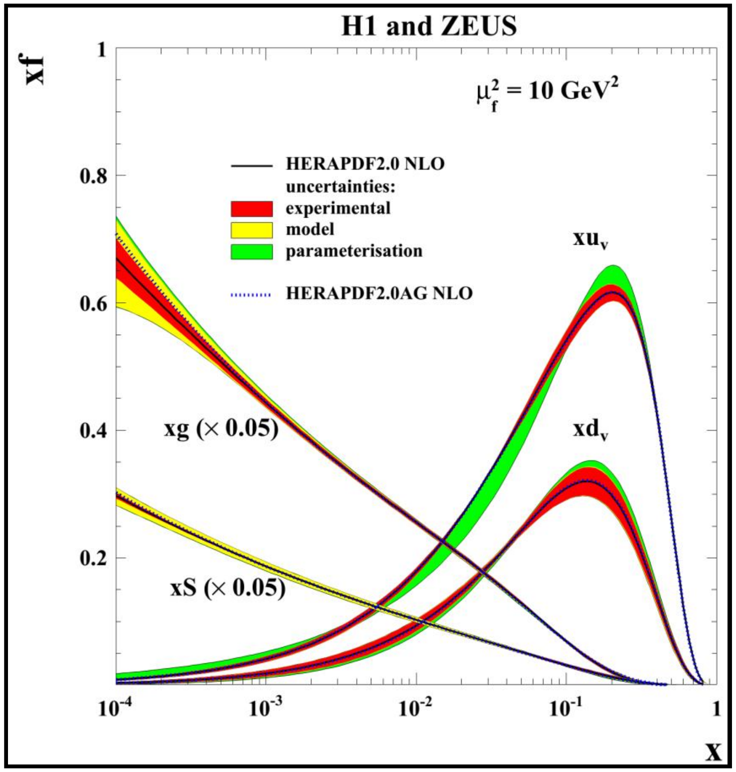
- **Experimental uncertainties** were determined using the Hessian method with the criterion $\Delta\chi^2 = 1$ (68 % CL)
- **Model uncertainties** were evaluated by varying the assumptions (all variations are added in quadrature)

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 uncertainties**:
  - variation in Q_0 (from 1.6 to 2.2 GeV^2)
  - parameterisation form of PDFs

Additional PDF sets

HERAPDF2.0 at NLO and NNLO with a scan of $\alpha_s(M^2_Z)$ insteps of 0.001
HERAPDF2.0 at NLO and NNLO with Q^2min = 10 GeV^2
HERAPDF2.0 at LO, NLO, NNLO with alternative gluon parameterisation (positive)
HERAPDF2.0FF3A and FF3B with fixed flavor number schemes at NLO

H1 and ZEUS Combined QCD and EW fit

- The structure functions can be separated into contributions from γ exchange, Z exchange and γ/Z interference

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

$$x\tilde{F}_3^{\pm} = k(a_e \mp P_e v_e) xF_3^{\gamma Z} + k^2 (2 v_e a_e \pm P_e (v_e^2 + a_e^2)) xF_3^Z$$

- In QPM, SFs expressed in terms of light quark vector and axial-vector couplings to Z boson

$$[F_2, F_2^{\gamma Z}, F_2^Z] = \sum [e_q^2, 2 e_q v_q, v_q^2 + a_q^2](xq + x\bar{q})$$

$$x\tilde{F}_3^{\pm} = k(a_e \mp P_e v_e) xF_3^{\gamma Z} + k^2 (2 v_e a_e \pm P_e (v_e^2 + a_e^2)) xF_3^Z$$

SM: $a_f = I_{f,L}^{(3)}$ $f = e, u, d$

$v_f = I_{f,L}^{(3)} - 2 e_q \sin^2\theta_W$

$$k = \frac{Q^2}{(Q^2 + M_Z^2)^2} \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}$$

- Calculations in on-shell scheme

$$G_F = \frac{2\pi\alpha}{2\sqrt{2} M_W^2} \left(1 - \frac{M_W^2}{M_Z^2}\right)^{-1} (1 + \Delta r)$$

$$\Delta r = \Delta r\, (\alpha, m_Z, m_W, m_t, m_H ..)$$

- Determinations of light-quark couplings, mass of W, Weinberg-angle from the simultaneous QCD + EW fit (for H1 additional 4 free polar. values)
  → QCD-EW fit following HERAPDF2.0 methodology

- New results: ZEUS: **Phys. Rev. D93 (2016) 092002**
  H1: **H1prelim-16-041**

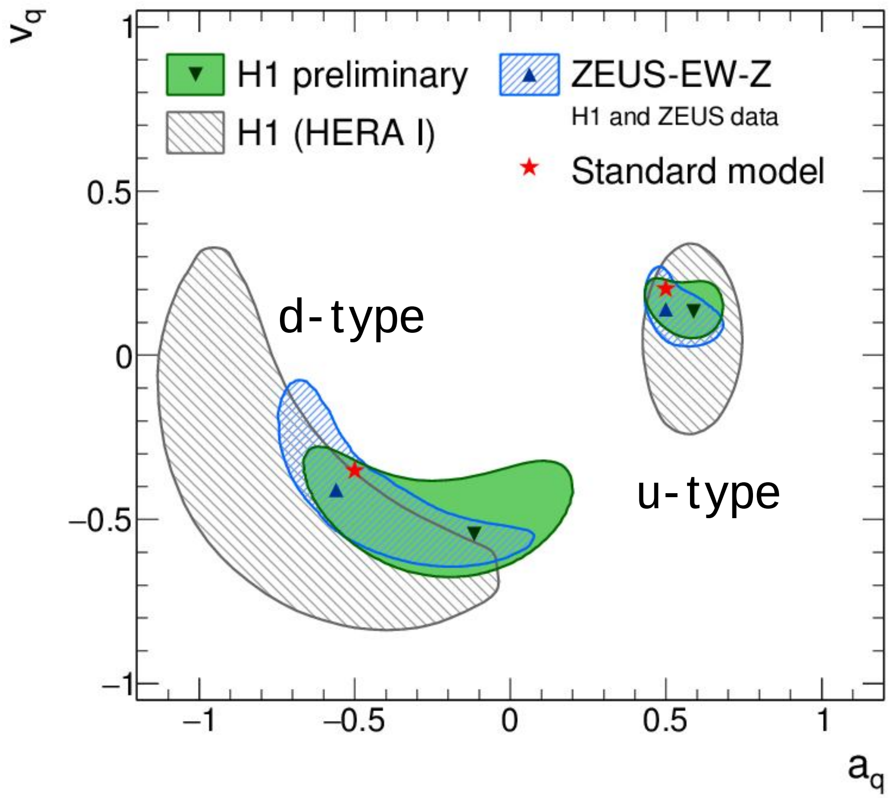
H1 and ZEUS results on ligh quark couplings to Z boson

Phys.Rev. D 93 (2016) 092002, H1prelim-16-041

- Input data:

