PDFs for Higgs Physics(and the LHC)

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First 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

The PDF4LHC Working Group Interim Report

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

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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.

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.

So basically, this is a factor of 2.

At the time of this prescription, neither CTEQ nor NNPDF had NNLO PDFs.

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
- 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

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

CERN–2011–002
17 February 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
G. Passarino
R. Tanaka

more extensive use of PDF and cross section correlations

- Correlations (of gg fusion production of Higgs to various processes shown) differ between PDFs more than I would have originally suspected
- Again, MSTW, CTEQ and NNPDF correlations tend to be similar

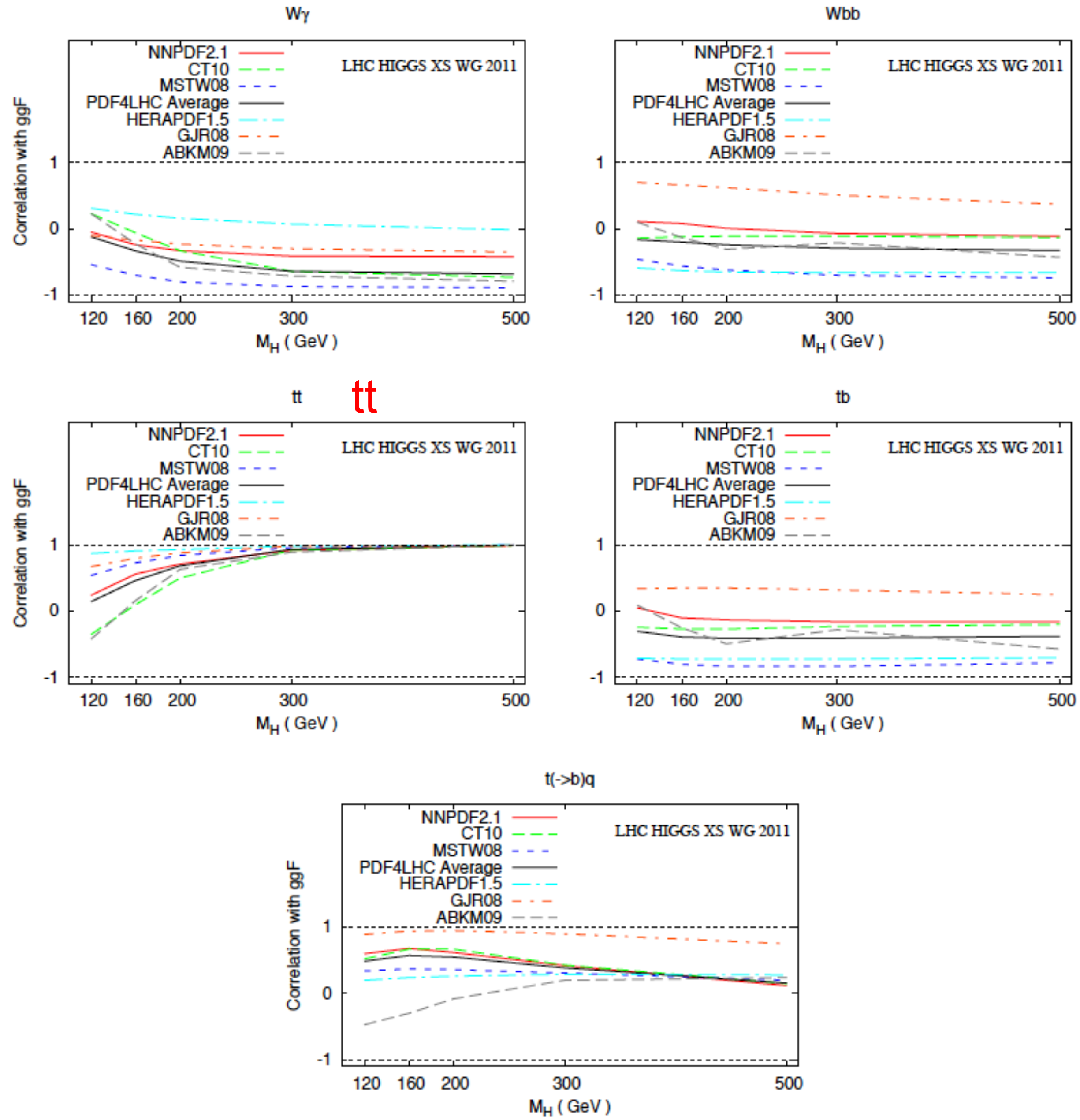

Fig. 15: Correlation between the gluon fusion gg $\rightarrow$ H process and other signal and background processes as a function of M_{H}. We show the results for the individual PDF sets as well as the up-to-date PDF4LHC average.

Followup

- Study of NNLO PDFs from 5 PDF groups (no new updates for JR)
  - drawing from what Graeme Watt had done at NNLO, 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)
- …and are now in YR3

Benchmark paper

- 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

arXiv:1211.5142v2 [hep-ph] 5 Apr 2013

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 com-

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.

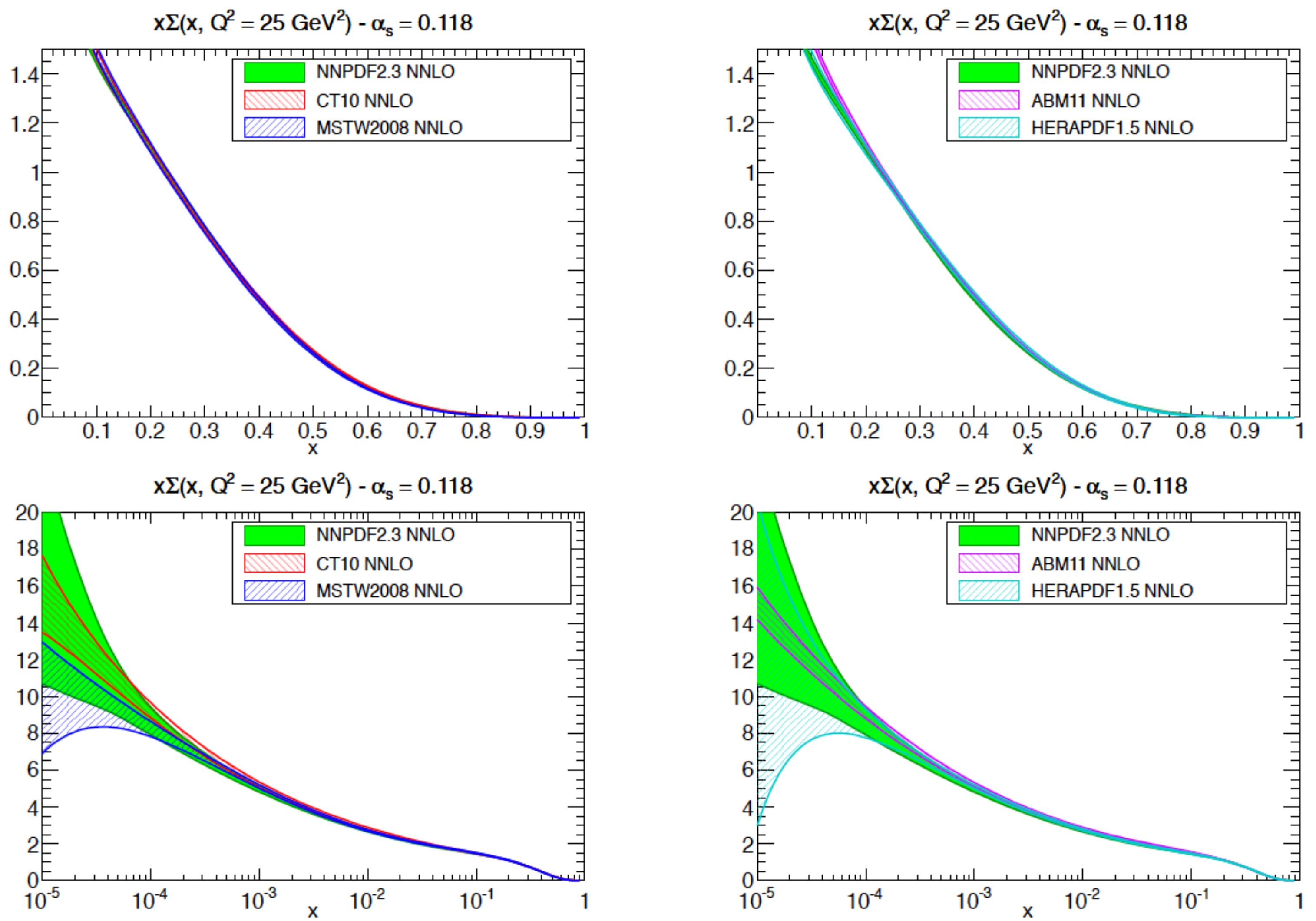
No updates of JR since 2009.

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

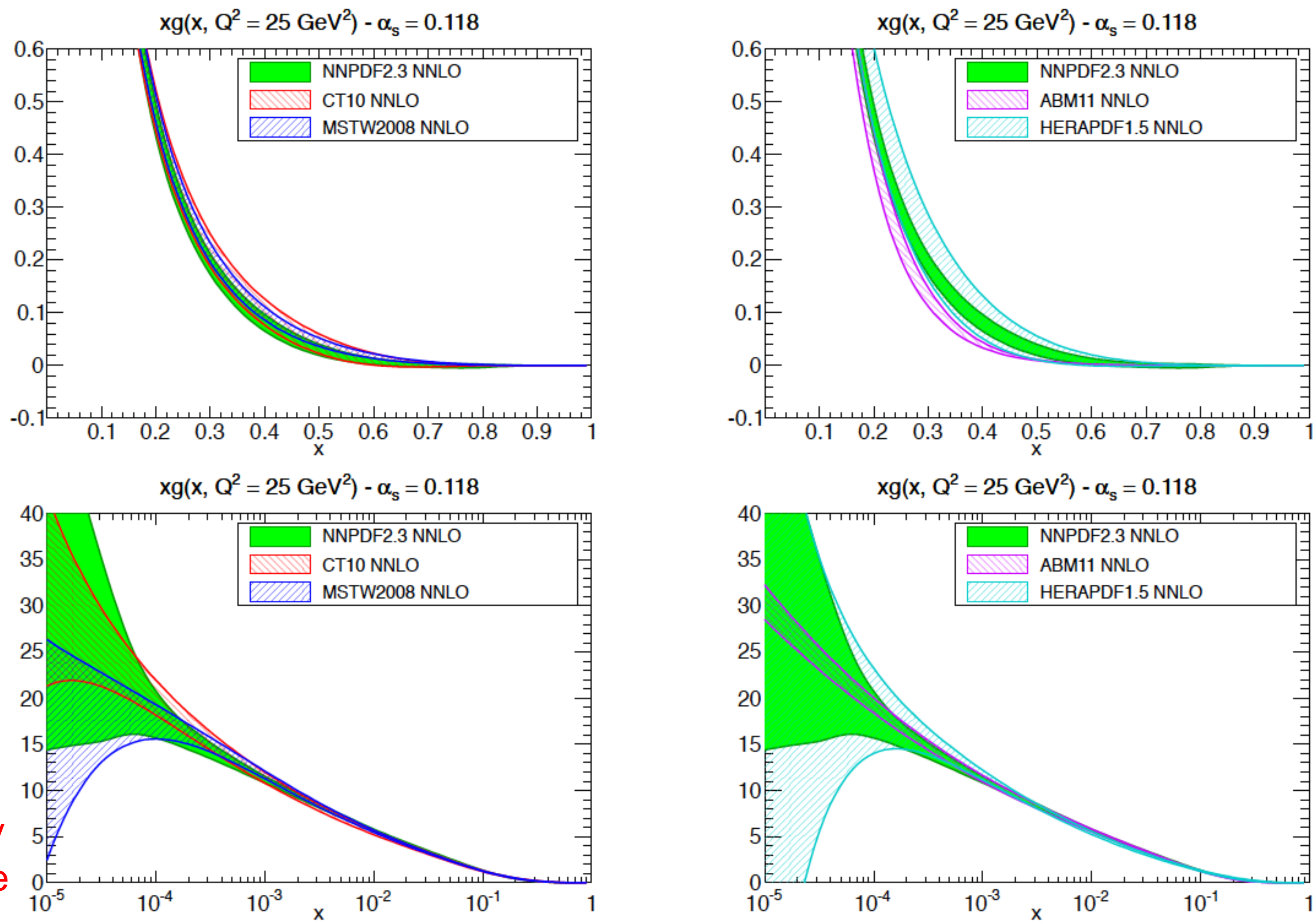
CT10, MSTW08 and NNPDF2.3 gluon distributions all in reasonable, but not perfect, agreement

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

Differences are larger for ABM11

HERAPDF uncertainties somewhat larger at low x; noticeably larger at high x due to lack of collider jet data

gluon PDF



PDF luminosities

gluon-gluon and gluon-quark luminosities in reasonable, but again not perfect, agreement for CT10, MSTW08 and NNPDF2.3 for full range of invariant masses

