Proton structure measurements and PDFs at HERA

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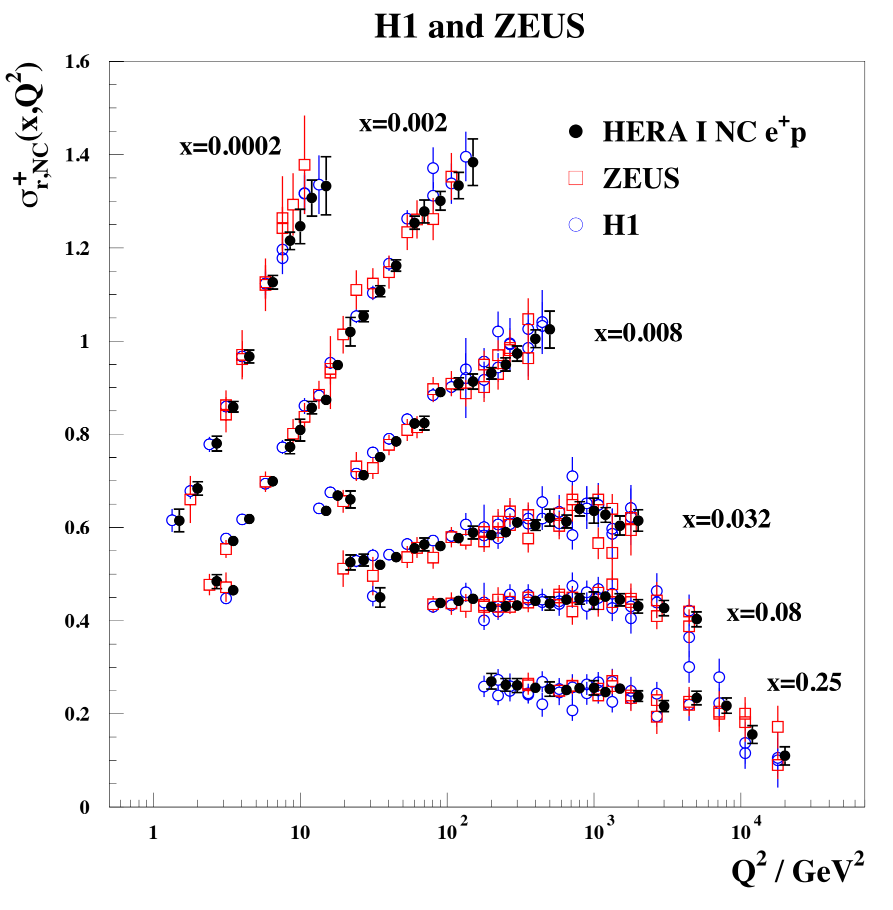
for H1 and ZEUS Collaborations

Ringberg workshop 2011

Scaling Violations at High Precision

JHEP 01 (2010) 109: combined H1 and ZEUS data from HERA I, $\mathcal{L}$~115 pb^{-1}

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$



H1 and ZEUS data averaged:

- global fit of 1402 measurements
- 110 sources of systematic errors
- account for systematic correlations (cross calibration of experiments)
- total uncertainty: *1-2%* for *Q^2<500 GeV^2*
- covered kinematics:

10^{-7}<x<0.65

0.05<Q^2<30000 GeV^2

Only HERA I, not ultimate precision

Determination of Parton Density Functions

Structure function factorization: for an exchange-Boson V (γ, Z, $W^{\pm}$)

$$F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

determined using measured cross sections

calculable in pQCD

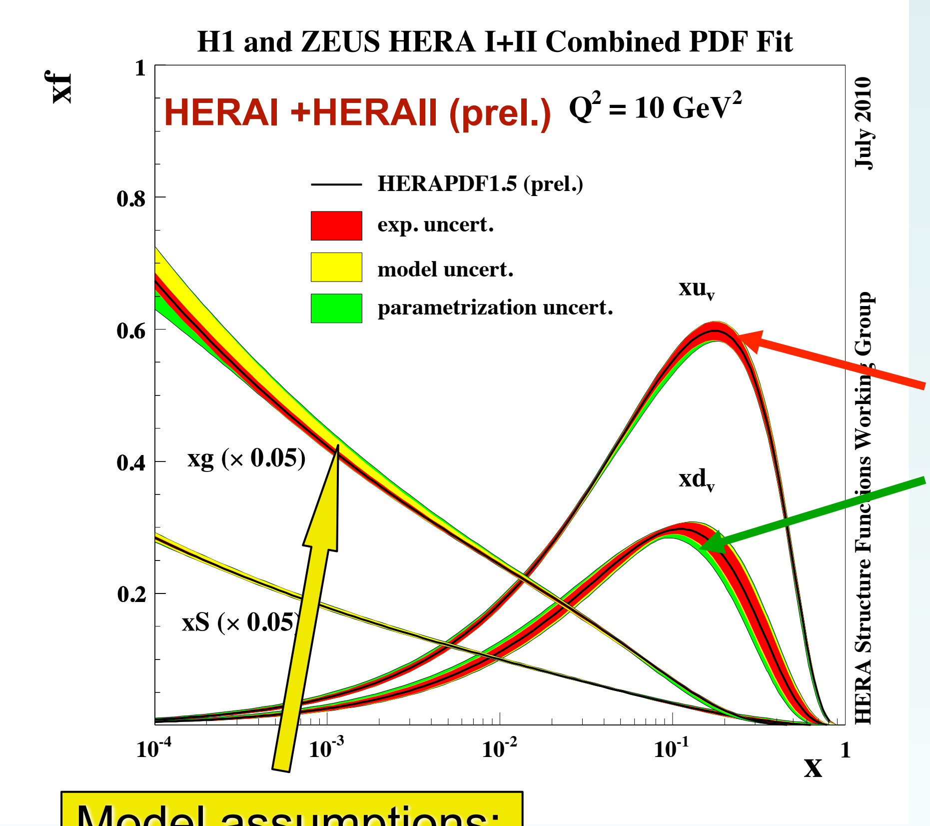
PDF

x-dependence of PDFs is not calculable in perturbative QCD:

- parameterize at a starting scale Q^2_0 : $f(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolve these PDFs using DGLAP equations to $Q^2>Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in (x, Q^2) – plane
- χ^2- fit to the experimental data

HERA Parton Density Functions

On the way to ultimate precision: **combined HERA I + HERAII data**



Model assumptions:

$Q_0^2 = 1.9\ GeV^2$, $\alpha_s(M_Z) = 0.1176$

$m_c = 1.4\ GeV$; $m_b = 4.75\ GeV$; $f_s(Q_0^2) = 0.31$

10 parameter fit, NLO DGLAP

Heavy quarks: massive

Variable Flavour Number Scheme

Scales: $\mu_r = \mu_f = Q^2$

Experimentally very precise

Parameterization at starting scale:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g}$$

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

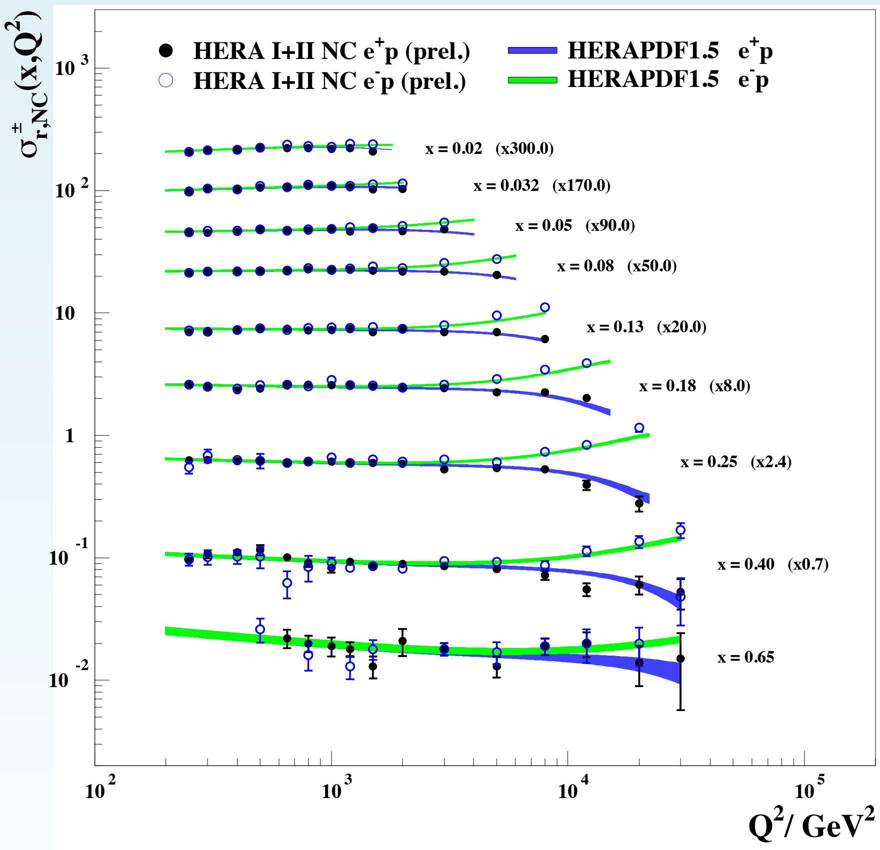
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$

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

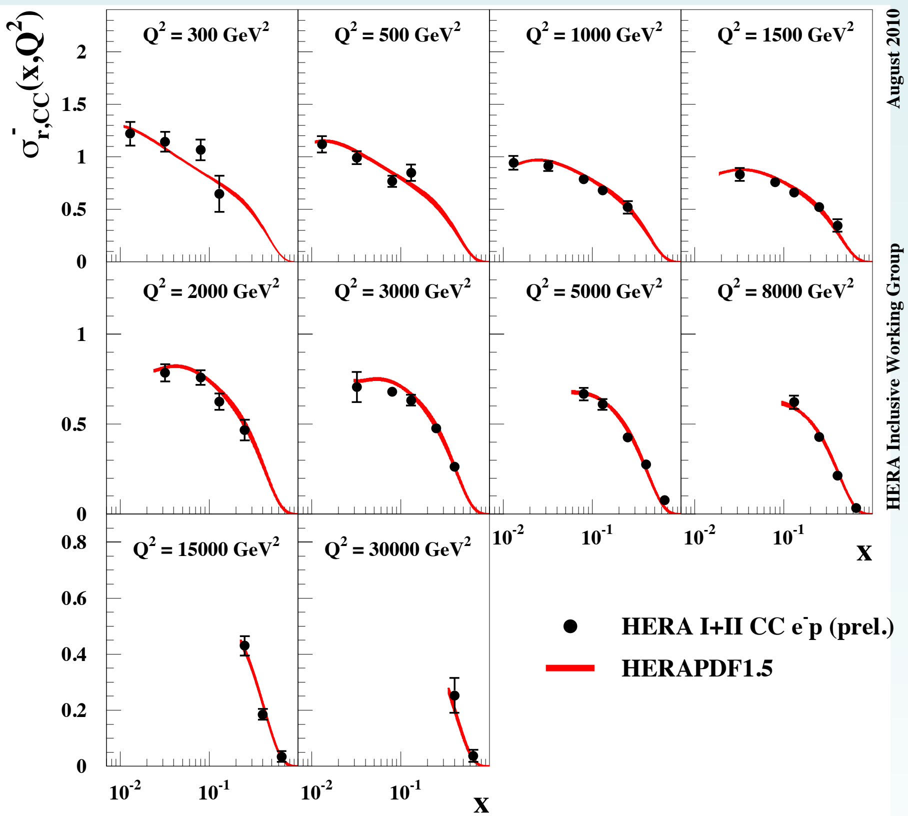
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}$$

HERA DIS Cross Sections vs HERAPDF

Neutral Current



Charged Current

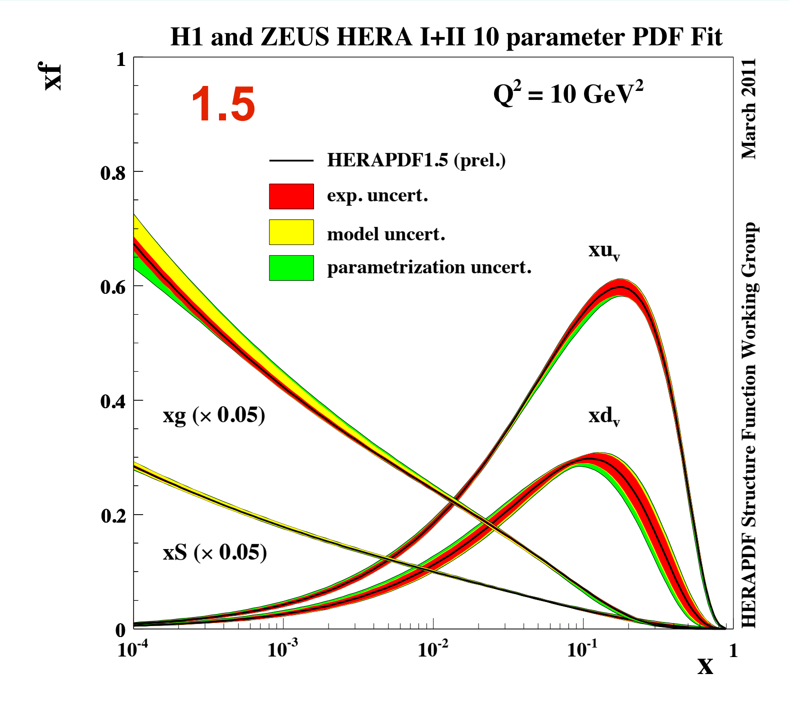


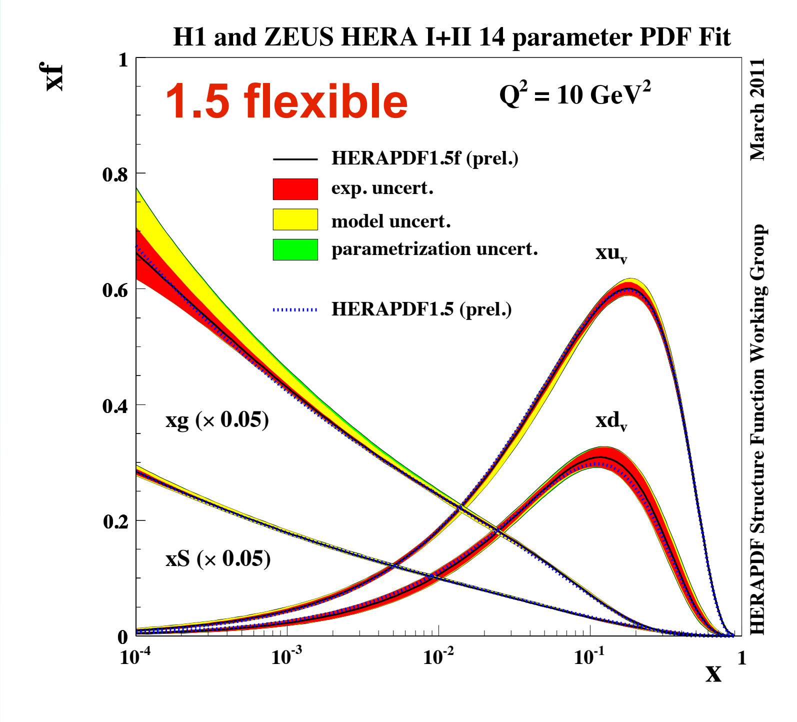
Improved precision at high Q^2 and high x

QCD using HERAPDF describes HERA NC and CC data very well

HERAPDF: Fit Improvements

HERAPDF1.5f : 14-parameter fit gluon more flexible at low-x





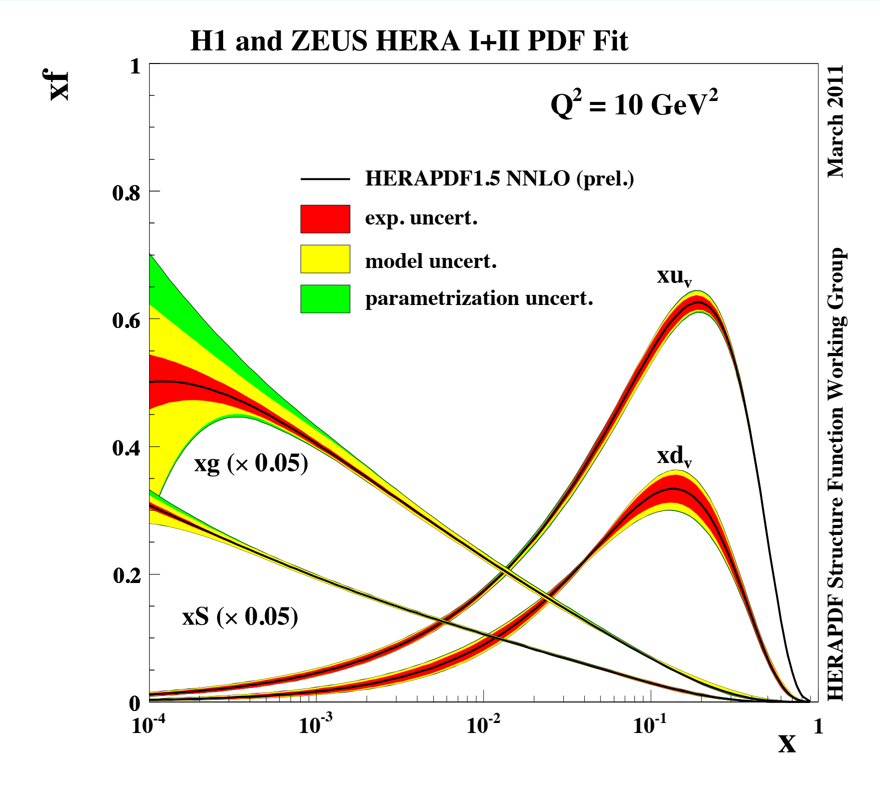
Small difference in total uncertainty

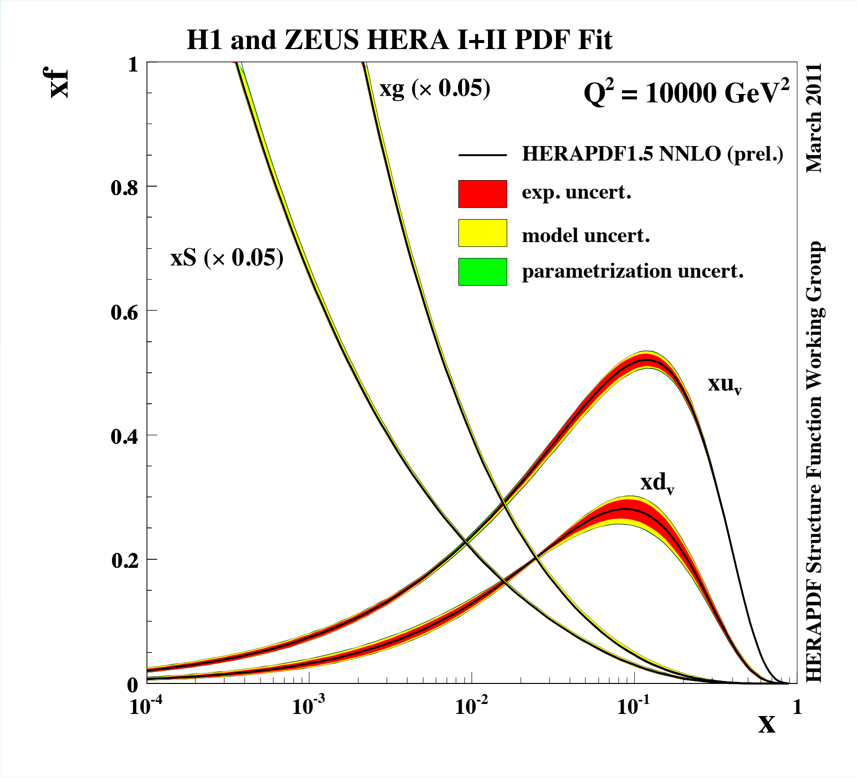
→ swap between **parametrisation** and **experimental** uncertainties

