PDFs for the Standard Model and Beyond

Joey Huston
Michigan State University
(PITTPACC)

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University of Pittsburgh

Introduction

- Cross sections at any hadron-hadron collider depend on PDFs determined by global fits to collider data, but (more importantly, at least so far) from DIS data (HERA and fixed target) and from fixed target Drell-Yan data
- For hadron collider predictions, global fit data taken at smaller Q^2 is evolved to higher Q^2 values using DGLAP evolution, at LO/NLO/NNLO

$$\sigma = \sum_{a,b} \int_0^1 \mathrm{d}x_1\, f_{a/A}(x_1,\mu_F^2) \int_0^1 \mathrm{d}x_2\, f_{b/B}(x_2,\mu_F^2) \Bigg\{ \int \mathrm{d}\hat{\sigma}_{ab}^{LO}\,(\alpha_s)\ \Theta_{\mathrm{obs}}^{(m)}$$

$$+\alpha_s(\mu_R^2)\left[\int \left(\mathrm{d}\hat{\sigma}_{ab}^{V}\left(\alpha_s,\mu_R^2\right) + \mathrm{d}\hat{\sigma}_{ab}^{C}\left(\alpha_s,\mu_F^2\right)\right)\ \Theta_{\mathrm{obs}}^{(m)} + \int \mathrm{d}\hat{\sigma}_{ab}^{R}(\alpha_s)\,\Theta_{\mathrm{obs}}^{(m+1)}\right]\Bigg\} + \dots$$

- In addition to the PDFs themselves, it is often useful to define a PDF luminosity

$$\frac{dL_{ij}}{d\hat{s}\,dy} = \frac{1}{s}\,\frac{1}{1+\delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + (1 \leftrightarrow 2)\right].$$

…or integrated over y

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
- Results in Higgs YR1 and YR2

The PDF4LHC Working Group Interim Report

Sergey Alekhin[1,2], *Simone Alioli*[1], *Richard D. Ball*[3], *Valerio Bertone*[4], *Johannes Blümlein*[1], *Michiel Botje*[5], *Jon Butterworth*[6], *Francesco Cerutti*[7], *Amanda Cooper-Sarkar*[8], *Albert de Roeck*[9], *Luigi Del Debbio*[3], *Joel Feltesse*[10], *Stefano Forte*[11], *Alexander Glazov*[12], *Alberto Guffanti*[4], *Claire Gwenlan*[8], *Joey Huston*[13], *Pedro Jimenez-Delgado*[14], *Hung-Liang Lai*[15], *José I. Latorre*[7], *Ronan McNulty*[16], *Pavel Nadolsky*[17], *Sven Olaf Moch*[1], *Jon Pumplin*[13], *Voica Radescu*[18], *Juan Rojo*[11], *Torbjörn Sjöstrand*[19], *W.J. Stirling*[20], *Daniel Stump*[13], *Robert S. Thorne*[6], *Maria Ubiali*[21], *Alessandro Vicini*[11], *Graeme Watt*[22], *C.-P. Yuan*[13]

[1] Deutsches Elektronen-Synchrotron, DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[2] Institute for High Energy Physics, IHEP, Pobeda 1, 142281 Protvino, Russia
[3] School of Physics and Astronomy, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland
[4] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg i. B., Germany
[5] NIKHEF, Science Park, Amsterdam, The Netherlands
[6] Department of Physics and Astronomy, University College, London, WC1E 6BT, UK
[7] Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
[8] Department of Physics, Oxford University, Denys Wilkinson Bldg, Keble Rd, Oxford, OX1 3RH, UK
[9] CERN, CH–1211 Genève 23, Switzerland; Antwerp University, B–2610 Wilrijk, Belgium; University of California Davis, CA, USA
[10] CEA, DSM/IRFU, CE-Saclay, Gif-sur-Yvetee, France
[11] Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy
[12] Deutsches Elektronensynchrotron DESY Notkestraße 85 D–22607 Hamburg, Germany
[13] Physics and Astronomy Department, Michigan State University, East Lansing, MI 48824, USA
[14] Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland
[15] Taipei Municipal University of Education, Taipei, Taiwan
[16] School of Physics, University College Dublin Science Centre North, UCD Belfeld, Dublin 4, Ireland
[17] Department of Physics, Southern Methodist University, Dallas, TX 75275-0175, USA
[18] Physikalisches Institut, Universität Heidelberg Philosophenweg 12, D–69120 Heidelberg, Germany
[19] Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, S-223 62 Lund, Sweden
[20] Cavendish Laboratory, University of Cambridge, CB3 OHE, UK
[21] Institut für Theoretische Teilchenhysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany
[22] Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

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.

Followup in 2013

- 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

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

Parton distribution benchmarking with LHC data

Richard D. Ball[1], Stefano Carrazza[2,3], Luigi Del Debbio[1], Stefano Forte[2,3], Jun Gao[4], Nathan Hartland[1], Joey Huston[5], Pavel Nadolsky[4], Juan Rojo[6], Daniel Stump[5], Robert S. Thorne[7], C.-P. Yuan[5]

[1] *Tait Institute, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland*
[2] *Dipartimento di Fisica, Università di Milano and*
[3] *INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[4] *Department of Physics, Southern Methodist University, Dallas, TX 75275, USA*
[5] *Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[6] *PH Department, TH Unit, CERN, CH-1211 Geneva 23, Switzerland*
[7] *Department of Physics and Astronomy, University College London, WC1E 6BT, UK*

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.

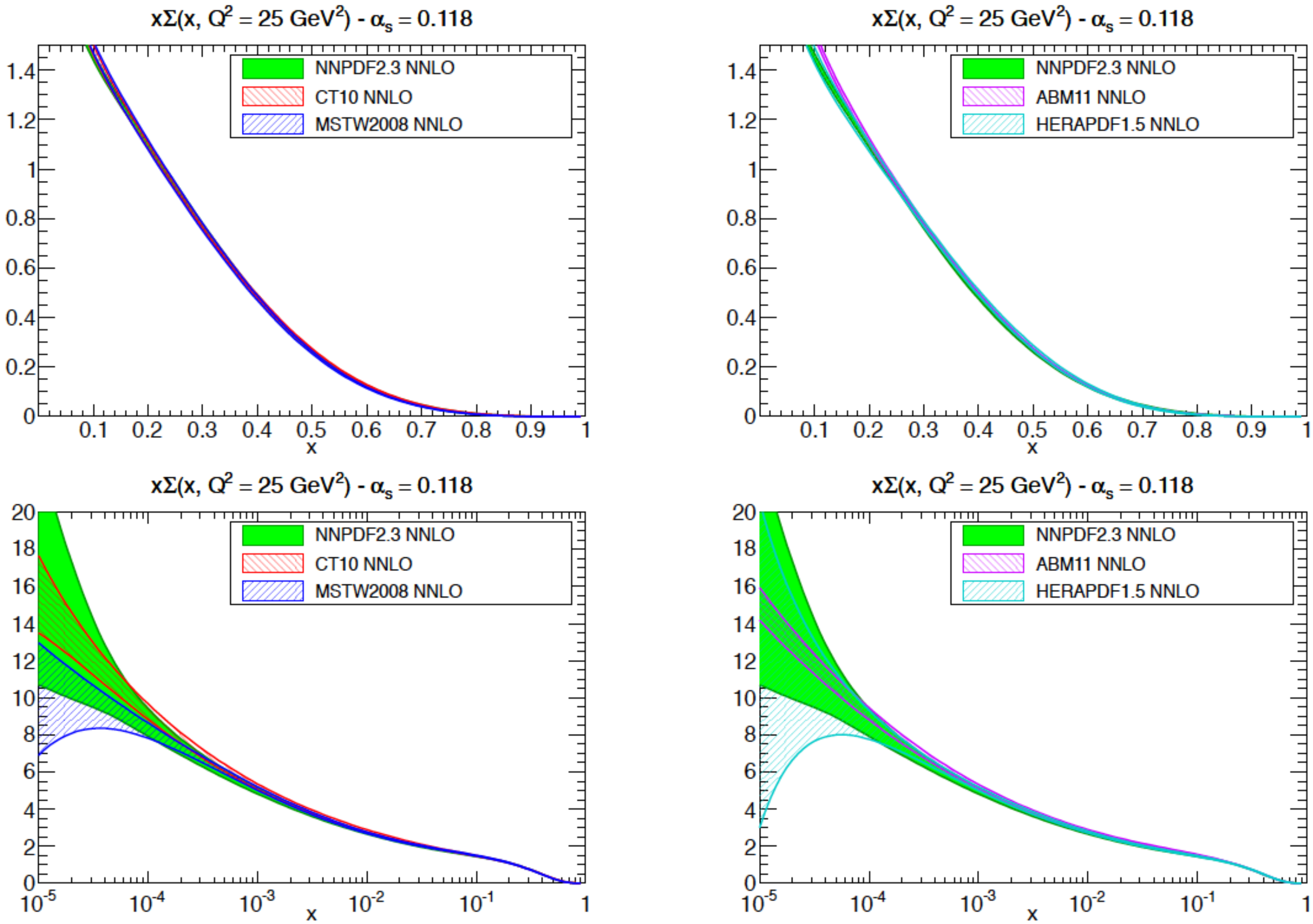
No updates of JR since 2009.

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

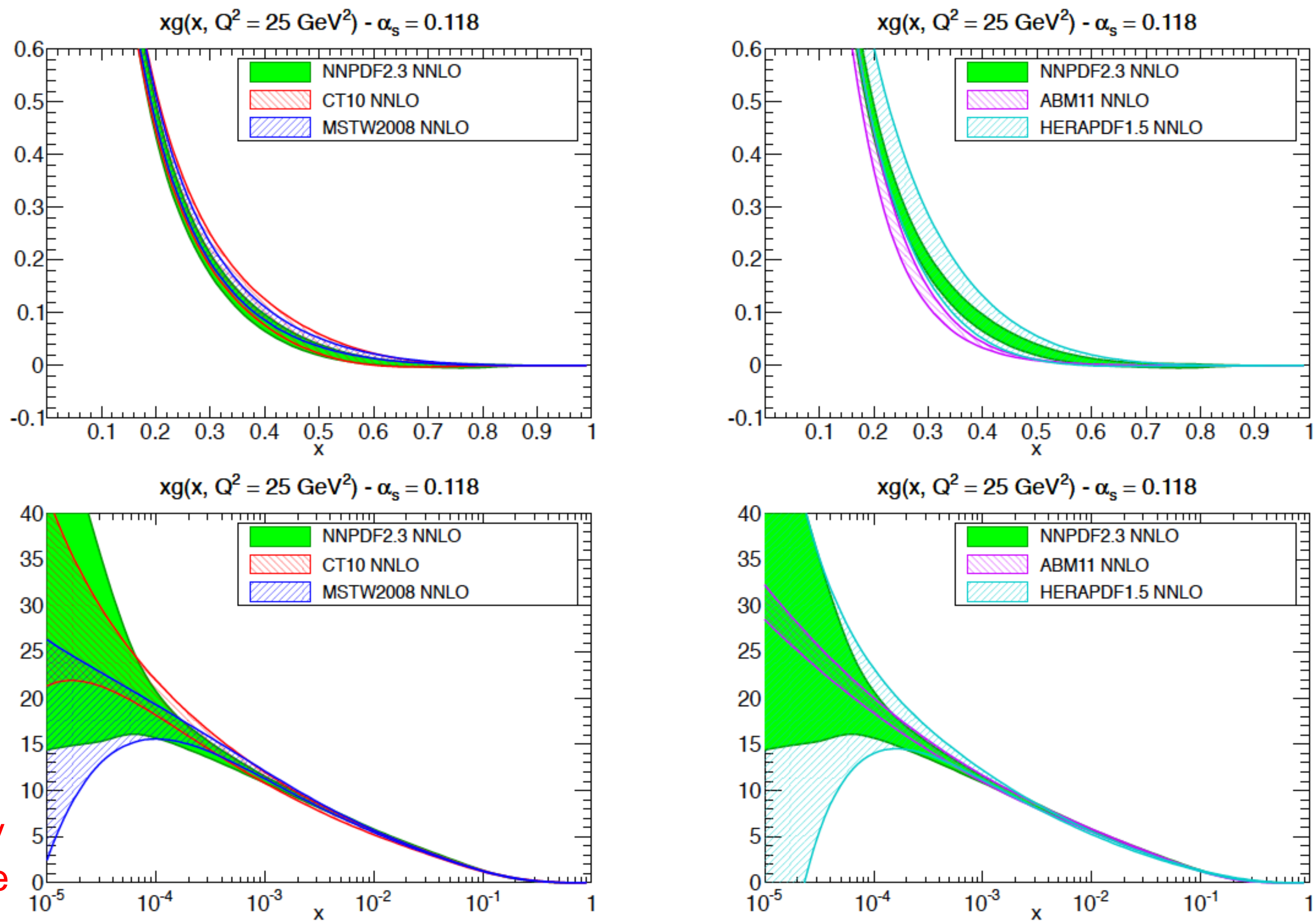
CT10, MSTW08 and NNPDF2.3 gluon distributions all in reasonable, but not perfect, agreement

