Parton Distribution Functions

Physics in Collision, Vancouver
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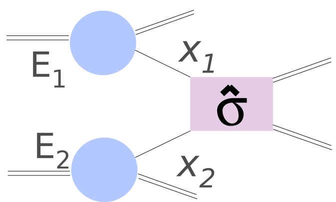
Outline:

- Introduction
- Proton Structure and DIS
- Parton Distribution Functions (PDFs)
- HERAPDFs
- Summary

Introduction

LHC: *pp* collisions at $\sqrt{s}$=7, 10, 14 TeV

Goal: Higgs and new physics
Main challenge: Background suppression
Main background: QCD



Hard processes >80% gluon-gluon fusion

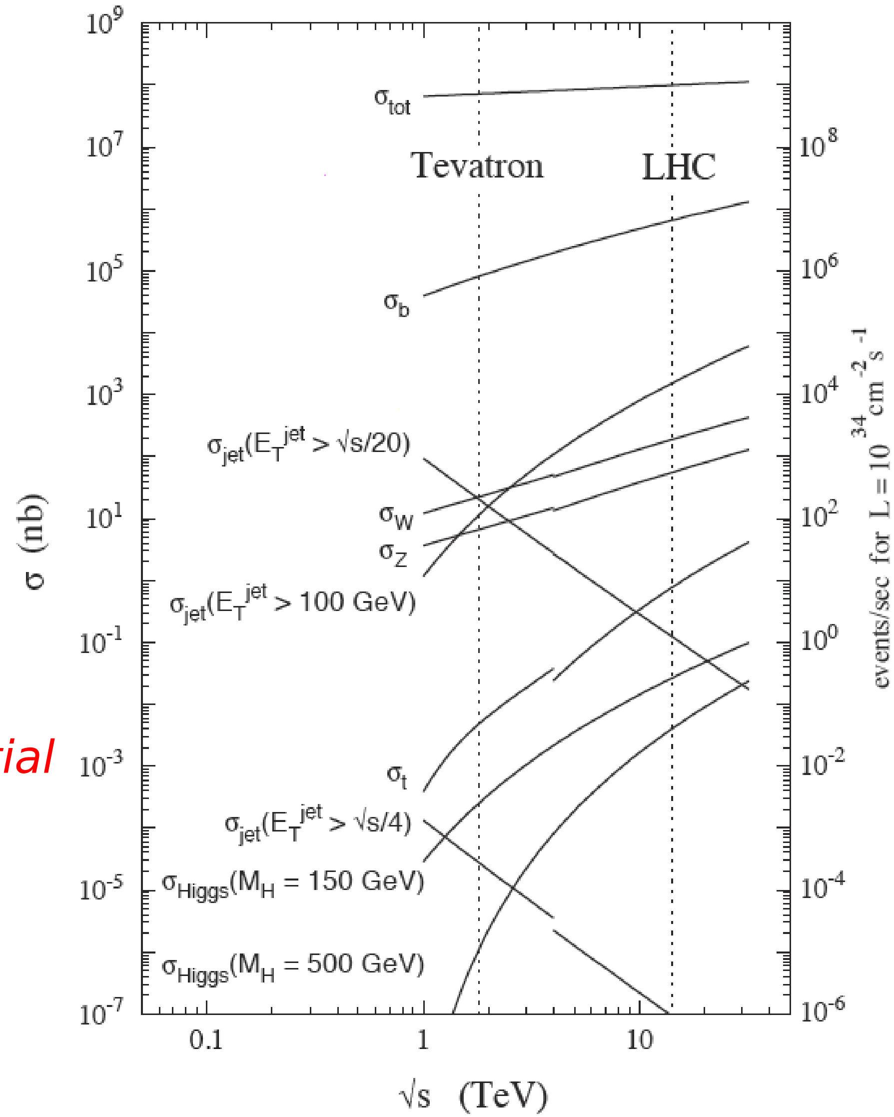
Precision of the gluon density is essential

Luminosity: e.g. $u\bar{d} \rightarrow W^+ \rightarrow l^+ \nu_l$

Precision of light quark densities is essential

Heavy quark treatment for the prediction of cross sections is important

Rate and cross sections of *pp* collisions



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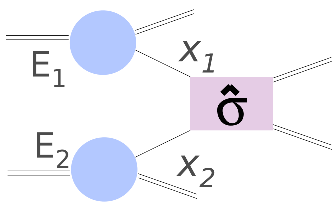

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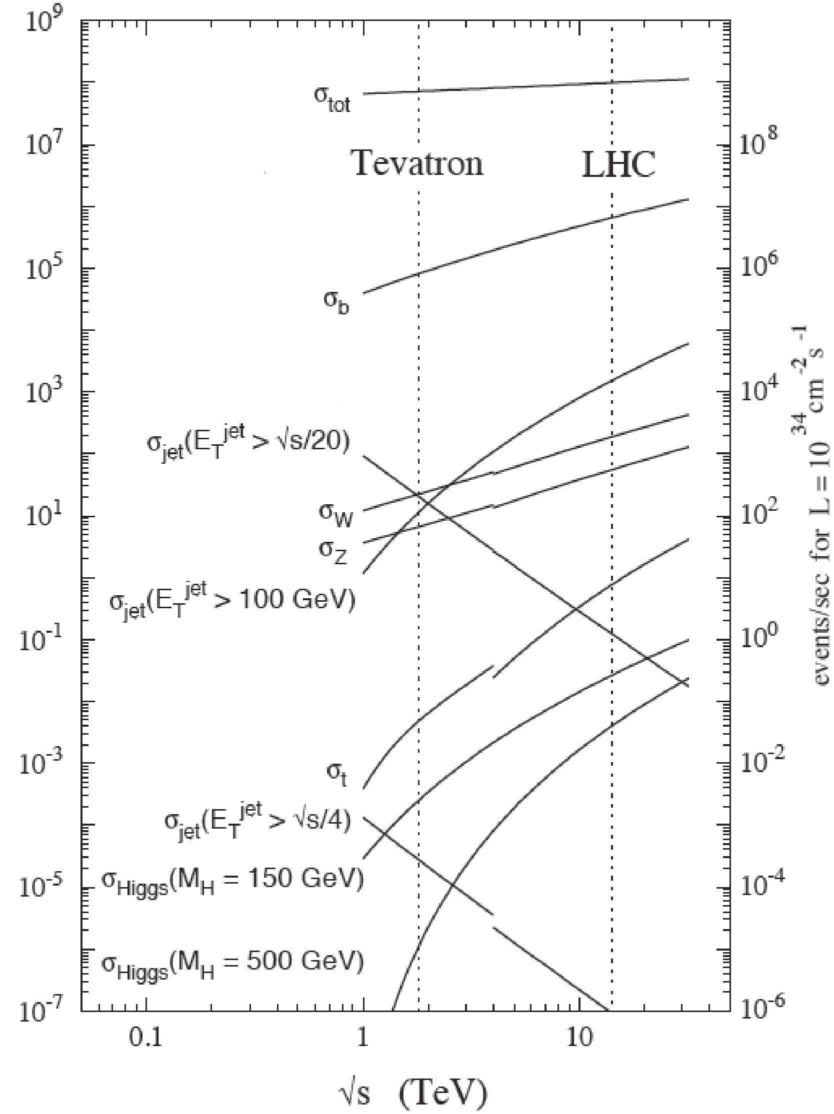
To understand LHC data we need to understand proton

Rate and cross sections of *pp* collisions

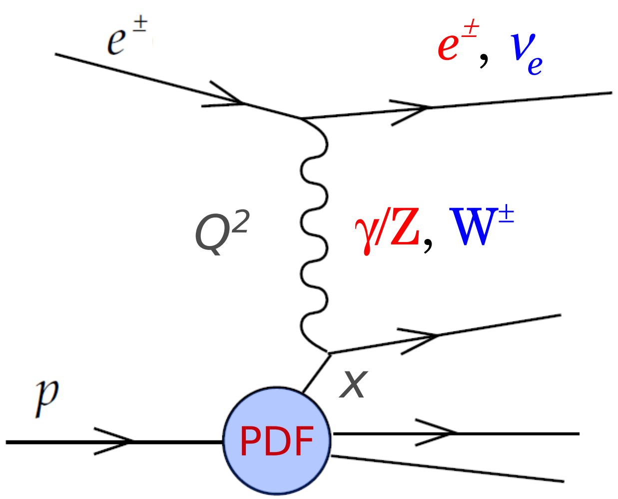


Parton Distribution Functions (PDFs)

Nucleon is made up of point like constituents (partons)

Probability for a parton to carry the fraction *x* of proton momentum
→ Parton Distribution Functions

Deep Inelastic Scattering (DIS) provides unique opportunity to study the structure of the proton



Neutral Current (NC): $ep \to eX$
Charged Current (CC): $ep \to \nu X$

Kinematics:

Q^2 - virtuality of exchanged boson

x – Bjorken scaling variable

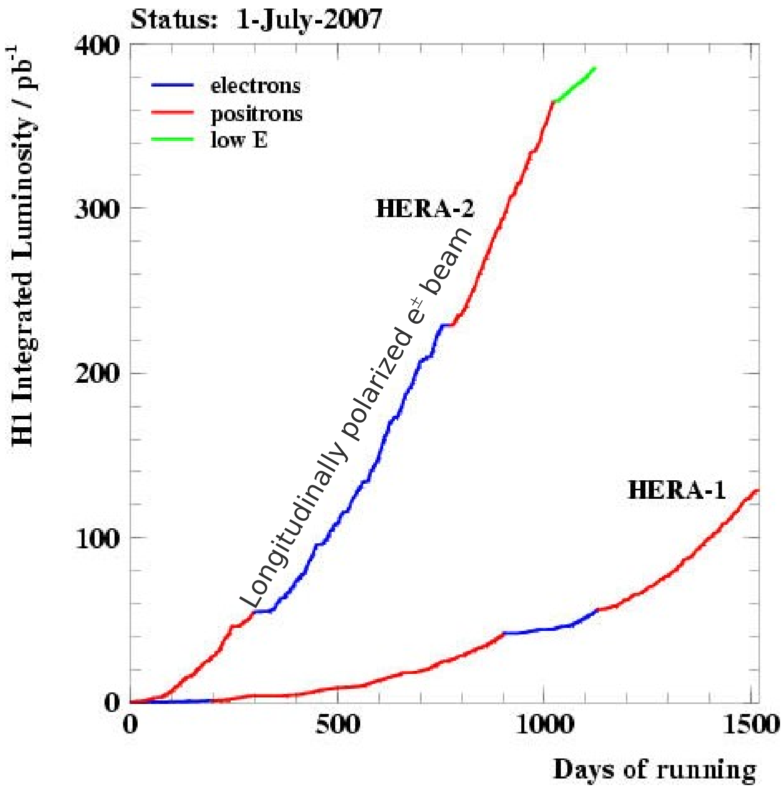
y – inelasticity

$Q^2 = sxy$ ($\sqrt{s}$ centre-of-mass energy)

PDFs are intrinsic property of nucleon, i.e assumed to be process independent

HERA Collider

World's only *ep* collider

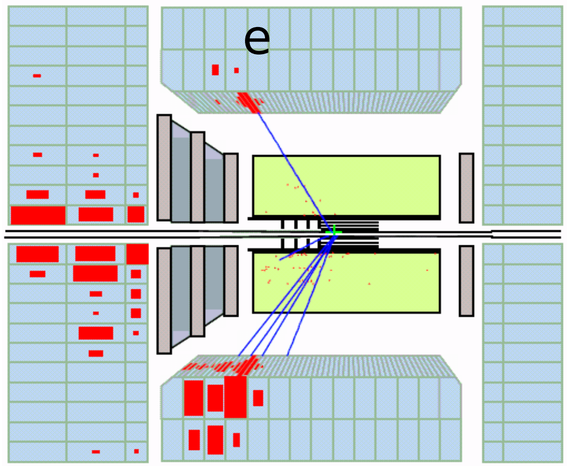


- $e^{\pm}$(27.5 GeV), p(460-920 GeV),
  $\sqrt{s}$ = 225-318 GeV
- Two collider experiments:
  H1 and ZEUS
- 1994-2000: HERA I data
  2003-2007 HERA II data
  (end of running 30.06.2007)
- ~0.5 fb^{-1} of luminosity recorded by the each experiment

ep Scattering at HERA

DIS cross section can be decomposed in terms of **structure functions**:

Neutral Currents



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

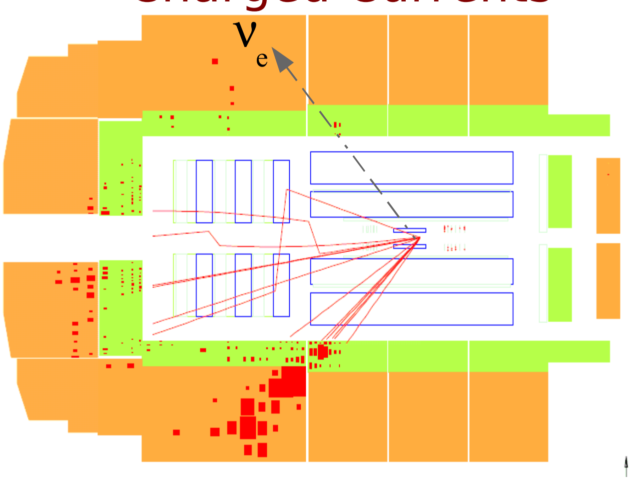
dominant contribution

important at high Q^2

sizable at high y

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

Charged Currents



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

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

ep Scattering at HERA

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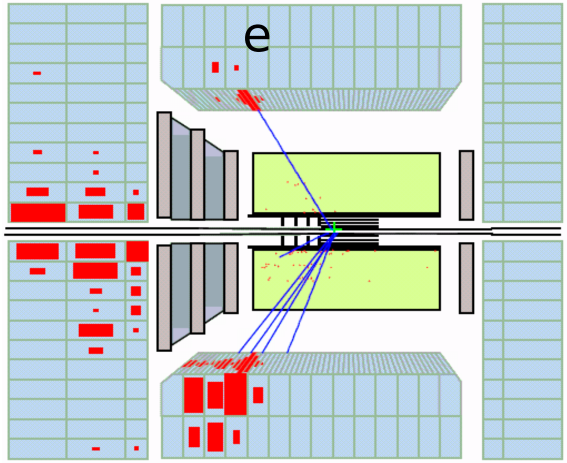

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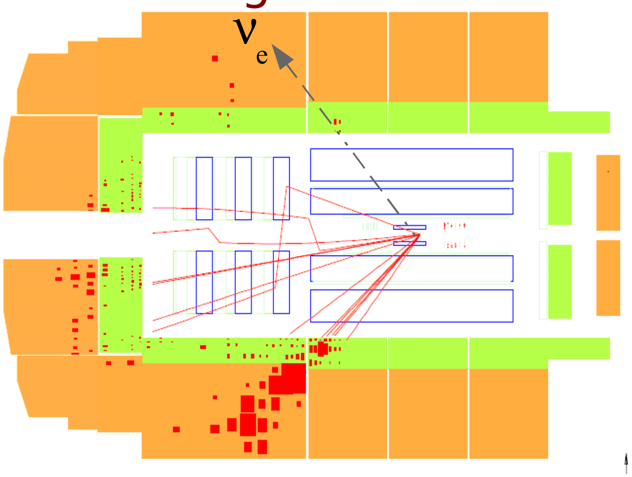

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PDFs

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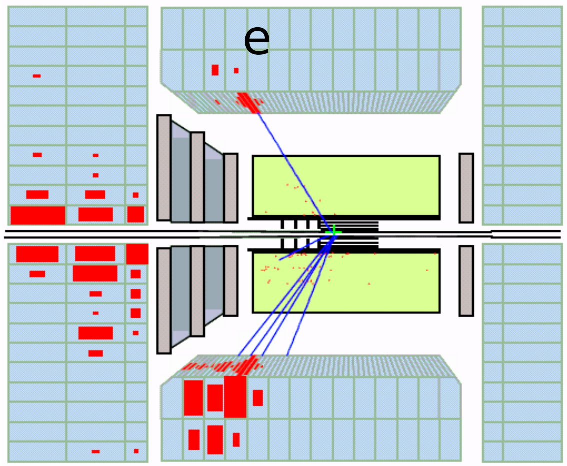

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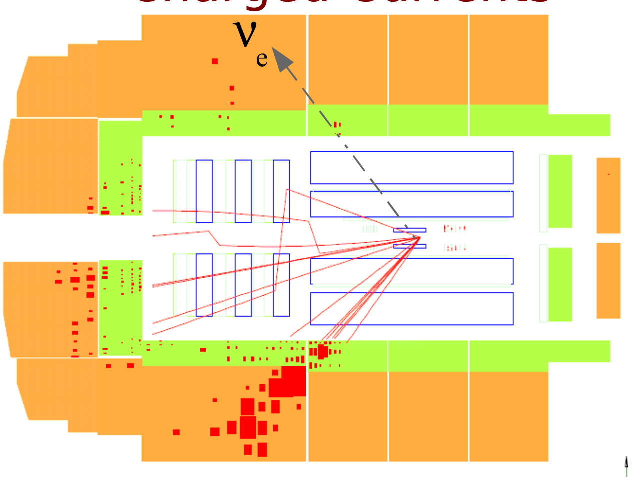


In LO e^+/e^- charged current cross sections are sensitive to different quark densities:

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

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

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

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

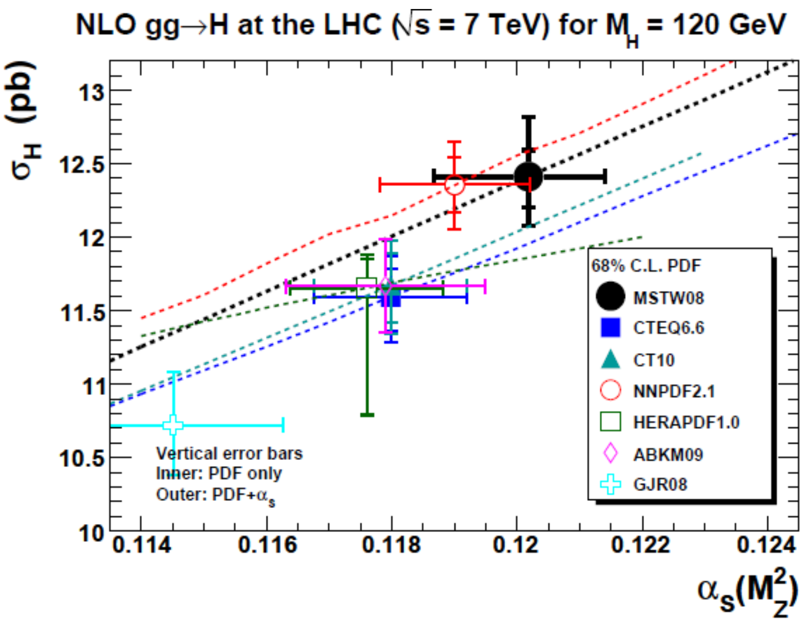
Main sources of difference between different PDFs:

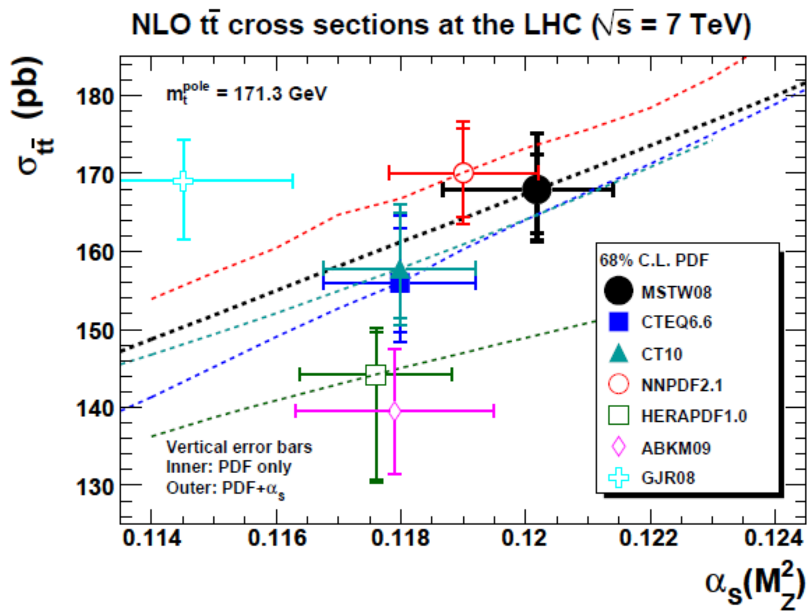
- inclusion of different data
- methods of determining 'best fit'
- uncertainty treatment/sources
- assumptions in procedure (parametrisation)
- heavy flavour treatment
- PDF and α_s correlation

