HELMHOLTZ GEMEINSCHAFT

Bundesministerium für Bildung und Forschung

HERAPDF

ICHEP2012 Melbourne

36th International Conference on High Energy Physics

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Melbourne Convention and Exhibition Centre

Ringailė Plačakytė
DESY

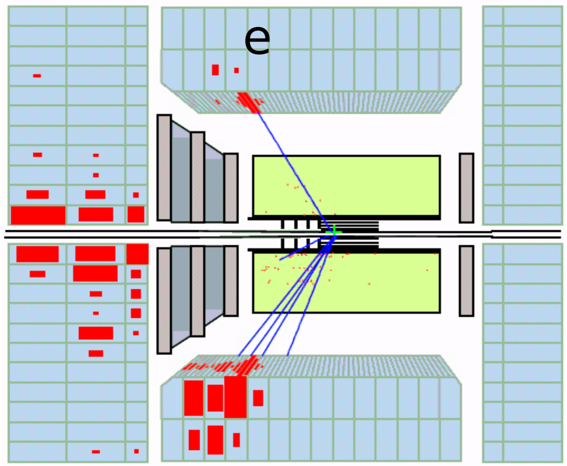
on behalf of:

H1 and ZEUS

ep Scattering at HERA

DIS cross sections provide an access to parton distribution functions in proton:

Neutral Currents



$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

dominant contribution

important at high Q^2

sizable at high y

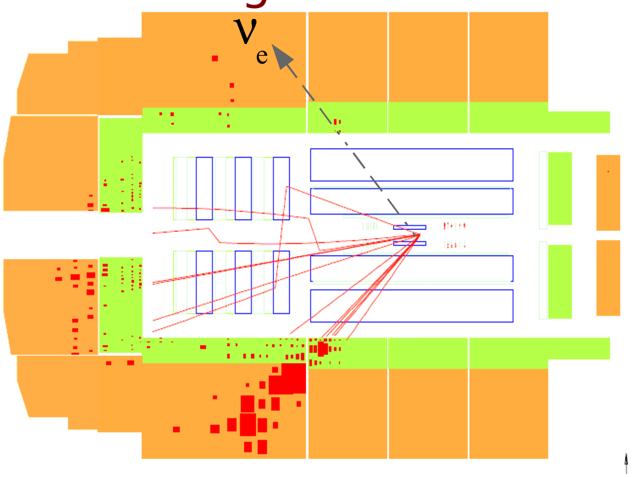
$$Y_\pm = 1 \pm (1-y)^2$$

PDFs

LO: $F_2 \approx x\sum e_q^2(q+\bar{q})$ (in NLO $(\alpha_s g)$ appears)

$xF_3 \approx x\sum 2e_q a_q(q-\bar{q})$

Charged Currents



In LO e^+/e^- charged current cross sections are sensitive to different quark densities:

$$e^+: \quad \tilde{\sigma}_{CC}^{e^+p} = x[\bar{u}+\bar{c}] + (1-y)^2 x[d+s]$$

$$e^-: \quad \tilde{\sigma}_{CC}^{e^-p} = x[u+c] + (1-y)^2 x[\bar{d}+\bar{s}]$$

HERAPDFs: Overview

HERAPDF: only HERA *ep* data

- uses consistent data with well understood correlations
- no need for nuclear corrections

provide compatible NLO and NNLO predictions with other PDF groups

Overview of HERAPDFs (this talk):

DATA	PDF set	
H1-ZEUS CC,NC HERAI	HERAPDF1.0 (NLO,NNLO)	
H1-ZEUS CC,NC HERAI+(prel.)II	HERAPDF1.5 (NLO,NNLO)	*recommended*
CC,NC HERAI+(prel.)II +jets	HERAPDF1.6	
CC,NC HERAI +charm	HERAPDF1.0+charm	
All data above	HERAPDF1.7	
Planned: H1-ZEUS HERAI+II	HERAPDF2.0 (NLO,NNLO)	

Part of HERAPDF project: **HERAFitter**
- open source QCD fitting tool to determine parton distribution functions

HERAPDF strategy and settings

NLO,NNLO DGLAP evolution (QCDNUM, arXiv:1005.1481)

PDFs parametrised (at starting scale Q^2_0) by:

$$xf(x,Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

A: overall normalisation
B: small x behavior
C: $x \rightarrow 1$ shape

- apply quark number and momentum sum rules

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

The optimal number of parameters chosen when no further improvements in the χ^2 are observed

- more flexible paramerisation than in HERAPDF1.0 used in fits with HERA II data

Q^2_0 = 1.9 GeV^2, α_s =0.1176, Q^2_{min}= 3.5 GeV^2, different HF schemes (RT in HERAPDF1.0)

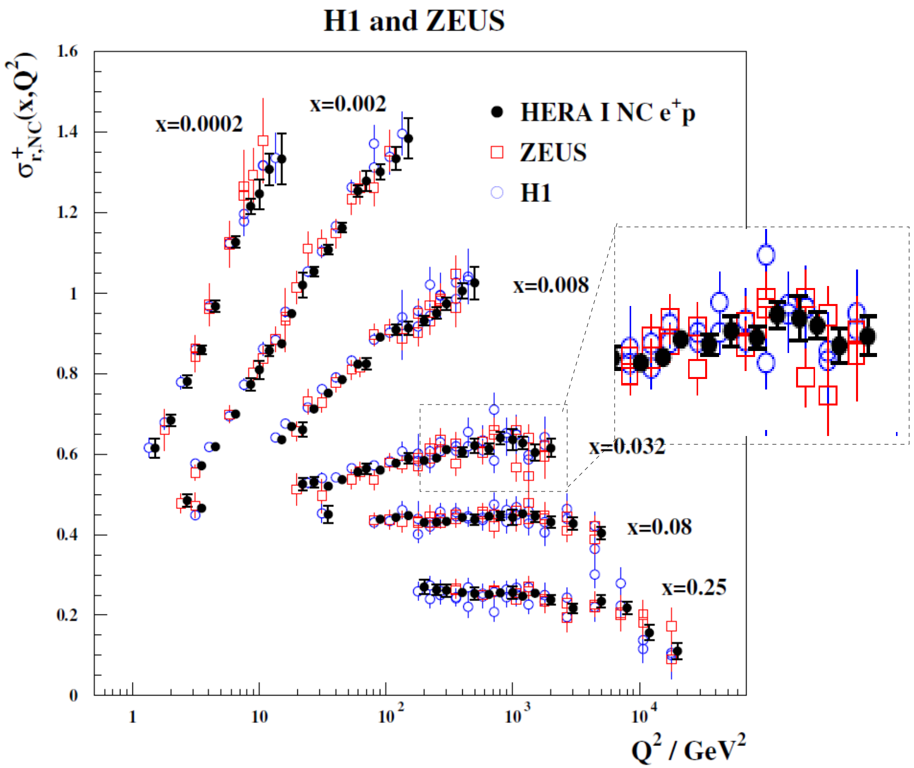
Uncertainties separated into:

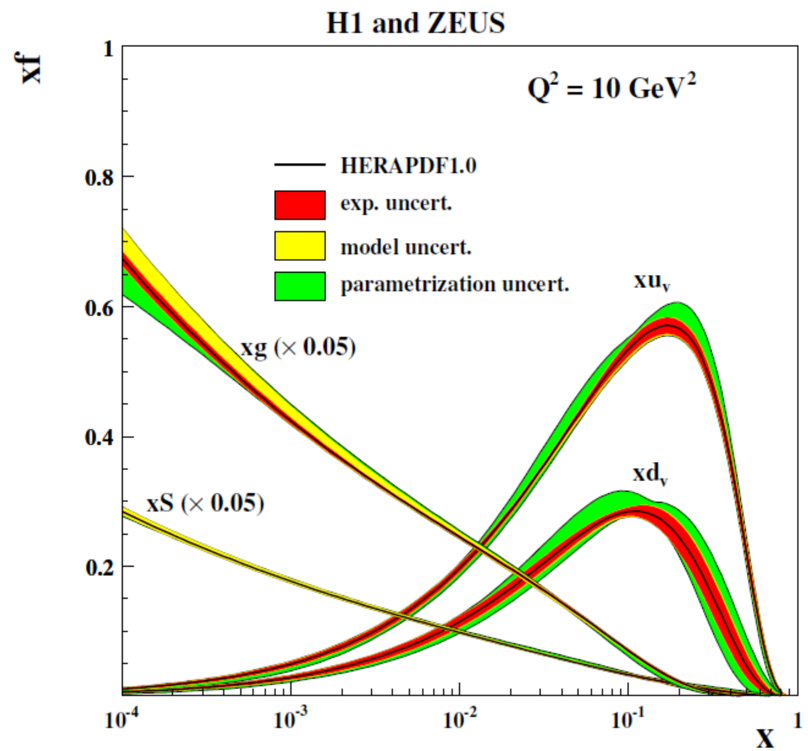
experimental	small uncertainties ($\Delta\chi^2=1$)
model	evaluated from variation of model parameters: Q^2_{min}, f_s, m_C, m_B
parametrisation	results from different parametrisation assumptions

HERAPDF1.0

HERAPDF1.0: QCD fit to combined H1 and ZEUS HERA I CC,NC data

- ultimate precision (experiments cross calibrate each other)





arXiv:0911.0884[hep-ex] https://www.desy.de/h1zeus/combined_results/index.php

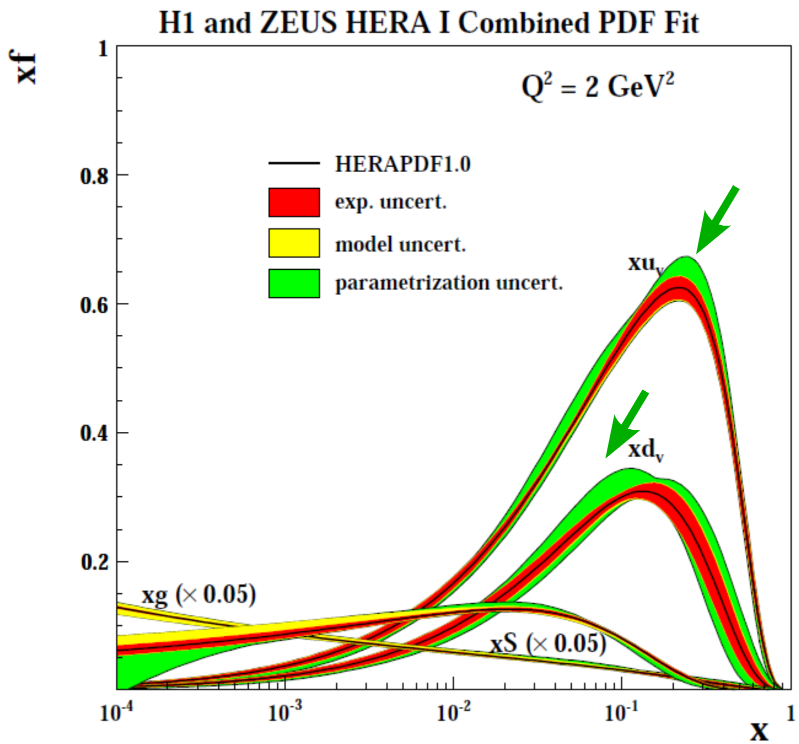
gluon – from F_2 scaling violation, F_L, *quarks* - from CC (flavour separation), NC

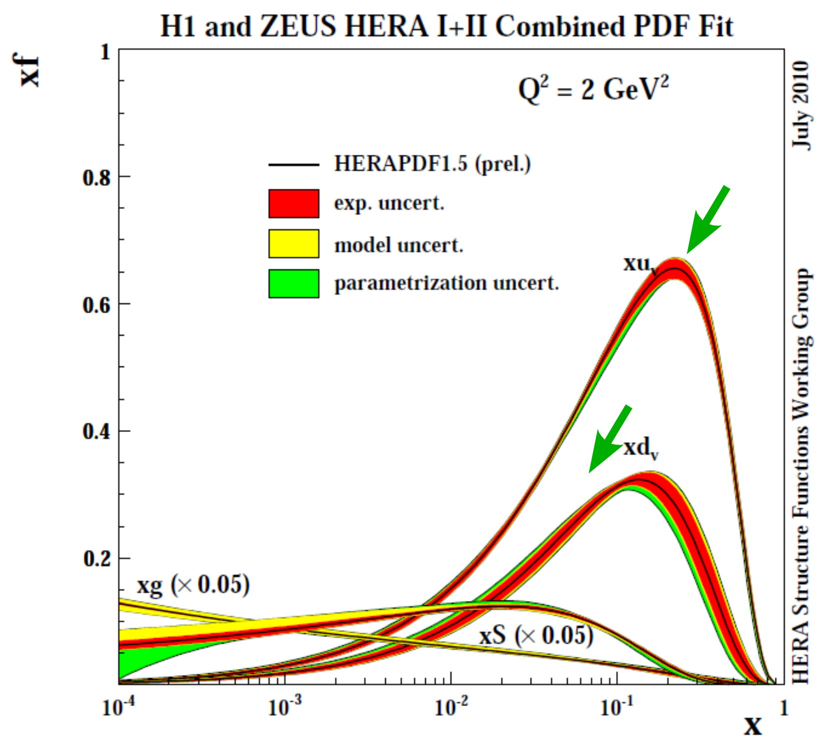
HERAPDF1.5

High precision HERA II high Q^2 data
(now in process of publishing!)

HERA I

HERA I + II

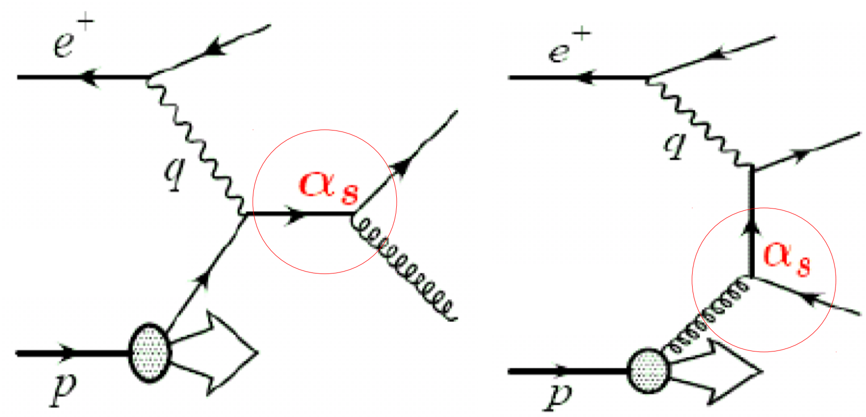




Reduced uncertainties (mainly valence quarks)

Inclusion of Jet Data: HERAPDF1.6

LO jet production in DIS:



Direct sensitivity to gluon and strong coupling constant

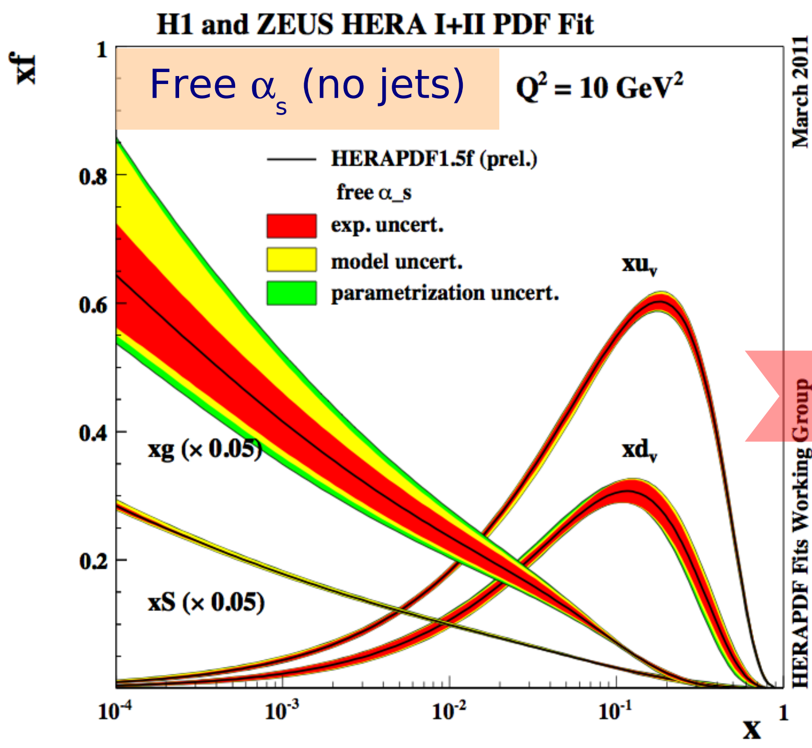
Reduce correlation of gluon and α_s in PDF fit