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

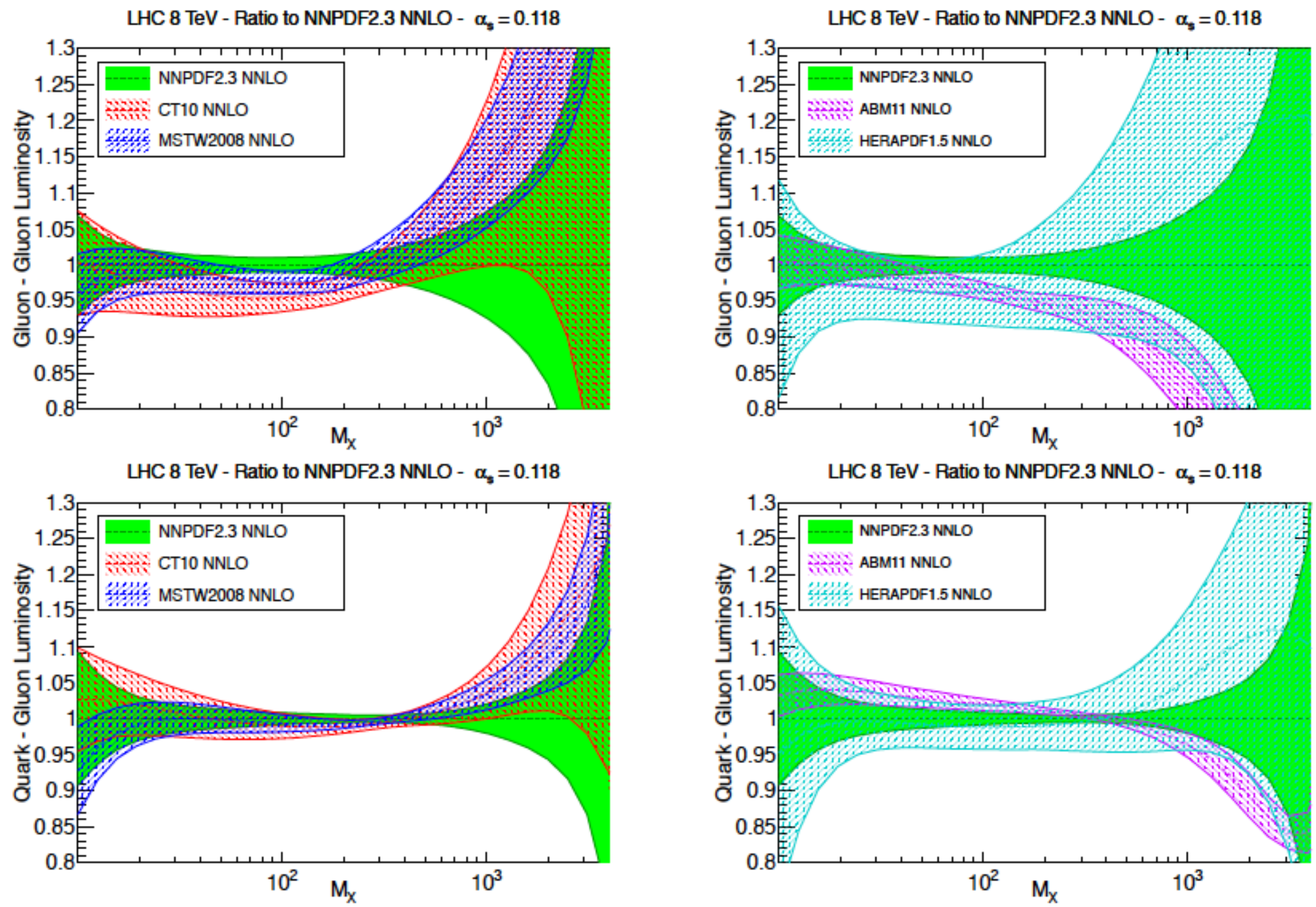


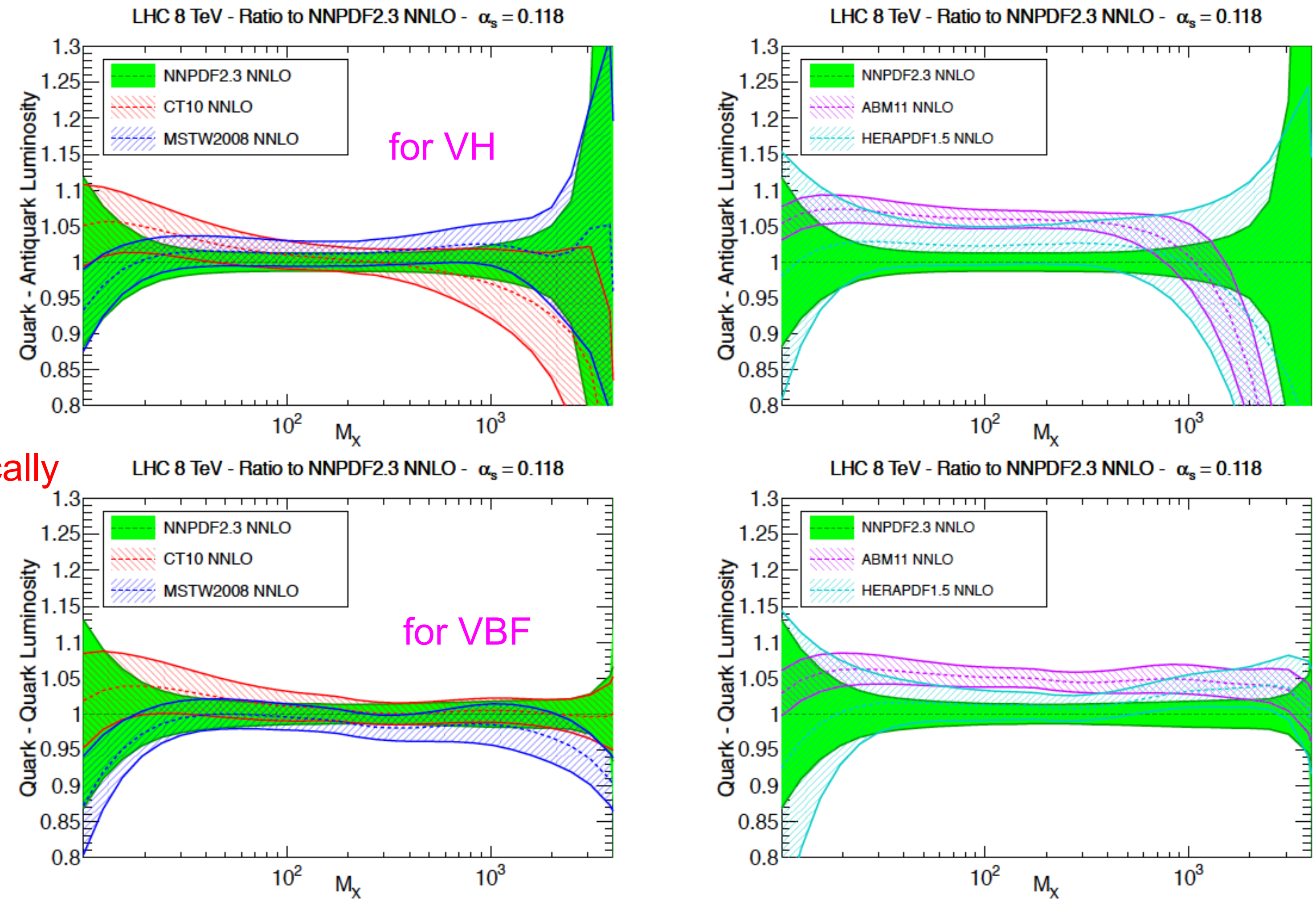
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5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

PDF luminosities

quark-quark and quark-antiquark

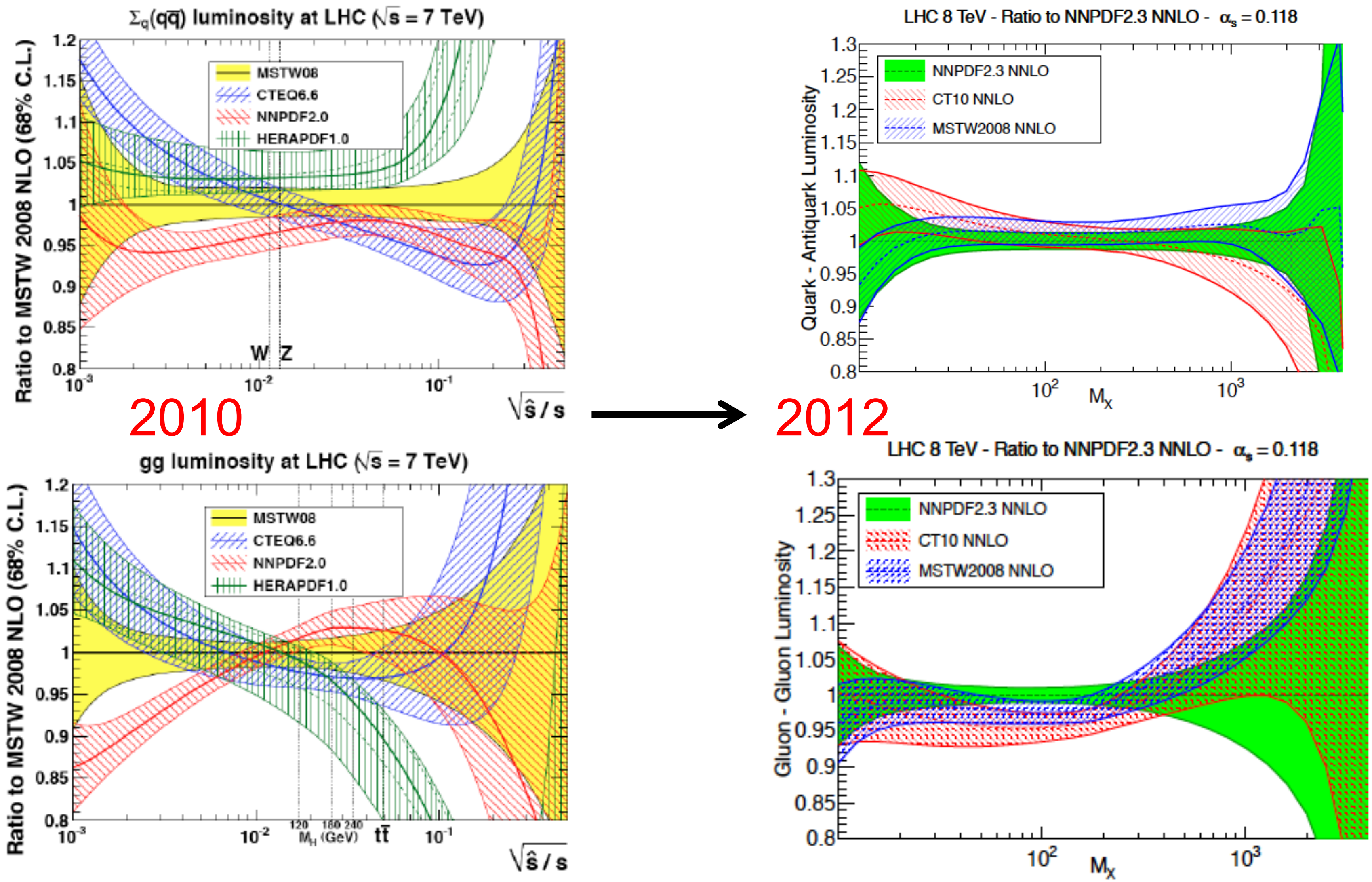
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range

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

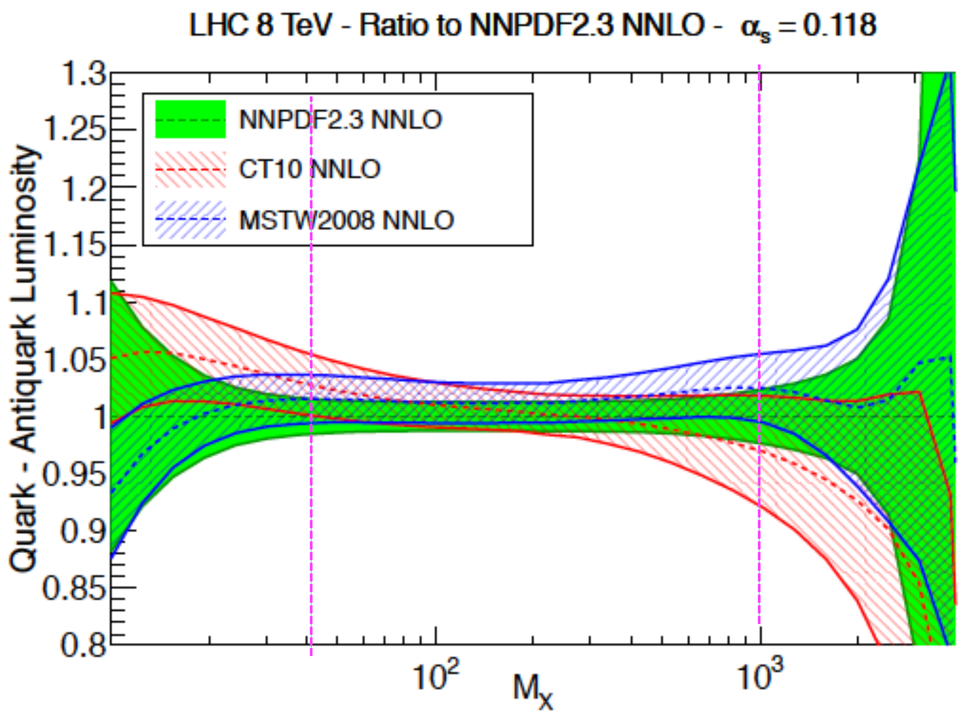


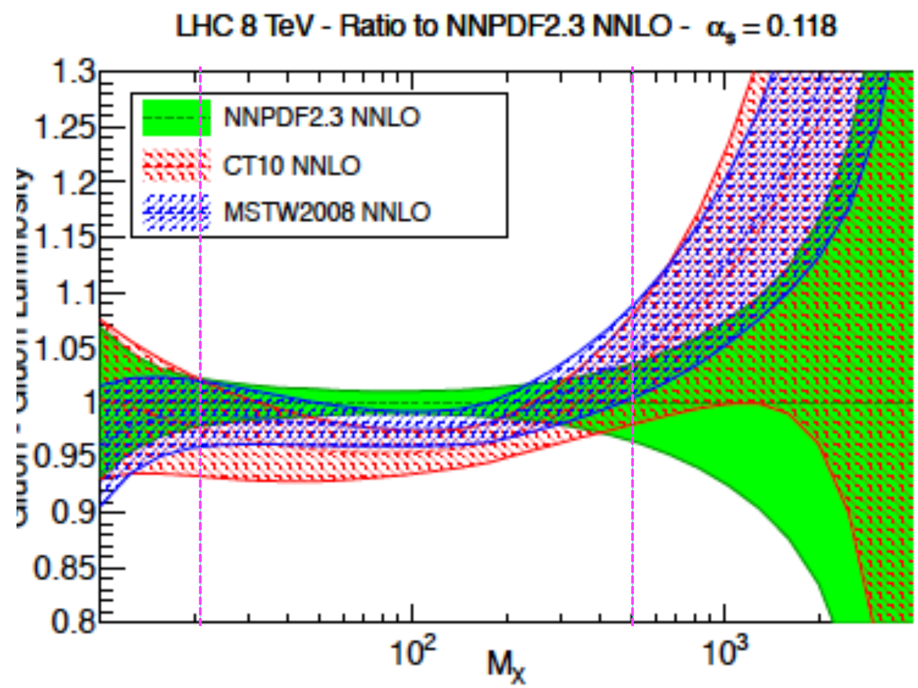
Uncertainties have improved

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



Gallia est omnis divisa in partes tres PDFs sunt





small x region

precision region

discovery region

small x

precision region

discovery region

BSM searches, SM cross sections provide information

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

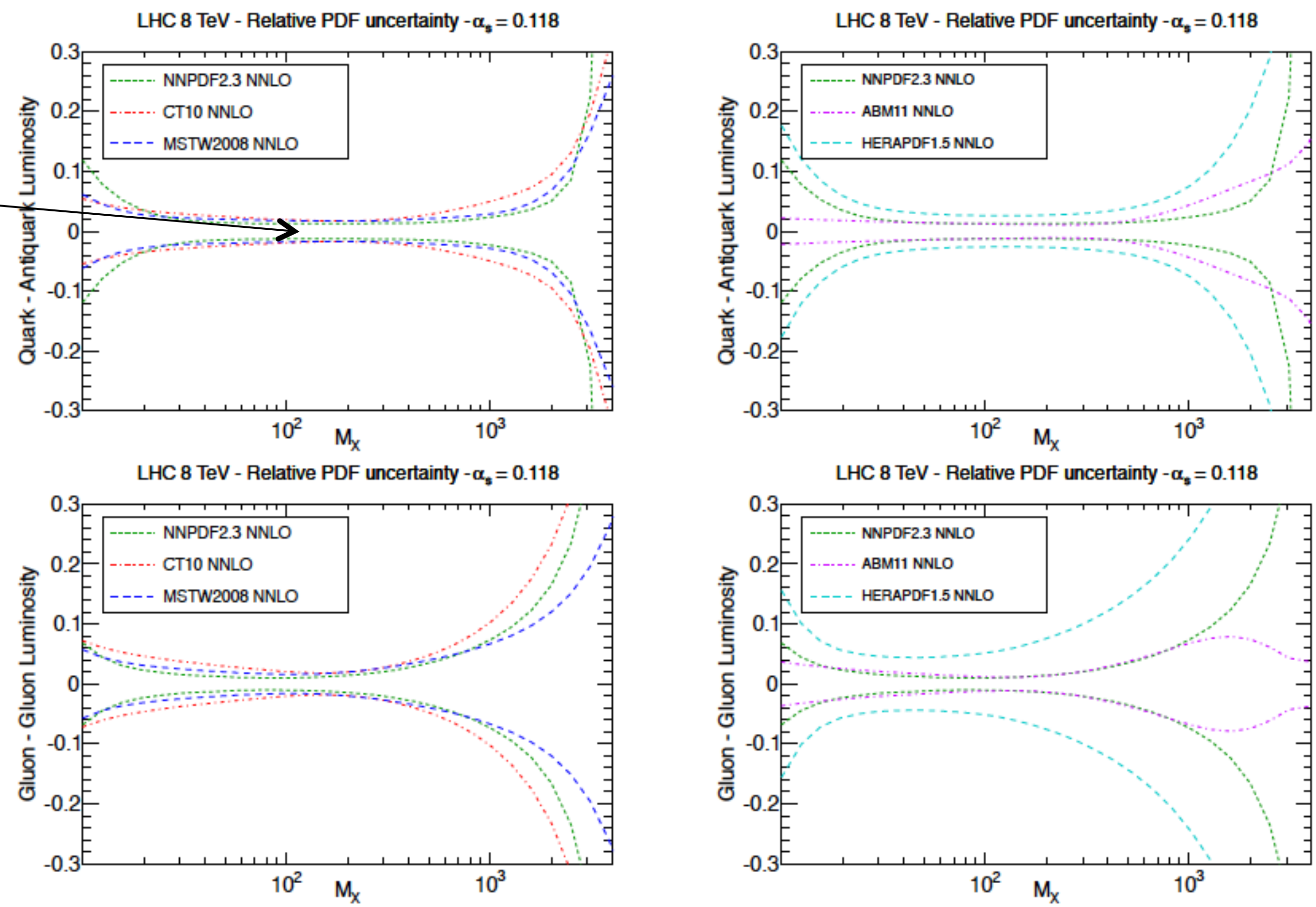
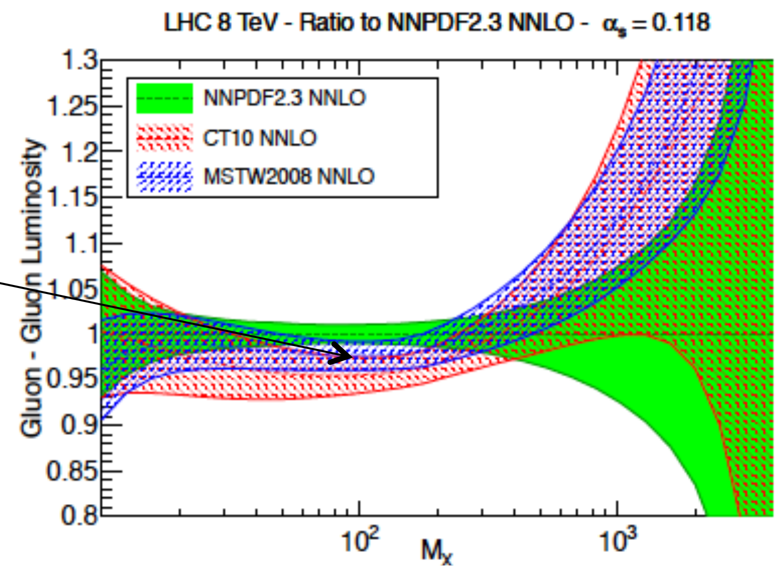
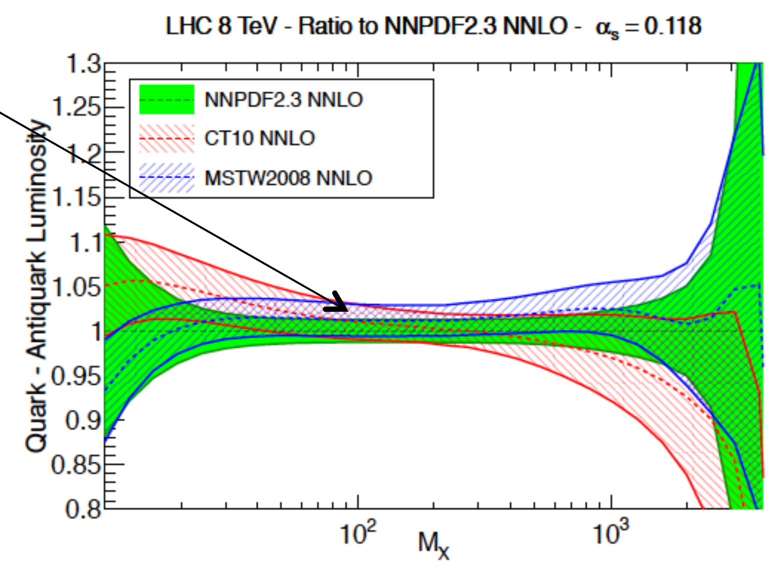


Figure 8: The relative PDF uncertainties in the quark-antiquark luminosity (upper plots) and in the gluon-gluon luminosity (lower plots), for the production of a final state of invariant mass M_X (in GeV) at the LHC 8 TeV. All luminosities are computed at a common value of $\alpha_s = 0.118$.