  H1: Only H1 data: NC + CC HERA-I and HERA-II

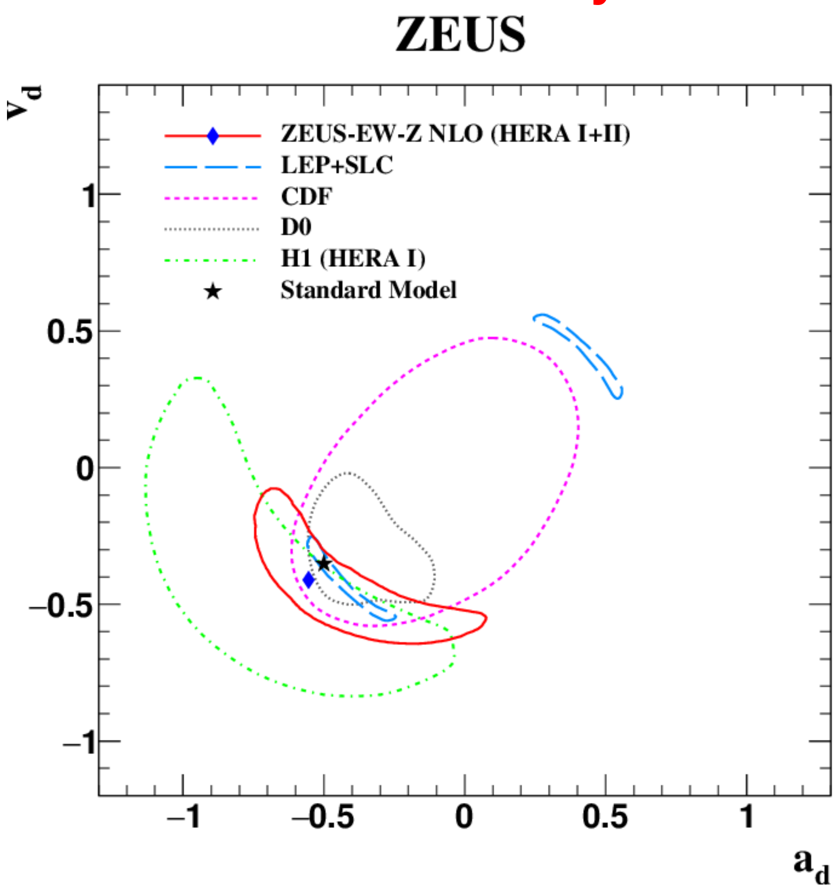
  ZEUS: Uncombined H1 and ZEUS data: NC + CC HERA-I and HERA-II

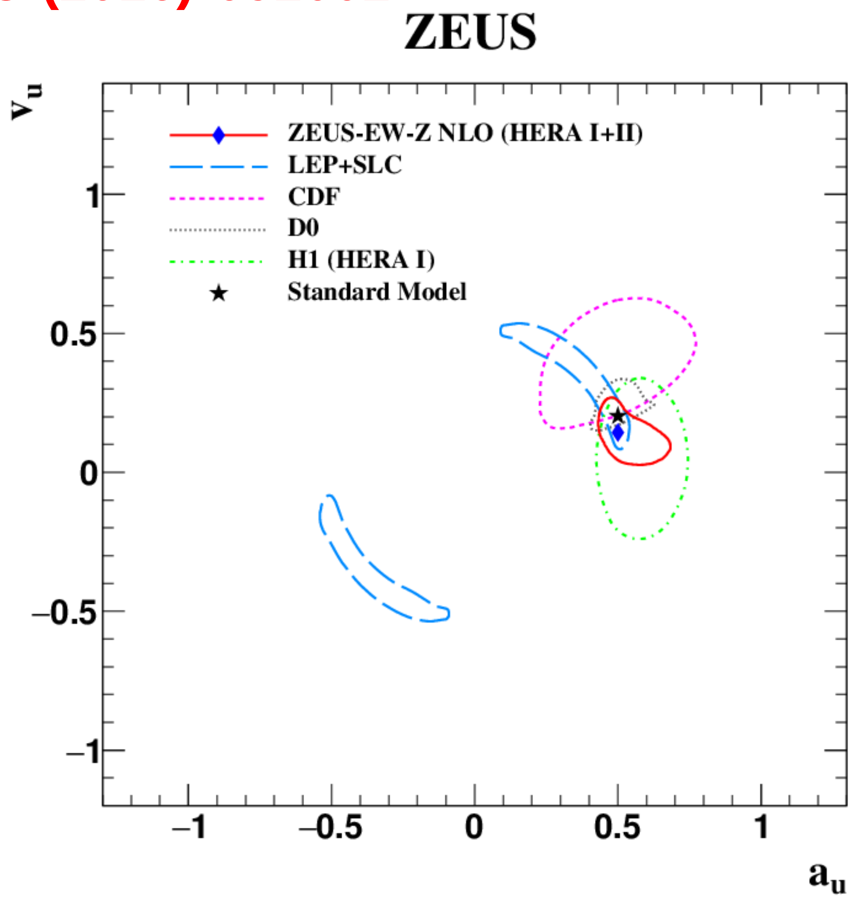


- Compatible results from H1 and ZEUS
- Results consistent with SM expectation
- Remarkable sensitivity of HERA data to u-type quark couplings
- Considerable improvement over published results of H1 from HERA-I data (Phys.Lett.B 632 (2006) 35)
  - → Significantly improved sensitivity using polarised HERA-II data
  - → Polarisation in HERA-II important particularly for vector couplings

