HERAPDF

QCD@LHC 2012

A M Cooper-Sarkar
on behalf of ZEUS and H1 collaborations

HERAPDF NLO uses the combined H1 and ZEUS data on:

- Inclusive Neutral and Charged Current processes for e^+p and e^-p scattering at 820,920 GeV proton beam energy from HERA-I (HERAPDF1.0) and HERA I+II (HERAPDF1.5)
- There are also studies adding data from the lower energy runs at 460, 575 proton beam energy and from adding combined HERA data on F2charm
- There are also fits adding separate H1 and ZEUS data on inclusive jet production to the inclusive cross section data (HERAPDF1.6)
- Finally HERAPDF1.7 uses ALL of these data sets

HERAPDF NNLO uses just the inclusive cross-section data because of incomplete NNLO calculations for jet data and for charm production

Furthermore the HERAPDF uses purely proton data

•No need for deuterium corrections--- arXiv:1102.3686- uncertainties in deuterium corrections can feed through to the gluon PDF in global fits including jet data

•No need for dubious corrections for FL when extracting F2 –arXiv:1101.5261

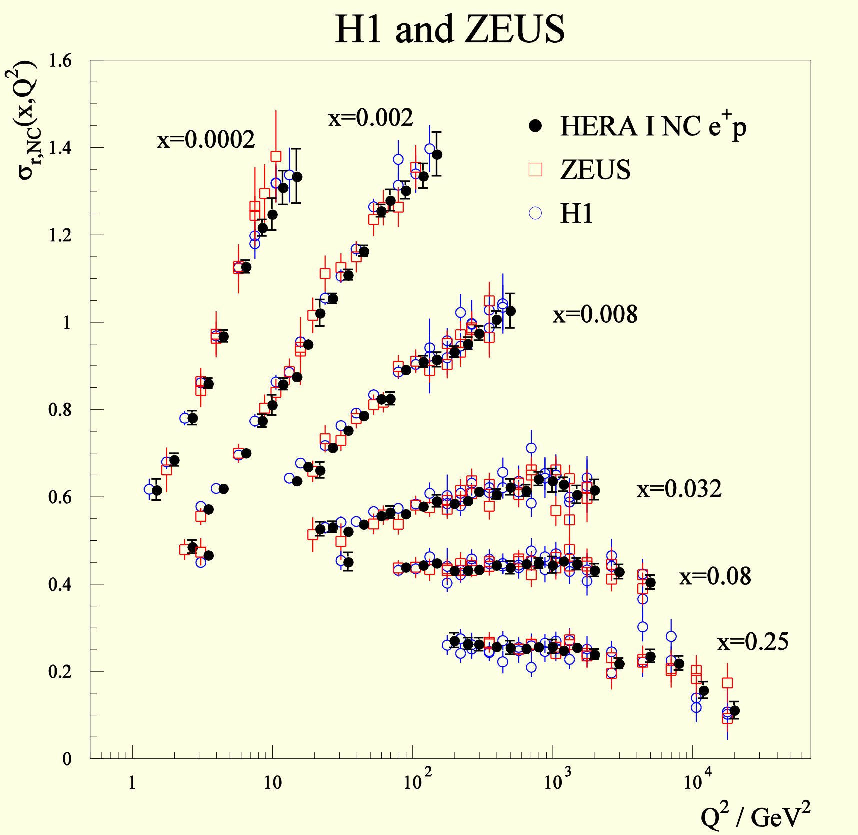
• No need for neutrino data heavy target corrections.

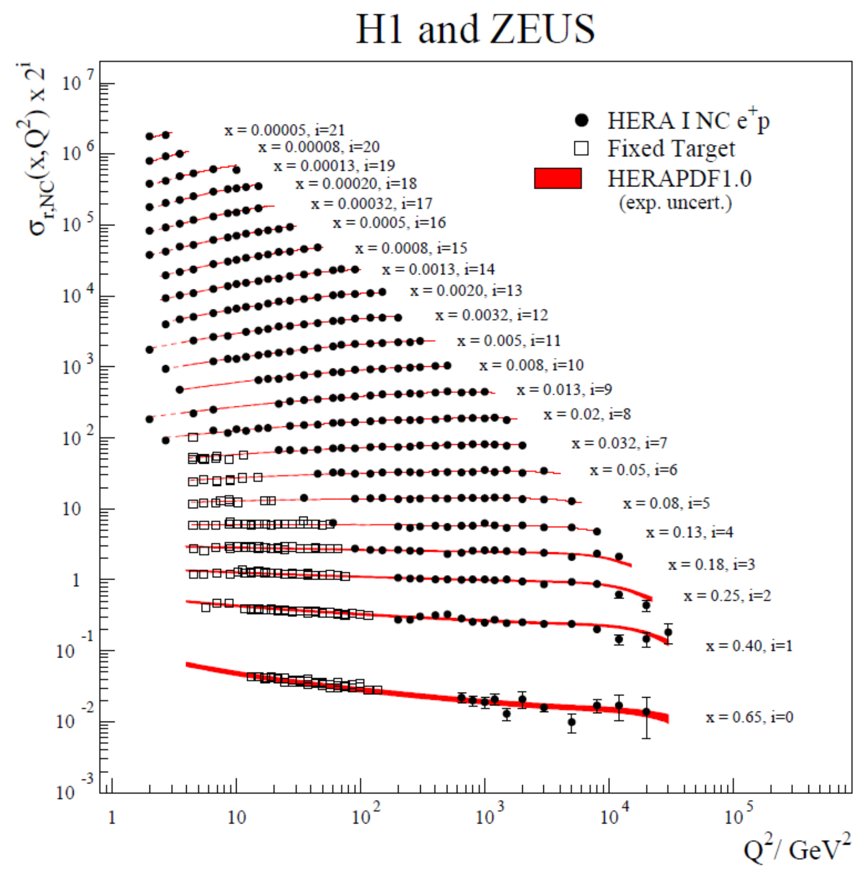
•No assumption on strong isospin needed to get the d-quark

•A very well understood consistent data set JHEP 1001 (2010) 109 +updates

The HERA data combination gives us a well understood ,consistent and accurate data set with systematic errors which are smaller than the statistical errors across most of the kinematic plane. The total errors are ~1% for Q^2 20-100 GeV^2 and less than 2% for most of the rest of kinematic plane.

This allows us to use the $\chi 2$ tolerance $\Delta\chi 2 = 1$ to set 68% limits on the PDFs from experimental sources





This page shows NC e+ combined data

Above : Results of the combination compared to the separate data sets

Right: the full NC e+ data

Where does the information on parton distributions come from?

CC e-p

$$\frac{d^2\sigma(e^-p)}{dxdy} = \frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(u+c) + (1-y)^2 x(\bar{d}+\bar{s})]$$

CC e+p

$$\frac{d^2\sigma(e^+p)}{dxdy} = \frac{G_F^2 M_W^4}{2\pi x(Q^2+M_W^2)^2}[x(\bar{u}+\bar{c}) + (1-y)^2 x(d+s)]$$

•The charged currents give us flavour information for high-x valence PDFs

NC e+ and e-

$$\frac{d^2\sigma(e\pm N)}{dxdy} = \frac{2\pi\alpha^2 s}{Q^4} Y_+ \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \pm \frac{Y_-}{Y_+} xF_3(x,Q^2)\right], \quad Y_\pm = 1 \pm (1-y)^2$$

$F_2 = F_2^\gamma - v_e P_Z F_2^{\gamma Z} + (v_e^2+a_e^2)P_Z^2 F_2^Z$

$xF_3 = \quad - a_e P_Z xF_3^{\gamma Z} + 2v_e a_e P_Z^2 xF_3^Z$

Where $P_Z^2 = Q^2/(Q^2 + M_Z^2)\ 1/\sin^2\theta_W$, and at LO

$[F_2, F_2^{\gamma Z}, F_2^Z] = \Sigma_i [e_i^2, 2e_i v_i, v_i^2+a_i^2][xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$

$[xF_3^{\gamma Z}, xF_3^Z] = \Sigma_i 2[e_i a_i, v_i a_i] \quad [xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$

So that $xF_3^{\gamma Z} = 2x[e_u a_u u_v + e_d a_d d_v] = x/3\,(2u_v+d_v)$

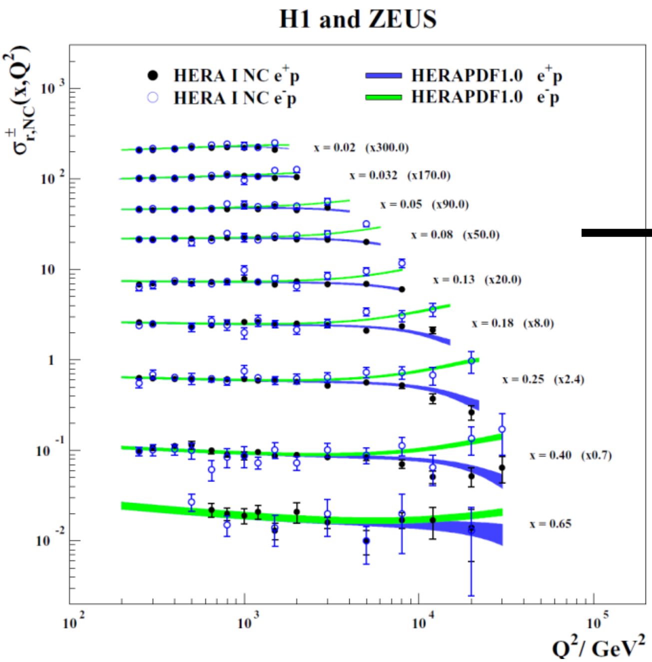
Where $xF_3^{\gamma Z}$ is the dominant term in xF_3

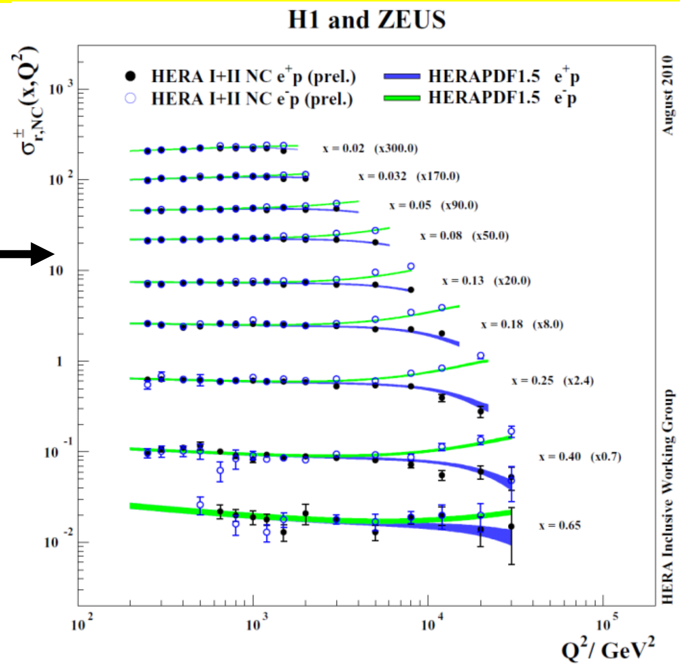
The neutral current F2 gives the low-x Sea

The difference between e- and e+ also gives a valence PDF for x>0.01- not just at high-x

And of course the scaling violations give the gluon PDF

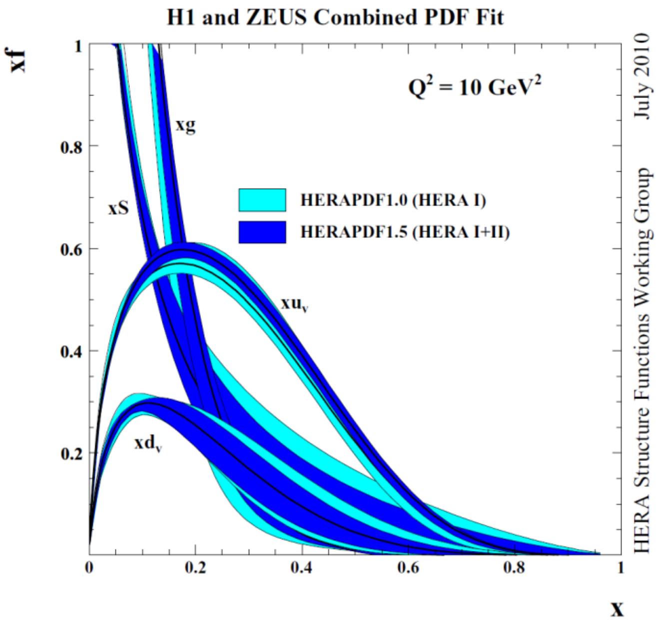
HERAPDF1.0 at NLO is already published (JHEP 1001 -109) and we have updated to HERAPDF1.5 NLO and NNLO : this is an update of data AND fit





Uses preliminary HERA I+II data combination (ZEUS-prel 10-018, H1prelim-10-042) in addition to the published HERA-1 combined data

~200pb-1 HERA-I
~700pb-1 HERA-II
But e- increases by ~factor 10



Gives increased precision at high-x

HERAPDF1.5 NLO is on LHAPDF5.8.6 with eigenvector PDFsets and model and parametrisation uncertainties and for a series of $\alpha_S(M_Z)$ values

However as we include more data sets and move to NNLO we have extended our central parametrisation.