HERAPDF NNLO

HERAPDF1.5NNLO is based on HERA I + II inclusive DIS data

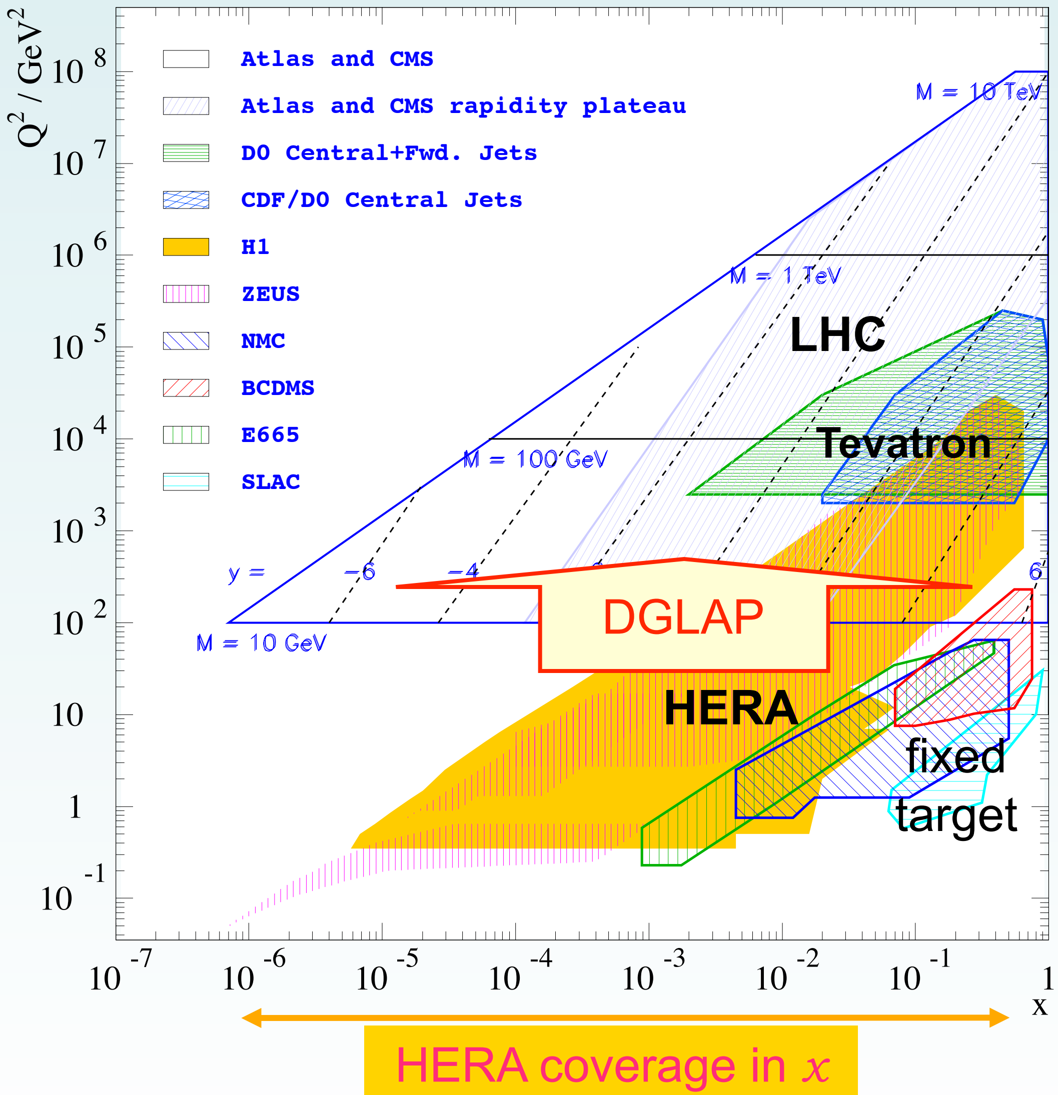
uses more flexible parametrisation





HERA PDF15NLO and NNLO recommended to be used for predictions

PDFs From HERA to Tevatron and the LHC



PDFs obtained from data of fixed target, HERA, Tevatron

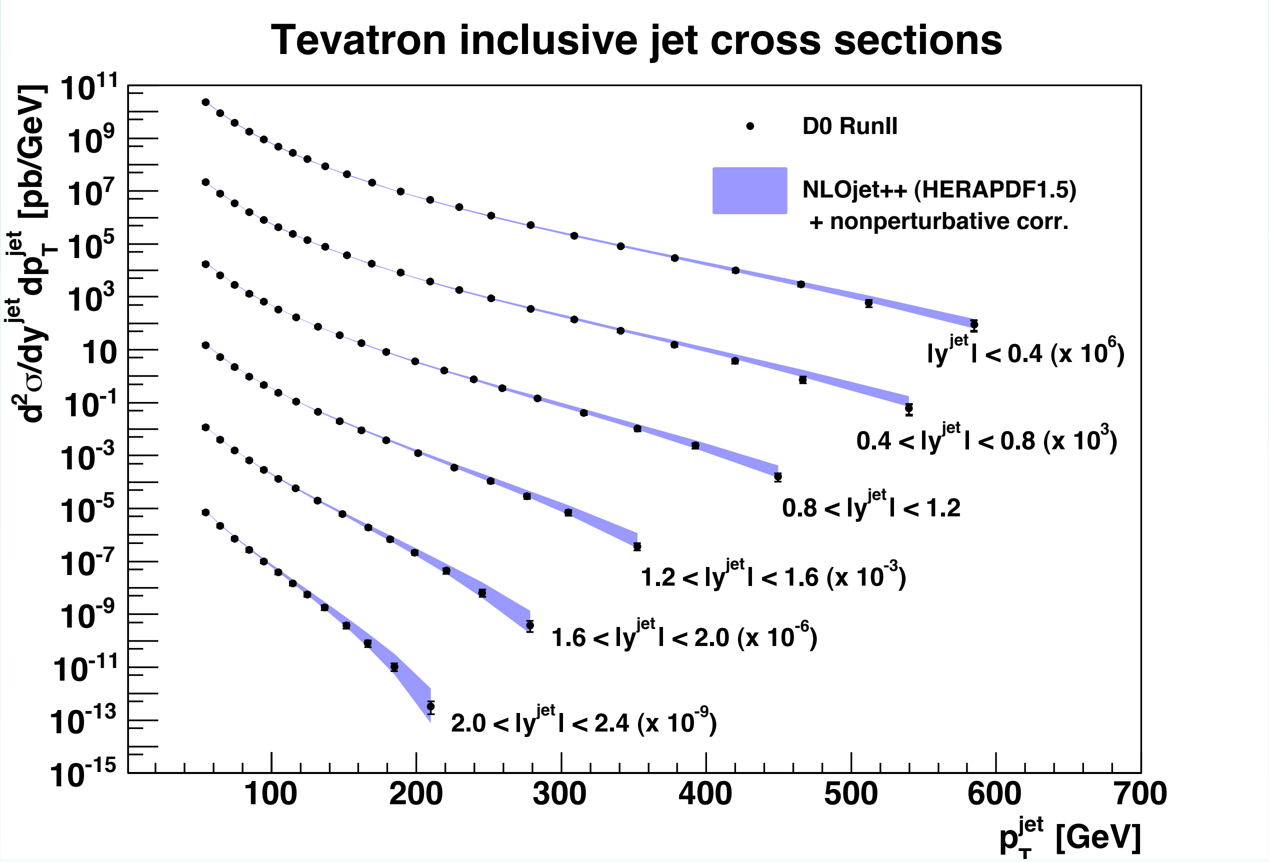
HERA measurements:

covers most of the (x,Q^2) plane, best constrain at low, medium x

From HERA to kinematics of Tevatron, LHC:

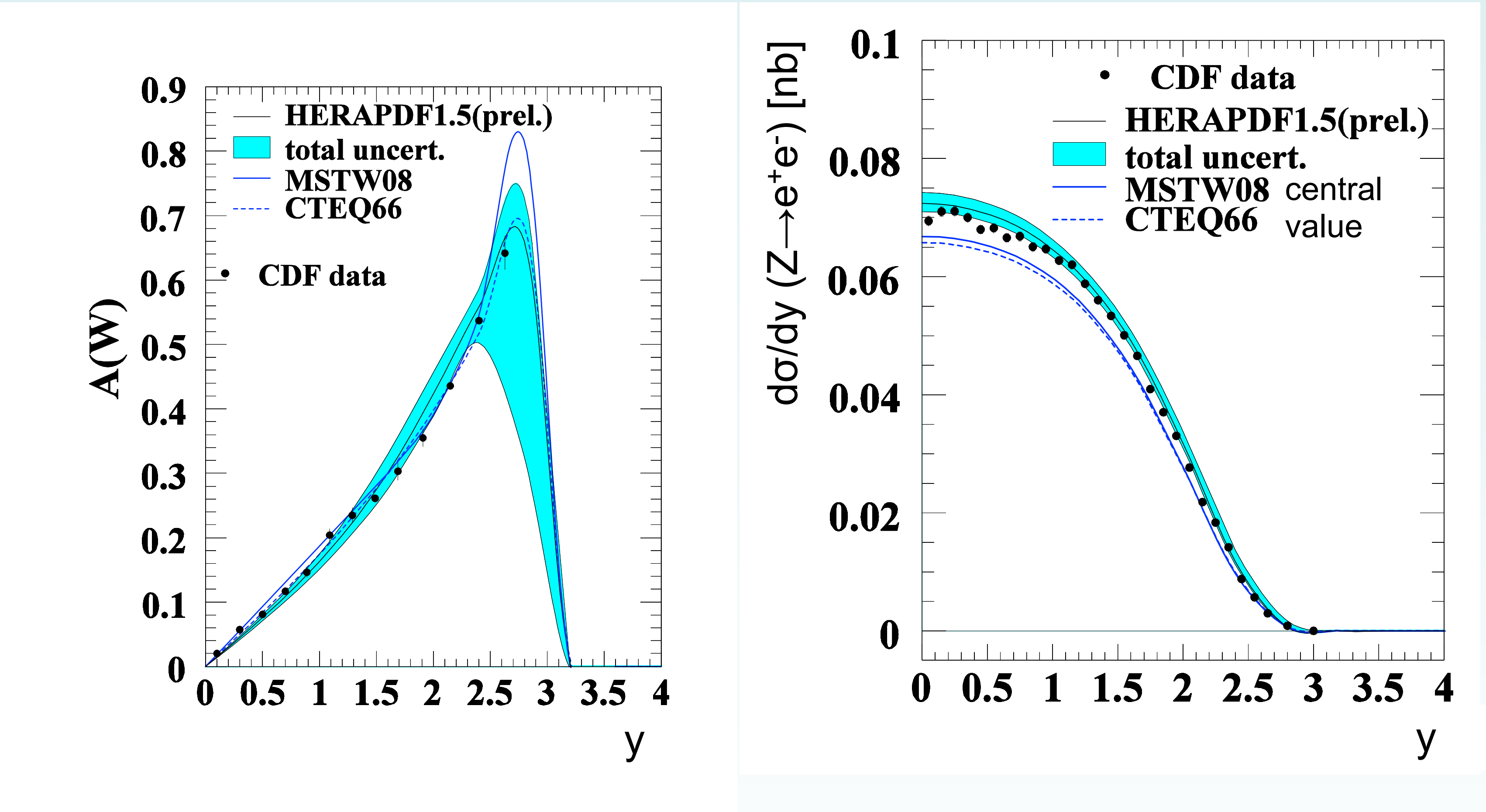
evolution in Q^2 via DGLAP

HERAPDF and Jets at Tevatron



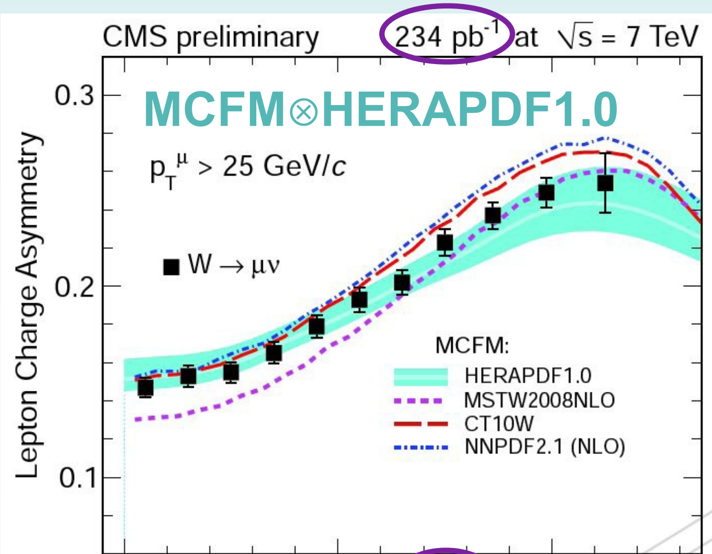
Prediction based on HERAPDF in agreement with Tevatron

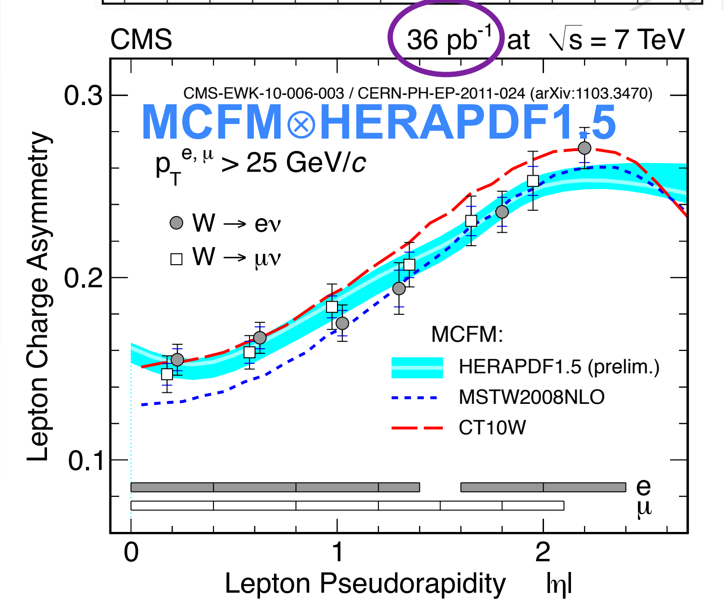
W and Z Production at Tevatron



Prediction based on HERAPDF agrees very well with Tevatron data

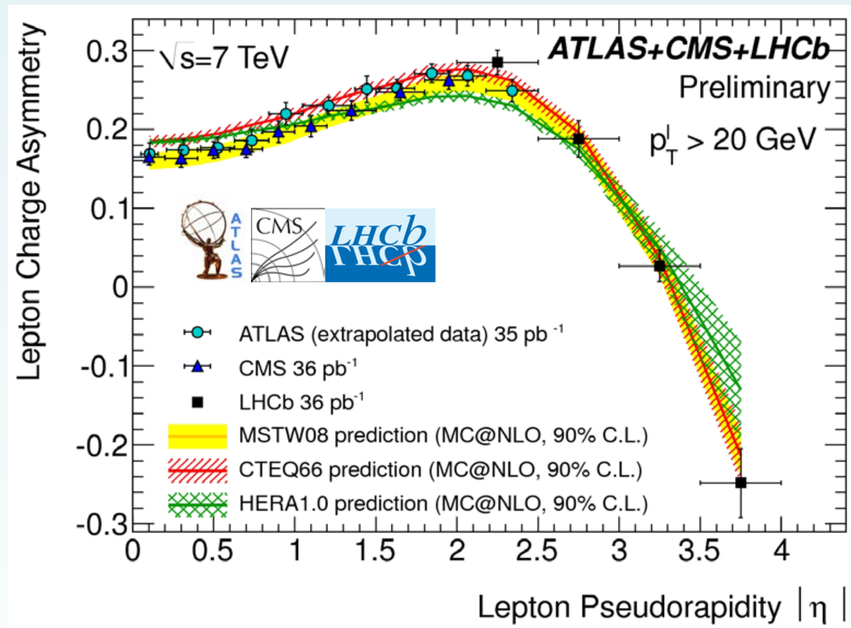
HERAPDF and the LHC measurements





W lepton asymmetry is sensitive to differences between u and d

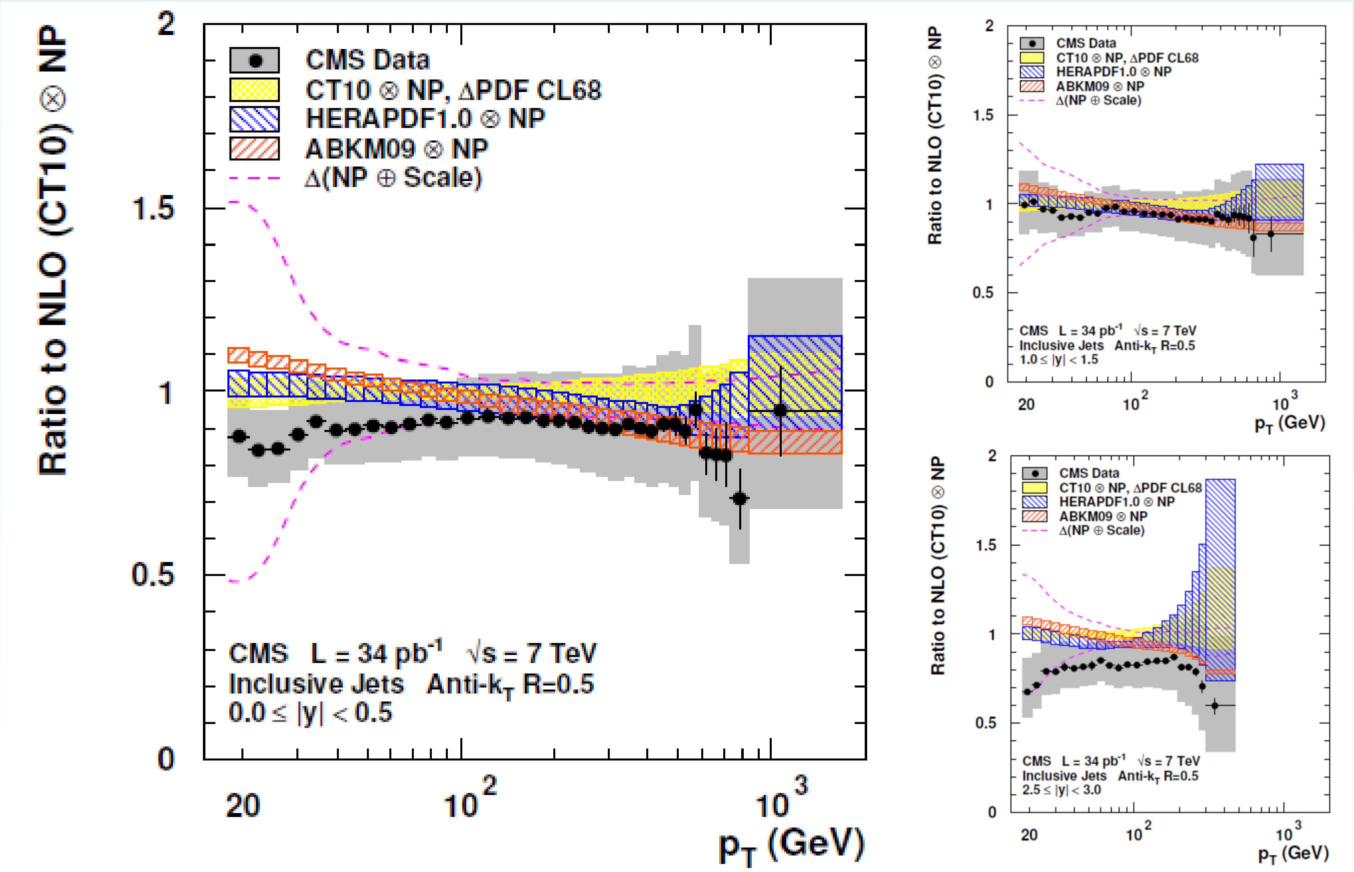
$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$



ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (arXiv:1103.3407)