Comparison to other data

Phys.Rev. D 93 (2016) 092002



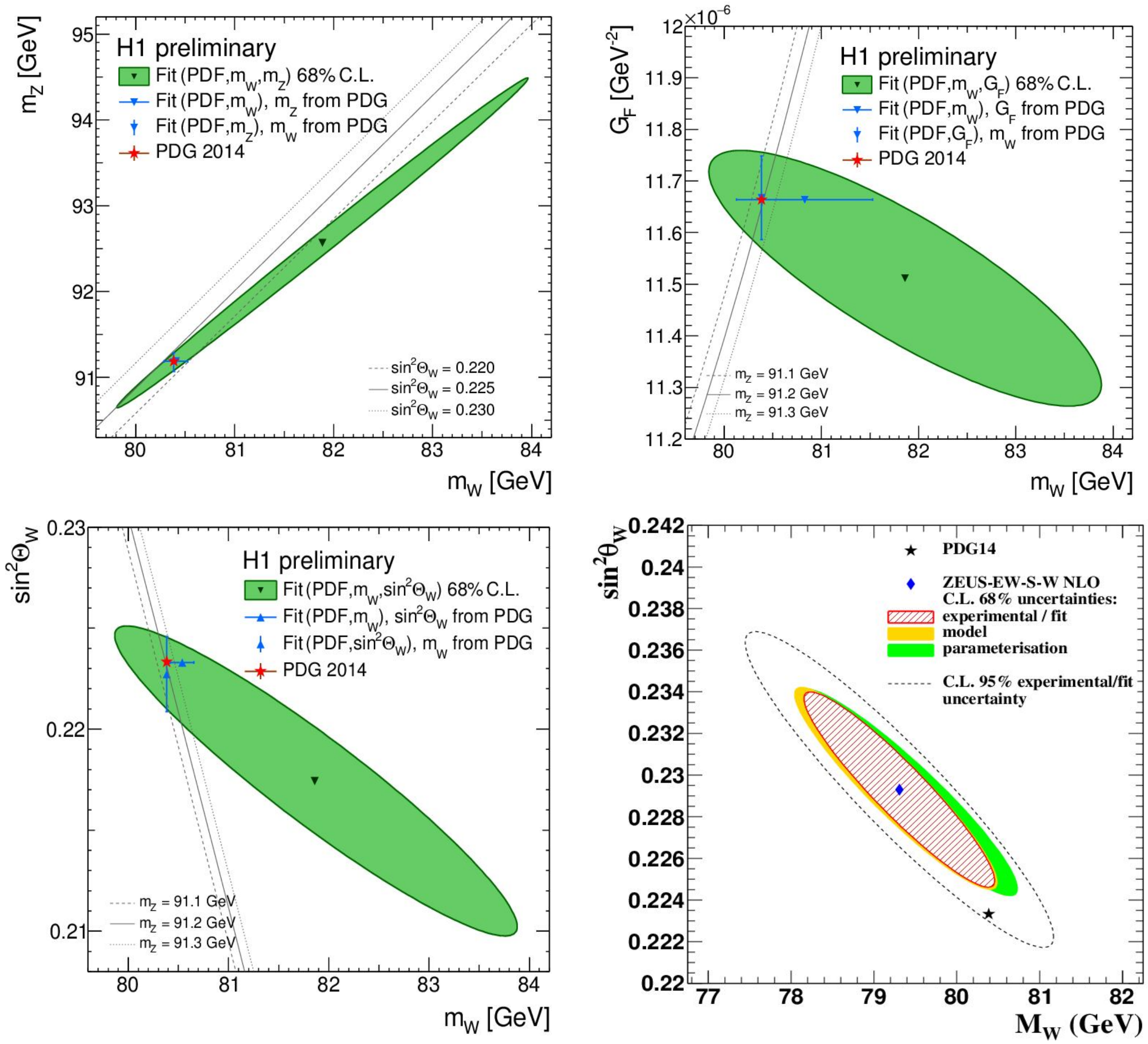


- Results consistent with other experiments
- LEP sign-ambiguity resolved
- u-type coupling highly accurate
  → the most precise determination of the axial-vector and vector couplings of the Z boson to u-type quarks

Standard Model parameters

Phys.Rev. D 93 (2016) 092002

H1prelim-16-041



$$G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2\theta_W}(1+\Delta r)$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Simultaneous extraction of EW parameters + PDFs

→ Different correlation of m_W to m_Z, $\sin^2\theta_W$ and G_F

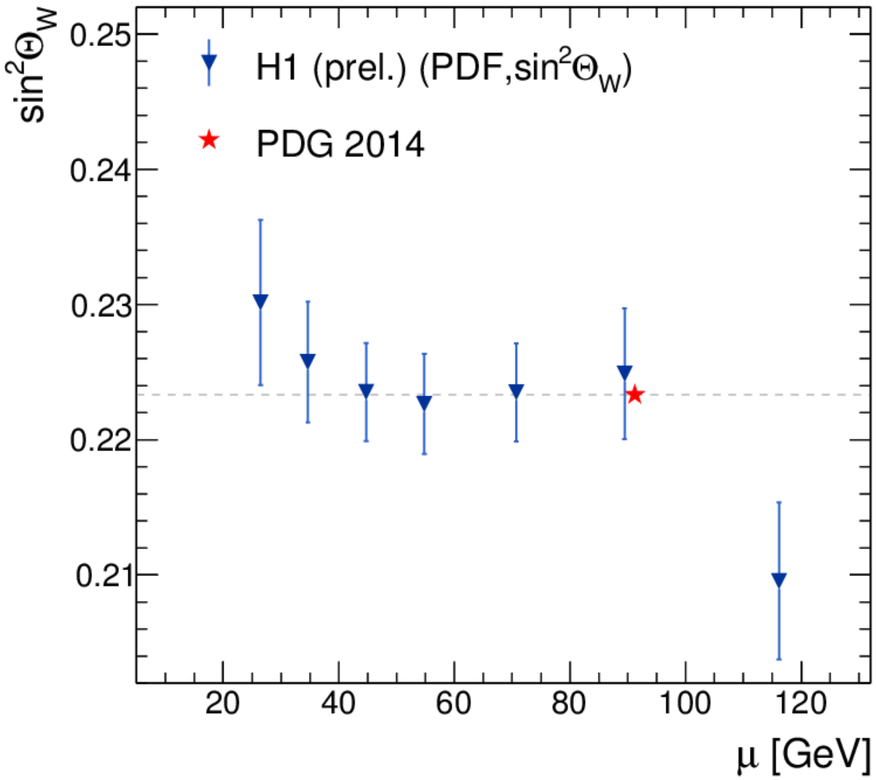
→ Agreement with PDG14 values

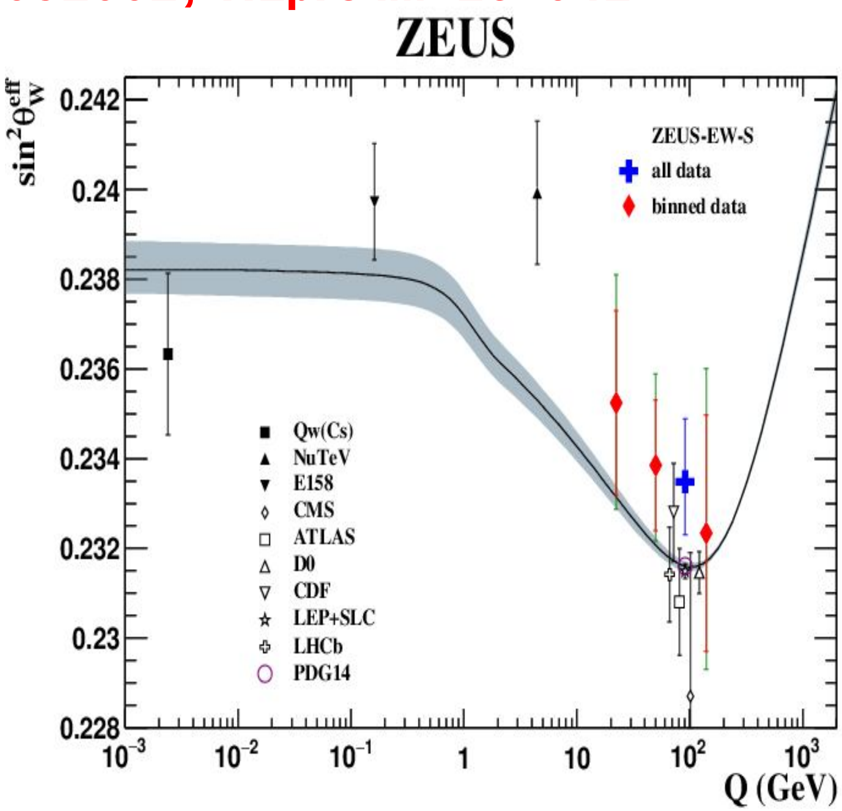
H1: $m_W = 80.407 \pm 0.118(\text{exp,pdf-fit}) \pm 0.005(m_Z, m_t, m_H)\,\text{GeV}$

