Probing QCD at HERA

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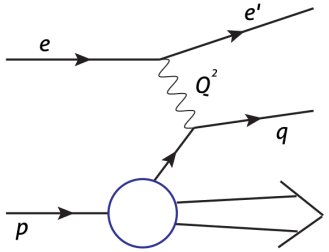
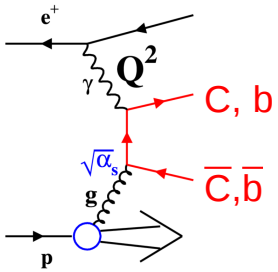
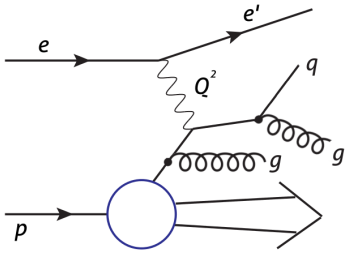
DESY
On behalf of H1 and ZEUS Collaborations



- Inclusive DIS



- Charm and beauty

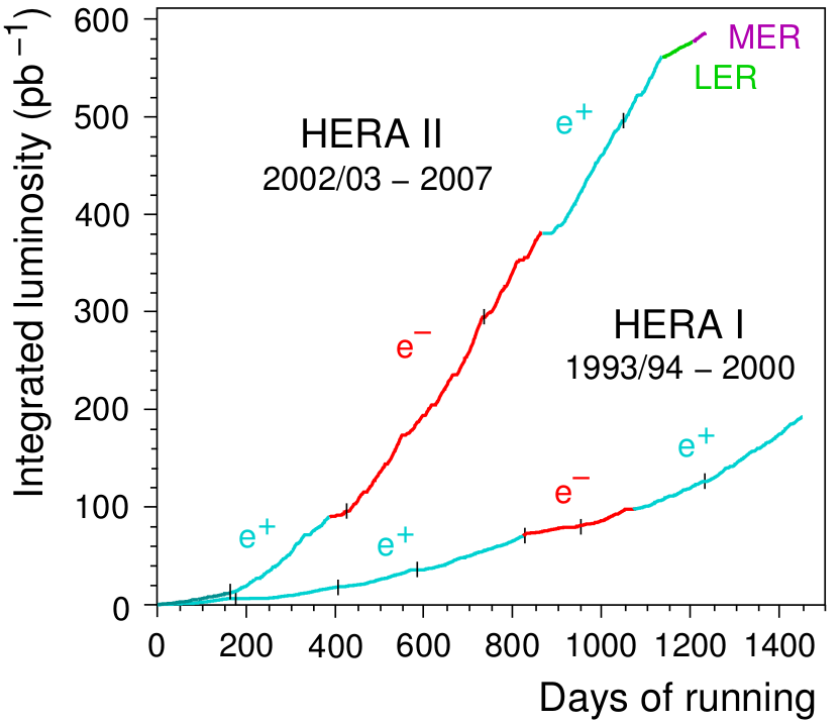


- Multijet production

ZEUS and H1 experiments

HERA is worlds only $e^{\pm}p$ collider :

operated during 1992 — 2007;
$e^{\pm}$ energy 27.5 GeV;
p energies 920, 820, 575 and 460 GeV.

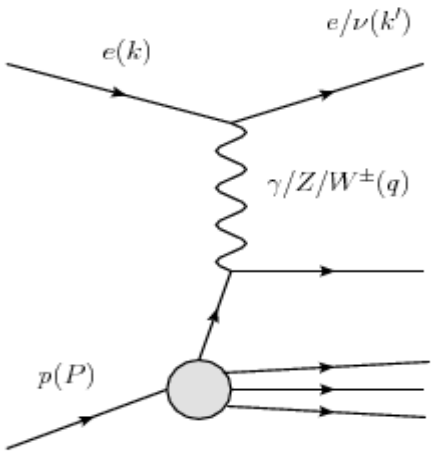


H1 and ZEUS — two collider experiments at HERA :

~ 0.5 fb^{-1} of luminosity recorded by each experiment.

HERA data provides unique opportunity to study the structure of the proton.

HERA data and the LHC



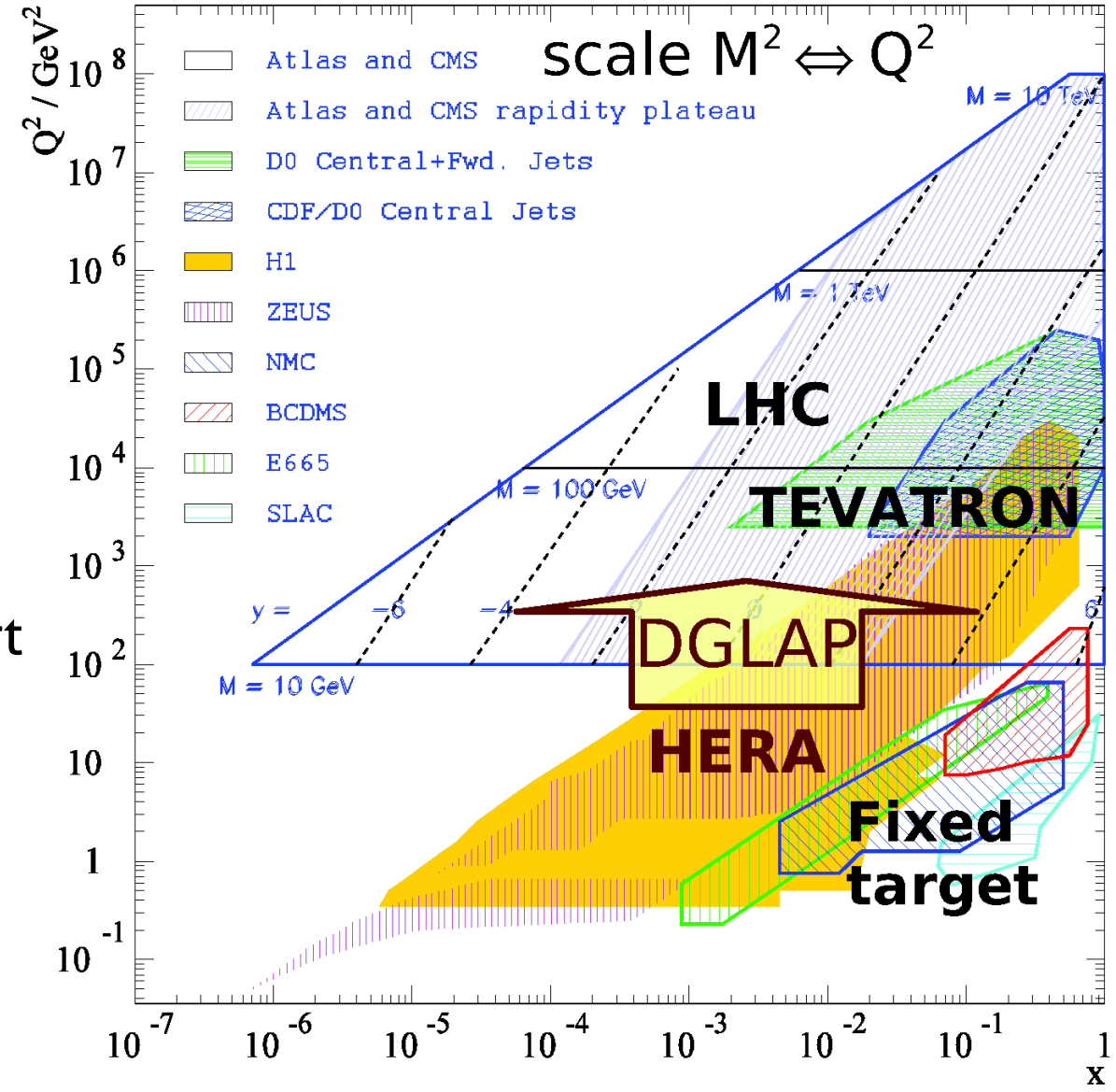
$Q^2 = -(k - k')$

$x = Q^2 / 2P \cdot q$

$y = P \cdot q / P \cdot k$

HERA data covers a large part of the LHC x range.

Evolution in Q^2 via DGLAP allows to extrapolate HERA PDFs into LHC region.