HERAPDF1.5 uncertainties larger in general

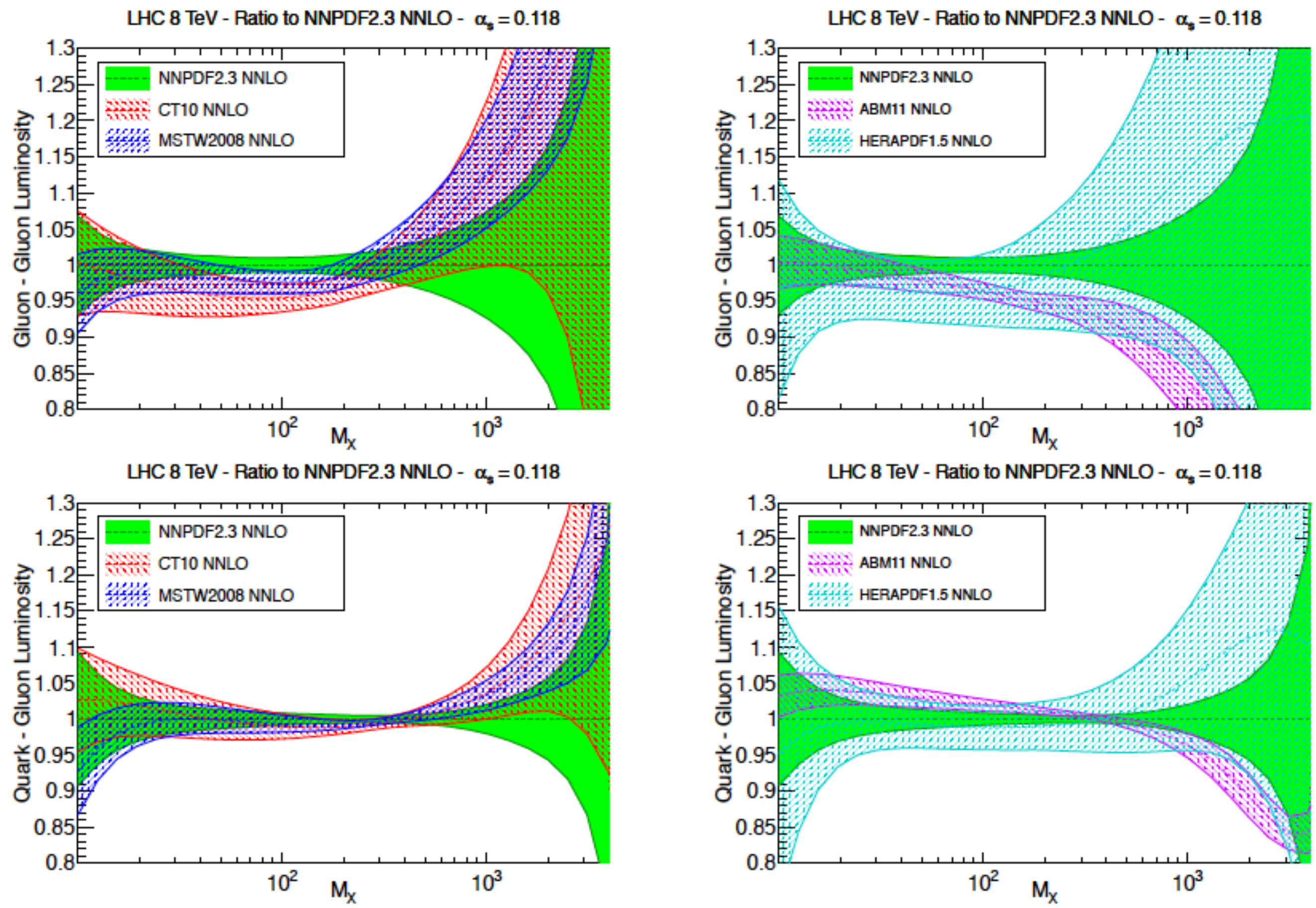


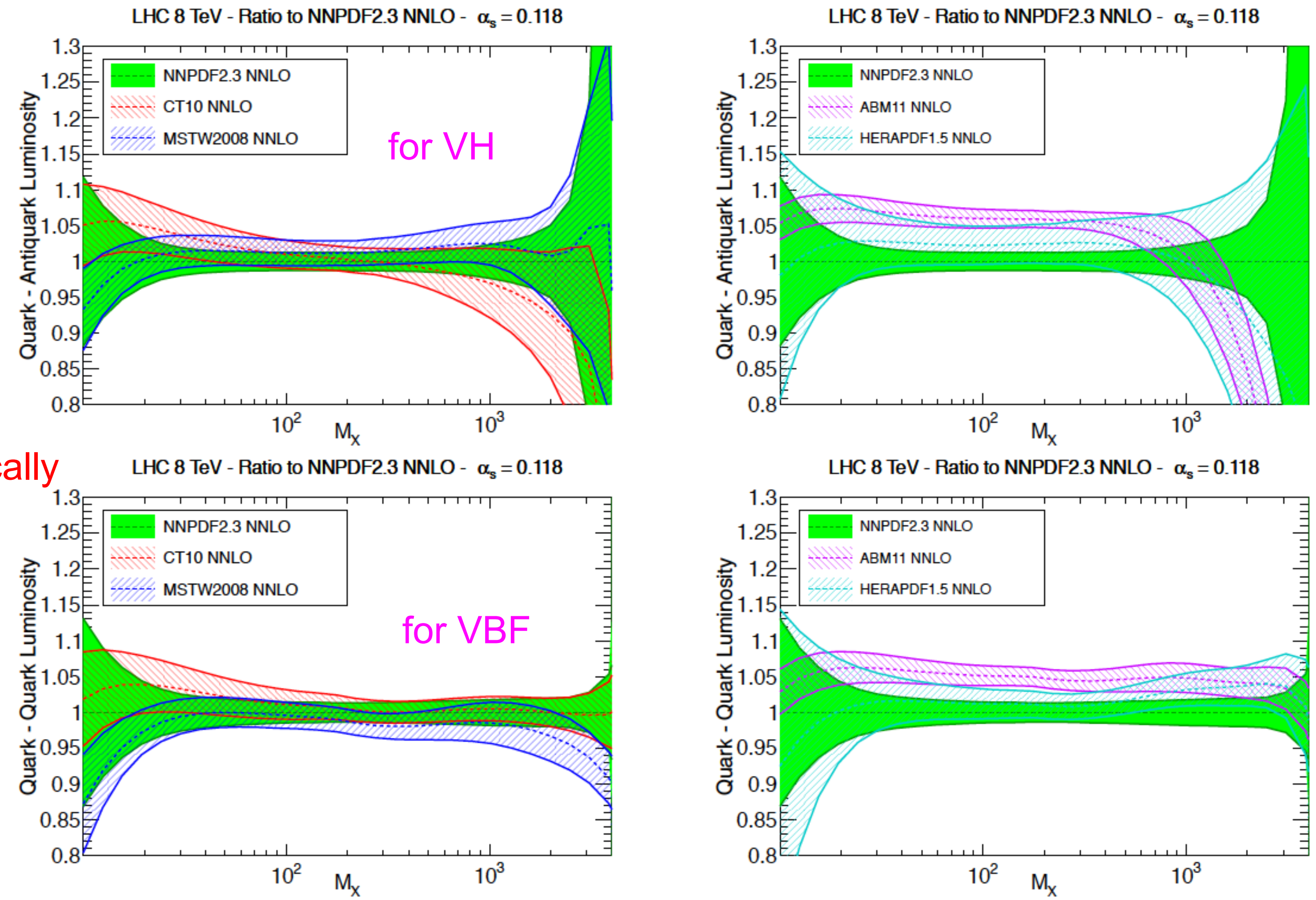
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5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

PDF luminosities

quark-quark and quark-antiquark

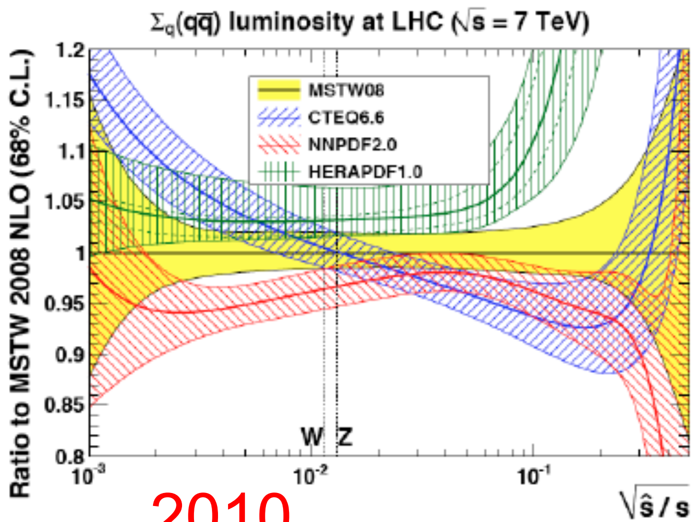
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range

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

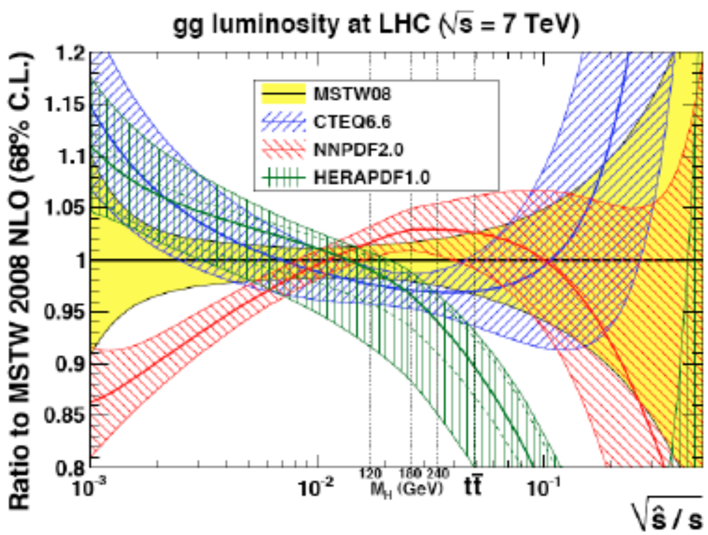


Uncertainties have improved

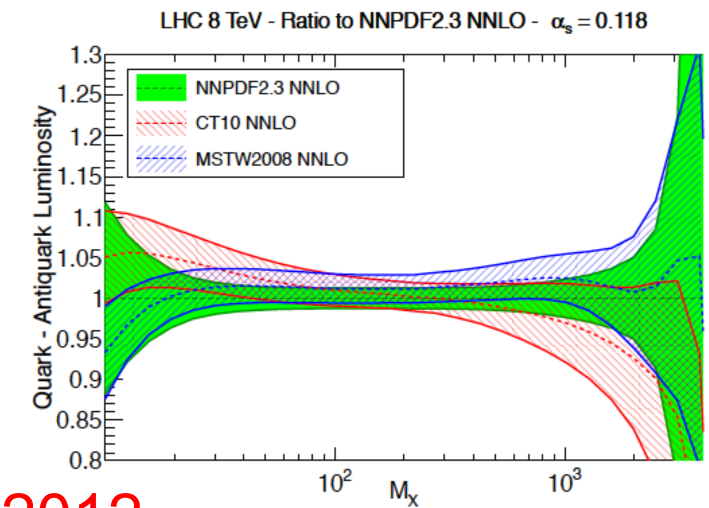
- …with additional data and in going from NLO to NNLO

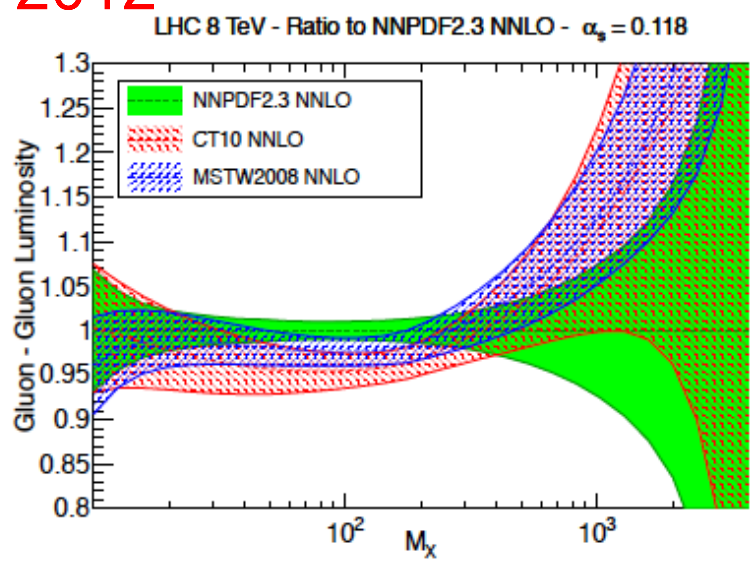


2010



→ 2012





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

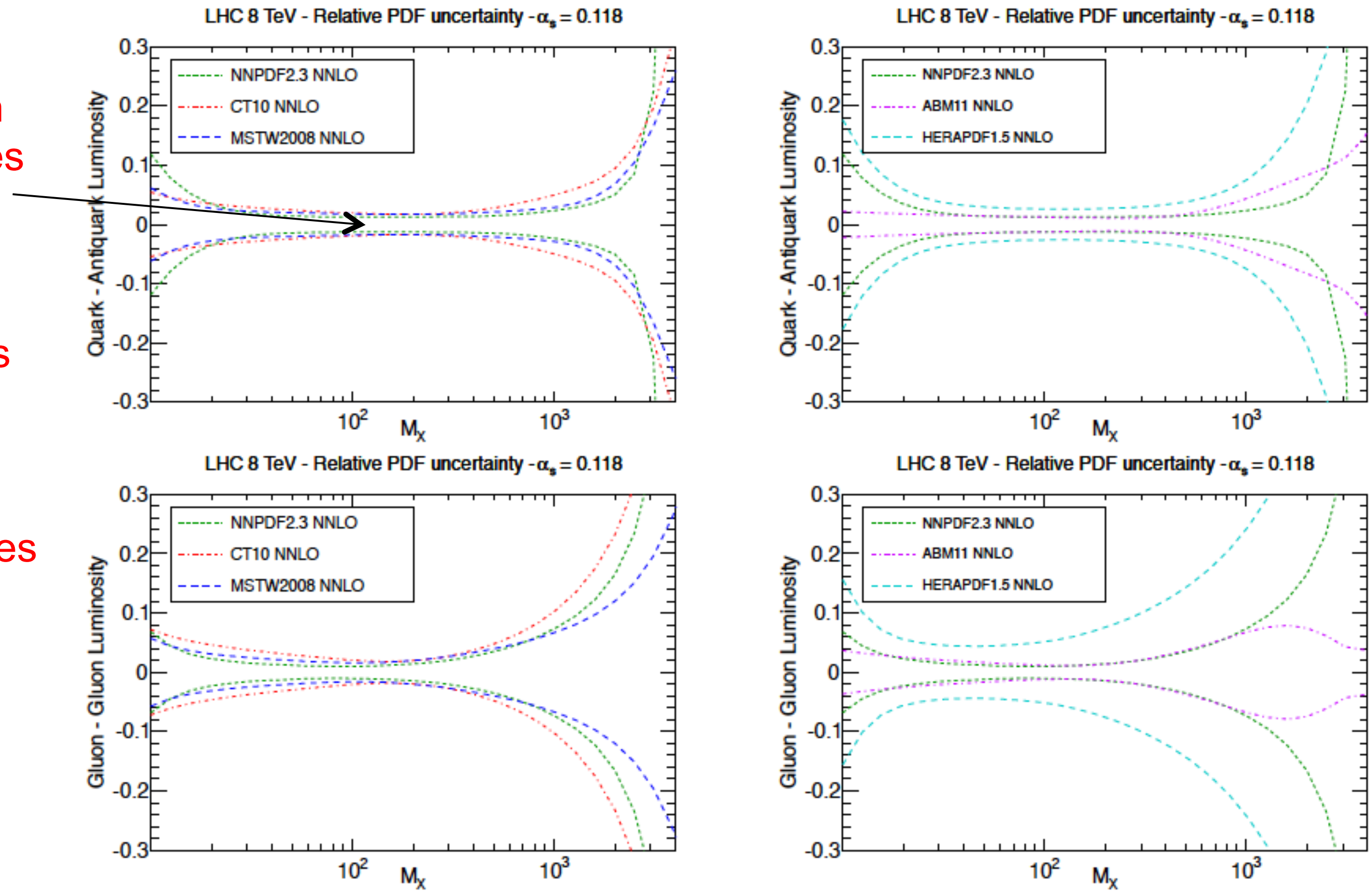
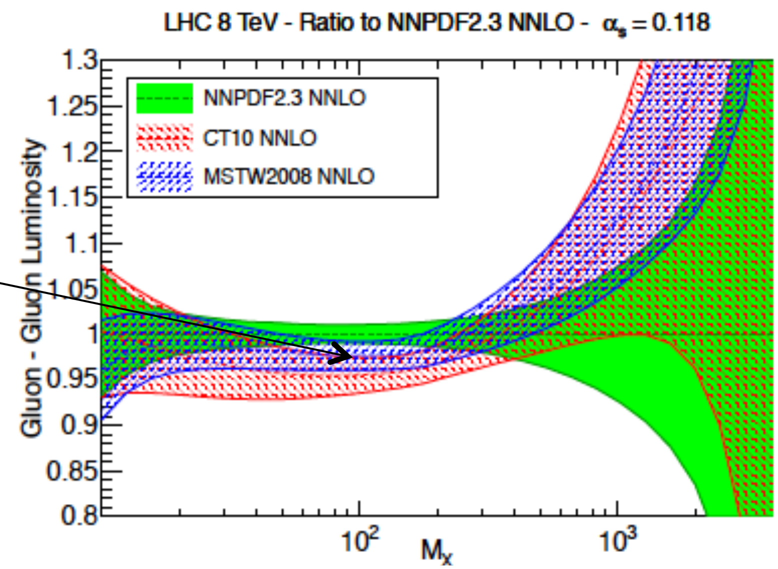
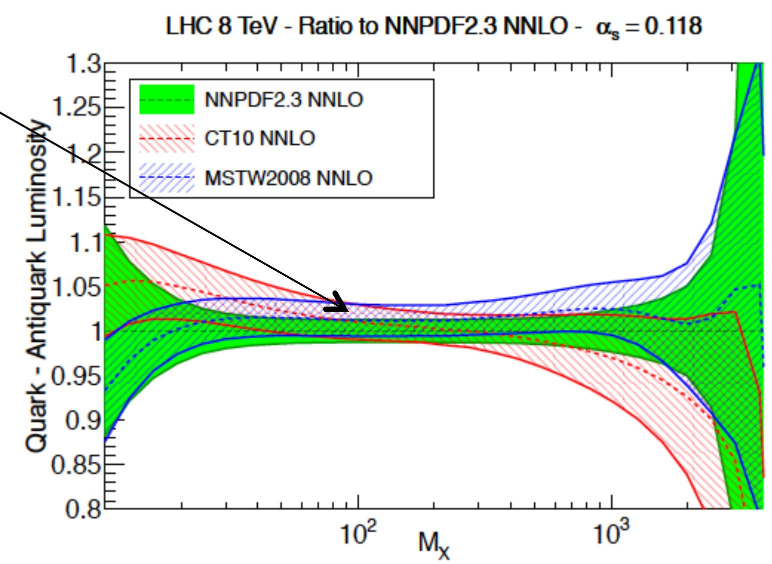


Figure 8: The relative PDF uncertainties in the quark-antiquark luminosity (upper plots) and in the gluon-gluon luminosity (lower plots), for the production of a final state of invariant mass M_X (in GeV) at the LHC 8 TeV. All luminosities are computed at a common value of $\alpha_s = 0.118$.

