PDF's for the LHC

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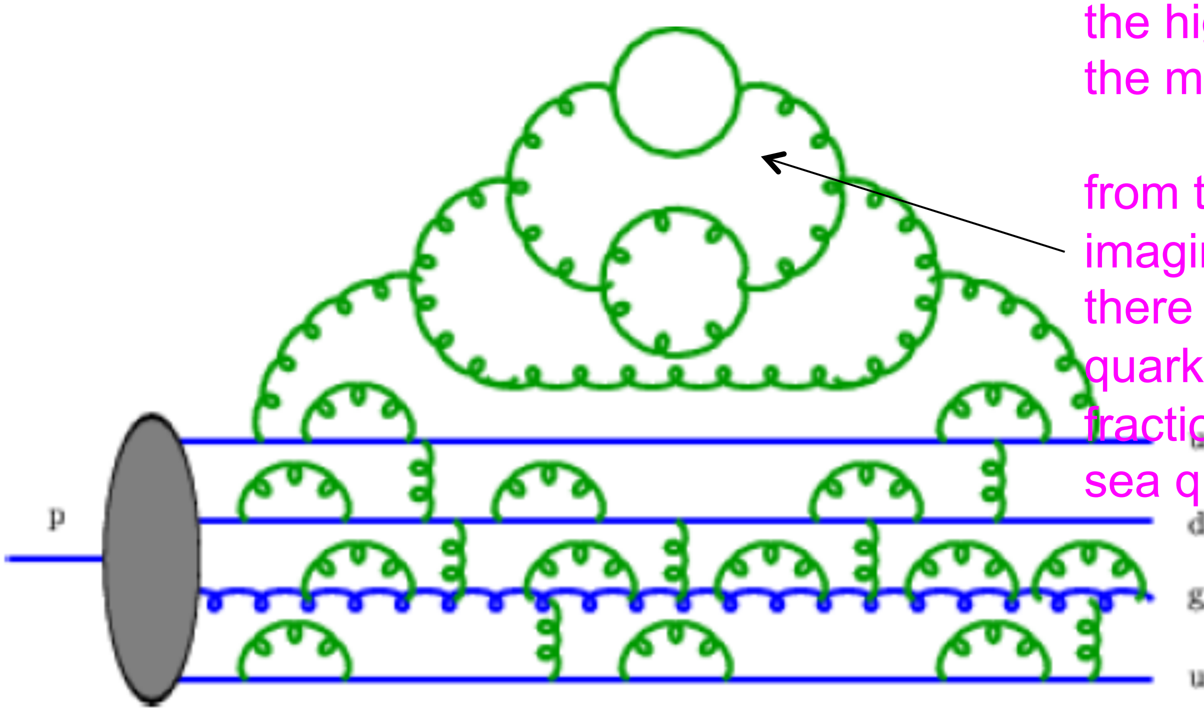
Hadrons and PDFs

- The proton is a dynamical object; the structure observed depends on the time-scale (Q^2) of the observation
- But we know how to calculate this variation (DGLAP)
- We just have to determine the starting points from fits to data

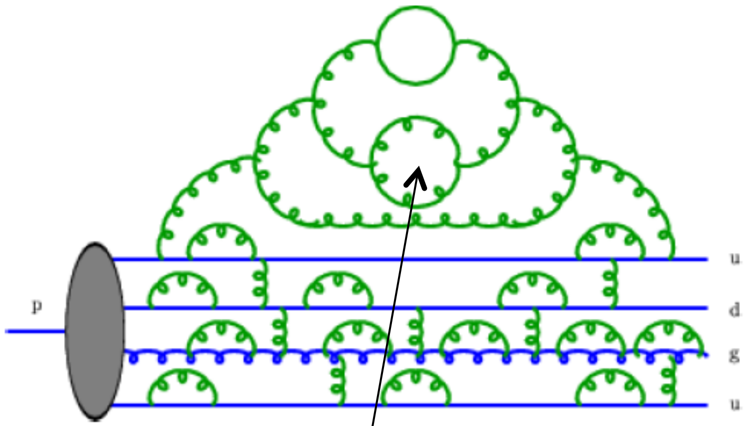
the higher the value of Q^2, the more detail we examine

from this picture, you can imagine that as Q^2 increases, there will be fewer valence quarks at high momentum fraction and more gluons and sea quarks at lower momentum



$f_i(x, Q^2) =$ number density of partons i
at momentum fraction x and probing scale Q^2

Hadrons and PDFs



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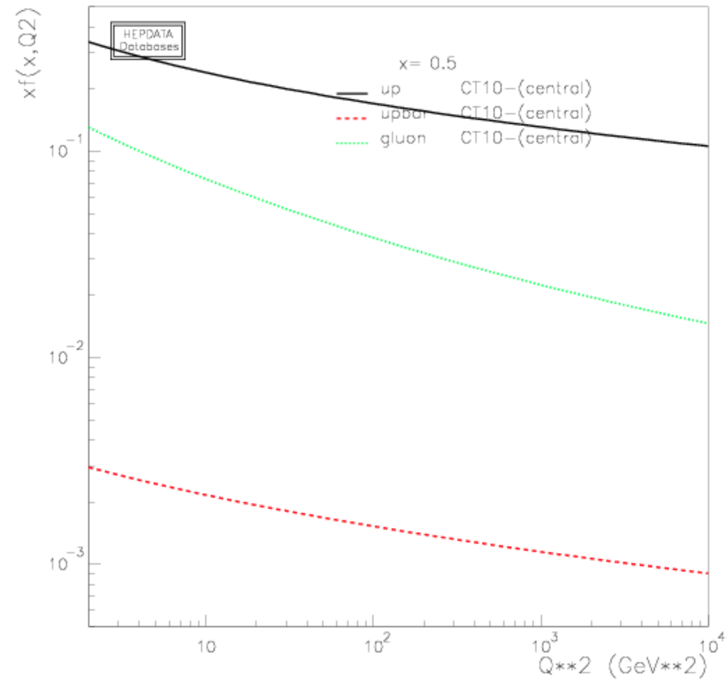
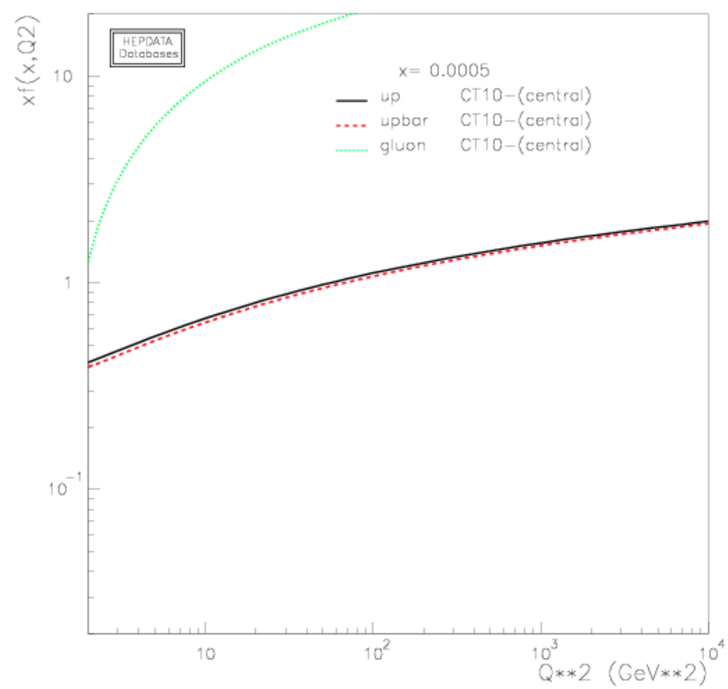
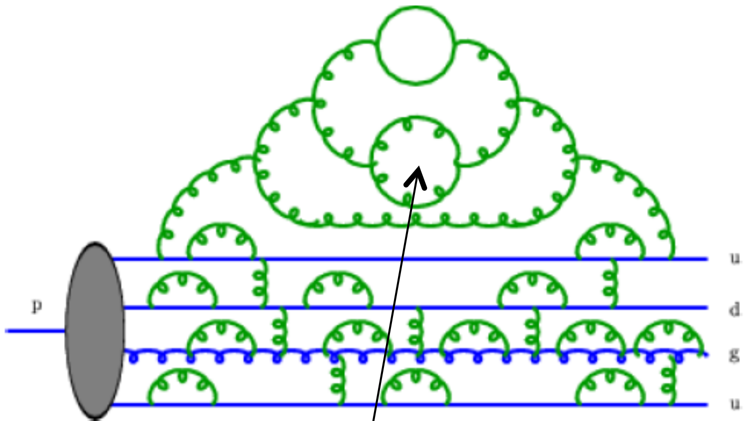




