

# PDFs for the LHC

A M Cooper-Sarkar  
DIS 2011

PDF4LHC comparisons 2010 updated to 2011

Updates: CT10, NNPDF2.1, HERAPDF1.5, ABM11

Treatment of heavy quarks: NNPDF2.1, HERAPDF, MSTW, ABM

Value of  $\alpha_s(M_Z)$ : NNPDF, HERAPDF, MSTW, CT/CTEQ

Does DIS data like low  $\alpha_s(M_Z)$ ? --- HERAPDF1.6+jets

The year of NNLO: CTEQ, NNPDF, HERAPDF join MSTW, JR, ABKM

The Tevatron Higgs limits: is it essential to use PDFs which are fitted to Tevatron jets?

Is it essential to use a global fit? Look at NNLO predictions NOT at NLO

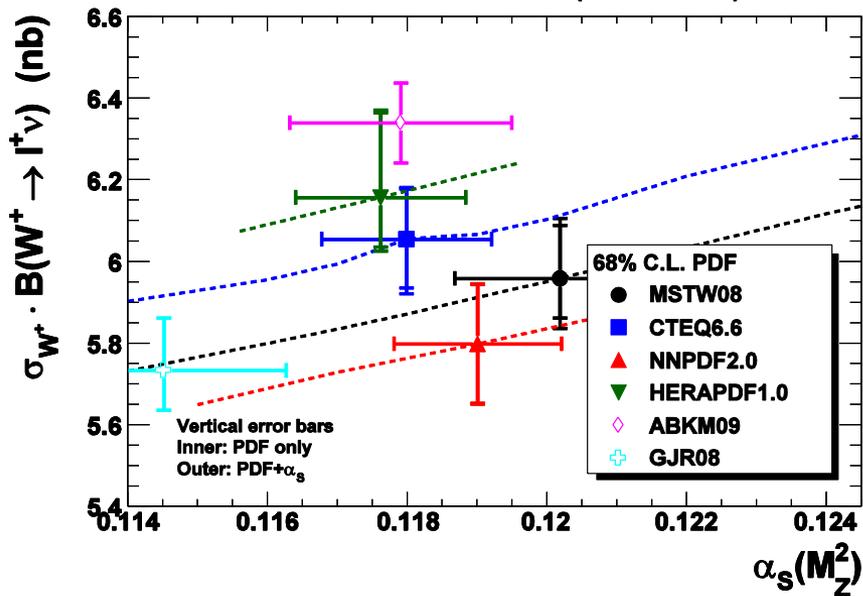
Global fits:

Doubts about deuterium corrections, and doubts about fixed target F2

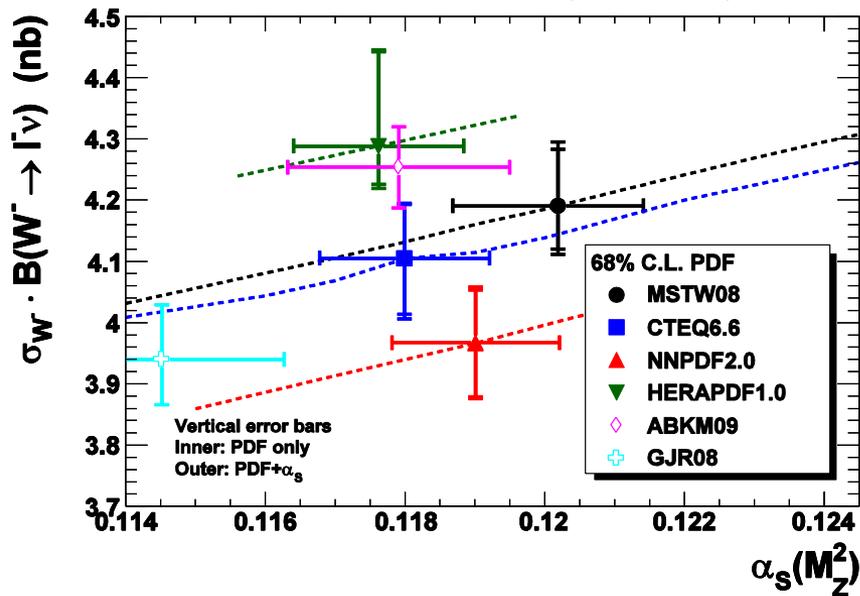
Early LHC W/Z data – some visible impact on PDFs– (NNPDF, HERAPDF)

Early LHC jet data

NLO  $W^+ \rightarrow \Gamma^+ \nu$  at the LHC ( $\sqrt{s} = 7$  TeV)



NLO  $W^- \rightarrow \Gamma^- \nu$  at the LHC ( $\sqrt{s} = 7$  TeV)

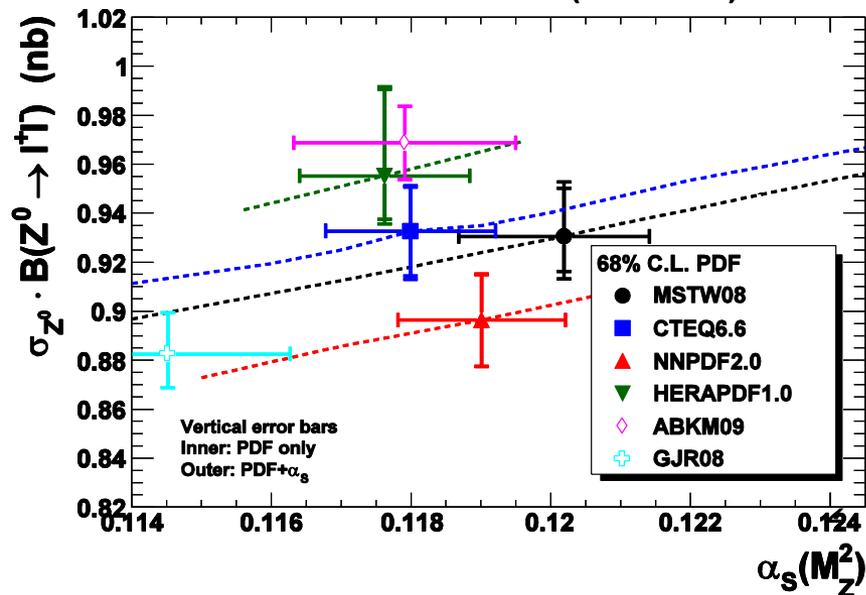


In 2010 the PDF4LHC group considered:  
MSTW08 CTEQ66  
HERAPDF1.0 NNPDF2.0  
ABKM09 GJR08

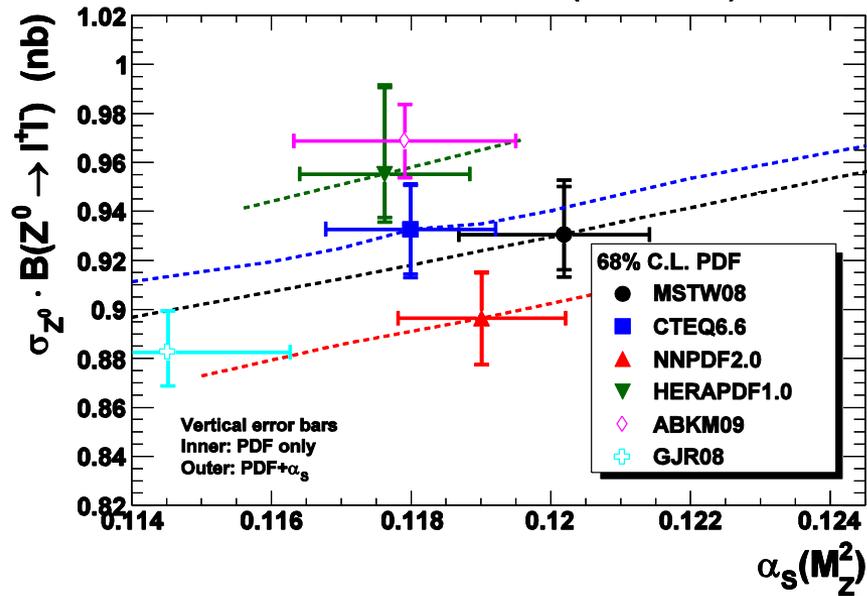
Plots from G.Watt – 68%CL

Overall disagreement  $\sim 8\%$  in W, Z cross-sections  
The PDF4LHC recommendation was to take the envelope of the NNPDF, MSTW, CTEQ predictions --even this may not be enough!

NLO  $Z^0 \rightarrow \Gamma^+ \Gamma^-$  at the LHC ( $\sqrt{s} = 7$  TeV)



## NLO $Z^0 \rightarrow \Gamma\Gamma$ at the LHC ( $\sqrt{s} = 7$ TeV)



**Thirdly**, different groups use different input data sets, e.g. the data used by CTEQ and MSTW are very similar and they do NOT include the latest most accurate HERA data which are used in HERAPDF1.0.

Not only are these new (2009) data more accurate they also have a different normalisation

This accounts for  $\sim 2.5\%$  upward shift of the HERAPDF prediction.

CT, NNPDF, ABM update to include these data

Why these disagreements?

**Firstly** groups use different values of  $\alpha_s(M_Z)$ , the effect of this can be seen on the figures. A common value would bring some of the predictions into better agreement.

HERAPDF, NNPDF, CTEQ and MSTW provide PDFs at a series of  $\alpha_s(M_Z)$  values

**Secondly** groups have different ways of accounting for heavy quark production. And use different values of the heavy quark mass.

Within any chosen scheme a change of quark mass from 1.4 to 1.65 GeV can change the W/Z cross-sections by  $\sim 2.5\%$

HERAPDF, NNPDF, MSTW provide PDFs at different  $m_c$  values

Fourthly there are some differences in philosophy regarding choices of PDF parametrisation and theoretical/model prejudices which are imposed

Let's look more closely at some of these points

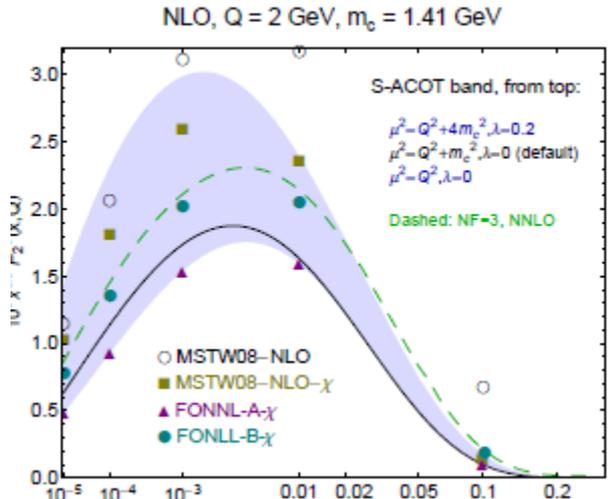
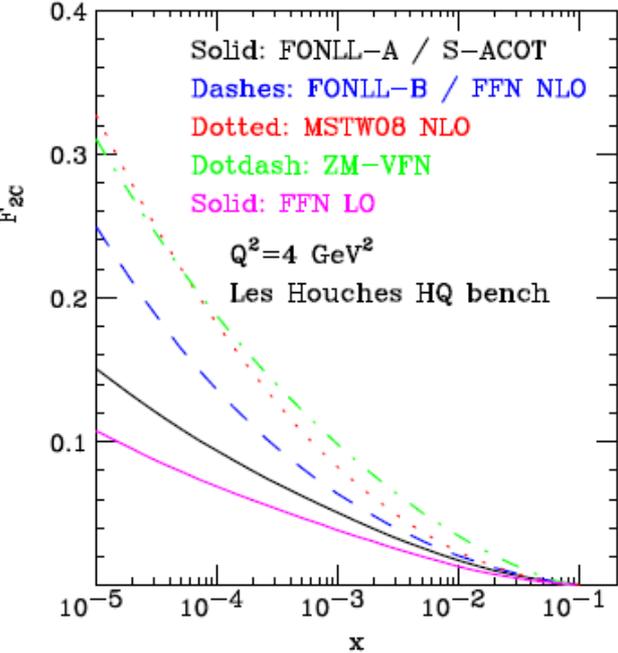
Heavy quark production.: there are two extremes-

Use only 3 massless parton flavours and calculate exact ME's for heavy quark production (FFN method)- wrong at high scale since  $\ln(Q^2/m_c^2)$  terms not resummed

Consider all partons as massless except that charm and beauty turn on abruptly at their kinematic thresholds (ZMVFN) – WRONG at low scale near these thresholds

A GMVFN (General-mass Variable Flavour Number Scheme) is supposed to give us the best of both worlds..

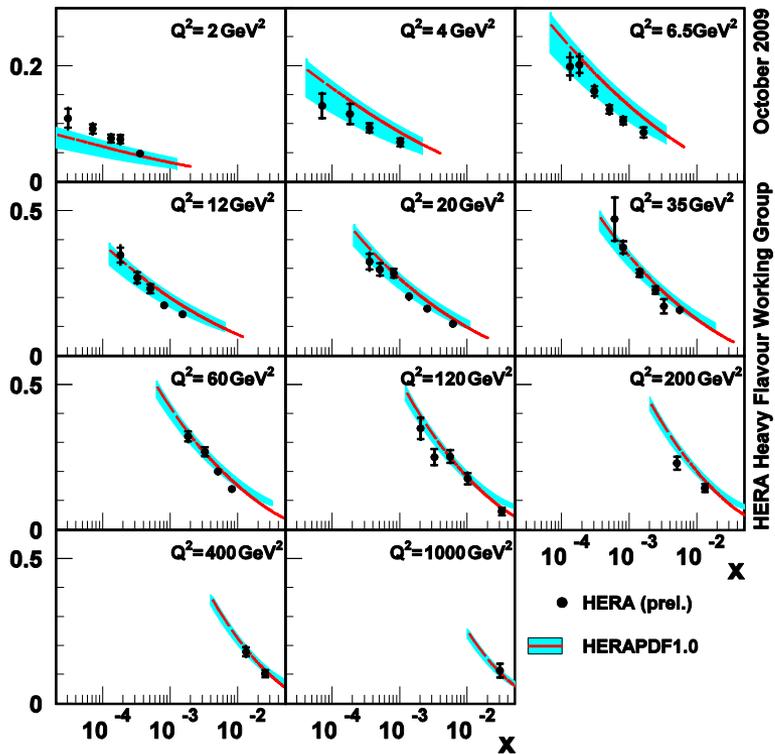
BUT there are different ways to do this...ACOT, Thorne, FO-NLL and there are tunable scale choices



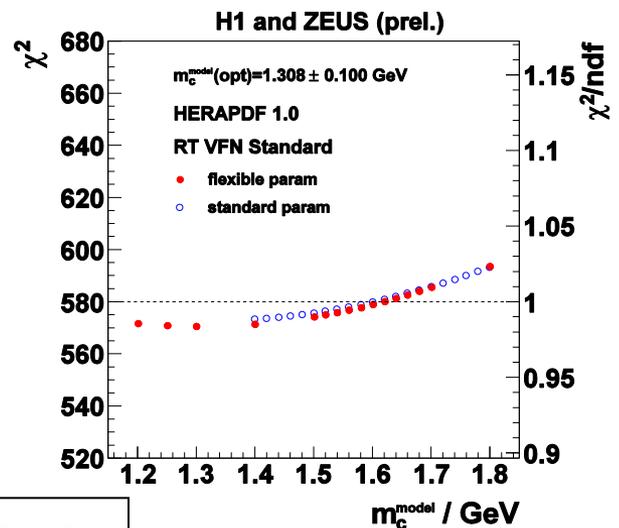
NNLO differences are not so large...

And a second question is  
What value of the charm mass should be used?

