Precision tests of QCD at HERA

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on behalf of the H1 and ZEUS Collaborations

Excited QCD 2013

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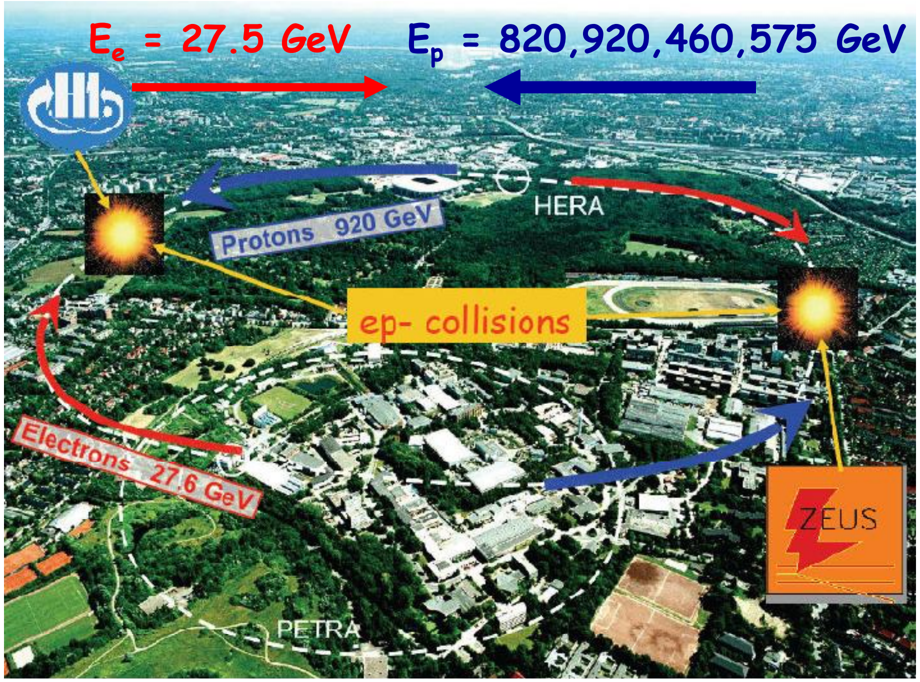
HERA and luminosity



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}

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

HERA-I (E_p = 820, 920 GeV) upgraded to HERA-II (E_p = 920 GeV)

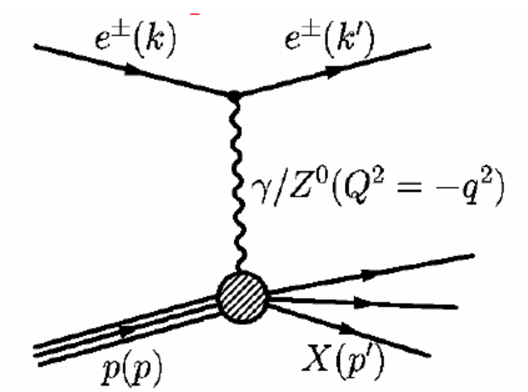
Since April 2007 until the end of June

- Low energy run – LER - (E_p = 460 GeV)
- Medium energy run – MER - (E_p = 575 GeV)

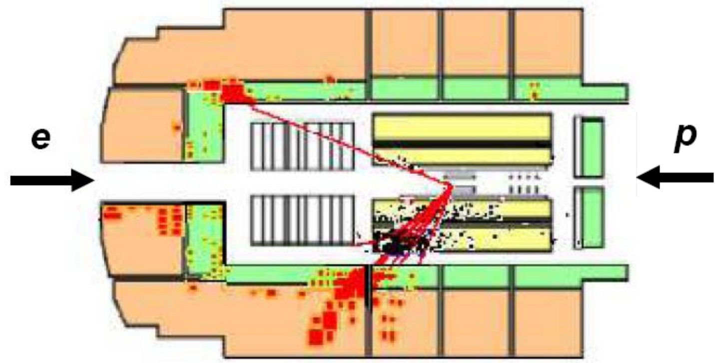
} Measurement of F_L

Inclusive Deep Inelastic Scattering (DIS)

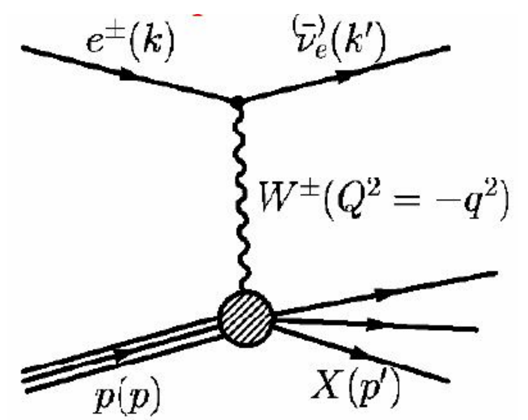
Neutral Current (NC)



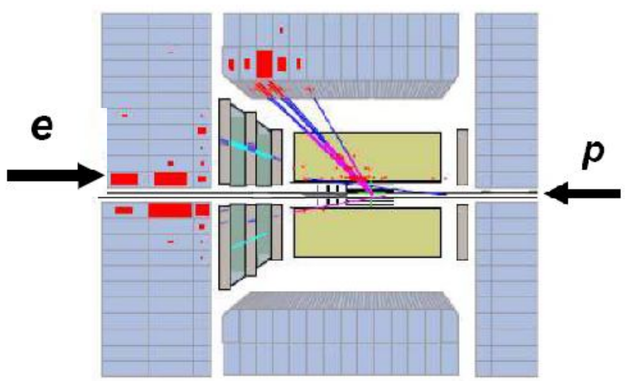
H1 NC event display



Charged Current (CC)



ZEUS CC event display



Virtuality of exchanged boson:

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

Fraction of proton momentum carried by struck quark

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

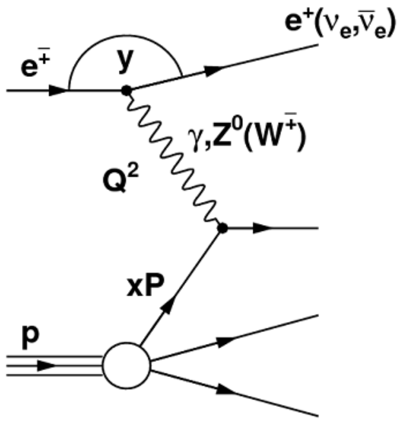
Fraction of energy transferred from incoming lepton at proton rest frame

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

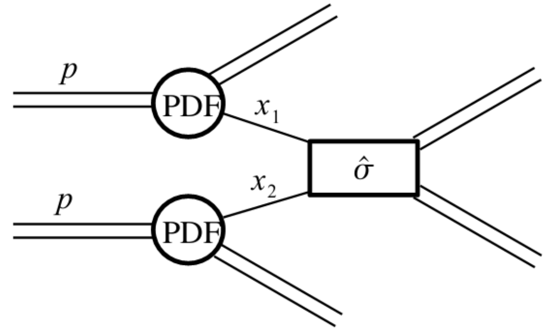
HERA Parton Denisty Functions (PDFs) and the LHC

HERA:

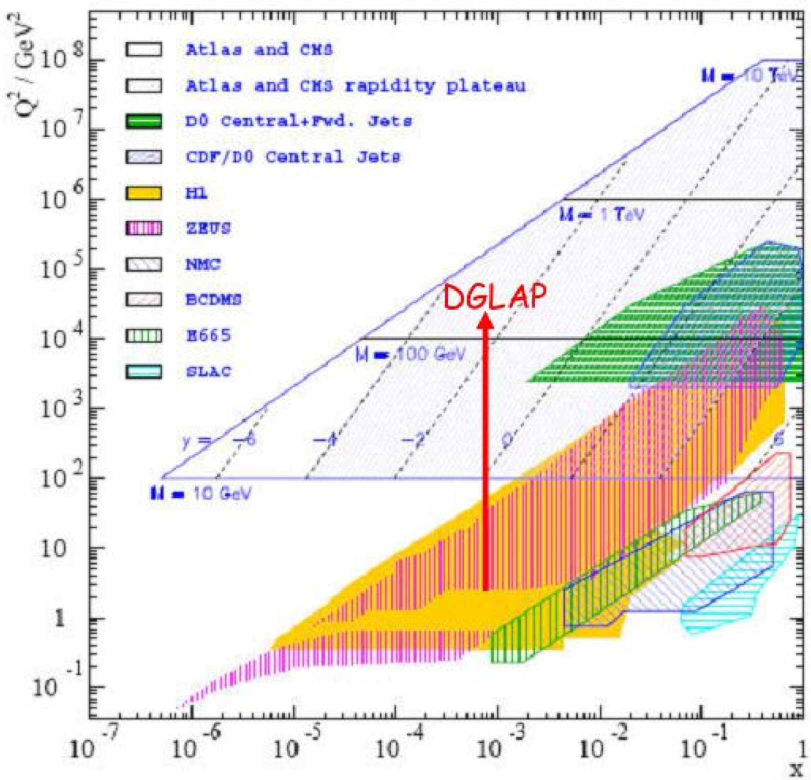
$$\sigma \propto PDF(x) \times \hat{\sigma}$$



LHC:



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



- 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.