HERAPDF and the LHC measurements

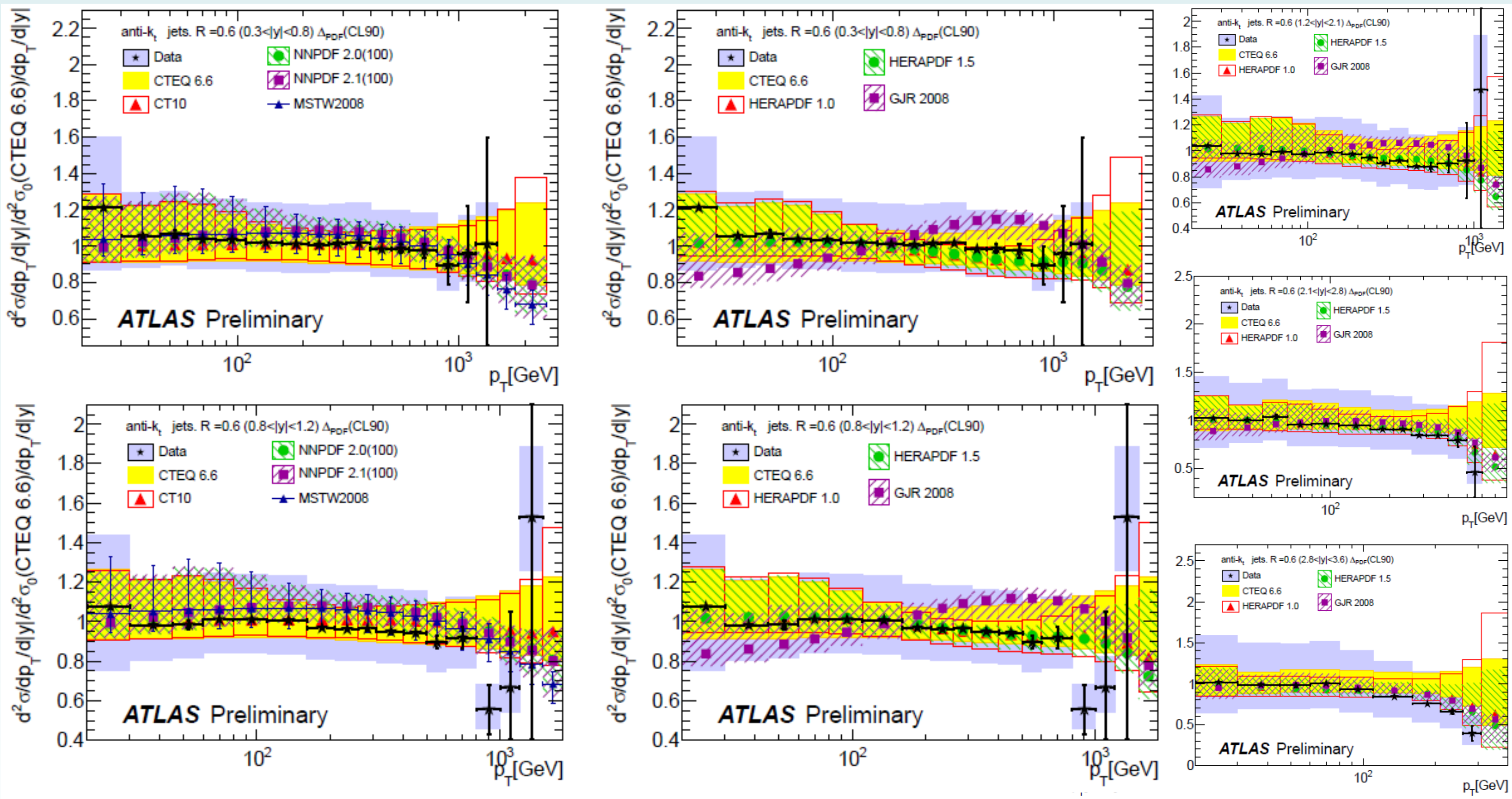
Jet production at CMS (CERN-CMS-NOTE-2011-004)



HERAPDF describes the LHC data well (similar level of agreement as other PDFs)

HERAPDF and the LHC measurements

Jet production at ATLAS



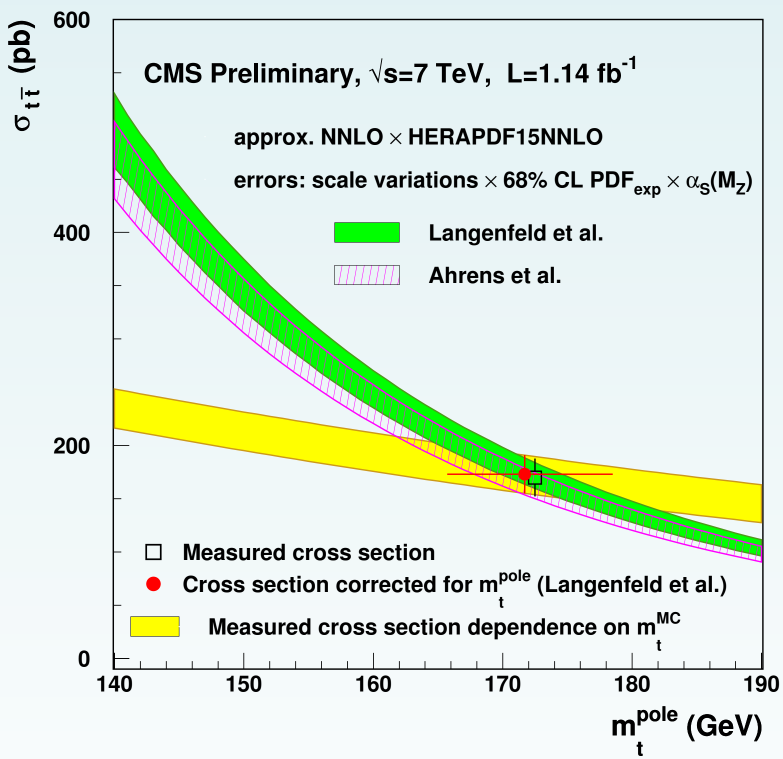
ATL-PHYS-PUB-2011-005

HERAPDF describes the LHC data well (similar level of agreement as other PDFs)

HERAPDF and the LHC measurements

Top quark at CMS: determination of m_t^{pole} and $m_t(m_t)$ from cross section

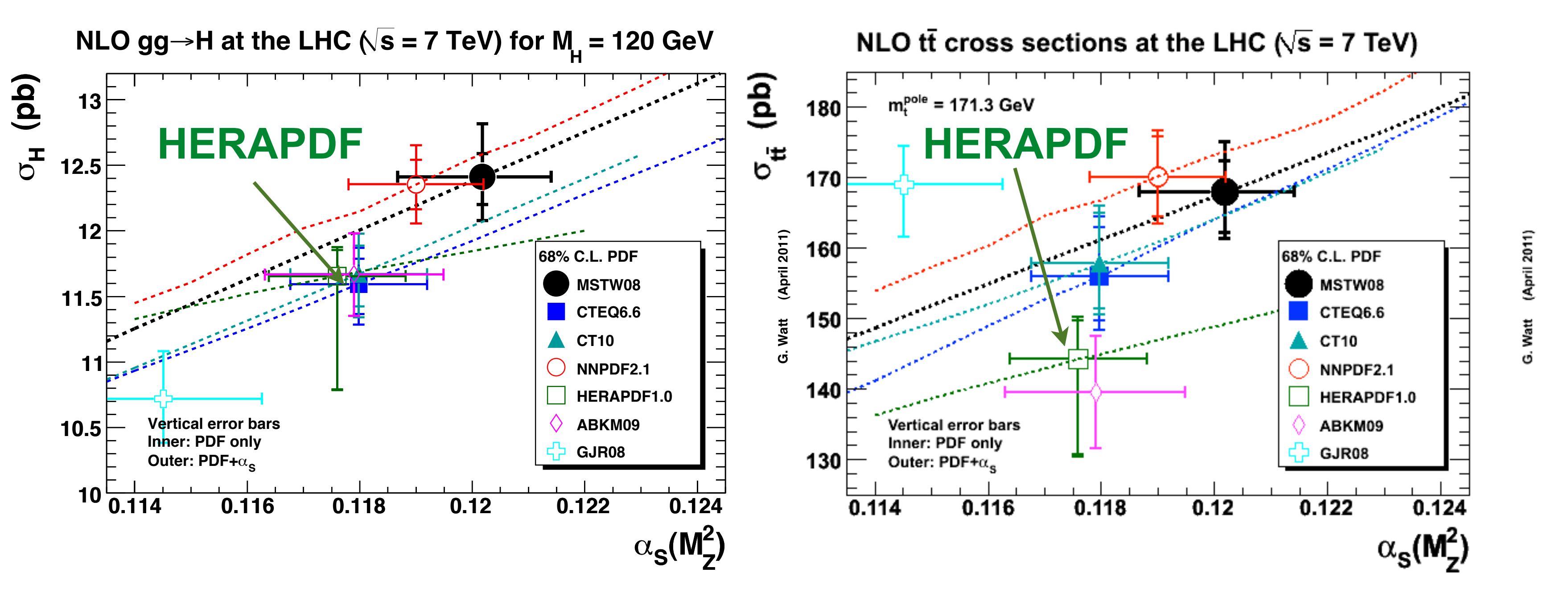
CMS-TOP-11-008



only experimental PDF error used

very good agreement with mstw08nnlo (within α_S uncertainty)

Benchmarking PDFs: LHC Cross Sections



Dominant uncertainty on HERAPDF : parameterization, model

Differences between the PDF groups:

- data used in the fit and estimation of uncertainties
- choice of α_S and running of strong coupling
- different treatment of heavy quarks

Learn more about α_s: PDF fits using HERA Jet Data

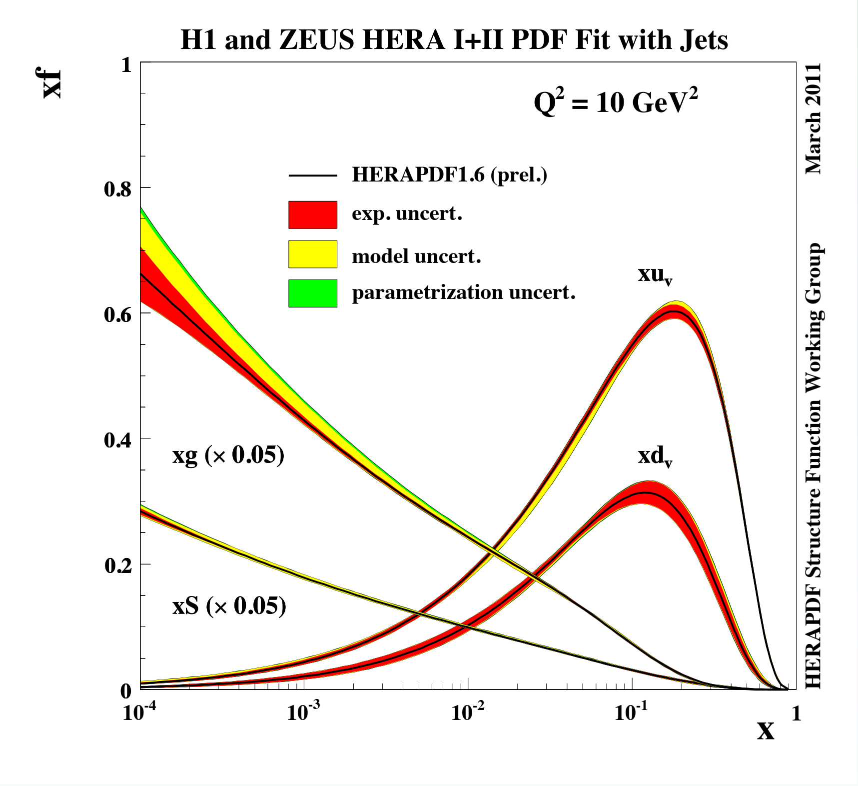
Inclusive DIS data:
combined H1+ZEUS HERAI+HERAII

Jet data:
H1 high Q^2 , Eur. Phys. J. C**65** (2010)
H1 low Q^2, Eur. Phys. J. C**67** (2010)

ZEUS inclusive jets PLB**547** (2002)
ZEUS inclusive+dijets Nucl. Phys. B**765** (2007)

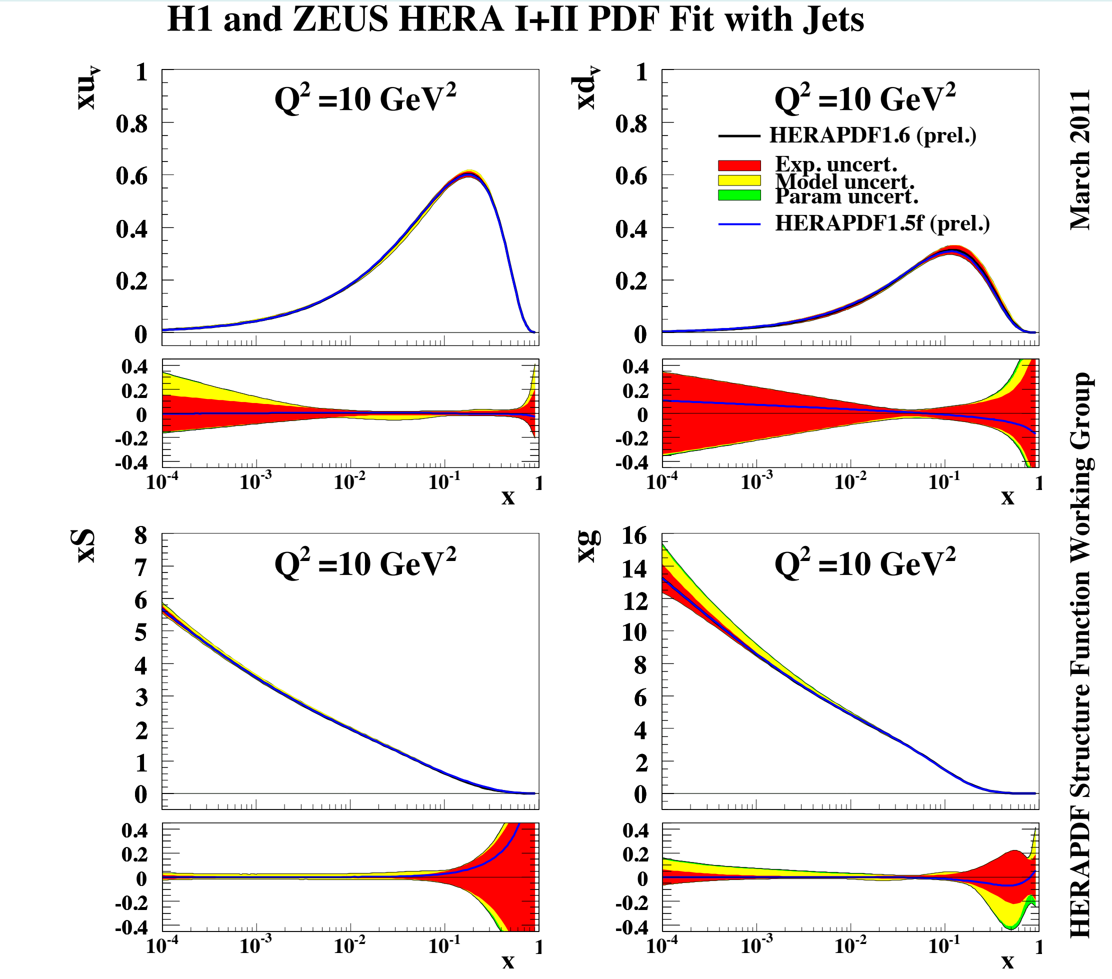
➡ HERA results on Jets: talk by R. Kogler

PDF Fit:
- flexible parametrisation
- $\alpha_s(M_Z)$ fixed



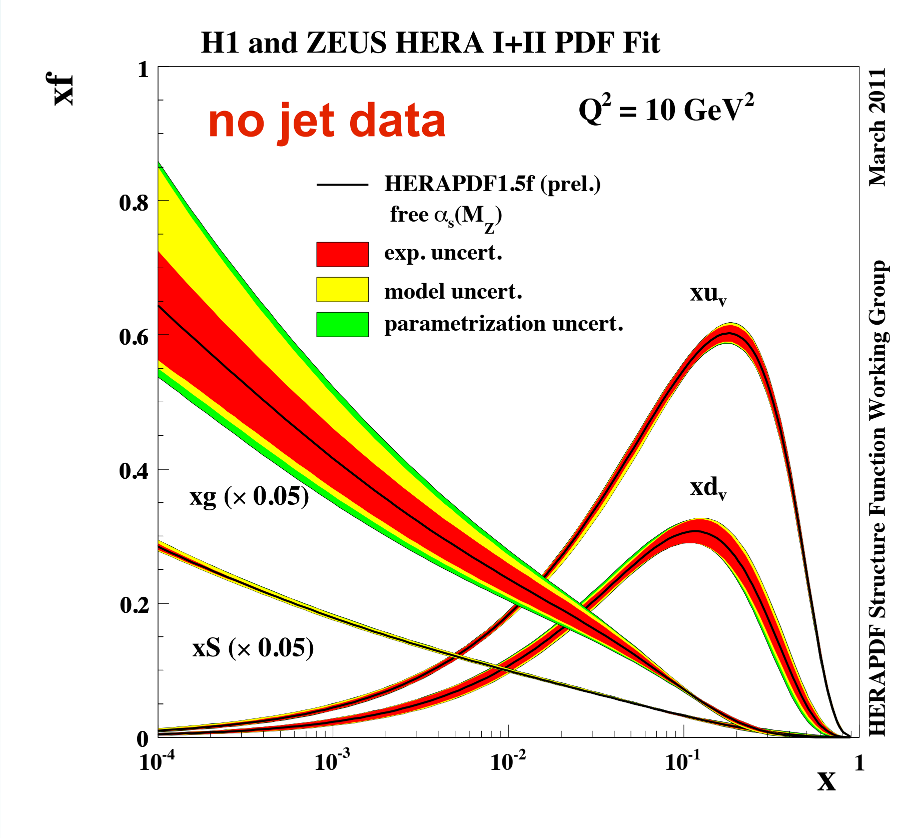
PDFs very similar to HERAPDF15f, no significant reduction of uncertainty

PDF fits using HERA Jet Data: Fixed α_s



Inclusion of jet data into the PDF fit **using fixed α_s** does not have large impact

PDF Fits with free α_s (Mz)



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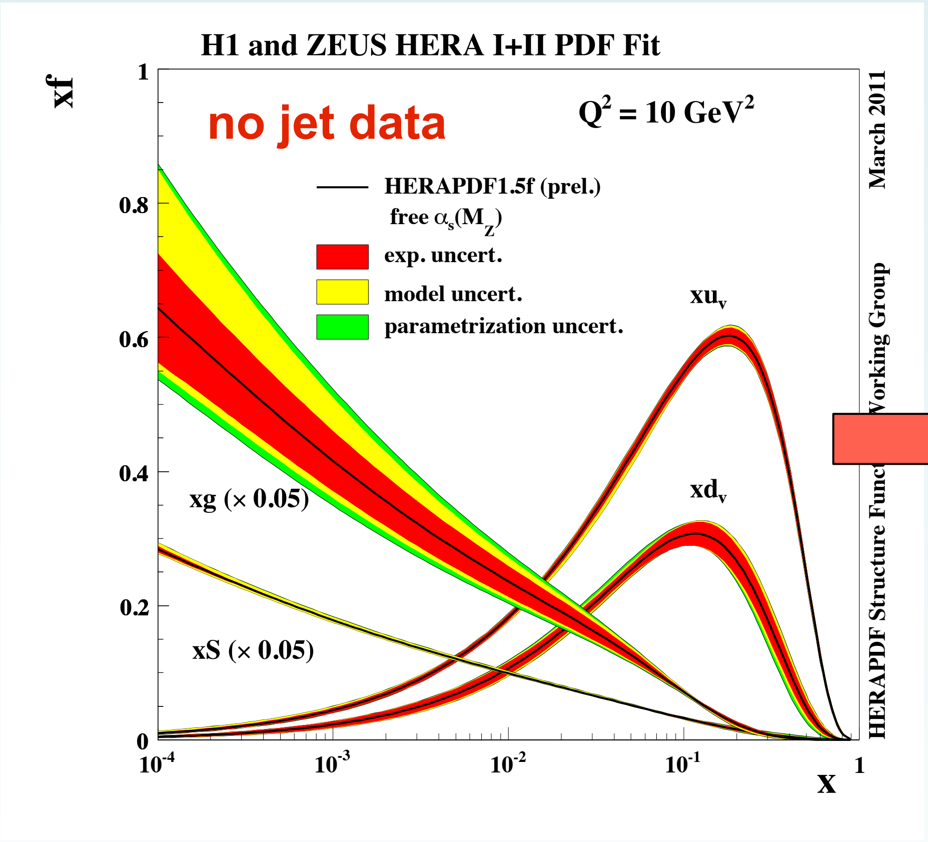
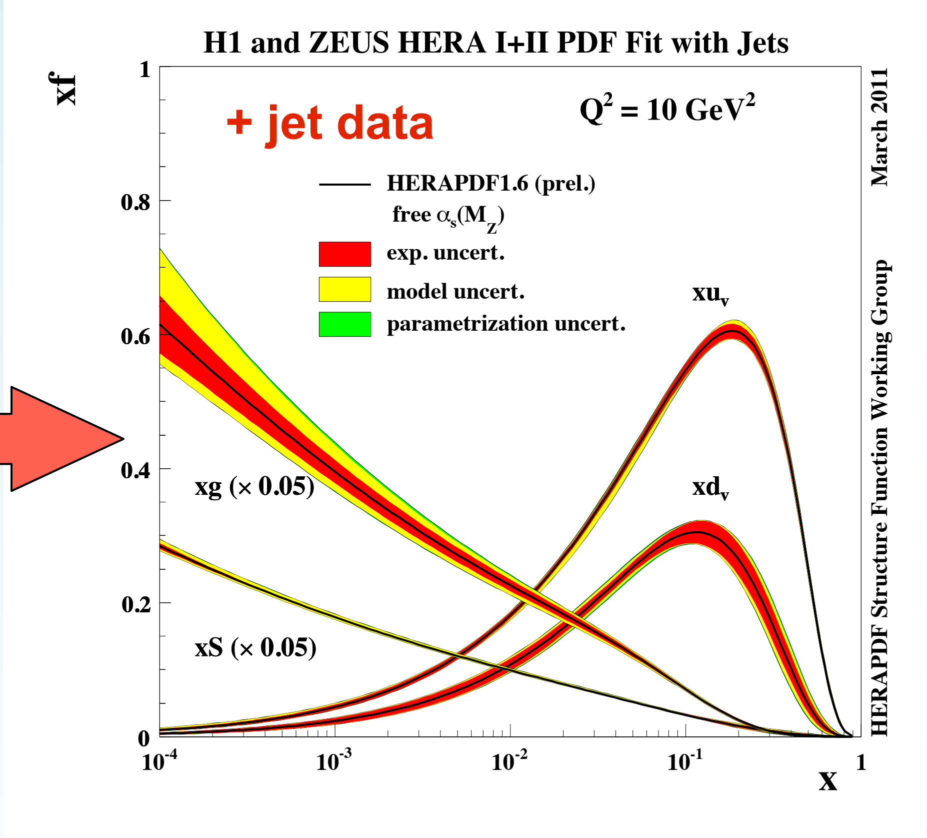
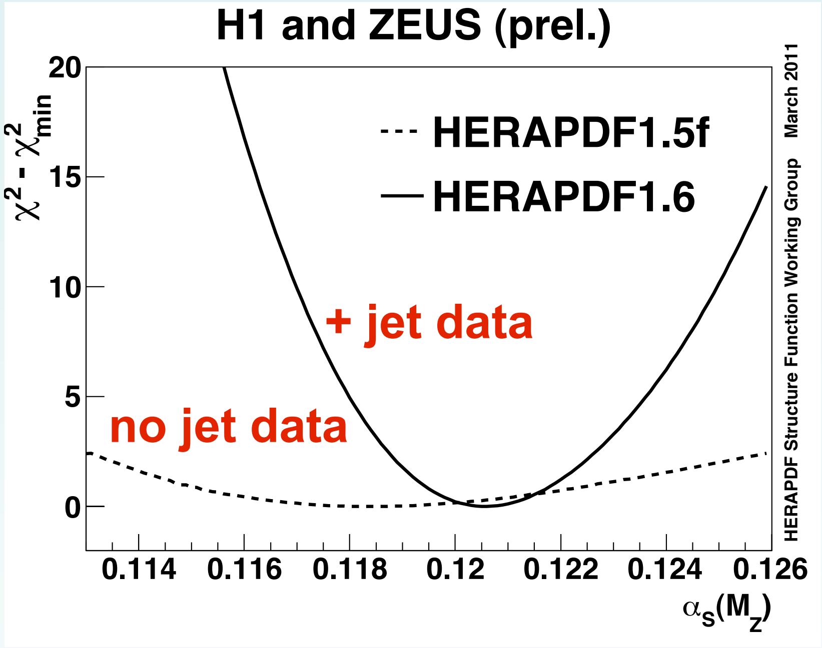