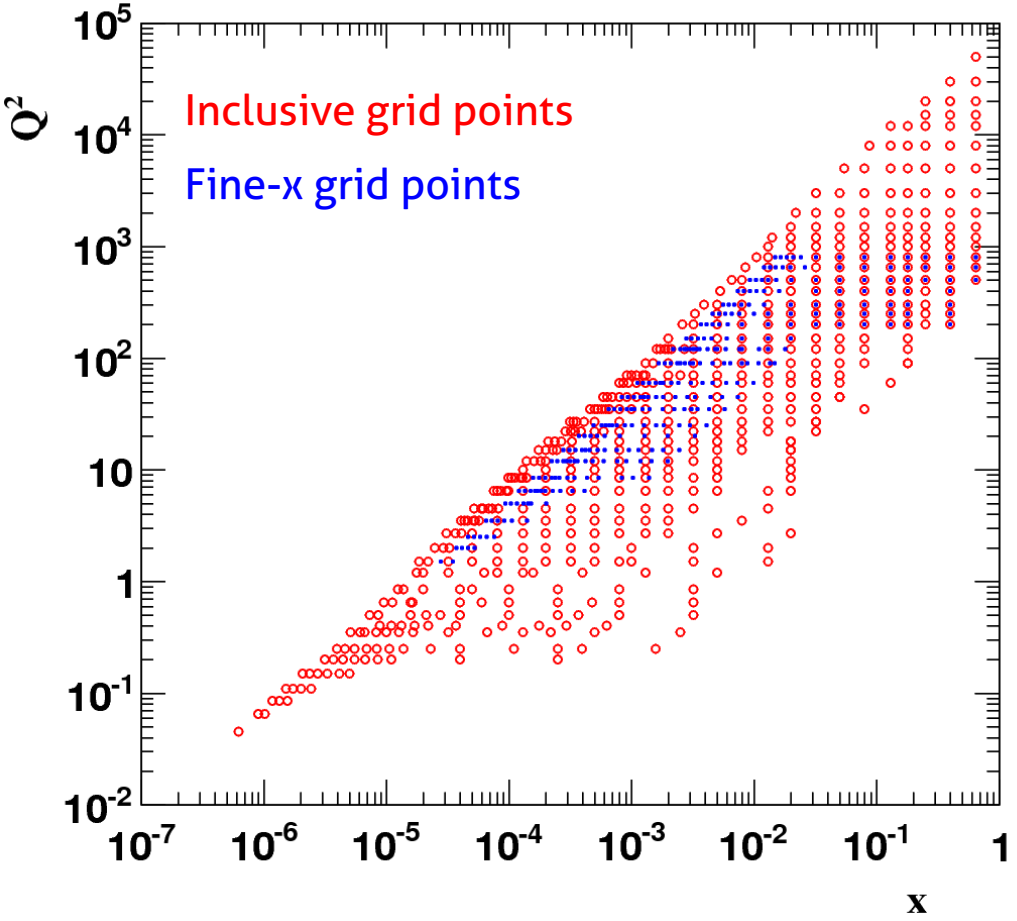


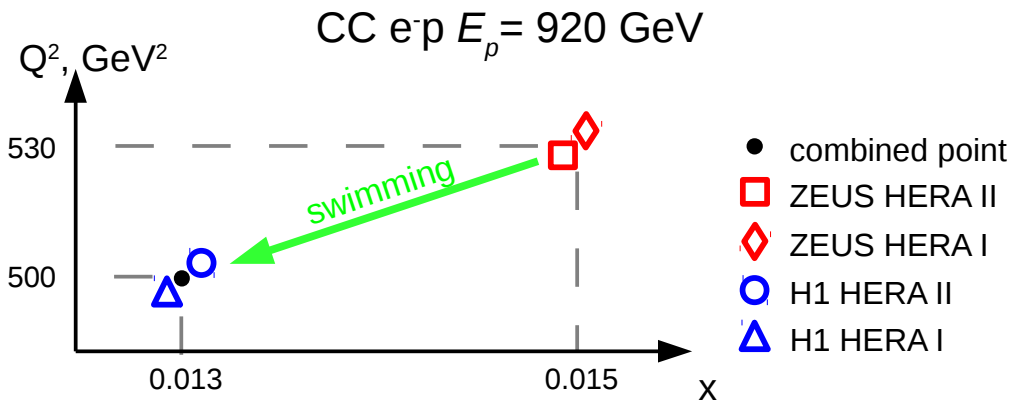
Combined Inclusive DIS

H1prelim-14-041, ZEUS-prel-14-005

H1 and ZEUS published all inclusive DIS data.
H1prelim-14-041, ZEUS-prel-14-005 ⇒ Combine the separate data.

All data points are swum to common Q^2 - x grids:



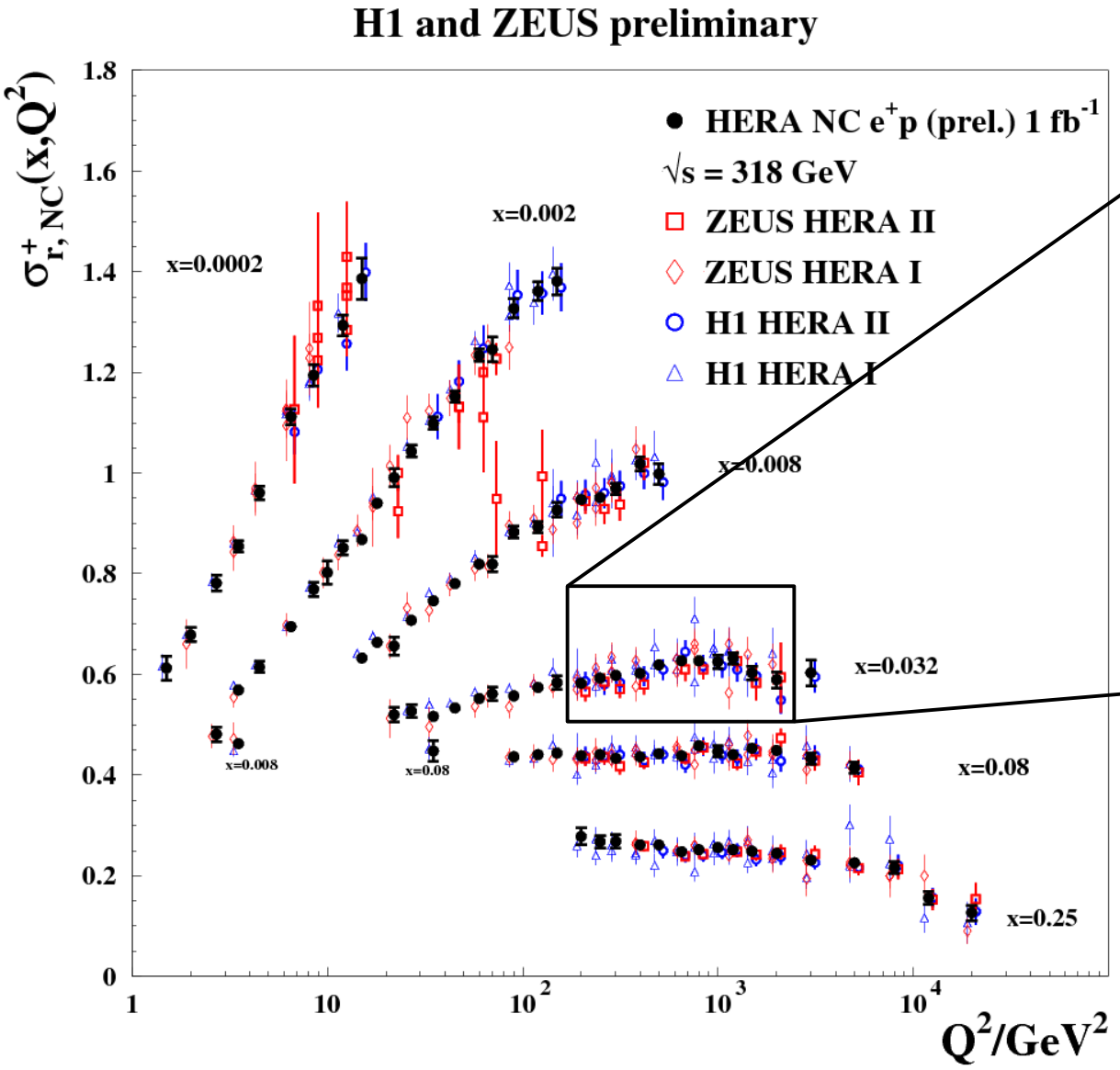


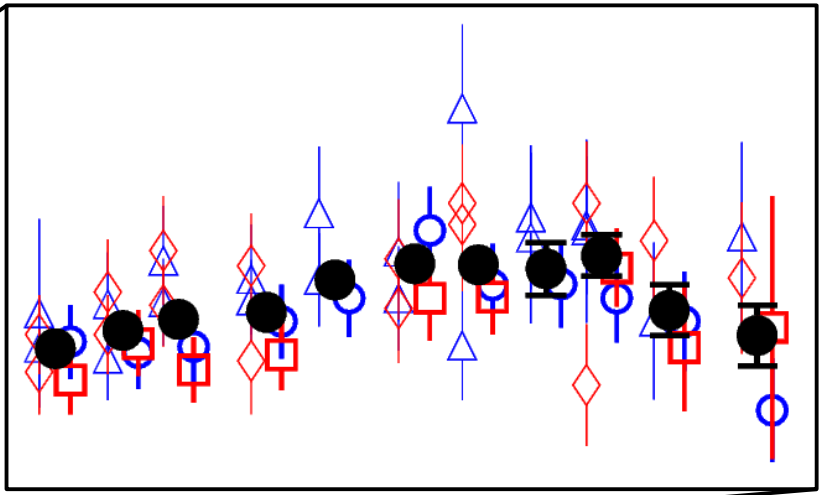
$$\sigma^{e\mp p}_{meas}(x_{grid}, Q^2_{grid}) = \frac{\sigma^{e\mp p}_{model}(x_{grid}, Q^2_{grid})}{\sigma^{e\mp p}_{model}(x_{meas}, Q^2_{meas})} \cdot \sigma^{e\mp p}_{meas}(x_{meas}, Q^2_{meas})$$