QCD fits with jet data
- allow to constrain simultaneously α_s and gluon

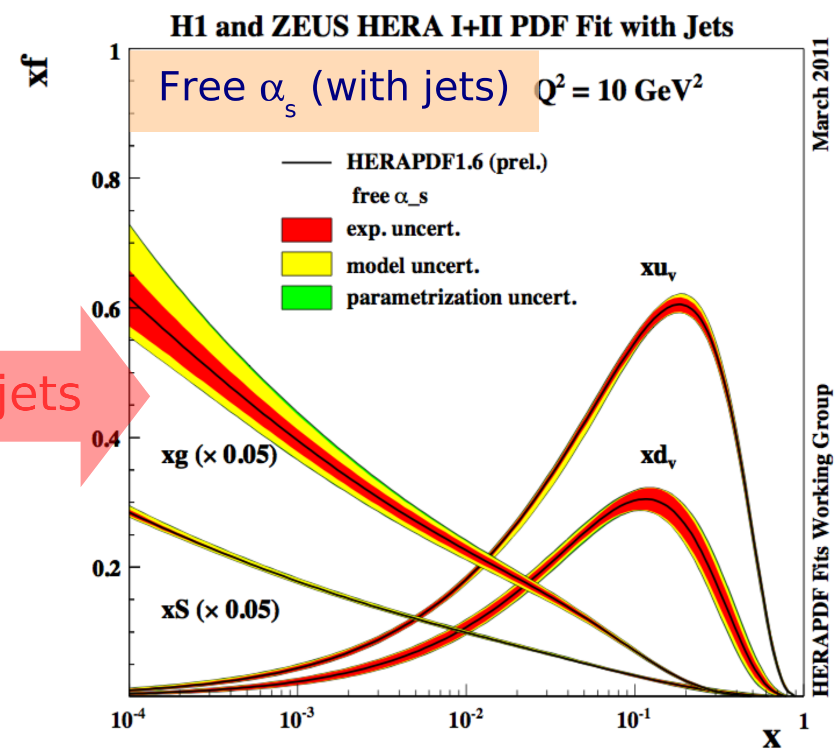
HERAPDF1.6:

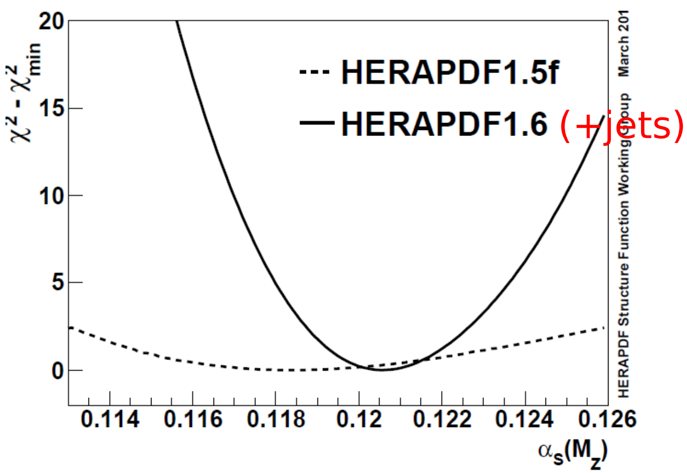
CC, NC HERA I+(prel.)II + 4 inclusive jet measurements from H1 and ZEUS

Inclusion of Jet Data: HERAPDF1.6



+ jets

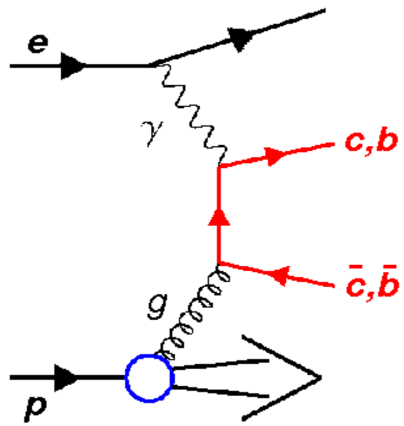




HERA jet data allow to constrain simultaneously α_s and gluon

→ $\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{mod}) \pm 0.0012(\text{had})\,^{+0.0045}_{-0.0036}(\text{th})$

Inclusion of Charm Data

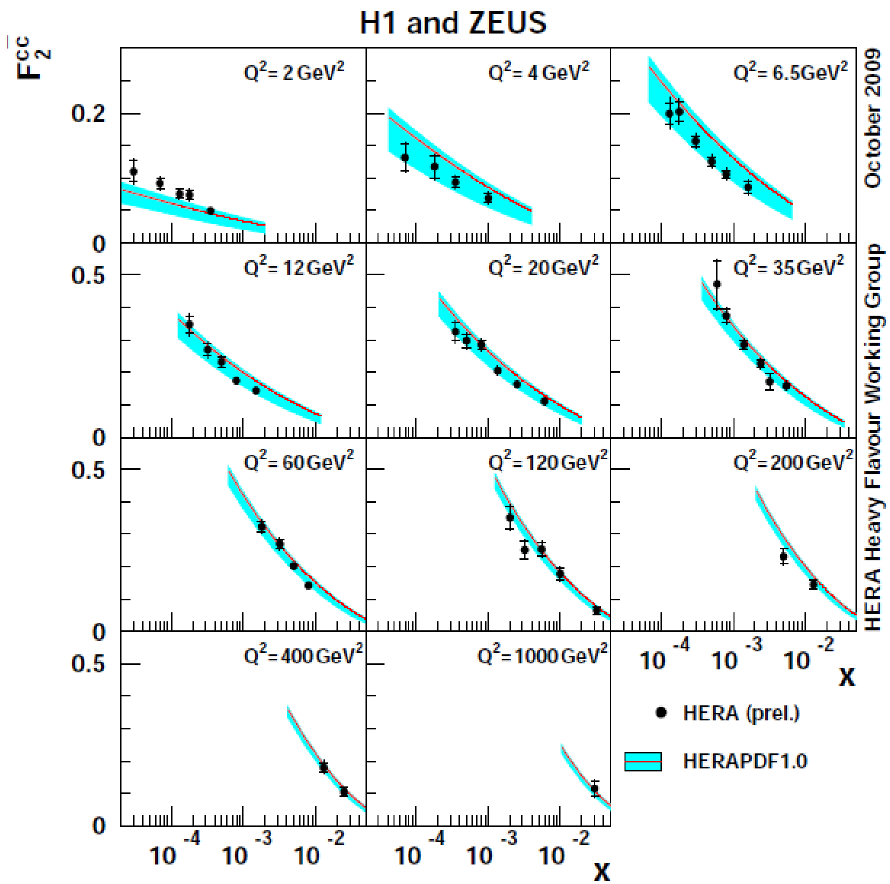


Direct access to the gluon

Heavy quark (HQ) treatment in PDFs is important

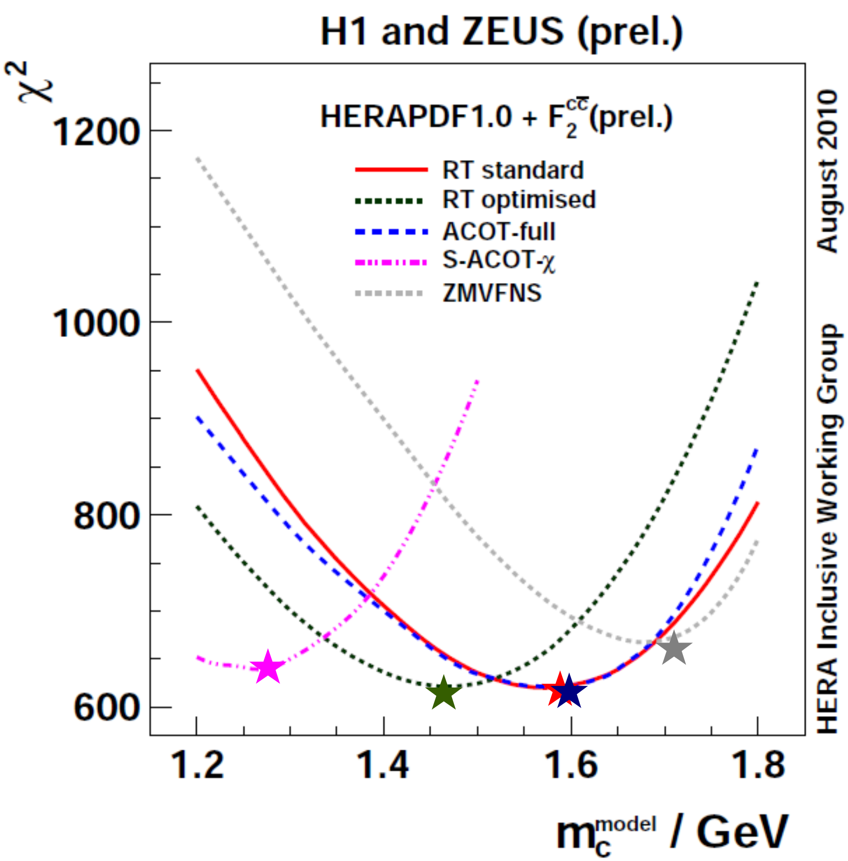
Different HQ schemes exist (different treatment of mass terms in perturbative calculation)

Combined HERA F_2^{cc} measurement

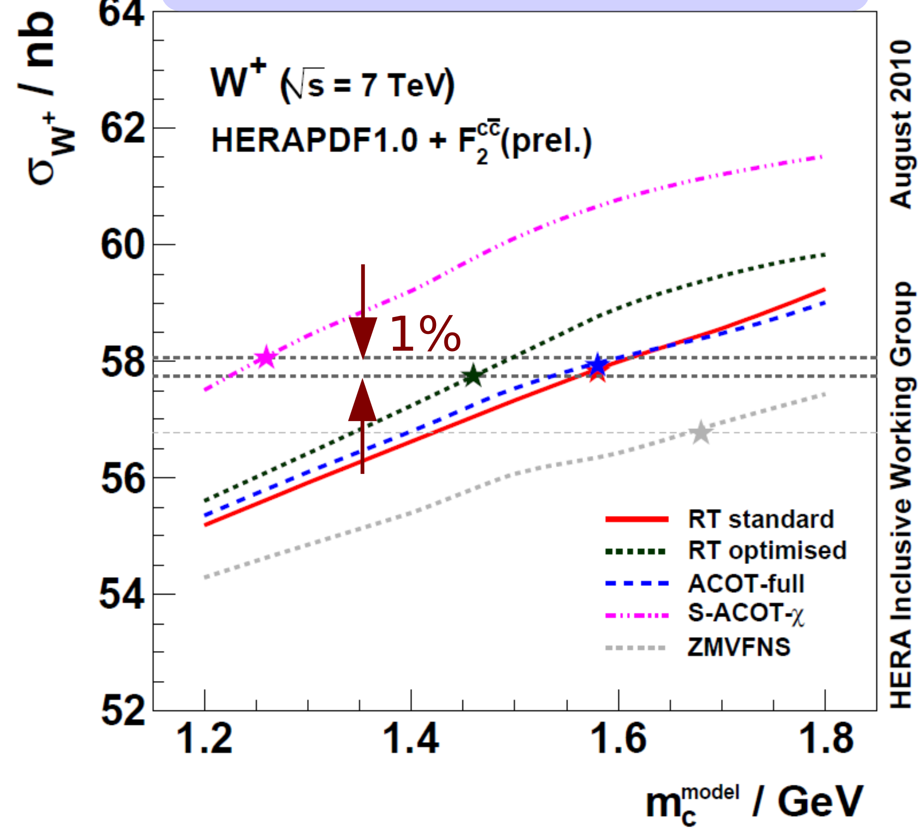


Data well described by HERAPDF prediction

Inclusion of Charm Data



W$^+$ cross section@LHC



Different schemes prefer different m_c^{model}

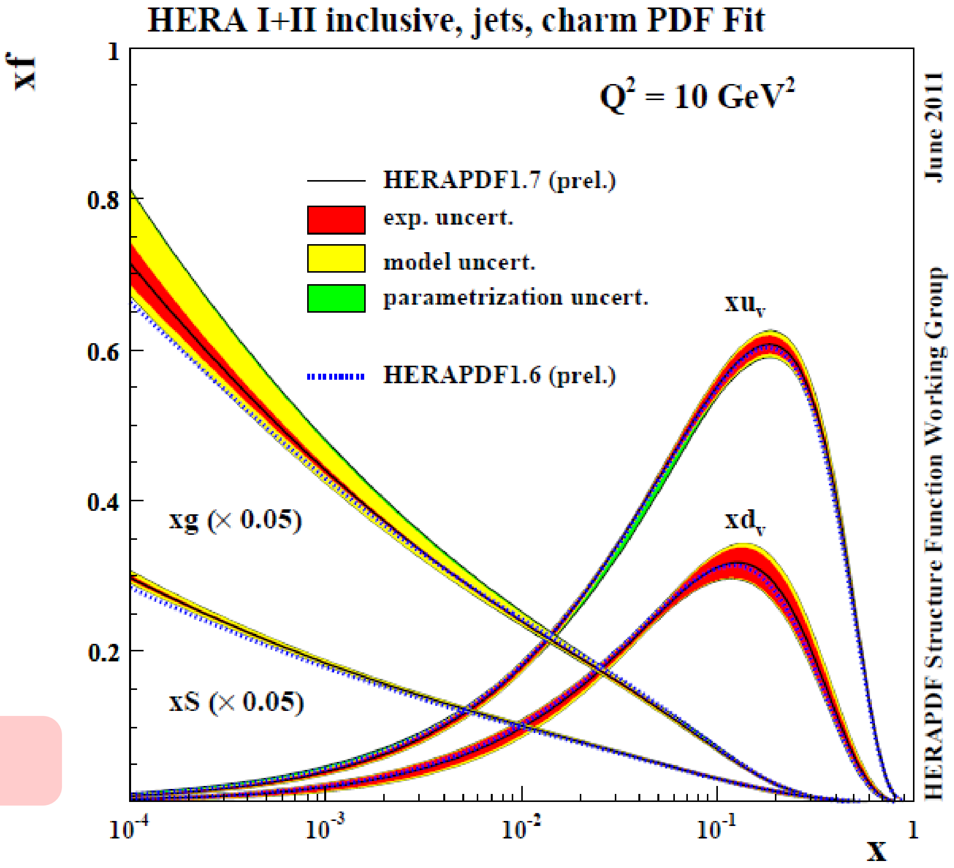
Variation between schemes ~7%
Significantly reduced at m_c^{model} (opt) (★)

HERA charm measurements help to reduce uncertainties of predictions for the LHC

Inclusion of All Data: HERAPDF1.7

What if fit all HERA data?
- inclusive + jets + charm + low energy data → **HERAPDF1.7**
→ important consistency check

- flexible parametrisation (as in HERAPDF1.5f)
- heavy flavour treatment as in HERAPDF1.0
  → motivates for RT optimised at m_c^{model}(opt)
- strong coupling constant = 0.119 (as supported by the jet data)



All data sets are very compatible

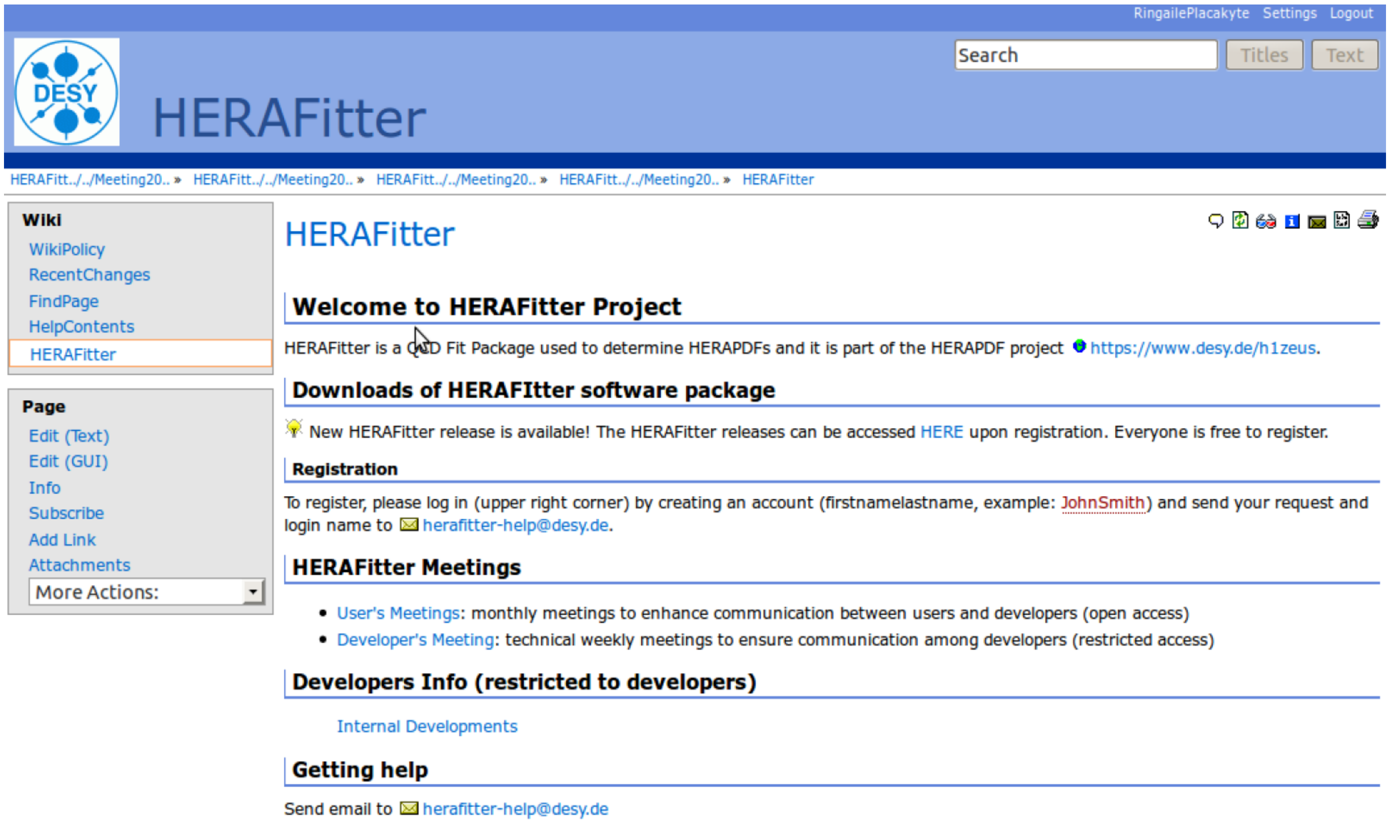
HERAFitter Project

HERAFitter: a set of PDF fitting tools for determination of the parton distribution functions