NNLO PDF uncertainties

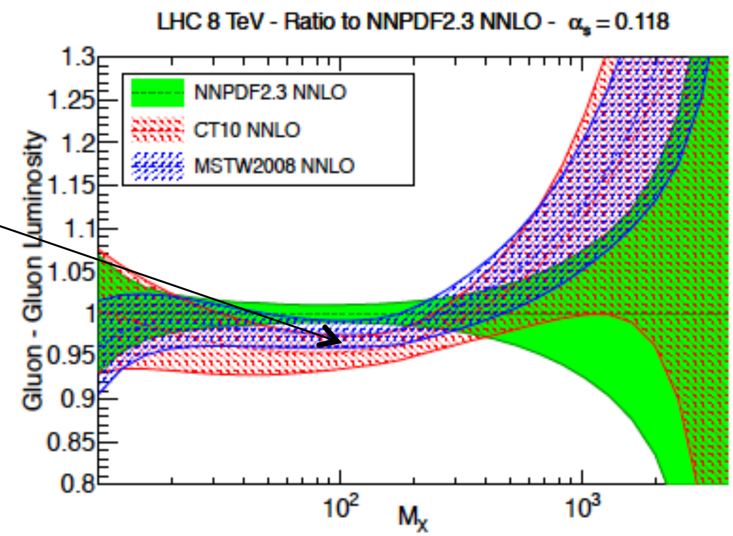
- Factor of 2 expansion of MSTW2008 error (previous prescription) basically works for gg initial states (like 125 Higgs)
- …but maybe an overestimate for qQ initial states, where there has been a nice convergence
- …in Joe's words, perhaps we've 'grown up', at last for that initial state

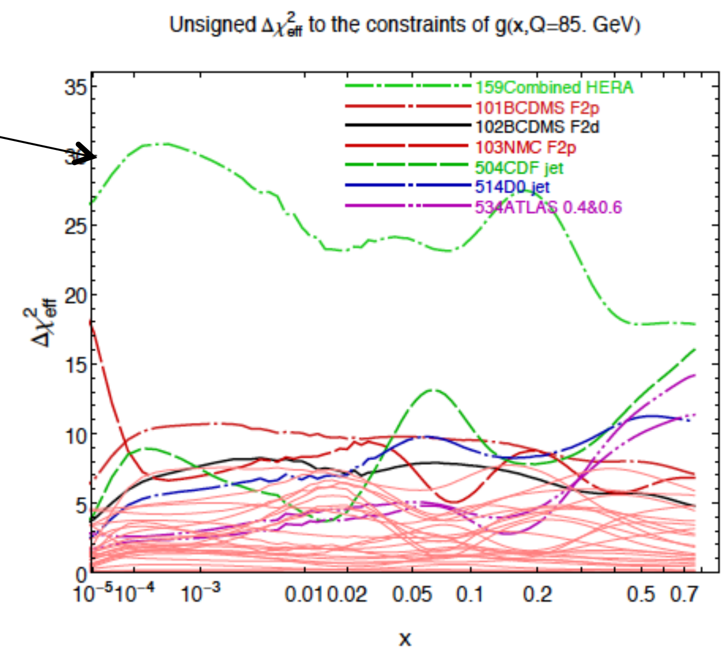




…but are they good enough?

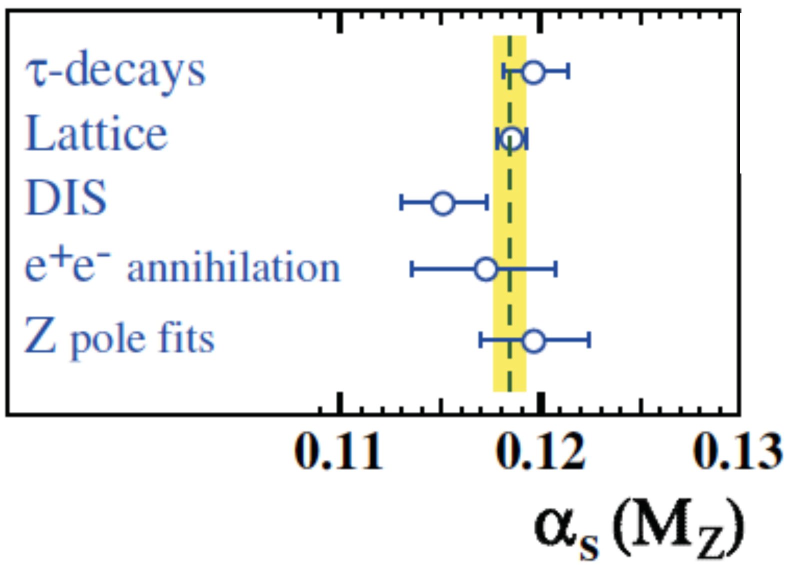
- Can we further improve the gg PDF luminosity uncertainty in the Higgs mass region?
  - PDF+α_s error is now the dominant theory error for ggF
- NNPDF2.3 marks the high edge and CT10 the low edge
  - full gg uncertainty is ~ factor of 2 more than any of the individual group uncertainties
- The gluon in this region is determined largely by the HERA combined Run 1 data set, but fixed target (NMC and BCDMS) have big impact as well
- There may be issues relating to specific heavy quark schemes/ charm quark masses
- This was a project that started at Les Houches
- Progress report in the writeup





$\alpha_s(m_Z)$

- Right now the Higgs Cross Section Working Group is using a mean value for $\alpha_s(m_Z)$ of 0.118 with 90% CL error of 0.002 (68%CL error of 0.012), or an inflation of the world average uncertainties; the α_s error is added in quadrature with the PDF error
- The world average is dominated by lattice results
- Are the lattice results are robust enough, so that an uncertainty of 0.012 (at 68% CL) may be an overestimate?
- So I may try to reduce the Higgs Working Group uncertainty, especially if we're successful in reducing the PDF uncertainty



variety of different calculations/groups results in very compatible results

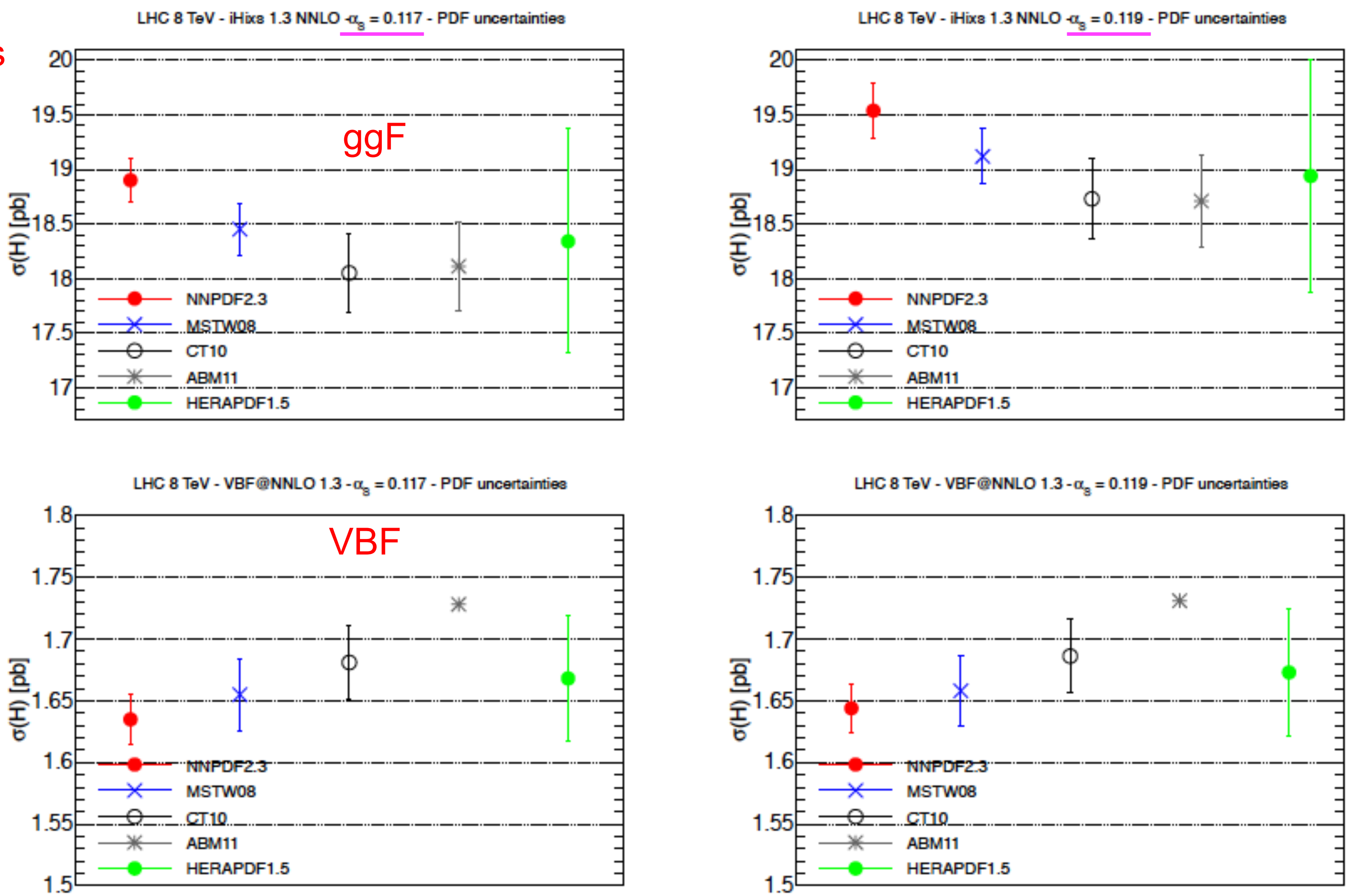
Figure 1-1. *Summary of values of $\alpha_s(M_Z^2)$ obtained for various sub-classes of measurements. The world average value of $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ is indicated by the dashed line and the shaded band. Figure taken from [1].*

8 TeV Higgs cross section predictions

cross sections calculated at NNLO using a scale of m_H

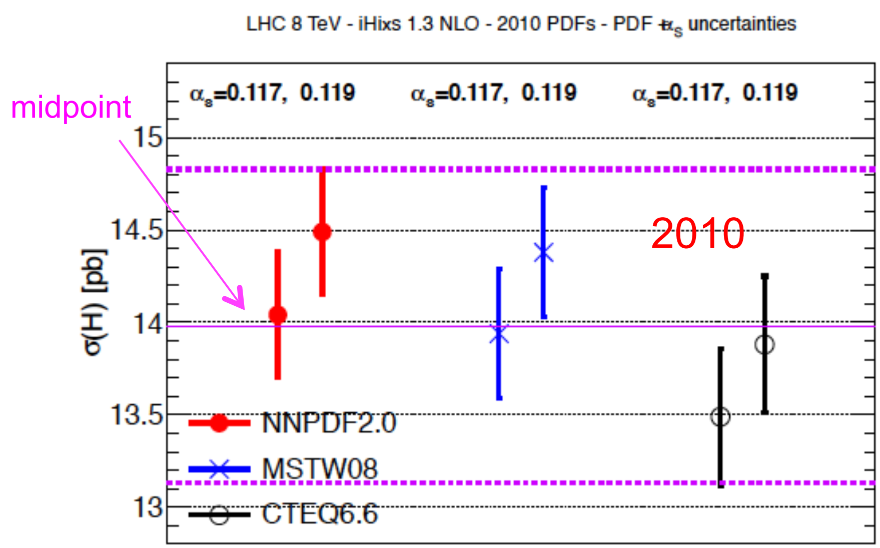
ABM11 and HERAPDF1.5 predictions within error envelope

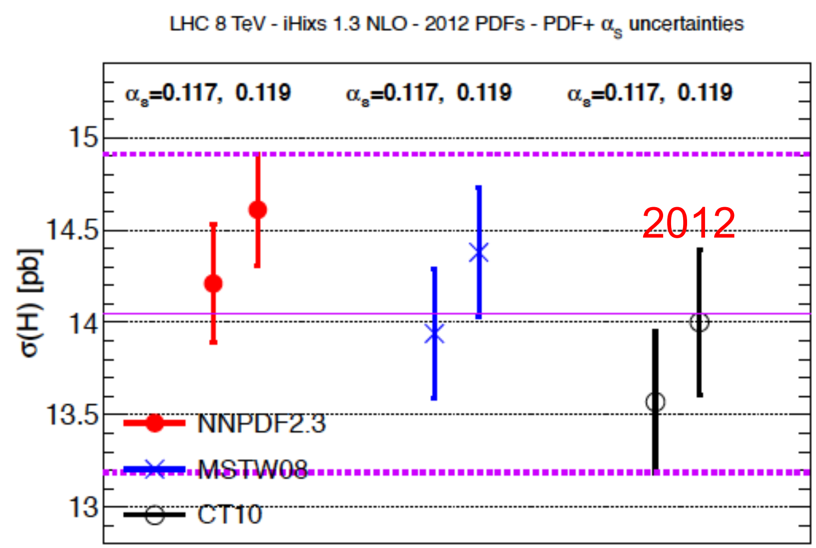
NB: ABM11 cross section would be lower if native value of α_s (0.1134) used



Revisit prescriptions (for 8 TeV cross sections for gg fusion)

