# Proton structure measurements and PDFs at HERA

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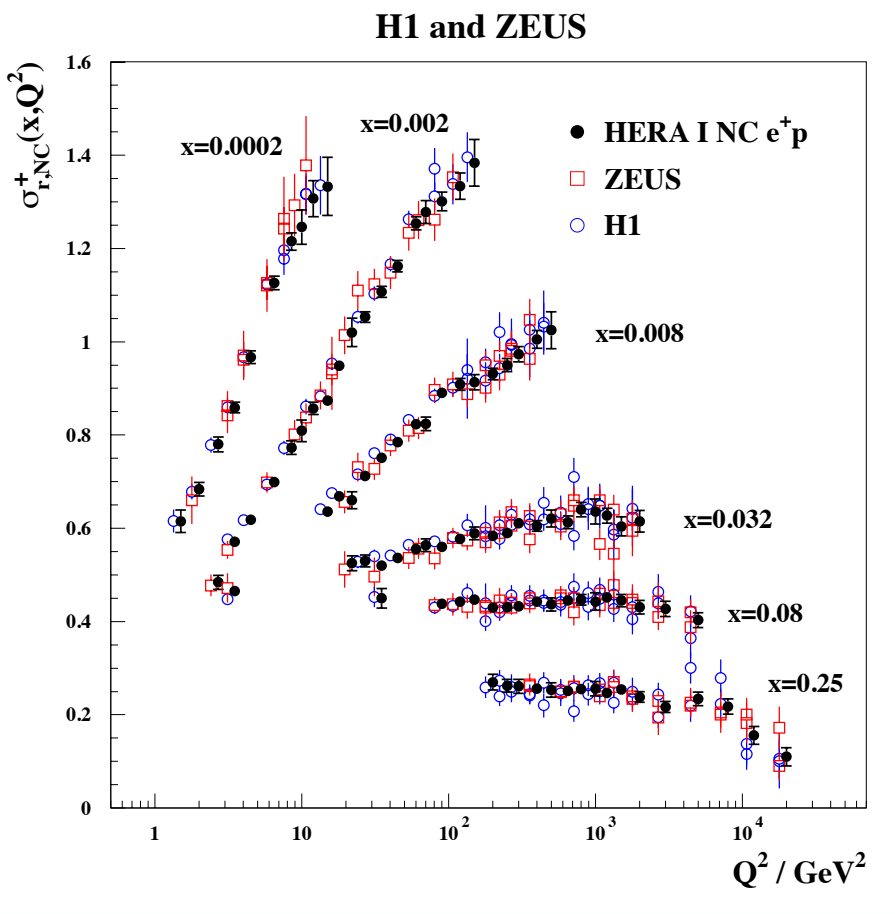
for H1 and ZEUS Collaborations

*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:

$$10^{-7}<x<0.65$$

$$0.05<Q^2<30000 \text{ GeV}^2$$

**Only HERA I, not ultimate precision**

# Determination of Parton Density Functions

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

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

determined using measured cross sections

calculable in pQCD

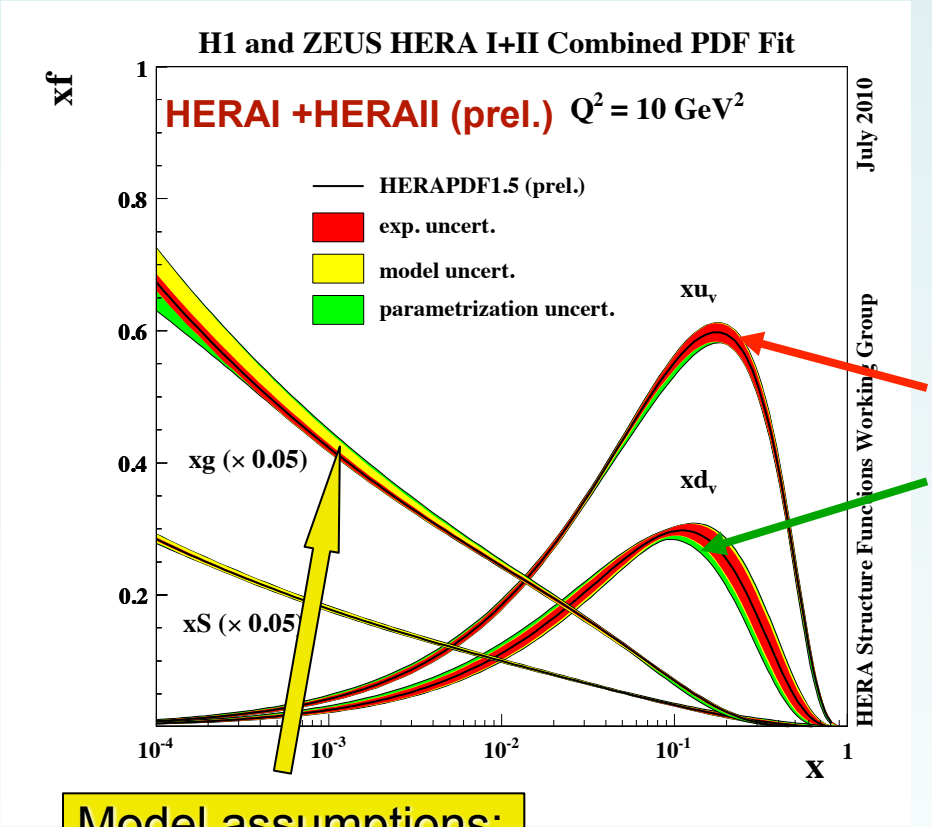
PDF

$x$-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
- $\chi^2$- fit to the experimental data

# HERA Parton Density Functions

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




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:

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

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

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

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

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

**Model assumptions:**

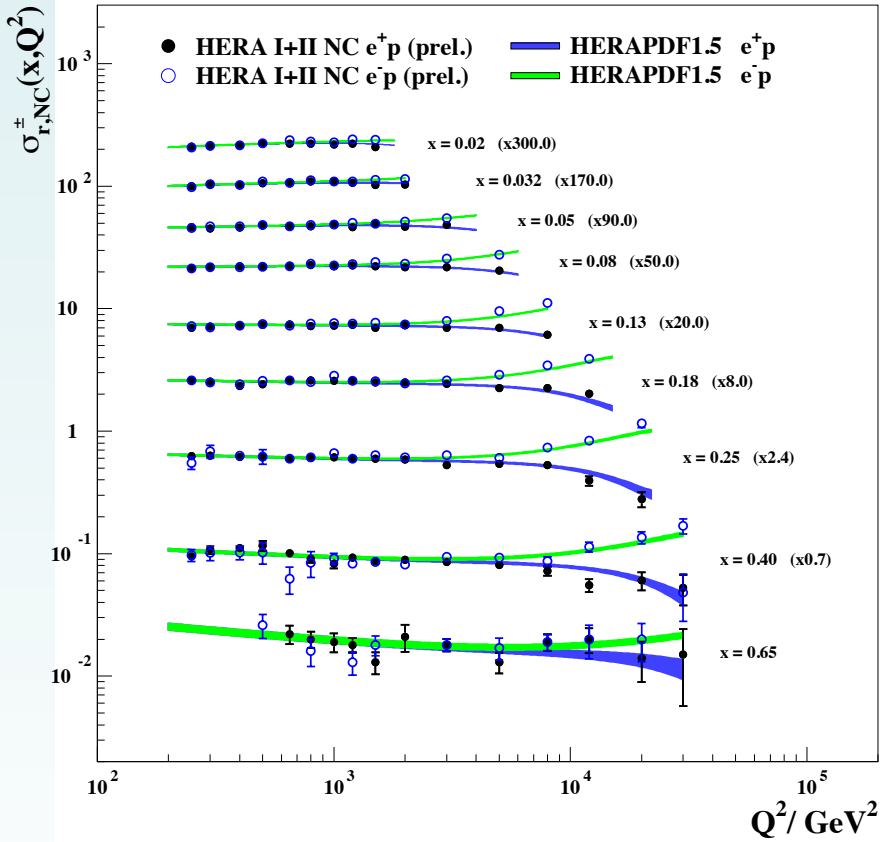
$Q_0^2 = 1.9\ GeV^2$, $\alpha_s(M_Z) = 0.1176$

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

# HERA DIS Cross Sections vs HERAPDF

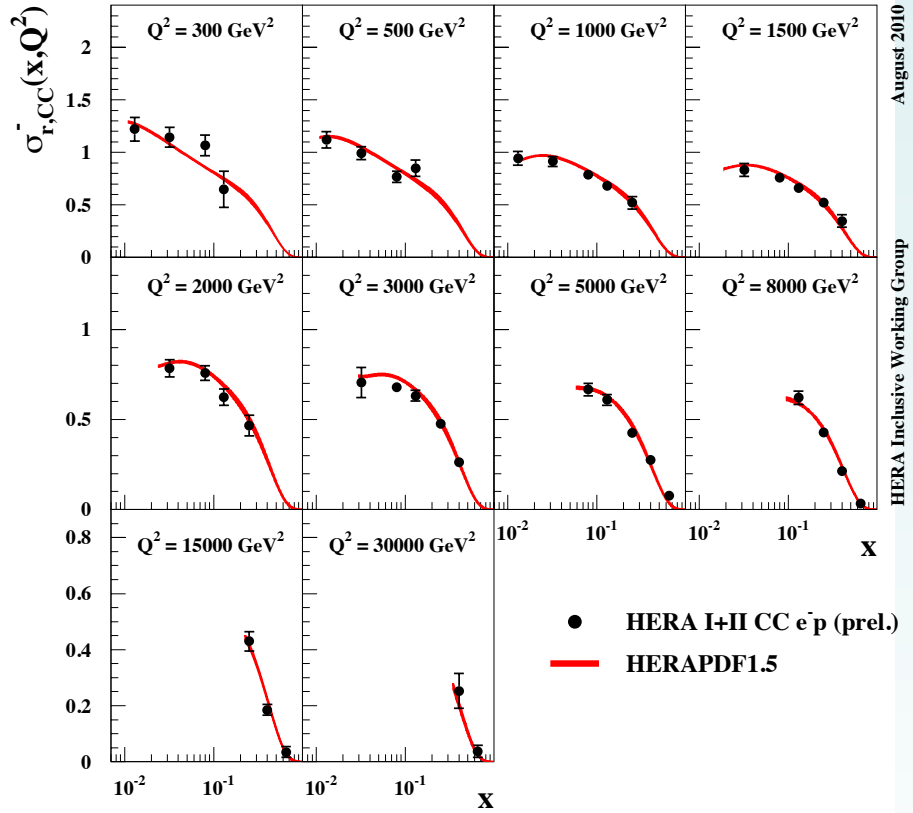
Neutral Current

H1 and ZEUS




Charged Current

H1 and ZEUS

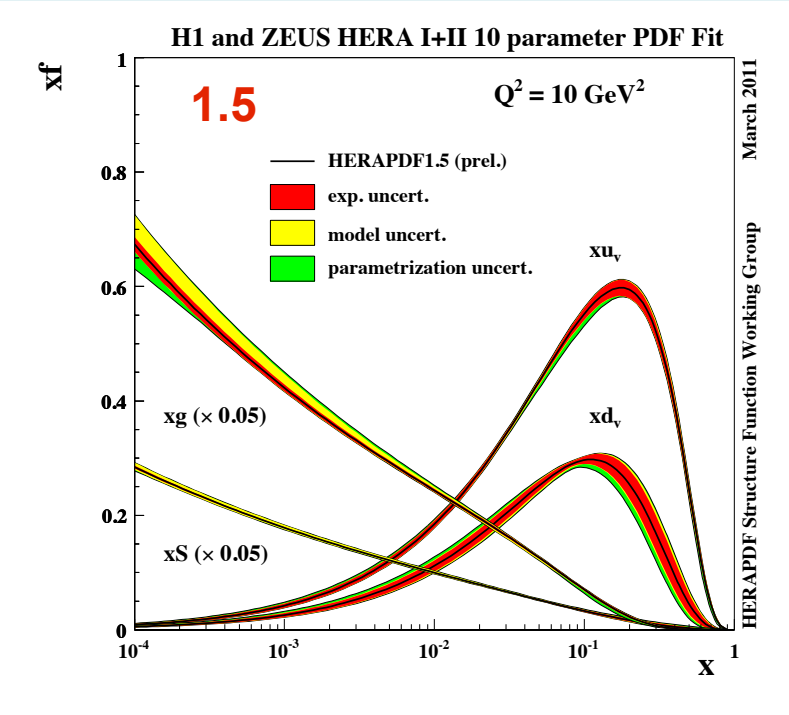


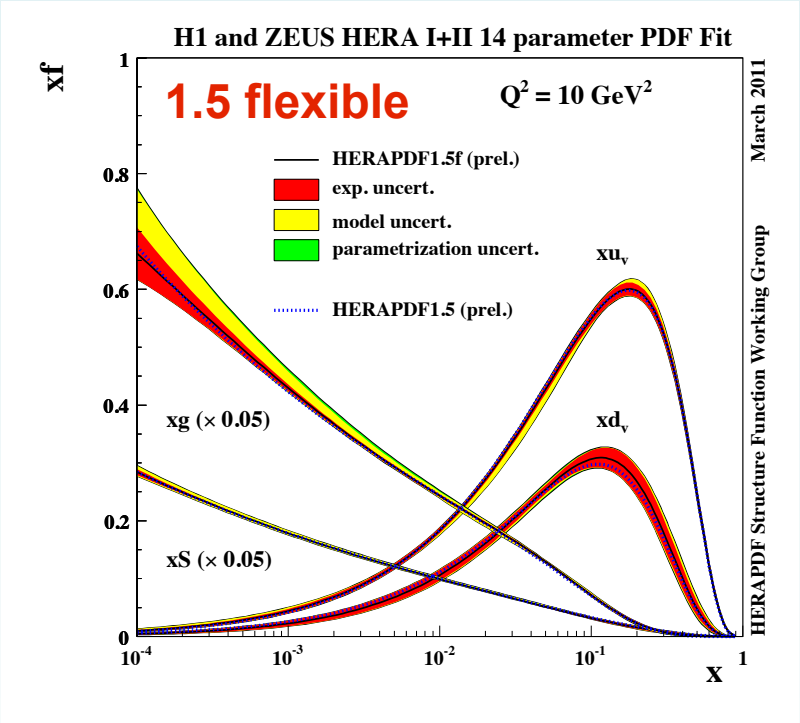

Improved precision at high $Q^2$ and high $x$

QCD using HERAPDF describes HERA NC and CC data very well

# HERAPDF: Fit Improvements

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



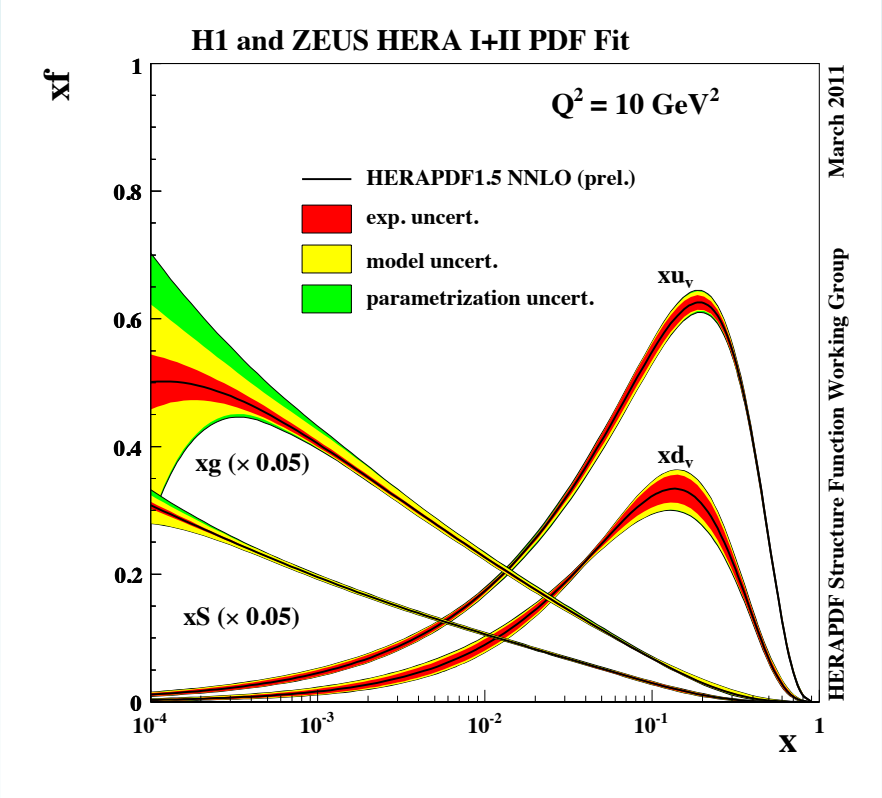

Small difference in total uncertainty

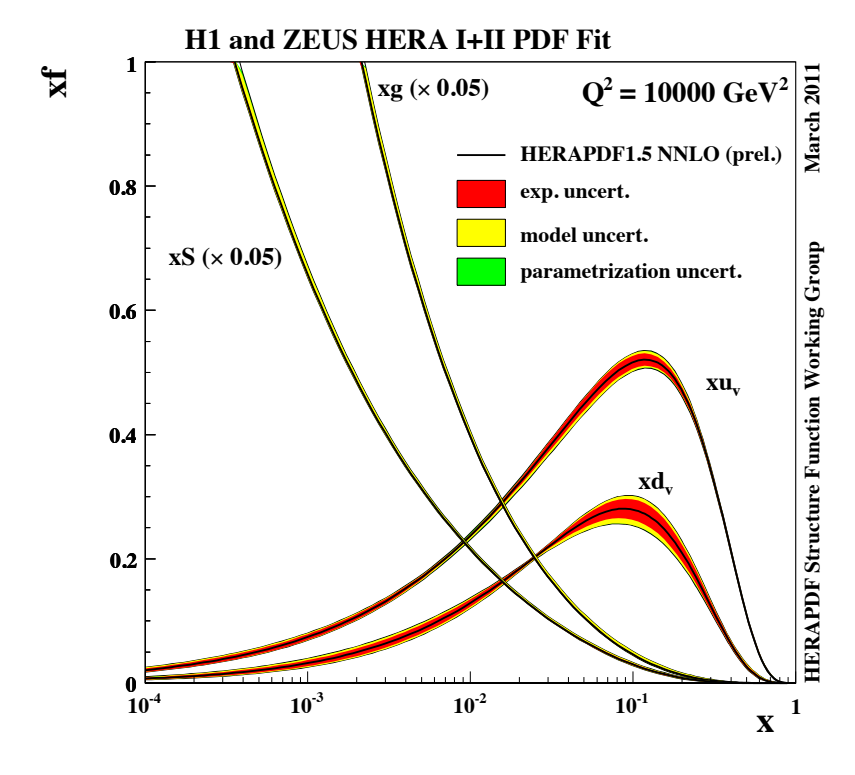
→ swap between **parametrisation** and **experimental** uncertainties