Precision measurements of QCD at HERA

Neutral current cross section - new results from HERA

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

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

Contribution from valence and see quarks (F_2)

Directly related to gluon in pQCD $F_L \sim \alpha_s \cdot xg(x,Q^2)$

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

Charged current cross section - new results from HERA

$$\frac{d^2\sigma_{CC}^{e^{\pm}p}}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}\sigma_{CC}^{\pm}$$

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

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

Sensitivity to the flavor of the valence distributions at high x

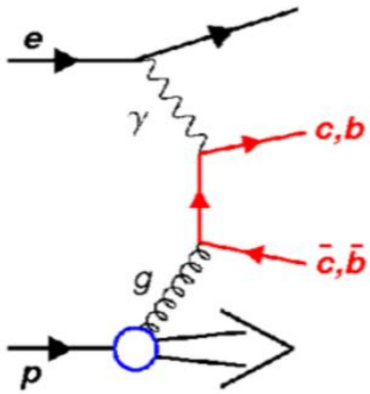
- Direct measure of structure functions (various linear combination of PDFs)
- HERA can disentangle proton PDFs with little assumptions

Precision measurements of QCD at HERA

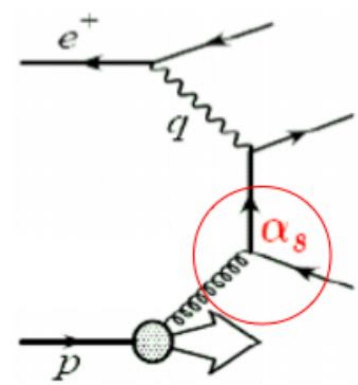
Charm contribution to the inclusive DIS - new result from HERA

- ~ 30% contribution to the inclusive DIS cross section (sizeable part)

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



- Measurement of the structure function F_2^{cc}, probing mass effects in the QCD evolution



Jet production in DIS - new measurements from HERA

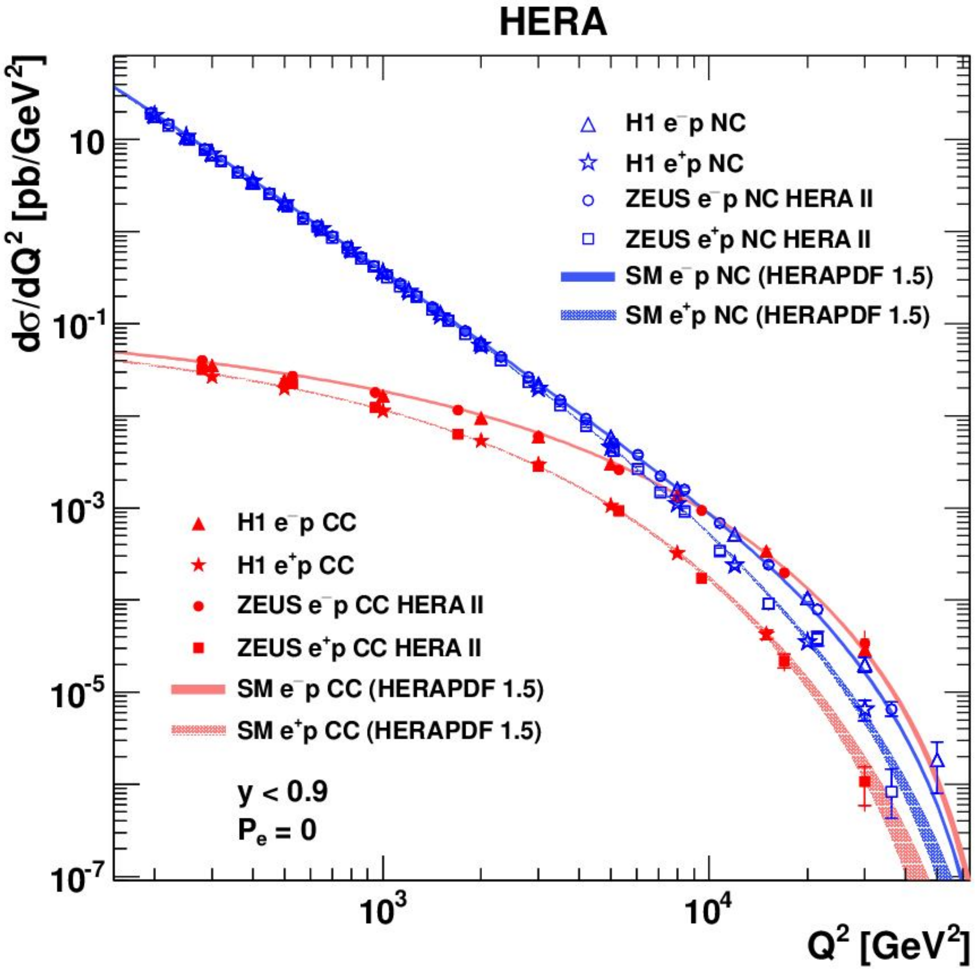
- Direct sensitivity to α_s and **gluon density**

Diffraction - new measurements from HERA

- New inputs for more precise DPDFs (not covered here): **EPJ C72 (2012) 2175** and **EPJ C72 (2012) 2074**

H1 and ZEUS HERA-II NC and CC cross sections at high Q^2

- Last pieces from H1 and ZEUS inclusive measurements (at nominal E_p = 920 GeV) – high Q^2 – FINALISED



JHEP 1209 (2012) 061	H1 NC and CC $e^{\pm}p$
arXiv:1208.6138	ZEUS NC e^+p
EPJ C70 (2010) 945	ZEUS CC e^+p
EPJ C62 (2009) 625	ZEUS NC e^-p
EPJ C61 (2009) 223	ZEUS CC e^-p

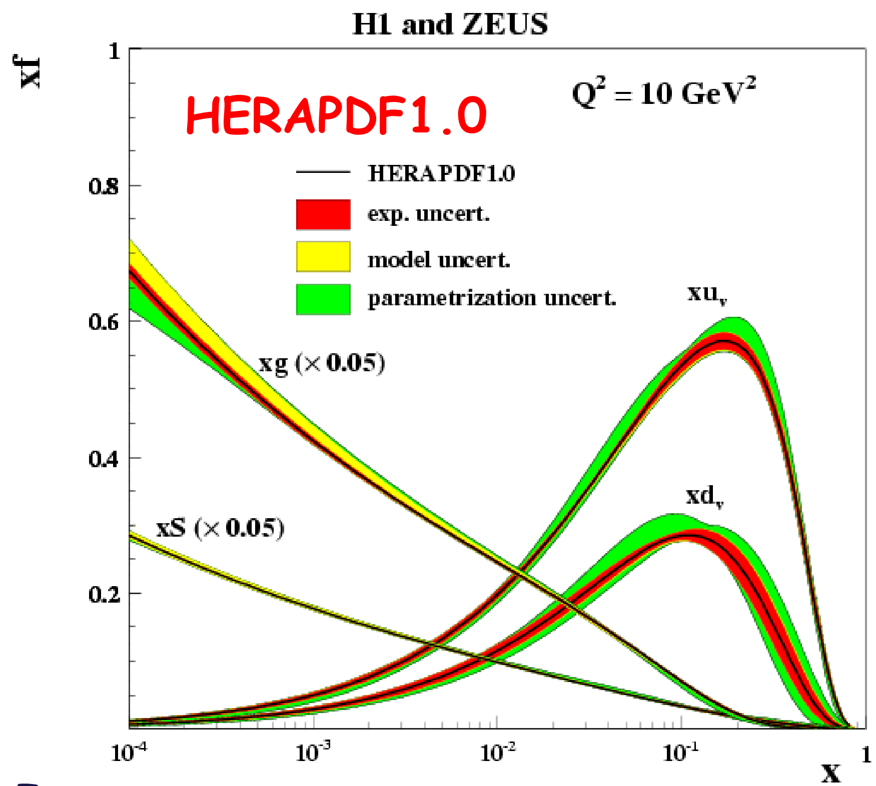
- EW unification at the $M_{W,Z}$ scale
- SM provides perfect description of data over many orders of magnitude

