PDFs for the LHC

A M Cooper-Sarkar

Low-x discussion

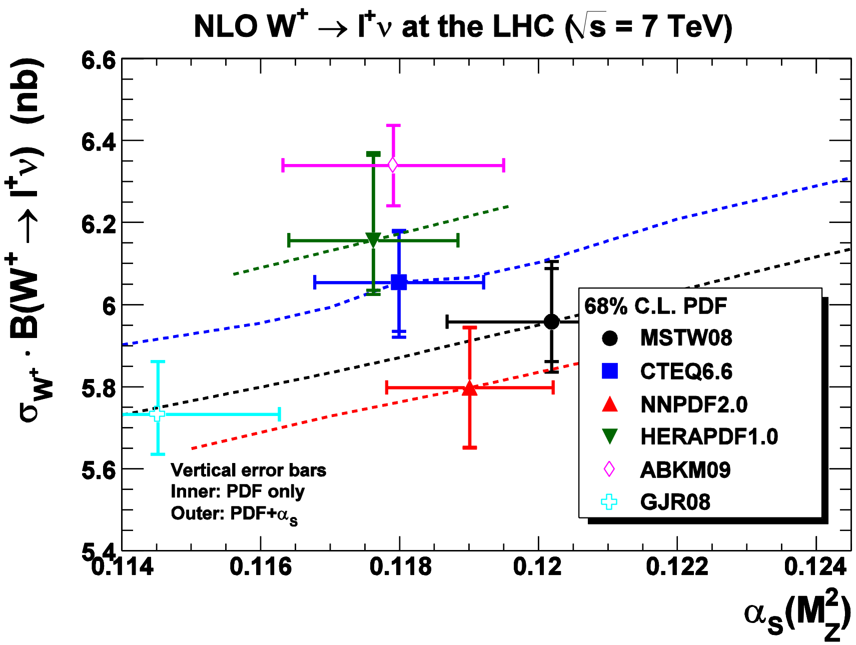
PDF4LHC comparisons 2010 updated to 2011

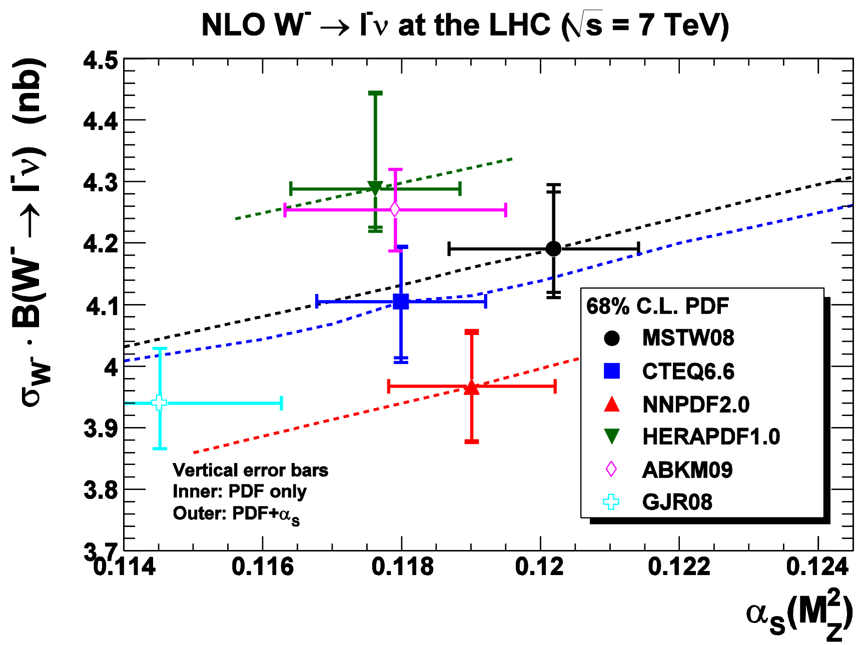
Updates: CT10, NNPDF2.1, HERAPDF1.5, ABM11
Treatment of heavy quarks: NNPDF2.1, HERAPDF, MSTW, ABM
Value of $\alpha_s(M_Z)$: NNPDF, HERAPDF, MSTW, CT/CTEQ
Does DIS data like low $\alpha_s(M_Z)$? --- HERAPDF1.6+jets

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
Doubts about use of the lowest x, Q2 data

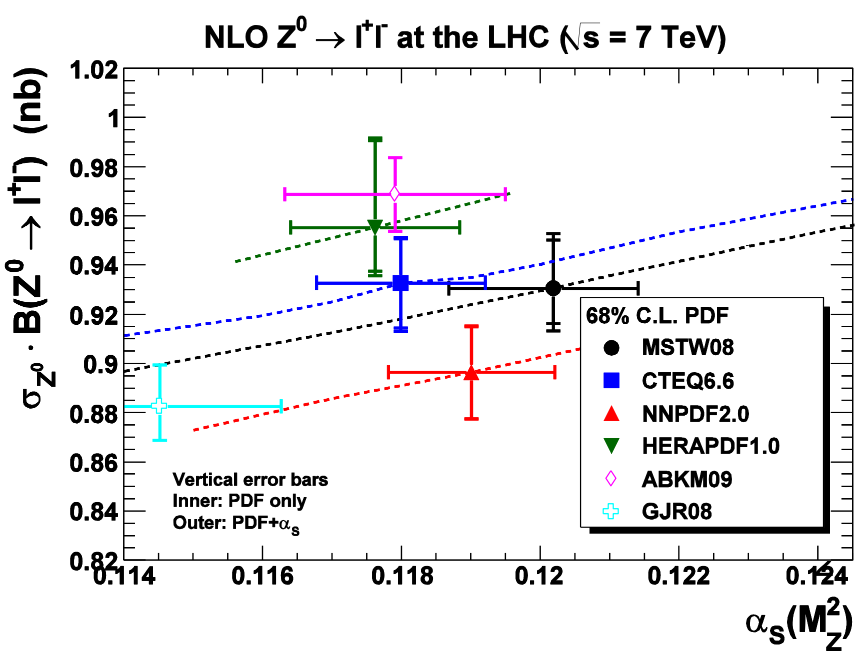
Early LHC W/Z data – some visible impact on PDFs– (NNPDF, HERAPDF)
Early LHC jet data



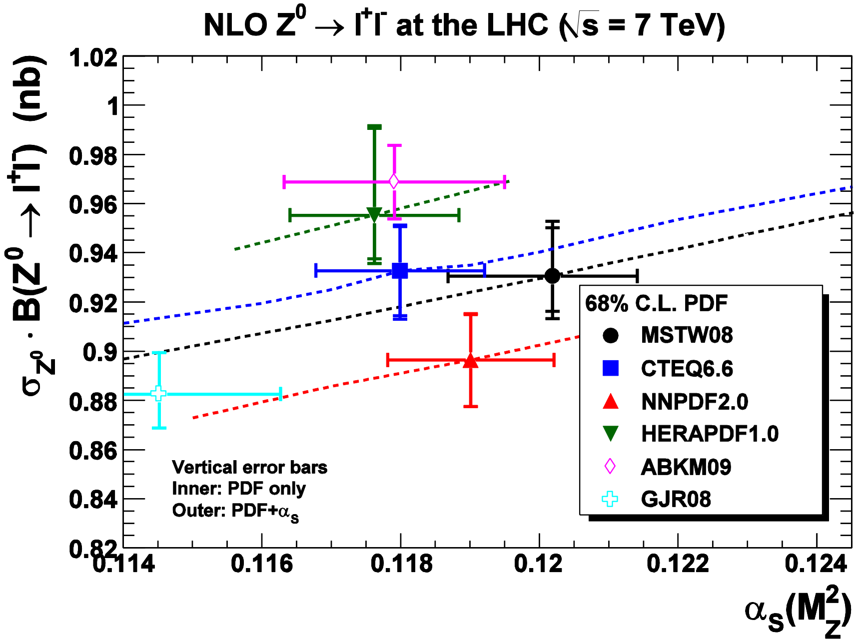


In 2010 the PDF4LHC group considered:
MSTW08 CTEQ66
HERAPDF1.0 NNPDF2.0
ABKM09 GJR08

Plots from G.Watt – 68%CL



Overall disagreement ~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!



Why these disagreements?

Firstly groups use different values of $\alpha_S(M_Z)$, the effect of this can been 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 ~2.5%
HERAPDF,NNPDF,MSTW provide PDFs at different mc values

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 ~2.5% upward shift of the HERAPDF prediction.
CT, NNPDF, ABM update to include these data

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 scheme and charm mass

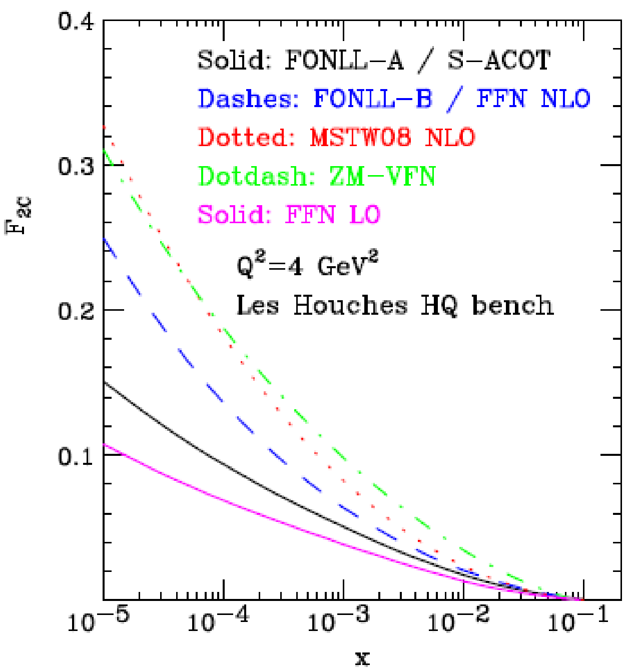
Heavy quark production.: there are two extremes-

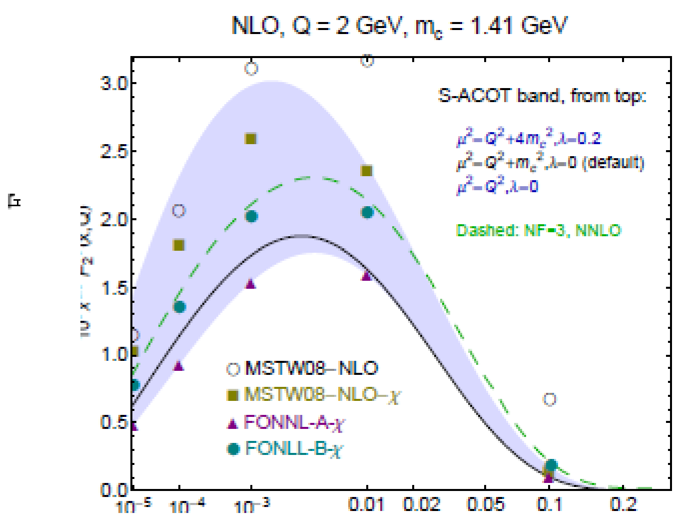
Use only 3 massless parton flavours and calculate exact ME's for heavy quark production (FFN method)- wrong at high scale since $\ln(Q^2/m_c^2)$ terms not resummed

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..

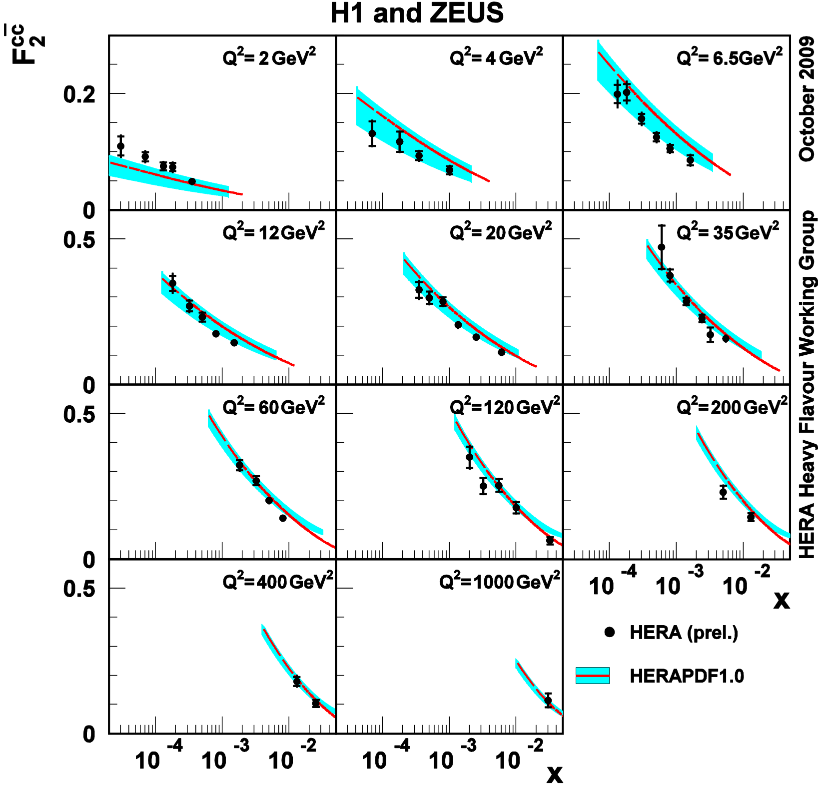
BUT there are different ways to do this...ACOT, Thorne, FO-NLL and there are tunable scale choices

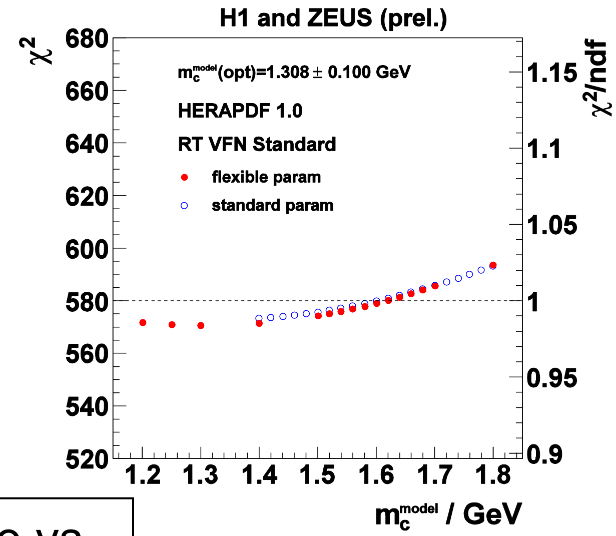




NNLO differences are not so large...