# H1 and ZEUS



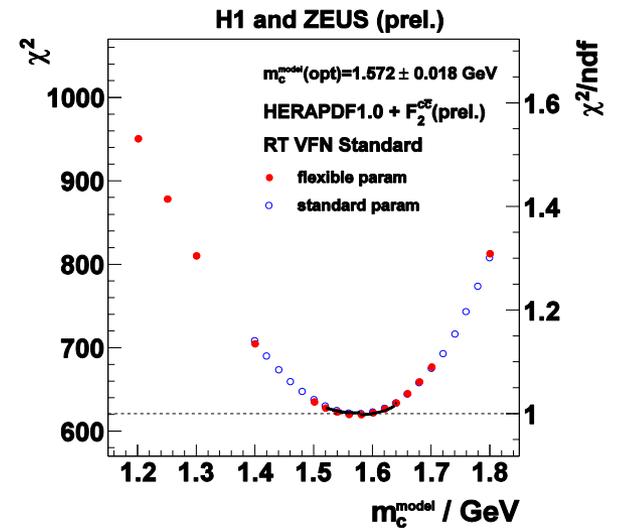
X2 profile vs charm mass



Without charm

H1 and ZEUS have also combined charm data recently

And these data show a preference for a charm mass  
 $m_c = 1.57 \pm 0.02 \text{ GeV}$   
 IF the standard Thorne VFN is used

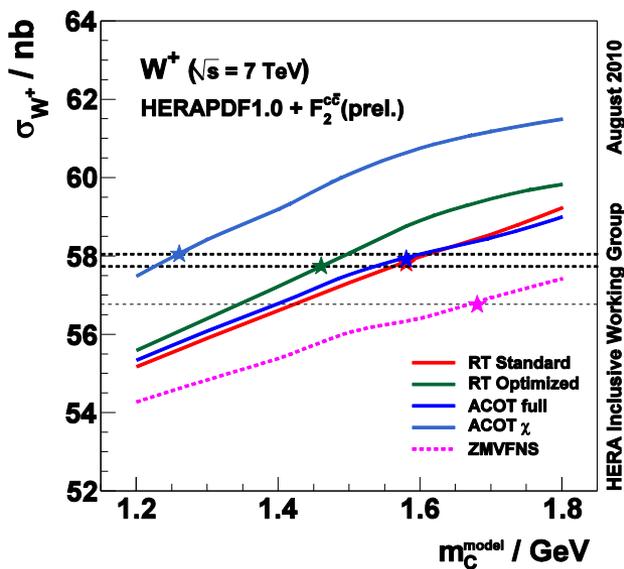
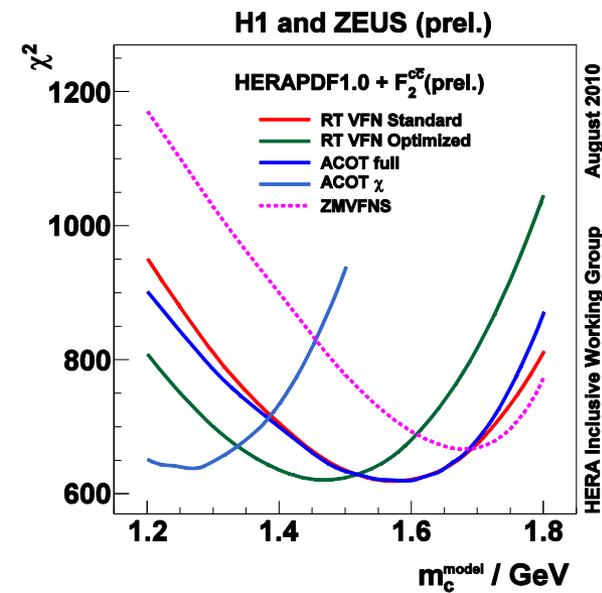


With charm

But the value of the preferred charm mass depends on the heavy quark scheme

Each scheme can be used to predict the W and Z cross-sections at the LHC as a function of charm mass parameter.

If a fixed value of  $m_c$  is used then the spread is considerable ( $\sim 7\%$ )- but if each prediction is taken at its own optimal mass value the spread is dramatically reduced ( $\sim 2\%$ ) even when a Zero-Mass (ZMVFN) approximation has been used



The PDFs MSTW08, CTEQ6.6, NNPDF2.0 do NOT use charm mass parameters at their optimal values- and explains part of their differences.

Now MSTW, NNPDF and HERAPDF provide a series of  $m_c$ ,  $m_b$  values

But what is the mass that is being used?  
 The pole mass?

The running mass has been measured independently would it be better to use this?

ABM have considered this in the FFN scheme

The schemes considered above all use the pole mass with VFN fits  
 AB(K)M have always used FFN. ABM now use the running mass.

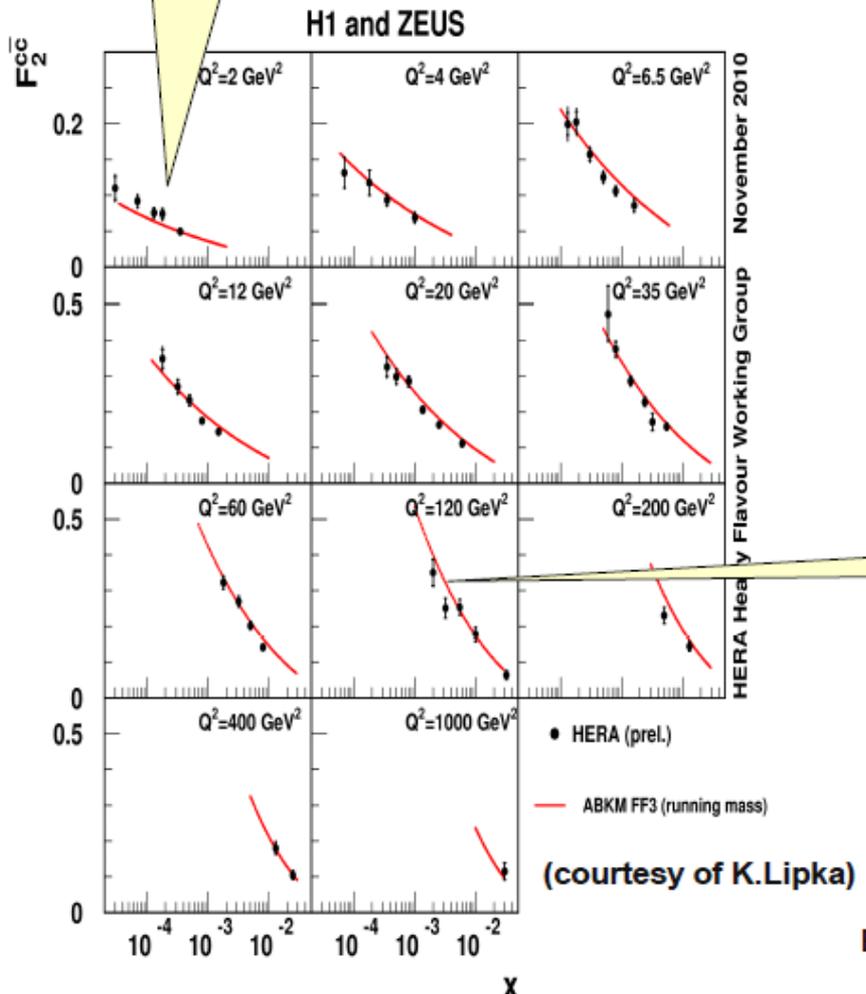
The NNLO(approx.) FFNS ABM *predictions* based on the running mass definition are  
 In nice agreement with the new HERA data

**N<sup>3</sup>LO corrections?**

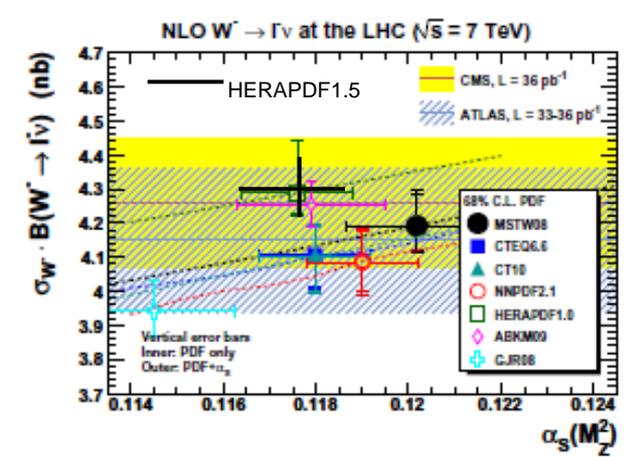
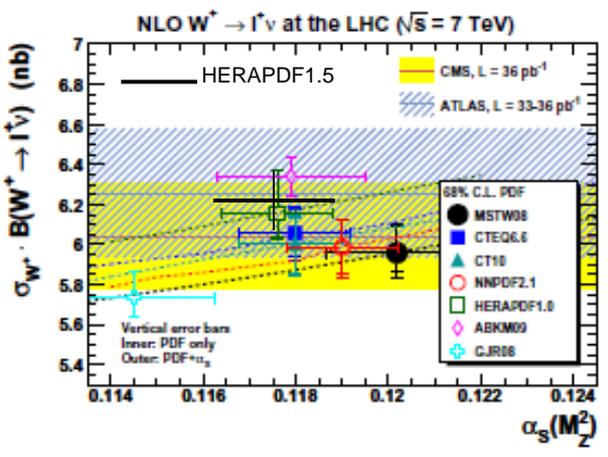
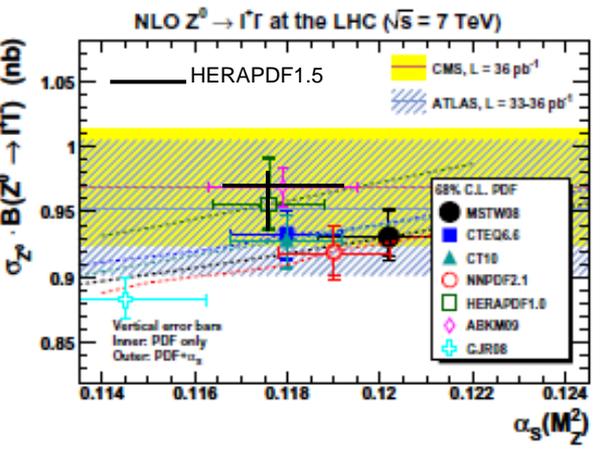
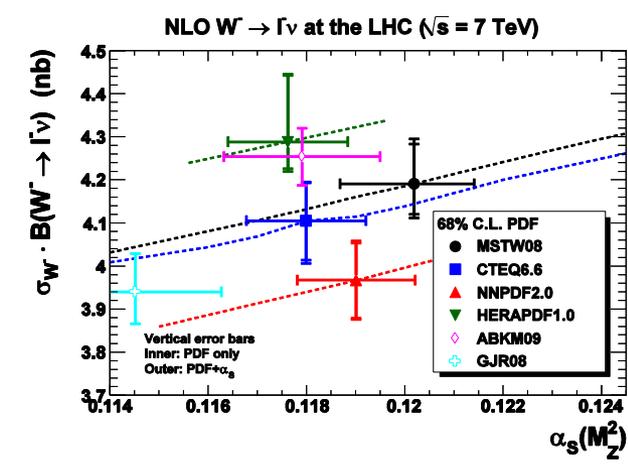
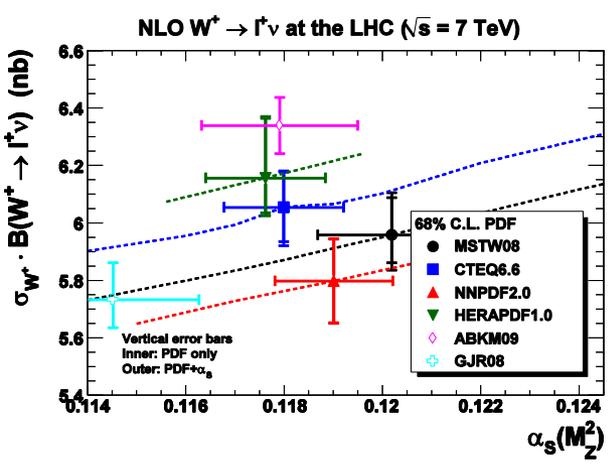
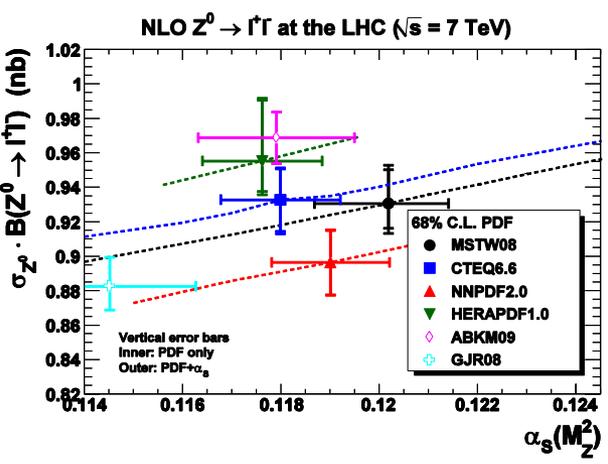
$$m_c(m_c) = 1.27 \pm 0.08 \text{ GeV (PDG '10)}$$

$$m_c(m_c) = 1.18 \pm 0.06 \text{ GeV (incl. } F_2 \text{ + PDG)}$$

The HERA data prefer  $m_c(m_c)$   
 close to the PDG value



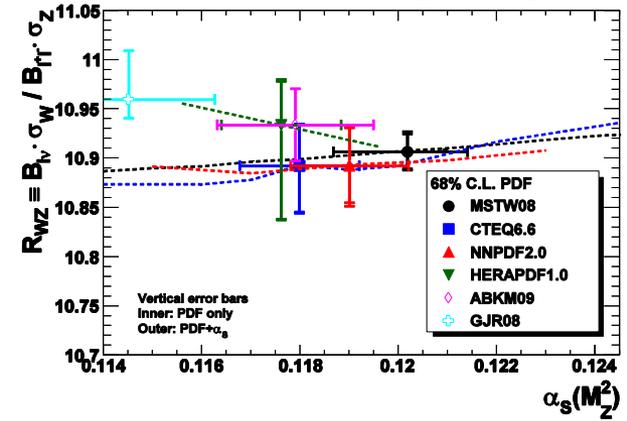
NNPDF2.0 has been updated to NNPDF2.1 using FONLL VFN  
CTEQ6.6 to CT10     ABKM09 to ABM11     HERAPDF1.0 to HERAPDF1.5



The use of the VFN scheme puts NNPDF2.1 closer to MSTW,  
 CT10 and CTEQ6.6 are very similar, HERAPDF1.5 is a little higher than 1.0 for W+,Z

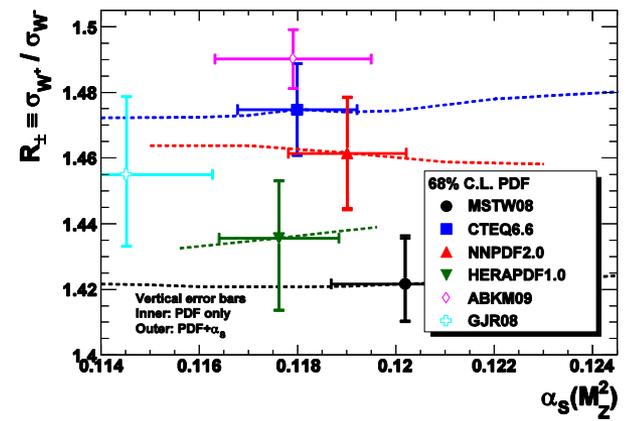
CMS and ATLAS data agree well with all predictions

NLO W/Z ratio at the LHC ( $\sqrt{s} = 7$  TeV)



W,Z ratios updated

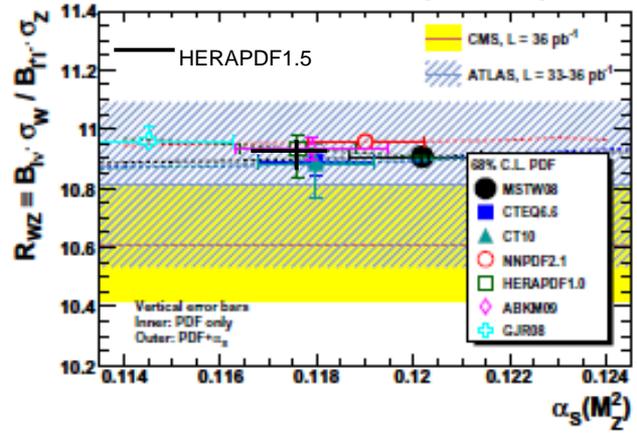
NLO W+/W- ratio at the LHC ( $\sqrt{s} = 7$  TeV)



Are ratios better predicted than the cross-sections?