→ developers: H1 and ZEUS, ATLAS, CMS

→ the first beta version released in September 2011

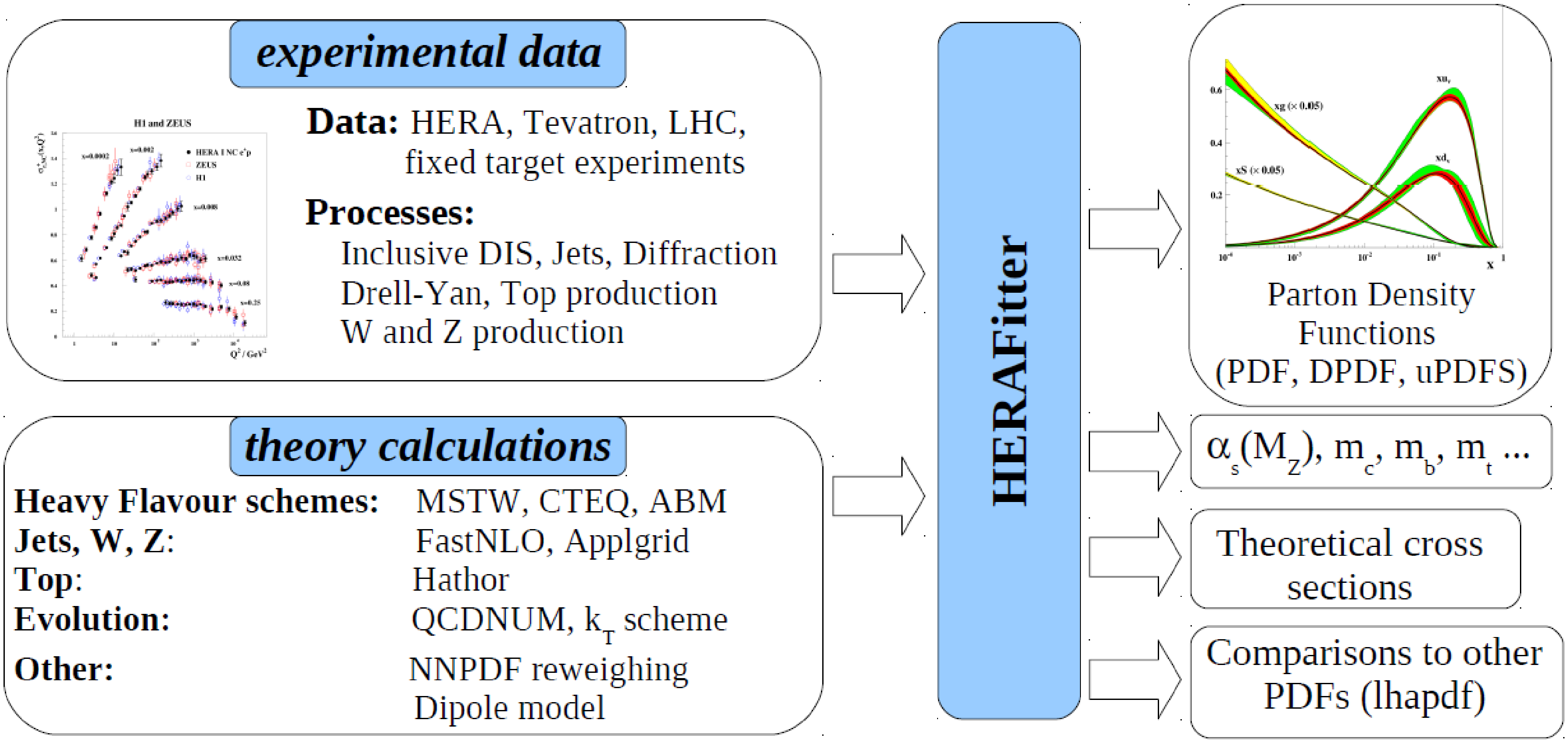
→ May 2012: beta2 release



HERAFitter package available online at http://projects.hepforge.org/herafitter/

HERAFitter: Structure

Modular structure of HERAfitter:



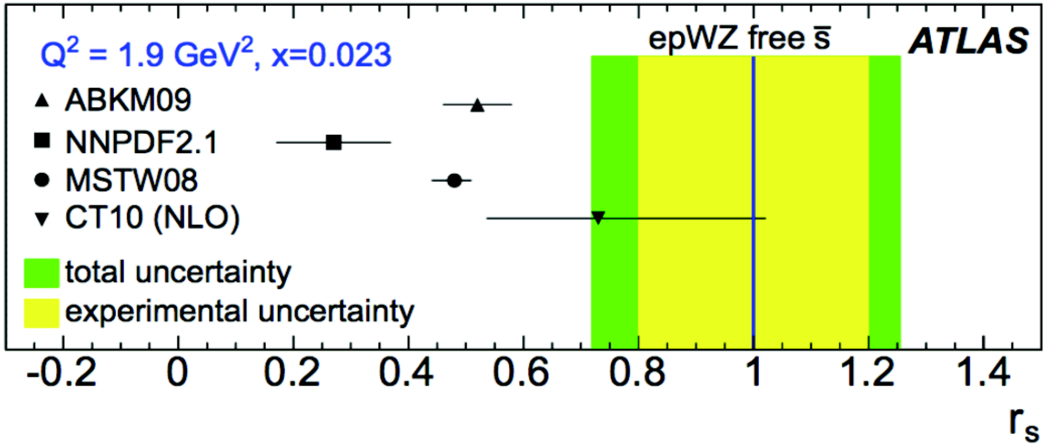
- active participation and support of many theory groups
- global benchmarking platform for PDFs and QCD

HERAFitter: Usage

New ATLAS result:
The differential $W^{\pm}$, Z cross section data of ATLAS (2010, 35/pb) were jointly analysed with $e^{\pm}p$ cross sections from HERA

arXiv:1203.4051v1

→ ratio of W/Z cross sections together with y_Z shape provide a constraint on s-quark density



First LHC publication using HERAFitter

HERAFitter mail-support: herafitter-help@desy.de
Monthly users' meetings: https://znwiki3.ifh.de/HERAFitter/HERAFitterMeetings

Summary

HERA provides unique determinations of the proton structure and compatible NLO and NNLO predictions with other PDF groups

- published final HERA II CC,NC data will follow by H1-ZEUS combination and HERAPDF2.0 set

- HERA jet and charm data provide additional constrains on gluon density and α_s, charm data help to reduce uncertainties of W,Z predictions at LHC

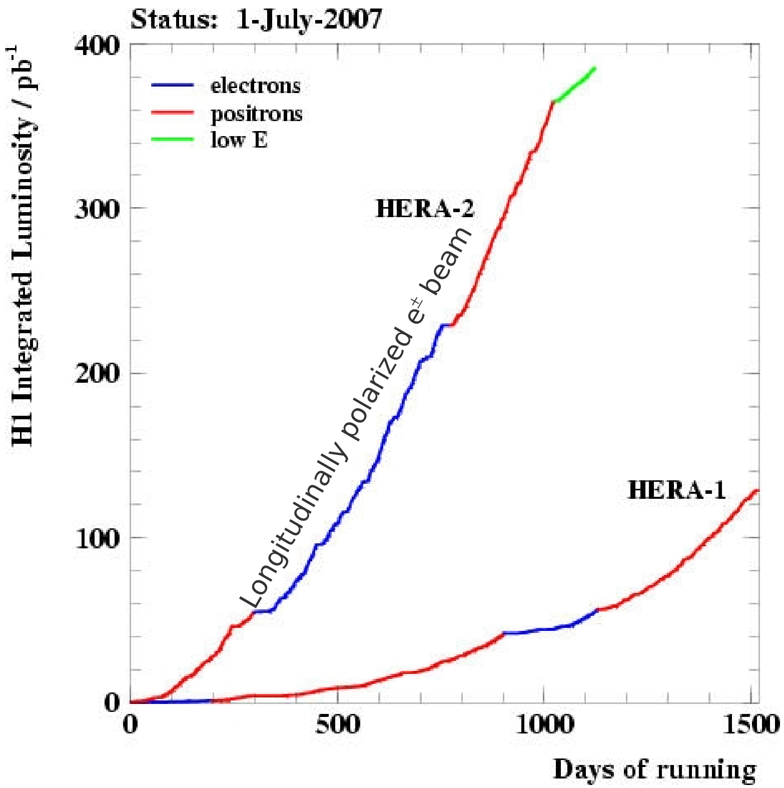
HERAFitter is open source QCD fit framework supported by many theory and experimental (H1, ZEUS, ATLAS and CMS) groups

- has the potential to increase the scientific output of the LHC data and to provide a flexible environment for theory benchmarking

Back-up slides

HERA Collider

World's only *ep* collider



- $e^{\pm}$(27.5 GeV), p(460-920 GeV), $\sqrt{s}$ = 225-318 GeV
- Two collider experiments: H1 and ZEUS

- 1994-2000: HERA I data
  2003-2007 HERA II data
  (end of running 30.06.2007)
- ~0.5 fb^{-1} of luminosity recorded by the each experiment

Deep Inelastic Scattering (DIS)

Structure function factorisation:

each structure function can be written as a convolution of a hard-scattering coefficient C and non-perturbative parton distributions:

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

determined using measured cross section

calculable in perturbative QCD

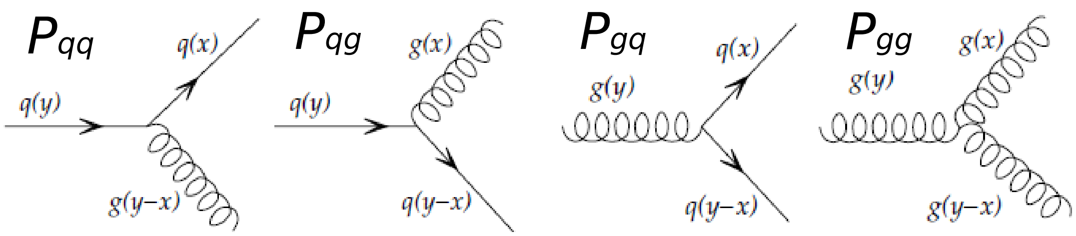
PDFs

PDF scale dependence is calculable in perturbative QCD (DGLAP evolution):

$$\frac{\partial q(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

Probability via splitting functions:



PDF Determination

Experimentally measured $\sigma(x,Q^2) \rightarrow F_2(x,Q^2)$

Q^2 dependence of F_2 is given in pQCD (DGLAP evolution equations)

x-dependence of PDFs is not calculable in pQCD

- parametrise PDFs at the starting scale Q^2_0
- evolve 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

HERAPDF strategy and settings

DGLAP at NLO $\rightarrow$ QCD predictions

PDFs parametrised (at starting scale Q^2_0) using standard parametrisation form:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{uv}}(1-x)^{C_{uv}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{dv}}(1-x)^{C_{dv}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

A: overall normalisation

B: small x behavior

C: $x \rightarrow 1$ shape

The optimal number of parameters chosen by saturation of the χ^2
- central fit with:
  10 free parameters for HERA I data
  13 for HERA I+II data

xg, xu_v, xd_v, $x\bar{U}$, $x\bar{D}$
where $x\bar{U}=x\bar{u}$ and $x\bar{D}=x\bar{d}+x\bar{s}$ at the starting scale ($x\bar{s}=f_s x\bar{D}$ with $f_s=0.31$)

A_g, A_{uv}, A_{dv} are fixed by sum rules

extra constrains for small x behavior of d- and u-type quarks:
$B_{uv}=B_{dv}$, $B_{\bar{U}}=B_{\bar{D}}$, $A_{\bar{U}}=A_{\bar{D}}(1-f_s)$ for $\bar{u}=\bar{d}$ as $x\rightarrow 0$

Data in PDF fits

DIS:

ep (HERA) data: quarks and gluon at small *x* (F_L), jets (moderate *x*), CC - flavour separation, heavy quark structure functions

fixed target data: higher *x*

neutrino DIS: flavour decomposition, *x*>0.01

Drell-Yan:

quark-antiquark annihilation – high *x* sea quarks, deuterium target – $\bar{u}/\bar{d}$ asymmetry

High Pt jets at colliders:

high *x* gluon

W/Z production:

different quark contributions

PDF Fit Groups

MSTW

– includes all type of data (not yet most recent HERA data). LO, NLO and NNLO

CTEQ

– includes all type of data (CT10 includes recent combined HERA data and more Tevatron data). NLO

NNPDFs

– includes all type of data (except HERA jets). NLO, recently also LO and NNLO

HERAPDF

– HERA (combined) data. NLO and NNLO

AB(K)M

– DIS and fixed target DY data. NLO and NNLO

GJR

– DIS, fixed target DY data and Tevatron jet data. NLO and NNLO (no jets)

PDF Fit Groups

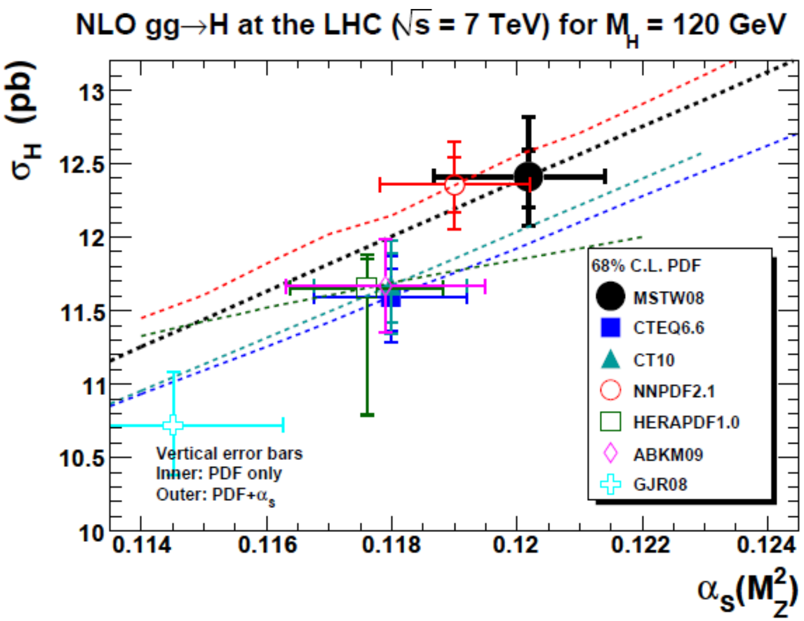
Main sources of difference between different PDFs:

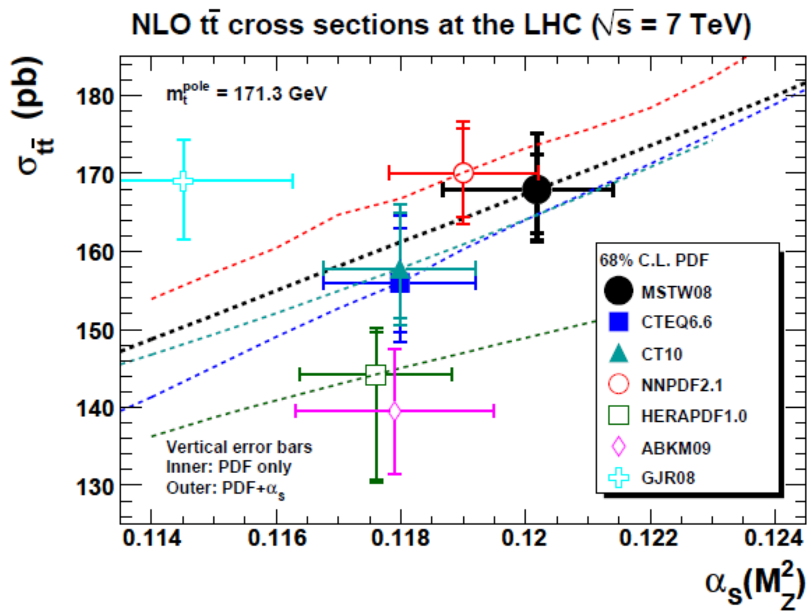
- inclusion of different data
- methods of determining 'best fit'
- uncertainty treatment/sources
- assumptions in procedure (parametrisation)
- heavy flavour treatment
- PDF and α_s correlation