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



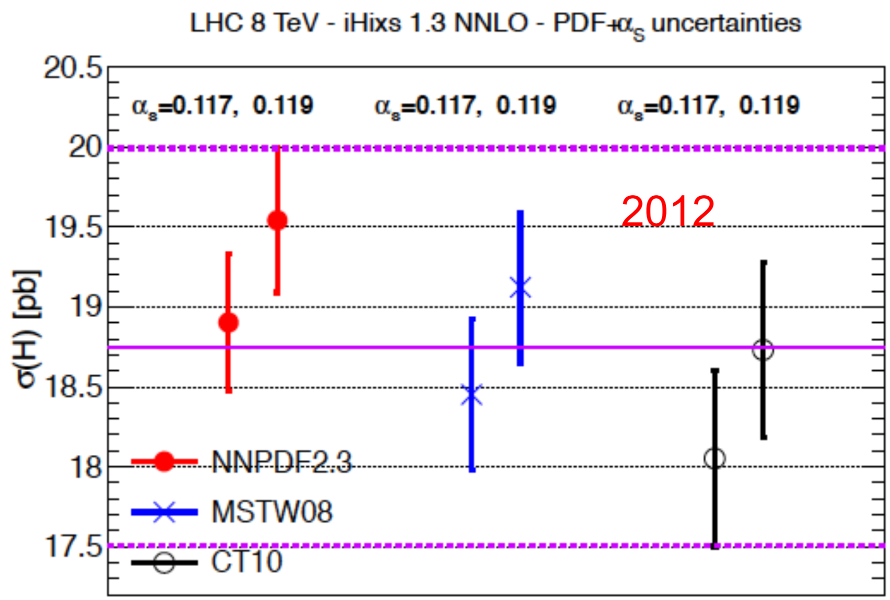


Revisit prescriptions (for 8 TeV cross sections for gg fusion)

2012 NNLO result

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

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



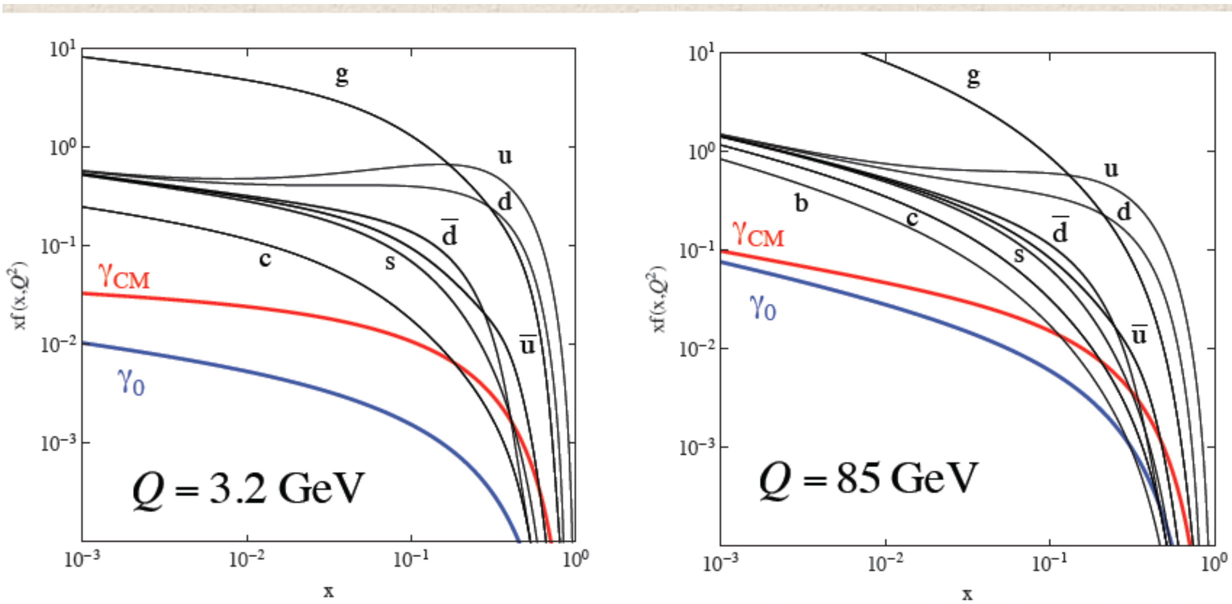
HXSWG 8 TeV NNLO cross section

NNLO+NNLL

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

Photon PDFs

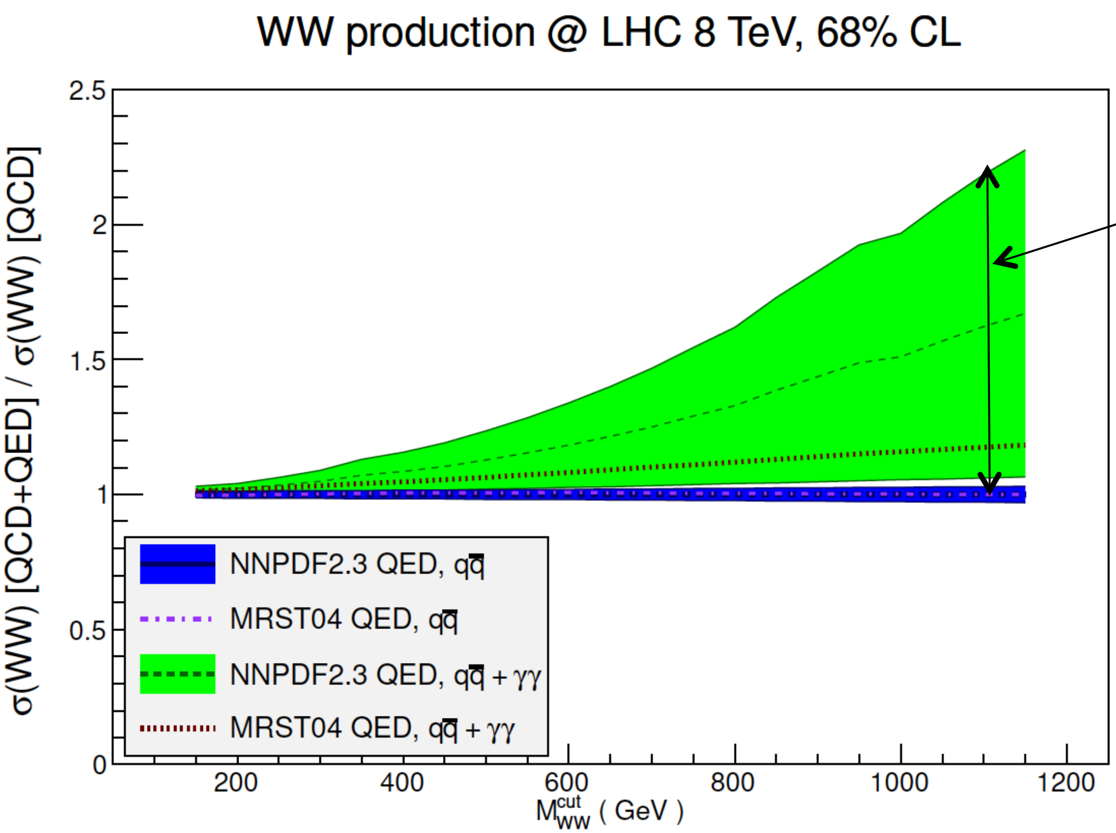
- Photon PDFs: photon PDFs can be larger than antiquark distributions at high x; the LHC is a $\gamma\gamma$ collider
- NNPDF has developed photon PDFs + QED corrections (in addition to MRST2004QED)
- CT10 in progress



- …plus, at Les Houches, a general re-visitation of QED and EWK corrections for 14 TeV cross sections, especially in the **Sudakov Zone**

WW production and the photon PDF

- photon-induced WW production can contribute significantly at high mass
- …and understanding high mass WW production will be important in the next run
- a better understanding of the photon PDF is thus crucial
  - first steps taken with LHC DY data

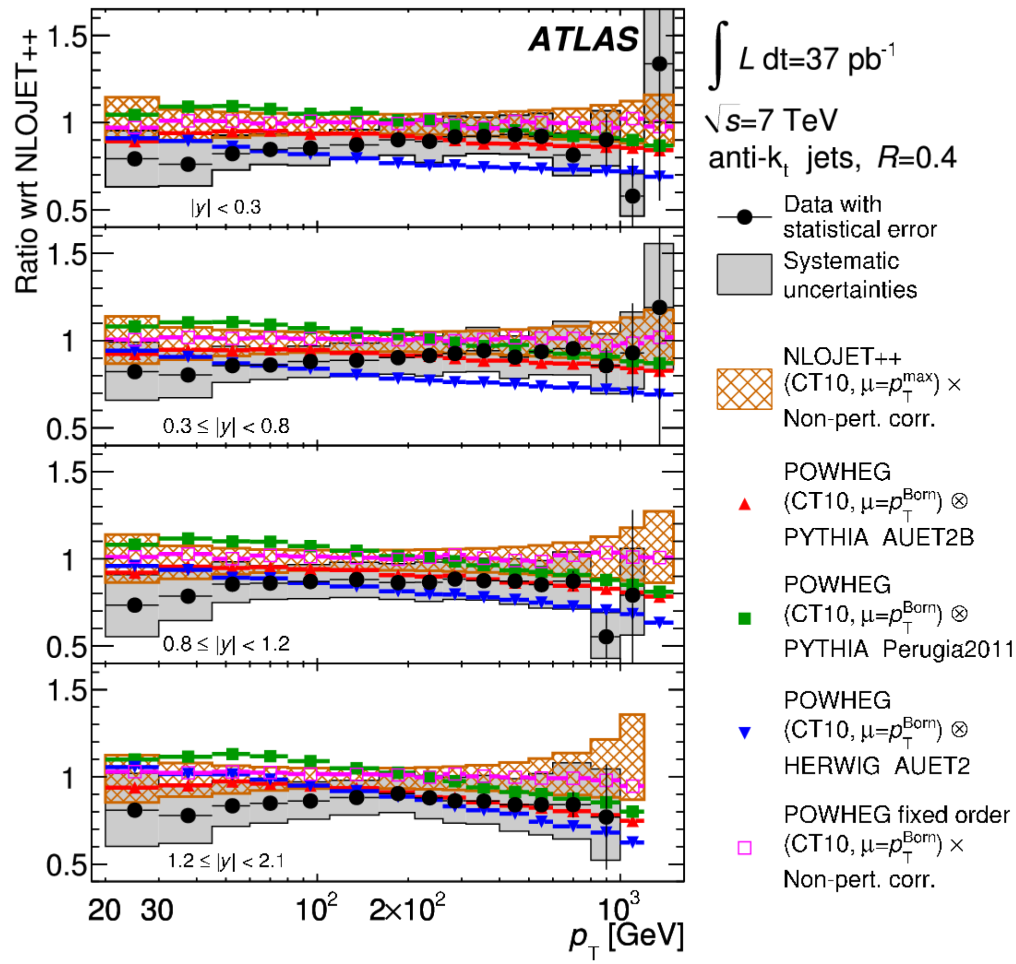


with currently a very large uncertainty due to lack of knowledge of the photon PDF

LHC data in global PDF fits

- LHC data will become increasingly important in global fits
- Not just inclusive jet data but for processes such as inclusive photon production, Drell-Yan, W/Z rapidity, ttbar mass and rapidity
- For any process to be used in a global PDF fit, correlated systematic errors must be provided
- 2010 inclusive jet data from ATLAS provides no discrimination
- Data from 2011/2012, with increased statistics and improved systematics may
- Note that LHC data is competing against HERA data where two experiments have been combined and statistical and systematic errors are a few percent
  - may be difficult to compete in the precision physics range a la gg->Higgs
  - but definitely will contribute in the discovery physics range

- 2010 ATLAS data lies below NLOJET++ prediction using CT10 at high p_T/y
- difference if Powheg used instead of fixed order? extra radiation?



- …but consider the 2012 inclusive jet measurement from CMS (8 TeV) where CT10 seems to provide a good description
- …with much higher statistics and improved systematics
- Errors aren't public yet so don't know the impact on global PDF fits

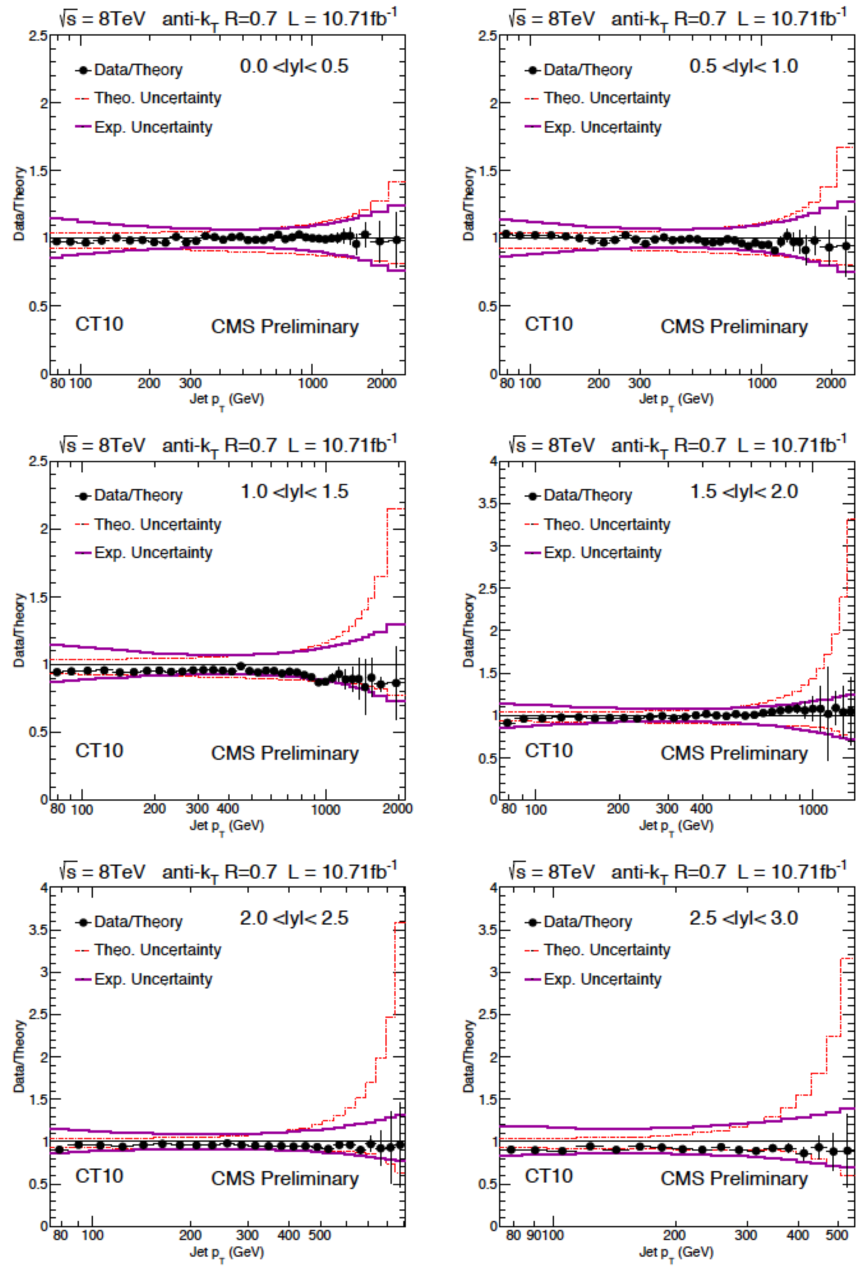


Figure 3: Ratio of data over theory at NLO times NP correction for the CT10 PDF set. For comparison the total theoretical (band enclosed by dashed red lines) and the total experimental systematic uncertainty (band enclosed by full magenta lines) are shown as well. The error bars correspond to the statistical uncertainty of the data.