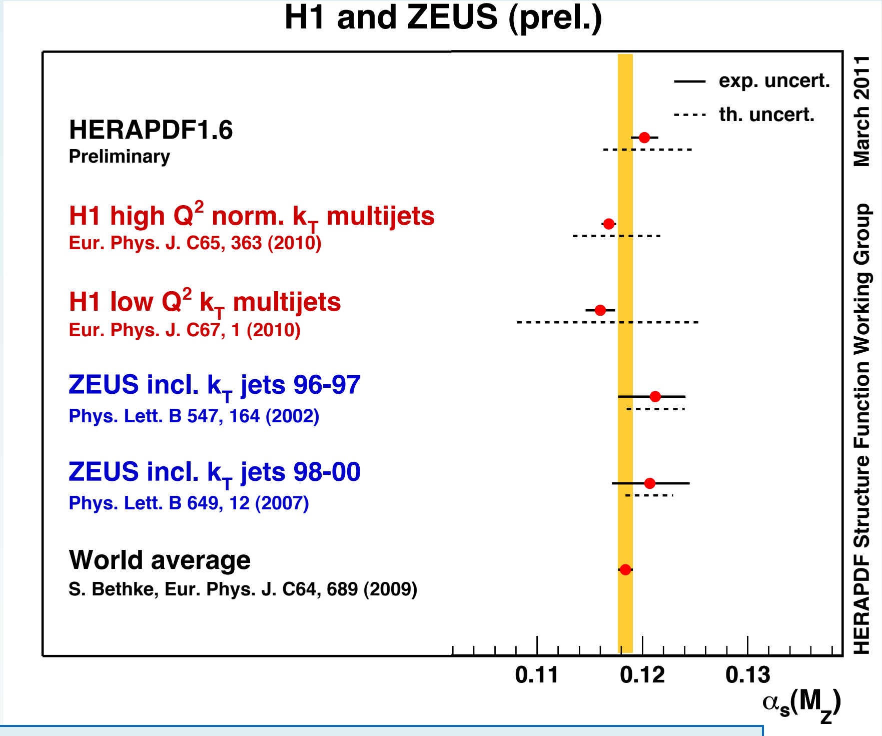


Inclusion of jet data into the PDF fit **decouples** the gluon and α_s (Mz)

PDF fits using HERA Jet Data: determine α_s (Mz)

Scan of the α_s (Mz) in the PDF fit





PDF and α_s (Mz) determined in the common fit:

$\alpha_s (M_Z) = 0.1202 \pm 0.0013_{exp} \pm 0.0007_{model/param} \pm 0.0012_{had} + 0.0045_{scale}$

From including the Jet data in the PDF fit we do learn about α_s (Mz)

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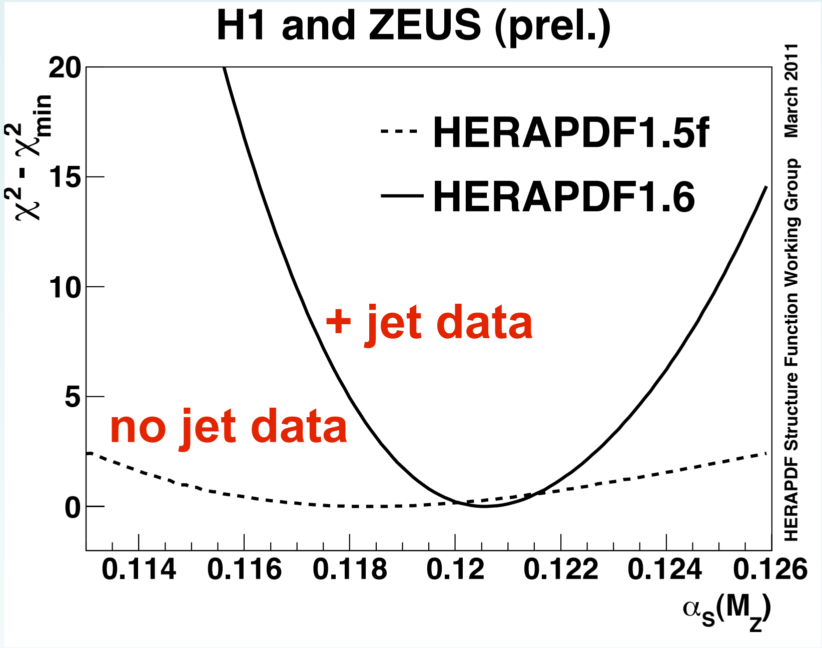

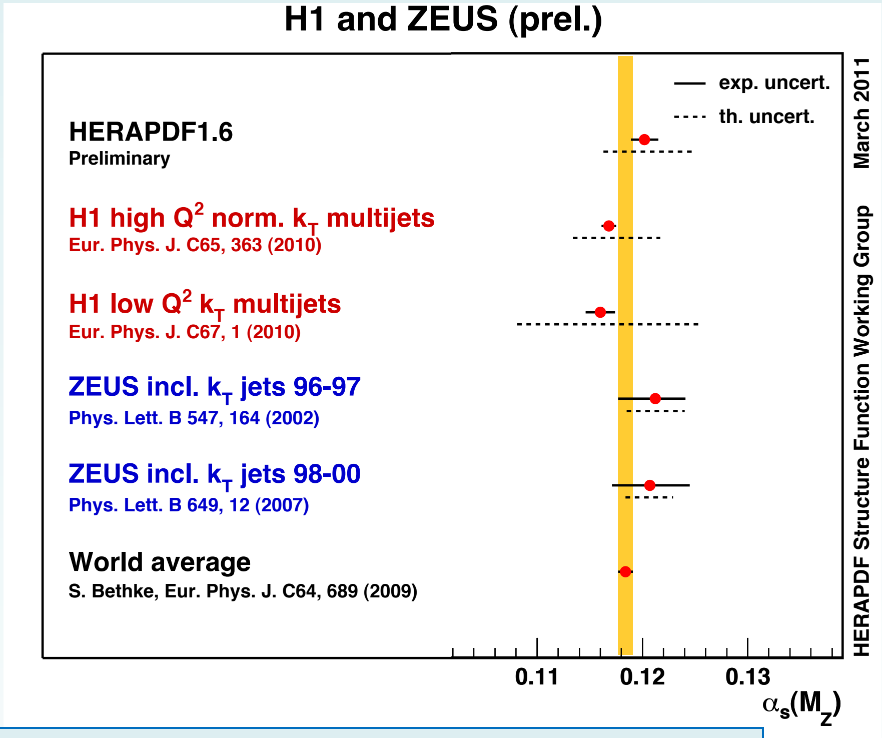

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What do we learn from heavy flavour production?

Heavy Quarks and PDF Fits

Factorization: $F_2^V(x, Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$

i - number of active flavours in the proton: defines the factorization (HQ) scheme

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- i fixed : Fixed Flavour Number Scheme (FFNS)

  only light flavours in the proton: i = *3 (4)*

  c- (b-) quarks massive, produced in boson-gluon fusion

  $Q^2 \gg m_{HQ}{}^2$: can be less precise, NLO coefficients contain terms ~ $ln(\frac{Q}{m_{HQ}})$

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- i variable: Variable Flavour Number Scheme (VFNS)

- Zero Mass VFNS: all flavours massless. Breaks down at $Q^2 \sim m_{HQ}^2$

- Generalized Mass VFNS: different implementations provided by PDF groups

  smooth matching with FFNS for $Q^2 \rightarrow m_{HQ}^2$ must be assured

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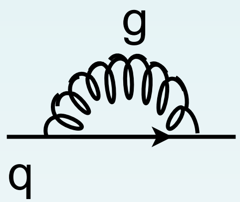
QCD analysis of the proton structure: treatment of heavy quarks essential

Heavy Quark Mass Definition in PDFs

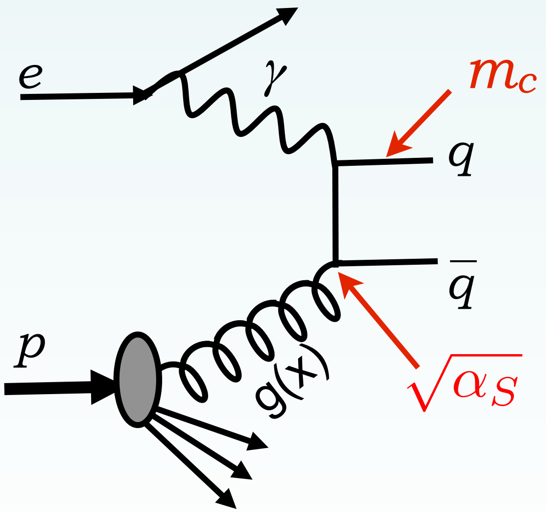
Usually HQ coefficient functions use a pole mass definition

BUT: pole mass defined for free quarks
Corrections due to loop integrals receive large contributions ~ $O(\Lambda_{QCD})$



large higher order corrections
bad convergence of perturbative series

Another way of defining quark mass: via renormalization



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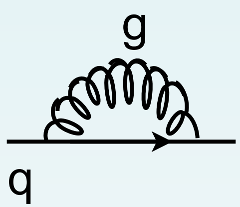

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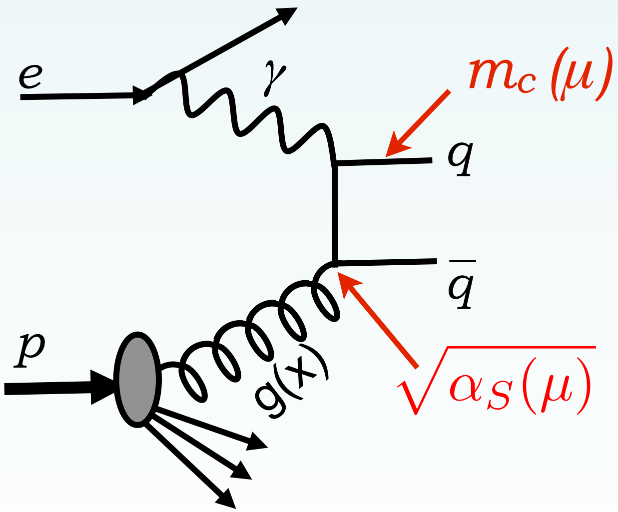

running coupling

running mass

Heavy Quark Mass Meaning in PDFs

Massive HQ coefficient functions are calculated at NLO using pole mass

Smith. et al NPB 395,162 (1993)

Used by the global fit groups: MSTW, CTEQ, ABKM, GJR, HERAPDF

ZMVFNS: m_{HQ} defines a threshold at which HQ appears as an active flavour

GMVFNS: m_{HQ} is also used as a parameter at which FFNS turns into VFNS

Heavy Quark Mass Values in PDFs

Massive HQ coefficient functions are calculated at NLO using pole mass

Smith. et al NPB 395,162 (1993)

Used by the global fit groups: MSTW, CTEQ, ABKM, GJR, HERAPDF

PDF group	m_c / m_b	HQ scheme
MSTW	1.4 / 4.75	GMVFNS
CTEQ	1.3 / 4.5	GMVFNS
JR	1.3 / 4.2	FFNS
ABKM	1.5 / 4.5	FFNS
HERAPDF	$1.4^{-0.05}_{+0.25}$ / 4.75	GMVFNS

PDG values: 1.66±0.18 / 4.79

PDF fits assume pole mass definition for heavy quarks

Values of m_c as used by most PDF groups too low wrt. PDG

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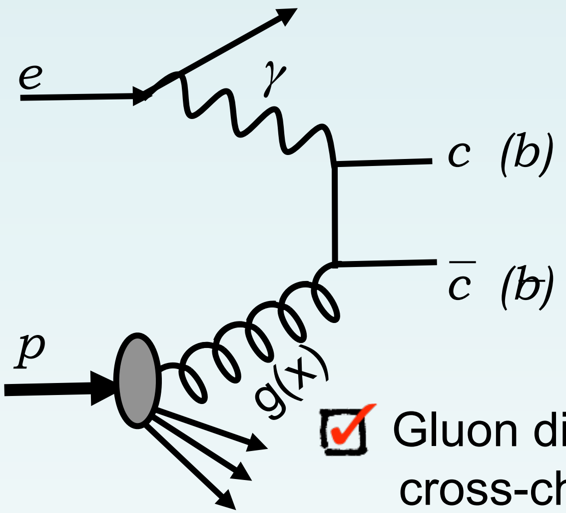
HQ treatment in PDF fits, meaning and values of HQ masses non trivial..

Heavy quark data can help!

Heavy Quark Production at HERA

Heavy quarks in *ep* scattering produced in boson-gluon fusion



Contribution to total DIS cross section:

charm: ~ 30% at large Q^2

beauty: at most few %

☑ Gluon directly involved:
cross-check of *g(x)* from NC and CC DIS cross sections

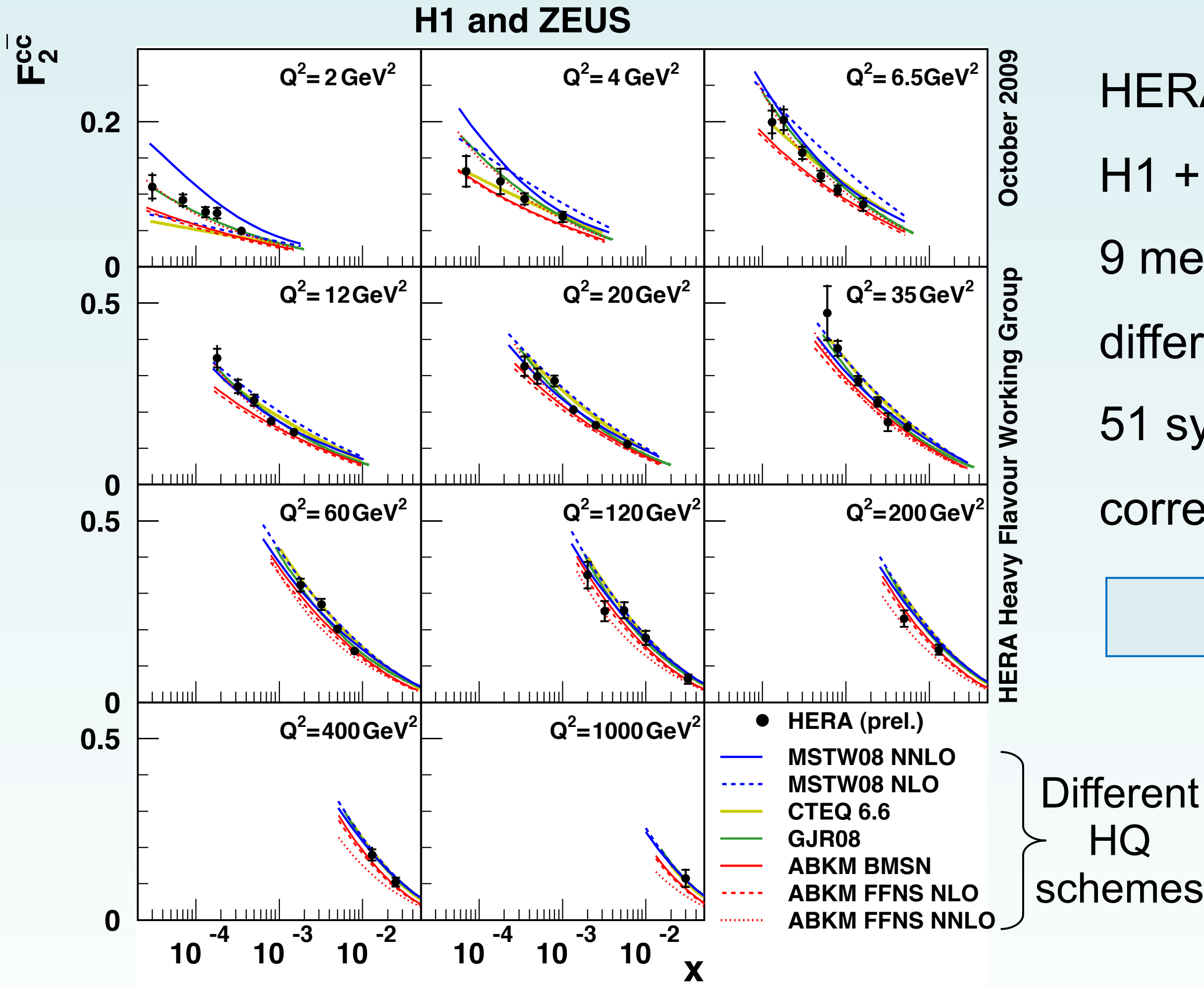
➡ HERA results on charm and beauty: talk by O. Behnke

☑ HQ contributions to the proton structure function F_2: (e.g. charm)

$$\sigma^{cc} \propto F_2^{cc}(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L^{cc}(x,Q^2)$$

→ Direct test of HQ schemes in PDF fits

Charm at HERA: Test HQ Schemes in PDFs



HERA Charm Measurement:

H1 + ZEUS

9 measurements

different charm tag methods

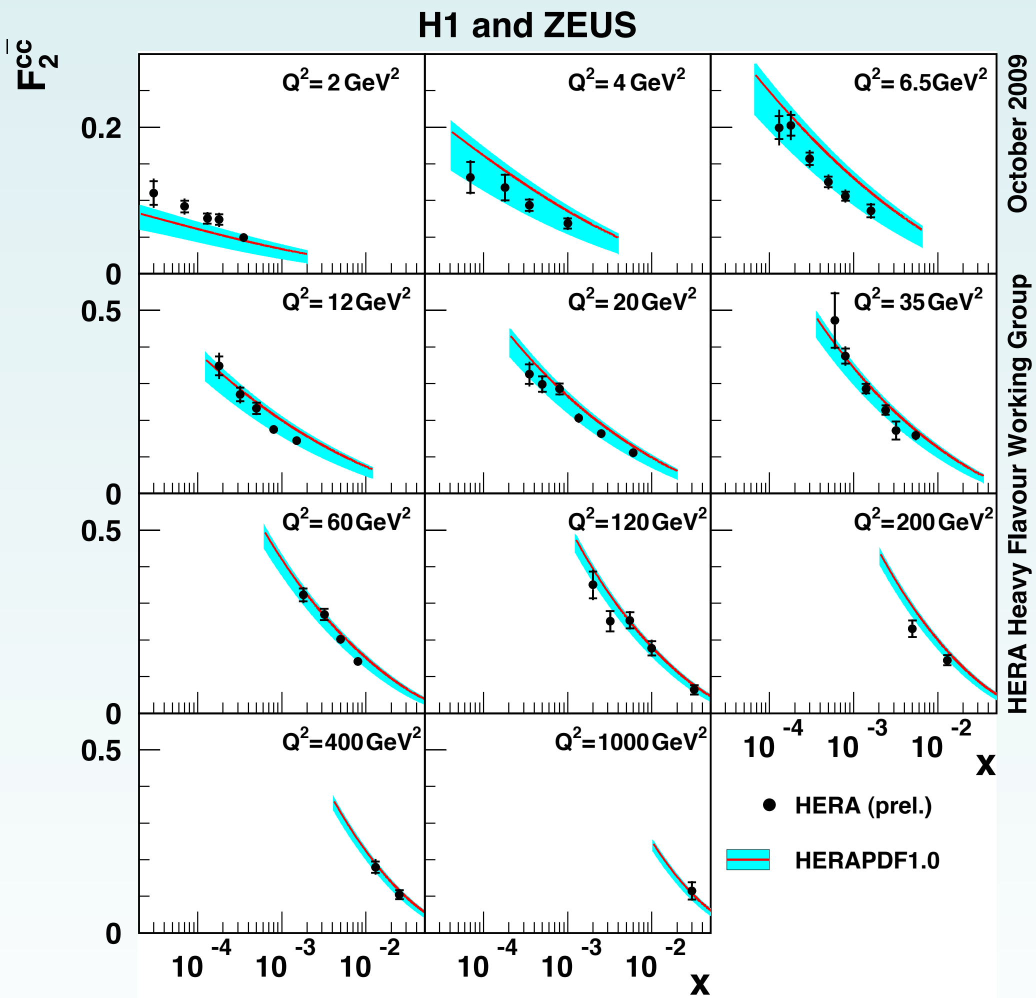
51 systematic error sources

correlations accounted for

Precision 5 - 10%

Data help understanding differences in HQ schemes

Charm at HERA: Test Choice of m_c in PDF



F^c_2 not included in HERAPDF1.0

but is well described

charm quark mass value varied in the PDF Fit:

m_c=1.4 GeV

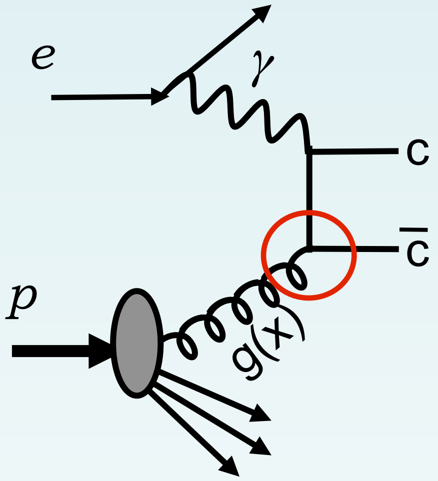
m_c=1.35 vs 1.65 GeV

PDG pole mass

PDFs obtained from inclusive data sensitive to the choice of m_c

Charm Data in the PDF Fit

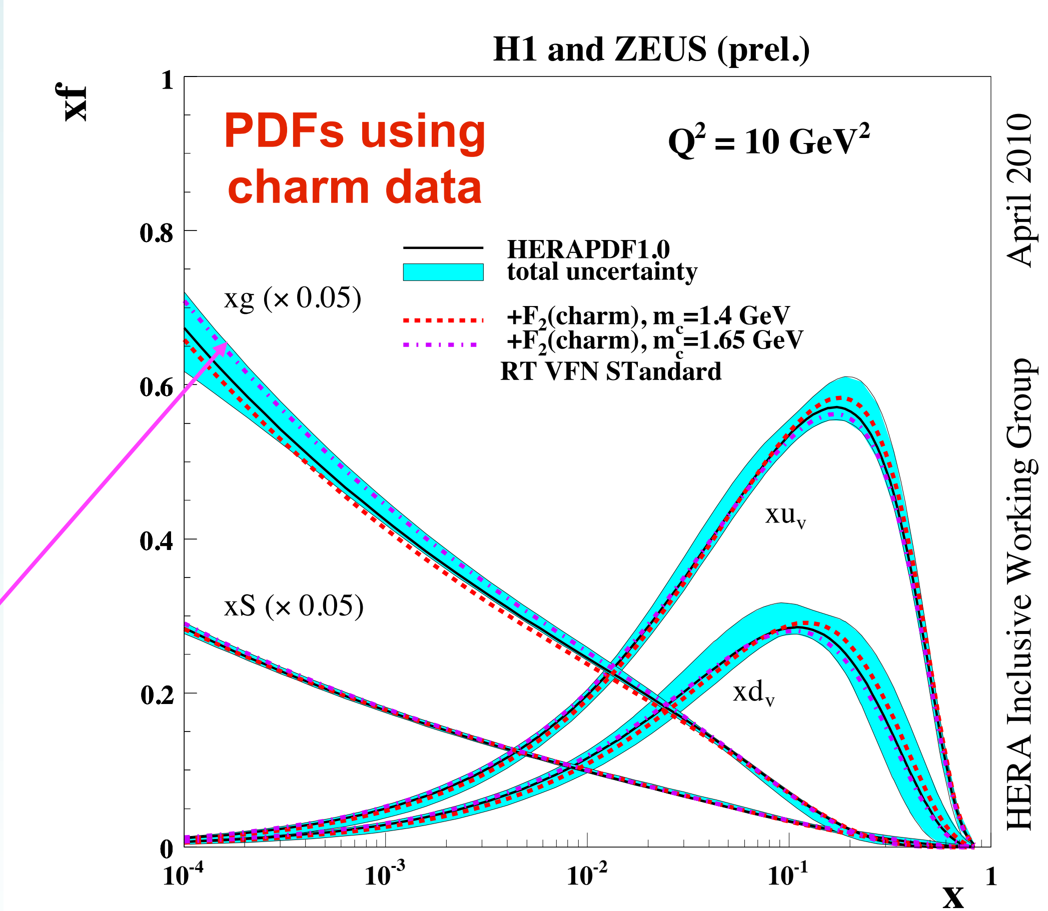
Charm production probes gluon directly. **Do charm data influence the gluon?**



Consider 2 values of m_c

m_c=1.65 GeV: **better fit**

steeper gluon distribution

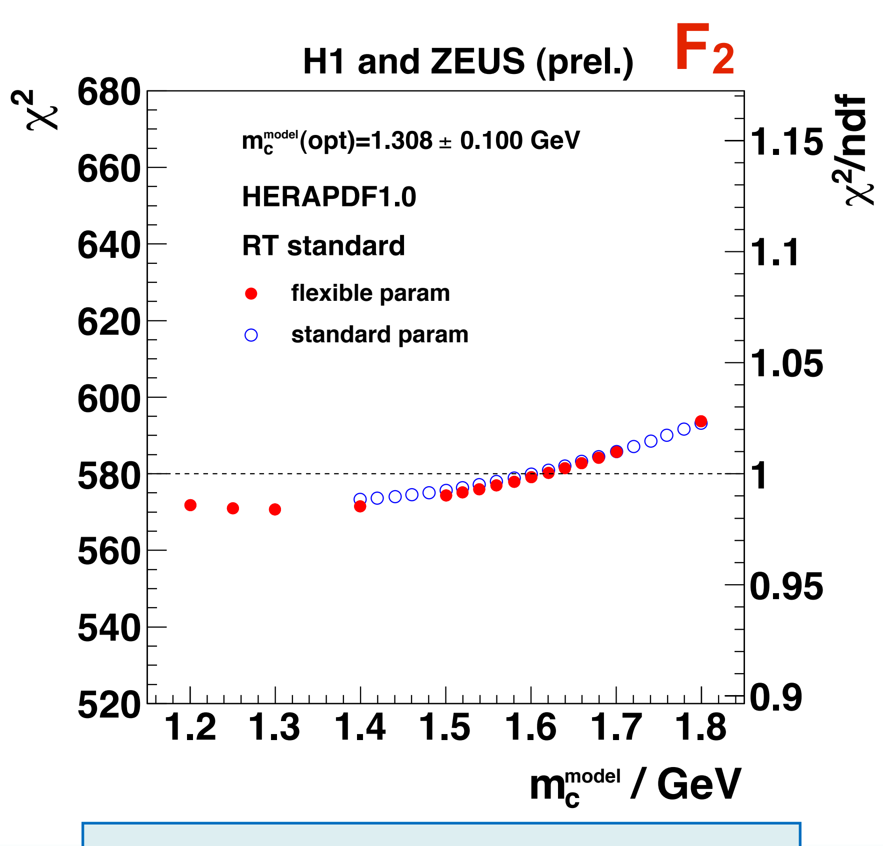


PDFs and PDF fit using charm data is sensitive to the value of m_c

Charm Mass as a Model Parameter in PDF

Study the sensitivity of the PDF fit to the value of m_c

PDF fit to inclusive DIS



Weak dependence on m_c

Charm Mass as a Model Parameter in PDF

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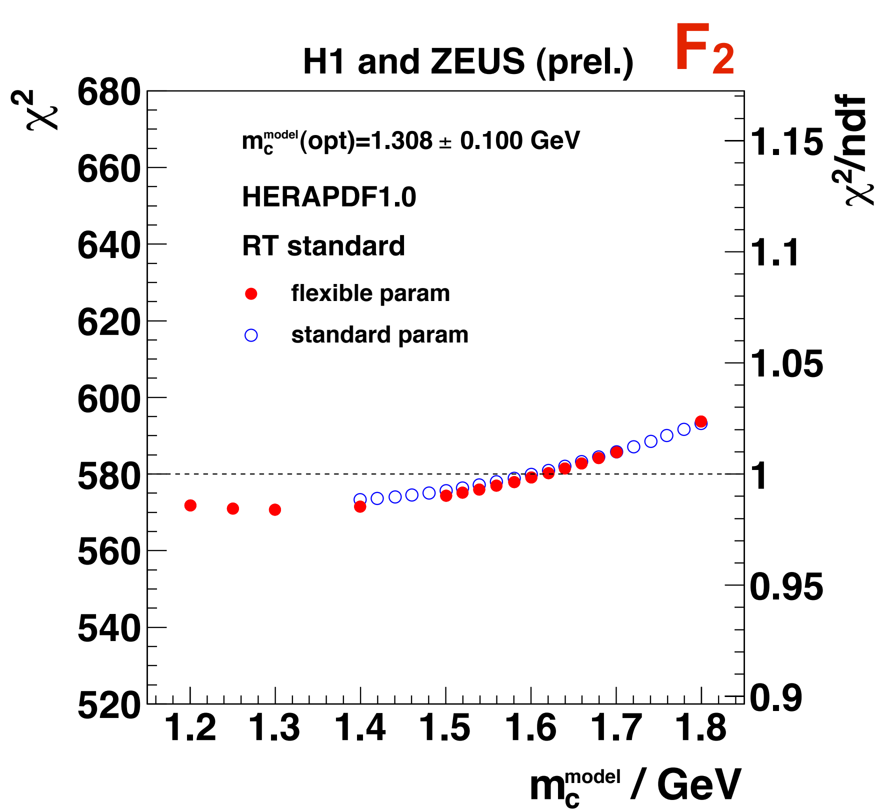
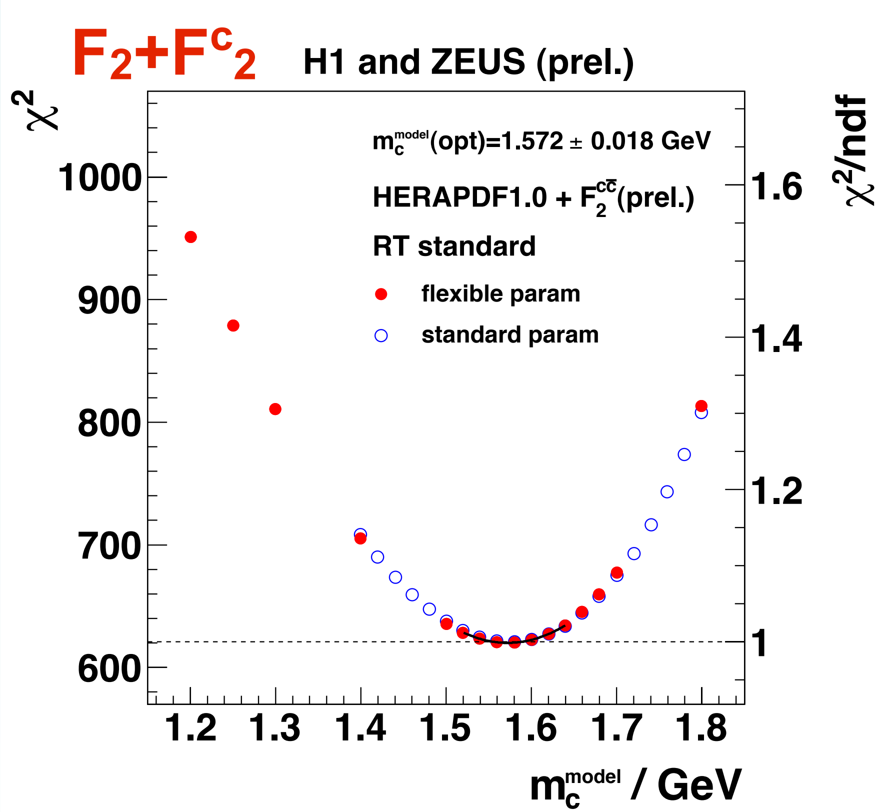
PDF fit to inclusive DIS



Weak dependence on m_c

PDF fit to inclusive DIS + charm data



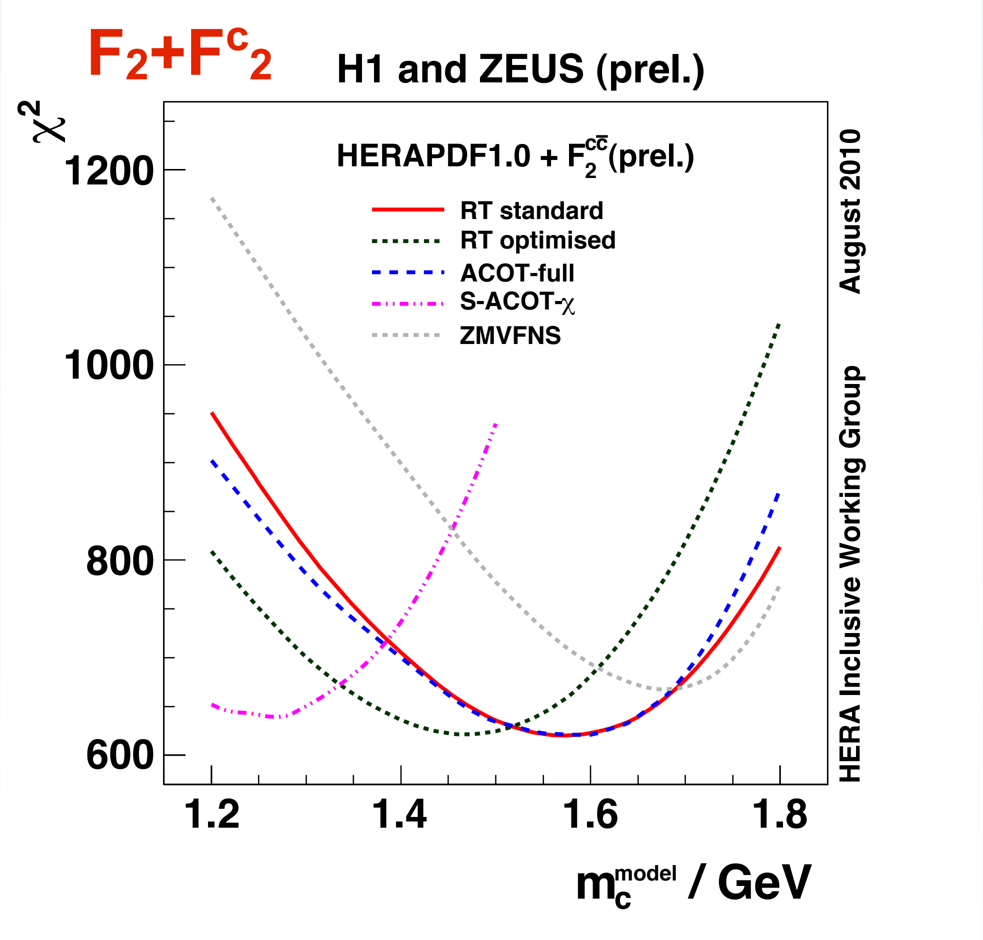
Strong dependence on m_c

Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)



Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)

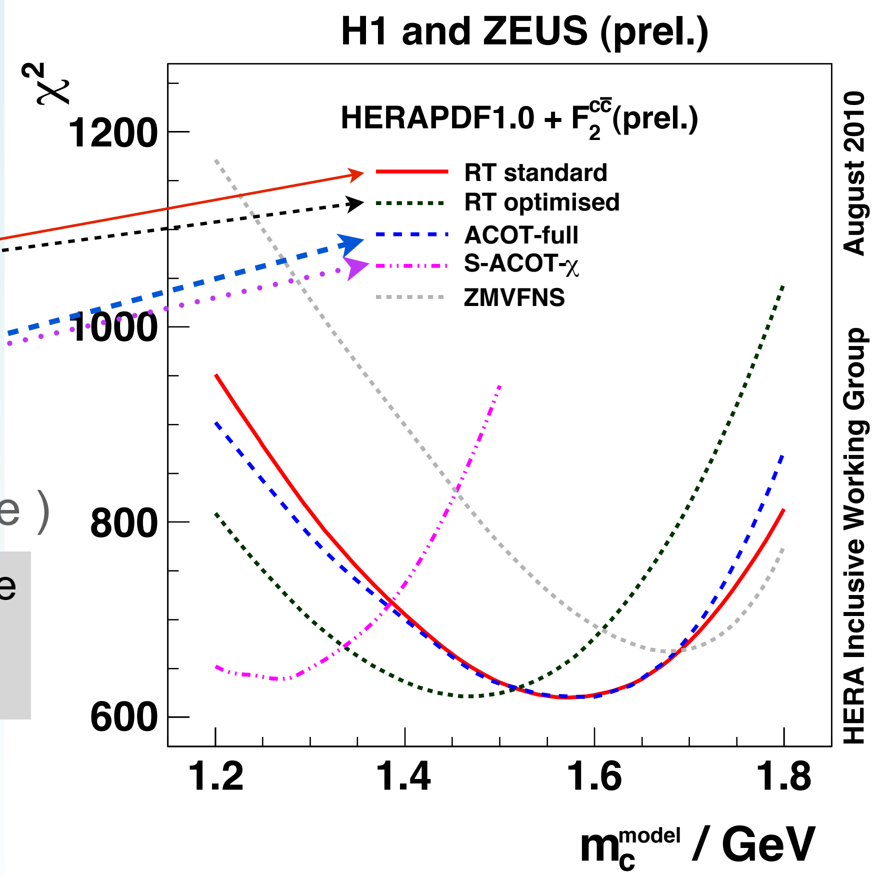
RT : MSTW PDFs

ACOT: CTEQ PDFs

ZMVFNS (not used any more)

NB: ZMVFNS does not describe

charm data even at $Q^2 >> m_c^2$



Different HQ Schemes in PDFs

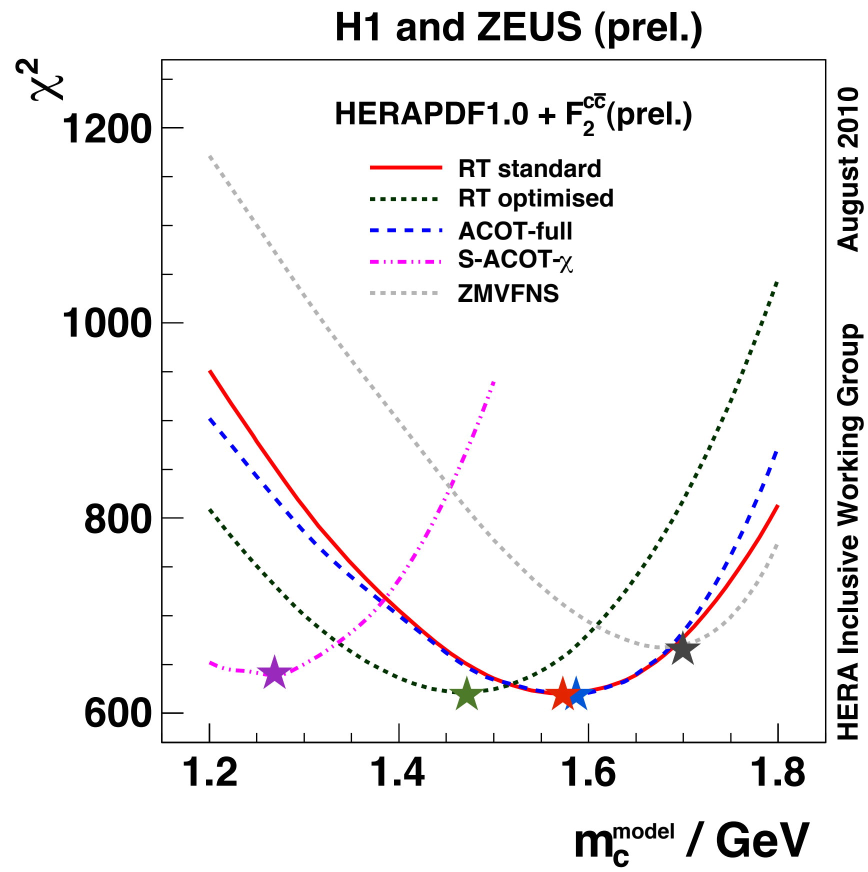
Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)