... lead to differences in the cross section predictions

PDF Fit Groups: Benchmarking (PDF4LHC)

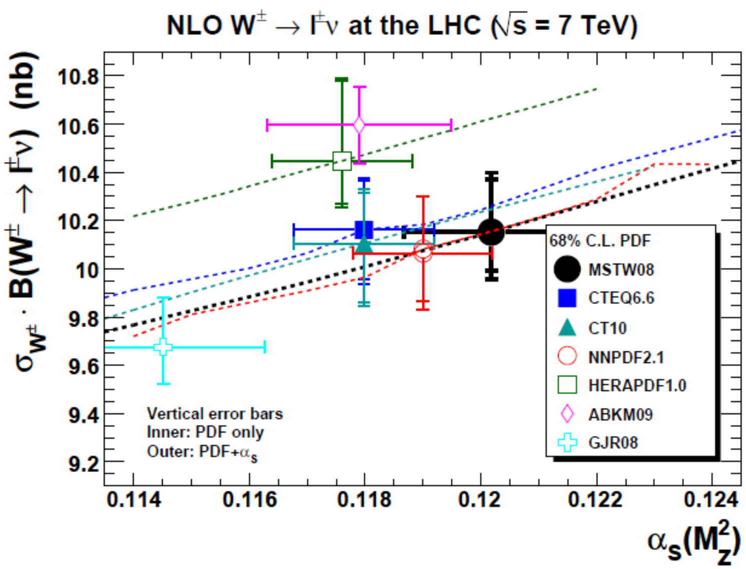
Different PDF lead to differences in cross section predictions

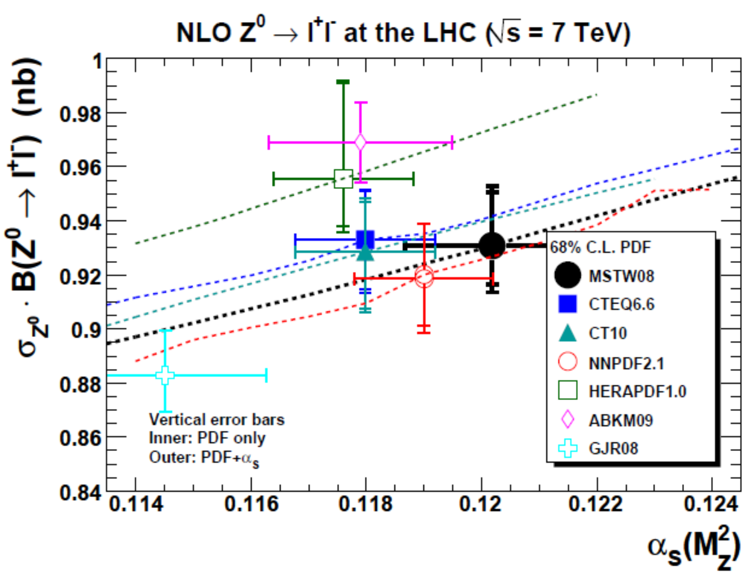




G.Watt
arXiv:1106.5788v1

PDF Fit Groups: Benchmarking





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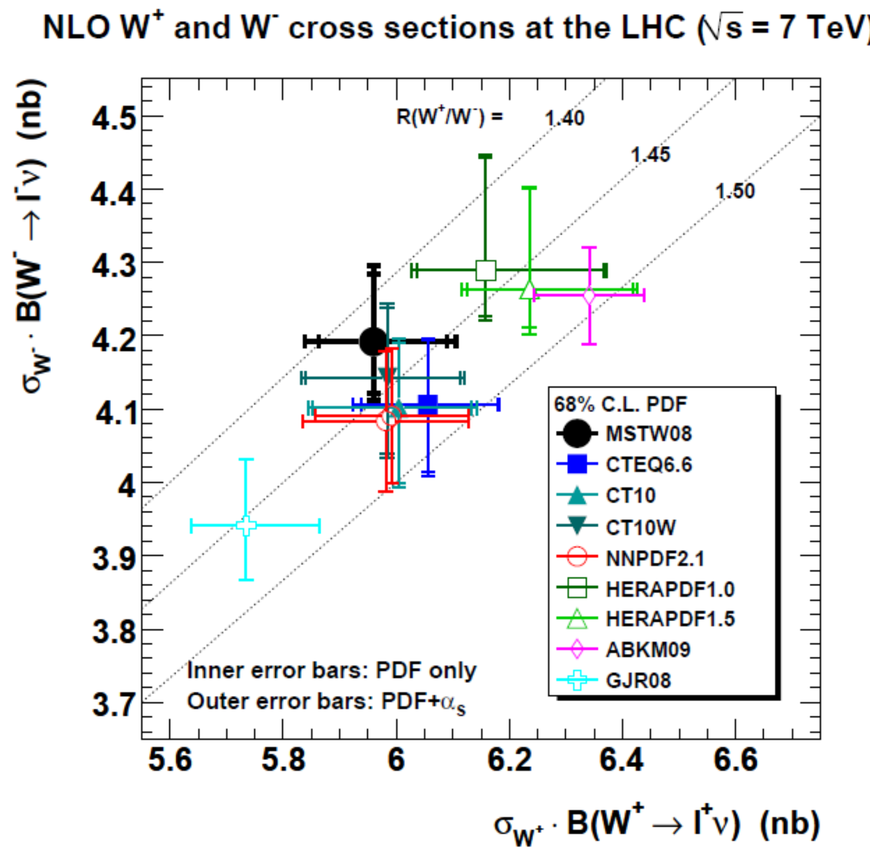

PDF Fit Groups: Benchmarking

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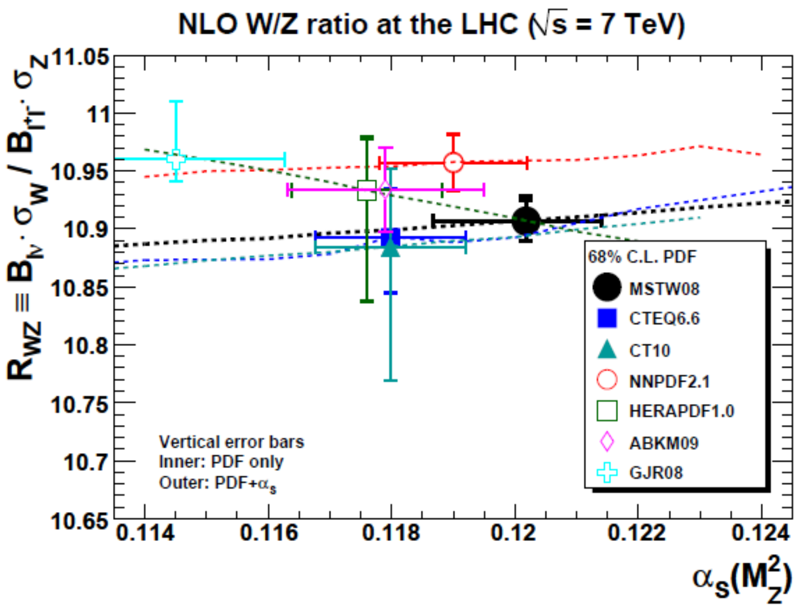
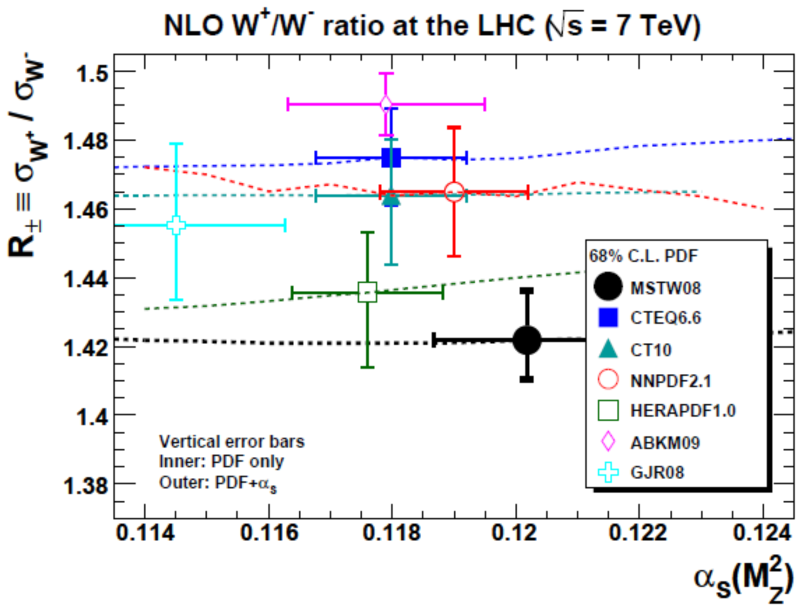




$(W^+ + W^-)/Z$ ratio has little sensitivity to PDFs

W^+/W^- ratio sensitive to u/d quark shapes

HERAPDFs

Now: closer look into HERA PDFs

- Parametrisation and uncertainties
- Recent improvements
- Comparisons with data (HERA, TEVATRON, LHC) and other PDFs

PDF determination in HERAPDF 1.0

DGLAP at NLO $\rightarrow$ QCD predictions

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

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

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
  - 14 for HERA I and 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 $x \rightarrow 0$

HERAPDF: Uncertainties

experimental

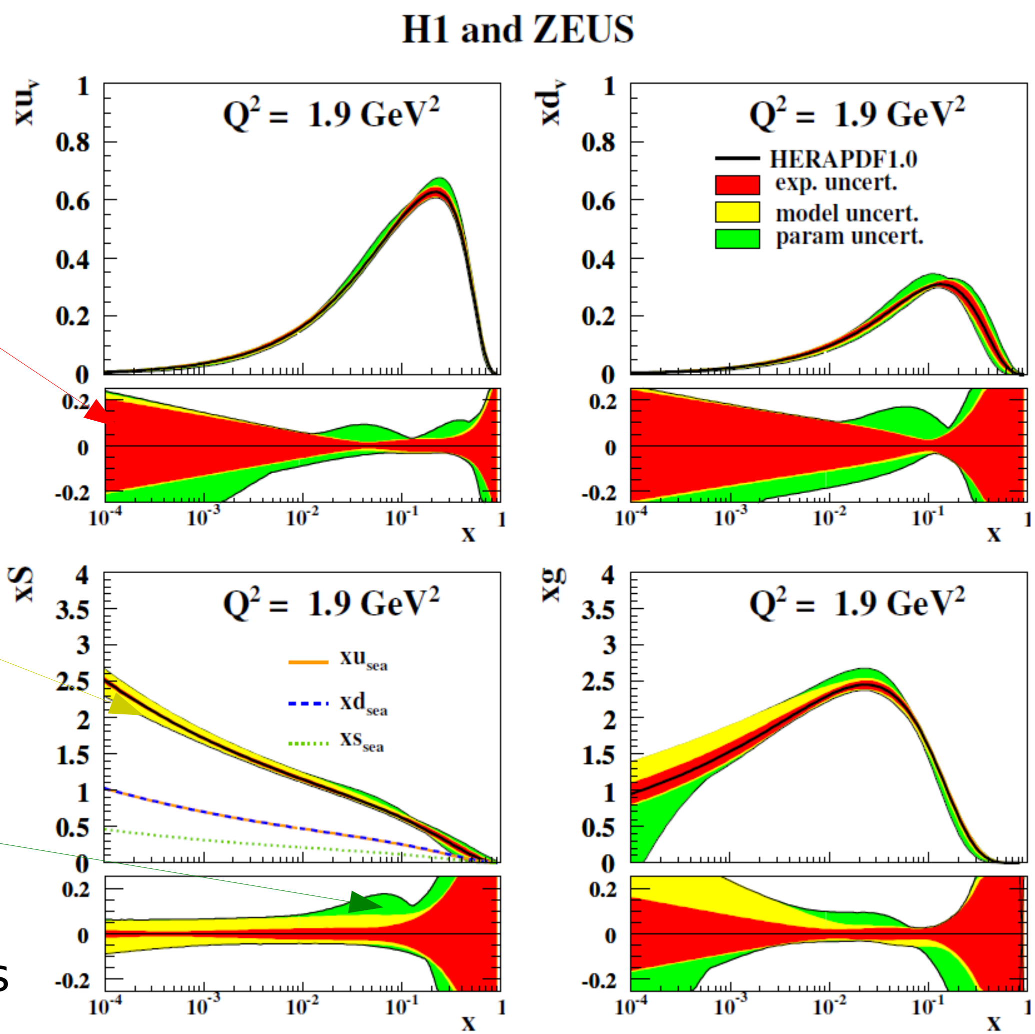
very small experimental uncertainties

model

model uncertainties from: Q^2_{min}, f_s, m_C, m_B

parametrisation

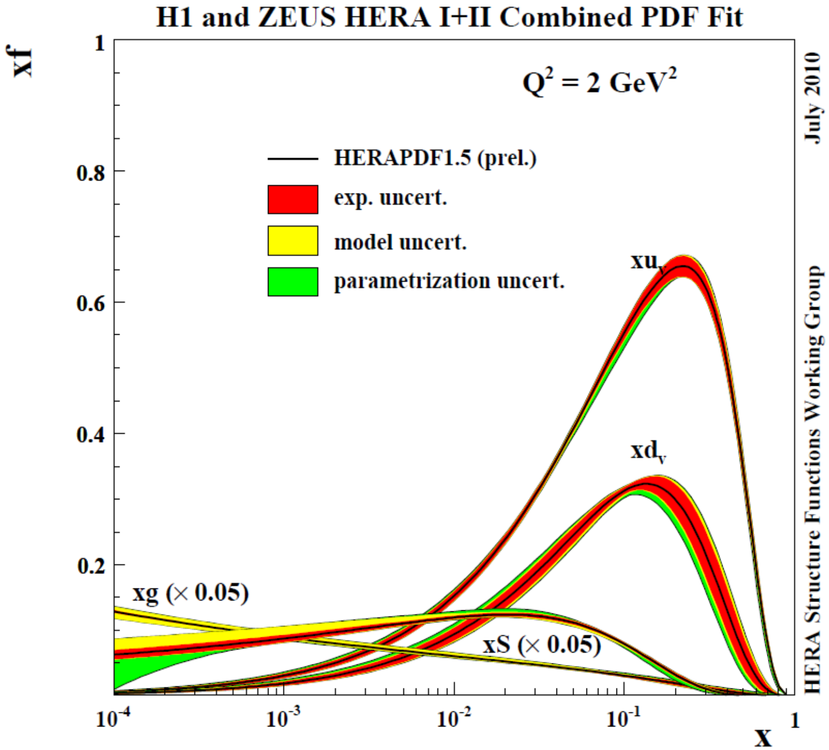
from different parametrisation assumptions

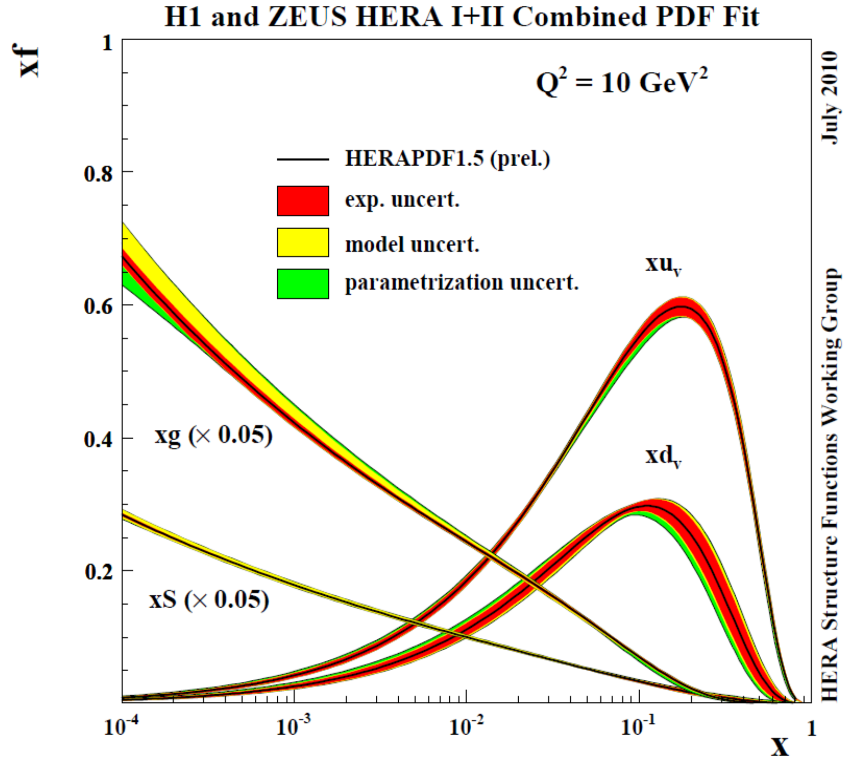


HERAPDF Fit

HERAPDF1.5: QCD fit to combined **HERA I+II data** (H1 and ZEUS)

