Recent results from HERA and their impact for LHC

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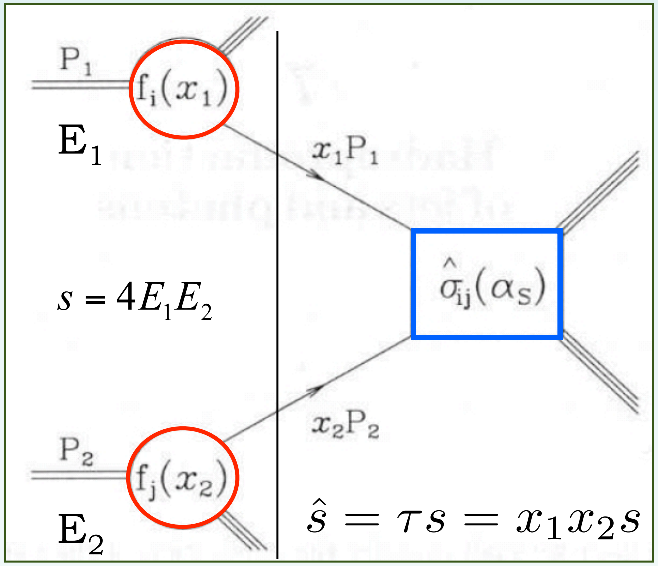
for the H1 and ZEUS Collaborations

Hadron Collider Physics Symposium 2011

Motivation: precision of the proton structure

Cross sections of processes in proton-(anti)proton collisions

proton structure *hard interaction*



Proton Structure described via probability for a parton i to carry the fraction x of proton momentum
(Parton Distribution Functions) $f_i(x,\mu^2)$

Factorization: PDF⊗ hard sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \boxed{\frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau}} \cdot \hat{s} \cdot \boxed{\hat{\sigma}_{ij}}$$

calculable in pQCD

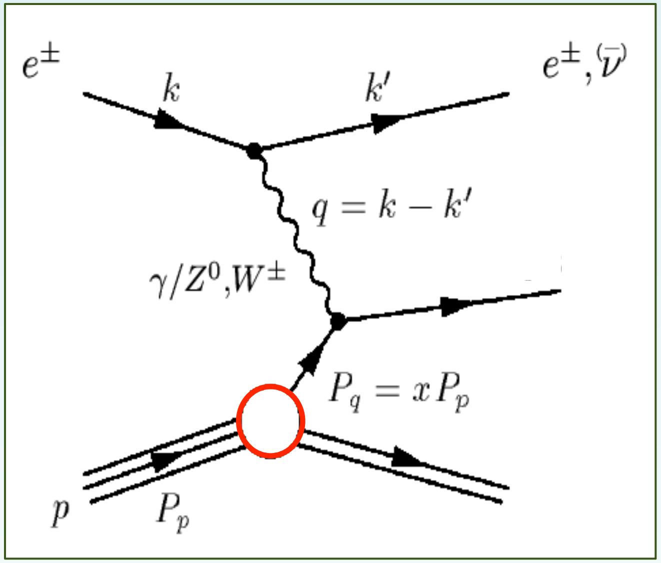
$$\tau \cdot \frac{dL_{ij}}{d\tau} \propto \int_0^1 dx_1 dx_2 (x_1 \underbrace{f_i(x_1,\mu_F^2)}_{\text{PDF}} \cdot x_2 \underbrace{f_j(x_2,\mu_F^2)}_{\text{PDF}}) + (1 \leftrightarrow 2)\delta(\tau - x_1 x_2)$$

Precision of PDFs essential

Proton PDFs and structure functions in DIS

PDFs extracted from structure function measurements in Deep Inelastic Scattering

electron-proton DIS



γ, Z Exchange: Neutral Current $ep \rightarrow e\,X$

$$\frac{d^2\sigma^{e^\pm P}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2 \mp Y_- xF_3 - y^2 F_L]$$

$$LO:\ F_2 \propto \sum_i (q_i(x) + \bar{q}_i(x))$$ dominant contribution

$$LO:\ F_3 \propto \sum_i (q_i(x) - \bar{q}_i(x))$$ γ/Z interference

$$NLO:\ F_L \propto x \cdot \alpha_S \cdot g(x, Q^2)$$ contribution from gluon

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

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

$s = (k+p)^2$ *center of mass energy*

y transferred energy fraction

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

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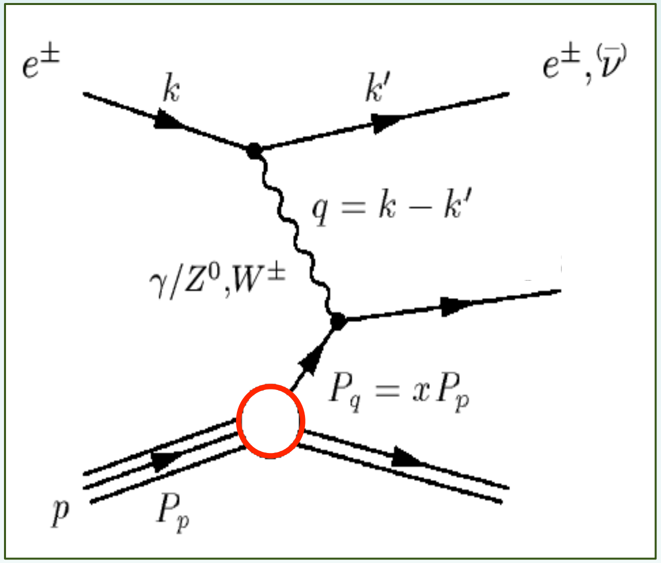

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$W^{\pm}$ Exchange: Charged Current $ep \rightarrow \nu\,X$

$$\sigma_{CC}^{e^+p} \propto x\{(\bar{u} + \bar{c}) + (1-y)^2(d+s)\}$$

$$\sigma_{CC}^{e^-p} \propto x\{(u + c) + (1-y)^2(\bar{d}+\bar{s})\}$$

sensitive to individual quark flavours

Determination of parton density functions

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

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

from measured cross sections

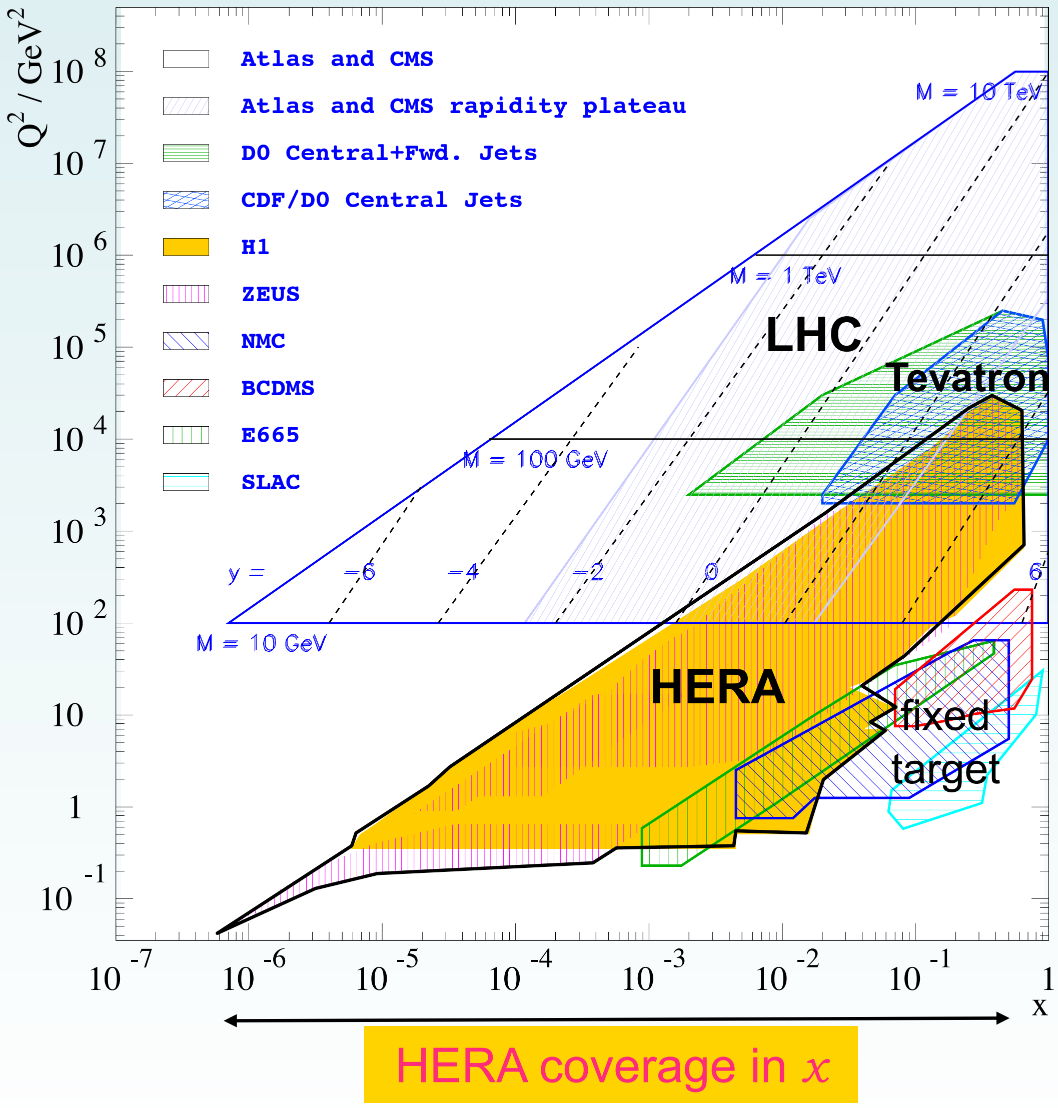
calculable in pQCD

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

Experiments sensitive to PDFs



PDFs obtained from data of fixed target, HERA, Tevatron

HERA measurements:

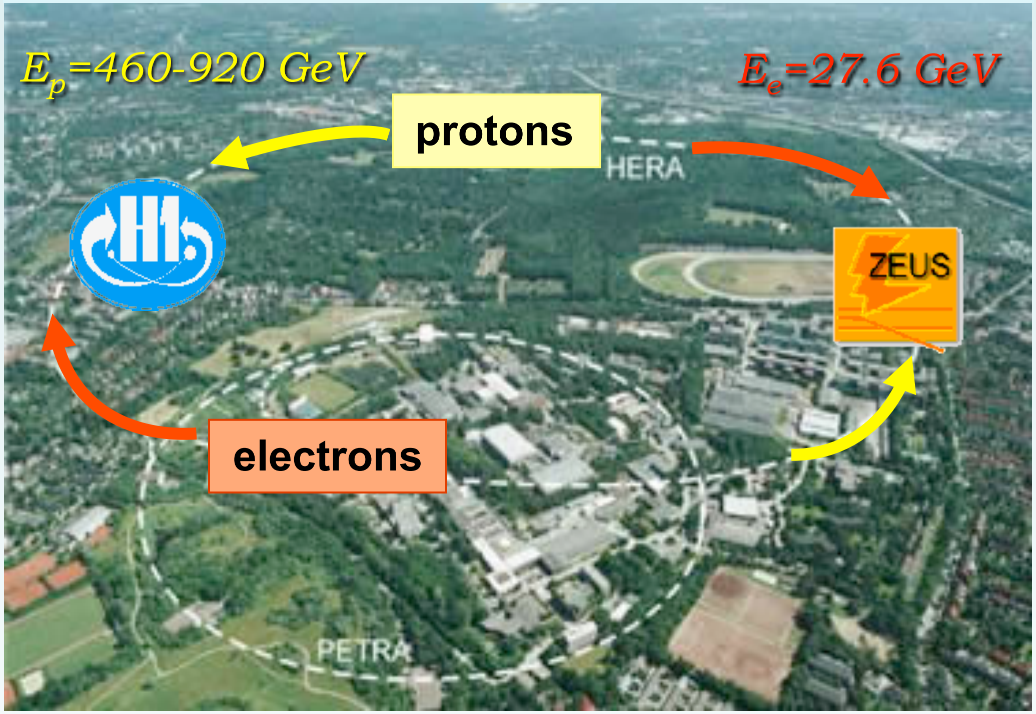
covers most of the (x,Q^2) plane,

best constraints at low, medium x

backbone of all available PDFs

Deep inelastic scattering at HERA

World-only *ep* collider



- HERA I : 1992-2000
- HERA II: 2003-2007
- collider experiments

H1 & ZEUS, $\sqrt{s}_{max} = 318\ GeV$

- integrated Luminosity

  $\sim 0.5\ fb^{-1}$/ experiment

HERA switched off June 2007, analyses ongoing on the way to final precision

H1 and ZEUS combine experimental data accounting for systematic correlations

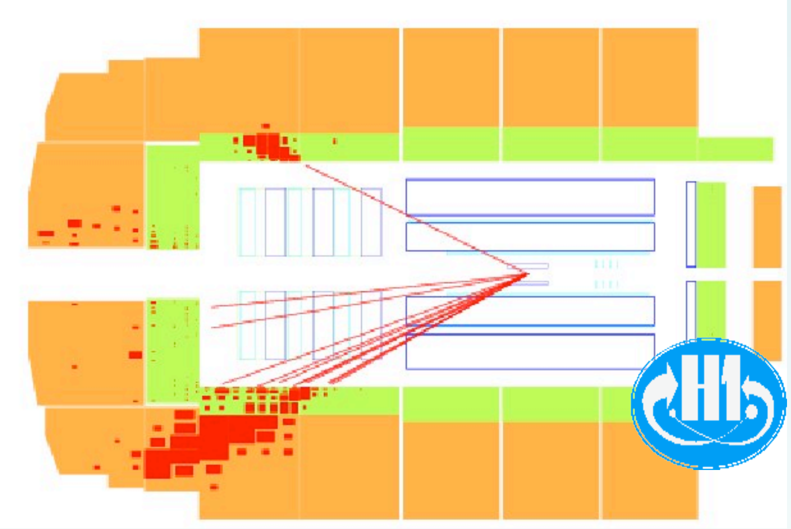
HERA performs the QCD analysis of (semi) inclusive DIS data (HERAPDF)

H1 and ZEUS collaborations provide/support the PDF Fitting Tool (HERAFitter)