NNLO PDF uncertainties

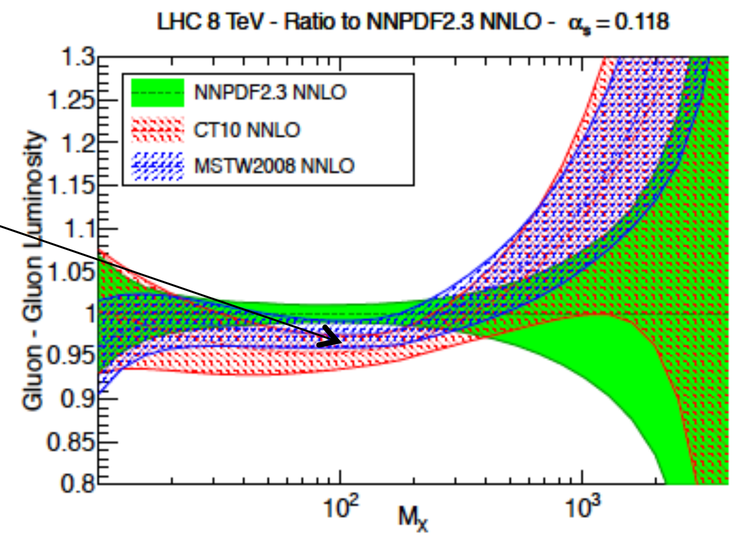
- Factor of 2 expansion of MSTW2008 error (previous prescription) basically works for gg initial states (like 125 Higgs)
- …but maybe an overestimate for qQ initial states, where there has been a nice convergence

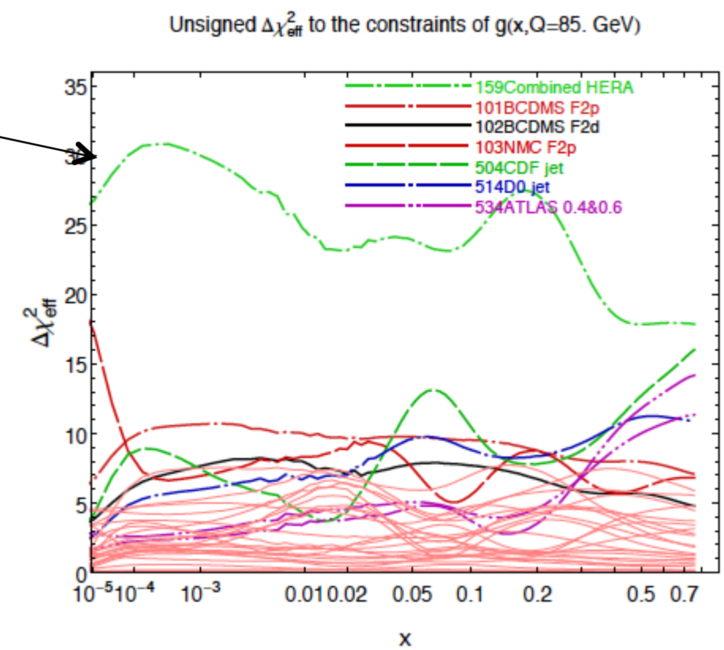




…but are they good enough?

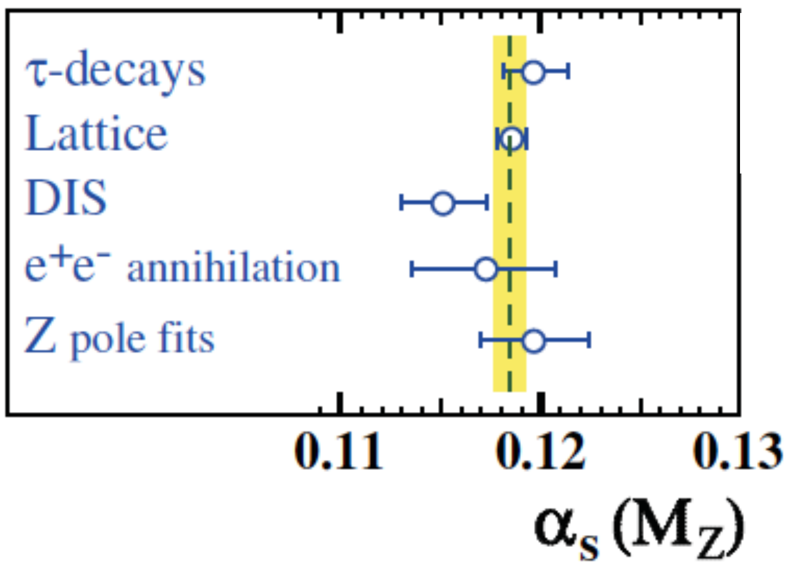
- Can we further improve the gg PDF luminosity uncertainty in the Higgs mass region?
  - PDF+α_s error is now the dominant theory error for ggF
- NNPDF2.3 marks the high edge and CT10 the low edge
  - full gg uncertainty is ~ factor of 2 more than any of the individual group uncertainties
- The gluon 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

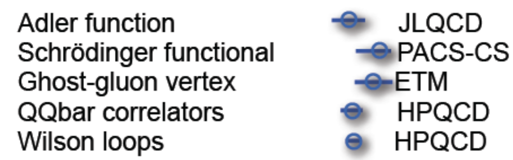




$\alpha_s(m_Z)$

- 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?





variety of different calculations/groups results in very compatible results

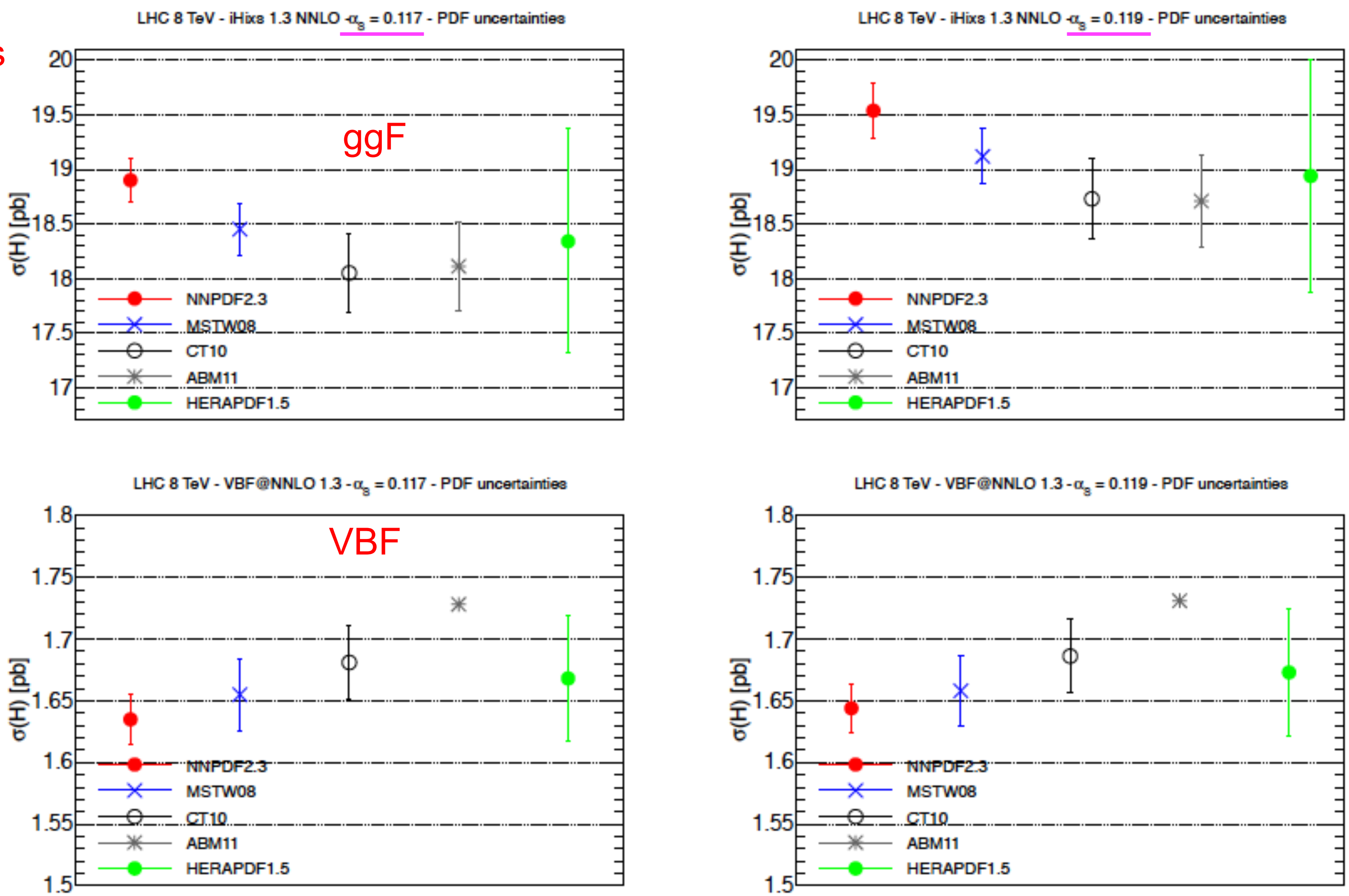
Figure 1-1. *Summary of values of $\alpha_s(M_Z^2)$ obtained for various sub-classes of measurements. The world average value of $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ is indicated by the dashed line and the shaded band. Figure taken from [1].*

8 TeV Higgs cross section predictions

cross sections calculated at NNLO using a scale of m_H

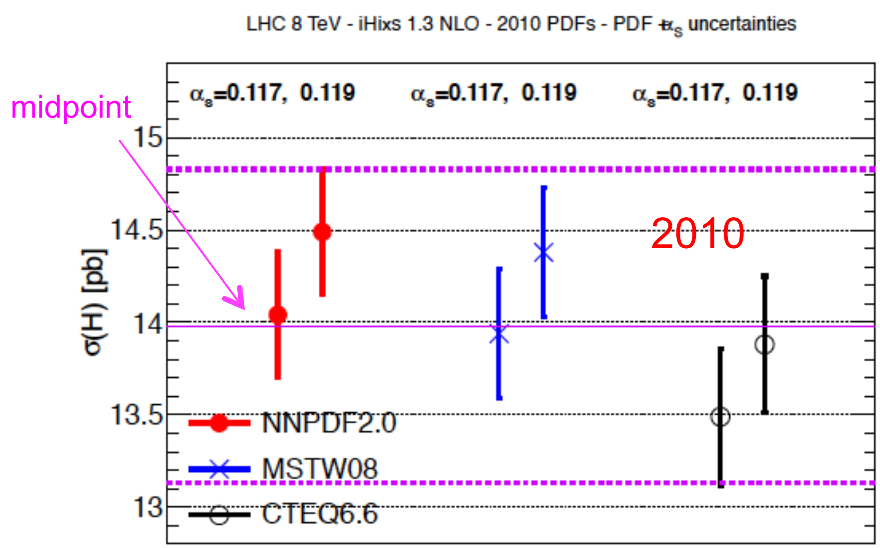
ABM11 and HERAPDF1.5 predictions within error envelope

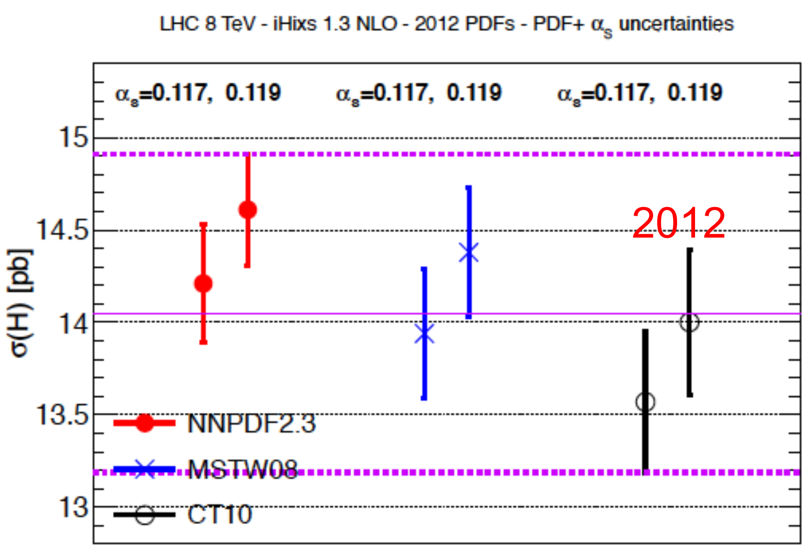
NB: ABM11 cross section would be lower if native value of α_s (0.1134) used



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

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



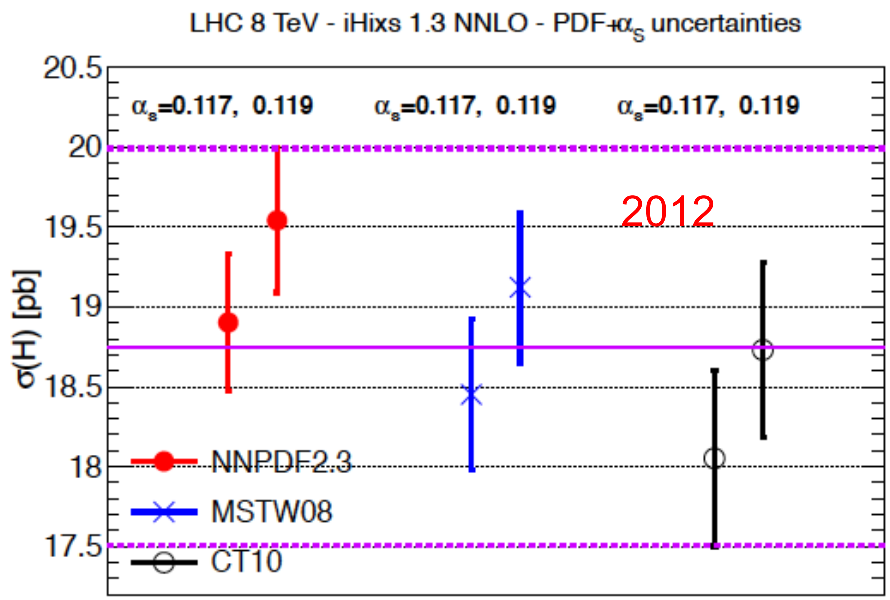


Revisit prescriptions (for 8 TeV cross sections for gg fusion)

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)



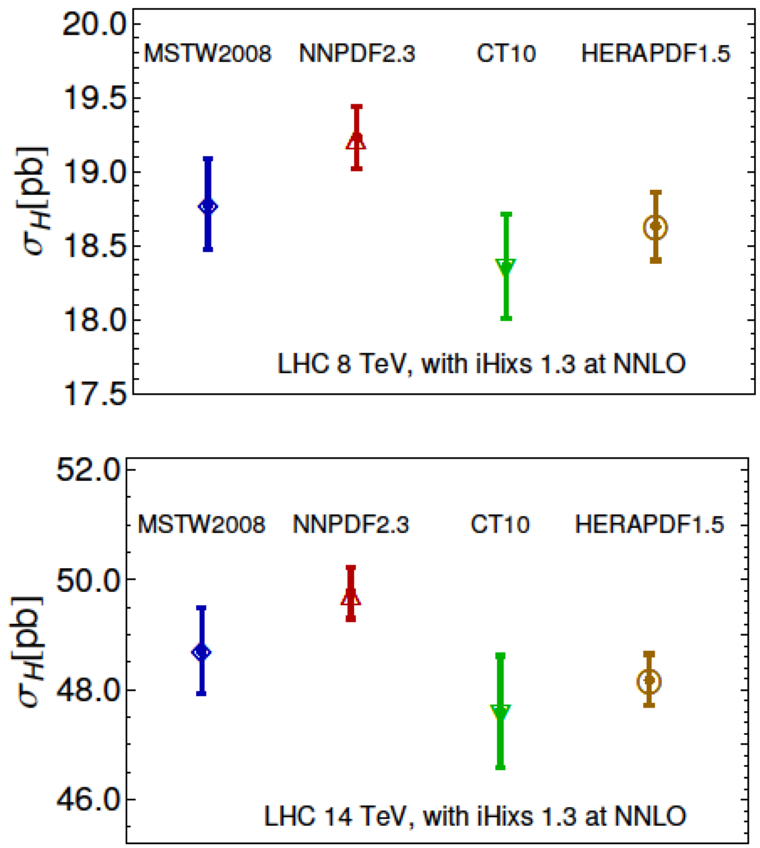
HXSWG 8 TeV NNLO cross section

NNLO+NNLL

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

Les Houches study

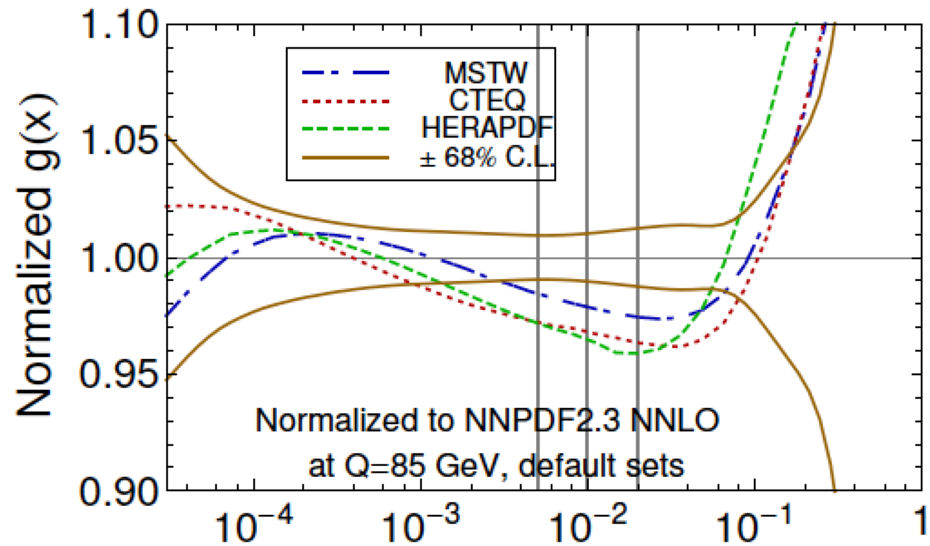
- The study used the PDFs that use a variable flavor number scheme, i.e. the 4 shown on the curves to the right
- The discrepancies present at 8 TeV persist at 14 TeV with the same pattern