- …whereas NNPDF2.3 (or MSTW08) seems to be below the data at high p_T

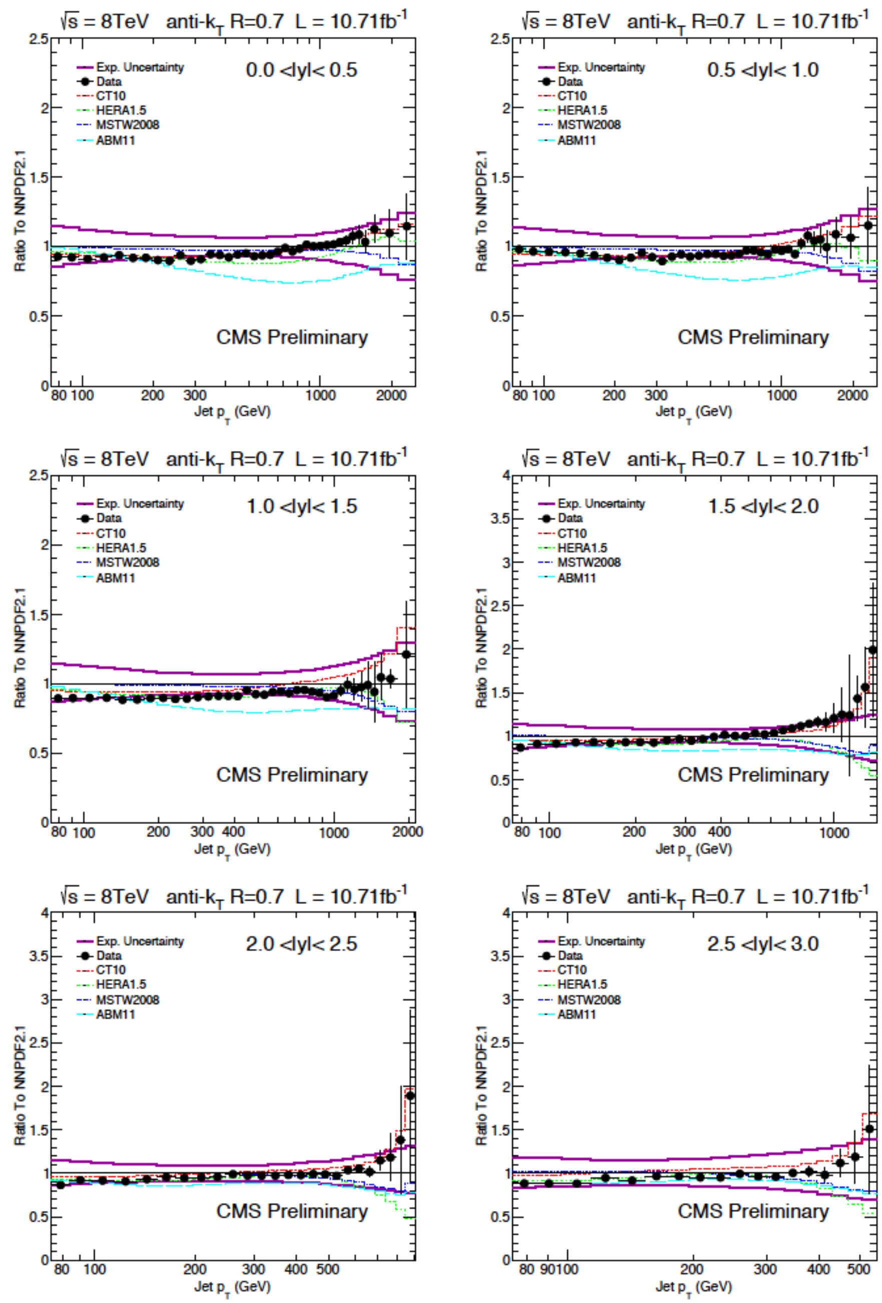
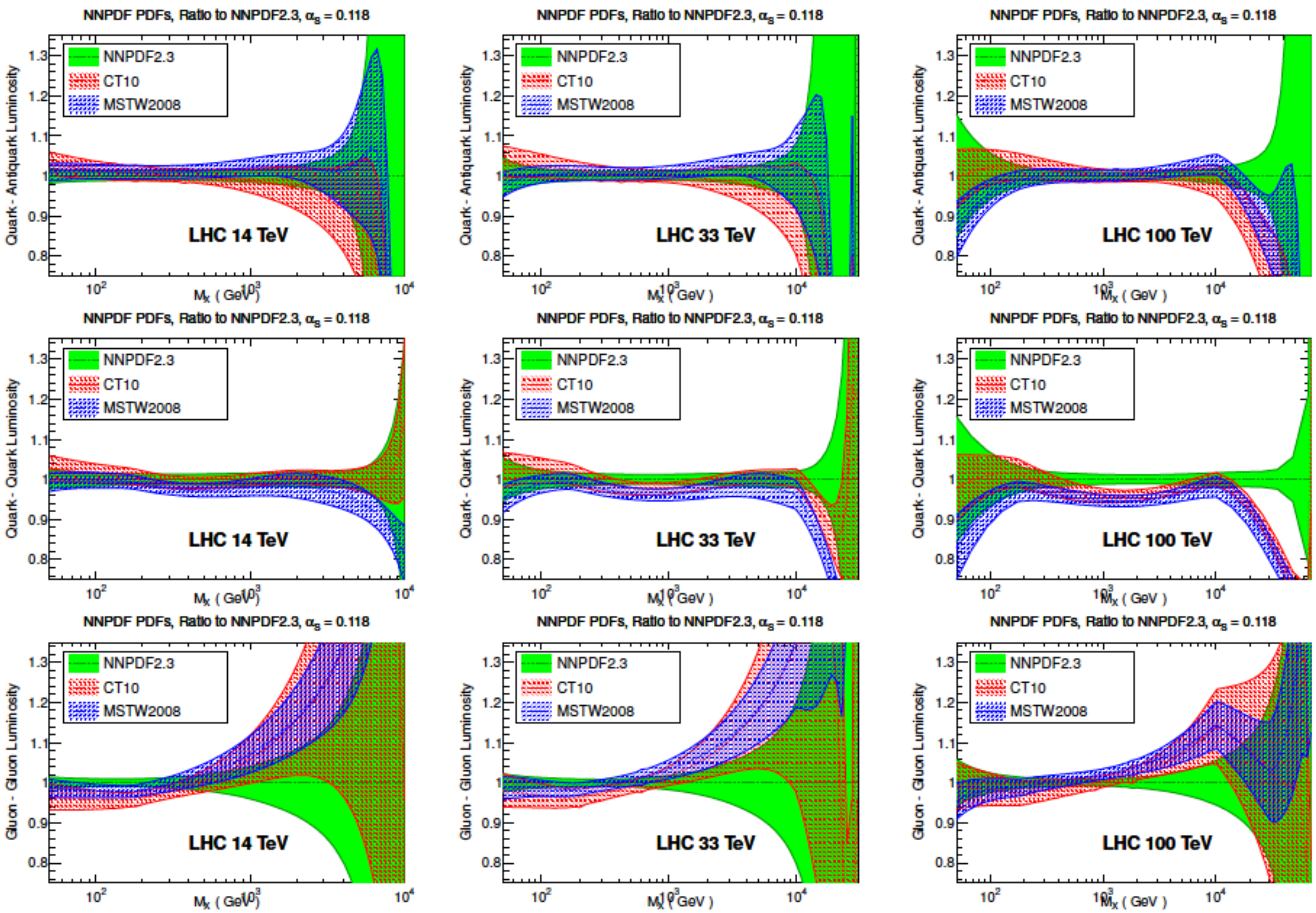


Figure 7: Ratio of data over theory at NLO times NP correction for the NNPDF2.1 PDF set. For comparison predictions employing four other PDF sets are shown in addition to the total experimental systematic uncertainty (band enclosed by full magenta lines). The error bars correspond to the statistical uncertainty of the data.

PDFs at higher energies: as part of the Snowmass exercise

PDFs are HERA/fixed target dominated for x<~0.05-0.1; LHC data at 14 TeV offers opportunity for shrinking uncertainties in new physics search range



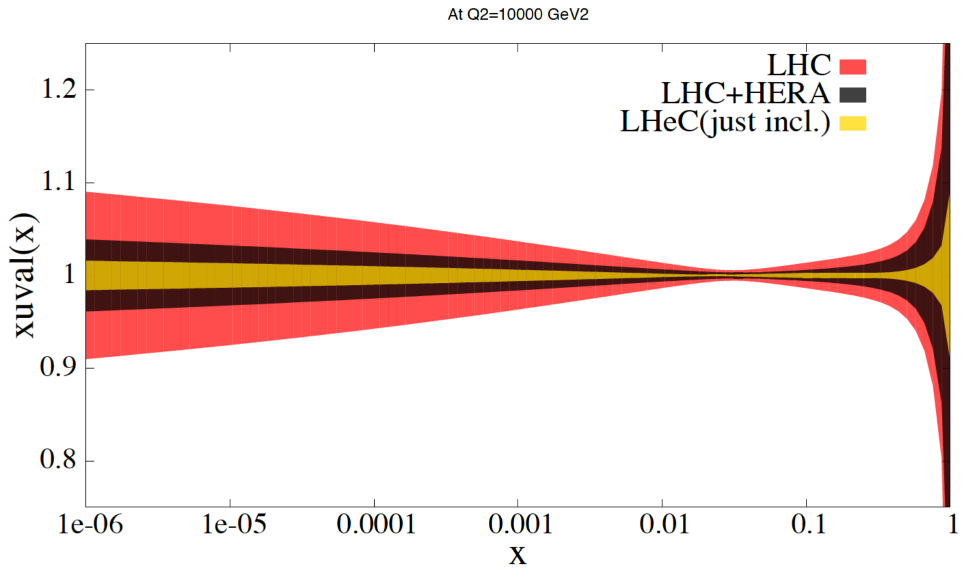
high masses always a problem, with current uncer- tainties

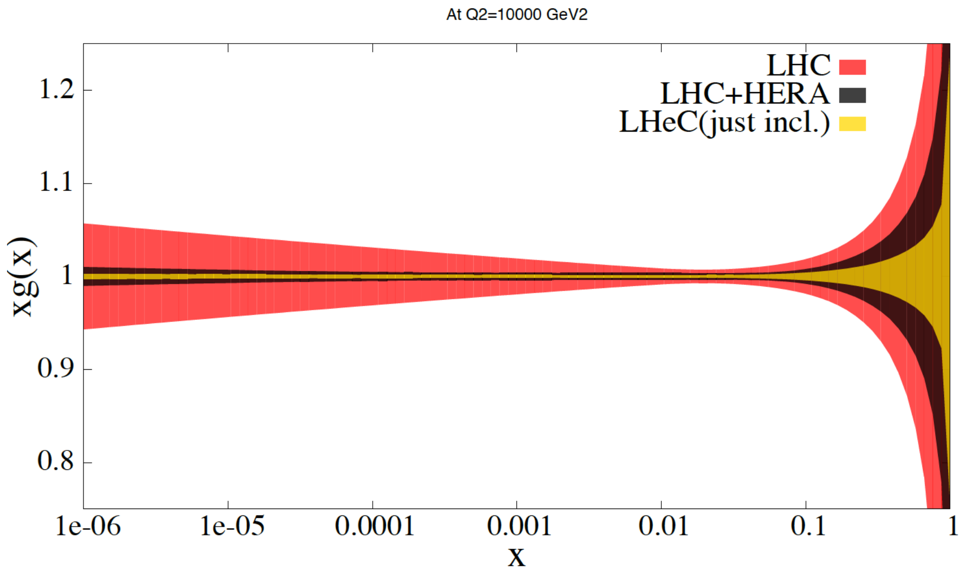
low masses become a problem at very high energy colliders

Workshop on Physics at a 100 TeV Collider at SLAC in April

Snowmass exercise with LHC data

- Use current LHC data in global PDF fits, find no great restraint
  - impact comes from inclusion of HERA data
- With 100 fb^{-1}, will have precision measurements of DY production from 60 to 1500 GeV, with systematic errors half of the current values, stat errors 5% at high mass
  - Phase 1 (300 fb^{-1}) and phase 2 (3000 fb^{-1}) will provide strong improvement in PDF uncertainties at high mass (BSM search region)





New PDF4LHC exercise

- Lay out a coherent coordinated plan for QCD(+EW) measurements, among ATLAS, CMS and LHCb, that can reduce PDF systematics using LHC data
  - again systematic errors will be very important
- Wiki will be up soon, followed by a short document

Nota bene

- For the PDFs to be fully NNLO, we need to use NNLO matrix elements for inclusive jet production, crucial to the determination of the high x gluon
- So far, we have them for the gg channel
  - corrections are sizeable; I would expect them to be smaller for the gq and qQ channels, following the Dixon conjecture