Neutral and charged current DIS at HERA

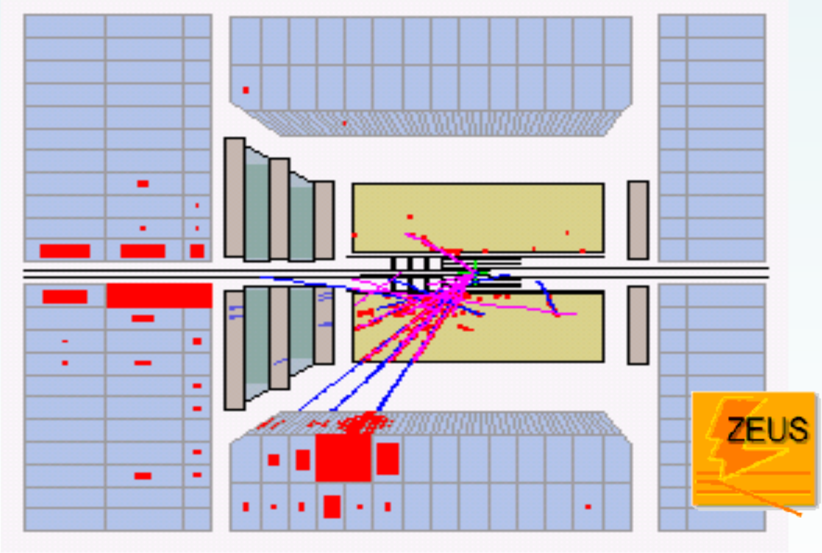
γ, Z : Neutral Current $ep \to e\,X$

Isolated energetic scattered $e^{\pm}$



$W^{\pm}$: Charged Current $ep \to \nu\,X$

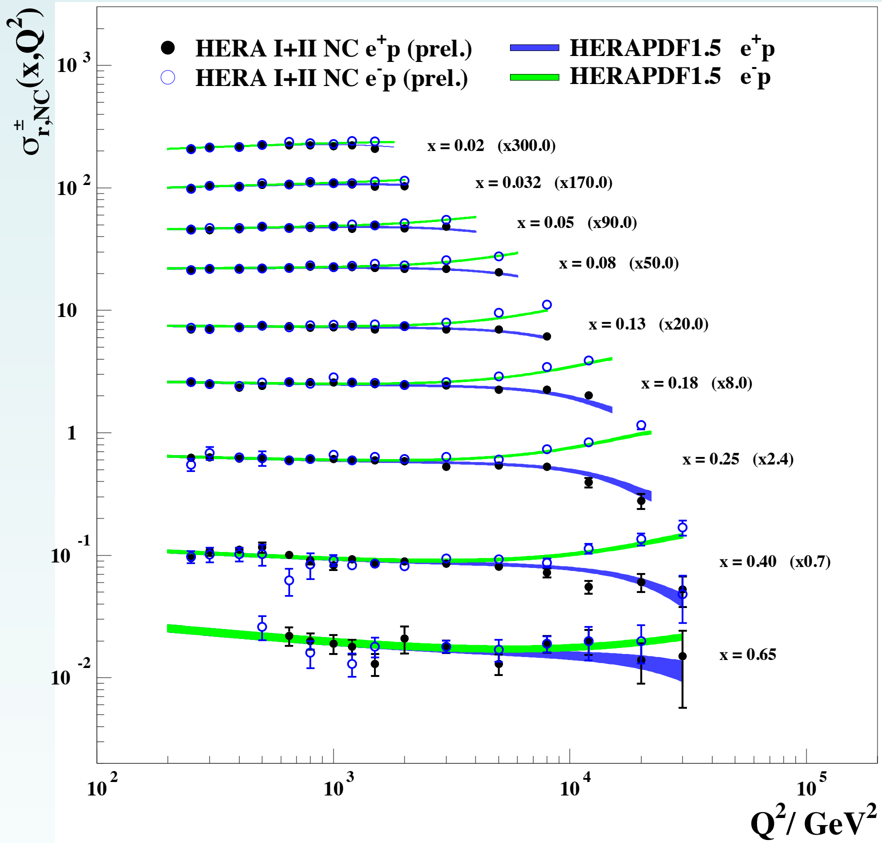
Large missing energy due to ν



Recent results on HERA DIS Cross Sections

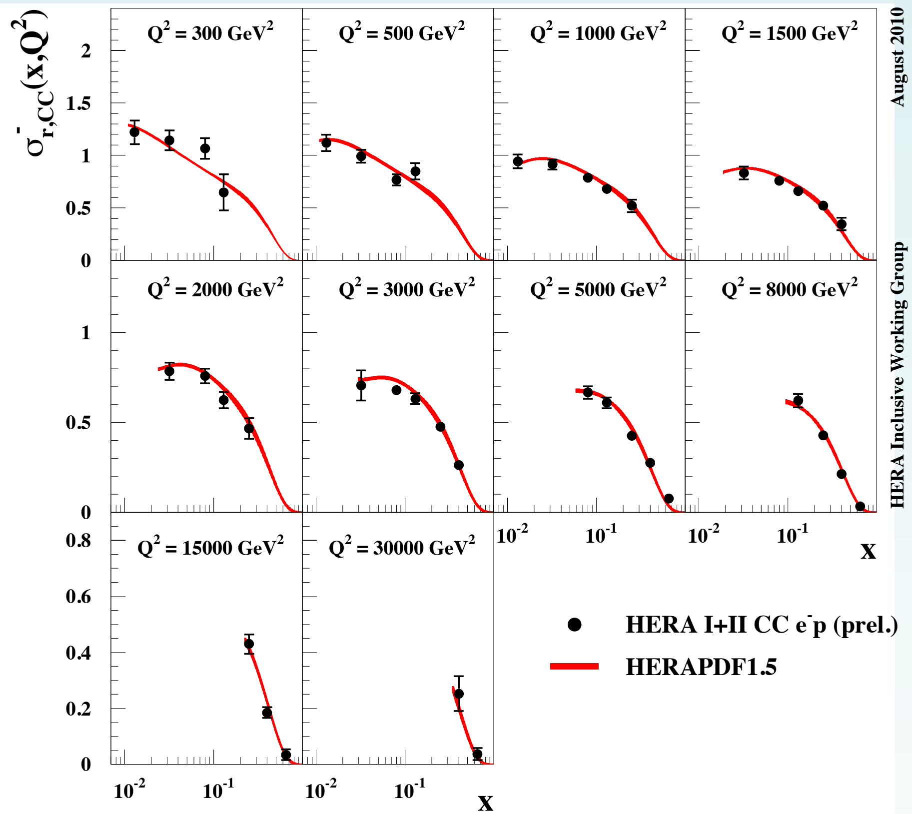
Neutral Current

H1 and ZEUS



Charged Current

H1 and ZEUS



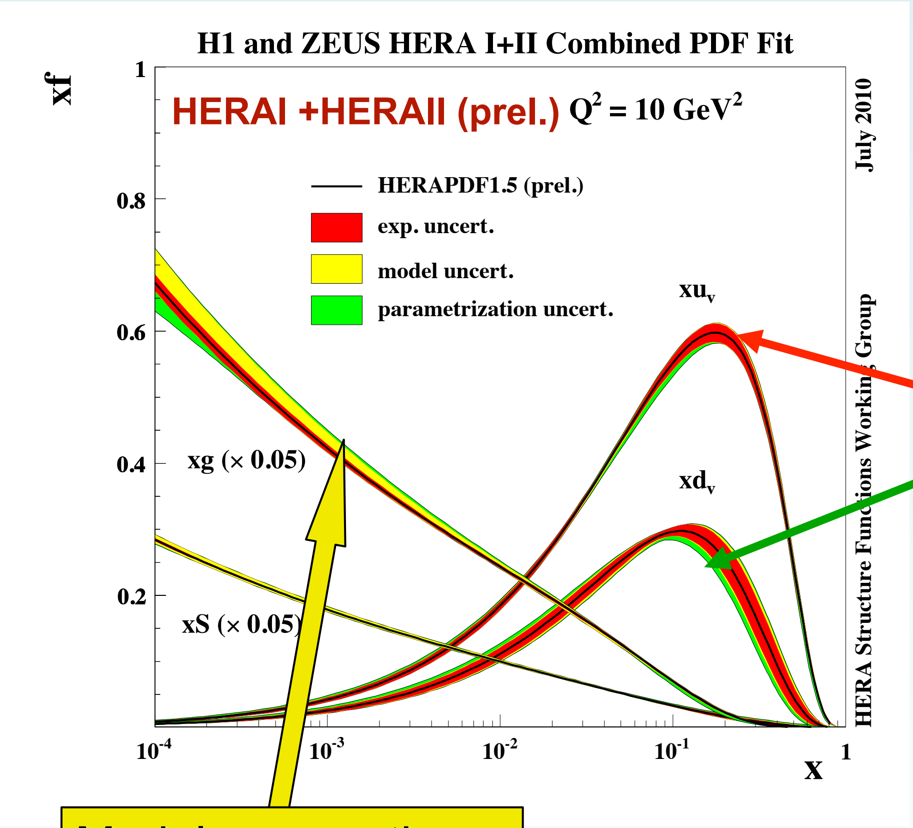
H1 and ZEUS measurements are combined accounting for correlations

Impressive precision up to high Q^2 and high x

QCD analysis of combined HERA NC and CC data: **HERAPDF**

HERA parton density functions

HERAPDF1.5: most precise DIS data, **recommended PDF** (HERA/PDF4LHC)



Model assumptions:

Q_0^2=1.9 GeV², $\alpha_s(M_Z)$=0.1176

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

DGLAP fit at NLO

Heavy quarks: massive

Variable Flavour Number Scheme

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

Experimentally very precise

Parameterization at starting scale:

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

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

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

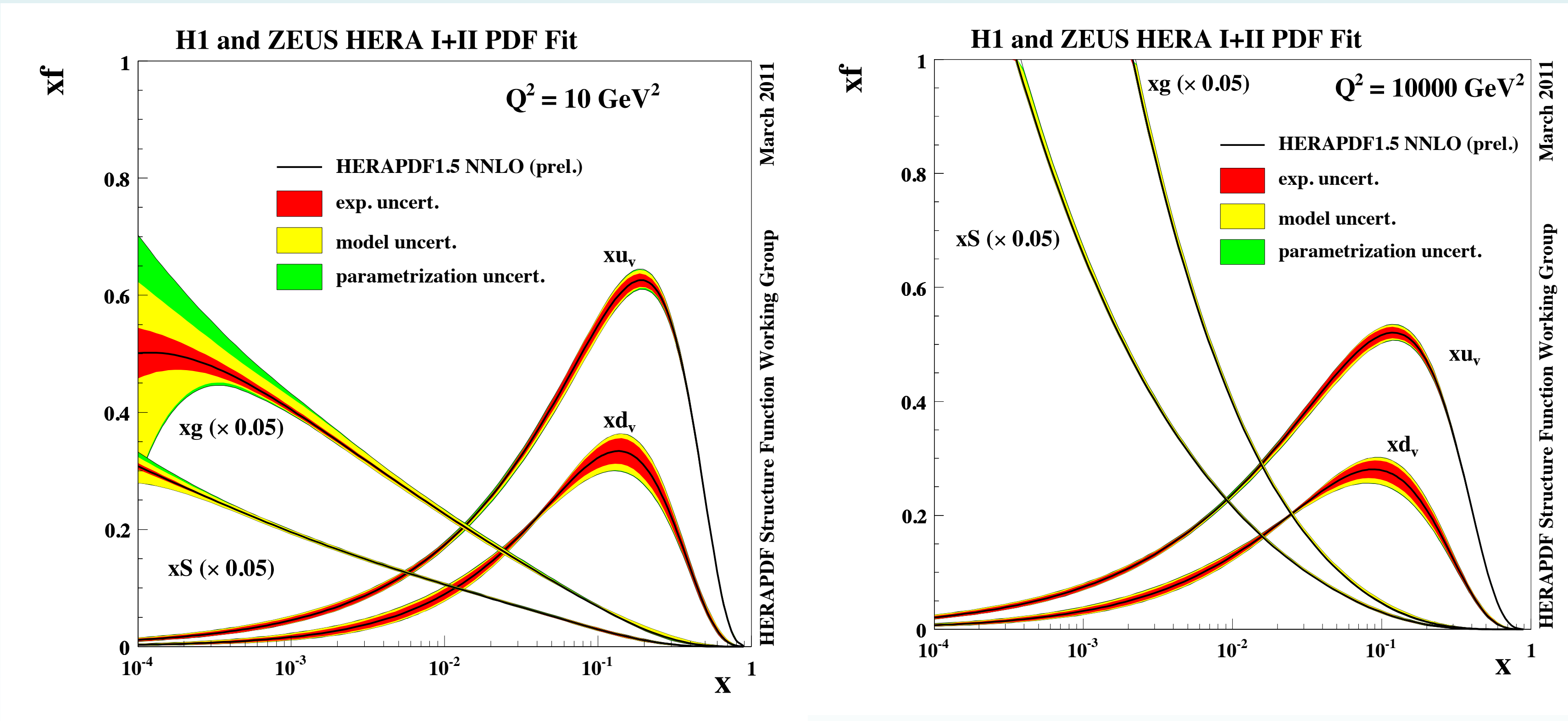
$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}$$

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

HERAPDF1.5 NNLO

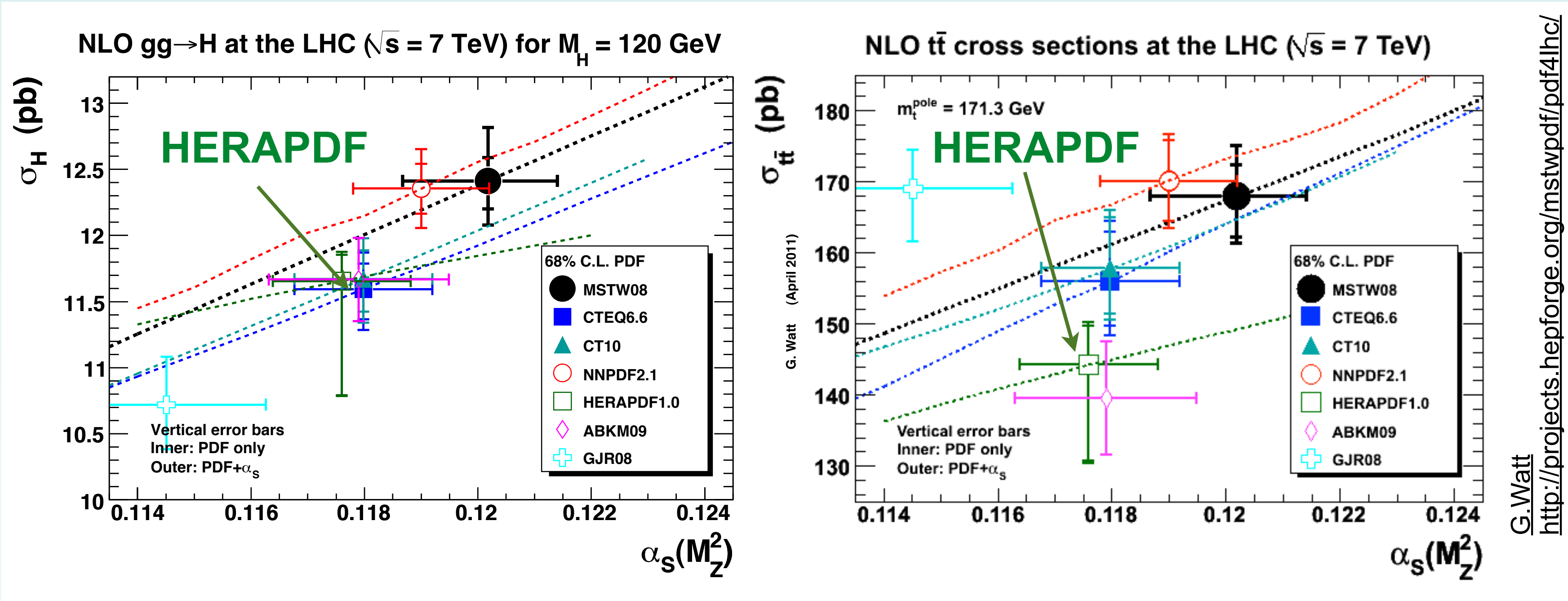
HERAPDF1.5NNLO is based on HERA I + II inclusive DIS data

uses more flexible parametrisation then NLO



HERAPDF1.5NNLO: eigenvectors available in LHAPDF
allows for many studies of parametrization and model parameters

