PDF update for Higgs

J. Huston (for Stefano Forte, Robert Thorne)
Michigan State University

Higgs Cross Section Working Group Meeting
06/12/2012

Some history: PDF4LHC

- In 2010, we carried out an exercise to which all PDF groups were invited to participate
- A comparison of NLO predictions for benchmark cross sections at the LHC (7 TeV) using MCFM with prescribed input files
- Benchmarks included
  - W/Z production/rapidity distributions
  - ttbar production
  - Higgs production through gg fusion
    - masses of 120, 180 and 240 GeV
- PDFs used include CTEQ6.6, MSTW08, NNPDF2.0, HERAPDF1.0 ABKM09, GJR08

arXiv:1101.0536v1 [hep-ph] 3 Jan 2011

The PDF4LHC Working Group Interim Report

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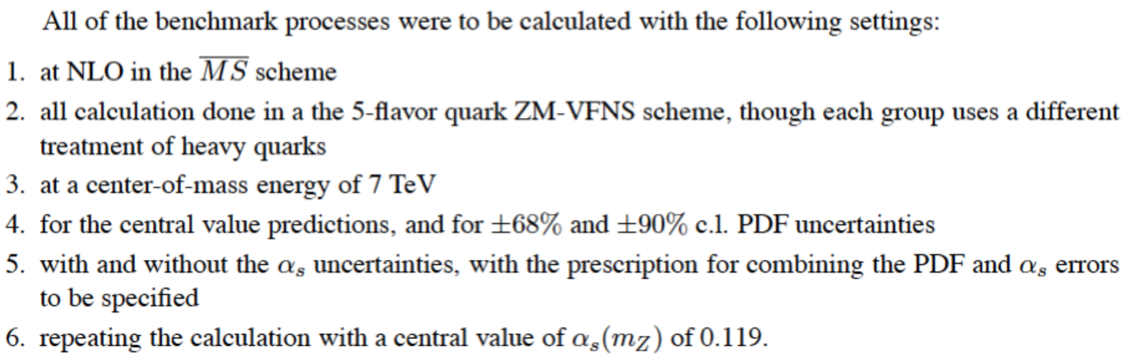
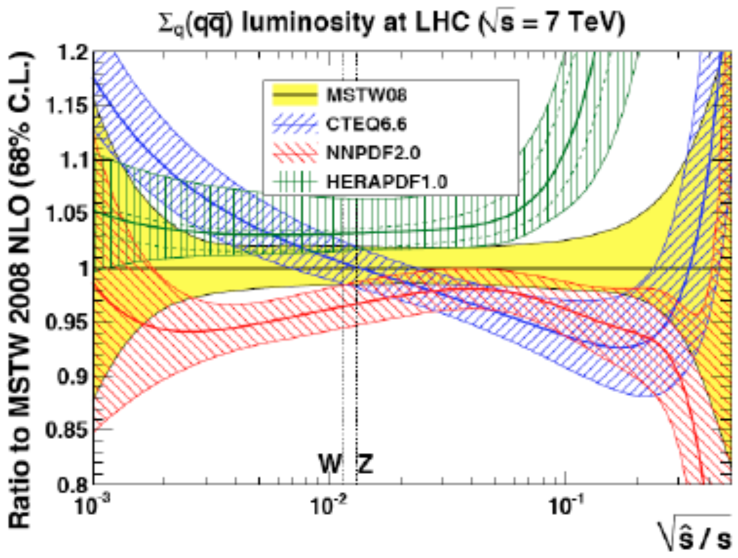


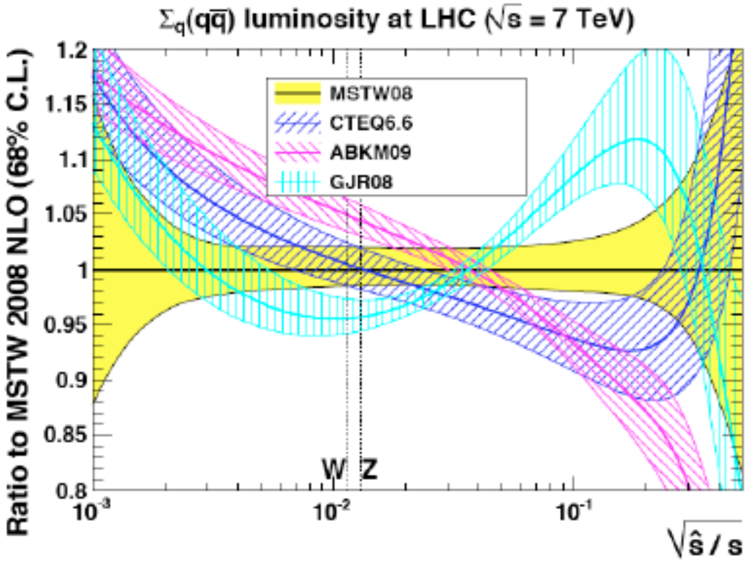
All of the benchmark processes were to be calculated with the following settings:

1. at NLO in the $\overline{MS}$ scheme
2. all calculation done in a the 5-flavor quark ZM-VFNS scheme, though each group uses a different treatment of heavy quarks
3. at a center-of-mass energy of 7 TeV
4. for the central value predictions, and for $\pm 68\%$ and $\pm 90\%$ c.l. PDF uncertainties
5. with and without the α_s uncertainties, with the prescription for combining the PDF and α_s errors to be specified
6. repeating the calculation with a central value of $\alpha_s(m_Z)$ of 0.119.

2010 PDF luminosities

- The qQ luminosities for the groups had different behaviors at low mass and at high mass
- The reasons can often be understood
    - NNPDF2.0 does not use a heavy quark flavor scheme; this suppresses the low x quark and anti-quark distributions (NNPDF2.1 does use such a scheme)
    - HERAPDF uses the HERA combined Run 1 dataset that prefers a higher normalization; the others had not included it yet
- The agreement tends to be much better in the W/Z region

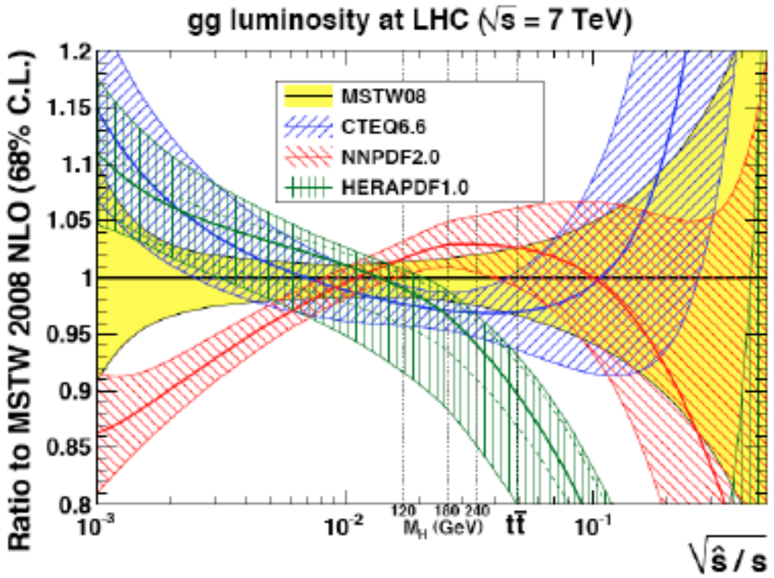


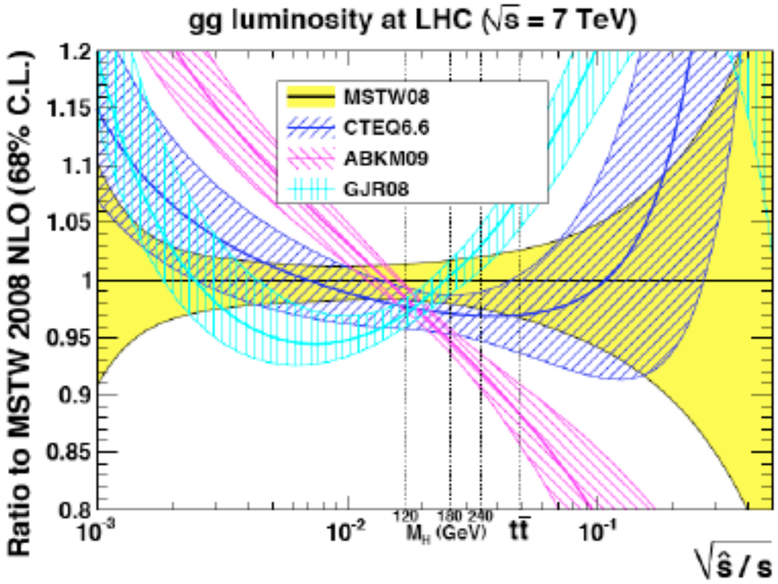


Plots by G. Watt arXiv: 1106.5788

2010 PDFs

- Larger differences are observed for gg luminosities, especially at high mass
  - critically depends on whether Tevatron inclusive jet data have been used or not

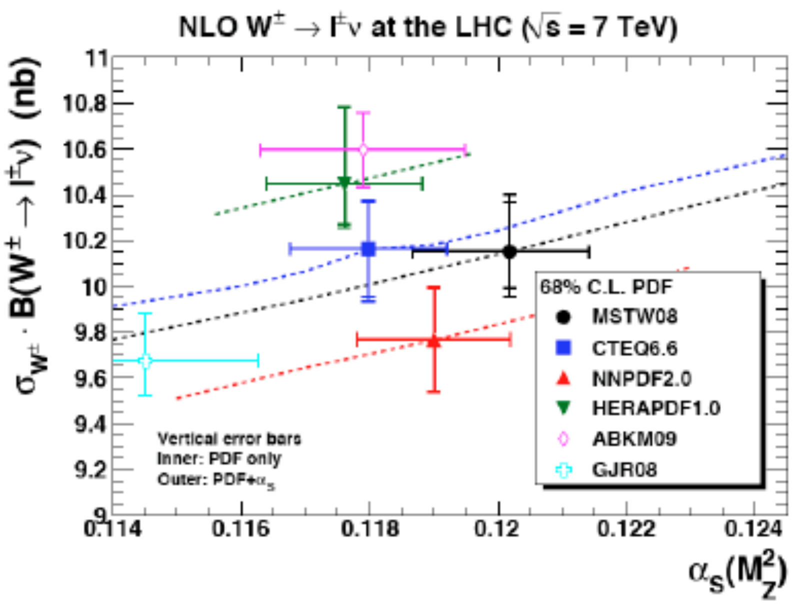


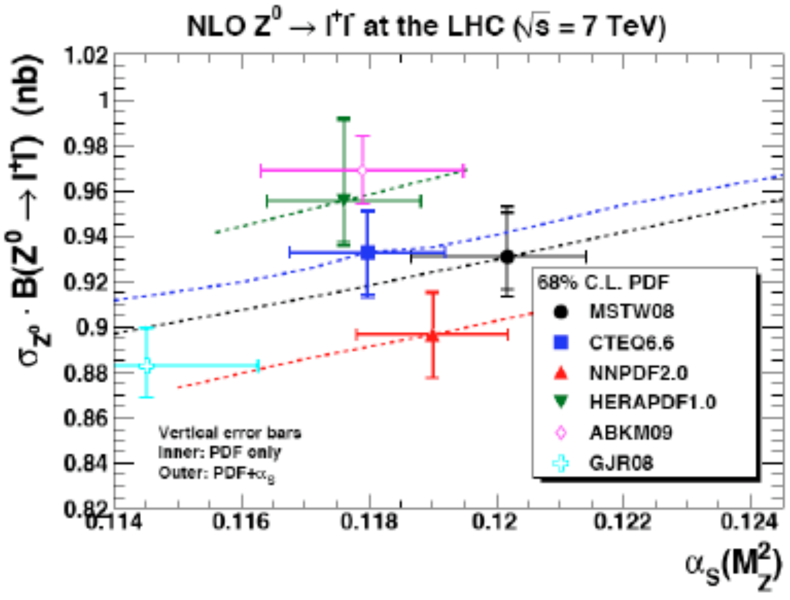


Plots by G. Watt arXiv: 1106.5788

2010 cross section comparisons

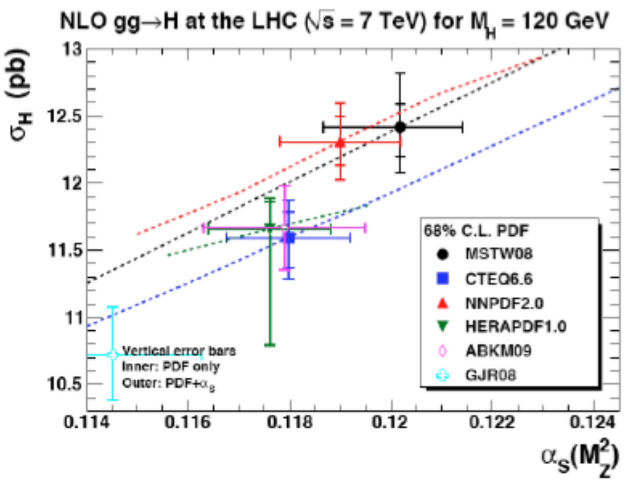
- Notice that the CTEQ and MSTW predictions for W/Z production are very close to each other
- Also, in general, there is very little dependence of the cross sections on the value of $\alpha_s(m_Z)$ (as expected)
- And of course, the higher qQ luminosities observed earlier lead to higher predictions for W/Z cross sections for HERAPDF

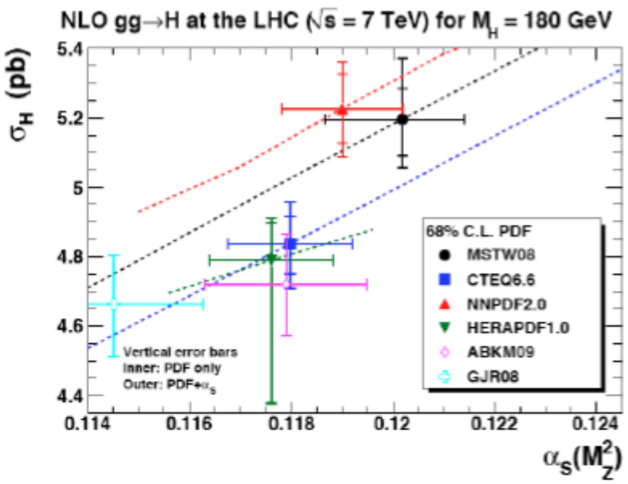




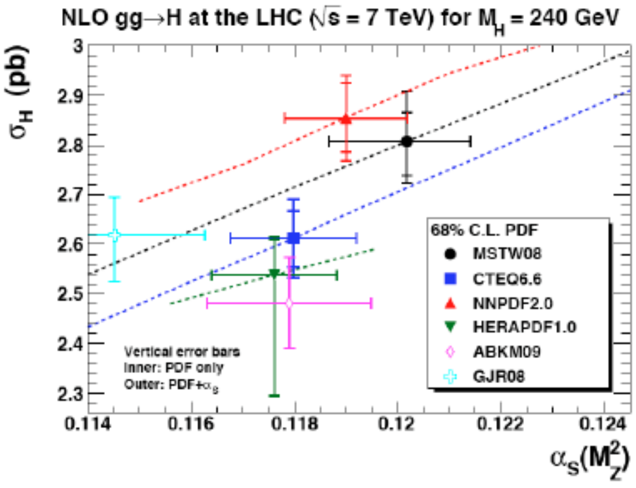
2010 cross section comparisons

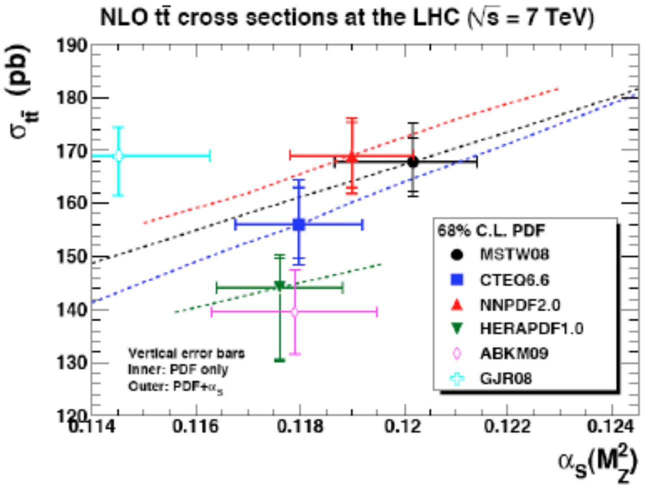
- Larger gg differences and greater dependence on α_s lead to larger differences in Higgs/tT cross section





Note that there tends to be two groupings

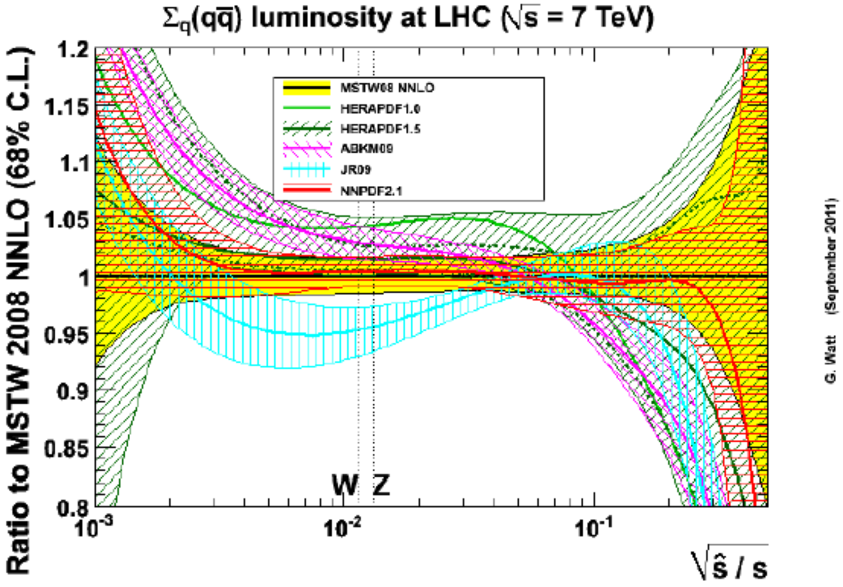


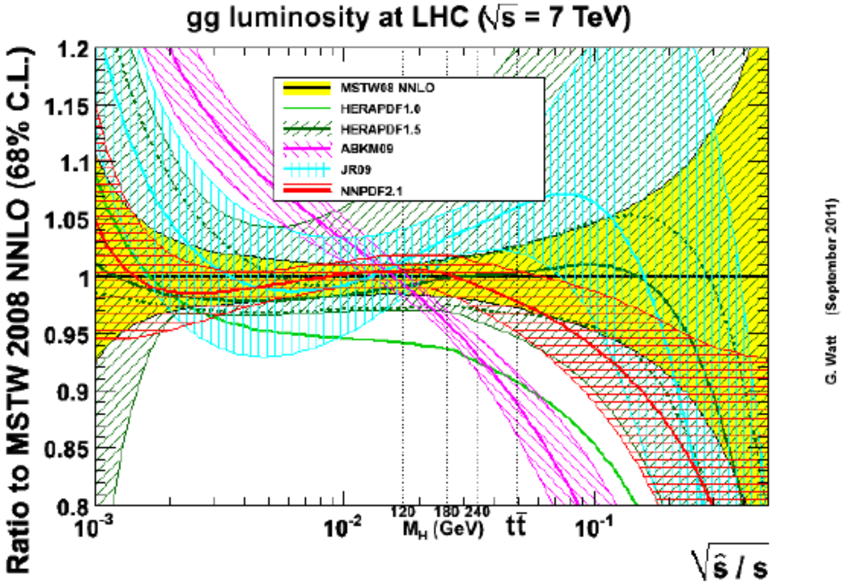


Plots by G. Watt arXiv: 1106.5788

Comparison of NNLO PDF luminosity functions

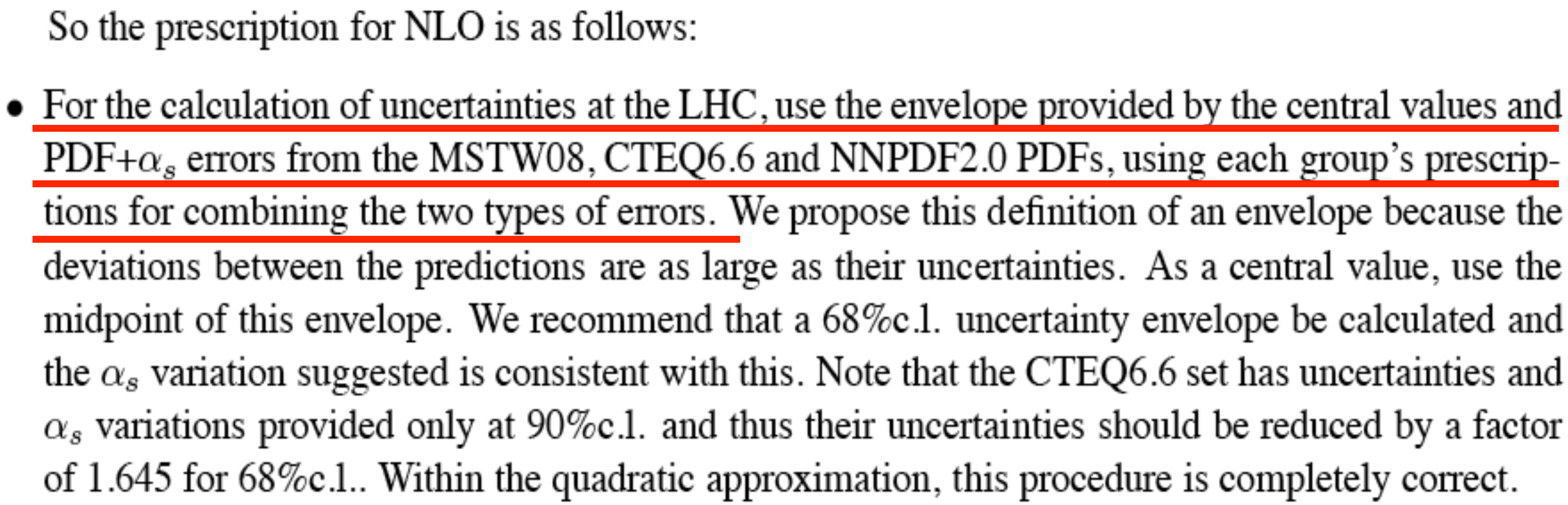
- NNLO trends are similar to those observed at NLO





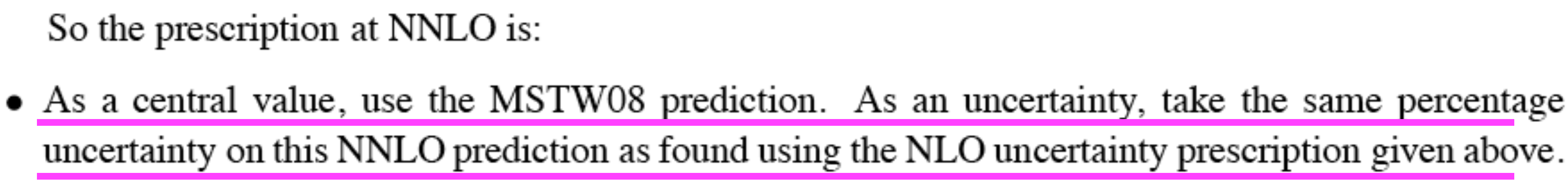
Plots by
G. Watt
arXiv:
1106.5788

PDF4LHC recommendations(arXiv:1101.0538)



So the prescription for NLO is as follows:

- For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+α_s errors from the MSTW08, CTEQ6.6 and NNPDF2.0 PDFs, using each group's prescriptions for combining the two types of errors. We propose this definition of an envelope because the deviations between the predictions are as large as their uncertainties. As a central value, use the midpoint of this envelope. We recommend that a 68%c.l. uncertainty envelope be calculated and the α_s variation suggested is consistent with this. Note that the CTEQ6.6 set has uncertainties and α_s variations provided only at 90%c.l. and thus their uncertainties should be reduced by a factor of 1.645 for 68%c.l.. Within the quadratic approximation, this procedure is completely correct.



So the prescription at NNLO is:

- As a central value, use the MSTW08 prediction. As an uncertainty, take the same percentage uncertainty on this NNLO prediction as found using the NLO uncertainty prescription given above.