ZEUS: $m_W = 80.68 \pm 0.28_{(\text{exp/fit})}{}^{+0.12}_{-0.01(\text{mod})}{}^{+0.23}_{-0.10(\text{par})}\,\text{GeV}$ $\quad \sin^2\theta_W = 0.2252 \pm 0.0011_{(\text{exp/fit})}{}^{+0.0003}_{-0.0001(\text{mod})}{}^{+0.0007}_{-0.0001(\text{par})}$

Scale dependence of $\sin^2\theta_W$

Phys.Rev. D 93 (2016) 092002, H1prelim-16-041





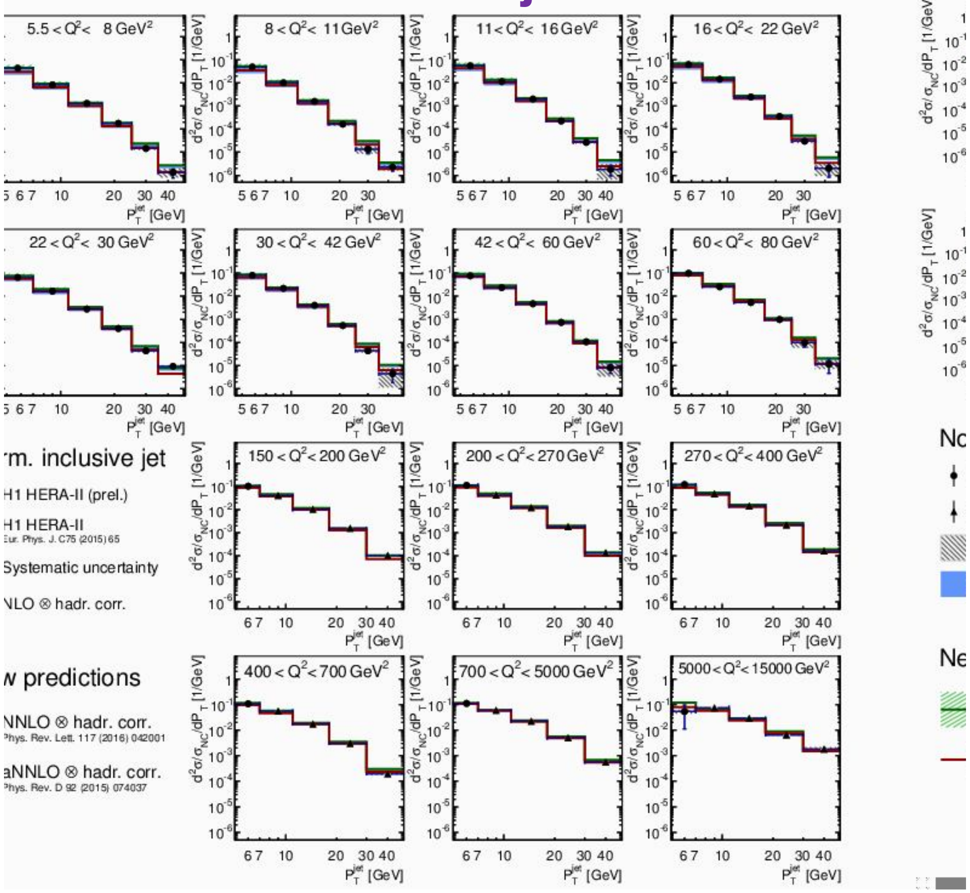
- Unique measurement of weak mixing angle at different scales taking advantage of space-like momentum transfer
- Results are compatible with precise value from PDG14 and the SM prediction for the running of the $\sin^2\theta_W$

Multijet production in DIS at low Q^2

H1prelim-16-061, H1prelim-16-062

- To obtain low Q^2 cross sections, the data are corrected for acceptance and resolution effects using a regularised unfolding procedure as it was done at high Q^2 (Eur. Phys. J. C75 (2015) 65)

Inclusive jets



- **Inclusive jet, dijet and trijet** cross sections, absolute and normalised to NC (full cancellation of normalisation uncertainties and partial cancellation of other exp. uncertainties) are measured in Q^2 and P_T jet bins $5.5 < Q^2 < 80$ GeV^2 and $P_T^{jet} > 4.5$ GeV (incl. jet)

- First ever comparisons with brand new NNLO QCD calculations are presented for some of these norm. jet cross sections:
  - **full NNLO from NNLOJET** Phys. Rev. Lett. 117 (2016) 042001
  - **approximate NNLO from JetViP** Phys. Rev. **D 92 (2015) 074037**

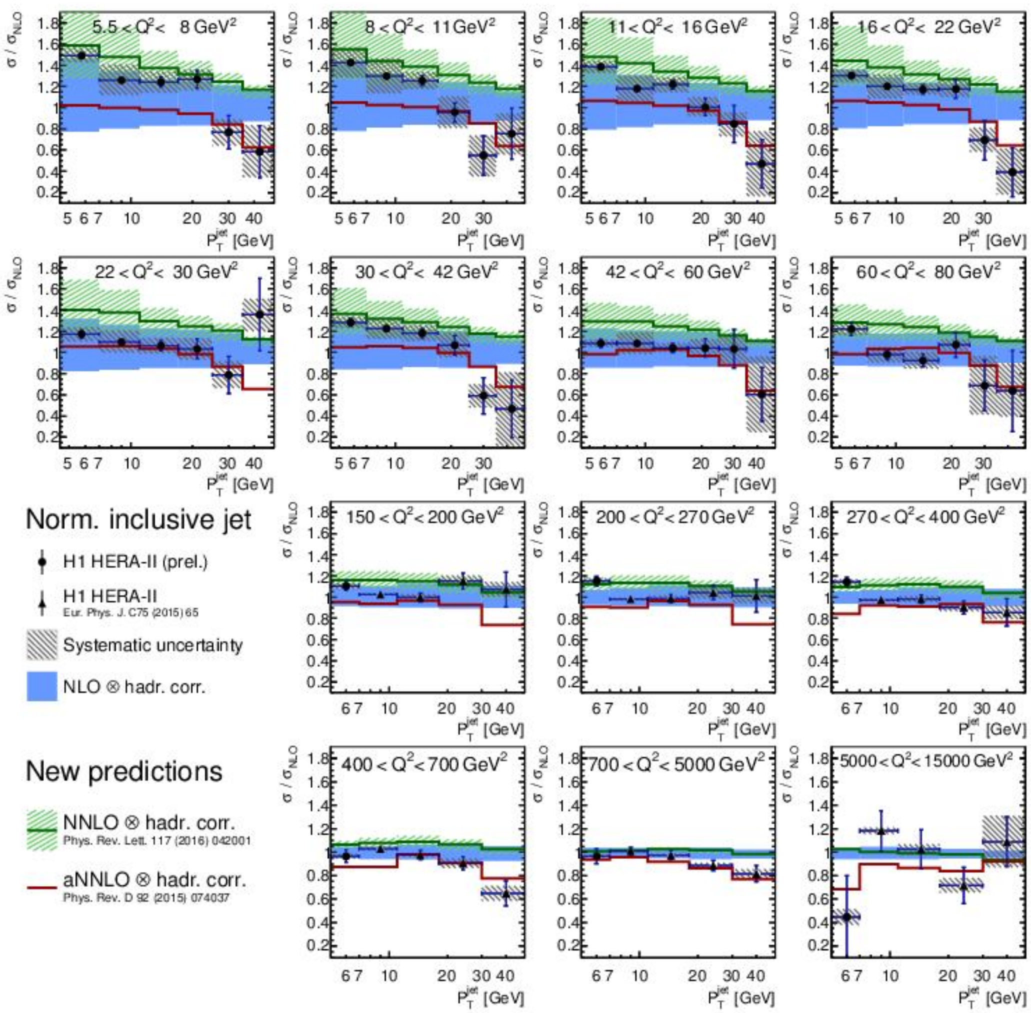
- Also, new cross sections for $5 < p_T^{jet} < 7$ GeV in the range $150 < Q^2 < 15\,000$ GeV^2