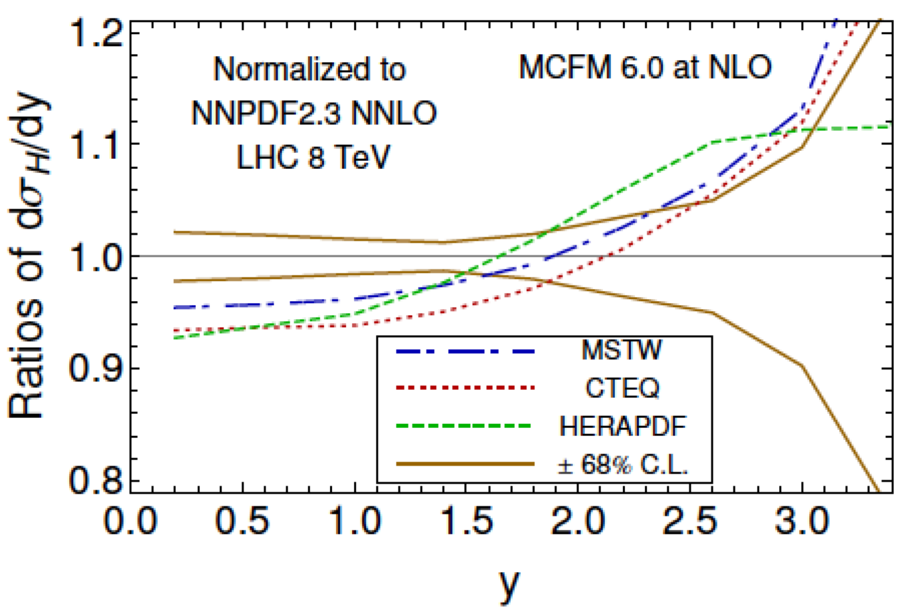


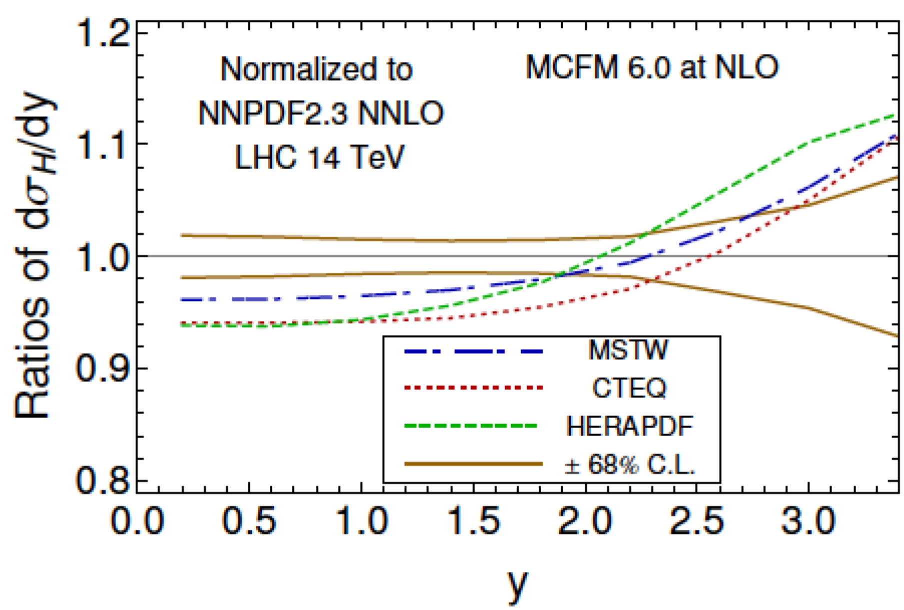
σ_H [pb]	CT10	MSTW'08	NNPDF2.3	HERAPDF 1.5
LHC 8 TeV	18.36±0.35	18.78±0.31	19.23±0.21	18.63±0.23
LHC 14 TeV	47.60±1.02	48.71±0.77	49.76±0.47	48.18±0.47

Gluon distributions and Higgs y

- On the right some obvious shape differences as a function of x can be seen
- These shape differences translate into different predictions for Higgs rapidity as seen below

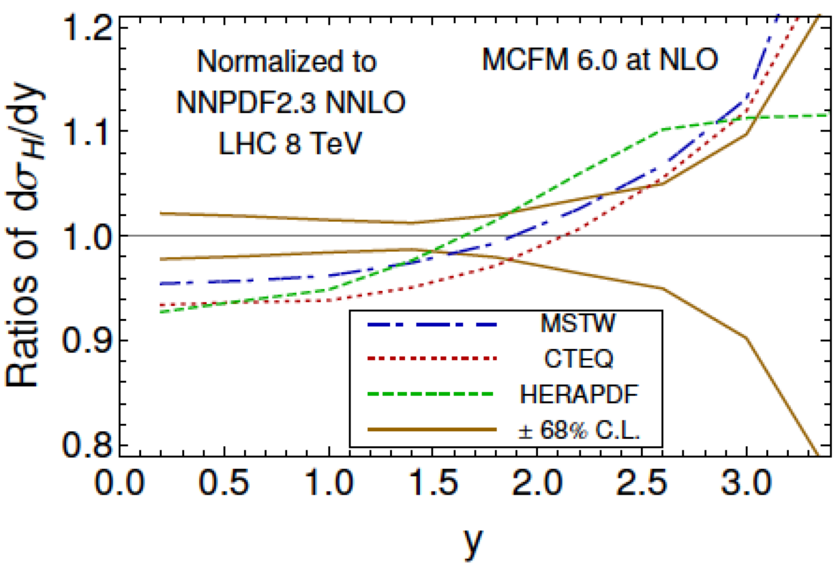


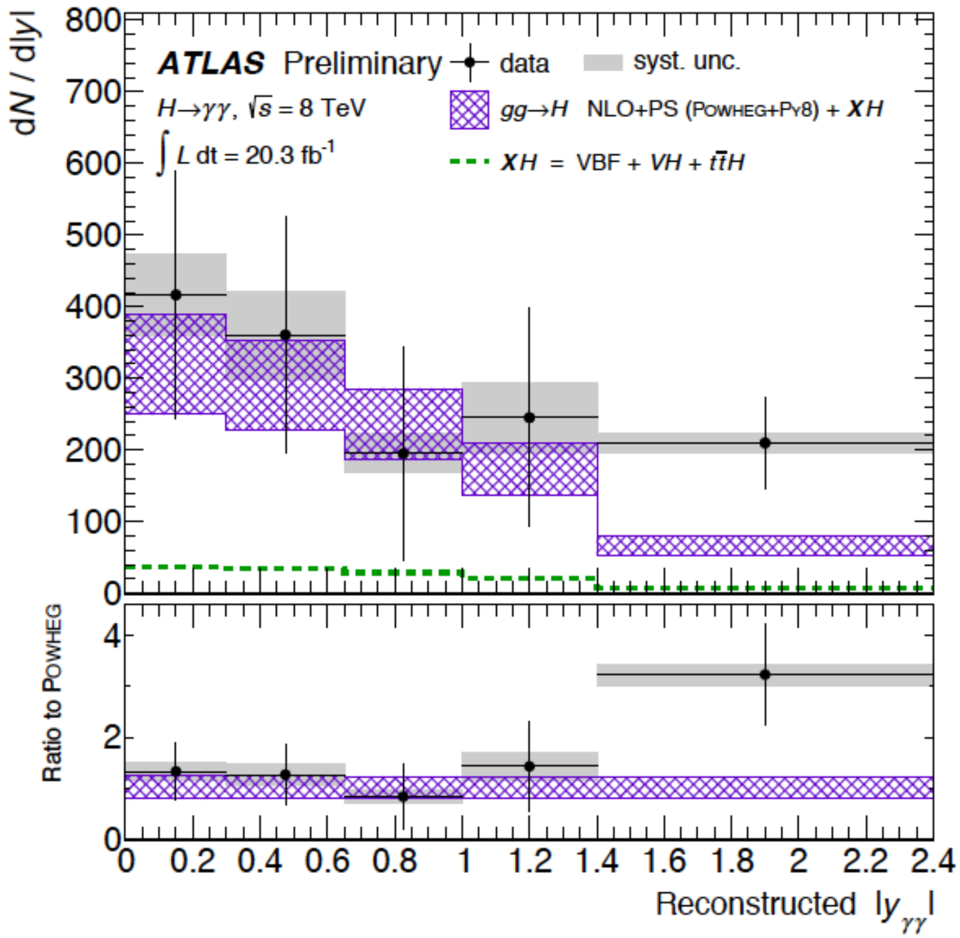




Gluon distributions and Higgs y

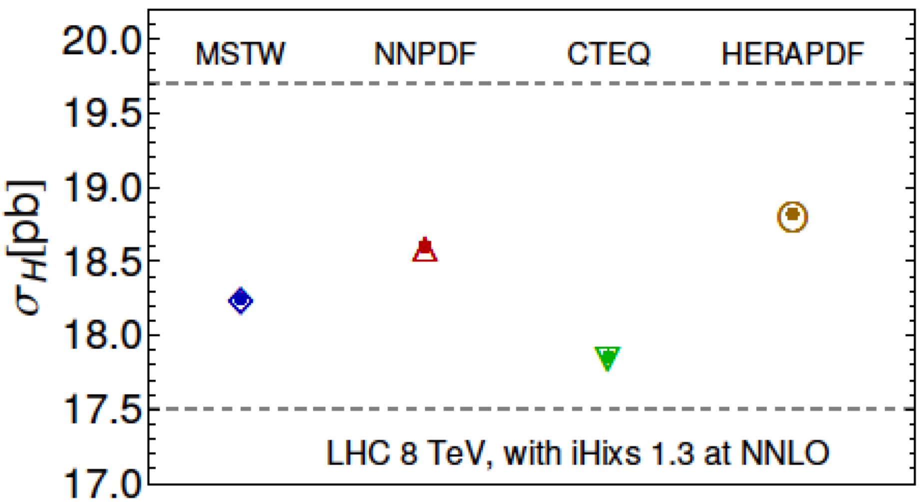
- These shape differences translate into different predictions for Higgs rapidity
- So the best cross section to use for the PDF determination is the Higgs rapidity distribution
- Alas, we're not quite there for using the Higgs rapidity distribution to tune PDFs

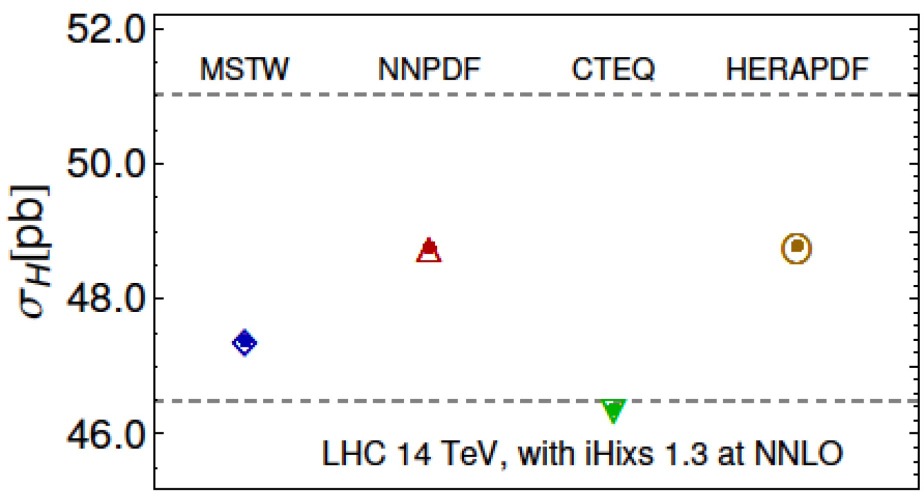




Results of fits to HERA1 only

- Square 1: benchmark comparison of NNLO neutral-current DIS structure functions for four fitting codes with same toy PDF->good agreement
- Then, fit to one well-defined (and important) dataset: HERA Run 1
- Result: all predictions for Higgs cross sections (except HERA1) decrease
- All predictions within (expanded) PDF uncertainty of NNPDF2.3
- …but hierarchy remains the same
- …why?

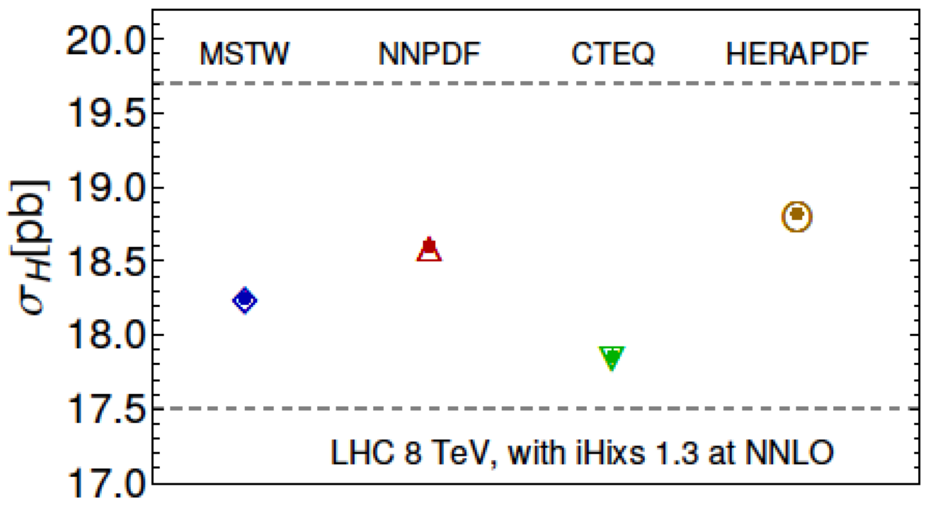


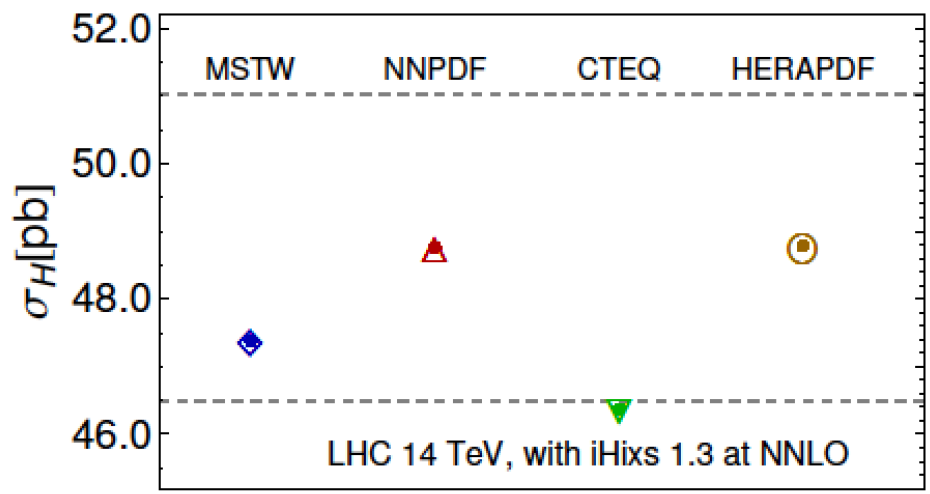


Results of fits to HERA1 only

- All predictions (except HERA1) decrease

566 data points	CTEQ	MSTW	NNPDF	HERAPDF
χ^2	521.8	514.8	548.5	535.0
lum. shift	-0.19	0.27	0.16	0.18
max. shift	1.64	1.51	1.82	1.81
σ_H[pb], 8 TeV	17.86	18.25	18.60±1.10	18.82
σ_H[pb], 14 TeV	46.37	47.38	48.76±2.26	48.78





Gluon-gluon luminosities

- …as a function of mass
- Again, as noted before, all predictions are within the expanded uncertainties