→ Lepton probe behaves as expected

QCD analysis of HERA data

General approach for PDF determination

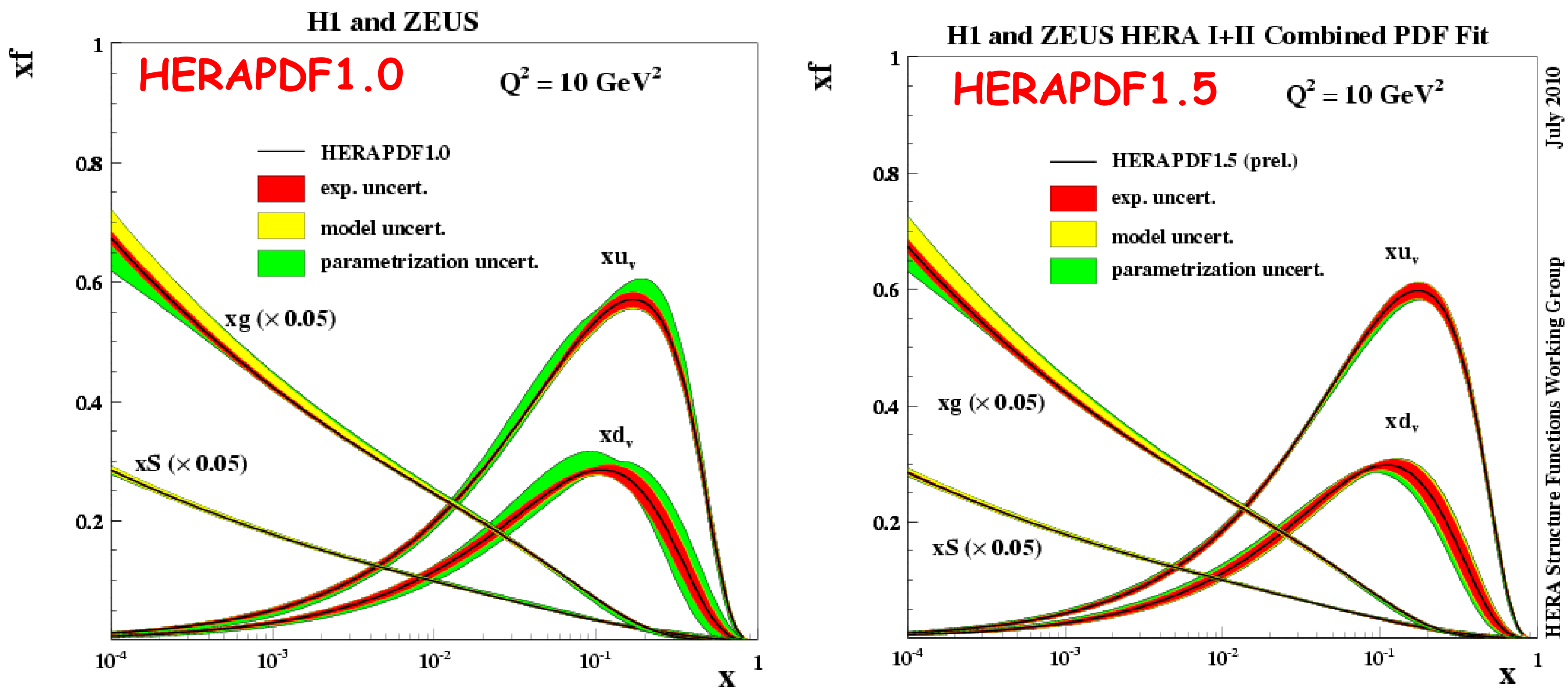
- At low starting scale Q_0^2 PDfs parametrised by $Ax^B(1 - x)^c(1 + Dx + \ldots)$
- Evolve these functions using the **DGLAP equations** to higher Q^2 and calculate x-sections
- Compare the calculation to experimental data and adjust the free parameters by χ^2 minimisation
- Heavy flavours treated according to RT-VFNS
- Fixed strong coupling constant: $\alpha_s = 0.1176$
- **HERAPDF1.0** obtained from combined HERA-I data from H1 and ZEUS experiments (**JHEP 1001:109(2010)**)



- Latest DGLAP analyses use open source **HERAFitter** 'package' which gives possibility to further improve PDFs by adding measurements from other experiments (Developers: H1, ZEUS, ATLAS and CMS)

Inclusion of preliminary HERA-II high Q^2 data

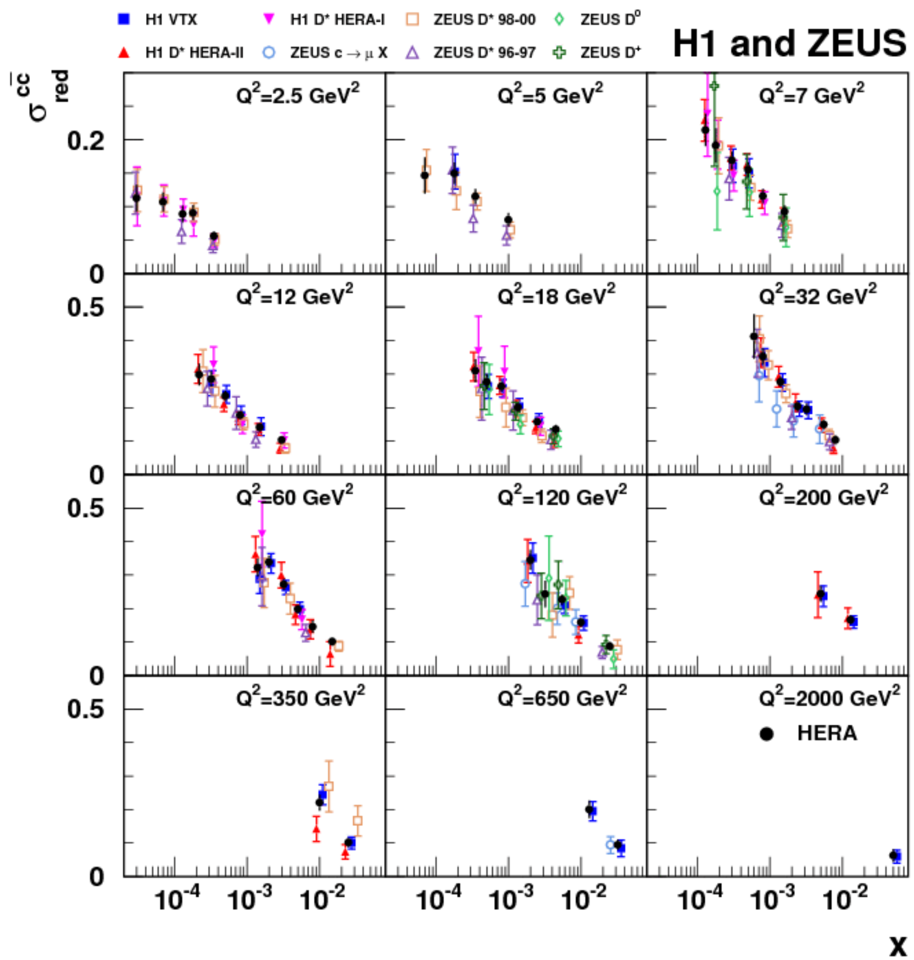
H1prelim-10-142 and ZEUS-prel-10-018

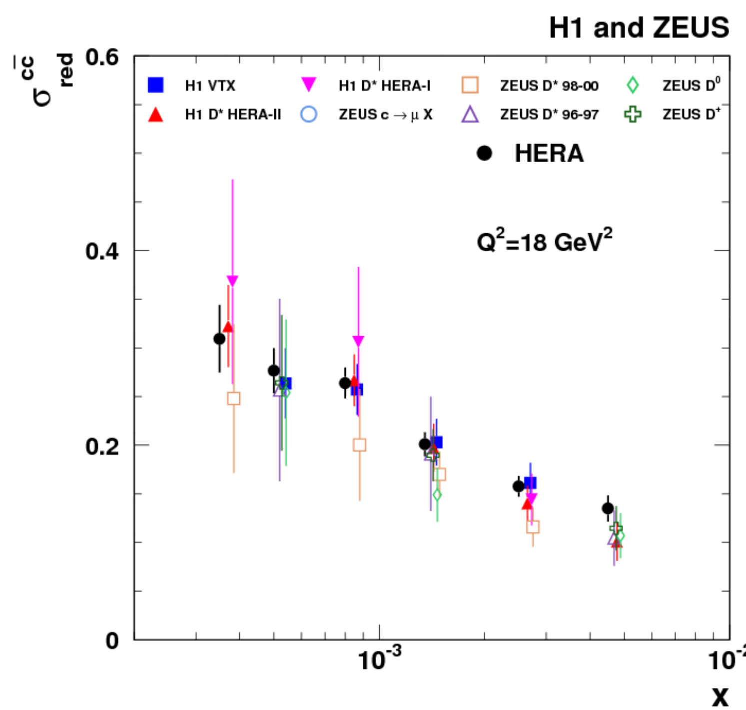


- Inclusion of the HERA-II high Q^2 data improves uncertainties of PDFs in the high x region especially visible for the valence quark distributions