Hadrons and PDFs



$f_i(x,Q^2)$ = number density of partons i
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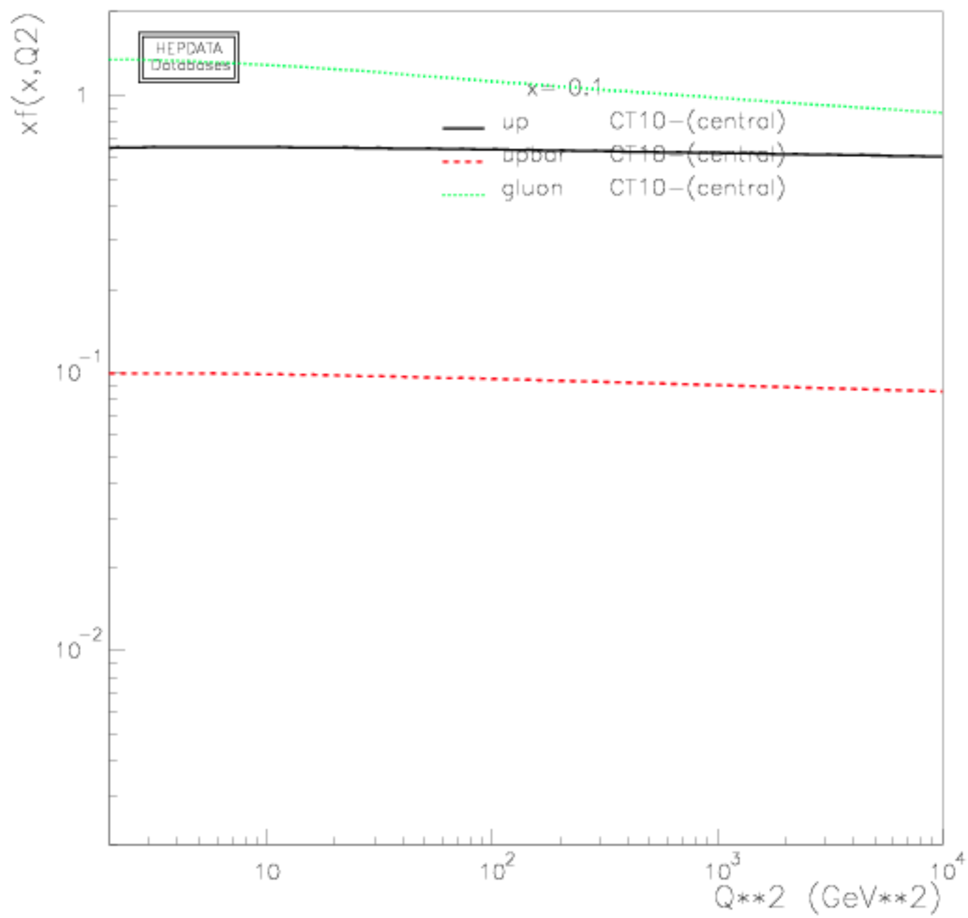
from this picture, you can imagine that as Q^2 increases, there will be fewer valence quarks at high momentum fraction and more gluons and sea quarks at lower momentum

consider x=0.1; not easy to see scaling violations here.



Parton distribution functions and global fits

- Calculation of production cross sections at the LHC relies upon knowledge of pdf's in the relevant kinematic region
- Pdf's are determined by global analyses of data from DIS, DY and jet production
- Three major groups that provide semi-regular updates to parton distributions when new data/ theory becomes available
  - MRS->MRST98->MRST99 ->MRST2001->MRST2002 ->MRST2003->MRST2004 ->MSTW2008
  - CTEQ->CTEQ5->CTEQ6 ->CTEQ6.1->CTEQ6.5 ->CTEQ6.6->CT09->CT10
  - NNPDF->NNPDF2.0->NNPDF2.1->NNPDF2.2->NNPDF2.3

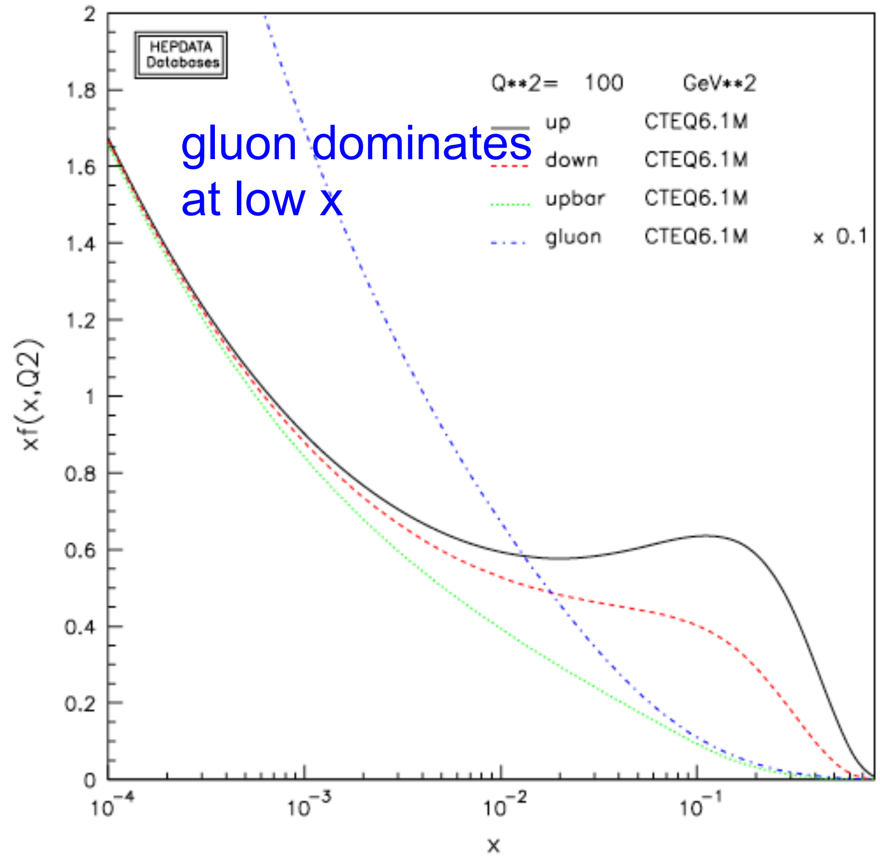


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

Global fits

- With the DGLAP equations, we know how to evolve pdf's from a starting scale Q_0 to any higher scale
  - remember the divergences from the initial state that we absorbed into the pdfs
- …but we can't calculate what the pdf's are ab initio
  - one of the goals of lattice QCD
- We have to determine them from a global fit to data
  - factorization theorem tells us that pdf's determined for one process are applicable to another
  - extremely important proof

- So what do we need
  - a value of Q_o (1.3 GeV for CTEQ, 1 GeV for MSTW) lower than the data used in the fit (or any prediction)
  - a parametrization for the pdf's
  - a scheme for the pdf's
  - hard-scattering calculations at the order being considered in the fit
  - pdf evolution at the order being considered in the fit
  - a world average value for α_s
  - a lot of data
    - with appropriate kinematic cuts
  - a treatment of the errors for the experimental data
  - MINUIT

LHC

- We can determine PDFs at LO (not very well), NLO and NNLO
- These PDFs are evaluated in the relevant expressions for the hard scattering cross sections we are interested .

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

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

- In addition to the PDFs themselves, it is often useful to

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

…or integrated over y

Some PDF 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]

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

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.

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.

Note each PDF uses native value of $\alpha_s(m_Z)$ and PDF+α_s errors around that central choice.

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.

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 and are now in YR3
- They have been utilized in a subsequent PDF4LHC recommendation (see PDF4LHC meeting May 2014)

Benchmark paper

- Not officially a PDF4LHC document used as input to PDF4LHC 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]

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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.

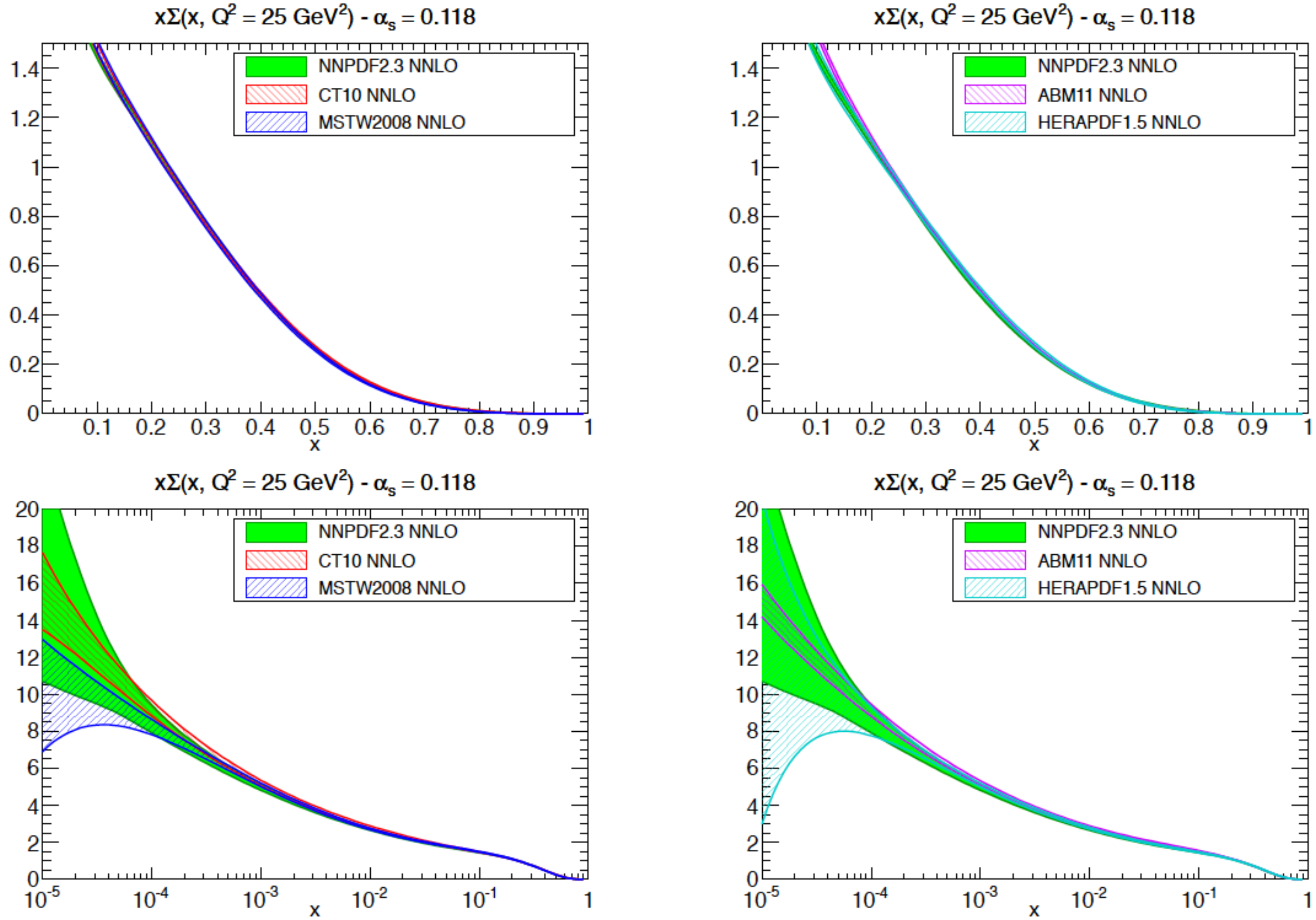
No updates of JR since 2009.