Different HQ schemes prefer

different optimal★ m_c



Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)

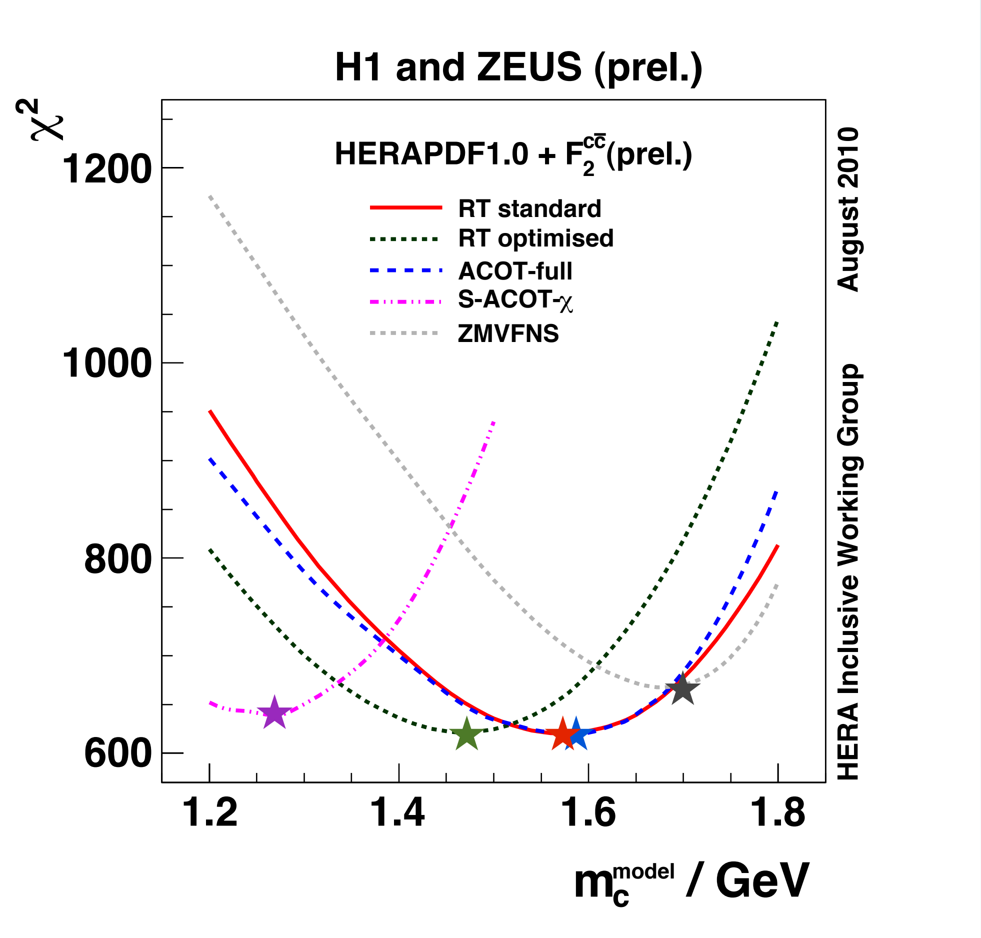
Different HQ schemes prefer

different optimal★ m_c

↓

parameter of a specific

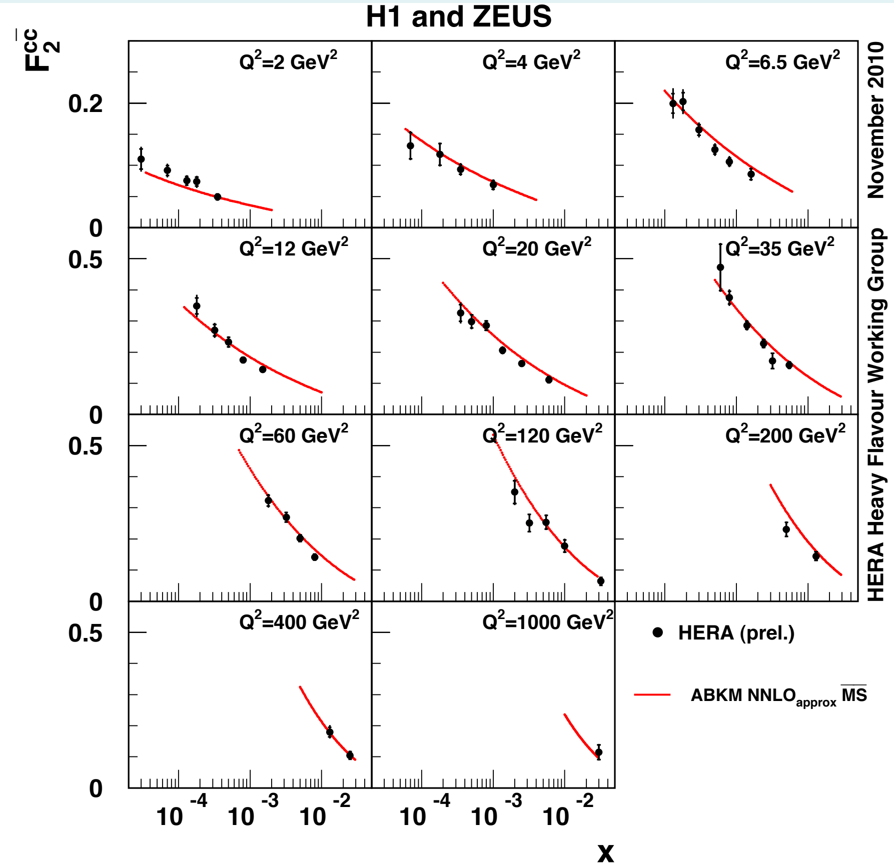
HQ scheme in PDF fits



What is the Meaning of m_c in PDF Fits?

Recent theory developments: (ABKM group, DESY, *arXiv:1011.5790*)

HQ coefficient functions provided in $\overline{\text{MS}}$ scheme using running m_{HQ}



Perturbative series converge better

Consistent treatment of HQ in PDF fits

$m_c(m_c)$ determined using DIS data

What happens if HERA charm data are included?

From including the charm data in the PDF fit we can learn about m_c (m_c)

HERAPDF1.7: DIS+ low energy+jets+charm

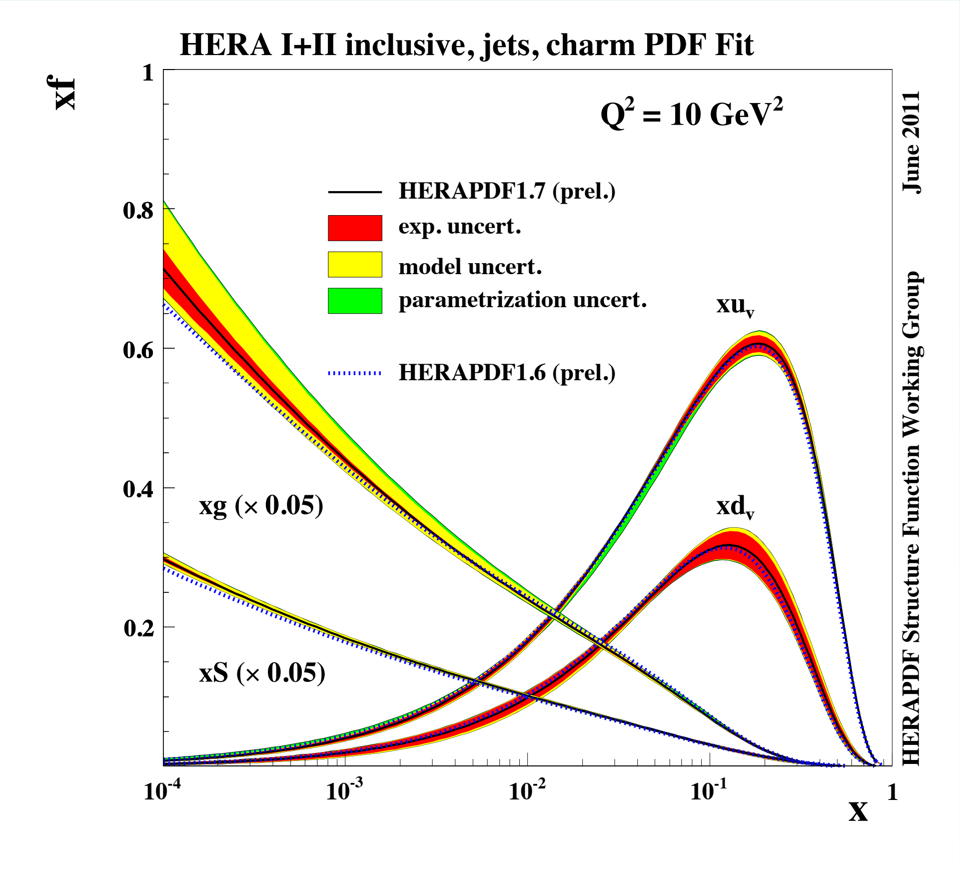
Flexible parametrization

heavy flavours:

m_c=1.5±0.15 GeV

α_S (M_Z)=0.119

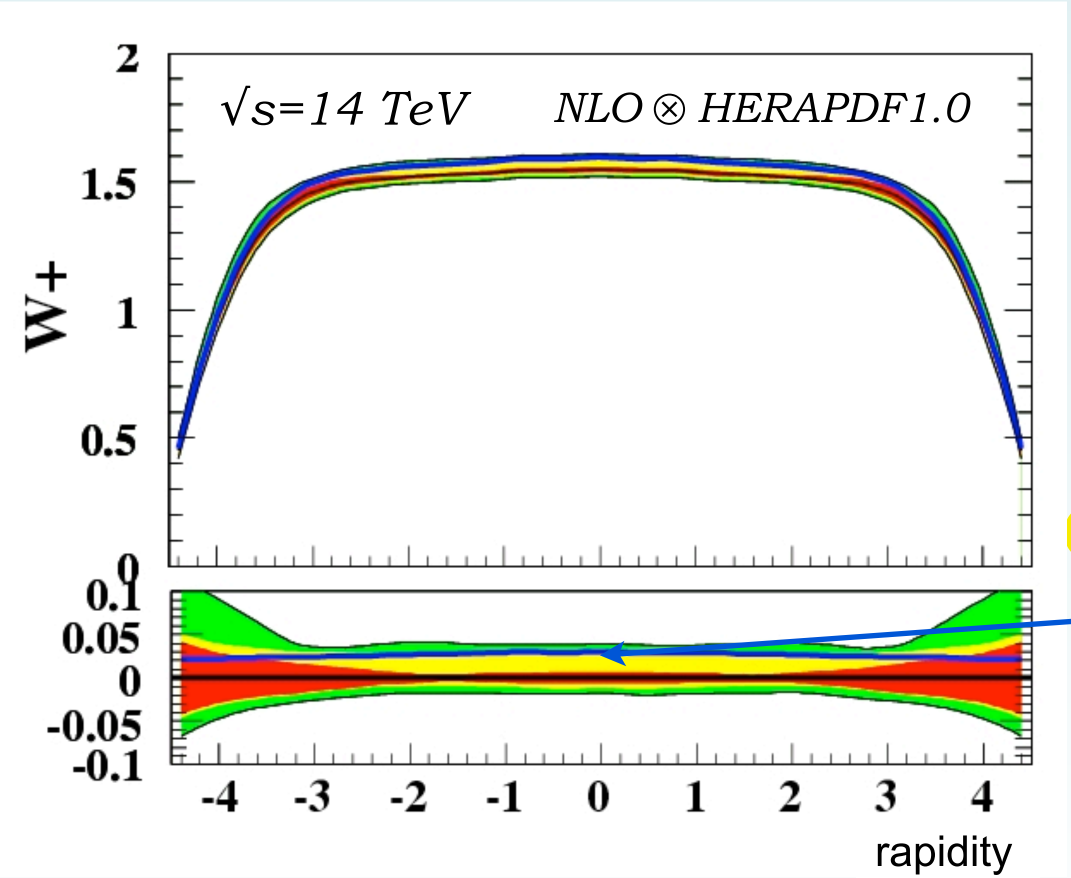
steeper gluon as HERAPDF1.6



Including the jet and the charm data: decouple the gluon from α_S and m_c

Heavy Quarks in PDFs and W/Z at LHC

Prediction of W± cross section @ LHC: dominant uncertainty due to PDF



Prediction using m_c=1.4 GeV

Error band: PDF uncertainty

Experimental error

Parametrization variation

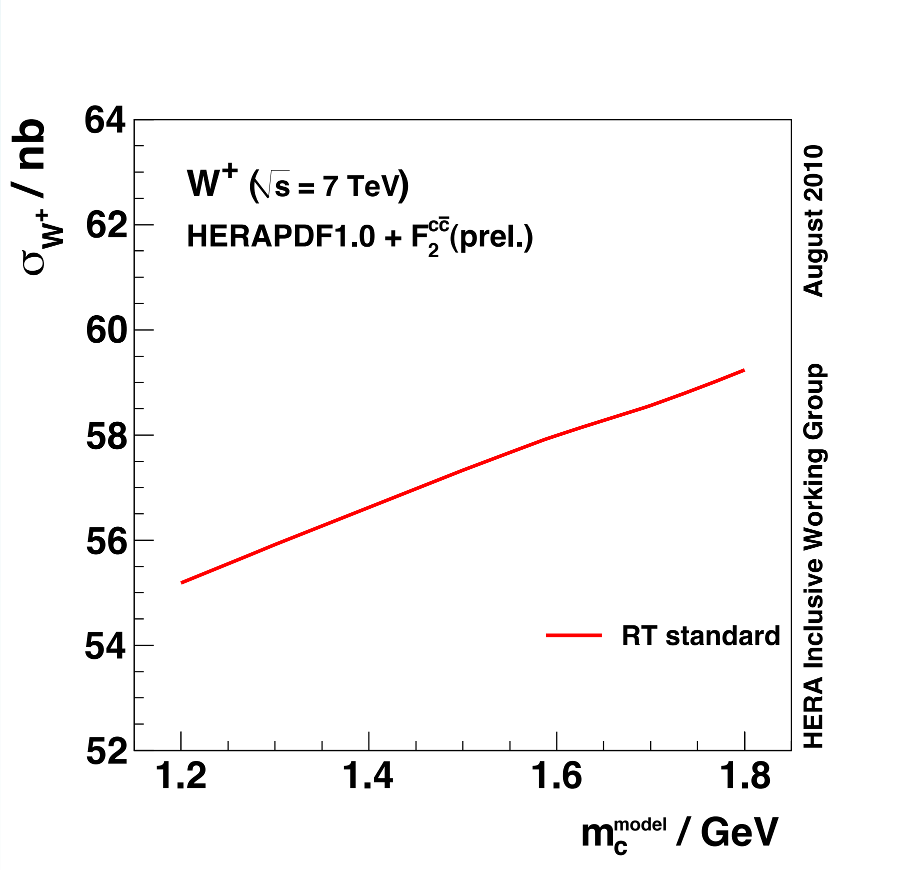
Model assumptions

including m_c variation

m_c variation in PDF: significant uncertainty on W@LHC in central region

Heavy Quarks in PDFs and W/Z at LHC

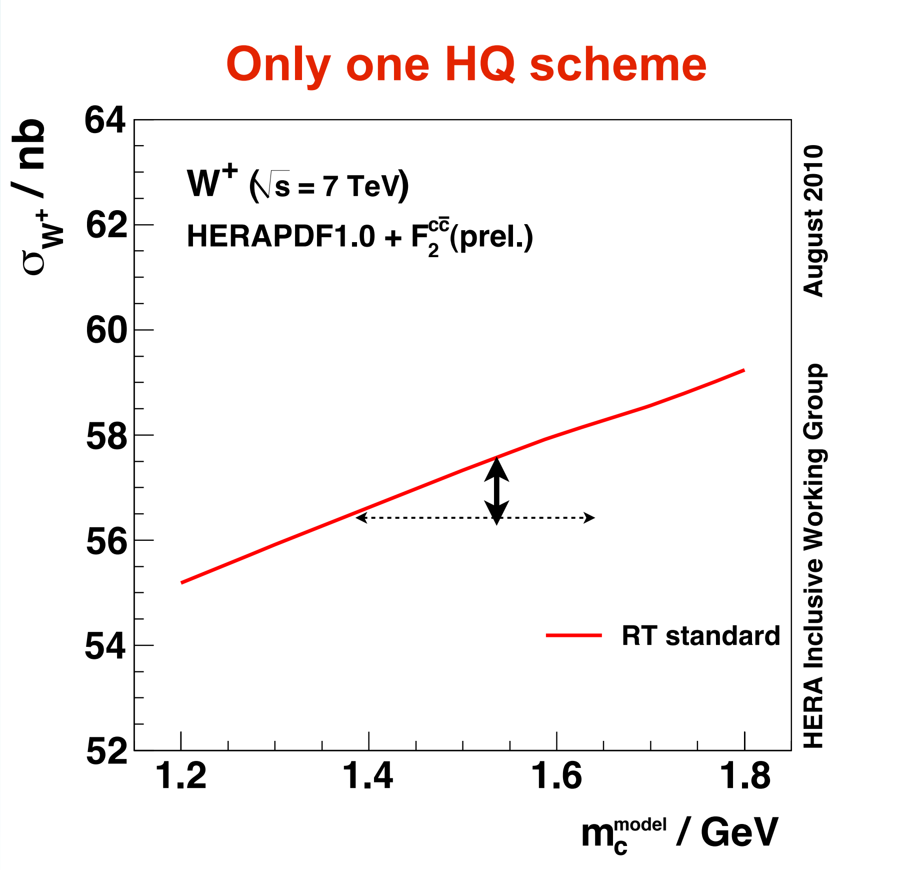
Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