Inclusion of charm data

arXiv:1211.1182

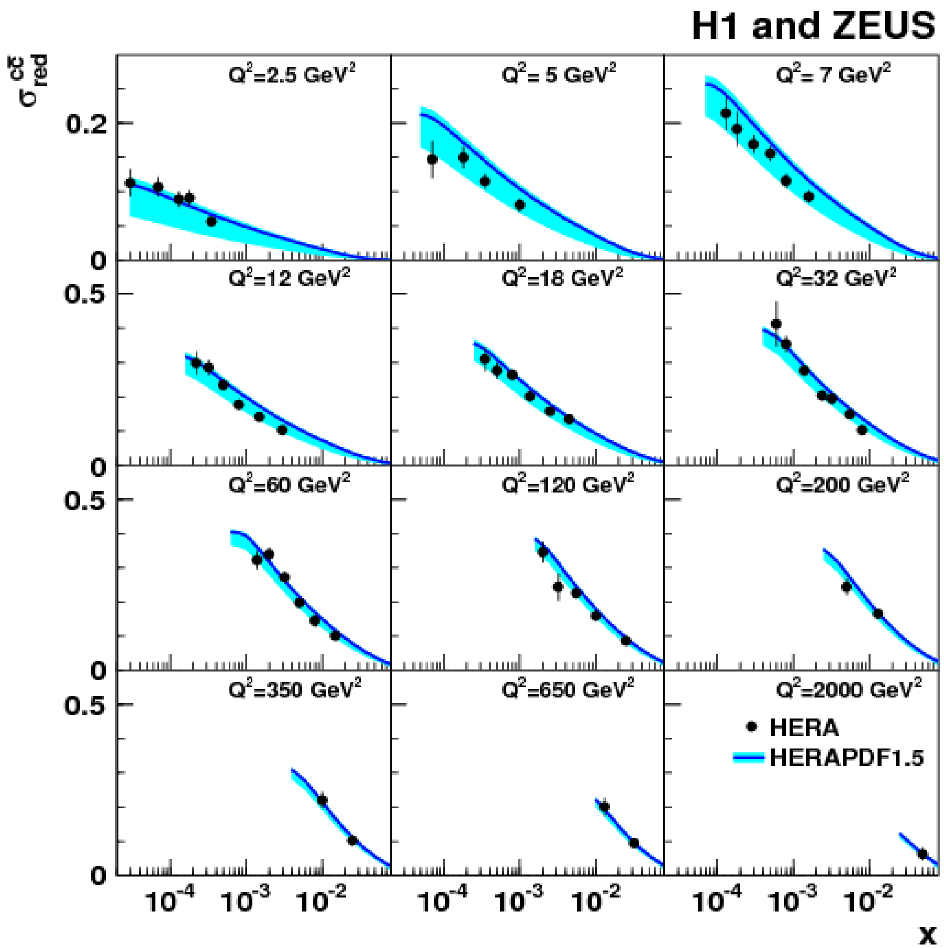




- Significant improvement in precision obtained by combining H1 and ZEUS data

Inclusion of charm data

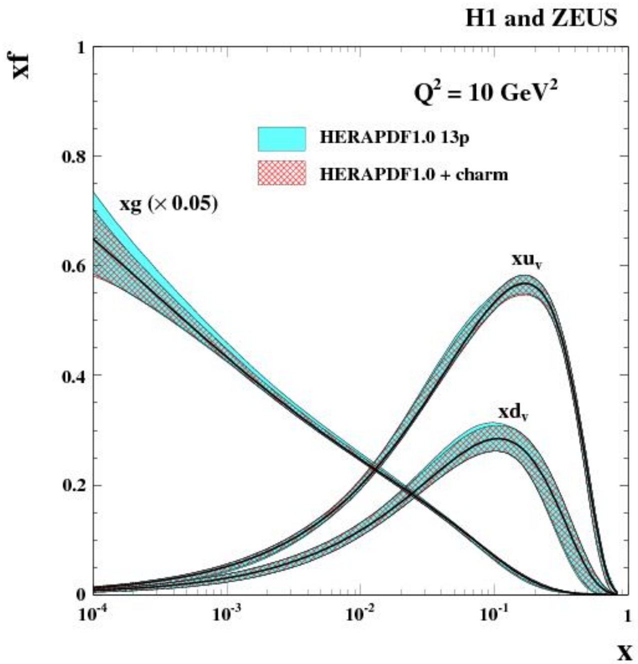
arXiv:1211.1182

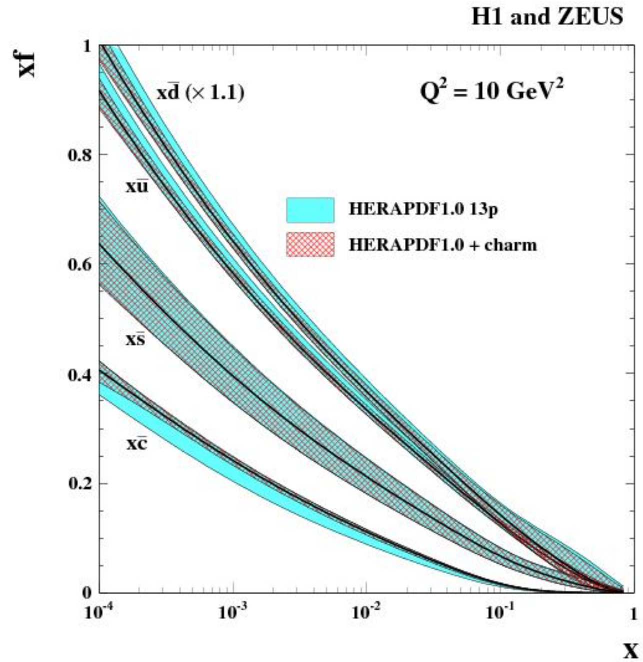


- Reasonable agreement with HERAPDF1.5 when taking into account uncertainty on m_c ($1.35 < m_c < 1.65$ GeV)