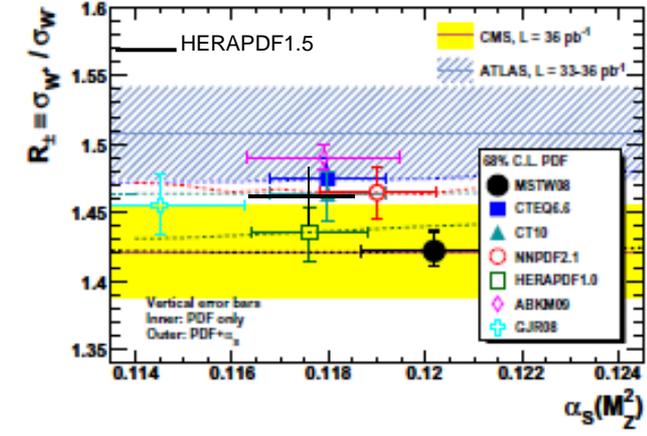
- The W/Z ratio is YES- ~1% spread – this is obvious when you think about the quark flavours which enter
- The W+/W- ratio is still NOT ~>5% and this shows up more strongly in the W and lepton asymmetries- this is a u-valence – d-valence difference in a previously unmeasured region of x

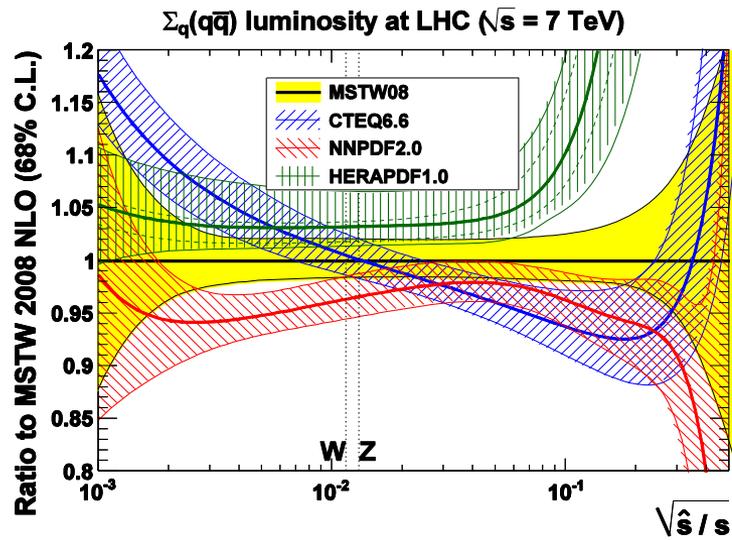
NLO W/Z ratio at the LHC ( $\sqrt{s} = 7$  TeV)



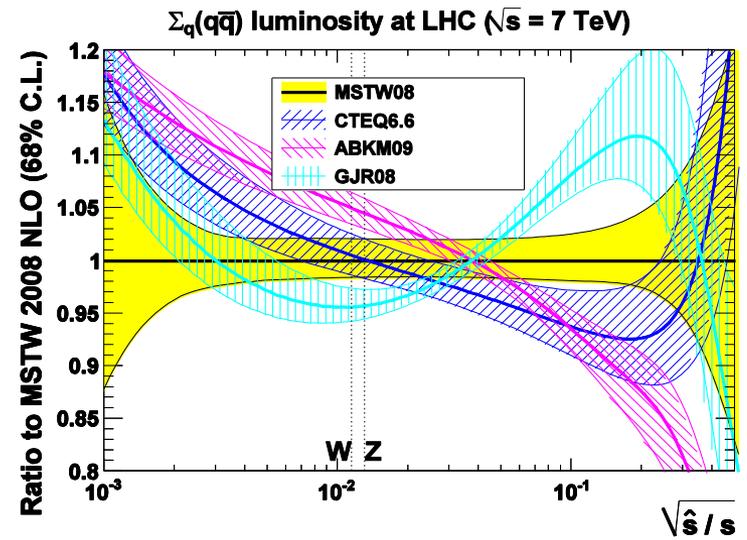
Is there an ATLAS/CMS discrepancy?

NLO W+/W- ratio at the LHC ( $\sqrt{s} = 7$  TeV)

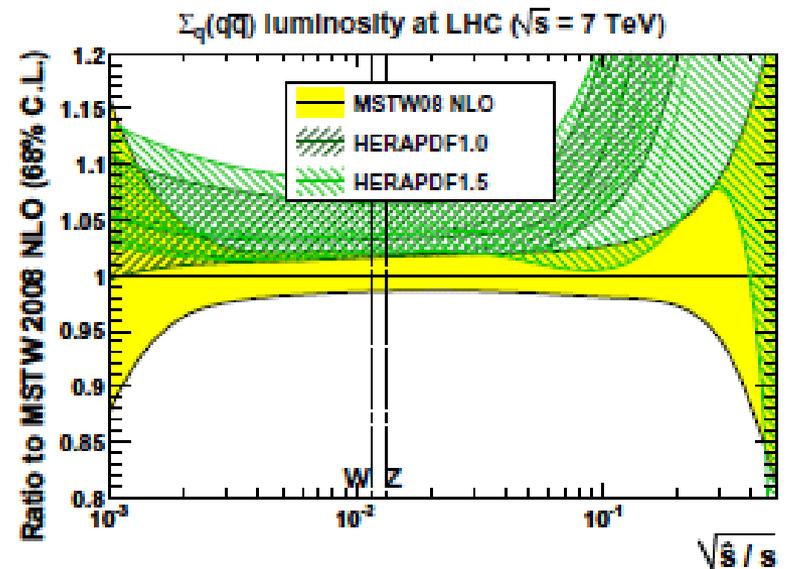
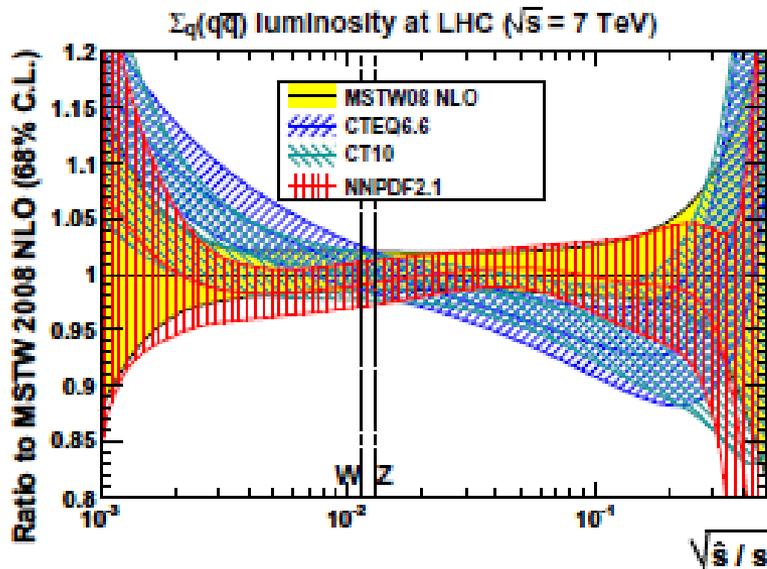




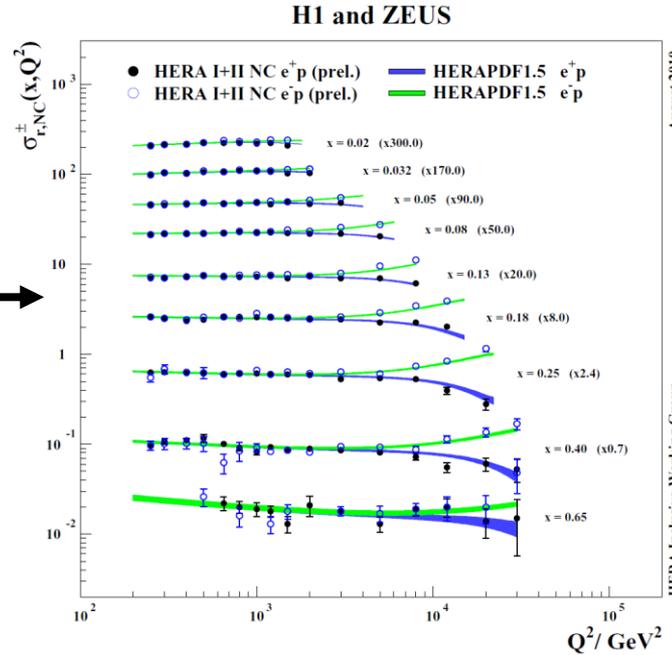
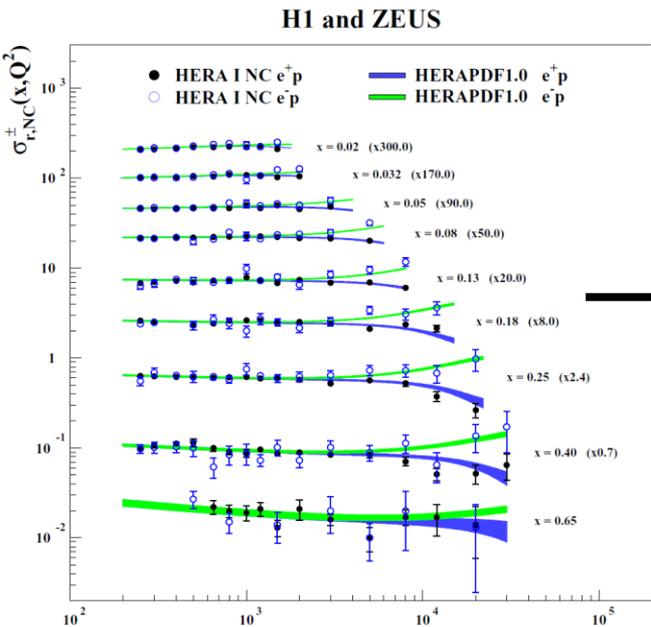
W/Z production depends on q-qbar luminosity



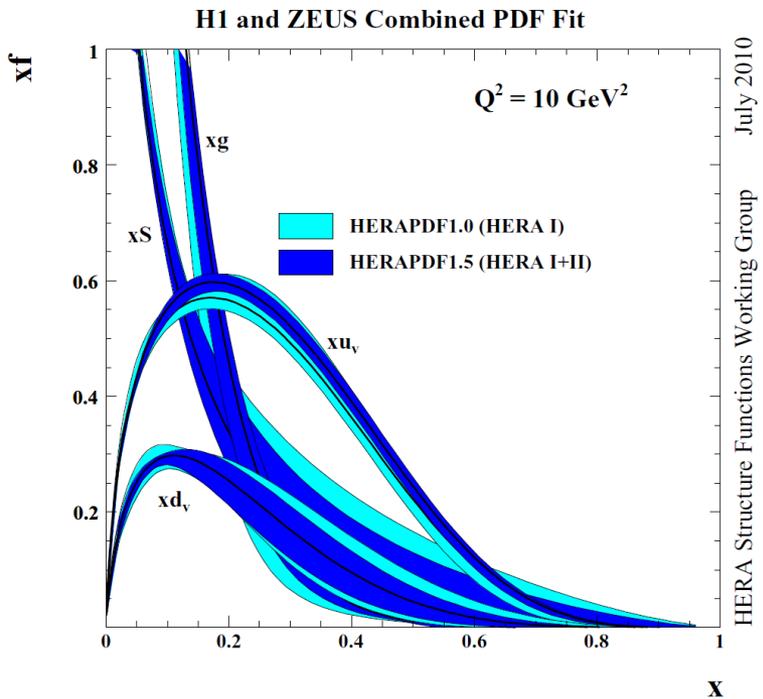
Update with NNPDF2.1, CT10 and with HERAPDF1.5



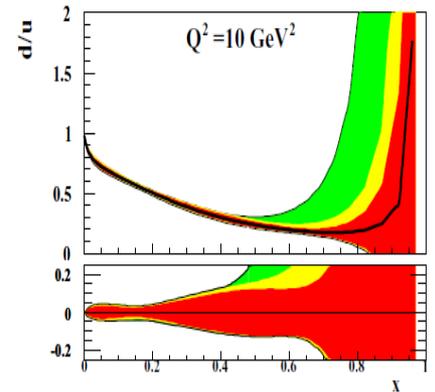
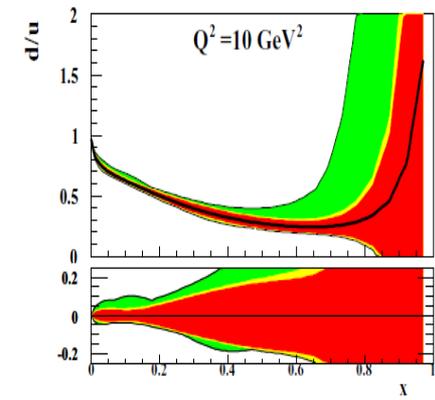
# Features of the updates HERAPDF1.5: update of data AND fit



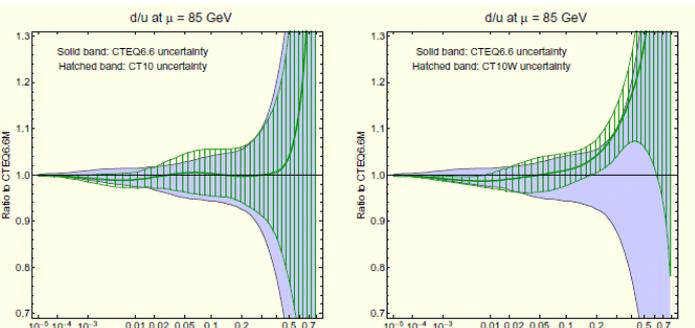
Uses preliminary HERA I+II data combination



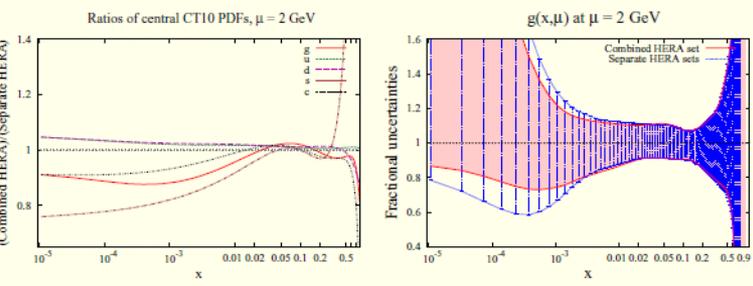
Gives increased precision at high-x



# Features of the updates: CT10



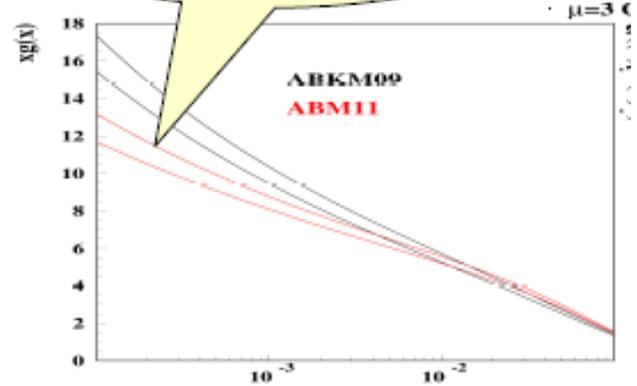
d/u ratio for CT10 and CT10W



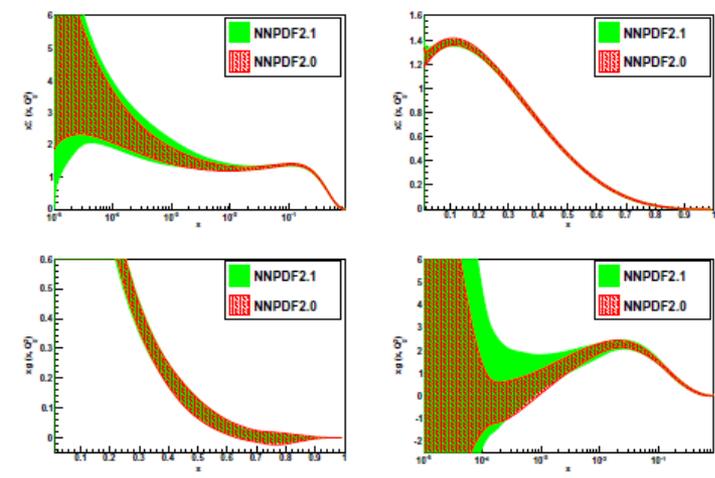
Effect of adding HERA-I combined data

# Features of the updates: ABM11

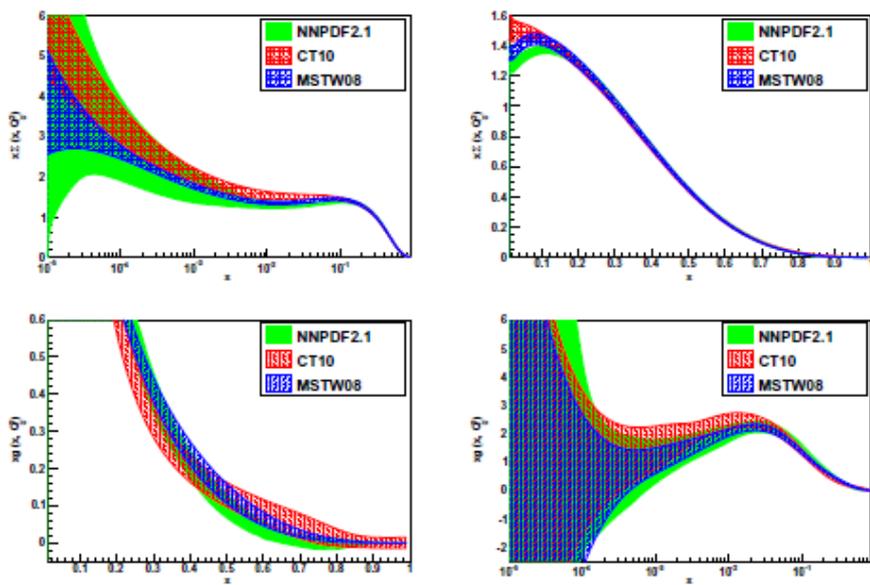
Impact of new inclusive HERA data: normalization and shape



# Features of the updates: NNPDF2.1



Compare NNPDF2.1 and CT10 to MSTW08



# Considering the value of $\alpha_s(M_Z)$ – very important for Higgs

The table shows the values of  $\alpha_s(M_Z)$  used by the PDF groups at **NLO** and at **NNLO** plus the values from more recent studies.