χ^2 / ndf = 1685 / 1620

Combined Inclusive DIS

H1prelim-14-041, ZEUS-prel-14-005

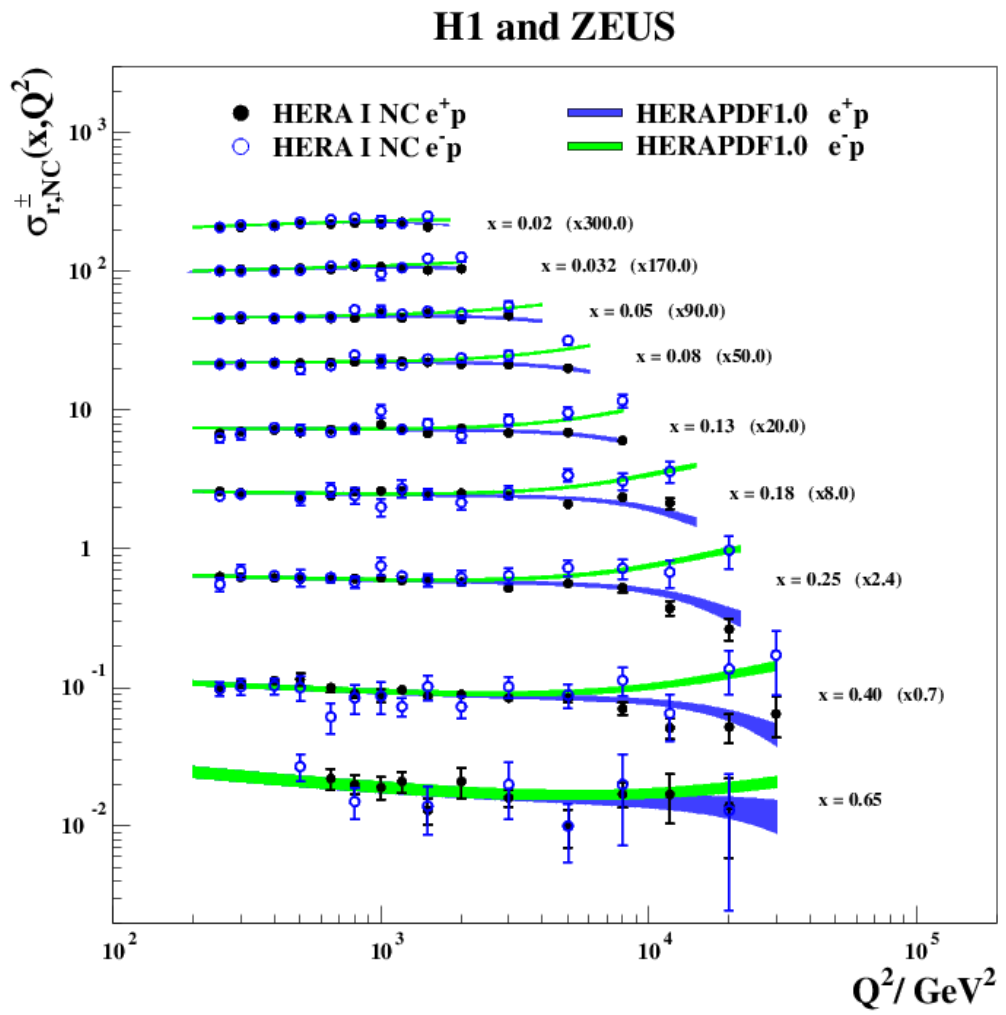


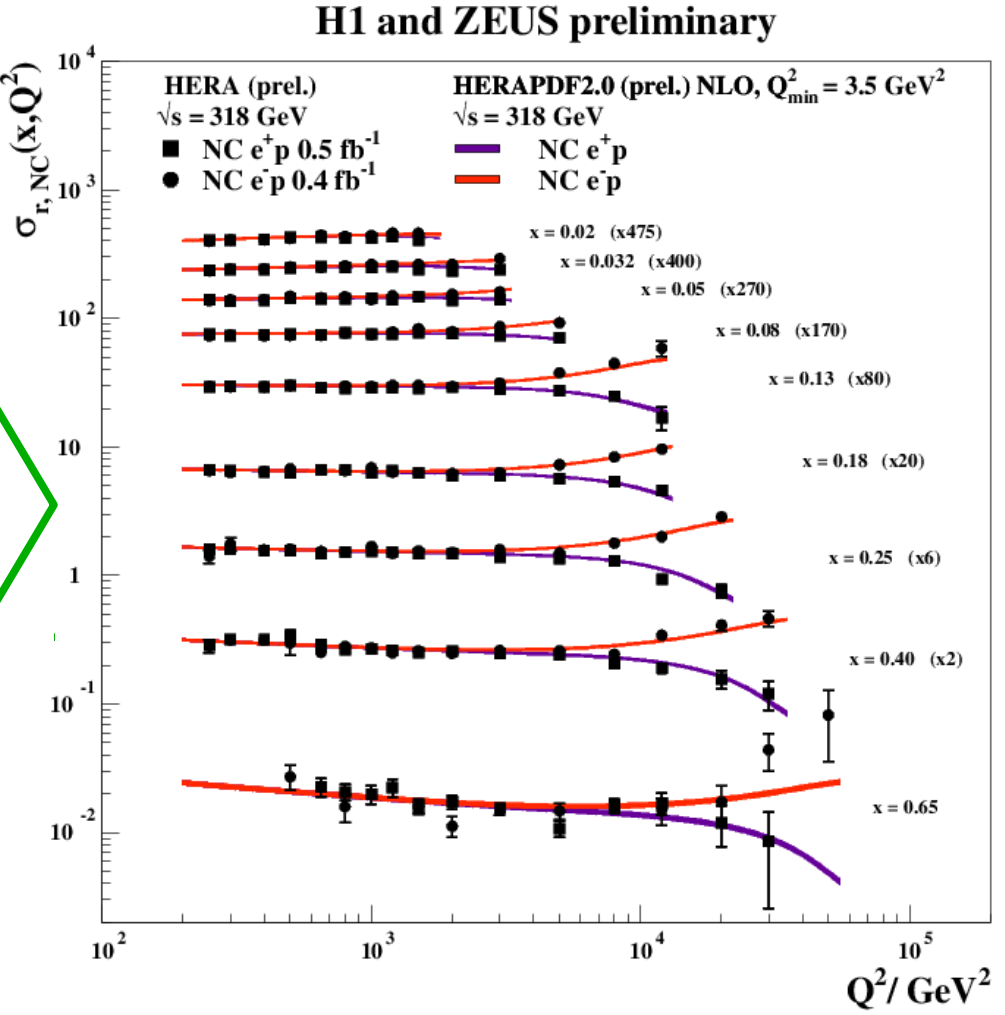


- 2927 data points combined to 1307
- up to 8 data points combined to 1
- data consistent between two experiments and data taking periods

Combined Inclusive DIS

H1prelim-14-041, ZEUS-prel-14-005





- Significant increase of statistics
- Significant reduction of systematic uncertainties

QCD analysis of combined DIS data

H1prelim-14-042, ZEUS-prel-14-007

Neutral Current :

$$\frac{d^2\sigma_{NC}^{e^{\mp}p}}{dxdQ^2}=\frac{2\pi\alpha^2\cdot Y_+}{xQ^4}\cdot\left(F_2(x,Q^2)\pm\frac{Y_-}{Y_+}\cdot x\cdot F_3(x,Q^2)-\frac{y^2}{Y_+}\cdot F_L(x,Q^2)\right)$$

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

$$F_2=\frac{4}{9}\left(xU+x\bar{U}\right)+\frac{1}{9}\left(xD+x\bar{D}\right)$$

$$x\cdot F_3\sim xu_v+xd_v$$

Charged Current :

$$\frac{d^2\sigma_{CC}^{e^{\mp}p}}{dxdQ^2}=\frac{G_F^2}{4\pi x}\cdot\kappa^2\cdot\left(Y_+\cdot W_2^{\mp}\pm Y_-\cdot x\cdot W_3^{\mp}-y^2\cdot W_L^{\mp}\right)$$

$$\kappa=\frac{M_W^2}{M_W^2+Q^2}$$

$$W_2^-=x\left(U+\bar{D}\right)\qquad W_2^+=x\left(D+\bar{U}\right)$$

$$xW_3^-=x\left(U-\bar{D}\right)\qquad xW_3^+=x\left(D-\bar{U}\right)$$

Parton Density Functions parametrization at starting scale $Q^2 = 1.9\ GeV^2$:

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

$$xu_v(x)=A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2)$$

$$xd_v(x)=A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x)=A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x)$$