Inclusion of charm data

arXiv:1211.1182



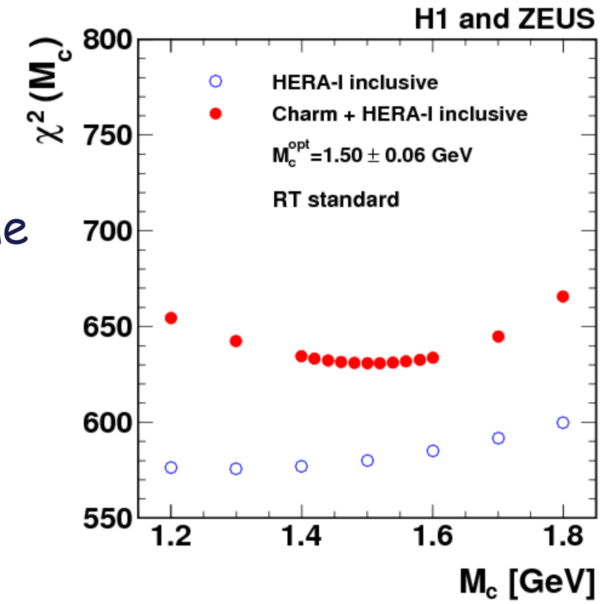


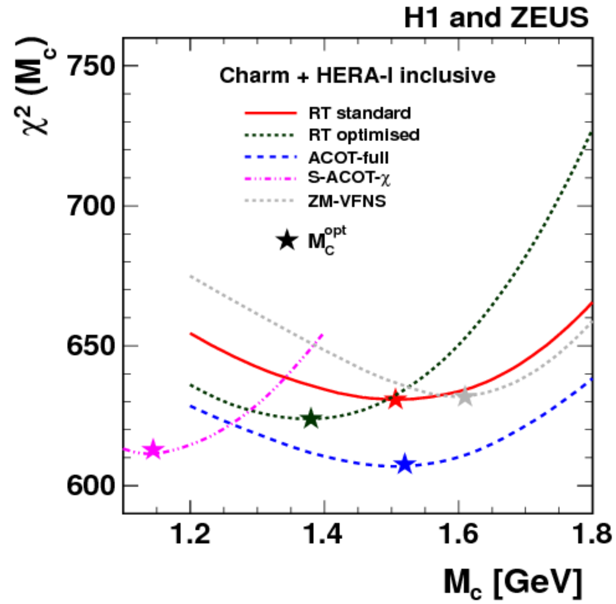
- The uncertainties of the valence quark distribution functions unaffected
- The uncertainty on the gluon distribution function reduced (due to the constraints that the charm data put on the gluon through the $\gamma g \rightarrow c\bar{c}$)
- The uncertainty on the $x\bar{c}$ distribution function is considerably reduced due to the constrained range of m_c

Inclusion of charm data

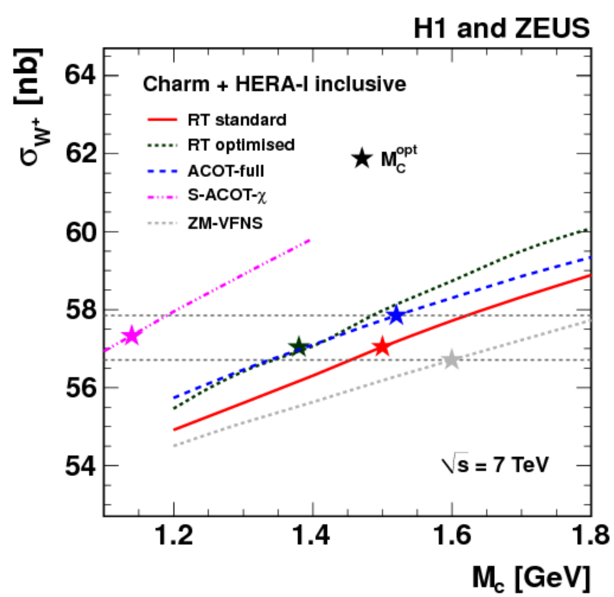
- ❑ Increased sensitivity to charm mass
- ❑ The σ^{cc} allows to determine the optimal charm mass parameter (M_c^{opt}) for the various VFNS schemes

arXiv:1211.1182





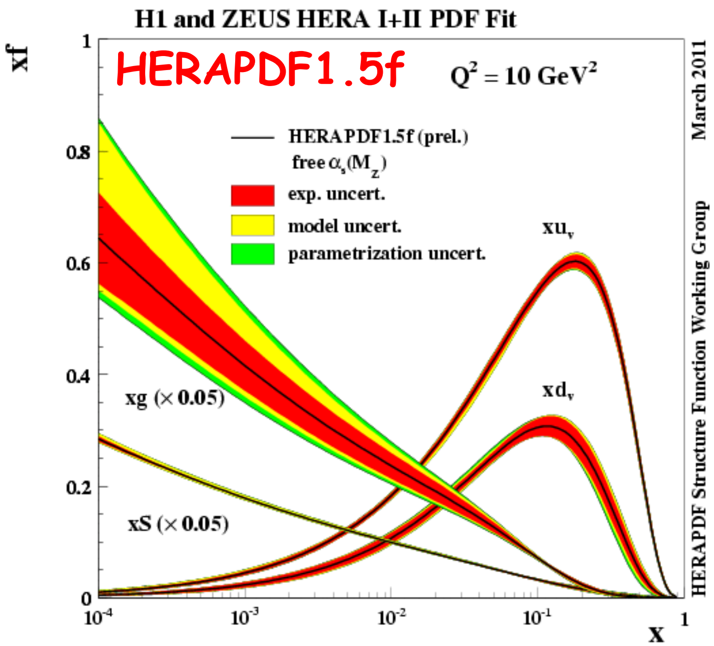
- ❑ For all implementations of VFNS a similar monotonic dependence of the $W^{\pm}$ (and Z) production cross sections at the LHC on M_c is observed → significant spread of about 6% between the predictions
- ❑ When using the M_c^{opt} for each scheme the spread of predictions is significantly reduced

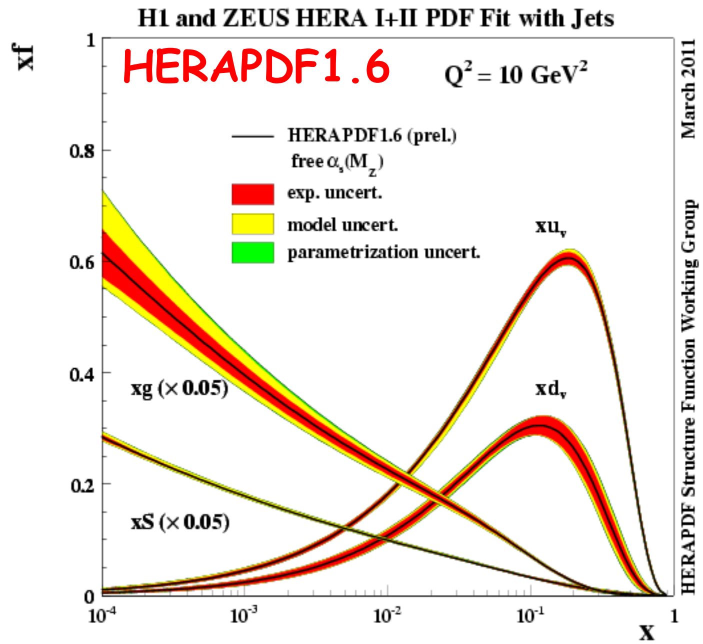


Inclusion of JETS

H1prelim-11-034 and ZEUS-prel-11-001

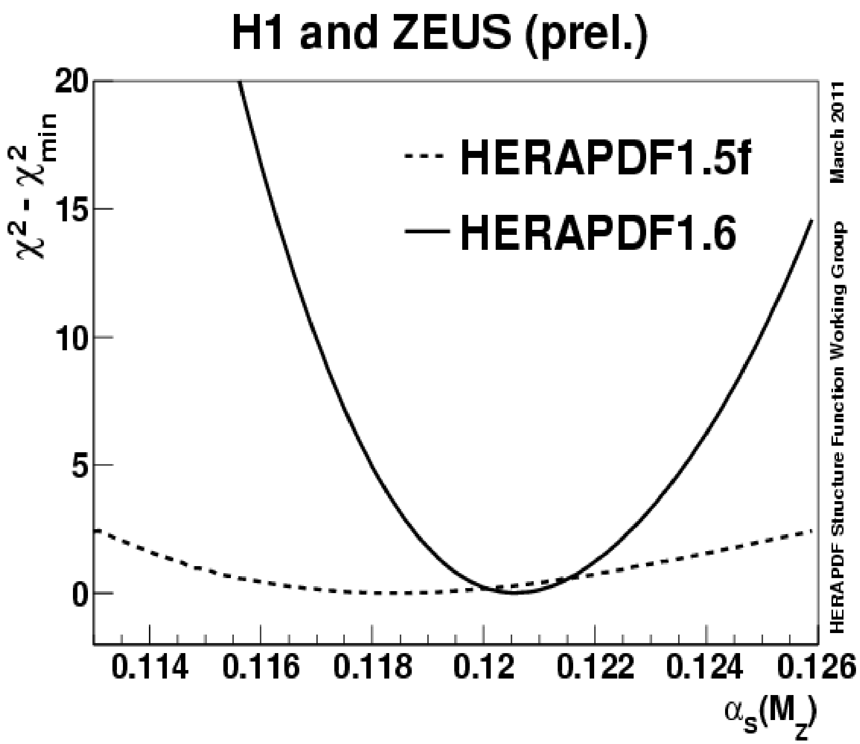
- **HERAPDF1.6**: the same input as for HERAPDF1.5 + 4 inclusive jet measurements from H1 and ZEUS
- HERAPDF1.6 to be compared to **HERAPDF1.5f** - the same input as HERAPDF1.5 but treating **$\alpha_s(M_Z)$ as a free parameter** as in HERAPDF1.6