HERAPDF, NNPDF, CTEQ and MSTW all provide PDFs using a **series of  $\alpha_s(M_Z)$  values** which can be used to evaluate  $\alpha_s(M_Z)$  uncertainty.

It is established that PDF and  $\alpha_s(M_Z)$  uncertainty may be combined in quadrature.

NLO	ABKM	CTEQ	GJR	HERA	NNPDF	MSTW
$\alpha_s(M_Z)$ in PDF	0.118	0.118	0.1135	0.1176	0.119	0.120
$\alpha_s(M_Z)$ 2011	↓			0.1202 ±0.0019	0.1191 ±0.0006	
NNLO	0.1135 ±0.0014		0.1124 ± 0.002	0.1176 <del>0.1145</del>		0.1171

There is a split into low and high values at NNLO.

- For JR the low value is required by the dynamical approach.
- For ABKM critics say it is low because Tevatron jets are not included- -  
there is an idea that DIS data prefer lower values of  $\alpha_s(M_Z)$ —see next slide
- However ABM say it is because they use  $\sigma$  rather than F2 in their fits to NMC fixed target data...see slide 20.. and they still get low  $\alpha_s(M_Z)$  even when including jets

There is an idea that DIS data prefer lower values of  $\alpha_s(M_Z)$ .

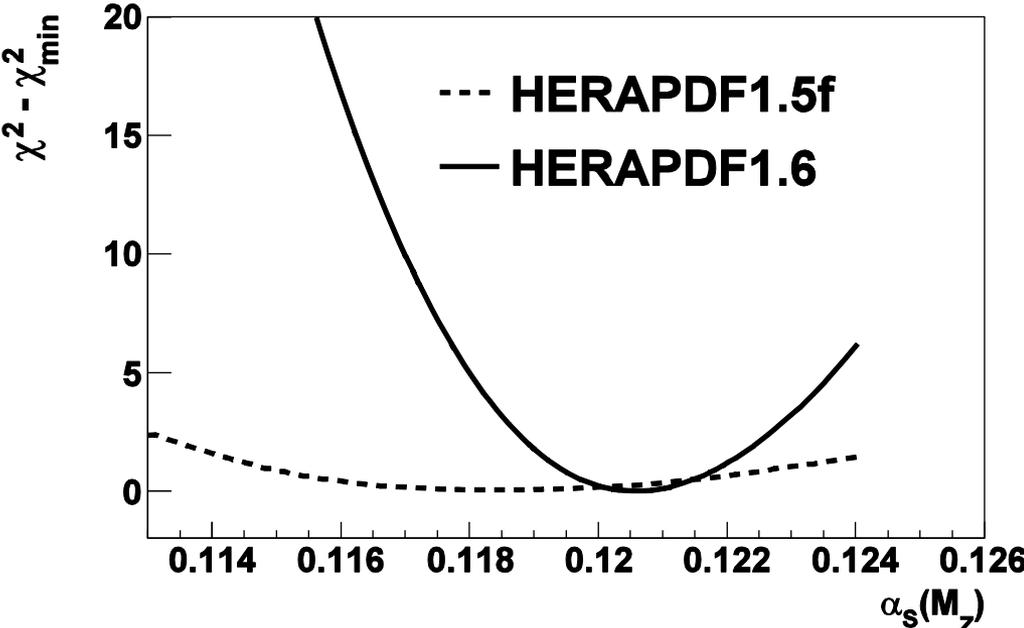
- MSTW challenge this – this is basically only BCDMS, HERA data prefer higher values
- NNPDF say DIS only value is 0.1177 rather than 0.1191
- NNPDF study shows that the variation of  $\chi^2$  for HERA data is very flat.

Now we have heard from HERA themselves.

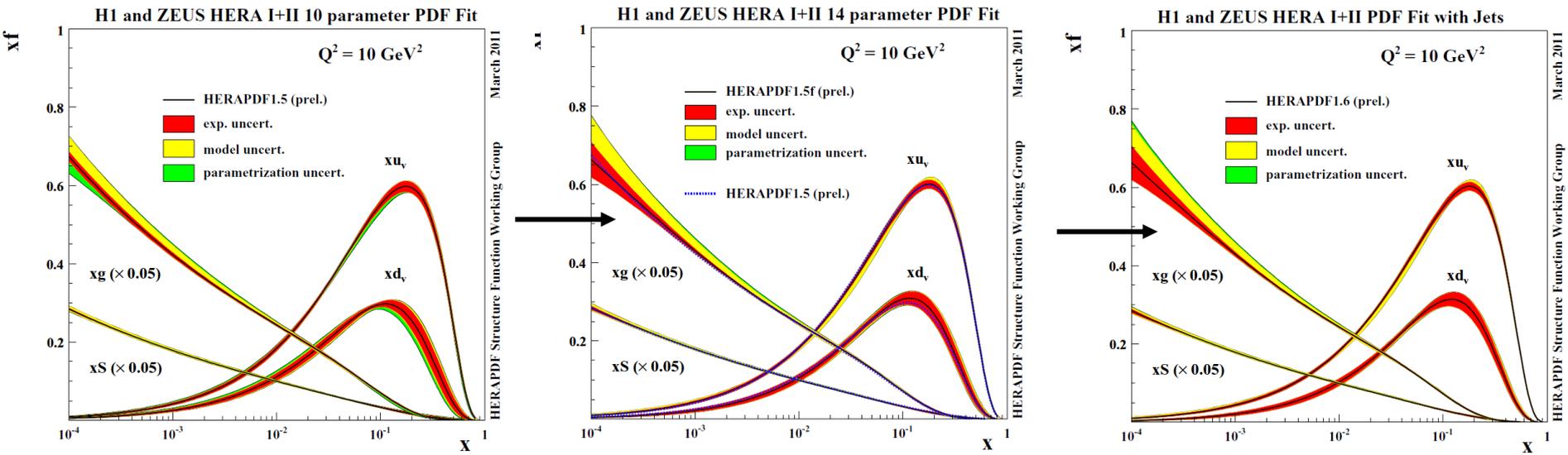
They have used their preliminary HERA I+II data combination and they agree that the  $\chi^2$  dependence on is very flat – and the model dependence is large.

BUT if the DIS jet data are added there is a different story AND alphas is larger  
 $\alpha_s(M_Z) = 0.1202 \pm 0.0019$  (excluding scale error)

$\alpha_s$  scan

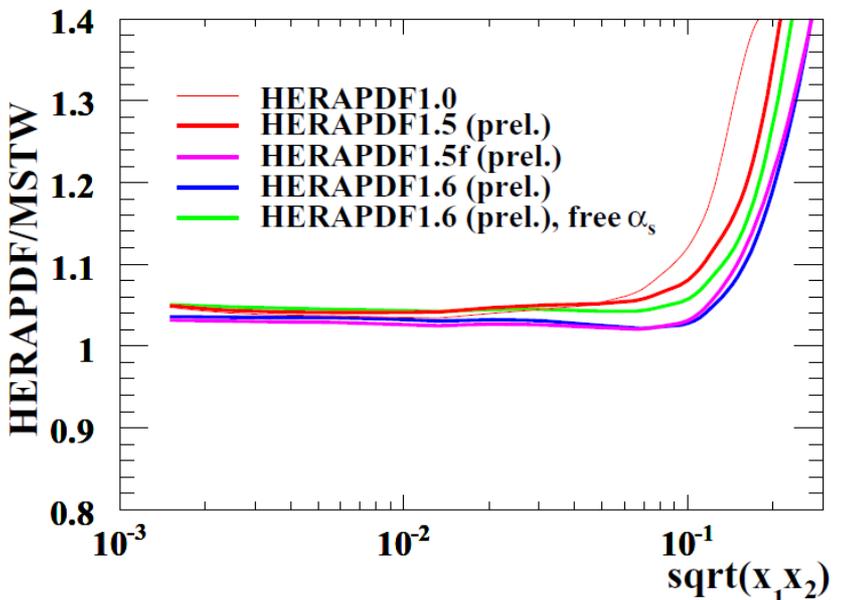
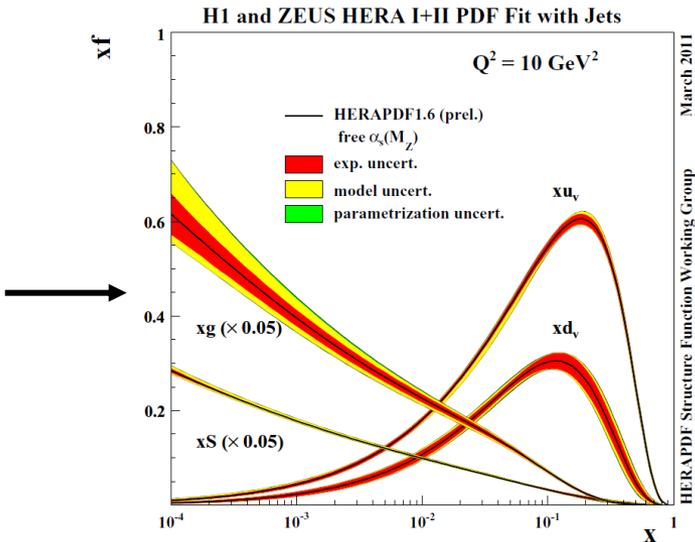


# HERAPDF has updated from their standard parametrisation HERAPDF1.5 to a more flexible parametrisation HERAPDF1.5f and then added jets HERAPDF1.6



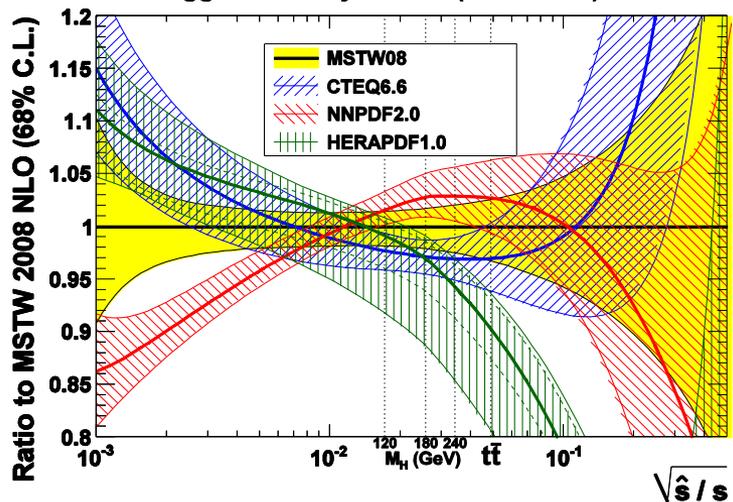
And then freed  $\alpha_s(M_Z)$  – the q-qbar luminosity becomes closer to MSTW

$\alpha_s(M_Z) = 0.1202 \pm 0.0019$



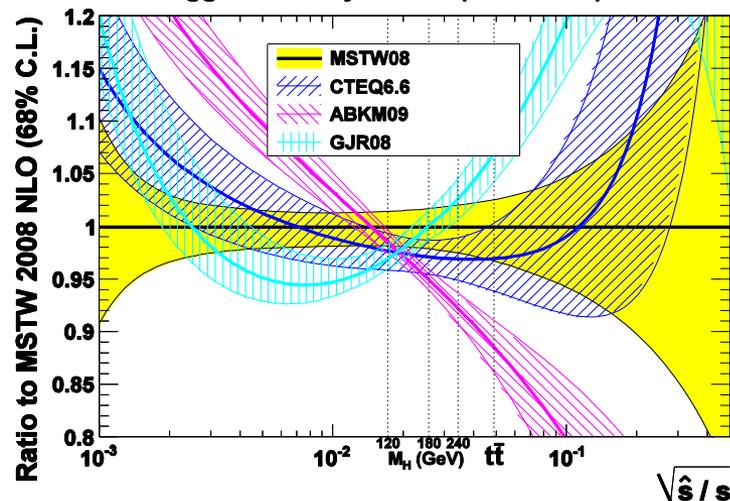
# Gluon-gluon luminosity is important for Higgs production

gg luminosity at LHC ( $\sqrt{s} = 7$  TeV)



g-g luminosity updates

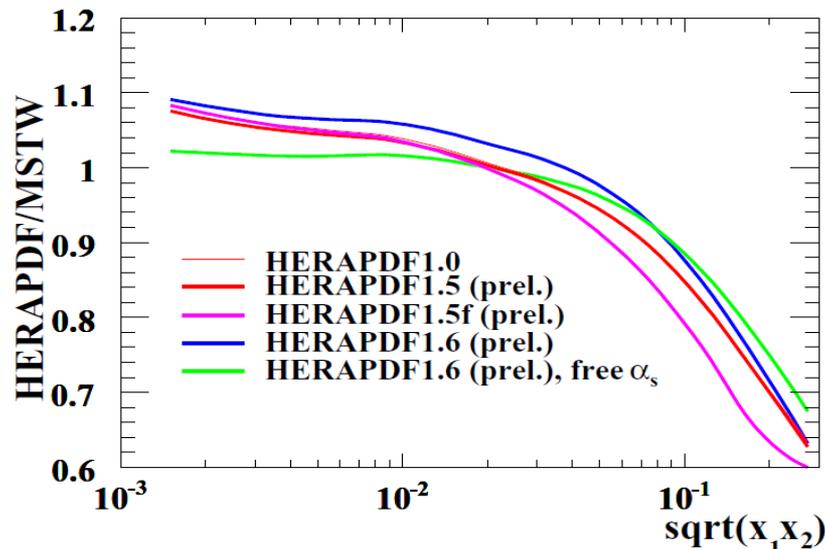
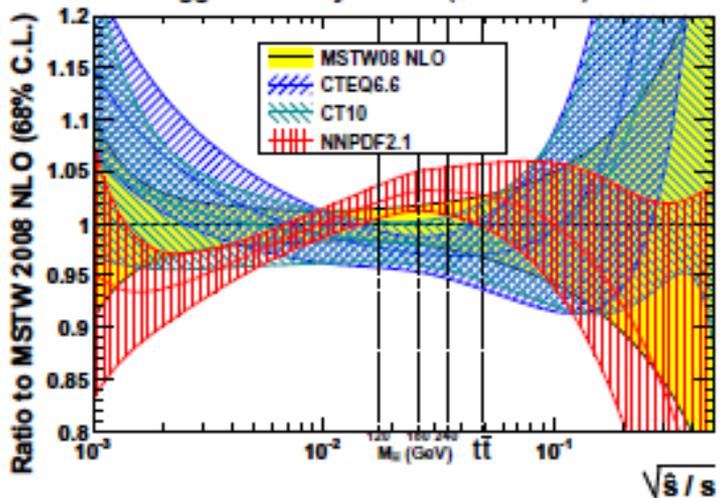
gg luminosity at LHC ( $\sqrt{s} = 7$  TeV)