A reminder of the PDF parametrization: u_valence, d_valence, U and D type Sea and the gluon are parametrised by the form

$$xf(x,Q_0^2)=Ax^B(1-x)^C(1+Dx+Ex^2+\varepsilon\sqrt{x})$$

	A	B	C	D	E	ε
uv	Sum rule	free	free	free	free	var
dv	Sum rule	free	free	var	var	var
UBar	=(1-fs)ADbar	=BDbar	free	var	var	var
DBar	free	free	free	var	var	var
glue	Sum rule	free	free	var	var	var

A'g	B'g
free	free

extended gluon parametrisation $Ag\, x^{Bg} (1-x)^{Cg} (1+Dx+Ex^2) - A'g\, x^{B'g} (1-x)^{Cg}$

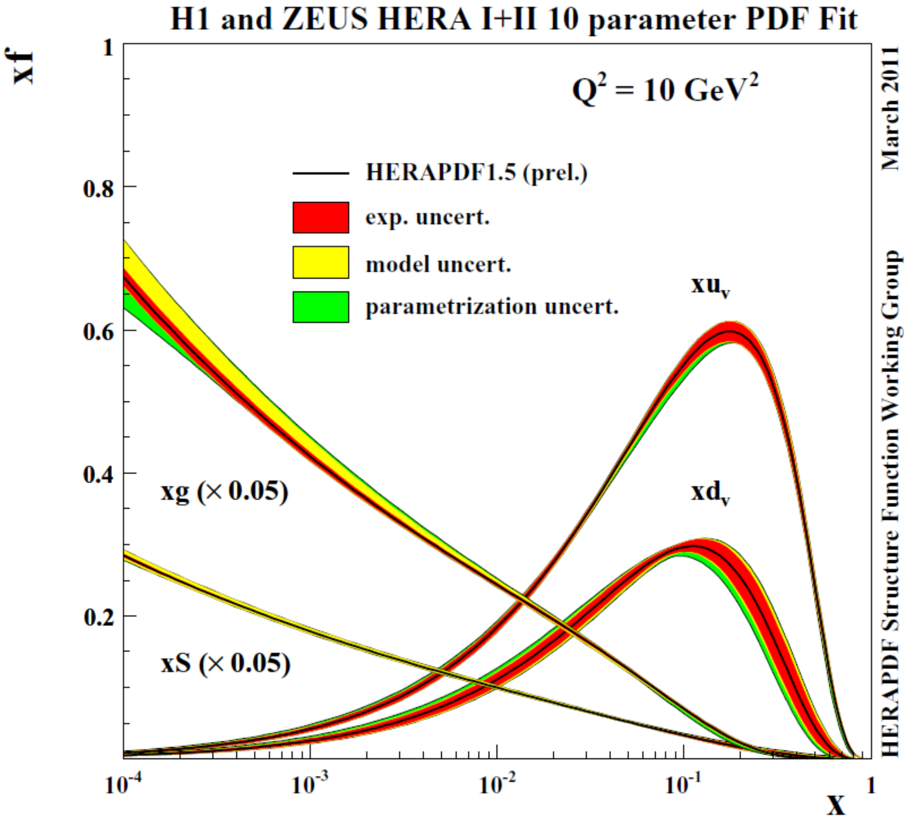
The table summarises our **extended parametrization choices** and the parametrization variations that we consider in our uncertainty estimates (and we also vary the starting scale Q^2_0). **NOTE we have made the gluon more flexible and we have freed low-x d-valence from u-valence**

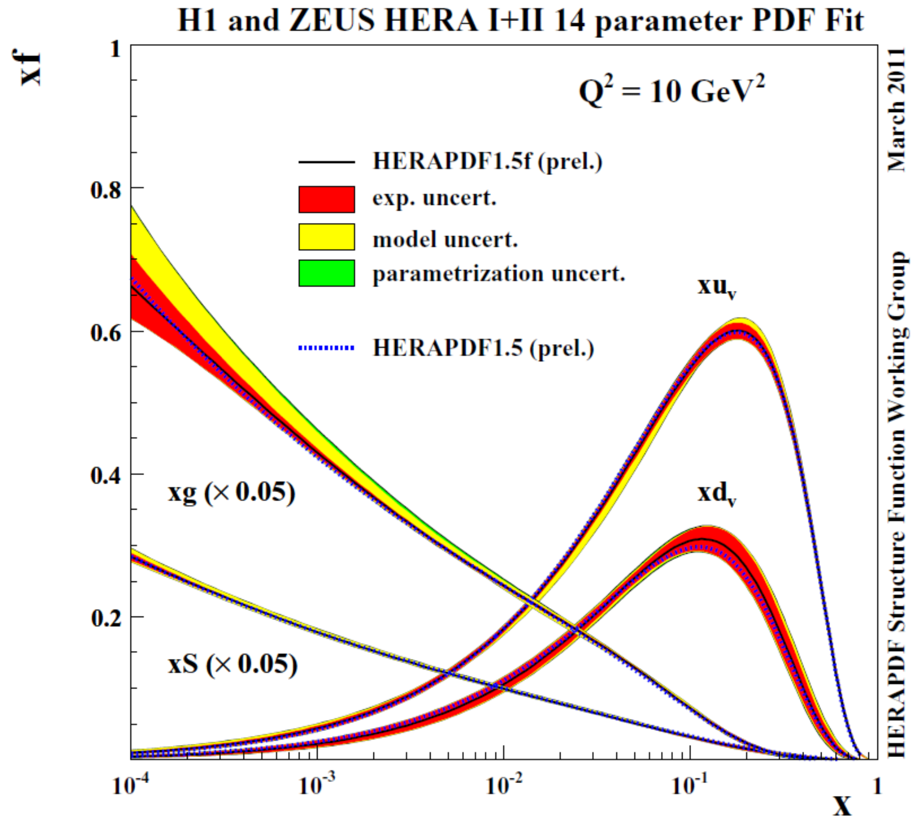
We also consider model uncertainties on the PDFs by varying m_c, m_b, f_s, Q^2_{min}

PDFs are also supplied for a range of $\alpha_s(M_Z)$ values

How does the extended parametrisation affect the NLO PDFs?- not much

HERAPDF1.5 **HERAPDF1.5f**

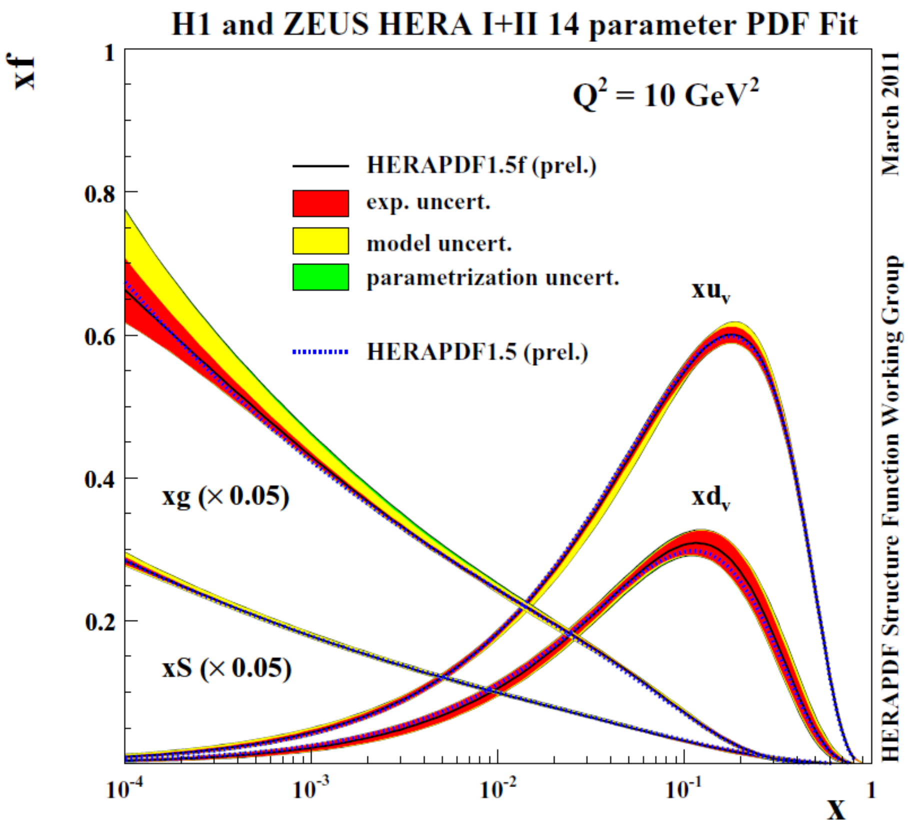




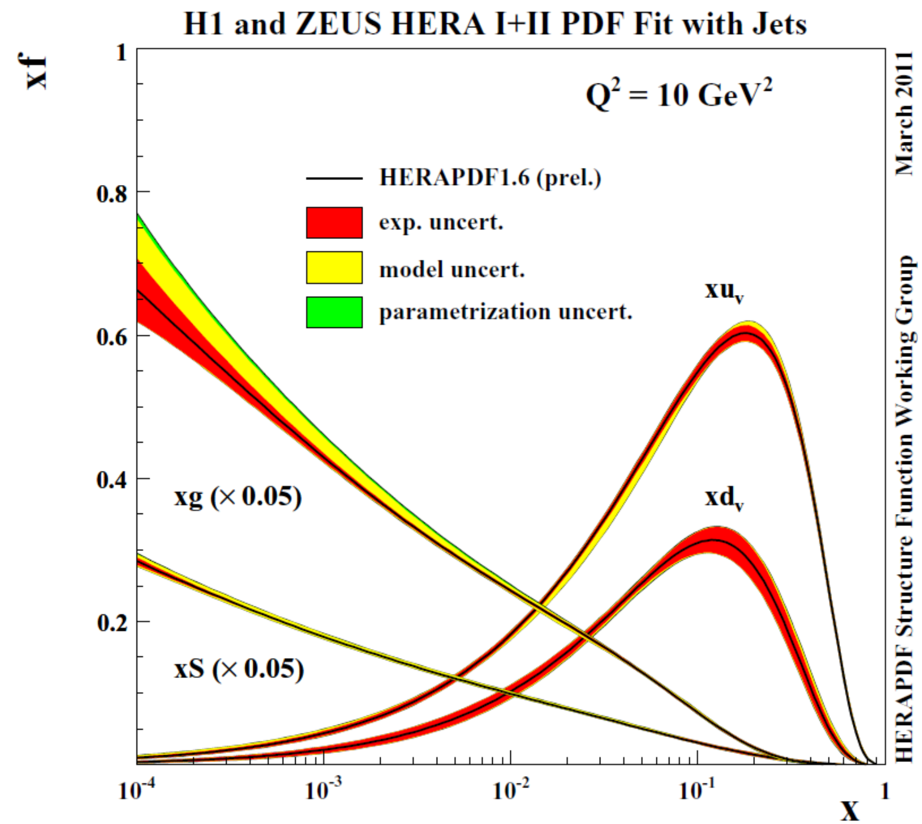
i) The level of total uncertainty is similar- but we swap parametrisation uncertainty for experimental uncertainty- and there is slightly more uncertainty on low-x gluon

ii) The central values have shifted such that the flexible parametrisation has a softer high-x Sea and a suppressed low-x d-valence- but these changes are within our error bands

Using this extended parametrization we added HERA jet data (as yet uncombined) to the fit (ZEUS-prel-11-001 ,H1prelim-11-034)

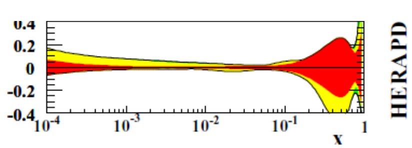


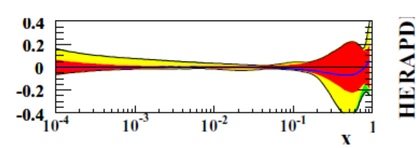
Without jets



With jets

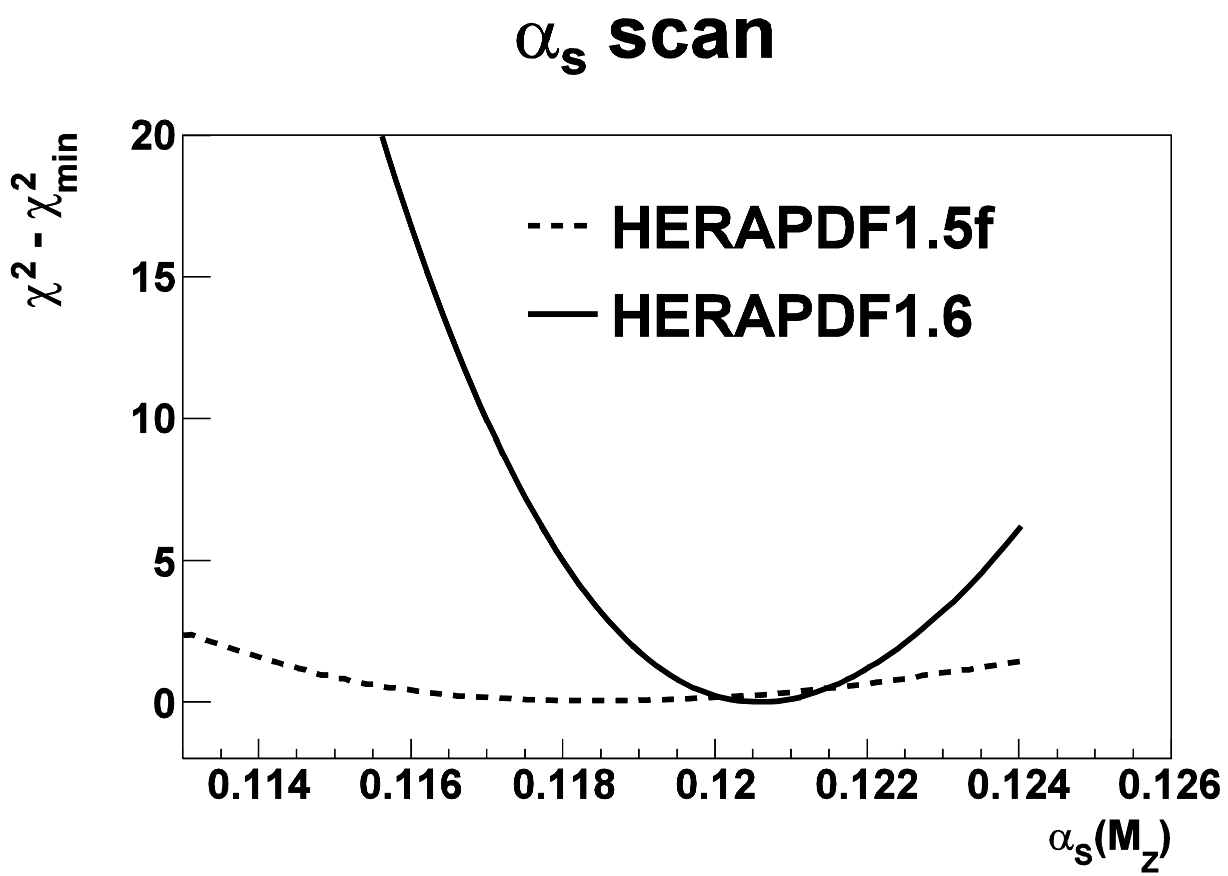
There is little difference in the size of the uncertainties after adding the jet data –but there is a marginal reduction in high-x gluon uncertainty.