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





X2 profile vs charm mass

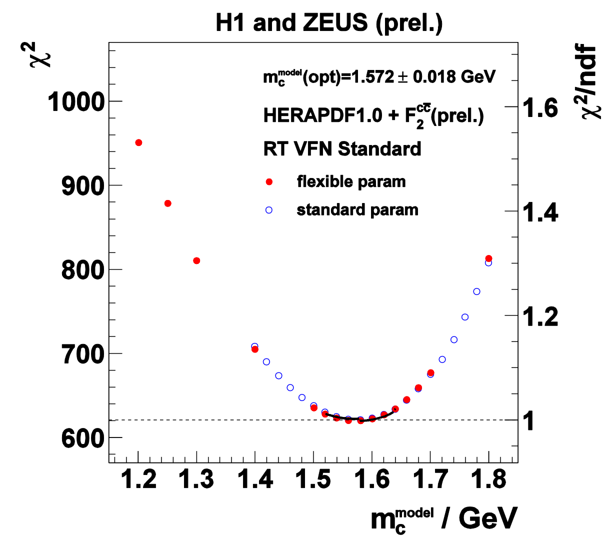
Without charm

H1 and ZEUS have also combined charm data recently

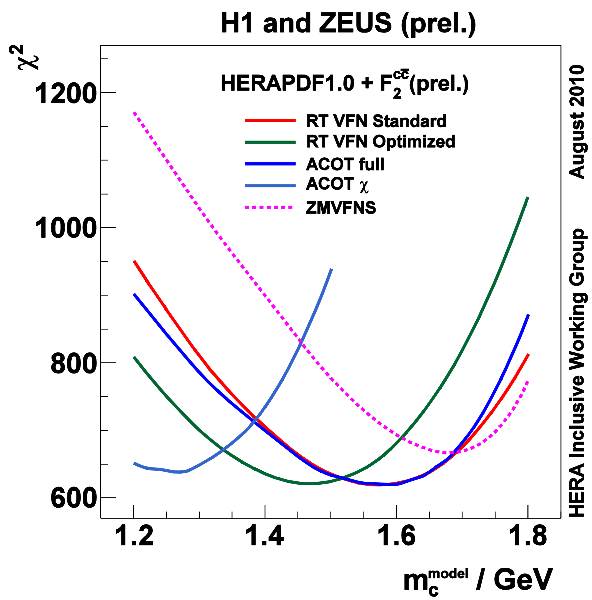
And these data show a preference for a charm mass

m_c = 1.57 ± 0.02 GeV

IF the standard Thorne VFN is used



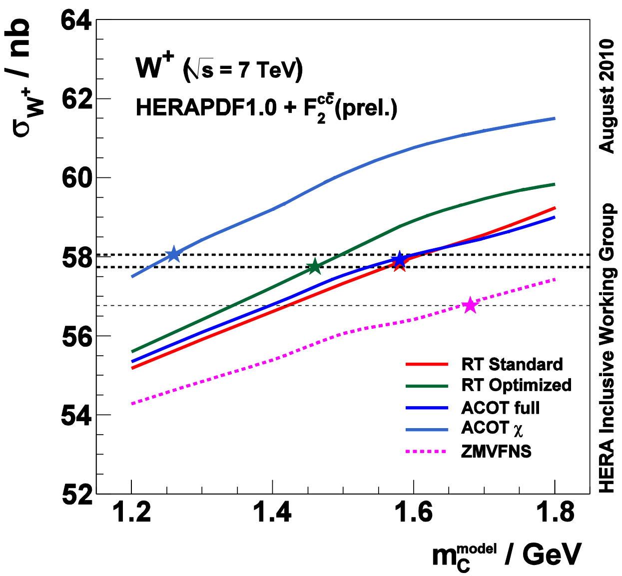
With charm



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 mc is used then the spread is considerable (~7%)- but if each prediction is taken at its own optimal mass value the spread is dramatically reduced (~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 mc, mb values

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

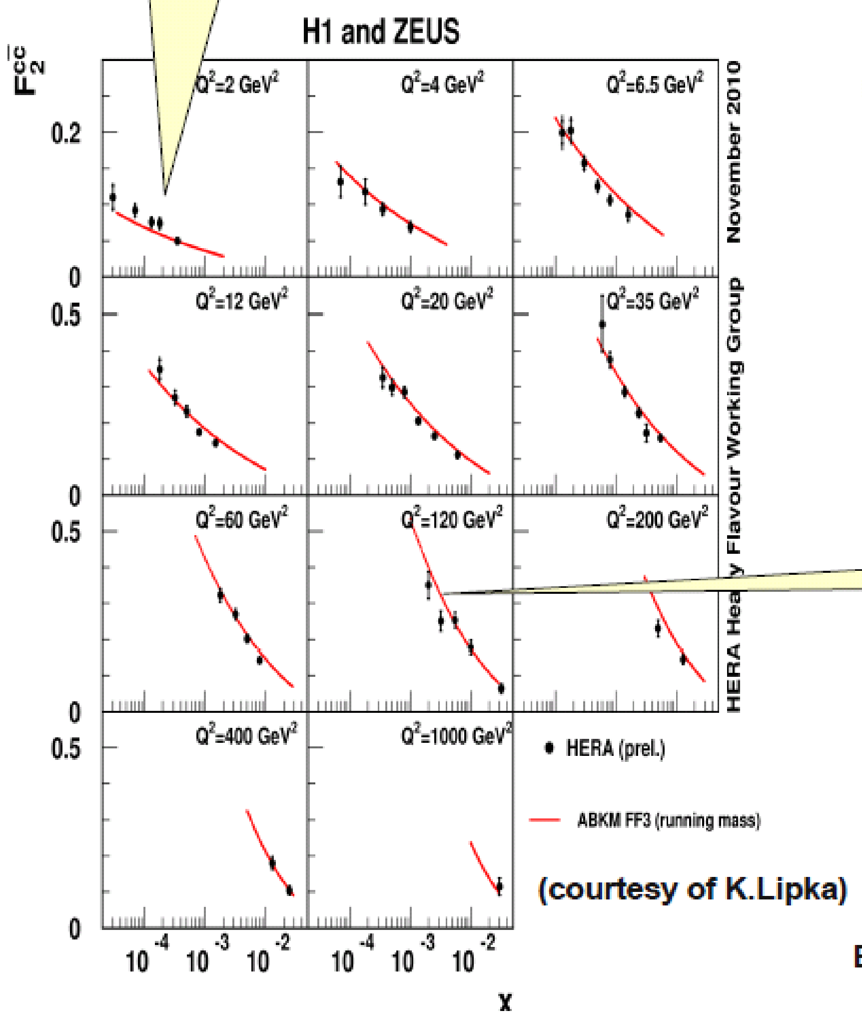
The running mass has been measured independently would it be better to use this?

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^{3}LO corrections?



$m_c(m_c)$=1.27±0.08 GeV (PDG '10)

$m_c(m_c)$=1.18±0.06 GeV (incl.F_2 +PDG)

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

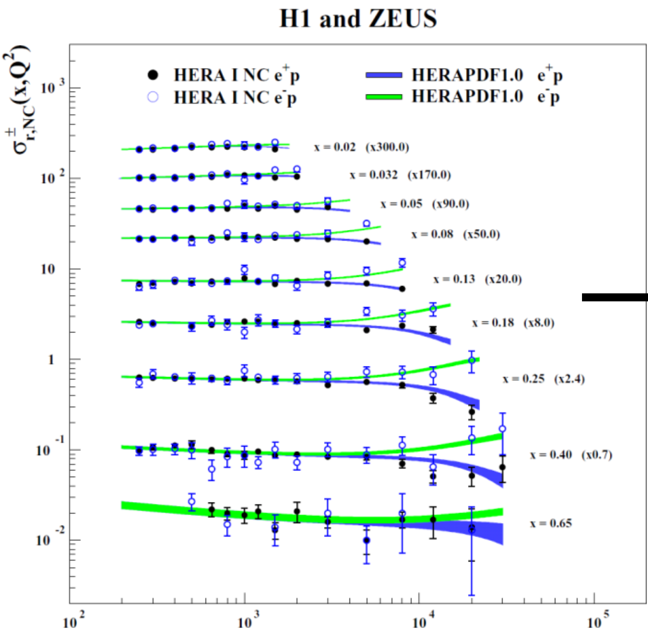
(courtesy of K.Lipka)

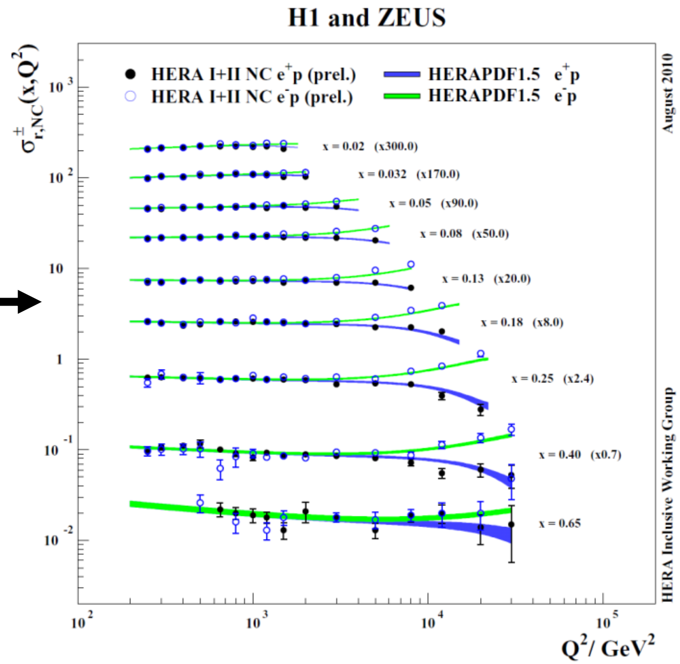
PDF Updates at NLO --some updates to the data sets