Casimir for biggest color representation final state can be in

Simplistic rule

$C_{i1} + C_{i2} - C_{f,max}$

L. Dixon

Casimir color factors for initial state

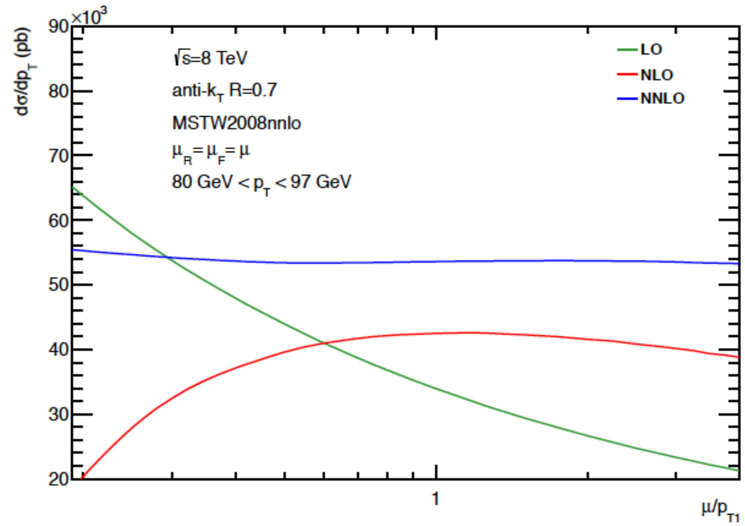


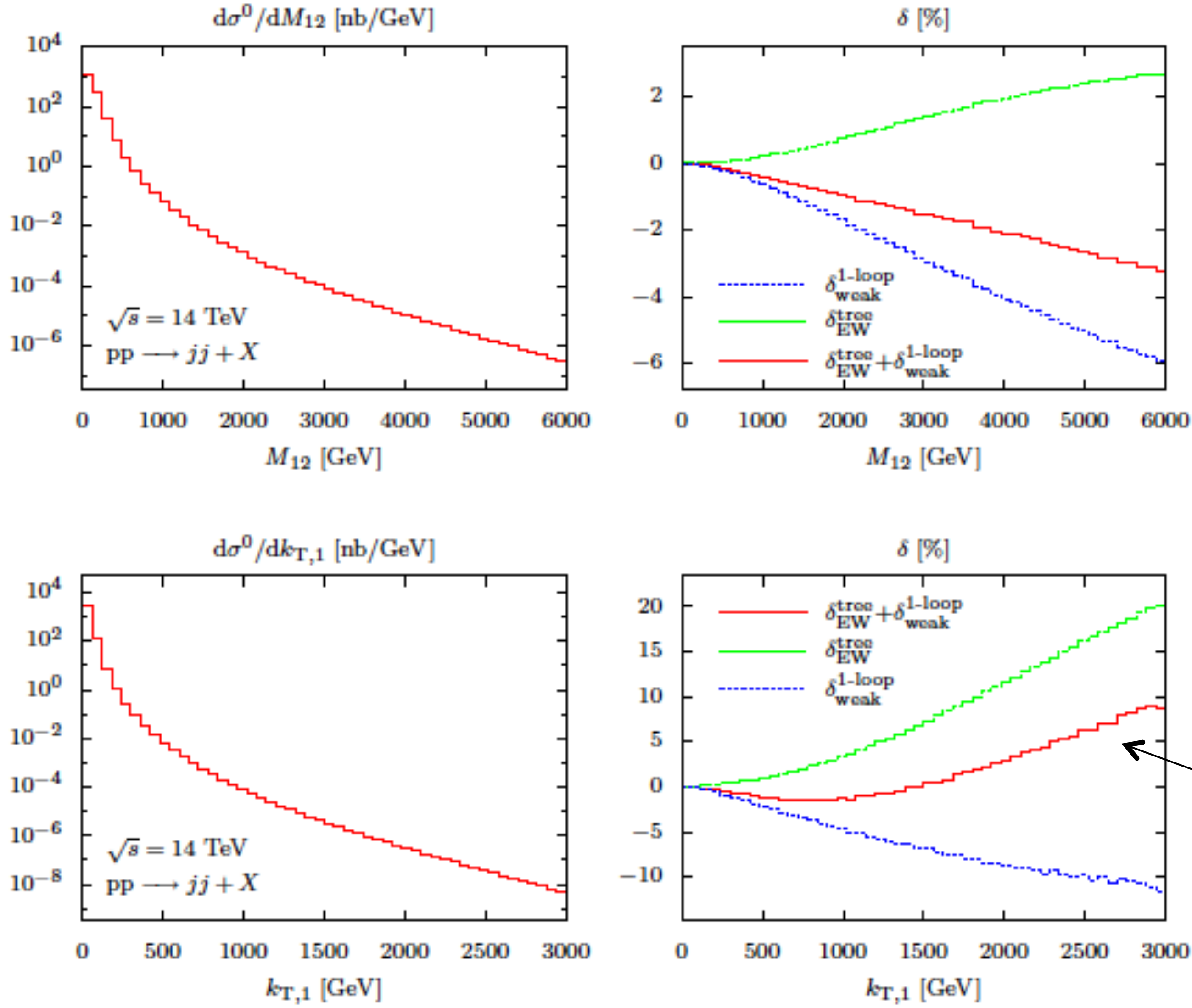
FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

We know that NLO describes jet sections for R=0.6 and R=0.7 better than for R=0.4 and R=0.5; need extra gluon that's in NNLO?

Completion of NNLO this year? Nigel won't take bets any more

Weak corrections to dijet production – numerical results

S.D., Huss, Speckner '12



Weak corrections
- small for integrated XS
- growing in distributions for larger scales

Cancellations between tree and loop corrections (cut-sensitive!)

total EW impact starts to become noticeable at high p_T

NNLO QCD+NLO EW wishlist

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

add a column here for current exp precision and that expected at 14 TeV

N. Glover, S. Dittmaier

NNLO QCD + NLO EWK wishlist

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass $\rightarrow$ PDF fits (gluon at high x) $\rightarrow \alpha_s$ CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + b$ for bottom PDF

Table 2: Wishlist part 2 – jets and heay quarks

N. Glover, S. Dittmaier

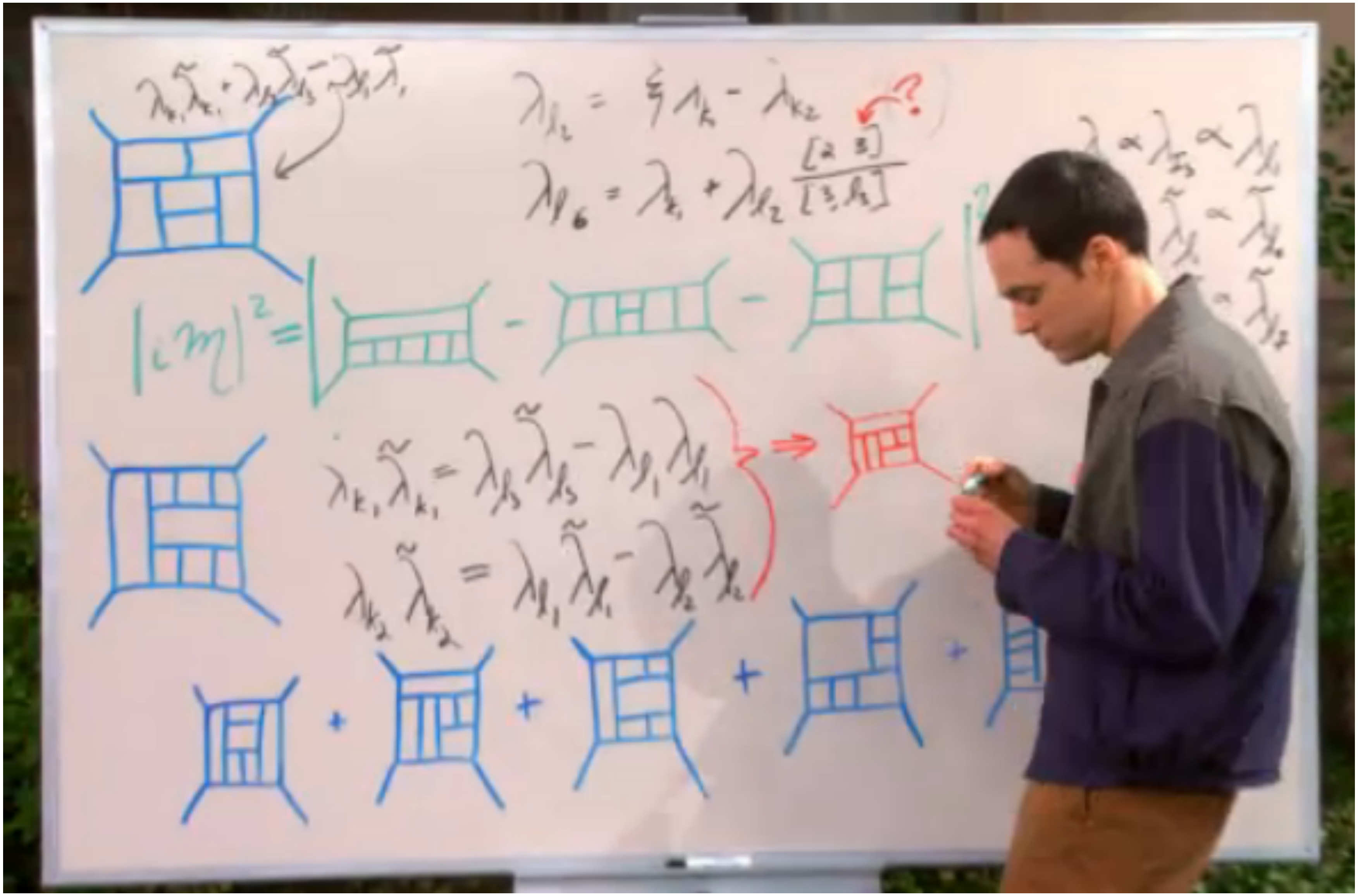
NNLO QCD + NLO EWK wishlist

N. Glover,
S. Dittmaier

Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$\mathrm{V+j}$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$\mathrm{Z+j}$ for gluon PDF $\mathrm{W+c}$ for strange PDF
$\mathrm{V+jj}$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $\mathrm{H+jj}$ final state
$\mathrm{VV'}$	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$\mathrm{gg} \to \mathrm{VV}$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$\mathrm{V}\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$\mathrm{Vb\bar{b}}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $\mathrm{VH} \to \mathrm{b\bar{b}}$
$\mathrm{VV'}\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$\mathrm{VV'V''}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\mathrm{VV'+j}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$\mathrm{VV'+jj}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons ($\mathrm{V = W, Z}$)

The frontier



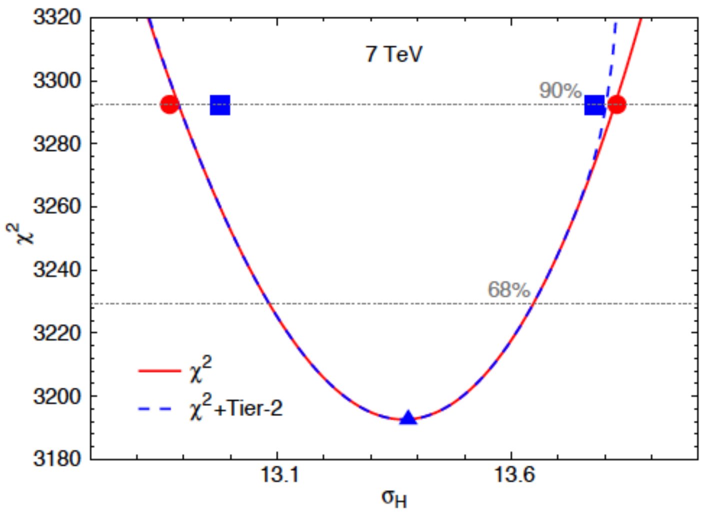
what we left at Les Houches for the BSM session

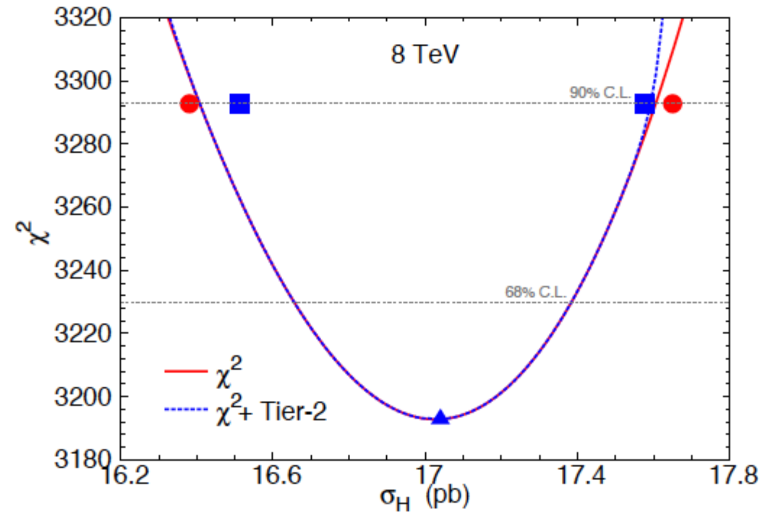
Summary

- (Relatively) new NLO (and NNLO) PDFs are available: CT10, NNPDF2.3, HERAPDF1.5, ABM11, in addition to MSTW2008
  - expect new updates for all 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) 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
- Ongoing work on trying to understand the differences among CT10, NNPDF2.3, MSTW08 and HERAPDF1.5 for gg PDF luminosities
- A new prescription (somewhat more sophisticated) is being developed; more powerful tools (such as meta-PDFs) will also be used in the near future

Scaling issues: 90%CL->68%CL

- New CT paper dealing with PDF and α_s uncertainties for gg->Higgs production, comparing Hessian and Lagrange Multiplier Techniques

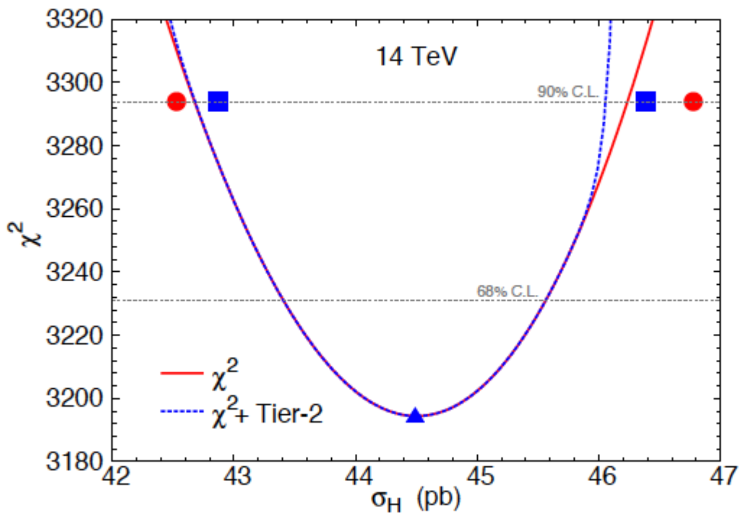




LM technique not dependent on assumption of quadratic χ^2 behavior, so more robust than Hessian

Tier 2 penalty prevents the fit to any one experiment from degrading too Much

all predictions at NNLO using $\mu=m_H$



curves are LM calculations of global fit χ^2 vs Higgs σ with (blue) and without (red) 'Tier 2 penalty'

The blue (red) points are the Hessian determination of the of the PDF uncertainty with (without) the Tier 2 penalty

PDF+α_s uncertainties

- LM estimates of PDF(+α_s) uncertainties slightly larger than Hessian determinations, but close, especially for the combined PDF+α_s errors

	90% CL			68% CL		
Method	7 TeV	8 TeV	14 TeV	7 TeV	8 TeV	14 TeV
LM (PDF-only)	+3.2/-3.7	+3.2/-3.7	+3.5/-4.1	+2.0/-2.2	+2.0/-2.3	+2.2/-2.4
Hessian (PDF-only)	+3.0/-3.0	+3.2/-3.1	+4.3/-3.6	+1.8/-1.8	+1.9/-1.9	+2.6/-2.2
LM (PDF + α_s)	+4.8/-5.0	+4.6/-4.6	+5.2/-5.2	+2.9/-3.2	+2.8/-2.9	+3.4/-3.2
Hessian (PDF + α_s)	+4.7/-4.6	+4.8/-4.7	+5.4/-5.0	+2.9/-2.8	+2.9/-2.8	+3.3/-3.0

- The 68% CL errors agree with the naïve scaling factor of 1.645

Fits of the fits: META PDFs

PDFs from different groups have different physics inputs. But if we only focus on the phenomenological studies at the LHC with the limited x and Q ranges, the idea of META PDF is reasonable and also feasible. → fits to PDFs from global PDF fits

Procedure (for LHC):
1, selecting a specific x-Q range, and a parameterization form to describe all the PDFs at an initial scale above the bottom quark mass;
2, check that the fitted PDFs can well represent the original PDFs at the x-Q range studied;
3, choosing a scheme to combine the PDF measurements of different groups in the new PDF parameter space;

Benefits:
1, A nature way to compare and combine the LHC predictions from different PDF groups independent of the process, works similarly as the PDF4LHC prescriptions but directly in the PDF parameter space;
2, Especially desirable for including results from large number of PDF groups, in this case also minimizing numerical computation efforts for massive NNLO calculations
3. **Possible to explore eigenvector directions that saturate the combined uncertainty for important LHC cross sections.**

→ for example, eigenvector directions that describe the gg->Higgs uncertainty

Jun Gao, Pavel Nadolsky

Further development: reweighting schemes

We explore several possible choices for the META PDF

→ Scheme A: assuming a quadratic dependence of $\chi^2(N|f)$ on PDF parameters x_i, it is straightforward to prove that for the HERA-like fit ($\Delta\chi^2=1$), HERAPDF or ABM, the PDF reweighting with weight $\sim\exp[-\chi^2(N|f)/2]$ is exactly equivalent to the corresponding refitting. Gaussian→ Gaussian.