However, the jet data allow us to make a competitive measurement of $\alpha_S(M_Z)$

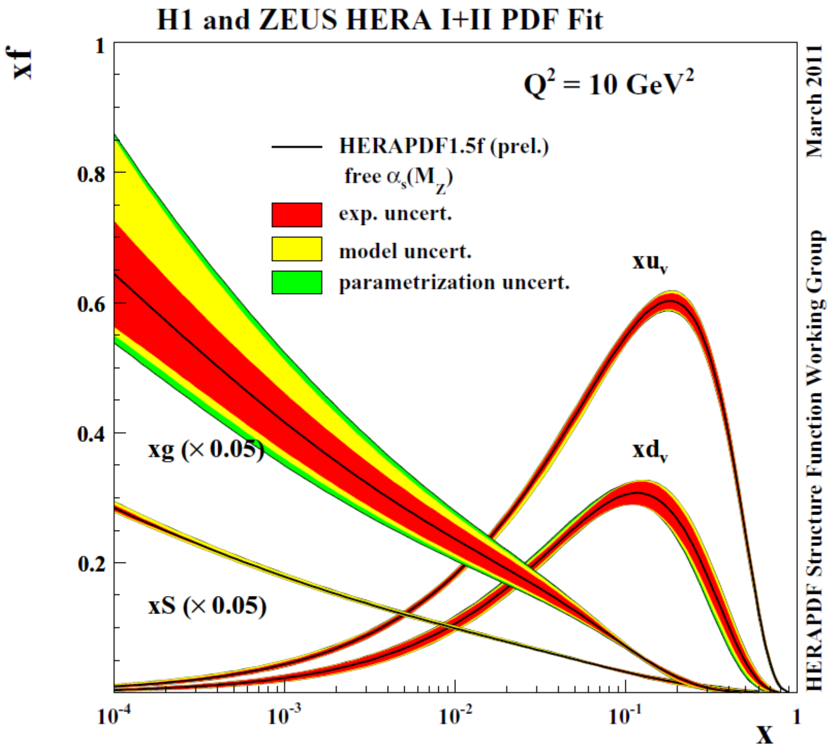
The χ2 scan of HERAPDF1.5f (no jets) and HERAPDF1.6 (with jets) vs $\alpha_S(M_Z)$



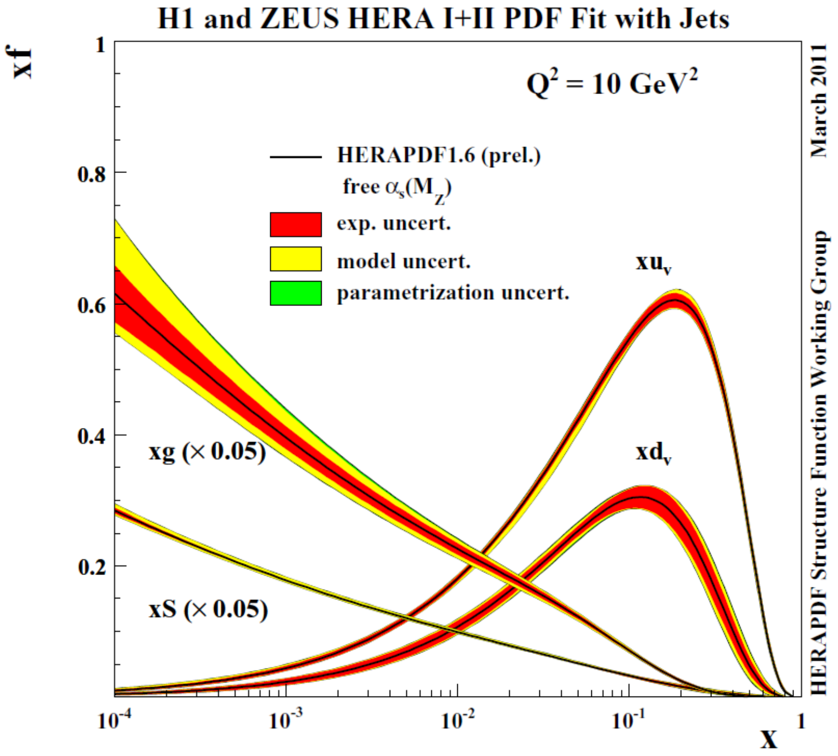
$\alpha_S(M_Z)$ =0.1202 ± 0.0013 (exp) ± 0.0007(model/param) ± 0.0012(hadronisation)

+0.0045/-0.0036 (scale)

$\alpha_S(M_Z)$ = 0.1202 ± 0.0019 ± scale error



Free $\alpha_S(M_Z)$ no jets

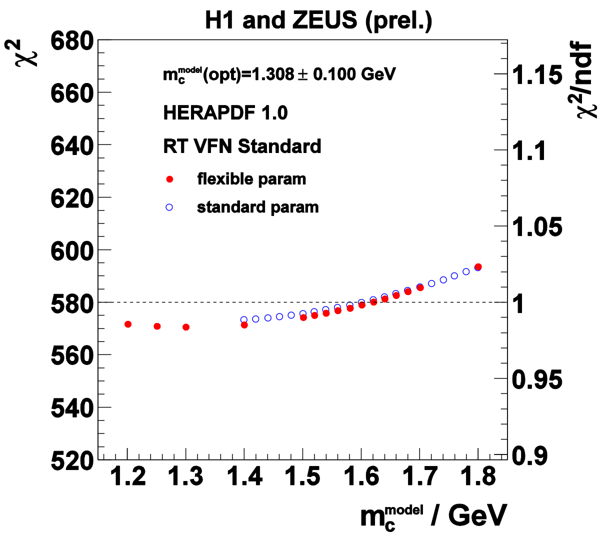


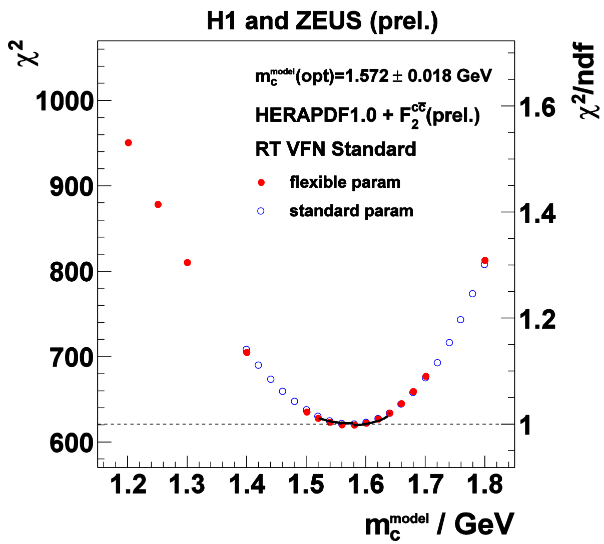
Free $\alpha_S(M_Z)$ with jets

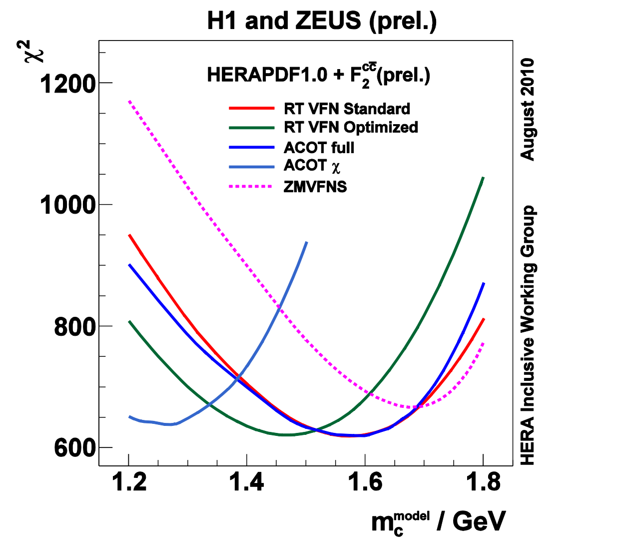
PDFs with free$\alpha_S(M_Z)$ with and without jet data included in the fit

The addition of the jet data ensure that the **PDF uncertainty on the gluon due to the uncertainty on $\alpha_S(M_Z)$ is not very large**

We have also made specific studies of the addition of the HERA combined F2charm data (ZEUS prel 10- 009,H1prelim 10 -045)

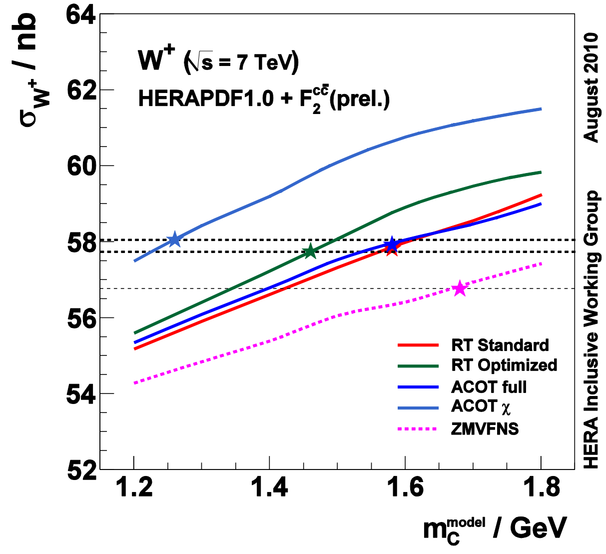






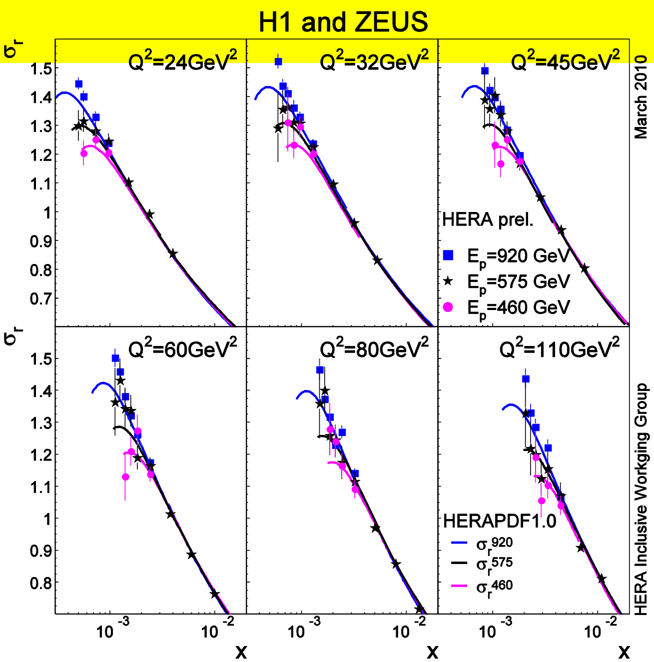
In HERAPDF1.0,1.5 we present a model uncertainty of mc 1.35 to 1.65 GeV on the charm mass . The inclusive data have no sensitivity to mc (left). The combined charm data do (middle). However the value depends on the scheme chosen to calculate the heavy quark contributions (right).