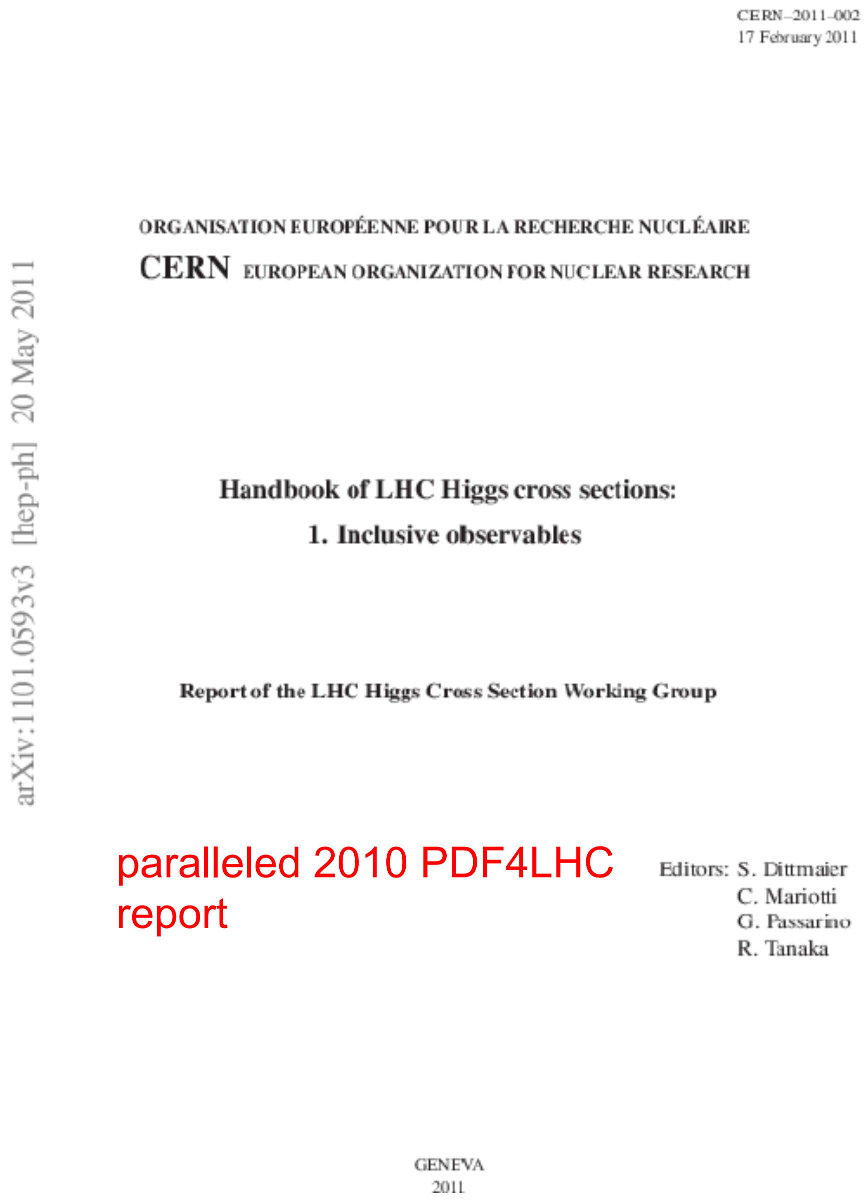
Of course, there is the freedom/encouragement to use any individual PDF desired for comparison to measured cross sections. This has been the norm for the LHC results.

More benchmarking

2 studies in 2011 Les Houches proceedings(1203.6803)

- Benchmarking for inclusive DIS cross sections
  - with S. Alekhin, A. Glazov, A. Guffanti, P. Nadolsky, and J. Rojo
  - excellent agreement observed between CTEQ code with alternative DIS calculation provided by A. Guffanti
- Benchmark comparison of NLO jet cross sections
  - J. Gao, Z. Liang, H.-L. Lai, P. Nadolsky, D. Soper, C.-P. Yuan
  - compare EKS results with FastNLO (NLOJET++)
  - excellent agreement between the two if care is taken on settings for jet algorithm, recombination scheme, QCD scale choices

Higgs Yellow Reports



CERN–2011–002
17 February 2011

arXiv:1101.0593v3 [hep-ph] 20 May 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

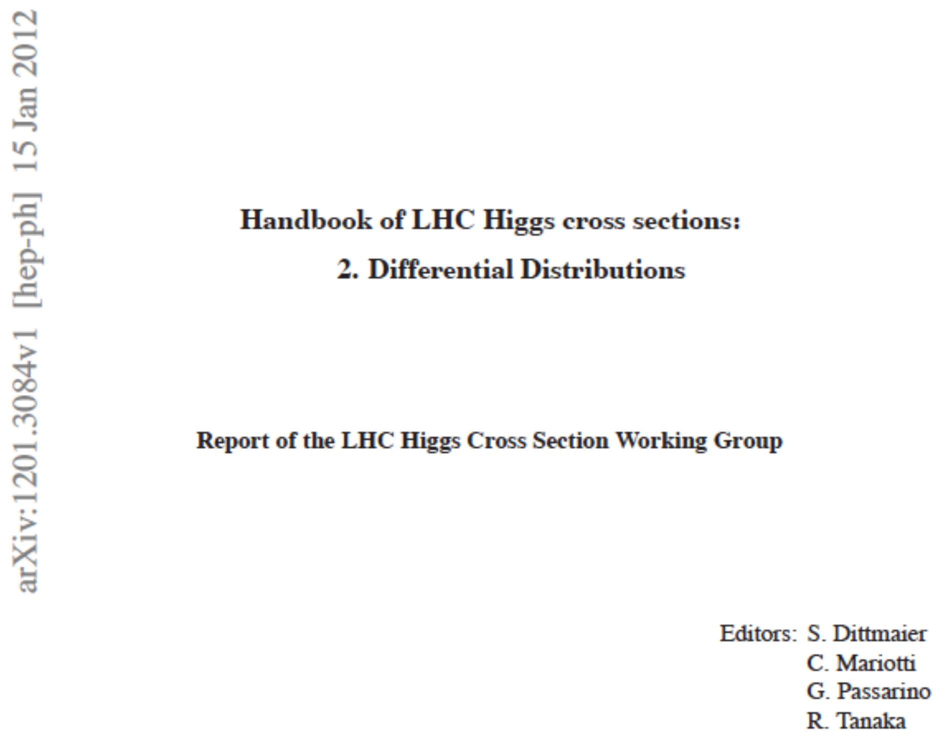
Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

paralleled 2010 PDF4LHC report



arXiv:1201.3084v1 [hep-ph] 15 Jan 2012

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
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R. Tanaka

more extensive use of PDF and cross section correlations

- Correlations differ between PDFs more than I would have originally suspected
- Again, MSTW, CTEQ and NNPDF correlations tend to be similar

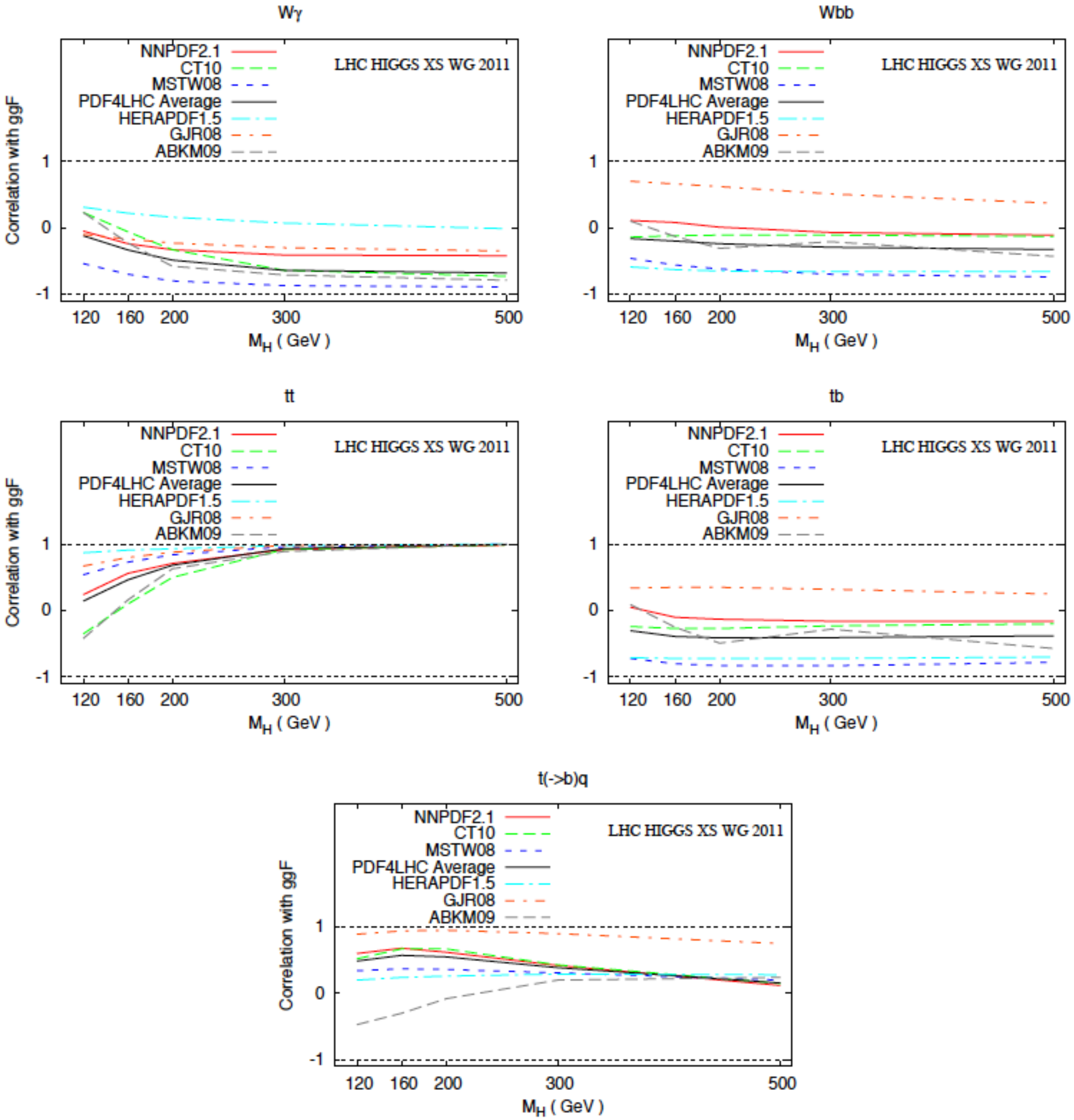

Fig. 15: Correlation between the gluon fusion gg → H process and other signal and background processes as a function of M_H. We show the results for the individual PDF sets as well as the up-to-date PDF4LHC average.

Followup

- Study of NNLO PDFs from 5 PDF groups (no new updates for JR)
  - drawing from what Graeme Watt has done, but now including CT10 NNLO, and NNPDF2.3 NNLO
    - HERAPDF has upgraded to HERAPDF1.5; ABM09->ABM11
  - using a common values of α_s (0.118) as a baseline; varying in range from 0.117 to 0.119)
  - including a detailed comparisons to LHC data which have provided detailed correlated systematic error information, keeping track of required systematic error shifts, normalizations, etc
    - ATLAS 2010 W/Z rapidity distributions
    - ATLAS 2010 inclusive jet cross section data
    - CMS 2011 W lepton asymmetry
    - LHCb 2010 W lepton rapidity distributions in forward region
- The effort was led by Juan Rojo and Pavel Nadolsky and has resulted in an independent publication
- The results from this paper will be utilized in a subsequent PDF4LHC document(s)

…on the archive last Monday

- Not officially a PDF4LHC document but will be used as input to future recommendations
- Comparisons only at NNLO, but NLO comparisons available at http://nnpdf.hepforge.org/html/pdfbench/catalog

CERN-PH-TH/2012-263
Edinburgh 2012/21
SMU-HEP-12-16
LCTS/2012-26
IFUM-1003-FT

Parton distribution benchmarking with LHC data

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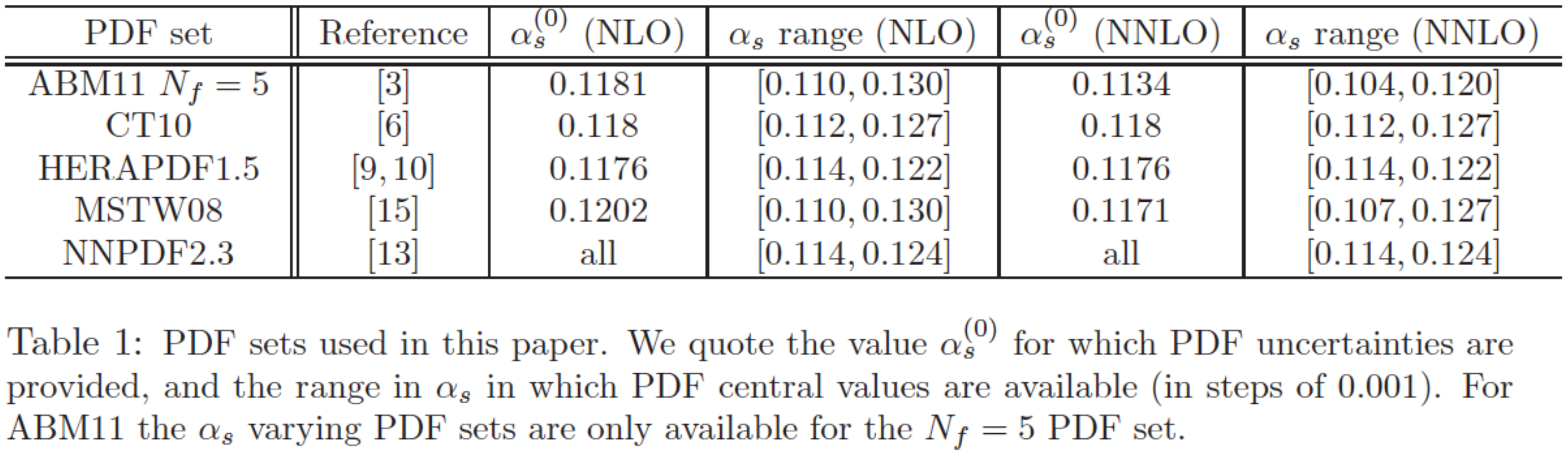
Abstract:

We present a detailed comparison of the most recent sets of NNLO PDFs from the ABM, CT, HERAPDF, MSTW and NNPDF collaborations. We compare parton distributions at low and high scales and parton luminosities relevant for LHC phenomenology. We study the PDF dependence of LHC benchmark inclusive cross sections and differential distributions for electroweak boson and jet production in the cases in which the experimental covariance matrix is available. We quantify the agreement between data and theory by computing the χ^2 for each data set with all the various PDFs. PDF comparisons are performed consistently for common values of the strong coupling. We also present a benchmark comparison of jet production at the LHC, comparing the results from various available codes and scale settings. Finally, we discuss the implications of the updated NNLO PDF sets for the combined PDF+α_s uncertainty in the gluon fusion Higgs production cross section.

PDFs used in the comparison



PDF set	Reference	$\alpha_s^{(0)}$ (NLO)	α_s range (NLO)	$\alpha_s^{(0)}$ (NNLO)	α_s range (NNLO)
ABM11 $N_f = 5$	[3]	0.1181	$[0.110, 0.130]$	0.1134	$[0.104, 0.120]$
CT10	[6]	0.118	$[0.112, 0.127]$	0.118	$[0.112, 0.127]$
HERAPDF1.5	[9, 10]	0.1176	$[0.114, 0.122]$	0.1176	$[0.114, 0.122]$
MSTW08	[15]	0.1202	$[0.110, 0.130]$	0.1171	$[0.107, 0.127]$
NNPDF2.3	[13]	all	$[0.114, 0.124]$	all	$[0.114, 0.124]$

Table 1: PDF sets used in this paper. We quote the value $\alpha_s^{(0)}$ for which PDF uncertainties are provided, and the range in α_s in which PDF central values are available (in steps of 0.001). For ABM11 the α_s varying PDF sets are only available for the $N_f = 5$ PDF set.

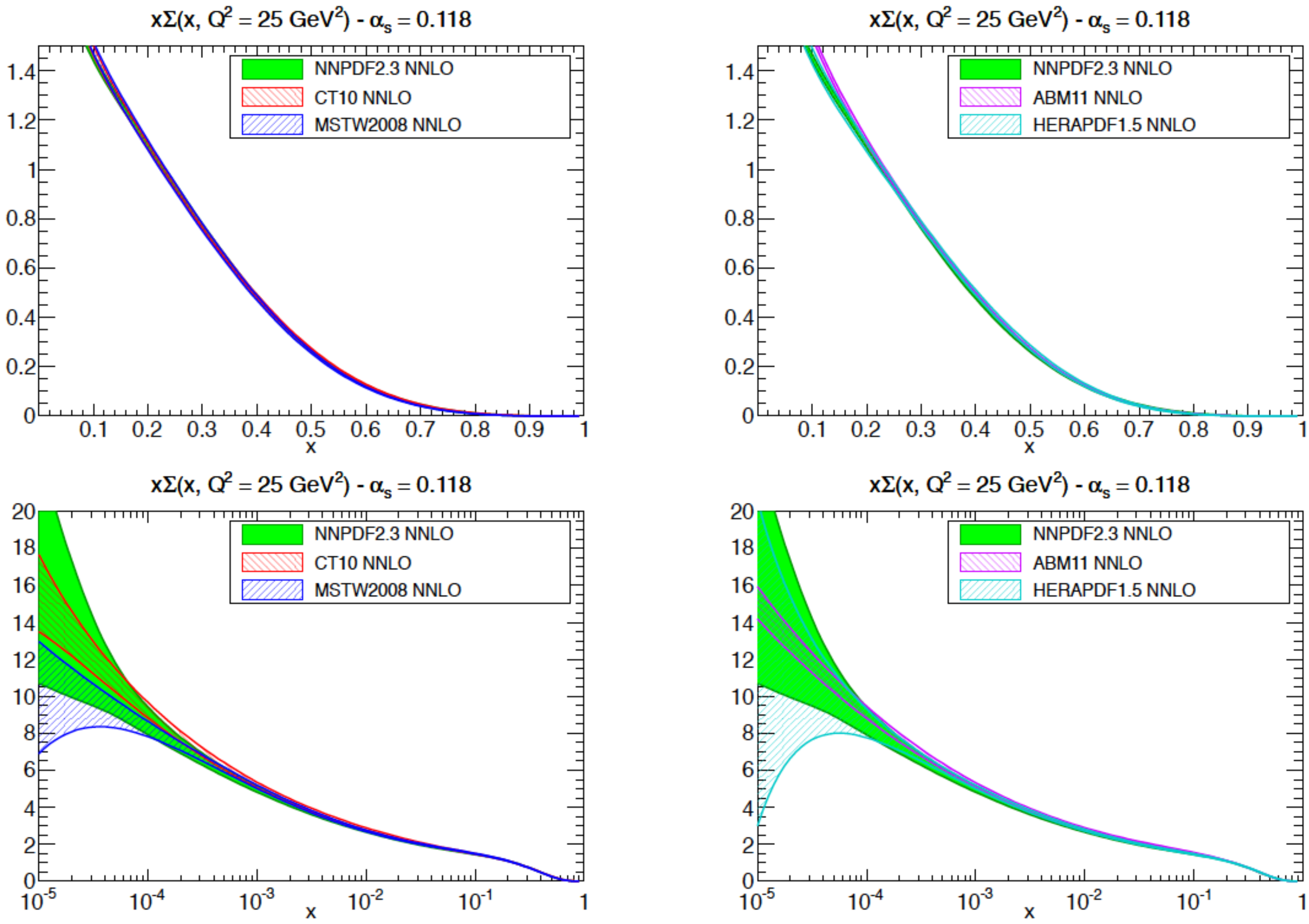
No updates of JR since 2009, but one should be forthcoming in the near future.

PDF comparisons

…results for other values of α_s and at NLO available on the HEPFORGE website

good agreement for all sets for quark singlet distribution

quark singlet PDFs



Comparison of PDFs

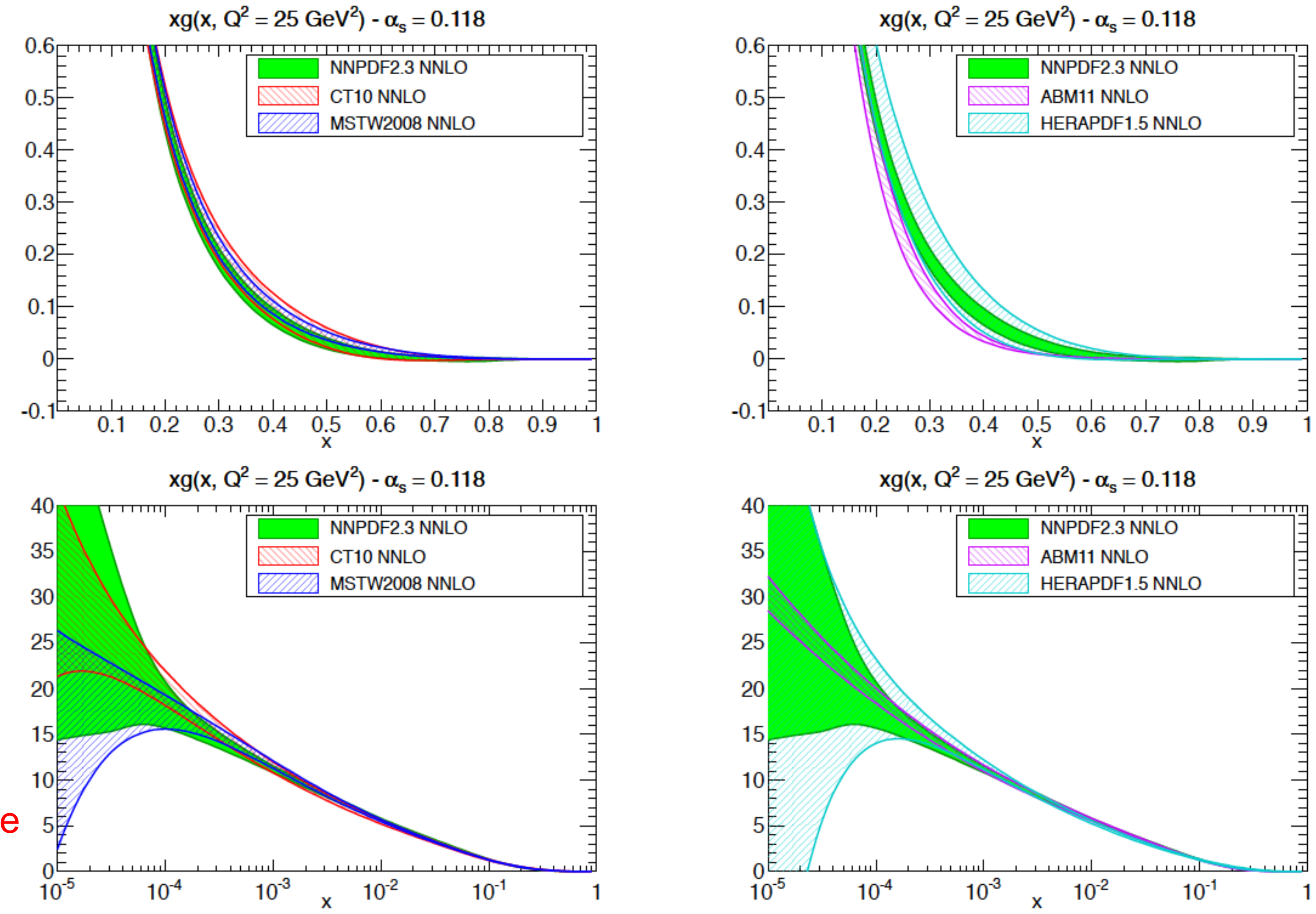
CT10, MSTW08 and NNPDF2.3 gluon distributions all in reasonable agreement

The 1-sigma uncertainty bands overlap for all values of x

Differences are larger for ABM11

HERAPDF uncertainties similar to other PDF sets at low x; larger at high x due to lack of collider jet data

gluon PDF



PDF luminosities

gluon-gluon and gluon-quark luminosities in reasonable agreement for CT10, MSTW08 and NNPDF2.3 for full range of invariant masses