... lead to differences in the cross section predictions

PDF Fit Groups: Benchmarking (PDF4LHC)

Different PDF lead to differences in cross section predictions

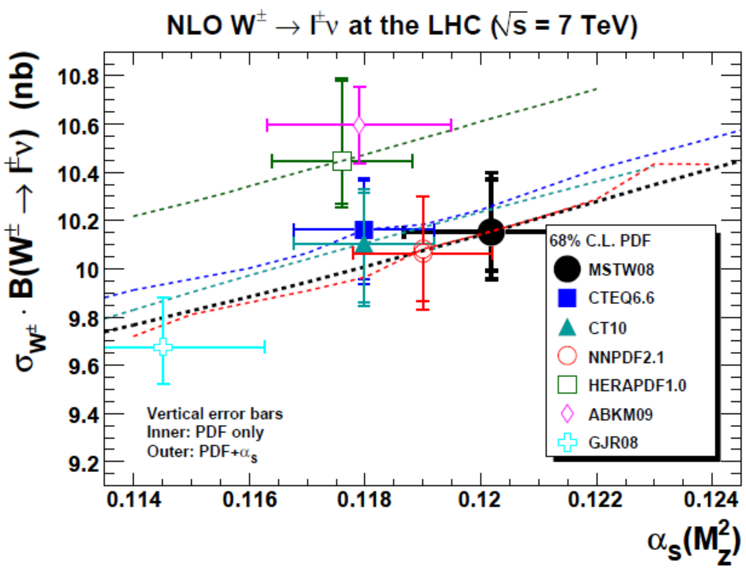


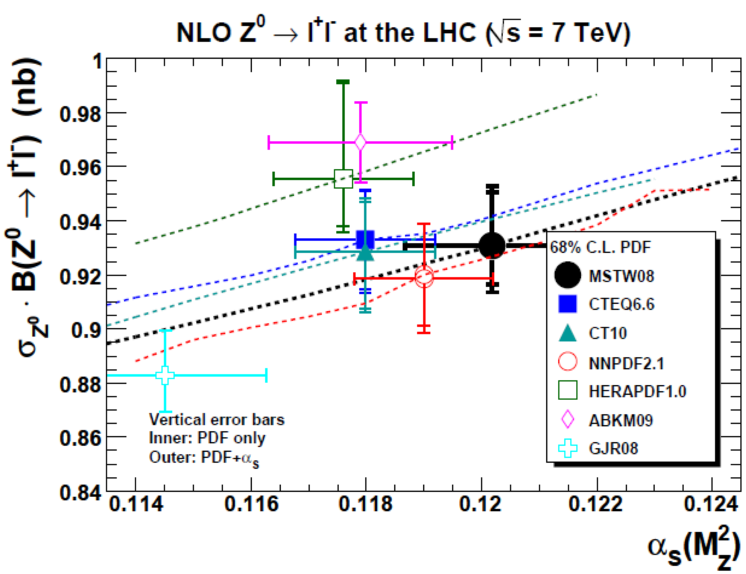


G.Watt

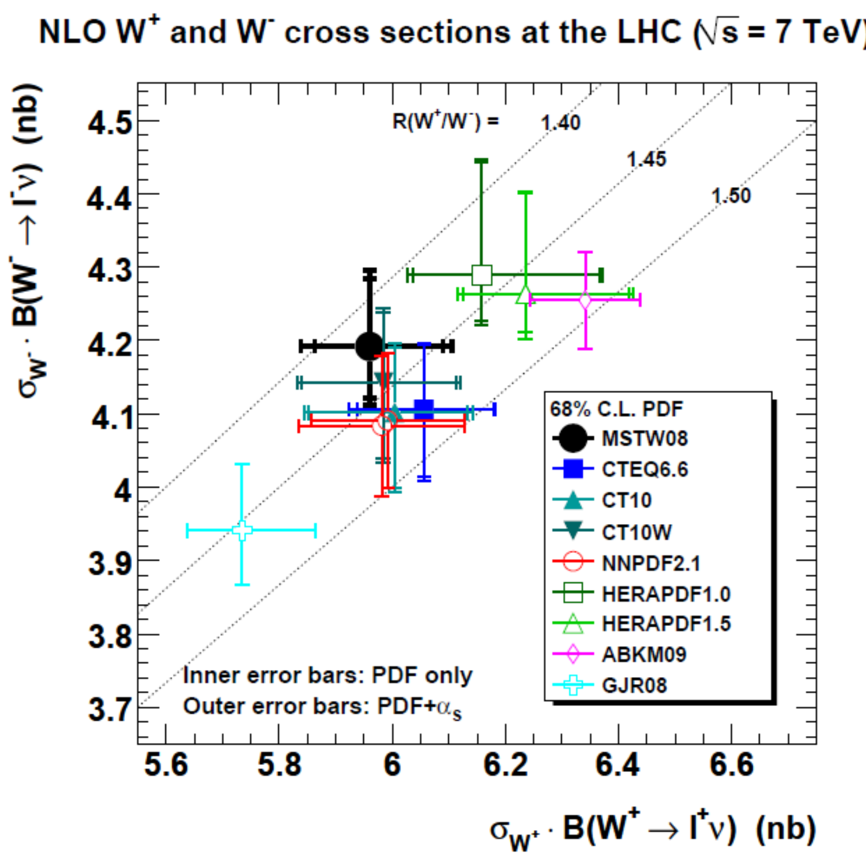
arXiv:1106.5788v1

PDF Fit Groups: Benchmarking



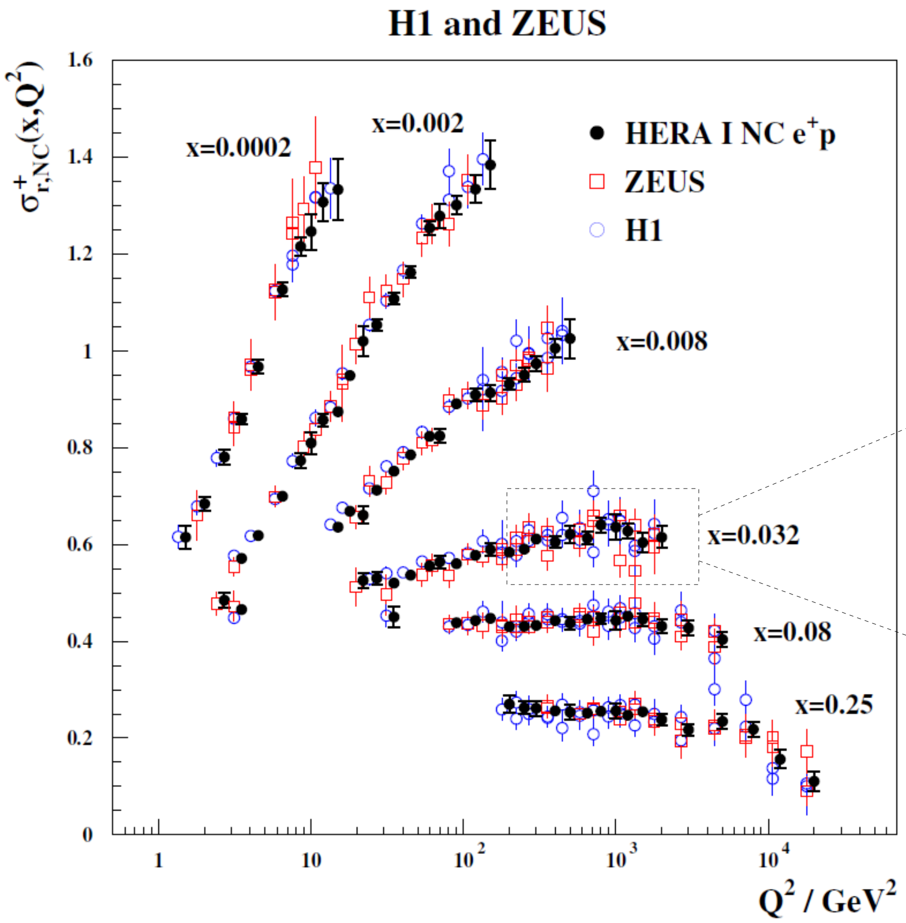


G.Watt



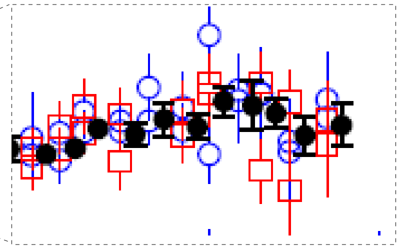
Combination of HERA data

H1 and ZEUS neutral and charged current data from HERA I period were combined



arXiv:0911.0884[hep-ex]

- ultimate precision (experiments cross calibrate each other)



- good consistency of the data: χ^2/ndf = 637/656

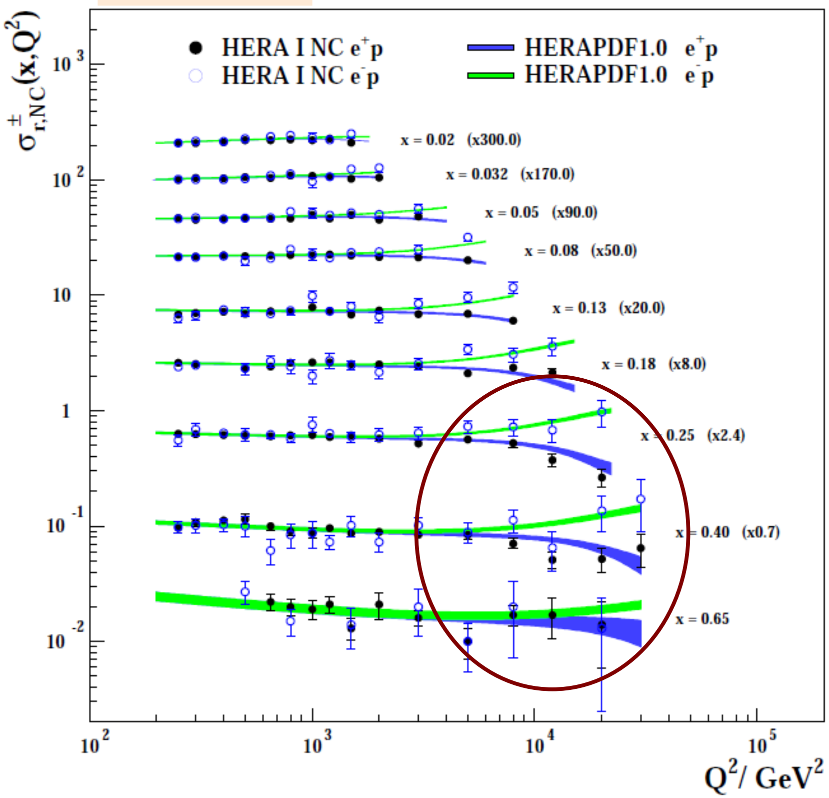
QCD analysis of combined data → HERAPDF 1.0

HERAPDF 1.5

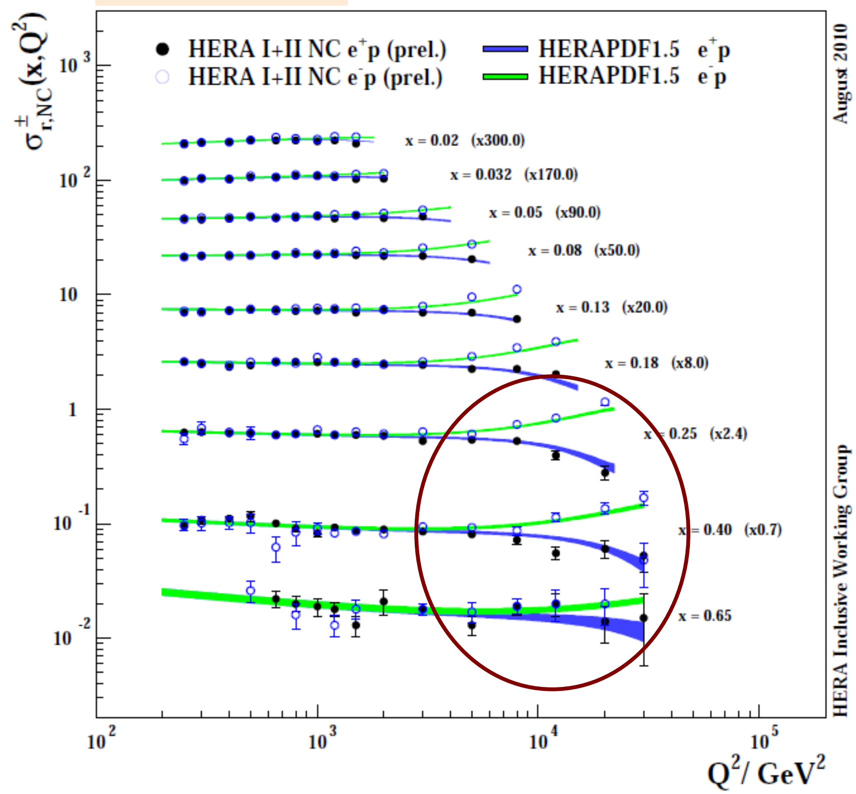
HERAPDF1.0: combined inclusive HERA I arXiv:0911.0884[hep-ex]