741 data points



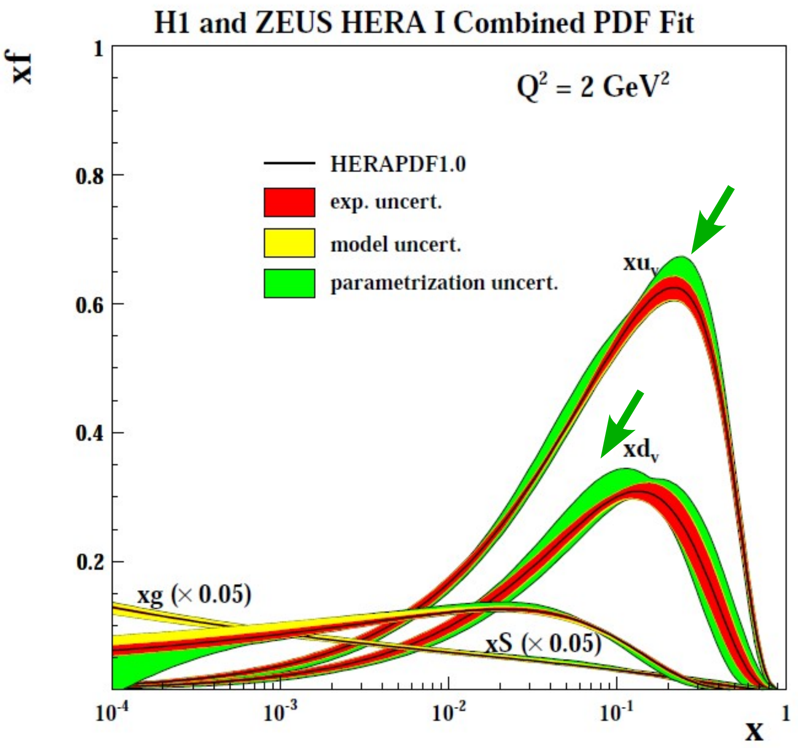


https://www.desy.de/h1zeus/combined_results/index.php

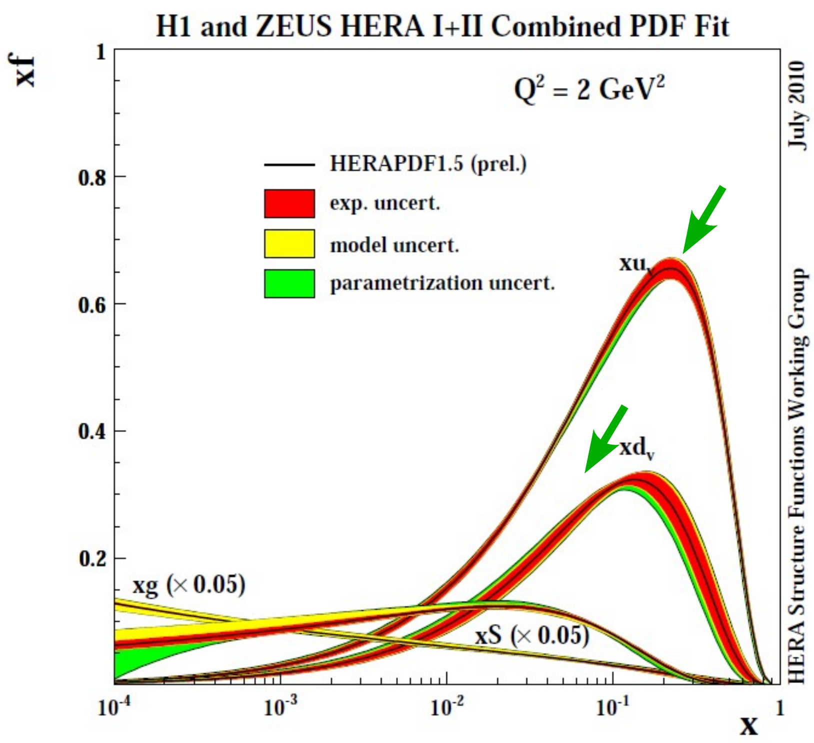
Recent Improvement in HERAPDFs

High precision HERA II high Q^2 data released in summer 2010

HERA I



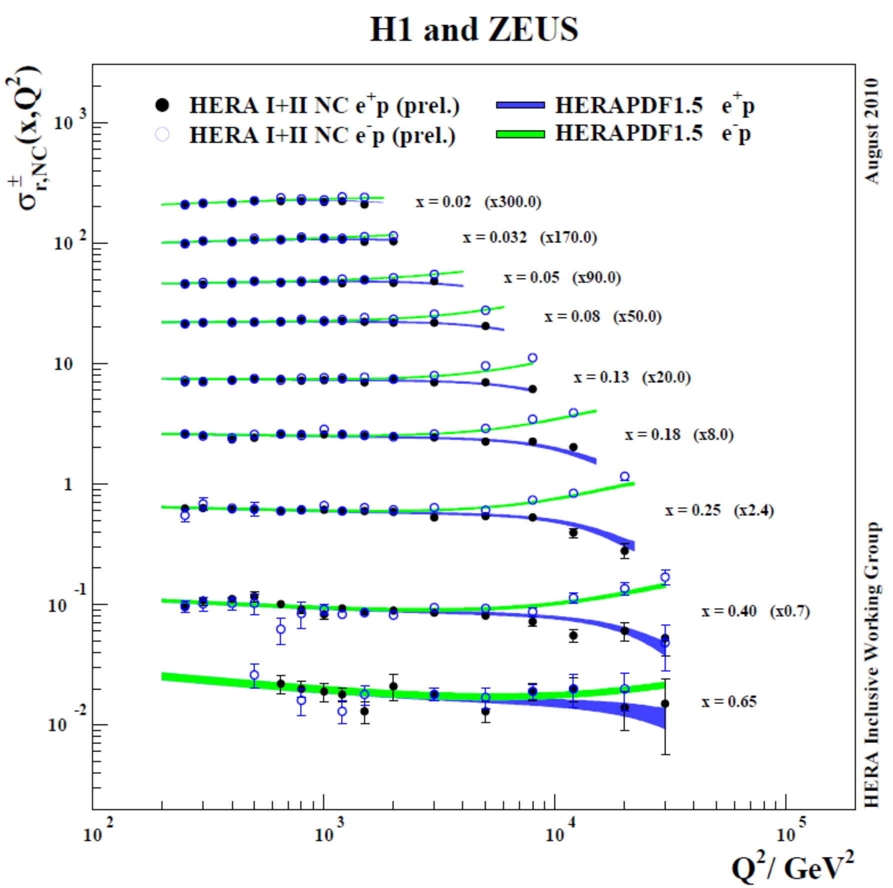
HERA I + II



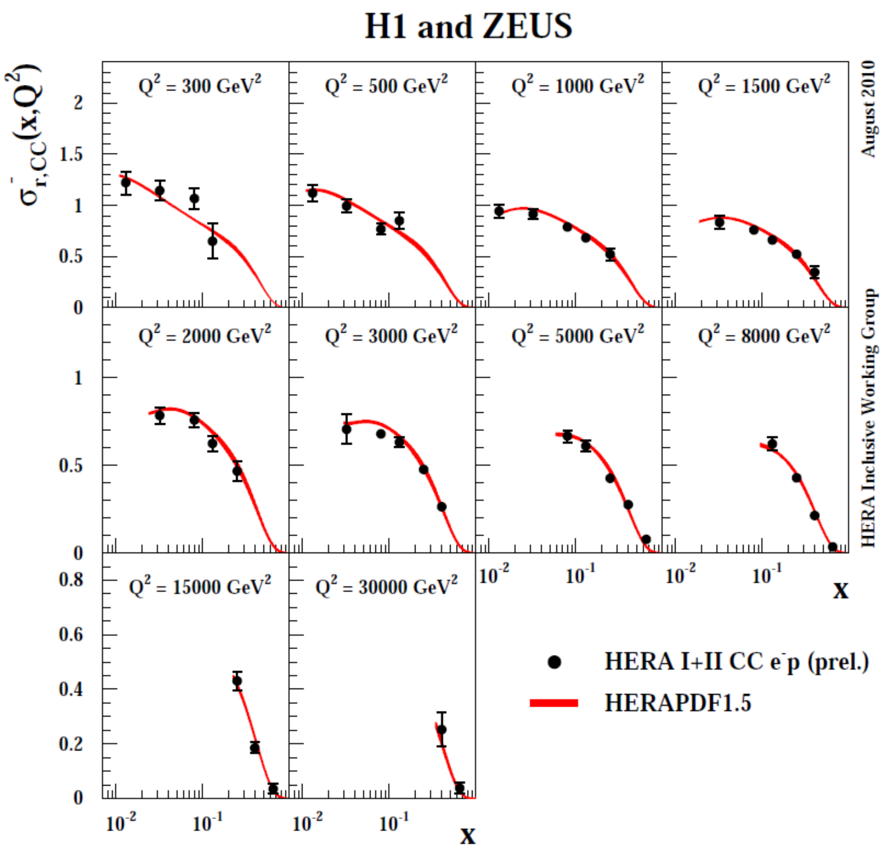
Reduced uncertainties (mainly valence quarks)

HERA DIS Cross Sections vs HERA PDFs

Neutral Currents



Charged Currents

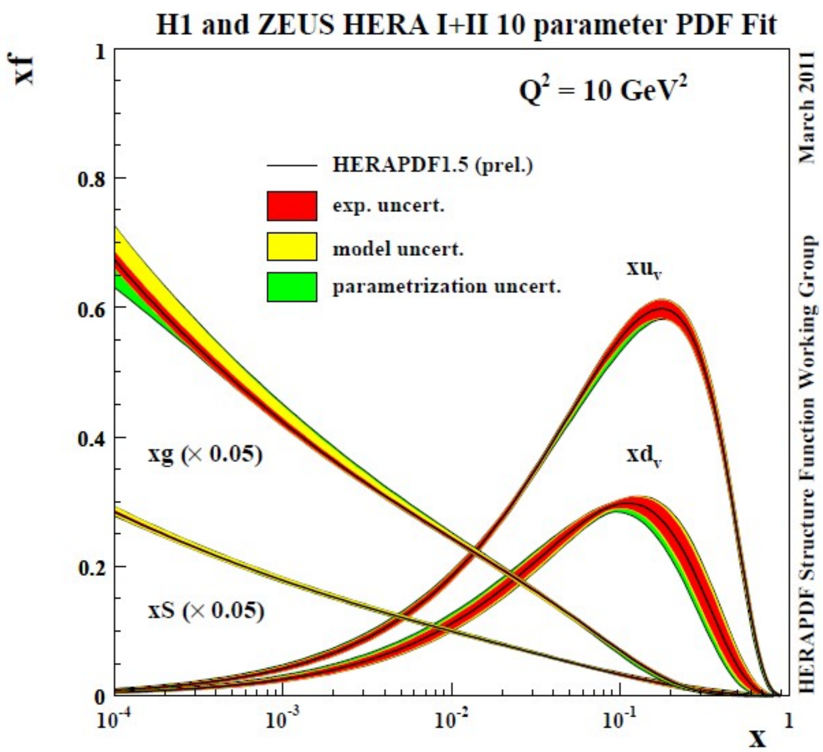


HERA PDF fit describes NC and CC data very well

HERAPDF1.5f

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

HERAPDF1.5



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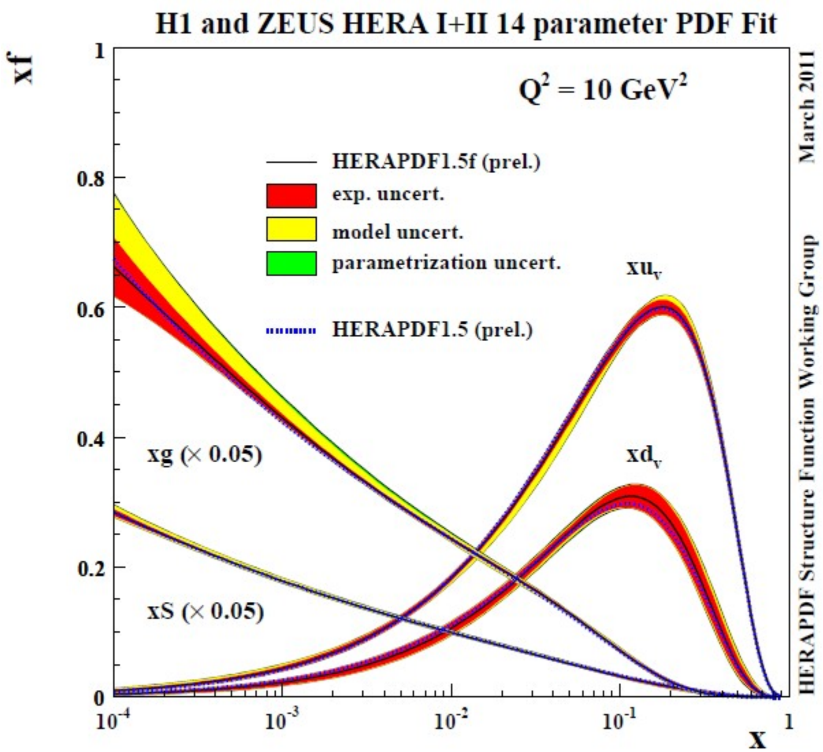
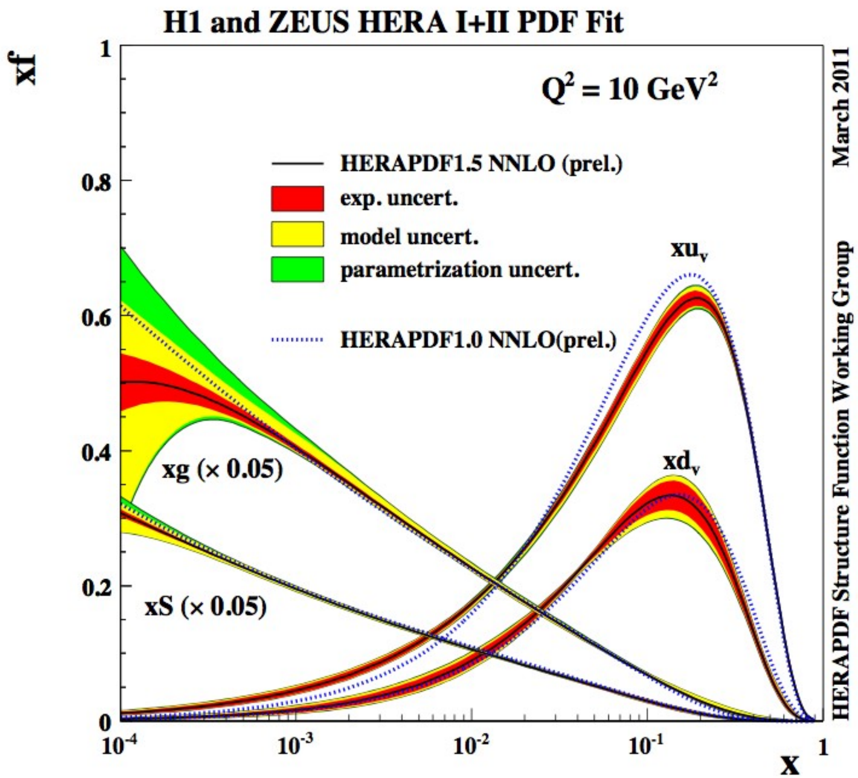


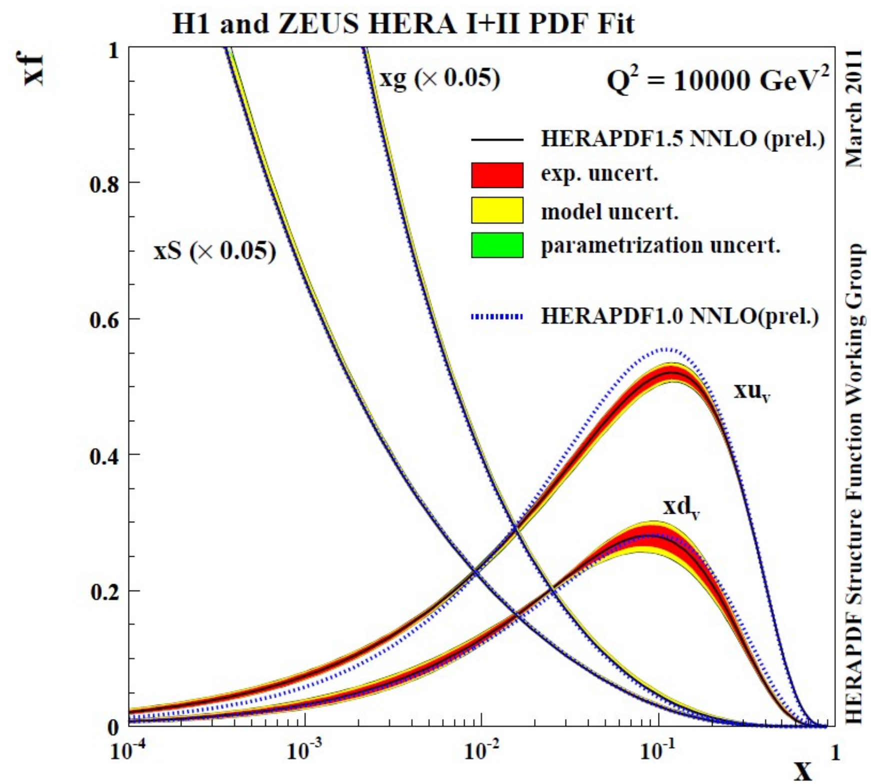
Small difference in total uncertainty
→ swap between **parametrisation** and experimental uncertainties

HERAPDF at NNLO

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

→ uses more flexible parametrisation form

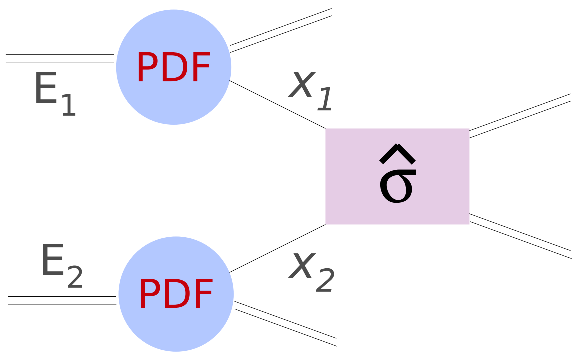




HERA PDFs can be used for NNLO predictions at LHC

Proton-Proton Collisions

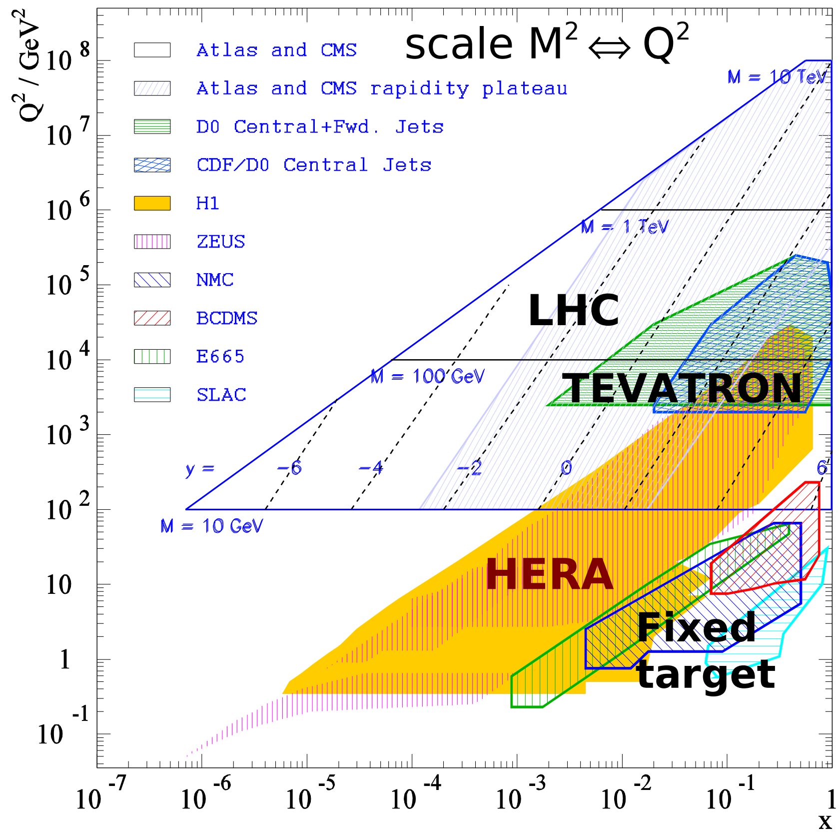
Same PDFs can be used to predict *pp* collisions



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

Factorisation:

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



HERA covers *x* range of the LHC

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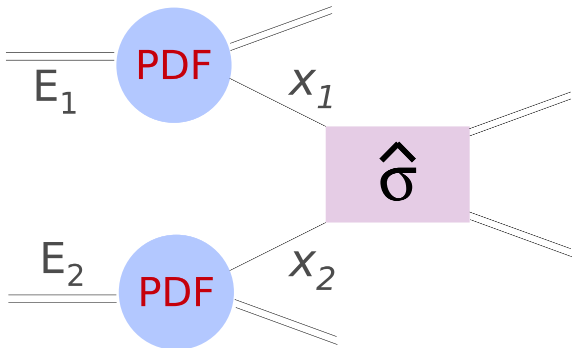

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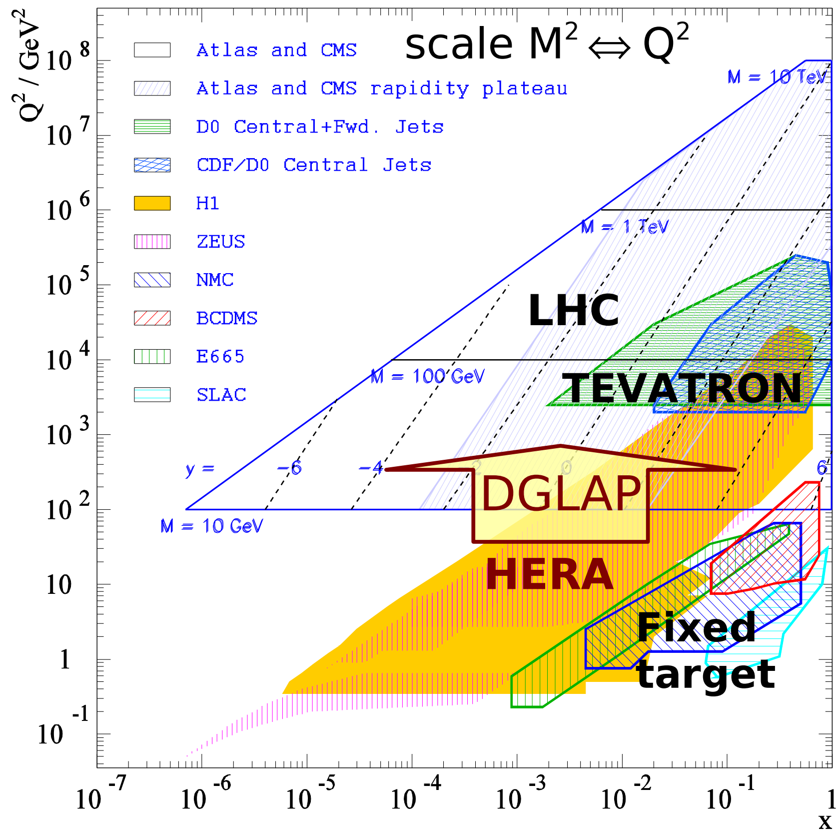