# HERAPDF NNLO

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

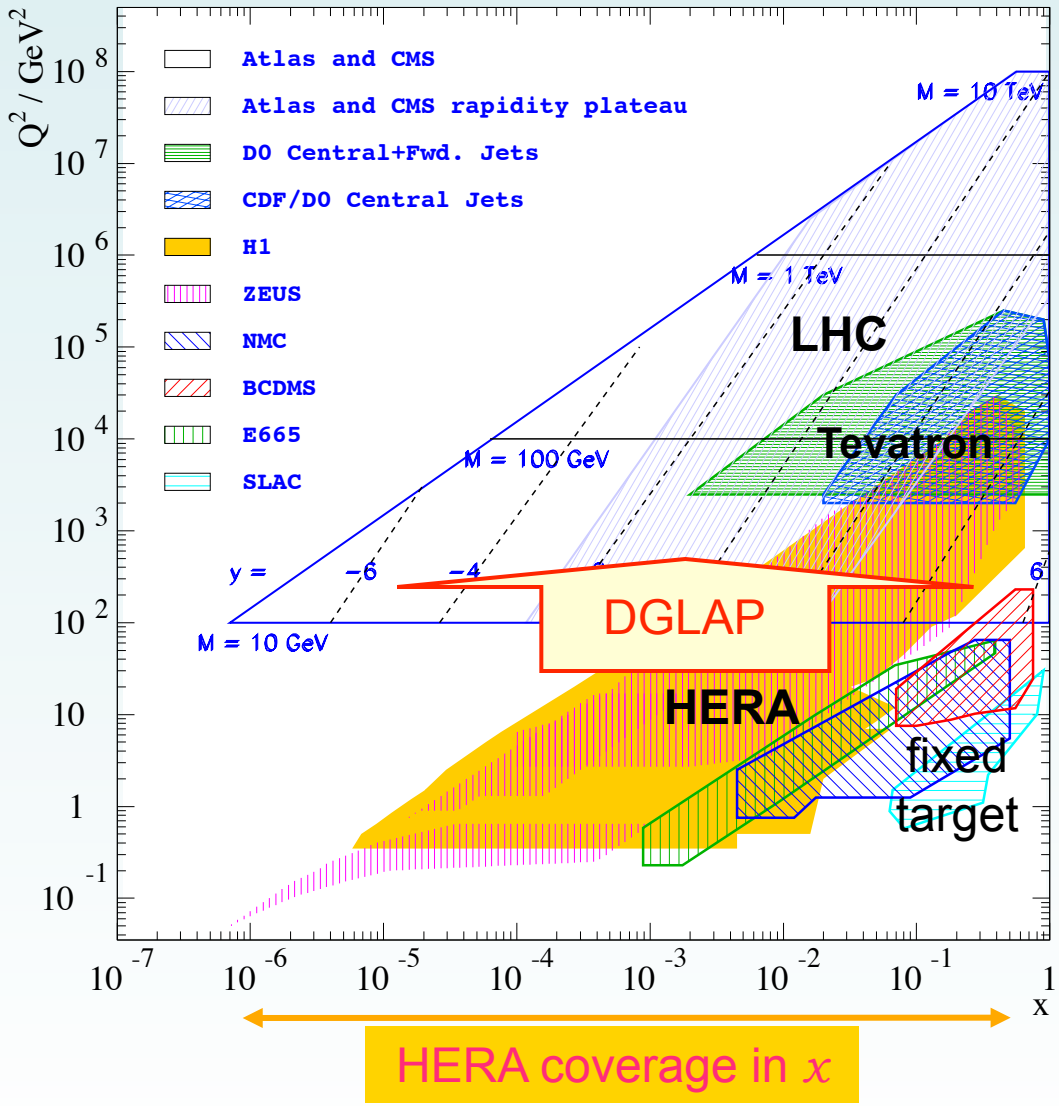
uses more flexible parametrisation




HERA PDF15NLO and NNLO recommended to be used for predictions

# PDFs From HERA to Tevatron and the LHC




HERA coverage in $x$

PDFs obtained from data of fixed target, HERA, Tevatron

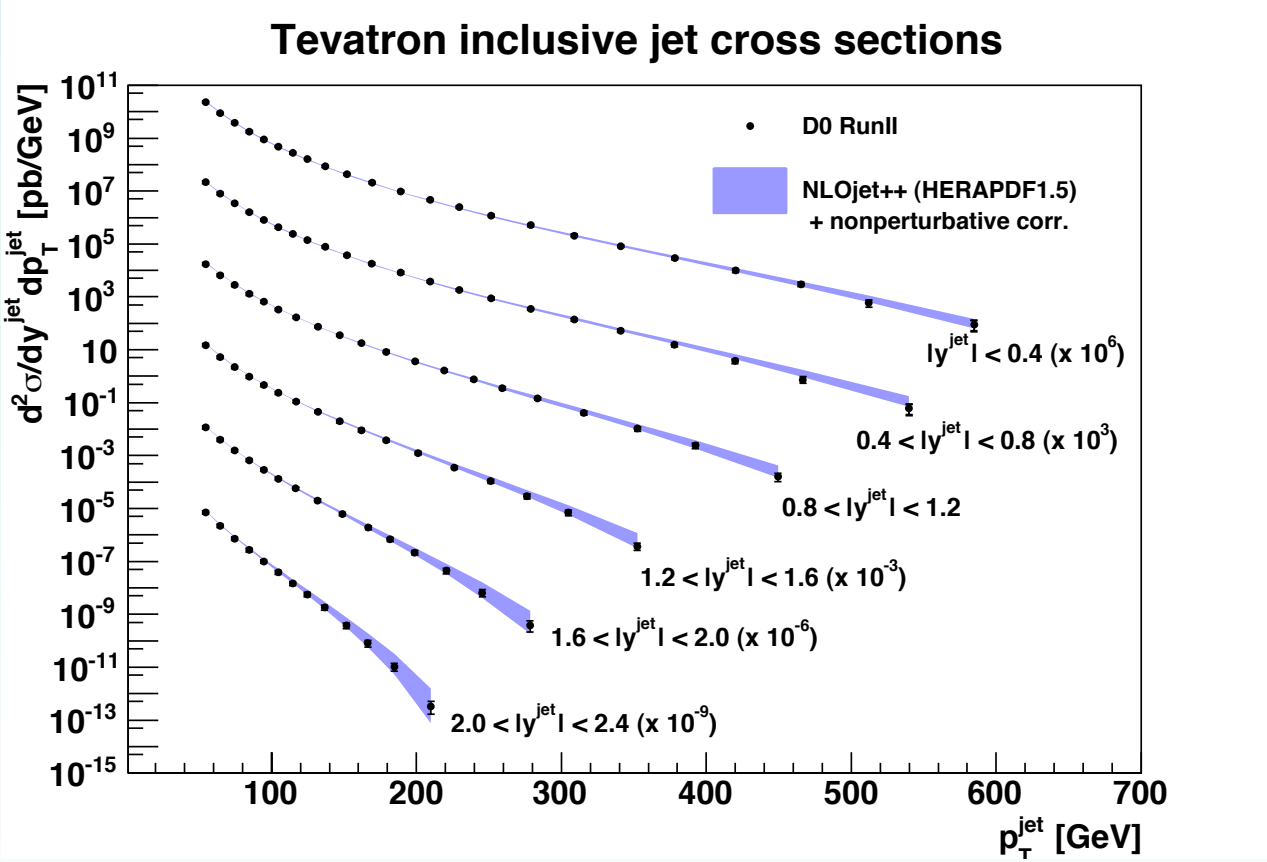
**HERA measurements:**

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

From HERA to kinematics of Tevatron, LHC:

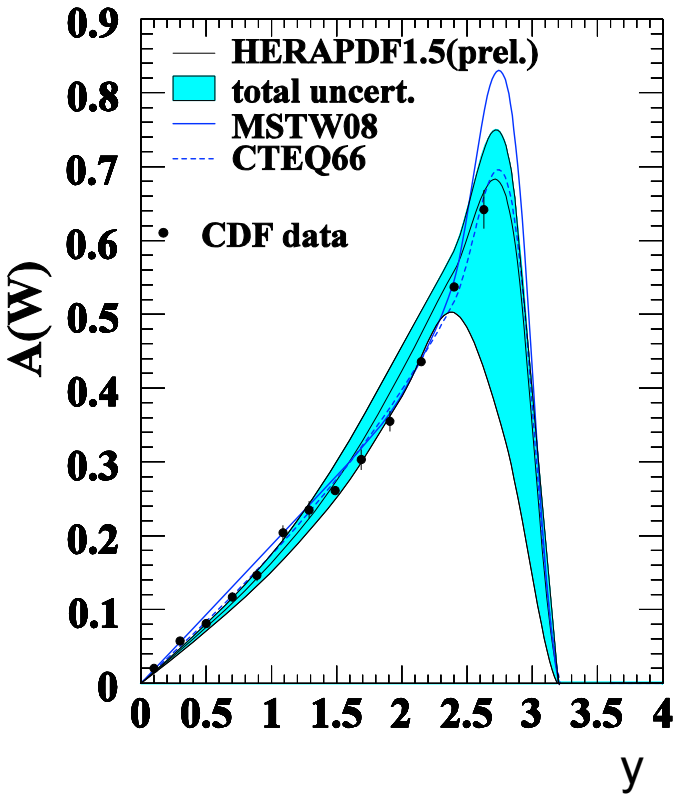
evolution in $Q^2$ via DGLAP

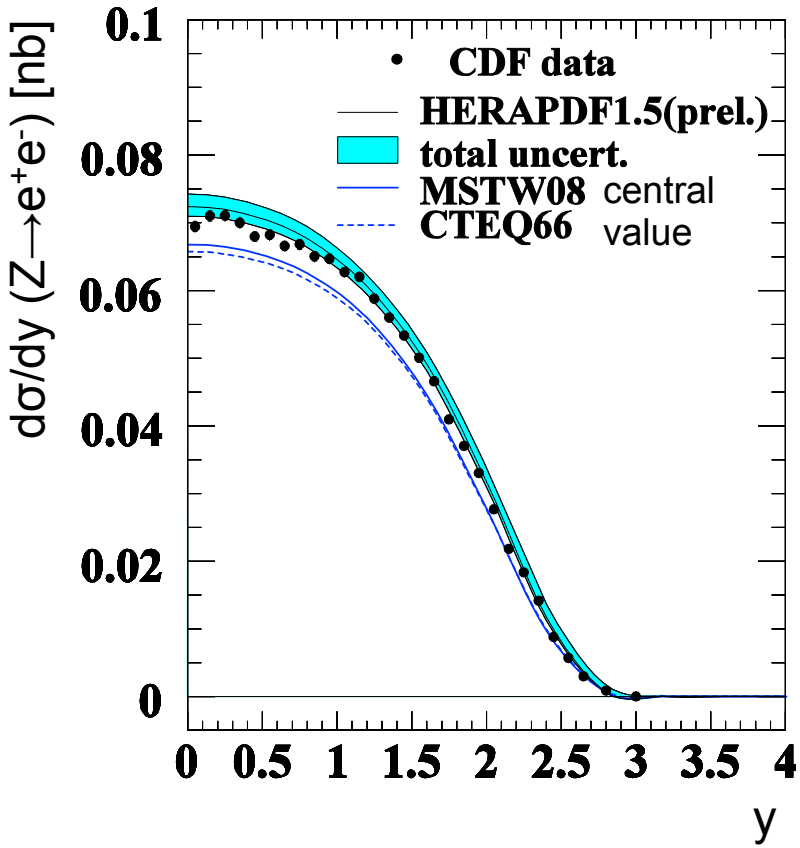
# HERAPDF and Jets at Tevatron




Prediction based on HERAPDF in agreement with Tevatron

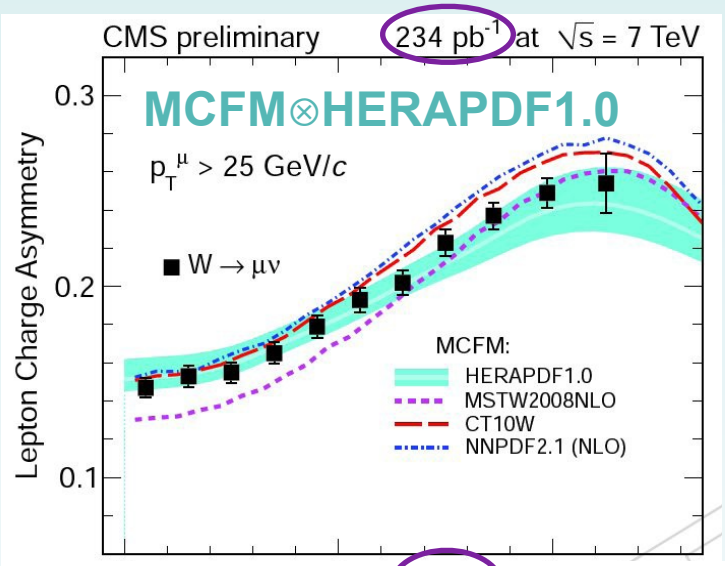
# W and Z Production at Tevatron

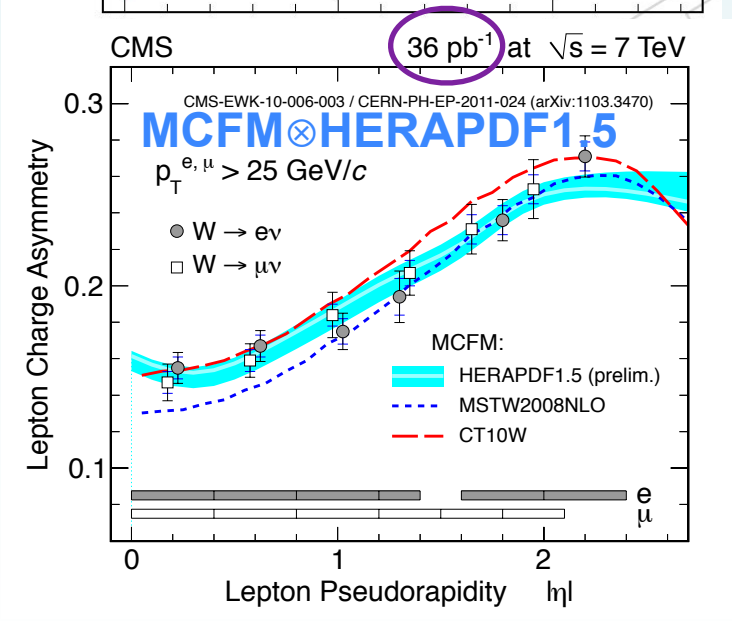



Prediction based on HERAPDF agrees very well with Tevatron data

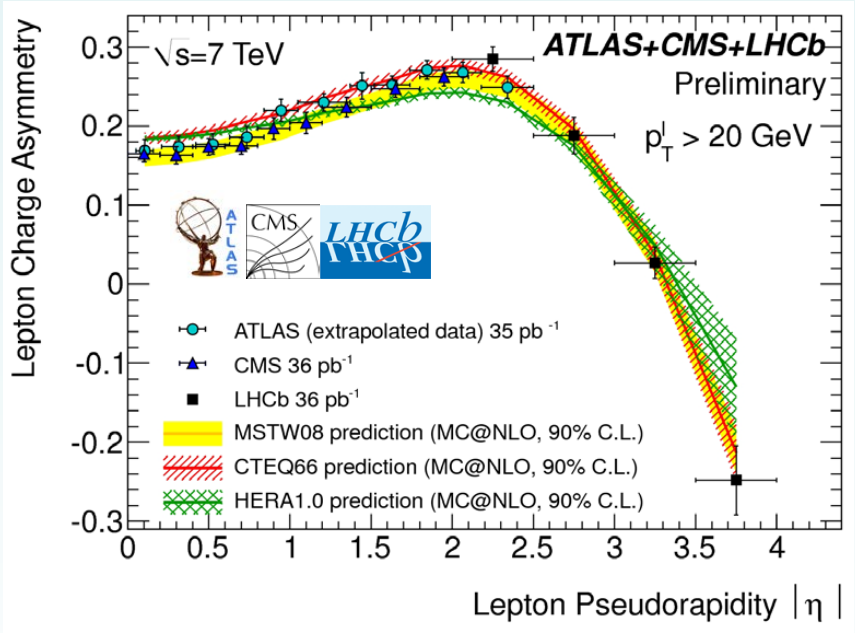
# HERAPDF and the LHC measurements




W lepton asymmetry is sensitive to differences between u and d

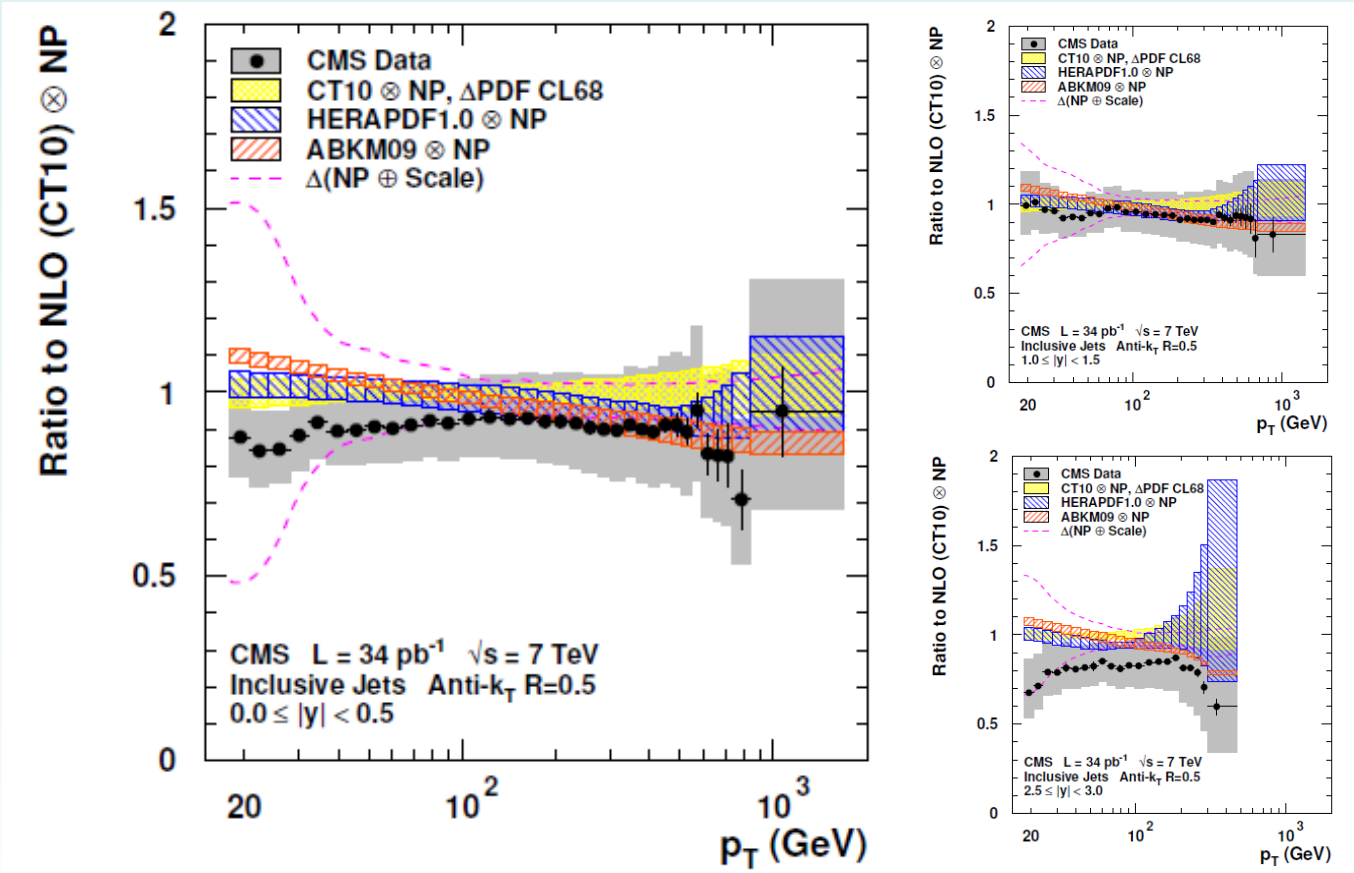
$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$