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

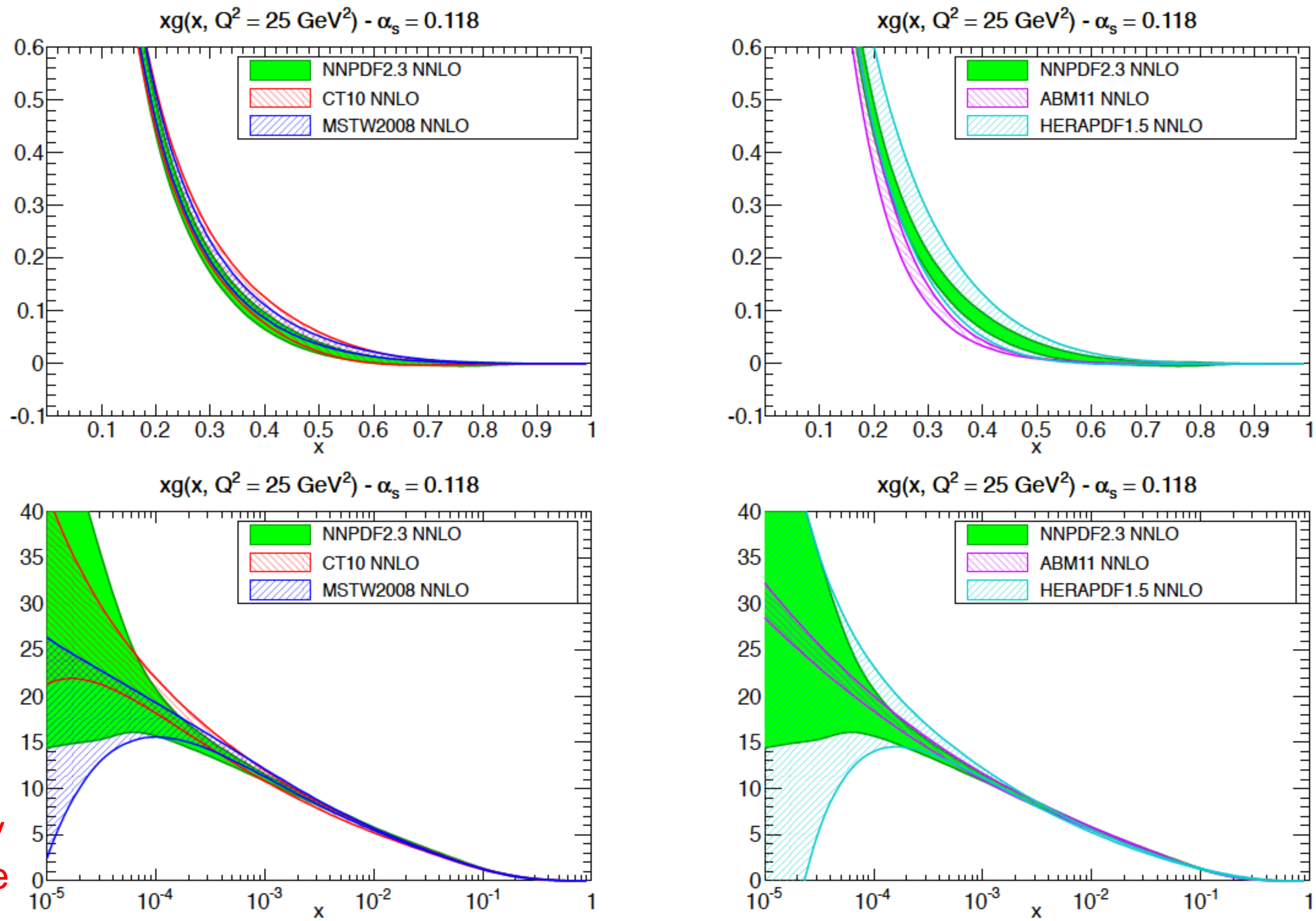
CT10, MSTW08 and NNPDF2.3 gluon distributions all in reasonable, but not perfect, agreement