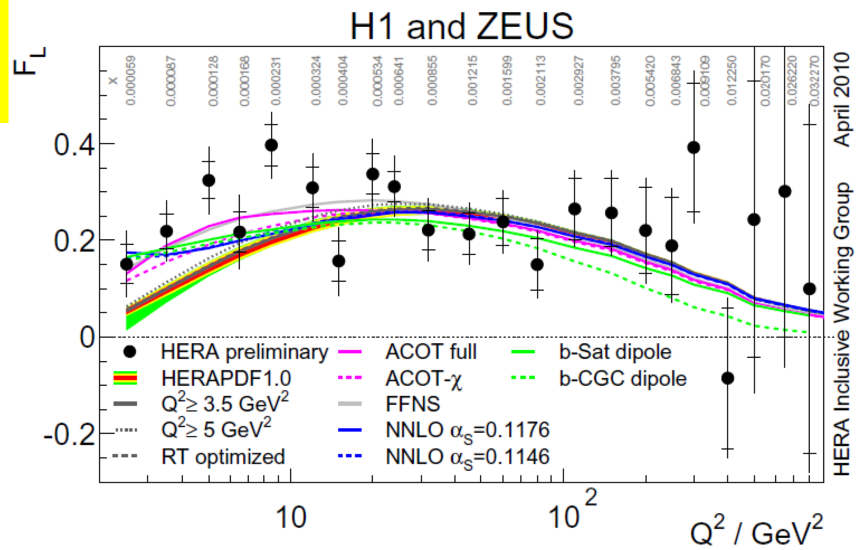
The use of the optimal charm mass for the chosen scheme has consequences for the predictions of LHC W, Z cross sections.



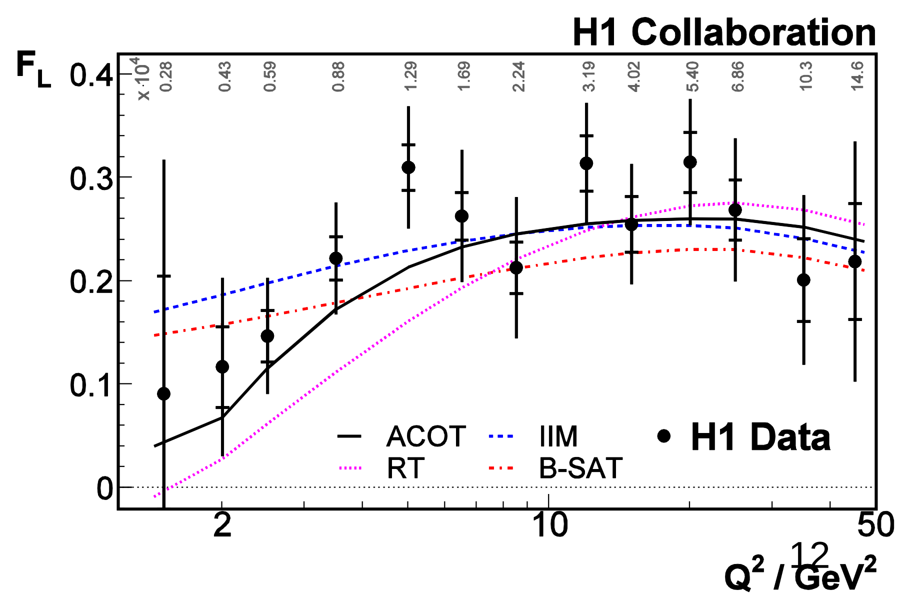
The charm data will help to reduce uncertainties

H1 and ZEUS have also combined the e+p NC inclusive data from the lower proton beam energy runs (P_P = 460 and 575) and produced a common FL measurement (ZEUS prel 10-001 , H1prelim 10-043)



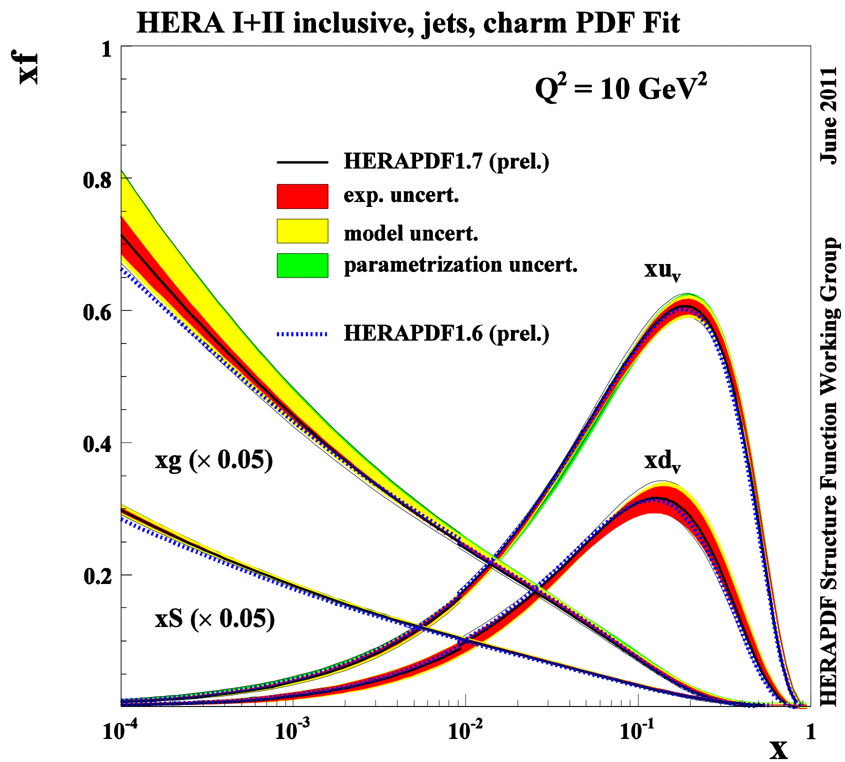


But H1 have extended the range of these data
EPJC71 (2011) 1579
This has yet to be combined with ZEUS data

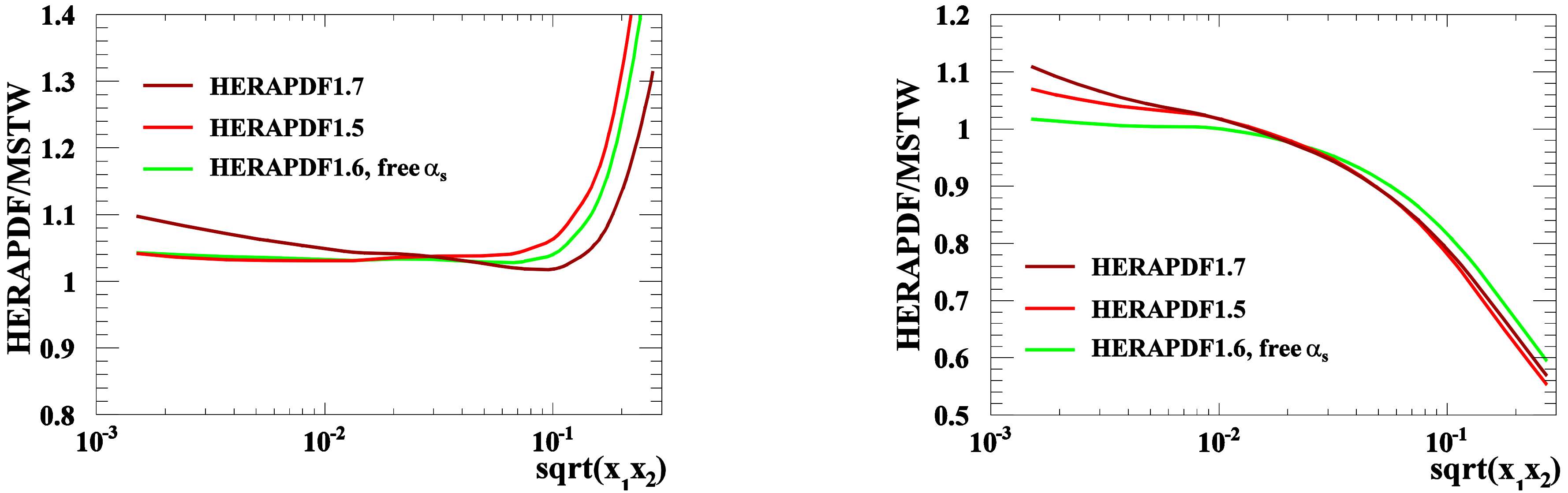


We have now put together all the data sets:
HERA –I +II high energy inclusive, HERA-II low energy inclusive , F2charm and the separate H1 and ZEUS jet data to make HERAPDF1.7 NLO using the extended parametrization.(ZEUS prel-11-010)

All the data sets are very compatible and
•the addition of charm motivates us to change our standard VFN to the RT optimised version, with its preferred value of the charm mass parameter mc=1.5 GeV,
•whereas the jet data motivate us to raise our standard NLO $\alpha_S(M_Z)$ value to $\alpha_S(M_Z) = 0.119$



HERAPDF1.7 has a steeper gluon at low-x than our previous PDFS. This is because of the use of the RT optimized GMVFN scherme



Comparing HERAPDF1.5, 1.6, 1.7 to MSTW2008

The hard high-x sea is softest for 1.7 – relaxing the parametrisation, adding jets, adding more data sets.

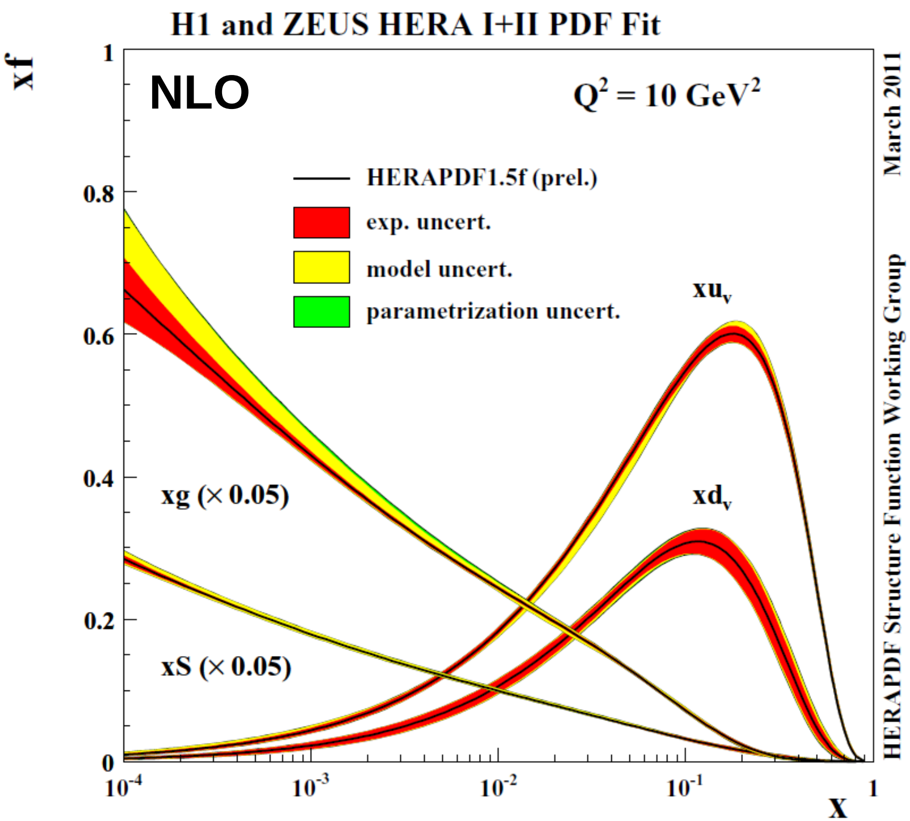
We also see that the low-x distributions are a bit steeper for 1.7 for gluon and quark

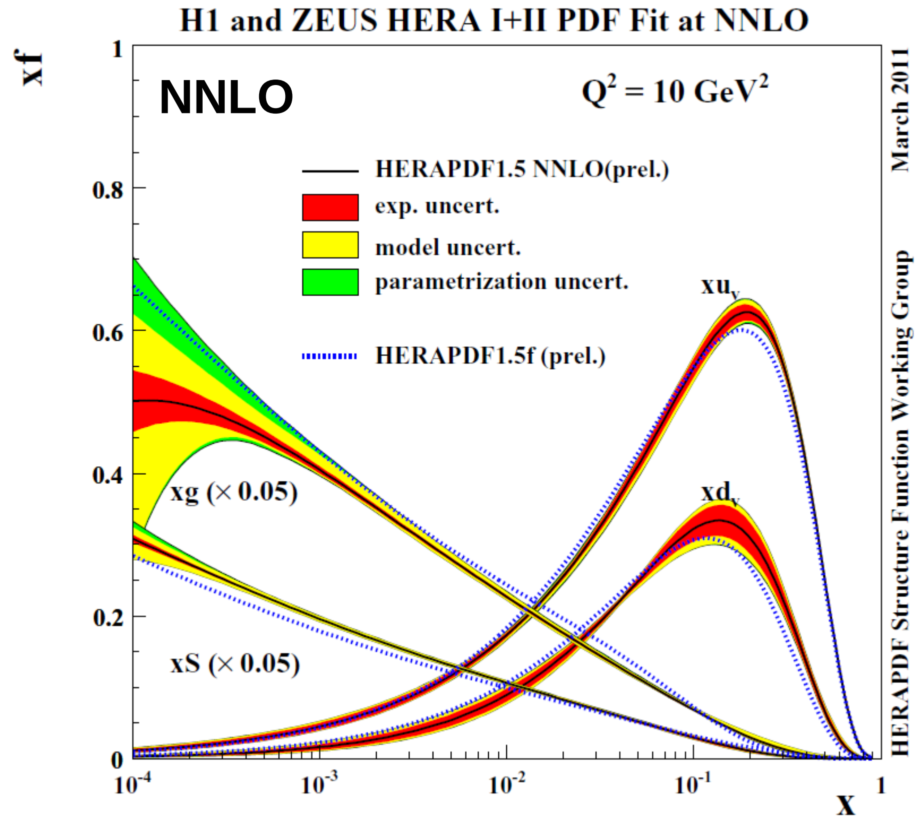
This is because the shape of the low-x gluon is steeper for RTOPT mc=1.5 (and this is a bit mitigated by the higher alphas value).