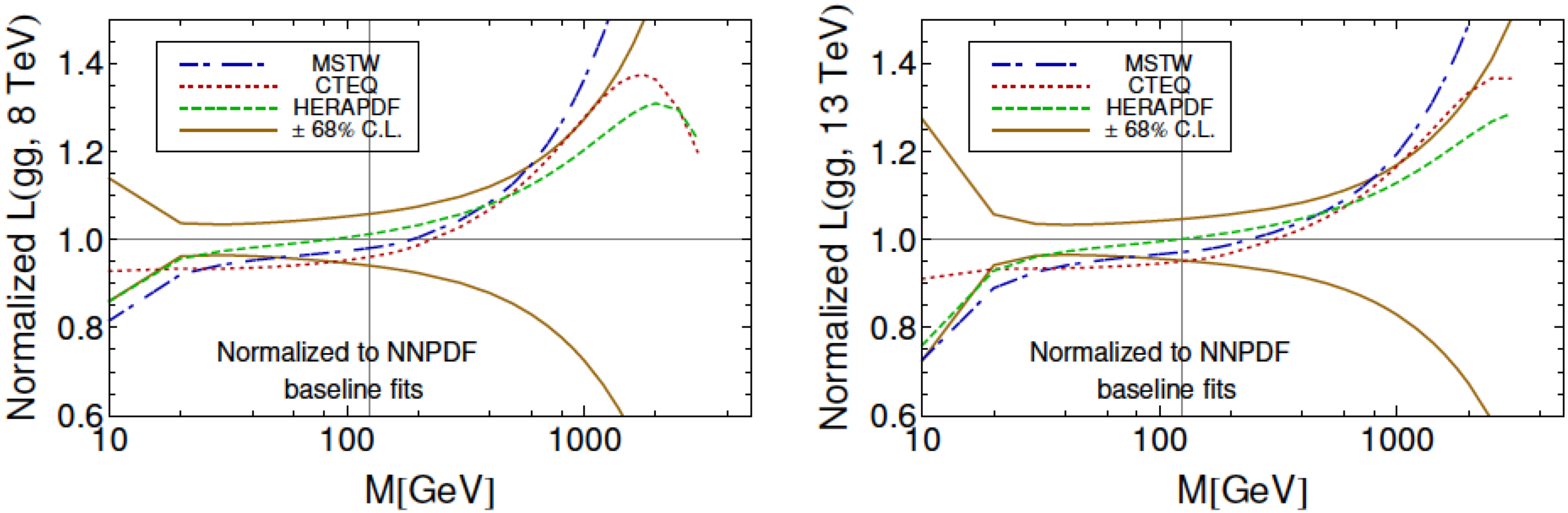


Fig. IV.14: Comparison of the gluon-gluon parton luminosity as a function of invariant mass at the LHC 8 and 13 TeV from the HERA-1-only NNLO fits, normalized to the NNPDF central prediction. The

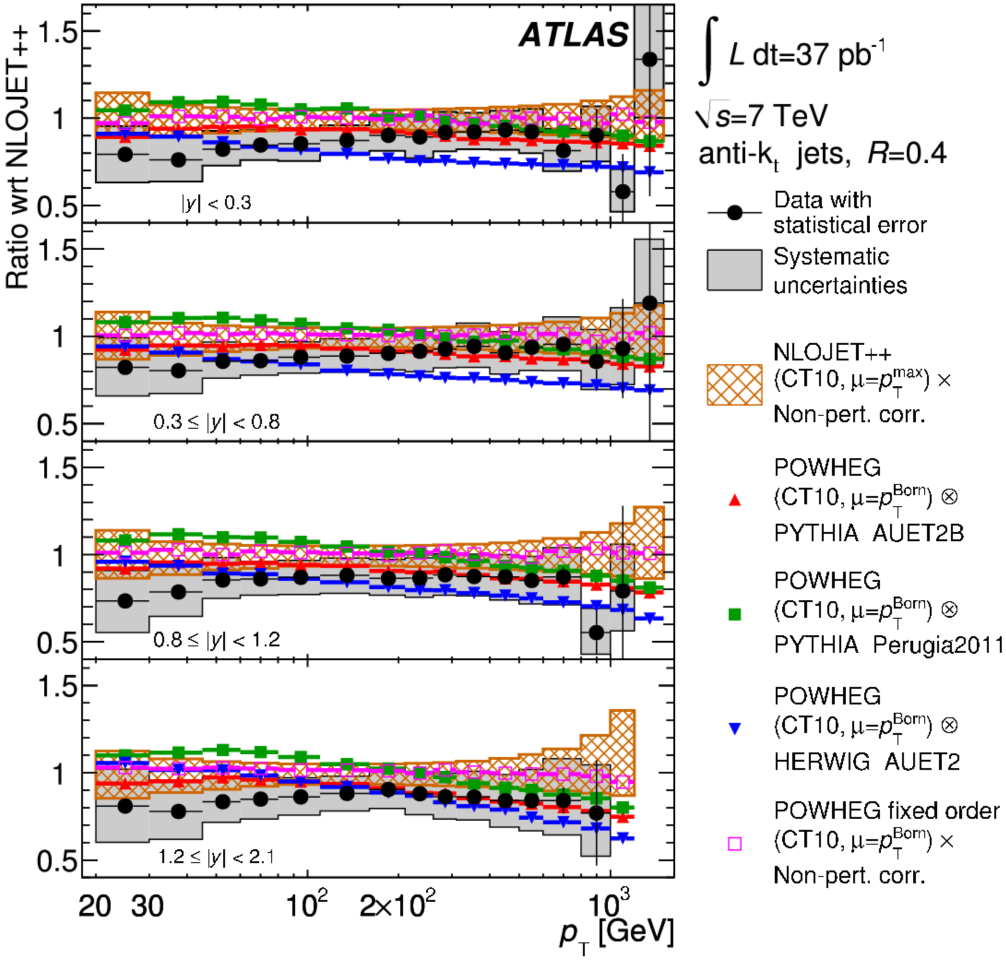
Summary (of study)

- Lots of other detail in the Les Houches writeup
  - exact defintions of χ^2
  - checks of parametrisation,scale choices, heavy quark schemes, …
- HERA-1 only fits prefer smaller Higgs cross sections
- Predictions using HERA-1 follow same pattern as with full global data sets
- Next step (post-Les Houches): add additional data sets into comparisons sequentially, ensuring all groups use exactly the same data points, uncertainties, definition of the systematic uncertainties, etc
  - in progress
- Compare the impact of LHC data sensitive to the gluon PDF

LHC data in global PDF fits

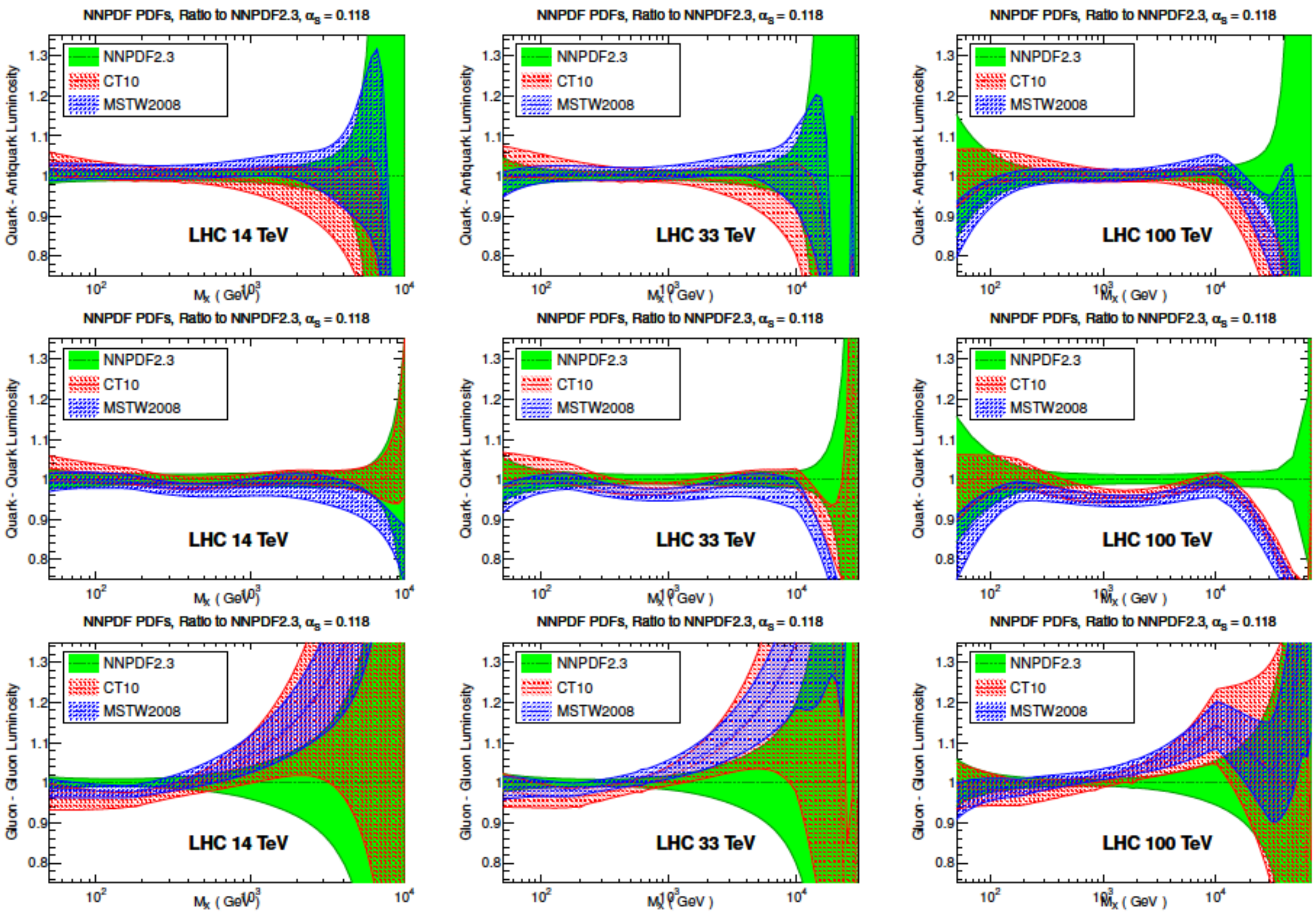
- LHC data will become increasingly important in global fits
- Not just inclusive jet data but for processes such as inclusive photon production, Drell-Yan, W/Z rapidity, ttbar mass and rapidity
- For any process to be used in a global PDF fit, correlated systematic errors must be provided
- 2010 inclusive 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?



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

On to 100 TeV

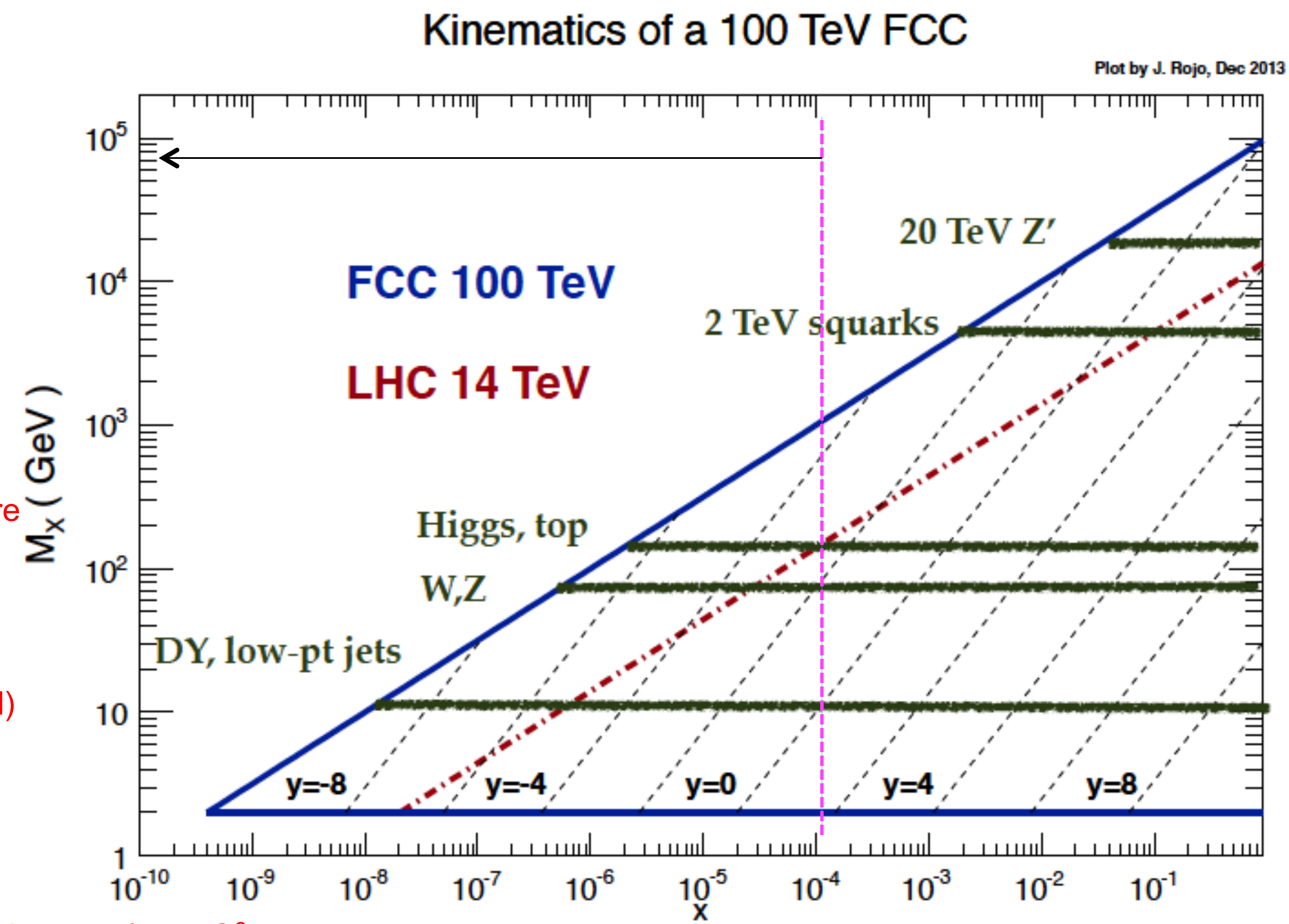
will access smaller x, larger Q^2

currently have no constraints on PDFs for x values below 1E-4

we don't know where at low x, BFKL effects start to become important

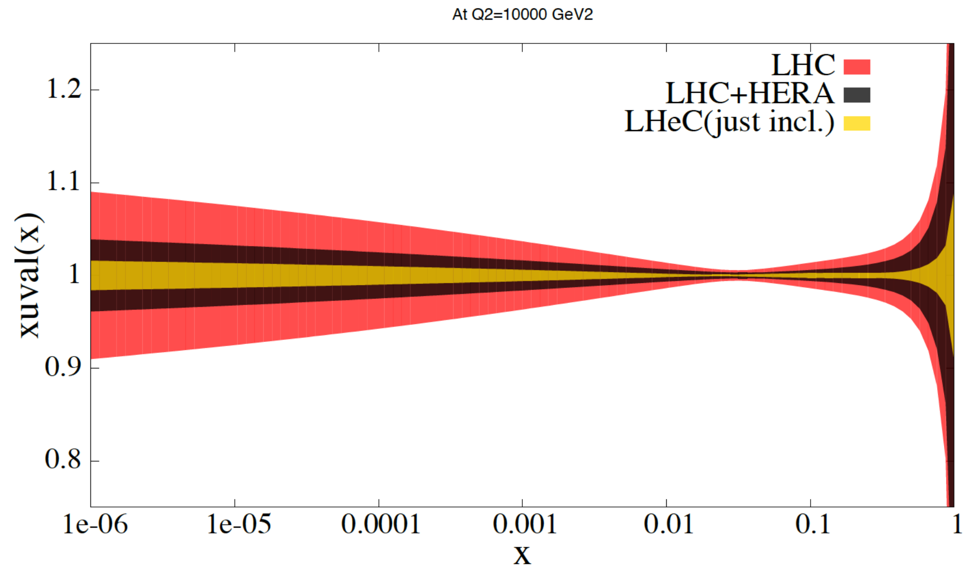
poor constaints (still) as well for high x PDFs

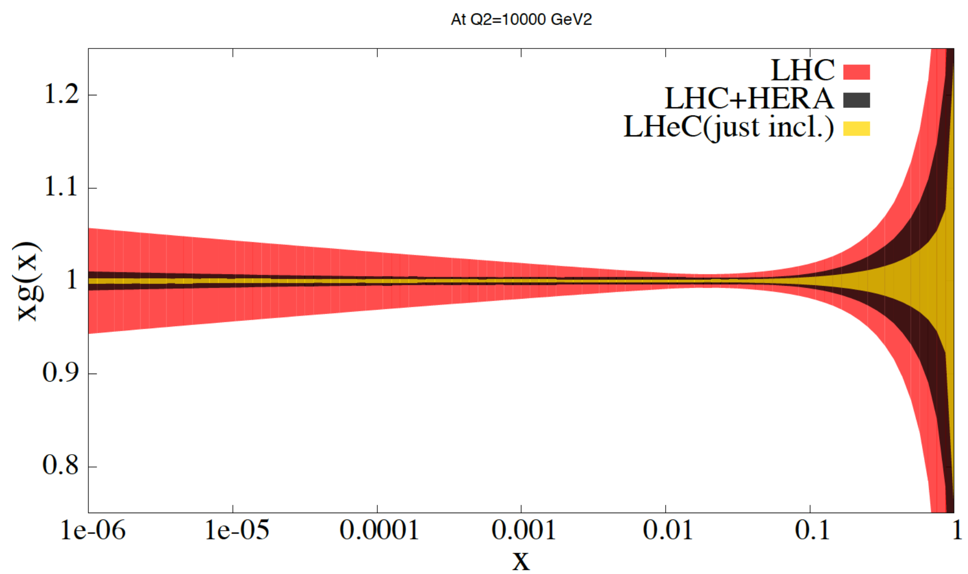
at high masses (Q^2), rely on DLAP evolution; we know at large Q^2, EW effects also become important