HERAPDF in benchmarking effort



Dominant uncertainty on HERAPDF : parameterisation, 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

HERAPDFs and HERAPDF approach

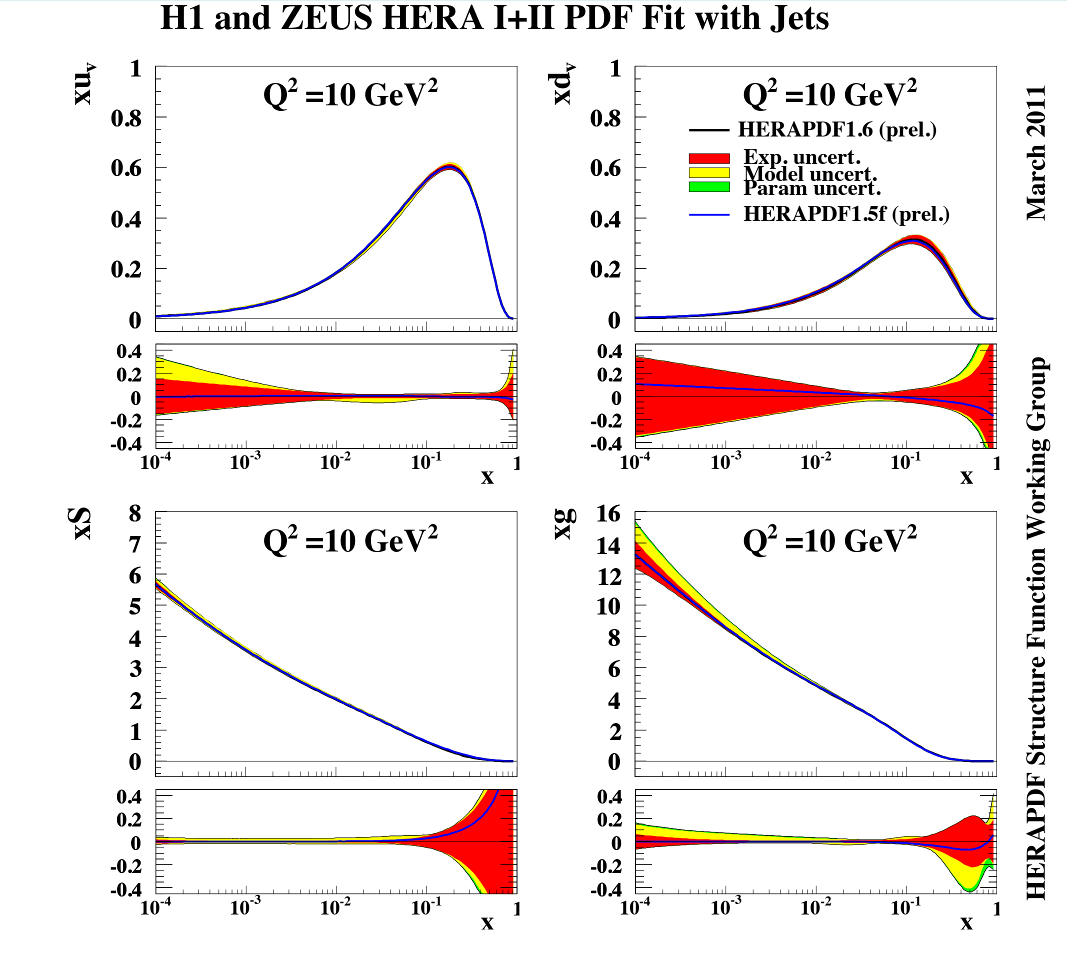
HERAPDF sets are based **only** on combined H1 and ZEUS data
proper correlations of the systematic uncertainties:
use $\Delta\chi^2 = 1$ criterion for proper statistical uncertainties;
no need for nuclear corrections

HERAPDF tools allow for usage of different Heavy Flavour schemes
- close collaboration with theory groups MSTW, CTEQ, ABKM
- test and tune different pheomenological approaches

PDF fit is performed in line with the analysis of experimental data
- most precise inclusive DIS cross sections in the broad kinematic range
- semi-inclusive data provide further constraints
- test assumptions on the PDF parametrization and model parameters

examples:
- choice of α_S and running of strong coupling
- different treatment of heavy quarks

PDF fits using HERA jet data: fixed α_s



Inclusive DIS data:
combined HERAI+HERAII

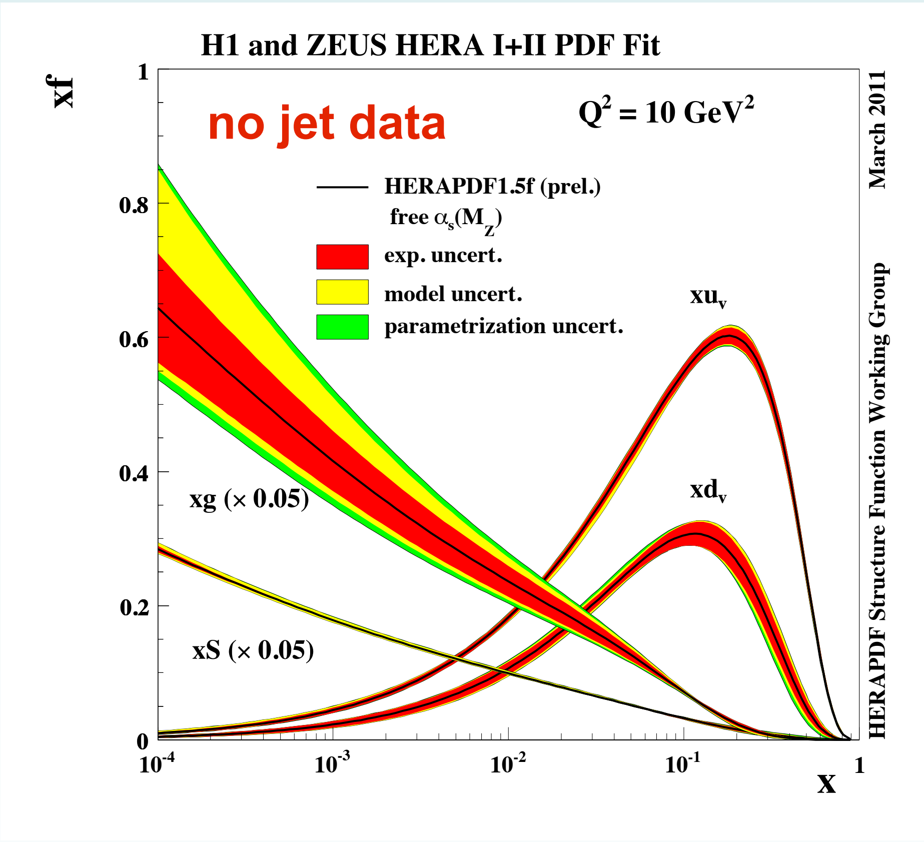
Jet data:
H1 high Q^2 , *EPJ C**65** (2010)*
low Q^2, *EPJ C**67** (2010)*

ZEUS incl. jets *PLB**547** (2002)*
incl.+2jets *NP B**765** (2007)*

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

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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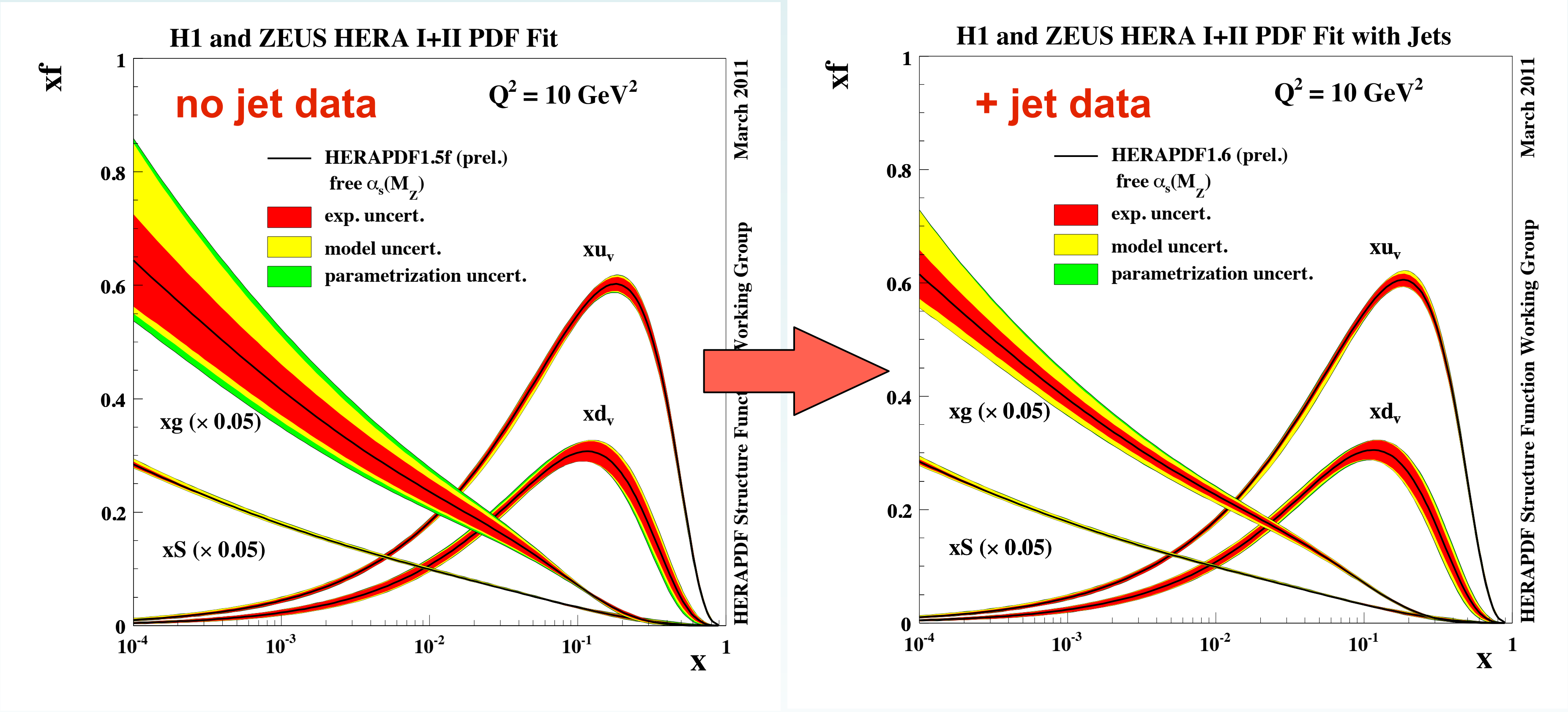
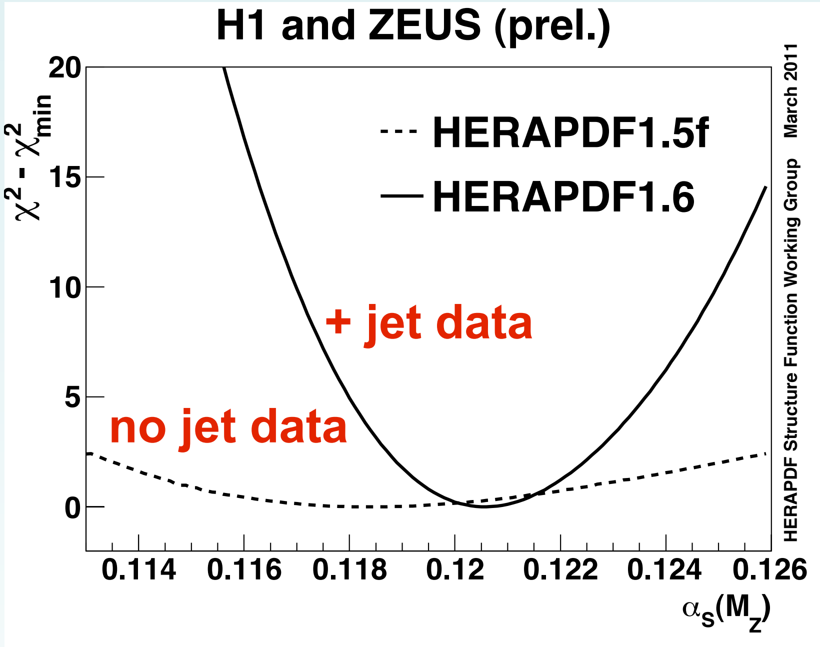
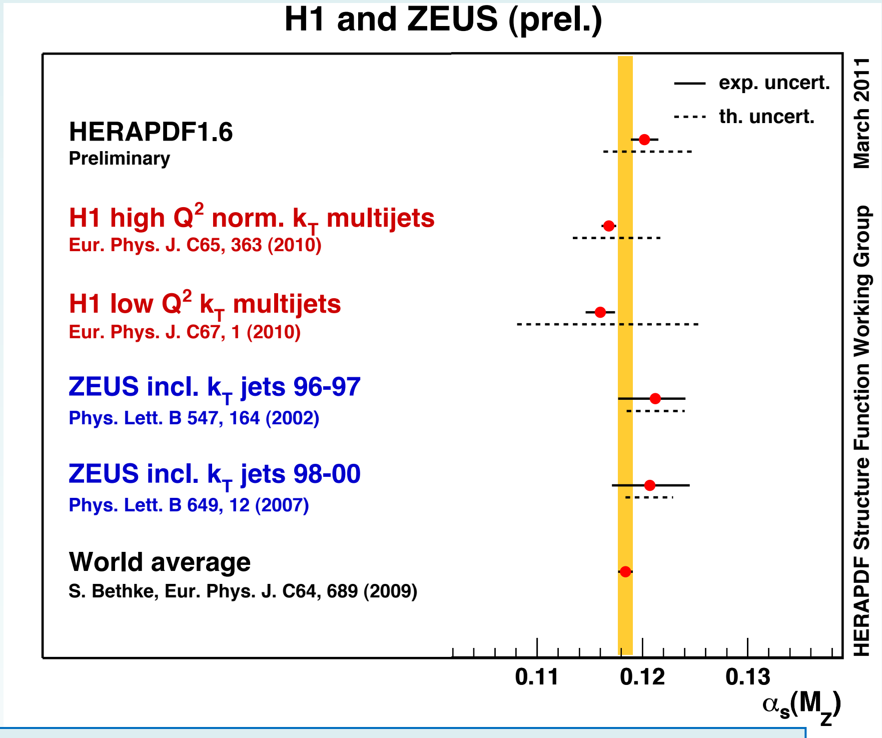