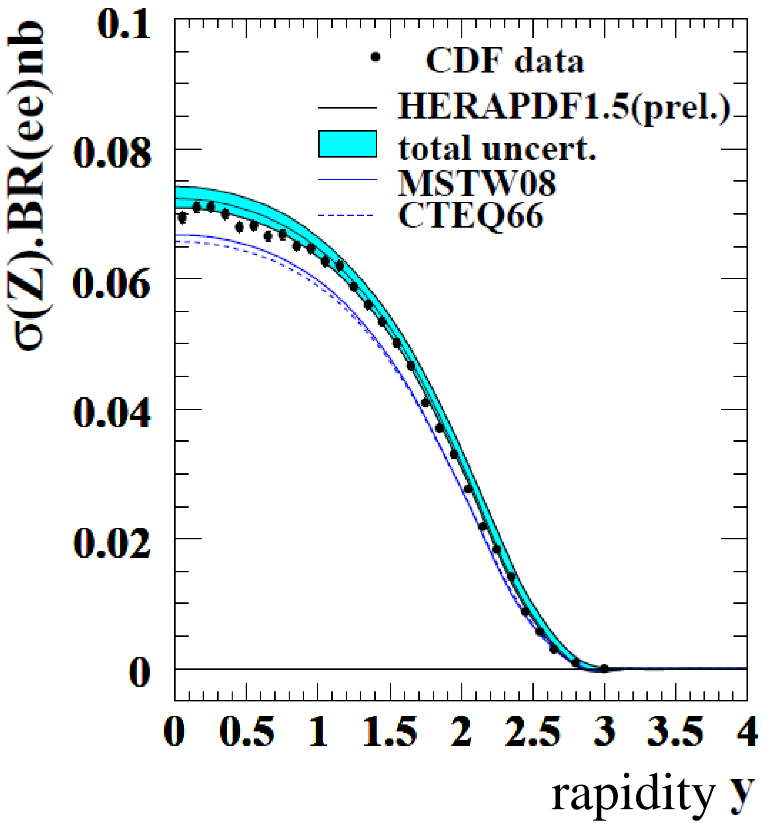
HERA covers *x* range of the LHC

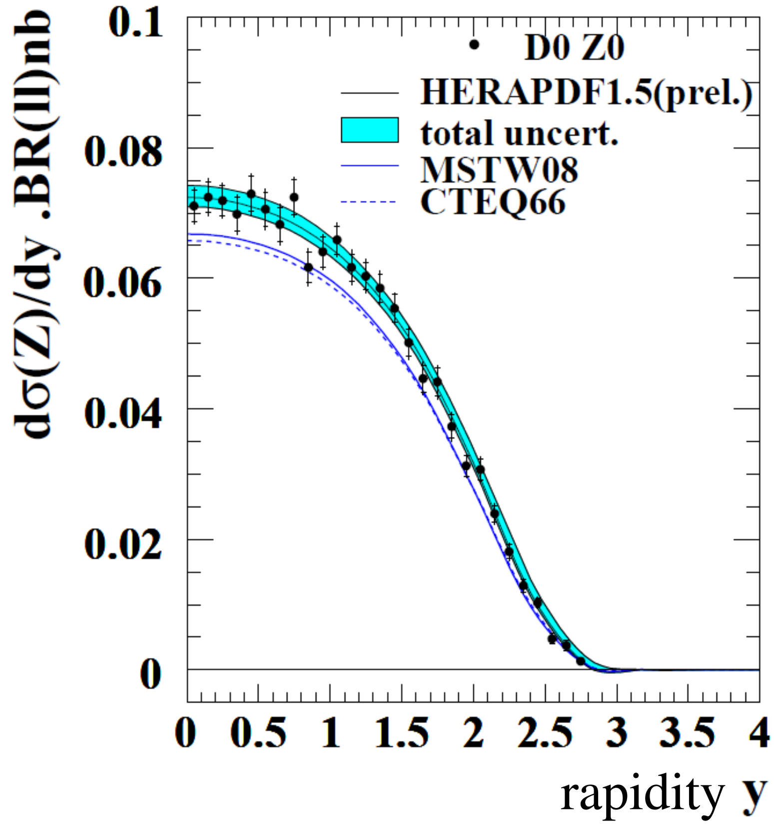
evolution in Q^2 via DGLAP

HERAPDF Predictions for Tevatron

$\sqrt{s}$ = 1.96 TeV

Z rapidity



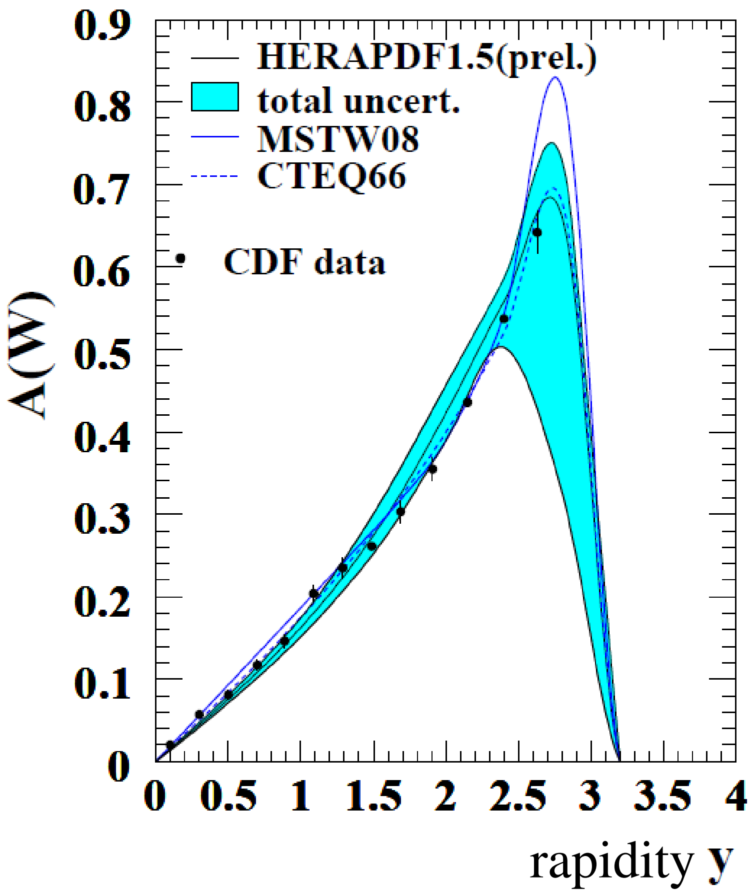


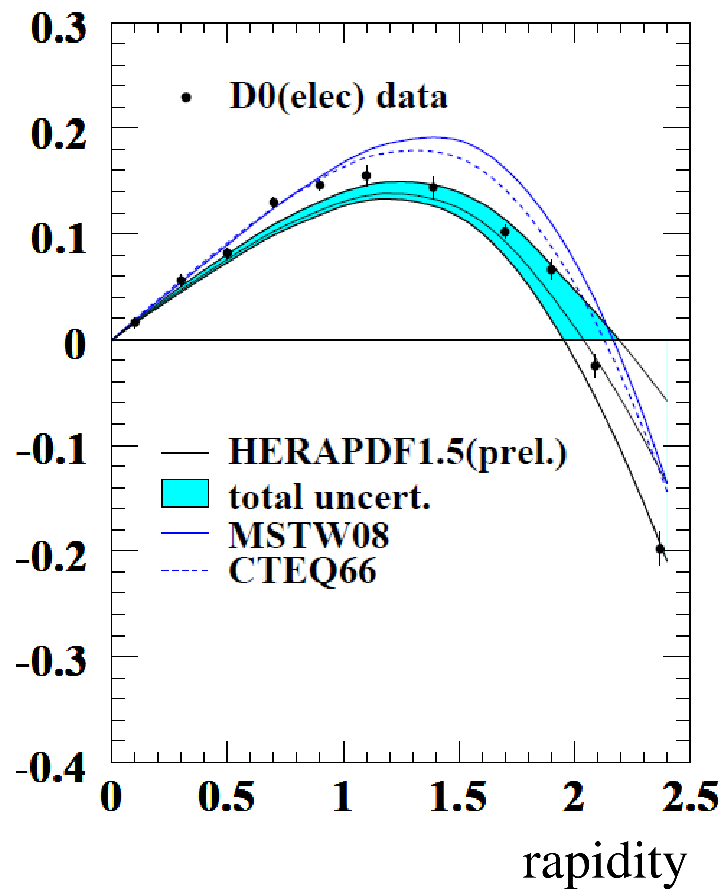
Predictions based on HERA PDFs describe Tevatron data well

HERAPDF Predictions for Tevatron

$\sqrt{s}$ = 1.96 TeV

W and W(lepton) asymmetry





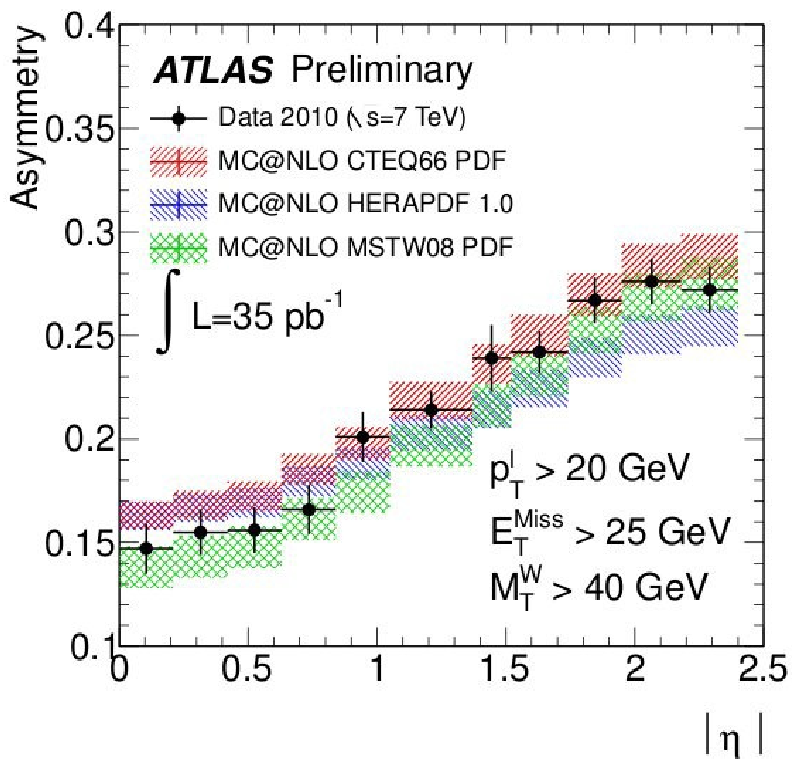
Predictions based on HERA PDFs describe Tevatron data well

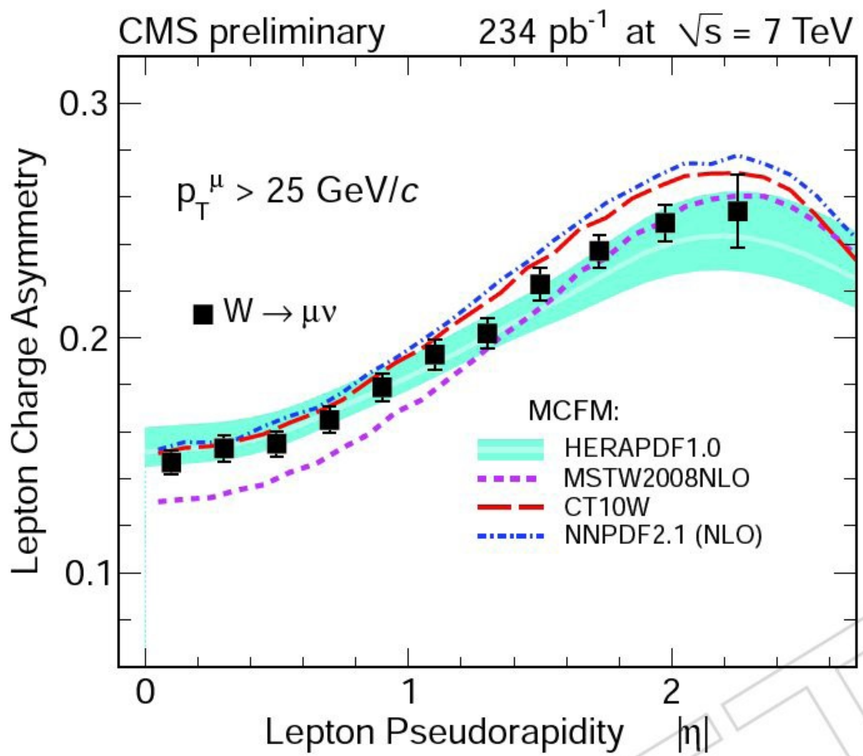
HERAPDF Predictions for Asymmetries at LHC

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

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

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





Newest results from ATLAS and CMS (LP2011)

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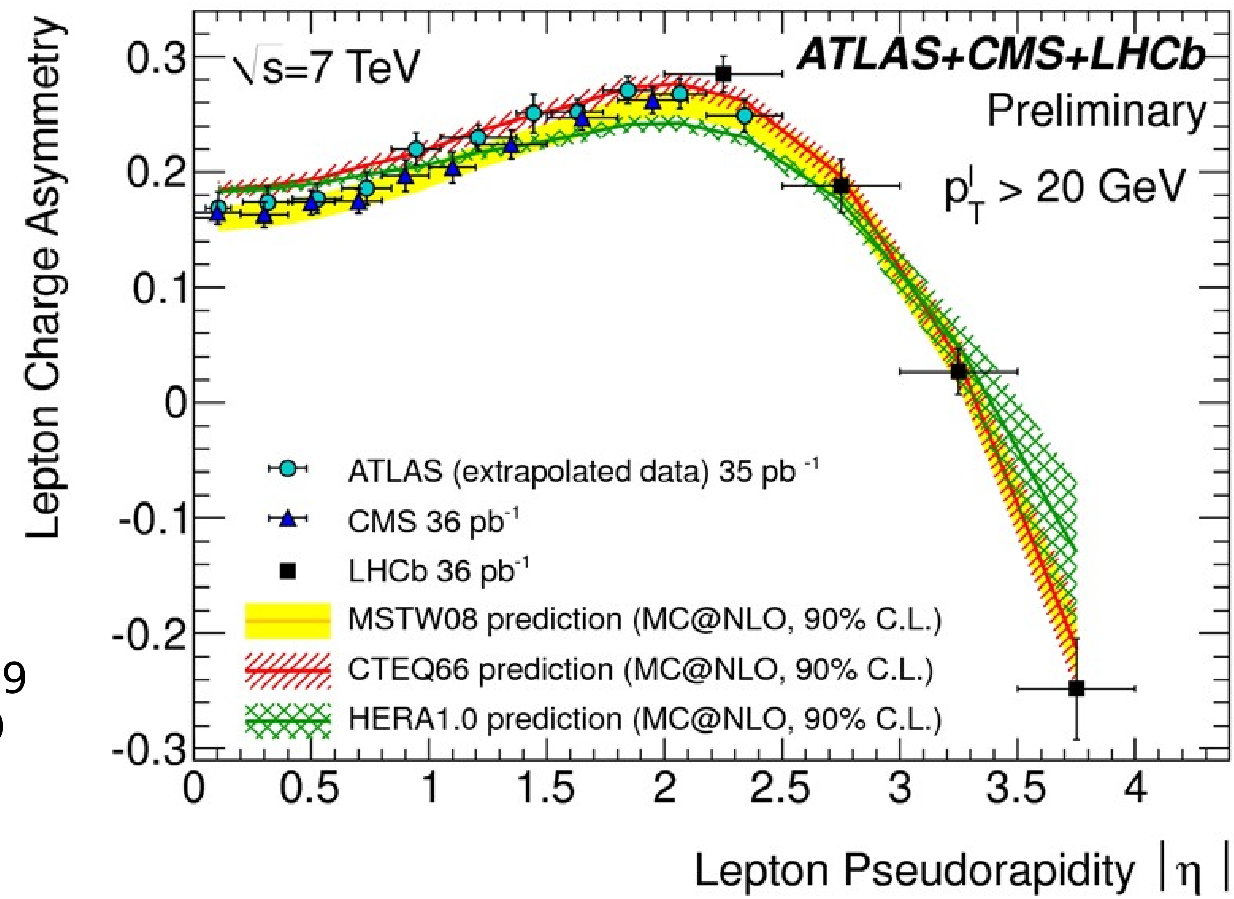
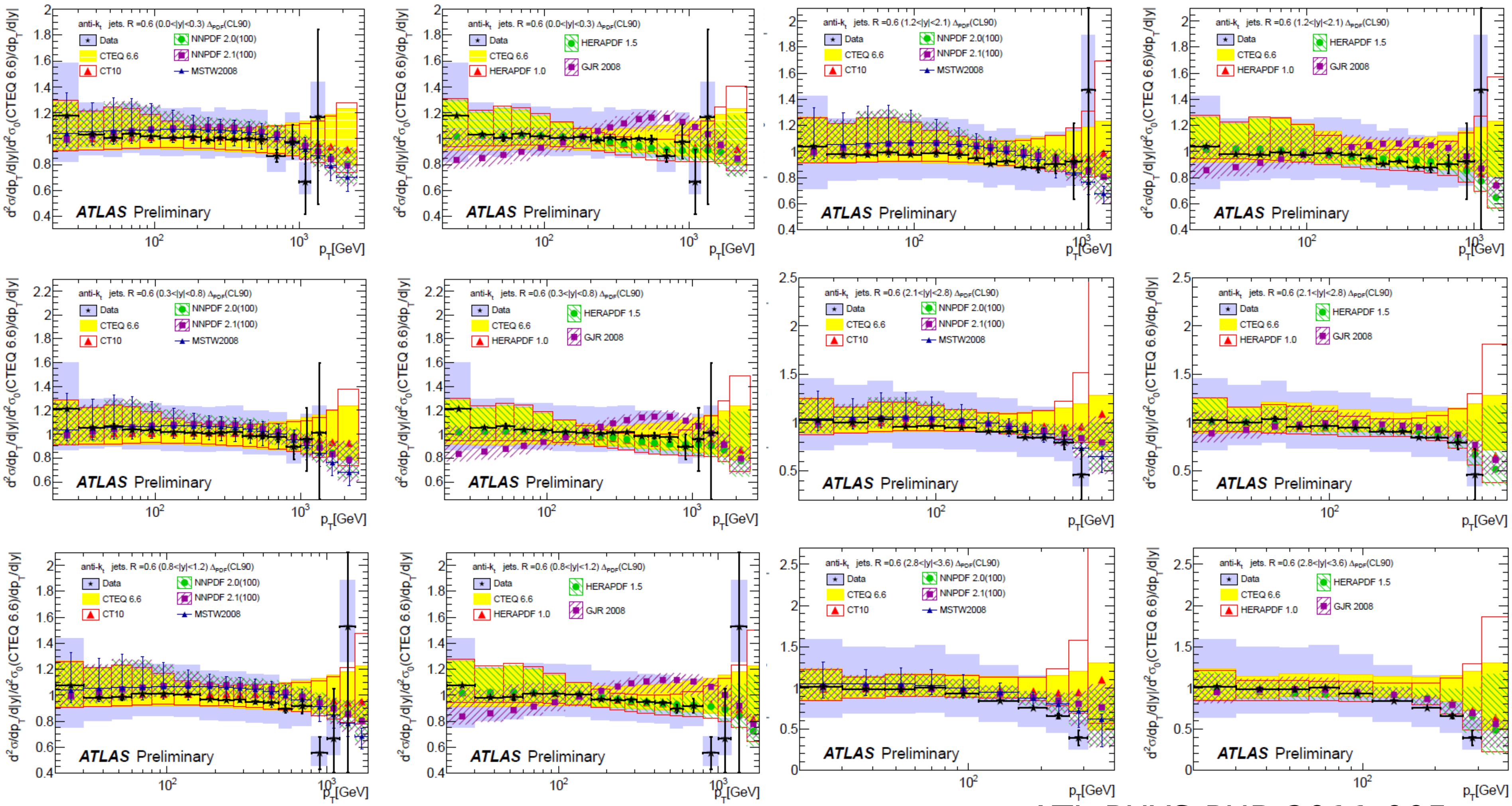


ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006
(arXiv:1103.3407)

Newest results from LHC (LP2011)

HERAPDF Predictions for Jets at LHC

Inclusive jet cross section as a function of jet p_T in different regions of rapidity



ATL-PHYS-PUB-2011-005

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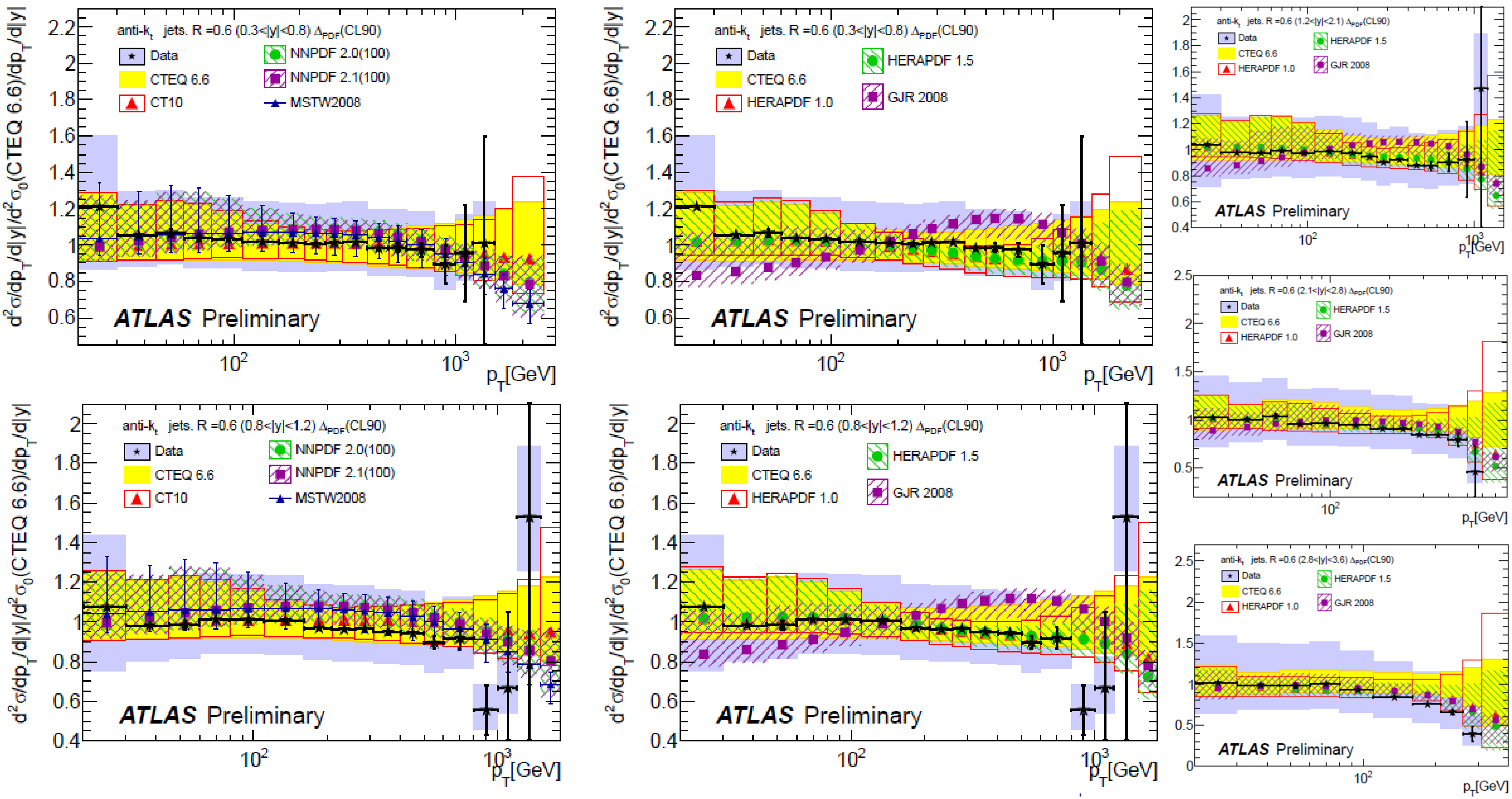

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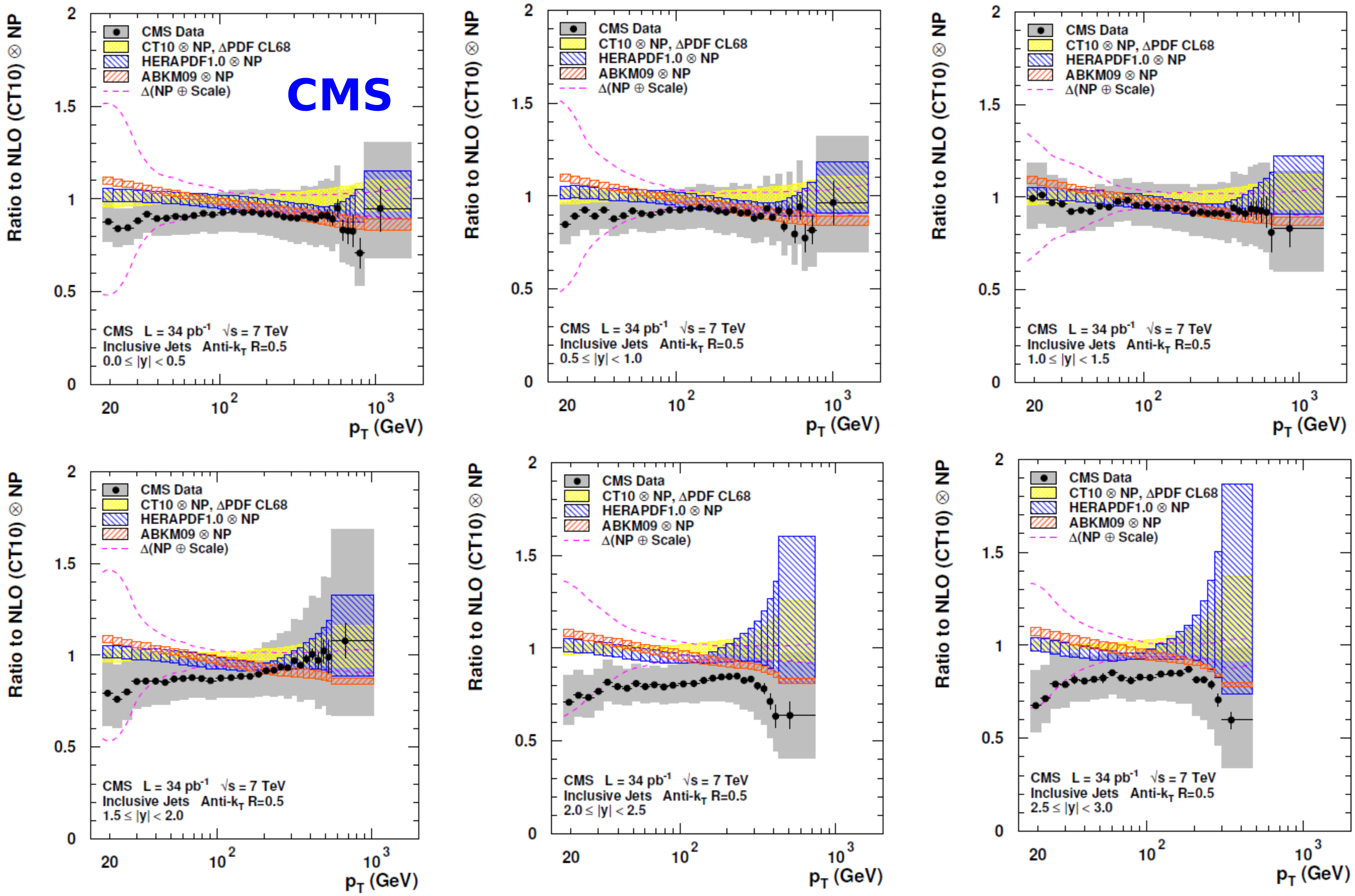
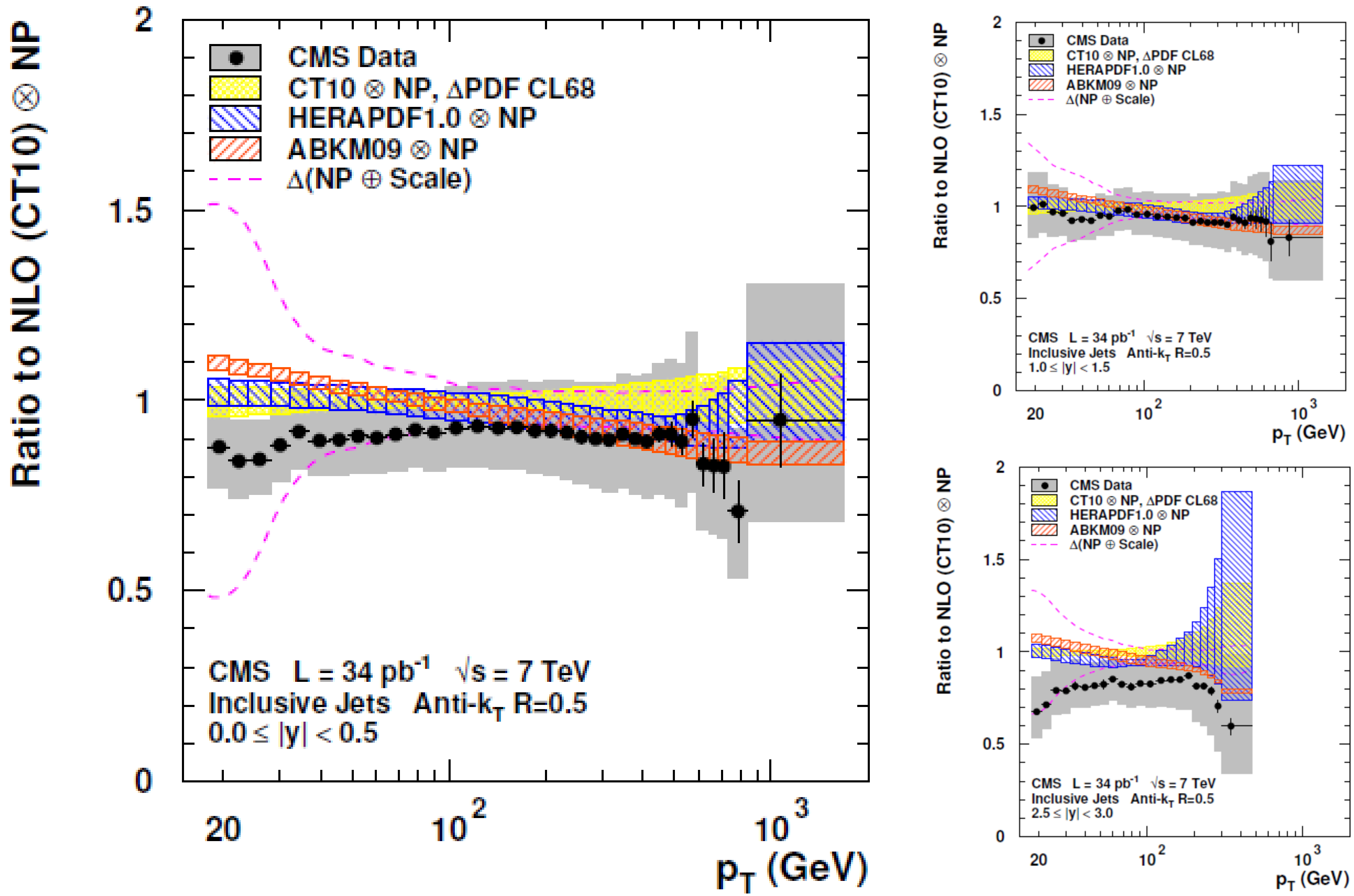


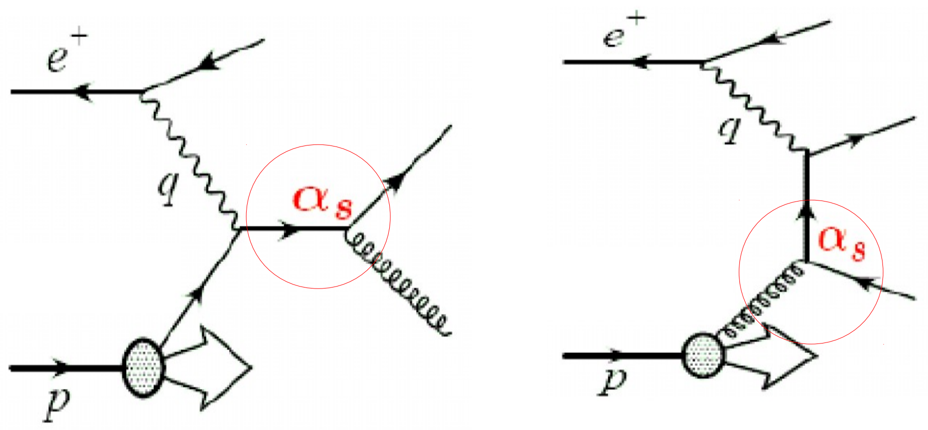
HERAPDF Predictions for Jets at LHC



Predictions based on HERA PDFs describe LHC data quite well
(same level of agreement as other PDFs)

Constraints on PDFs from HERA Jet Data

LO jet production in DIS:



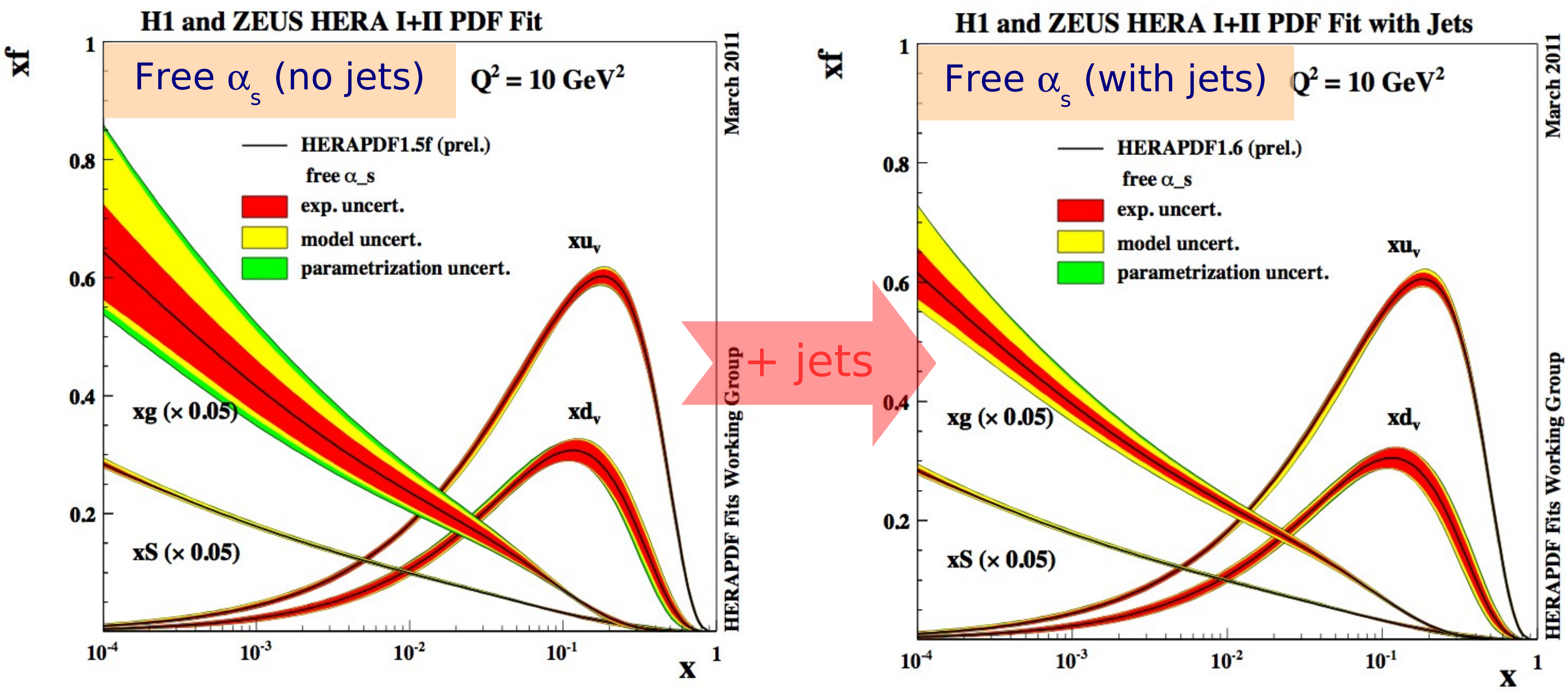
Direct sensitivity to gluon and strong coupling constant

Reduce correlation of gluon and α_s in PDF fit

HERAPDF fit with jet data:

- allow to constrain simultaneously α_s and gluon

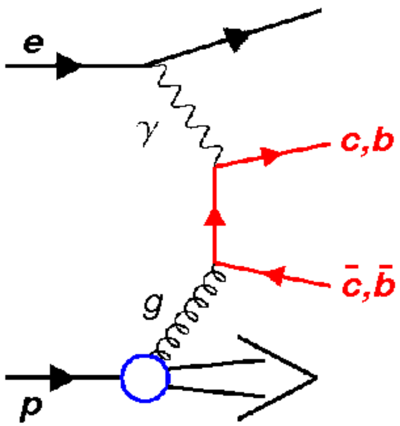
HERAPDF Fits Including Jet Data



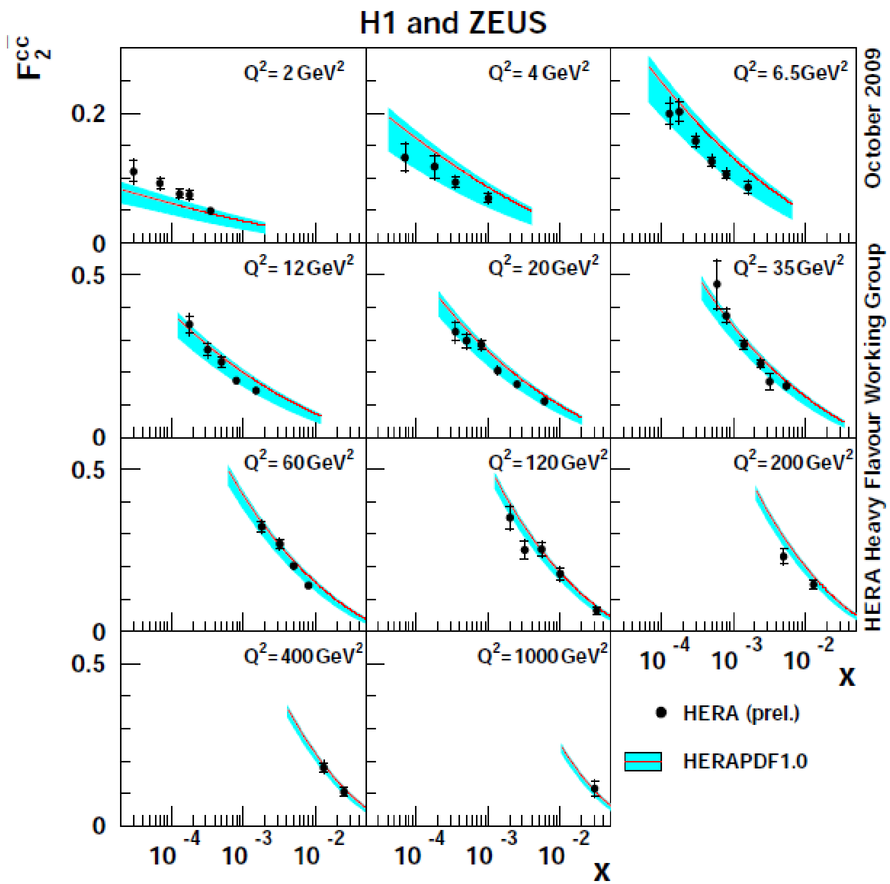
HERA jet data allow to constrain simultaneously α_s and gluon

→ more see the talk by Thomas Schoerner-Sadenius

HERA Charm Data: what Can we Learn?