HERAPDF1.5 uncertainties larger in general

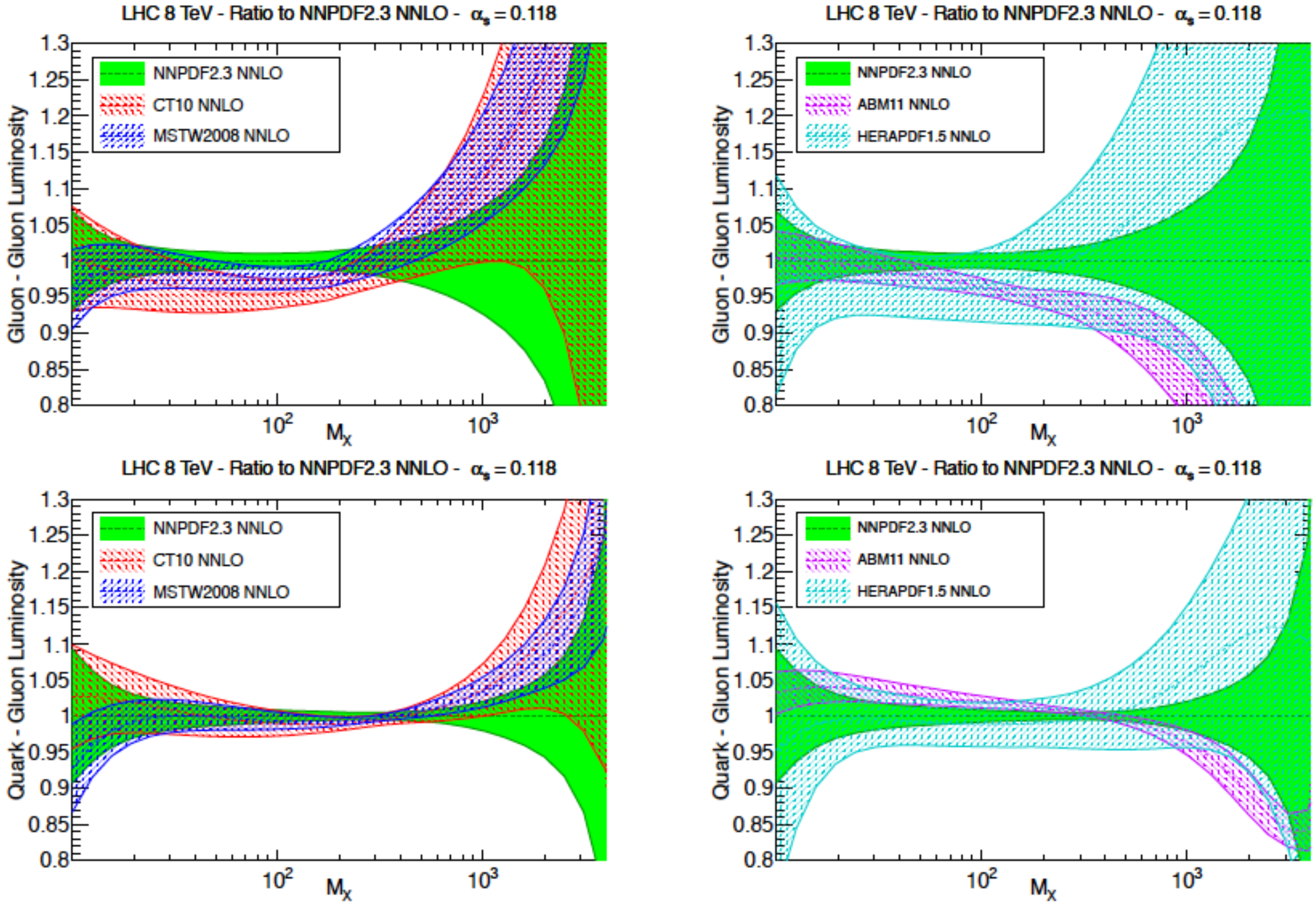
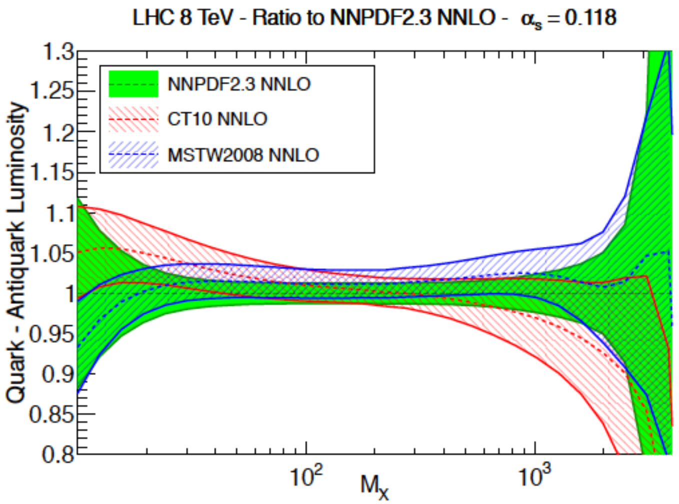


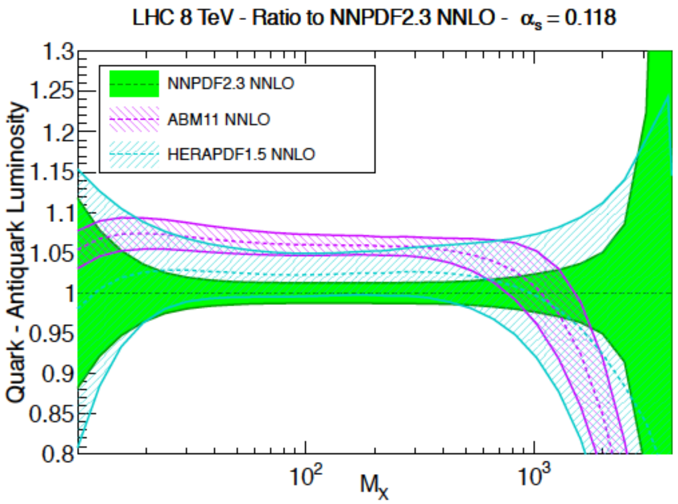
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5 and MSTW08. All luminosities are computed at a common value of $\alpha_s = 0.118$.

PDF luminosities

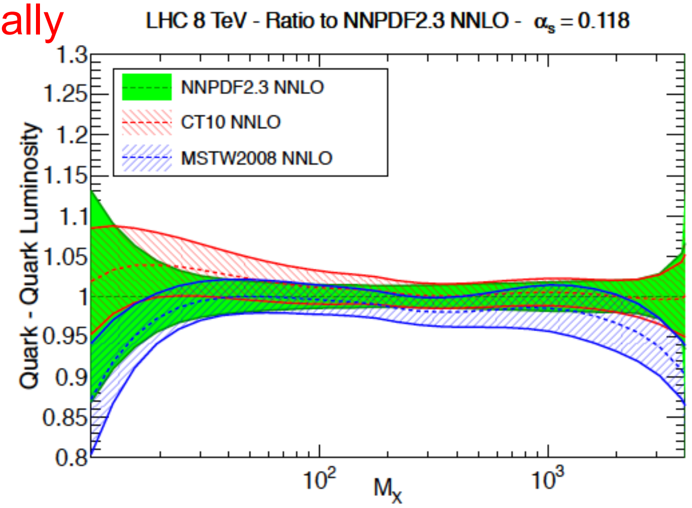
quark-quark and quark-antiquark

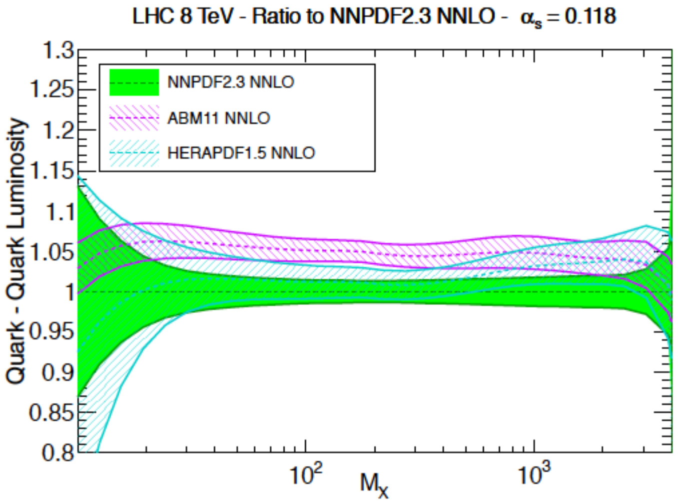
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range





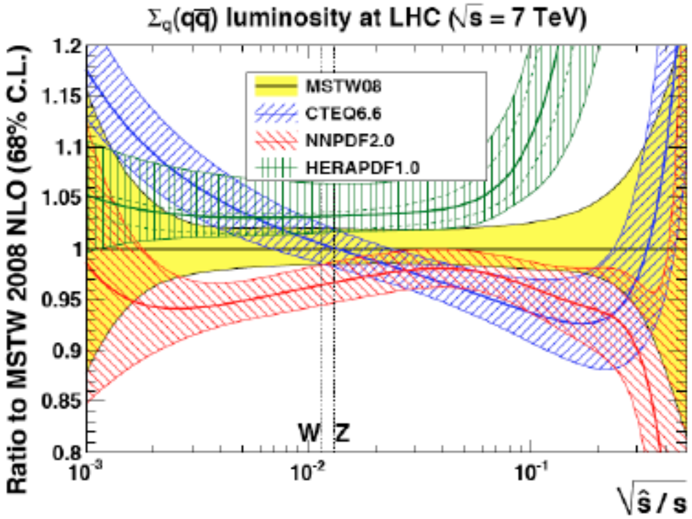
ABM11 systematically larger at small mass, then falls off more rapidly at high mass

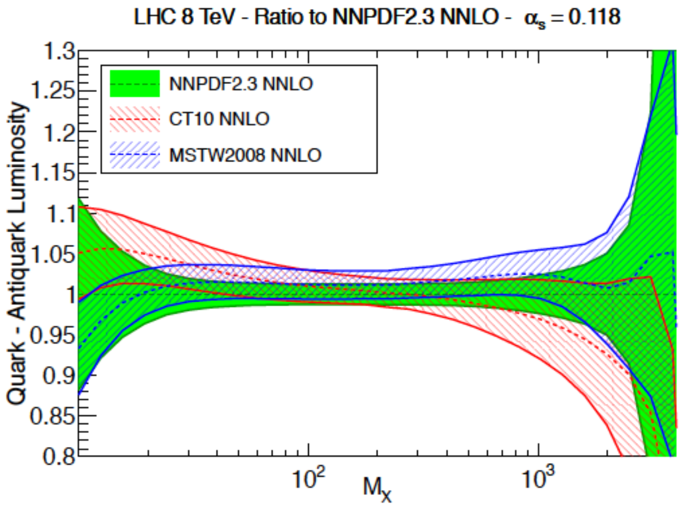


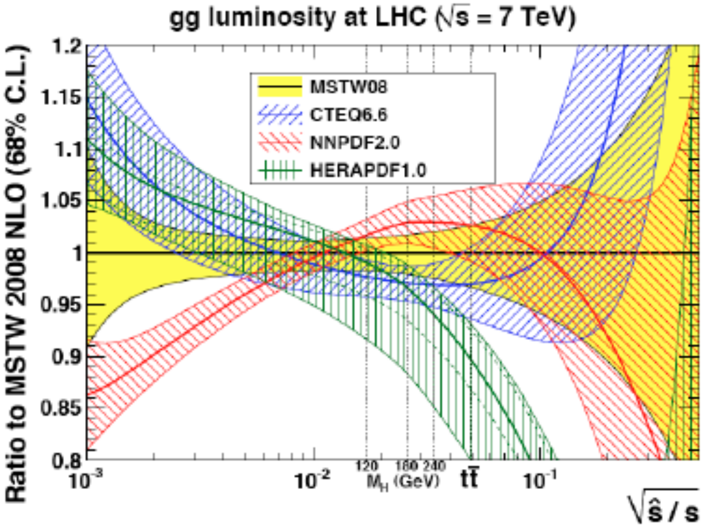


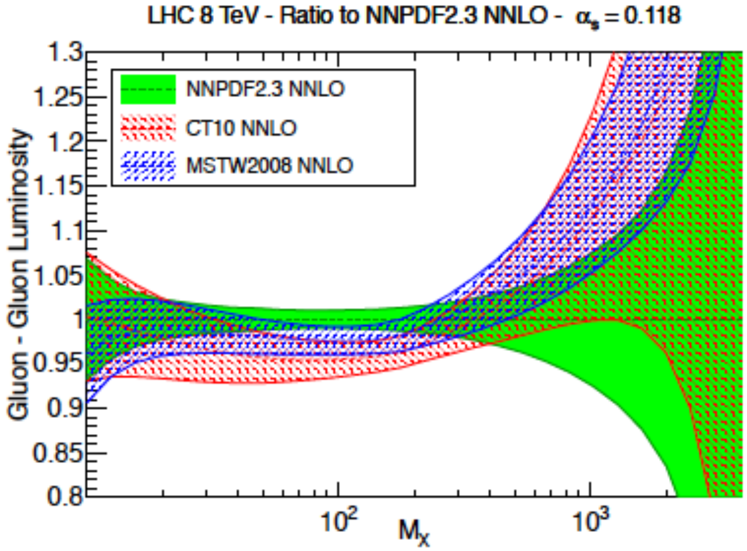
Uncertainties have improved

- …with additional data and in going from NLO to NNLO



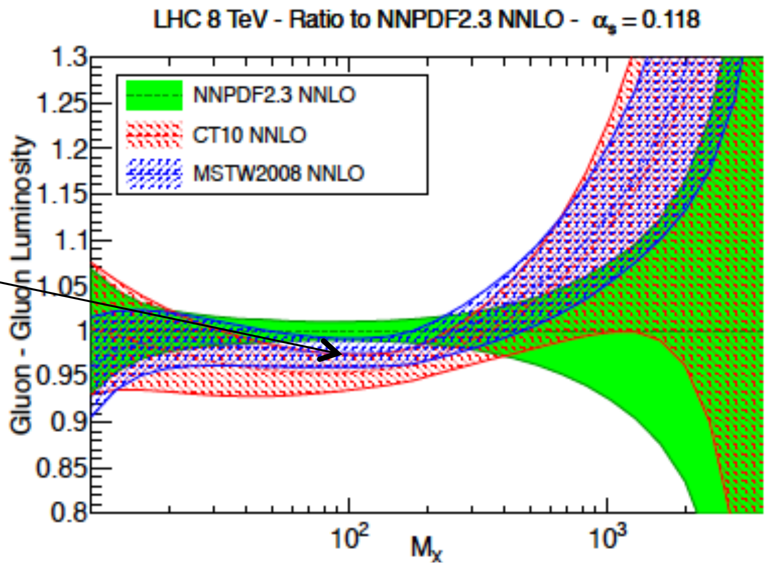


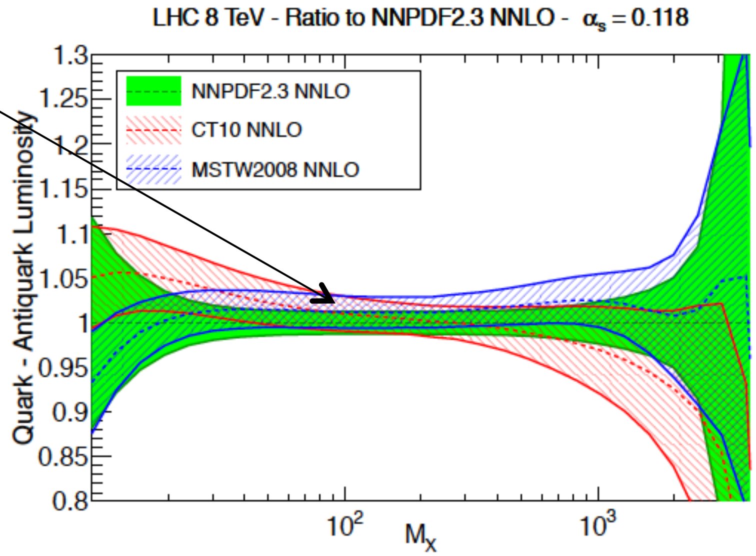




NNLO PDF uncertainties

- Factor of 2 expansion of MSTW2008 error basically works for gg initial states (like 125 Higgs)
- …but maybe an overestimate for qQ initial states





Compare relative luminosity uncertainties

good agreement in size of uncertainties between the 3 global PDFs

larger uncertainties of HERAPDF1.5 apparent

ABM11 uncertainties smaller at high mass

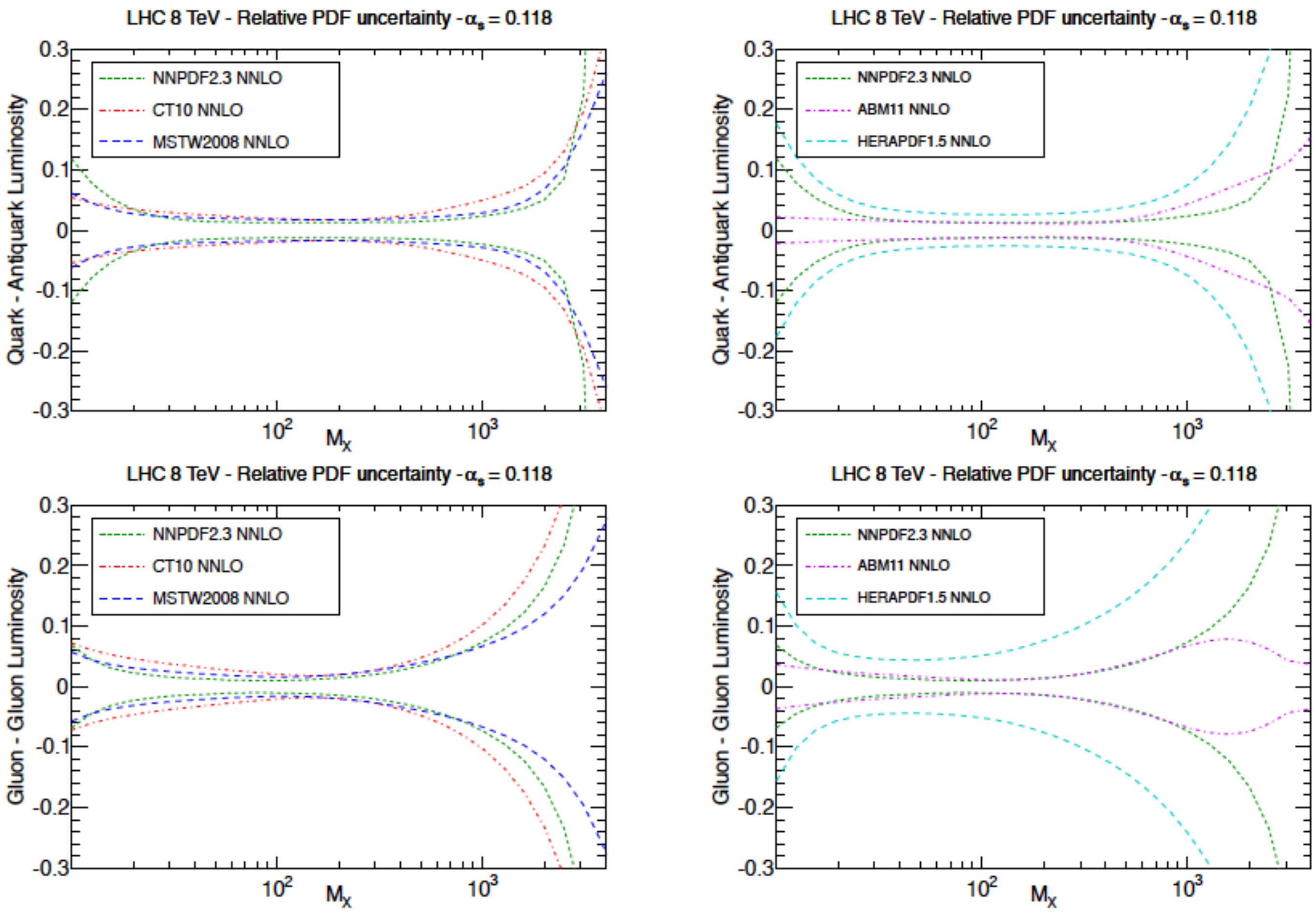


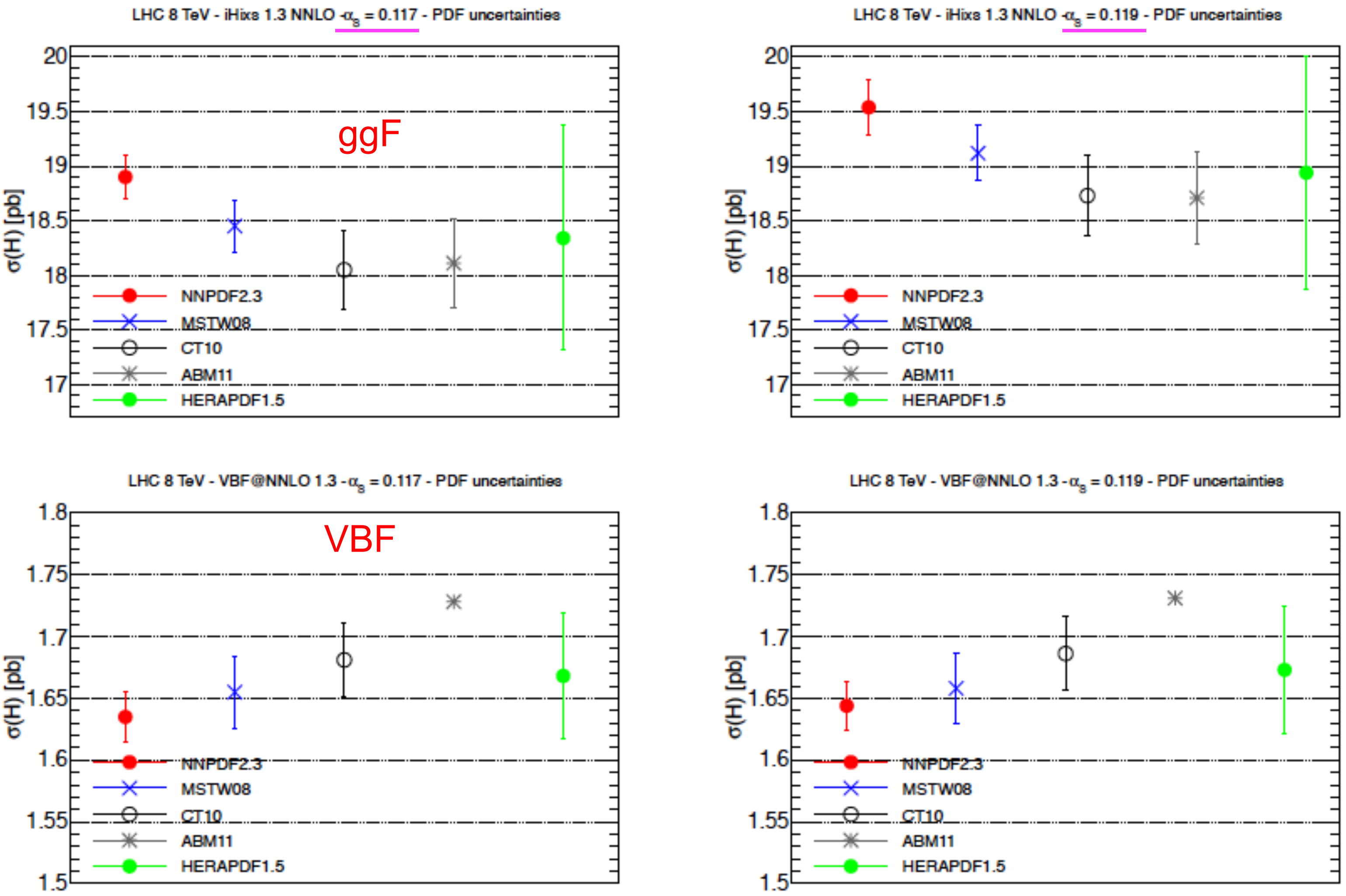
Figure 8: The relative PDF uncertainties in the quark-antiquark luminosity (upper plots) and in the gluon-gluon luminosity (lower plots), for the production of a final state of invariant mass M_X (in GeV) at the LHC 8 TeV. All luminosities are computed at a common value of $\alpha_s = 0.118$.