Larger m_c → more gluons, less charm → more light quarks → larger σ_W

Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



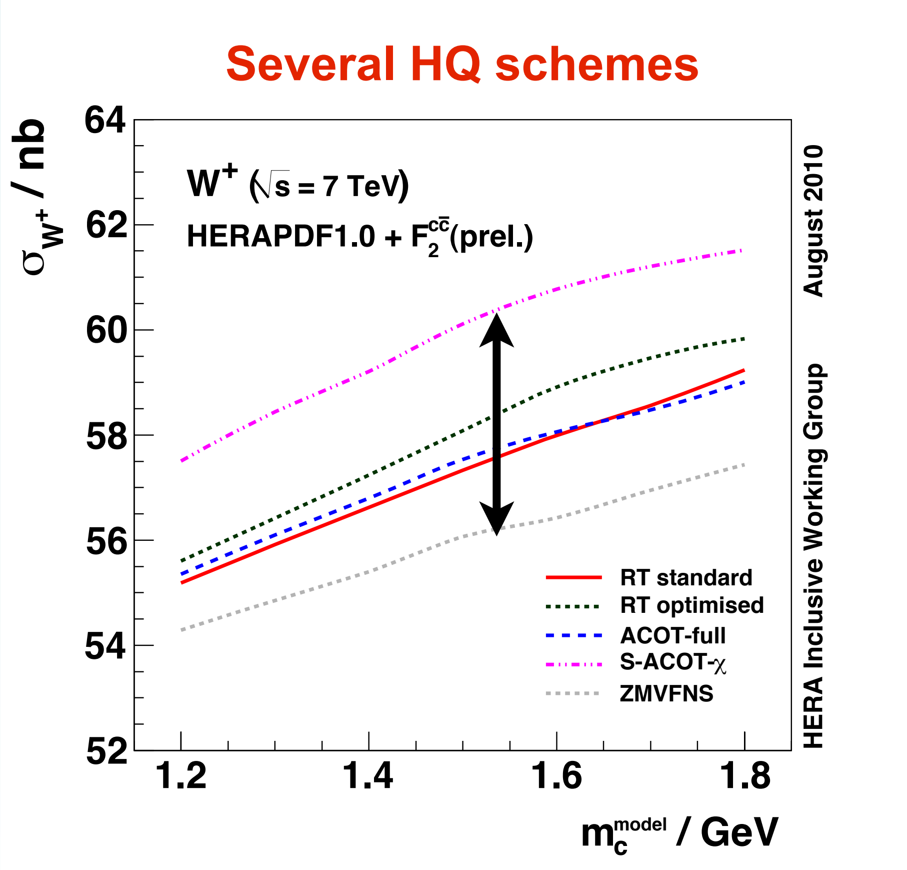
m_c variation in PDF

1.4 < m_c < 1.65 GeV

3% uncertainty on W prediction

Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



m_c variation in PDF

1.4 < m_c < 1.65 GeV

3% uncertainty on W prediction

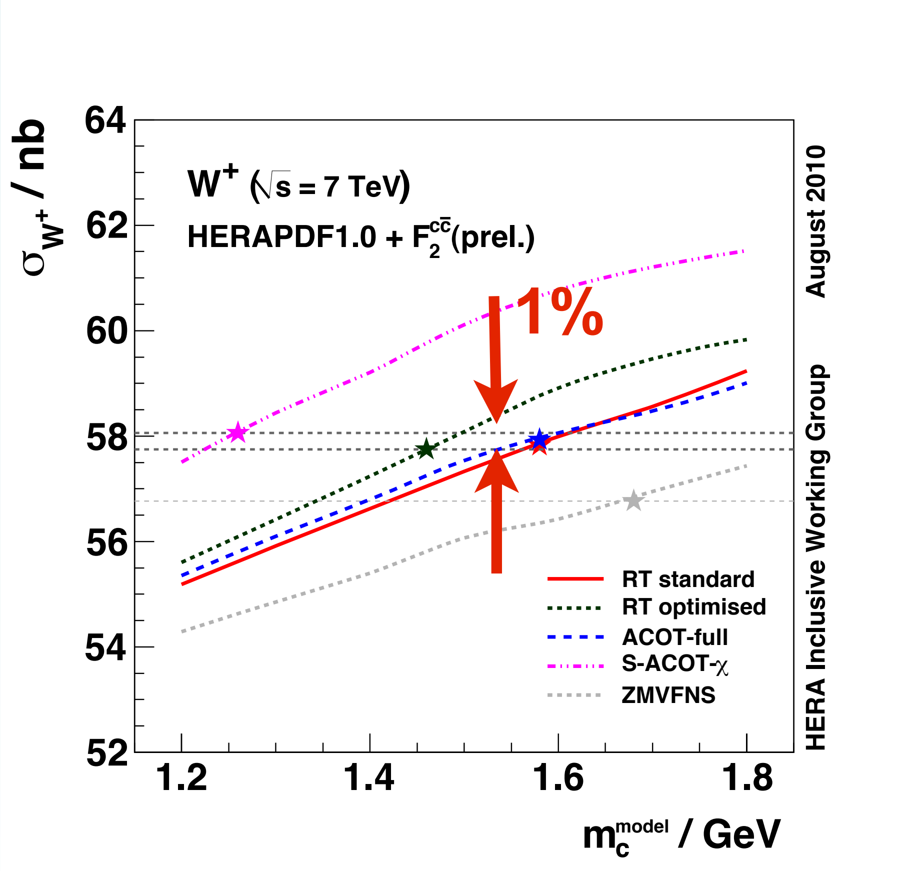
Using different HQ schemes:

+ 7% uncertainty

Large uncertainty on σ_W prediction due to HQ treatment in PDFs

Charm at HERA and W/Z at LHC

Use the optimal m_c for HQ schemes in PDFs fixed by HERA charm data



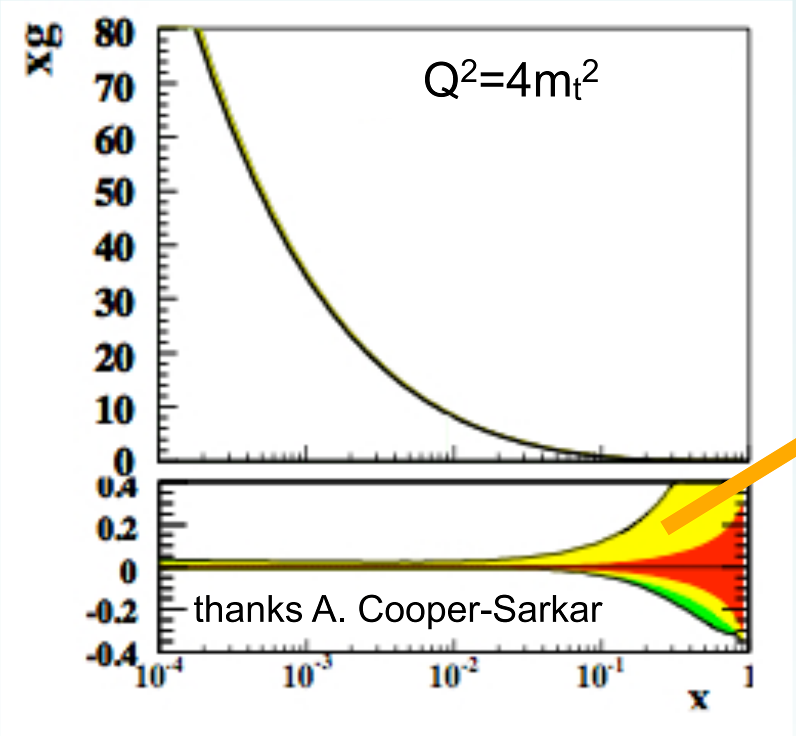
★ Optimal m_c using F_2+F_2^c

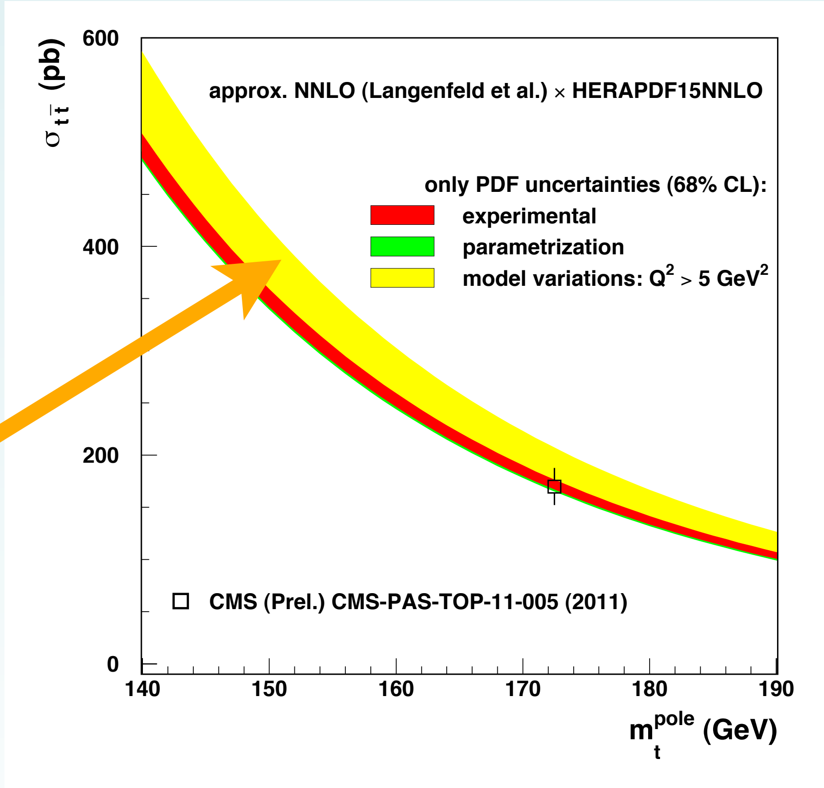
ZMVFNS not considered

Uncertainty on σ_W prediction due to HQ treatment in PDFs reduced to 1 %

(HERA)PDF and the LHC measurements

Top quark at CMS: cross section @ approx. NNLO





Dominant uncertainty: variation of Q^2_{min} imposed on data used in the fit

top quark production at the LHC has potential to constrain the high-x gluon

Summary

- **Understanding of the LHC data demands precise PDFs**

  HERA DIS data provide highest precision

- **Heavy quarks and strong coupling: quite some issue in QCD analyses**

  HERA charm and jet data provide constraints in PDF fits

  Example: PDF uncertainties on predictions for W and Z at the LHC

  More to learn using the LHC data

PDFs from HERA to the LHC is a success

Common effort of experiments and theory needed

Back up

Combination Procedure

Minimized value:

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma_j^i m^i b_j - \mu^i\right)^2}{(\delta_{i,stat}\mu^i)^2 + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2$$

μ^i measured value at point i

δ_i statistical, uncorrelated systematic error

γ_j^j – correlated systematic error

b_j – shift of correlated systematic error sources

m^i – true value (corresponds to min χ^2)

Measurements performed sometimes in slightly different range of (x,Q^2)

swimming to the common (x,Q^2) grid via NLO QCD in massive scheme

HERAPDF1.5f:

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

A_g, A_{u_v}, A_{d_v} are constrained by the sum rules.

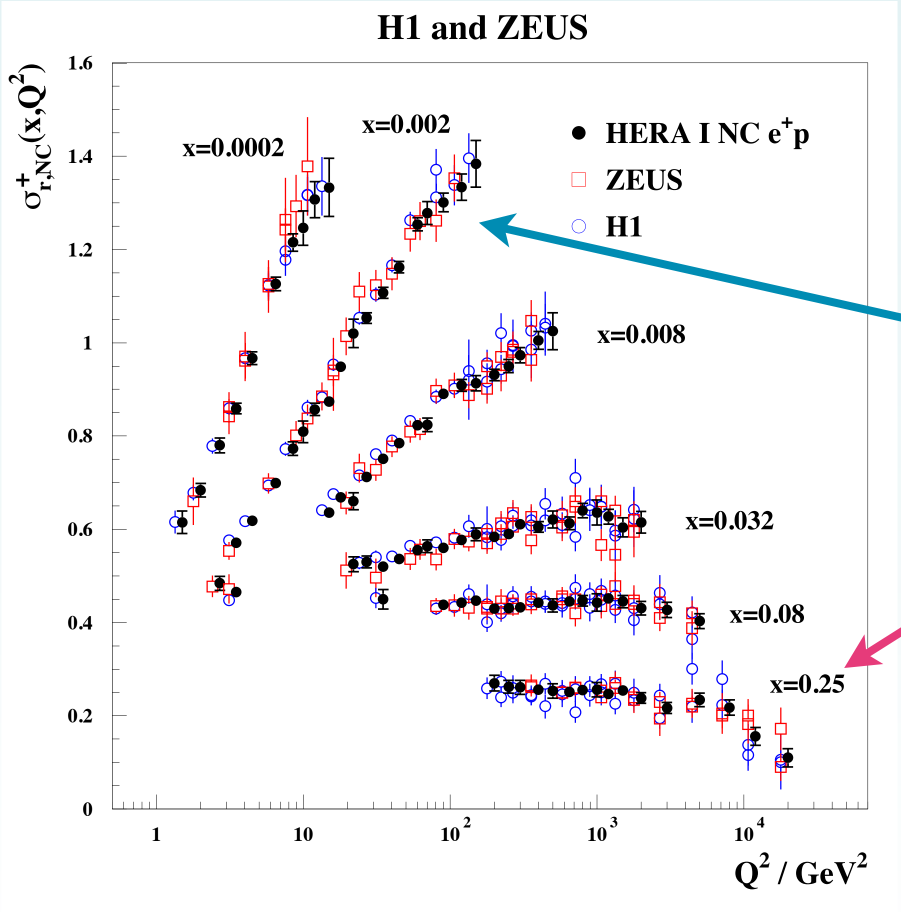
$B_{\bar{U}} = B_{\bar{D}}$ $\quad C'_g = 25,\ A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$

HERAPDF1.5 (10 parameter fit) $A'_g = B'_g = 0,\ B_{d_v} = B_{u_v}$ $\quad D_{u_v} = 0$

Scaling Violations at Highest Precision

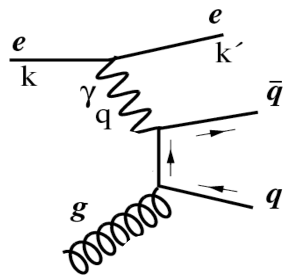
JHEP 01 (2010) 109: combined H1 and ZEUS data from HERA I, $\mathcal{L}$~115 pb^{-1}

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$



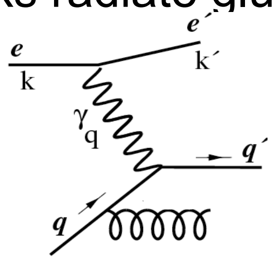
small x : F_2 rises with Q^2

gluon splits into quark pair

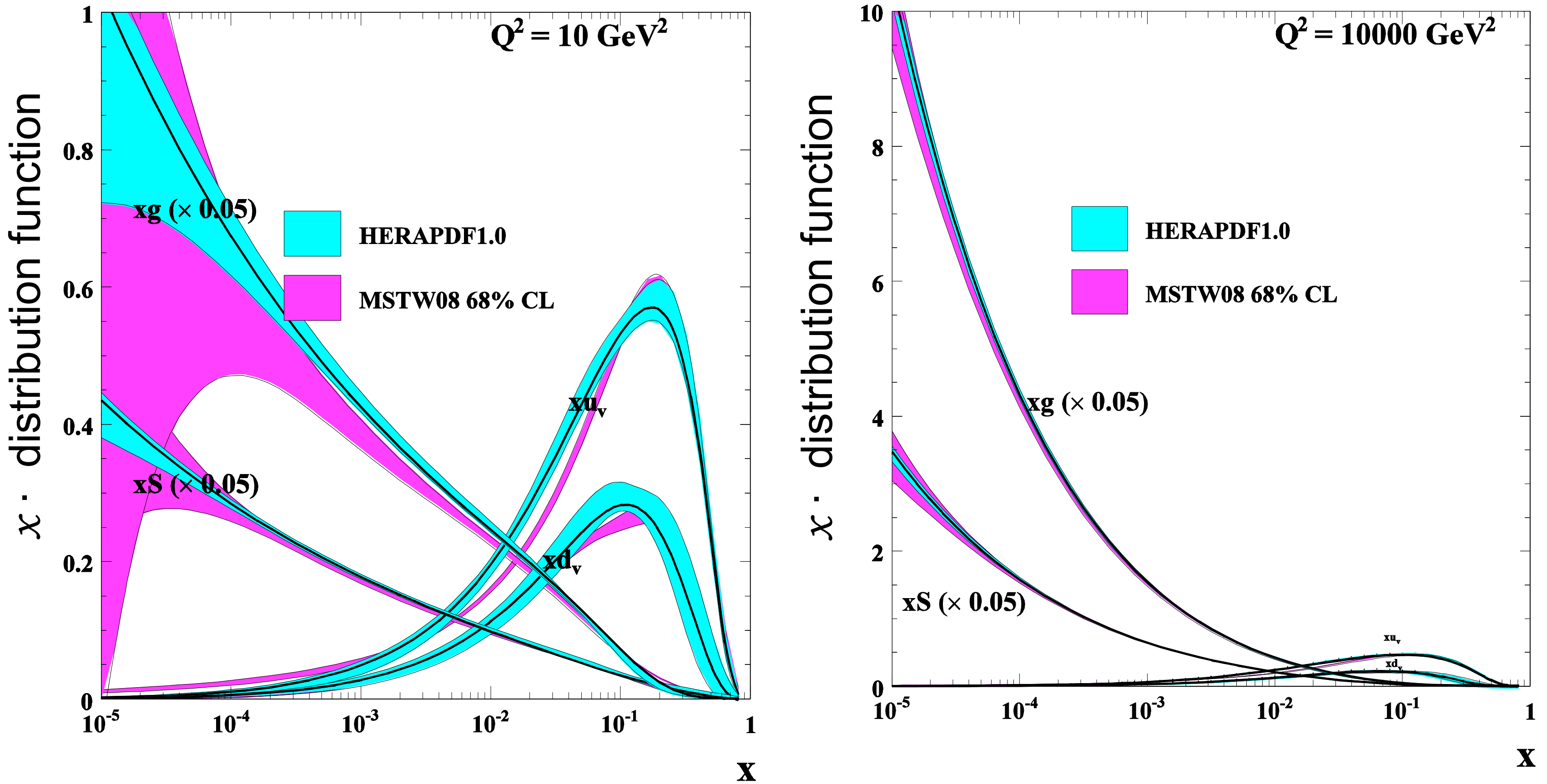


large x : F_2 falls with Q^2

quarks radiate gluons



HERA PDFs vs global QCD analysis



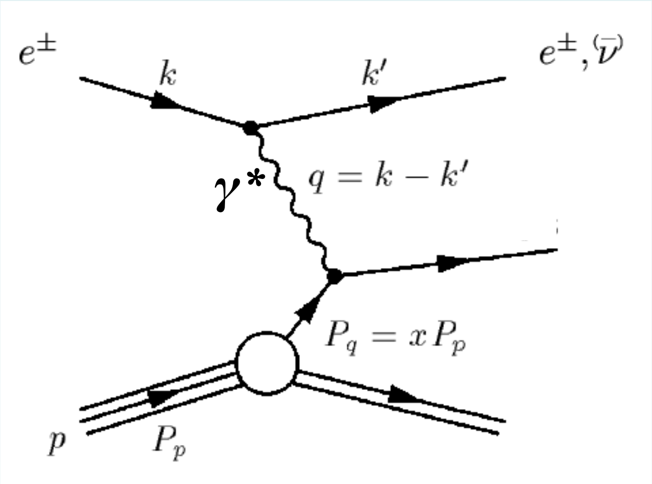
HERAPDF compared to one of the global PDF Fit results:

- much better precision in gluon and sea
- differences in valence

ep Scattering in Quark-Parton Picture

Think of scattering of longitudinal and transverse polarized photons:

y (or $Y_{\pm}=1\pm(1-y)^2$) related to photon polarization



cross section:

$$\sigma \sim \sigma_T + 2(1-y)/Y_+ \, \sigma_L$$

transverse polarized γ helicity ±1

longitudinally polarized γ helicity 0

Kinematics:

$x=-q^2/2p\cdot q$ *Bjorken scaling variable*

$Q^2=-q^2$ *photon virtuality*

$y=p\cdot q/p\cdot k$ *transferred γ energy fraction*

ep Scattering in Quark-Parton Picture

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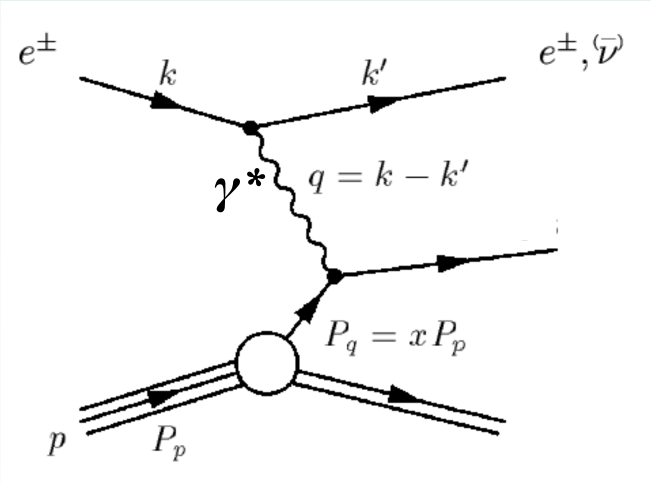


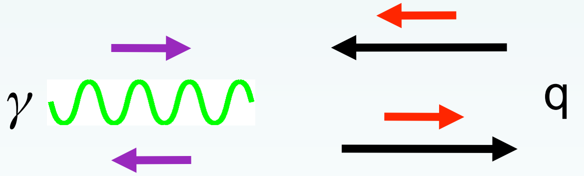
cross section:

$$\sigma \sim \sigma_T + 2(1-y)/Y_+ \, \sigma_L$$

transverse polarized γ helicity ±1

longitudinally polarized γ helicity 0

Parton Model: scattering off a quark ($s=½$):



helicity conservation ⇨ $\sigma_L=0$

Kinematics:

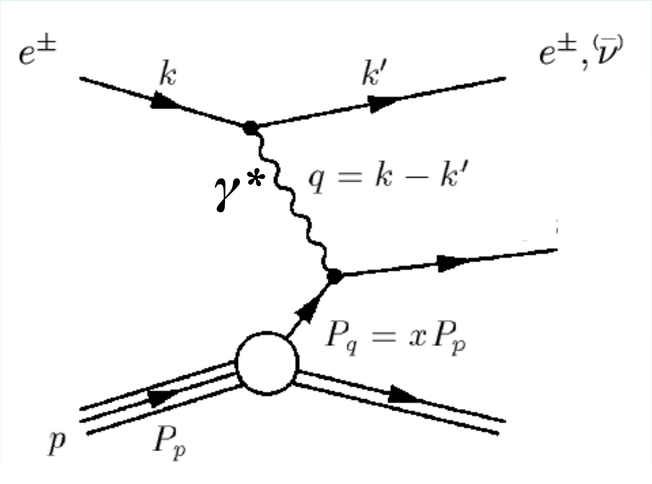
$x=-q^2/2p\cdot q$ *Bjorken scaling variable*