Combined HERA F_2^{cc} measurement



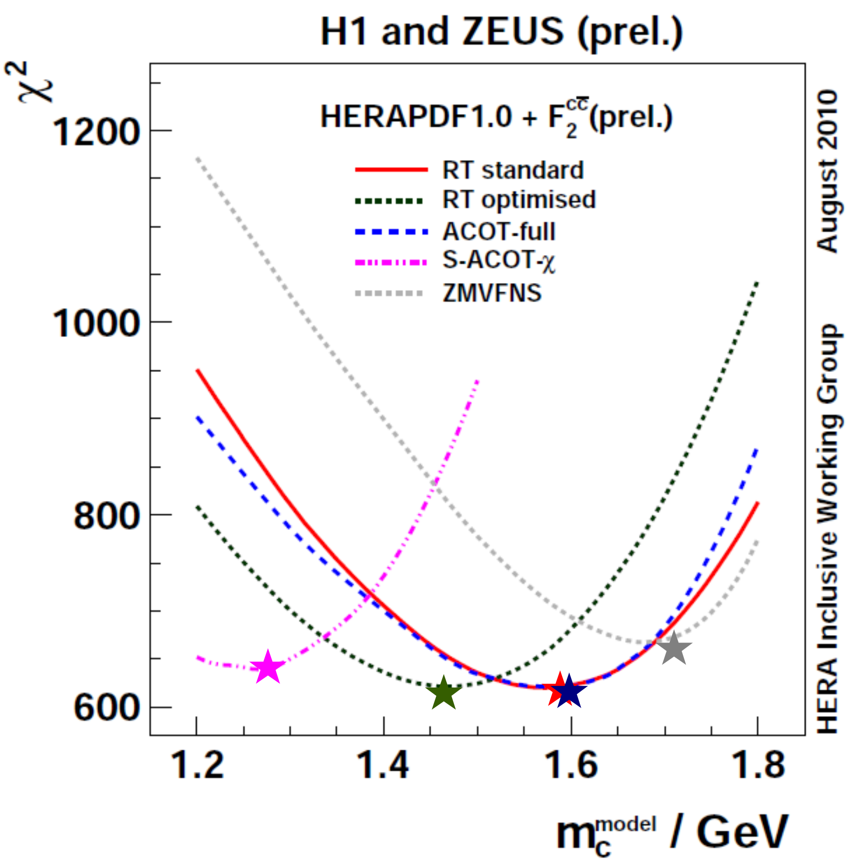
Direct access to the gluon

Heavy quark (HQ) treatment in PDFs is important

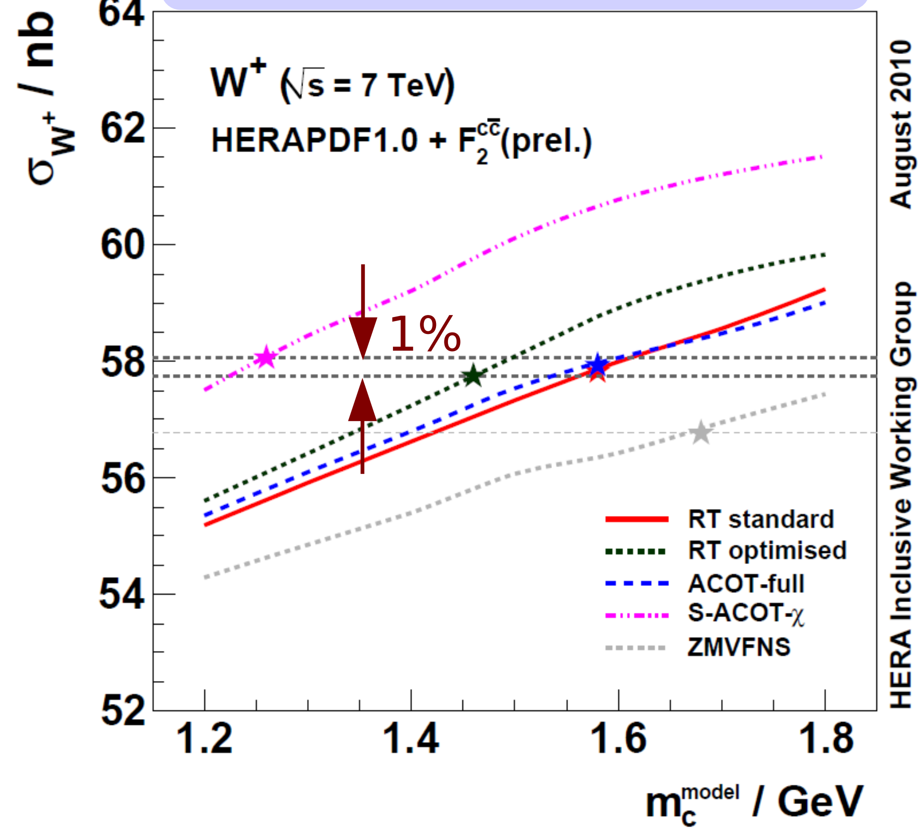
Different HQ schemes exist (different treatment of mass terms in perturbative calculation)

Data well described by HERAPDF prediction

Constraints on PDFs from HERA Charm Data



Z 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

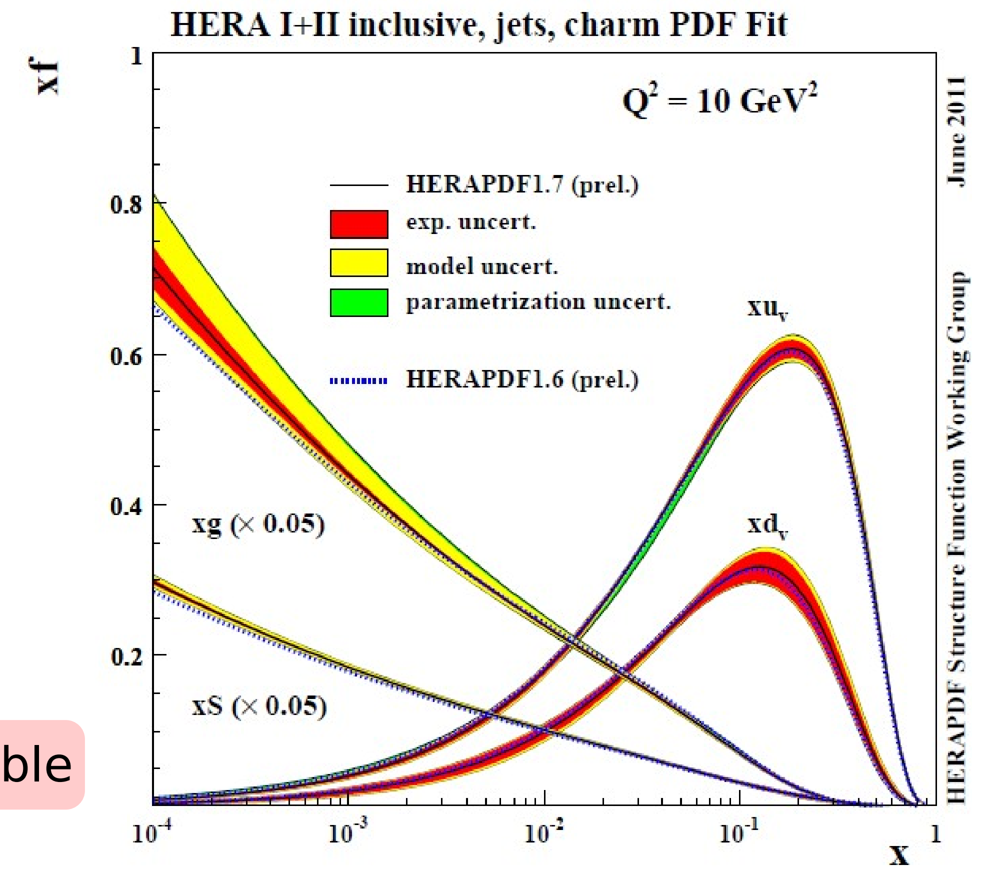
PDFs with all HERA data

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)
- rise strong coupling constant from 0.1176 to 0.119 (as supported by the jet data)



All the data sets are very compatible

Summary

HERA provides unique determinations of the proton structure

Different PDFs lead to differences in cross section predictions
→ important to understand these differences! (PDF4LHC)

HERAPDFs describe Tevatron and LHC data well
→ provides compatible NLO (and NNLO) predictions with other PDF groups

Different HERA data used to obtain best precision in PDFs
→ soon with final HERA data!

Back-up slides

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:

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

determined using measured cross section

calculable in perturbative QCD

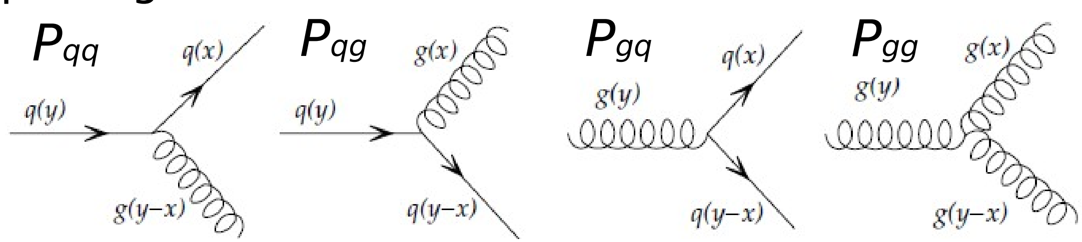
PDFs

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 Fit Groups

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

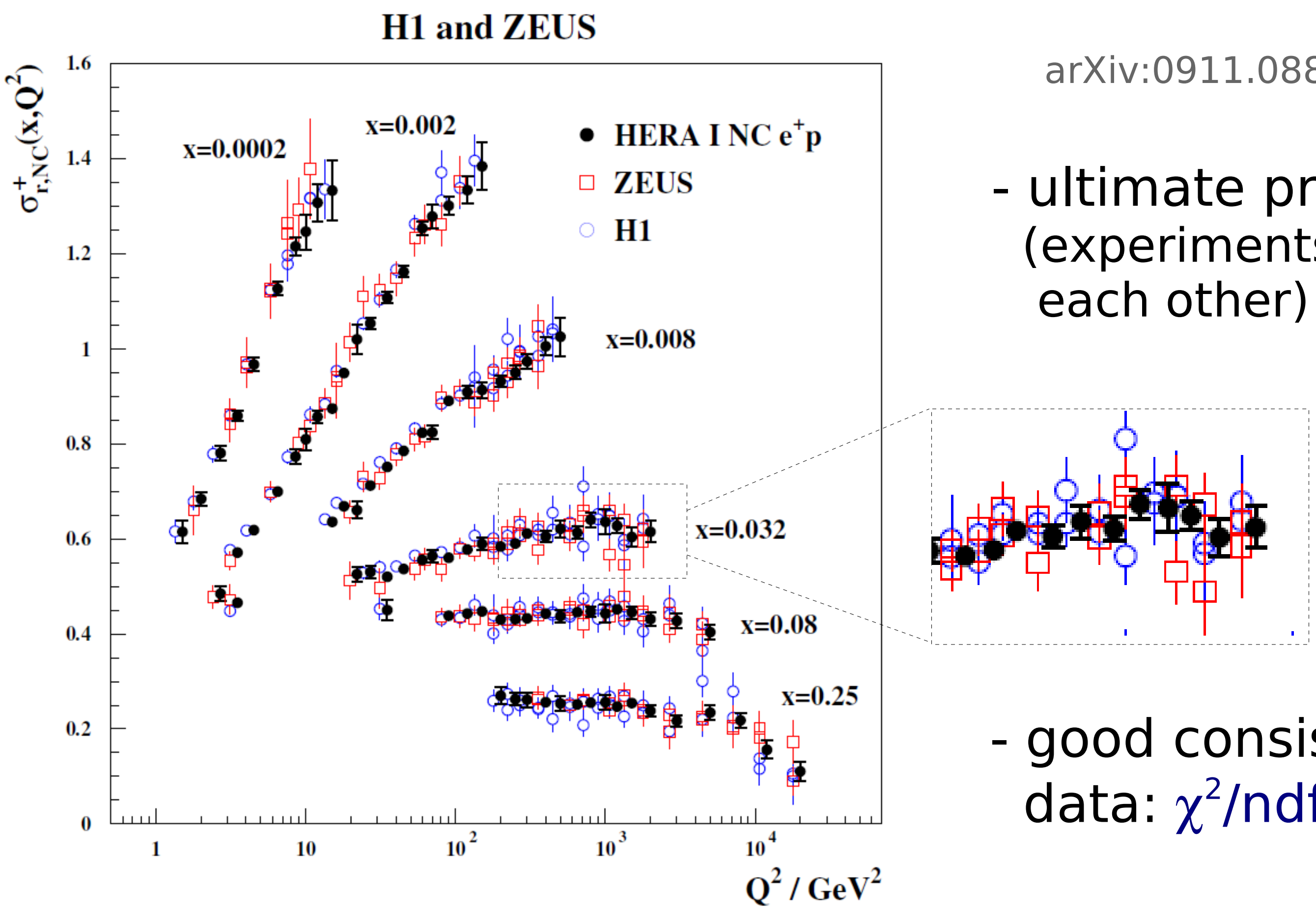
– 21 parameters, $\Delta\chi^2 = 1$

GJR

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

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)

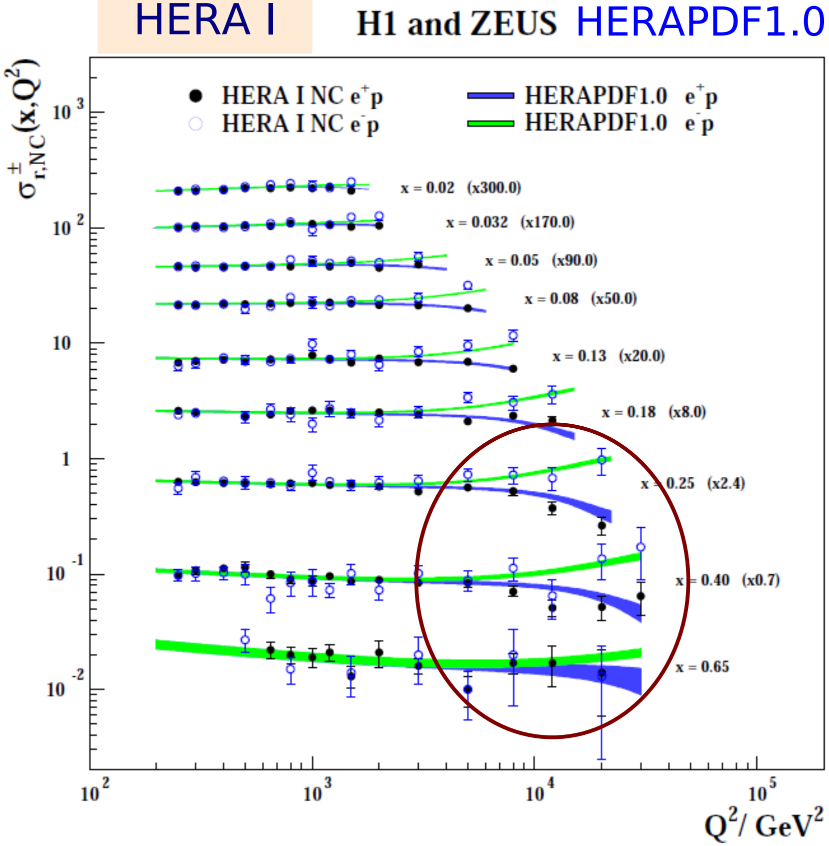
- good consistency of the data: χ^2/ndf = 637/656

QCD analysis of combined data → HERAPDF 1.0

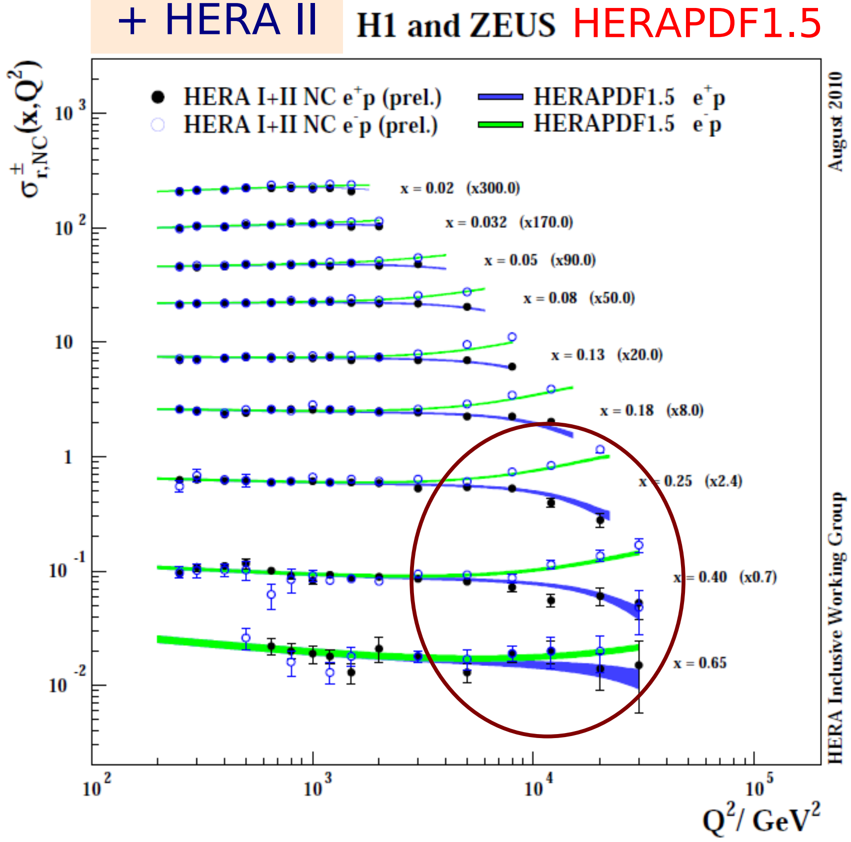
HERAPDF 1.5

HERAPDF1.0: combined inclusive HERA I arXiv:0911.0884[hep-ex]
HERAPDF1.5: combined inclusive HERA I and HERA II data