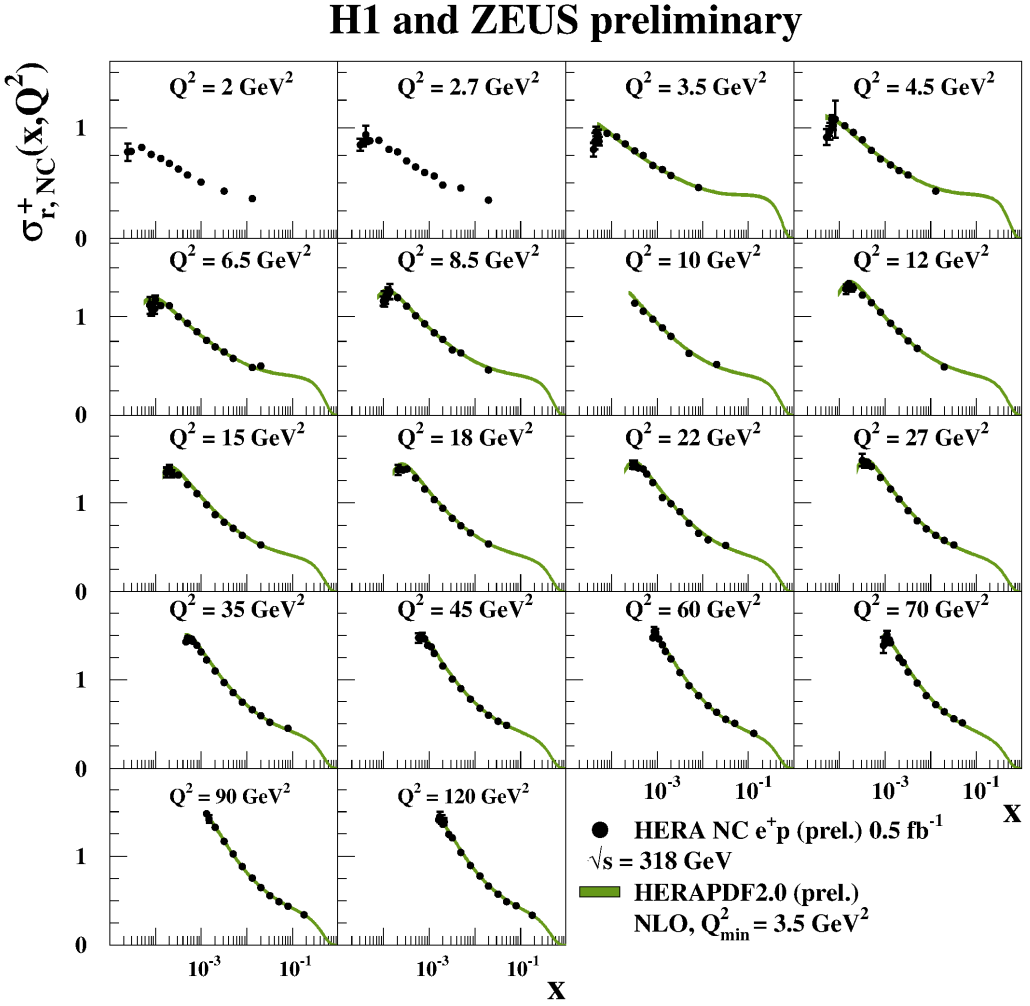
$$x\bar{D}(x)=A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

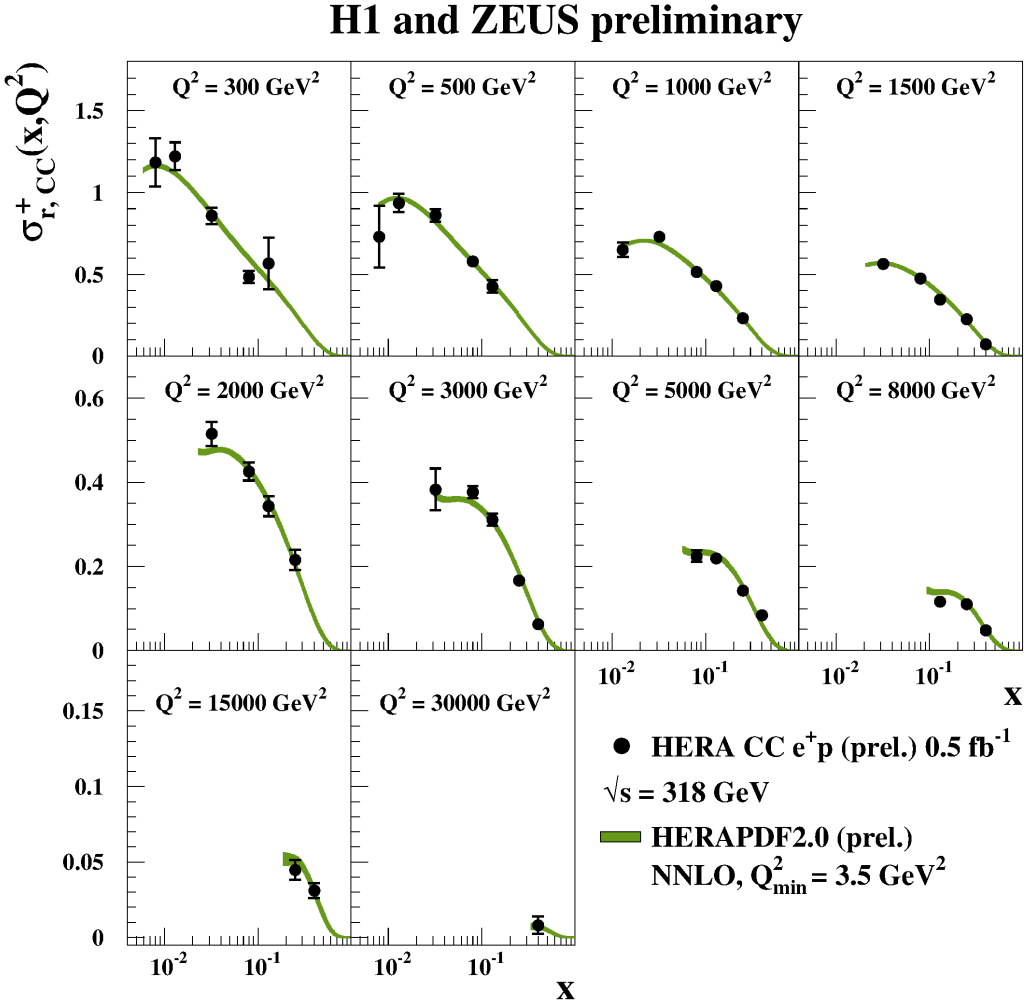
- fixed or calculated by sum-rules
- set equal

- Evolve to any Q^2 with DGLAP at NLO or NNLO.
- Use Thorne-Roberts GMVFN scheme for Heavy quarks.

HERAPDF 2.0 (prel.)

H1prelim-14-042, ZEUS-prel-14-007



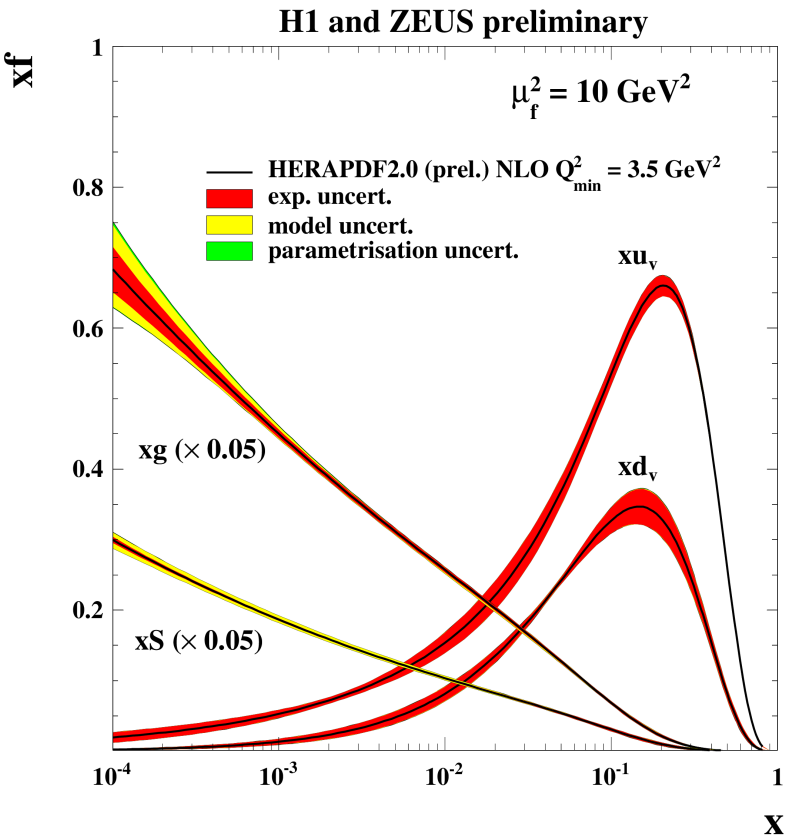


Reasonable description of NC and CC by NLO and NNLO.

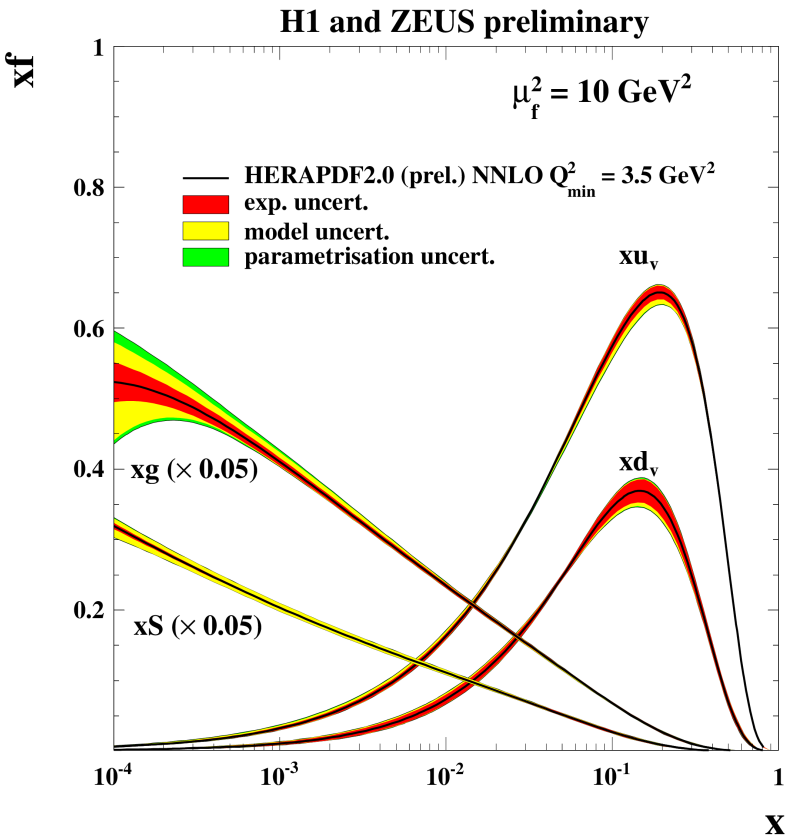
HERAPDF 2.0 (prel.) : Q^2_{min} = 3.5 GeV^2