Multijet production in DIS at low Q^2

H1prelim-16-061, H1prelim-16-062

Detailed ratio to NLO prediction

Inclusive jets

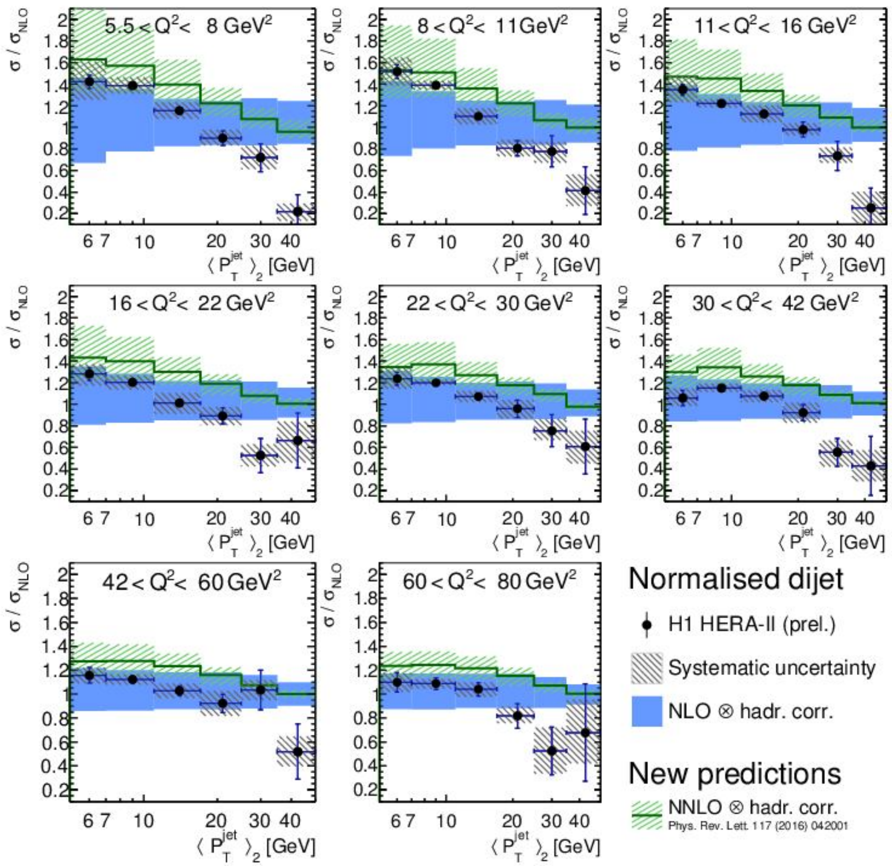


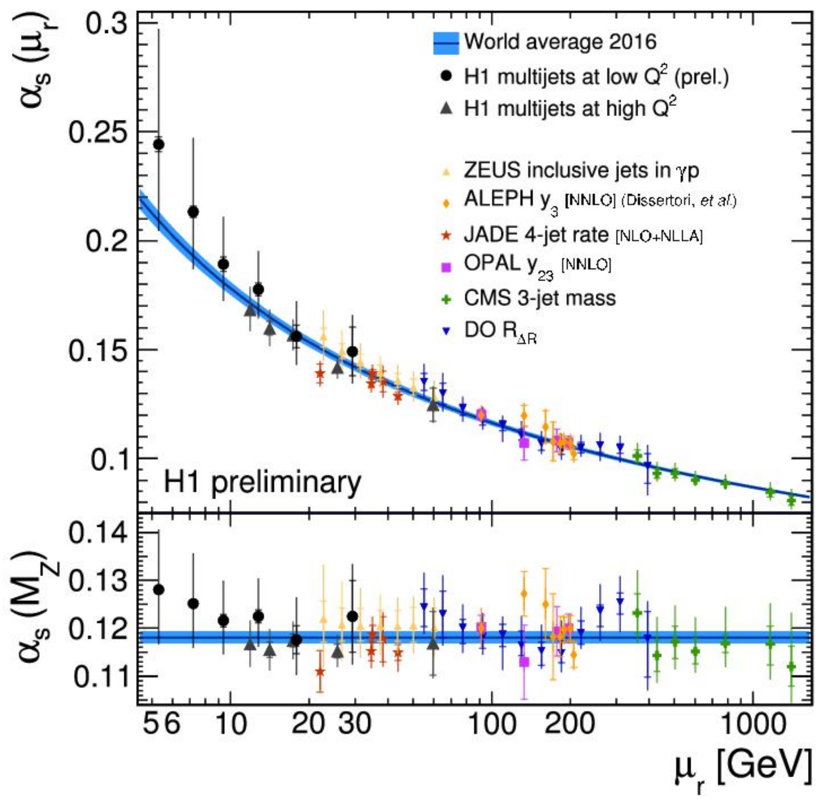
- Data reasonably described by NLO (from NLOJET++), but NLO scale uncertainty large
- Improved description of data (particularly in shape) by NNLO

  → Significantly reduced scale uncertainty for higher values of jet p_T
- Improved inclusive jet data description with aNNLO at high-p_T