HERA I

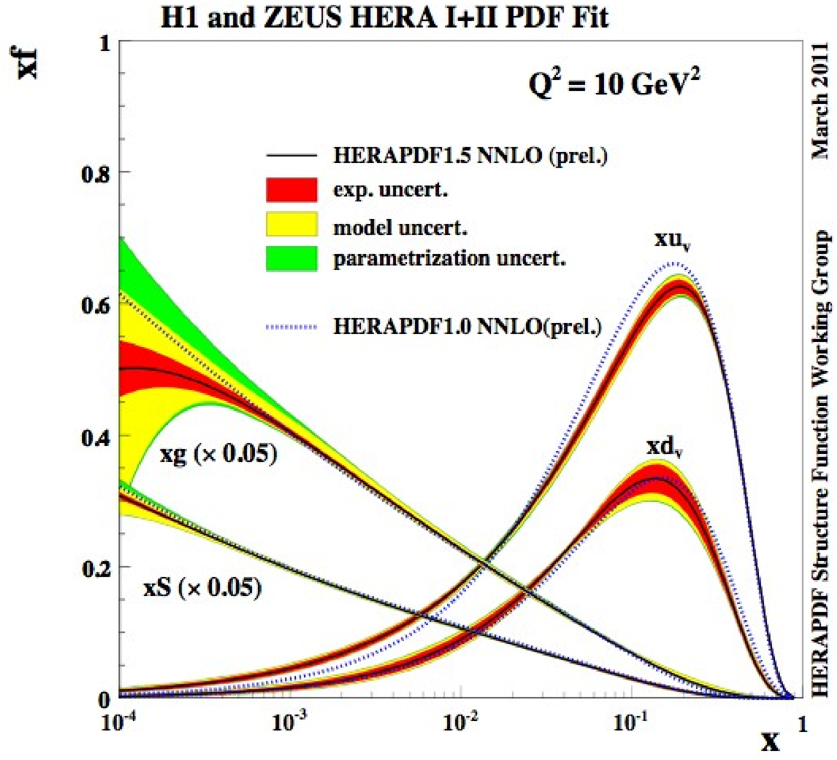


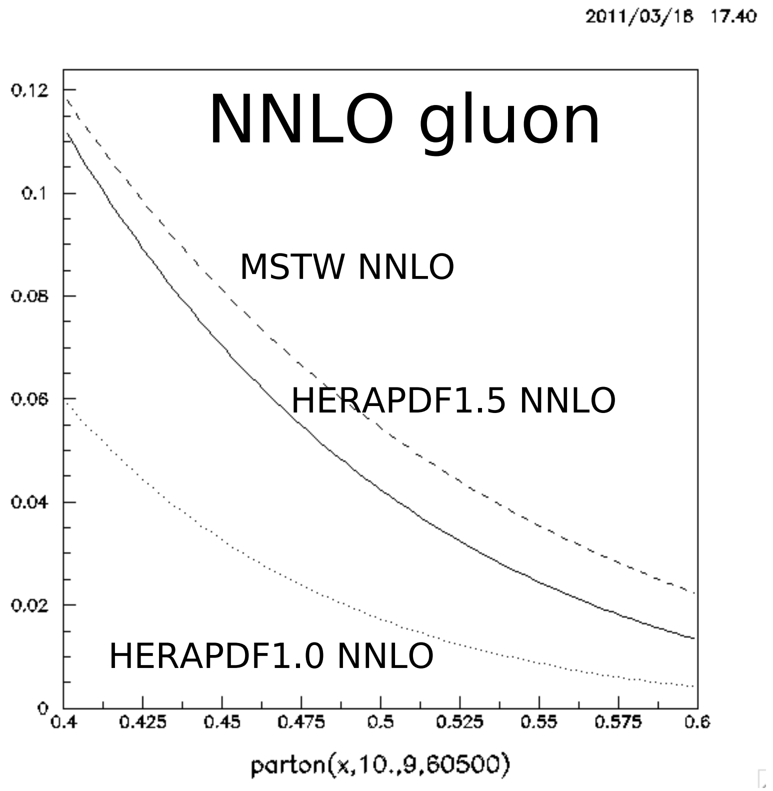
+ HERA II



Improved data precision → Improved PDFs

HERAPDF1.0 NNLO vs HERAPDF1.5 NNLO



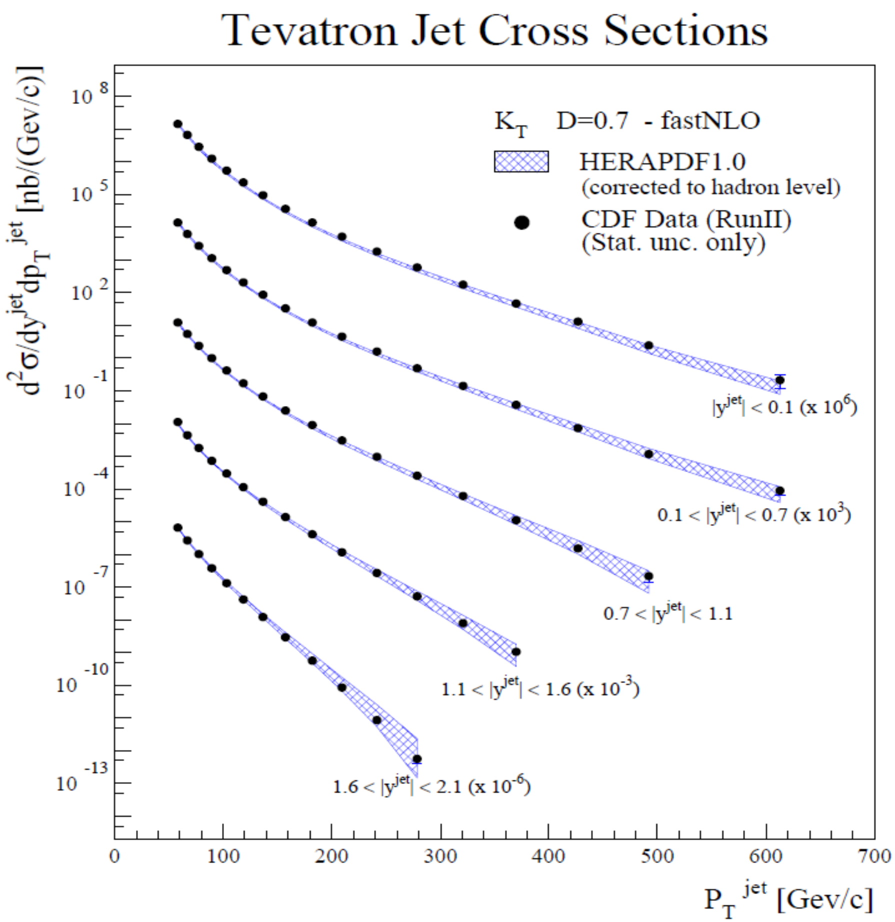


HERAPDF1.5NNLO has a harder high-x gluon than HERAPDF1.0
- hence, would give a better agreement with Tevatron data

HERAPDF1.5 NNLO uncertainties are comparable to NNPDFs

HERAPDF Predictions for Tevatron

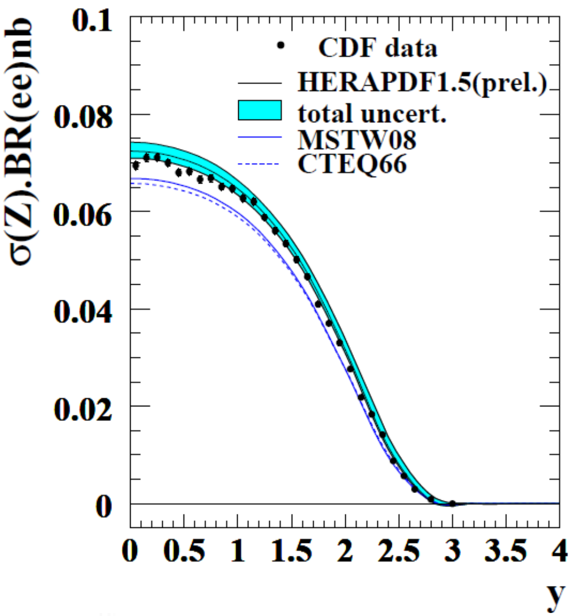
$\sqrt{s}$ = 1.96 TeV

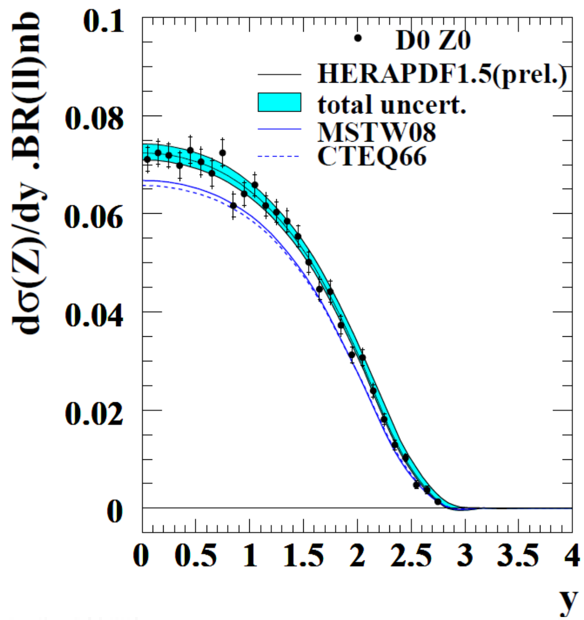


→ if these data are fitted the resulting PDFs are within the HERAPDF1.5 errors bands

Predictions based on HERA PDFs describe Tevatron data well

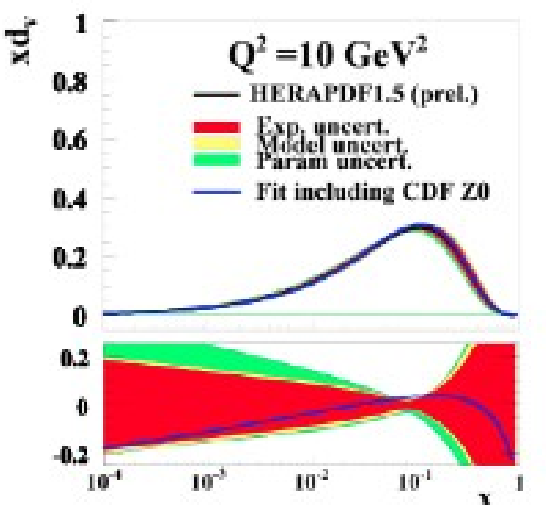
HERAPDF Predictions for Tevatron: Z rapidity

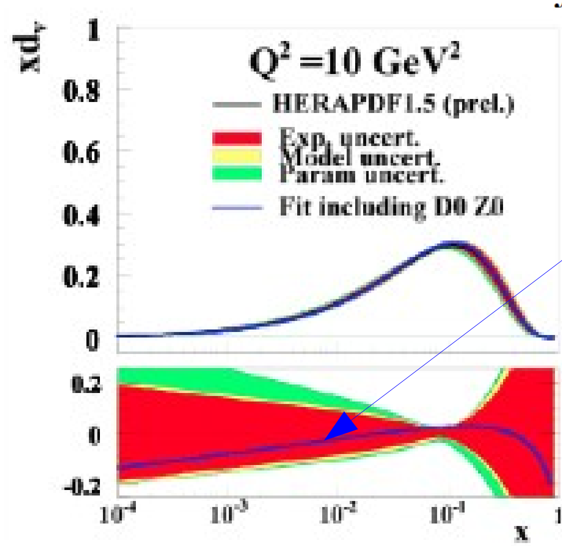




The description of CDF and D0 Z rapidity by HERAPDF1.5:

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

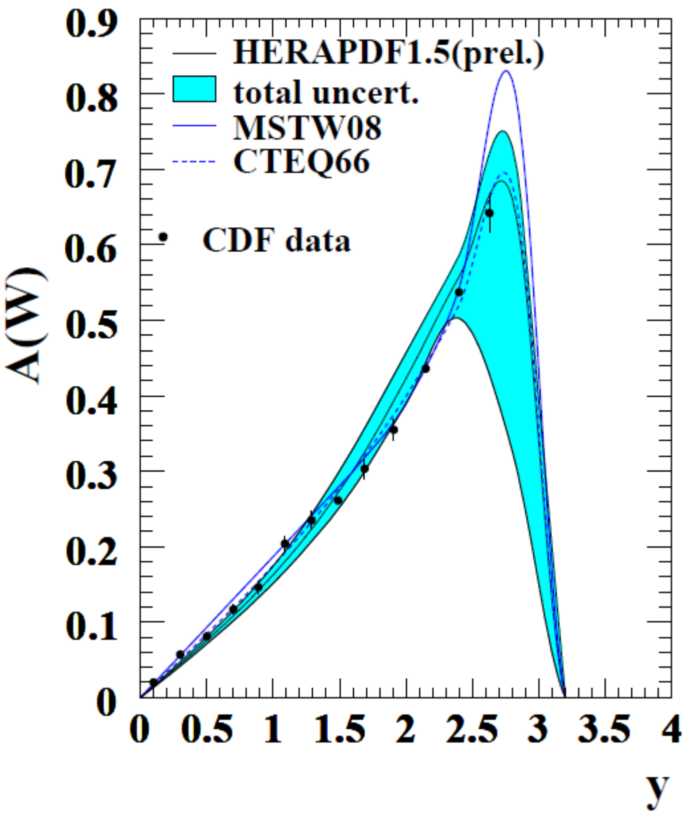


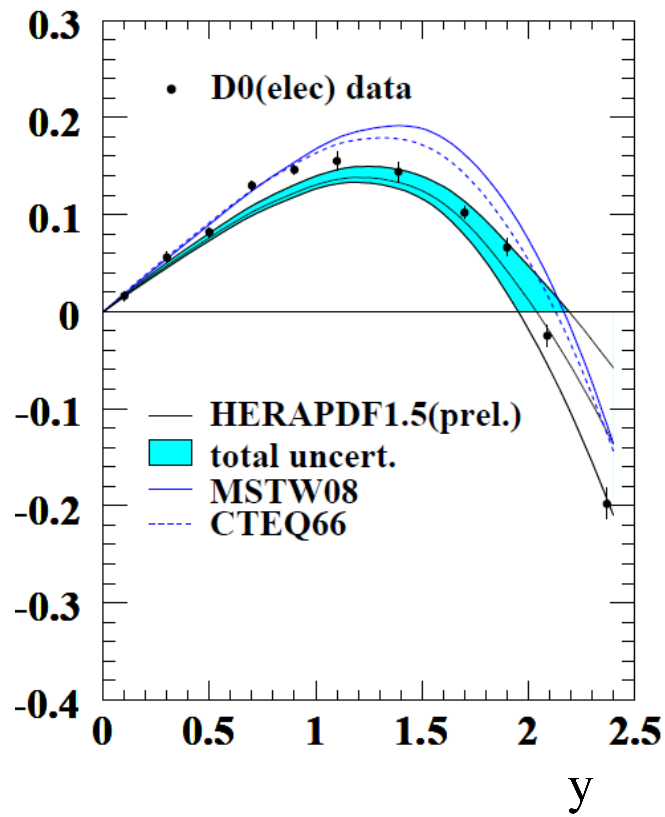


fit including TEVATRON data

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

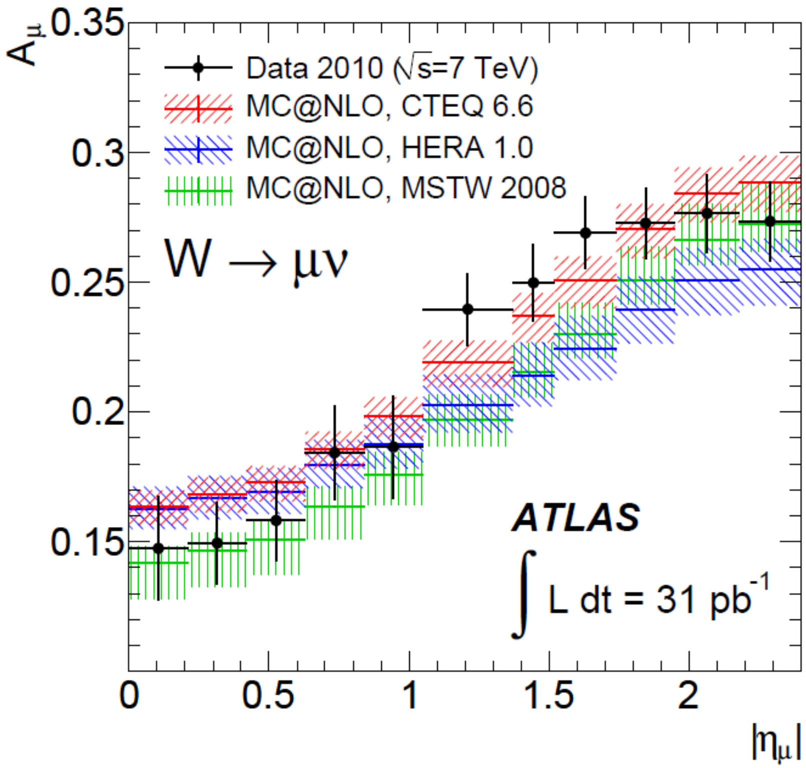
→ the resulting PDFs lie within the HERAPDF1.5 error band

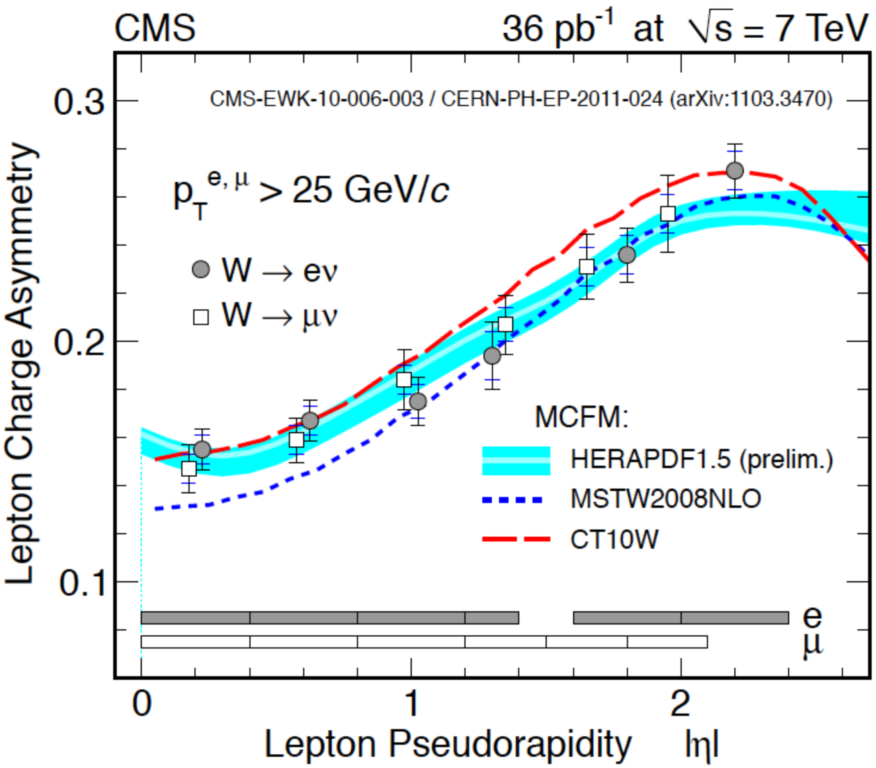
HERADF Predictions for Asymmetries at LHC

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

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

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



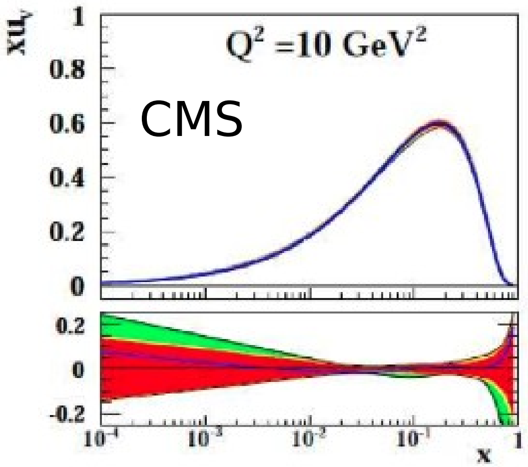


Predictions based on HERA PDFs describe LHC data well

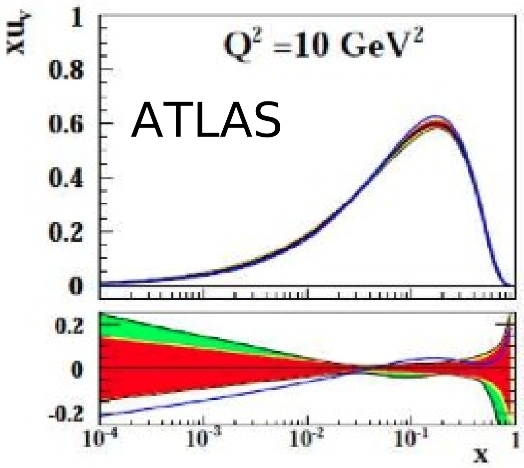
HERADF Predictions for Asymmetries at LHC