Focus on W.Z predictions at the LHC

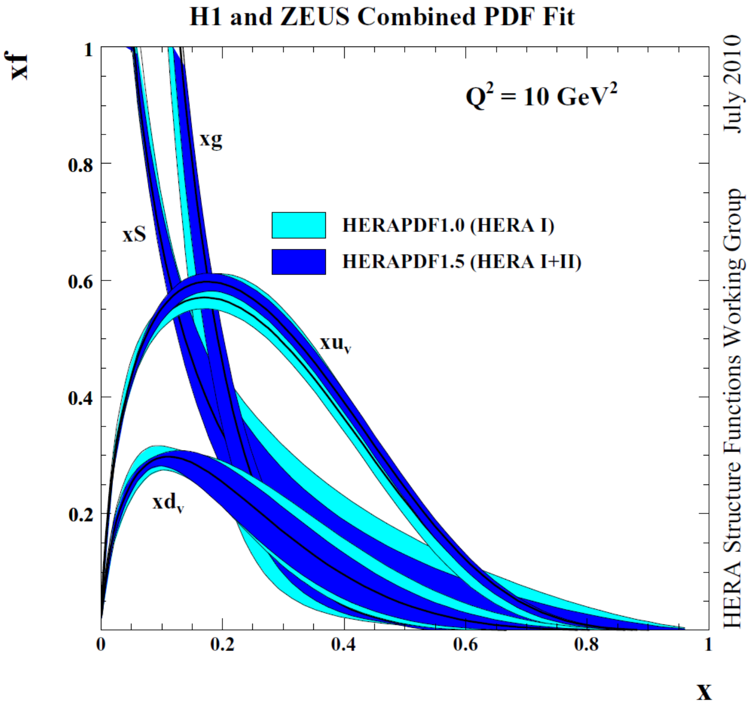
Updates of q-qbar luminosity plots

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

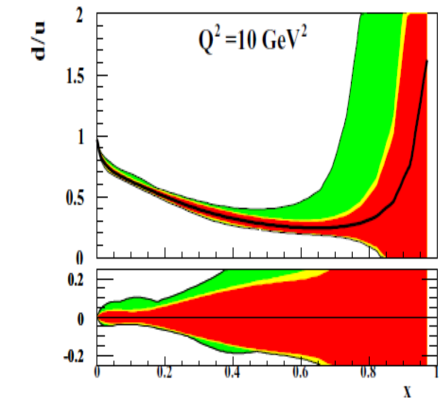


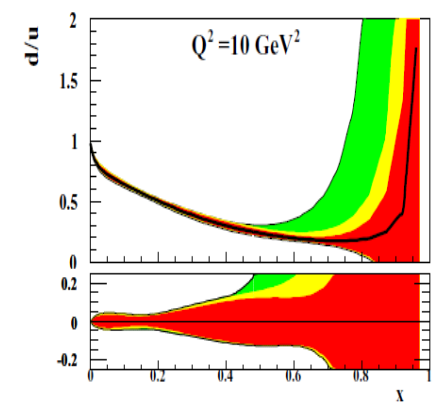


Uses preliminary HERA I+II data combination



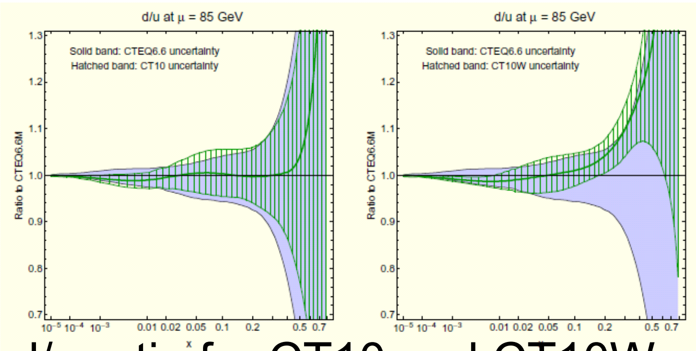
Gives increased precision at high-x



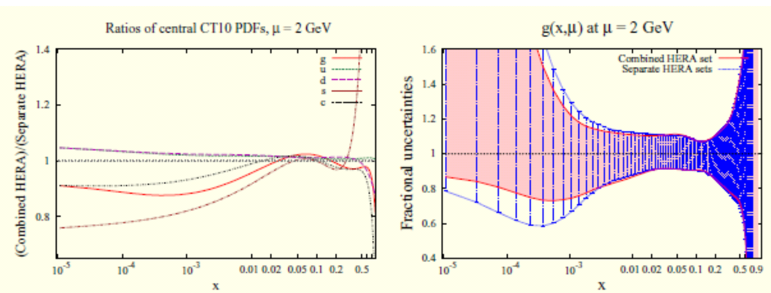


Features of the updates: CT10

Particular attention to Tevatron lepton asymmetry



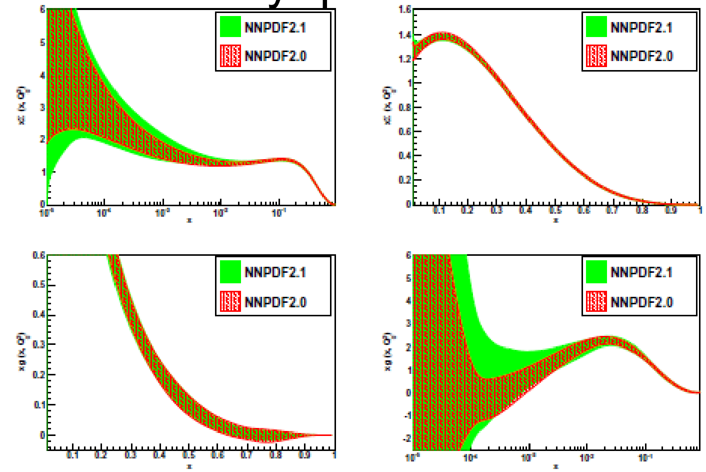
d/u ratio for CT10 and CT10W



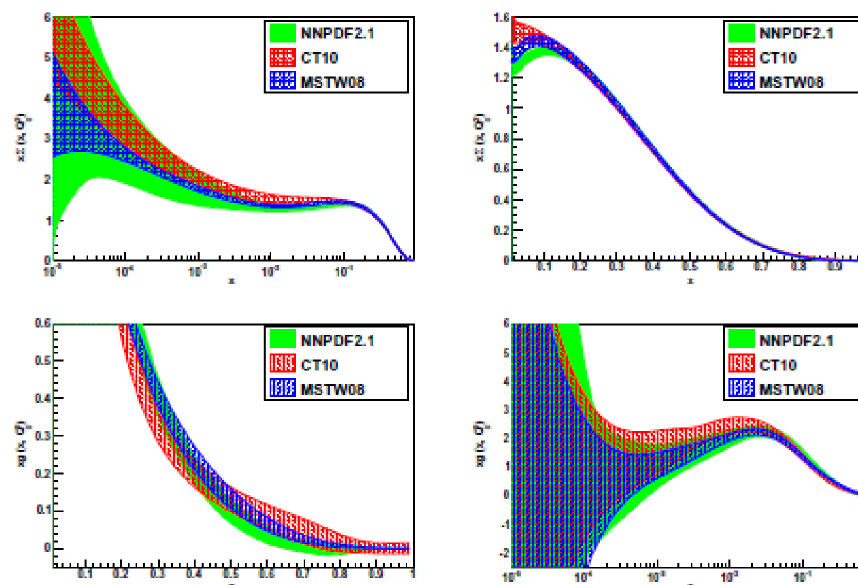
Effect of adding HERA-I combined data

Features of the updates: NNPDF2.1

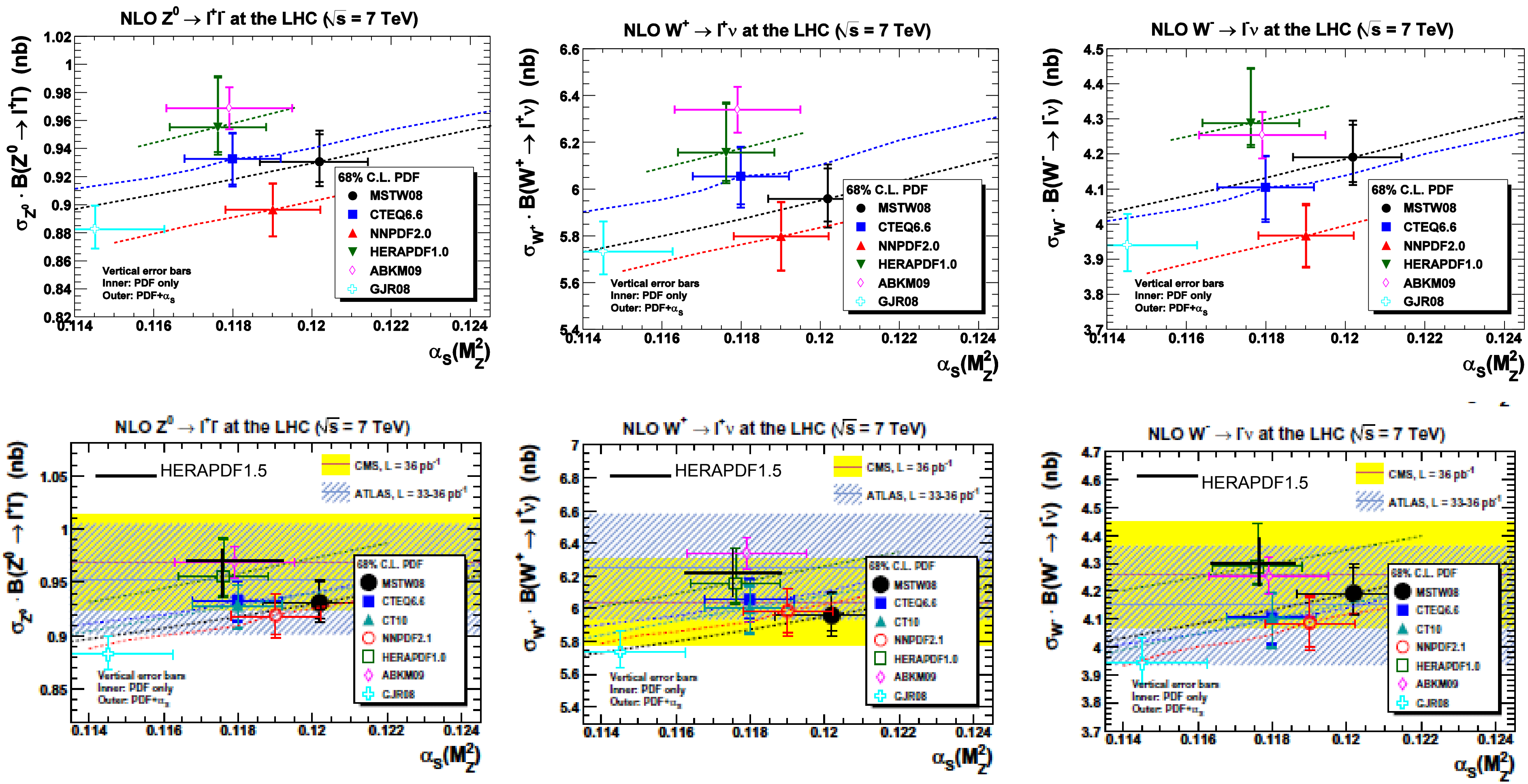
update of heavy quark scheme



Compare NNPDF2.1 and CT10 to MSTW08



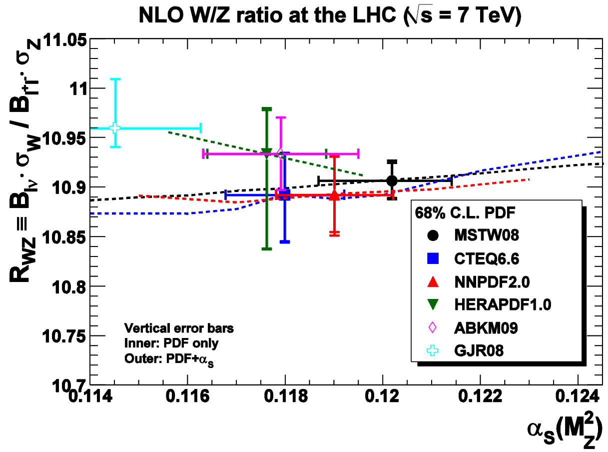
NNPDF2.0 has been updated to NNPDF2.1 CTEQ6.6 to CT10
HERAPDF1.0 to HERAPDF1.5



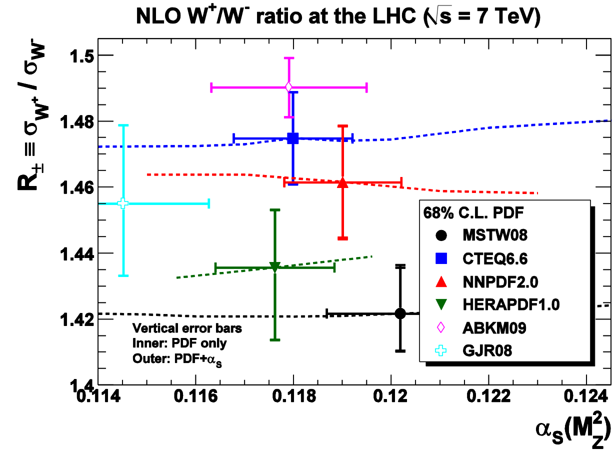
The use of the VFN scheme puts NNPDF2.1 closer to MSTW,

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

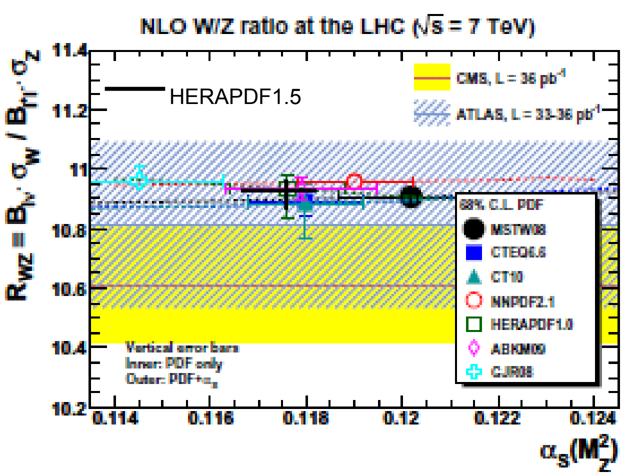


W,Z ratios updated

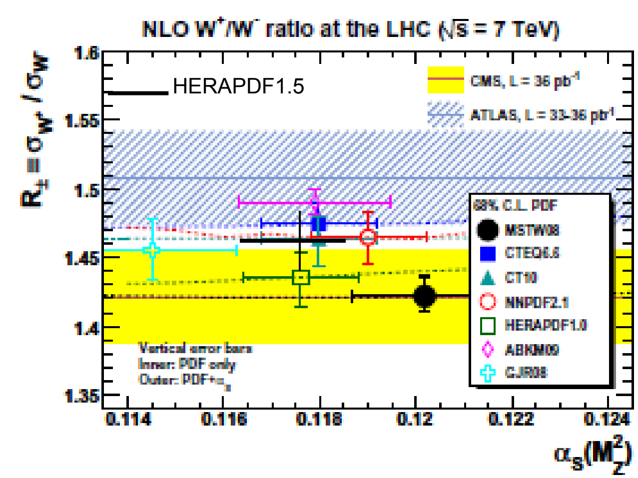


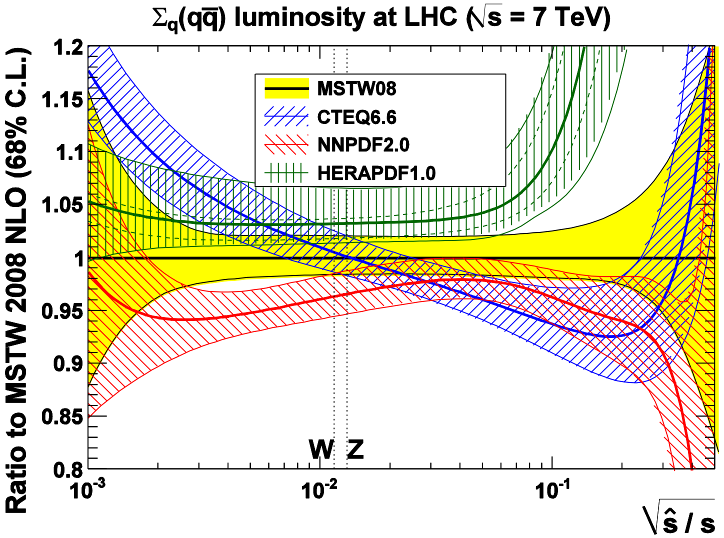
Are ratios predicted more consistently than the cross-sections?

- 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



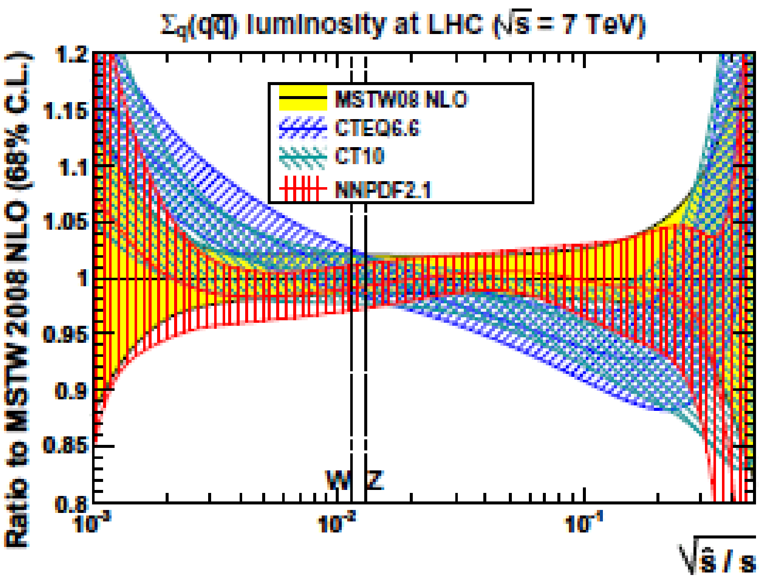
Is there an ATLAS/CMS discrepancy?

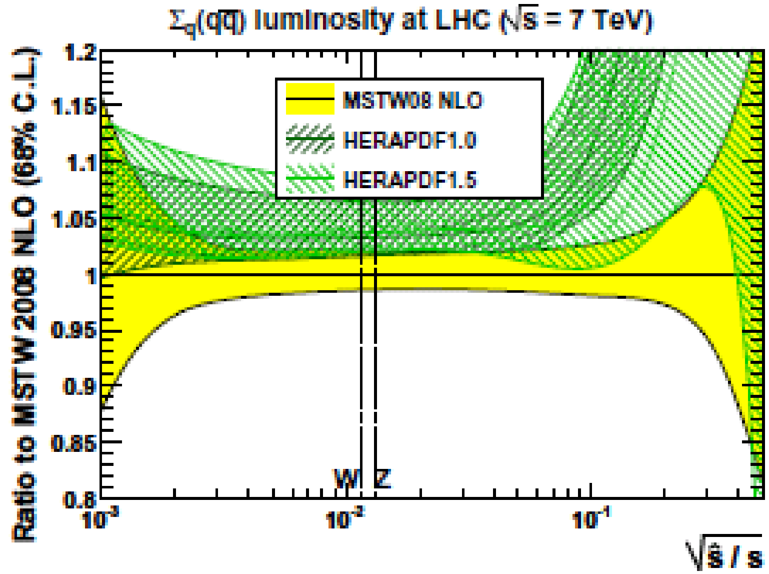




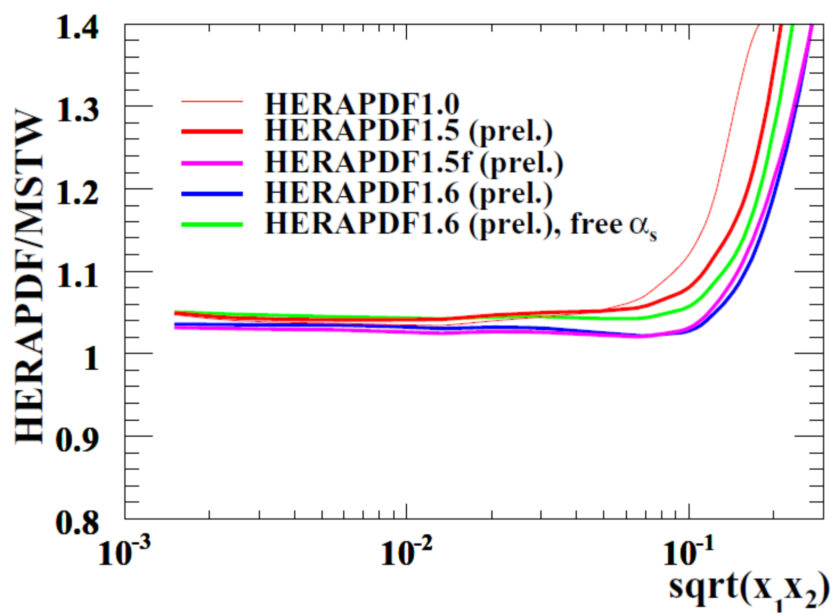
W/Z production depends on q-qbar luminosity

Update with NNPDF2.1, CT10





Update with HERAPDF1.5 and with HERAPDF1.5f, 1.6, and free alphas



The value of $\alpha_S(M_Z)$

Updates on gluon luminosity plots

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 ~~0.1145~~		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 σ rather than F2 in their fits to NMC fixed target data…see later.. 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 χ2 for HERA data is very flat.