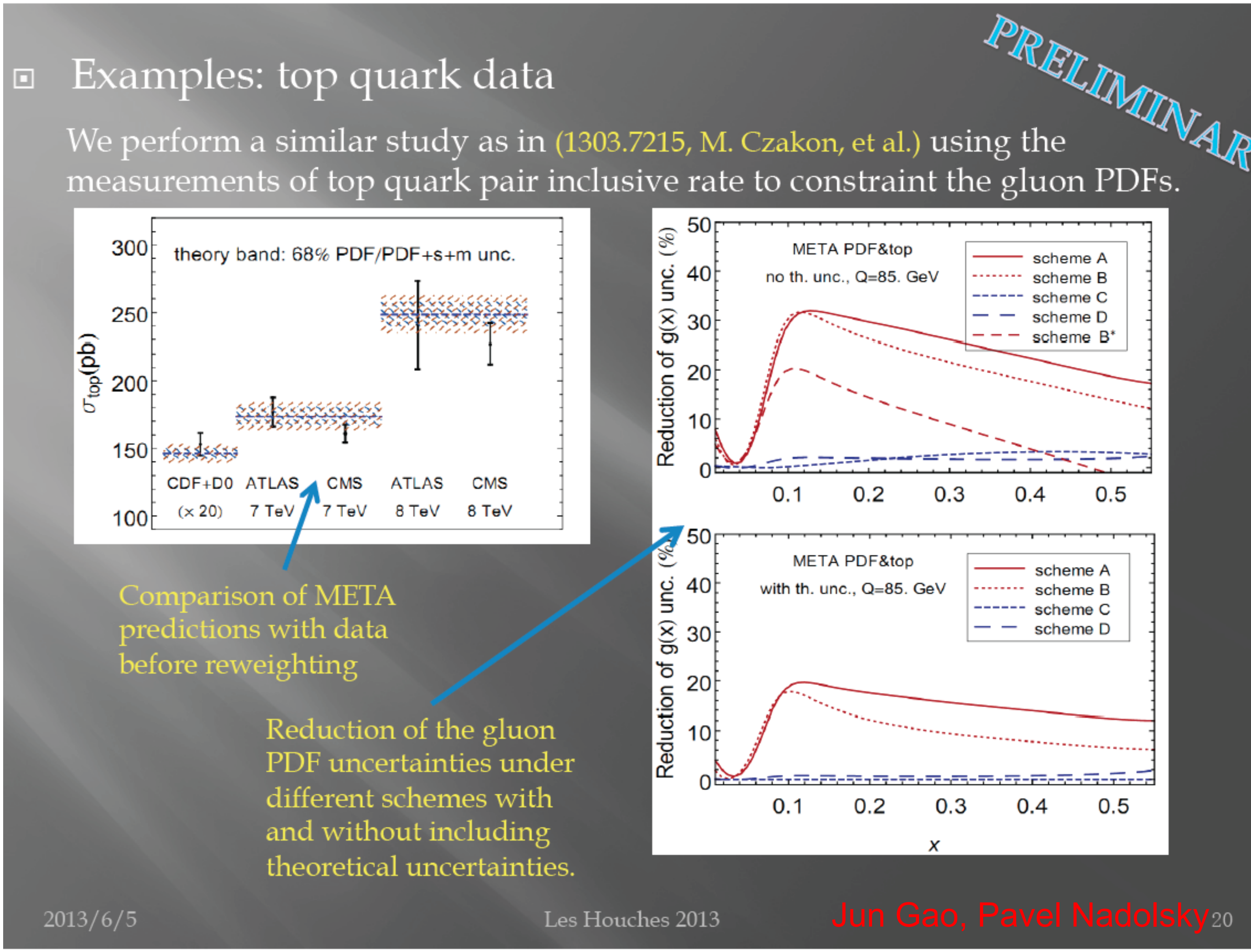
→ Scheme D: one variation of scheme A can be motivated by the CTEQ total χ^2 tolerance criterion. $\Delta\chi^2=100$ for 90%, translated to $\Delta\chi^2=h_0=37$ for 68%, and the weight function $\sim\exp[-\chi^2(N|f)/(2h_0)]$.

Scheme B: using the same weight $\sim\exp[-(\chi^2-(n-1)\ln\chi^2)/2]$ as NNPDF, but only keep up to the quadratic terms on x_i in the exponential, so we still get a Gaussian after reweighting.

Scheme B*: first generating 50,000 unweighted MC replicas based on the prior of META PDF, then reweight them using the exact NNPDF function form.

Scheme C: MSTW-like, here we fix the best-fit and eigenvector directions. The new PDF uncertainties are determined by the minimum of the original displacements and the newly allowed ones (according to MSTW dynamic tolerance) by data N in each of the directions.

Meta-PDFs



effect of tolerance on impact of new data in global fits needs to be better understood

CTEQ/MSTW may be different than NNPDF?

investigate for Les Houches Writeup

use-cases for META-PDFS or equivalent

Comparisons to 2011 data

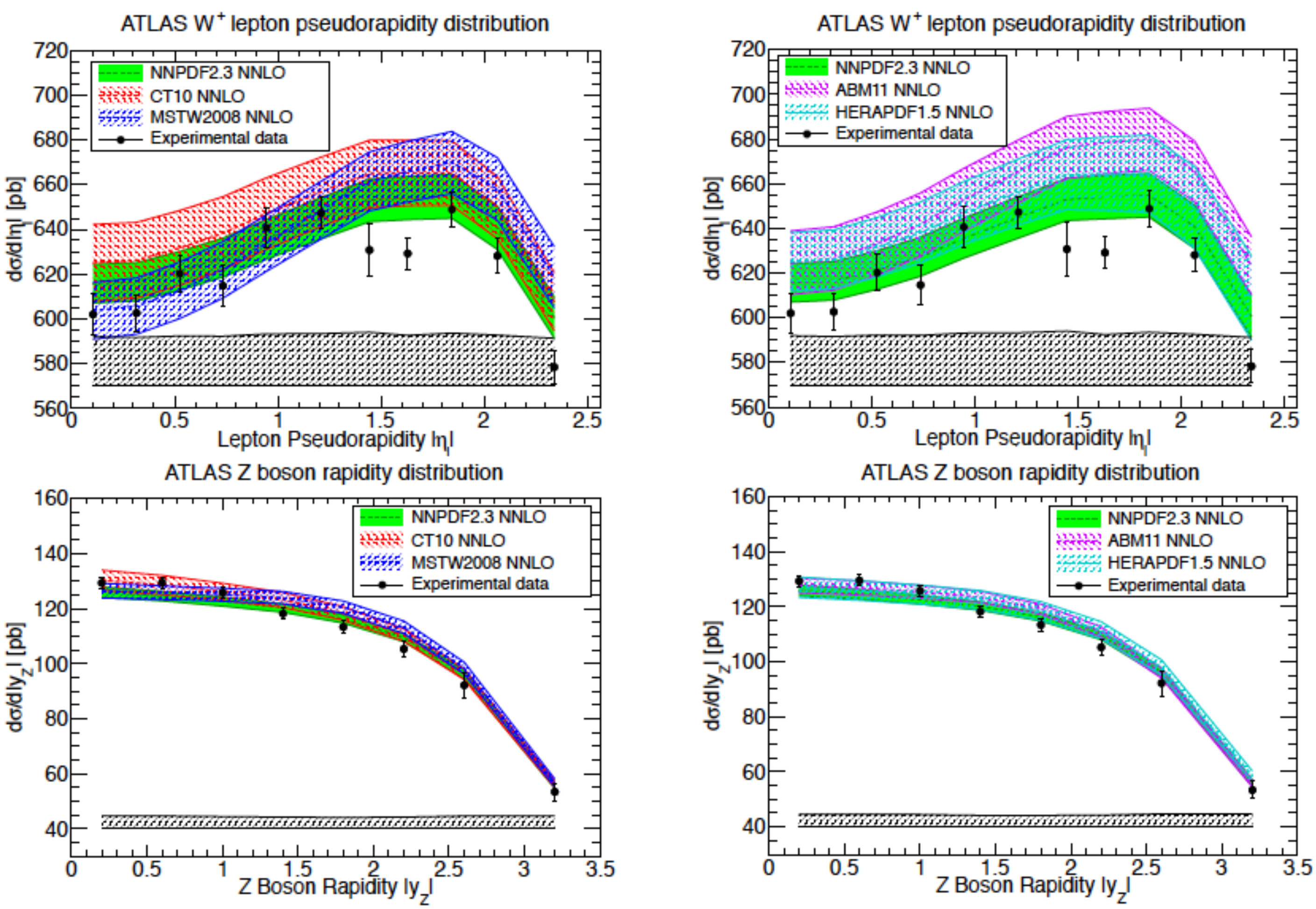


Figure 12: Comparison of the ATLAS electroweak vector boson production data with the NNPDF2.3, CT10 and MSTW2008 predictions with $\alpha_s = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics (including normalization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

Comparisons to 2011 data

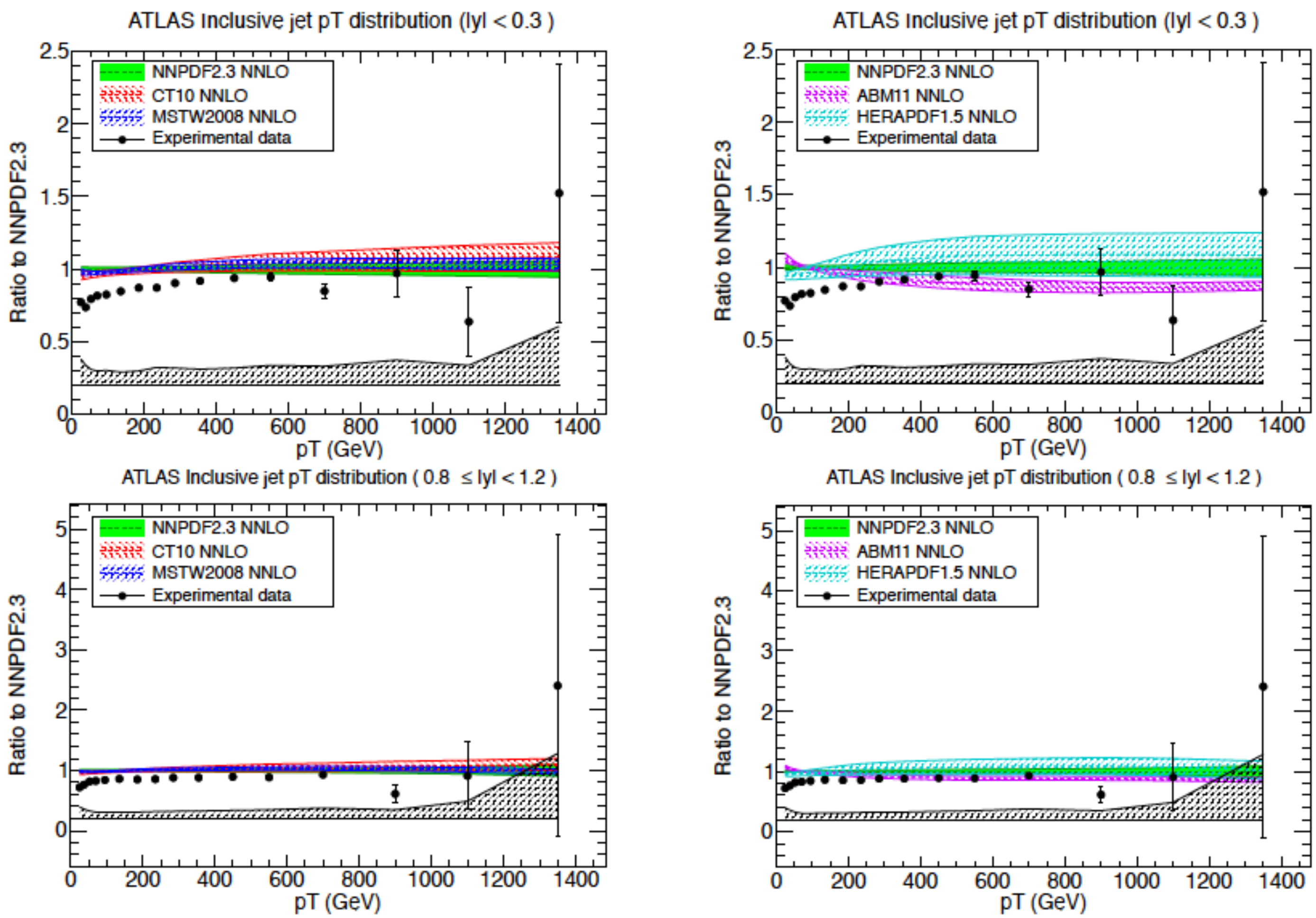


Figure 14: Comparison of the ATLAS $R = 0.4$ inclusive jet production data from the 2010 dataset with the NNPDF2.3, CT10 and MSTW2008 NNLO PDF sets and $\alpha_S = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics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

Comparisons to 2011 data

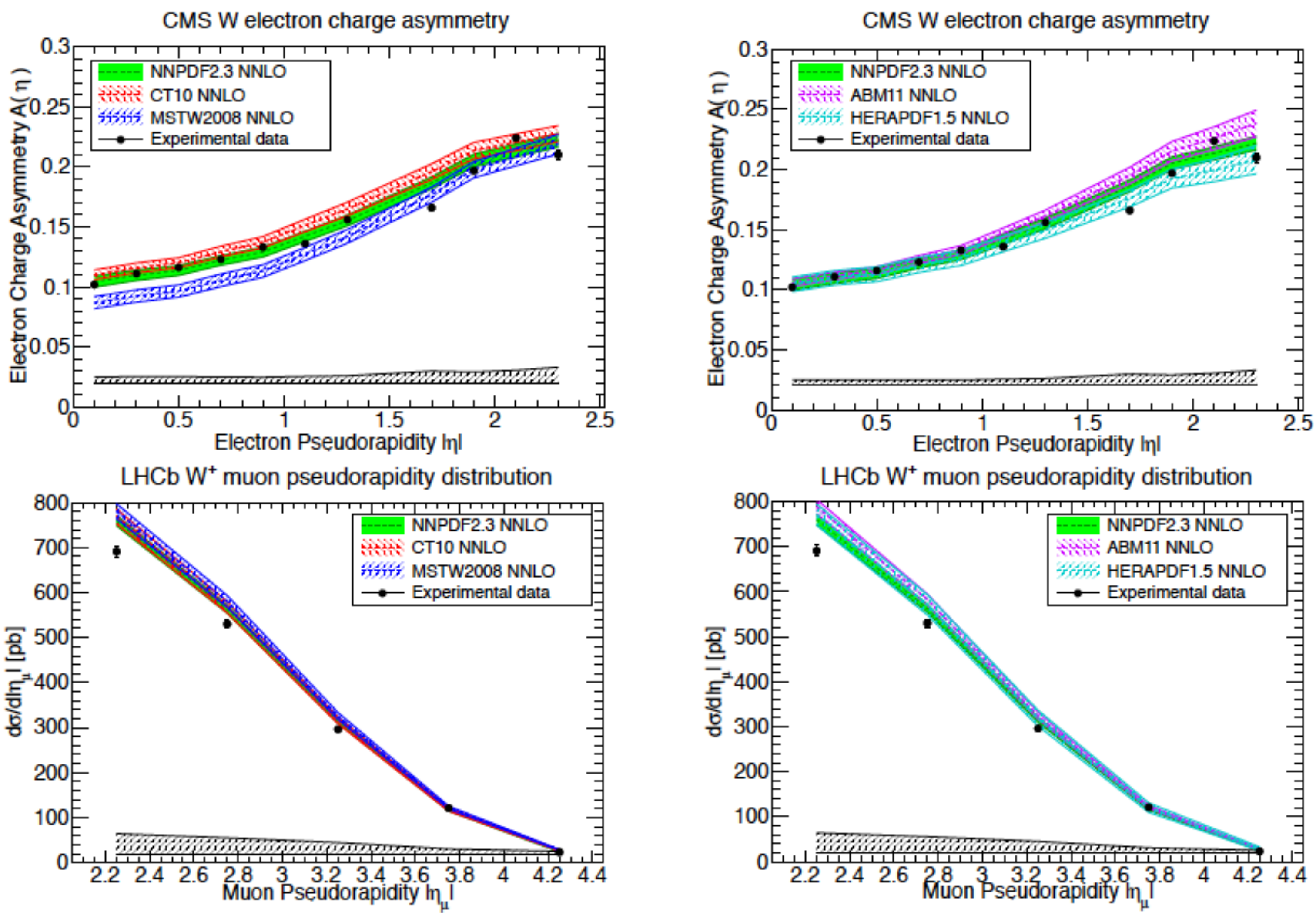


Figure 13: Same as Fig. 12 for CMS and LHCb W production.