H1prelim-14-042, ZEUS-prel-14-007

NLO



NNLO



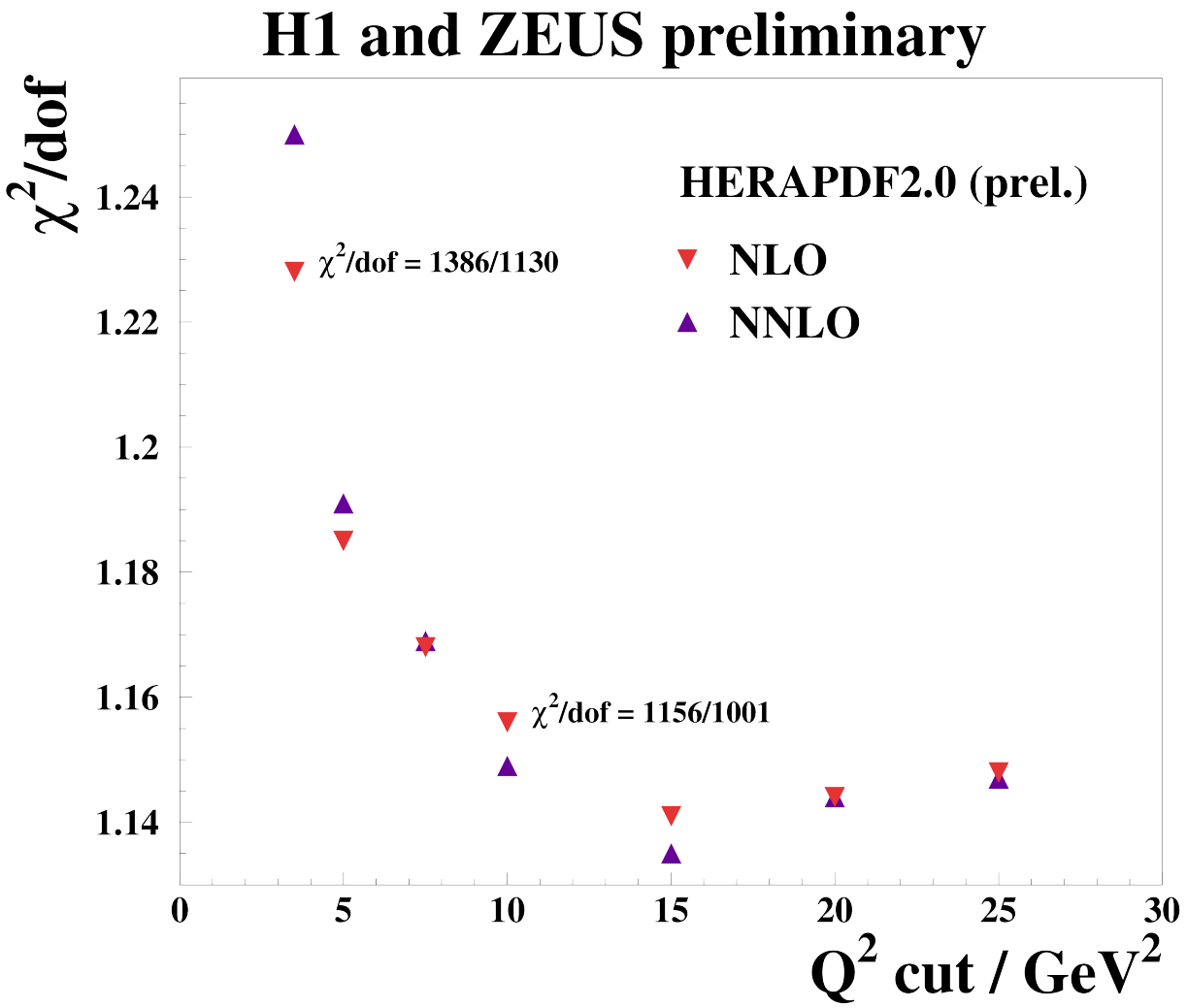
Experimental unc. - estimated using Hessian method at 68% CL.

Model unc. - from variation of quark masses, α_s, etc.

Parametrization unc. - extra fit parameters and starting scale variation.

HERAPDF 2.0 (prel.) : Q^2_{min} variation

H1prelim-14-042, ZEUS-prel-14-007



for Q^2_{min} = 3.5 GeV²

NLO : χ^2 / ndf = 1385 / 1130

NNLO : χ^2 / ndf = 1414 / 1130

for Q^2_{min} = 10 GeV²

NLO : χ^2 / ndf = 1156 / 1001

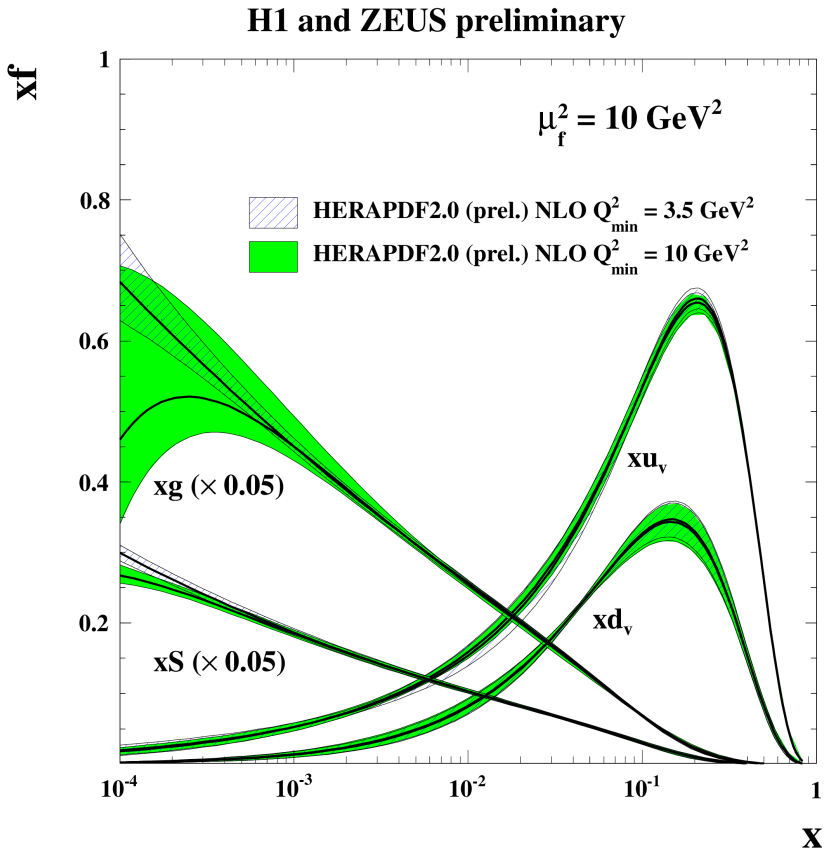
NNLO : χ^2 / ndf = 1150 / 1001

χ^2 appears to saturate for Q^2_{min} = 10 GeV².

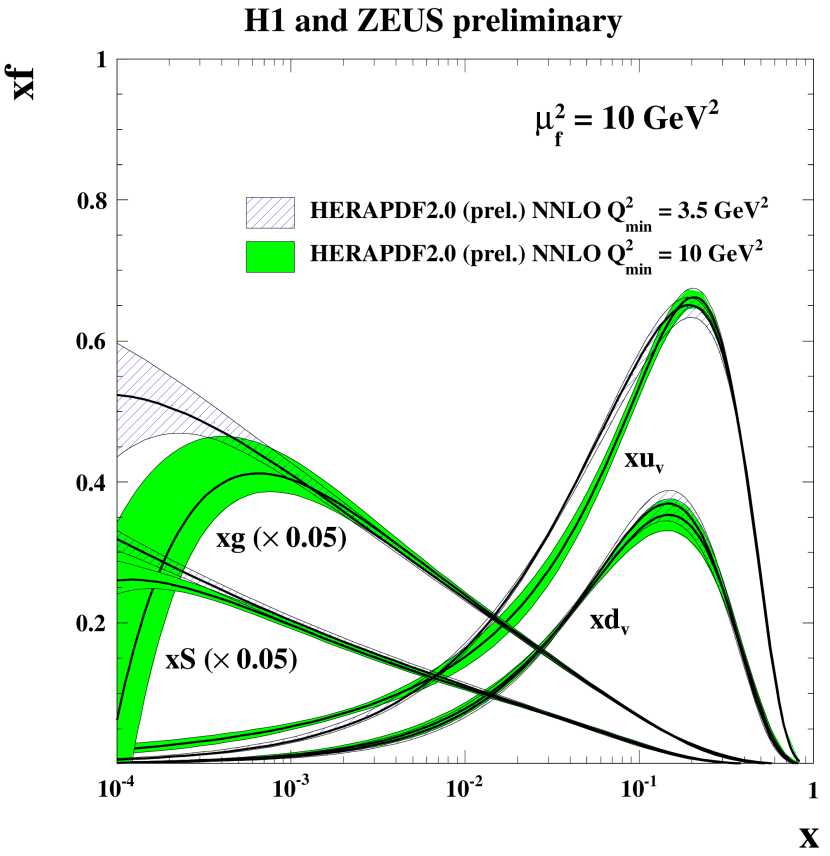
HERAPDF 2.0 (prel.) : Q^2_{min} = 10 GeV^2