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

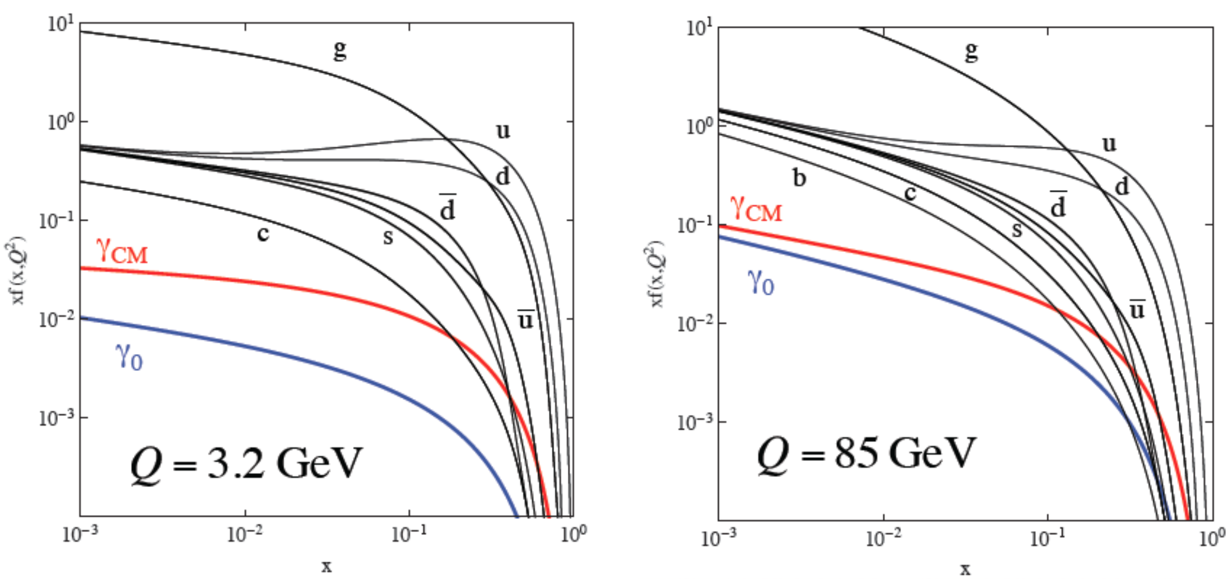
- Lay out a coherent coordinated plan for QCD(+EW) measurements, among ATLAS, CMS and LHCb, that can reduce PDF systematics using LHC data
  - again systematic errors will be very important
- Wiki is now up, PDF4LHC meeting in May

https://twiki.cern.ch/twiki/bin/view/PDF4LHC/WebHome

- …and hopefully update the PDF4LHC prescription to take into account the more modern PDFs

Photon PDFs

- Photon PDFs: photon PDFs can be larger than antiquark distributions at high x; the LHC is a γγ collider; even more true of a 100 TeV collider
- NNPDF has developed photon PDFs + QED corrections (in addition to MRST2004QED)
- CT10 in progress (see talk of C. Schmidt at DIS2014)
  - fitting to photon production in DIS



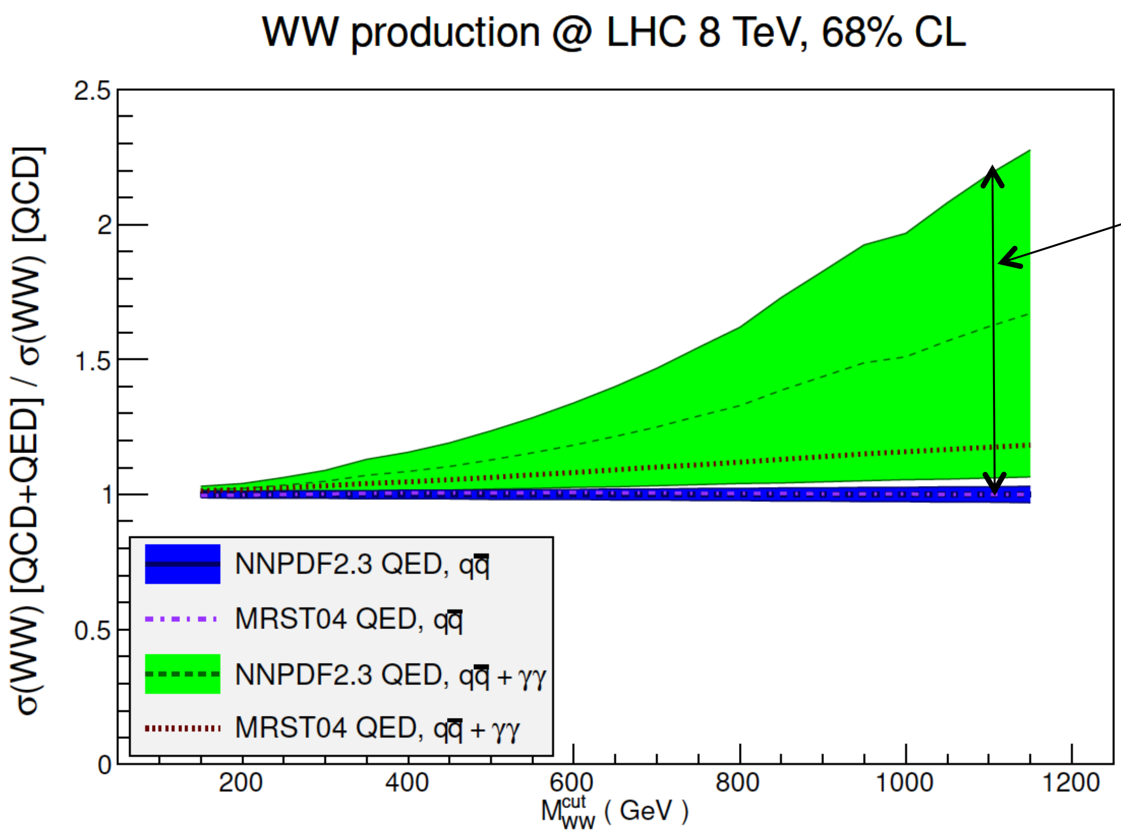
γ momentum fraction:

$p^\gamma(Q)$	$\gamma(x,Q_0)=0$	$\gamma(x,Q_0)_{CM}$
$Q = 3.2$ GeV	0.05%	0.34%
$Q = 85$ GeV	0.22%	0.51%

allow for non-perturbative component of photon at Q_o

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

EW corrections

- At high Q^2, logs of $\alpha \ln(Q^2/m_W^2)$ become large; EW corrections become as large as higher order QCD corrections
- Need EW evolution for PDFs
  - W and Z PDFs
  - Ciafaloni and Comelli, 2002, 2005
- …in Les Houches proceedings, a *dictionary* for QCD+EW corrections has been provided by Stefan Dittmaier

Meta-PDFs:arXiv:1401.0013

- Take NNLO PDFs

NNLO	*Initial scale*	a_s	*Error type*	*Error sets*
CT10	*1.3*	*0.118*	*Hessian*	*50*
MSTW'08	*1.0*	*0.1171*	*Hessian*	*40*
NNPDF2.3	*1.414*	*0.118*	*MC*	*100*

- Choose a meta-parametrisaton of PDFs at initial scale of 8 GeV (away from thresholds) for 9 PDF flavors (66 parameters in total)

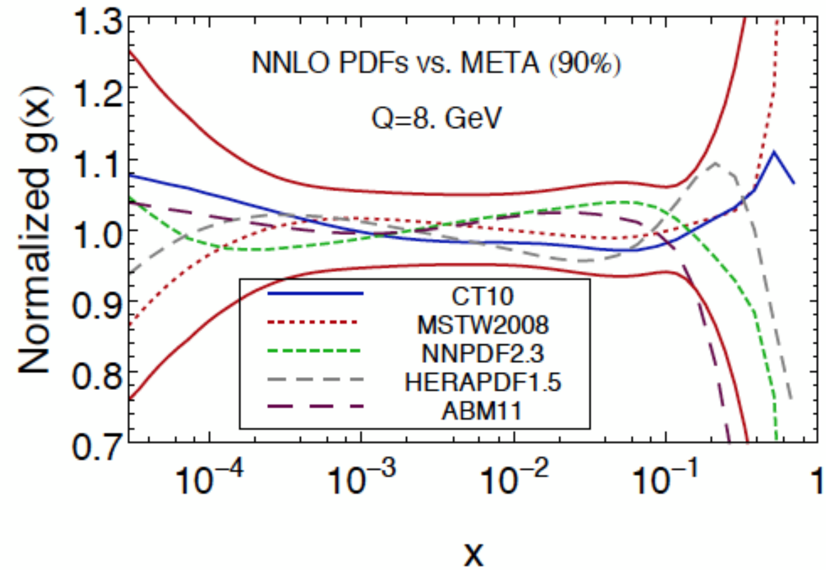
$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i \geq 4} a_i \left[T_{i-3}(y(x)) - 1\right]}$$

- Generate MC replicas for all 3 groups and merge with equal weights, finding meta parameters for each of the replicas by fitting PDFs in x ranges probed at LHC
- Construct 50 eigenvectors using Hessian method
- These 50 eigenvectors provide a very good representation of the PDF uncertainties for all of the 3 PDF error families above

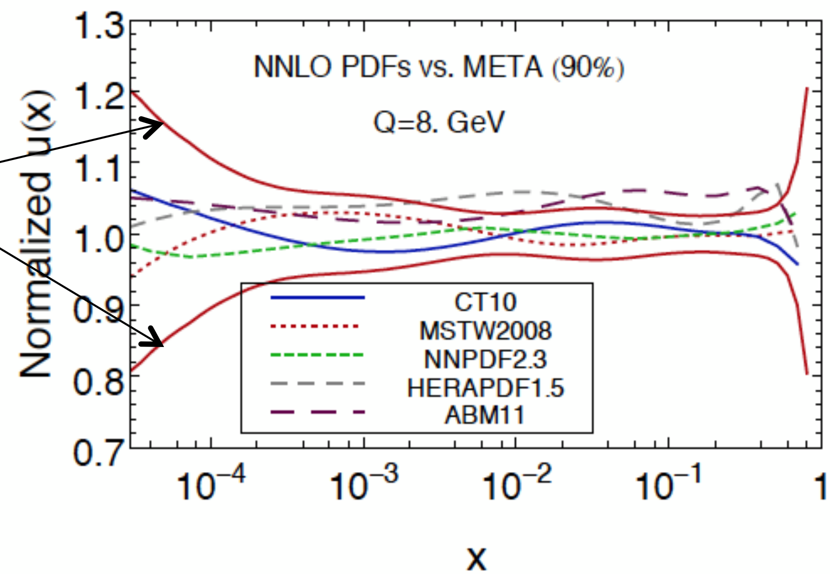
J. Gao, P. Nadolsky

meta-PDFs

- The meta-PDFs provide both an average of the chosen PDFs, as well as a good estimation of the total PDF uncertainty



meta-PDF uncertainty band



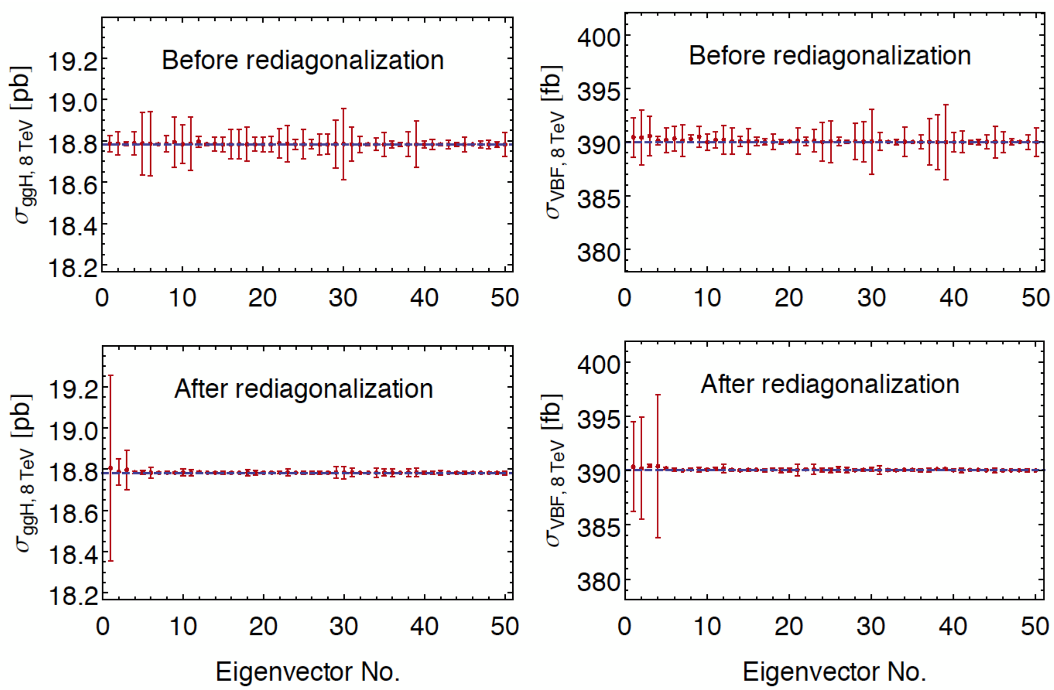
Higgs observables

- Select global set of Higgs cross sections at 8 and 14 TeV (46 observables in total; more can be easily added if there is motivation)

production channel	$\sigma(inc.)$	$\sigma(\|y_H\| > 1)$	$\sigma(p_{T,H} > m_H)$	scales
$gg \to H$	iHixs1.3 [32] at NNLO	MCFM6.3 [33] at LO	—	m_H
$b\bar{b} \to H$	iHixs at NNLO	—	—	m_H
VBF	VBFNLO2.6 [34] at NLO	same	same	m_W
HZ	VHNNLO1.2 [35] at NNLO	CompHEP4.5 [36] at LO	CompHEP at LO	$m_Z + m_H$
$HW^\pm$	VHNNLO at NNLO	—	—	$m_W + m_H$
HW^+	CompHEP at LO	same	same	$m_W + m_H$
HW^-	CompHEP at LO	same	same	$m_W + m_H$
$H + 1jet$	MCFM at LO	same	same	m_H
$Ht\bar{t}$	MCFM at LO	CompHEP at LO	CompHEP at LO	$2m_t + m_H$
HH	Hpair [37] at NLO	—	—	$2m_H$

Data set diagonalization (arXiv:0904.2424)

- There are 50 eigenvectors, but can re-diagonalize the Hessian matrix to pick out directions important for the Higgs observables listed on previous page; with rotation of basis, 50 eigenvectors become 6



J. Gao,
J. Huston
P. Nadolsky
(in progress)

It's possible to define a few eigenvectors which completely encompass the PDF and α_s uncertainties for CT10, MSTW08 and NNPDF2.3 for Higgs production for 8-14 TeV

arXiv:1004.4624

- Treat α_s input as another eigenvector; α_s and PDF uncertainties can be added in quadrature ($\alpha_s(m_Z)$=0.118+/0.0012)
- So 7 eigenvectors to represent all PDF+α_s uncertainty

LHC	$\Delta\alpha_s(M_Z)$	GGH inc.	GGH $0j$ exc.	GGH $1j$ exc.	GGH $2j$ inc.	VBF inc.
LHC 8 TeV	$+1\sigma$	2.2%	1.6%	3.0%	4.8%	-0.23%
	-1σ	-2.2%	-1.6%	-2.8%	-4.8%	0.11%
LHC 14 TeV	$+1\sigma$	2.1%	1.4%	2.6%	4.5%	0.05%
	-1σ	-2.0%	-1.4%	-2.5%	-4.4%	-0.09%

❖ using PDF α_s series of the META PDFs

NNLO QCD+NLO EW wishlist

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

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

justify the requested precision based on current/extrapolated experimental errors

S. Dittmaier, N. Glover, J. Huston

NNLO QCD + NLO EWK wishlist

Process	known	desired	details
$t\bar{t}$	$\sigma_{\rm tot}$ @ 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
$t\bar{t} + \mathrm{j}$	$d\sigma$(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
$\gamma + \mathrm{j}$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + \mathrm{b}$ for bottom PDF

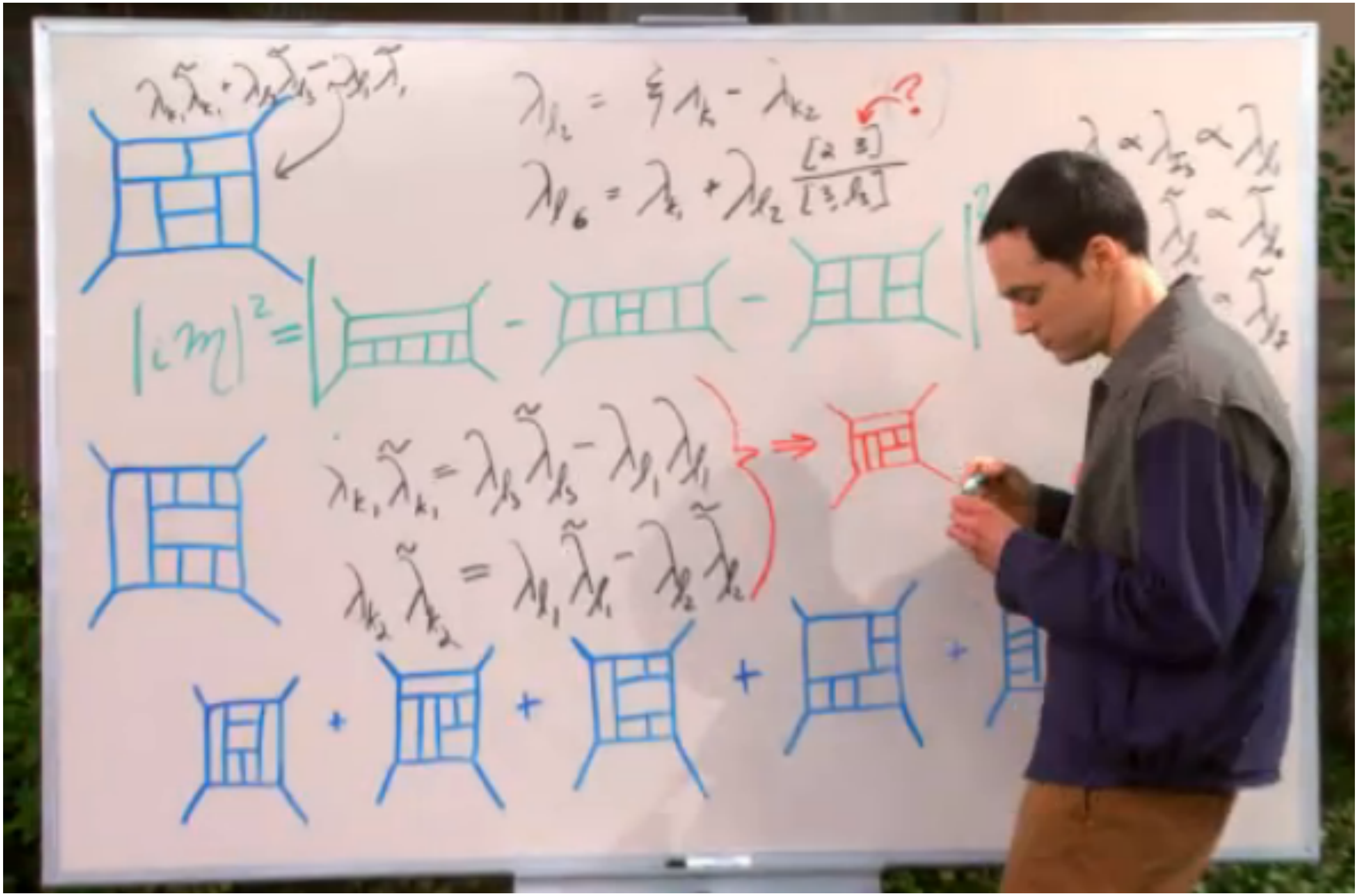
Table 2: Wishlist part 2 – jets and heay quarks