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

# HERAPDF and the LHC measurements

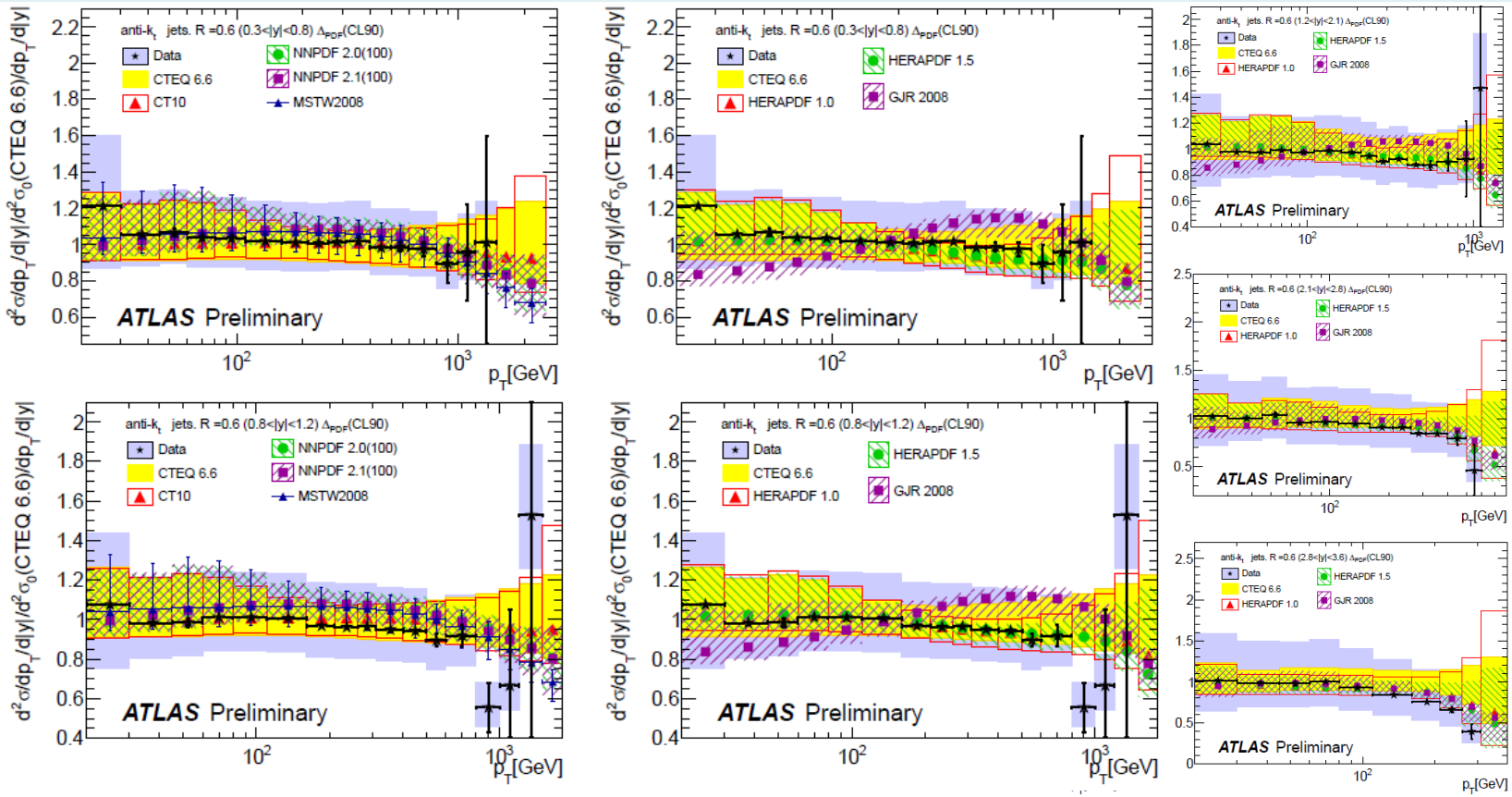
Jet production at CMS (CERN-CMS-NOTE-2011-004)




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

# HERAPDF and the LHC measurements

Jet production at ATLAS



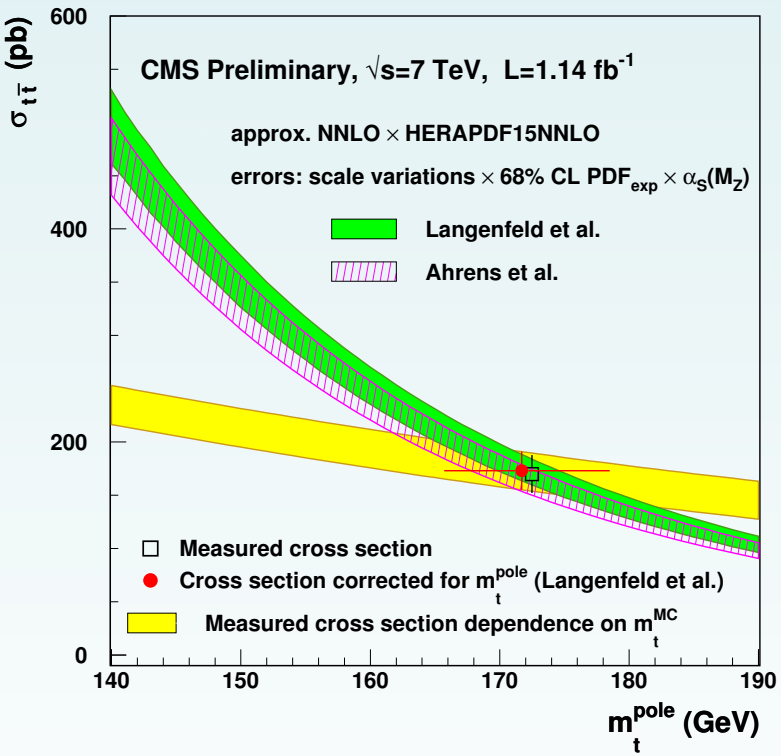

ATL-PHYS-PUB-2011-005

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

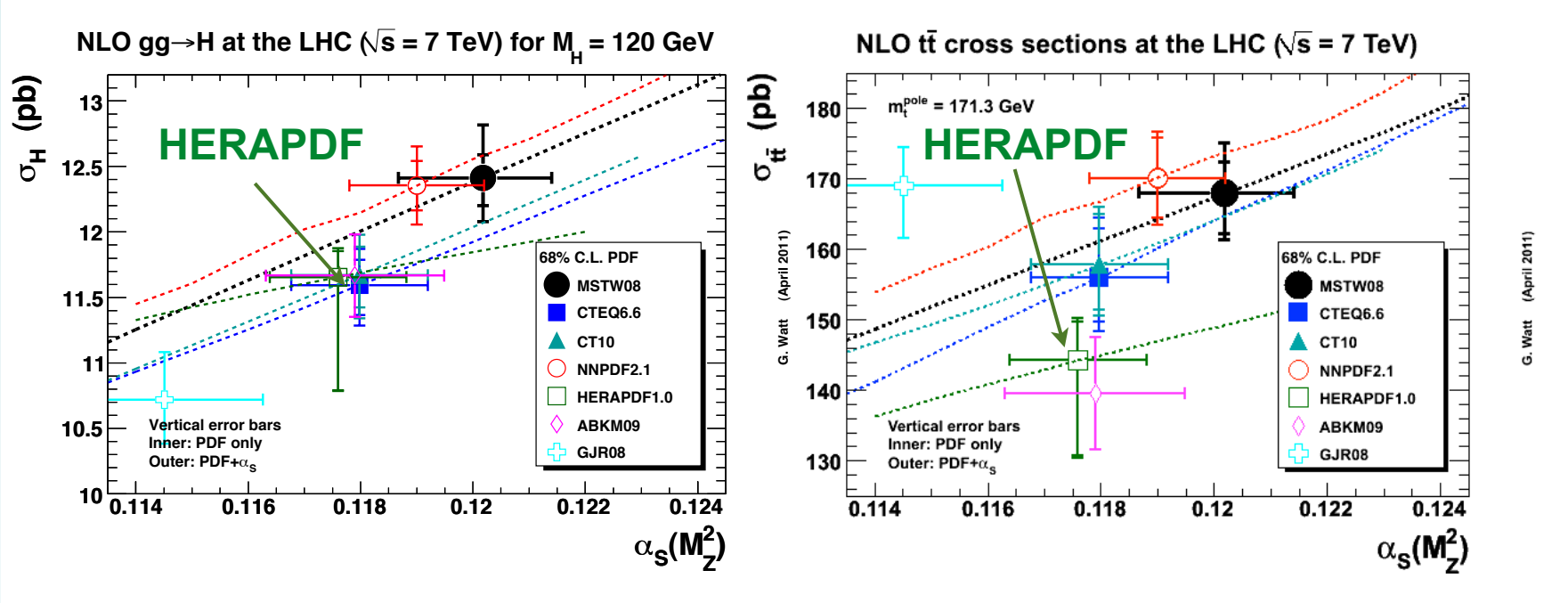
CMS-TOP-11-008




only experimental PDF error used

very good agreement with mstw08nnlo (within $\alpha_S$ 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 $\alpha_S$ and running of strong coupling
- different treatment of heavy quarks

# Learn more about $\alpha_s$: PDF fits using HERA Jet Data

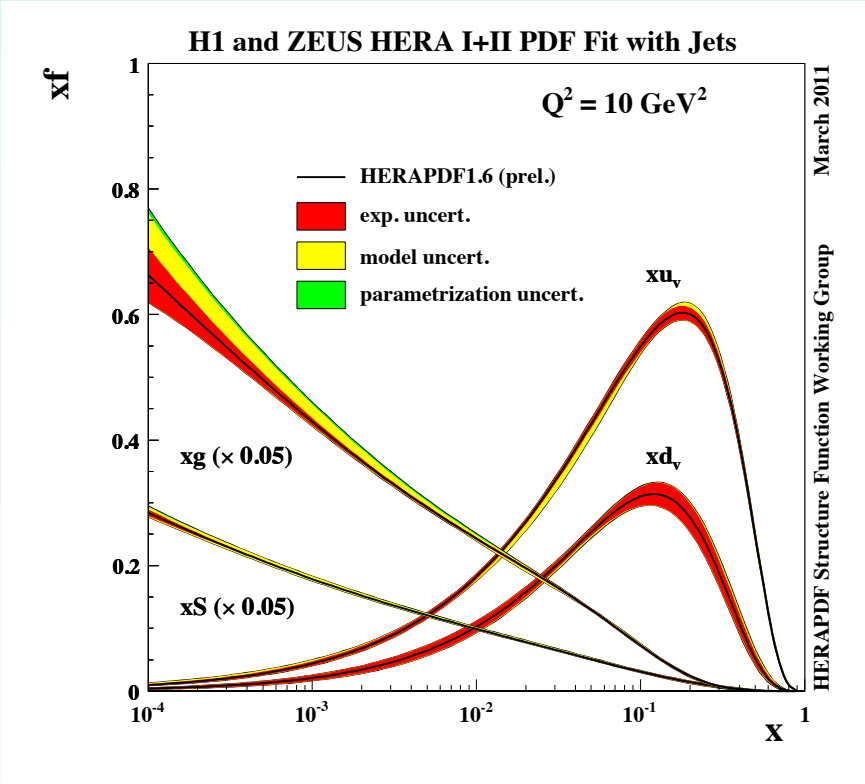
**Inclusive DIS data:**
combined H1+ZEUS HERAI+HERAII

**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)

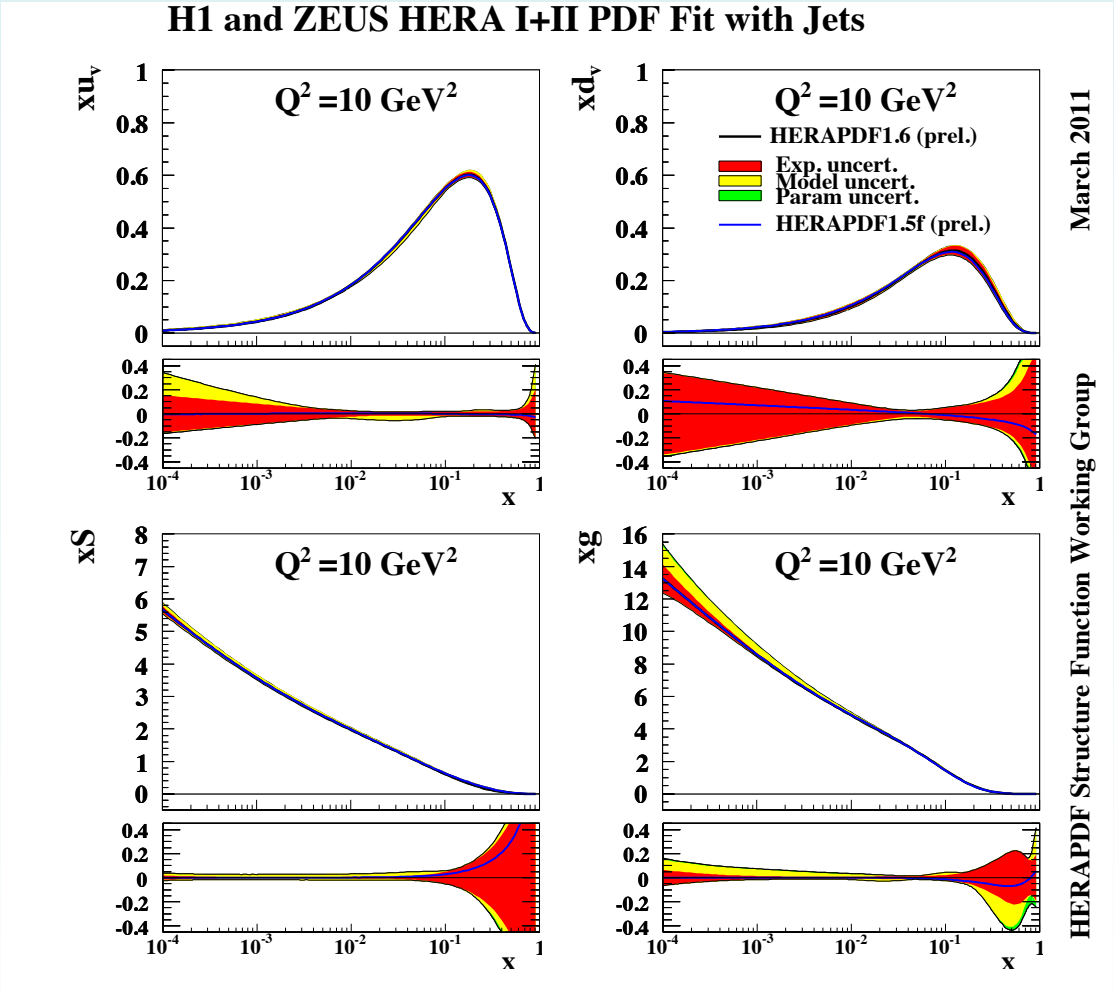
➡ HERA results on Jets: talk by R. Kogler