HERAPDF1.5: combined inclusive HERA I and HERA II data

HERA I H1 and ZEUS HERAPDF1.0



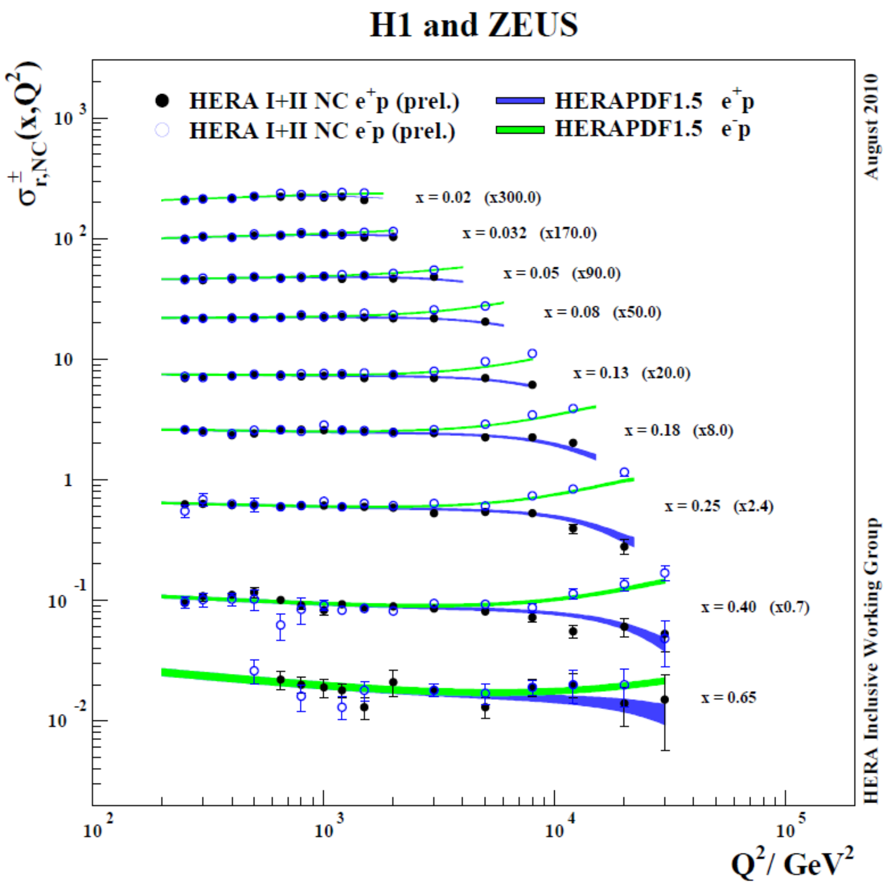
+ HERA II H1 and ZEUS HERAPDF1.5



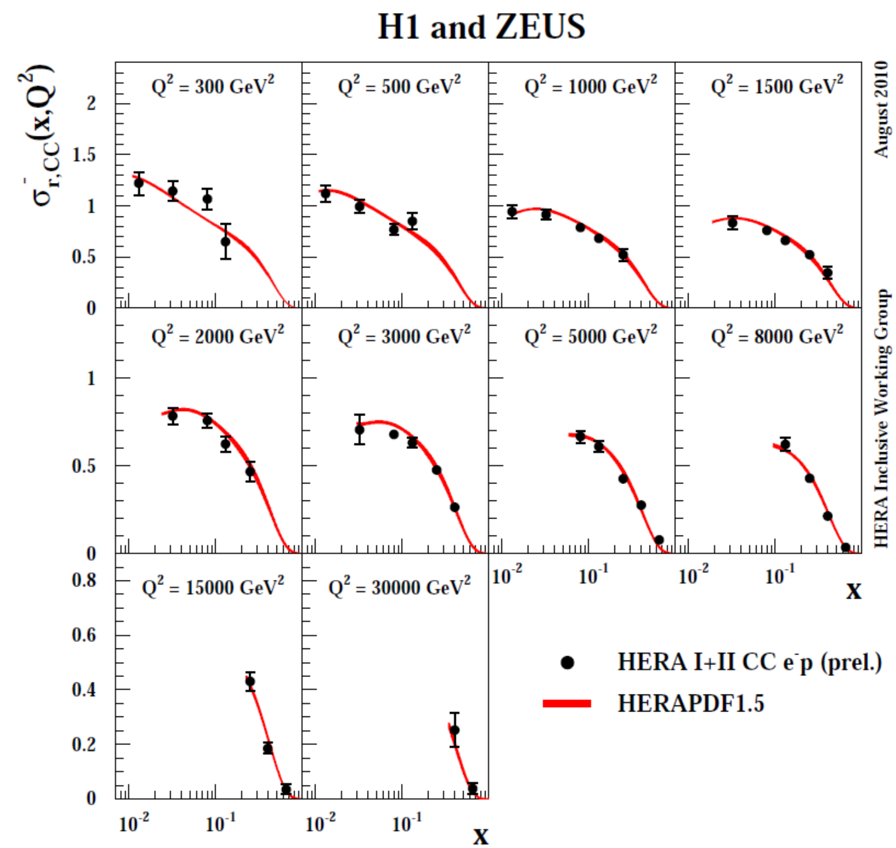
Improved data precision → Improved PDFs

HERA DIS Cross Sections vs HERA PDFs

Neutral Currents



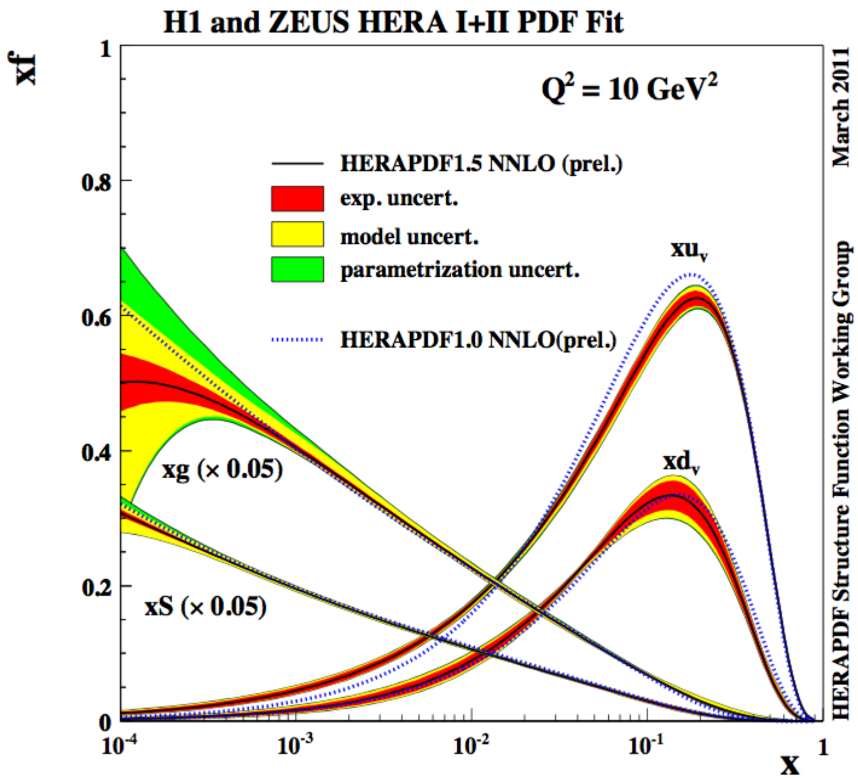
Charged Currents

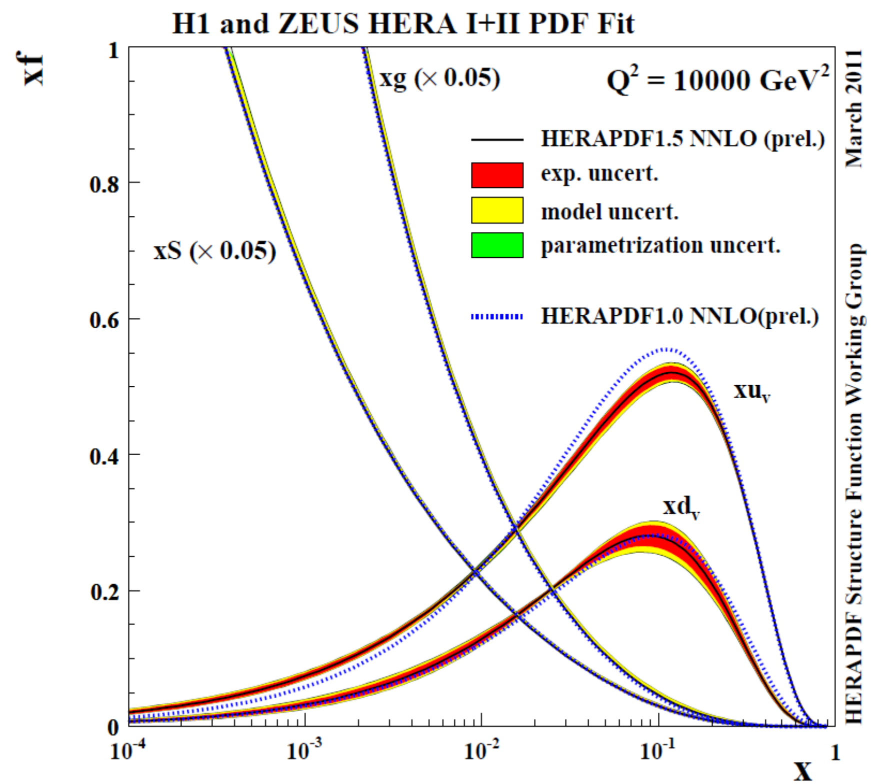


HERA PDF fit describes NC and CC data very well

HERAPDF at NNLO

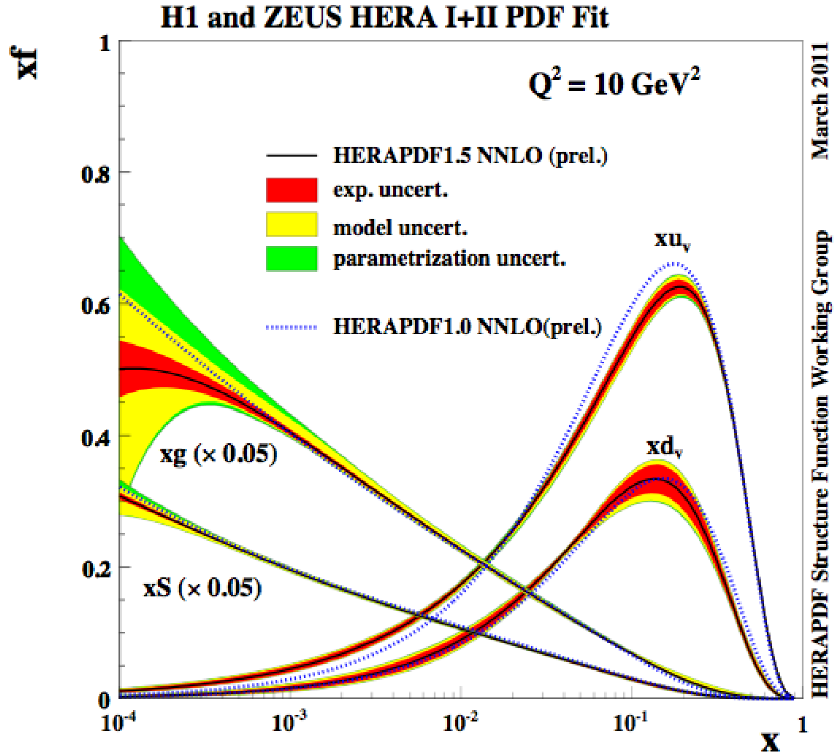
NNLO HERAPDF1.5 fit is based on HERA I + II inclusive ep data
→ uses more flexible parametrisation form

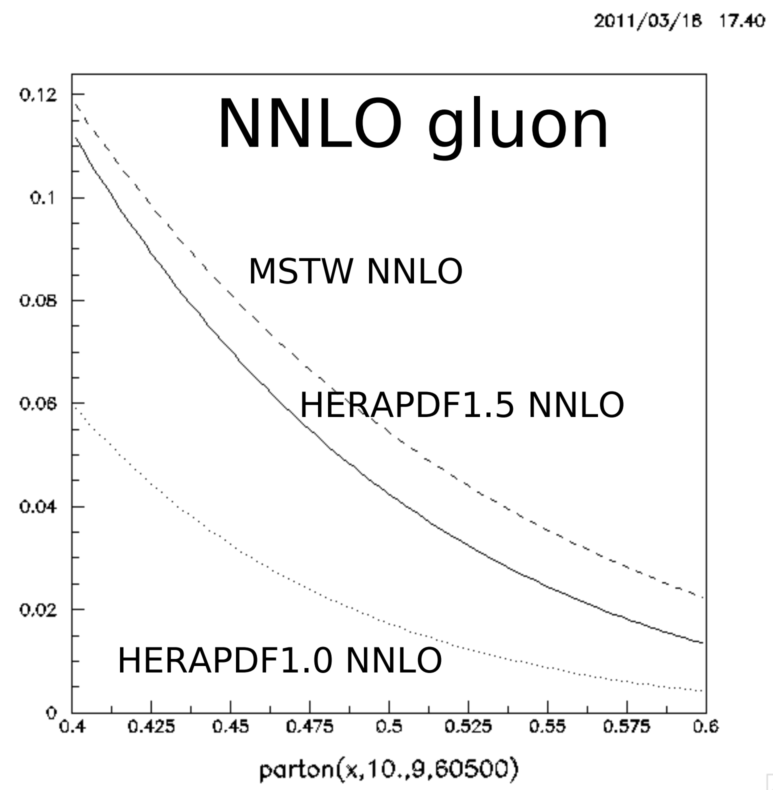




HERA PDFs can be used for NNLO predictions at LHC

HERAPDF1.0 NNLO vs HERAPDF1.5 NNLO





HERAPDF1.5NNLO has a harder high-x gluon than HERAPDF1.0
- hence, would give a better agreement with Tevatron data

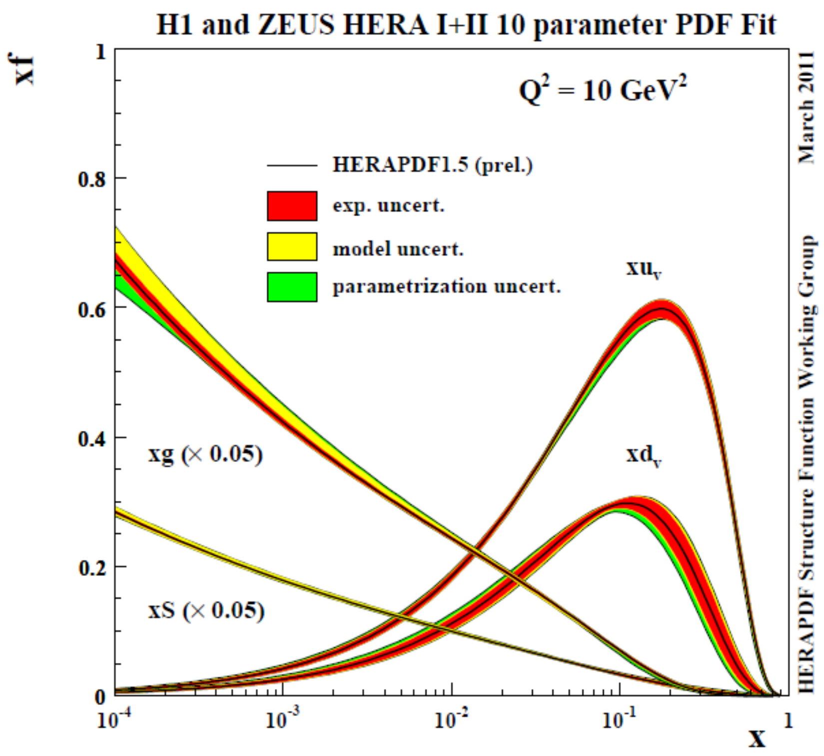
HERAPDF1.5 NNLO uncertainties are comparable to NNPDFs

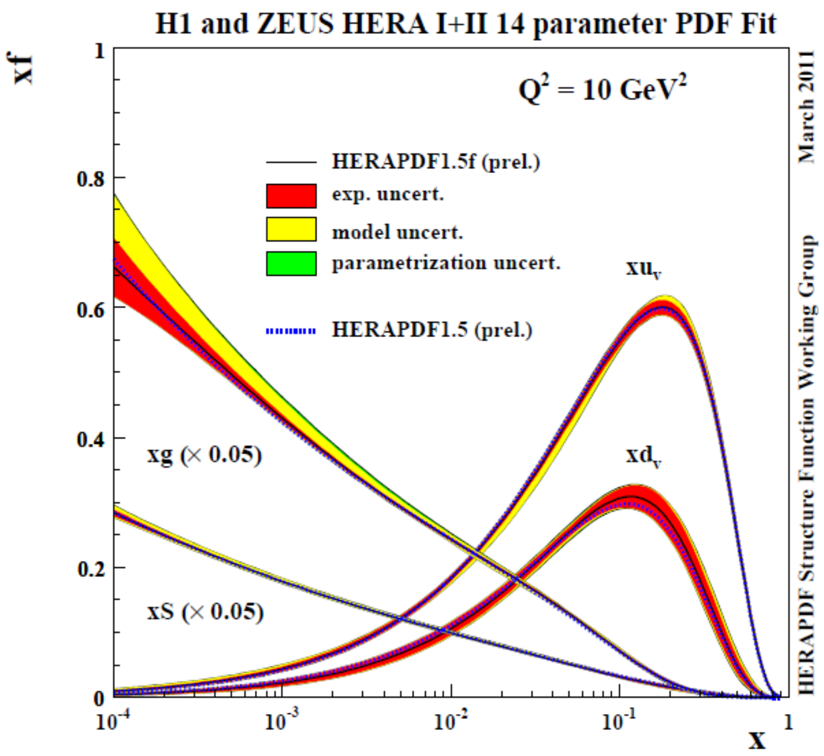
HERAPDF1.5f

HERAPDF1.5f - more flexible parametrisation
→ gluon more flexible and low-*x* *d*-valence is freed from *u*-valence

HERAPDF1.5

HERAPDF1.5f

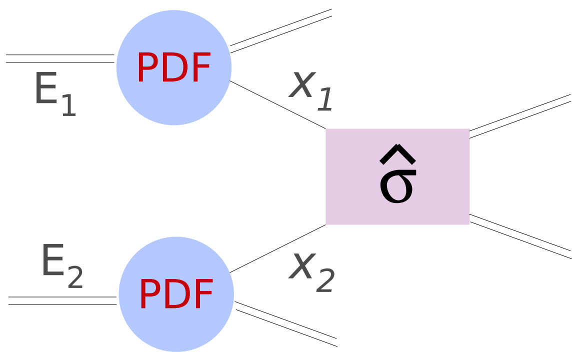




Small difference in total uncertainty
→ swap between **parametrisation** and experimental uncertainties

Proton-Proton Collisions

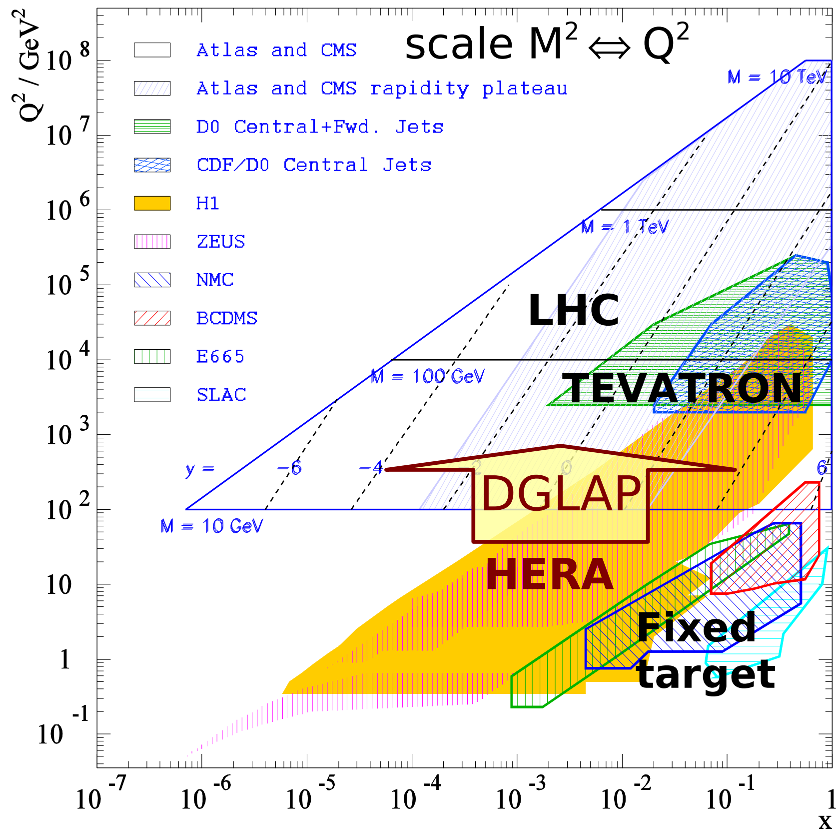
Same PDFs can be used to predict *pp* collisions