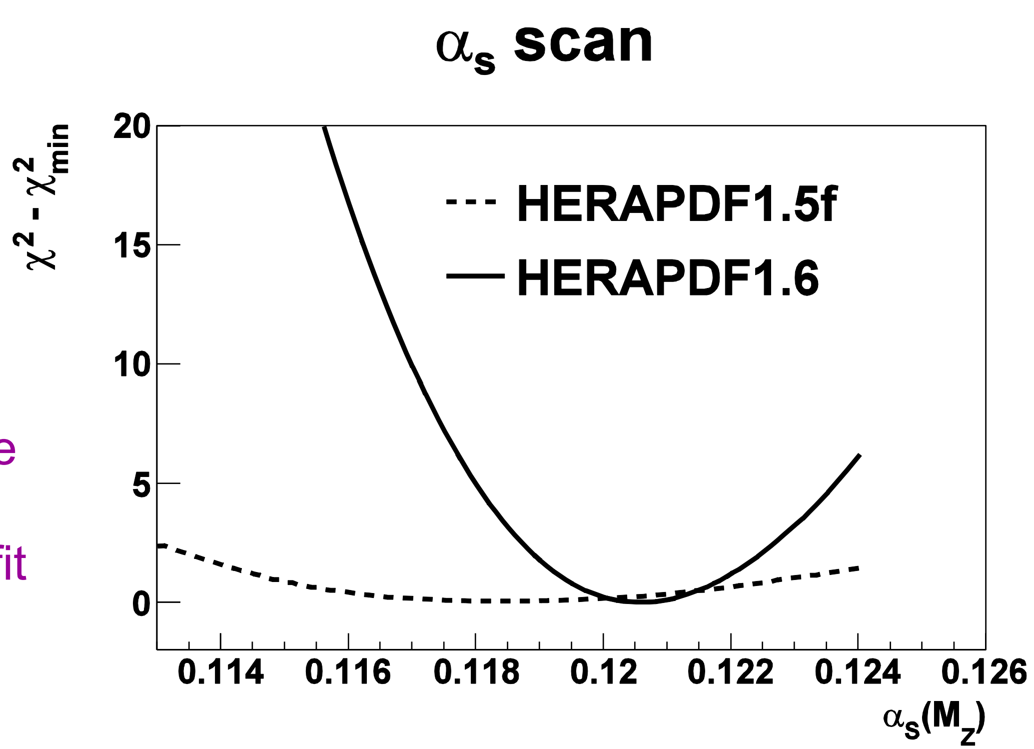
Now we have heard from HERA themselves.

They have used their preliminary HERA I+II data combination and they agree that the χ2 dependence on is very flat – and the model dependence is large.

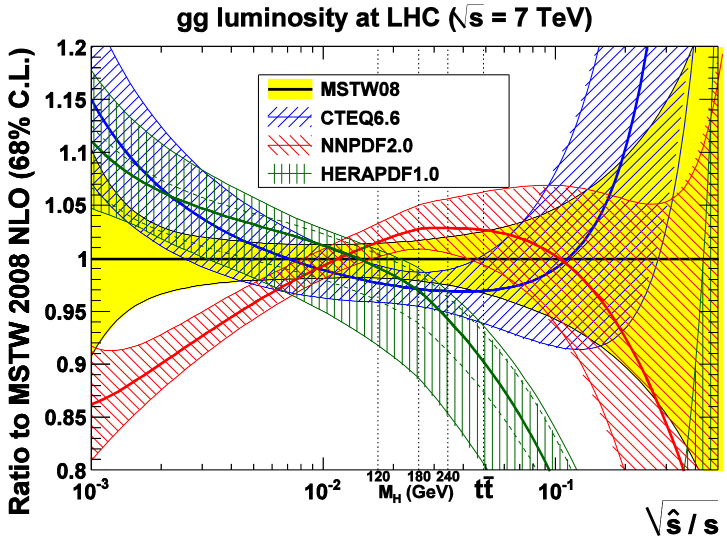
BUT if the DIS jet data are added there is a different story AND alphas is larger

$\alpha_S(M_Z) = 0.1202 \pm 0.0019$ (excluding scale error)

for HERAPDF1.6 the scales used for the central values ARE the scales that the data prefers as judged by the χ2 of the fit

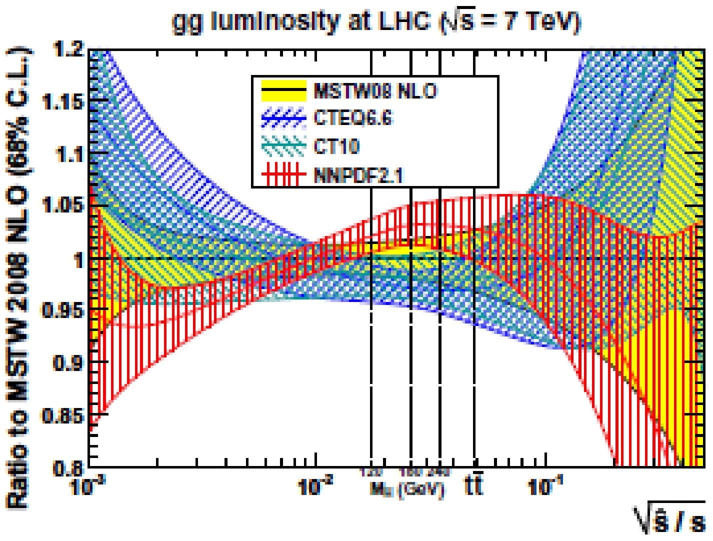


Gluon-gluon luminosity is important for Higgs production



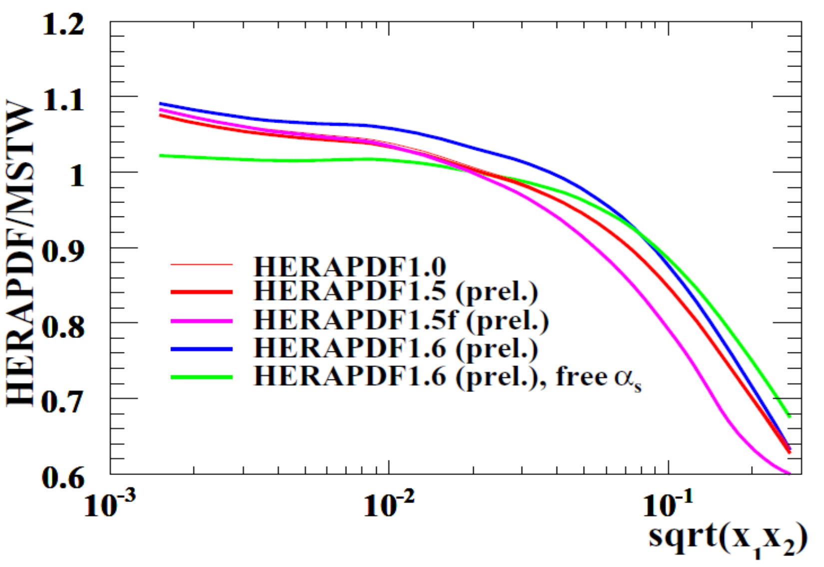
g-g luminosity updates

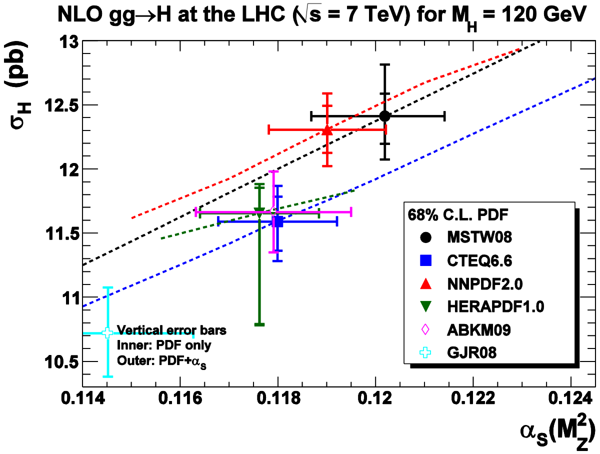
CT10 and NNPDF2.1 are both closer to MSTW than CTEQ6.6 and NNPDF2.0



HERAPDF1.6 moves closer to MSTW

Note how the larger value of $\alpha_s(M_Z)$ brings better agreement at low scale

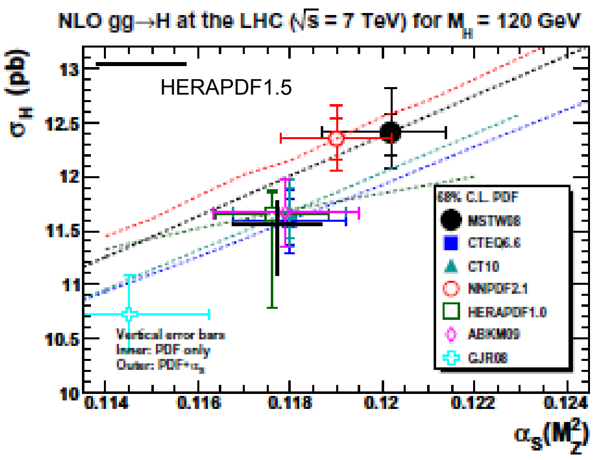


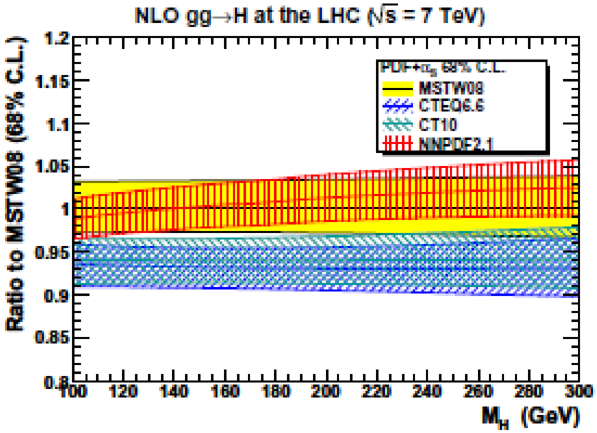


Higgs cross-sections update

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

Features of the updates: ABM11

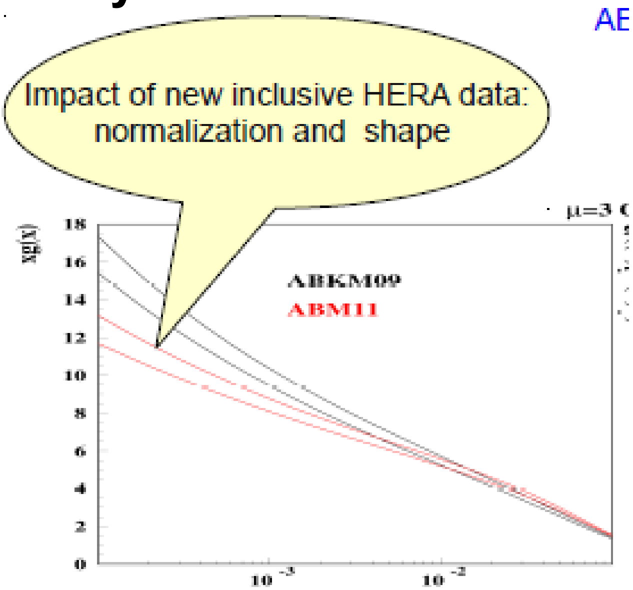
PDF updates NNLO

NNPDF and HERAPDF with CTEQ on its way

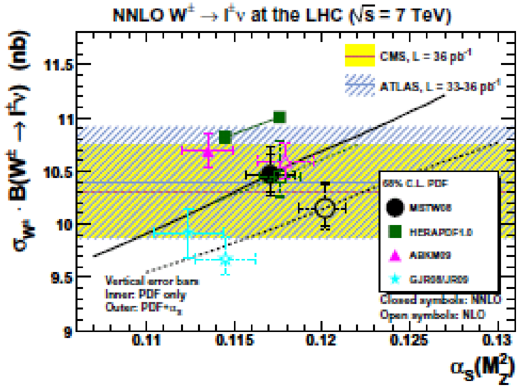
MSTW, AB(K)M and (G)JR already NNLO but
ABKM09 is update to ABM11

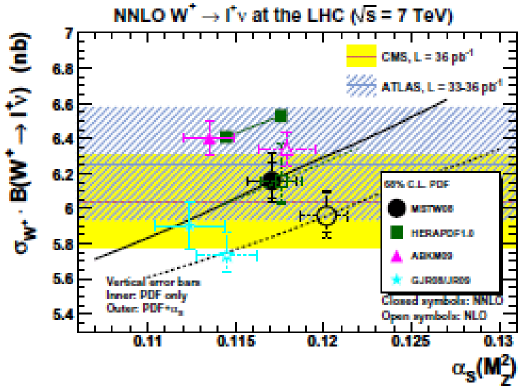
Focus on the Higgs

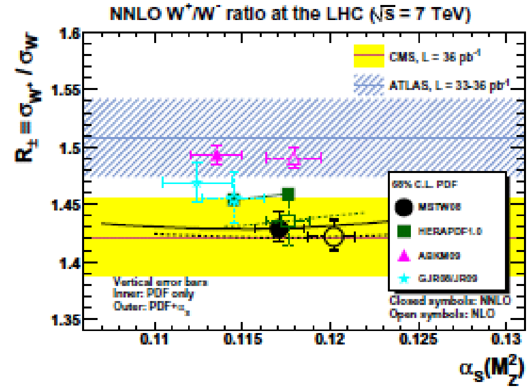
Update of ABKM09 to ABM11 using newly combined HERA data