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

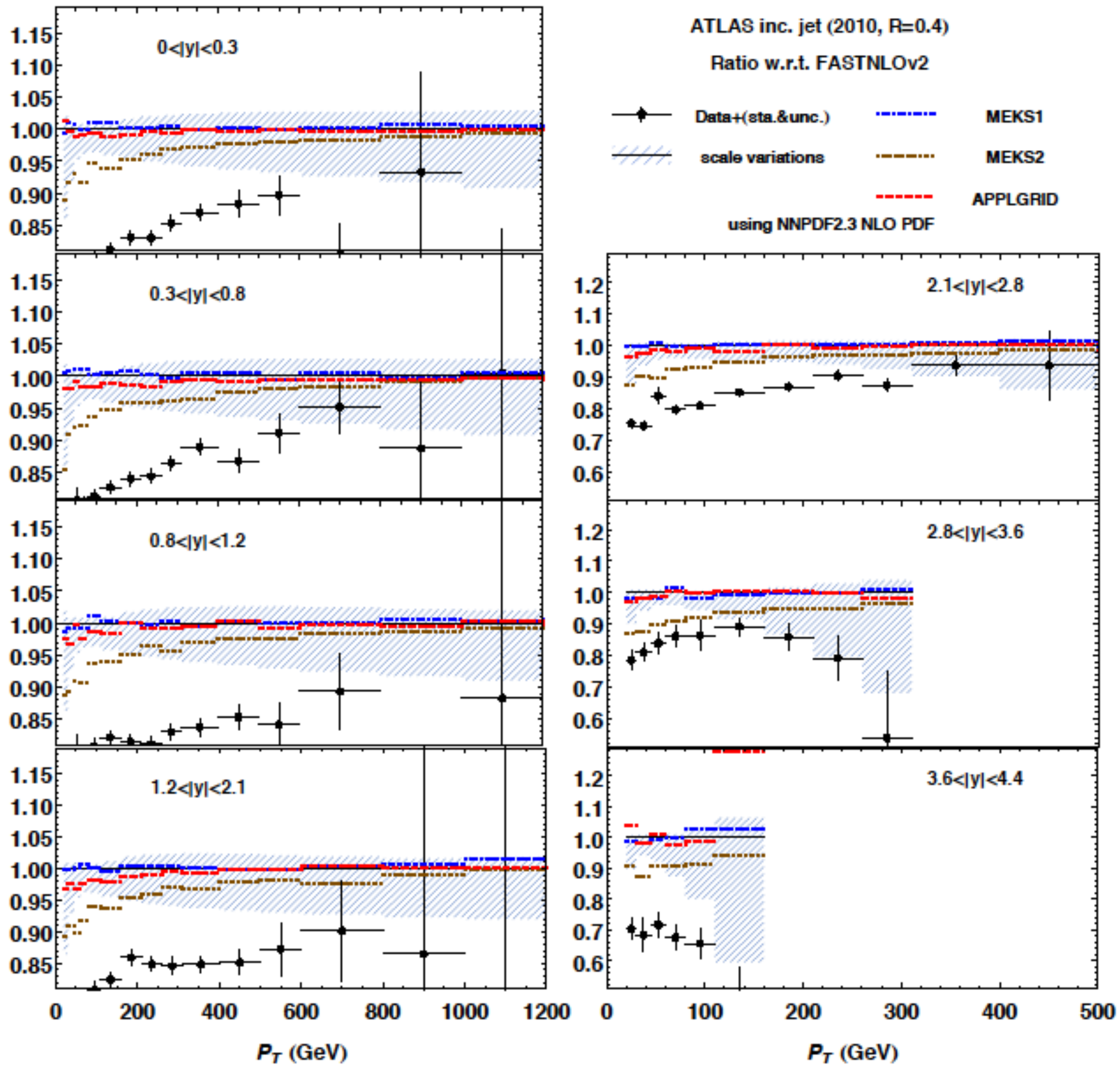


Figure 1: Comparisons of NLO theoretical predictions for 2010 ATLAS single-inclusive jet production ($R = 0.4$) from various numerical programs. NNPDF2.3 NLO PDFs are used with $\alpha_s(M_Z) = 0.119$.

scale $=p_T j^{et}$

scale $=p_T j^{et,max}$

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

ATLAS choice

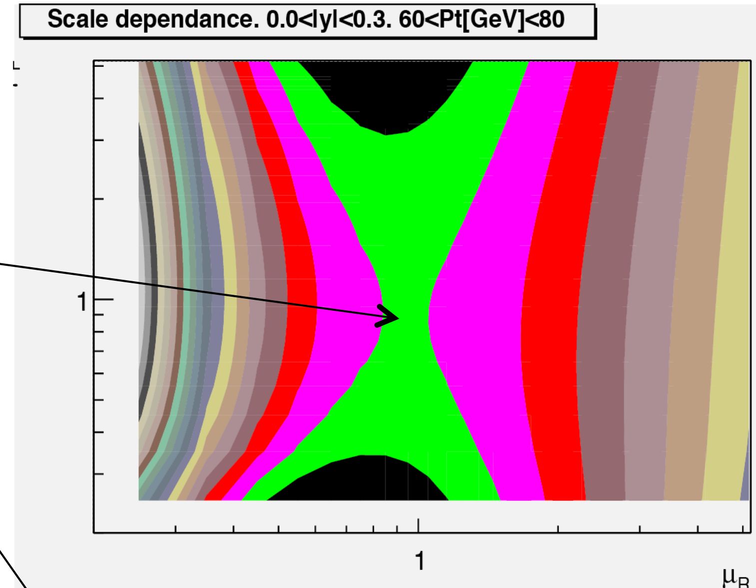
hatched is FASTNLO uncertainty band for $p_T/2$ to $2p_T$

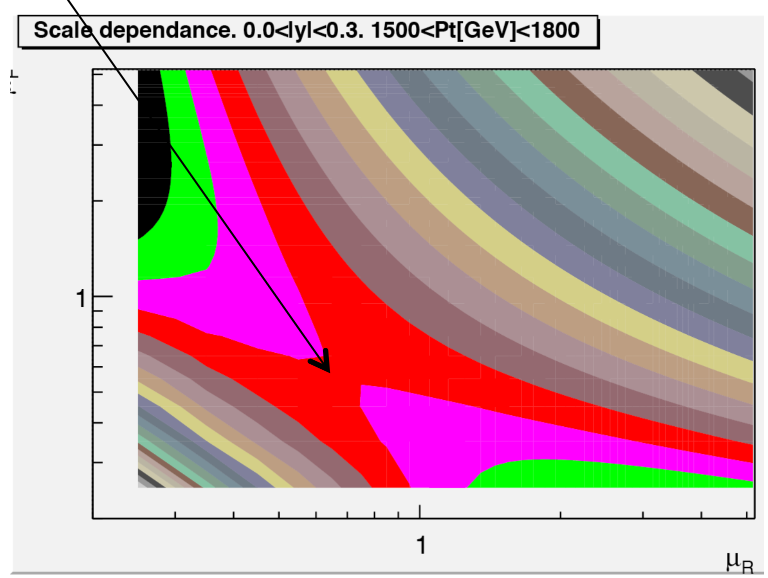
could we agree on a common scale, like p_T^{jet}?

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

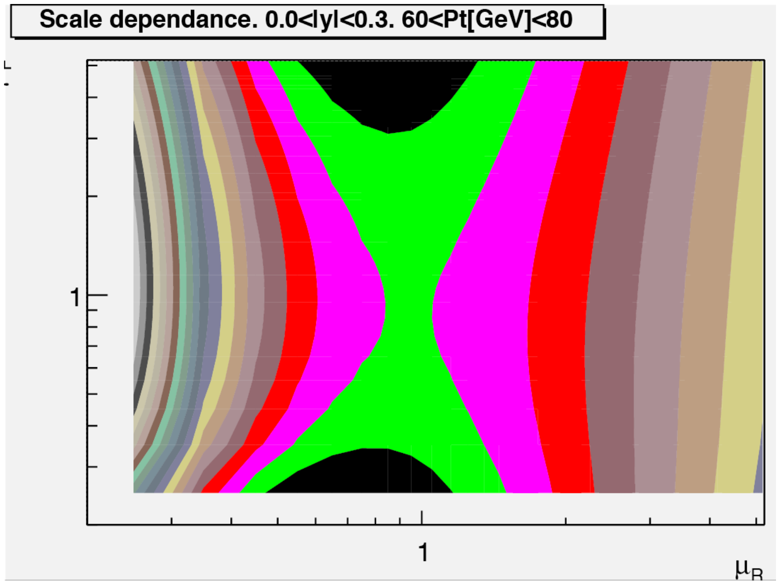
R=0.4
antikT

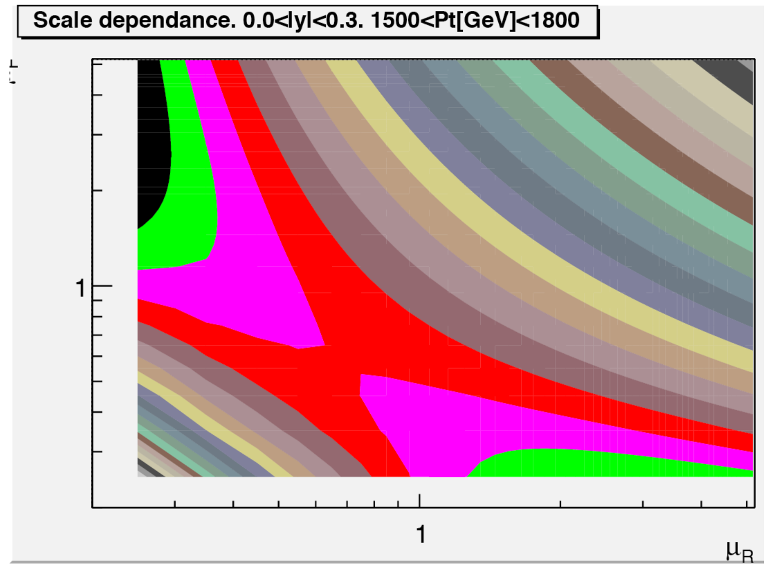




Scale dependence also depends on jet size;

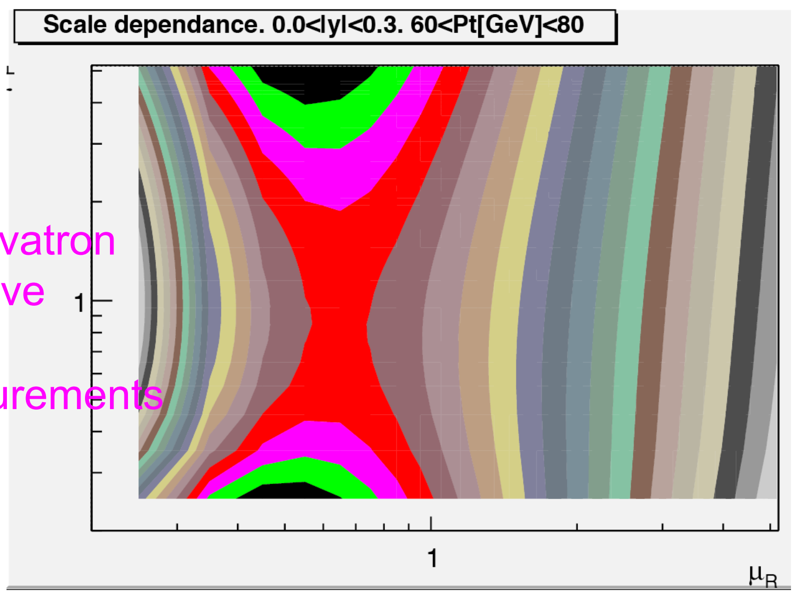
R=0.4
antikT

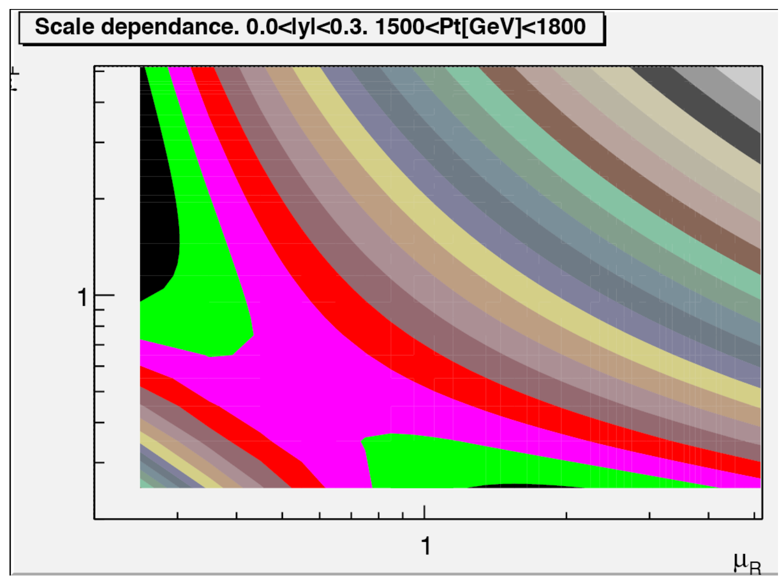




R=0.6
antikT

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:

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

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).

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

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