Multijet production in DIS at low Q^2

Dijets **H1prelim-16-061, H1prelim-16-062**





$\langle P_T^{jet} \rangle_2 > 5.0$ GeV , $P_T^{jet} > 4$ GeV

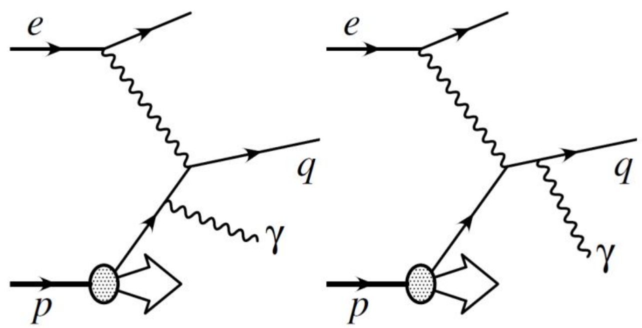
- Description of the data similar as in case of incl. jets
- No NNLO predictions for trijets available yet

- New normalised multijet data used for extraction of $\alpha_s(M_Z)$
  - Examine running of $\alpha_s(\mu)$ in range $6 < \mu < 30$ GeV
  – exp. precision about 0.4 %

Prompt photon accompanied by jet in DIS

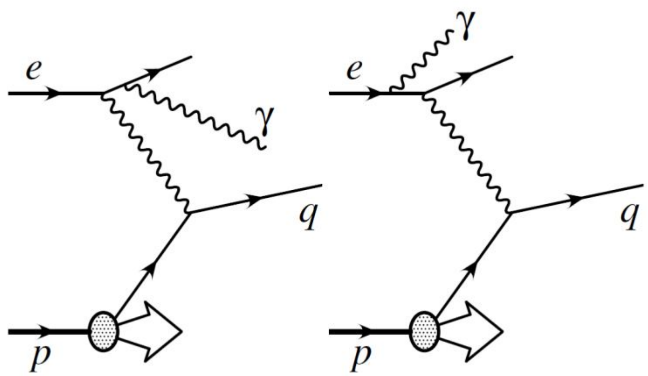
ZEUS-prel-16-001

- Photons are emitted from incoming or outgoing quark (QQ-photons) or lepton (LL-photons)



QQ – photons

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



LL - photons

- γ is radiated from incoming or outgoing lepton (theoretically very well determined)

- Prompt photons unaffected by parton hadronisation

→ Provide information on the structure of the proton and give a probe of underlying partonic process

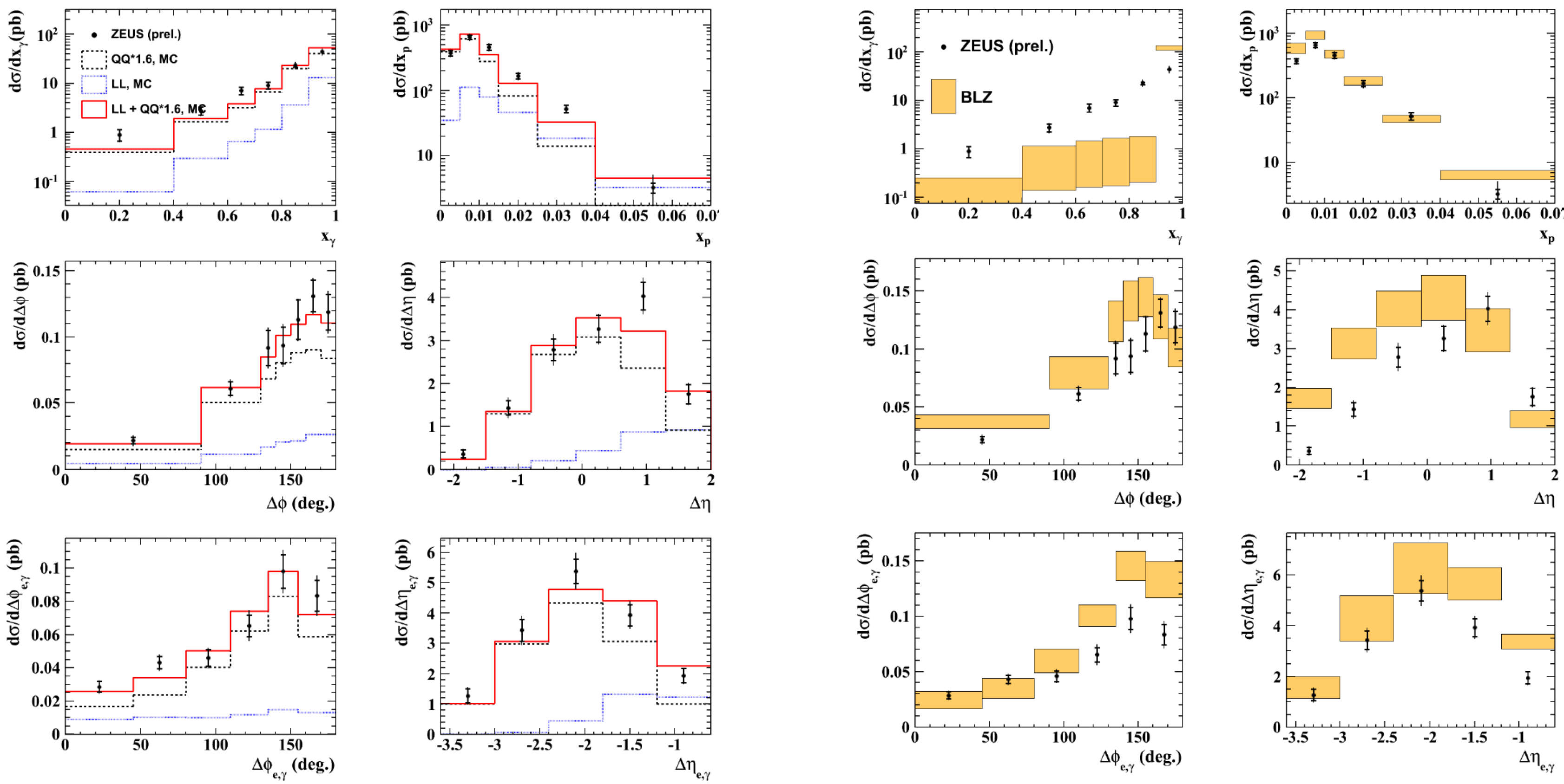
→ Complements previous result (Phys. Lett. B 715 (2012) 88)

Prompt photon accompanied by jet in DIS

ZEUS-prel-16-001

- x_γ, x_p – fraction of incoming photon (proton) energy taken by γ+jet (parton)

  $\Delta\phi, \Delta\eta$ ($\Delta\phi_{e,\gamma}$, $\Delta\eta_{e,\gamma}$) - separations of photon and jet (scattered electron)



- ❑ Djangoh (LL) and Pythia (QQ)*1.6
  - ➢ Reweighting of Pythia by 1.6 provides good description
- ❑ BLZ (Baranov, Lipatov, Zotov) model
  - ➢ x_γ and $\Delta\eta$ distribution not described by k_T-factorisation