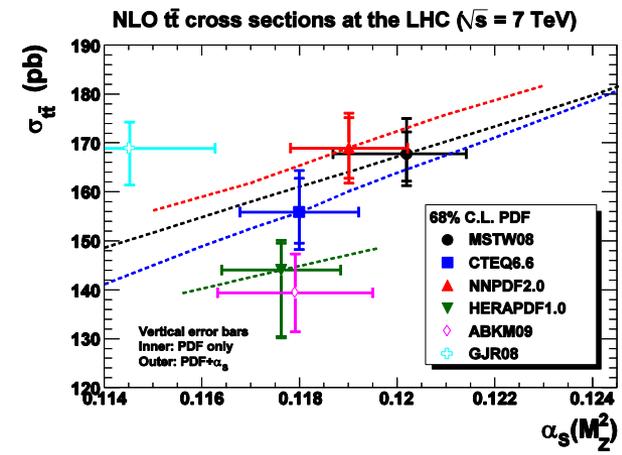
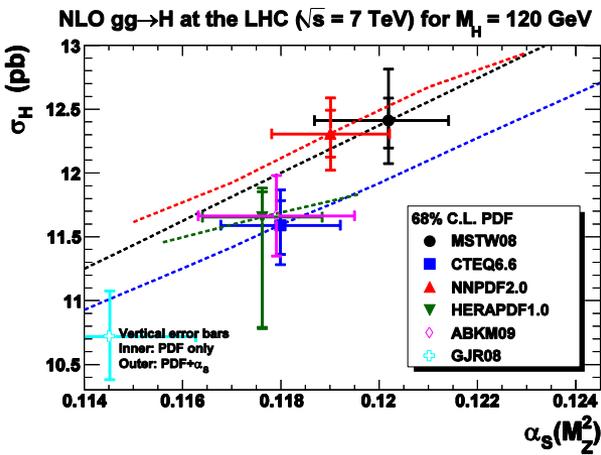
HERAPDF1.6 moves closer to MSTW  
Note how the larger value of  $\alpha_s(M_Z)$  brings better agreement at low scale

CT10 and NNPDF2.1 are both closer to MSTW than CTEQ6.6 and NNPDF2.0

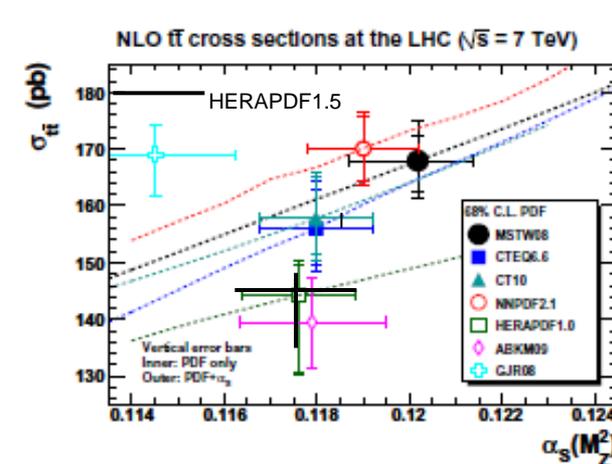
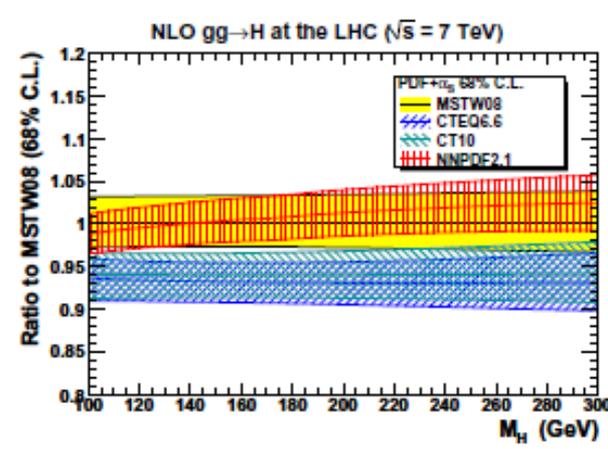
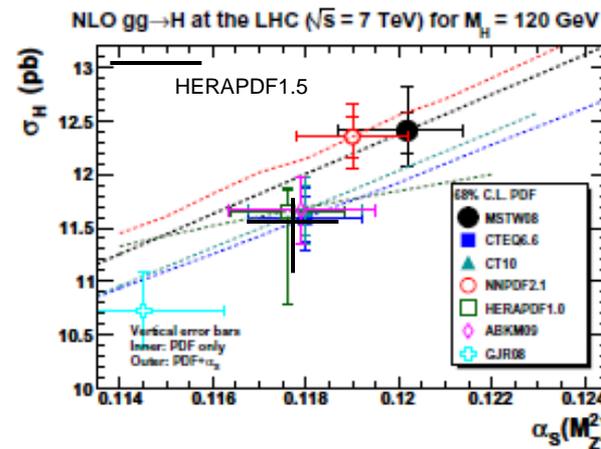
gg luminosity at LHC ( $\sqrt{s} = 7$  TeV)



# Higgs and t-bar cross-sections update

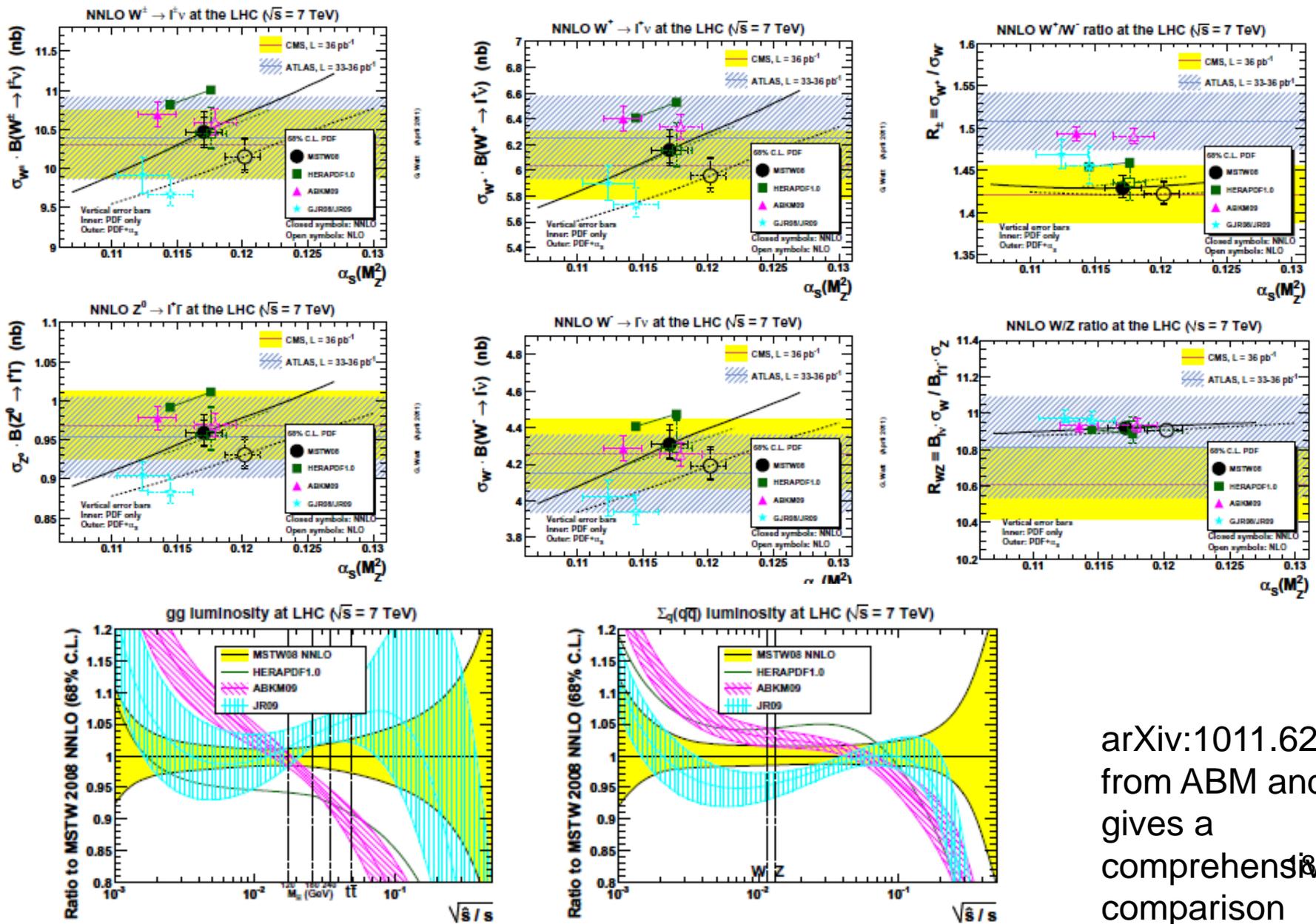


Large spread in cross-sections > 15%. For Higgs there is MSTW/NNPDF(2.0 or 2.1) Vs CTEQ/CT10/HERA/ABKM.  
 Strong dependence on  $\alpha_s(M_Z)$  so use of a common value would help.



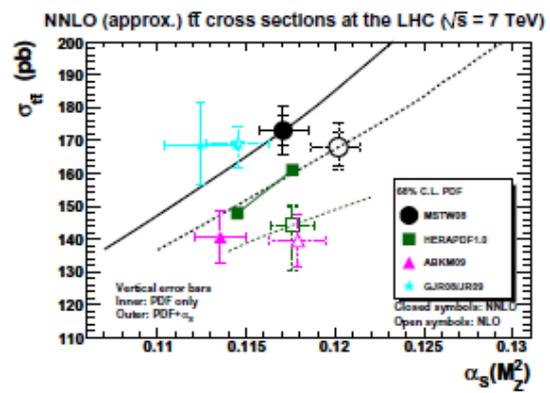
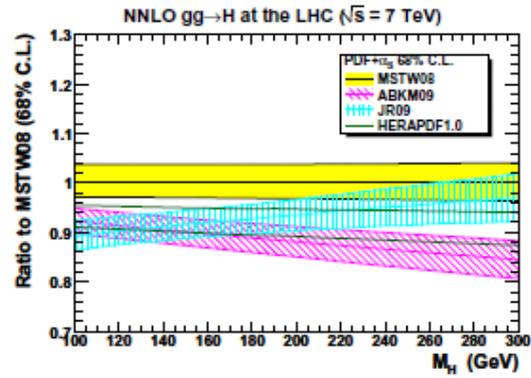
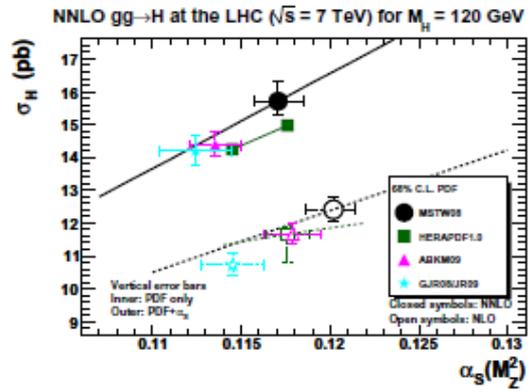
But for Higgs we had better consider NNLO

Until this year there were fewer NNLO PDFs: MSTW, ABKM, JR and HERAPDF1.0 (for two values of  $\alpha_s(M_Z)$  without error band)



arXiv:1011.6259  
 from ABM and JR  
 gives a  
 comprehensive  
 comparison

# NNLO predictions for t-tbar and Higgs



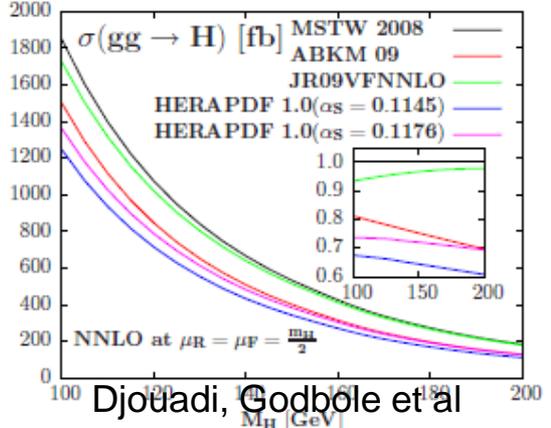
The PDF4LHC recommendation at NNLO is to use the MSTW08 result but increase the errors by ~2 (to reflect the NLO envelope).

However the other NNLO PDF predictions are consistently below those of MSTW- partly due to  $\alpha_s(M_Z)$ . This has been used to challenge the Tevatron Higgs exclusion region

## Why was MSTW08 favoured ?

- Because it is a global fit. Are global fits actually the best?- see criticisms of the use of deuterium target data and NMC F2 ..next slides.

- Because it fits Tevatron jet data well- determining high-x gluon BUT...AB(K)M and HERAPDF also describe Tevatron jet data

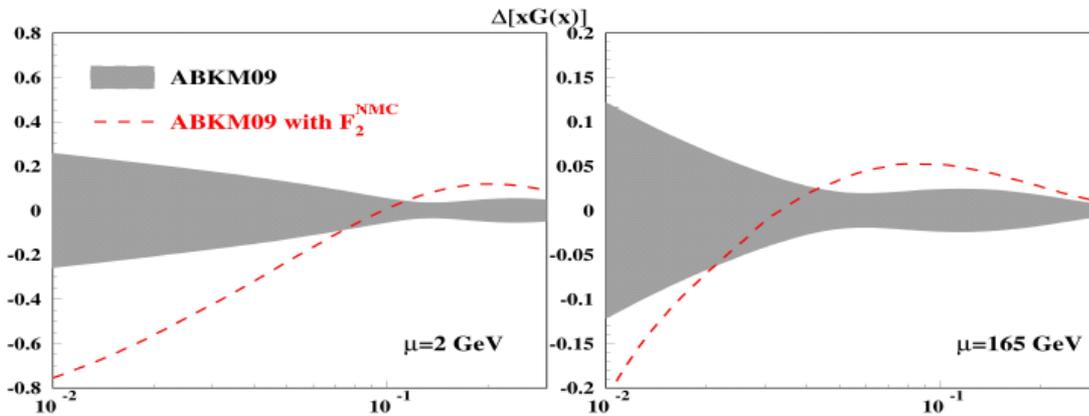
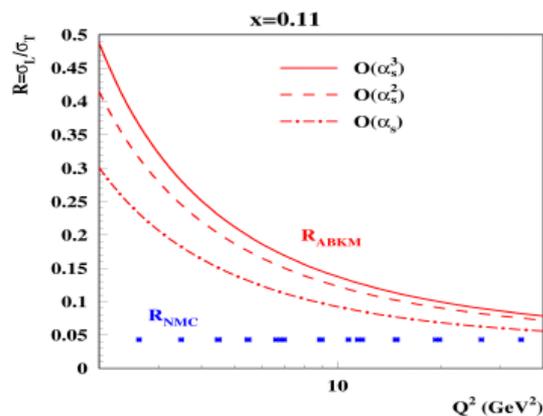


However, the MAIN development of 2011 is more NNLO PDFs

# Criticisms of the use of fixed target data-1

NMC data are usually used as F2. To get this some correction must be made for FL but the corrections made were based on old theory and old prejudices.

ABM find considerable differences in their fits if they use F2 rather than  $\sigma$



But both NNPDF and MSTW say this effect is negligible. However they work with fixed  $\alpha_s(M_Z)$ . ABM have  $\alpha_s(M_Z)$  free in the fit

$\alpha_s(M_Z)$	$\alpha_s(M_Z)$ with $\sigma_{\text{NMC}}$	$\alpha_s(M_Z)$ with $F_2^{\text{NMC}}$
NLO	0.1179(16)	0.1195(17)
NNLO	<b>0.1135(14)</b>	0.1170(15)
NNLO + $F_L$ at $\mathcal{O}(\alpha_s^3)$	0.1122(14)	0.1171(14)

NMC may have an impact on  $\alpha_s(M_Z)$  determinations from PDF fits  
 Only affects LHC Higgs XS if PDG  $\alpha_s(M_Z) = 0.1184 \pm 0.0007$  value not trusted

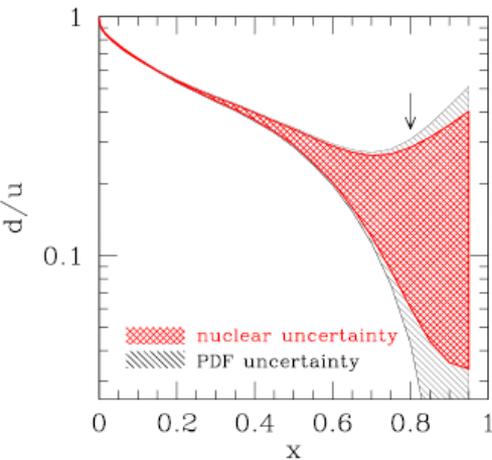
# Criticisms of the use of fixed target data-2

Accardi et al – have been considering corrections for the deuterium targets. They conclude that the uncertainties are larger than is usually accounted for

And of course this uncertainty affects the d-quark.