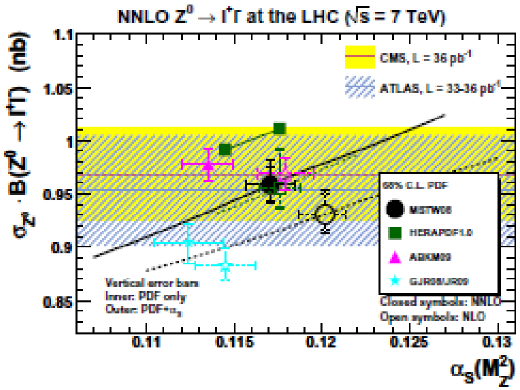


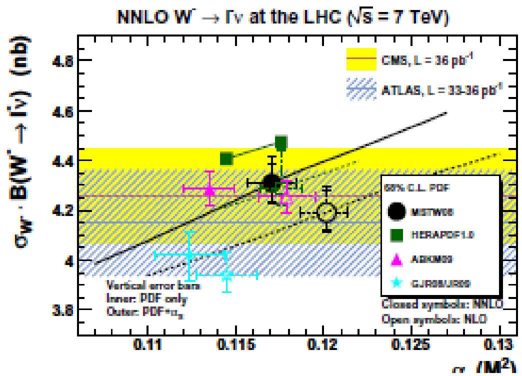
Until this year there were fewer NNLO PDFs: MSTW, ABKM, JR and HERAPDF1.0 (for two values of $\alpha_s(M_Z)$ without error band)

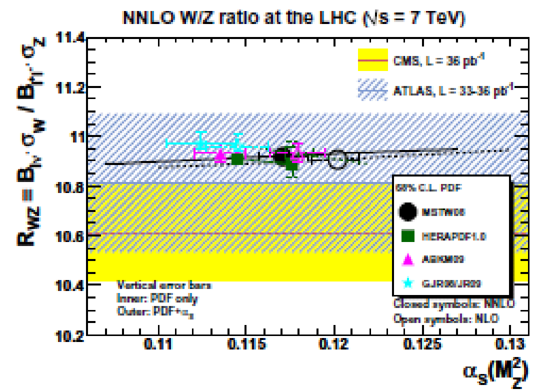


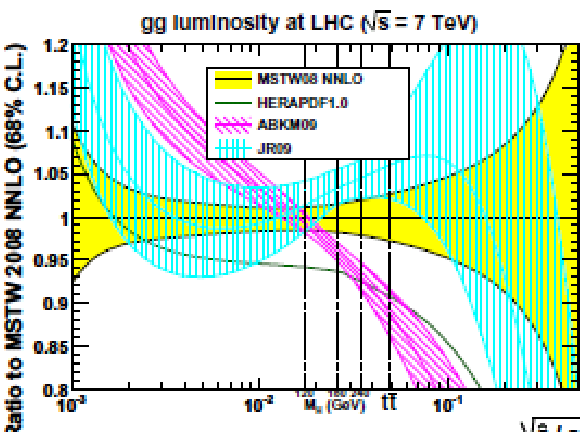


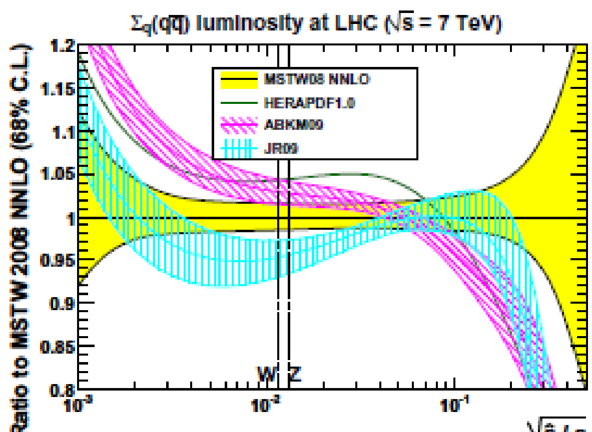






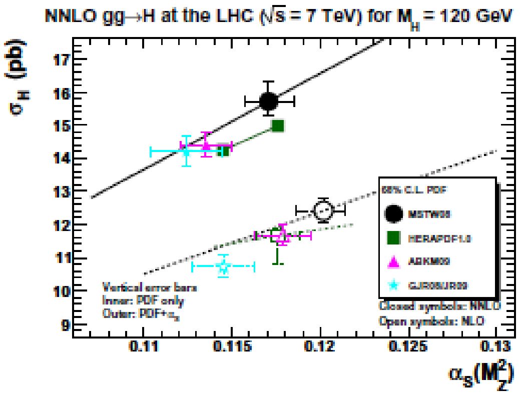


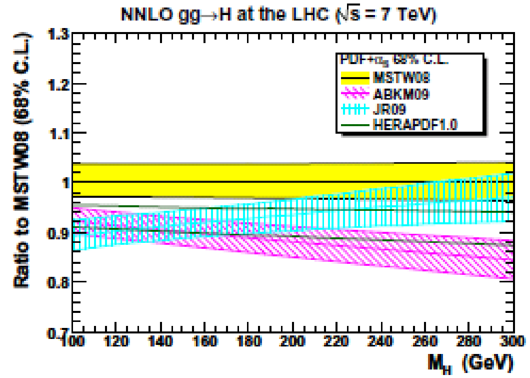


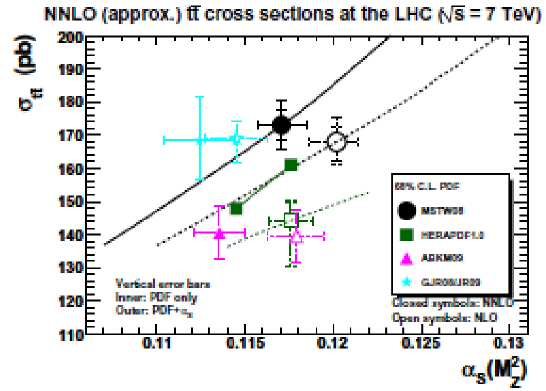


arXiv:1011.6259 from ABM and JR gives a comprehensive comparison

NNLO predictions for t-tbar and Higgs







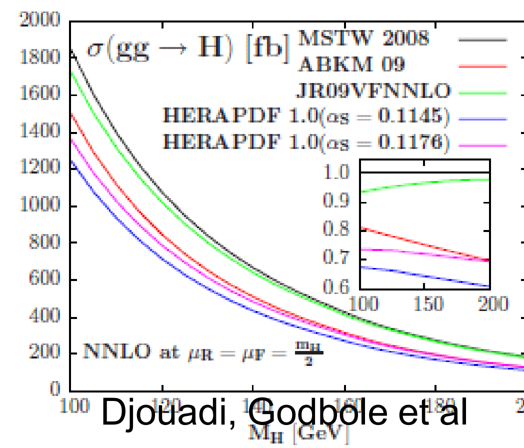
The PDF4LHC recommendation at NNLO is to use the MSTW08 result but increase the errors by ~2 (to reflect the NLO envelope).

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



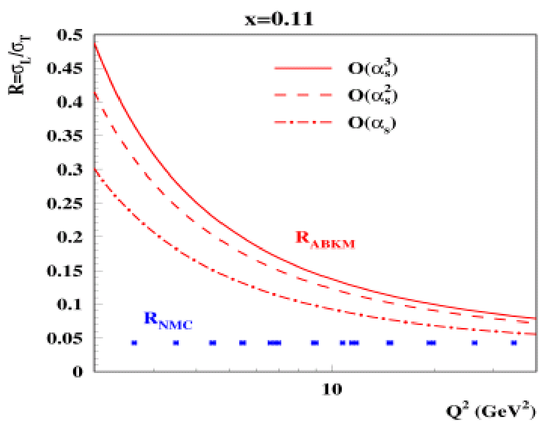
Djouadi, Godbole et al

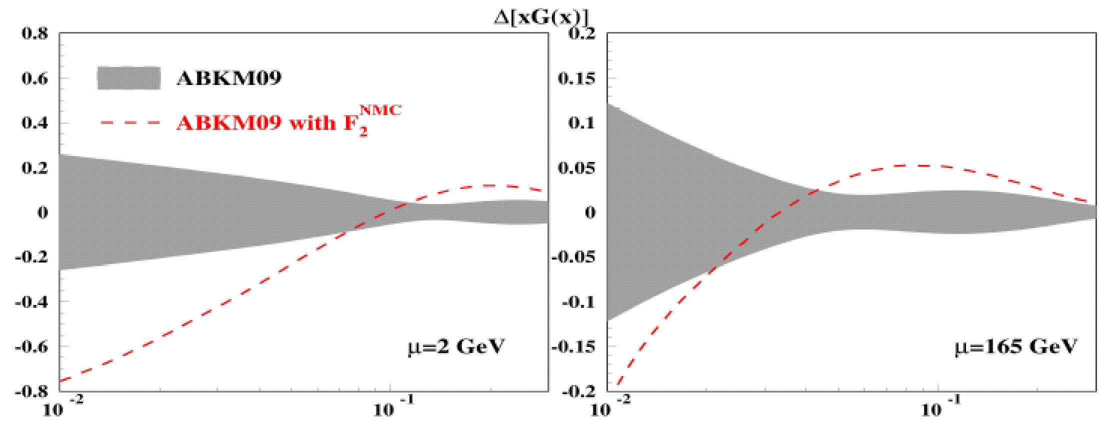
However, the MAIN development of 2011 is more NNLO PDFs

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 σ





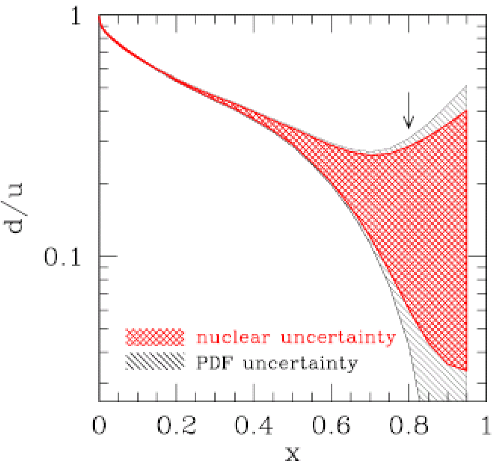
But both NNPDF and MSTW say this effect is negligible. However they work with fixed $\alpha_s(M_Z)$. ABM have $\alpha_s(M_Z)$ free in the fit

$\alpha_s(M_Z)$	$\alpha_s(M_Z)$ with $\sigma_{\rm NMC}$	$\alpha_s(M_Z)$ with $F_2^{\rm NMC}$
NLO	0.1179(16)	0.1195(17)
NNLO	**0.1135(14)**	0.1170(15)
NNLO $+F_L$ at $O(\alpha_s{}^3)$	0.1122(14)	0.1171(14)

NMC *may* gave 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 (JLAB)– have been considering corrections for the deuterium targets. They conclude that the uncertainties are larger than is usually accounted for



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

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 form 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.

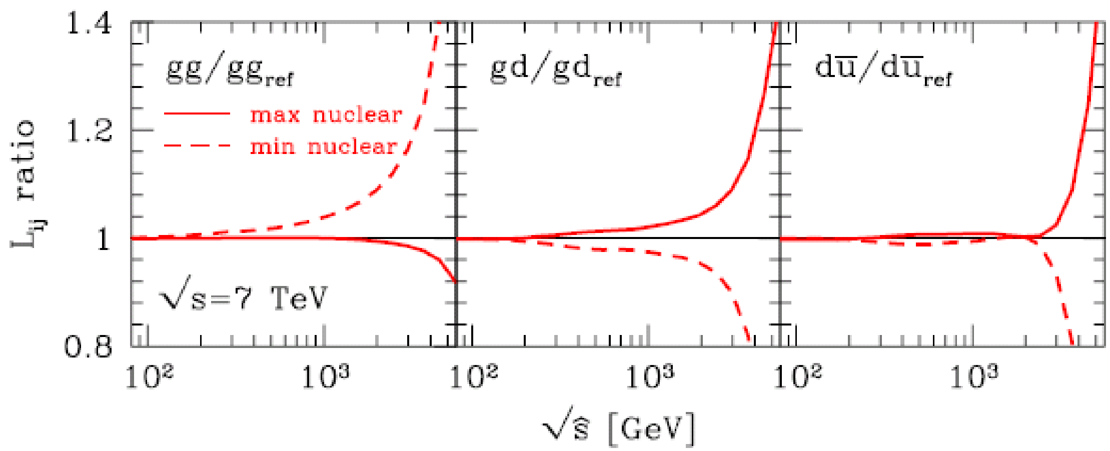
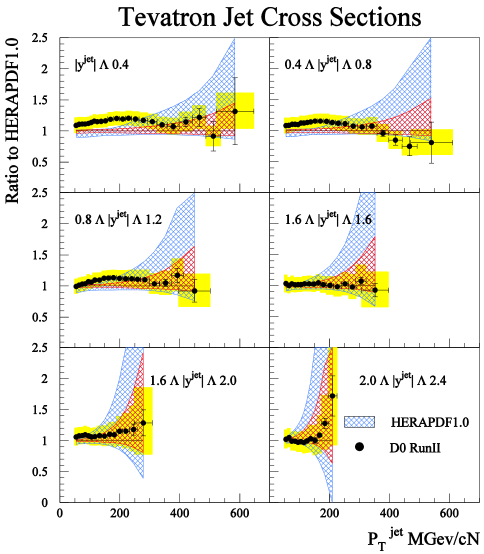
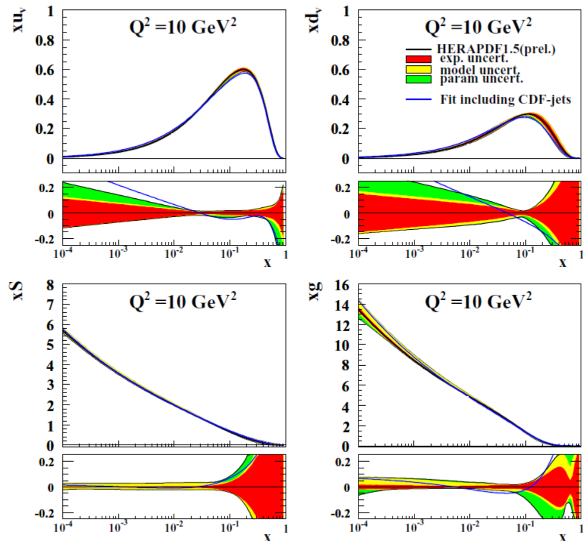