$Q^2=-q^2$ *photon virtuality*

$y=p\cdot q/p\cdot k$ *transferred γ energy fraction*

Proton Structure Functions

Cross Section of ep scattering expressed via proton structure functions



$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1 + (1 - y)^2)F_2 - y^2 F_L \pm xF_3\right]$$

measured

Kinematics:

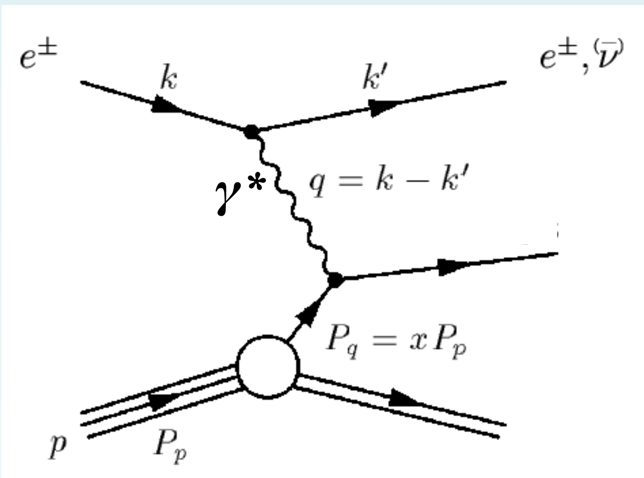
$x = -q^2/2p \cdot q$ *Bjorken scaling variable*

$Q^2 = -q^2$ *photon virtuality*

$y = p \cdot q / p \cdot k$ *transferred γ energy fraction*

Proton Structure Functions

Cross Section of ep scattering expressed via proton structure functions



$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1 + (1-y)^2)F_2 - y^2 F_L \pm xF_3\right]$$

measured

Quark-Parton-Model:

$F_L \sim \sigma_L \;= 0$

$$F_2 = \sum_q x e_q^2 (q(x) + \bar{q}(x))$$

Parton Distribution Functions (PDFs):
probability to find a q in a proton carrying x fraction of its momentum

Kinematics:

$x = -q^2/2p\cdot q$ *Bjorken scaling variable*

$Q^2 = -q^2$ *photon virtuality*

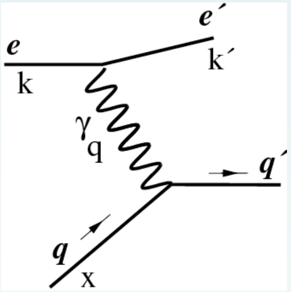
$y = p\cdot q\,/\,p\cdot k$ *transferred γ energy fraction*

Another way to access the gluon directly: F_L

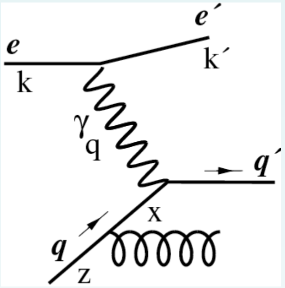
Remind of photon- scattering: $F_2 \sim (\sigma_T + \sigma_L), F_L \sim \sigma_L$

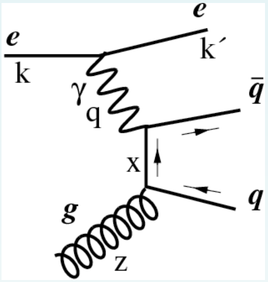
Angular momentum conservation: spin ½ quark absorbs spin-1 photon

QPM



QCD





quark helicity ± ½ , F_L=0

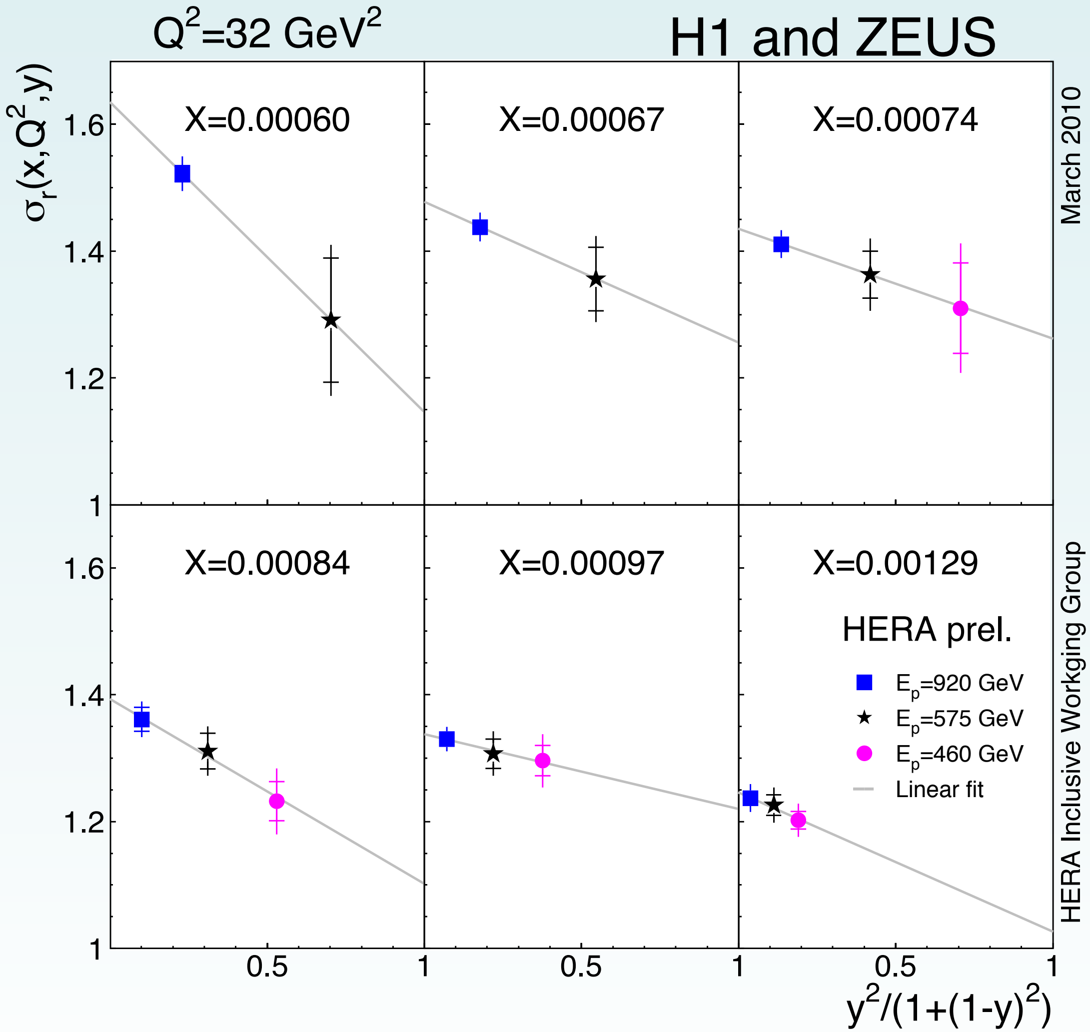
off-shell quarks may absorb longitudinal photons

QCD: $$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 (1 - \frac{x}{z}) z g(z) \right]$$

quarks radiating a gluon

gluons splitting into quarks

Extraction of F_L



measurements @ same Q^2, x

E_p=920 GeV

E_p=575 GeV

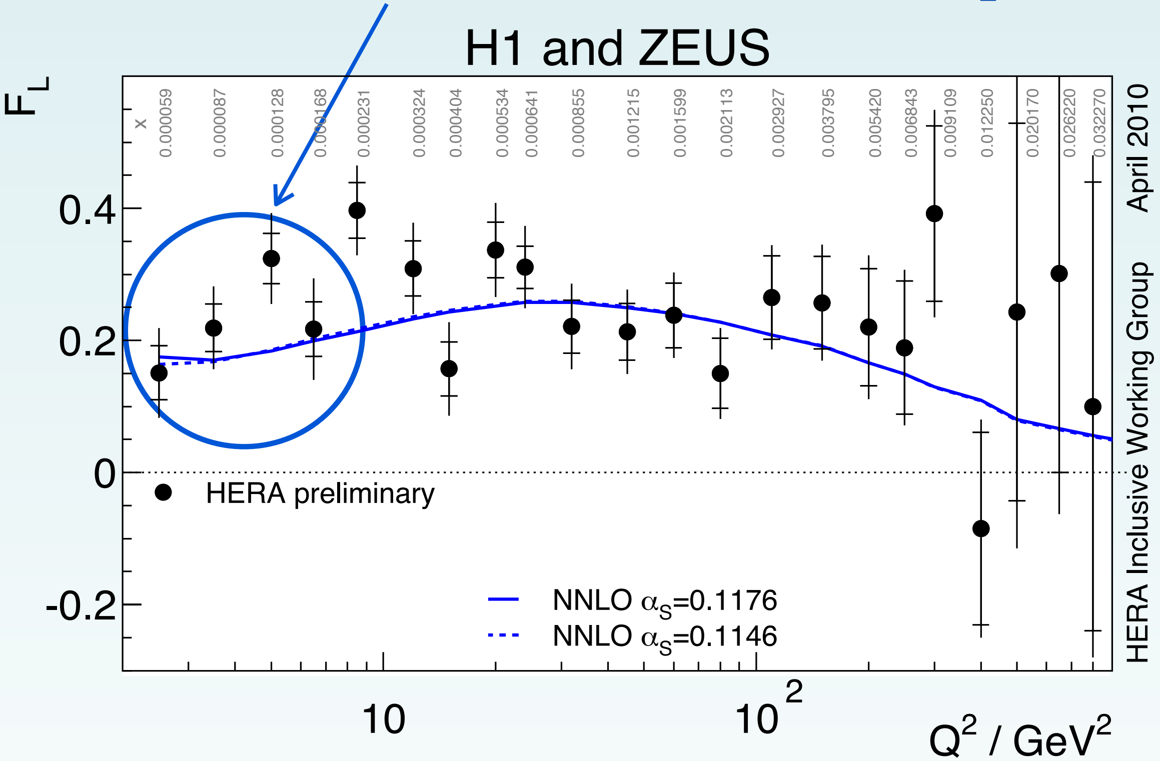
E_p=460 GeV

Intercept: F_2

Slope: F_L

HERA PDF Fits at NNLO

QCD using NNLO PDF predicts different F_L shape



First HERA PDF Fits at NNLO:

lhapdf grids available https://www.desy.de/h1zeus/combined_results/

NNLO has impact on F_L at low Q^2

HQ Contribution to the Proton Structure

Can be determined experimentally: e.g. "charm structure function":

$$F_2^{cc} \propto \frac{Q^2 \times \alpha_s}{m_c^2} \int \frac{dx}{x} \times e_c^2 \, g(x_g, Q^2) \times C(\ldots)$$

- use and combine different charm tagging methods

  measure cross sections of charm and beauty production in DIS:

$$\sigma^{cc} \propto F_2^{cc}(x, Q^2) - \frac{y^2}{1+(1-y)} F_L^{cc}(x, Q^2)$$

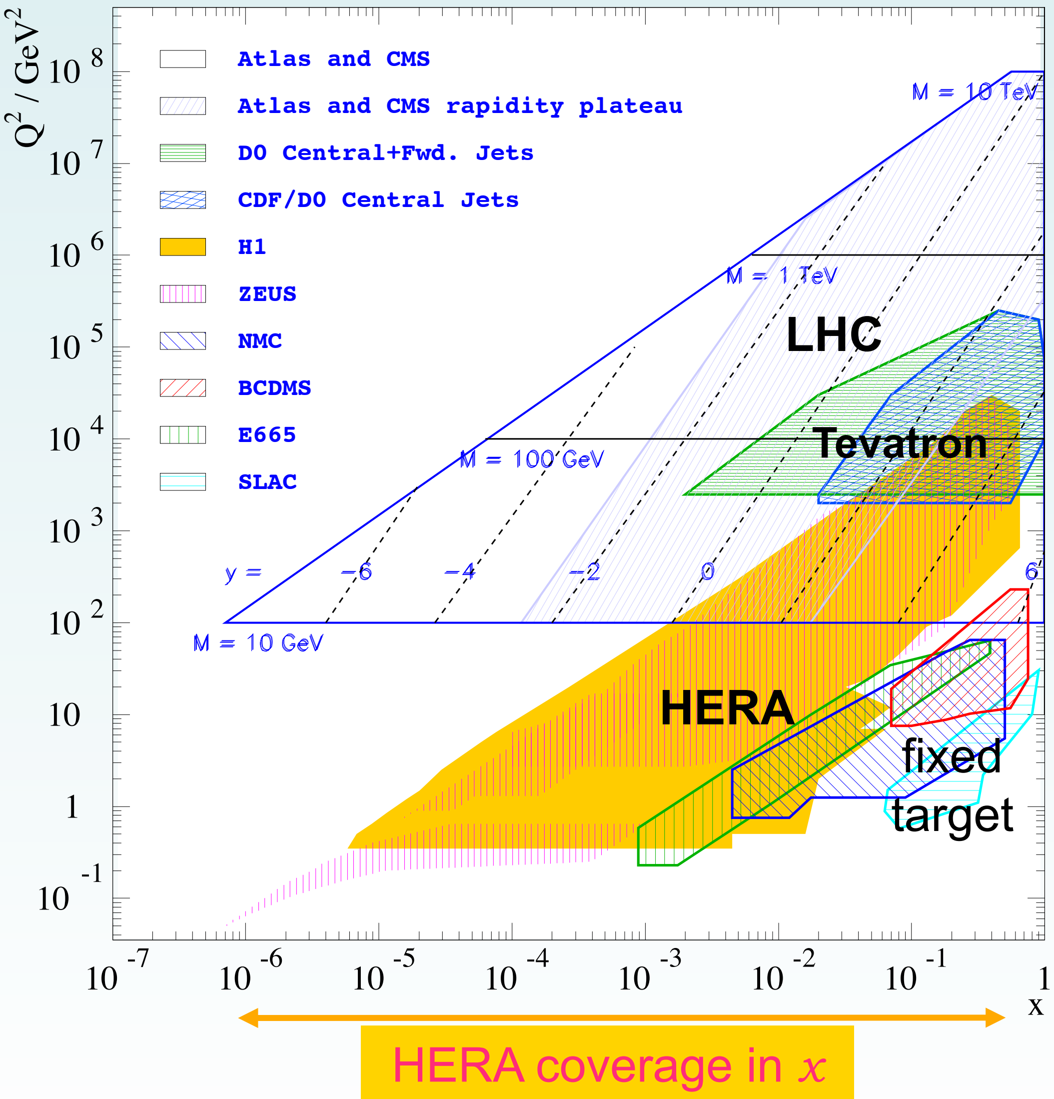
- Direct test of different schemes of HQ treatment in PDF fits

- Can be included in the full QCD analysis of DIS cross sections

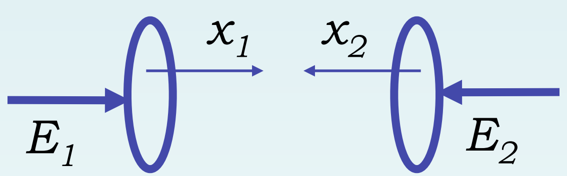
  additional constrain on the gluon density in the proton

  reduce parameterization uncertainty

PDFs From HERA to Tevatron and the LHC



Kinematics in pp collisions



Center-of-mass energy:

$$s = 4 \cdot E_1 \cdot E_2$$

2-parton interaction:

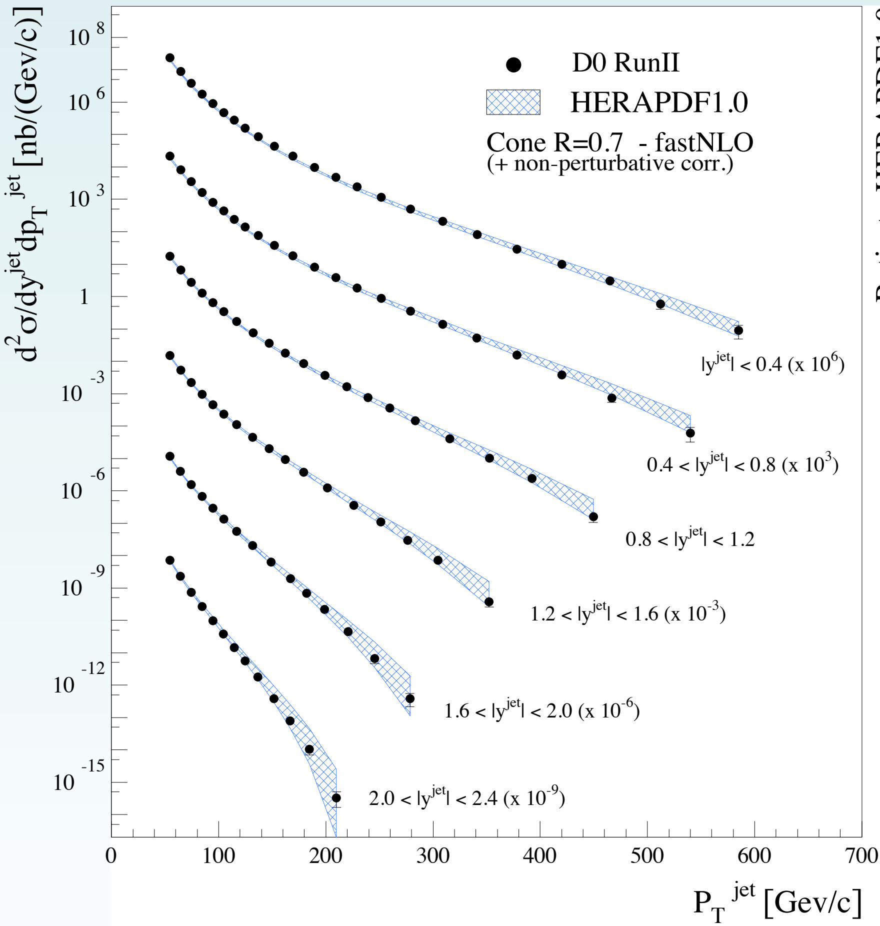
$$\hat{s} = x_1 \cdot x_2 \cdot s \geq M$$

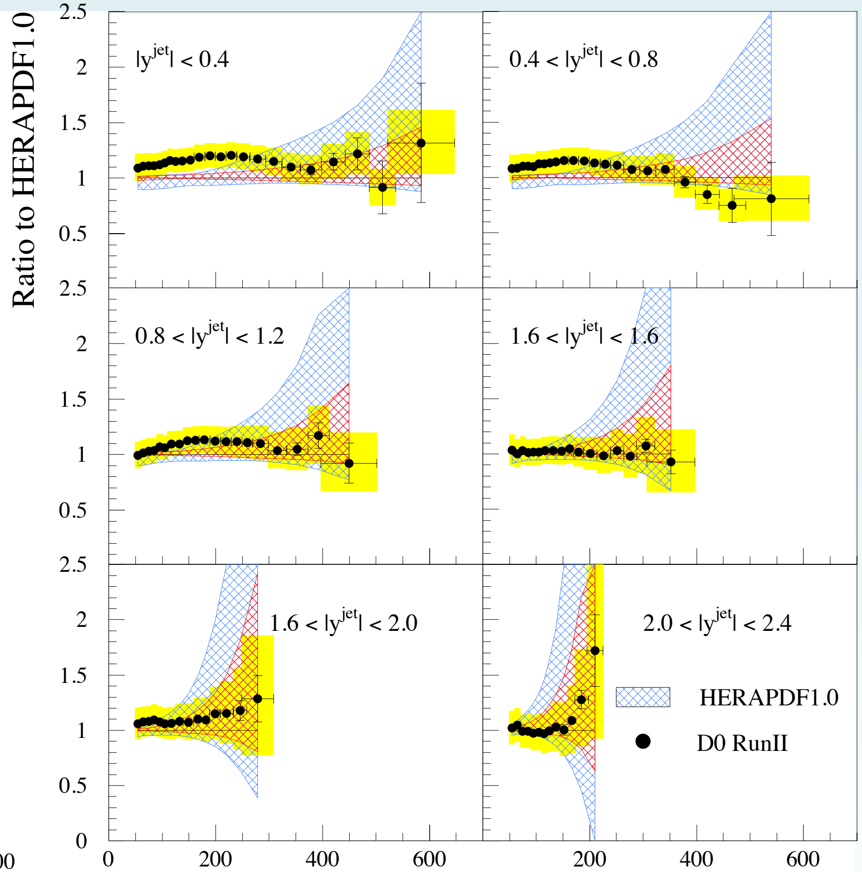
Energy scale $M = Q$

$$x_{1,2} = \frac{M}{\sqrt{s}} \cdot exp(\pm y)$$

rapidity

HERAPDF vs Jets at TEVATRON





only PDF uncertainties shown

Predictions based on HERAPDF in agreement with TEVATRON data