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



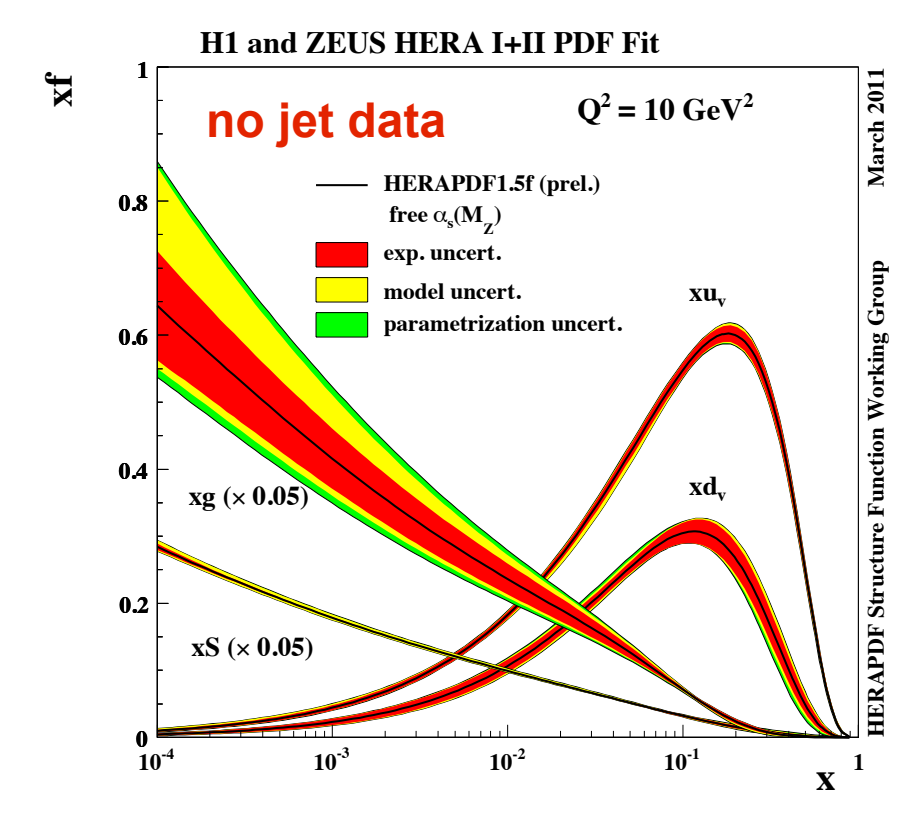

PDFs very similar to HERAPDF15f, no significant reduction of uncertainty

# PDF fits using HERA Jet Data: Fixed $\alpha_s$




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

# PDF Fits with free $\alpha_s$ (Mz)



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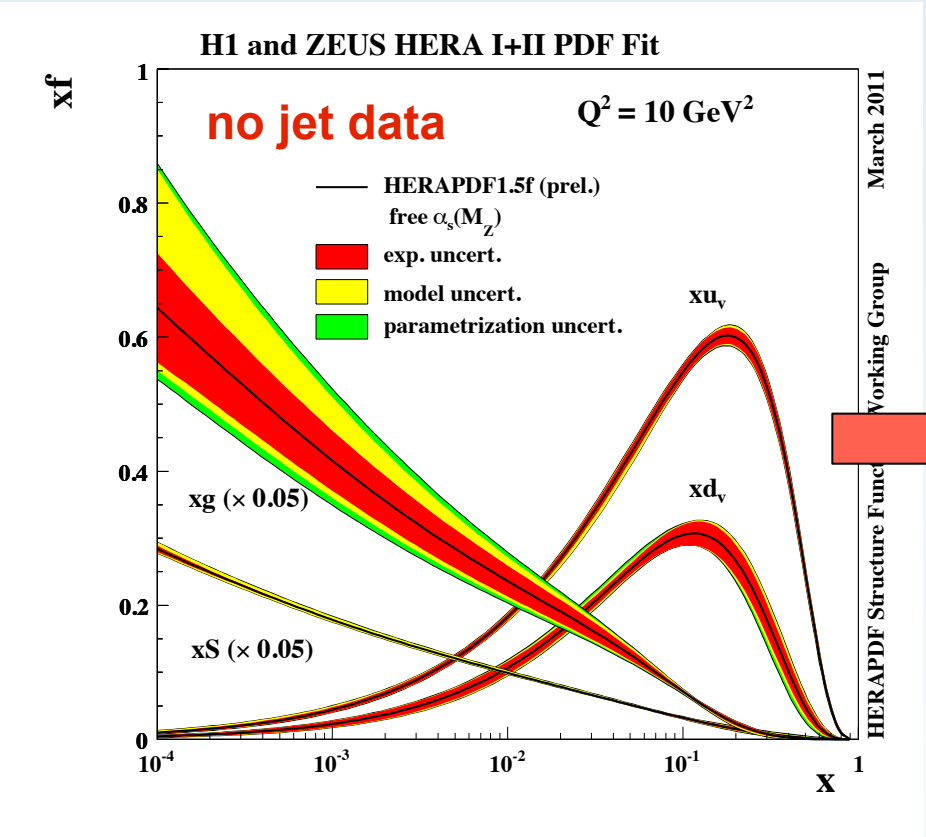
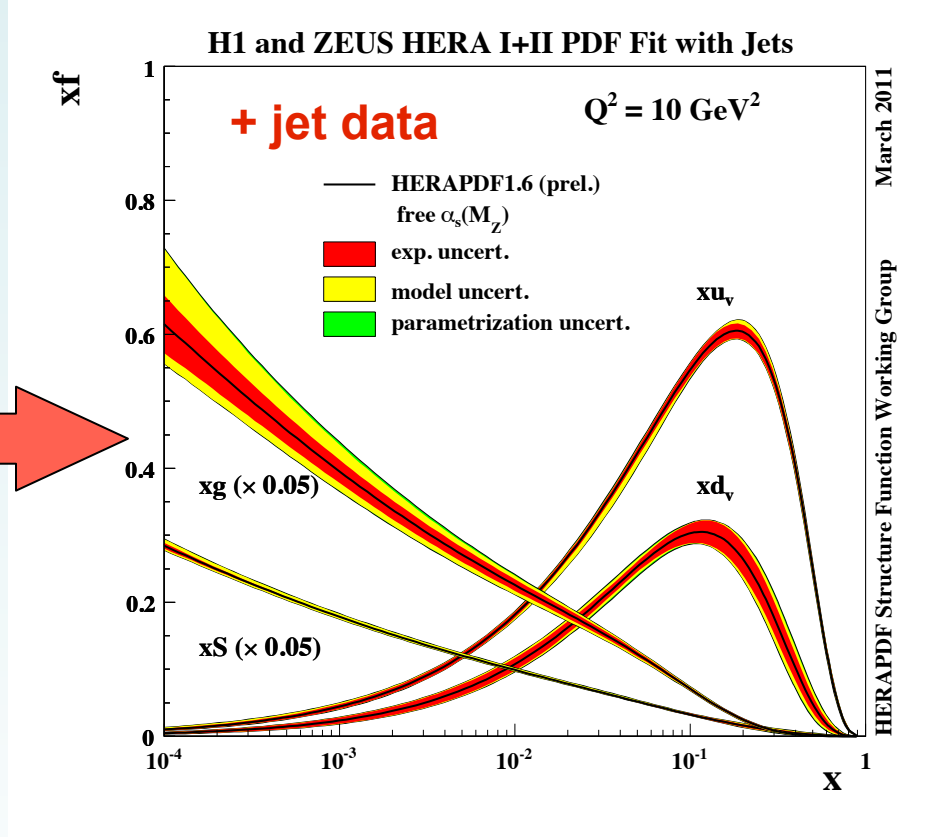
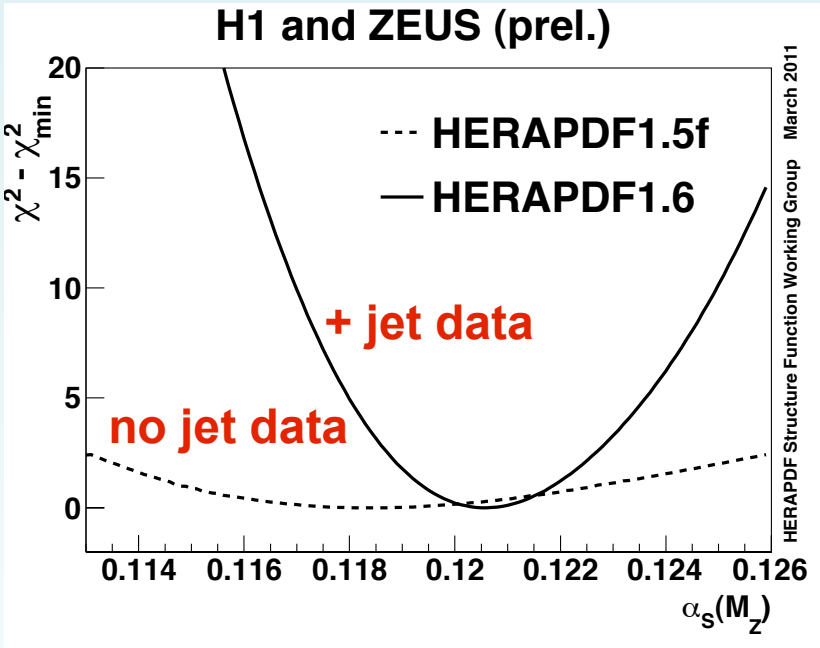


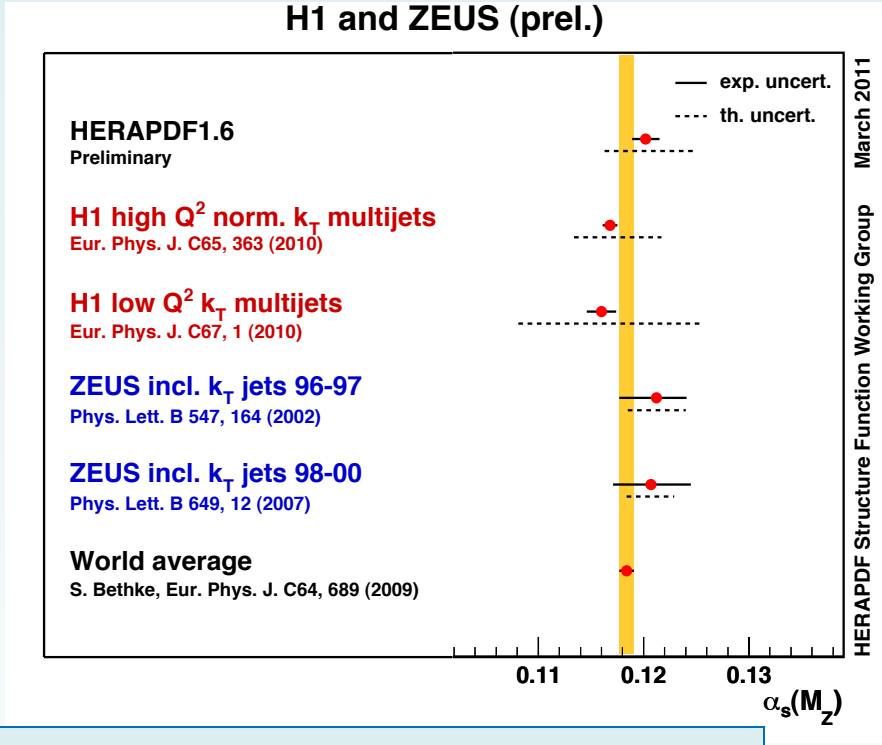




Inclusion of jet data into the PDF fit **decouples** the gluon and $\alpha_s$ (Mz)

# PDF fits using HERA Jet Data: determine $\alpha_s$ (Mz)

Scan of the $\alpha_s$ (Mz) in the PDF fit




PDF and $\alpha_s$ (Mz) determined in the common fit:

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

From including the Jet data in the PDF fit we do learn about $\alpha_s$ (Mz)

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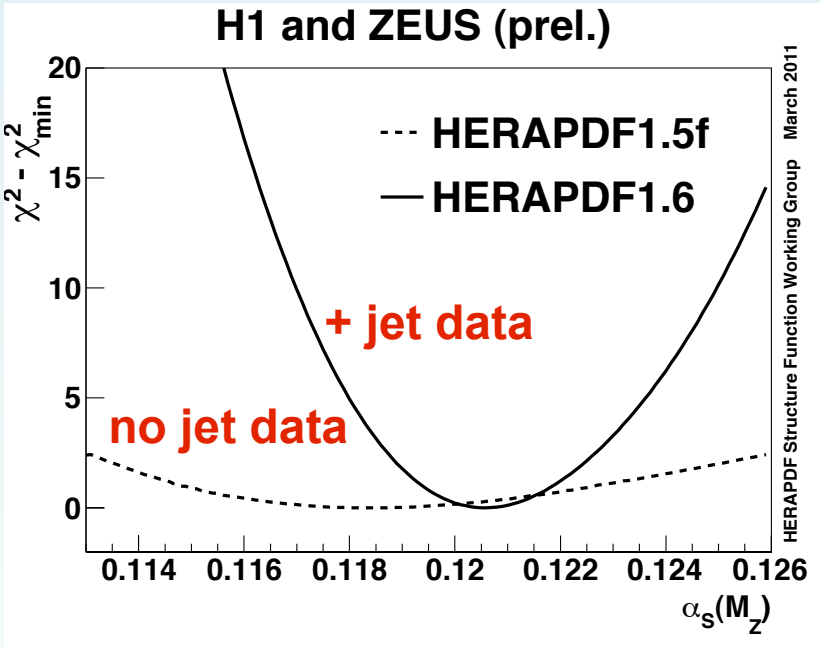


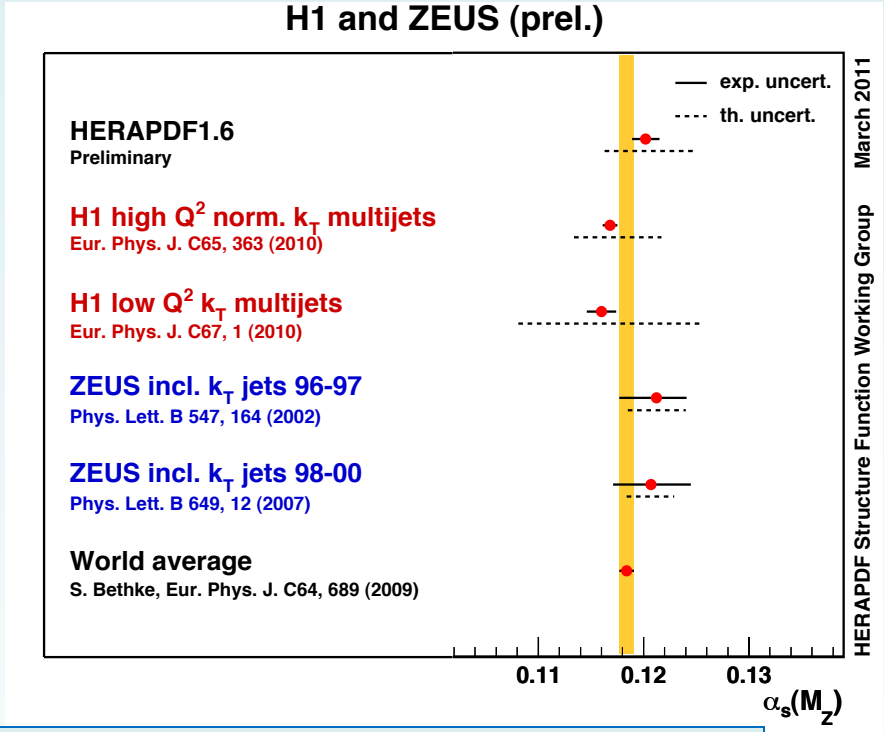


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**What do we learn from heavy flavour production?**

# Heavy Quarks and PDF Fits

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

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

- Generalized Mass VFNS: different implementations provided by PDF groups

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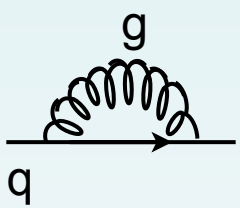
QCD analysis of the proton structure: treatment of heavy quarks essential

# Heavy Quark Mass Definition in PDFs

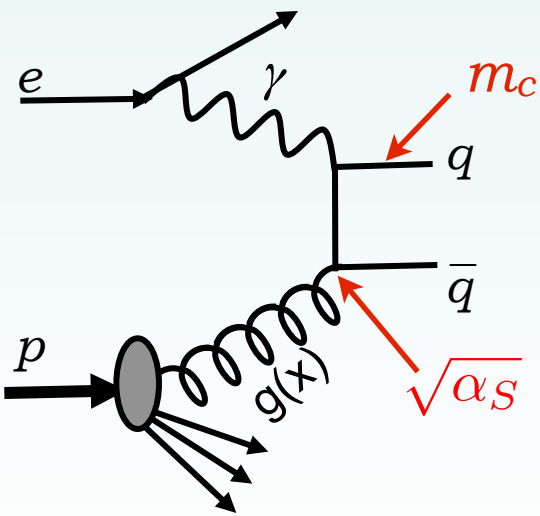
Usually HQ coefficient functions use a pole mass definition

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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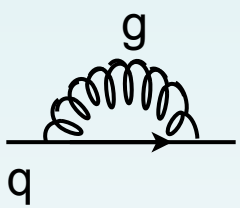


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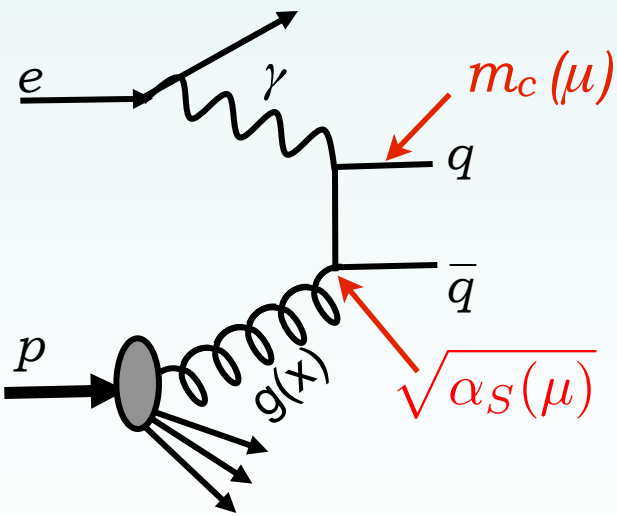



running coupling

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

# 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

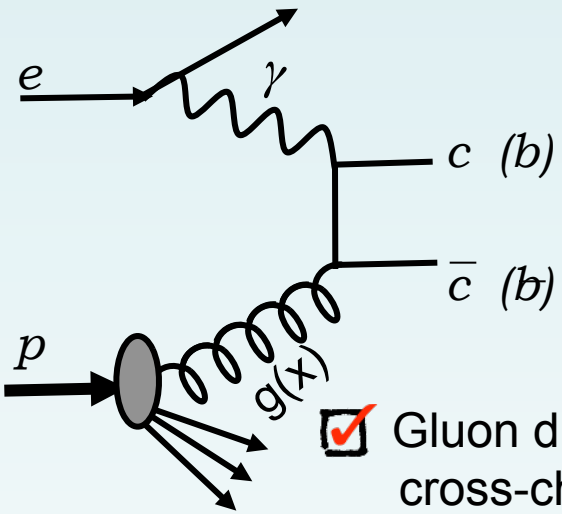
Values of $m_c$ as used by most PDF groups too low wrt. PDG

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

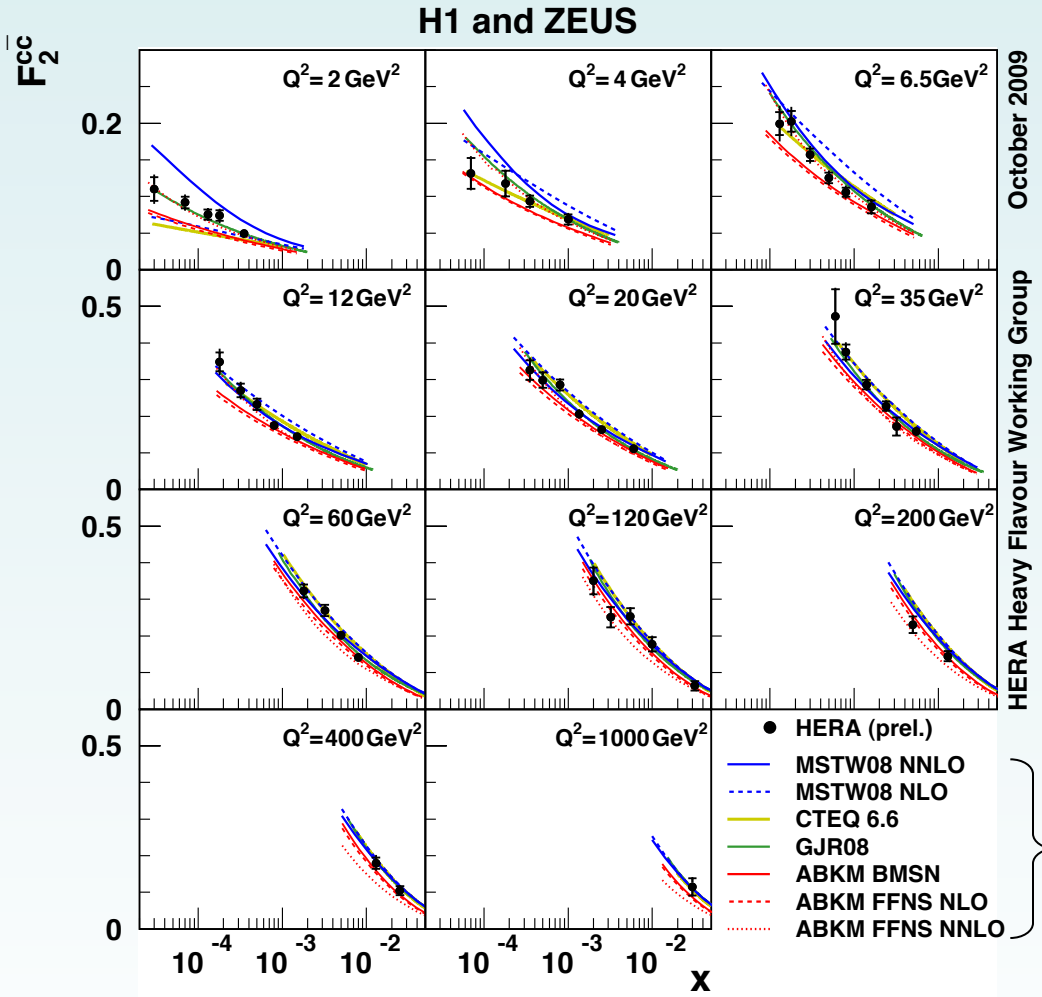
➡ HERA results on charm and beauty: talk by O. Behnke