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

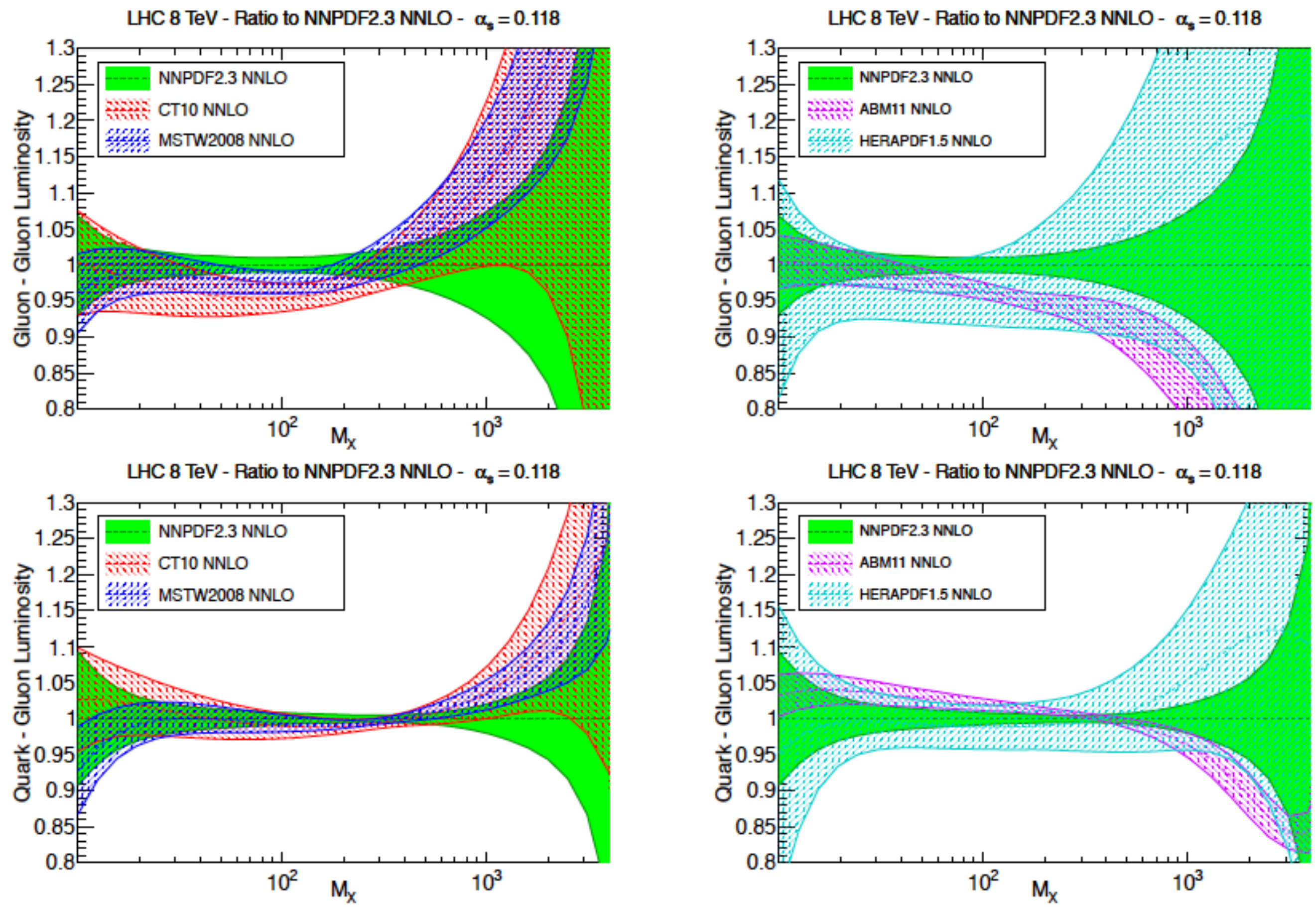


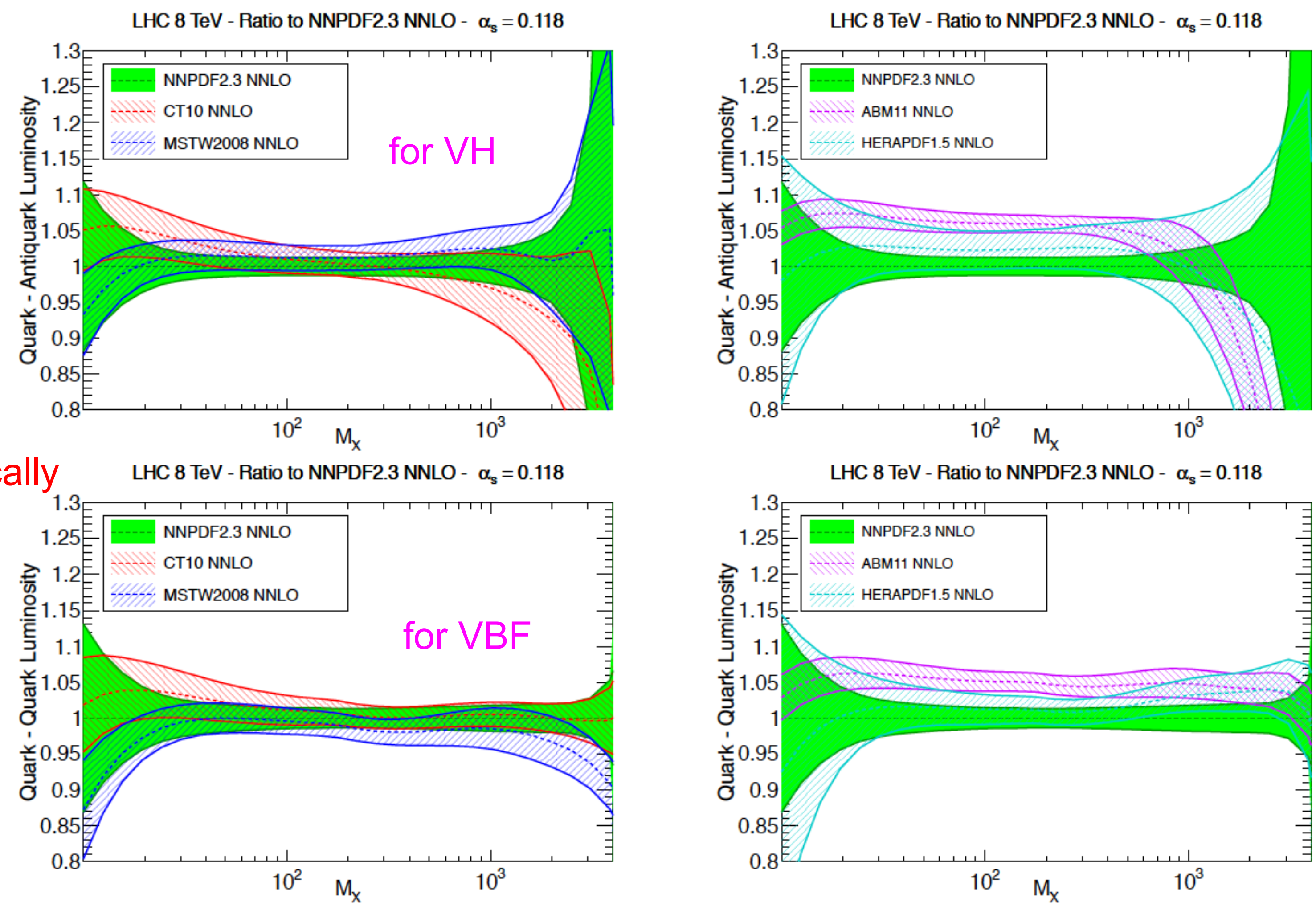
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5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

PDF luminosities

quark-quark and quark-antiquark

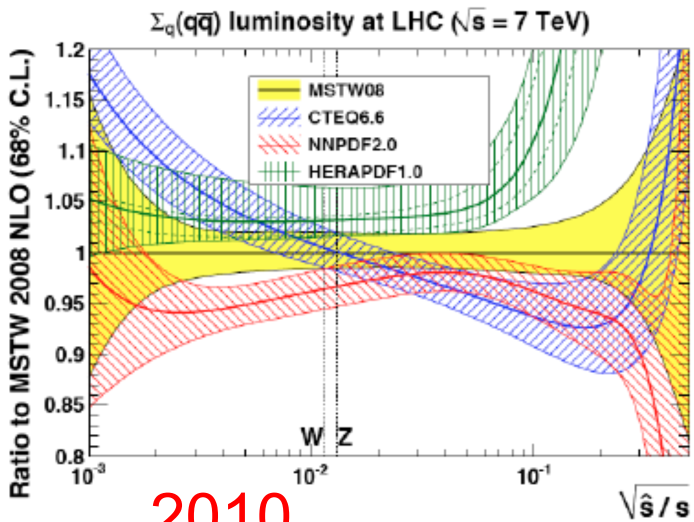
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range

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

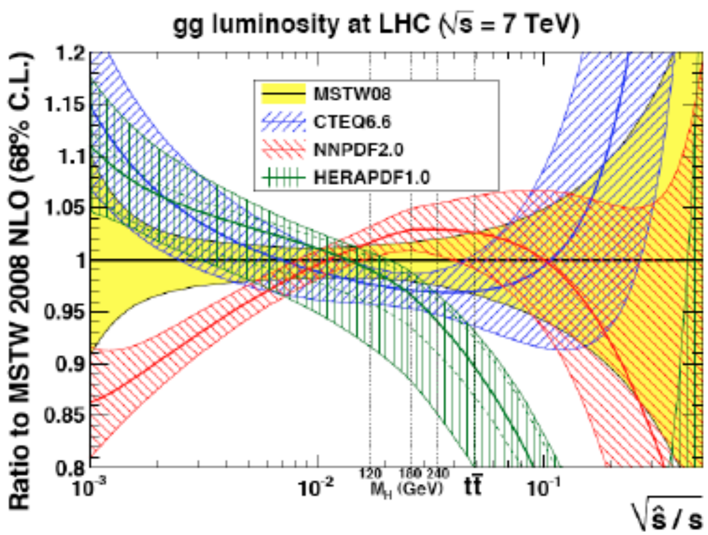


Uncertainties have improved

- …with additional data and in going from NLO to NNLO (and other theory improvements)