They also conclude that this can affect the determination of the high-x gluon when Tevatron jet data are fitted at the same time as deuterium fixed target data.

High pt jet production receives contributions from qq, qg and gg. Since the u quark is well known the variation on the d from deuterium corrections is compensated by an anti-correlated shift in the gluon density.



The high-x uncertainty on the d/u ratio due to deuteron wave function and off shell effects as well as PDF uncertainty.

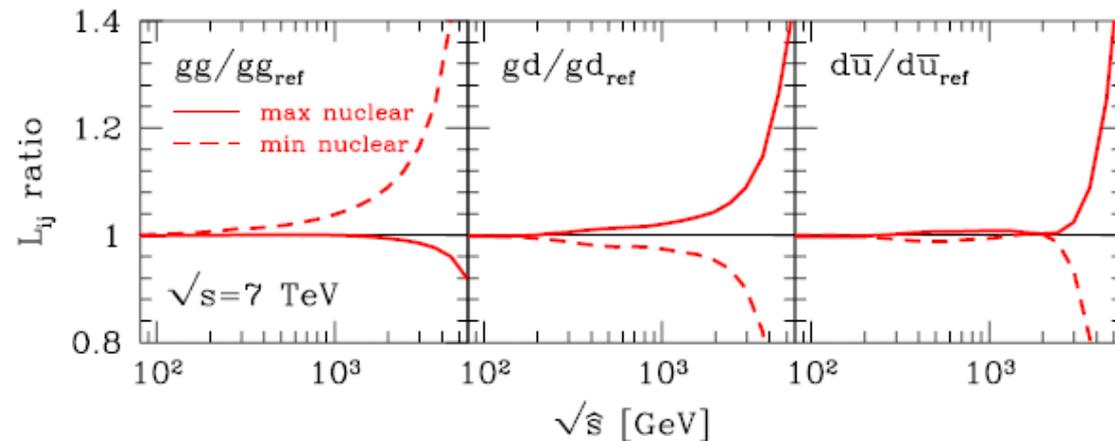
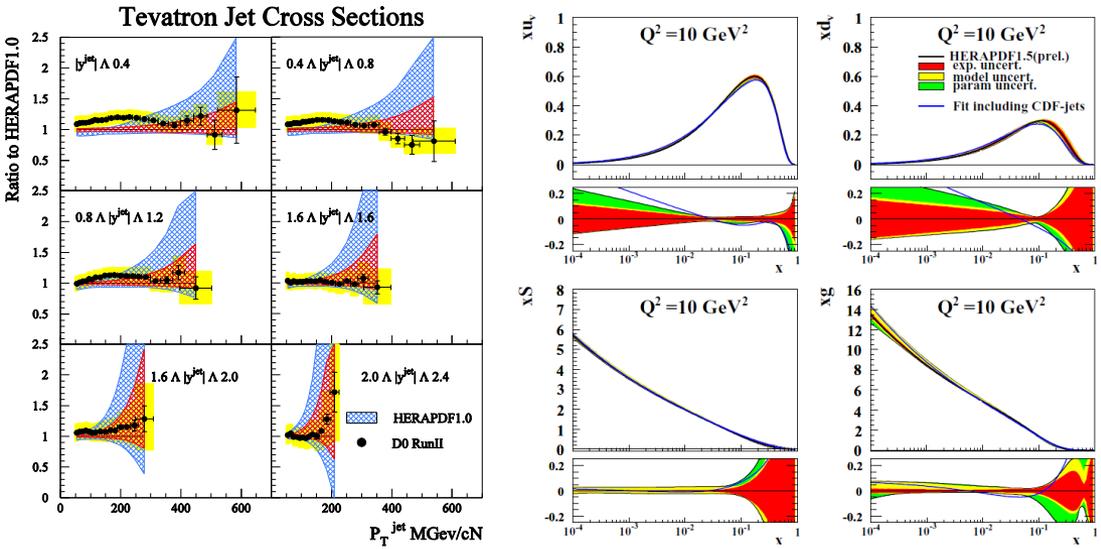


Illustration in terms of parton luminosities for LHC 7 TeV 21

# How well are Tevatron jet data described by non-global fits?



But the real question is how well does an NNLO fit describe these data?

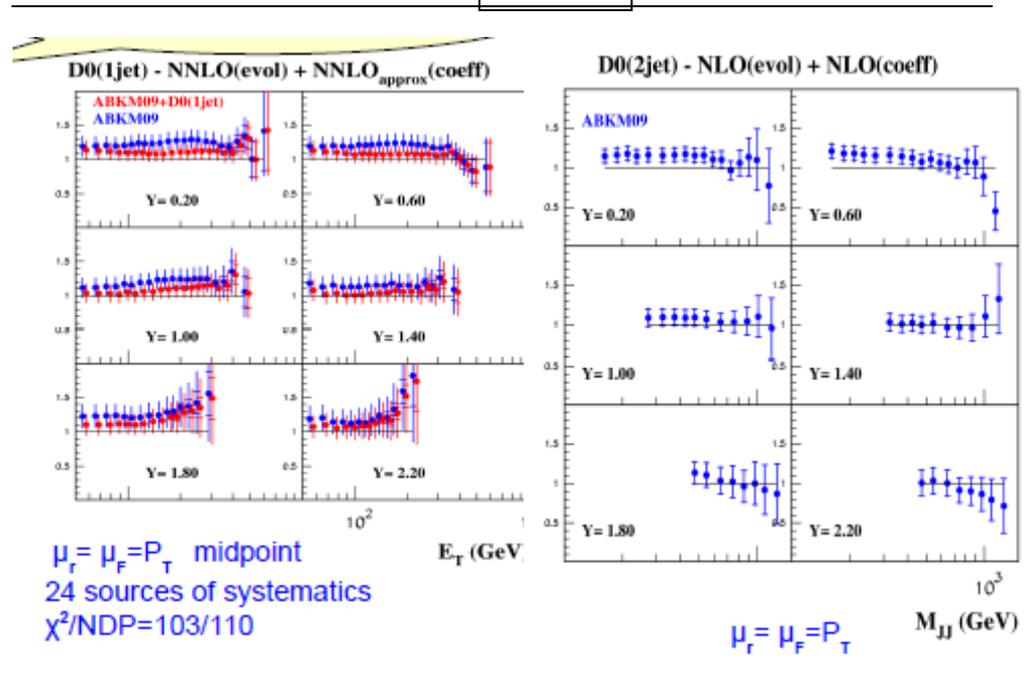
For HERAPDF1.5 NNLO the description is MUCH better  $\chi^2/dp=72/76$  for CDF even for the central PDF

ABM

HERAPDF1.5  $\chi^2/dp = 176/76$  for CDF and  $245/110$  for D0 for the central PDF

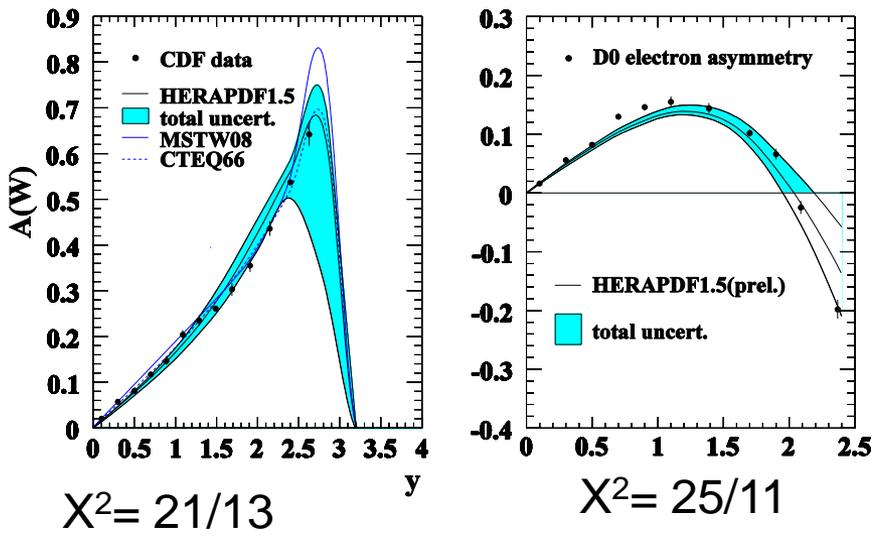
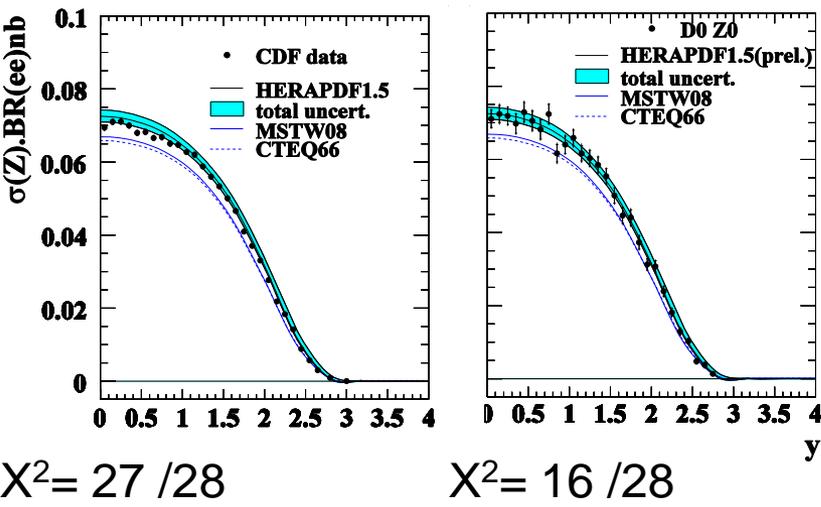
However this ignores the error band of the fit. If these data are included in an NLO fit we get  $\chi^2/dp = 113/76$  and  $157/110$  resp.

The resulting PDF is at the edge of HERAPDF1.5 (68%CL) error bands

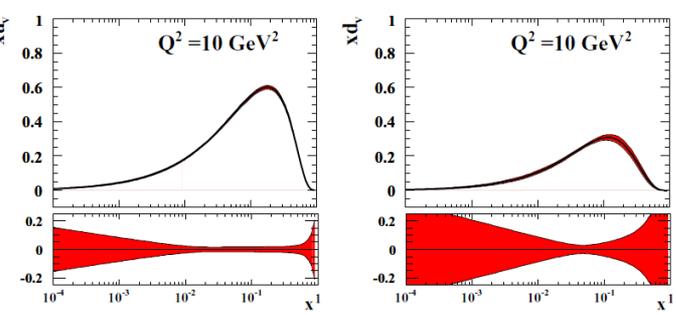


The Higgs cross section can go up by  $\sim 1-2\sigma$

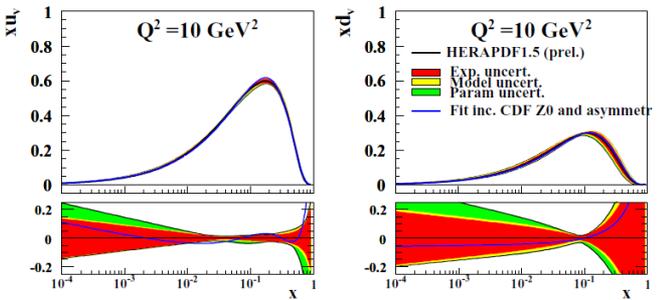
# And how well can HERAPDF describe Tevatron W/Z data?



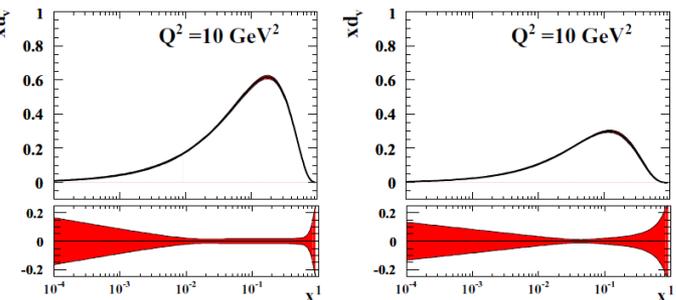
Before fitting Tevatron W/Z data



HERAPDF1.5 central PDF gives a good description of Tevatron W/Z data even before fitting.

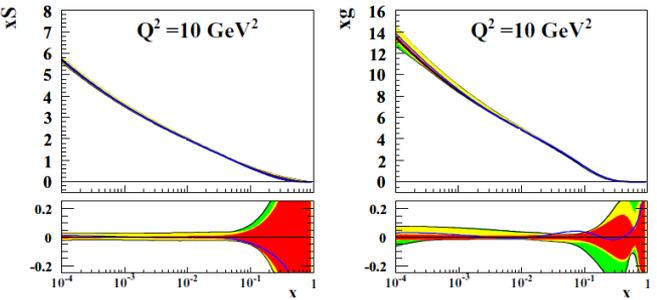


After fitting Tevatron W/Z data

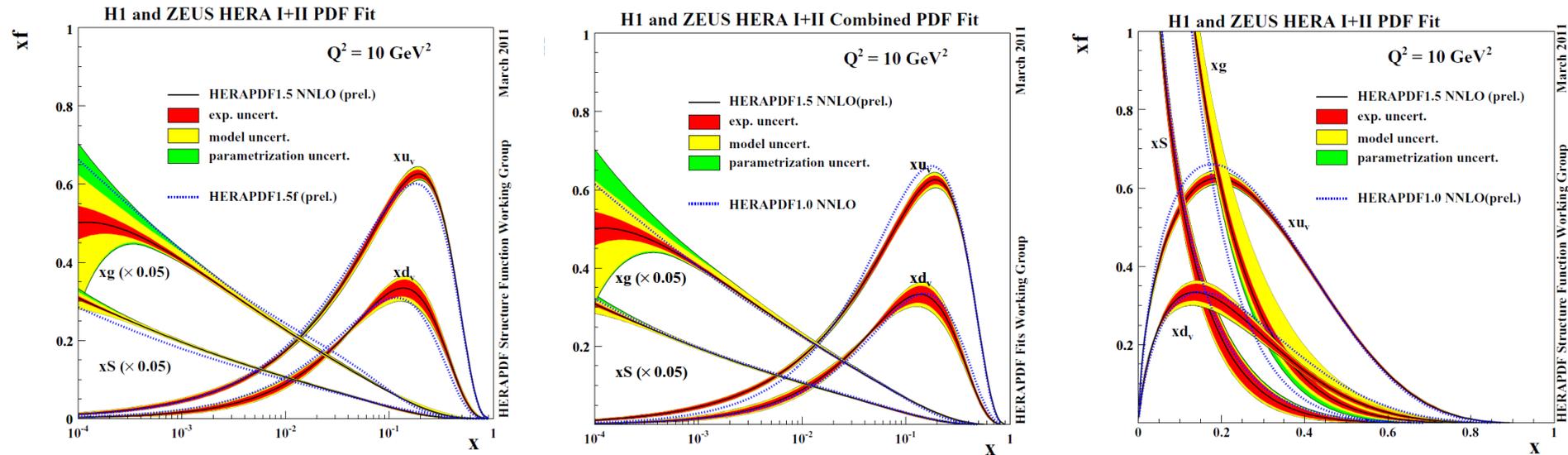


Fitting results in a PDF which is within the error bands.

However PDF uncertainties on the d-valence quark are much reduced.



# The year of NNLO: HERAPDF1.5 NNLO



Same data set as for HERAPDF1.5(f) and use of flexible parametrisation as for 1.5f.

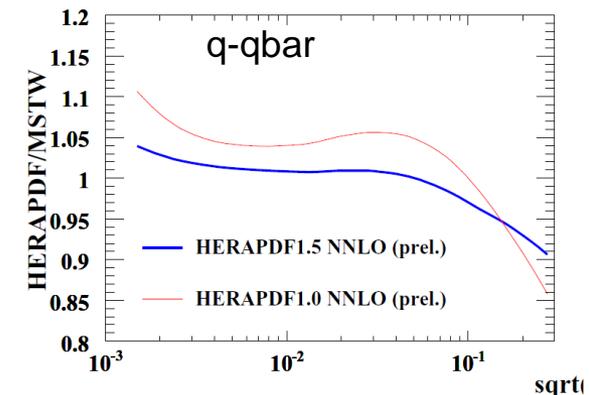
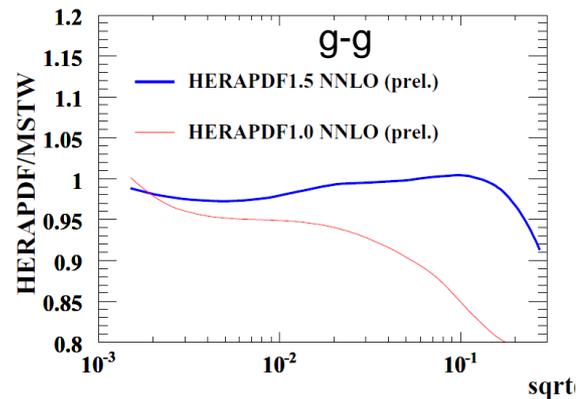
The NNLO PDFs differ from NLO in a similar manner as for MSTW08 (same heavy quark treatment).