☑ 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

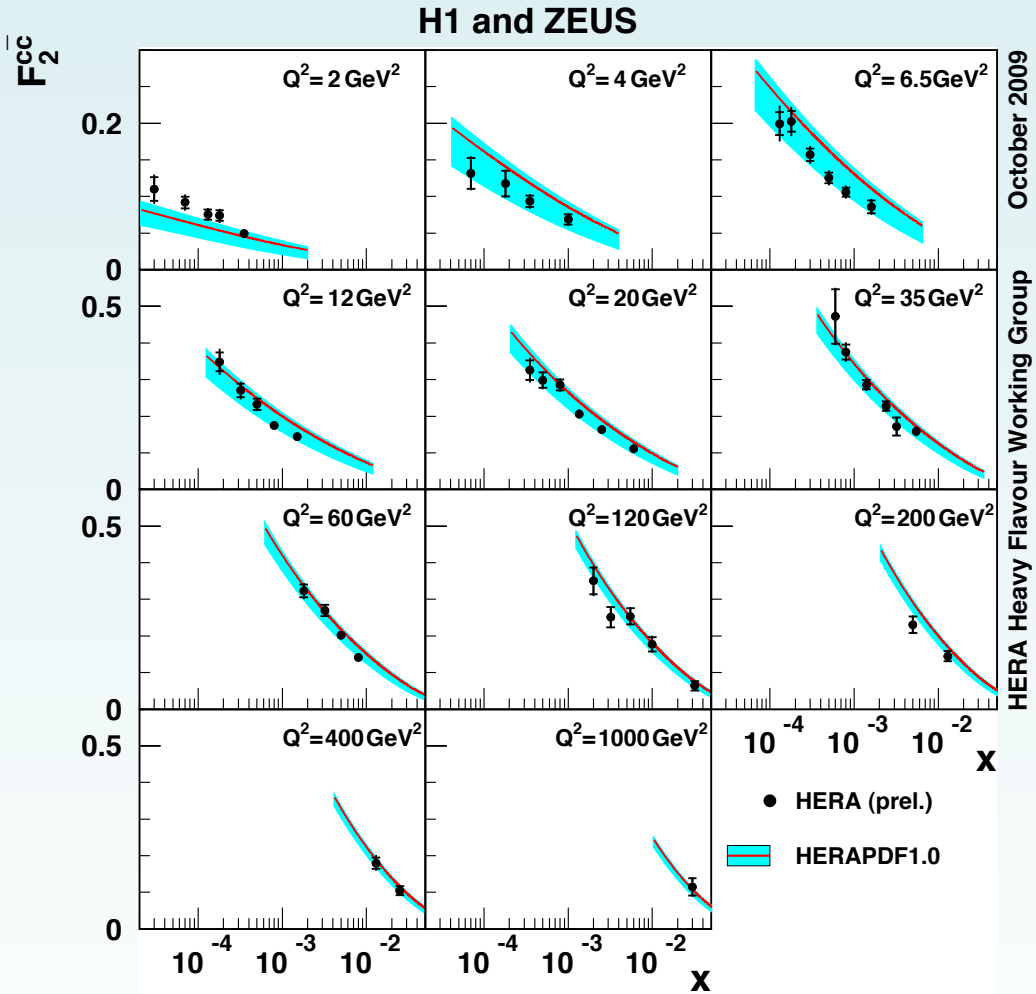
correlations accounted for

Precision 5 - 10%

Different HQ schemes

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

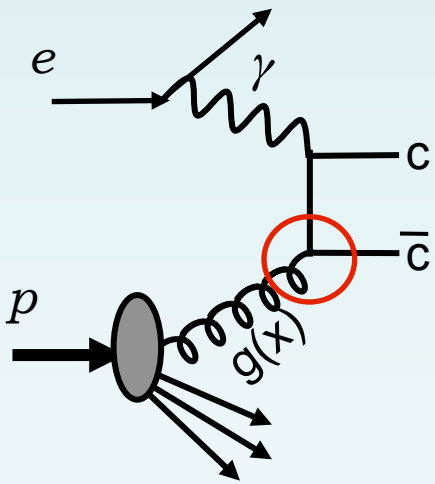
$m_c$=1.35 vs 1.65 GeV

PDG pole mass

PDFs obtained from inclusive data sensitive to the choice of $m_c$

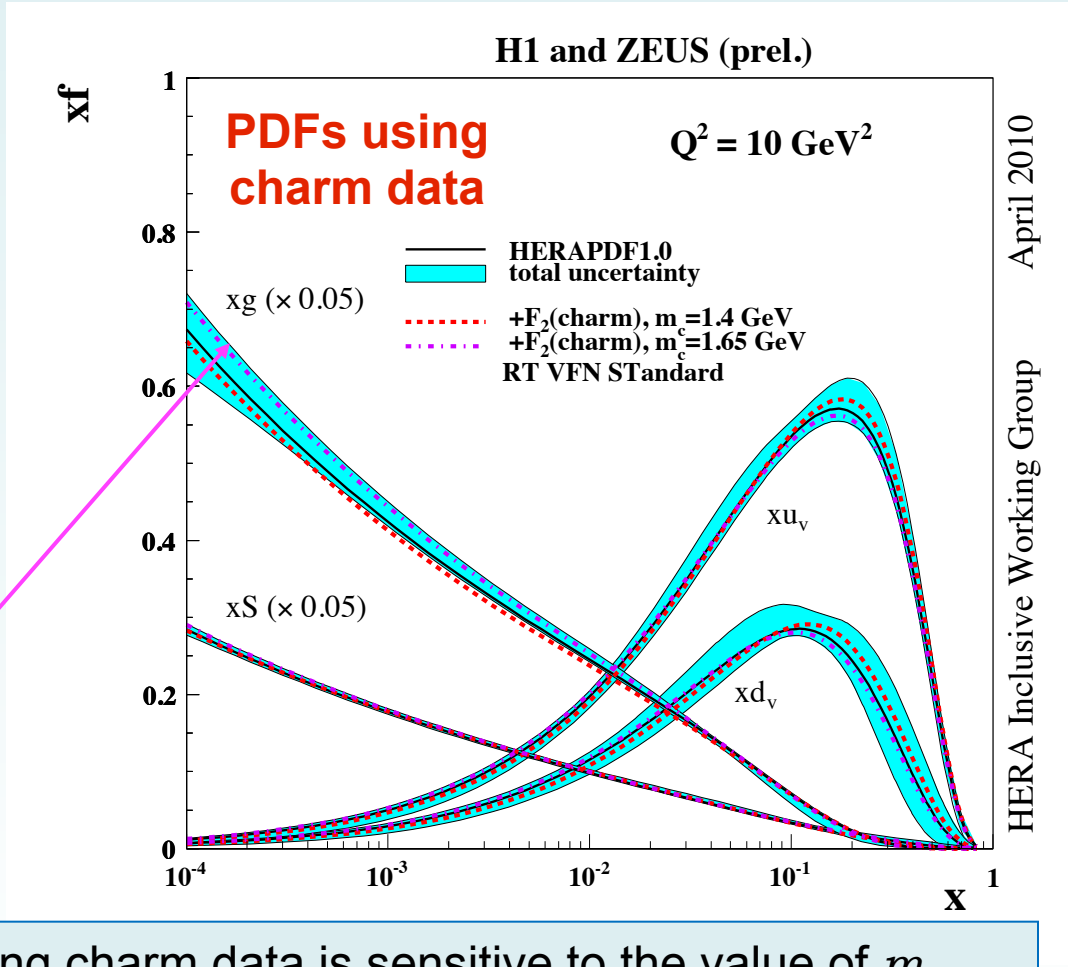
# Charm Data in the PDF Fit

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

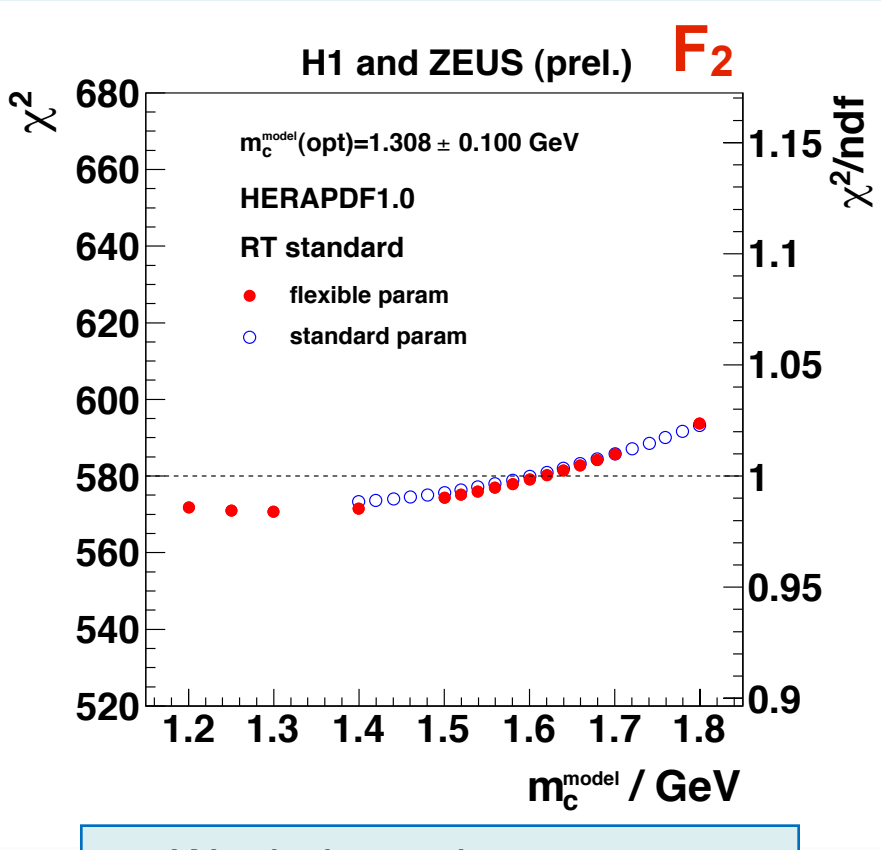



PDFs and PDF fit using charm data is sensitive to the value of $m_c$

# 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

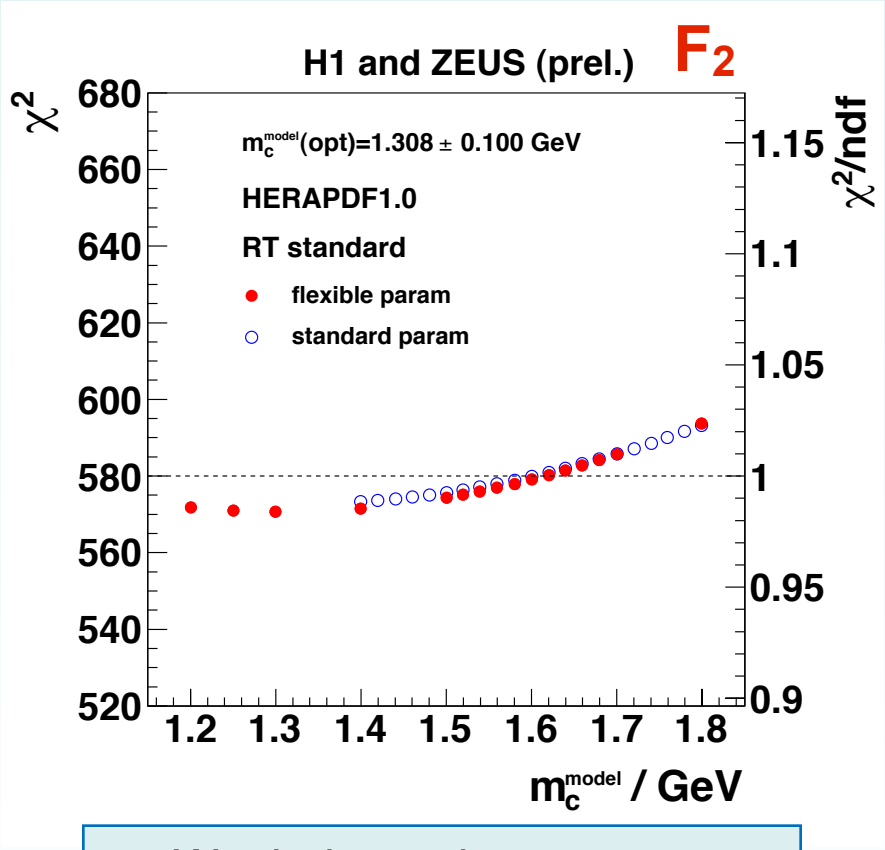



Weak dependence on $m_c$

# Charm Mass as a Model Parameter in PDF

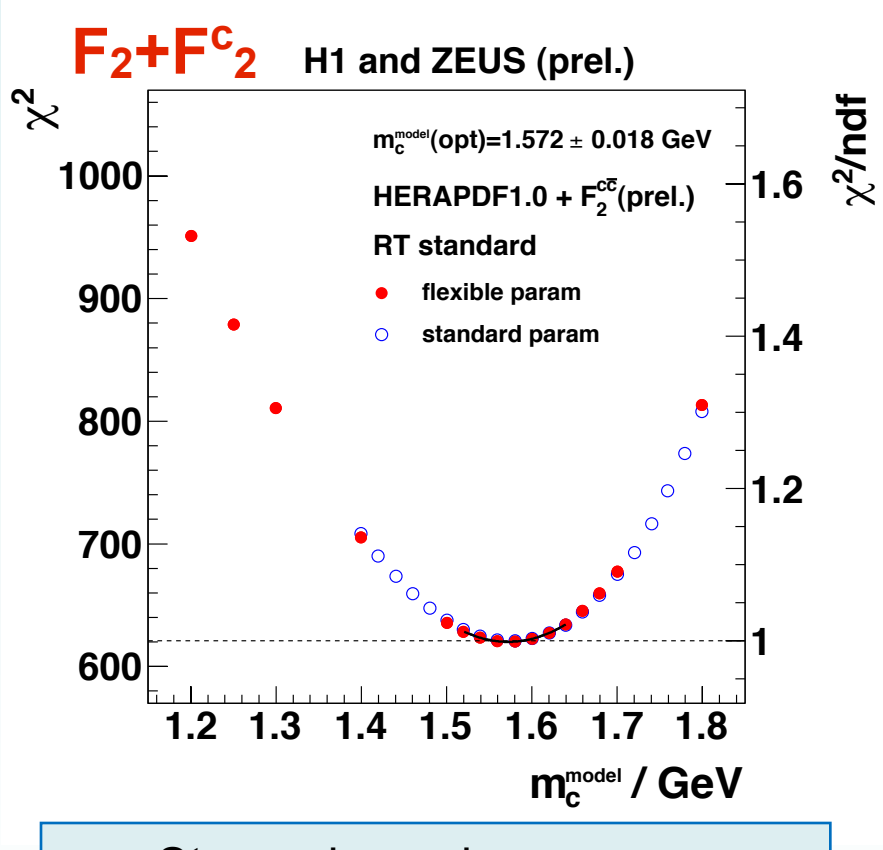
**Study the sensitivity of the PDF fit to the value of $m_c$**

PDF fit to inclusive DIS




Weak dependence on $m_c$

PDF fit to inclusive DIS **+ charm data**



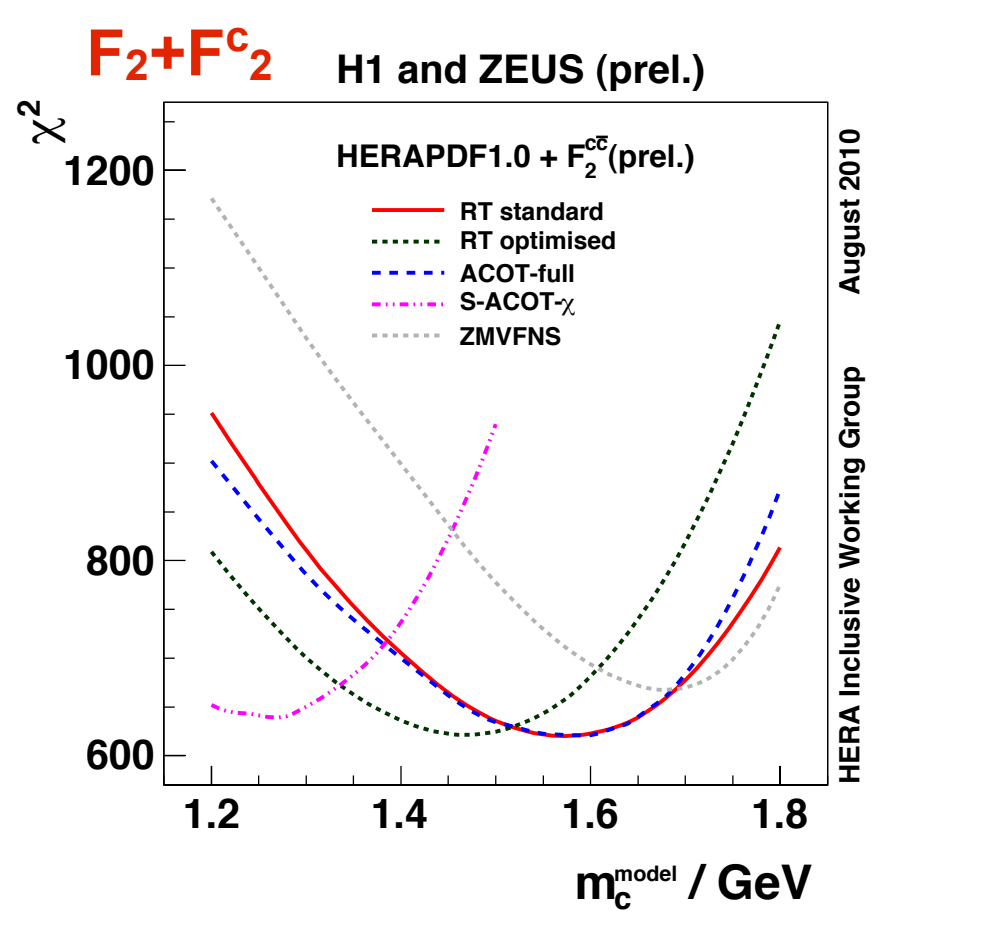

Strong dependence on $m_c$

# 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

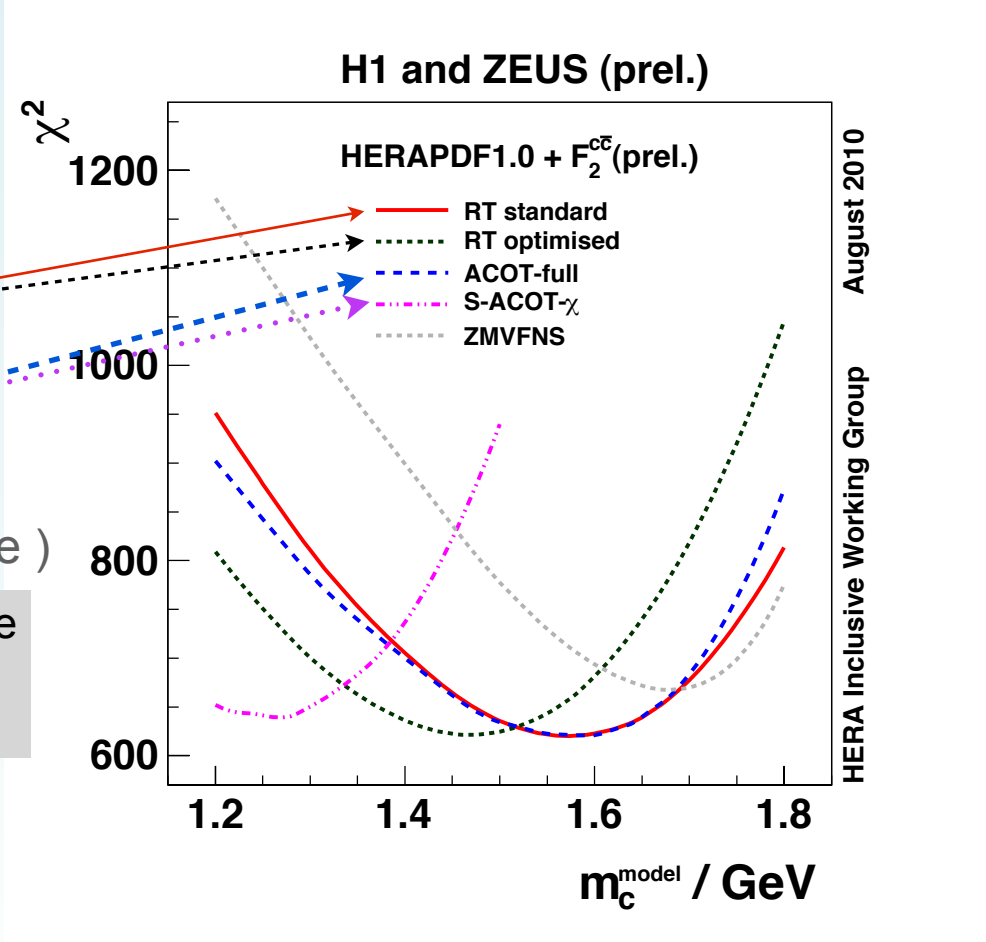
(used by different PDF groups)