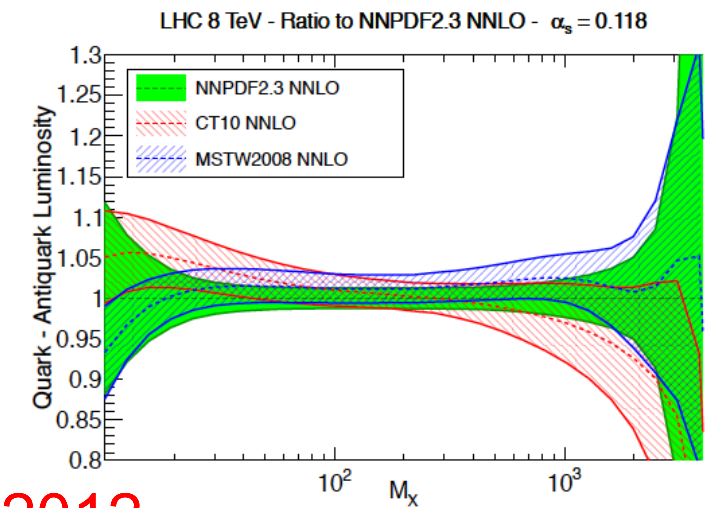


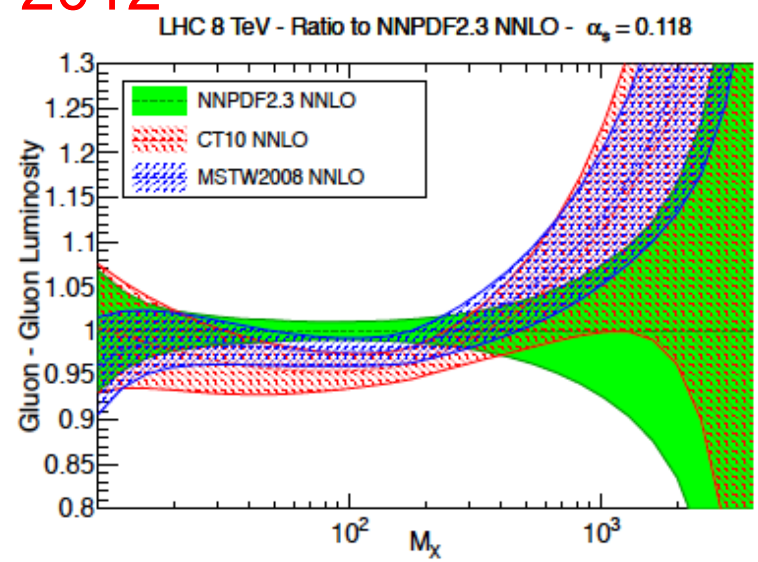
2010



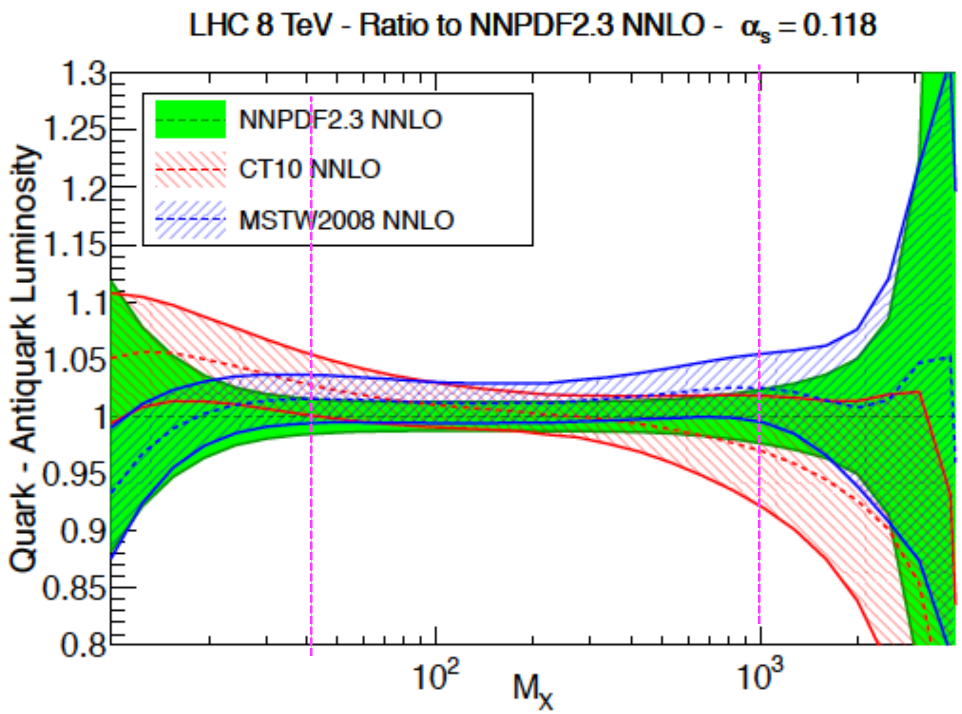
→

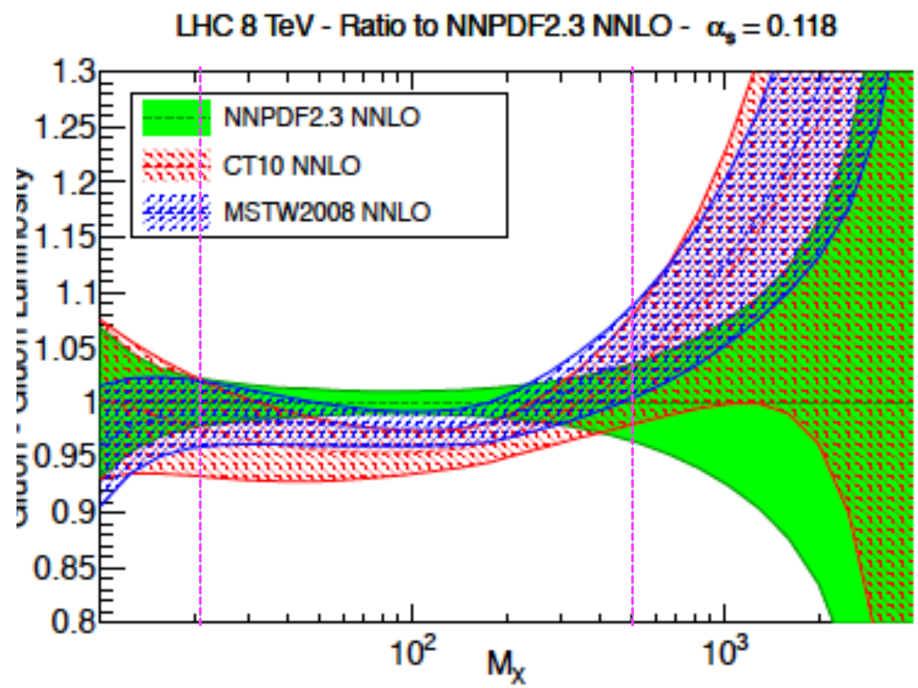
2012





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

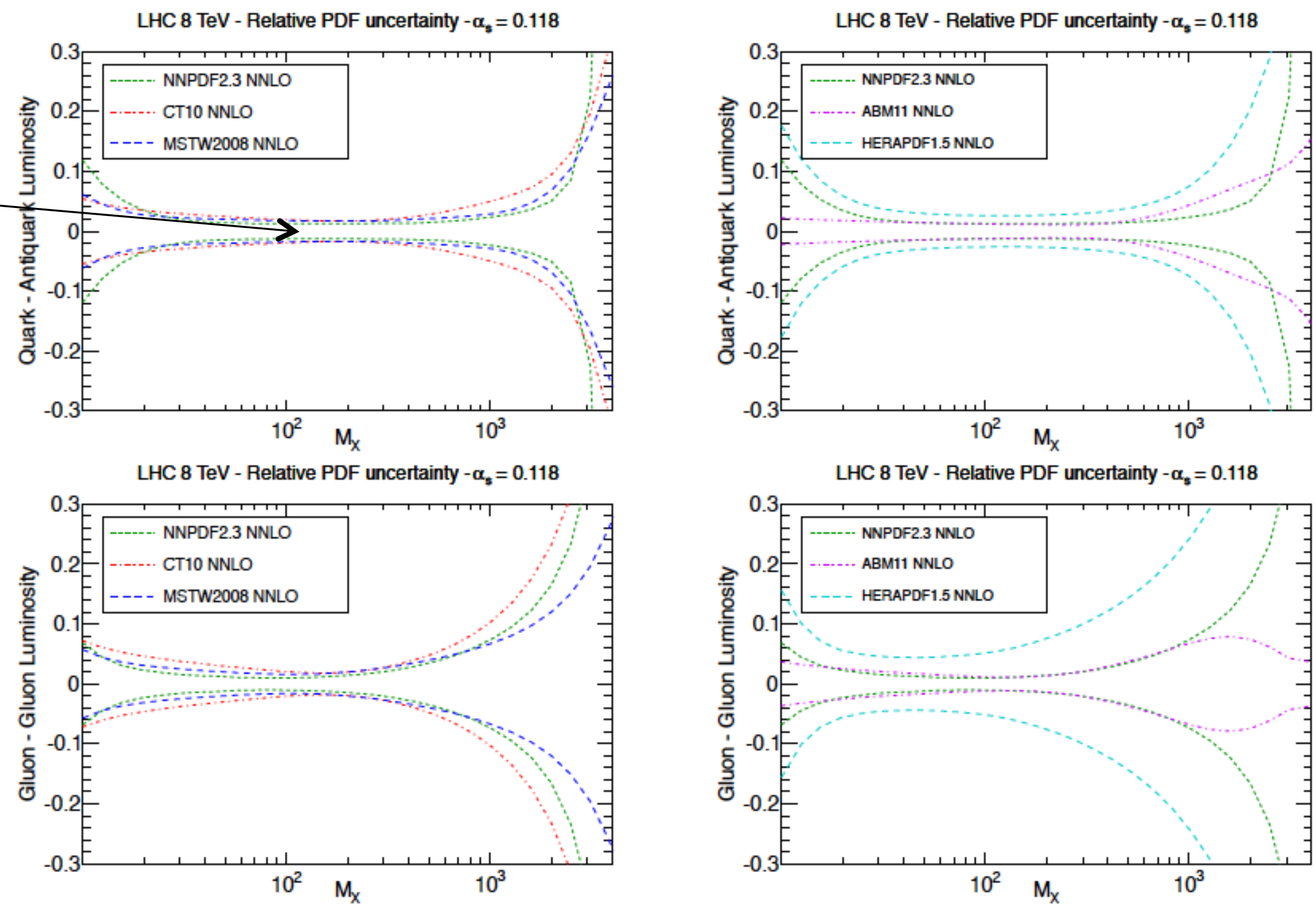
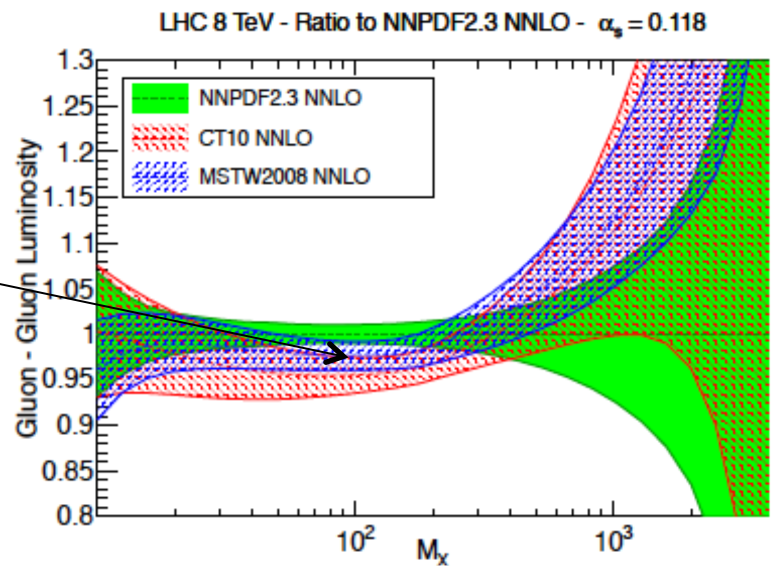
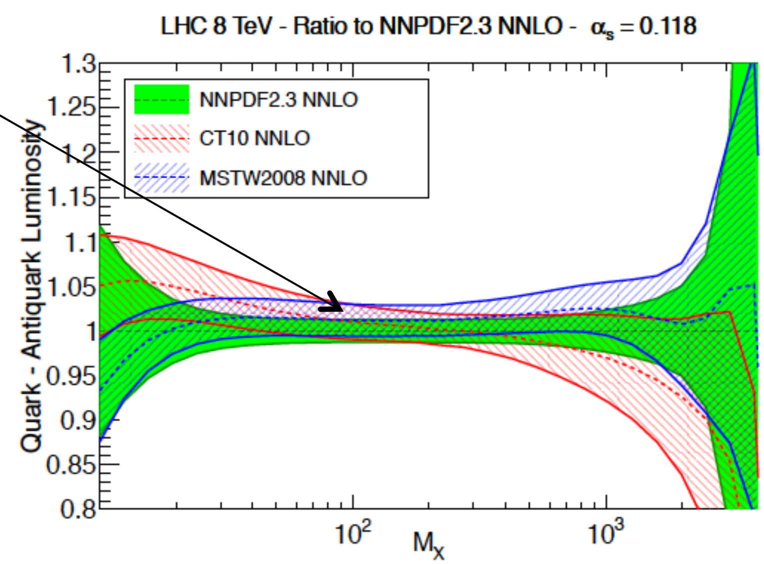


Figure 8: The relative PDF uncertainties in the quark-antiquark luminosity (upper plots) and in the gluon-gluon luminosity (lower plots), for the production of a final state of invariant mass M_X (in GeV) at the LHC 8 TeV. All luminosities are computed at a common value of $\alpha_s = 0.118$.