- The jet data significantly reduce the correlation between the gluon PDF and α_s → improved precision of the gluon PDF and an unbiased determination of $\alpha_s(M_Z)$

α_s from HERAPDF1.6



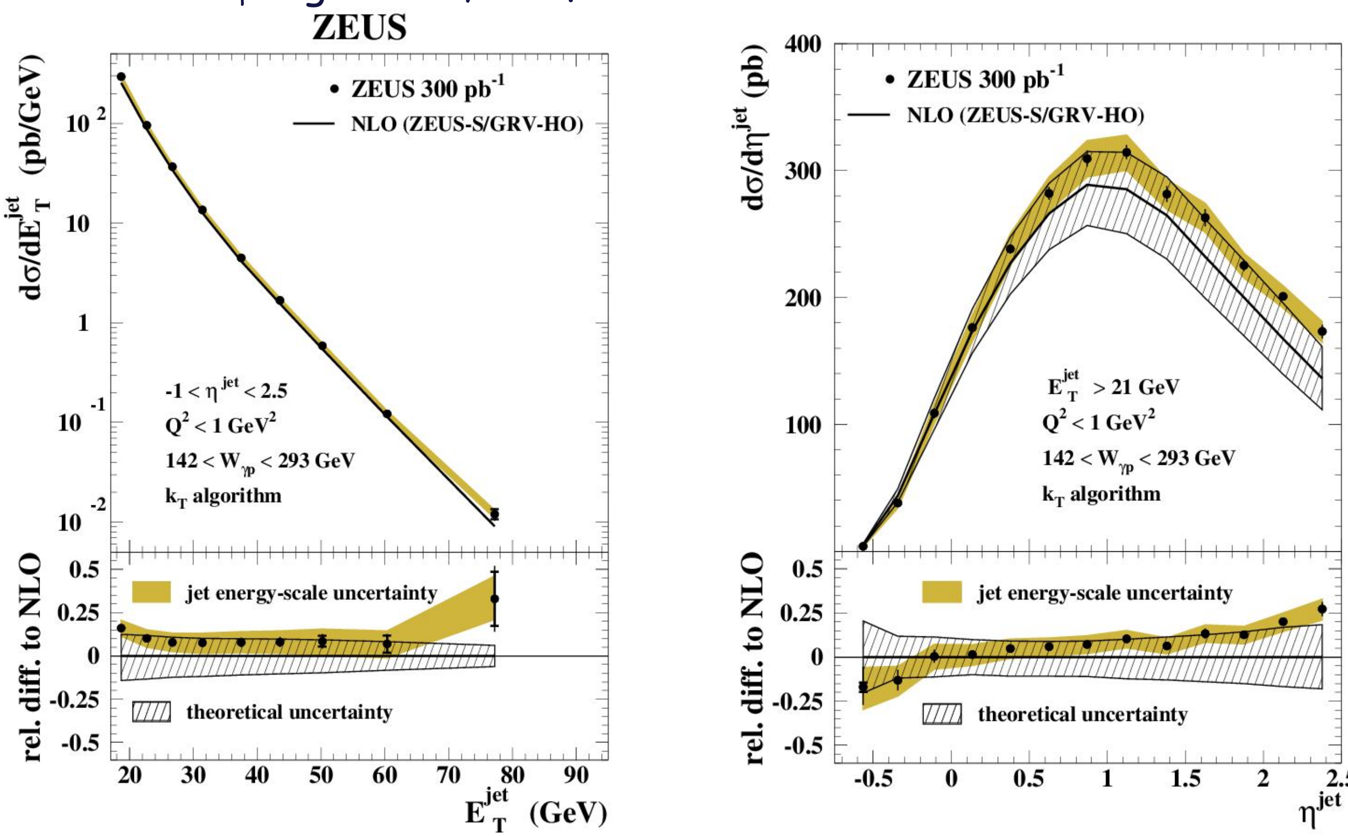
- Local minimum in $\Delta X^2(\alpha_s)$ pronounced only after including jet data

$$\alpha_S(M_Z) = 0.1202 \pm 0.0013(exp.) \pm 0.0007(mod/param.) \pm 0.0012(had)\ ^{+0.0045}_{-0.0036}(th)$$

Inclusive jets in photoproduction

Nucl. Phys. B864 (2012), 1

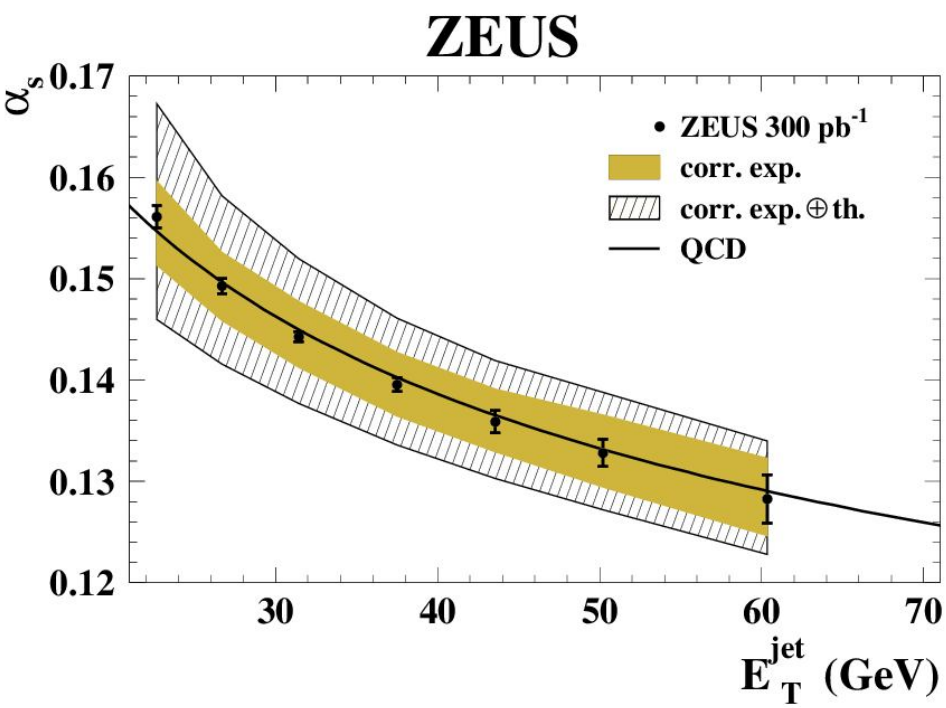
- Kinematic selection: $Q^2 < 1$ GeV^2, $0.2 < y < 0.85$, $142 < W_{\gamma p} < 293$ GeV
  k_T algorithm, $-1 < \eta^{jet} < 2.5$



- Reasonable description of data with NLO pQCD calculations for $E_T^{jet} > 21$ GeV

Inclusive jets in photoproduction

Nucl. Phys. B864 (2012), 1



- The α_s values determined in each E_T^{jet} value from the analysis of the measured $d\sigma/dE_T^{jet}$ via NLO QCD fit ($21 < E_T^{jet} < 71$ GeV)
- Data are compared with QCD prediction of α_s at two loops

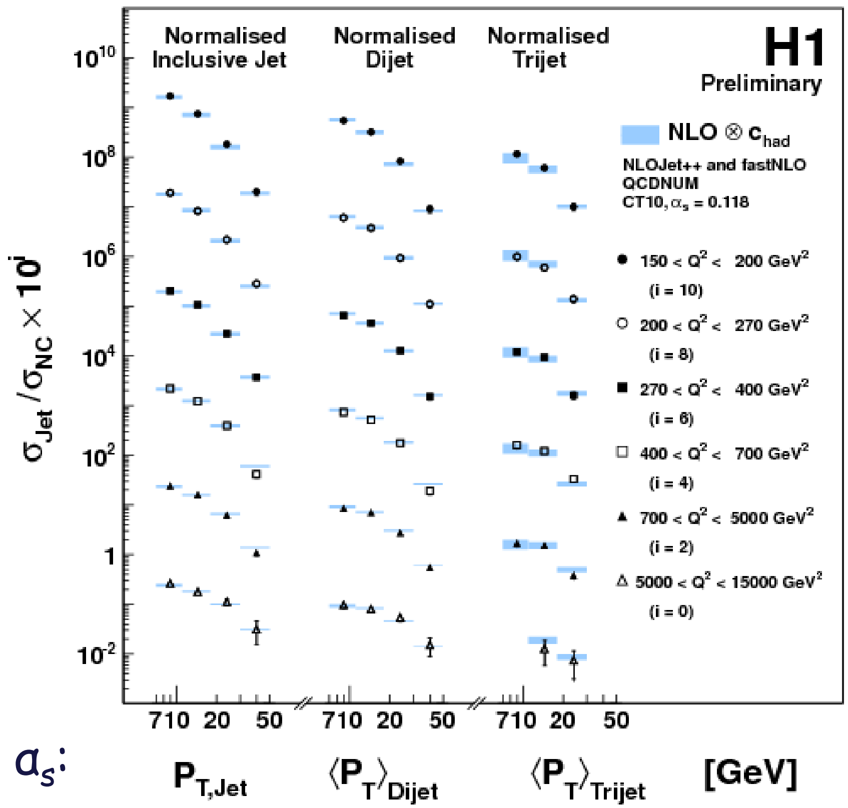
$$\alpha_S(M_Z) = 0.1206 \,^{+0.0023}_{-0.0022}\,(\mathrm{exp})\,^{+0.0042}_{-0.0035}\,(\mathrm{th})$$