Inclusion of jet data into the PDF fit **decouples** the gluon and α_s (Mz)

α_s (Mz) from PDF fits including HERA jet data

Scan of the α_s (Mz) in the PDF fit





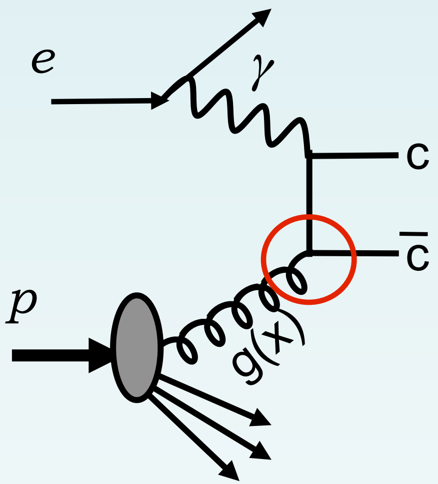
PDF and α_s (Mz) determined in the common fit:

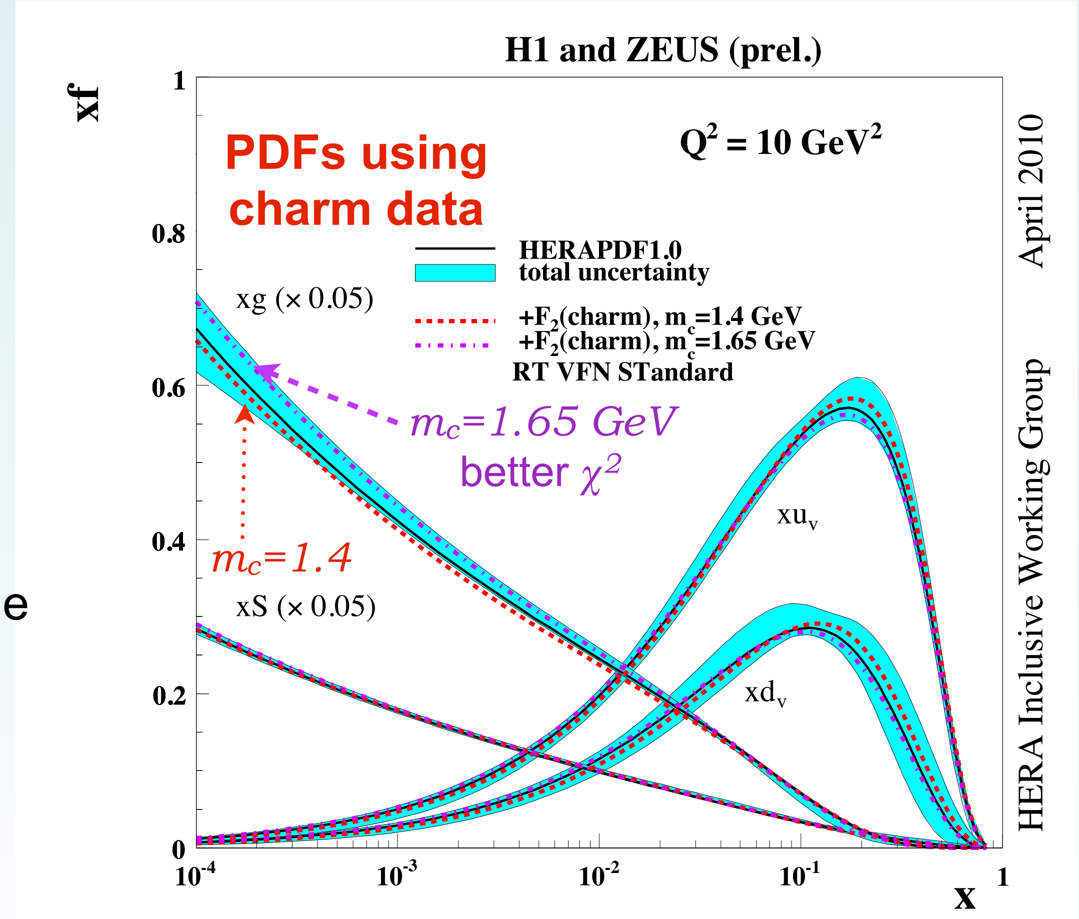
$\alpha_s (M_z) = 0.1202 \pm 0.0013_{exp} \pm 0.0007_{model/param} \pm 0.0012_{had} + 0.0045_{scale}$

From including the Jet data in the PDF fit: determine gluon and α_s (M_z)

Charm data in the PDF fit

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





Heavy quark treatment in PDFs is quite some issue

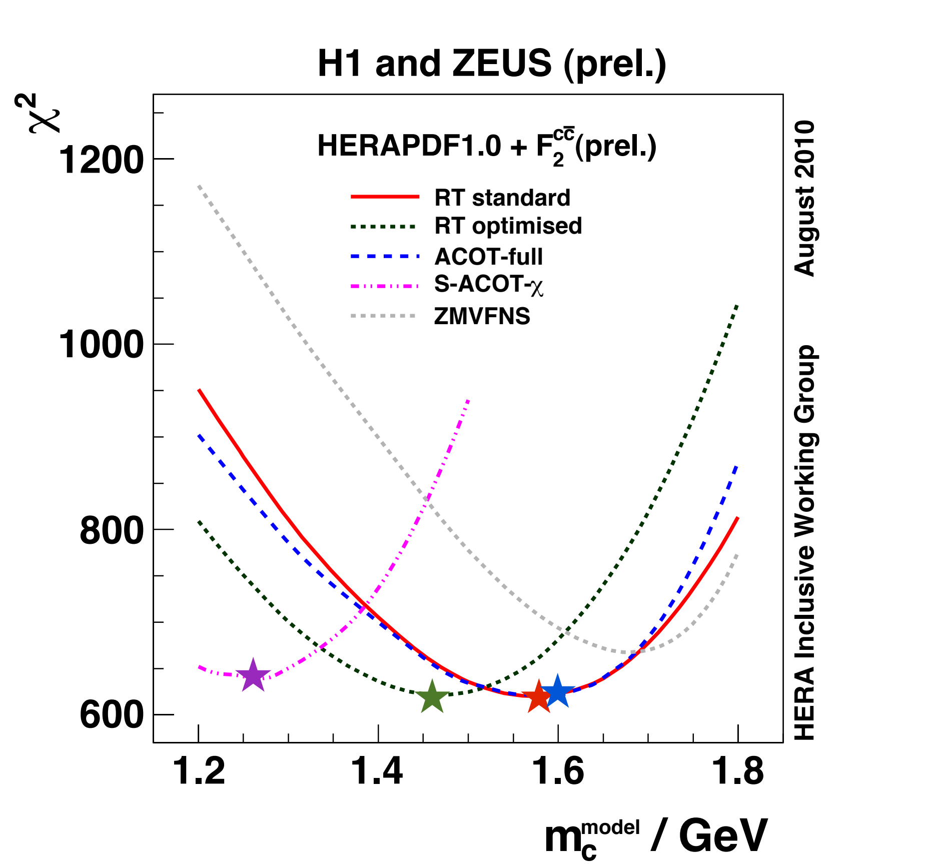
different schemes exist, (treatment of mass terms in perturbative calculation) assume different m_c

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

Charm data in the PDF fit

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

➥ pin down the value of m_c for different heavy quark schemes



Different HQ schemes prefer

different optimal m_c (★)

↓

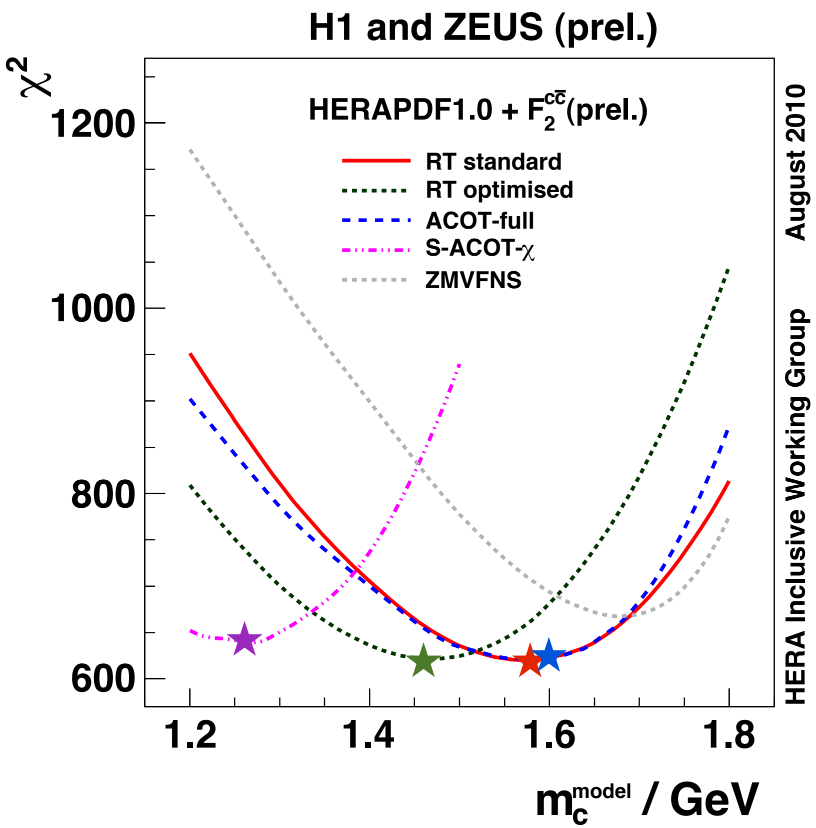
parameter of a specific

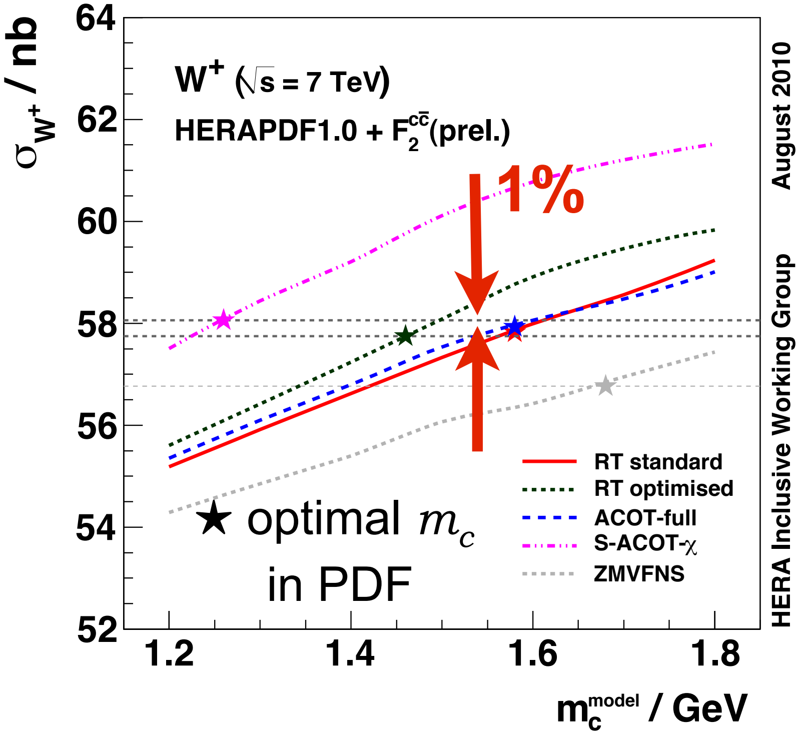
HQ scheme in PDF fits

From including the charm data in the PDF fit we do learn about m_c^{model} in the fit