The low-x gluon is more uncertain than at NLO - **NNLO DGLAP is NOT a better fit to low-x,  $Q^2$  data.**

HERAPDF1.5 NNLO has a harder high-x gluon than 1.0

Both the g-g and the q-qbar NNLO luminosities of HERAPDF1.5 are closer to MSTW than HERAPDF1.0 hence Higgs predictions also closer

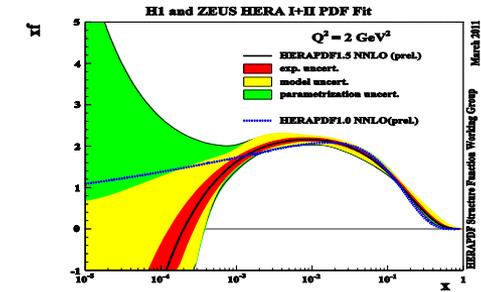
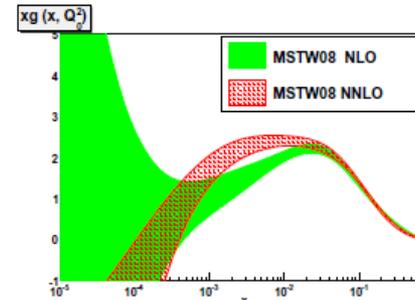
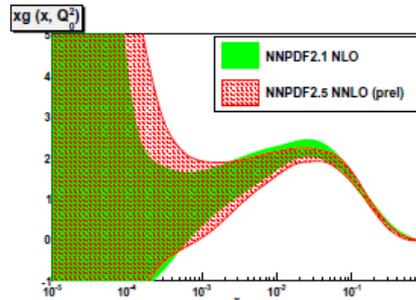
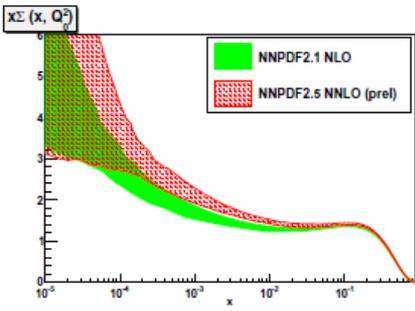
PDFs are available in an  $\alpha_s(M_Z)$  series, but the standard value is 0.1176



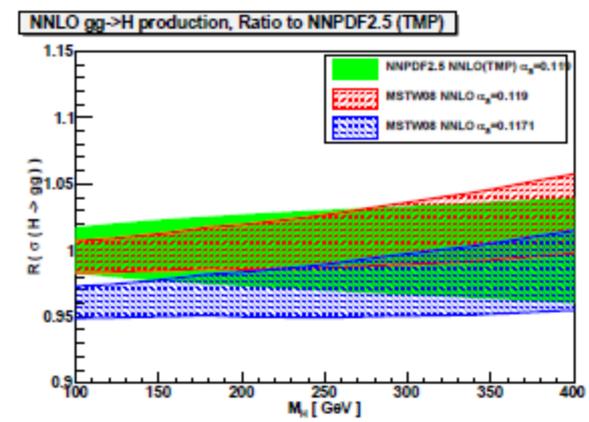
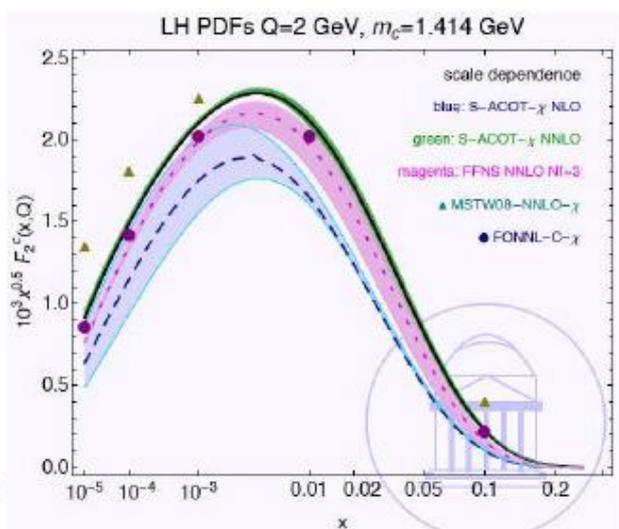
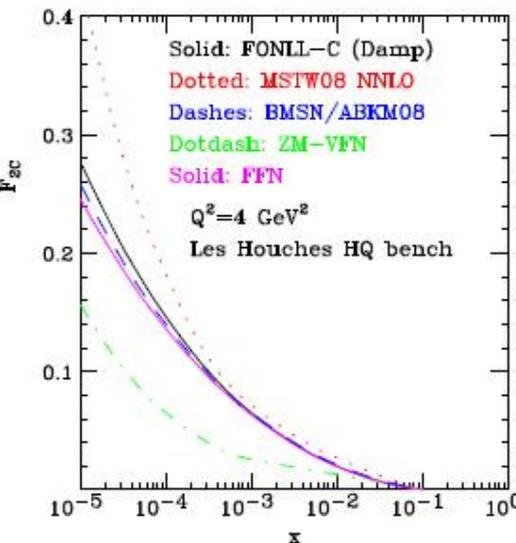
# NNLO -- NNPDF2.5

# Compare MSTW

# Compare HERAPDF1.5



NNPDF use the FONLL scheme to treat heavy quarks in VFN, HERAPDF use Thorne's scheme, ABM and JR use FFN formulations- there are differences between these schemes



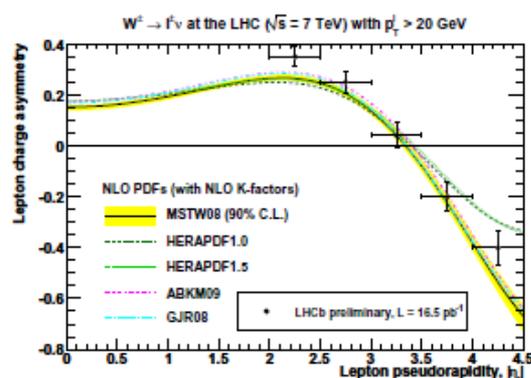
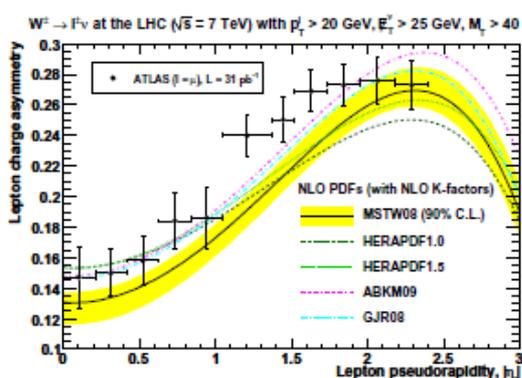
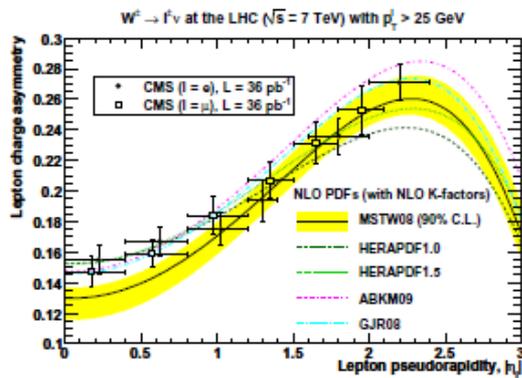
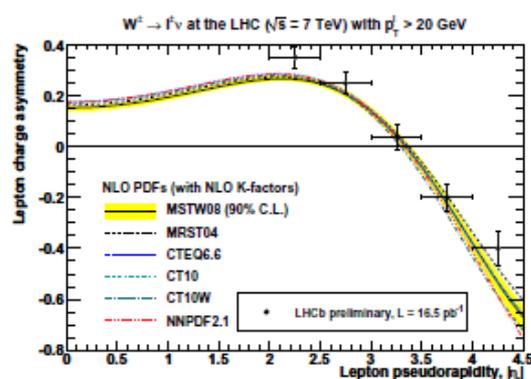
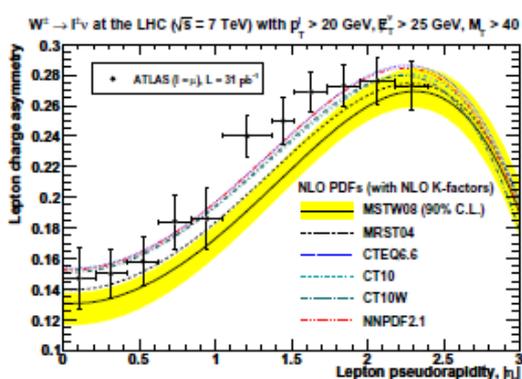
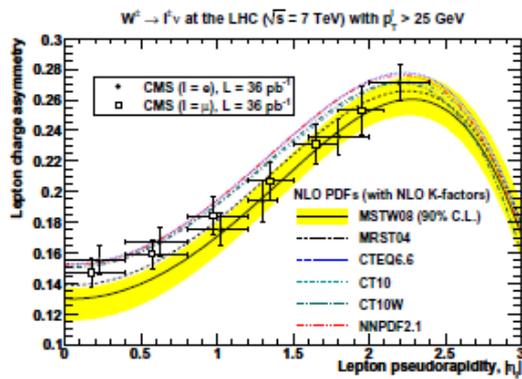
NNPDF2.1 NNLO/MSTW08 agree for the NNLO Higgs at  $\pm 5\%$

Better agreement with common  $\alpha_s(M_Z)$

Crucial to compare results at same  $\alpha_s$

NNLO CT is also nearly ready ..it will use SACOT

And now we have LHC W/Z data- we have already seen the total cross-sections and ratios. Let us look at rapidity distributions both for lepton asymmetry and Z0 production.



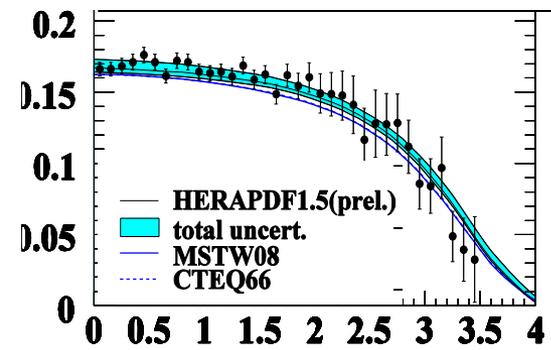
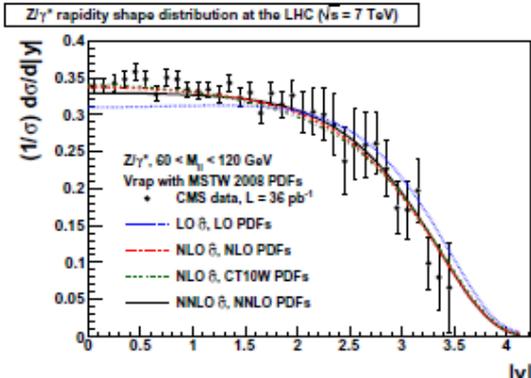
Data: CMS for  $p_T^l > 25$  GeV

Data: ATLAS [arXiv:1103.2929]

Data: LHCb preliminary

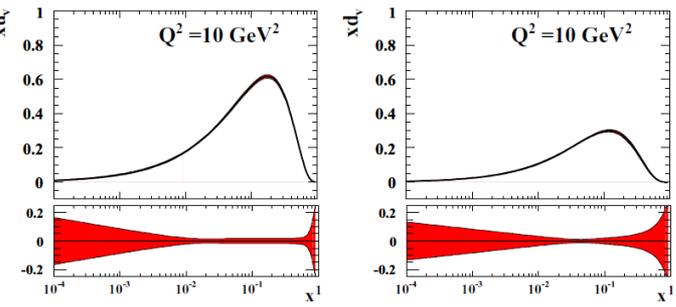
These data are well described by almost all the PDFs

but what improvement if any can they bring if included in the fits?

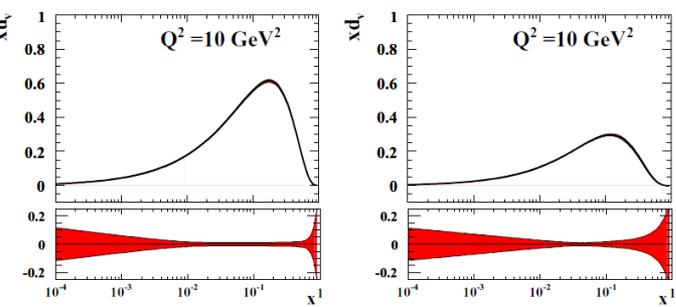


# Improvement in HERAPDFs from adding CMS W-asymmetry by re-fitting

HERAPDF uncertainties after including Tevatron W/Z data

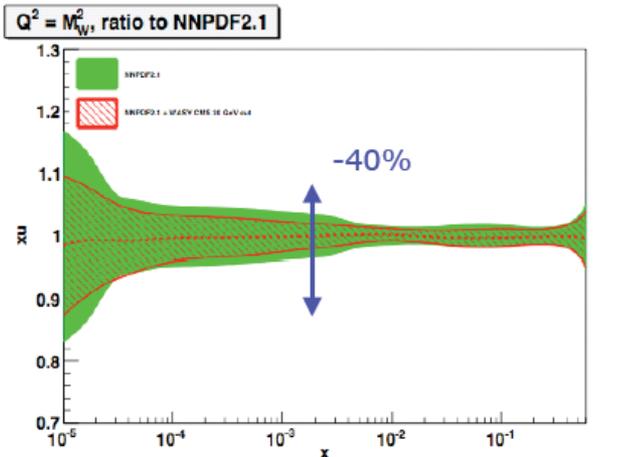
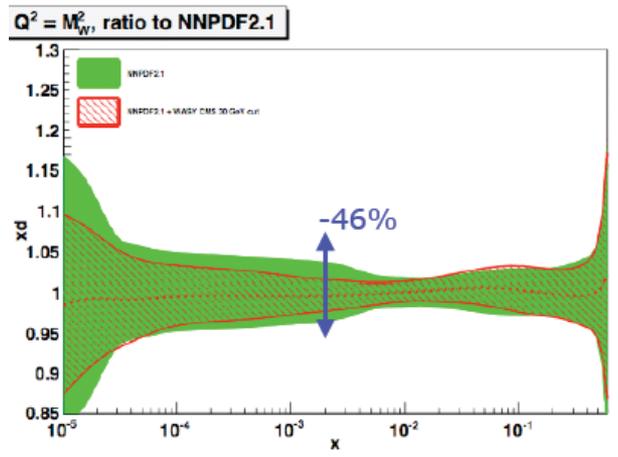


HERAPDF uncertainties after including Tevatron W/Z data + CMS W-asymmetry



Improvement in u and d-valence at low-x

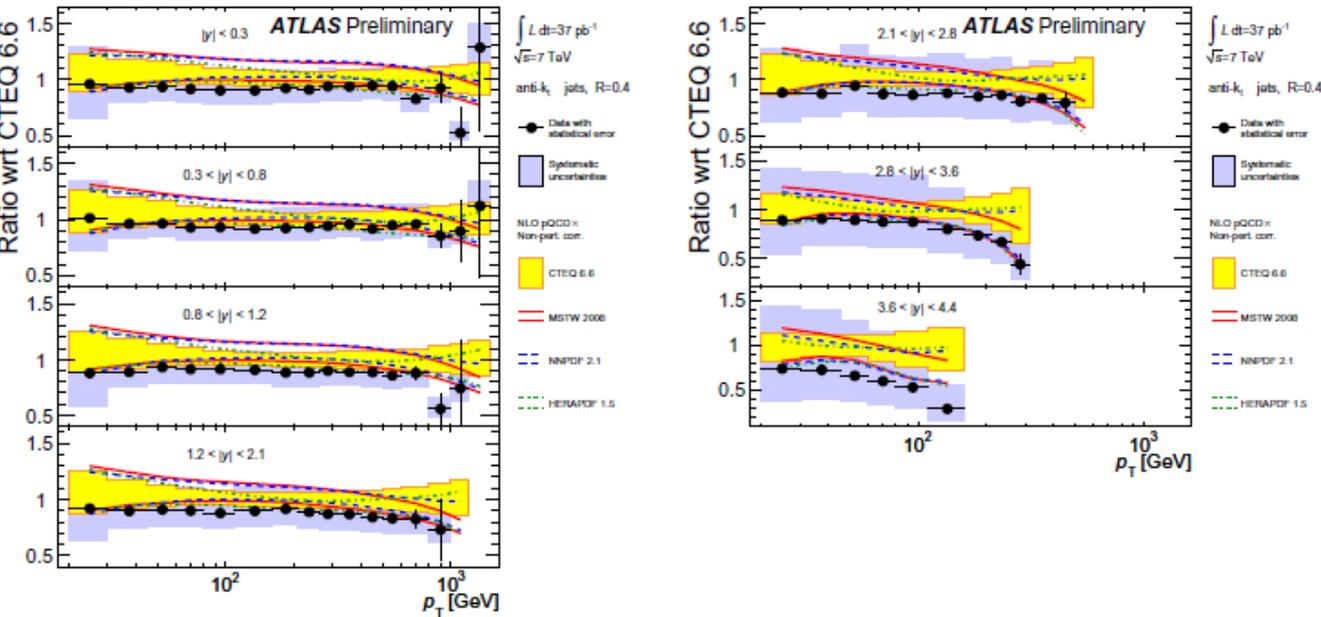
# Improvement in NNPDFs from adding CMS W-asymmetry by reweighting



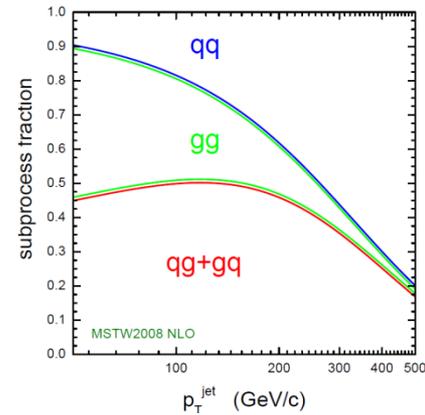
Improvement in u and d at low-x

And how well is LHC jet data described?