But the soft high-x gluon is rather similar for 1.7 and 1.5. the hardest high-x gluon is for 1.6 with larger $\alpha_S(M_Z)$ – the correlation of $\alpha_S(M_Z)$ to the gluon PDF modifies the gluon shape

And so to NNLO: ZEUS-prel-11-002/H1prelim-11-042. For these fits only HERA I+II high energy inclusive data are used

First compare HERAPDF1.5 NLO and NNLO both with extended parametrization





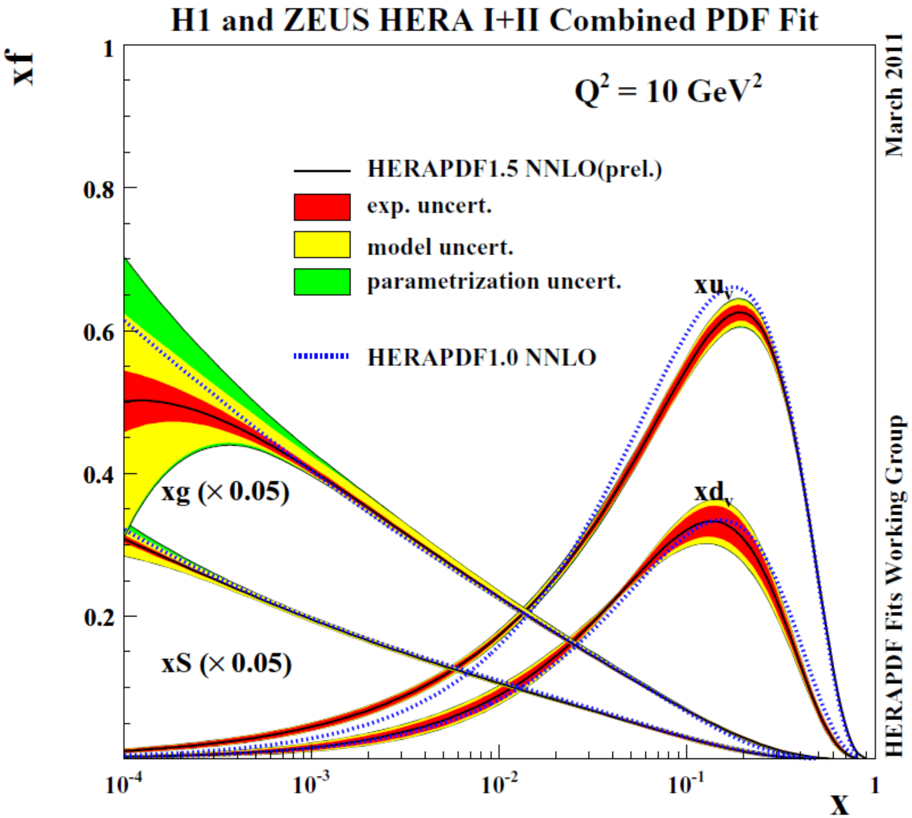
What are the differences?

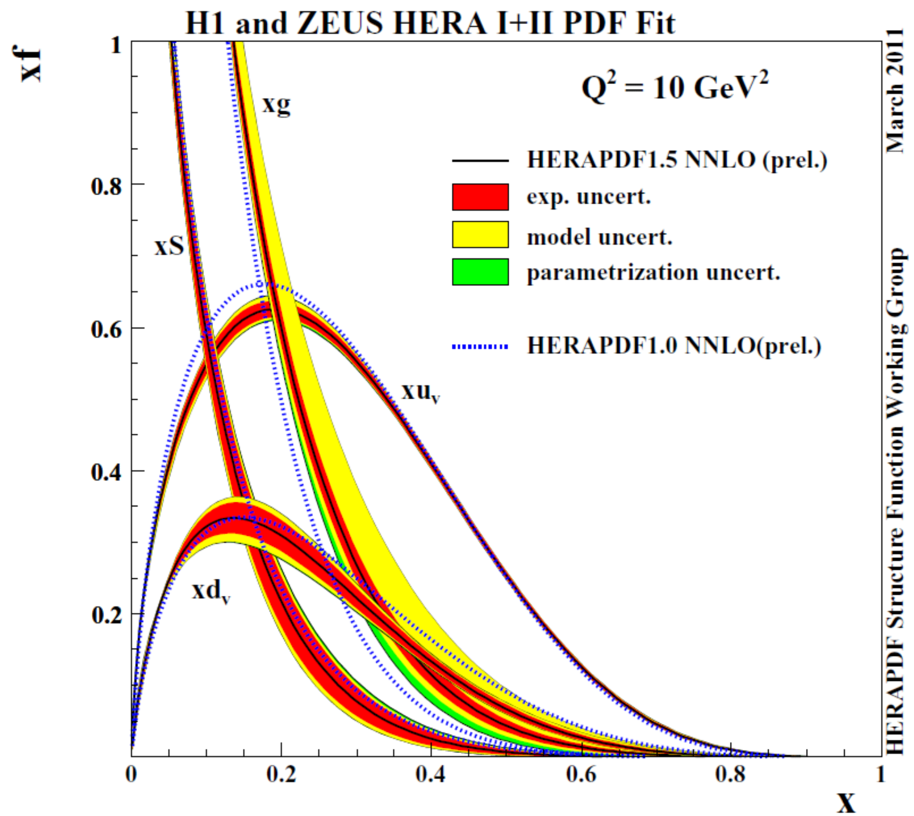
- Valence not much
- Sea a little steeper
- Gluon more valence like

On these plots both NLO and NNLO have $\alpha_s(M_Z) = 0.1176$

The low-x gluon has greater uncertainty NNLO DGLAP is NOT a better fit than NLO to low-x,Q^2 data

Now compare HERAPDF1.5NNLO to HERAPDF1.0 NNLO

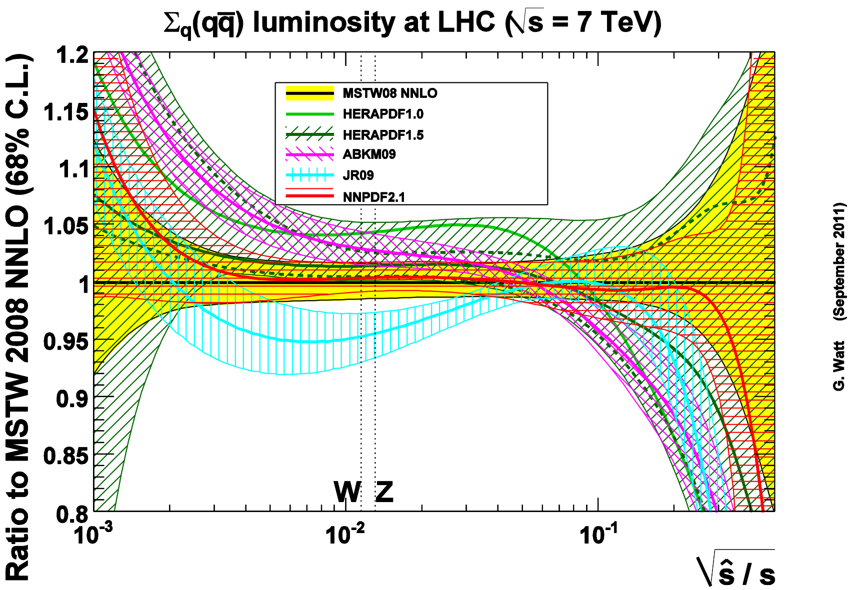


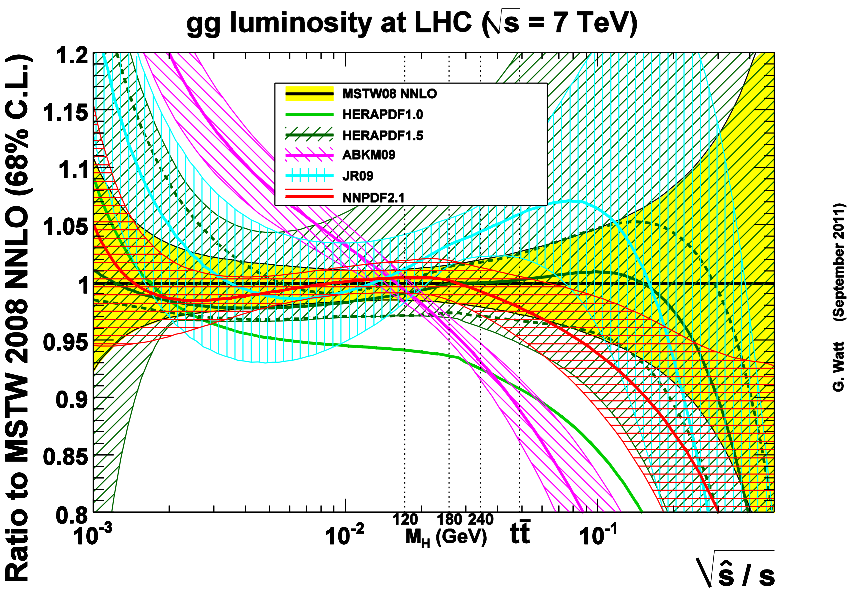


Previously we did not issue an error band on the 1.0 NNLO fits – the errors were in fact asymmetric and this is what led us to the extended parametrisation. Here we compare at $\alpha_S(M_Z)$=0.1176, which is our recommended central value for NNLO

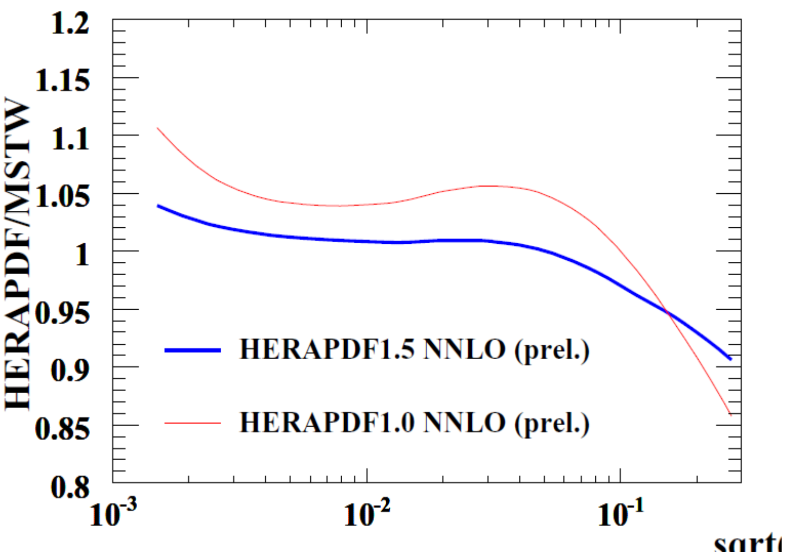
The HERAPDF1.5 NNLO is available for a series of $\alpha_S(M_Z)$ values and with model and parametrisation uncertainties on LHAPDF5.8.6

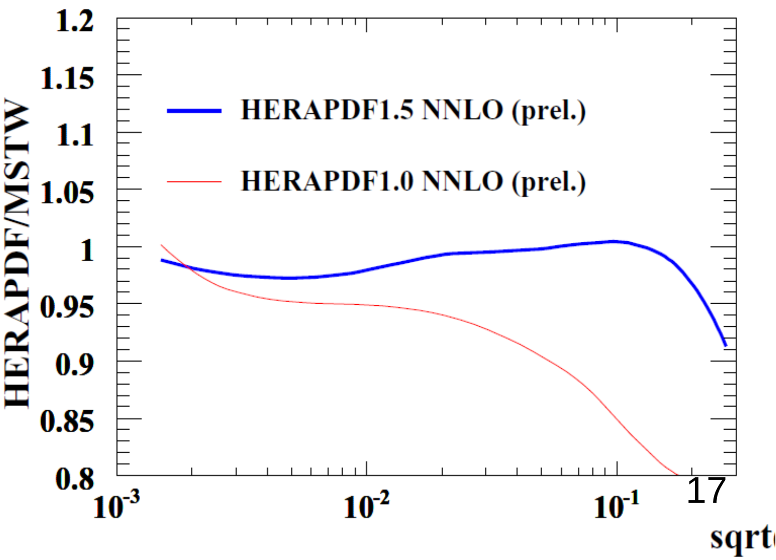
HERAPDF1.5 NNL0 has a harder high-x gluon than HERAPDF1.0.