NNLO PDF uncertainties

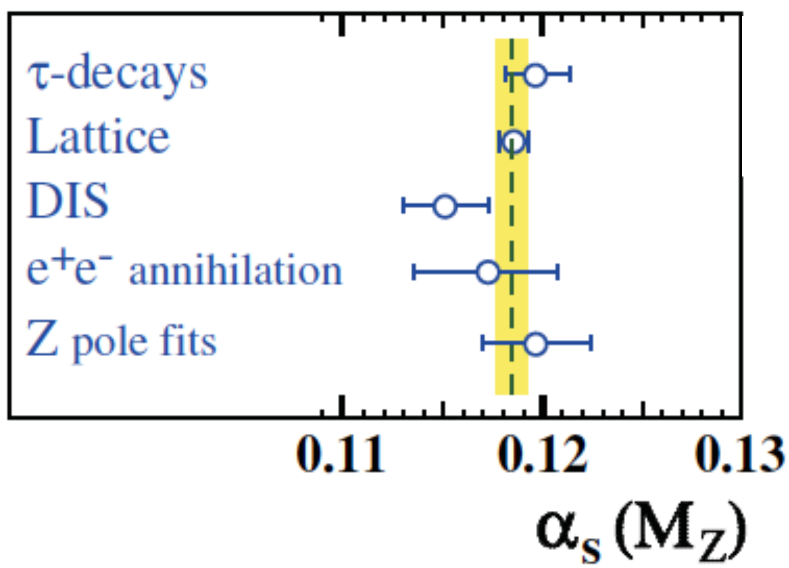
- Factor of 2 expansion of MSTW2008 error (previous prescription) basically works for gg initial states (like 125 Higgs)
- …but maybe an overestimate for qQ initial states, where there has been a nice convergence





$\alpha_s(m_Z)$

- 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

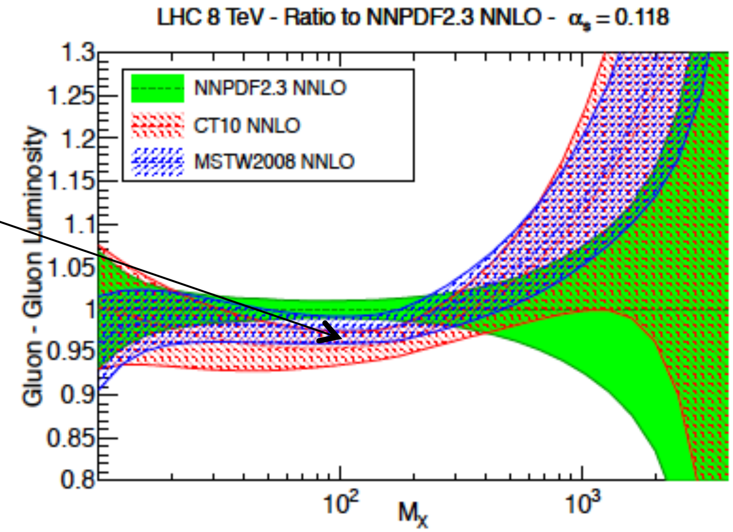
Figure 1-1. *Summary of values of $\alpha_s(M_Z^2)$ obtained for various sub-classes of measurements. The world average value of $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ is indicated by the dashed line and the shaded band. Figure taken from [1].*

Update of recommendation

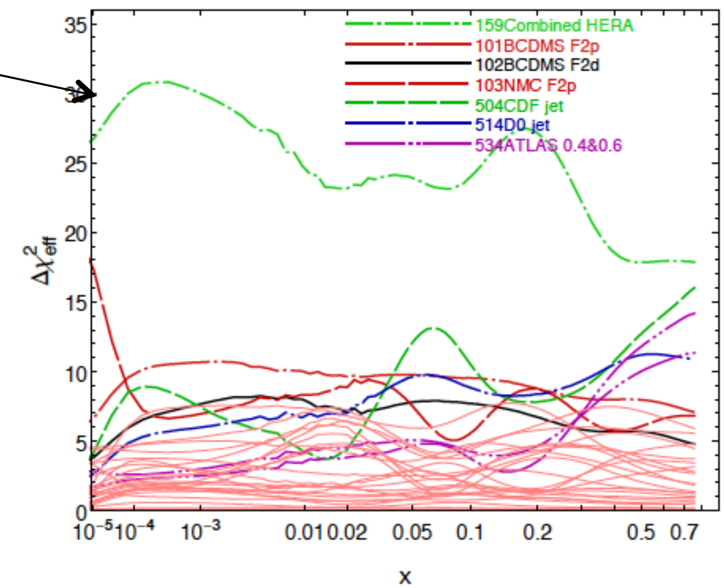
- Use updated versions of PDFs present in the old recommendations
  - CTEQ6.6->CT10
  - MSTW08->MSTW08
  - NNPDF2.1->NNPDF2.3
- Use central value of $\alpha_s(m_Z)$=0.118 for each set
- PDF uncertainty (at NLO and NNLO) given by envelope of these three sets
- α_s error given by variation of +/-0.0012 around central value of 0.118
- Add PDF + α_s errors in quadrature

…but are the uncertainties good enough (for Higgs physics)?

- 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



Unsigned $\Delta\chi^2_{eff}$ to the constraints of g(x,Q=85. GeV)

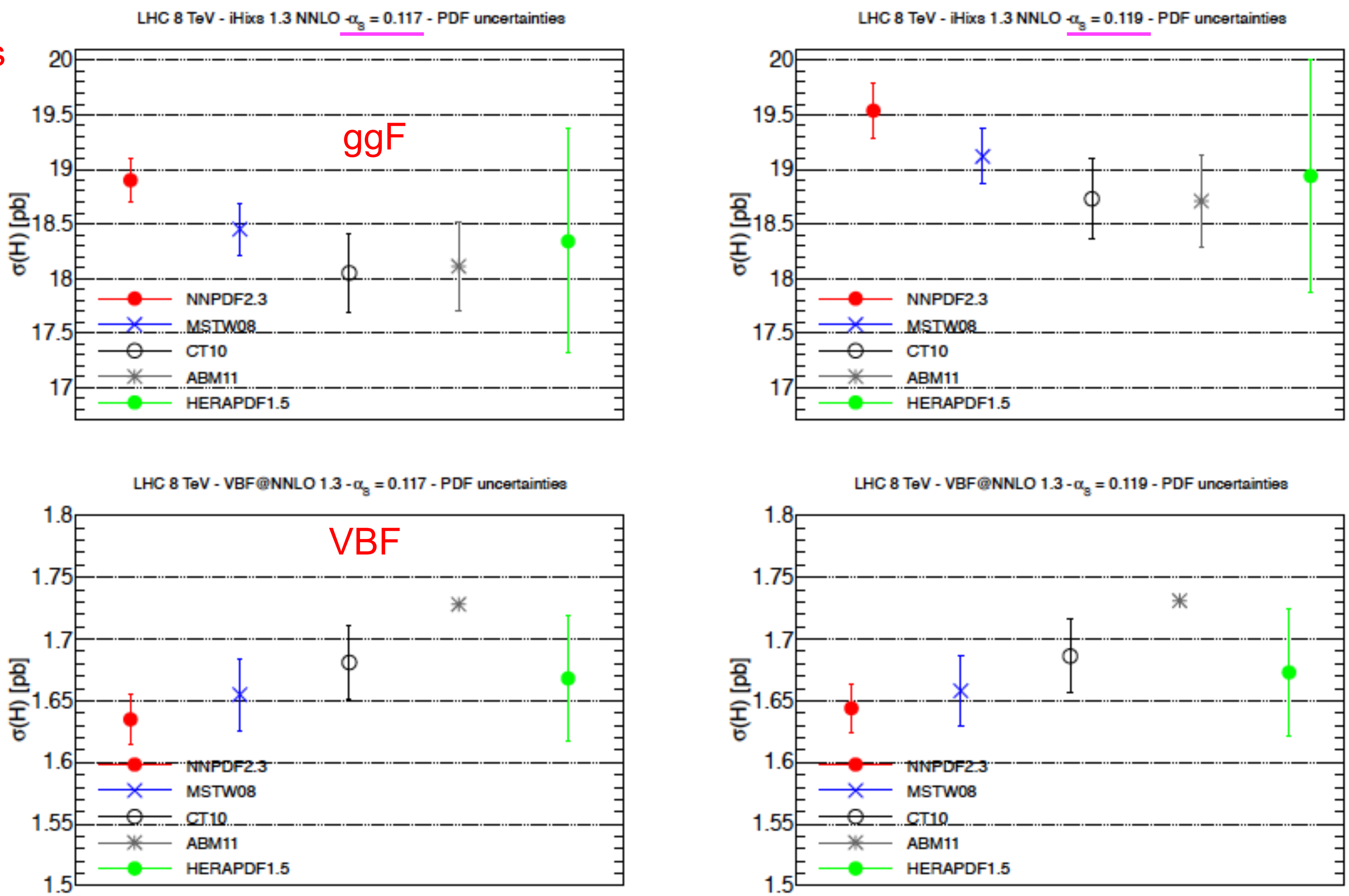


8 TeV Higgs cross section predictions

cross sections calculated at NNLO using a scale of m_H

ABM11 and HERAPDF1.5 predictions within error envelope

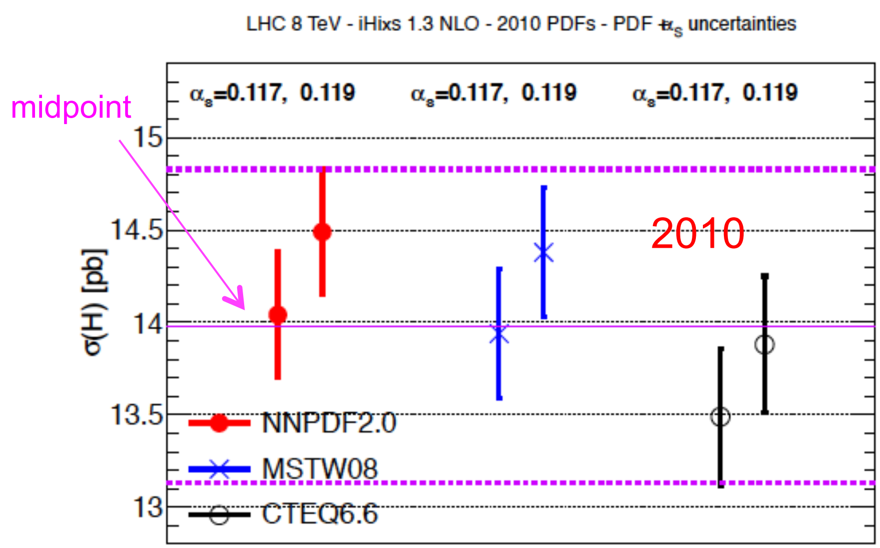
NB: ABM11 cross section would be lower if native value of α_s (0.1134) used