8 TeV Higgs cross section predictions

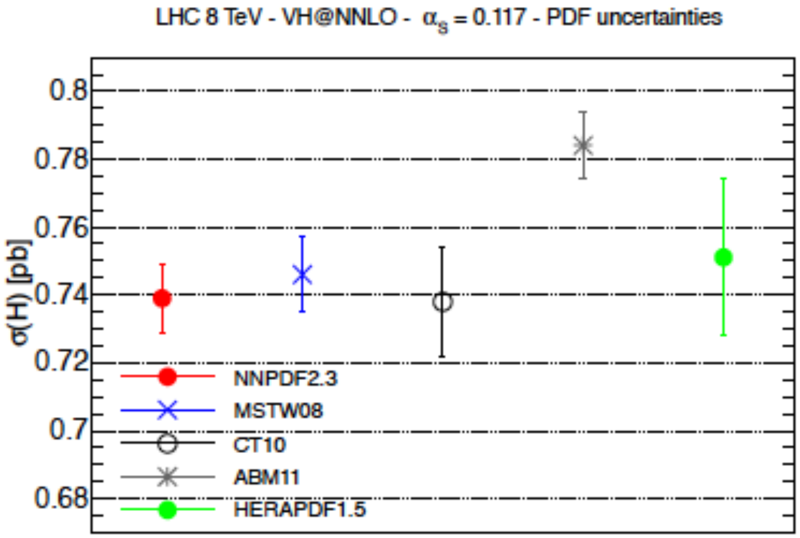
cross sections calculated at NNLO using a scale of m_H

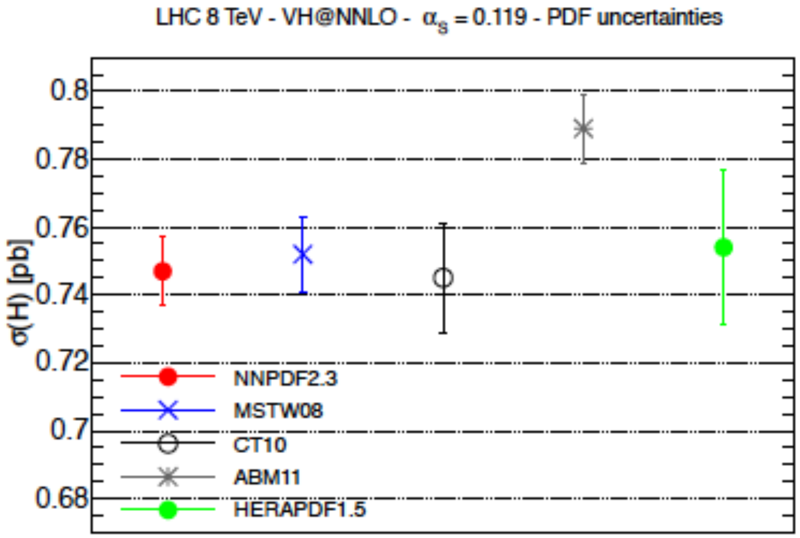
ABM11 and HERAPDF1.5 predictions within error envelope

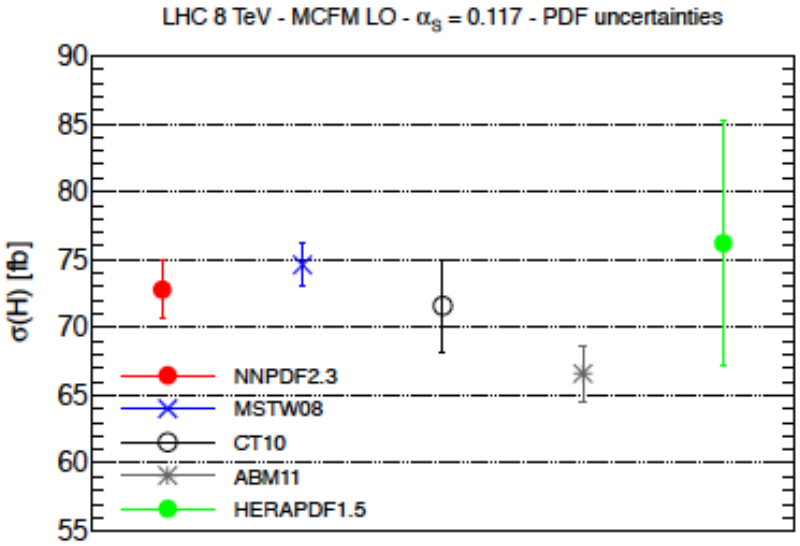
NB: ABM11 cross section would be lower if native value of α_s (0.1134) used

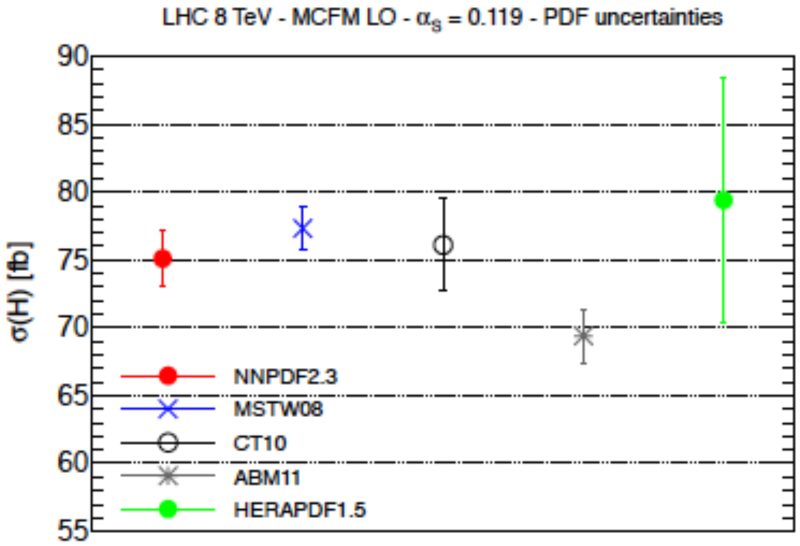


More 8 TeV Higgs cross section predictions

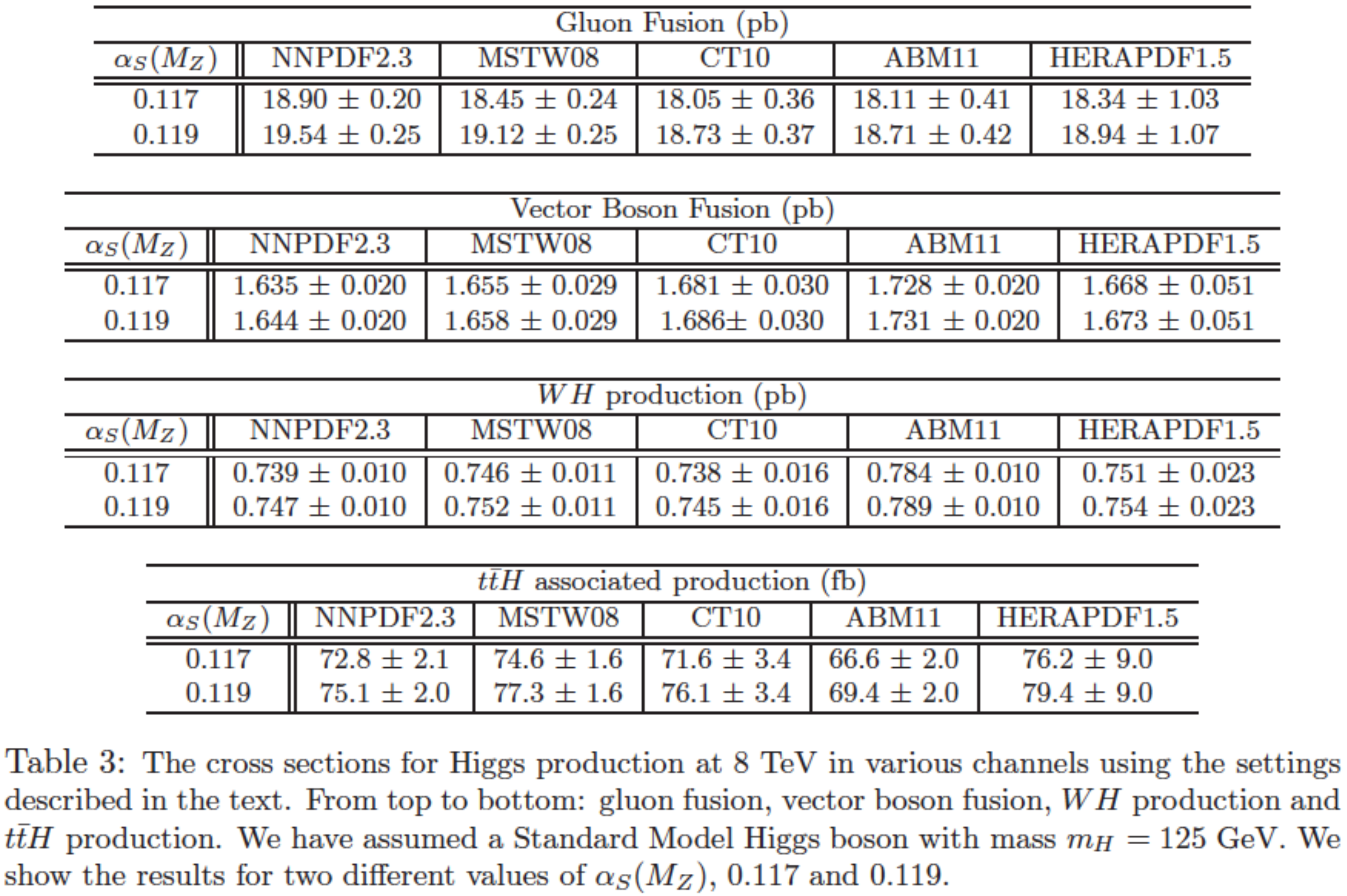

LHC 8 TeV - VH@NNLO - $\alpha_s = 0.117$ - PDF uncertainties


LHC 8 TeV - VH@NNLO - $\alpha_s = 0.119$ - PDF uncertainties


LHC 8 TeV - MCFM LO - $\alpha_s = 0.117$ - PDF uncertainties


LHC 8 TeV - MCFM LO - $\alpha_s = 0.119$ - PDF uncertainties

8 TeV NNLO Higgs Cross Section Predictions



Gluon Fusion (pb)

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.117	18.90 ± 0.20	18.45 ± 0.24	18.05 ± 0.36	18.11 ± 0.41	18.34 ± 1.03
0.119	19.54 ± 0.25	19.12 ± 0.25	18.73 ± 0.37	18.71 ± 0.42	18.94 ± 1.07

Vector Boson Fusion (pb)

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.117	1.635 ± 0.020	1.655 ± 0.029	1.681 ± 0.030	1.728 ± 0.020	1.668 ± 0.051
0.119	1.644 ± 0.020	1.658 ± 0.029	1.686± 0.030	1.731 ± 0.020	1.673 ± 0.051

WH production (pb)

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.117	0.739 ± 0.010	0.746 ± 0.011	0.738 ± 0.016	0.784 ± 0.010	0.751 ± 0.023
0.119	0.747 ± 0.010	0.752 ± 0.011	0.745 ± 0.016	0.789 ± 0.010	0.754 ± 0.023

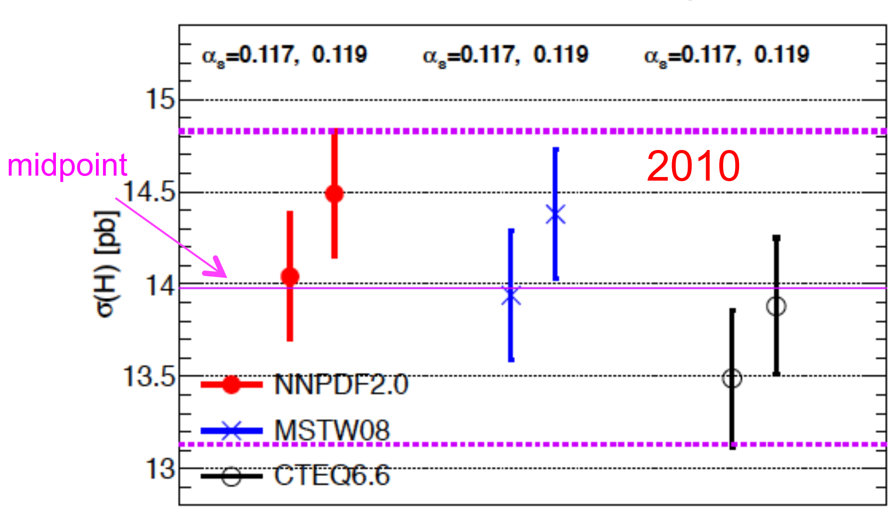
$t\bar{t}H$ associated production (fb)

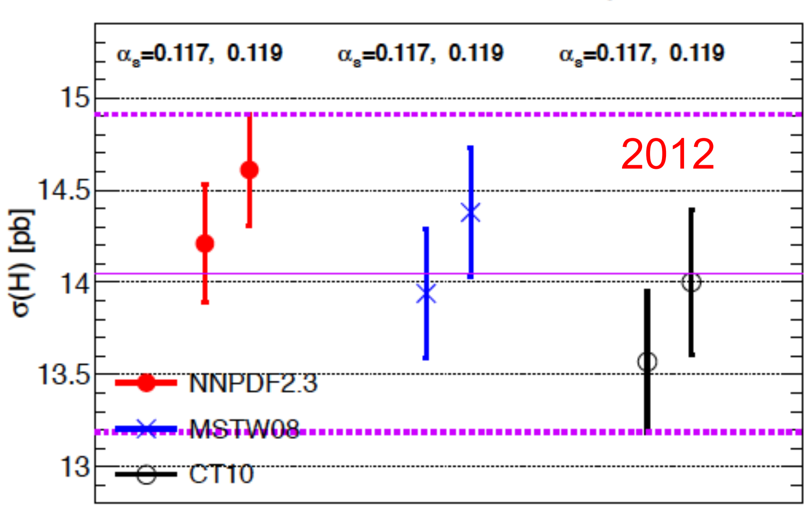
$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.117	72.8 ± 2.1	74.6 ± 1.6	71.6 ± 3.4	66.6 ± 2.0	76.2 ± 9.0
0.119	75.1 ± 2.0	77.3 ± 1.6	76.1 ± 3.4	69.4 ± 2.0	79.4 ± 9.0

Table 3: The cross sections for Higgs production at 8 TeV in various channels using the settings described in the text. From top to bottom: gluon fusion, vector boson fusion, WH production and $t\bar{t}H$ production. We have assumed a Standard Model Higgs boson with mass $m_H = 125$ GeV. We show the results for two different values of $\alpha_S(M_Z)$, 0.117 and 0.119.

Revisit prescriptions (for 8 TeV cross sections)

$$\sigma_H^{\mathrm{NLO}} = 13.98 \pm 0.85 \text{ pb}, \qquad (\pm 6.1\% \text{ "PDF} + \alpha_s\text{"}) \rightarrow \sigma_H^{\mathrm{NLO}} = 14.05 \pm 0.86 \text{ pb}, \qquad (\pm 6.1\% \text{ "PDF} + \alpha_s\text{"})$$


LHC 8 TeV - iHixs 1.3 NLO - 2010 PDFs - PDF +α_s uncertainties


LHC 8 TeV - iHixs 1.3 NLO - 2012 PDFs - PDF+ α_s uncertainties

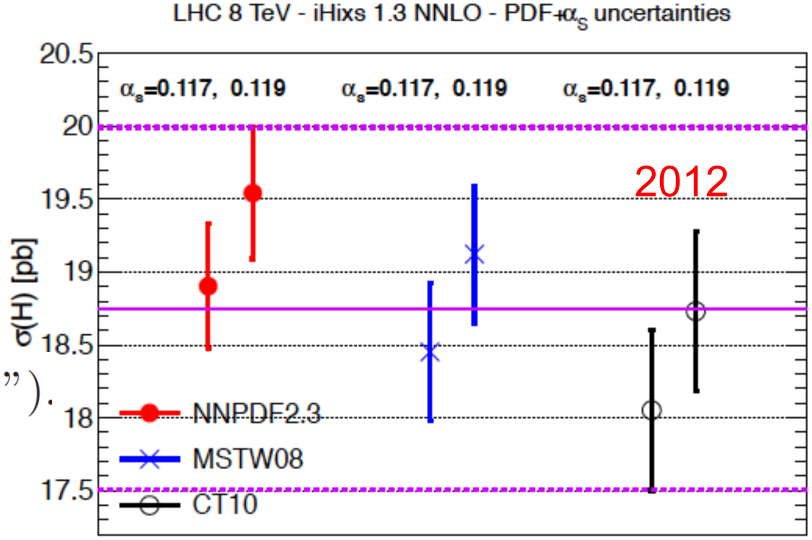
$$\sigma_H^{NNLO} = 18.75 \pm 1.24 \;\; \text{pb}, \qquad (6.6\% \text{ "PDF} + \alpha_s\text{"}).$$

Compare to MSTW08 NNLO value of 18.45 pb (2010 prescription)

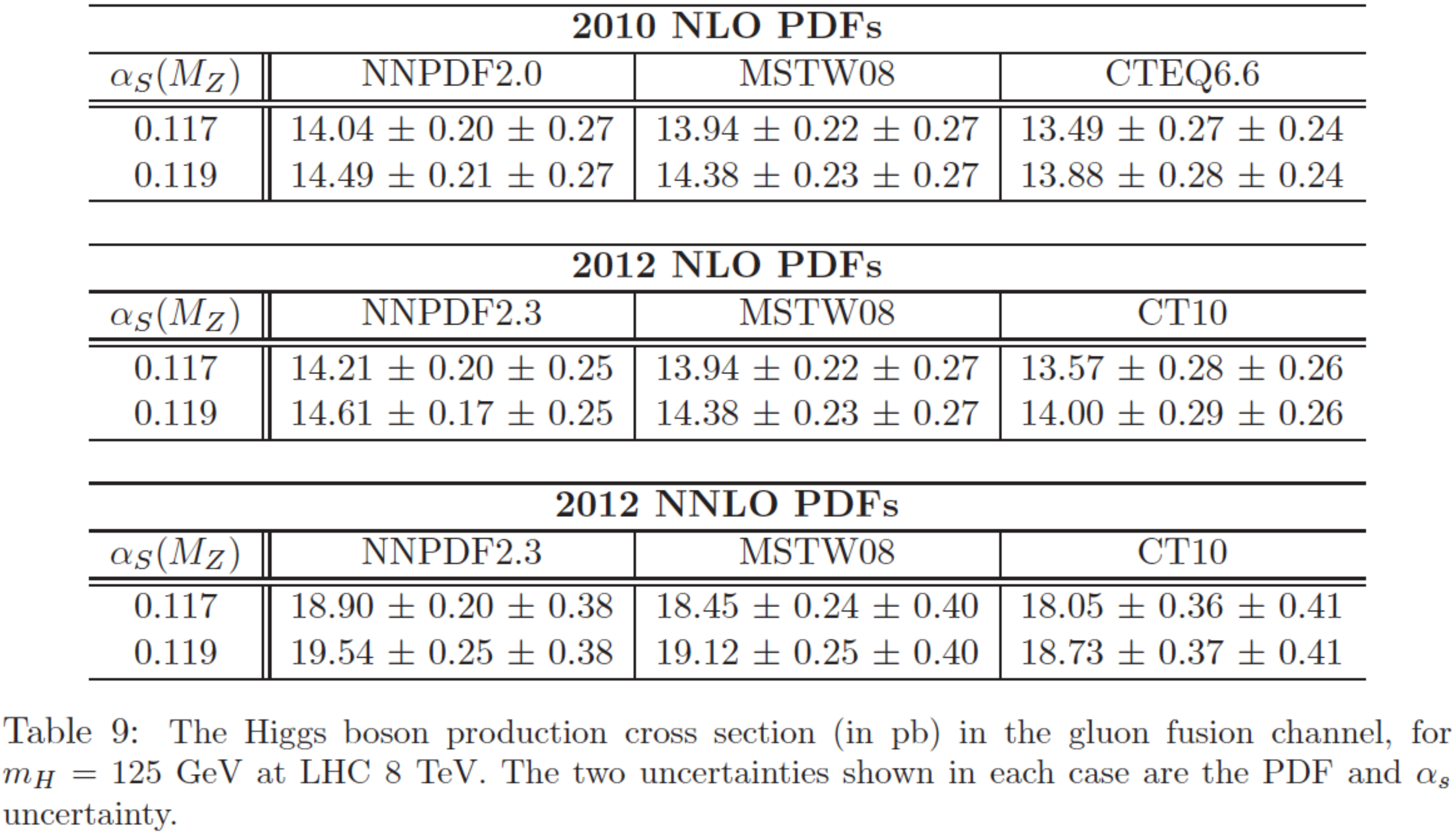
HXSWG 8 TeV NNLO cross section

$$\sigma_H^{\mathrm{NNLO}} = 19.52 \pm 1.41 \text{ pb}, \qquad (\pm 7.2\% \text{ "PDF} + \alpha_s\text{"}).$$

NNLO+NNLL


LHC 8 TeV - iHixs 1.3 NNLO - PDF+α_s uncertainties

Higgs cross section predictions



2010 NLO PDFs

$\alpha_S(M_Z)$	NNPDF2.0	MSTW08	CTEQ6.6
0.117	14.04 ± 0.20 ± 0.27	13.94 ± 0.22 ± 0.27	13.49 ± 0.27 ± 0.24
0.119	14.49 ± 0.21 ± 0.27	14.38 ± 0.23 ± 0.27	13.88 ± 0.28 ± 0.24

2012 NLO PDFs

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10
0.117	14.21 ± 0.20 ± 0.25	13.94 ± 0.22 ± 0.27	13.57 ± 0.28 ± 0.26
0.119	14.61 ± 0.17 ± 0.25	14.38 ± 0.23 ± 0.27	14.00 ± 0.29 ± 0.26

2012 NNLO PDFs

$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10
0.117	18.90 ± 0.20 ± 0.38	18.45 ± 0.24 ± 0.40	18.05 ± 0.36 ± 0.41
0.119	19.54 ± 0.25 ± 0.38	19.12 ± 0.25 ± 0.40	18.73 ± 0.37 ± 0.41

Table 9: The Higgs boson production cross section (in pb) in the gluon fusion channel, for $m_H = 125$ GeV at LHC 8 TeV. The two uncertainties shown in each case are the PDF and α_s uncertainty.

8 TeV tT cross section predictions

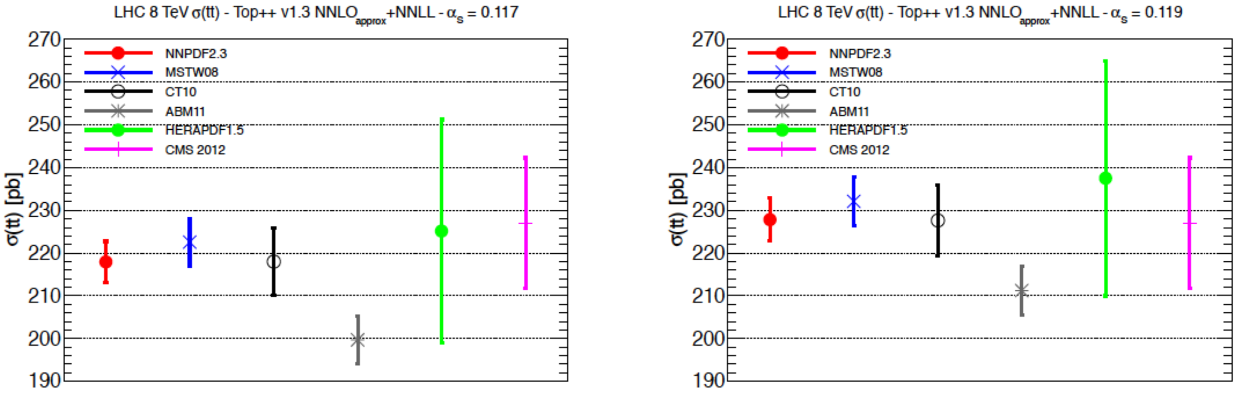


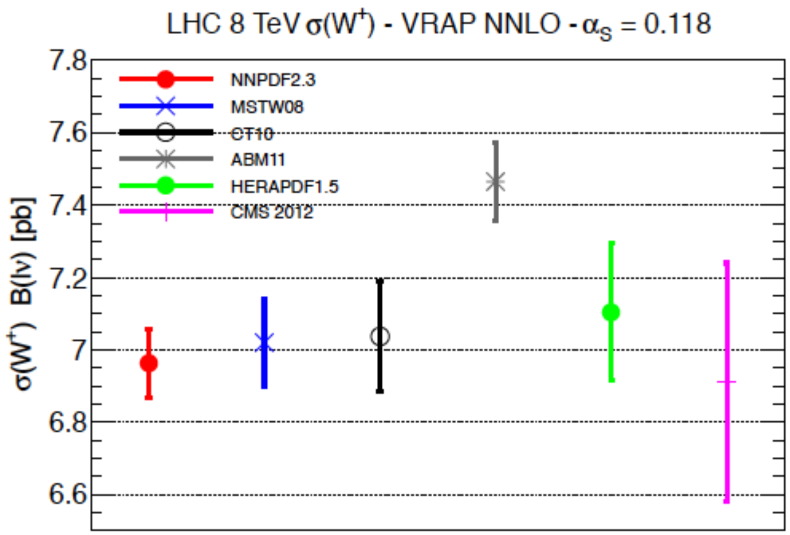
Figure 10: Comparison of the predictions for the top quark pair production at LHC 8 TeV obtained using various NNLO PDF sets. Left plot: results for $\alpha_S(M_Z) = 0.117$. Right plot: results for $\alpha_S(M_Z) = 0.119$. In both cases we also show the recent CMS 8 TeV measurement.

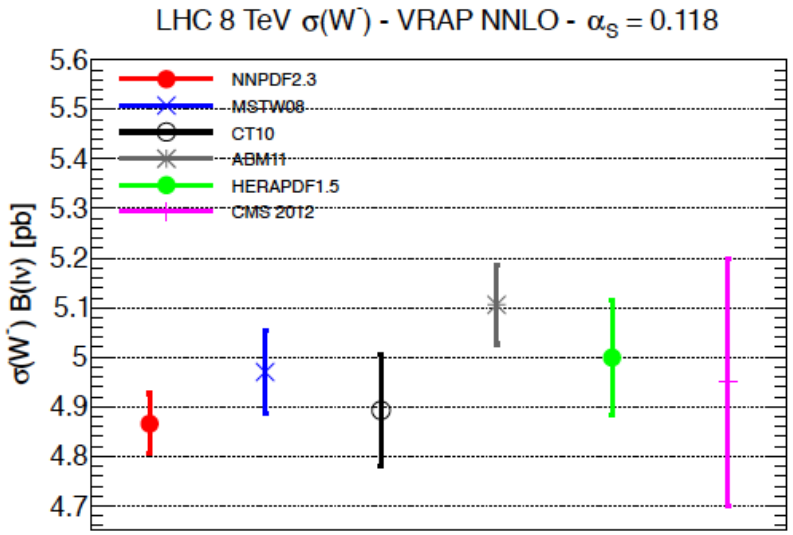
…with the data in 2012 and with the completion of the NNLO top cross section, top will provide very useful information on the gg PDF luminosity

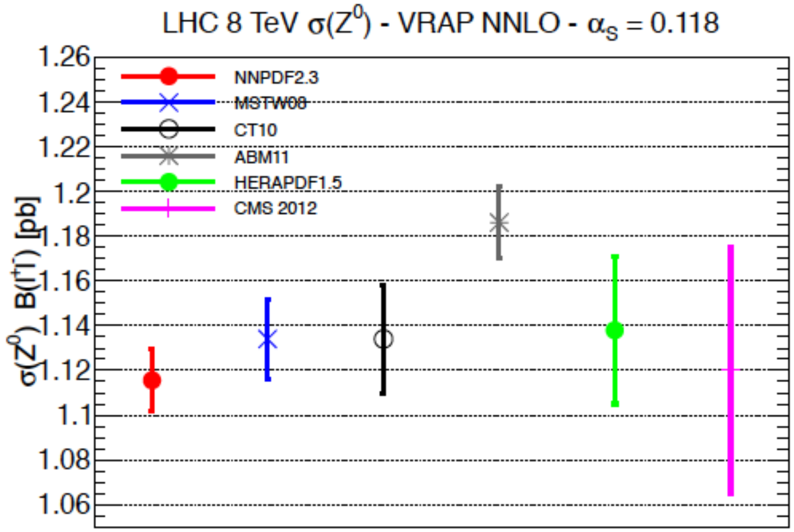
	$t\bar{t}$ production (pb)				
$\alpha_S(M_Z)$	NNPDF2.3	MSTW08	CT10	ABM11	HERAPDF1.5
0.117	217.9 ± 4.8	222.5 ± 5.5	218.0 ± 7.8	199.7 ± 5.5	225.1 ± 26.1
0.119	227.8 ± 5.0	232.1 ± 5.8	227.6 ± 8.2	211.2 ± 5.8	237.5 ± 27.5

Table 4: Same as Tab. 3 for the cross sections for top quark pair production at 8 TeV at NNLO$_{\text{approx}}$+NNLL, using `top++` with the settings described in the text. We have assumed a top quark mass of $m_t = 173.2$ GeV.