$\hat{\sigma}$ – perturbative QCD cross section

Factorisation:

$$\sigma \approx \hat{\sigma} \otimes \text{PDF}$$

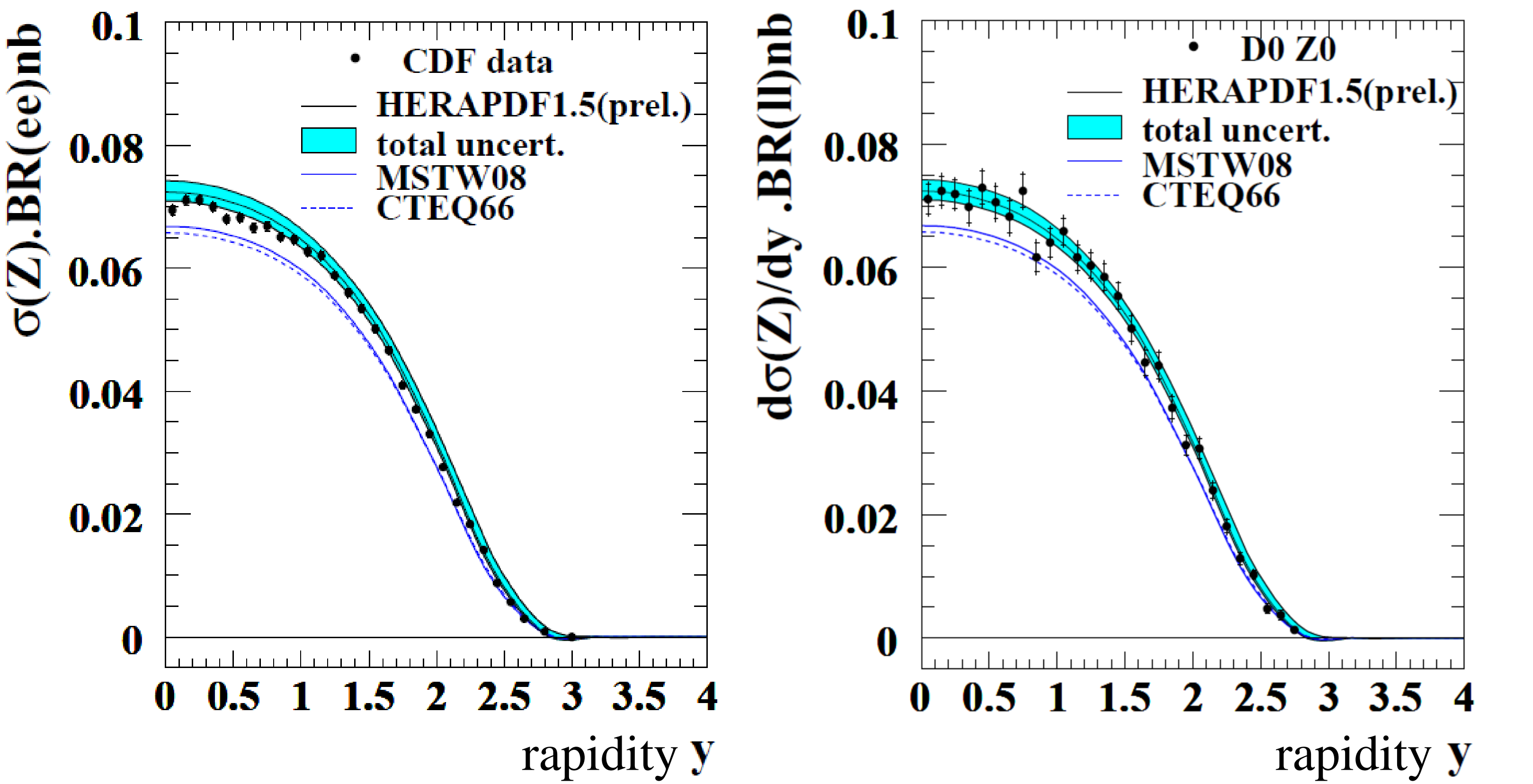


HERA covers *x* range of the LHC
evolution in Q^2 via DGLAP

HERAPDF Predictions for Tevatron

$\sqrt{s}$ = 1.96 TeV

Z rapidity

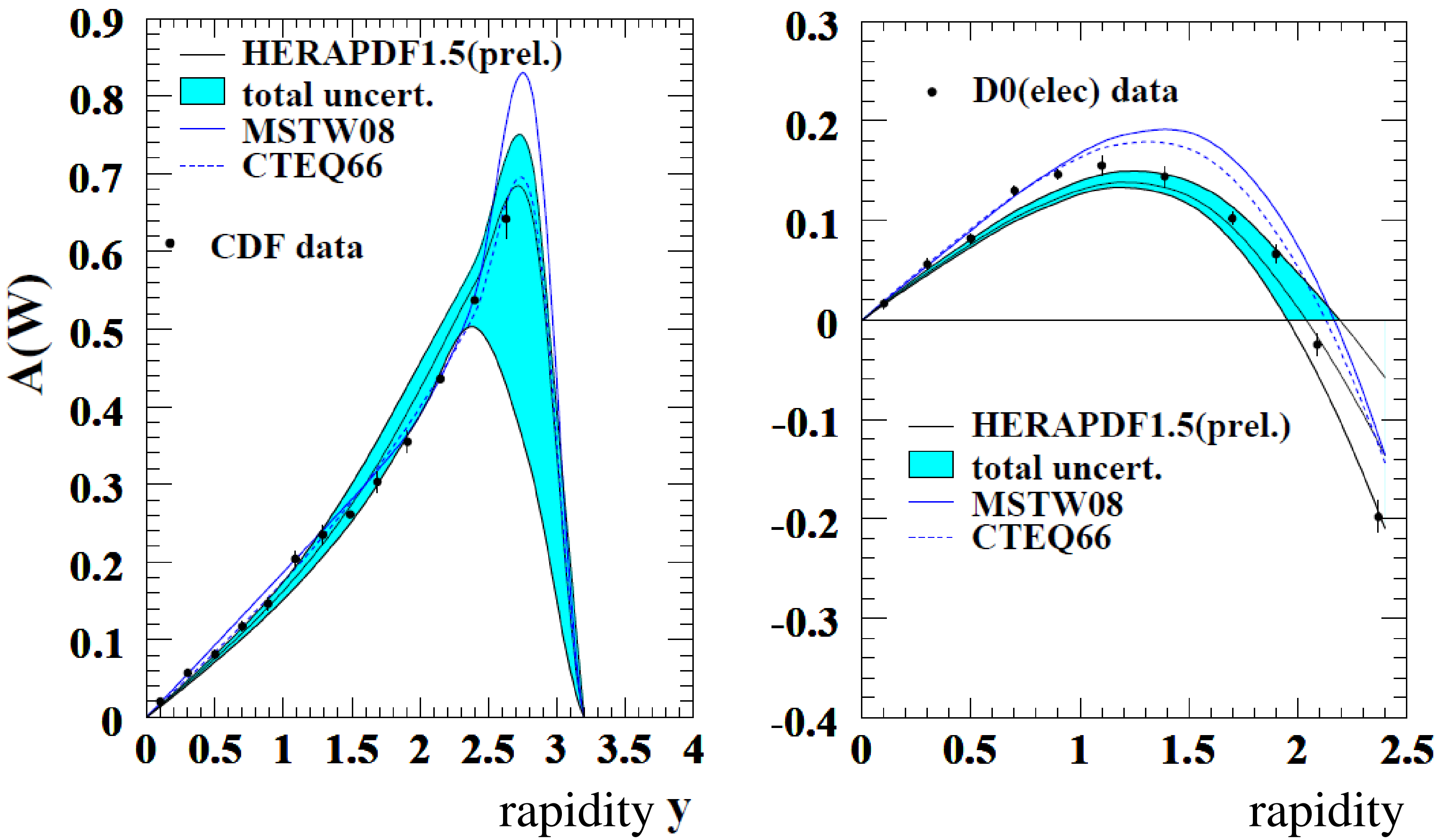


Predictions based on HERA PDFs describe Tevatron data well

HERAPDF Predictions for Tevatron

$\sqrt{s}$ = 1.96 TeV

W and W(lepton) asymmetry



Predictions based on HERA PDFs describe Tevatron data well

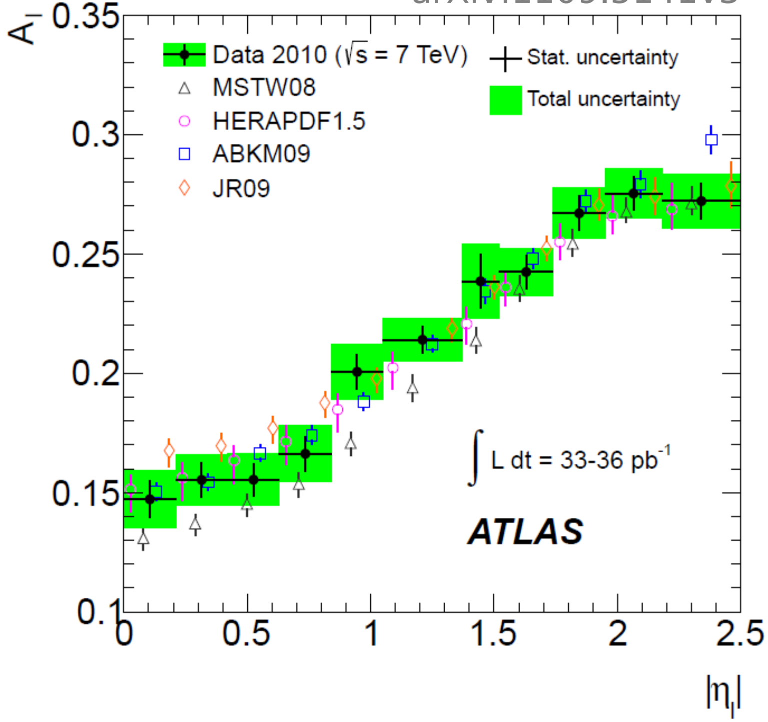
HERAPDF Predictions for Asymmetries at LHC

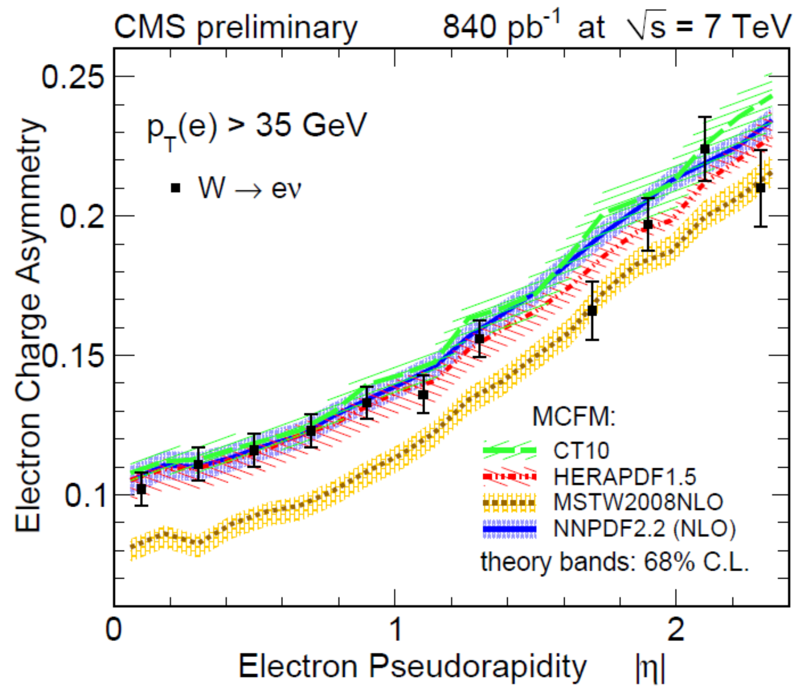
W lepton asymmetry is sensitive to differences between u and d:

$$A_W = \frac{W^+ - W^-}{W^+ + W^-}$$

in terms of valence quarks: $$A_W \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$

arXiv:1109.5141v3





Latest results from ATLAS and CMS

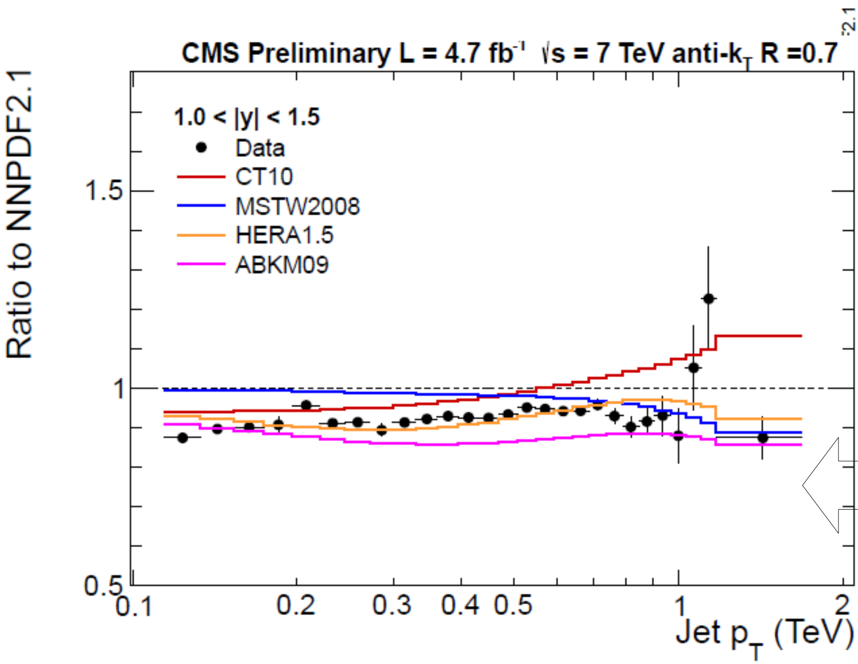
Example: Predictions for Jets at LHC

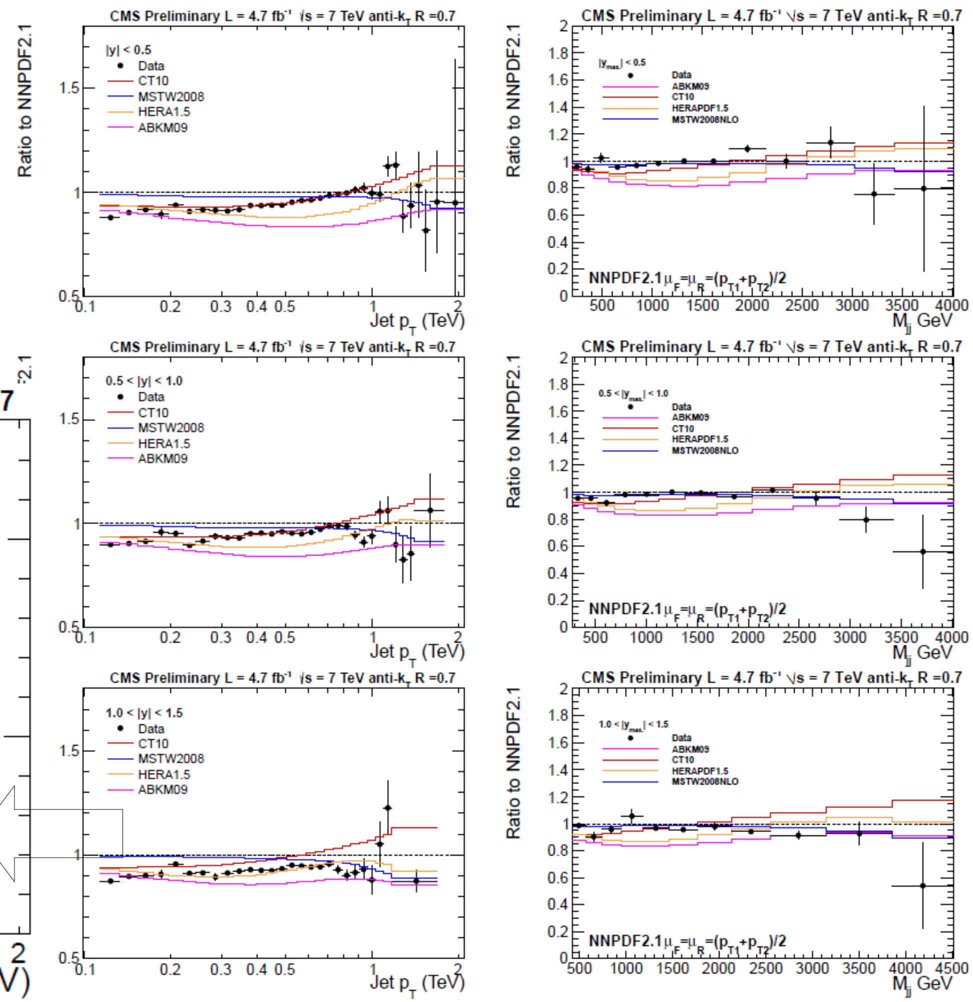
CMS-PAS-QCD-11-004

Jets have sensitivity to gluon and strong coupling constant

→ can help to understand and constrain gluon PDF at high-x

(important for new physics)