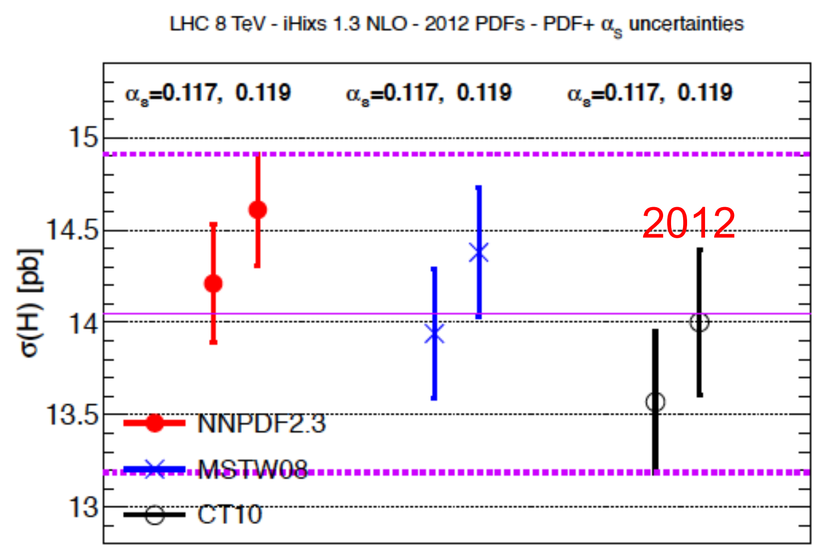


Revisit prescriptions (for 8 TeV cross sections for gg fusion)

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

NEW



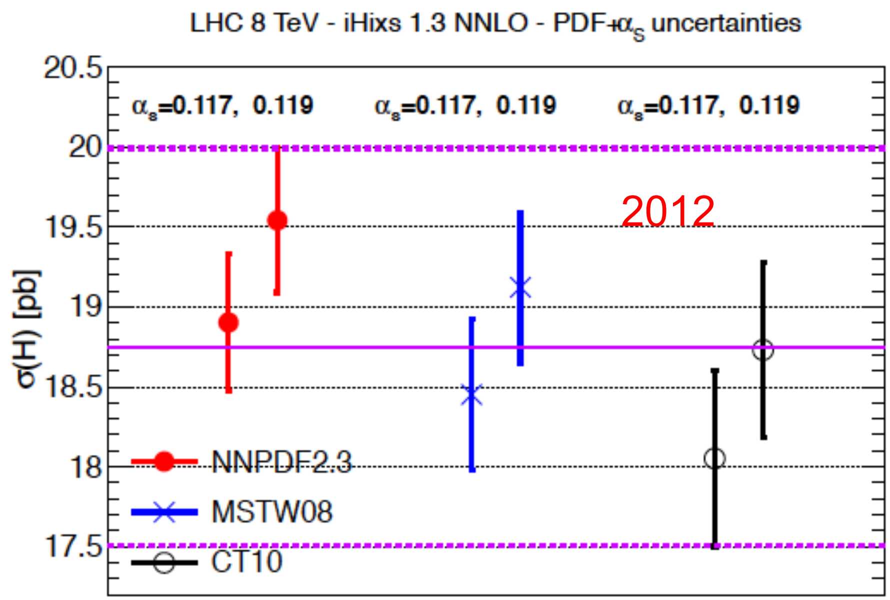


Revisit prescriptions (for 8 TeV cross sections for gg fusion)

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)



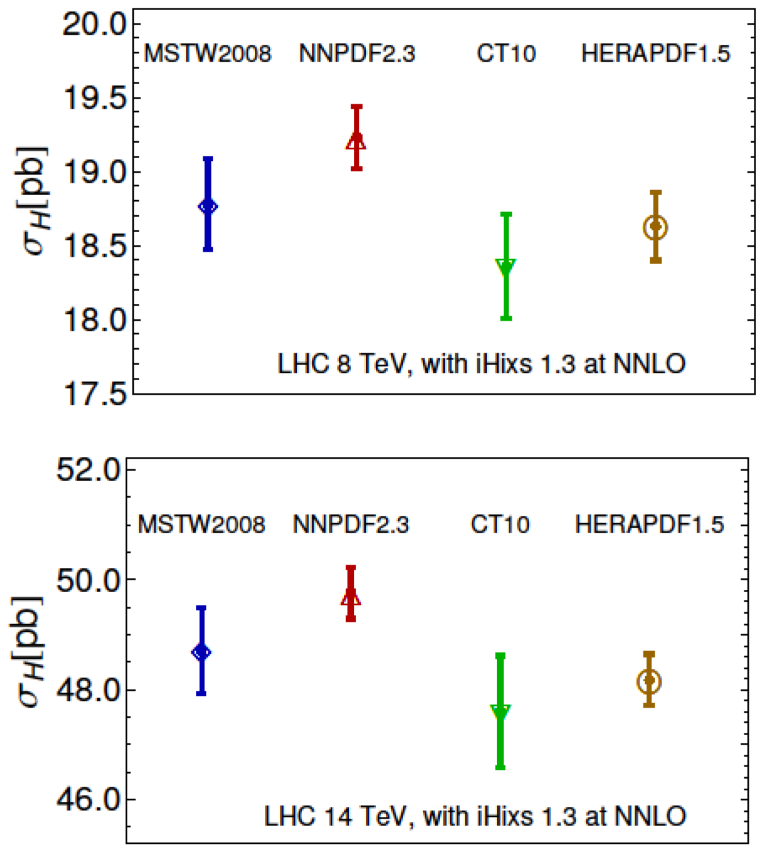
HXSWG 8 TeV NNLO cross section

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

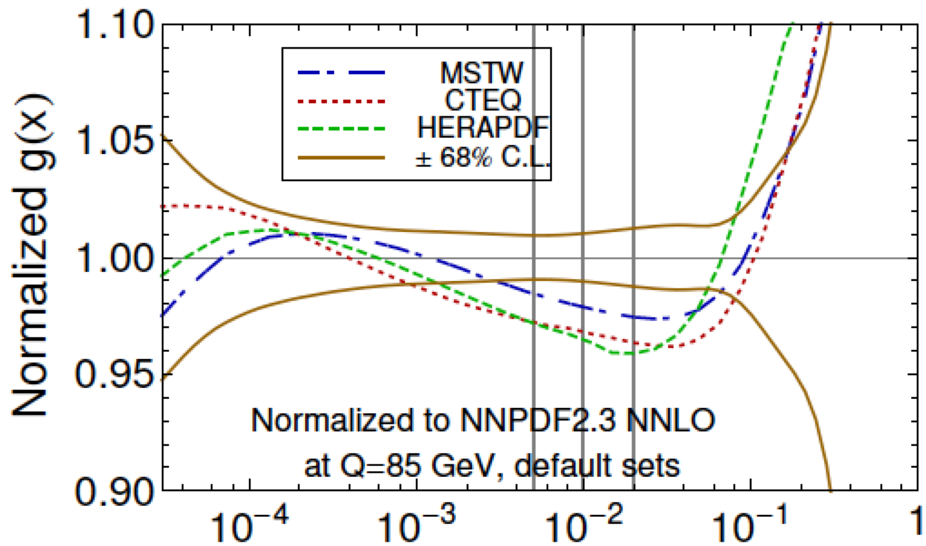
- The study used the PDFs that use a variable flavor number scheme, i.e. the 4 shown on the curves to the right
- The discrepancies present at 8 TeV persist at 14 TeV with the same pattern