NNLO QCD + NLO EWK wishlist

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
$\mathrm{gg \to VV}$	$d\sigma$(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 $\mathrm{VH \to b\bar{b}}$
$\mathrm{VV'\gamma}$	$d\sigma$(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
  - HERA2.0 data set should have an impact
- 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
- 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
- Les Houches 2013 SM proceedings should be on archive this week

Wu Ki Tung Award for Early Career Research on QCD

- See information at

http://tigger.uic.edu/~varelas/tung_award/

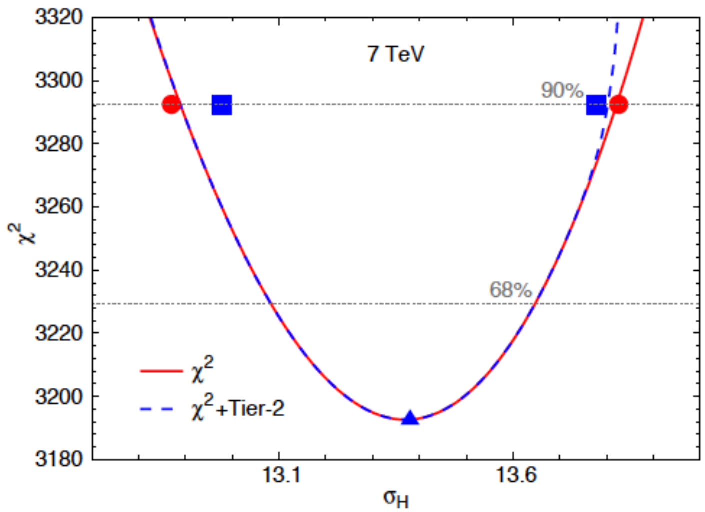
- Contribute at

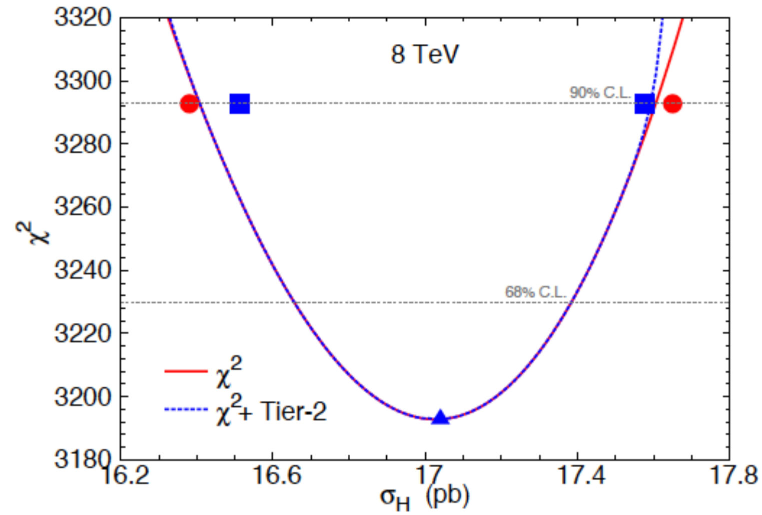
https://www.givingto.msu.edu/gift/?sid=1480

- **MSU will match any donations**

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

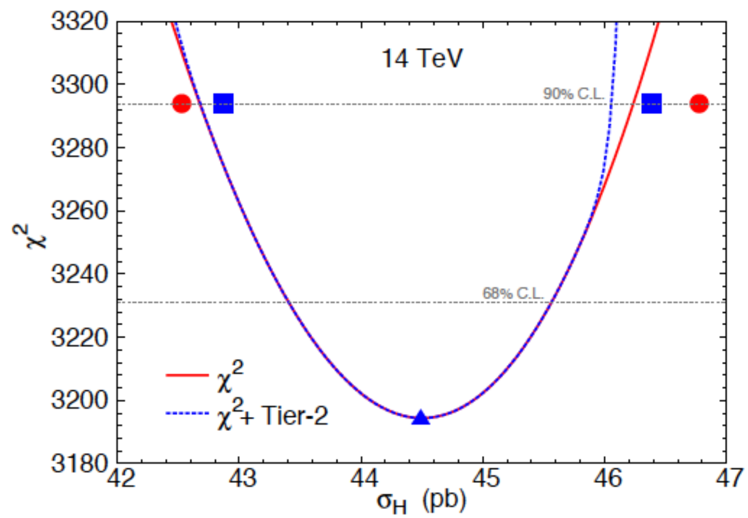




LM technique not dependent on assumption of quadratic χ^2 behavior, so more robust than Hessian

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

all predictions at NNLO using μ=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.

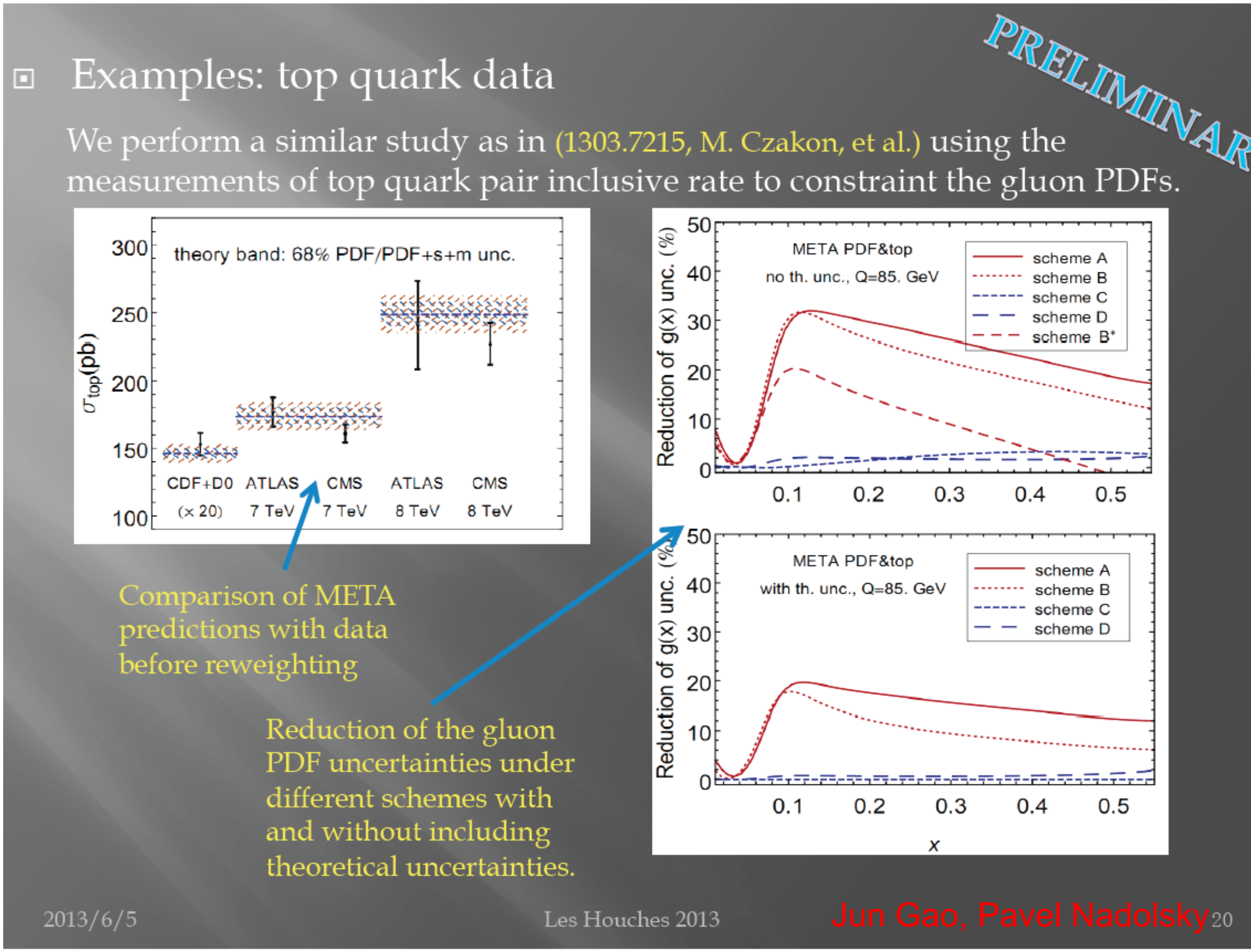
Scheme D: one variation of scheme A can be motivated by the CTEQ total χ^2 tolerance criterion. $\Delta\chi^2=100$ for 90%, translated to $\Delta\chi^2=h_0=37$ for 68%, and the weight function $\sim\exp[-\chi^2(N|f)/(2h_0)]$.

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

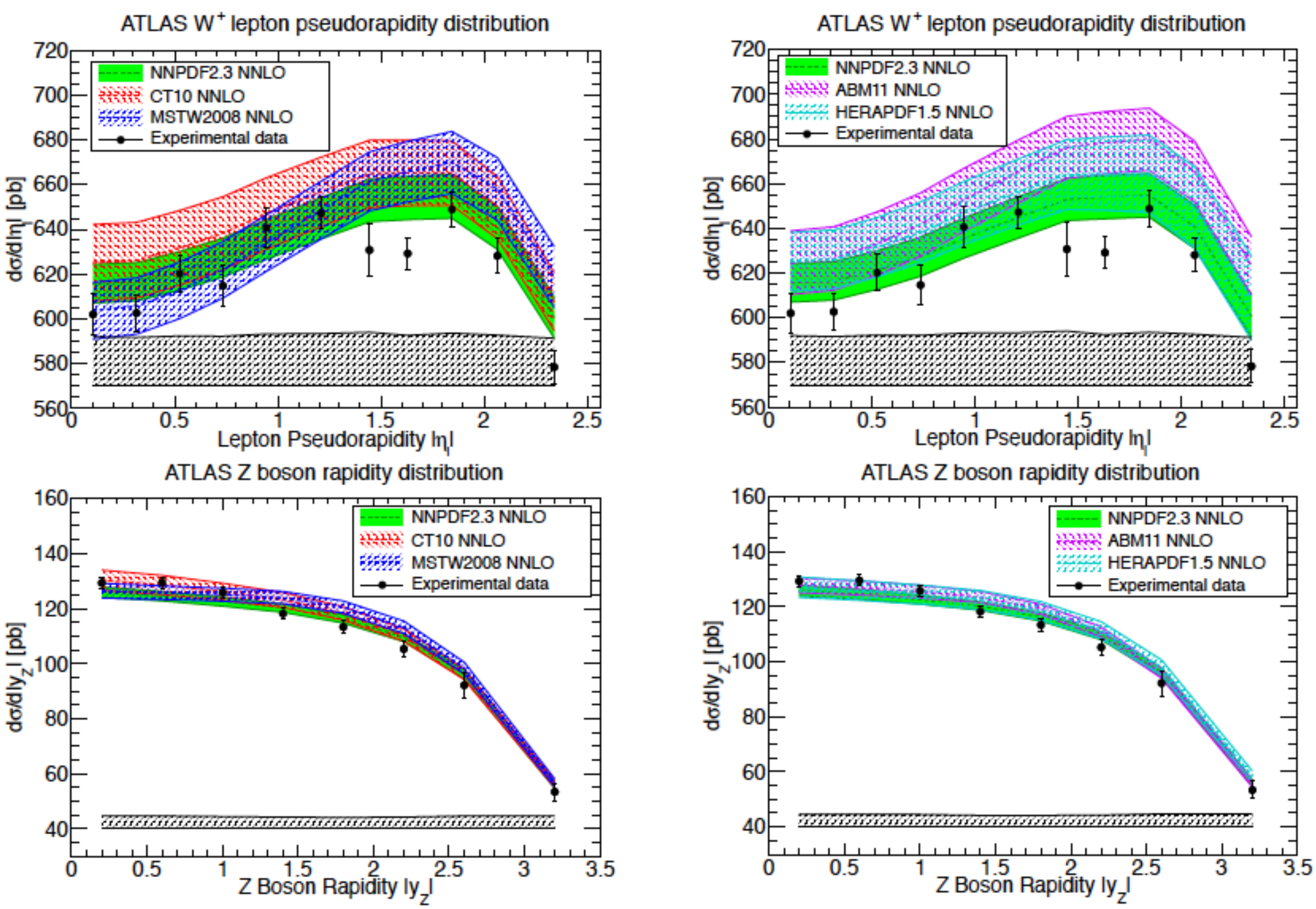


Figure 12: Comparison of the ATLAS electroweak vector boson production data with the NNPDF2.3, CT10 and MSTW2008 predictions with $\alpha_s = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics (including normalization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

Comparisons to 2011 data

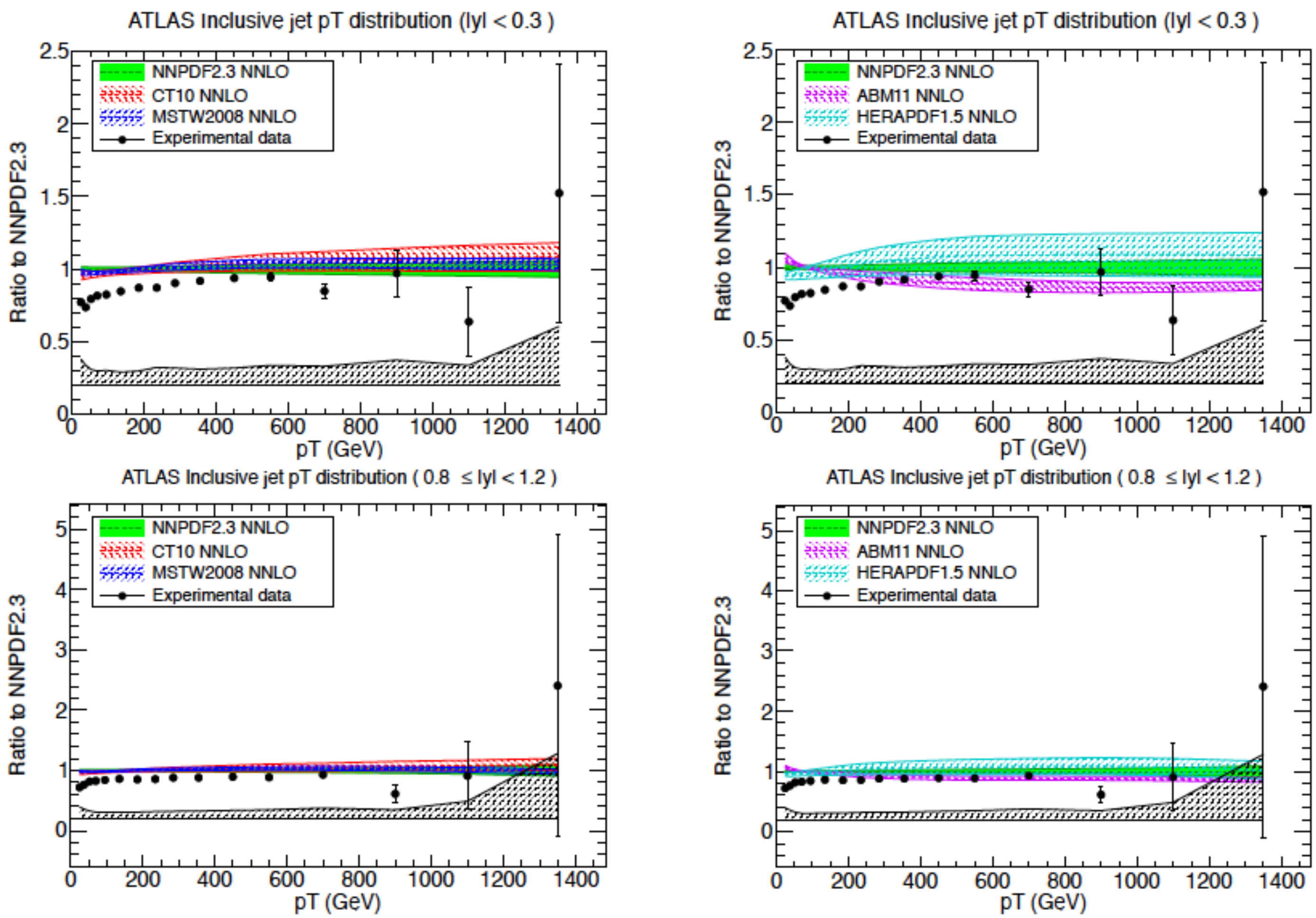


Figure 14: Comparison of the ATLAS $R = 0.4$ inclusive jet production data from the 2010 dataset with the NNPDF2.3, CT10 and MSTW2008 NNLO PDF sets and $\alpha_S = 0.118$. The error bars correspond to statistical uncertainties, while the band in the bottom of the plot indicates the correlated systematics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