- The dominant uncertainties due to missing higher orders and due to photon PDFs at high η^{jet}

Normalised multijet cross sections at high Q^2 in DIS

H1prelim-12-031

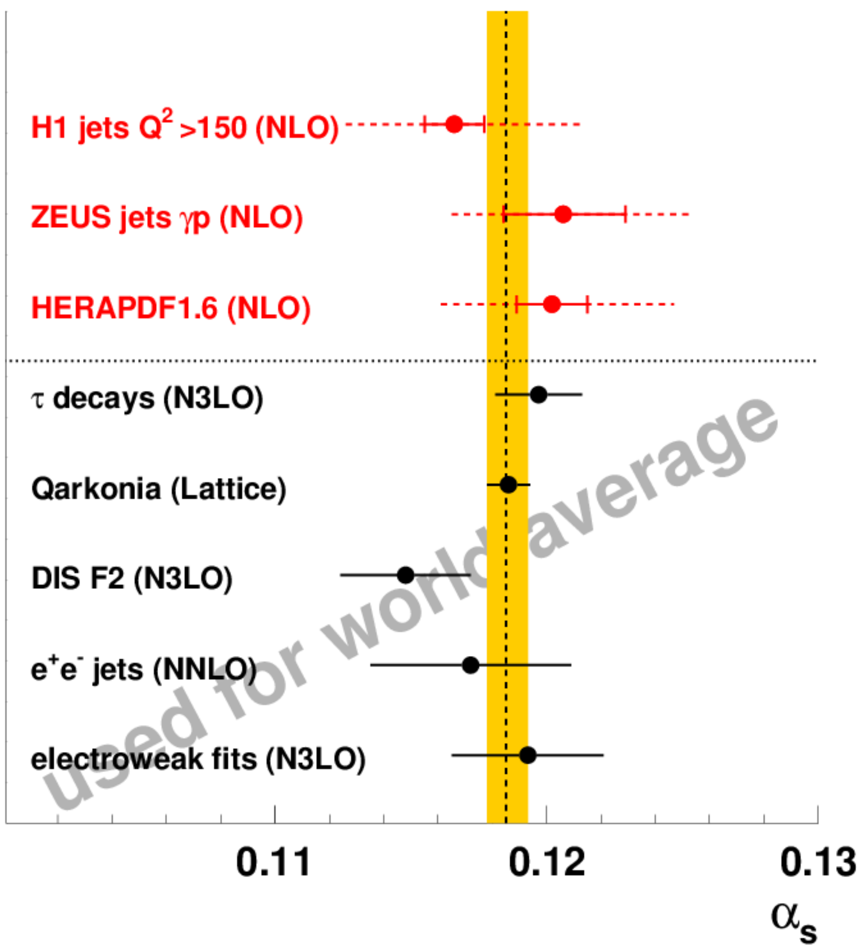
- Kinematic selection: $150 < Q^2 < 1500$ GeV^2, $0.2 < y < 0.7$, $7 < P_T < 50$ GeV
  $5 < P_{T,i} < 50$ GeV, $M_{1,2} > 16$ GeV (HERA-II)
- Compared to a previously published result on multijet cross sections:
  - an extended range in jet pseudorapidity
  - an improved hadronic energy scale uncert. of 1%
- Measured cross sections described well with NLO QCD predictions
- Theoretical uncertainties dominated by missing higher orders in pQCD



- Combined NLO fit to normalised inclusive, dijet and trijet cross sections to extract α_s:

$$\alpha_S(M_Z) = 0.1163 \pm 0.0008\,(\text{exp.}) \pm 0.0011\,(\text{had}) \pm 0.0014\,(\text{pdf})^{+0.0044}_{-0.0035}\,(\text{th})$$

Summary on recent α_s measurements at HERA



- ❑ HERA measurements of α_s consistent with world average
- ❑ Due to the uncertainty coming from the terms beyond NLO, α_s measurements from HERA have sizable theoretical uncertainties
- ❑ HERA measurements are statistically as precise as the measurements included in the world average

Summary

- New measurements on NC and CC from HERA-II at high Q^2 from both experiments → improvement for the valence quark distributions
- New combined measurement of charm production cross section at HERA → used as input for a detailed NLO QCD analysis
- Jet measurements from HERA improve the gluon PDF and provide simultaneous determination of PDFs and α_s
- New jet measurements from both experiments → new and more precise α_s from HERA

- HERA experiments are providing unprecedented knowledge about proton structure
- HERA results are important inputs for LHC predictions

Backup

Averaging procedure

- Swim all points to a common x-Q^2 grid
- Moved 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties

  χ^2 minimization in which the parameters are the true values of the cross section and the correlated systematic error parameters (arXiv:0904.0929)
- Evaluate "procedural uncertainties"

$$\chi^2_{\exp}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \Gamma^i_j b_j - \mu^i\right]^2}{\Delta_i^2} + \sum_j b_j^2$$

- Exploit differences between H1 and ZEUS in detectors, methods and systematics to "cross-calibrate" and to reduce the systematic uncertainties.

- For multiplicative error sources small biases to lower cross section values may occur. This can be avoided modifying the χ^2 definition as:

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

$$\gamma^i_j = \Gamma^i_j/\mu^i \qquad \delta_{i,\mathrm{stat}} = \Delta_{i,\mathrm{stat}}/\mu^i \qquad \delta_{i,\mathrm{uncor}} = \Delta_{i,\mathrm{uncor}}/\mu^i$$

QCD analysis

- ❑ DGLAP analysis based only on the HERA data:
- no need for heavy target corrections
- no strong isospin assumptions
- ❑ Some parameters in parametrisation functions constrained by the number and momentum sum rules

$\sum mom. = 1 \quad \int u_v\, dx = 2 \quad \int d_v\, dx = 1$

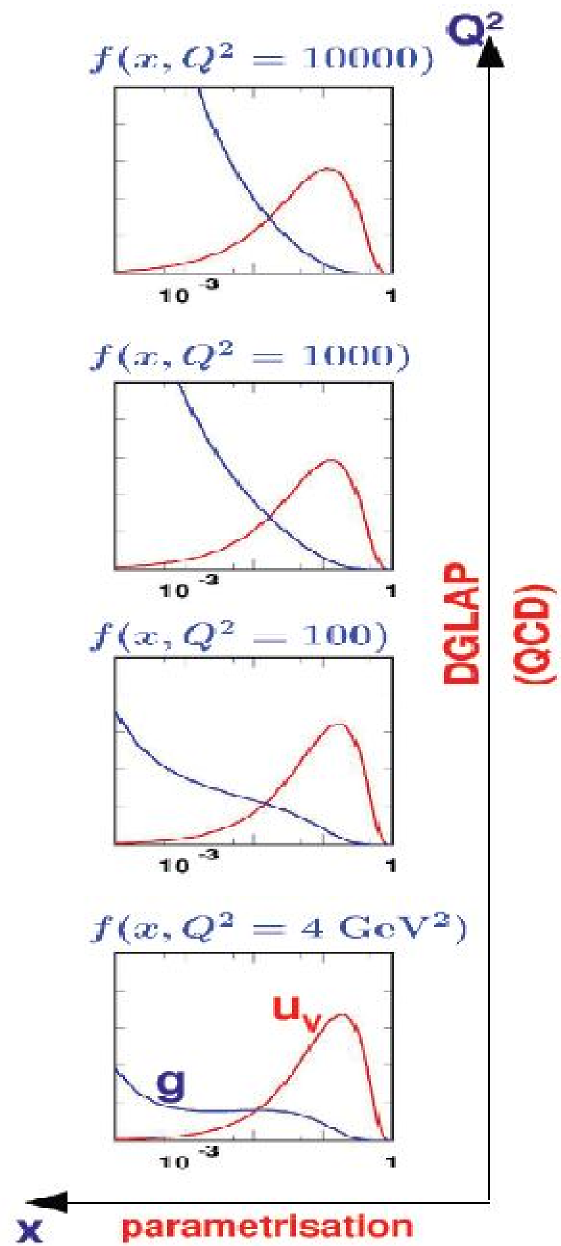
Fitted PDFs: $xg, xu_v, xd_v, x\bar{U} = x\bar{u} + (x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s} + (x\bar{b})$