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

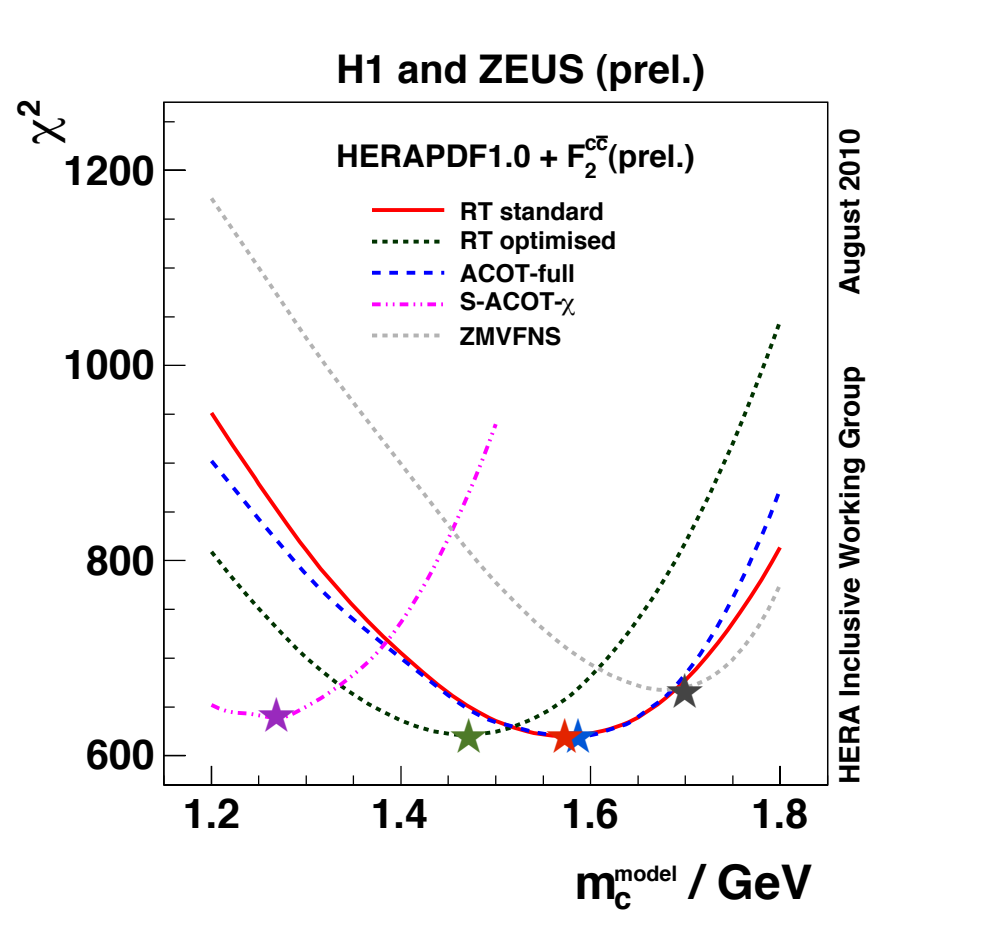
## Value of $m_c$ : how different for various HQ schemes in PDF Fits?

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)

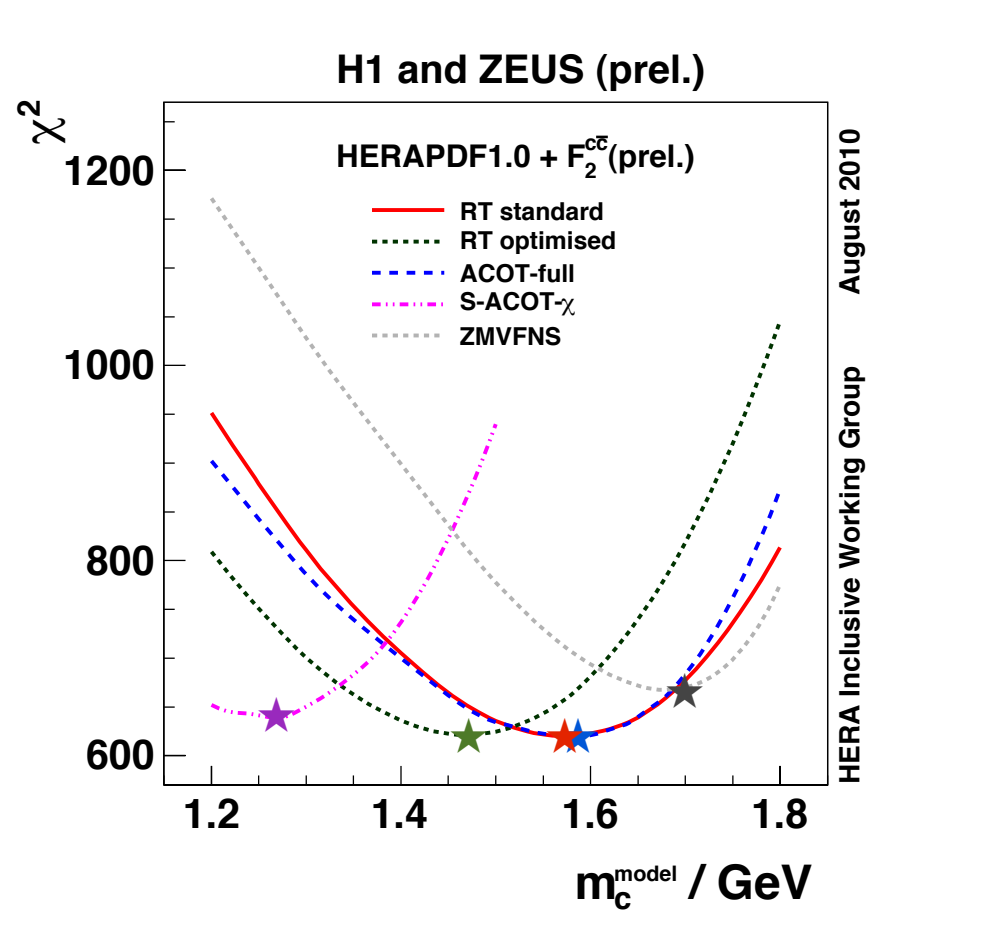
Different HQ schemes prefer

different optimal★ $m_c$

↓

parameter of a specific

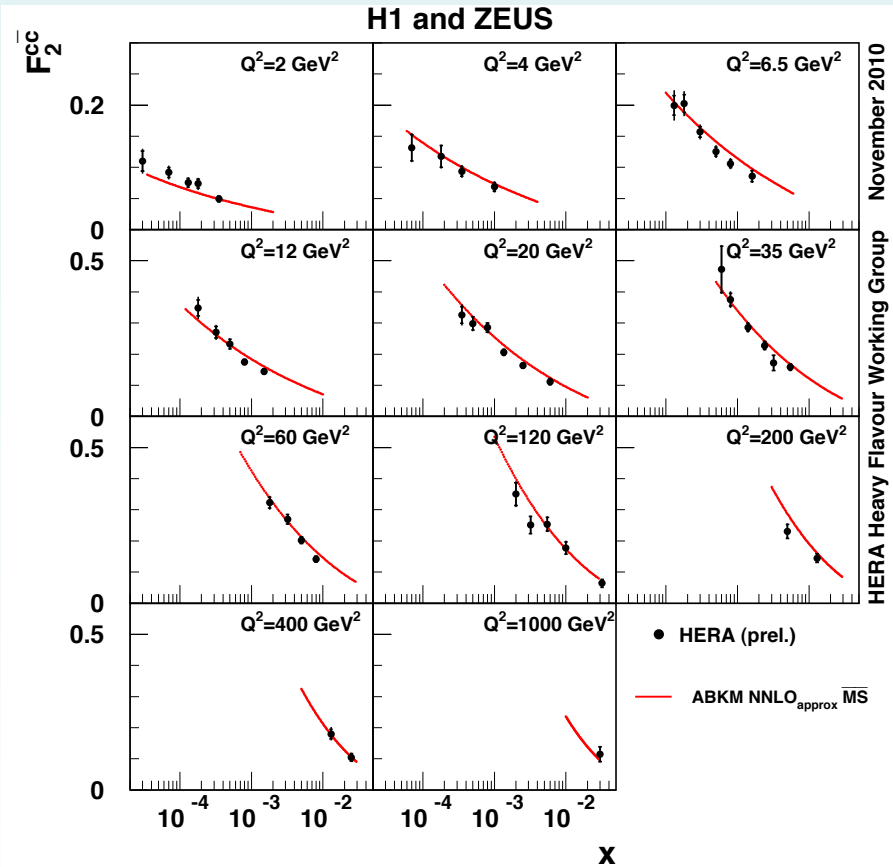
HQ scheme in PDF fits



# 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

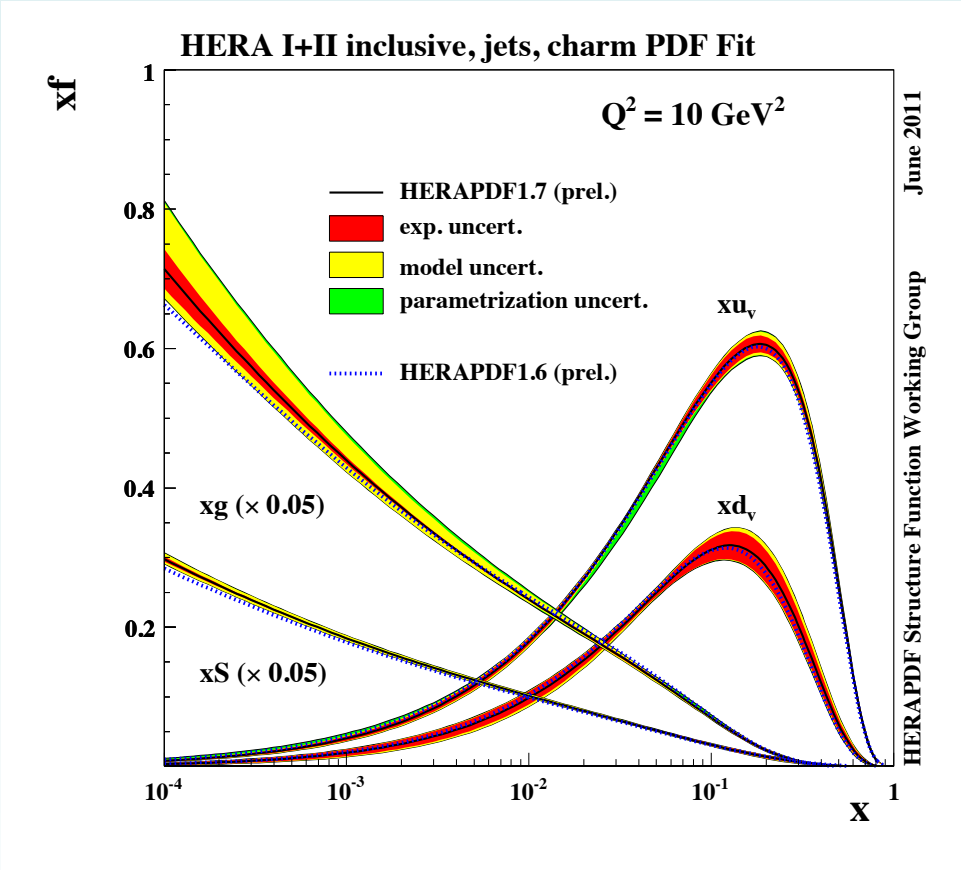
Flexible parametrization

heavy flavours:

$m_c$=1.5±0.15 GeV

$\alpha_S$ ($M_Z$)=0.119

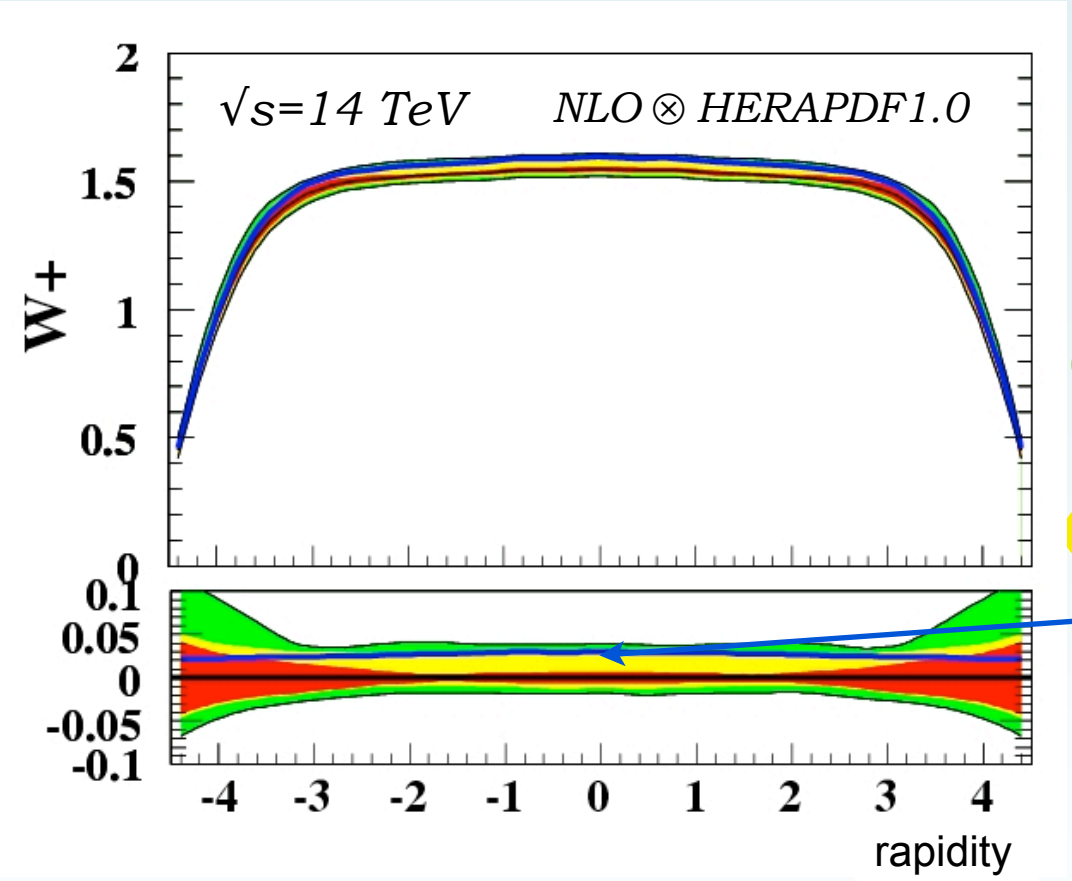
steeper gluon as HERAPDF1.6




Including the jet and the charm data: decouple the gluon from $\alpha_S$ 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

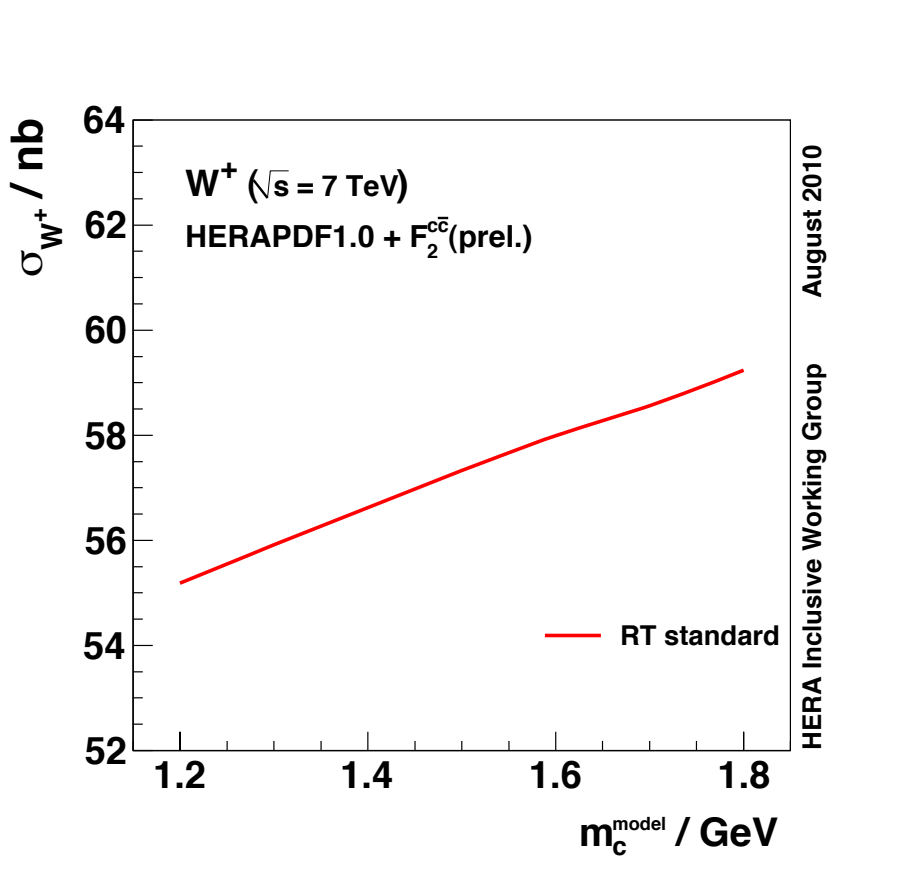
Model assumptions

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

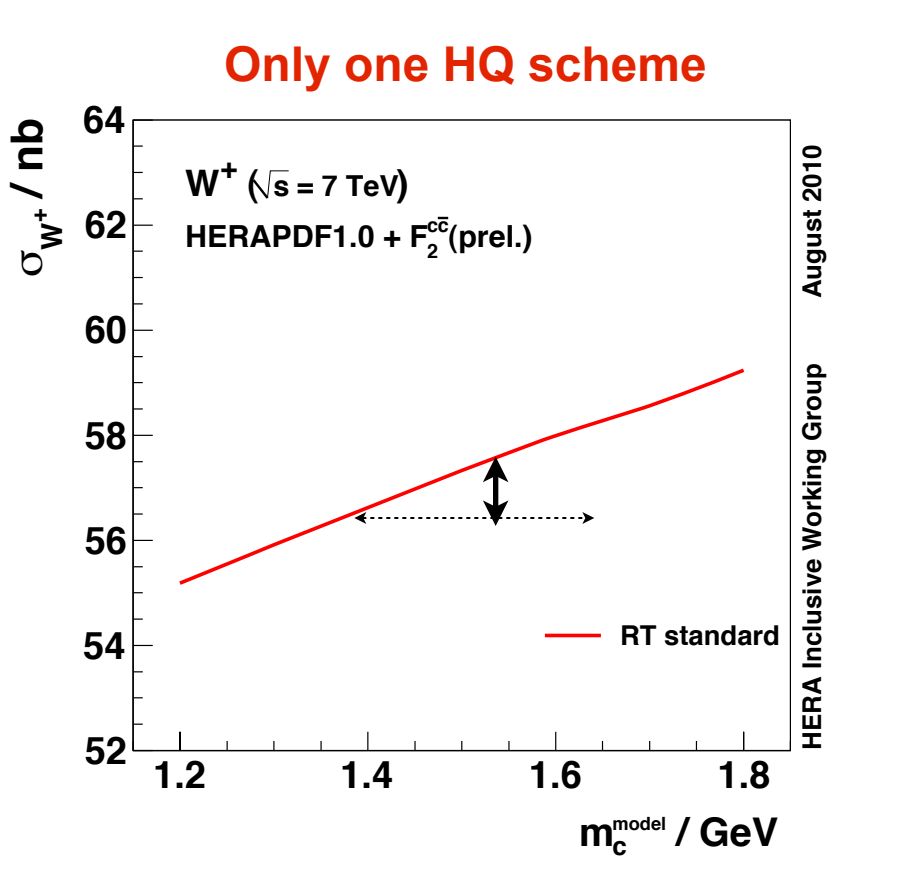
**Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions**