Value of m_c in PDF important for W/Z at LHC

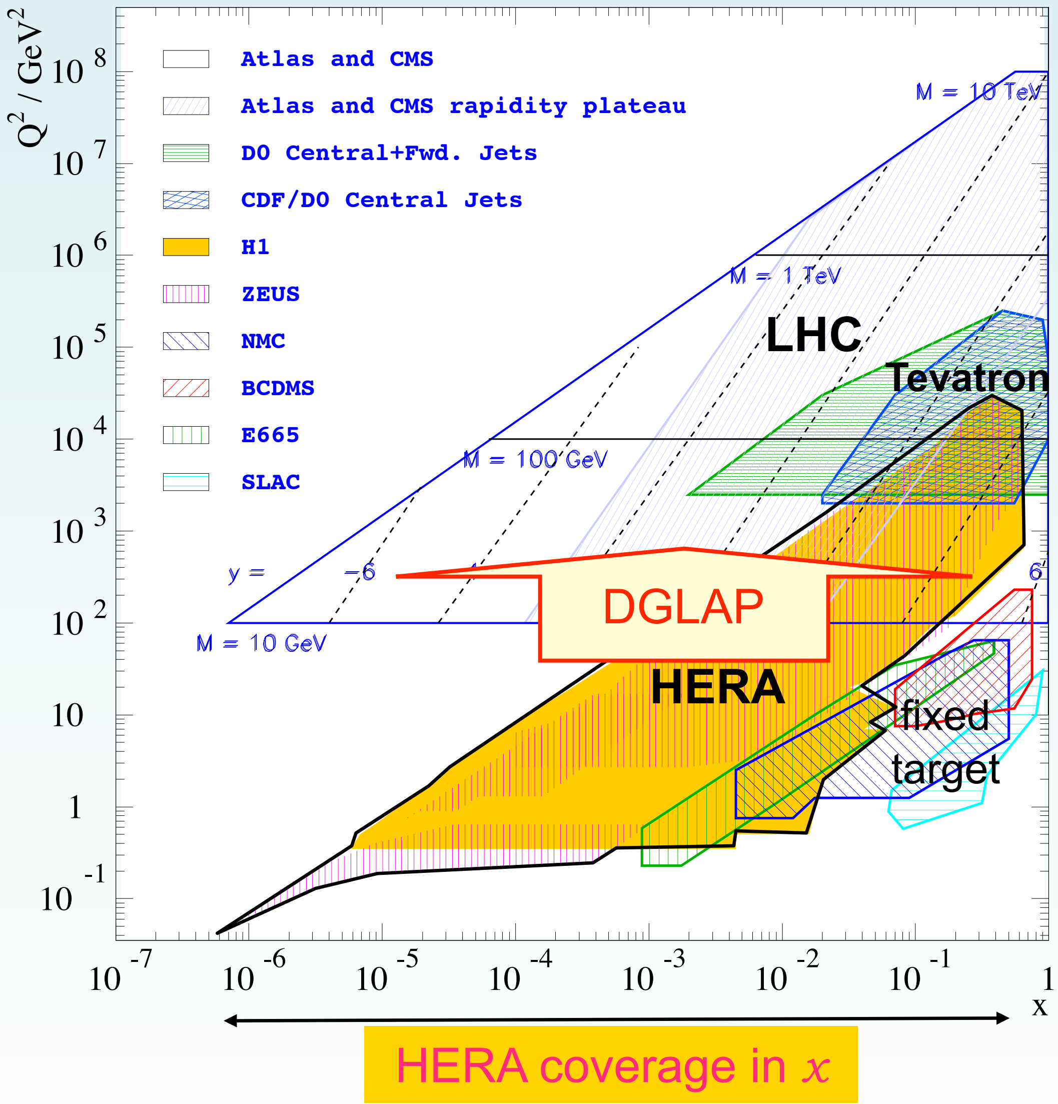
Dominant error on predictions for W and Z cross sections due to m_c in PDF different heavy flavour schemes use their preferred assumptions:





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

PDFs from HERA to Tevatron and LHC



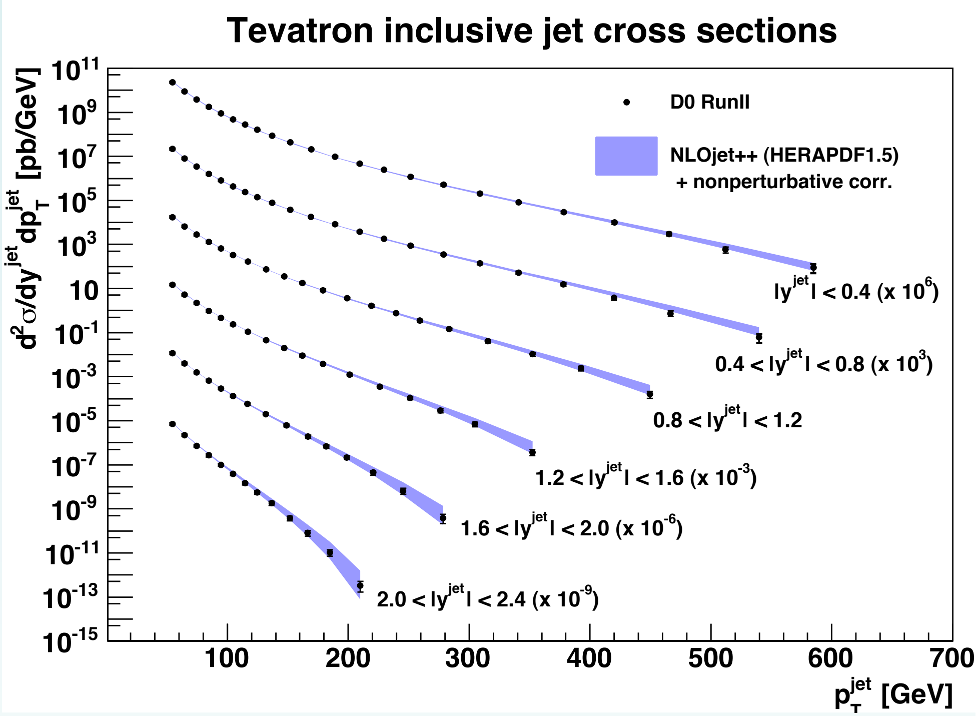
PDFs:

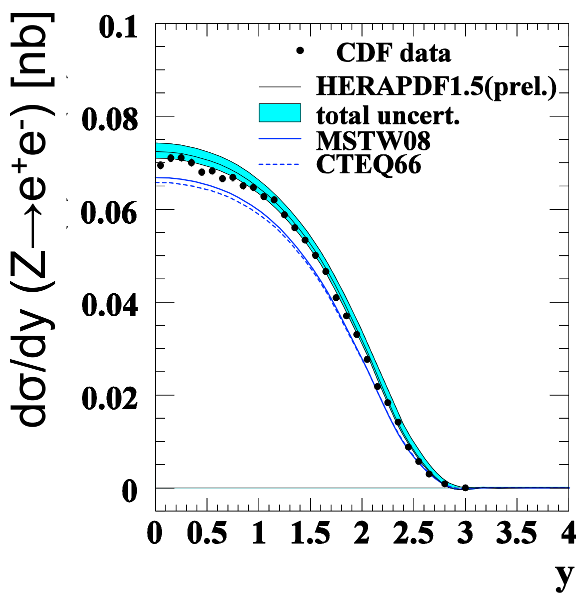
intrinsic property of nucleon
i.e process independent

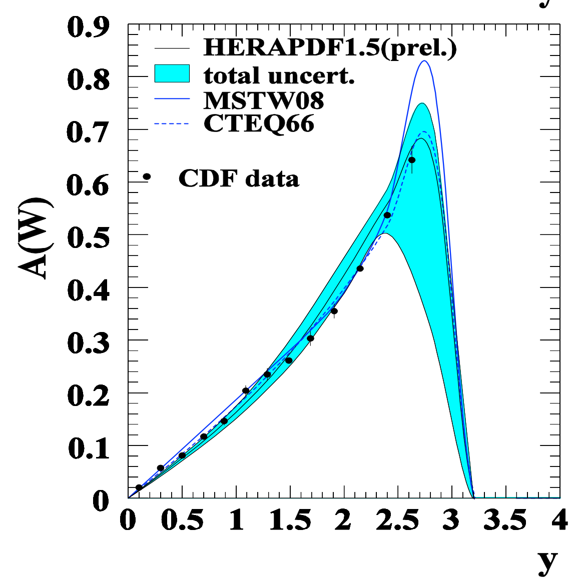
From HERA to kinematics of Tevatron, LHC:

evolution in Q^2 via DGLAP

HERAPDF and measurements at Tevatron





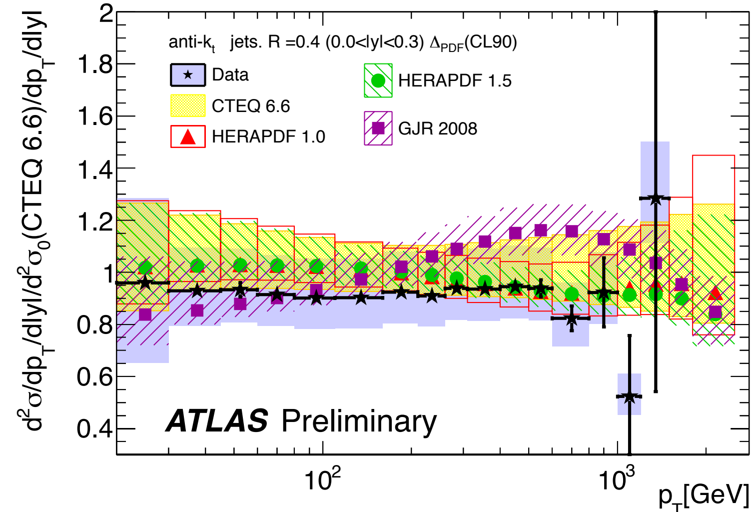


Prediction based on HERAPDF agrees well

with Tevatron measurements of jets or W and Z production

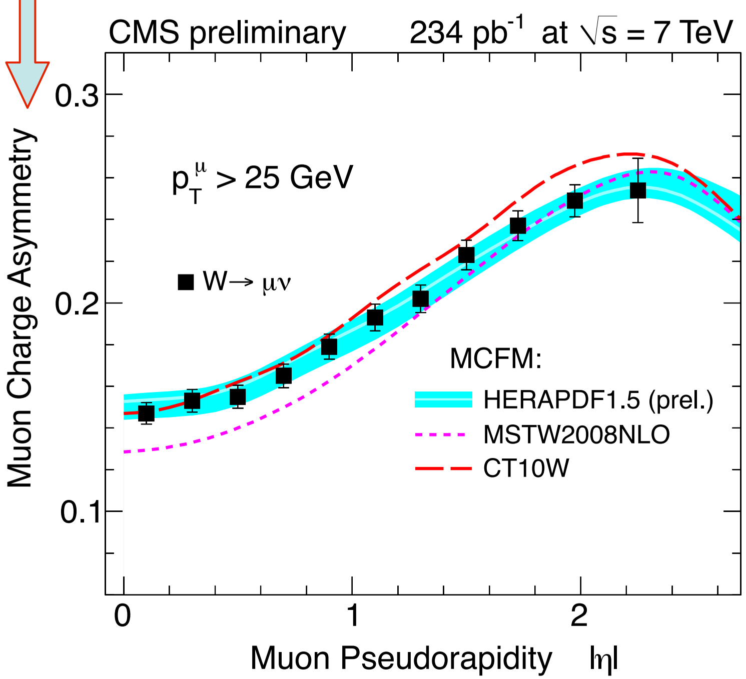
HERAPDF and measurements at the LHC

Jet production measurement:
sensitive to gluon distribution, $\alpha_S\,(M_Z)$

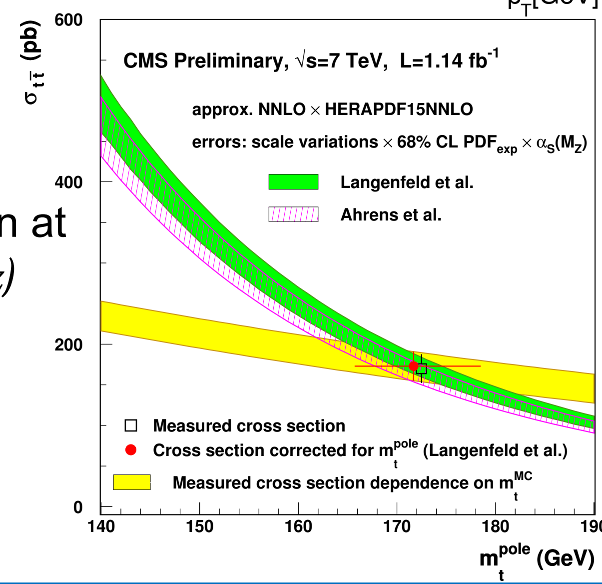


W muon charge asymmetry:
sensitive to difference between u and d

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



Top pair production:
sensitive to gluon at high x, $\alpha_S\,(M_Z)$



HERAPDF describes well the results; LHC data will put further PDF constraints

Tool for PDF fits: HERAFitter

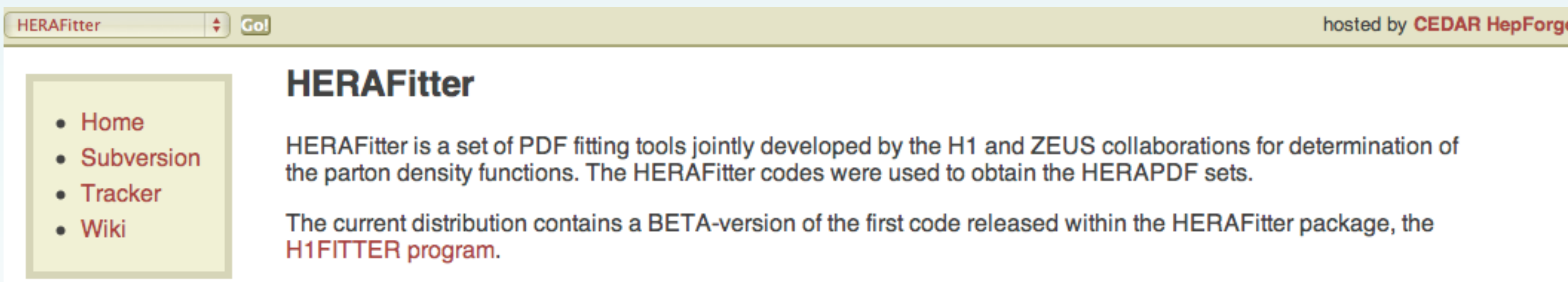
Developed/supported by HERA experts, follows HERAPDF approach:

✓ experimentalists perform QCD analysis of the PDF-sensitive data and tune/test phenomenology