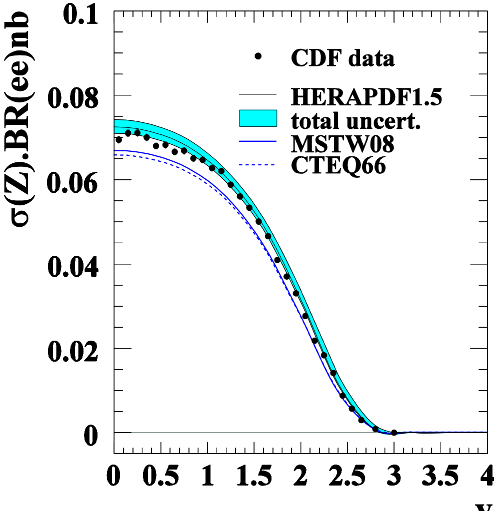
Watt's NNLO luminosity plots- the upper error on HERAPDF1.5NNLO high-x g-g is quite large



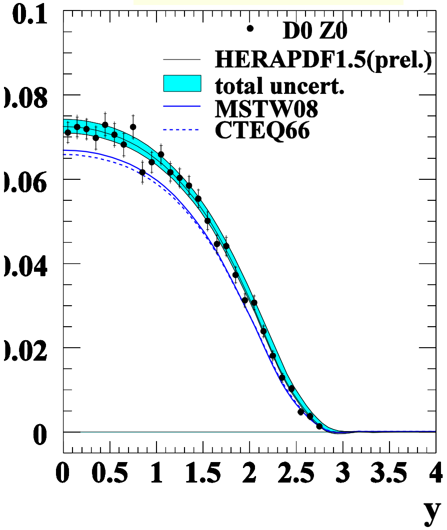


FInally how does HERAPDF measure up to Tevatron data

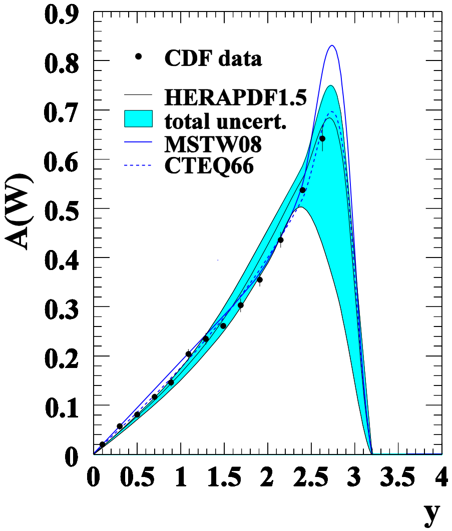
χ2=27/28



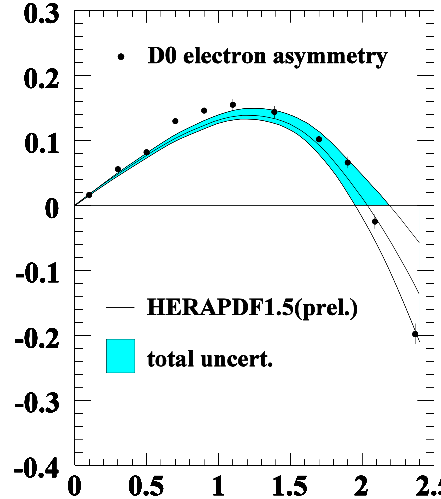
χ2=16/28



χ2=19/13



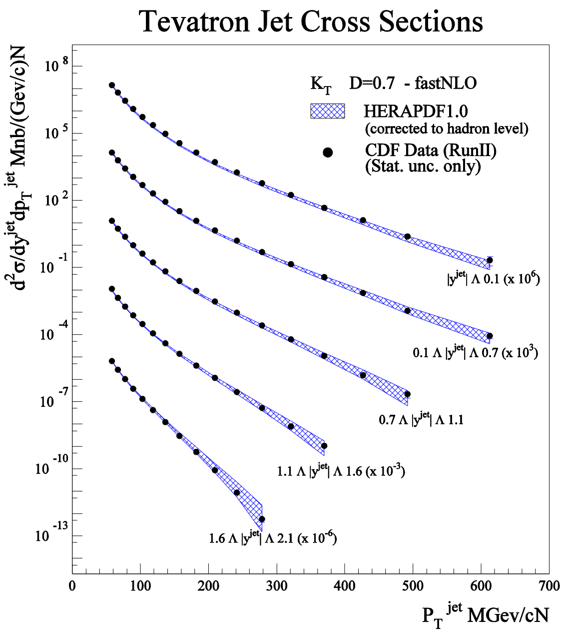
χ2=25/11



Pretty well for Tevatron W and Z data – even before fitting –and if these data are fit (χ2 given after fit) the resulting PDFs lie within the HERAPDF1.5 error bands

Descriptions for HERAPDF 1.6,1.7 are similar

What about Tevatron jet data?– it ‘looks’ OK



But it is not sufficent for it to ‘look’ OK. The correlations are so large that one needs to do a fit including correlations. For HERAPDF 1.5 central settings

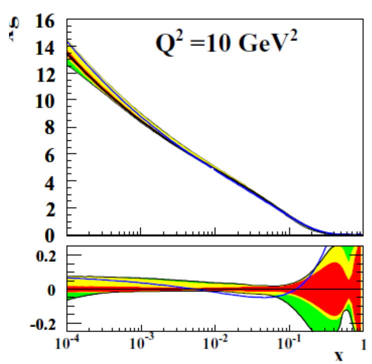
χ2/dp = 176/76 for CDF jets

However this ignores the error band of the fit. If these data are included in an NLO fit we get χ2/dp = 113/76 and The resulting PDF is still within the error bands- although at the edge of (68%CL) error bands

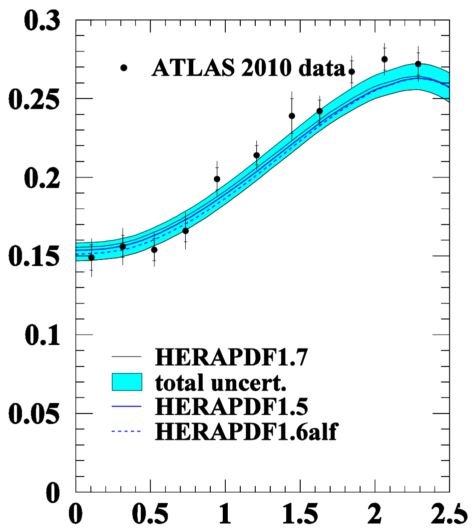
Making the χ2 calculation again for recent HERAPDFs:

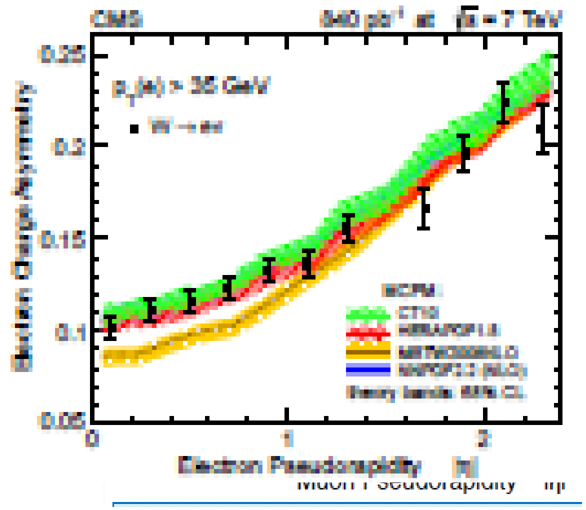
At NLO HERAPDF1.6 $\alpha_S(M_Z)$ =0.1202 gives the best fit for its central settings χ2/dp = 122/76 for CDF jets- it has the hardest high-x gluon

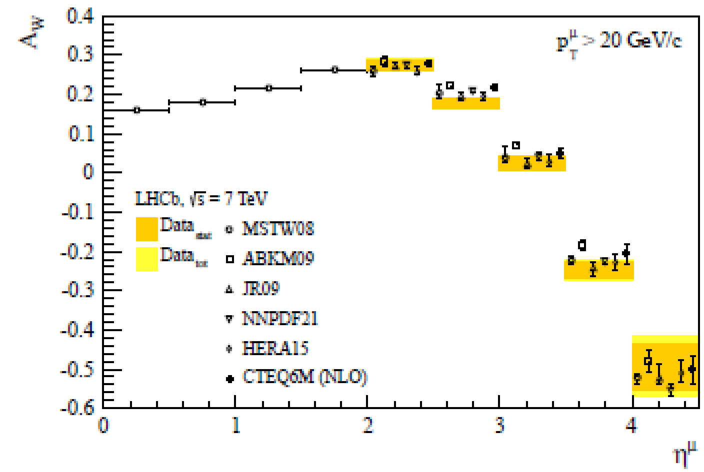
At NNLO HERAPDF1.5 gives χ2/dp=72/76 already a very good description even before the data are input to the fit --- because it has a relatively hard high-x gluon



FInally how does HERAPDF measure up to LHC data





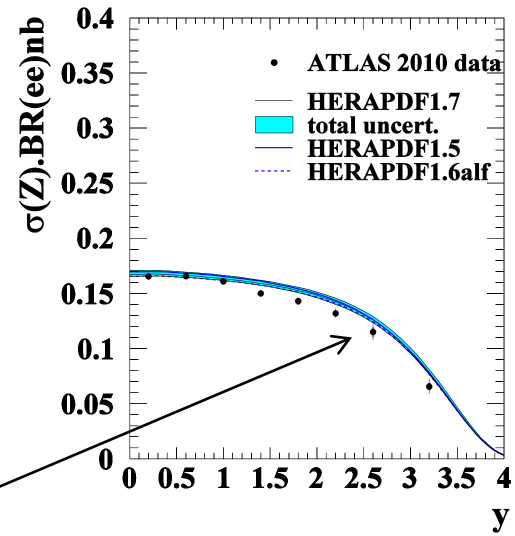


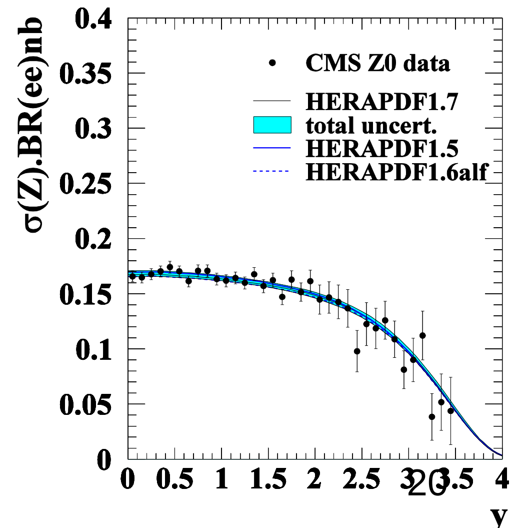
HERAPDF1.7(1.6,1.5) vs ATLAS 2010 muon and electron data combined data

HERAPDF1.5 vs CMS 2011 data and LHCb data

ATLAS and CMS Z0 data compared to HERAPDF1..7

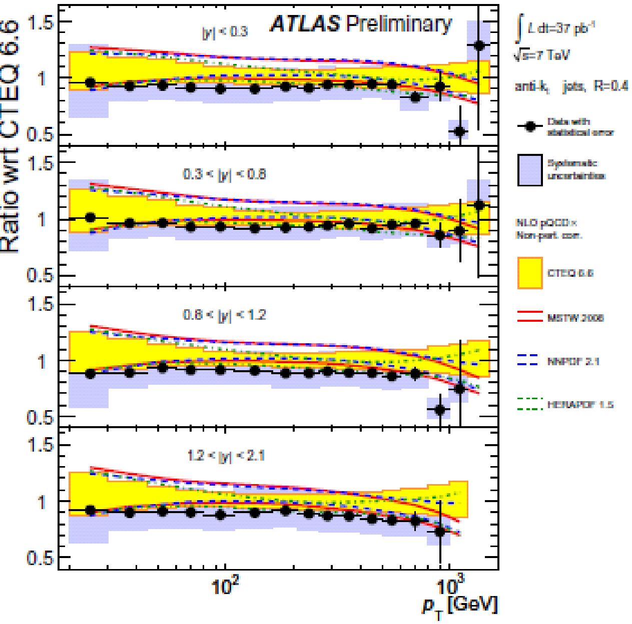
The ATLAS Z shape is fitted better with increased low x strangeness

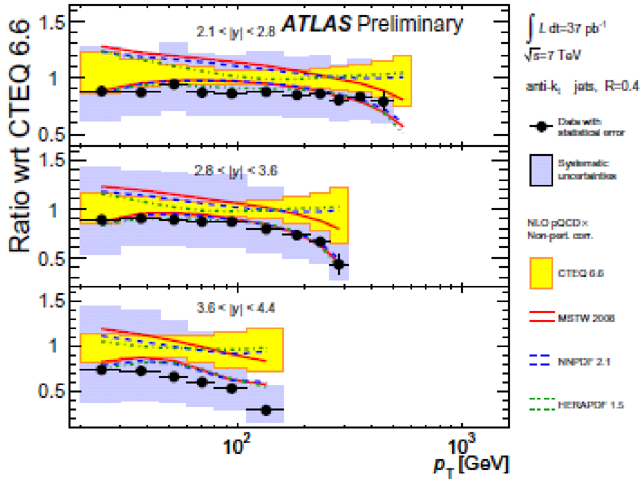




ATLAS jet data

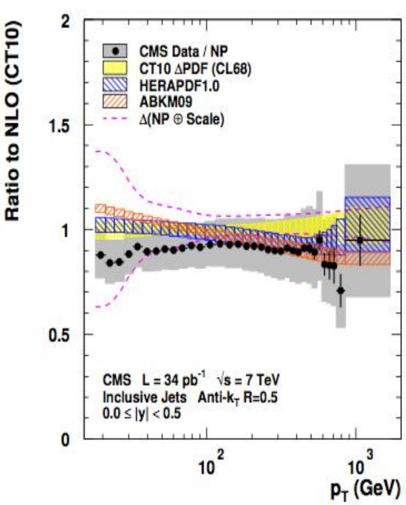
And how well is LHC jet data described?