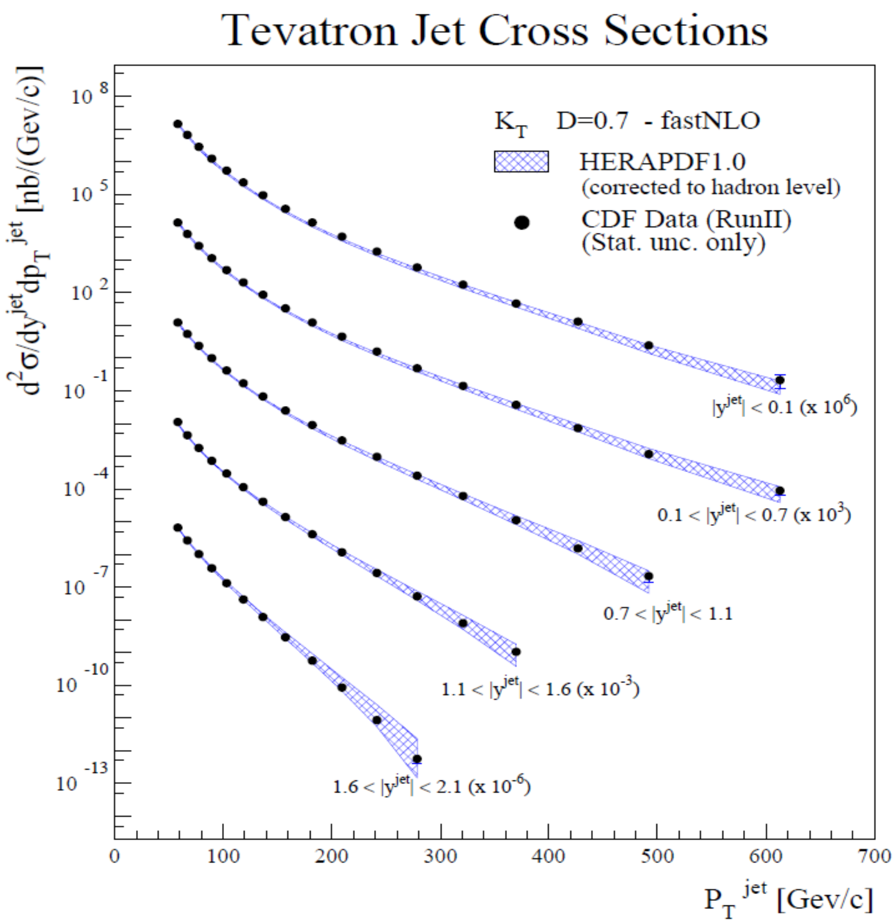




Experimental uncertainties are comparable to theoretical ones
→ using data in QCD fits can improve PDF uncertainties (correlations needed!)

HERAPDF Predictions for Tevatron

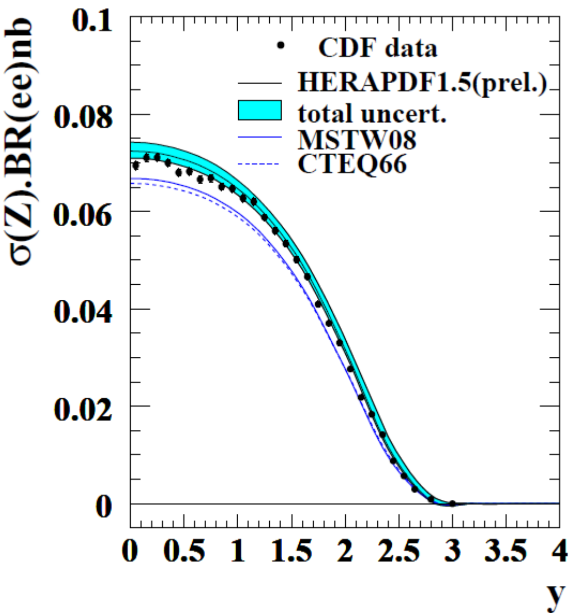
$\sqrt{s}$ = 1.96 TeV

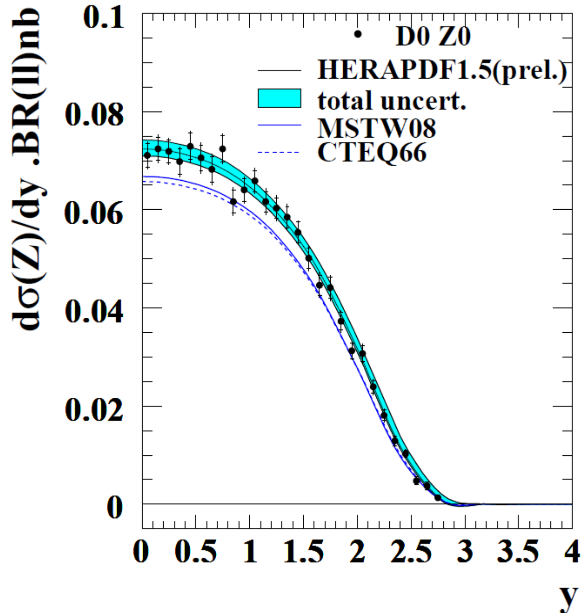


→ if these data are fitted the resulting PDFs are within the HERAPDF1.5 errors bands

Predictions based on HERA PDFs describe Tevatron data well

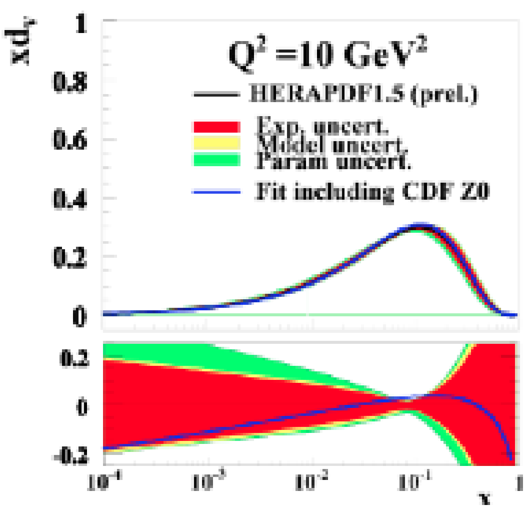
HERAPDF Predictions for Tevatron: Z rapidity

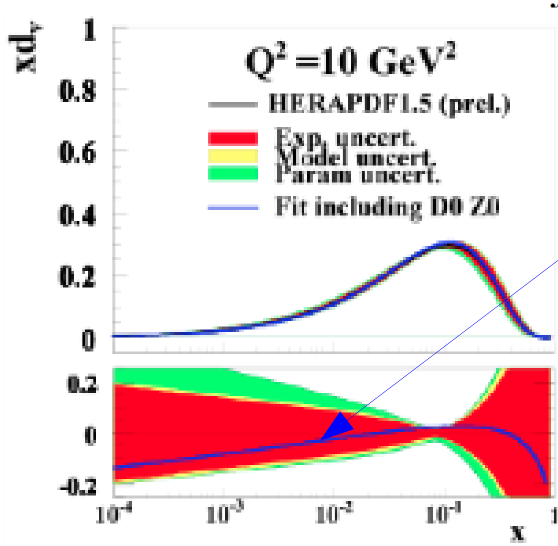




The description of CDF and D0 Z rapidity by HERAPDF1.5:

without fitting these data (not taking into account PDF uncert):
$\chi2$/dof=36/28 CDF
$\chi2$/dof=23/28 D0
After fitting these data:
$\chi2$/dof=27/28 CDF
$\chi2$/dof=16/28 D0

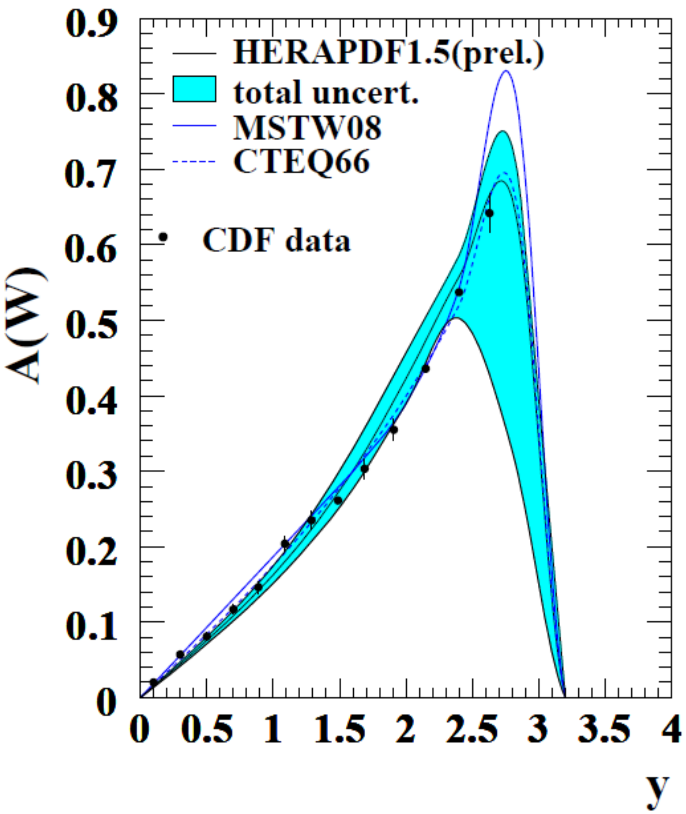


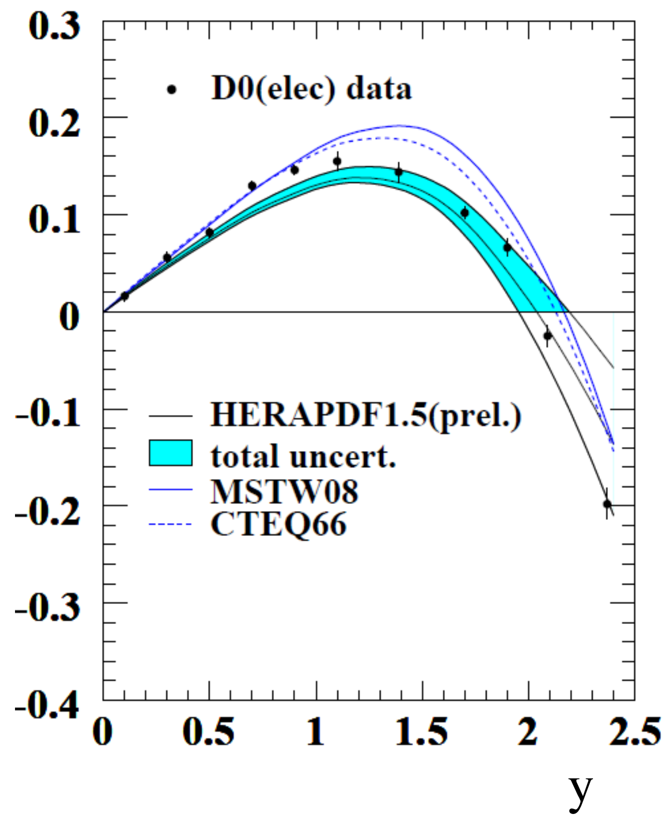


fit including TEVATRON data

Impact of Tevatron Z rapidity data on PDF shape is within uncertainties of HERAPDF

HERAPDF Predictions for Tevatron: W asymmetry





Even without fitting the asymmetry data the agreement is quite good

After fit:

- $\chi 2$/dof=19/13 CDF
- $\chi 2$/dof=25/11 D0

→ the resulting PDFs lie within the HERAPDF1.5 error band

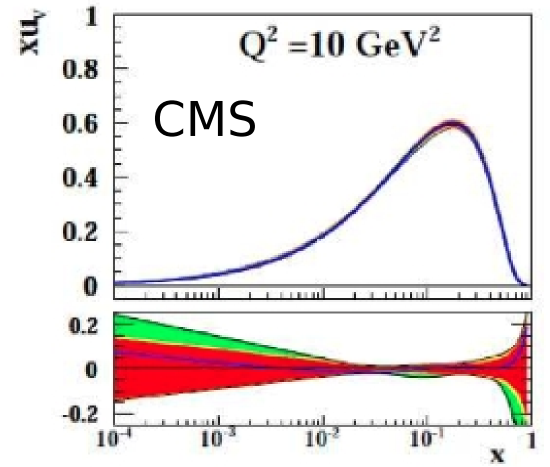
HERADF Predictions for Asymmetries at LHC

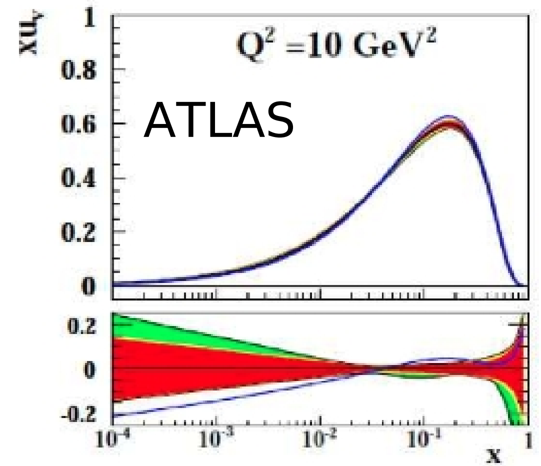
Early LHC data are described fairly well

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

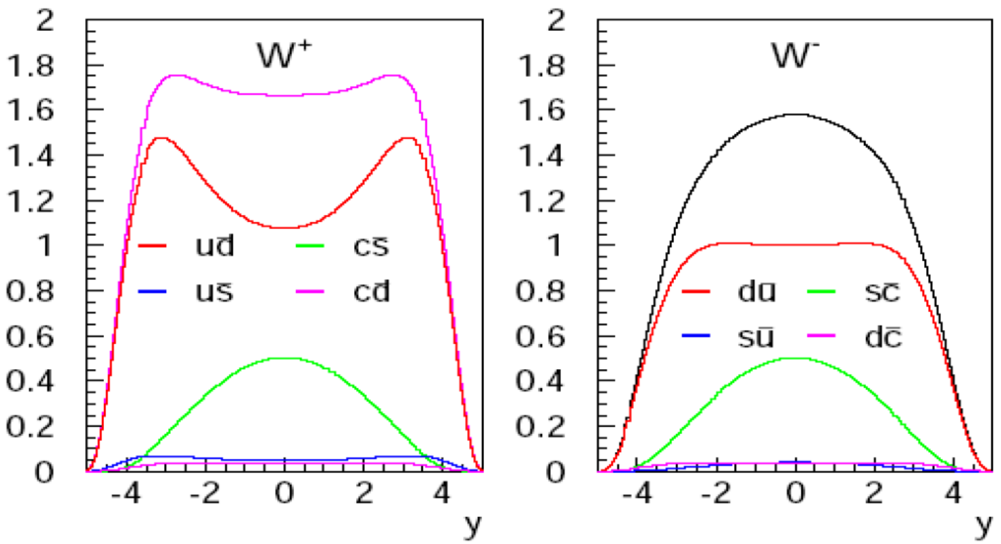
	Before fit	After fit
- W asymmetry CMS:	χ^2/dof=6.5/12	3.7/12
- W asymmetry ATLAS:	χ^2/dof=30/11	16/11