✓ very close collaboration with theory groups

✓ implies possibility to use different available heavy flavour schemes

Open source code, available on HEPForge:http://projects.hepforge.org/herafitter/



β-release includes

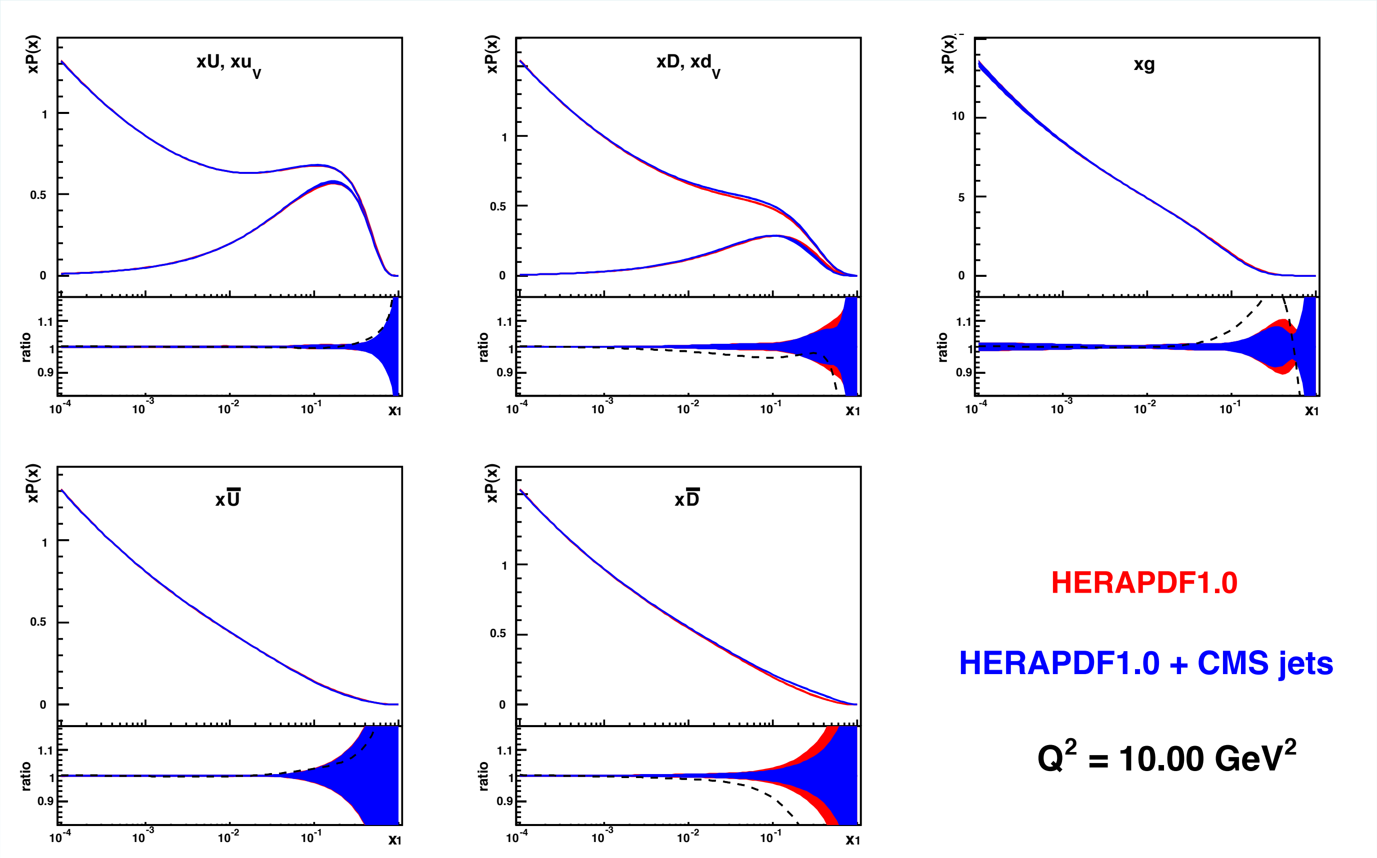
DIS and some semi-inclusive data + examples how to include new data

different statistical methods of uncertainty treatment, etc..

Already used in ATLAS and CMS

Tool for PDF fits: HERAFitter

CMS jets included in the PDF fit (arXiv:1106.0208) no correlations published yet



Many results are in the approval procedure, correlations has to be studied.

Expect soon more constraints from Drell-Yan, Jets, top pair production...

Summary

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

HERA DIS data provide highest precision at low and medium x

- **Heavy quarks and α_S: 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

- **HERAFitter tool developed to produce PDF fits, taking lessons learned at HERA with strong support from theorists**

Developers and Fitters are welcome

Back up

Combination Procedure

Minimized value:

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

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

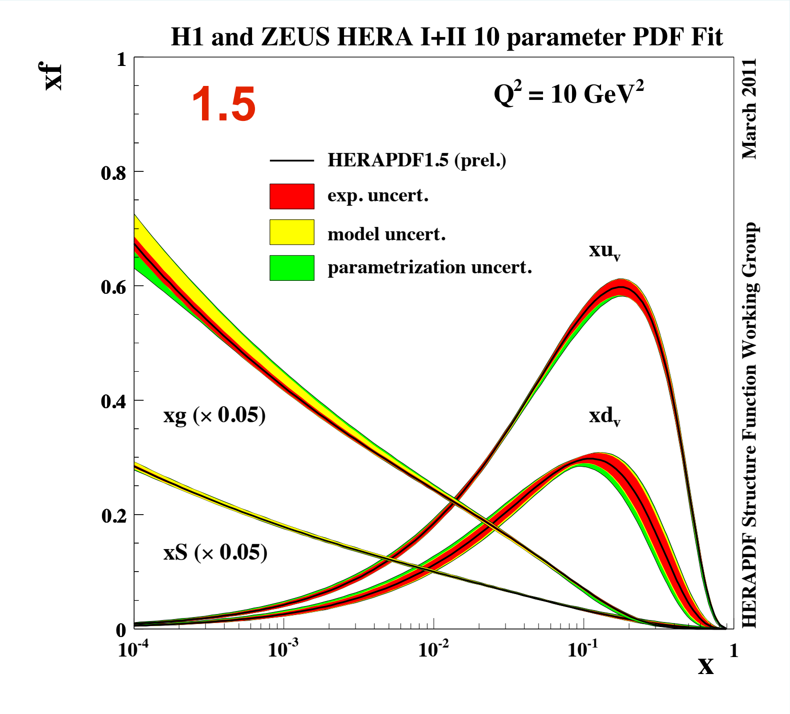
m^i – true value (corresponds to min χ^2)

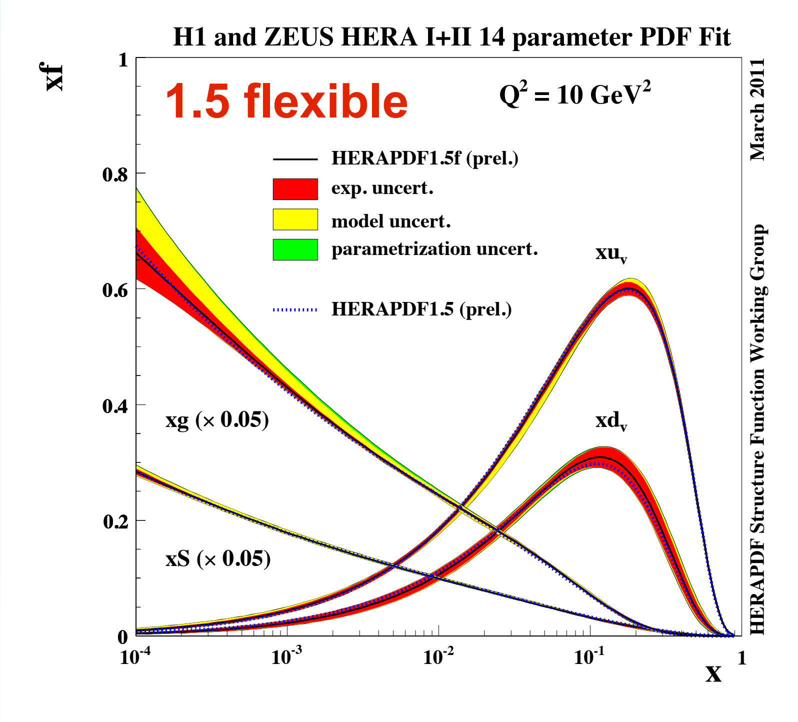
Measurements performed sometimes in slightly different range of (x,Q^2)

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

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

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) $A'_g = B'_g = 0,\ B_{d_v} = B_{u_v}$ $\quad D_{u_v} = 0$

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

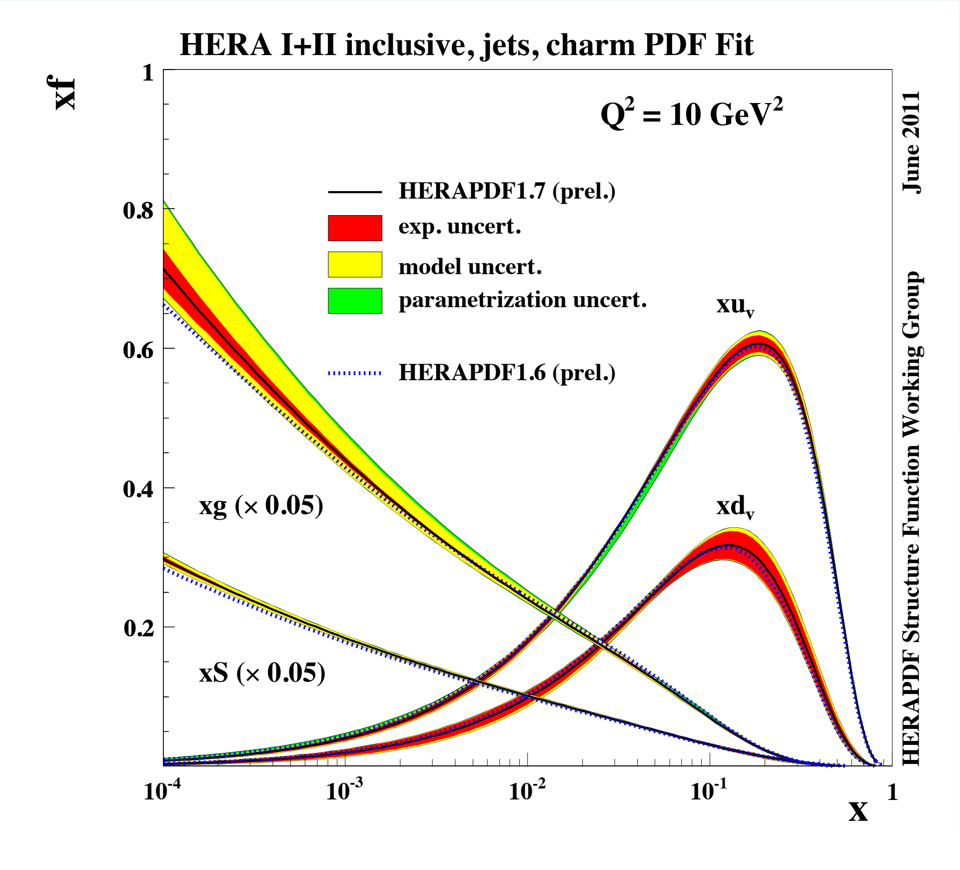
Flexible parametrization

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

PDF Group Landscape

MSTW

- 28 parameters, 20 eigenvectors; inflated $\Delta\chi^2$ to 5-20 for eigenvectors (data incomparability)

CTEQ

- 26 eigenvectors; inflated $\Delta\chi^2$ to ~40 for eigenvectors

NNPDFs

- minimises χ^2 and expand about the best fit

HERAPDF

- 10 eigenvectors (now more flexibility added to PDFs); $\Delta\chi^2 = 1$, model and parametrisation uncertainties

AB(K)M

- 21 parameters, $\Delta\chi^2 = 1$

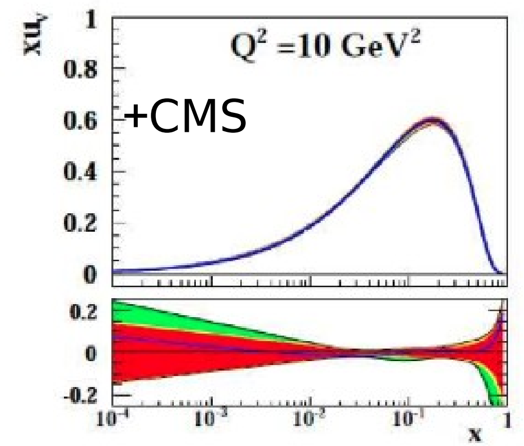
GJR

- 20 parameters, use $\Delta\chi^2$ to ~20, strong constrains on input form of PDFs

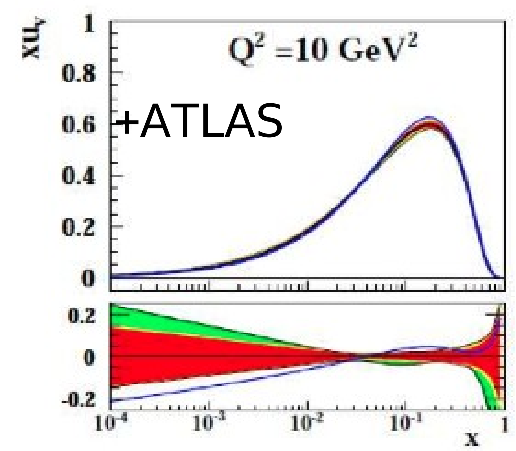
W Asymmetry data in the fits

Early LHC data are described fairly well

→ if these data are fit, the PDFs lie within the HERAPDF1.5 error band



	Before fit	After fit
- W asymmetry CMS:	χ^2/dof=6.5/12	3.7/12
- W asymmetry ATLAS:	χ^2/dof=30/11	16/11



ATLAS and CMS pull u valence quark
in opposite directions

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

- *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 ~ $ln(\frac{Q}{m_{HQ}})$

- *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

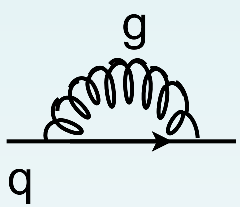
  smooth matching with FFNS for $Q^2 \rightarrow m_{HQ}^2$ must be assured

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

Heavy Quark Mass Definition in PDFs

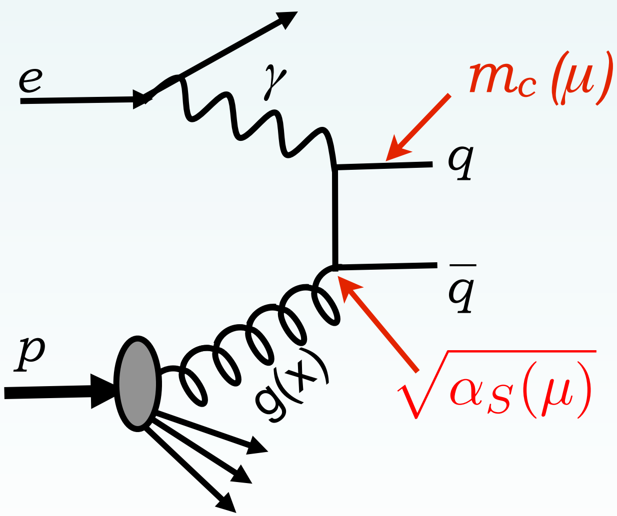
Usually HQ coefficient functions use a pole mass definition

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



running coupling

running mass

Heavy Quark Mass Meaning/Value 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

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

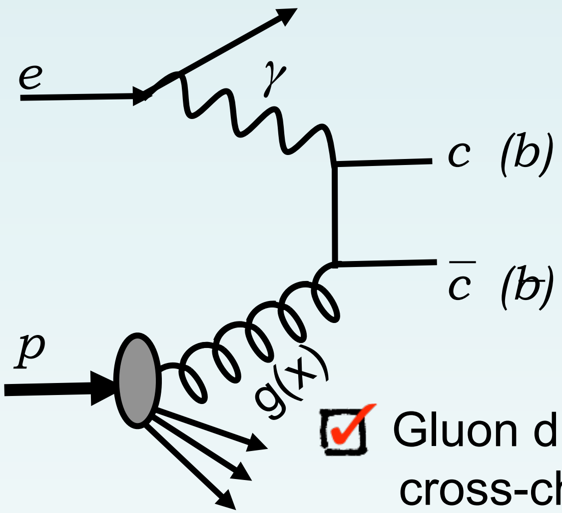
PDG values: 1.66±0.18 / 4.79

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 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 %