Uncertainties

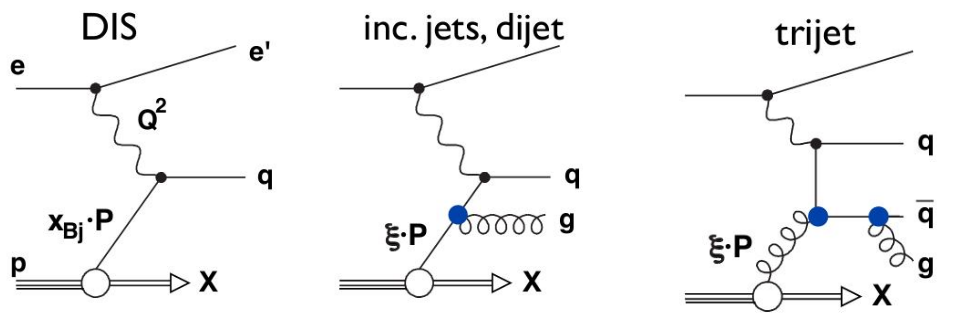
- ❑ Experimental – using $\Delta\chi^2 = 1$ criterion
- ❑ Model – from variation of theory parameters:

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	$1.35^{(a)}$	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	$1.5^{(b)}$	$2.5^{(c,d)}$

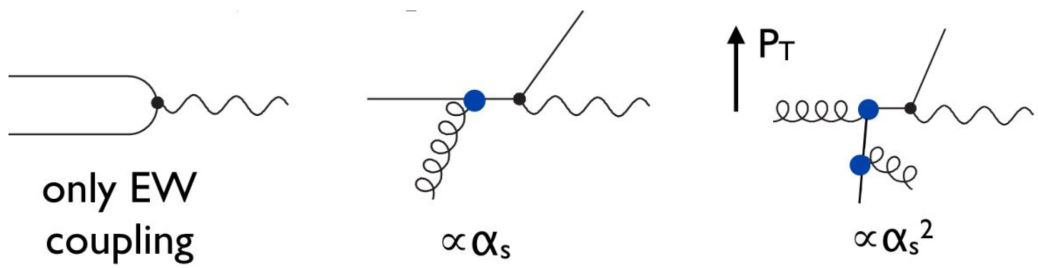
- ❑ Parameterisation – from extra D, E, … terms in parameterisation



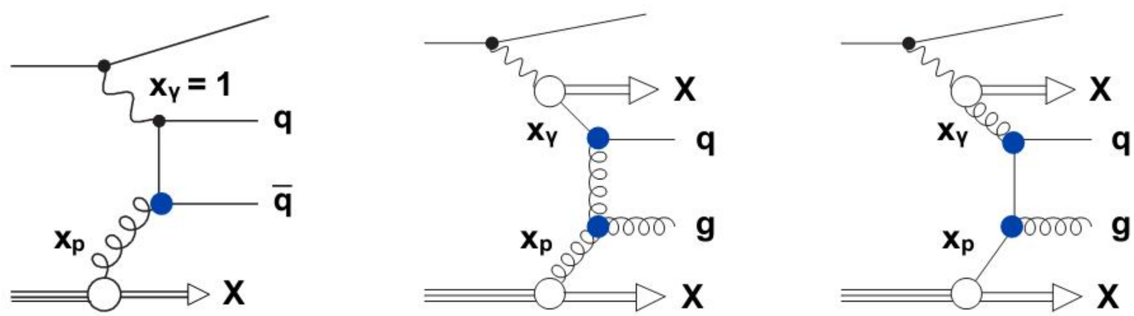
Jet production in DIS



Boost to Breit frame, $2xP + q = 0$



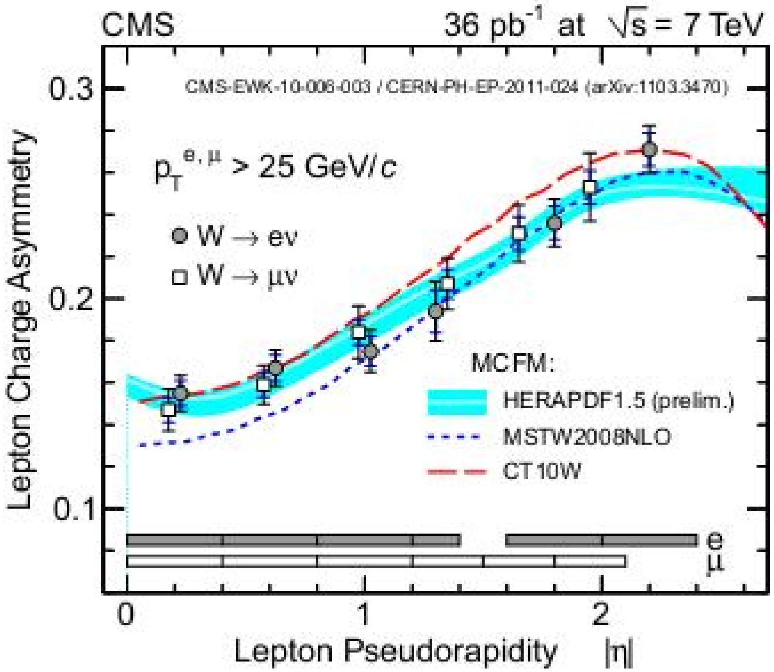
Jet production in photoproduction

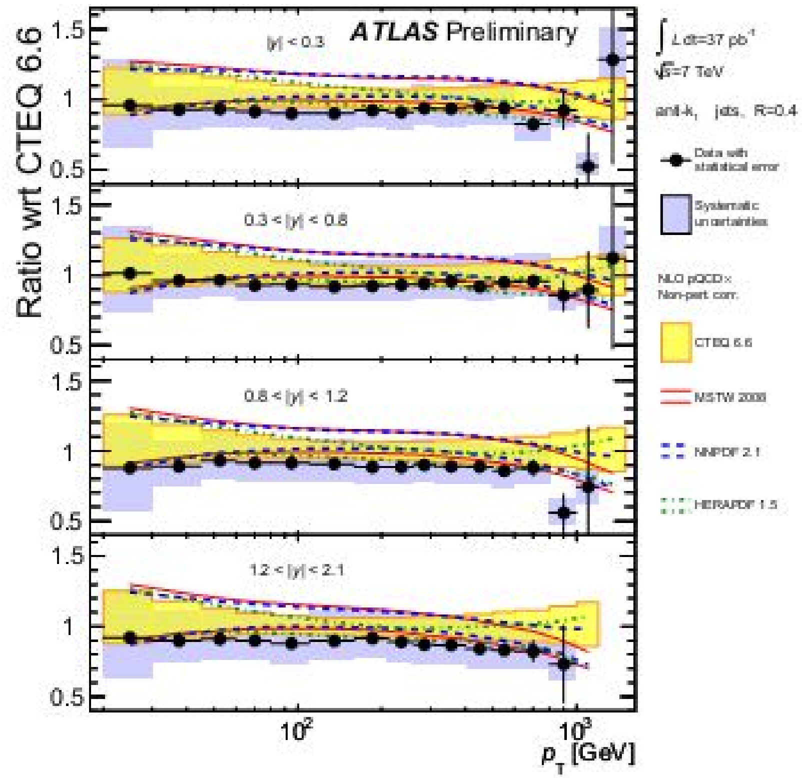


direct photoproduction

resolved photoproduction

HERAPDF predictions for LHC





- W decay lepton asymmetry data from CMS

- ATLAS jet data in the central region in ratio to the predictions of CTEQ6.6