Larger $m_c$ → more gluons, less charm → more light quarks → larger $\sigma_W$

# Heavy Quarks in PDFs and W/Z at LHC

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



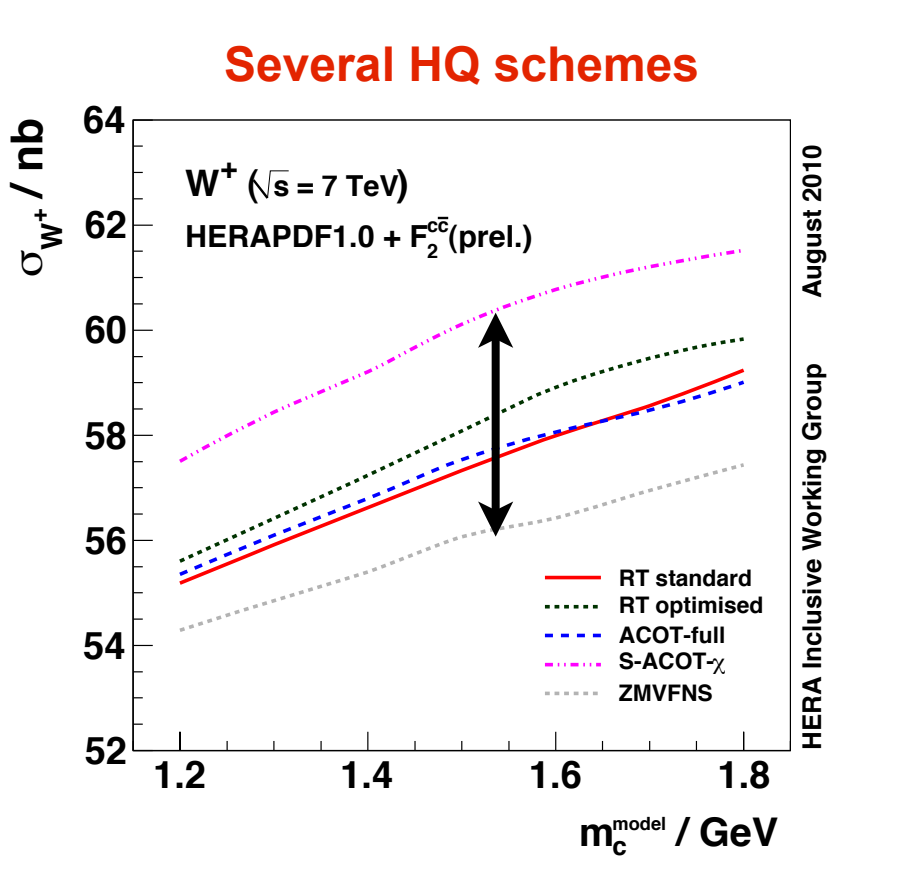

$m_c$ variation in PDF

$1.4 < m_c < 1.65$ 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

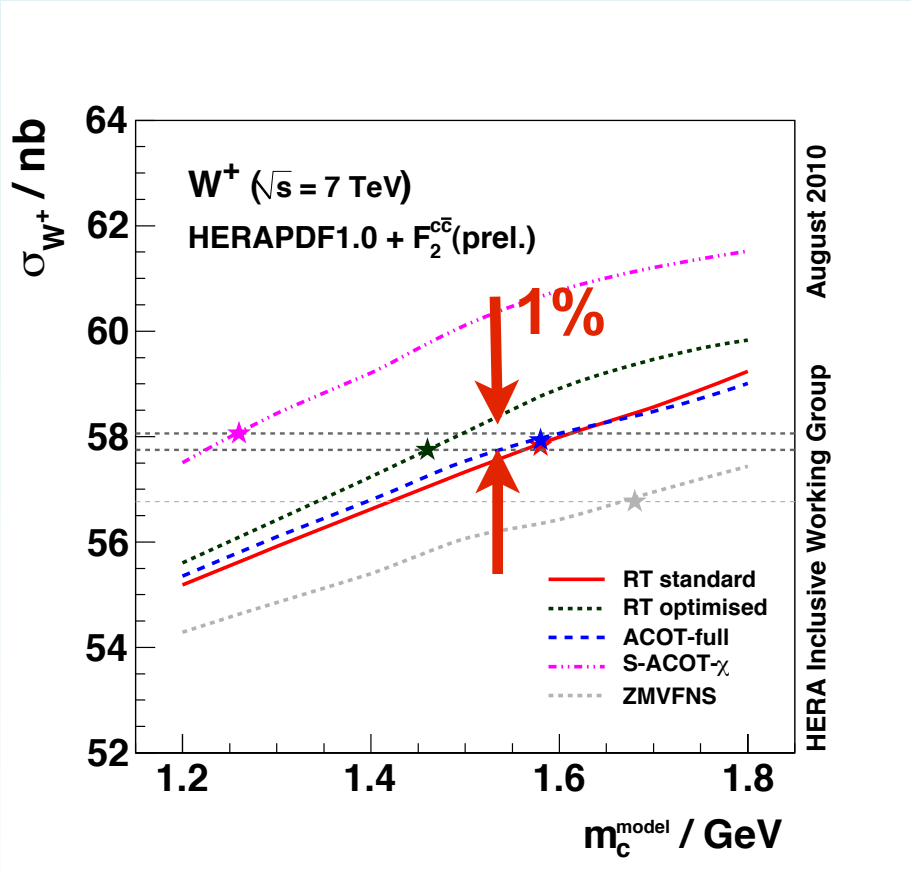
Using different HQ schemes:

+ 7% uncertainty

Large uncertainty on $\sigma_W$ 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**



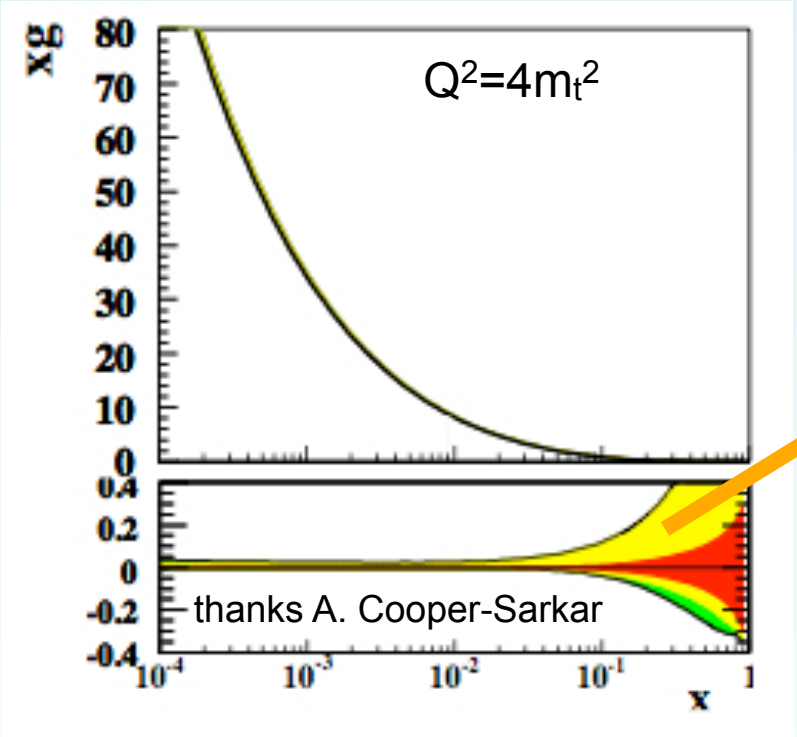

★ Optimal $m_c$ using $F_2$+$F_2{}^c$

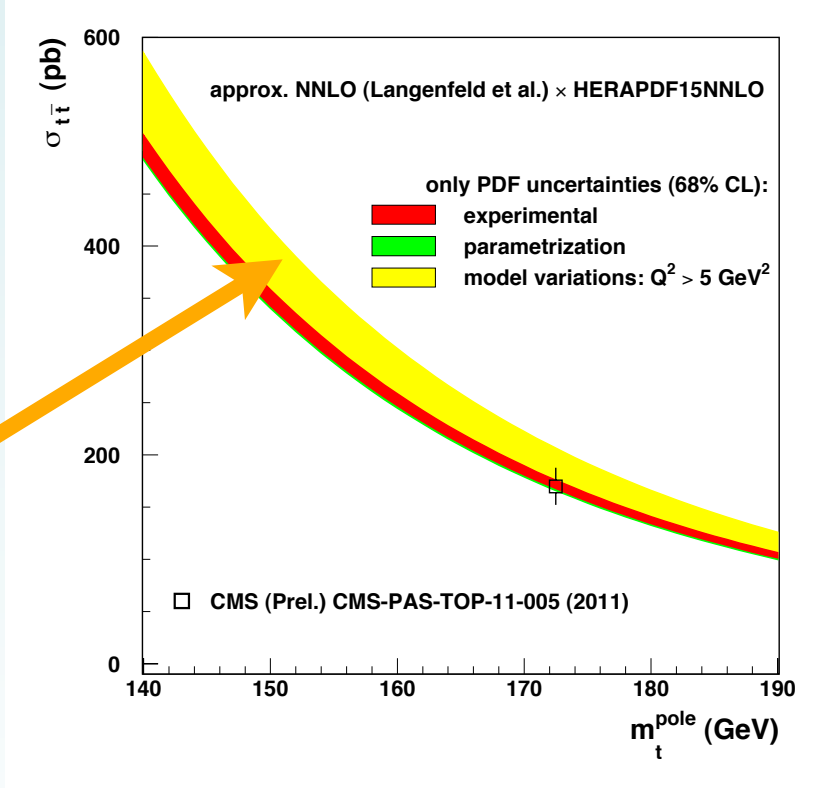
ZMVFNS not considered

Uncertainty on $\sigma_W$ 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:

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

$\mu^i$ measured value at point i

$\delta_i$ statistical, uncorrelated systematic error

$\gamma^j_j$ – correlated systematic error

$b_j$ – shift of correlated systematic error sources

$m^i$ – true value (corresponds to min $\chi^2$)

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.

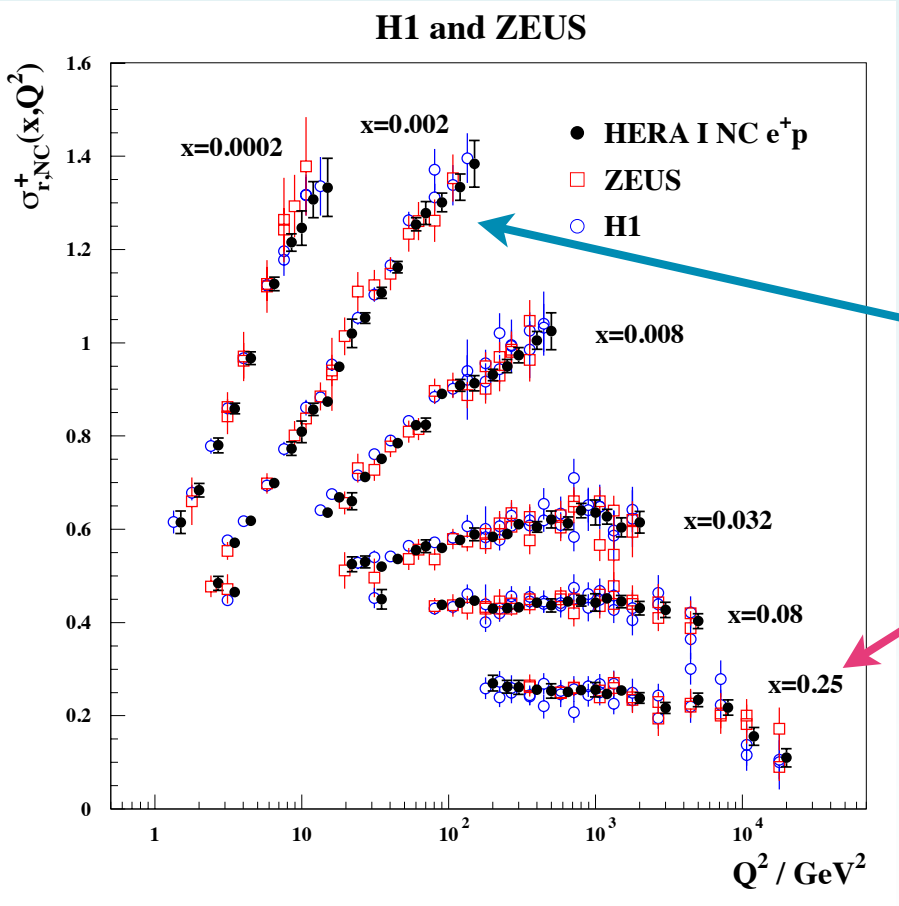
$B_{\bar{U}} = B_{\bar{D}}$ $\quad C'_g = 25, A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$

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

# Scaling Violations at Highest Precision

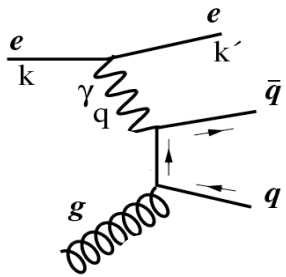
*JHEP 01 (2010) 109:* combined H1 and ZEUS data from HERA I, $\mathcal{L}$ ~115 pb$^{-1}$

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



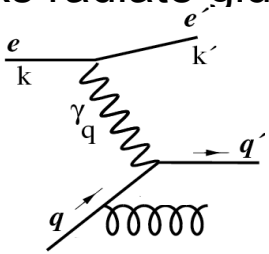

small $x$ : $F_2$ rises with $Q^2$

gluon splits into quark pair

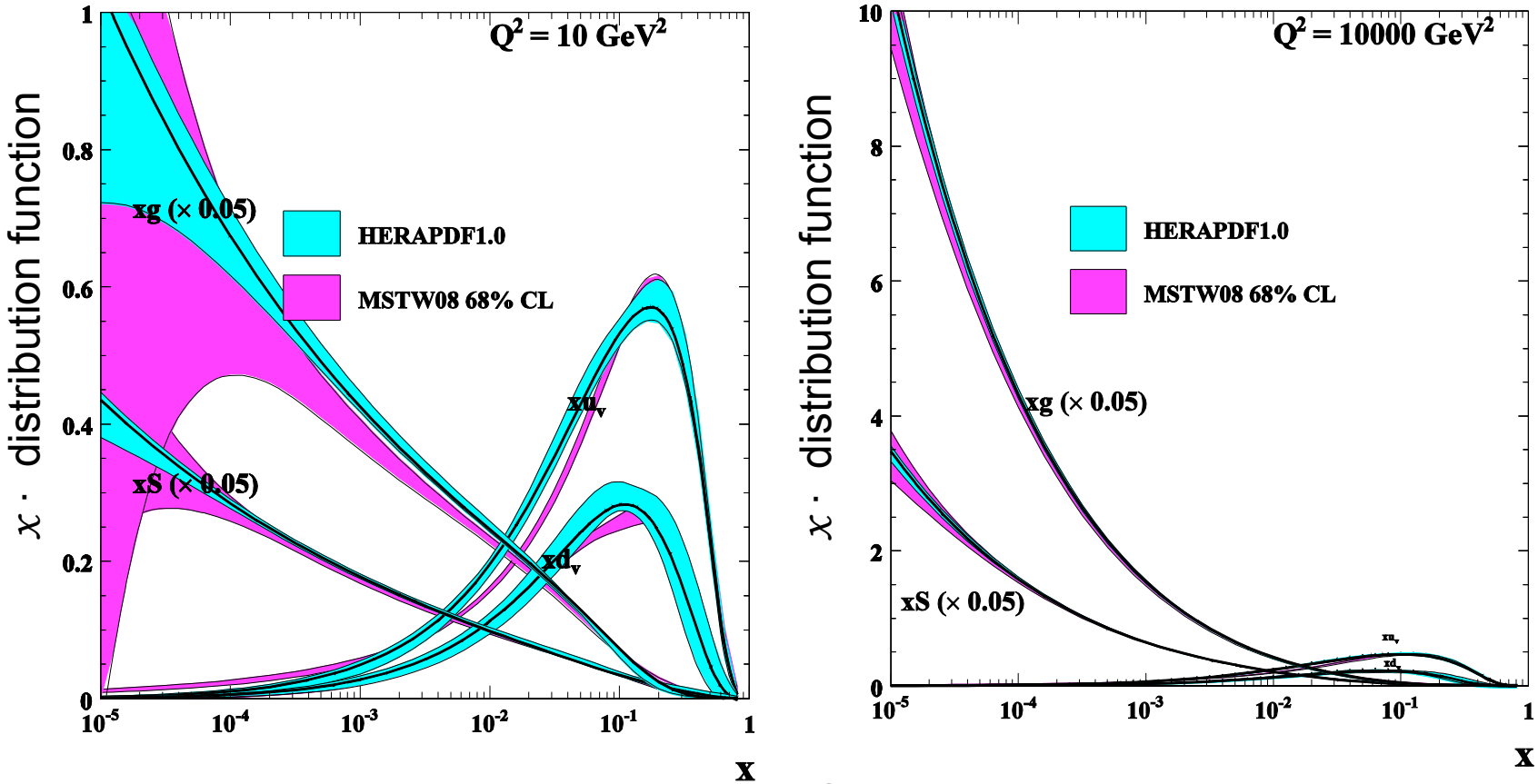



large $x$ : $F_2$ falls with $Q^2$

quarks radiate gluons



# HERA PDFs vs global QCD analysis



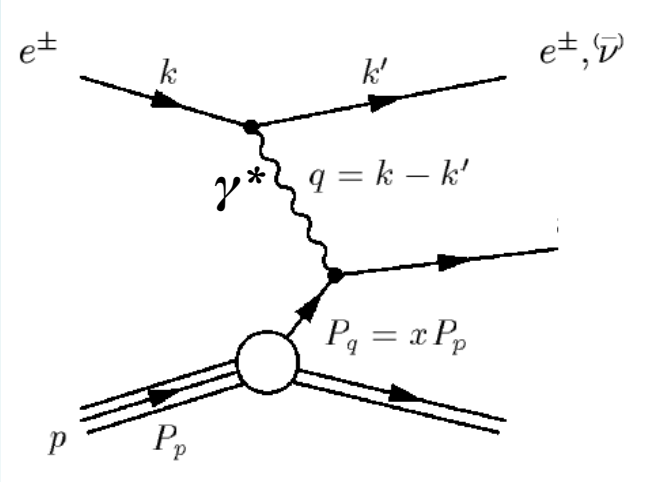

**HERAPDF** compared to one of the global PDF Fit results:

- 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:

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

$\sigma_T$ → transverse polarized $\gamma$ helicity ±1

$\sigma_L$ → longitudinally polarized $\gamma$ 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 $\gamma$ energy fraction*