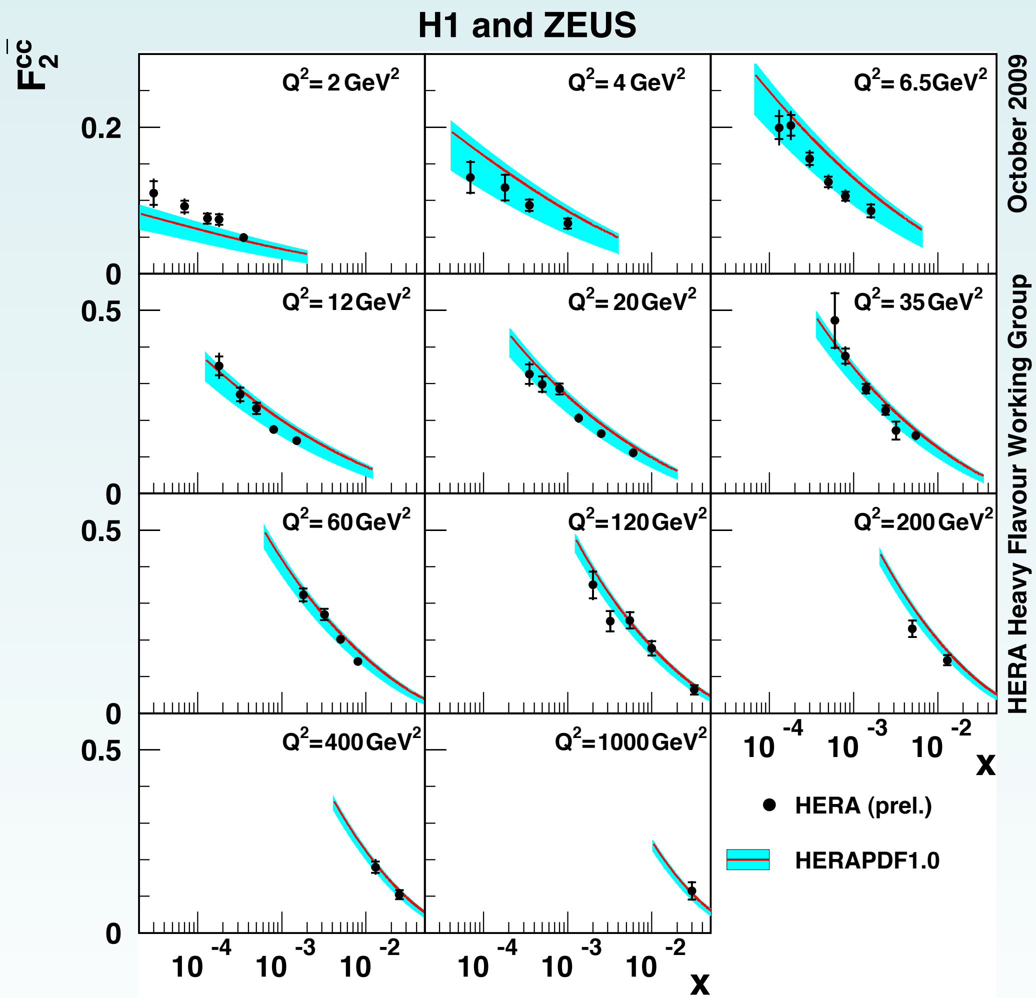
- Gluon directly involved:
  cross-check of *g(x)* from NC and CC DIS cross sections

- 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 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

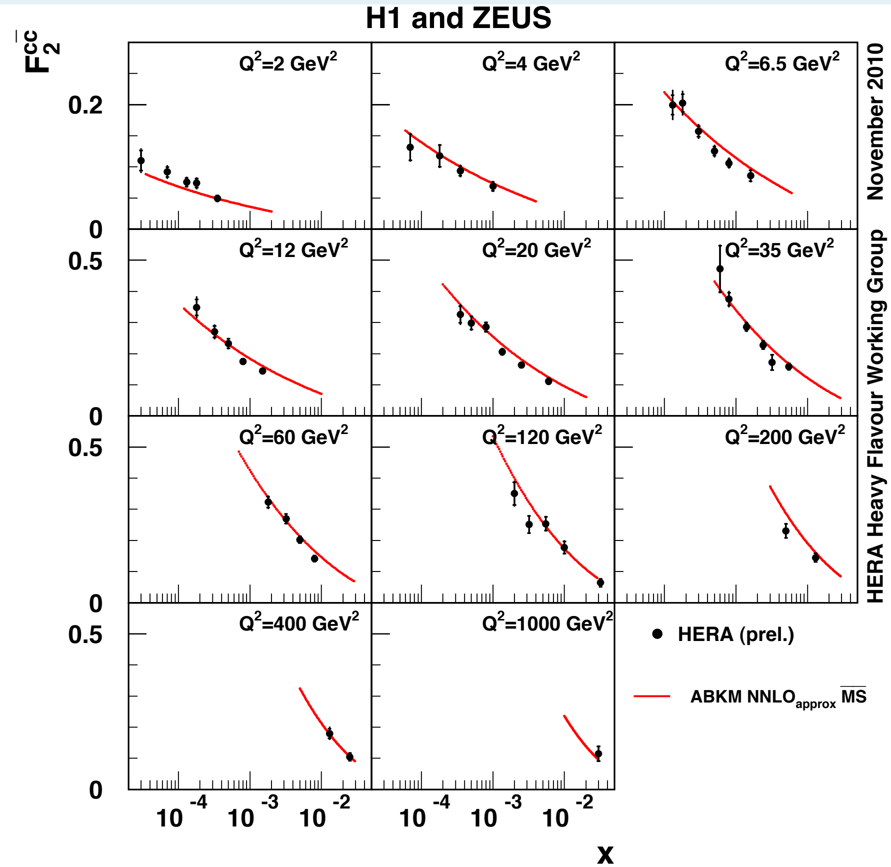
PDG pole mass

PDFs obtained from inclusive data sensitive to the choice of m_c

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

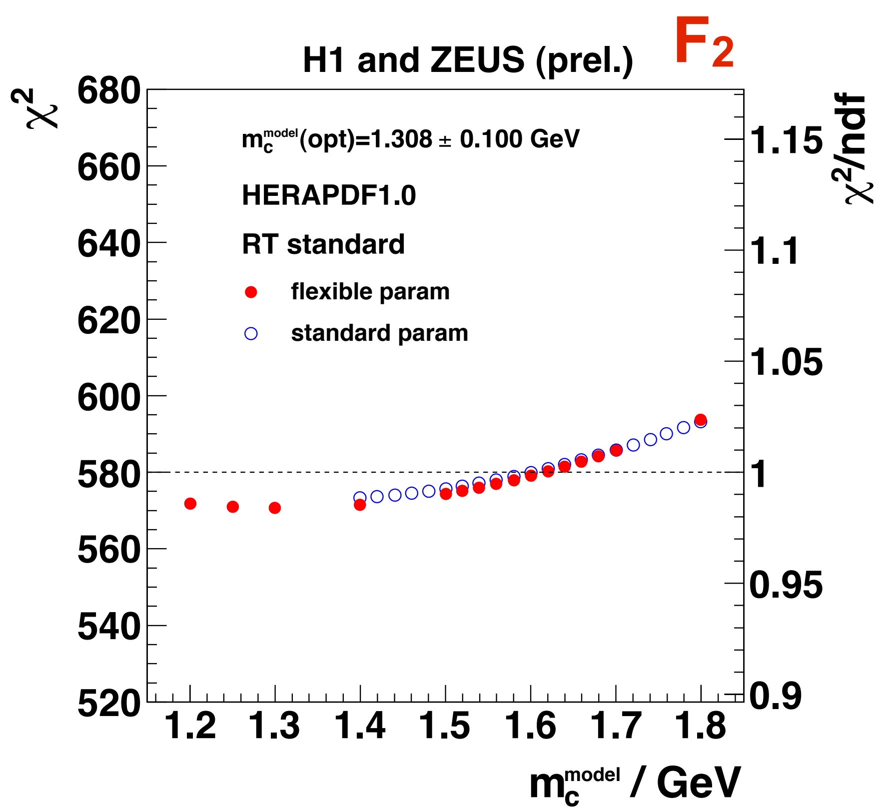
$m_c(m_c)$ determined using DIS data

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

Charm Mass as a Model Parameter in PDF

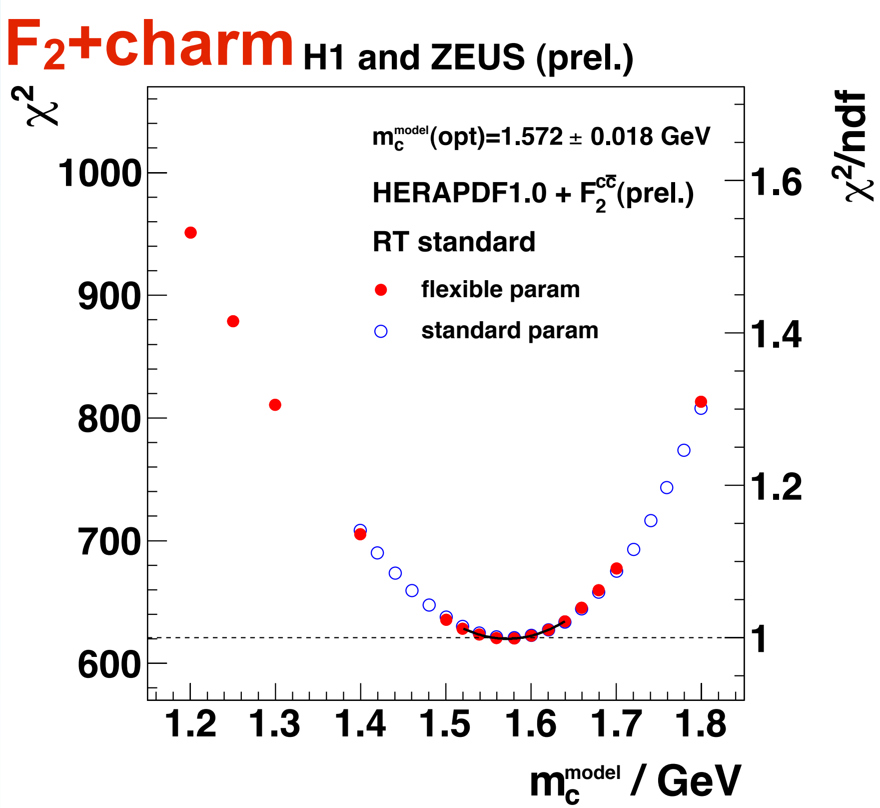
Study the sensitivity of the PDF fit to the value of m_c

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)