Illustration in terms of parton luminosities for LHC 7 TeV

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



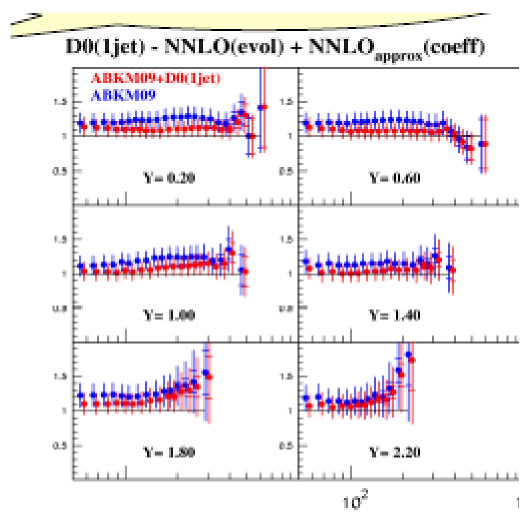


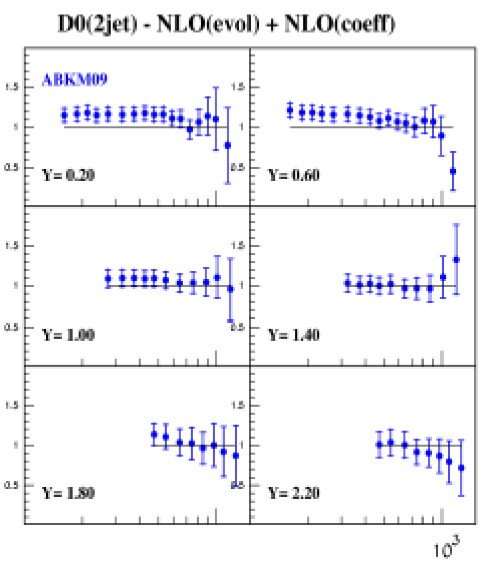
But the real question is how well does an NNLO fit describe these data?
For HERAPDF1.5 NNLO the description is MUCH better $\chi2$/dp=72/76 for CDF even for the central PDF

HERAPDF1.5 $\chi2$/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 $\chi2$/dp = 113/76 and 145/110 resp.
The resulting PDF is at the edge of HERAPDF1.5 (68%CL) error bands

ABM



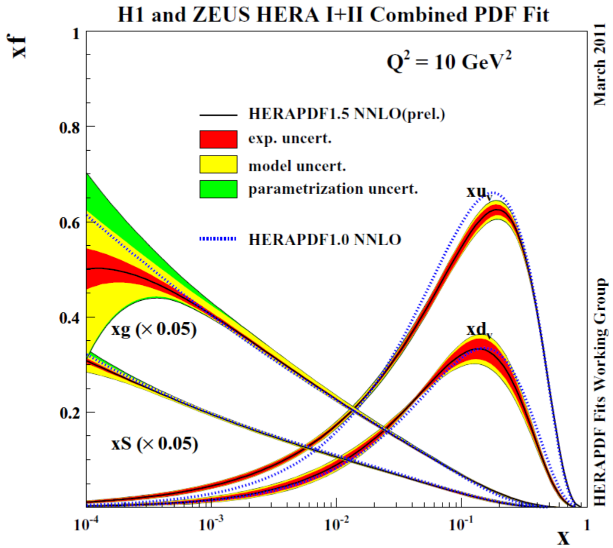


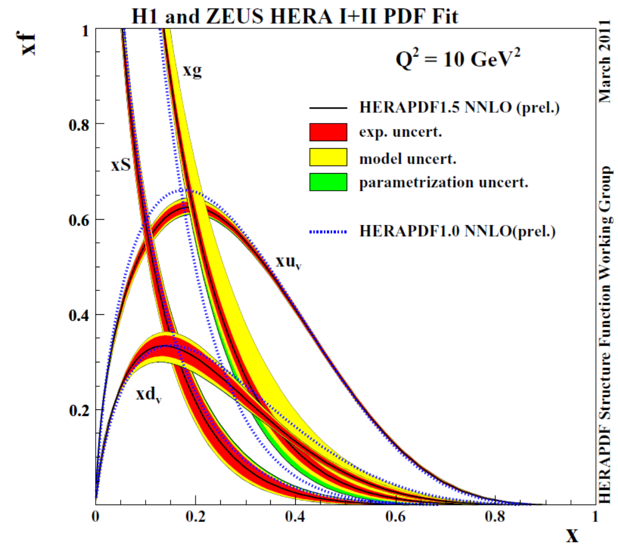
$\mu_r = \mu_F = P_T$ midpoint
24 sources of systematics
χ^2/NDP=103/110

$\mu_r = \mu_F = P_T$

The Higgs cross section can go up by ~1-2σ

The year of NNLO: HERAPDF1.5 NNLO





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

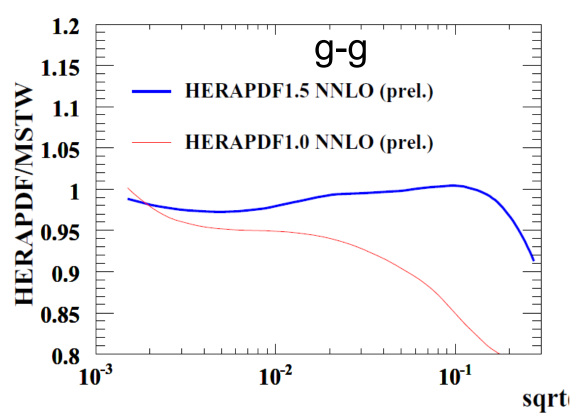
The NNLO PDFs differ from NLO in a similar manner as for MSTW08 (same heavy quark treatment).

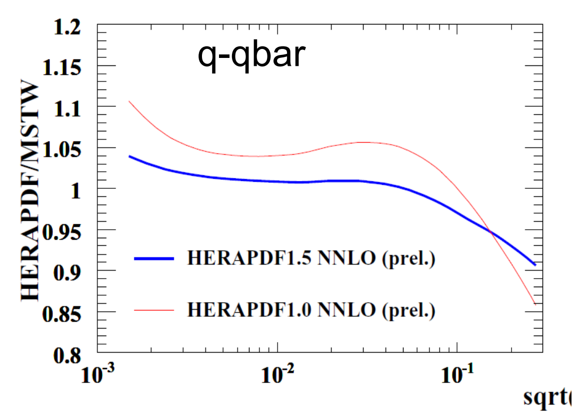
The low-x gluon is more uncertain than at NLO - NNLO DGLAP is NOT a better fit to low-x,Q^2 data.

HERAPDF1.5 NNL0 has a harder high-x gluon than 1.0

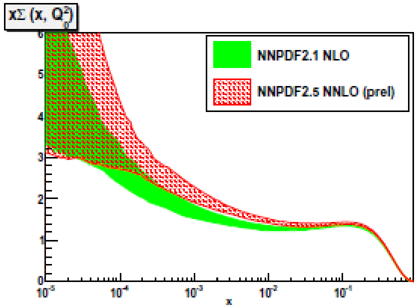
Both the g-g and the q-qbar NNLO luminosities of HERAPDf1.5 are closer to MSTW than HERAPDF1.0 hence Higgs predictions also closer

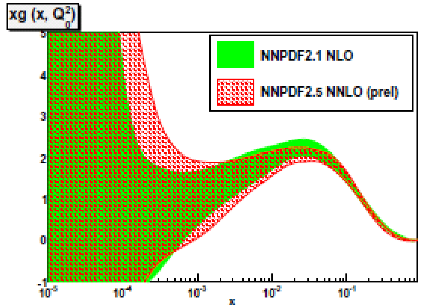
PDFs are available in an $\alpha_s(M_Z)$ series, but the central NNLO value is 0.1176



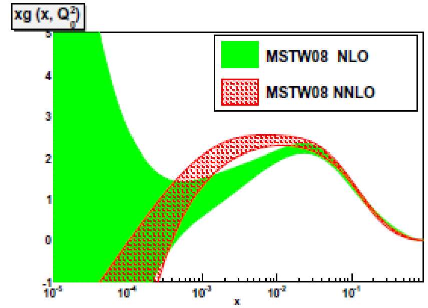


NNLO -- NNPDF2.5

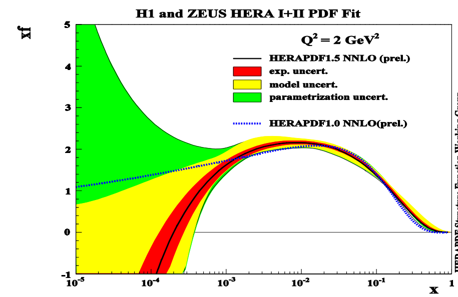




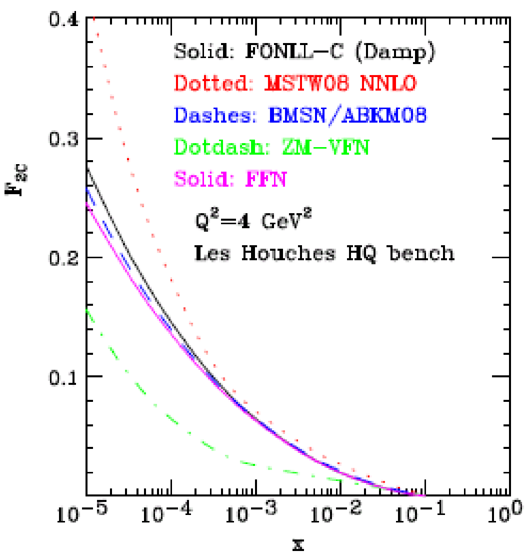
Compare MSTW

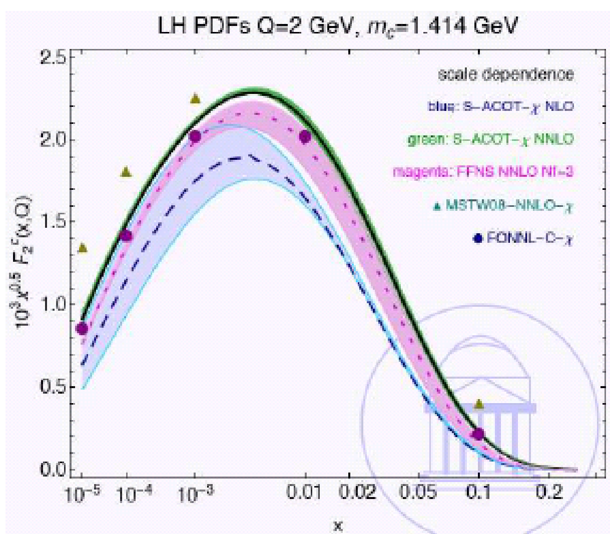


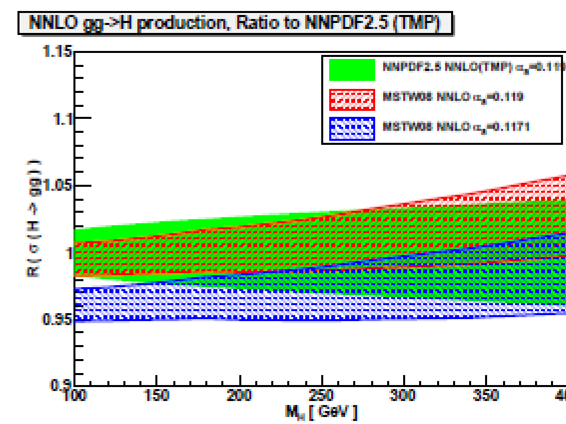
Compare HERAPDF1.5



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- but it's not so bad as at NLO







NNPDF2.1 NNLO/MSTW08 agree for the NNLO Higgs at ±5%

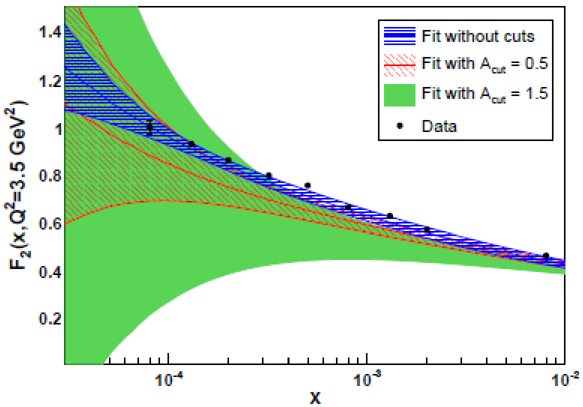
Better agreement with common $\alpha_s(M_Z)$
Crucial to compare results at same α_s

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

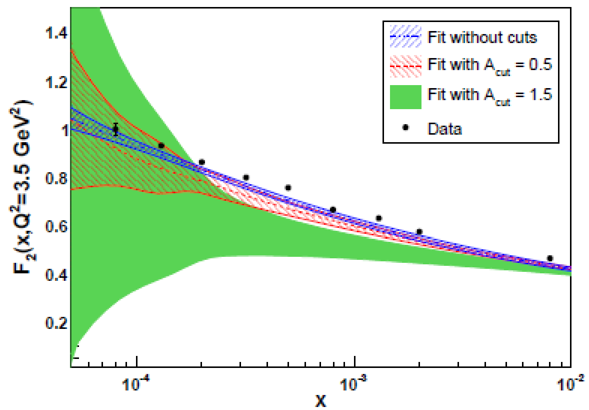
LHC data

Focus on low-x

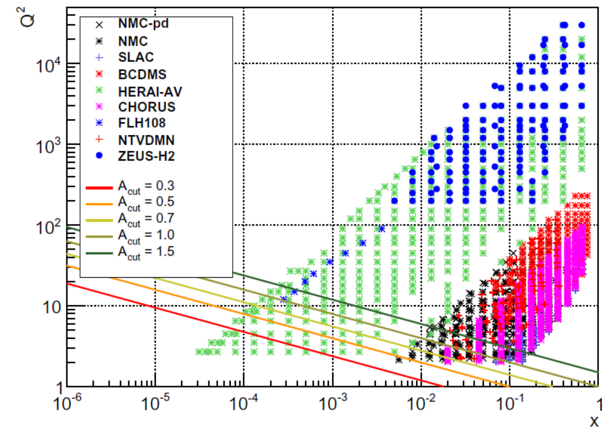
IS NLO DGLAP applicable for the low-x,Q^2 part of the kinematic plane?