Summary

- **Finalisation of HERA inclusive NC and CC DIS cross sections and QCD fits**
  - H1 and ZEUS have combined all inclusive unpolarised measurements into one coherent data set for e^+p and e^-p collisions at $\sqrt{s}$ = 318, 300, 251 and 225 GeV
  - The combined inclusive HERA data are used as a sole input to the QCD analysis resulting in the set of parton distribution functions HERAPDF2.0
- **Determination of electroweak parameters from H1 and ZEUS**
  - High sensitivity to light quark couplings and SM parameters
  - Provide important complementary tests of SM
- **Hard QCD**
  - Inclusive jets, dijets, trijets cross sections as well as those normalised to incl. NC cross section are now available for the whole Q^2 range, based on H1 data
  - First ever comparisons with brand new NNLO QCD calculations is presented for some of these normalised jet cross sections; scale uncertainty is visibly reduced, shape is better described as compared to NLO
  - Experimental precision of α_s determination based on these data is now ~0.4% and is significantly better than theory uncertainty
  - New results on prompt photon production in DIS from ZEUS data
    → direct tests of hard process

H1 and ZEUS NC and CC cross sections and PDFs

- H1 and ZEUS published high precision measurements of NC and CC cross sect.
  Q^2 from **0.045 GeV^2** to **40000 GeV^2**
  x from **$6 \cdot 10^{-7}$** to **0.65**

- ➢ Allow PDFs to be extracted solely from these data

- To get high precision measurements of PDFs **H1 and ZEUS results** are **combined** → HERAPDF sets

- **HERAPDF1.0 NLO**: based on published NC+CC HERA-I data - published (JHEP01 (2010) 109)

- **HERAPDF1.5 NLO, NNLO and LO**: based on preliminary NC+CC HERA-I + HERA-II data - preliminaries

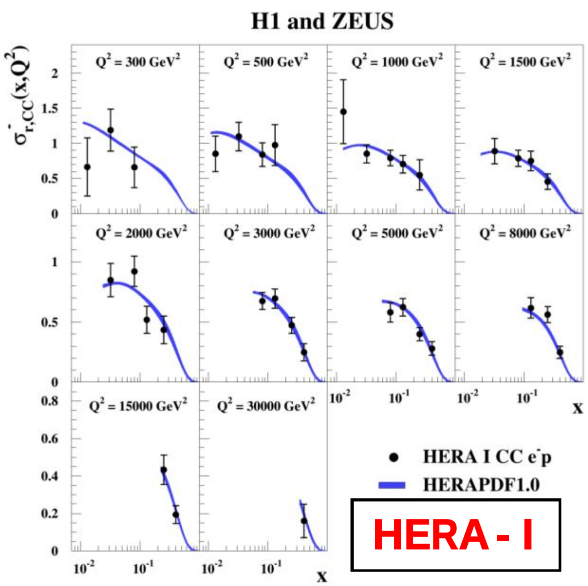
- ➢ **This talk**: recently published results based on the combinations of complete HERA data and the QCD fit from this data:
  HERAPDF2.0 (at NLO, NNLO and LO)

  QCD fits are performed using HERAFitter package (www.herafitter.org)

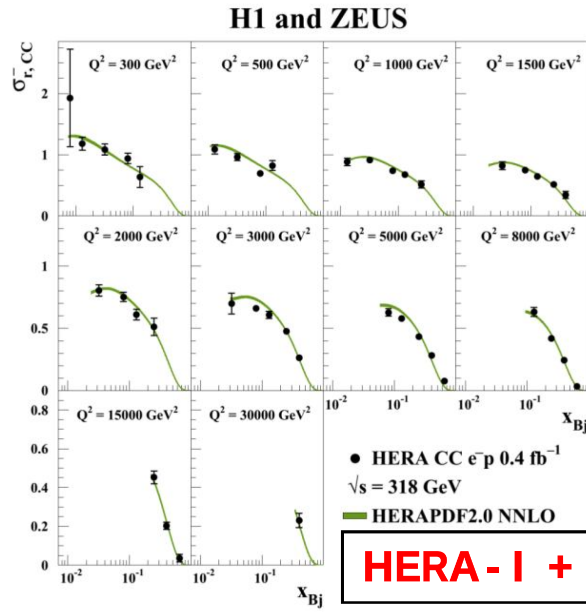
  Eur.Phys.J. C75 (2015) no.12, 580

CC combined data – flavour decomposition

Eur.Phys.J. C75(2015) 580

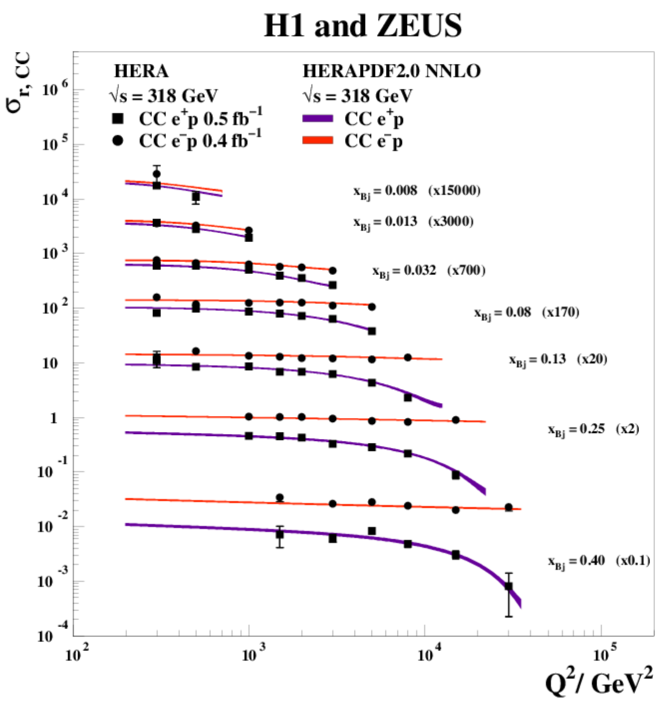


HERA - I



HERA - I + HERA - II

- Inclusion of the HERA II data reduces errors and provides new data points
- Improvement also in QCD predictions



Helicity effects

$$\sigma_{cc}^{e^+p} \sim (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$

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

$$\sigma_{cc}^{e^-p} \sim (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s})$$