8 TeV W/Z cross sections







2010 to 2012 comparison

- Better agreement in going from NLO to NNLO

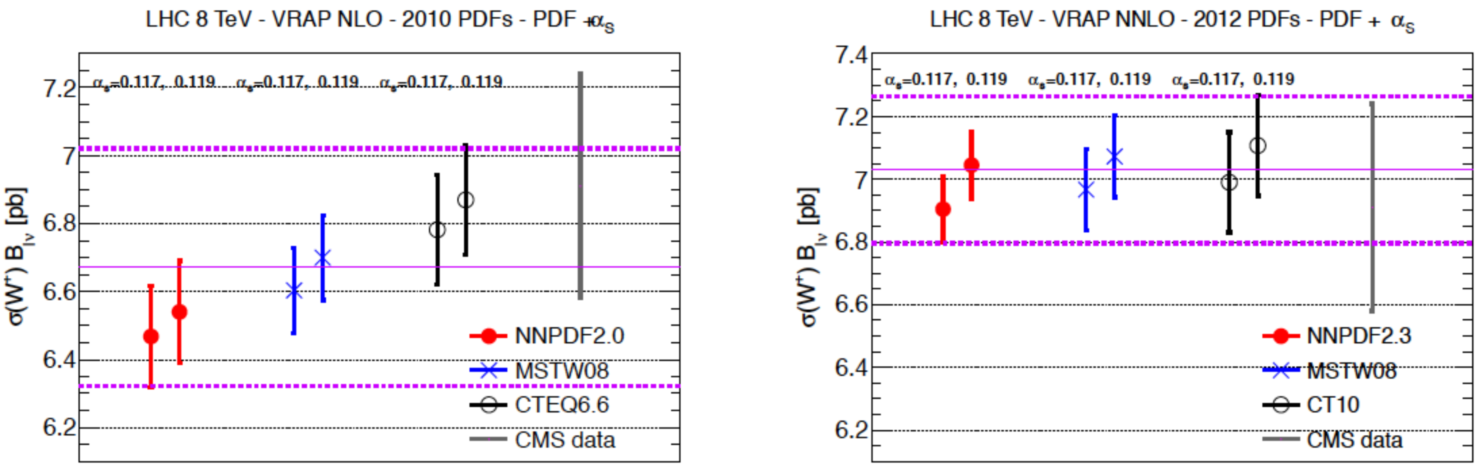


Figure 21: The W^+ production cross sections determined using the same PDFs and envelope as in Figs. 19-20. The left plot shows 2010 NLO PDFs, the right plot 2012 NNLO PDFs. The recent 8 TeV CMS measurement is also shown.

8 TeV cross section ratios

Here the uncertainty is larger than individual PDF errors, even though mostly qQ initial states.

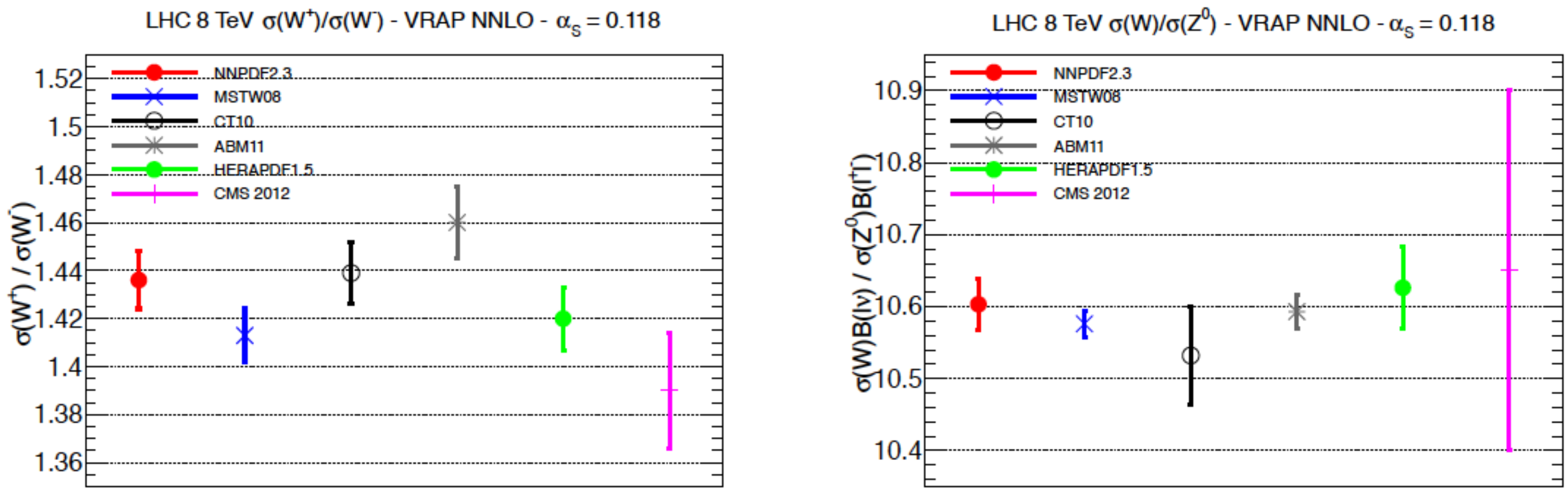
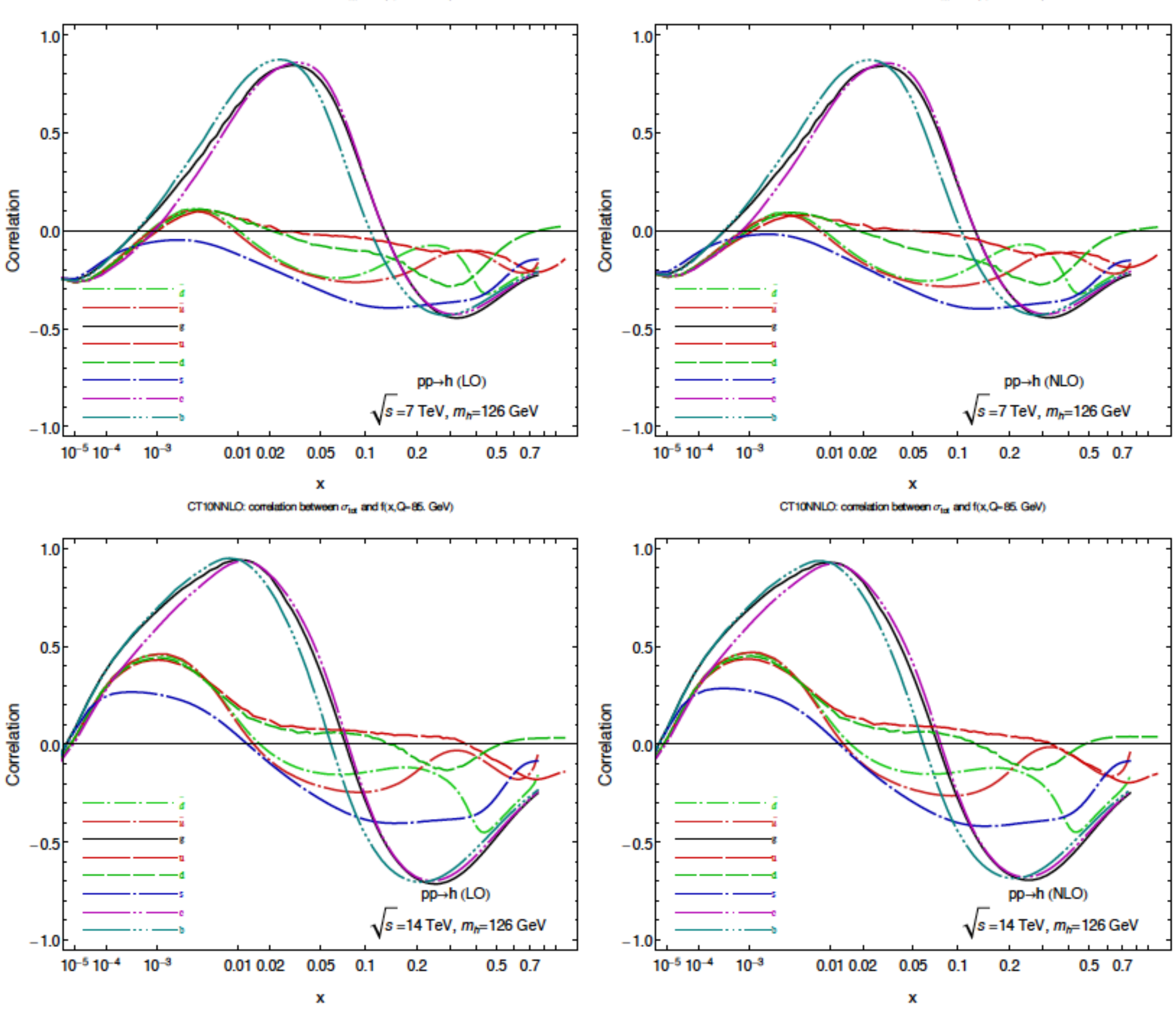


Figure 11: Comparison of the predictions for inclusive cross sections for electroweak gauge boson production between different PDF sets at LHC 8 TeV. In all cases the branching ratios to leptons have been included. From top to bottom and from left to right we show the W^+, W^-, and Z inclusive cross sections, and then the W^+/W^- and W/Z ratios. All cross sections are compared at a common value of $\alpha_S(M_Z) = 0.118$. We also show the recent CMS 8 TeV measurements.

Back to correlations

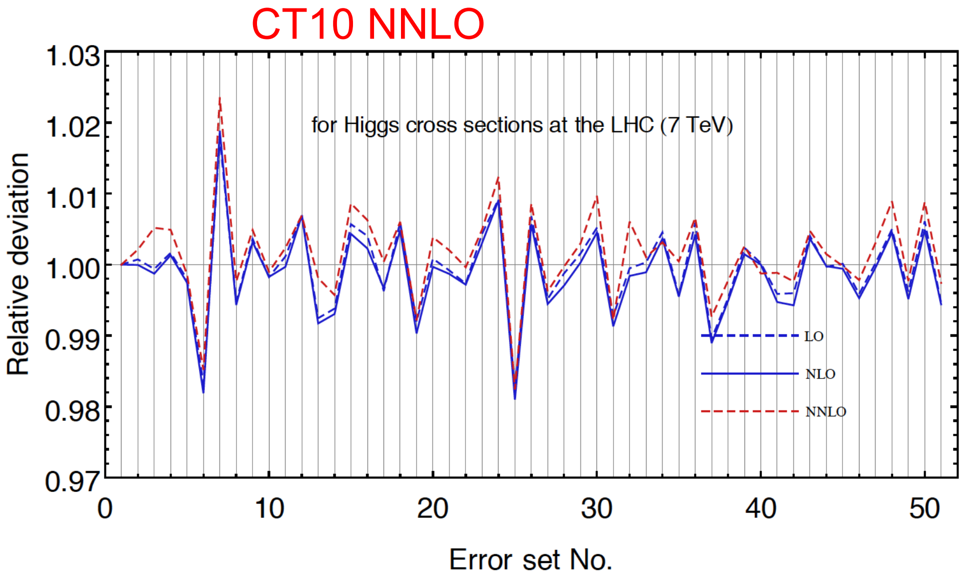
- A 126 Higgs produced through ggF is strongly correlated with the gluon distribution in the x-range around m_{Higgs}/sqrt(s)
  - and anti-correlated with the higher x gluon distribution
- The correlation is the same whether LO or NLO (or NNLO) matrix elements are used

using CT10NNLO PDFs: Jun Gao and Pavel Nadolsky (preliminary)



Correlations

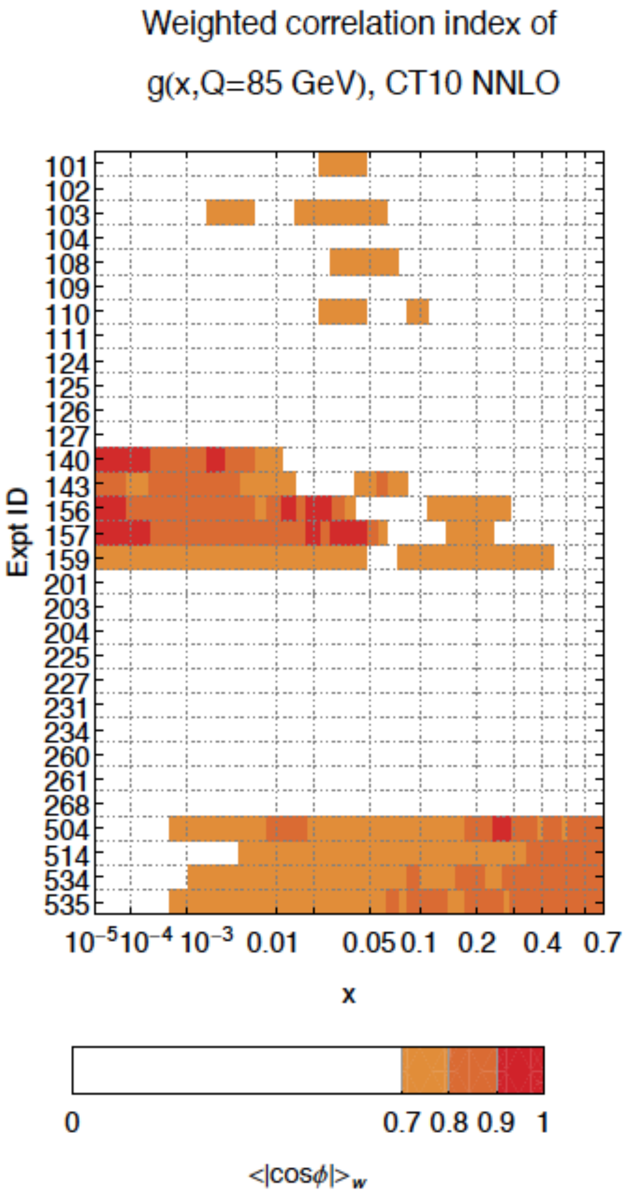
- The ggF Higgs cross section at 7 TeV depends primarily on a few eigenvectors, presumably relating to the low x gluon distribution
  - I haven't had a chance to check yet exactly what the PDF components are
- You can also effectively directly probe the PDF direction sensitive to the Higgs cross section using the Lagrange Multiplier technique
  - study in progress



Correlations with the gluon

- Here are the experiments that are most sensitive to the gluon distribution (for CT10 NNLO but should be similar for other PDFs)
  - HERA and the Tevatron/LHC jet experiments

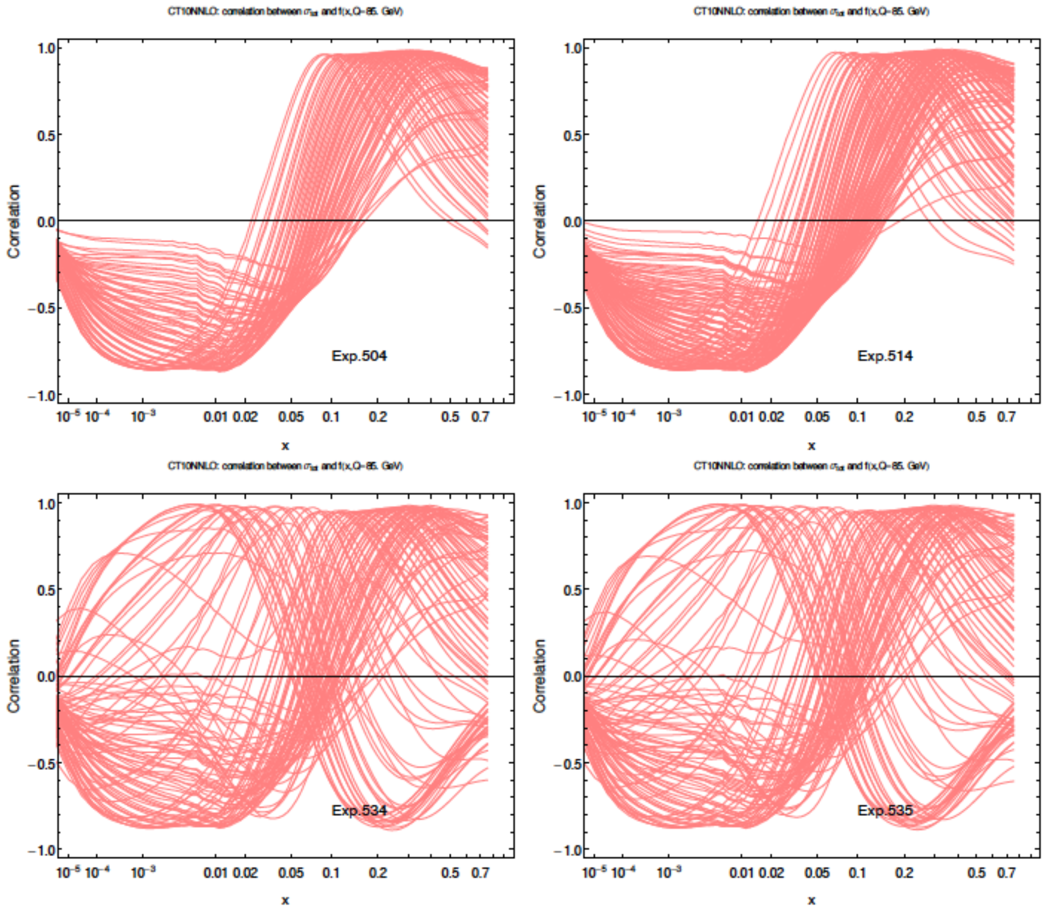
101	**BCDMS F_2^p**
102	BCDMS F_2^d
103	**NMC F_2^p**
104	NMC F_2^d/F_2^p
108	CDHSW F_2^p
109	CDHSW F_3^p
110	**CCFR F_2^p**
111	CCFR xF_3^p
124	NuTeV neutrino dimuon SIDIS
125	NuTeV antineutrino dimuon SIDIS
126	CCFR neutrino dimuon SIDIS
127	CCFR antineutrino dimuon SIDIS
140	**H1 F_2^c**
143	**H1 σ_r^c for $c\bar{c}$**
156	**ZEUS $F_2^c(67)$**
157	**ZEUS $F_2^c(80)$**
159	**Combined HERA1 NC and CC DIS**
201	E605 Drell-Yan process, $\sigma(pA)$
203	E866 Drell-Yan process, $\sigma(pd)/(2\sigma(pp))$
204	E866 Drell-Yan process, $\sigma(pp)$
225	CDF Run-1 W charge asymmetry
227	CDF Run-2 W charge asymmetry
231-234	D0 Run-2 W charge asymmetry
260	D0 Run-2 Z rapidity distribution
261	CDF Run-2 Z rapidity distribution
268	ATLAS combined W Z data
504	**CDF Run-2 inclusive jet production**
514	**D0 Run-2 inclusive jet production**
534	**ATLAS inclusive jet (R=0.4)**
535	**ATLAS inclusive jet (R=0.6)**



arXiv:1203.6803

Correlations between jet data and the gluon

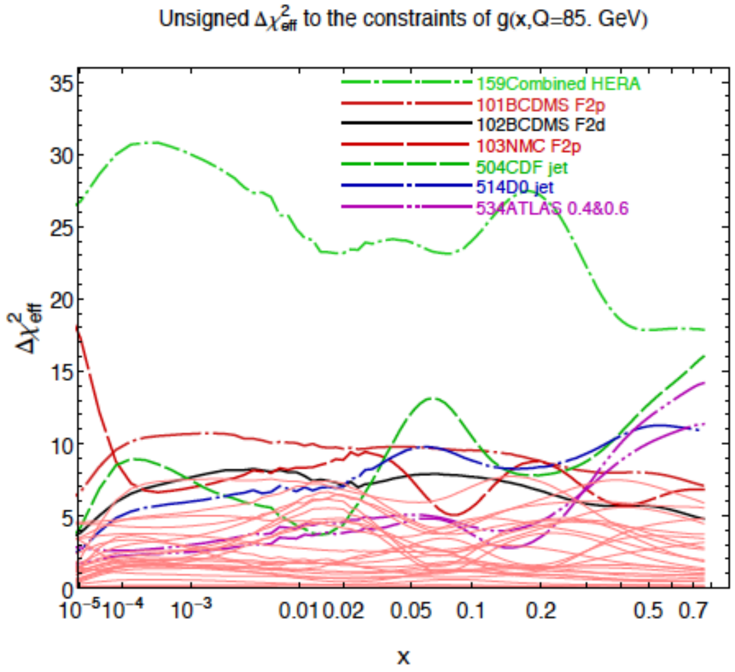
- Correlations are shown for each data point for each cross section
- As expected, Tevatron jet cross sections are mostly strongly correlated with the high x gluon, LHC jet cross sections with the low x gluon

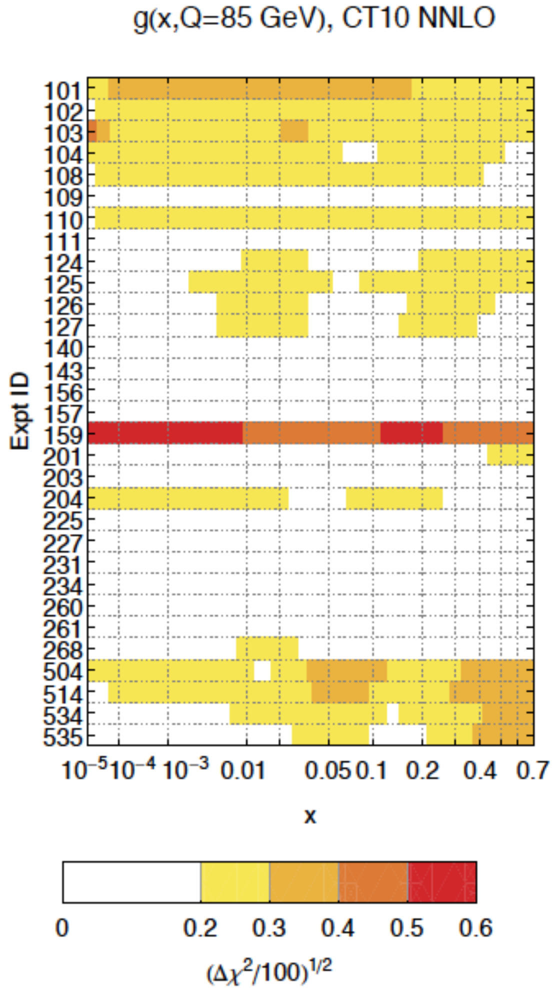


- Effective χ^2 changes: estimation of χ^2 changes of individual experiments when going along the gradient direction of an observable (similar to LM method); **represent the constraint powers of individual experiment**

- Currently, the HERA combined data provide the greatest constraint on the low x gluon distribution
- LHC jet data can provide a more important role, if the systematic errors can be reduced
- The completion of the NNLO inclusive jet cross section calculation is also crucial to reduce the theoretical uncertainty

$$\Delta\chi^2_{eff}(iexp, X) \equiv \sum_{i=1}^{N_{PDF}} |\chi_i^2(iexp) - \chi_0^2(iexp)| \frac{(X_i - X_0)^2}{\sum_j (X_j - X_0)^2}$$





Using $\Delta\chi^2_{eff}$ We can easily estimate the effects of new data sets, like isolated photon, W and Z production at large p_T, without redoing the fit.