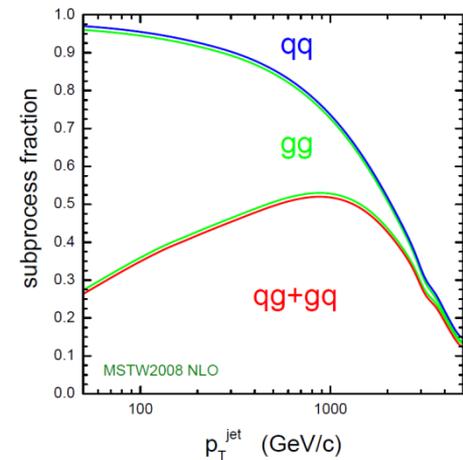
ATLAS jet data



inclusive jet production at Tevatron ( $\eta^{\text{jet}} = 0$ )



inclusive jet production at LHC ( $\eta^{\text{jet}} = 0$ )



Jet data will also soon be discriminating for PDFs

The PDFs that fit the Tevatron jets best are not necessarily those that fit the LHC jets best. The mixture of q-q, q-g, g-g induced jets is different.

HERAPDF1.5 is doing the best job at LHC

# Summary

PDF4LHC comparisons 2010 updated to 2011

Updates: CT10, NNPDF2.1, HERAPDF1.5(6) all NLO and NNPDF2.5, HERAPDF1.5 ABM11 at NNLO

Treatment of heavy quarks: still some differences in GMVFN schemes

NNPDF2.1, HERAPDF, MSTW provide series of  $m_c$ ,  $m_b$  values

ABM uses FFN and running mass

Value of  $\alpha_s(M_Z)$ : NNPDF, HERAPDF, MSTW, CT/CTEQ favour larger values but provide PDFs for a series of  $\alpha_s(M_Z)$  values

ABM/GJR favour a smaller value

Does DIS data like low  $\alpha_s(M_Z)$ ? NO!

Does including Tevatron jet data in ABM fits raise  $\alpha_s(M_Z)$ ? also NO.

The Higgs controversy: is it essential to fit Tevatron jets to make a meaningful prediction? NO- but in fact both ABM and HERAPDF can describe these data well. (Particularly at NNLO)

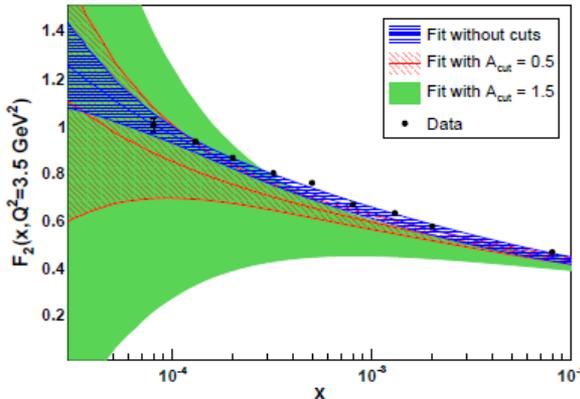
Is it essential to use a global fit? NO and there are doubts about fixed target deuterium corrections and doubts about the use of fixed target F2 data.

BUT HERAPDF1.5 NNLO is much closer to MSTW2008 NNLO than 1.0 AND NNPDF2.5 NNLO is close to MSTW2008 if the same  $\alpha_s(M_Z)$  is used AND ABM11 Higgs cross-section is larger if Tevatron jet data are included: The Tevatron Higgs limits are probably safe.

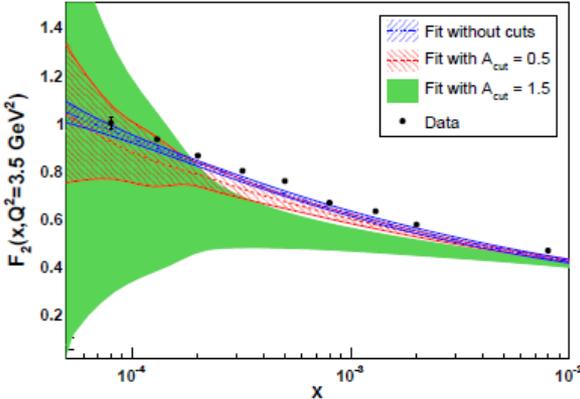
Early LHC W/Z data – have some visible impact on PDFs– (NNPDF, HERAPDF)

extras

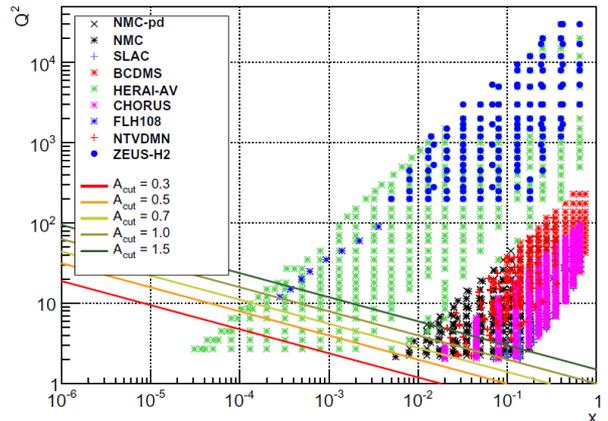
# IS NLO DGLAP applicable for the low-x, Q<sup>2</sup> part of the kinematic plane?



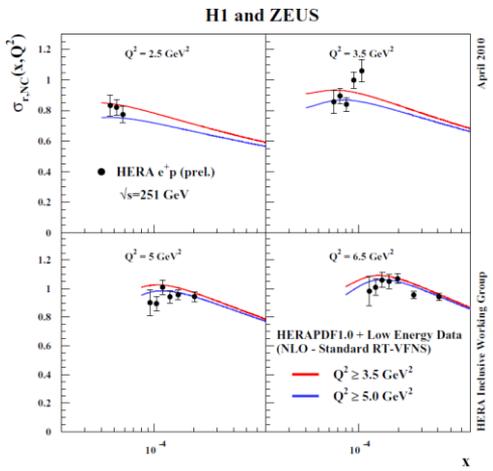
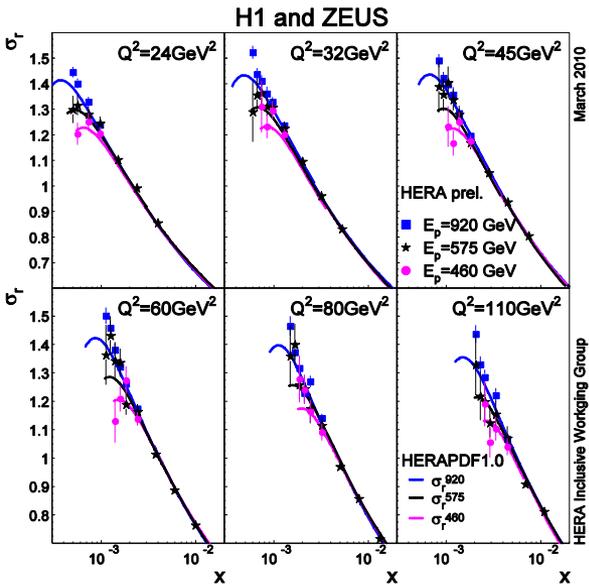
Before combined HERA-I



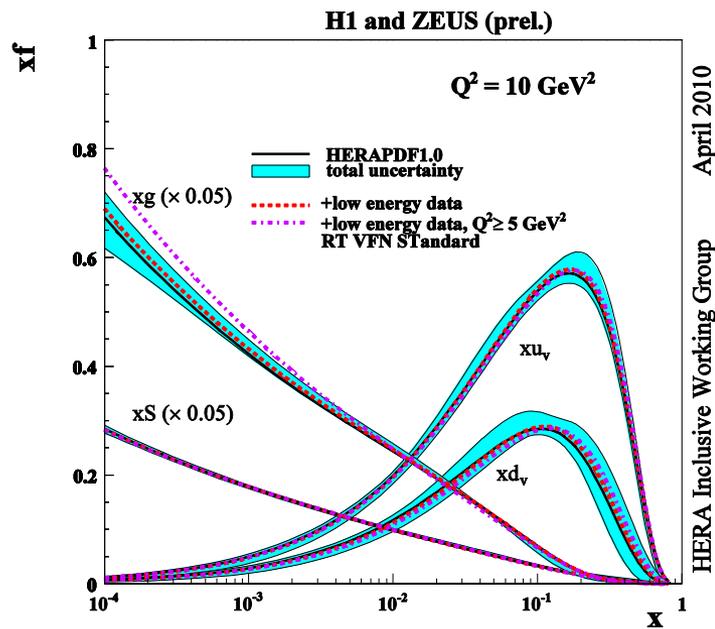
With combined HERA-I



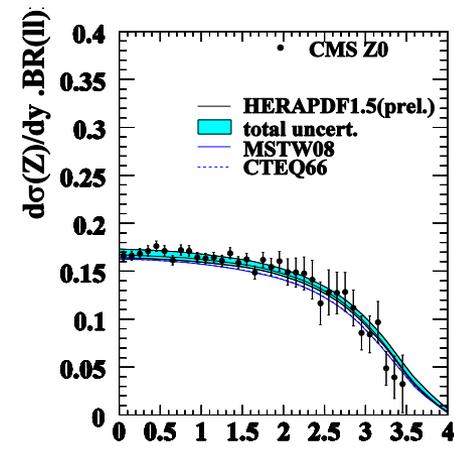
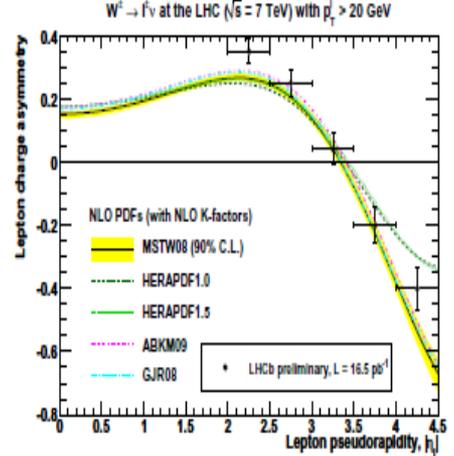
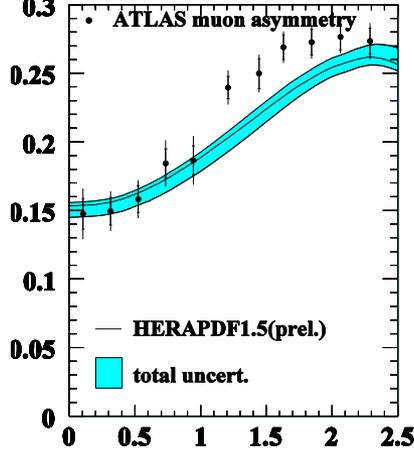
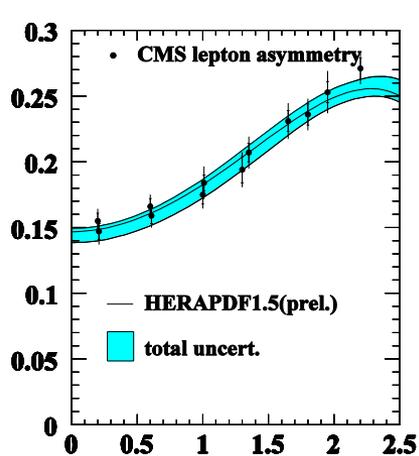
CTEQ say they do not confirm this tension, but when HERA combine their low energy run data the low x, Q<sup>2</sup> part of the data is not so well fit and the **gluon** which results from imposing harder Q<sup>2</sup> cuts or Q<sup>2</sup> > 0.5x<sup>-0.3</sup> cut is **steeper**- this seems NOT to be solved by NNLO



Not much effect at LHC W/Z scale- no sign of unusual behaviour



HERA Inclusive Working Group April 2010



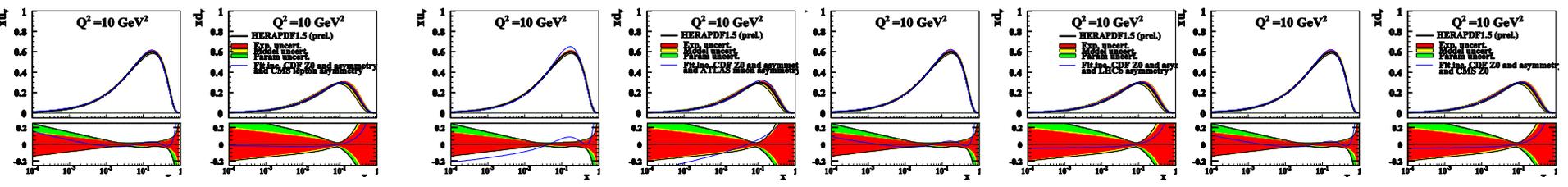
$\chi^2 = 6.5 / 12 \rightarrow 4.5 / 12$

$\chi^2 = 30 / 11 \rightarrow 14 / 11$

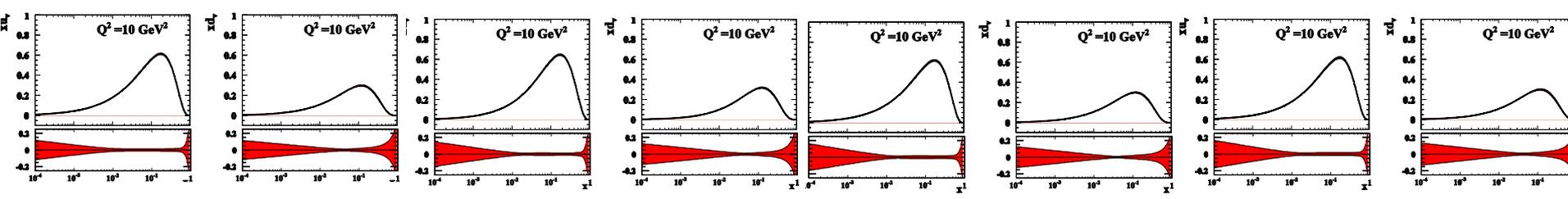
$\chi^2 = 9 / 5 \rightarrow 7.8 / 5$

$\chi^2 = 35 / 35 \rightarrow 16 / 35$

HERAPDF plus Tevatron W/Z plus LHC W/Z fit  $\chi^2$  for the LHC W/Z data



The new fit PDFs do not move (much) outside HERAPDF1.5 error bands



Only the CMS asymmetry data lead to any substantial further improvement in PDF uncertainties