ATLAS and CMS pull u valence quark
in opposite directions

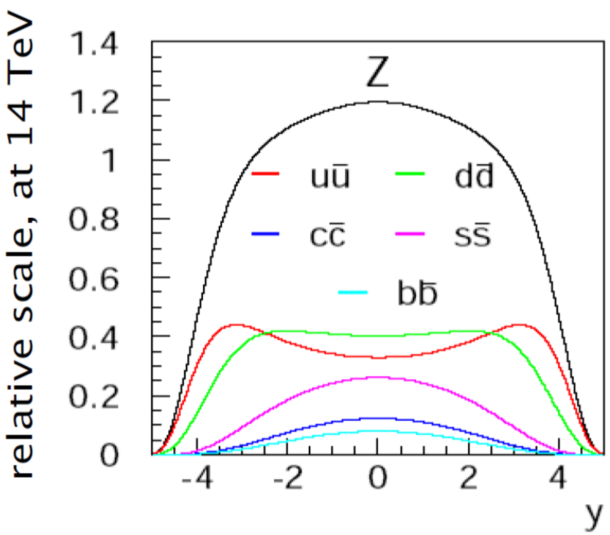




Proton-Proton Collisions: W/Z production



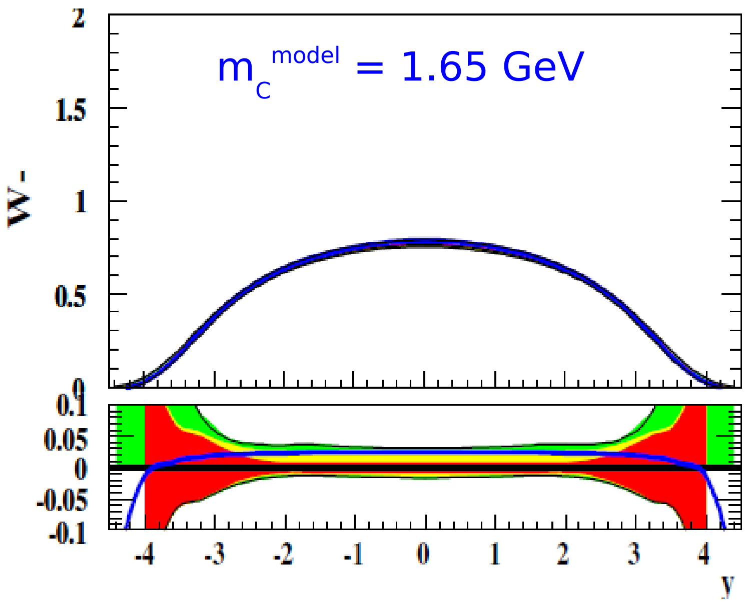
- for W **u** and **d** quarks dominate



- all flavours contribute to Z

Precise parton distributions are needed for LHC analyses

Impact on the LHC predictions



- variation of m_c^{model} changes predictions of Z/W cross sections at LHC by ~3%

A.M.Cooper-Sarkar, PDF4LHC, March 2010

- sensitivity to charm of the LHC cross section predictions comes from flavour sensitivity of the inclusive DIS data

$$xU = xu + xc \quad x\bar{U} = x\bar{u} + x\bar{c} \quad xD = xd + xs \quad x\bar{D} = x\bar{d} + x\bar{s}$$

- where *U* is fixed by F_2 data
  larger $m_c^{model} \rightarrow$ less *c* in sea $\rightarrow$ more *u (= d)*

- important at low Q^2 and low x

Heavy Quark treatment in QCD analysis

Factorisation:

$$F_2^{V,h}(x,Q^2) = \sum_{i=f,\bar{f},g} \int_x^1 dz \cdot C_2^{V,i}\left(\frac{x}{z}, \frac{Q^2}{\mu^2}, \frac{\mu_F^2}{\mu^2} \alpha_S(\mu^2)\right) f_{i/h}(z, \mu_F, \mu^2)$$

i - number of active flavours in the proton

m_c=1.5, m_b=4.7 GeV

QCD analysis of the proton structure: treatment of HQ essential

Different prescriptions how to treat heavy quarks in PDF fits (HQ schemes):

Fixed Flavour Number Scheme (FFNS) *i-fixed*

c(b) quarks massive, only light flavours in the proton i=3(4)

General-Mass Variable Flavour Number Scheme (GM-VFNS) *i-variable*

matched scheme, different implementation used by fit groups $\rightarrow m_c^{model}$

Zero-Mass Variable Flavour Number Scheme (ZMVFNS)

all flavours massless (breaks at $Q^2 \sim m_{HQ}^2$)

QCD analysis of F_2^{cc} data

- different implementations of general mass variable flavour number scheme for heavy flavour treatment used in this study:

RT standard	used by MSTW08
RT optimised [arXiv:1006.5925]	
ACOT-full	used by CTEQ4,5,6HQ
S-ACOT-χ	used by CTEQ6.5,6.6,CT10
ZMVFNS	used by NNPDF2.0

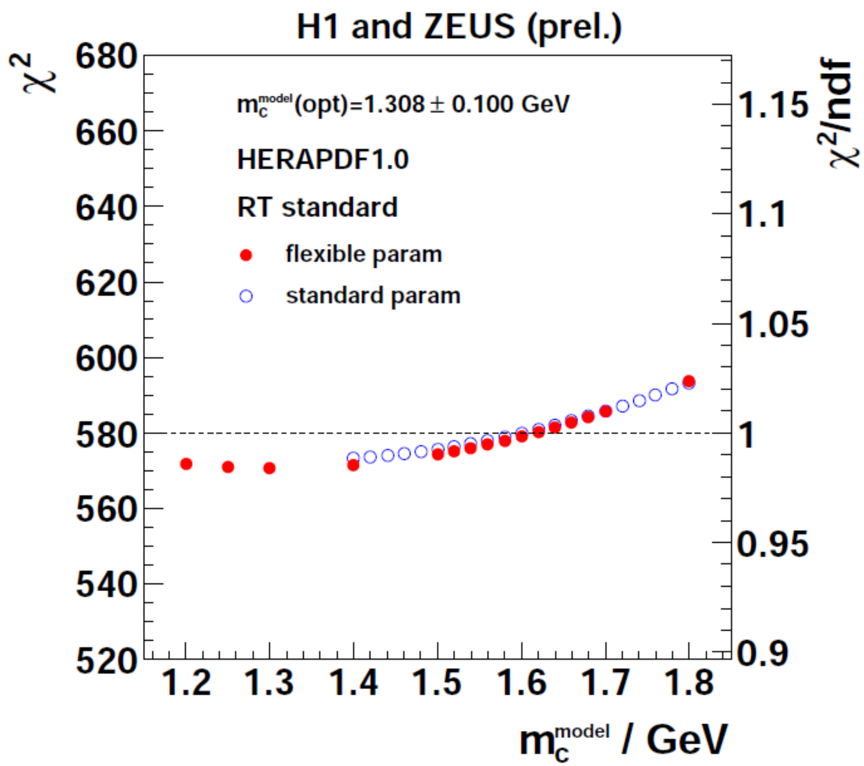
- the optimal value of parameter m_c^{model} is determined for each of these schemes (m_c^{model}(opt)), which gives the best description of the HERA data

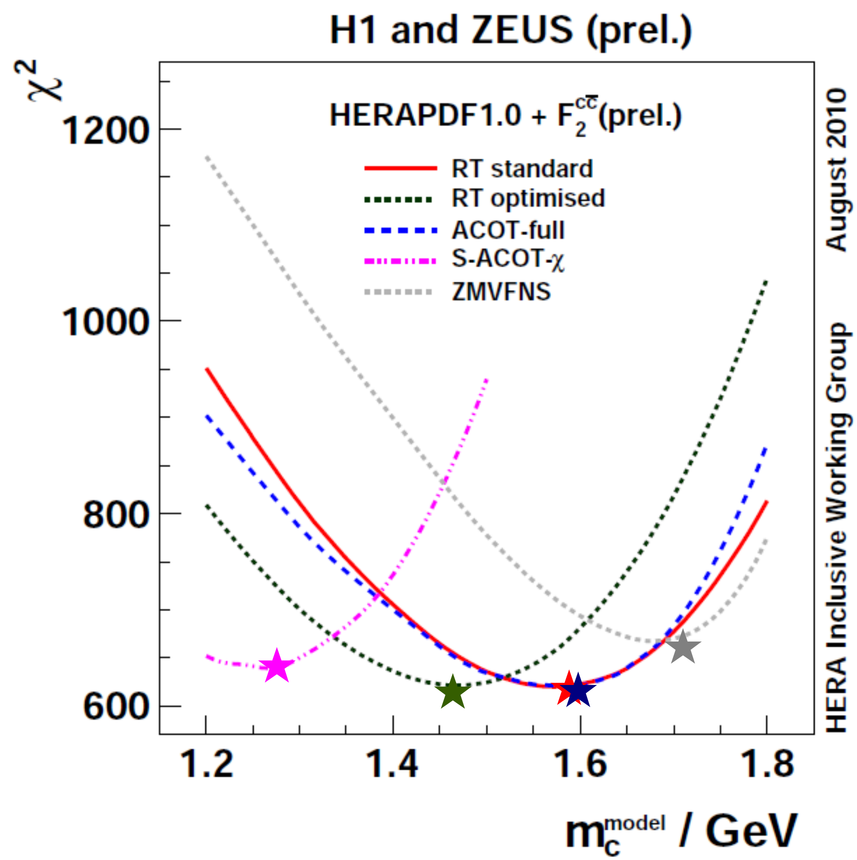
- PDFs are used in MCFM to calculate $Z/W^{\pm}$ cross-section predictions

Constraints on PDFs from HERA Charm Data

Inclusive ep data

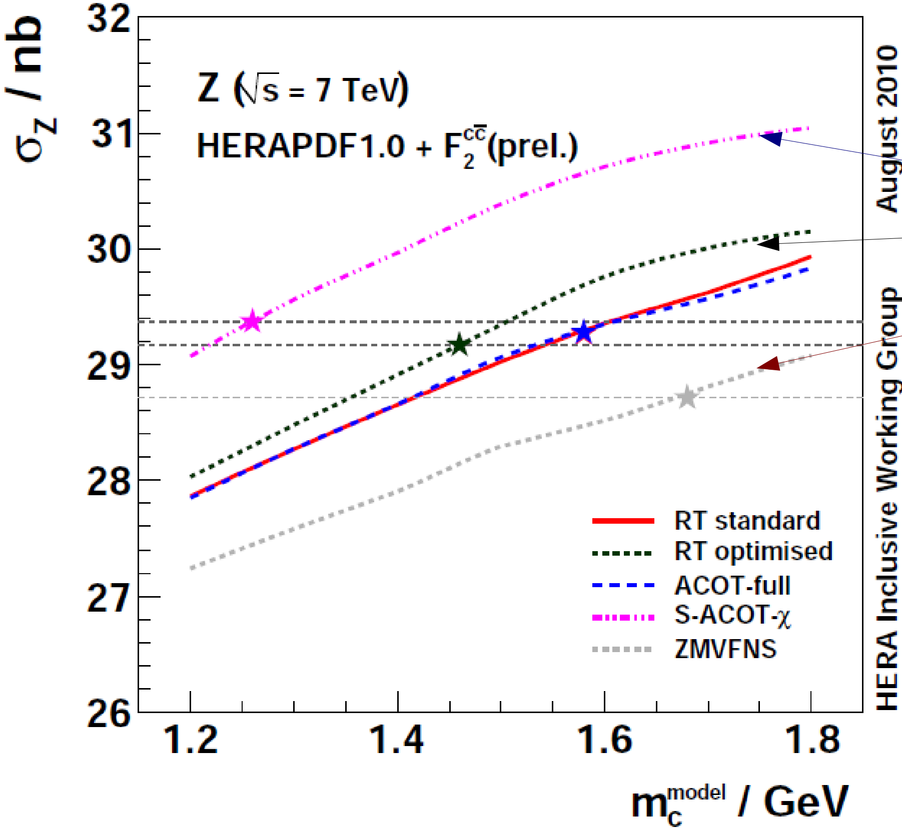
Different HQ schemes are tested

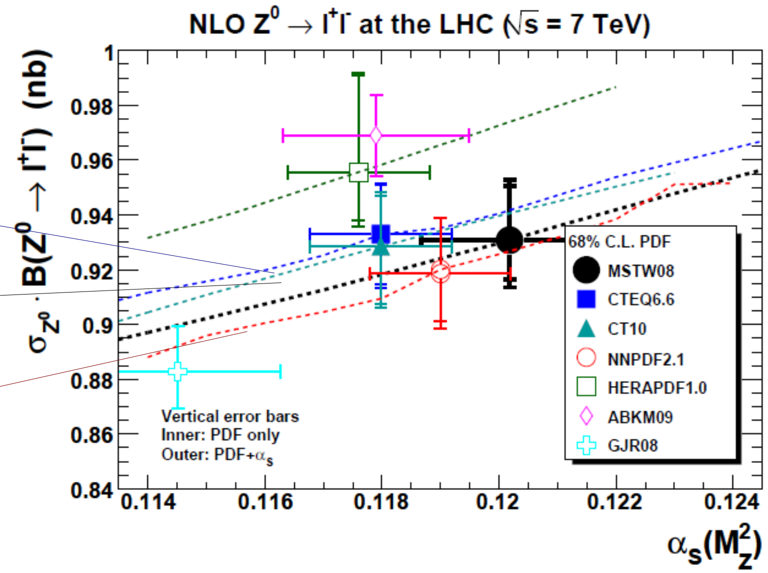




Different HQ schemes have different optimal m_c^{model}

Z/W cross sections at LHC





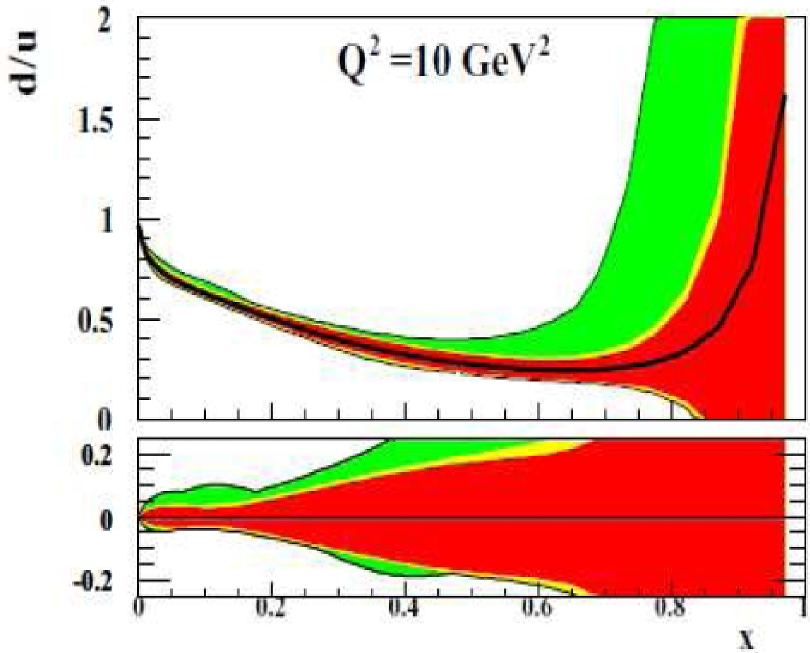
- comparison of Z cross sections as a function of $\alpha_S(M_Z^2)$

G.Watt, PDF4LHC 07.03.2011

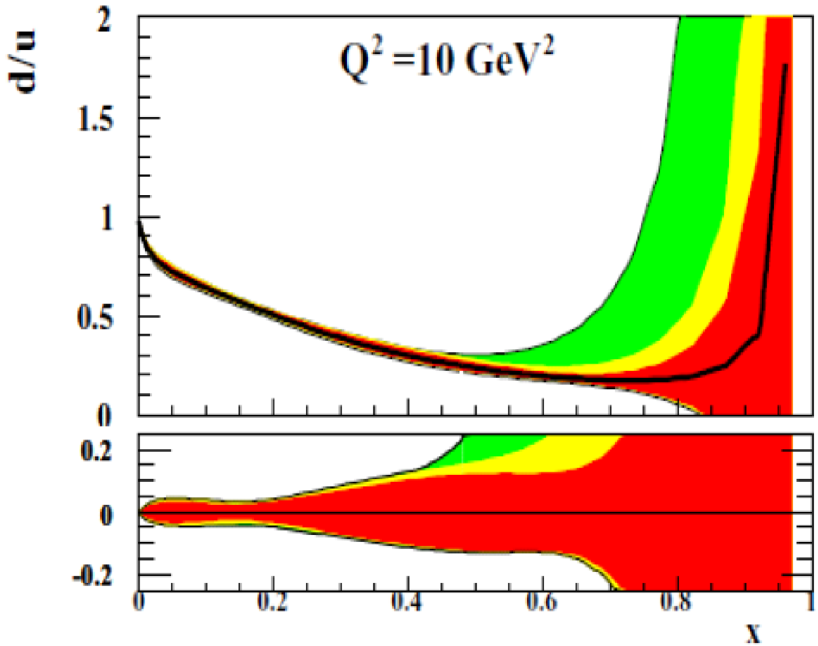
(symbols indicate value of m_c^{model}(opt))

HERAPDF 1.0 vs 1.5

HERAPDF1.0



HERAPDF1.5



Prediction based on HERAPDF1.5 have smaller experimental uncertainty in the u/d ratio