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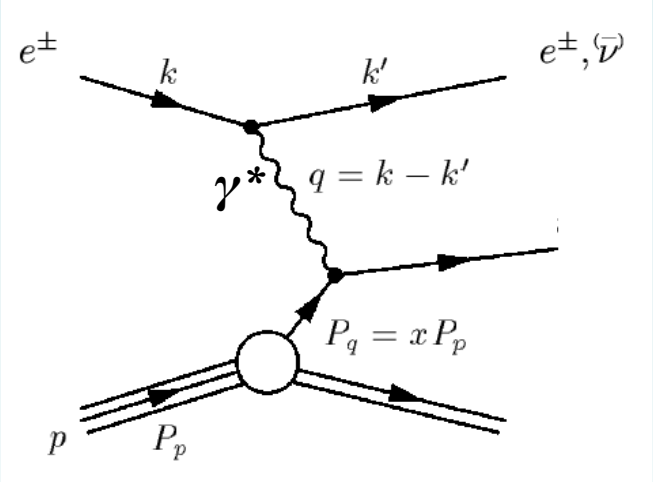
Think of scattering of longitudinal and transverse polarized photons:

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



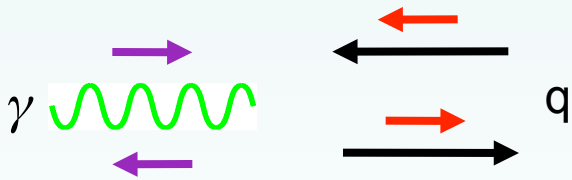

cross section:

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

transverse polarized $\gamma$ helicity ±1

longitudinally polarized $\gamma$ helicity 0

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




helicity conservation ⇨ $\sigma_L=0$

Kinematics:

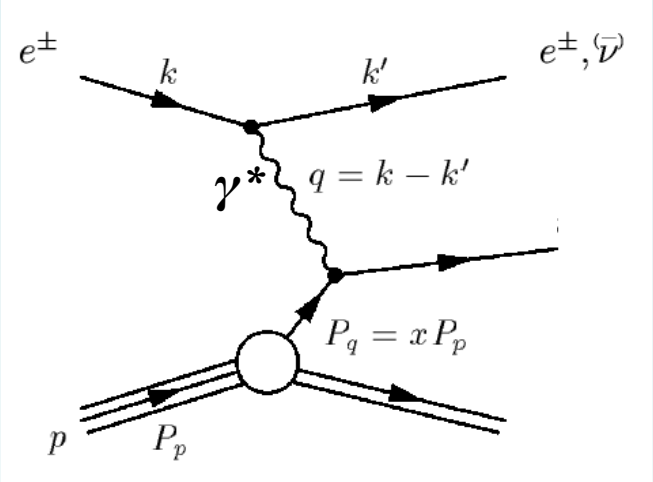
$x=-q^2/2p\cdot q$ *Bjorken scaling variable*

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

$y=p\cdot q\,/\,p\cdot k$ *transferred $\gamma$ 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:

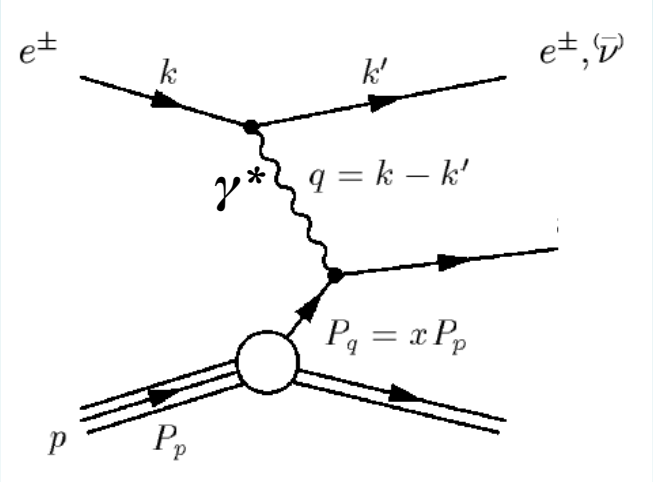
$x = -q^2 / 2p\cdot q$ *Bjorken scaling variable*

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

$y = p\cdot q / p\cdot k$ *transferred $\gamma$ 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*

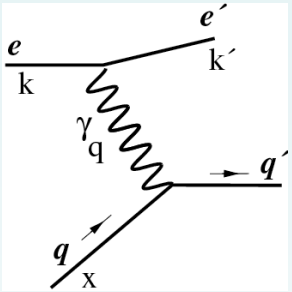
$y = p \cdot q / p \cdot k$ *transferred $\gamma$ energy fraction*

# Another way to access the gluon directly: $F_L$

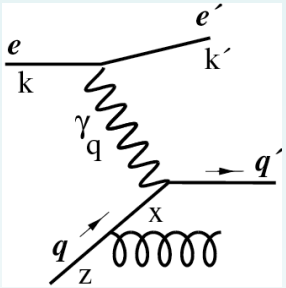
Remind of photon- scattering: $F_2 \sim (\sigma_T + \sigma_L), F_L \sim \sigma_L$

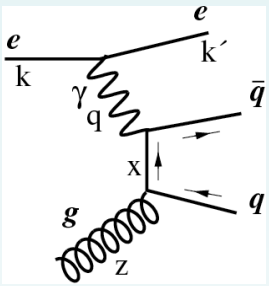
Angular momentum conservation: spin ½ quark absorbs spin-1 photon

**QPM**




**QCD**




quark helicity ± ½ , $F_L=0$

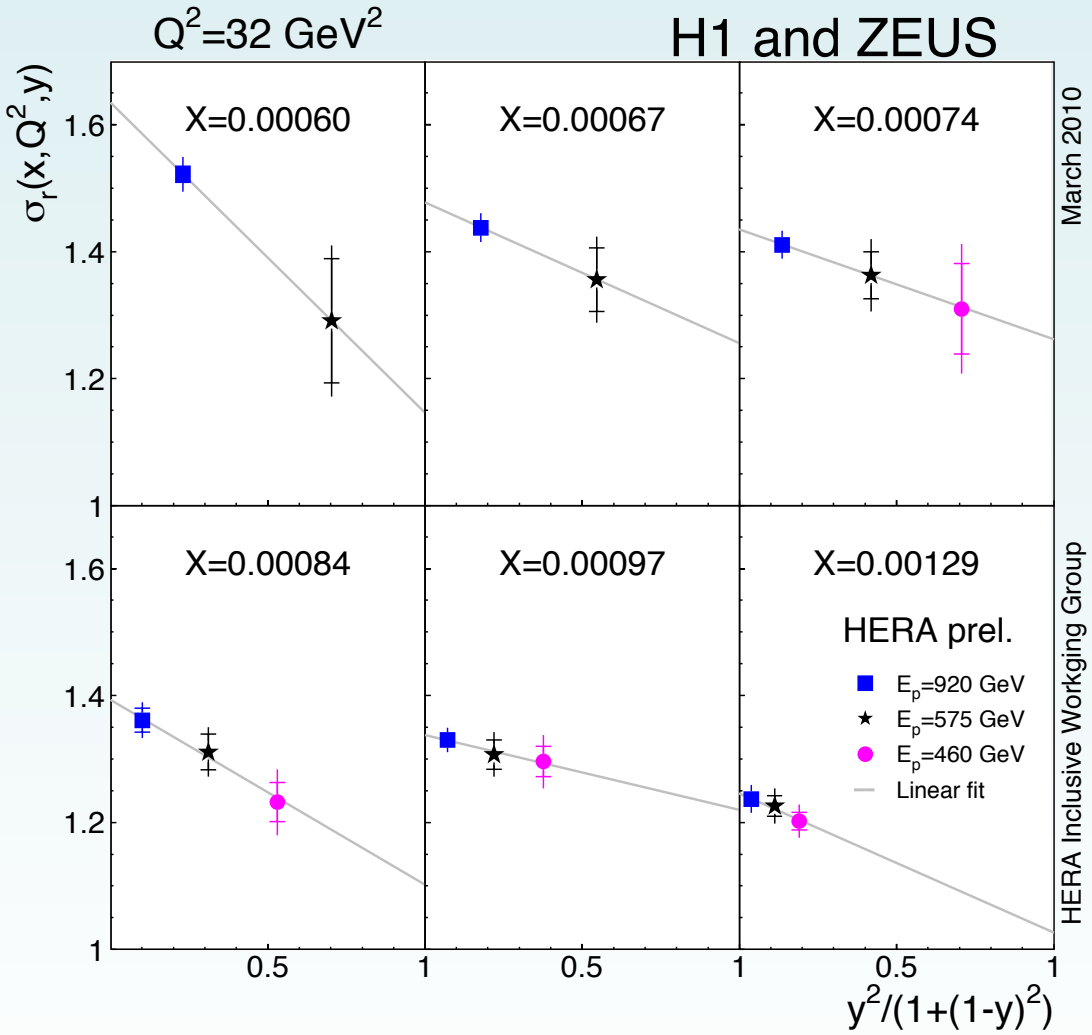
off-shell quarks may absorb longitudinal photons

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

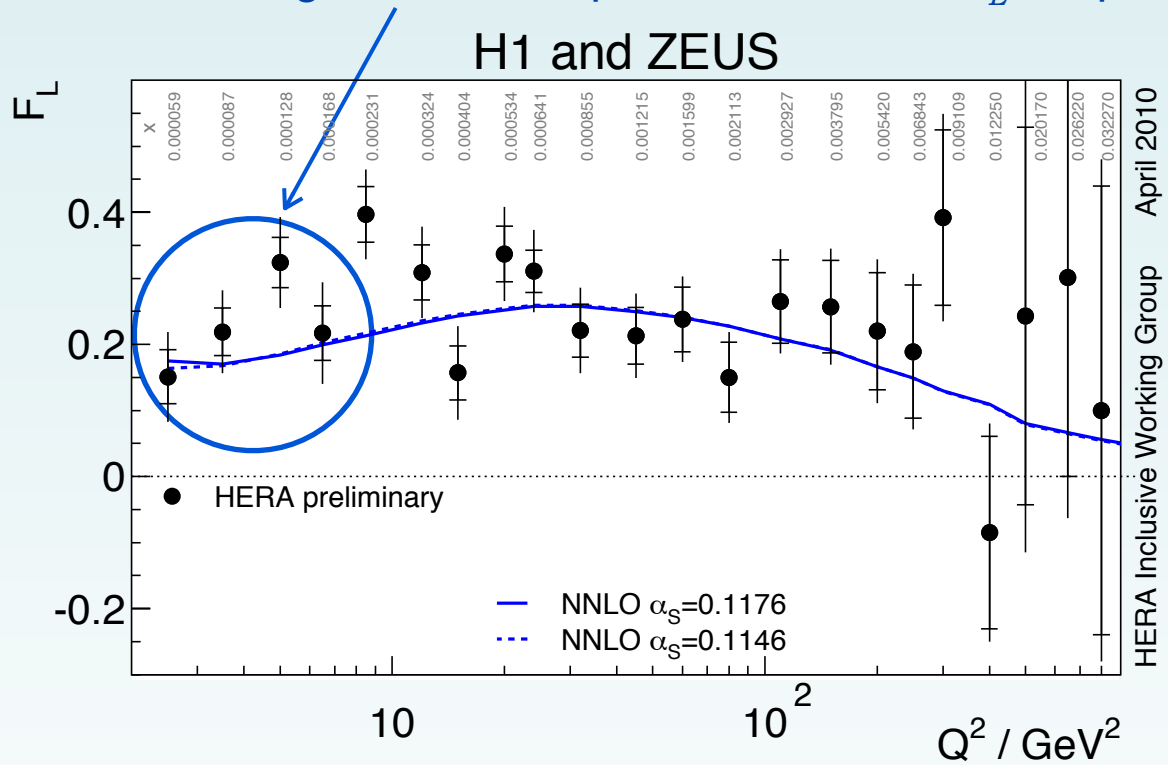
$E_p$=460 GeV

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:

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

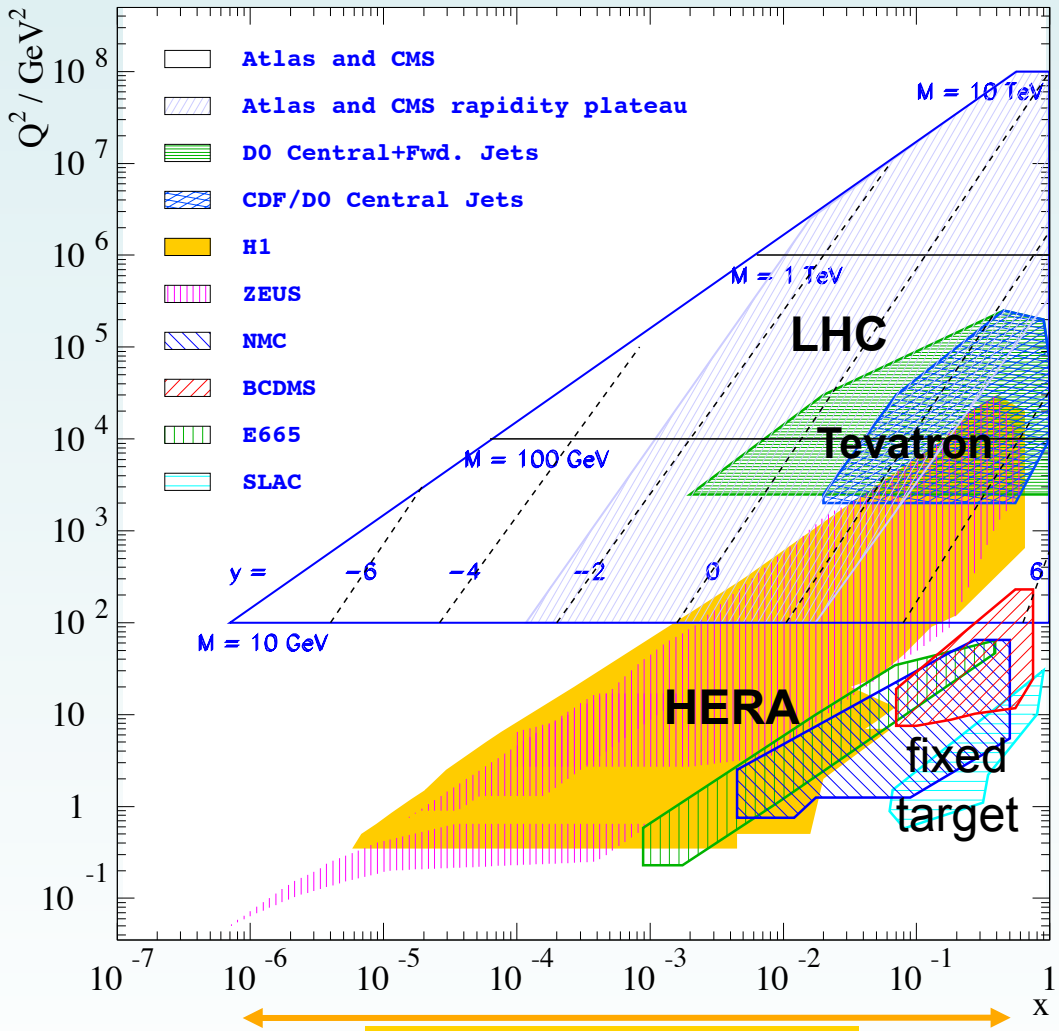
- Direct test of different schemes of HQ treatment in PDF fits

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

  additional constrain on the gluon density in the proton

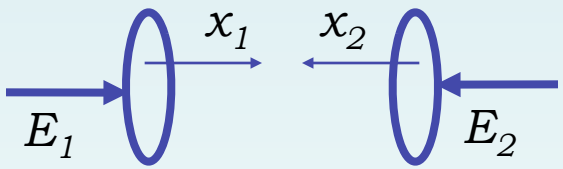
  reduce parameterization uncertainty

# PDFs From HERA to Tevatron and the LHC




HERA coverage in $x$

## Kinematics in pp collisions




Center-of-mass energy:

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

2-parton interaction:

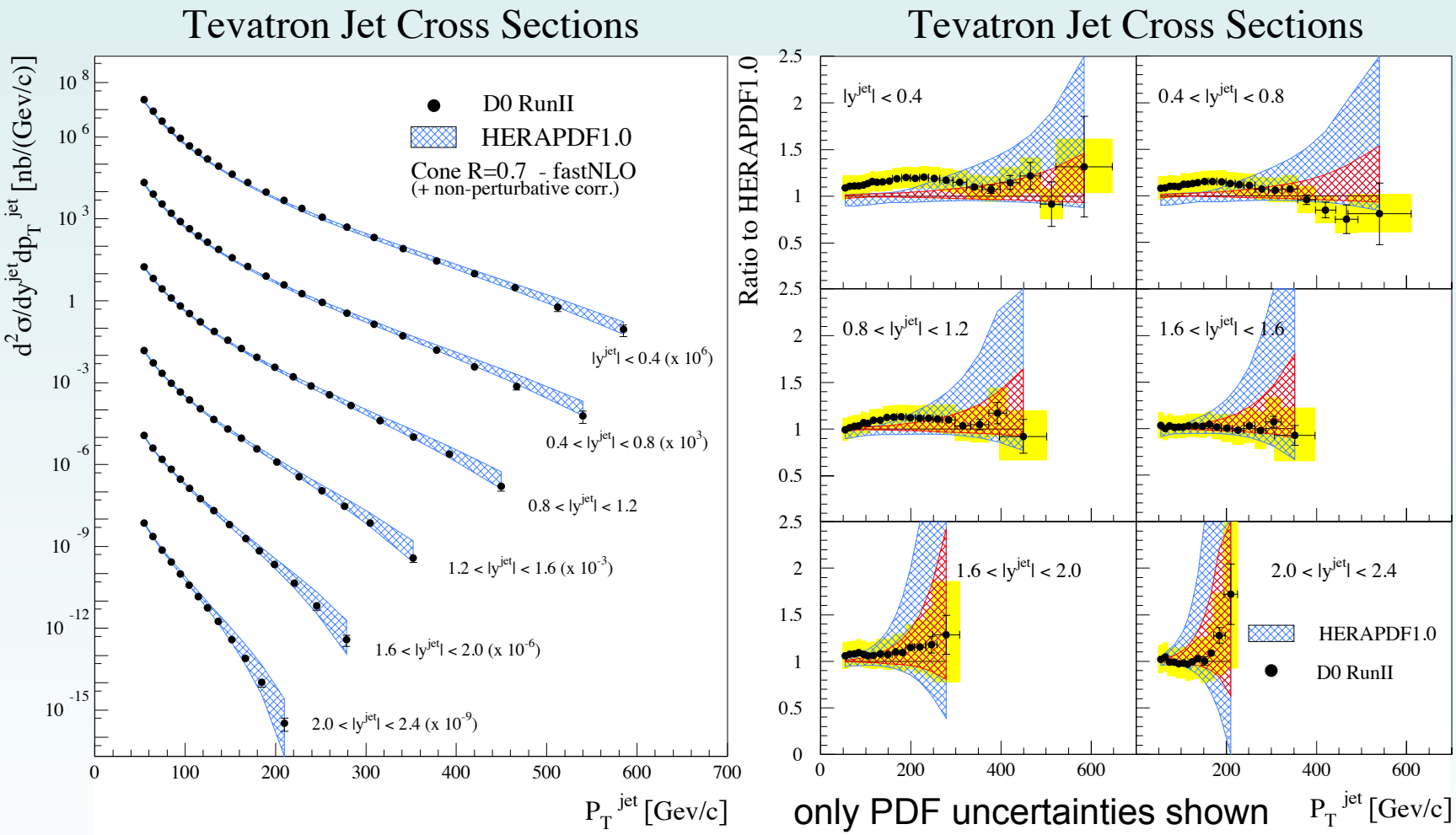
$$\hat{s} = x_1 \cdot x_2 \cdot s \geq M$$

Energy scale $M = Q$

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

rapidity

# HERAPDF vs Jets at TEVATRON




Predictions based on HERAPDF in agreement with TEVATRON data