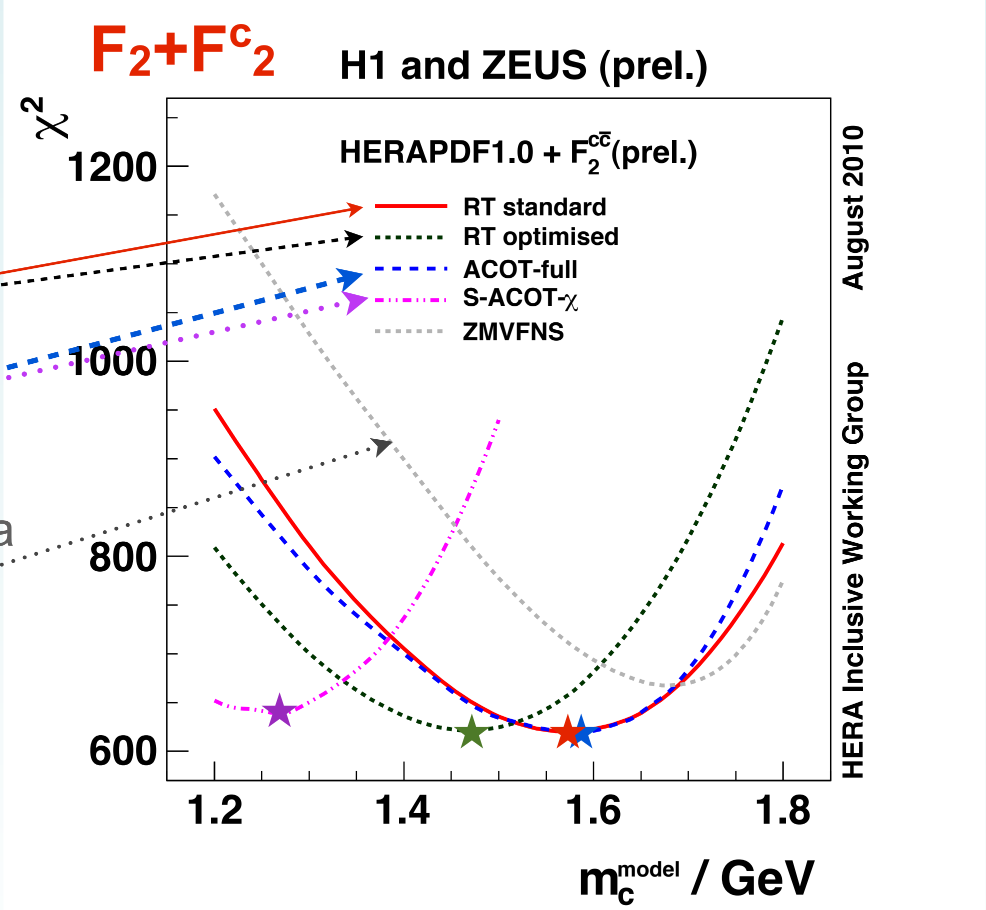
RT : MSTW PDFs

ACOT: CTEQ PDFs

ZMVFNS does not describe data
not used any more by NNPDF

Different HQ schemes prefer

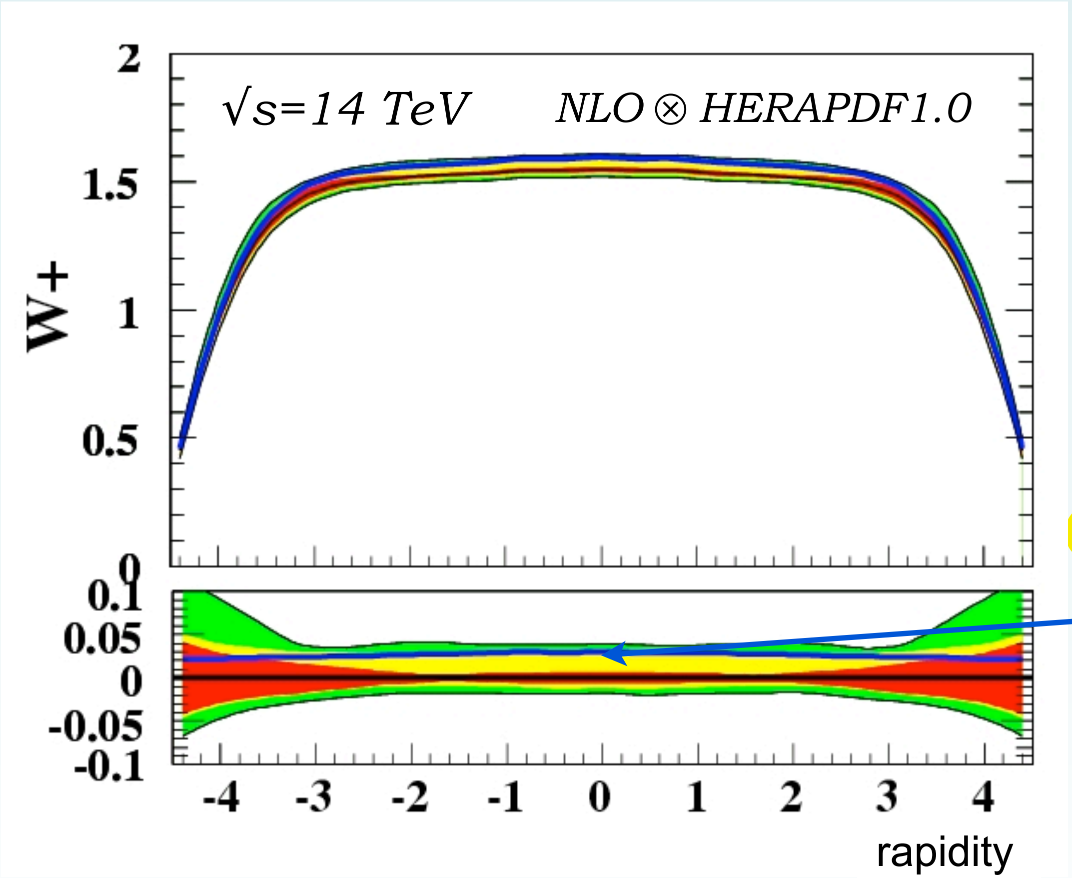
different optimal★ m_c



Inclusion of charm data into the PDF fit **decouples** the gluon 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

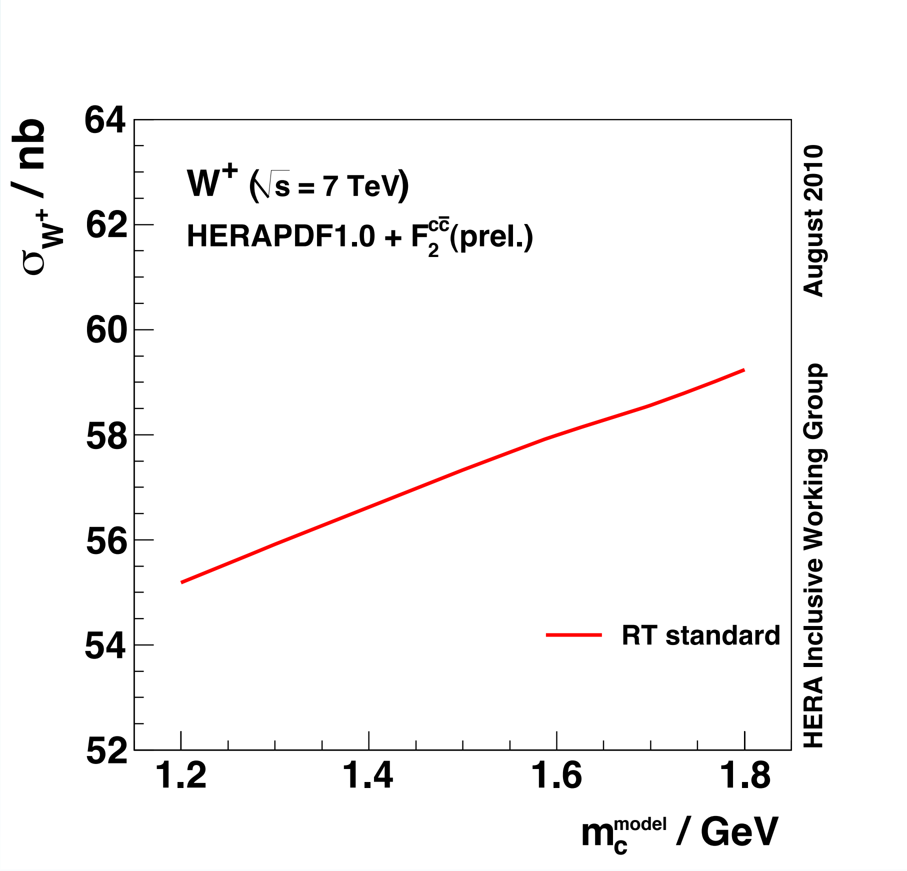
Model assumptions

including m_c variation

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

Charm at HERA and W/Z at LHC

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

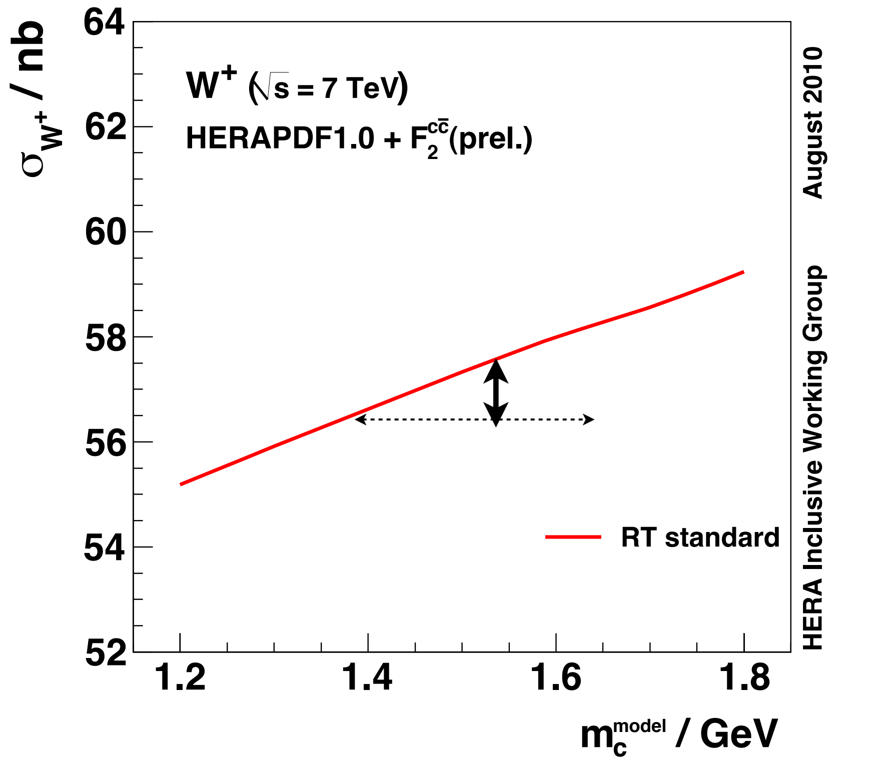


Larger m_c → more gluons, less charm → more light quarks → larger σ_W

Charm at HERA and W/Z at LHC

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

Only one HQ scheme



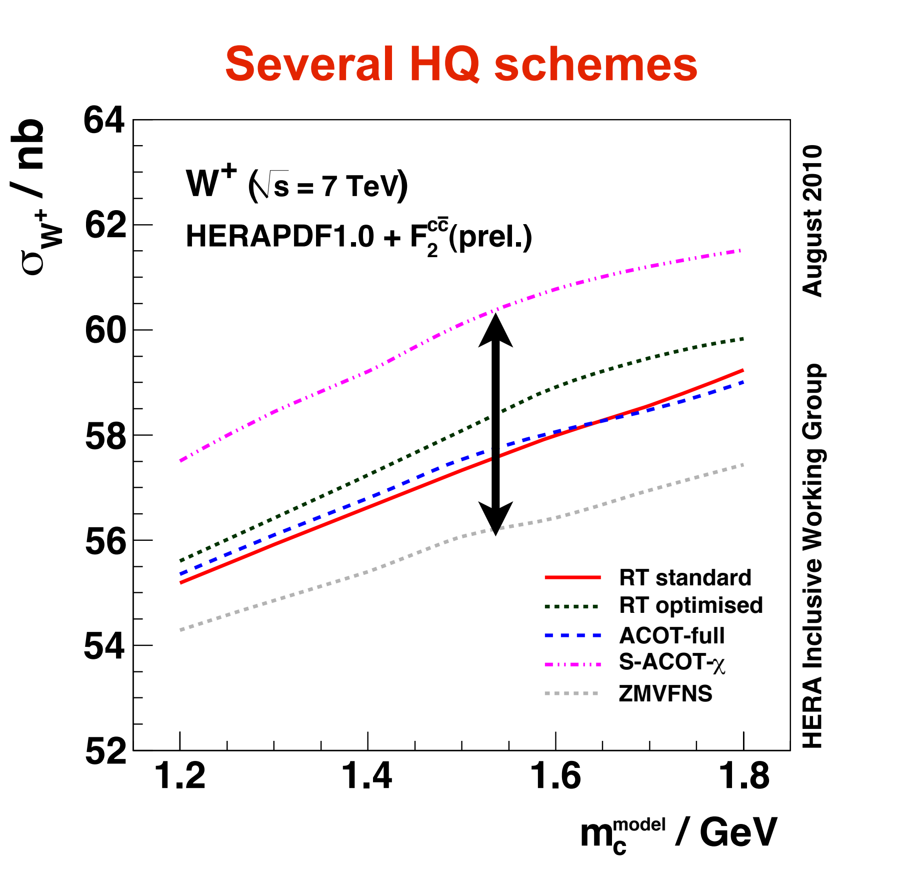
m_c variation in PDF

$1.4 < m_c < 1.65$ GeV

3% uncertainty on W prediction

Charm at HERA 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

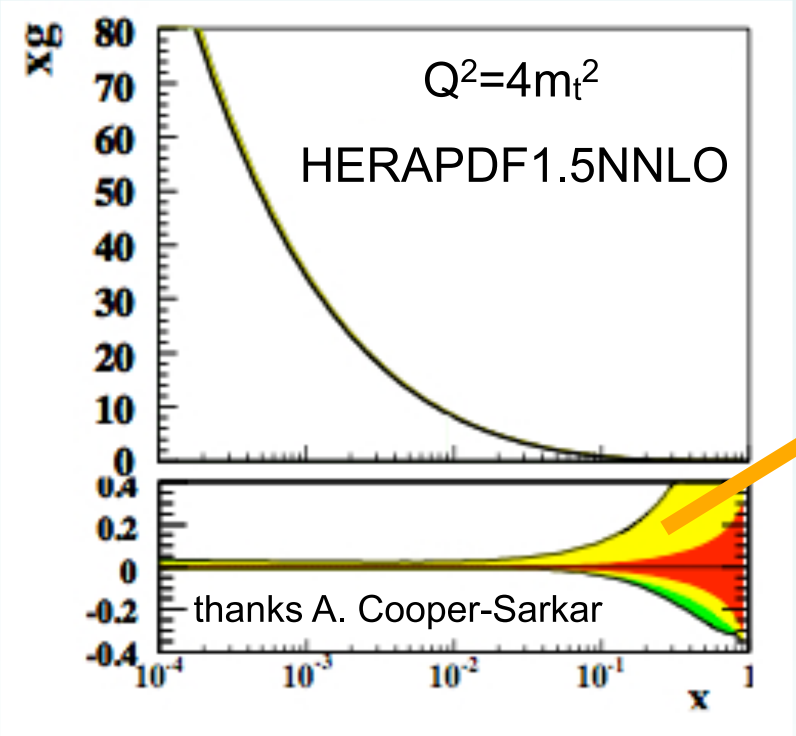
Using different HQ schemes:

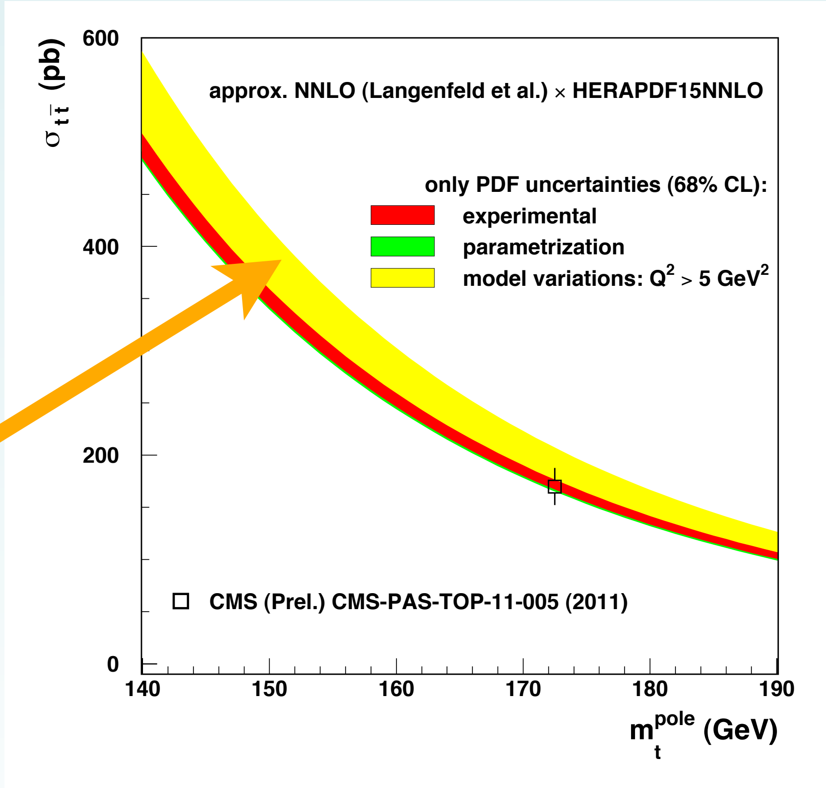
+ 7% uncertainty

Large uncertainty on σ_W prediction due to HQ treatment in PDFs

(HERA)PDF and top quark at the LHC

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