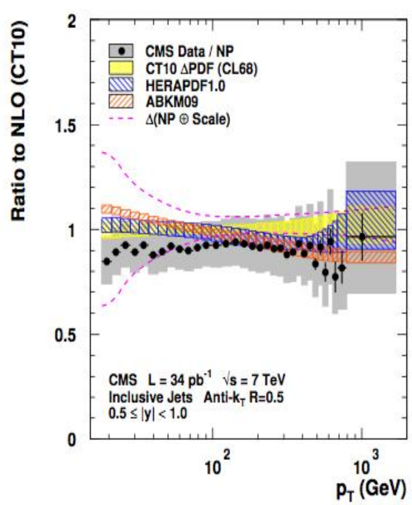




As usual I looks quite good but we must fit it. ATLAS data come with correlations

CMS jet data





HERAPDF1.5 χ2/dp = 58/90

HERAPDF1.6 $\alpha_s(M_Z)$=0.1202 χ2/dp = 52/90

HERAPDF1.7 χ2/dp = 56/90

HERAPDF1.5 NNLO χ2/dp = 44/90

All good fits, not much discrimination

Not such a hard gluon as the Tevatron

Summary

- The HERA inclusive data provide precision for the low-x Sea and gluon PDFs, the u-valence is also well measured, and the d-valence is measured without assumptions about nuclear corrections or strong isospin.

- Adding the HERA-II high Q^2 data reduces the uncertainties at high-x. So far this was preliminary, **now the input H1 (DESY-12-107) and ZEUS (DESY-12-145) data sets are finally ready- the HERA-II final combination has begun**

- Adding HERA jet data allows a measurement of $\alpha_S(M_Z)$ and the high-x gluon– further jet data sets will be added

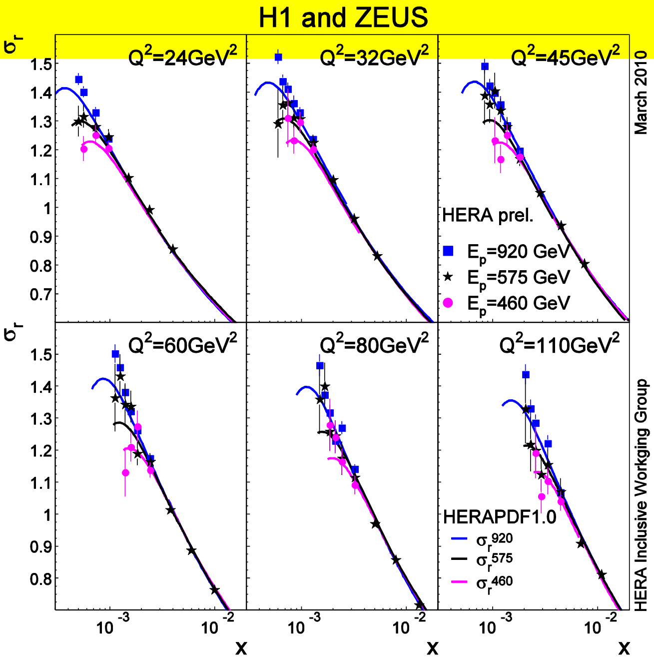
- Adding charm data allows a reduction in model uncertainties concerning the charm mass and scheme. **The charm combination paper is about to have its 3rd editorial board.**

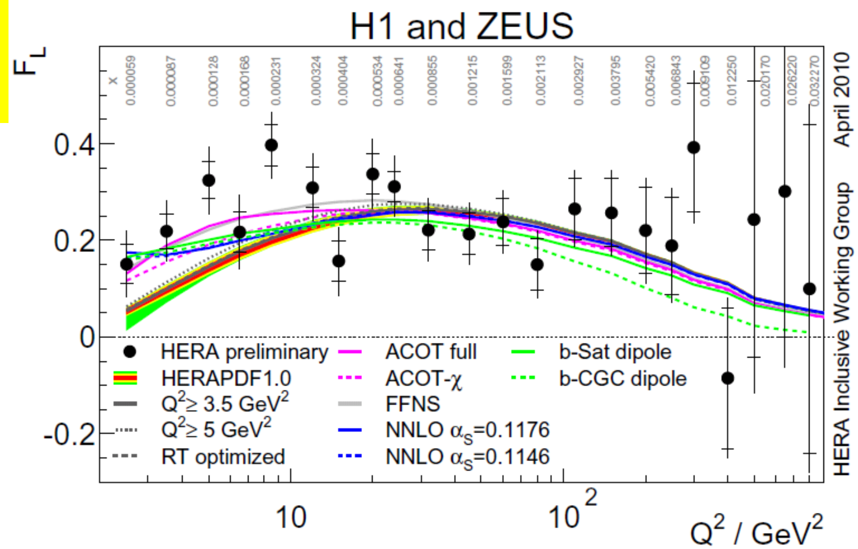
- Adding low energy data will allow us to investigate non-DGLAP behaviour at low x,Q^2

- HERAPDF gives a good description of Tevatron W, Z data and jet data (within its error bands) and a good description of LHC W ,Z and jet data

extras

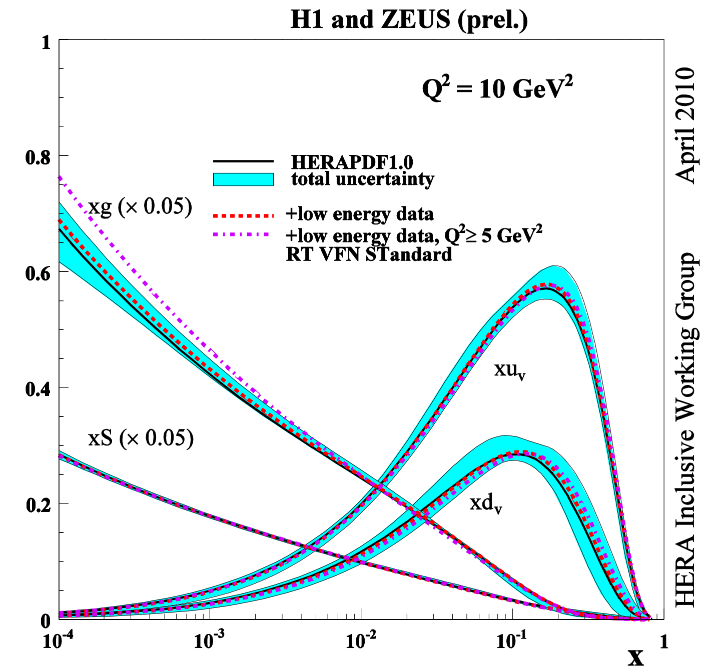
H1 and ZEUS have also combined the e+p NC inclusive data from the lower proton beam energy runs (P_P = 460 and 575) and produced a common FL measurement (ZEUS prel 10-001 , H1prelim 10-043)



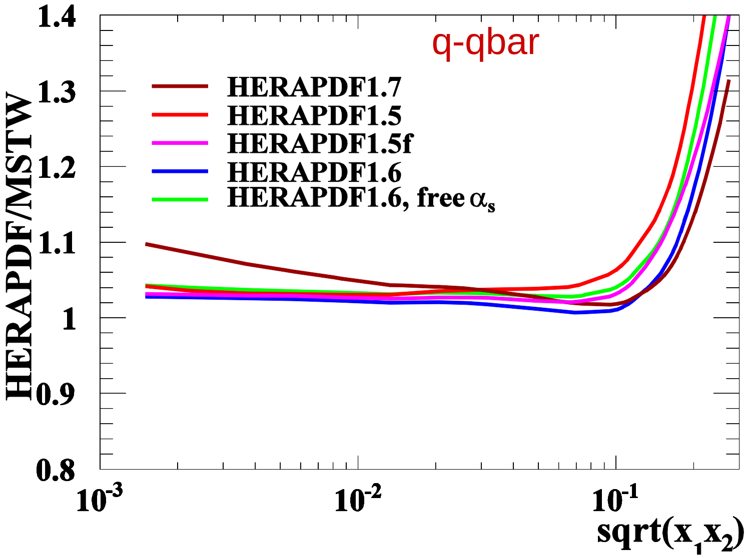


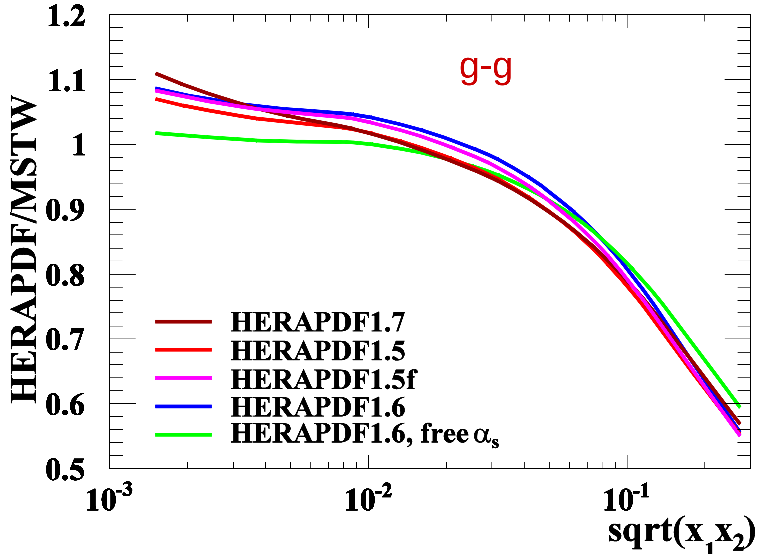
In HERAPDF1.0,1.5 we also present a model uncertainty from the variation of the minimum Q^2 cut on the data The low energy data are more sensitive to this cut.

If low Q^2 -and hence low x - data are cut -the resulting gluon is somewhat steeper.
This level of uncertainty is now covered by the extended parametrization



LHC at 7 TeV parton-parton luminosity plots for HERAPDF1.5 in ratio to MSTW2008





The q-qbar luminosity at NLO

HERAPDF1.5 is softer than 1.0 at high-x and 1.5f is even softer

Adding the jets to make it 1.6 makes the high-x sea even softer

Letting alphas be free so that $\alpha_S(M_Z)$=0.1202 rather than 0.1176 hardens the high-x quark distribution marginally

An HERAPDF1.7 is softest of all

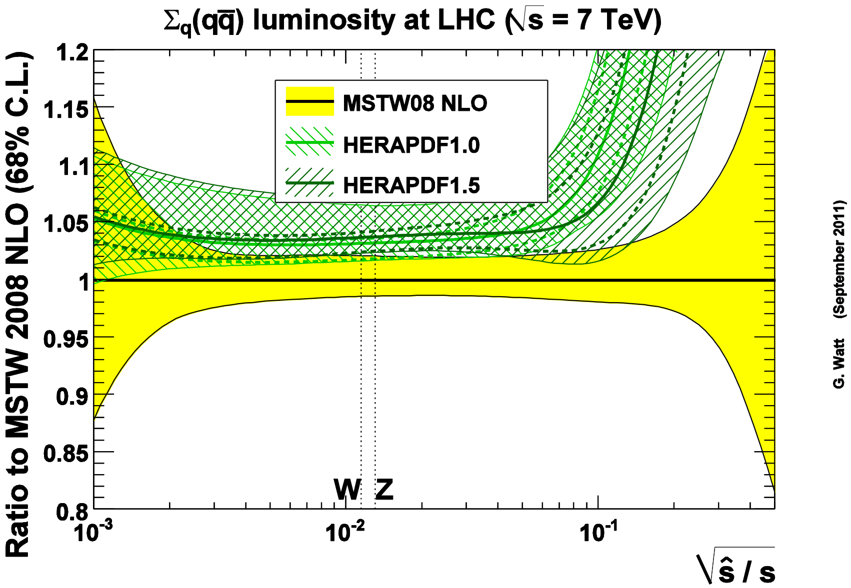
The g-g luminosity at NLO

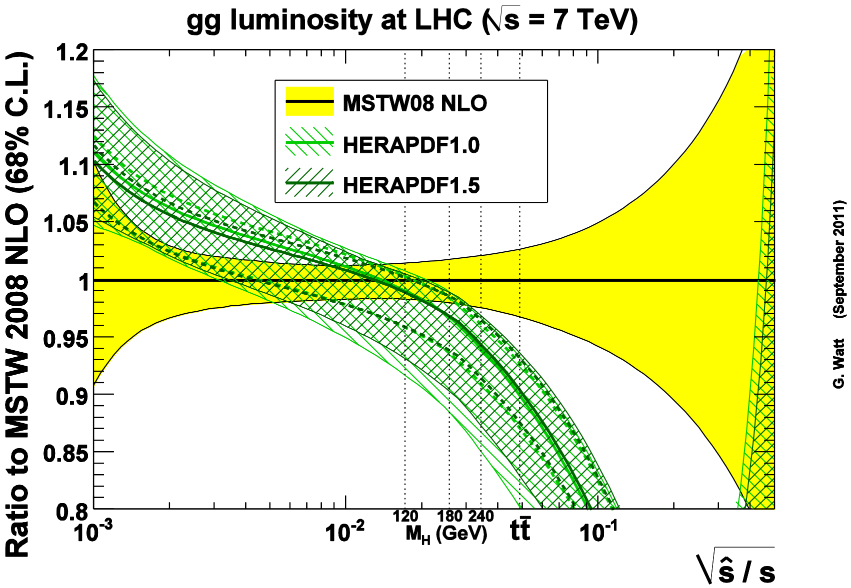
HERAPDF1.5 is on top of 1.0 and 1.5f is very similar

Adding the jets to make it 1.6 makes little difference, similarly for 1.7

But letting alphas be free so that $\alpha_S(M_Z)$=0.1202 rather than 0.1176 also reduces the low-x gluon and hardens the high-x gluon

LHC at 7 TeV parton-parton luminosity plots for HERAPDF in ratio to MSTW2008





From Graeme Watt

You can see that HERAPDF1.5 has a softer high-x sea than 1.0 but very similar gluon.