Comparisons to 2011 data

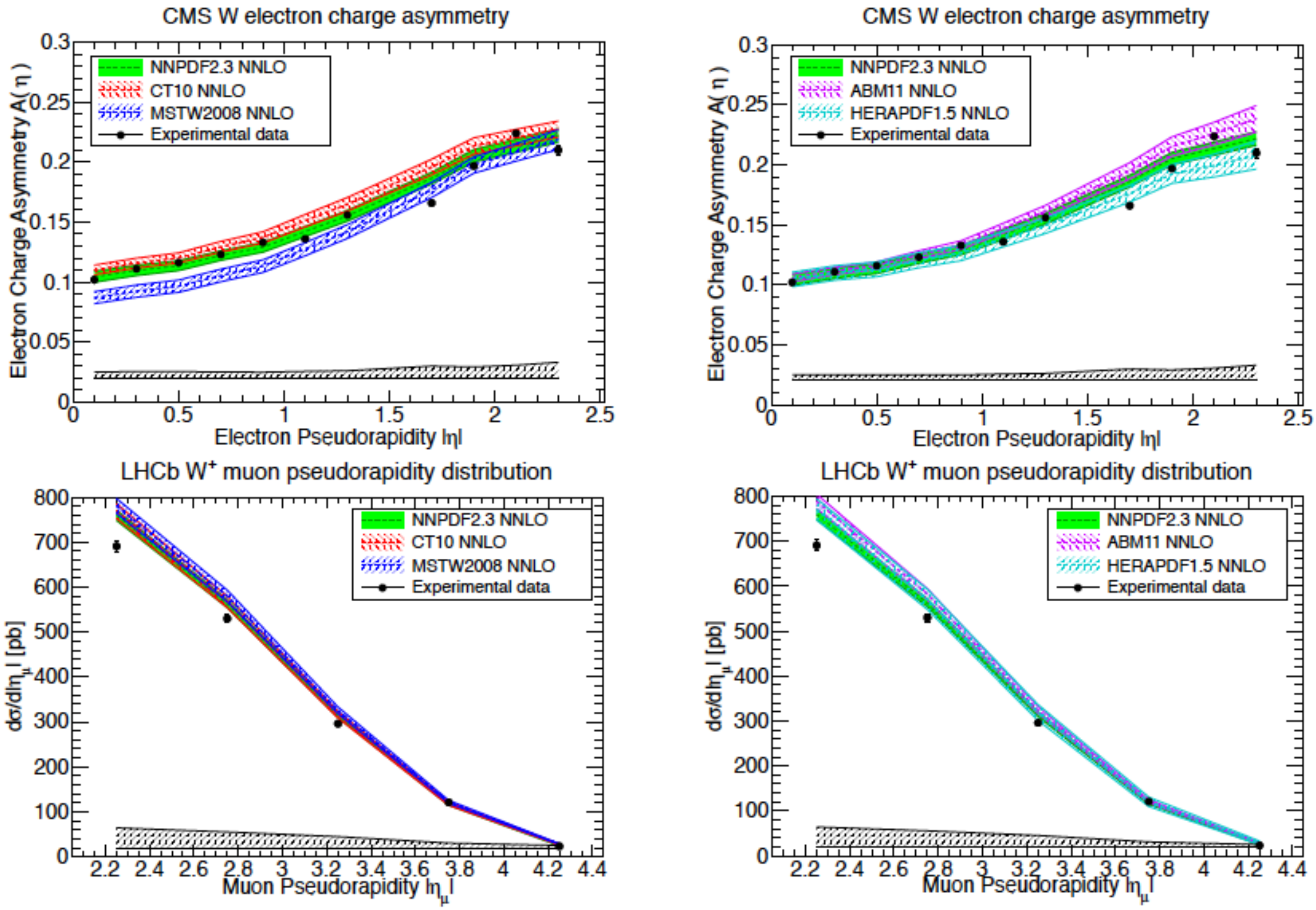


Figure 13: Same as Fig. 12 for CMS and LHCb W production.

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

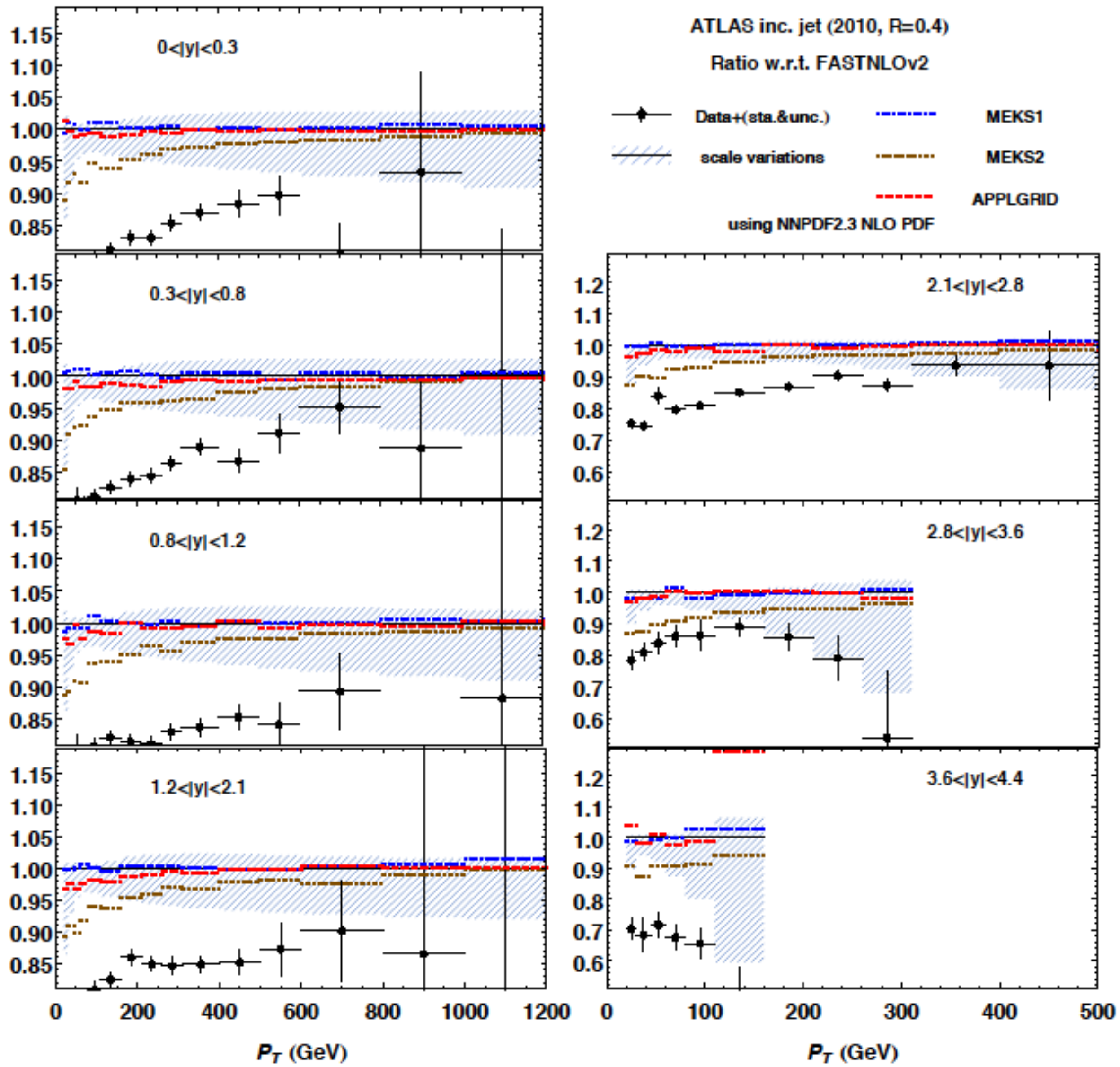


Figure 1: Comparisons of NLO theoretical predictions for 2010 ATLAS single-inclusive jet production ($R = 0.4$) from various numerical programs. NNPDF2.3 NLO PDFs are used with $\alpha_s(M_Z) = 0.119$.

scale $=p_Tj^{et}$

scale $=p_Tj^{et,max}$

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

↓

ATLAS choice

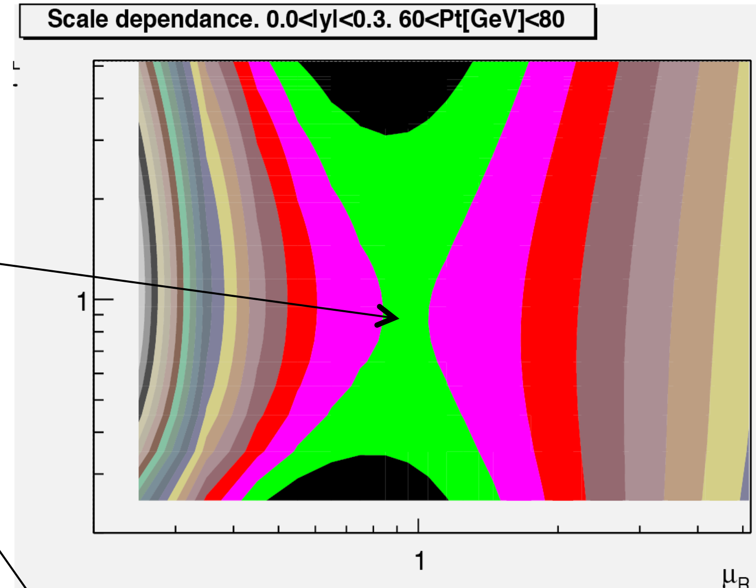
hatched is FASTNLO uncertainty band for $p_T/2$ to $2p_T$

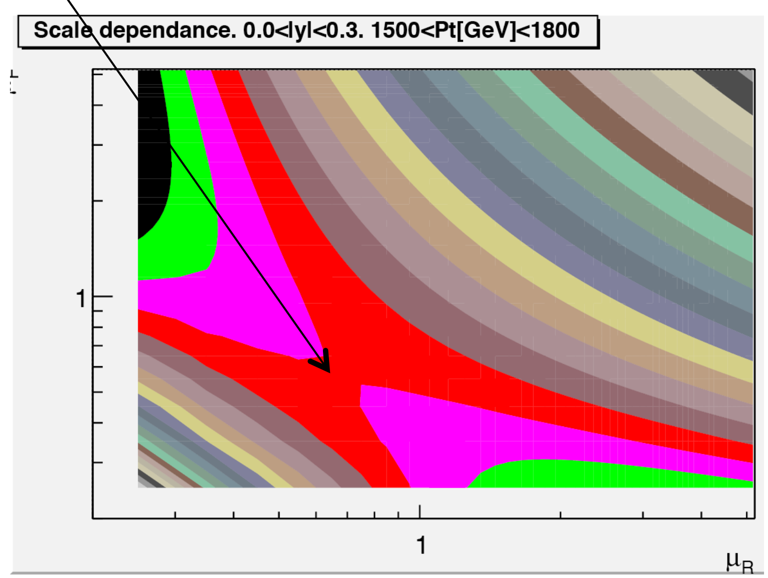
could we agree on a common scale, like p_T^{jet}?

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

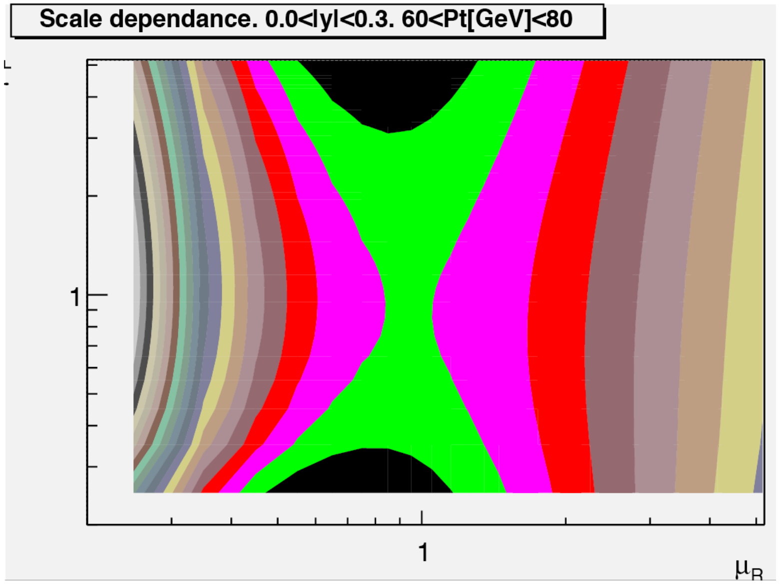
R=0.4
antikT

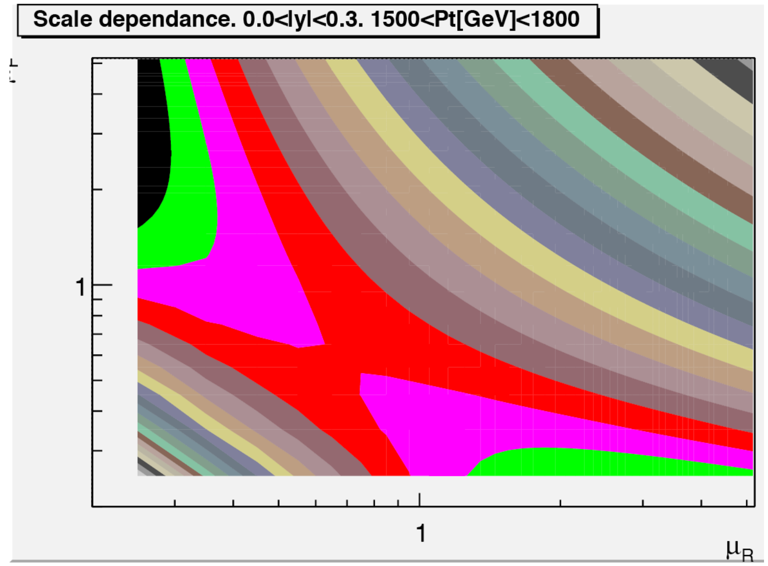




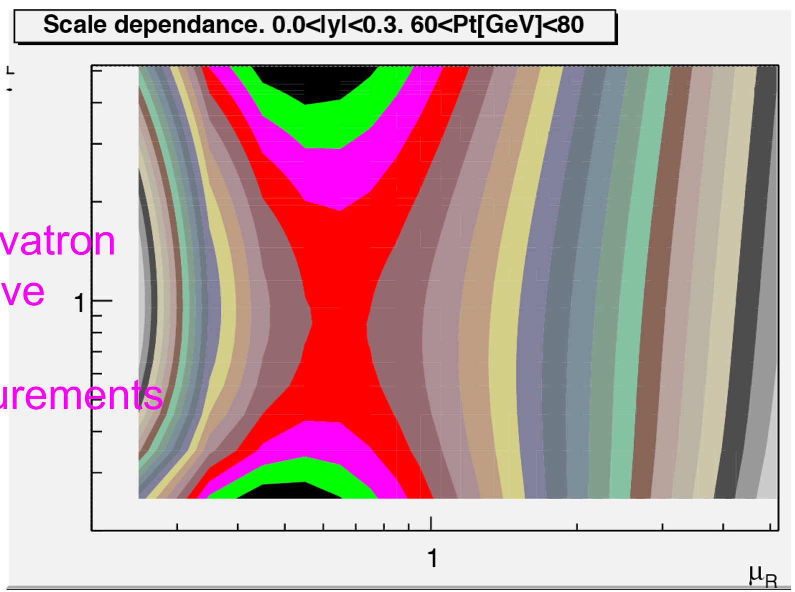
Scale dependence also depends on jet size;

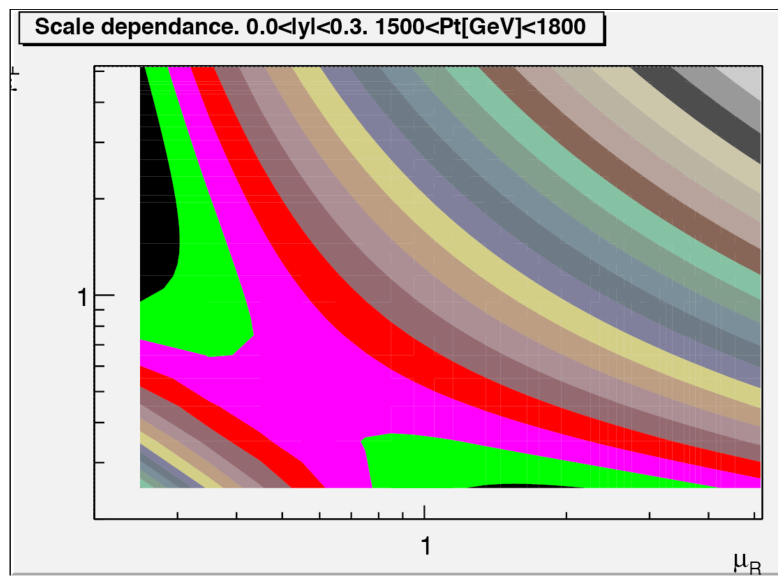
R=0.4
antikT





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).

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

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