Early LHC data are described fairly well

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

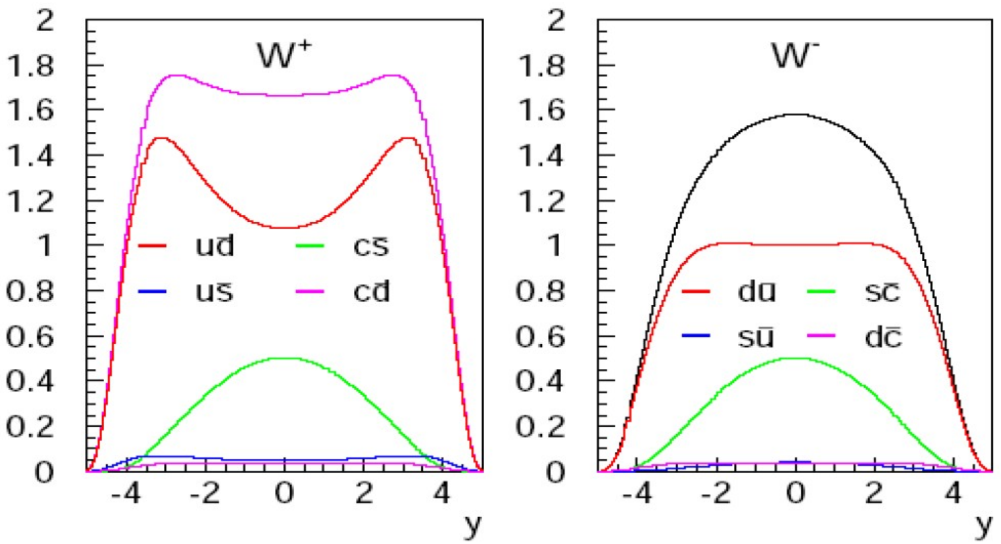


	Before fit	After fit
- W asymmetry CMS:	χ^2/dof=6.5/12	3.7/12
- W asymmetry ATLAS:	χ^2/dof=30/11	16/11

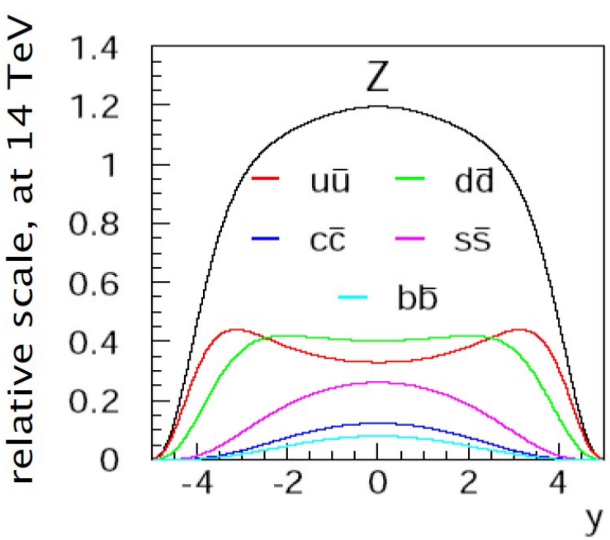


ATLAS and CMS pull u valence quark in opposite directions

Proton-Proton Collisions: W/Z production



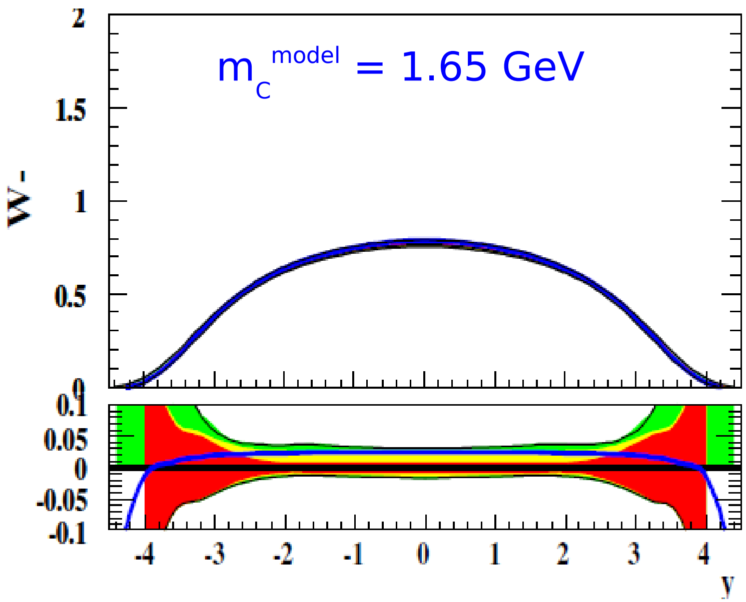
- for W **u** and **d** quarks dominate



- 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

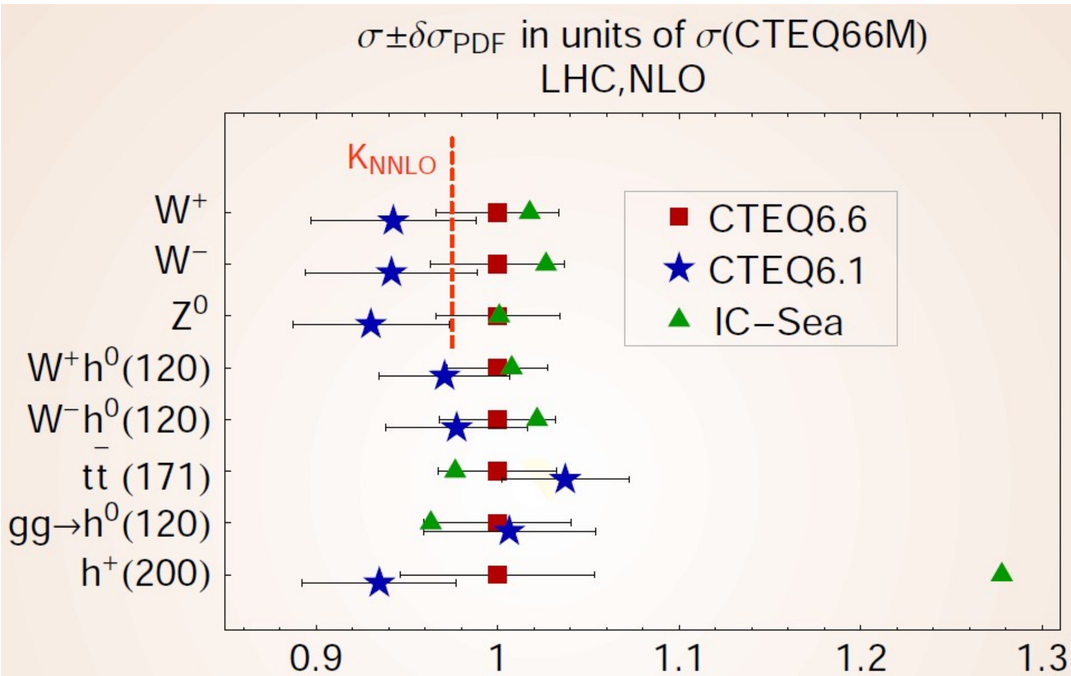
$$xU = xu + xc \quad x\bar{U} = x\bar{u} + x\bar{c} \quad xD = xd + xs \quad x\bar{D} = x\bar{d} + x\bar{s}$$

- 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

Impact on the LHC predictions

- similar effect was observed by CTEQ collaboration

General-mass CTEQ6.6 vs zero-mass CTEQ6.1



At the LHC

$\sigma_{Z,W}$ (CTEQ6.6) ≈ $1.06\sigma_{Z,W}$(CTEQ6.1)

Pavel Nadolski (MSU), DIS08, April 7, 2008

Significant variation of W,Z cross sections at the LHC while changing HQ schemes and/or changing m_c^{model}

- try to vary BOTH models and m_c^{model} under the condition that they fit the HERA charm data

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:

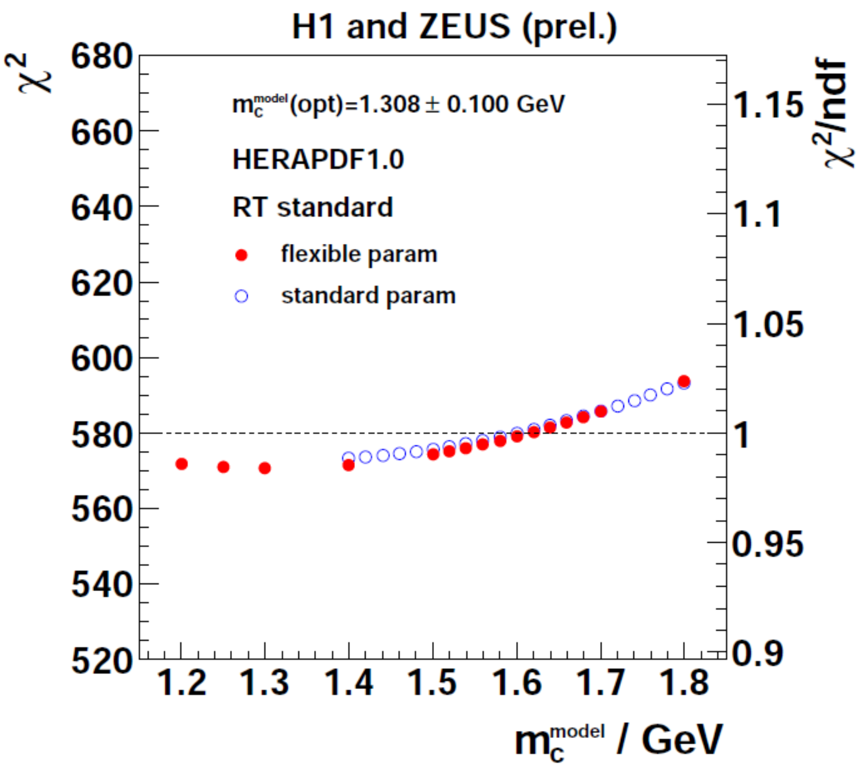
RT standard	used by MSTW08
RT optimised [arXiv:1006.5925]	
ACOT-full	used by CTEQ4,5,6HQ
S-ACOT-χ	used by CTEQ6.5,6.6,CT10
ZMVFNS	used by NNPDF2.0

- 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

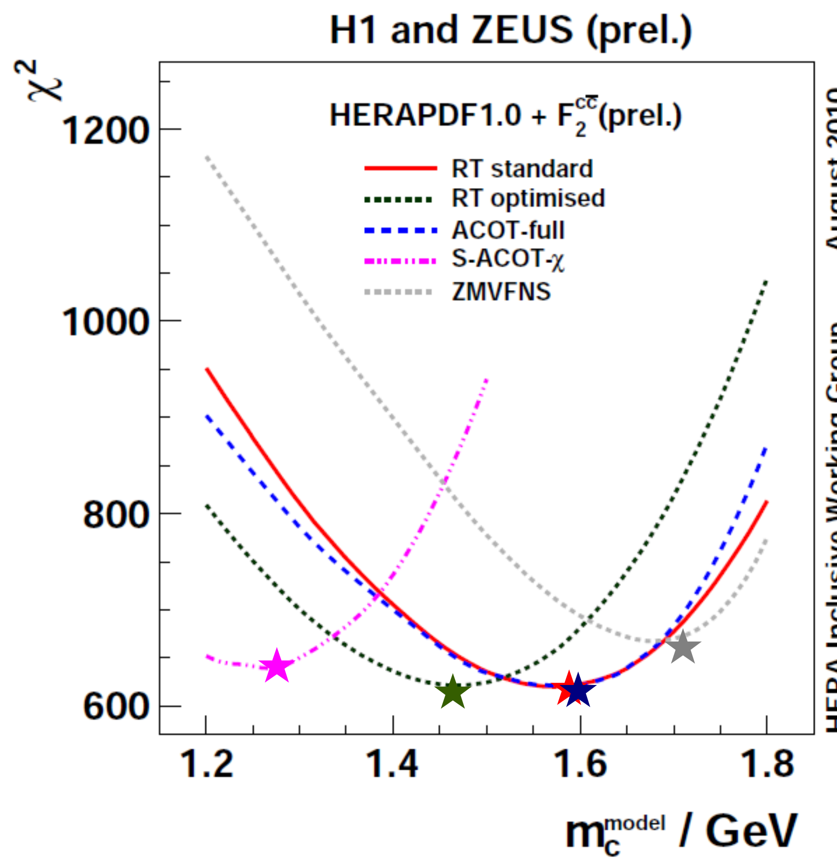
- PDFs are used in MCFM to calculate $Z/W^{\pm}$ cross-section predictions

Constraints on PDFs from HERA Charm Data

Inclusive ep data

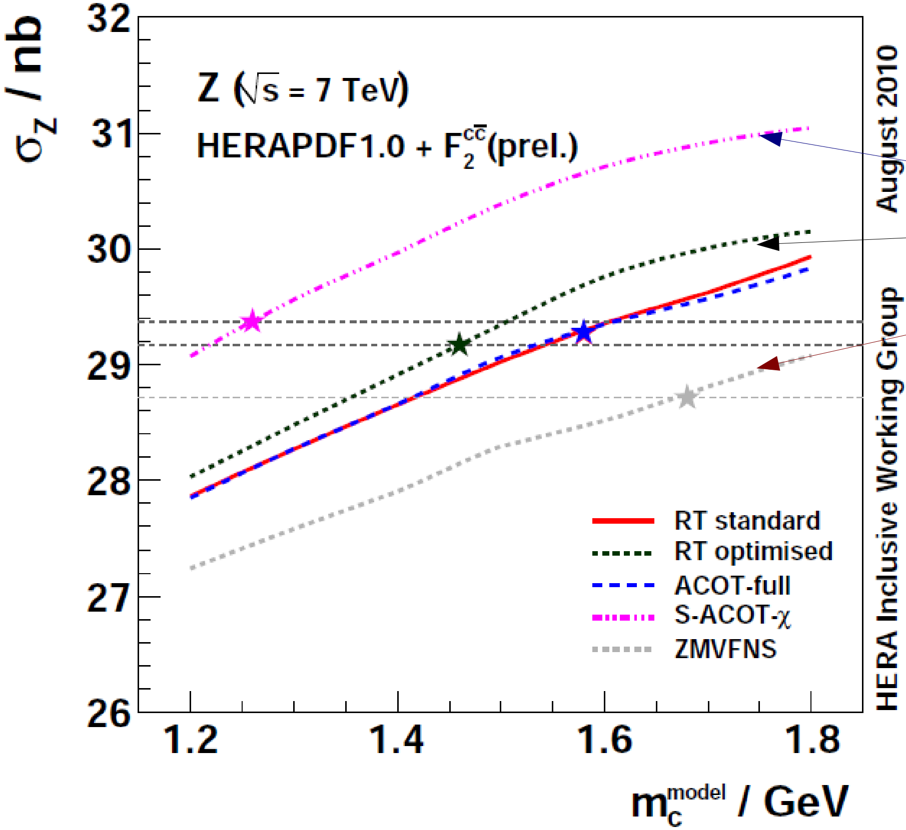


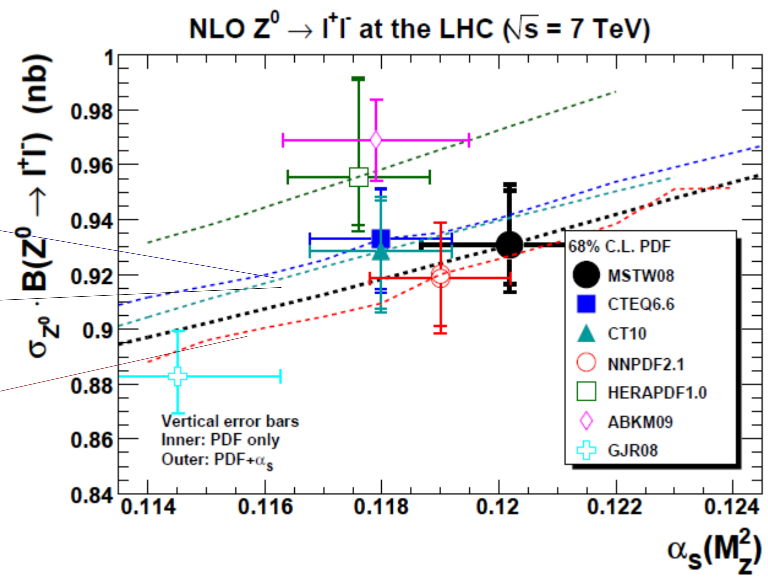
Different HQ schemes are tested



Different HQ schemes have different optimal m_c^{model}

Z/W cross sections at LHC





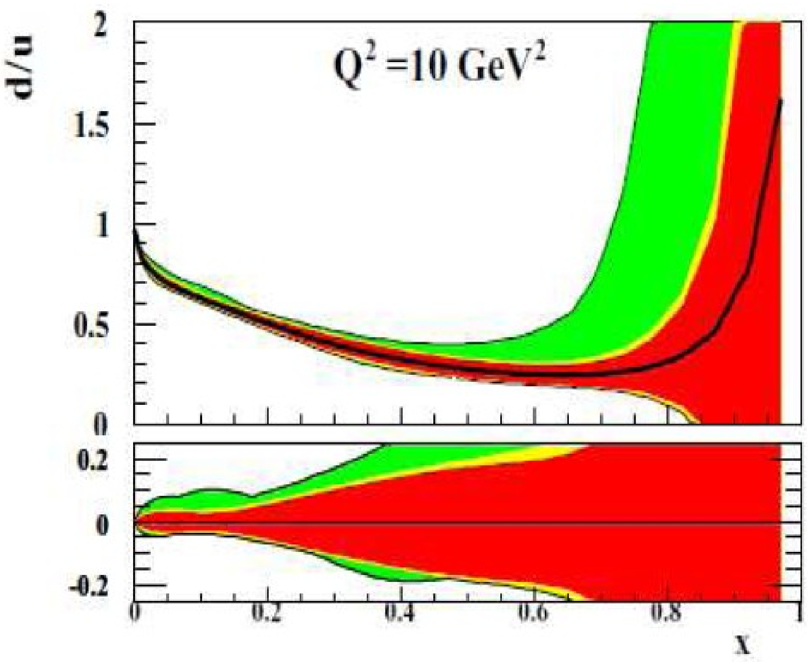
- comparison of Z cross sections as a function of $\alpha_S(M_Z^2)$

G.Watt, PDF4LHC 07.03.2011

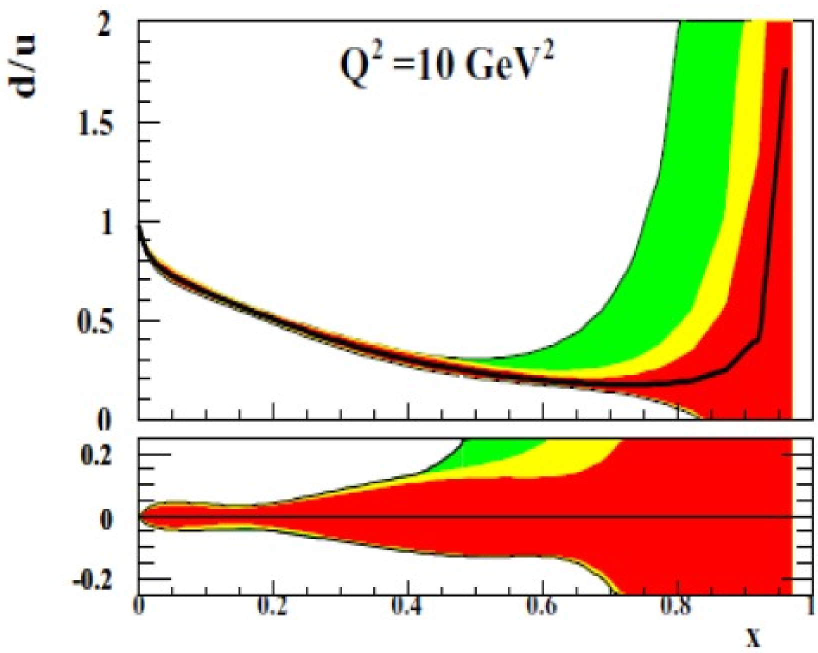
(symbols indicate value of m_c^{model}(opt))

HERAPDF 1.0 vs 1.5

HERAPDF1.0



HERAPDF1.5



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