So how about the other HERAPDFs. Again using central settings: HERAPDF1.5 χ2/dp = 176/76

HERAPDF1.5f χ2/dp = 169/76

HERAPDF1.6 χ2/dp = 167/76

HERAPDF1.6 () χ2/dp = 122/76

HERAPDF1.7 χ2/dp = 160/76

HERAPDF1.5NNLO χ2/dp=72/76

(Of course NNLO is not strictly correct for the jets but other PDF fitters do this)

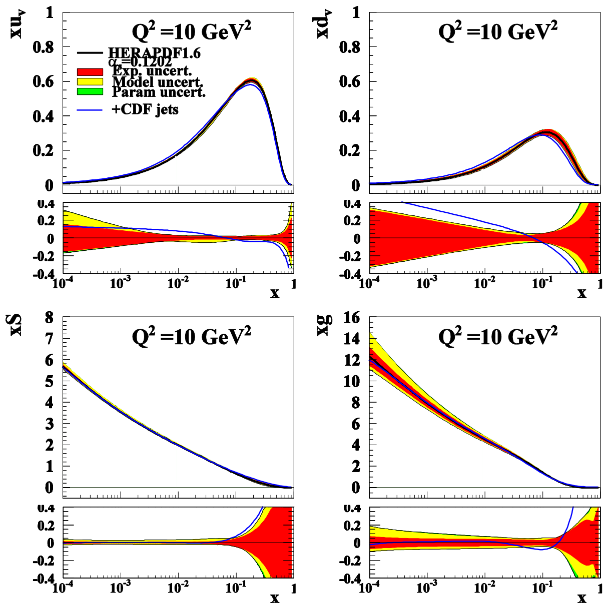
Going back to NLO PDFs:

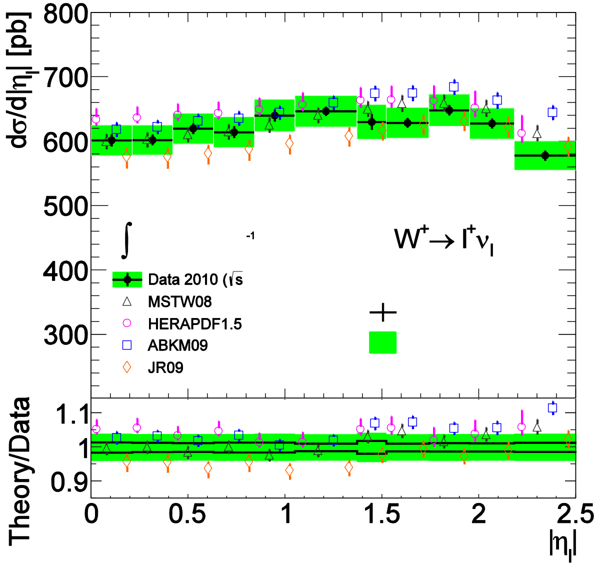
Only 1.6 with free larger αs(=0.1202) is actually a significantly better fit than 1.5.

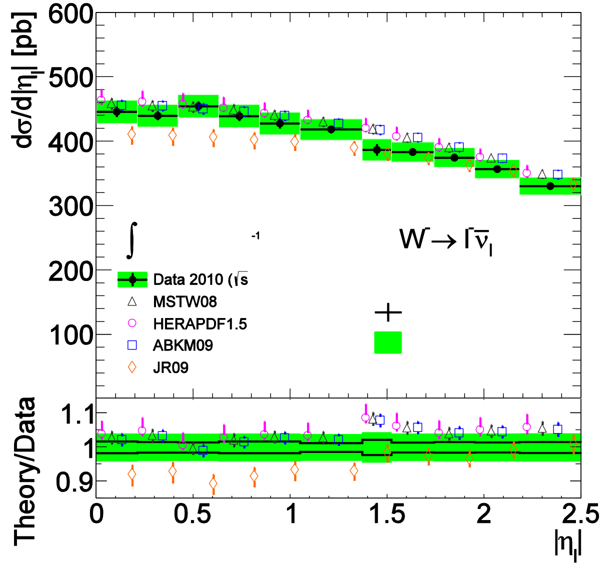
Of course one can fit the CDF jet data in a fit like 1.6 with HERAjets and αs=0.1202. Such a fit gives χ2/dp = 74/76, but the high-x gluon PDF has gone outside the error band!

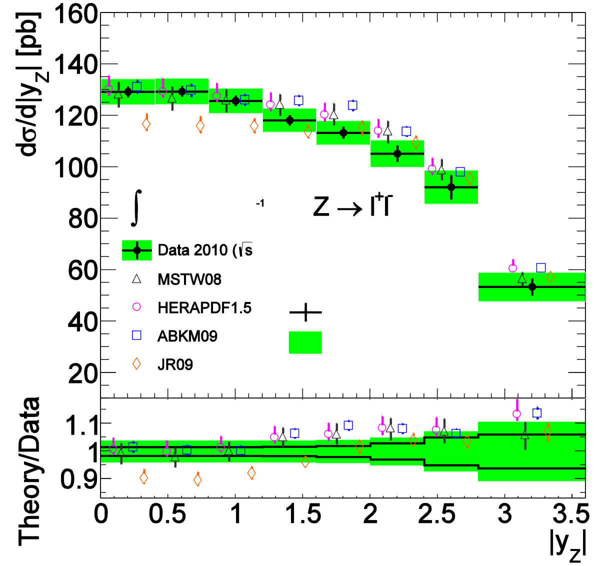
Conclusion CDF jets do want out NLO PDFs to have harder high-x gluon

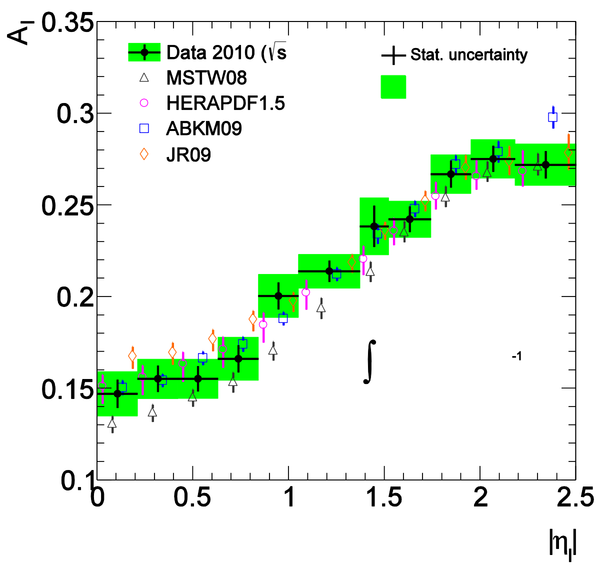
But 1.5NNLO is as good as any NNLO PDF



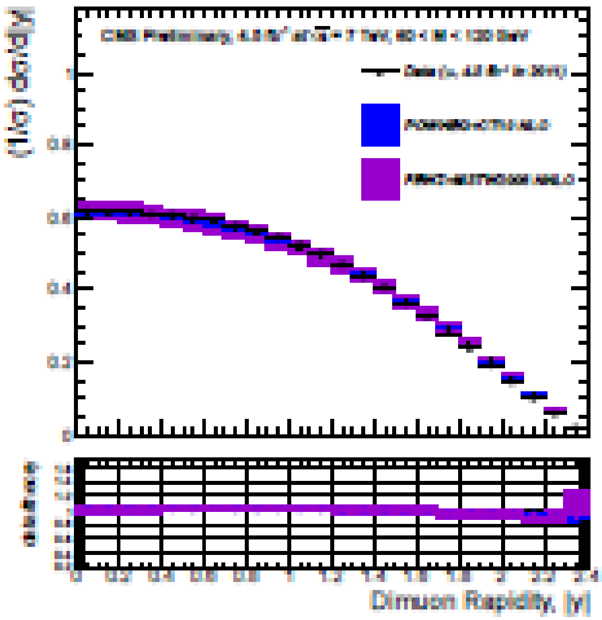
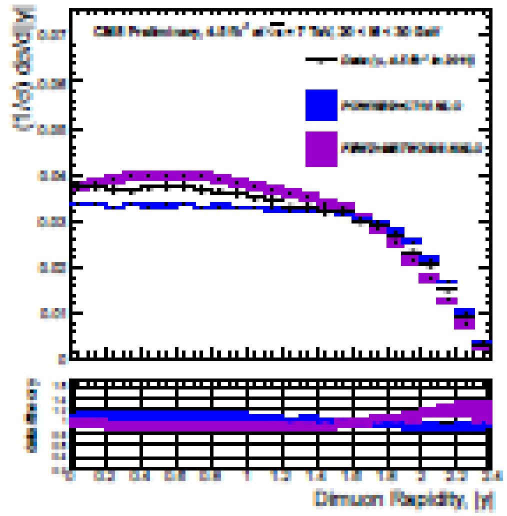
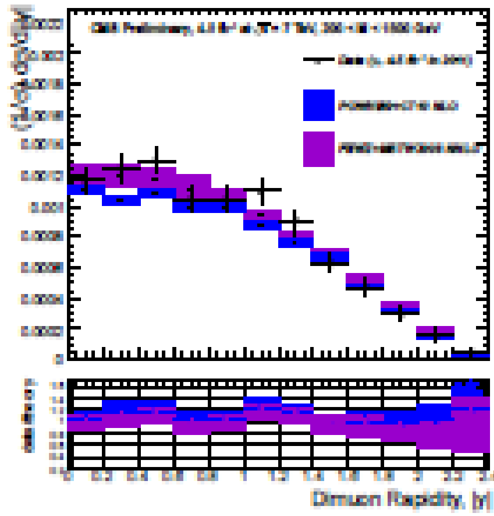


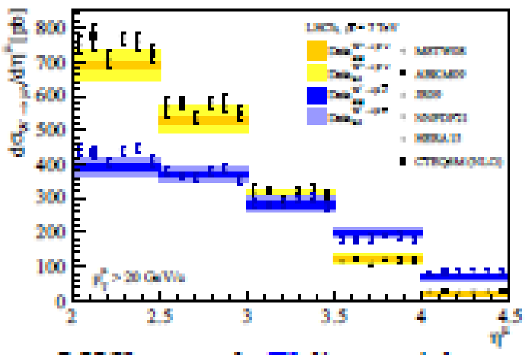


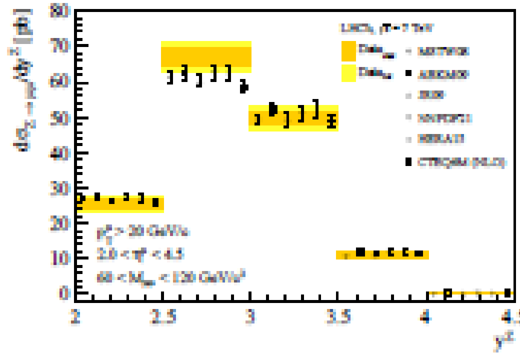


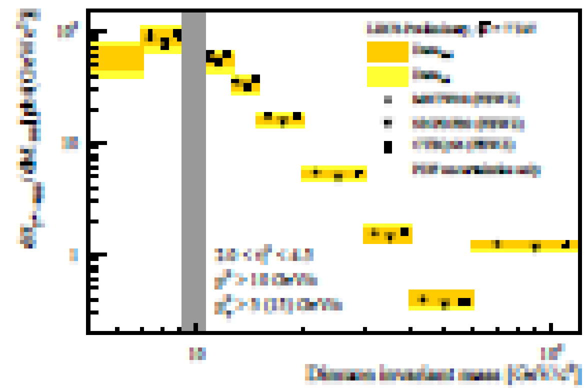


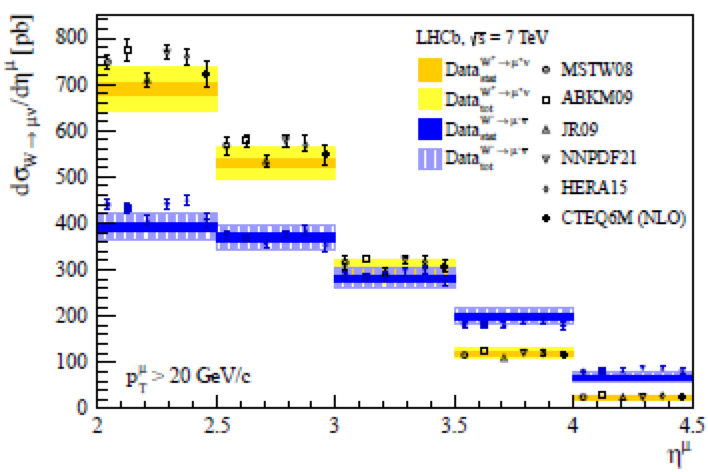
Comparison of ATLAS W+, W- lepton, Z0 and W-lepton asymmetry with HERAPDF1.5NNLO


(1/σ) dσ/d|y|
Dimuon Rapidity, |y|

(1/σ) dσ/d|y|
Dimuon Rapidity, |y|

Dimuon Rapidity, |y|


LHCb, √s = 7 TeV
MSTW08
ABKM09
JR09
NNPDF21
HERA15
CTEQ6M (NLO)
η^μ


LHCb, √s = 7 TeV
MSTW08
ABKM09
JR09
NNPDF21
HERA15
CTEQ6M (NLO)
y^Z


Dimuon invariant mass [GeV/c²]


LHCb, √s = 7 TeV
MSTW08
ABKM09
JR09
NNPDF21
HERA15
CTEQ6M (NLO)
p_T^μ > 20 GeV/c
dσ_{W→μν}/dη^μ [pb]
η^μ