H1prelim-14-042, ZEUS-prel-14-007

NLO

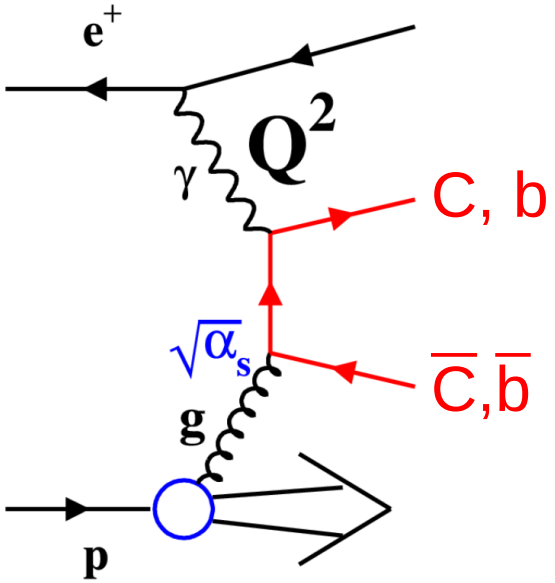


NNLO



- PDFs in good agreement for $x > 10^{-3}$
- Higher Q^2_{min} cut increases low x gluon uncertainty.

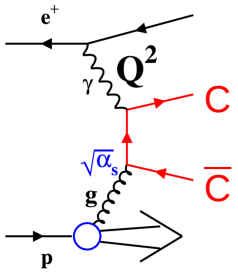
F_2^{cc} and F_2^{bb}



$$\frac{d^2\sigma_{NC}^{e^{\mp}p}}{dxdQ^2} = \frac{2\pi\alpha^2 \cdot Y_+}{xQ^4} \cdot \left(F_2(x,Q^2) \pm \frac{Y_-}{Y_+} \cdot x \cdot F_3(x,Q^2) - \frac{y^2}{Y_+} \cdot F_L(x,Q^2)\right)$$

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

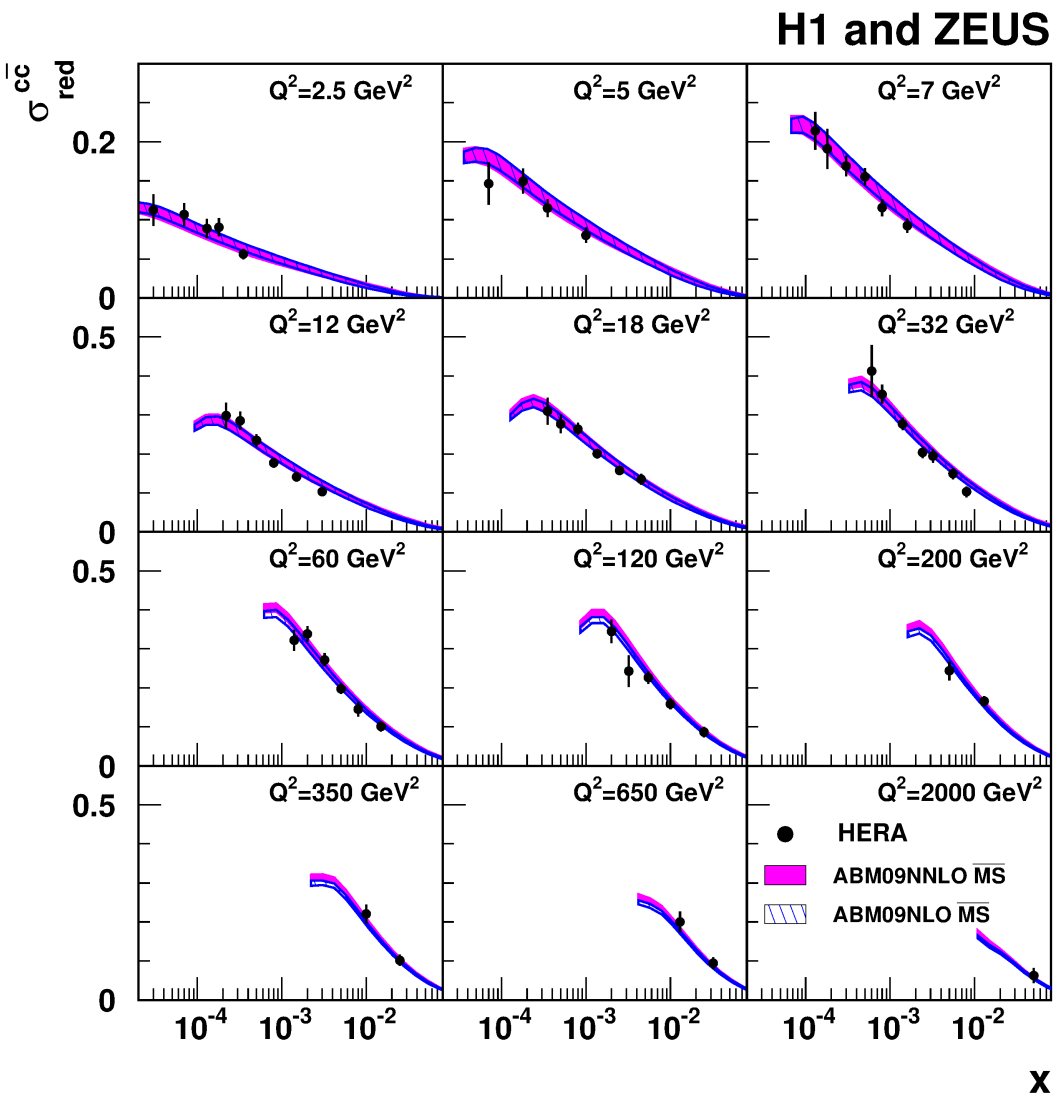
F_2^{cc} and F_2^{bb} are contributions to F_2 from events with $c\bar{c}$ and $b\bar{b}$ in the final state.



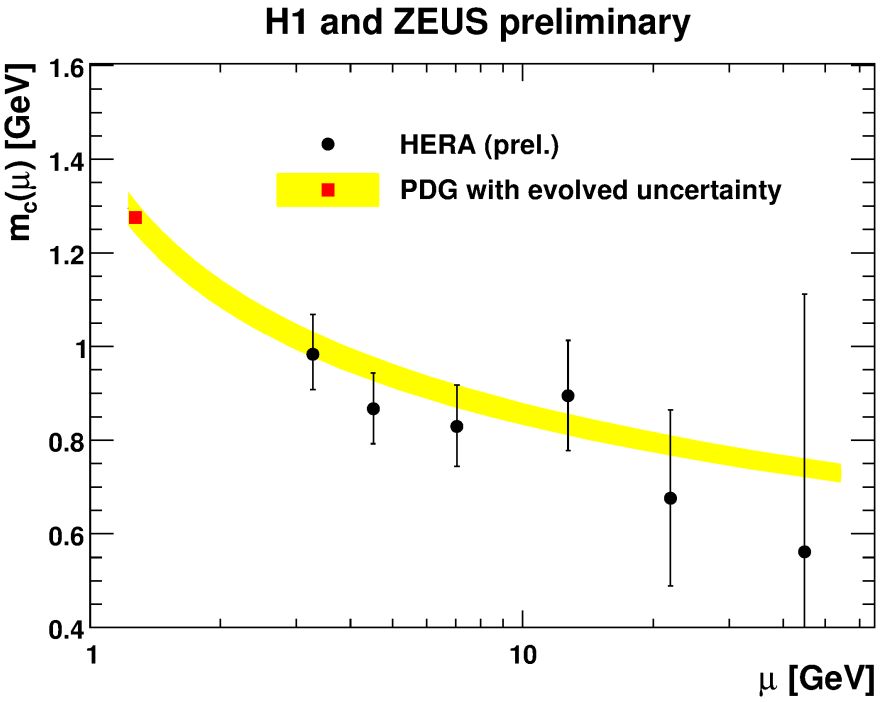
$F_2^{c\bar{c}}$

DESY-12-172 [E.P.J.C 73(2013)2311], ZEUS-prel-14-006

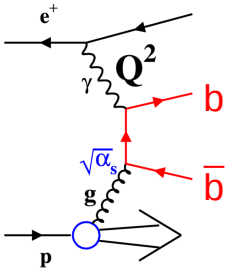
9 different H1 and ZEUS charm cross sections measurements were combined :



And used together with HERA I inclusive data in FFN scheme QCD fit for extracting running charm mass:



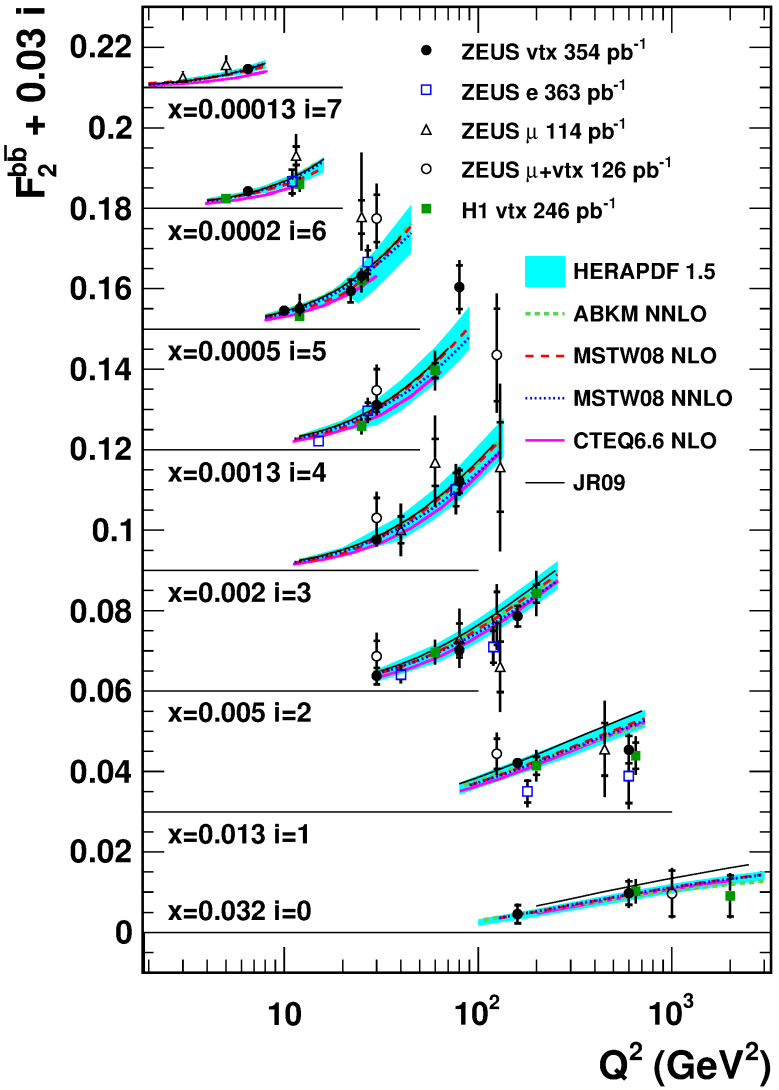
Running of $m_c(\mu_r)$ observed.



$F_2^{b\bar{b}}$

DESY-14-083 [JHEP09(2014)127]

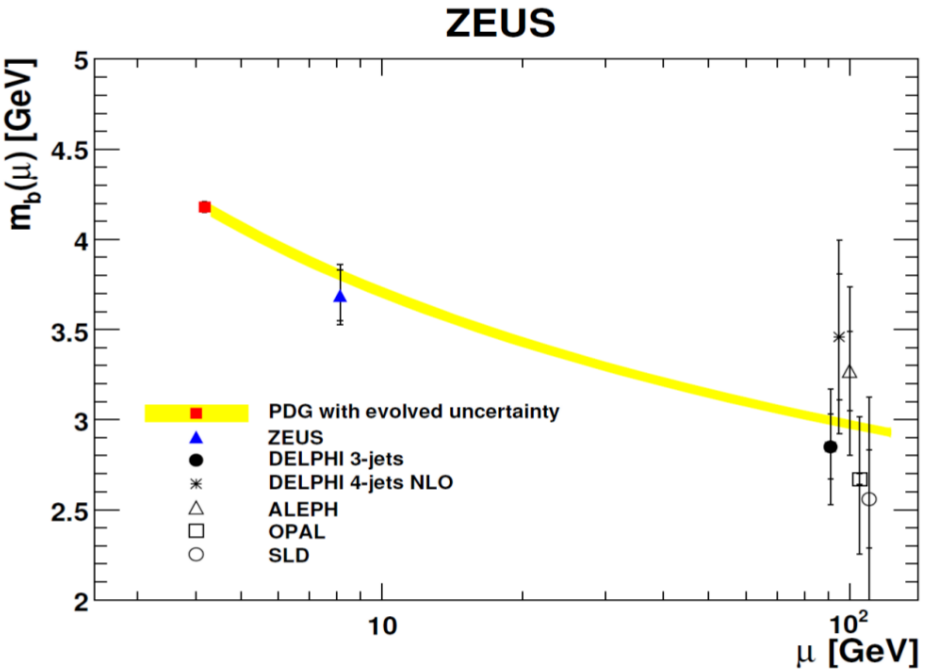
ZEUS prepared beauty structure functions measurements combination :



Extracted beauty mass:

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

And compared to PDG and LEP running beauty mass:



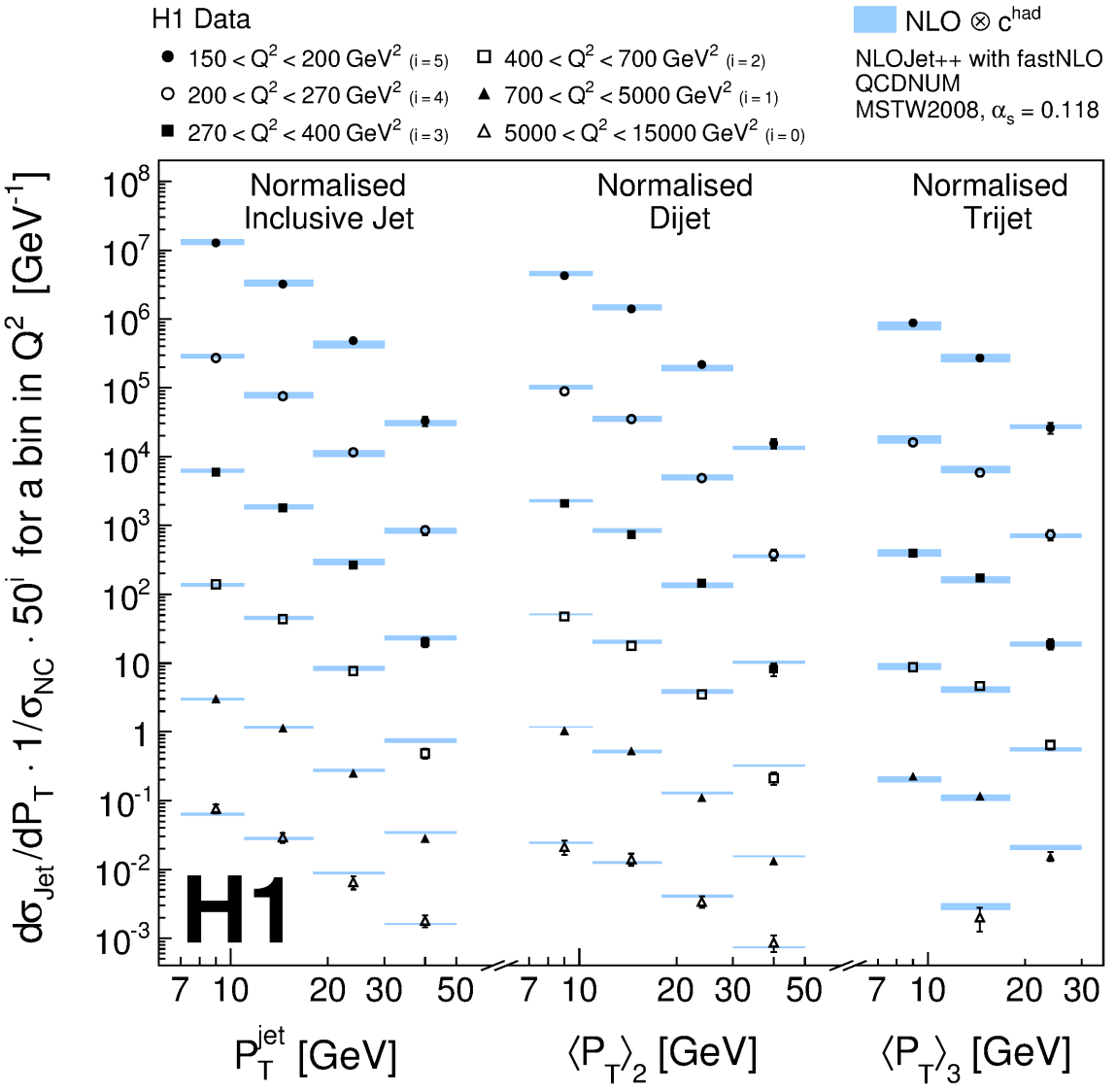
Consistent with running expected from PDG.