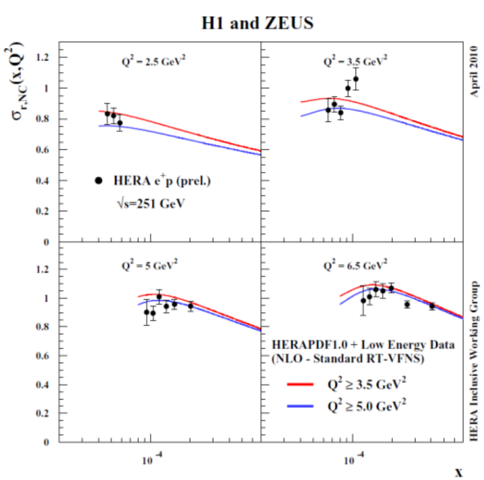
Before combined HERA-I



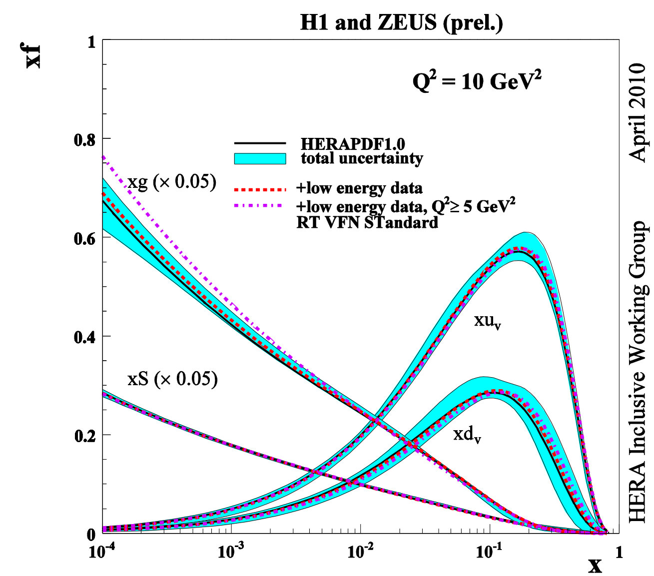
With combined HERA-I



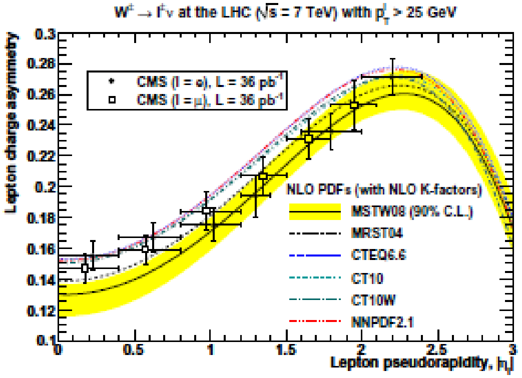
NNPDF saw some tension between the lowest x,Q2 and the rest of the data when they used the HERA combined data. CTEQ say they do not confirm this tension. HERA find that when they combine their low energy run data the low x,Q^2 part of the data is not so well fit and the **gluon** which results from imposing harder Q^2 cuts or $Q^2 > 0.5x^{-0.3}$ cut **is steeper-** this seems NOT to be solved by NNLO

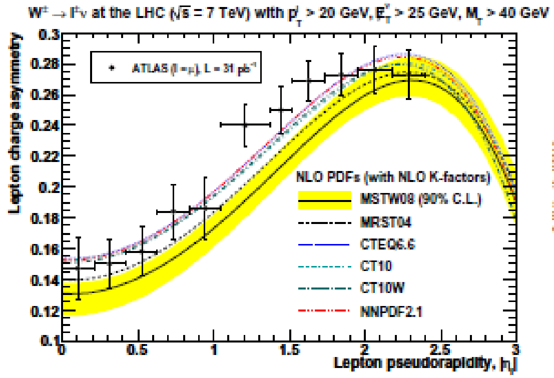


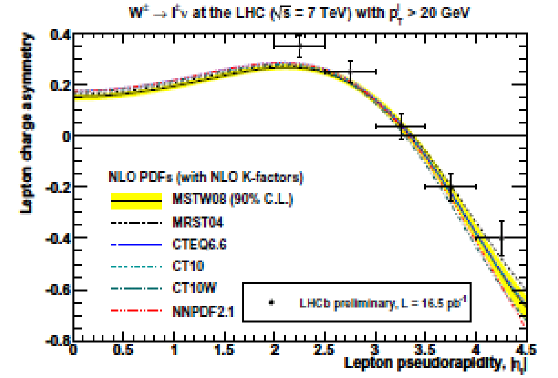
But since this difference is for x < 10^{-3} you don't expect much effect for W/Z production at the LHC- in the central region……..

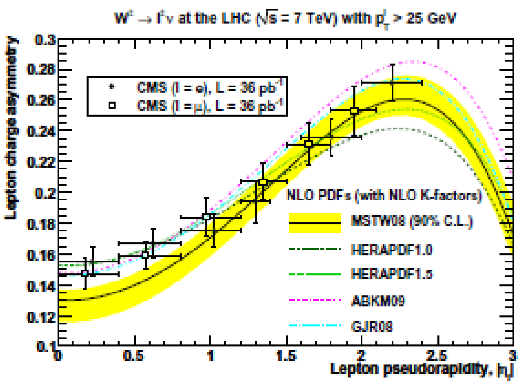


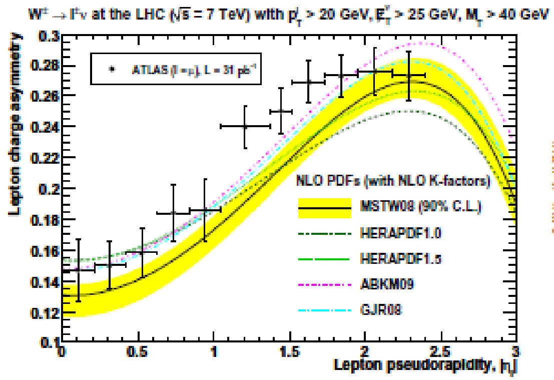
The LHC W/Z rapidity distributions for lepton asymmetry and Z0 production are well described by current PDFS.. Including LHCb which probes down to x = 7 10^{-5}

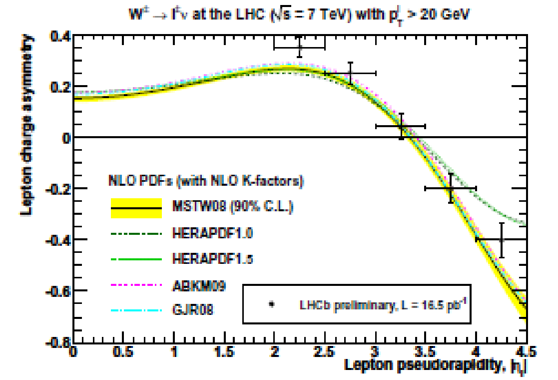












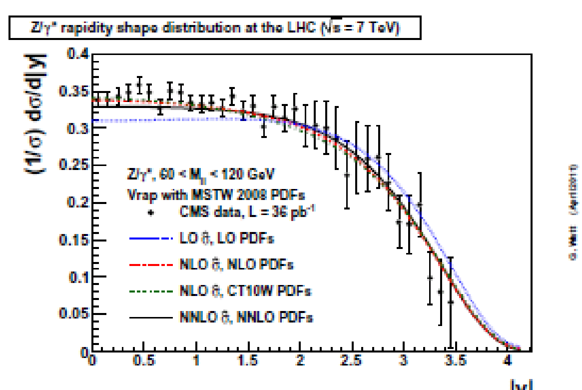
Watt **Data:** CMS for $p_T^{\ell} > 25$ GeV

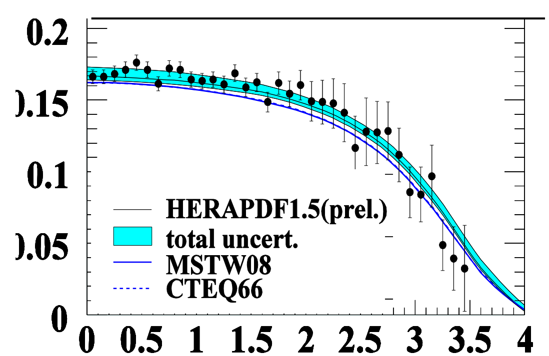
Watt **Data:** ATLAS [arXiv:1103.2929]

Data: LHCb preliminary

1

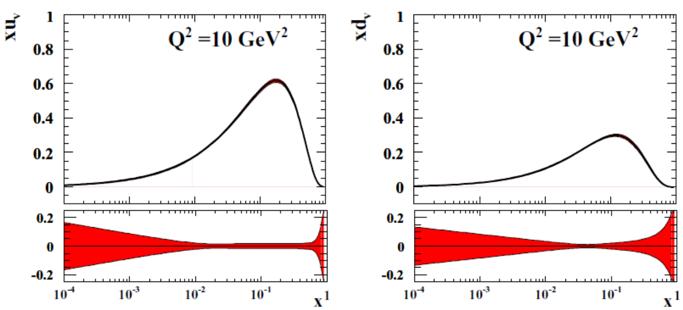
These data are well described by almost all the PDFs -- what improvement if any can they bring if included in the fits?



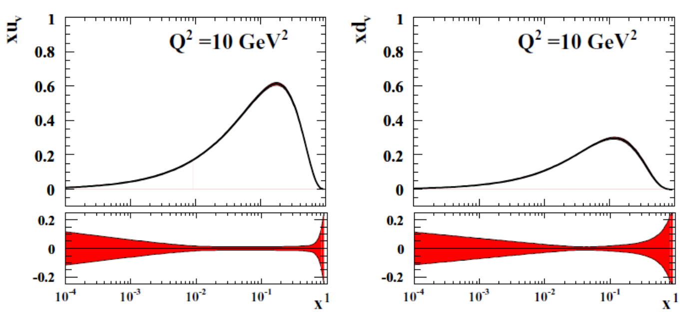


Improvement in HERAPDFs from adding CMS W-asymmetry by re-fitting

HERAPDF uncertainties after including Tevatron W/Z data

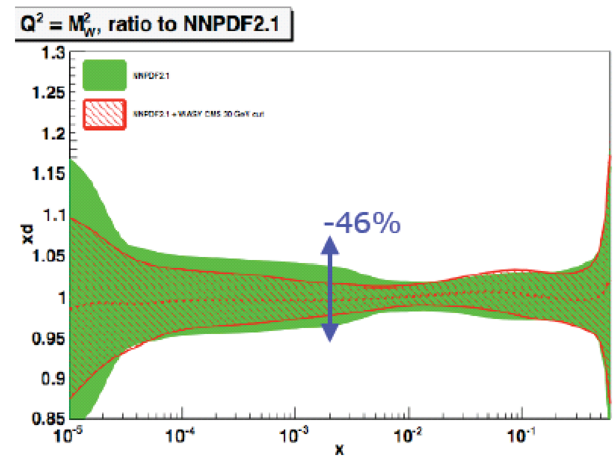


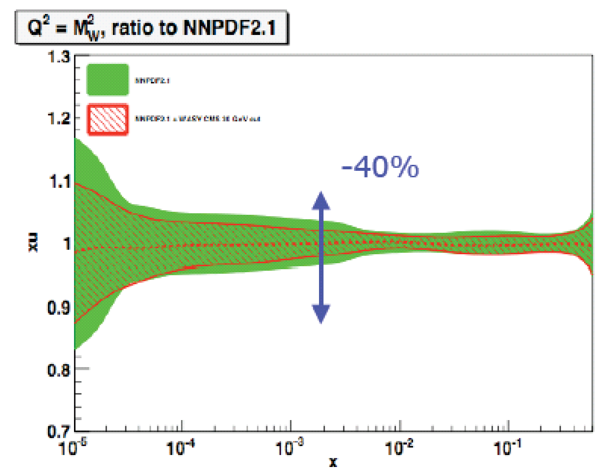
HERAPDF uncertainties after including Tevatron W/Z data + CMS W-asymmetry



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

Summary

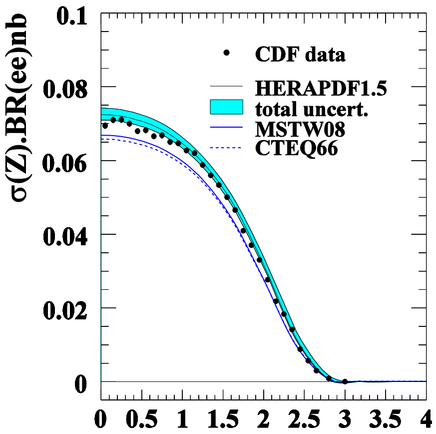
So there is still some controversy on:

- Heavy Quark Mass schemes/ value of mc
- Value of $\alpha_S(M_Z)$
- Use of fixed target data
- Use of low x, Q^2 data

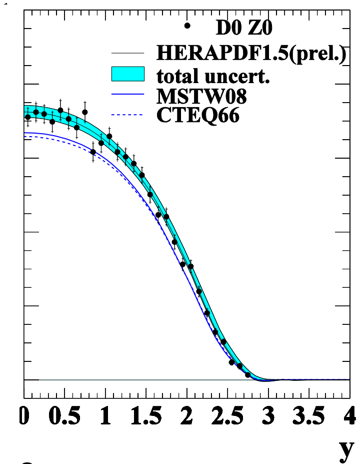
But so far LHC W/Z data looks well predicted by DGLAP down to x ~7 10^{-5}

extras

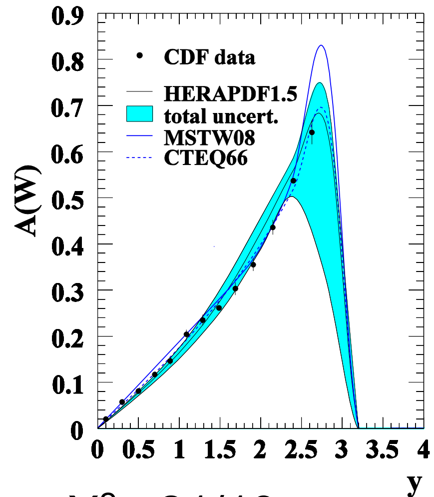
And how well can HERAPDF describe Tevatron W/Z data?



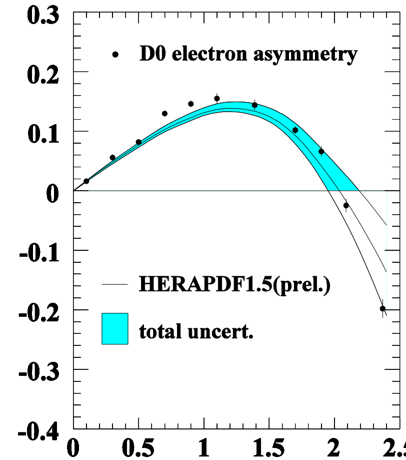
X^2= 27 /28



X^2= 16 /28

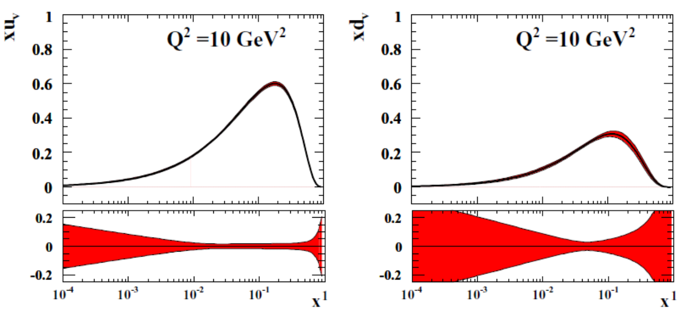


X^2= 21/13

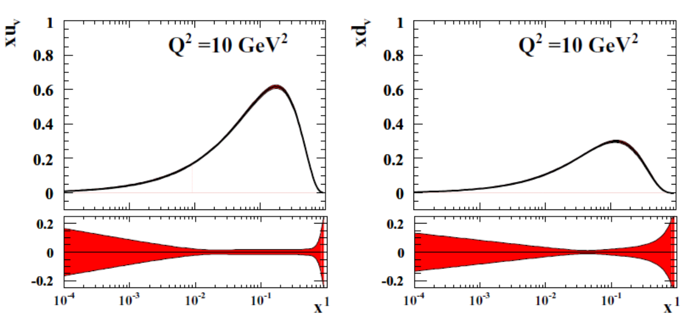


X^2= 25/11

Before fitting Tevatron W/Z data



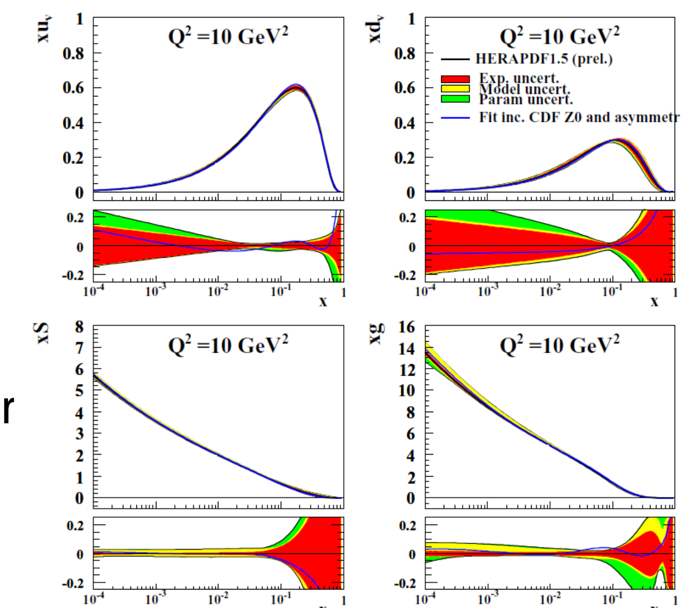
After fitting Tevatron W/Z data



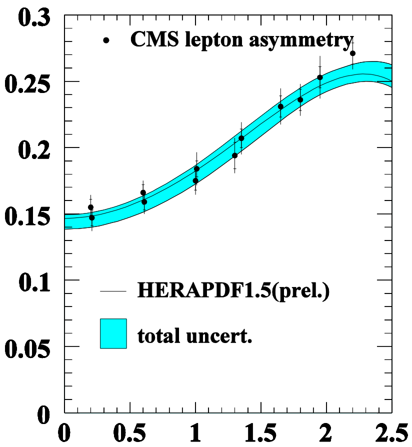
HERAPDF1.5 central PDF gives a good description of Tevatron W/Z data even before fitting.