ATLAS 2010 jet data

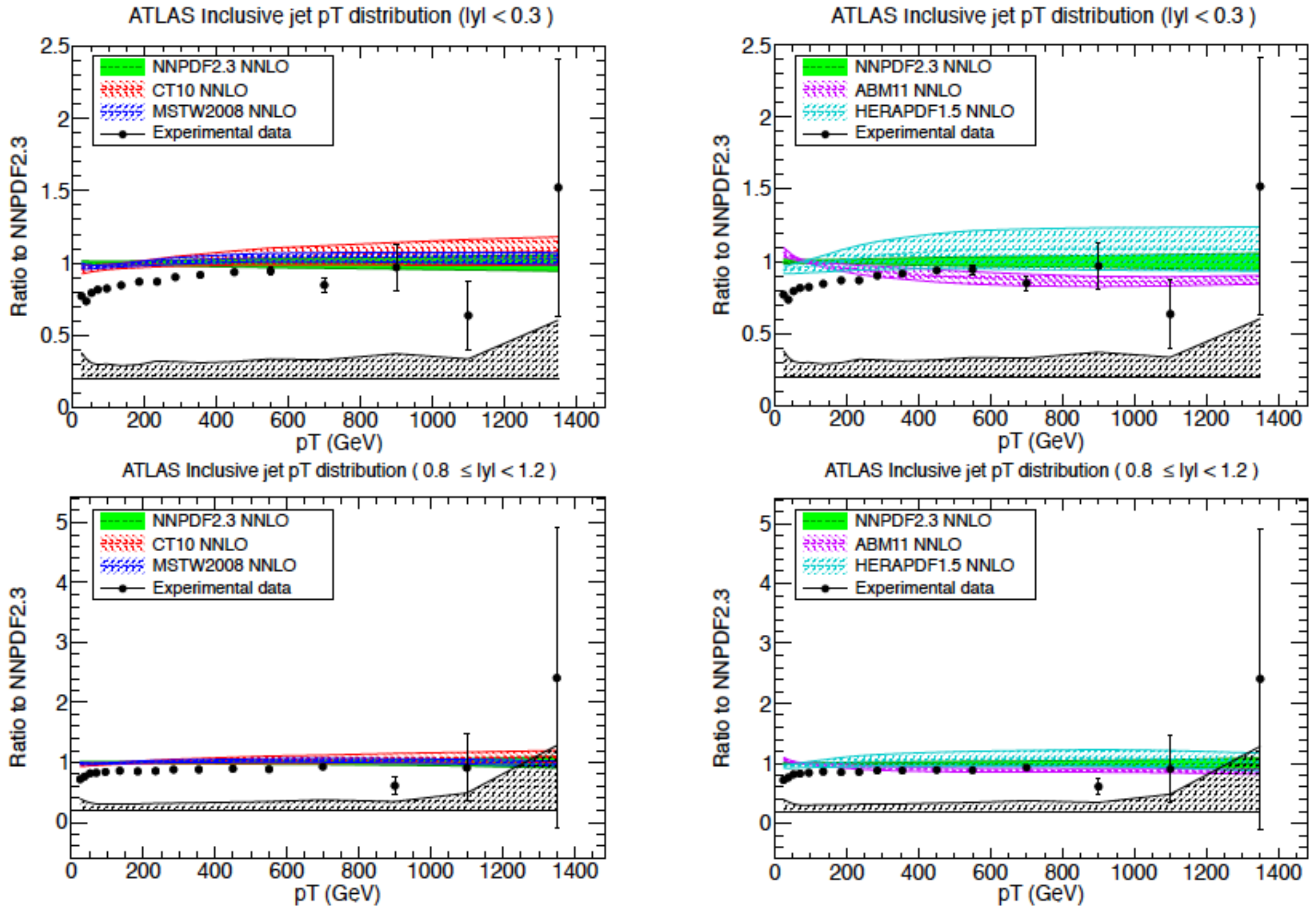


Figure 14: Comparison of the ATLAS $R = 0.4$ inclusive jet production data from the 2010 dataset with the NNPDF2.3, CT10 and MSTW2008 NNLO PDF sets and $\alpha_S = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics (including normalization errors)

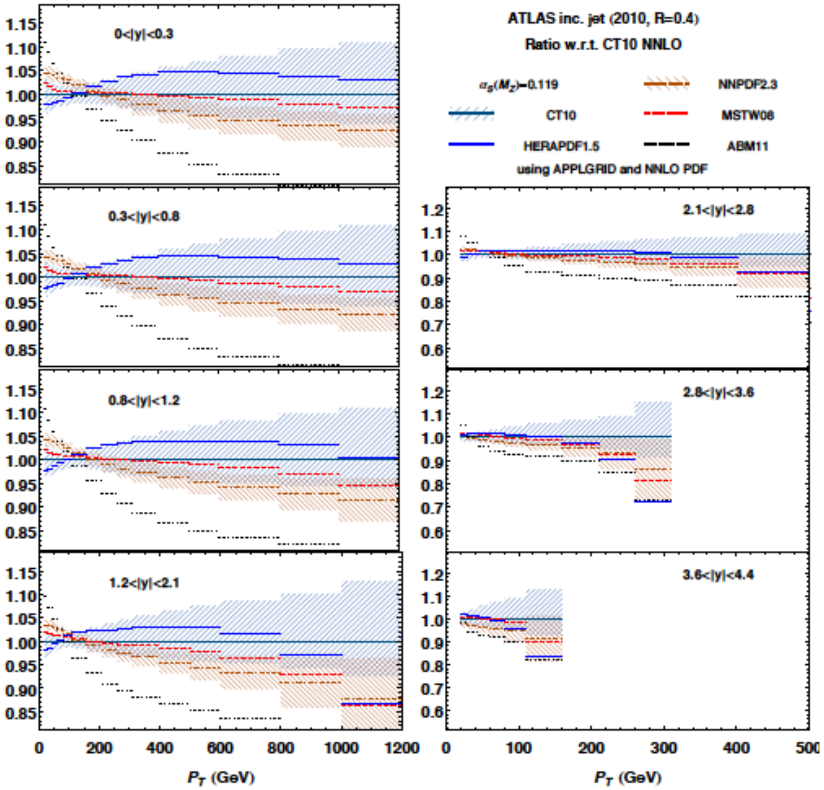
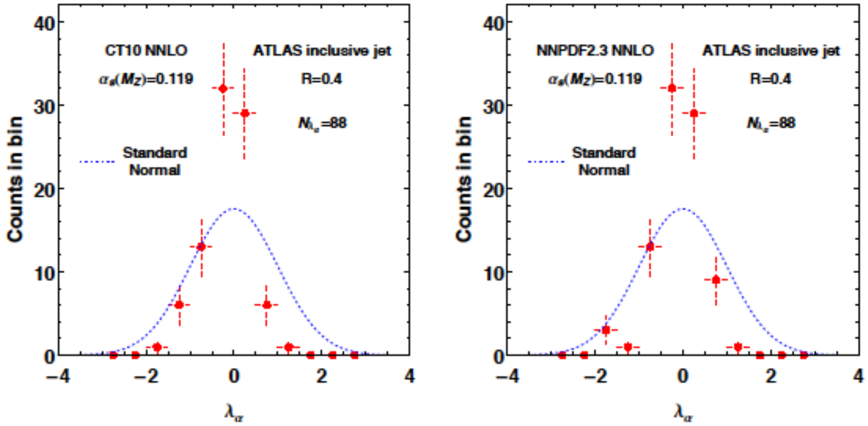


Figure 2: Comparisons of NLO theoretical predictions for 2010 ATLAS single-inclusive jet production ($R = 0.4$) from APPLGRID using various NNLO PDFs with $\alpha_s(M_Z) = 0.119$.

Systematic error shifts for ATLAS jet data for CT10 and NNPDF2.3 NNLO



also important to check that no major systematic errors need large shift

χ^2 for all PDFs are good (too good?) 2010 data not constraining for PDF fits?

PDFset($\alpha_s(M_Z) = 0.119$)	$\chi^2/d.o.f$	χ^2(res.)	χ^2(sys.)	$\lambda_{\alpha,lum.}$
ABM11 NNLO	0.81	44.4	28.5	-1.12
CT10 NNLO	0.81	47.4	25.5	-1.76
CT10 NLO	0.94	54.0	30.6	-1.18
HERA1.5 NNLO	0.85	50.7	25.8	-2.36
MSTW08 NNLO	0.79	45.7	25.1	-2.00
NNPDF2.3 NNLO	0.79	42.4	29.1	-1.88

Table I: Fit of 2010 ATLAS single-inclusive jet data ($R = 0.4$), including reduced χ^2, luminosity systematic shift, and the separate contributions to the total χ^2 from residuals and systematic shifts, using NLO theoretical predictions from FASTNLOv2 for various PDFs with $\alpha_s(M_Z) = 0.119$.

Summary

- New NLO (and NNLO) PDFs are available: CT10, NNPDF2.3, HERAPDF1.5, ABM11, in addition to MSTW2008 (which will be updated in the near future)
- Higgs cross section predictions have been updated using the new NLO and NNLO PDFs
- A new prescription based on the same families of PDFs would lead to a central prediction (and uncertainties) very similar to what was used in 2010
  - note that quark-quark luminosity uncertainties have been reduced; gluon-gluon luminosity uncertainties (at least in the 125 GeV range) have not
  - HERAPDF1.5 NNLO predictions consistent with those of CT10, NNPDF2.3 and MSTW2008 but with larger uncertainties
  - larger differences with ABM11; may be due to use FFN scheme; see talk of Robert Thorne at Friday's PDF4LHC meeting
- No explicit contribution from the PDF group is planned for YR3; there will be a PDF4LHC recommendation update
- Complete set of plots and comparisons at NLO and NNLO available at http://nnpdf.hepforge.org/html/pdfbench/catalog

The future looks bright

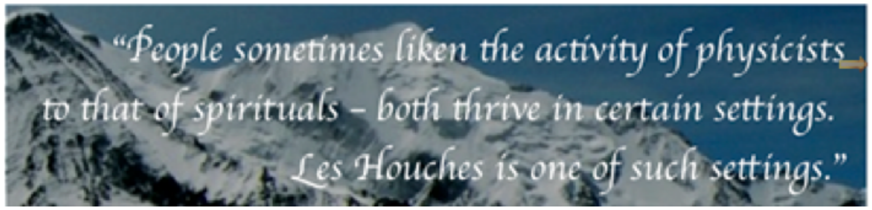
- New data from HERA and from the LHC should improve understanding of PDF uncertainties for Higgs cross sections
  - for example, PDF4LHC meeting on Friday will discuss new F_2^c results from HERA
  - we should use as input all relevant high-statistics LHC data
    - e.g. inclusive photon production, photon+jet, W+c, Drell-Yan, single top and top pair production, …
    - ratios thereof at different center-of-mass energies
    - this data must be reported with well-understood correlated systematic errors to be understood; also which errors are additive and which are multiplicative

Snowhouches

- Snowmass on the Mississippi

- Final meeting in Minneapolis 29/7 to 6/8
- http://www.snowmass2013.org
- To sign up for mailing lists send an email to <u>listserv@slac.stanford.edu</u> with the phrase 'Snowmass-higgs' or 'Snowmass-qcd' in the body

Les Houches Workshop Series
"Physics at TeV Colliders"
2013 Session: 3-21 June



"People sometimes liken the activity of physicists to that of spirituals – both thrive in certain settings. Les Houches is one of such settings."

- http://phystev.in2p3.fr/houches2013
- Please apply; there are a lot of Higgs issues to be addressed with the 2011/2012 data and theory progress
- QCD/SM Higgs in first half; BSM Higgs in 2nd half

We are trying for a great deal of synergy between the two workshops. There will be joint meetings (evo/vidyo) between the two. The mountains will be provided by Les Houches.

Some PDF issues

- What is the current (and ultimate) uncertainty of the LHC beam energy, how does it affect uncertainties in cross section comparisons, and how might ratios of cross sections lead to more precise comparisons (taking into account correlations)?
- What sort of errors/uncertainties are present in using NNLO PDFs with NNLO+NNLL predictions (i.e. do we need resummed PDFs); what sort of errors/uncertainties wold be present if NNLO PDFs were used with a NNNLO prediction for ggF?
- Revisiting theory uncertainties in PDF determination, i.e. scale choice for processes such as inclusive jet production
- …as well as issues regarding scale choices in LHC predictions (such as discussed in extra slides)

Extras

Scale uncertainty

- The Higgs cross section depends on the renormalization scale μ_R and factorization scale μ_F
- Consider default values for these two scales, $\mu_{o,F}$ and $\mu_{o,R}$ and expand around these values
- Can write the NLO Higgs cross section (actually any NLO cross section) near the reference scales as

$$\sigma(\mu_F,\mu_R) \approx \sigma(\mu_{0,F},\mu_{0,R})\left[1 + b_R \ln\left(\frac{\mu_R}{\mu_{0,R}}\right) + b_F \ln\left(\frac{\mu_F}{\mu_{0,F}}\right) + c_R \ln^2\left(\frac{\mu_R}{\mu_{0,R}}\right) + c_F \ln^2\left(\frac{\mu_F}{\mu_{0,F}}\right) + c_{RF} \ln\left(\frac{\mu_R}{\mu_{0,R}}\right)\ln\left(\frac{\mu_F}{\mu_{0,F}}\right)\right]$$

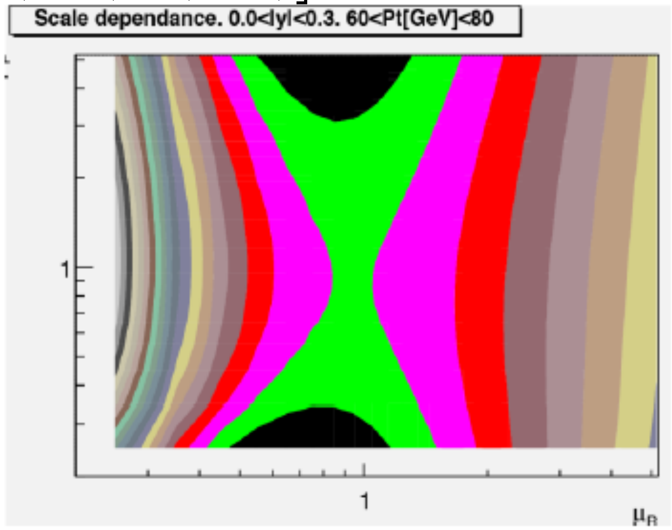
- …where the explicit logarithmic dependences have been factorized out; the b and c variables will depend on the kinematics
- In general, there will be a saddle point, where the local slope as a function of μ_R,μ_F is zero, i.e. the *b's* vanish
- Around the saddle point, can write the scale dependence as

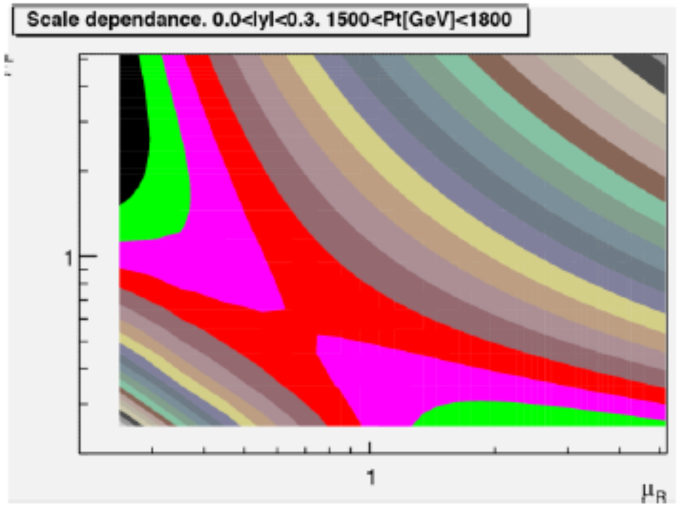
$$\sigma(\mu_F,\mu_R) \approx \sigma(\mu_{S,F},\mu_{S,R})\left[1 + c_R \ln^2\left(\frac{\mu_R}{\mu_{S,R}}\right) + c_F \ln^2\left(\frac{\mu_F}{\mu_{S,F}}\right) + c_{RF} \ln\left(\frac{\mu_R}{\mu_{S,R}}\right)\ln\left(\frac{\mu_F}{\mu_{S,F}}\right)\right]$$

Consider inclusive jet cross section at NLO

$$\sigma(\mu_F,\mu_R) \approx \sigma(\mu_{S,F},\mu_{S,R})\left[1 + c_R \ln^2\left(\frac{\mu_R}{\mu_{S,R}}\right) + c_F \ln^2\left(\frac{\mu_F}{\mu_{S,F}}\right) + c_{RF} \ln\left(\frac{\mu_R}{\mu_{S,R}}\right)\ln\left(\frac{\mu_F}{\mu_{S,F}}\right)\right]$$

- For $c_F>0, c_R<0$ and $c_F, |c_R| >> |c_{RF}|$, the saddle point axes are aligned with the plot axes, as shown at the top right
- At higher p_T values, $c_{RF}<0$ and $c_F, |c_R| << |c_{RF}|$, the saddle position rotates by about 45°
- The saddle position also depends on jet size and on rapidity (somewhat)
- In any case, the perturbative series is well-behaved for inclusive jet production, leading to stable predictions at NLO, using a scale related to the p_T of the jet
- …except perhaps when you go very far forward

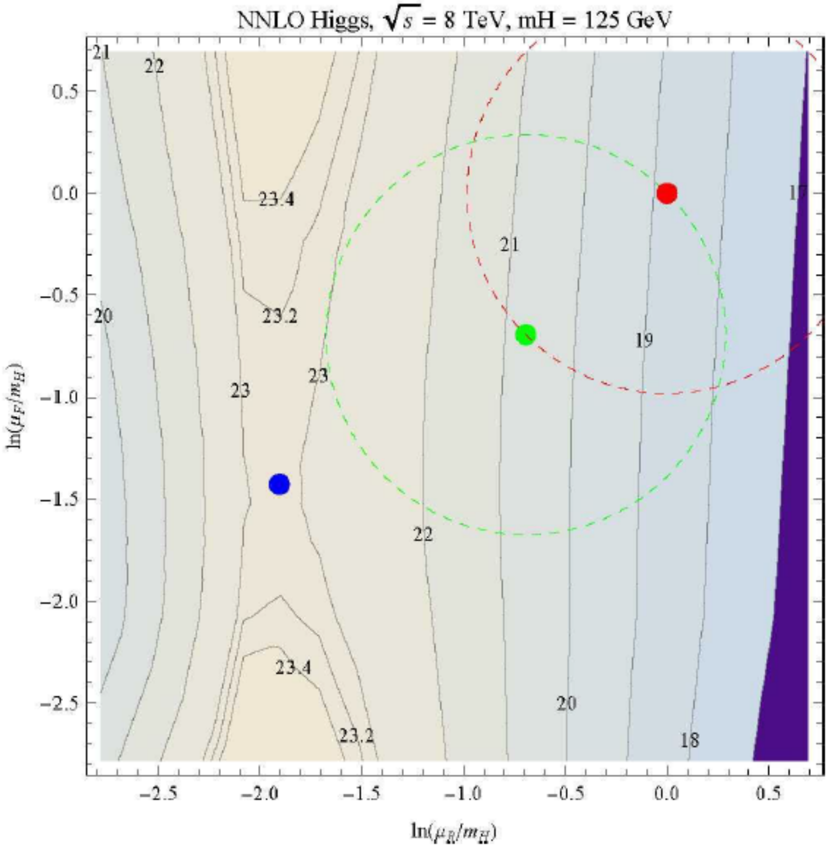


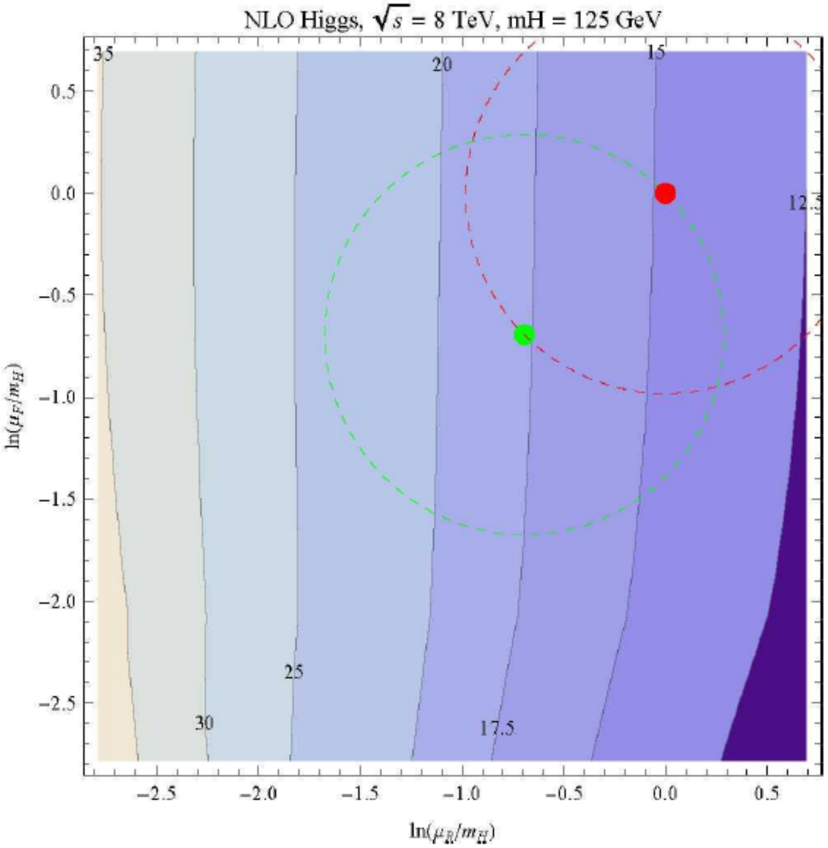


2-D plots for ggF for Higgs

- The NNLO scale dependence looks similar to that for low p_T inclusive jet production, steep at low values of μ_R, shallow in μ_F
- Note that there is no saddle point at NLO in the range of scales plotted; it looks similar to LO for inclusive jet production

ihixs

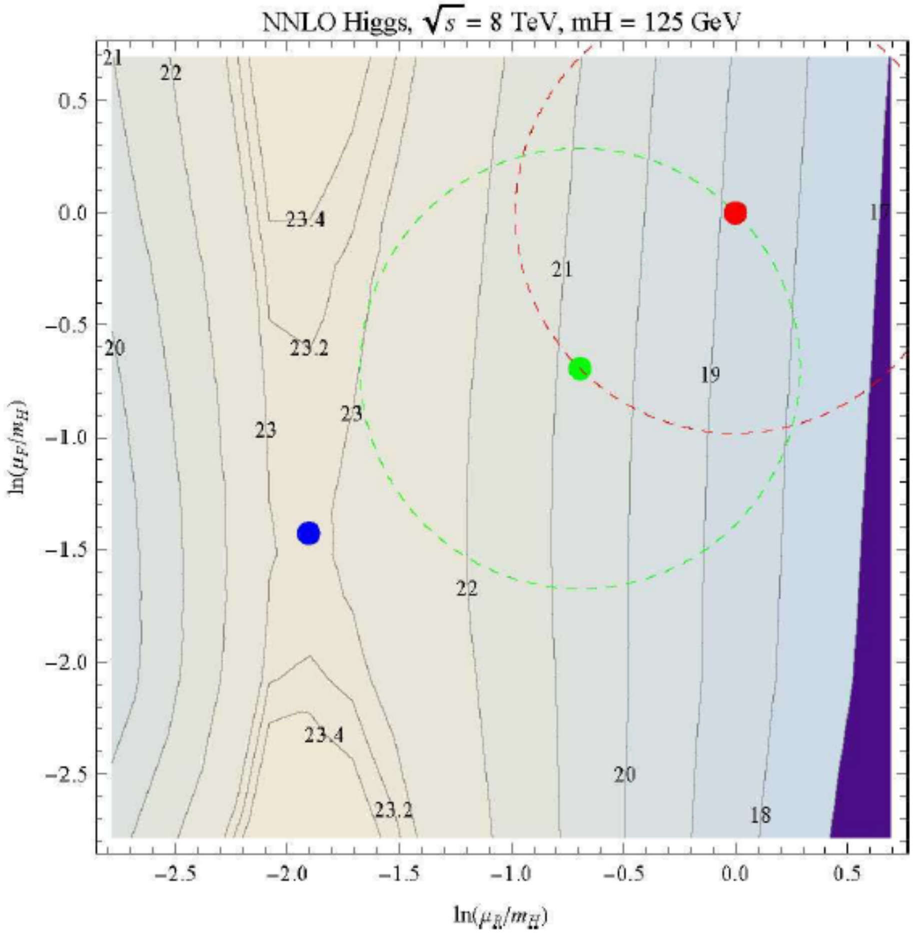




Achilleas Lazopoulos and Stephan Buehler, with Steve Ellis

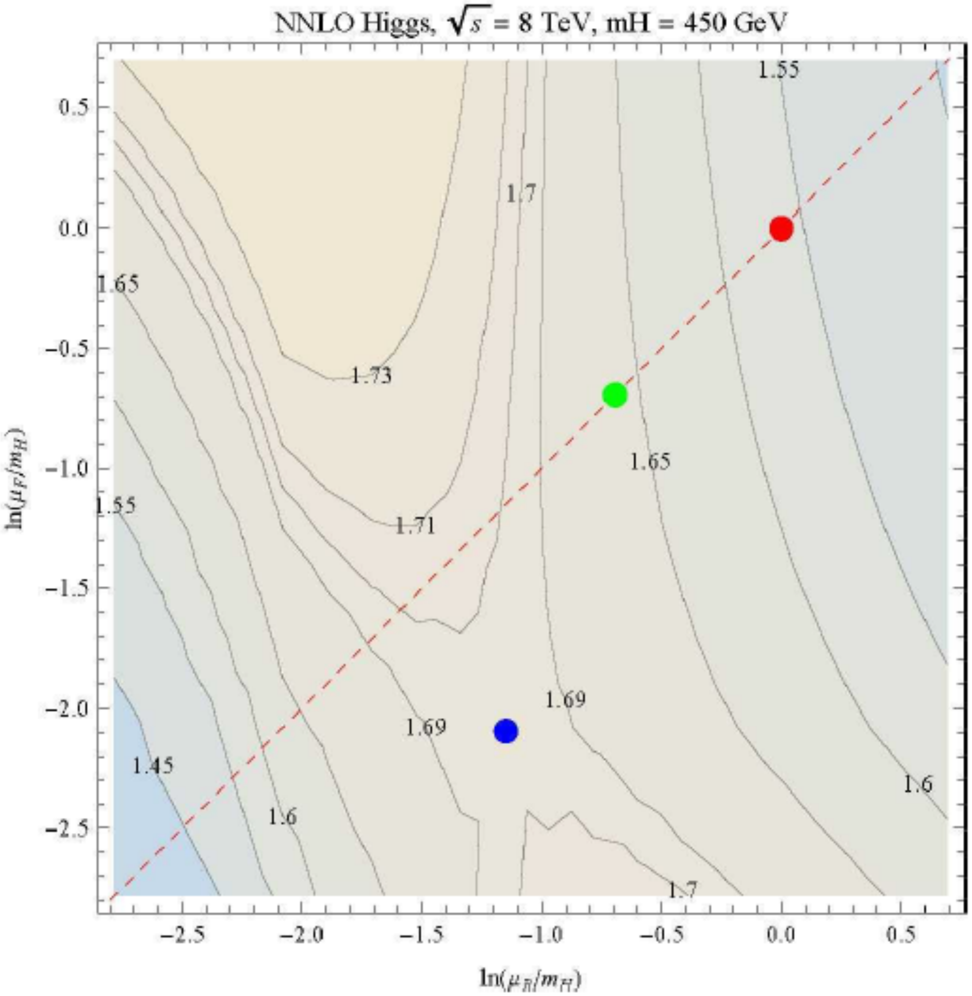
ggF at NNLO

- Note that the location of the saddle point is at ~($0.15m_H$, $0.24m_H$), i.e. outside of the range of uncertainties typically taken into account when using a scale of either m_H or $0.5\ m_H$
- Saddle point ~23.1pb compared to 20.7pb for $m_H/2$
- Maybe the saddle point is not magic, but it may be disturbing that it is not included in the uncertainty calculation