Multijet production at high Q^2

DESY-14-089 [arXiv:1406.4709]

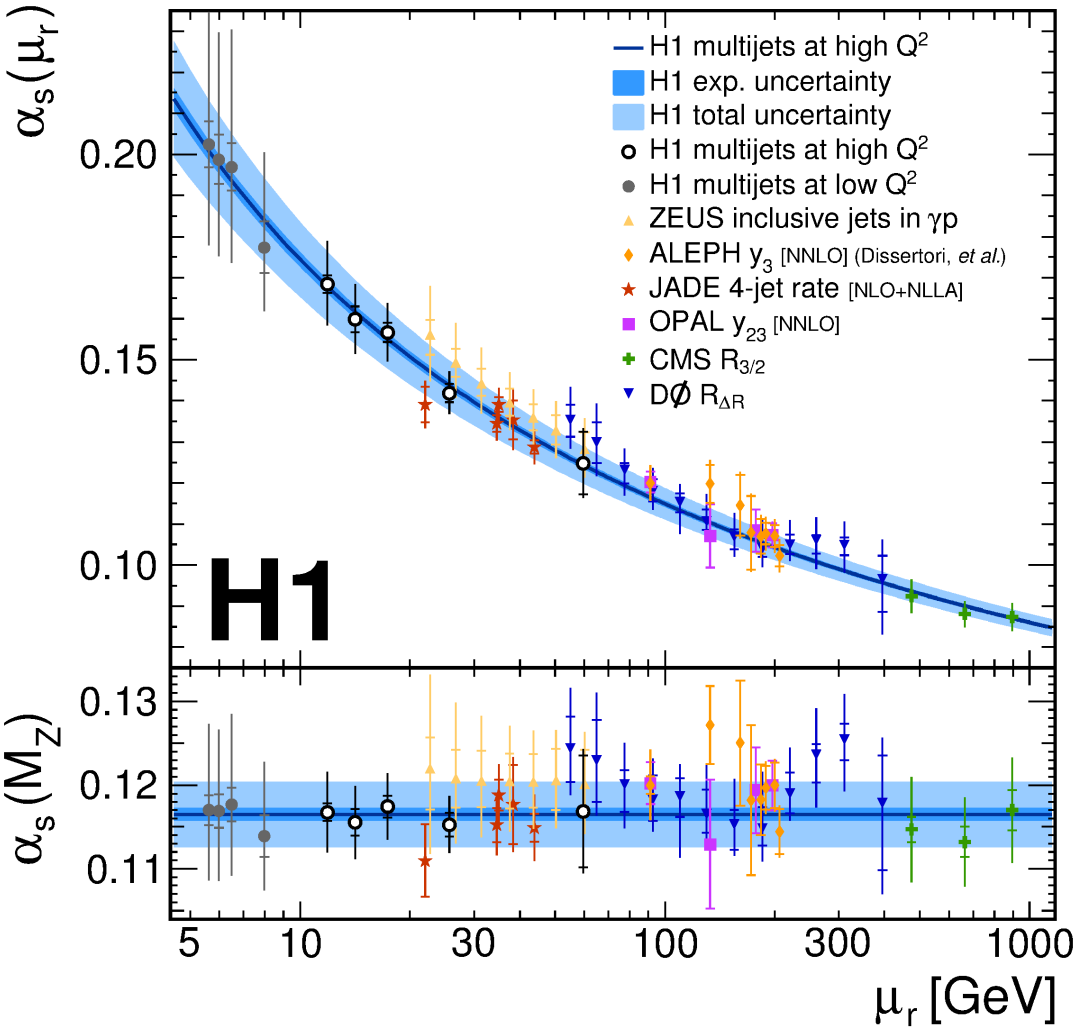
- H1 recently measured double differential inclusive jet, dijet and trijet cross sections.

- Measured absolute cross sections are normalized to NC DIS cross sections to benefit from cancelation of correlated systematic uncertainties.



Multijet production at high Q^2

DESY-14-089 [arXiv:1406.4709]



Simultaneous χ^2-fit to inclusive jet, dijet and trijet cross sections extracts:

$$\alpha_s(M_Z) = 0.1165 \pm 0.0008\,(exp.) \pm 0.0038\,(theo.)$$

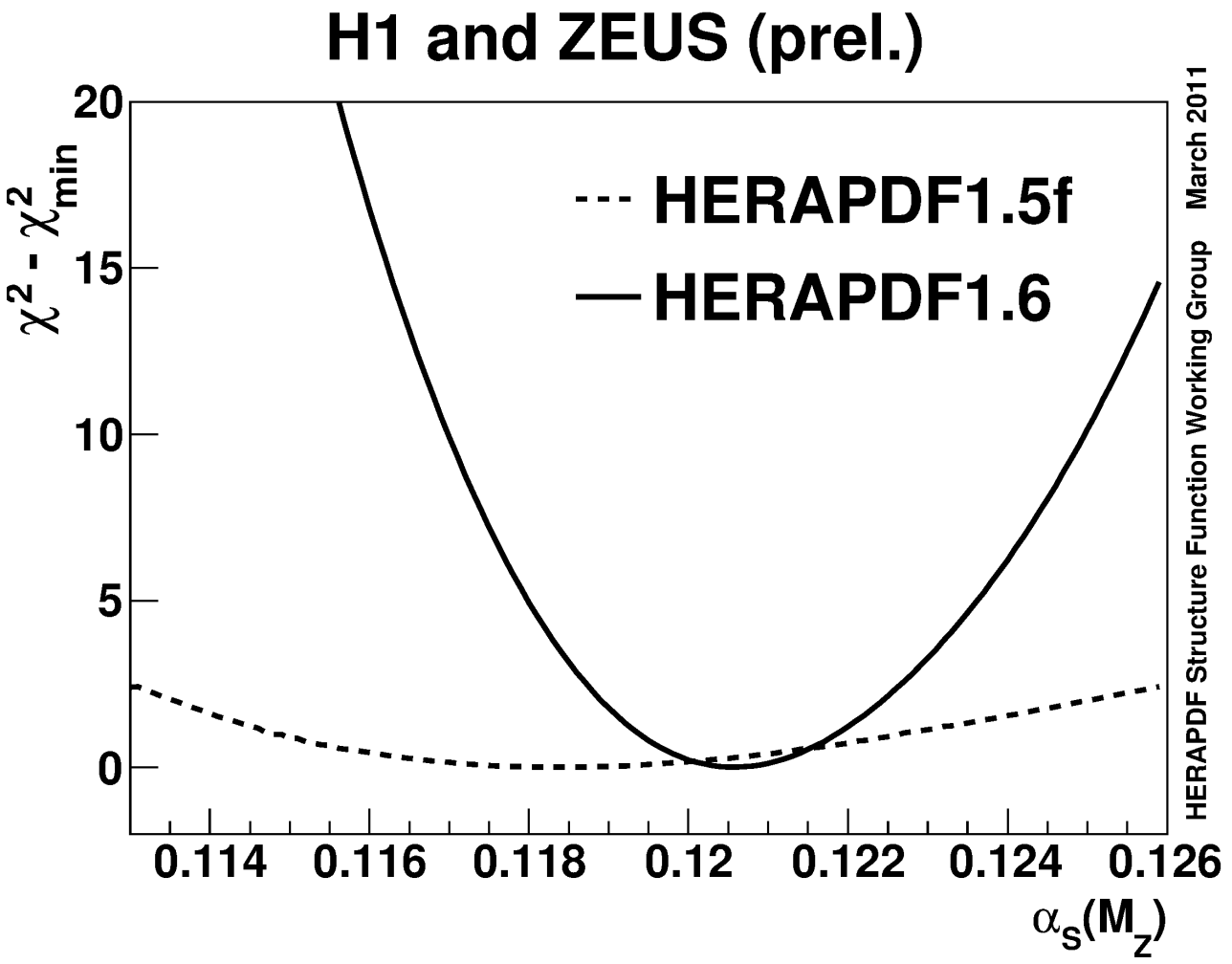
most precise value of $\alpha_s(M_Z)$ from jet cross sections, theory available at NLO only and gives dominant uncertainty.

The running of the strong coupling α_s as a function of scale μ_r shows good consistency with other jet data measurements.

HERAPDF : jet data

H1prelim-11-034, ZEUS-prel-11-001

Jet data is used in QCD fit with inclusive combined data for estimation of optimal strong coupling α_s:



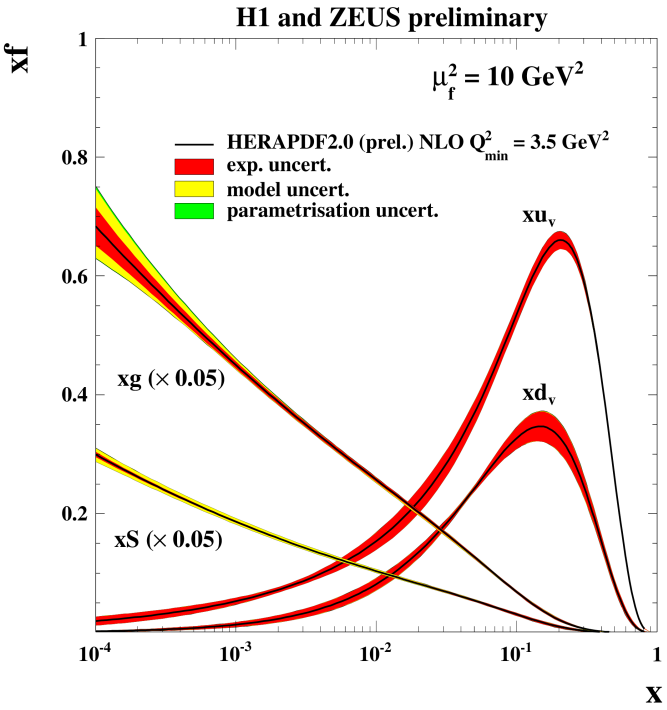
Jet data highly increase sensitivity to α_s.

Summary

- Combination of all final inclusive DIS measurements by the H1 and ZEUS collaborations provides cross sections of very high precision.

- Clean determination of proton's PDFs based solely on HERA ep collider data.

- Combined HERA DIS charm data is sensitive to charm mass: running of charm quark mass $m_c(\mu_r)$ observed.



- ZEUS DIS beauty data made possible first measurement of beauty mass at hadron collider.

- H1 measurement of jet production in DIS allows a precise determination of the strong coupling constant α_s.