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

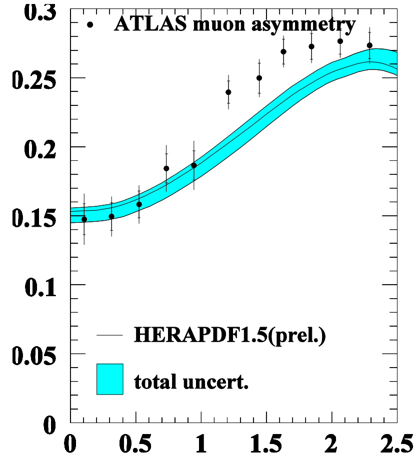
However PDF uncertainties on the d-valence quark are much reduced.



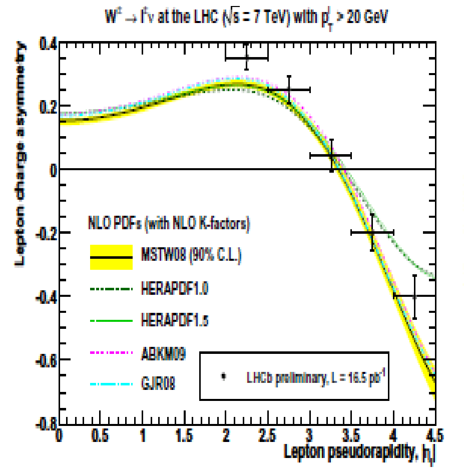
And how well can HERAPDF describe LHC W/Z data?



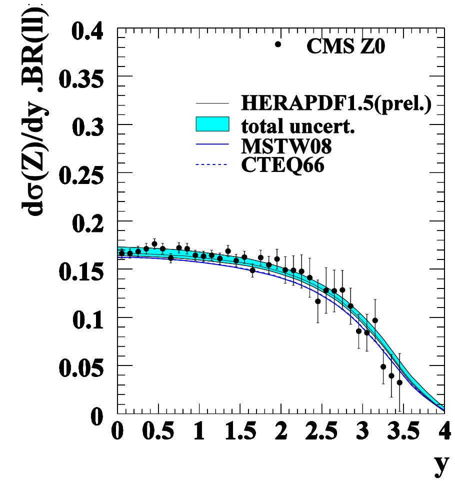
X^2= 6.5 /12→ 4.5/12



X^2= 30 /11→ 14/11

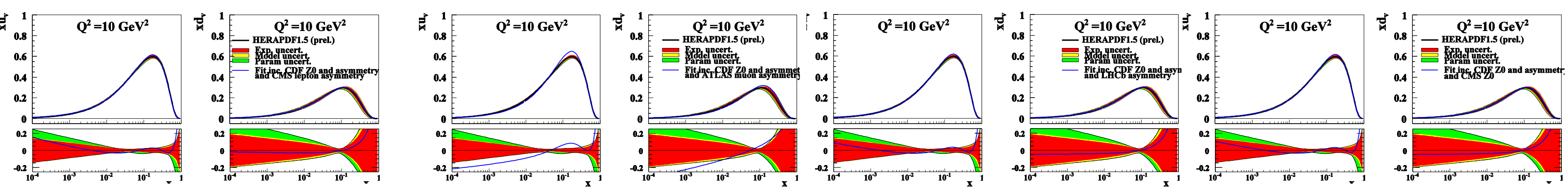


X^2= 9/5→ 7.8/5



X^2= 35/35→ 16/35

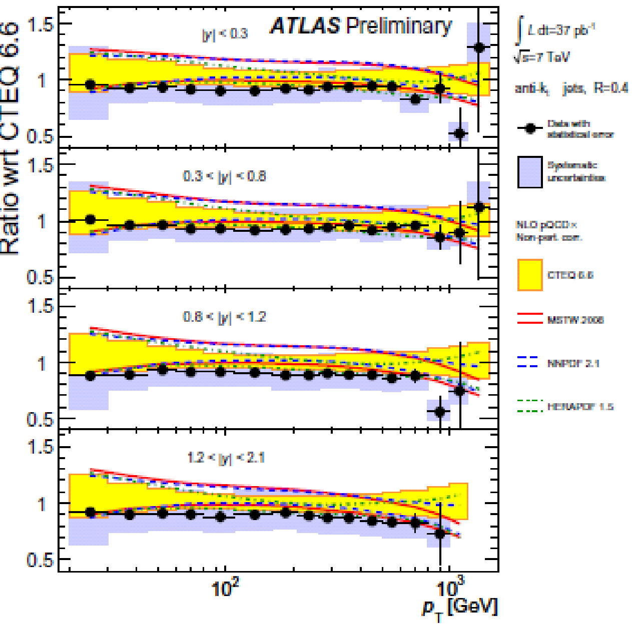
The χ2 are for the central values of HERAPDF1.5 and for a fit to HERA data plus Tevatron W/Z data plus LHC W/Z data

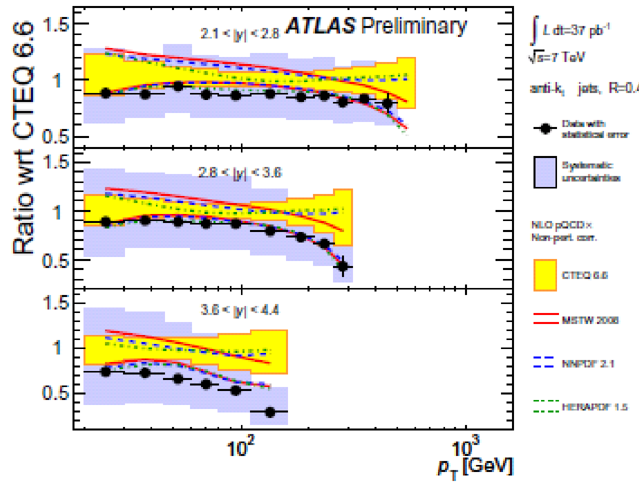


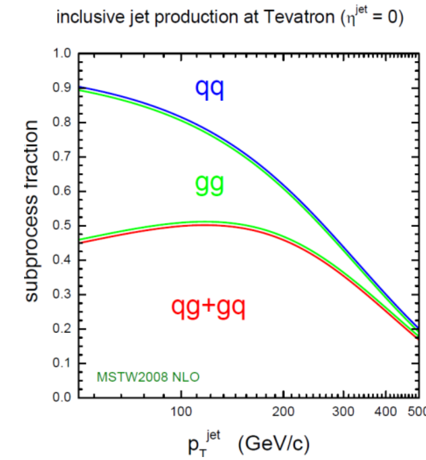
The new fit PDFs do not move (much)outside HERAPDF1.5 error bands

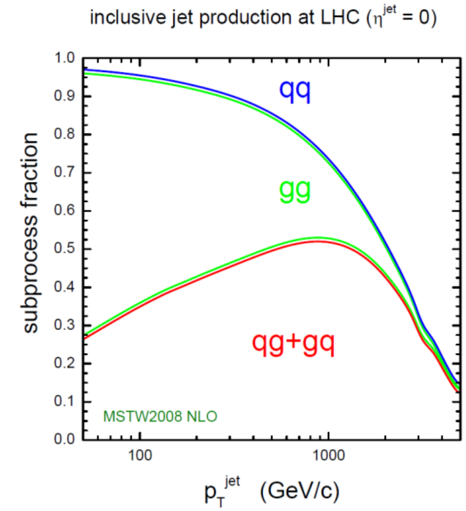
And how well is LHC jet data described?

ATLAS jet data





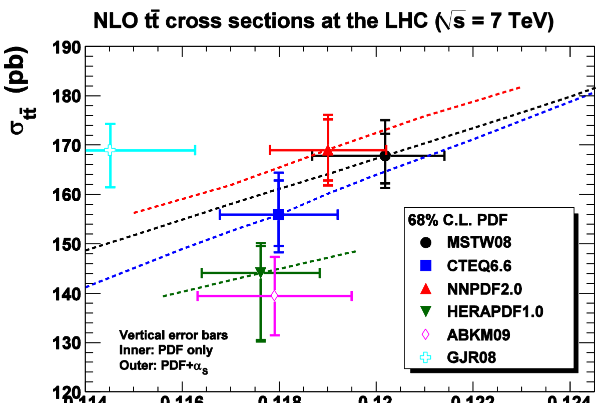


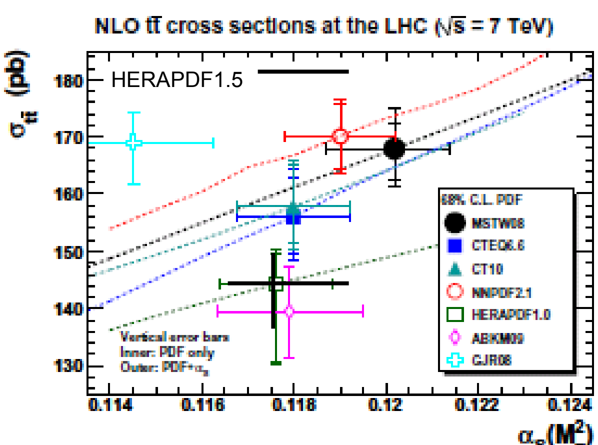


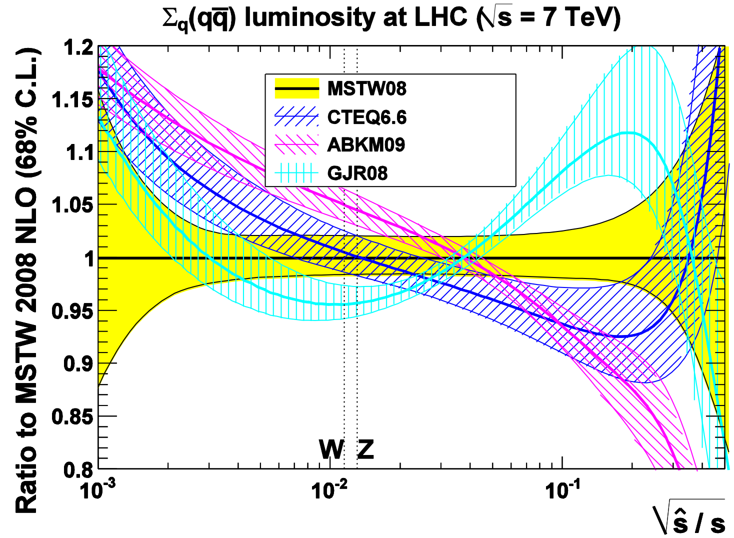
Jet data will also soon be discriminating for PDFs

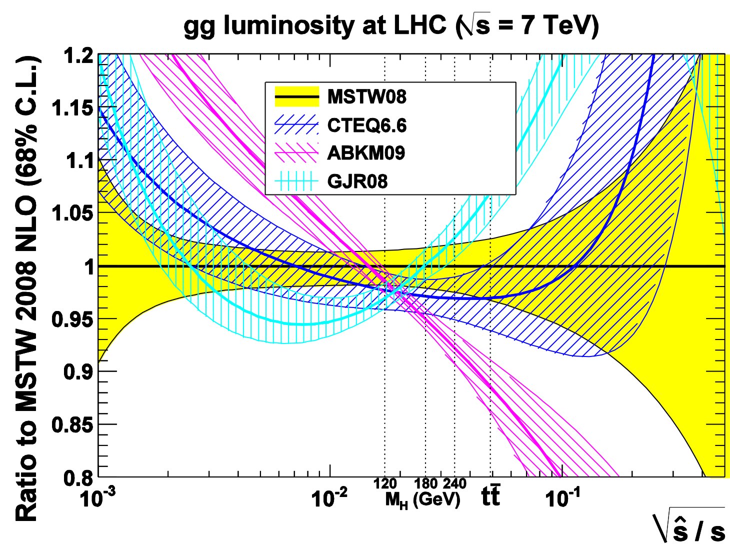
The PDFs that fit the Tevatron jets best are not necessarily those that fit the LHC jets best. The mixture of q-q, q-g, g-g induced jets is different.

HERAPDF1.5 is doing the best job at LHC


NLO $t\bar{t}$ cross sections at the LHC ($\sqrt{s}$ = 7 TeV)
$\sigma_{t\bar{t}}$ (pb)
68% C.L. PDF
MSTW08
CTEQ6.6
NNPDF2.0
HERAPDF1.0
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+α_S


NLO $t\bar{t}$ cross sections at the LHC ($\sqrt{s}$ = 7 TeV)
HERAPDF1.5
$\sigma_{t\bar{t}}$ (pb)
68% C.L. PDF
MSTW08
CTEQ6.6
CT10
NNPDF2.1
HERAPDF1.0
ABKM09
GJR08
Vertical error bars
Inner: PDF only
Outer: PDF+α_S
$\alpha_S(M_Z^2)$


$\Sigma_q(q\bar{q})$ luminosity at LHC ($\sqrt{s}$ = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
ABKM09
GJR08
W Z
$\sqrt{\hat{s}}$ / s


gg luminosity at LHC ($\sqrt{s}$ = 7 TeV)
Ratio to MSTW 2008 NLO (68% C.L.)
MSTW08
CTEQ6.6
ABKM09
GJR08
120 180 240
M_H (GeV)
$t\bar{t}$
$\sqrt{\hat{s}}$ / s