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

Structure functions F_2 and xF_3

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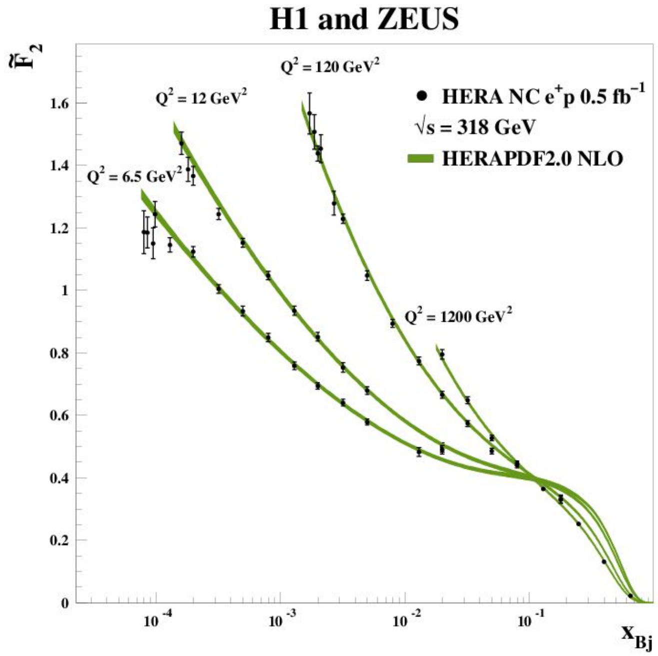
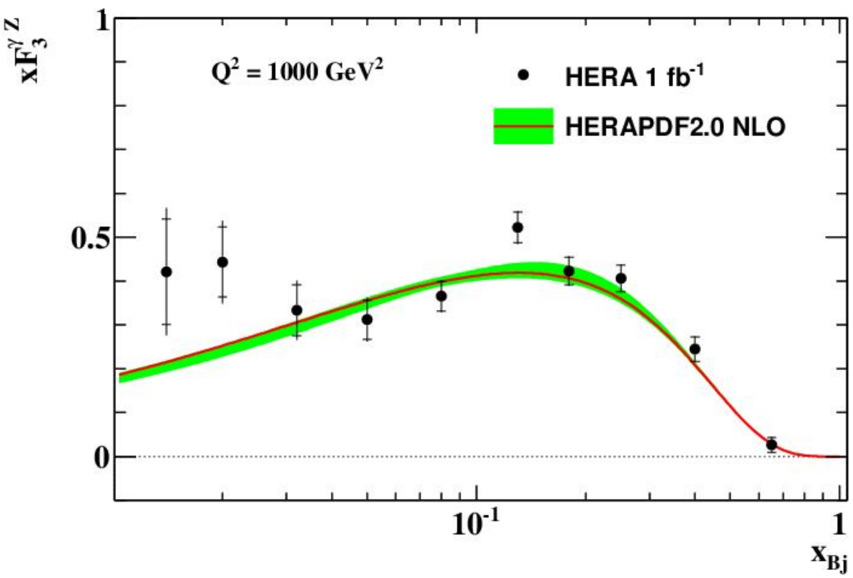


$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\,Y_+\left[F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right]$$

- **Scaling violations of F_2**
- F_2 rise towards low x becomes steeper as Q^2 increases

  → **Increasing gluon density**



- xF3 obtained from subtracting the NC e^+p from the NC e^-p cross sections

$$x\tilde{F}_3 = x\Sigma 2e_q a_q[q(x) - \bar{q}(x)]$$

$$x\tilde{F}_3^{\gamma Z} = x\tilde{F}_3(Q^2 + M_Z^2)/a_e k Q^2 \approx (2u_v + d_v)/3$$

→**Directly related to valence quarks**

- Integrated over the range 0.016 < x < 0.725

$$\text{HERAPDF2.0}: 1.165^{+0.042}_{-0.053}$$

$$\text{Data}: 1.314 \pm 0.057(\text{stat}) \pm 0.057(\text{syst})$$

Comparison to other sets of PDFs

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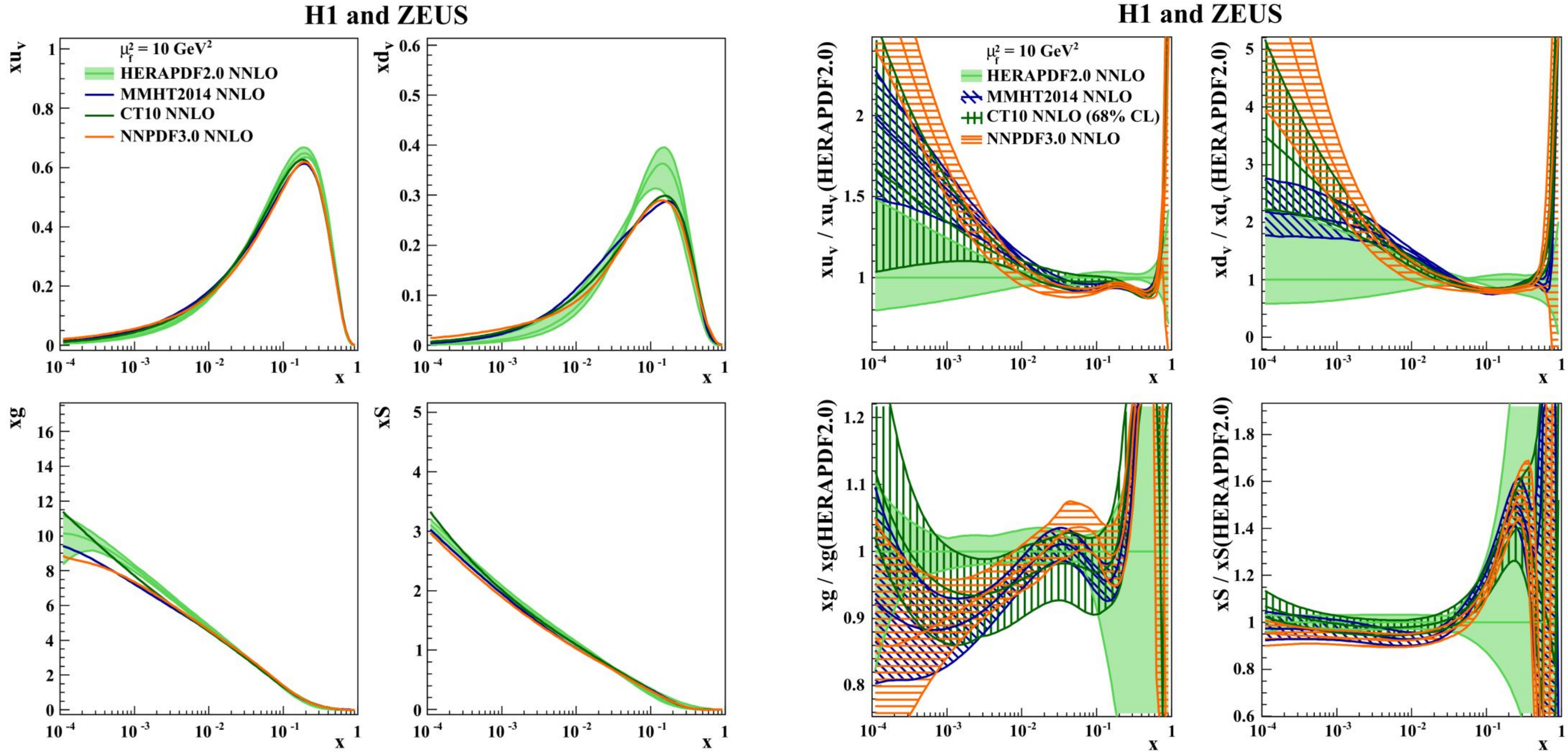

- Taking the full uncertainties into account, all PDFs are compatible
- The largest relative discrepancy at x~0.4 (~ 2.5σ) in the shape of the xu_v
- The gluon distribution of HERAPDF2.0 at NLO at high x is softer than that of the other PDFs

Trijet production in DIS at low Q^2