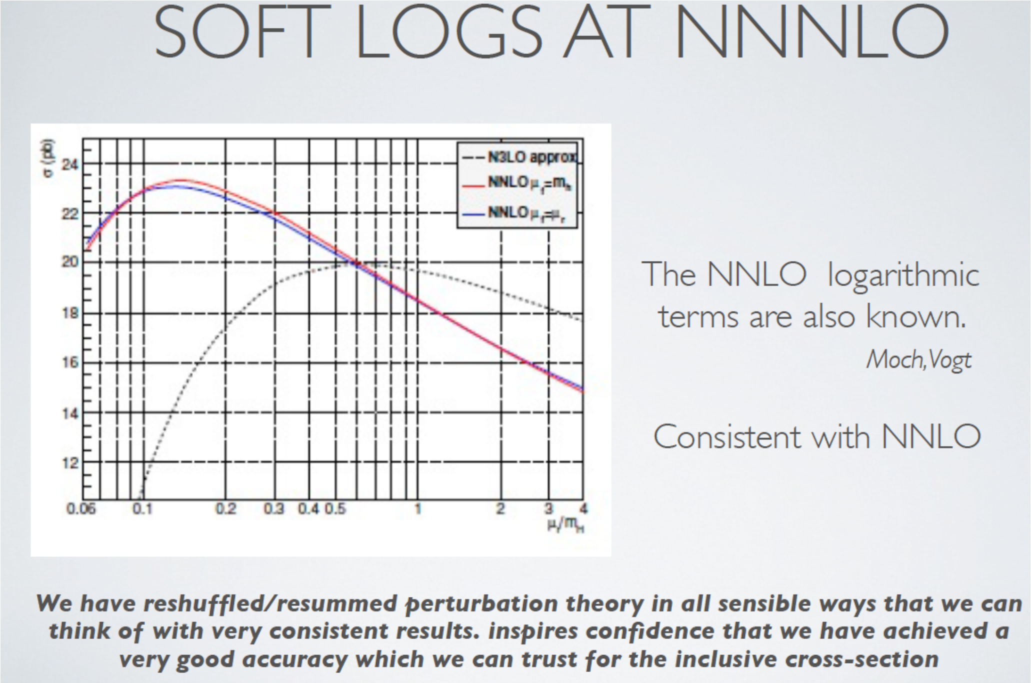
ggF at NNLO

- Now consider a 450 GeV Higgs produced by ggF
- There’s some rotation of the saddle region as you would expect from the jet analysis
- Saddle point also moves to smaller μ_F



Babis at GGI

- Points out that series is not well-behaved and that even NNLO might not be enough for precision predictions
- ~N^{3}LO prediction peaks near a scale of m_{Higgs}
- But normalization has not been determined; likely to have some additional positive corrections



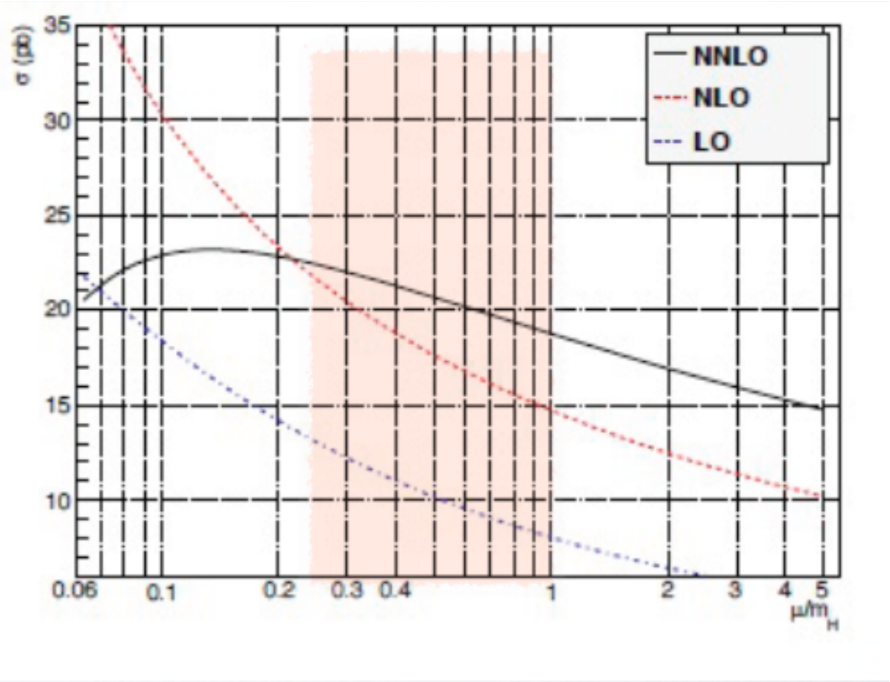
SOFT LOGS AT NNNLO

The NNLO logarithmic terms are also known.

Moch,Vogt

Consistent with NNLO

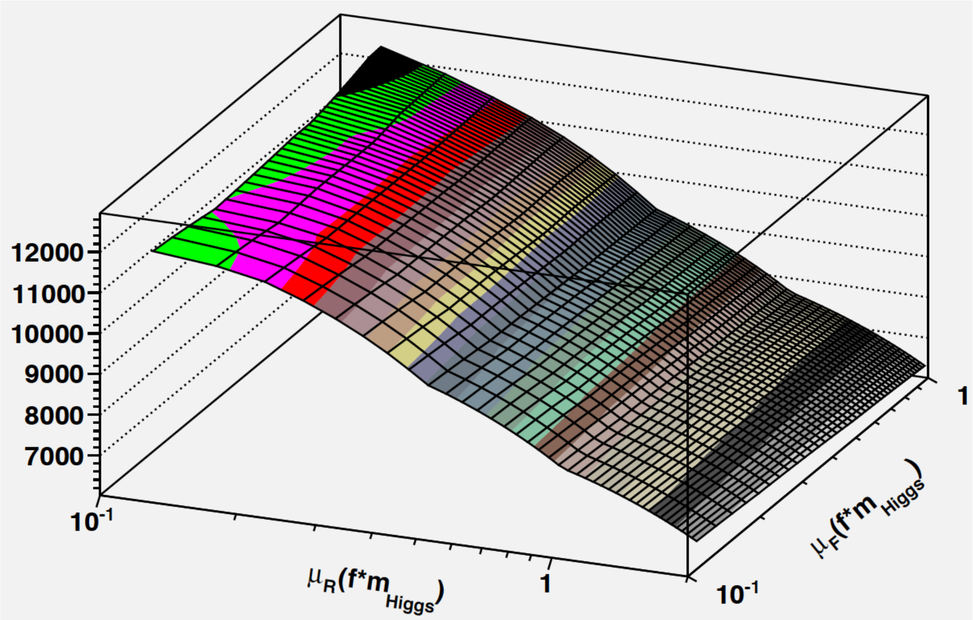
We have reshuffled/resummed perturbation theory in all sensible ways that we can think of with very consistent results. inspires confidence that we have achieved a very good accuracy which we can trust for the inclusive cross-section



- I don't really understand the ~NNNLO curve. Very large change in predicted cross section at low scales.
- claims that 5% precision might be achievable at NNNLO.
- good progress in the calculation, so maybe we don't have too long to wait; need Higgs + 1 jet at NNLO

Now look at Higgs+1 jet at NLO

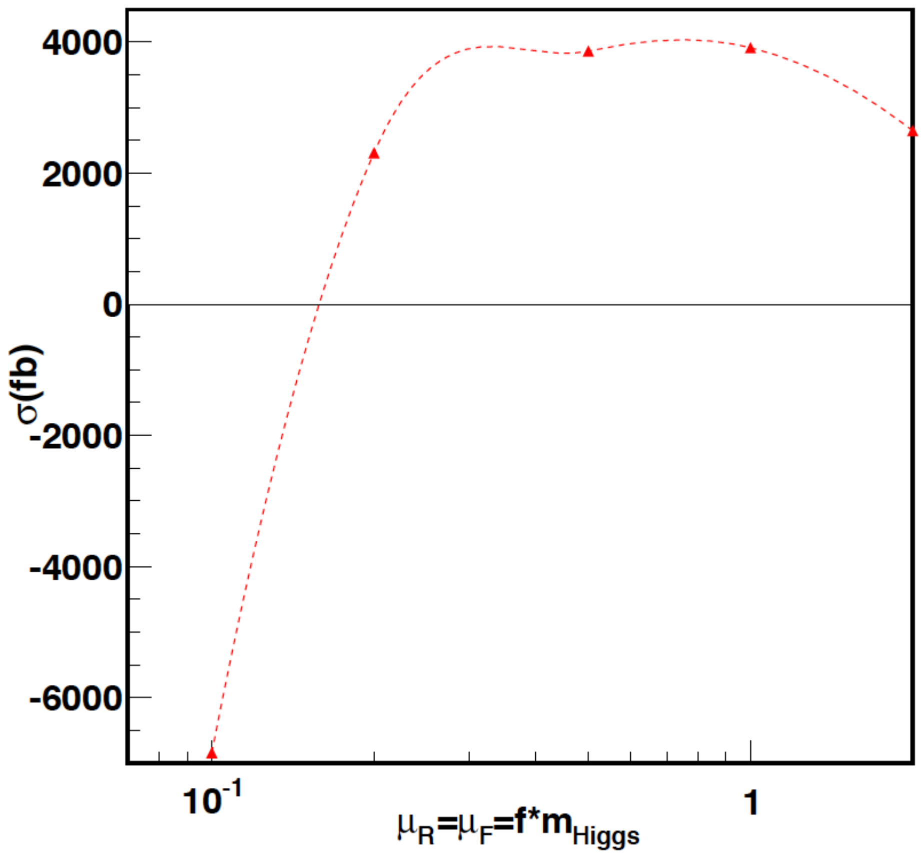
- This is for inclusive requiring only a 20 GeV/c cut on the jet; behavior is monotonic and no saddle point is present; scale uncertainties are large and ill-defined
    - …but better than inclusive Higgs production at NLO



Higgs+1 jet at NNLO in 2013 (N. Glover, private communication)

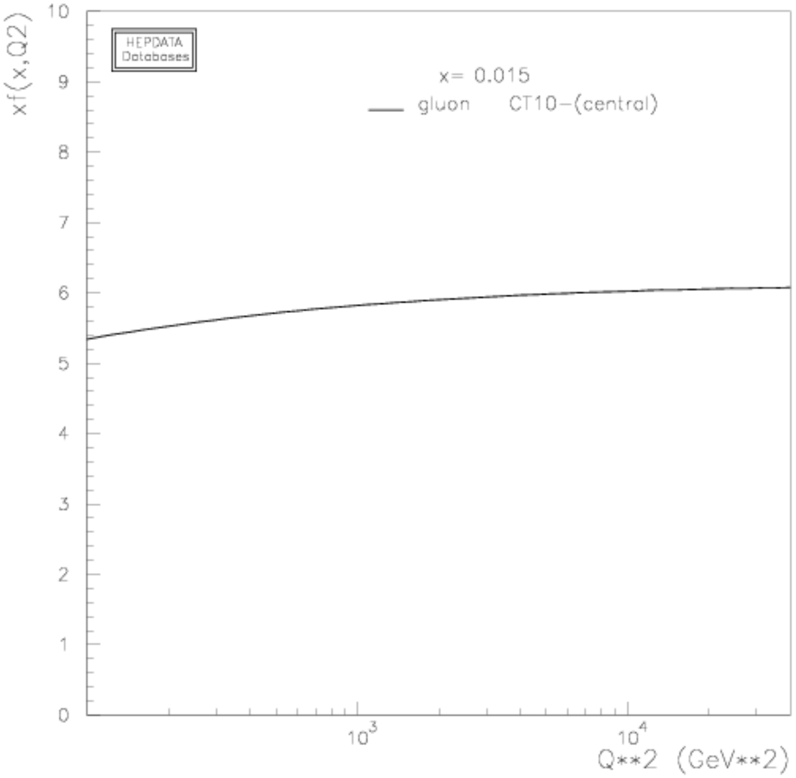
What about Higgs+2 jets?

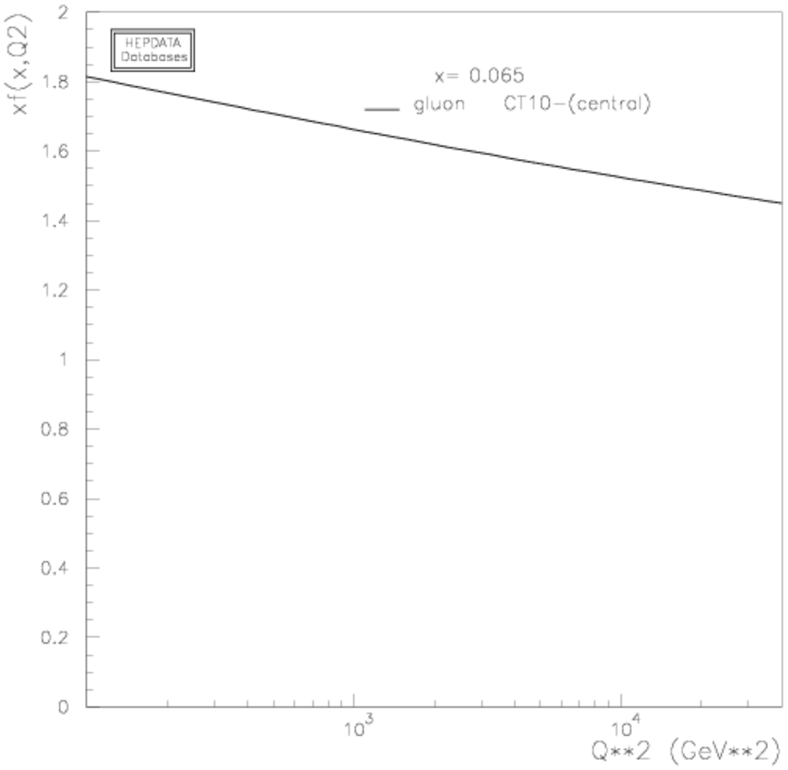
- Better behavior than for either inclusive Higgs or Higgs+1 jet



μ_F dependence

- As we have seen, the μ_F dependence is much flatter than the μ_R dependence for gg->Higgs (+jets)
- Mostly because ggF probes the gluon distribution in the region around the inflection point
- For the higher x values probed in the VBF region, this will change somewhat





Comparisons to 2011 data

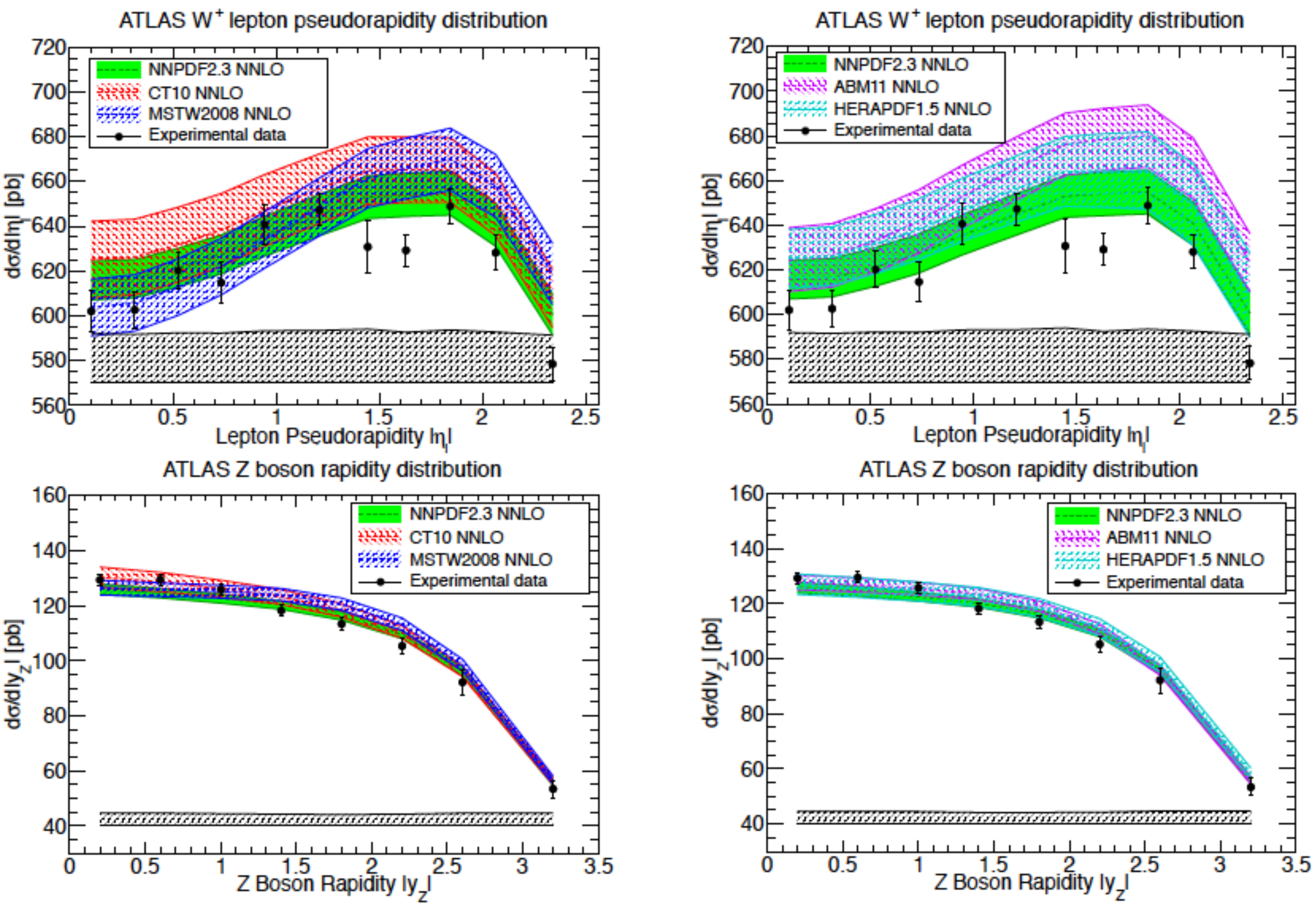


Figure 12: Comparison of the ATLAS electroweak vector boson production data with the NNPDF2.3, CT10 and MSTW2008 predictions with $\alpha_s = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics (including normalization errors).

Comparisons to 2011 data

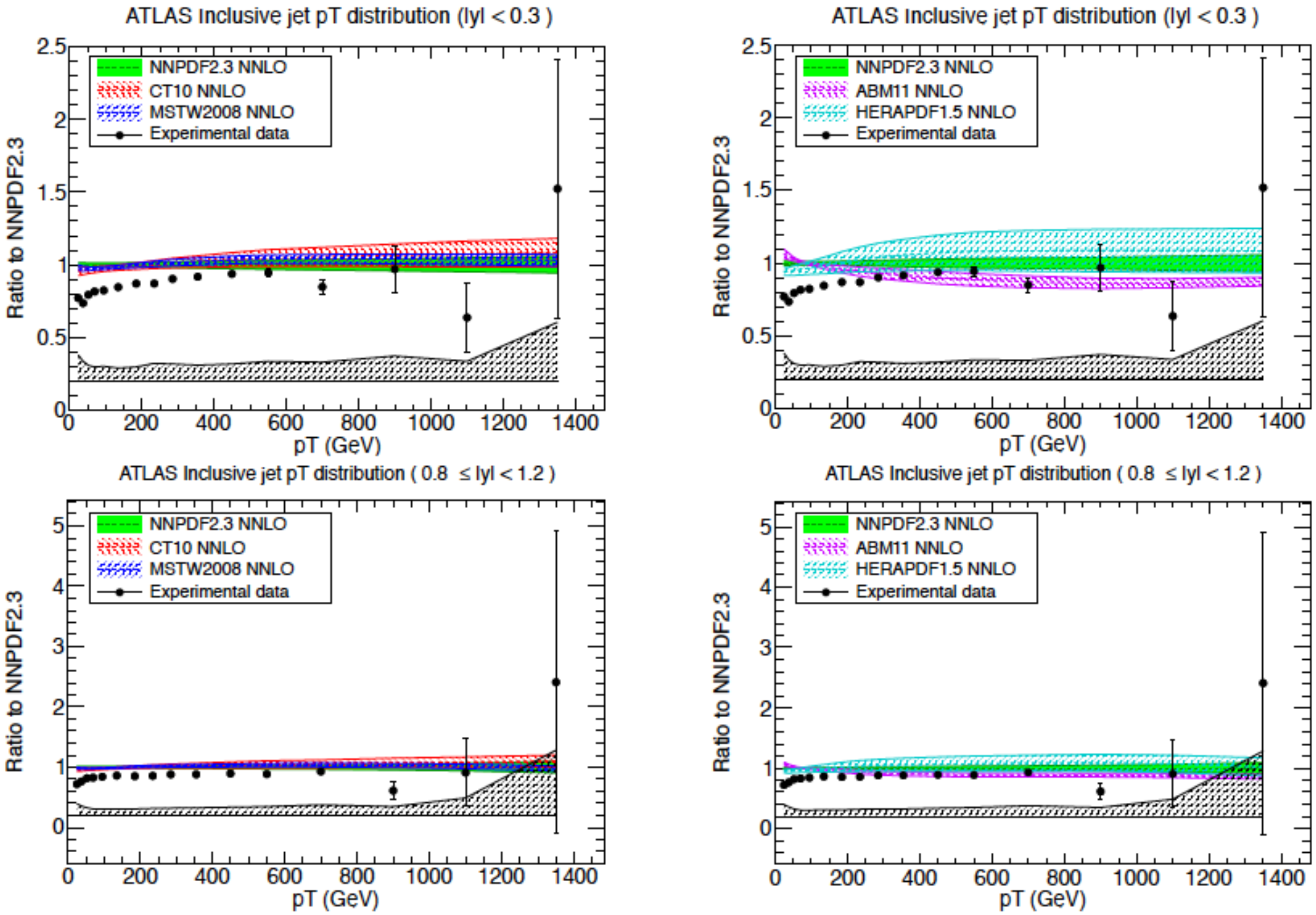


Figure 14: Comparison of the ATLAS $R = 0.4$ inclusive jet production data from the 2010 dataset with the NNPDF2.3, CT10 and MSTW2008 NNLO PDF sets and $\alpha_S = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics (including normalization errors)

Comparisons to 2011 data

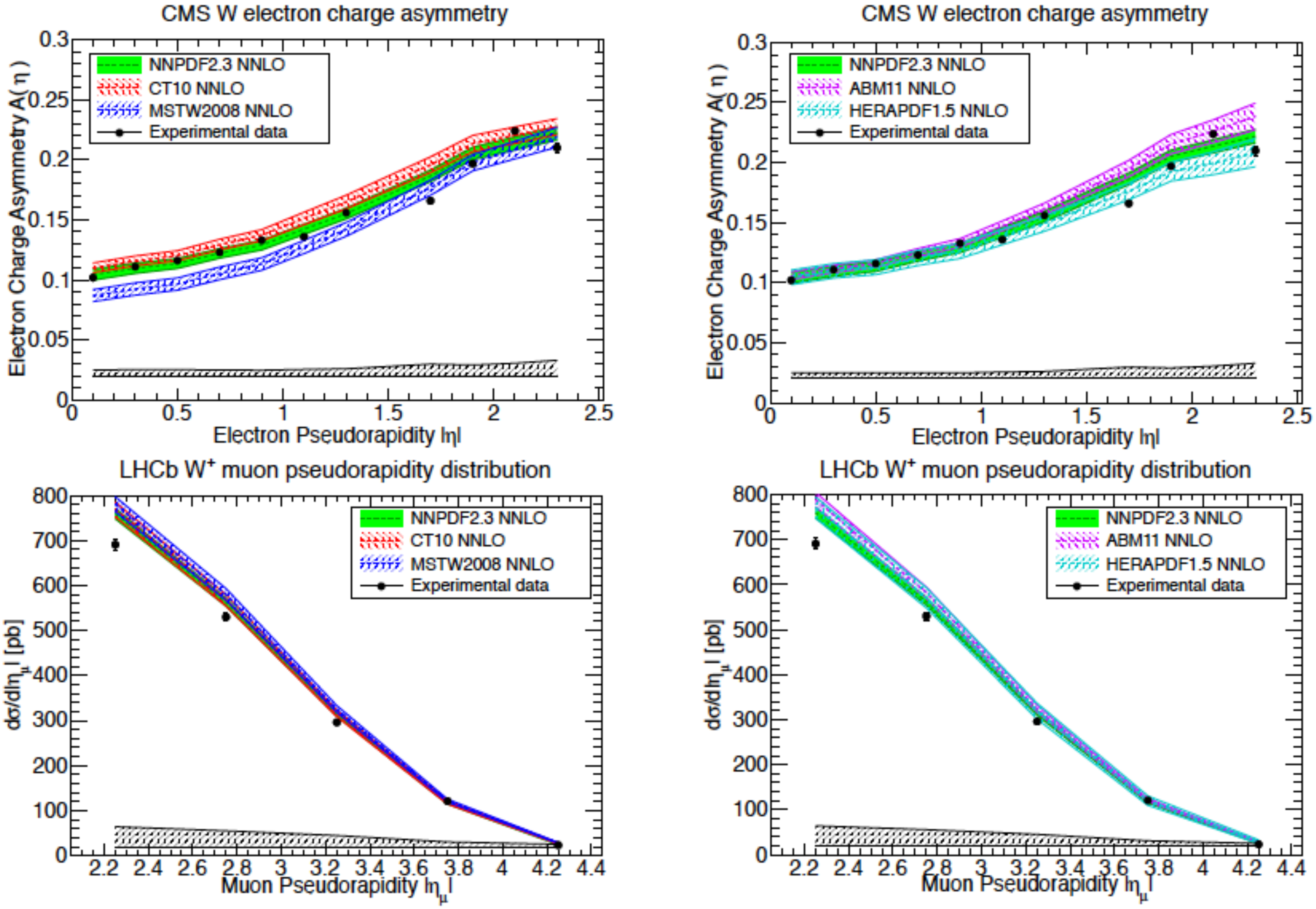


Figure 13: Same as Fig. 12 for CMS and LHCb W production.

Comparison of jet predictions

agreement at high p_T, some differences for APPLGRID at low p_T

larger differences at low p_T if scale of $p_T^{jet,max}$ is used

note unshifted data has poor agreement with theory

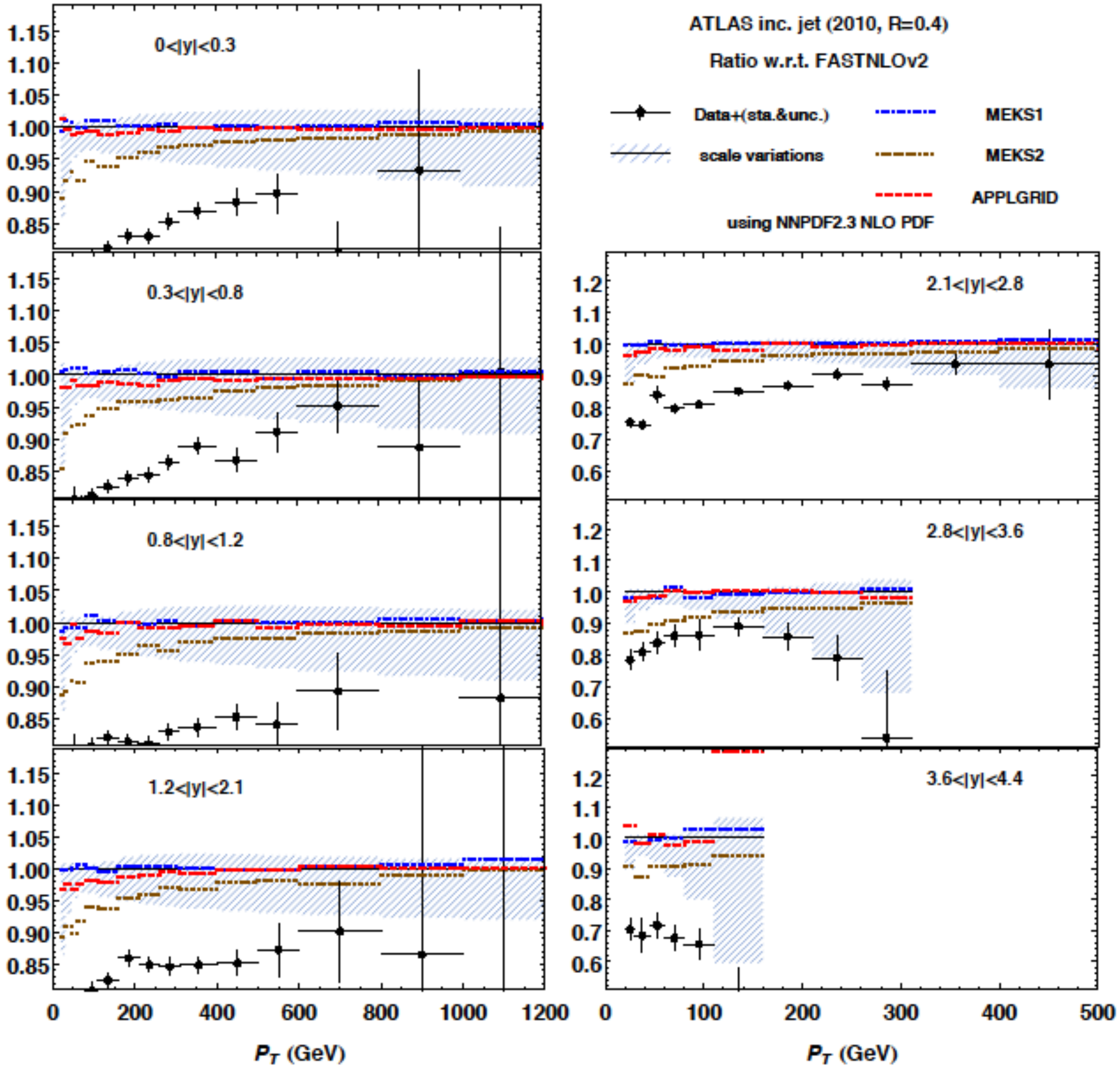


Figure 1: Comparisons of NLO theoretical predictions for 2010 ATLAS single-inclusive jet production ($R = 0.4$) from various numerical programs. NNPDF2.3 NLO PDFs are used with $\alpha_s(M_Z) = 0.119$.

scale =p_T^{jet}

scale =$p_T^{jet,max}$

scale =$p_T^{jet,max}$ in each rapidity bin

↓

ATLAS choice

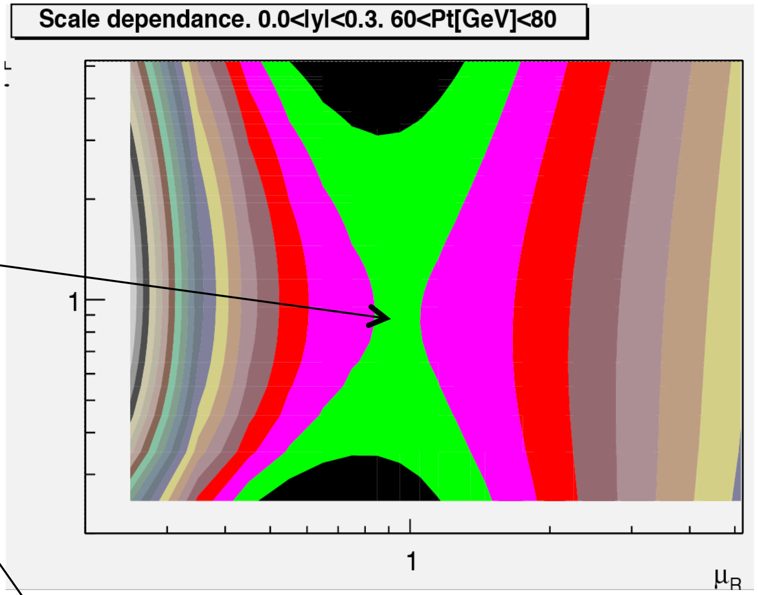
hatched is FASTNLO uncertainty band for $p_T/2$ to $2p_T$

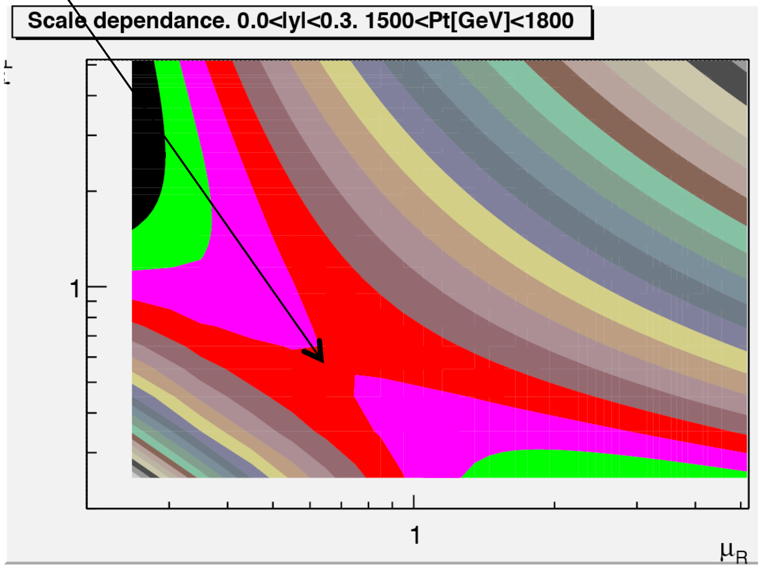
could we agree on a common scale, like p_T^{jet}?

Aside: Scale choices

- Take inclusive jet production at the LHC
- Canonical scale choice at the LHC is $\mu_r = \mu_f = 1.0 * p_T$
  - CDF used $0.5p_T$
  - CTEQ6.6/CT10 used this scale for determination of PDFs
  - new CT PDFs use p_T
- Close to saddle point for low p_T
- But saddle point moves down for higher p_T (and the saddle region rotates)
- Our typical scale choices don't work for all LHC kinematics; more extreme movements for some of measured cross sections
- Rather than look for some magic formula, we should try to understand what is going on the kinematic/scale point-of-view

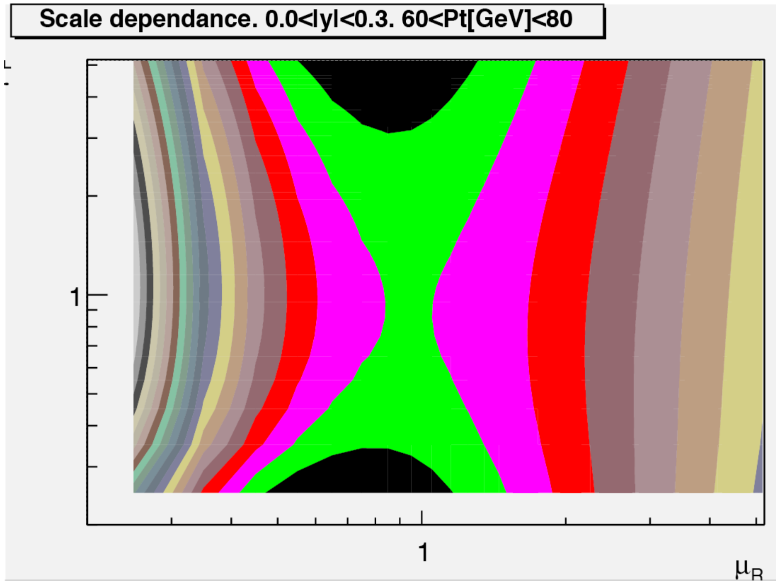
R=0.4
antikT

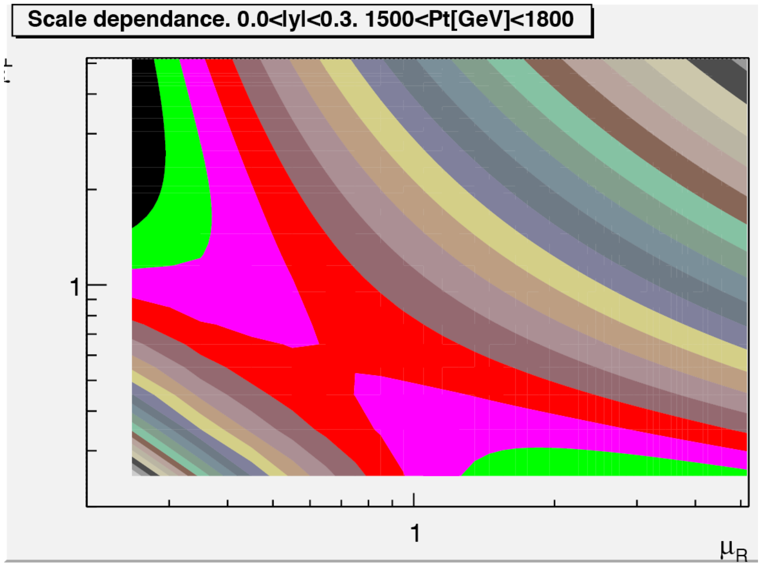




Scale dependence also depends on jet size;

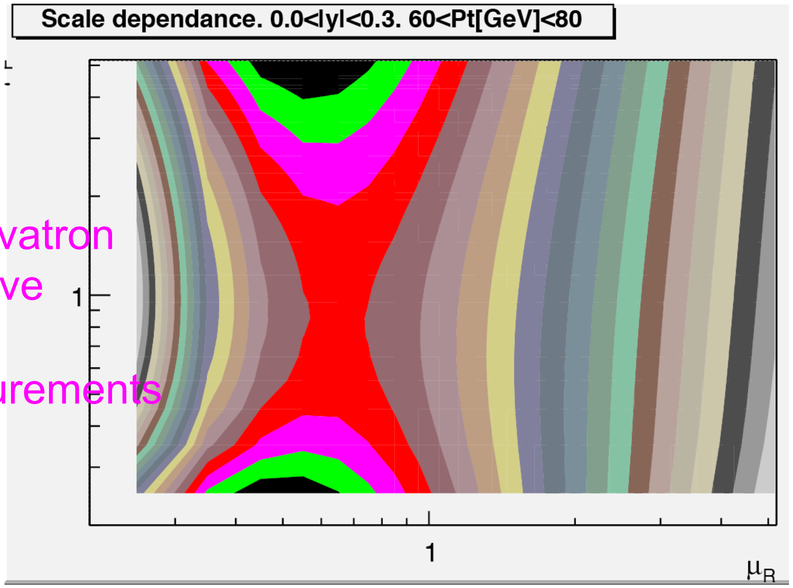
R=0.4
antikT

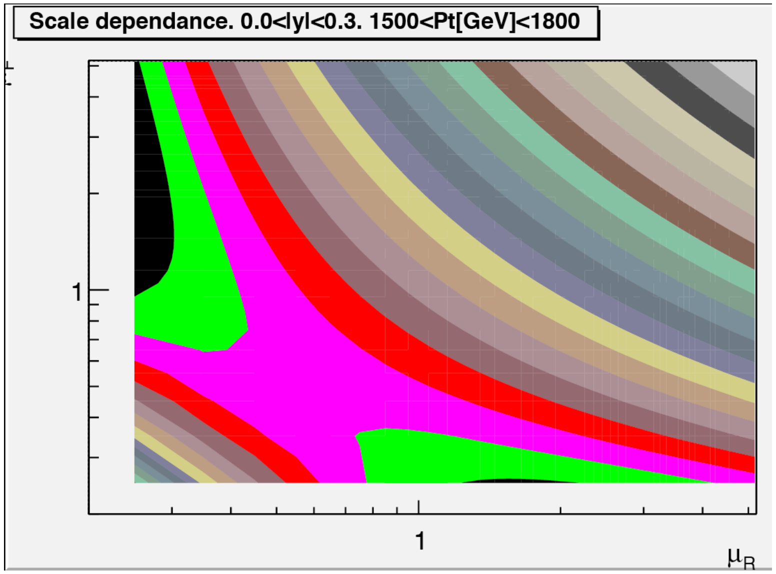




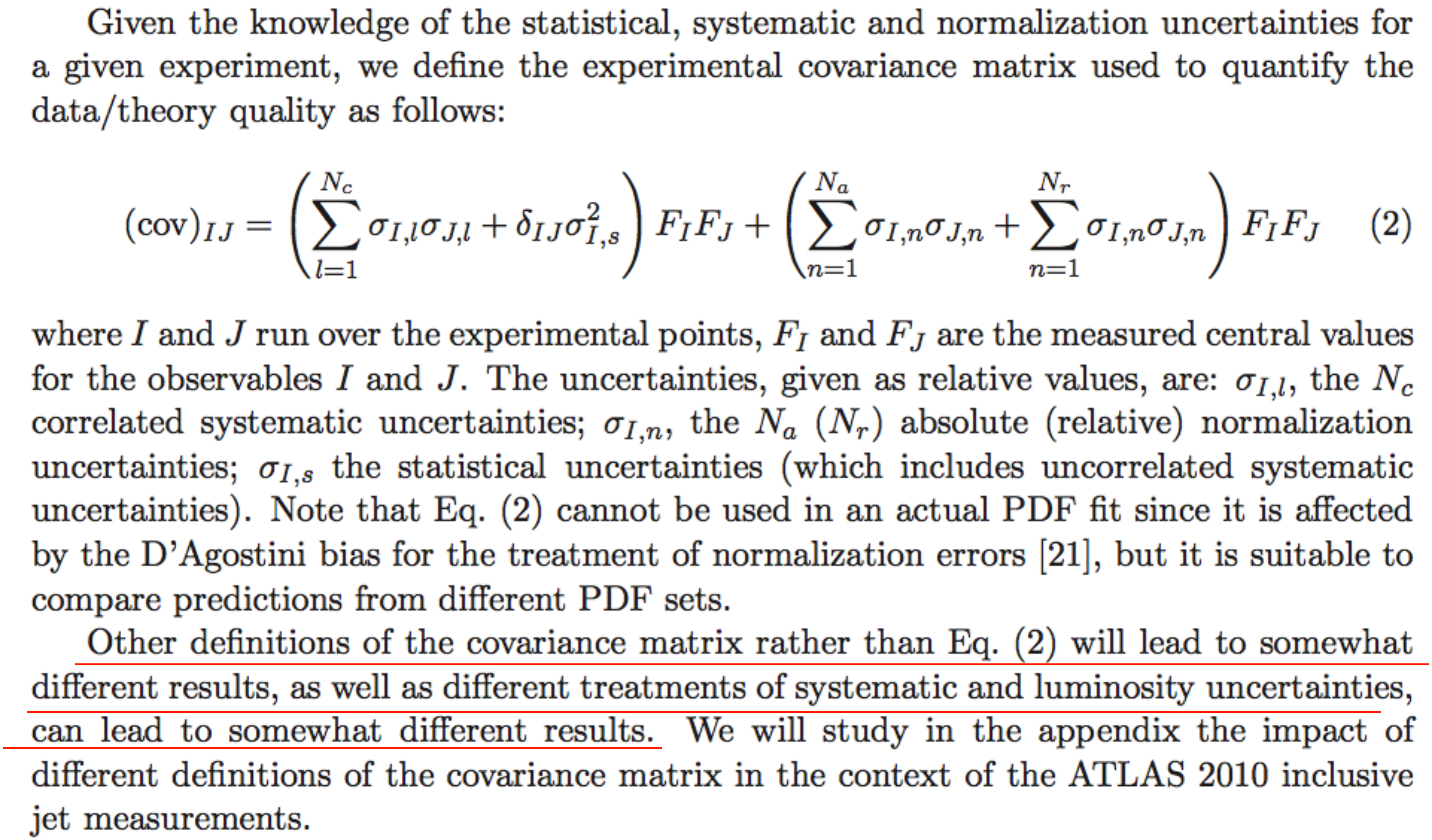
R=0.6
antikT

NB:Tevatron
inclusive
jet
measurements
with
R=0.7





Calculation of χ^2



Given the knowledge of the statistical, systematic and normalization uncertainties for a given experiment, we define the experimental covariance matrix used to quantify the data/theory quality as follows:

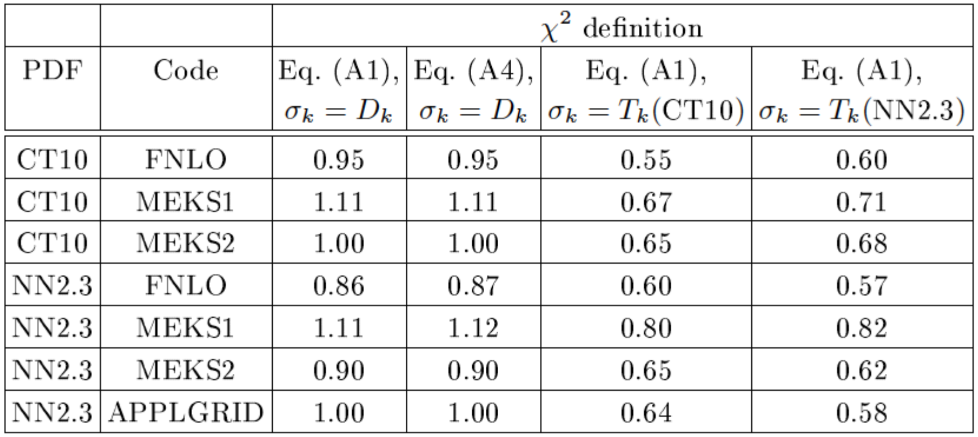
$$(\mathrm{cov})_{IJ} = \left(\sum_{l=1}^{N_c} \sigma_{I,l}\sigma_{J,l} + \delta_{IJ}\sigma_{I,s}^2 \right) F_I F_J + \left(\sum_{n=1}^{N_a} \sigma_{I,n}\sigma_{J,n} + \sum_{n=1}^{N_r} \sigma_{I,n}\sigma_{J,n} \right) F_I F_J \qquad (2)$$

where I and J run over the experimental points, F_I and F_J are the measured central values for the observables I and J. The uncertainties, given as relative values, are: $\sigma_{I,l}$, the N_c correlated systematic uncertainties; $\sigma_{I,n}$, the N_a (N_r) absolute (relative) normalization uncertainties; $\sigma_{I,s}$ the statistical uncertainties (which includes uncorrelated systematic uncertainties). Note that Eq. (2) cannot be used in an actual PDF fit since it is affected by the D'Agostini bias for the treatment of normalization errors [21], but it is suitable to compare predictions from different PDF sets.

Other definitions of the covariance matrix rather than Eq. (2) will lead to somewhat different results, as well as different treatments of systematic and luminosity uncertainties, can lead to somewhat different results. We will study in the appendix the impact of different definitions of the covariance matrix in the context of the ATLAS 2010 inclusive jet measurements.

Which χ^2?

- There are a number of χ^2 values being quoted that can differ greatly depending on the details of the definition



		χ^2 definition			
PDF	Code	Eq. (A1), $\sigma_k = D_k$	Eq. (A4), $\sigma_k = D_k$	Eq. (A1), $\sigma_k = T_k$(CT10)	Eq. (A1), $\sigma_k = T_k$(NN2.3)
CT10	FNLO	0.95	0.95	0.55	0.60
CT10	MEKS1	1.11	1.11	0.67	0.71
CT10	MEKS2	1.00	1.00	0.65	0.68
NN2.3	FNLO	0.86	0.87	0.60	0.57
NN2.3	MEKS1	1.11	1.12	0.80	0.82
NN2.3	MEKS2	0.90	0.90	0.65	0.62
NN2.3	APPLGRID	1.00	1.00	0.64	0.58

Table II: χ^2/N_{pt} values for the ATLAS inclusive jet production data ($\sqrt{s} = 7$ TeV, $R = 0.4$) obtained with various NLO PDFs, computer codes, and definitions of the χ^2 function. The cross sections are computed at NLO using FASTNLO (FNLO), MEKS with $\mu_{F,R}$ equal to the individual jet p_T (MEKS1) or p_T of the hardest jet (MEKS2), and APPLGRID. The correlation matrix is obtained from the raw experimental matrix as the percentage of the central experimental value (columns 1 and 2), CT10 theoretical prediction (column 3) and NNPDF2.3 theoretical prediction (column 4).

$$\chi^2(\{a\},\{\lambda\}) = \sum_{k=1}^{N_{pt}} \frac{1}{s_k^2}\left(D_k - T_k(\{a\}) - \sum_{\alpha=1}^{N_\lambda} \beta_{k\alpha}\lambda_\alpha\right)^2 + \sum_{\alpha=1}^{N_\lambda} \lambda_\alpha^2, \tag{A1}$$

$$\widetilde{\chi}^2(\{a\},\{\lambda_0(a)\}) = \sum_{i,j=1}^{N_{pt}} (D_i - T_i)\, C_{ij}^{-1}\, (D_j - T_j) \qquad C_{ij}^{-1} = \left[\frac{\delta_{ij}}{s_i^2} - \sum_{\alpha,\beta=1}^{N_\lambda} \frac{\beta_{i\alpha}}{s_i^2} \mathcal{A}_{\alpha\beta}^{-1} \frac{\beta_{j\beta}}{s_j^2}\right]$$

Sheldon tackles 6-loops