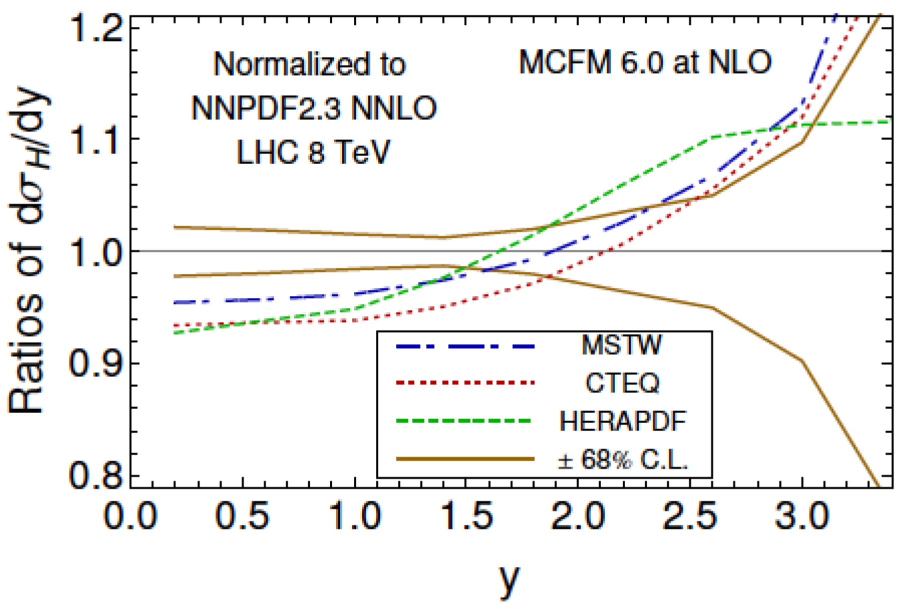


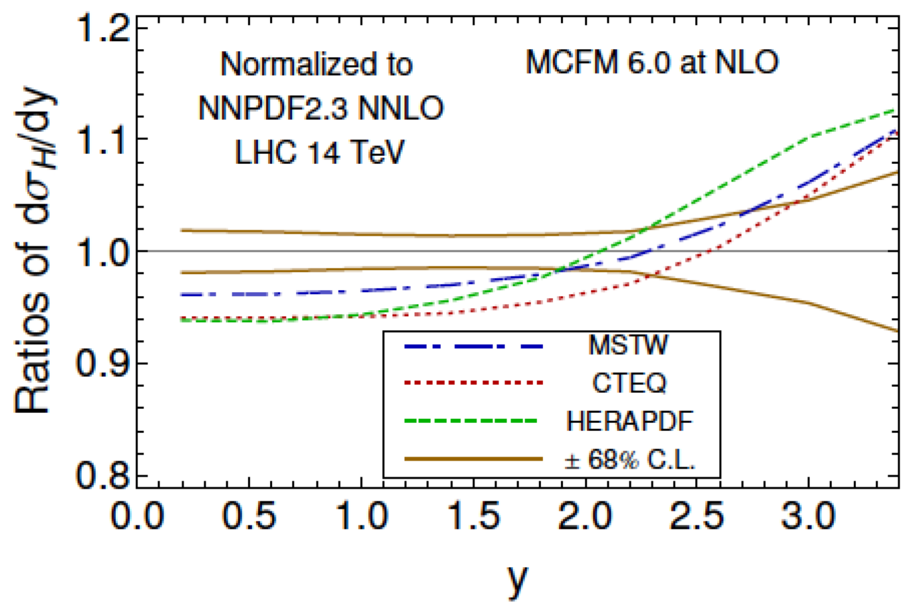
σ_H [pb]	CT10	MSTW'08	NNPDF2.3	HERAPDF 1.5
LHC 8 TeV	18.36±0.35	18.78±0.31	19.23±0.21	18.63±0.23
LHC 14 TeV	47.60±1.02	48.71±0.77	49.76±0.47	48.18±0.47

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

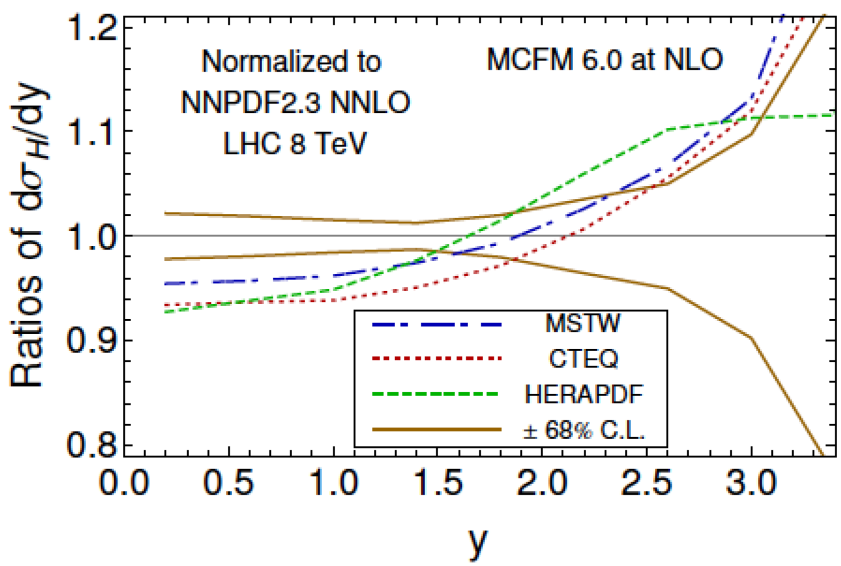


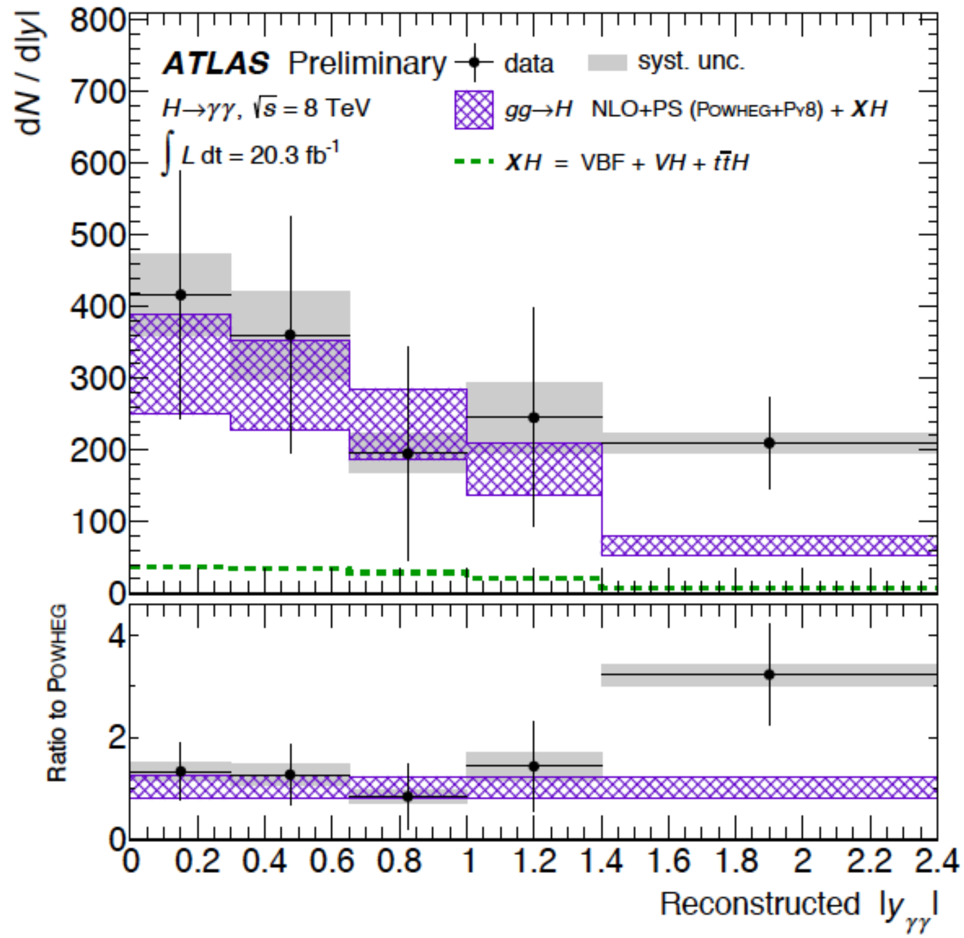




Gluon distributions and Higgs y

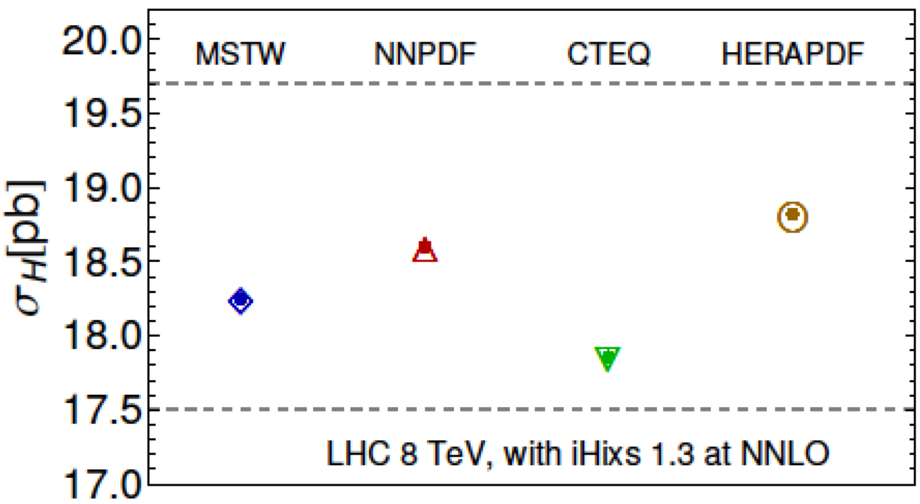
- These shape differences translate into different predictions for Higgs rapidity
- So the best cross section to use for the PDF determination is the Higgs rapidity distribution
- Alas, we're not quite there for using the Higgs rapidity distribution to tune PDFs

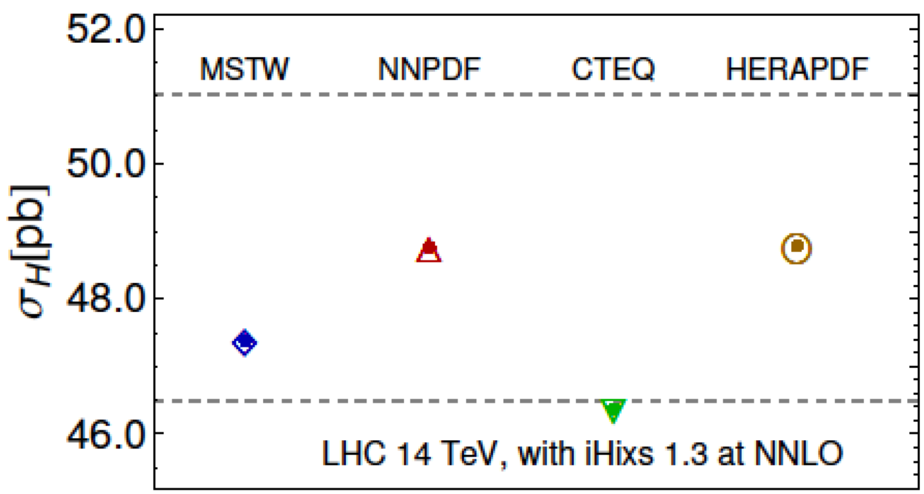




Results of fits to HERA1 only

- 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?

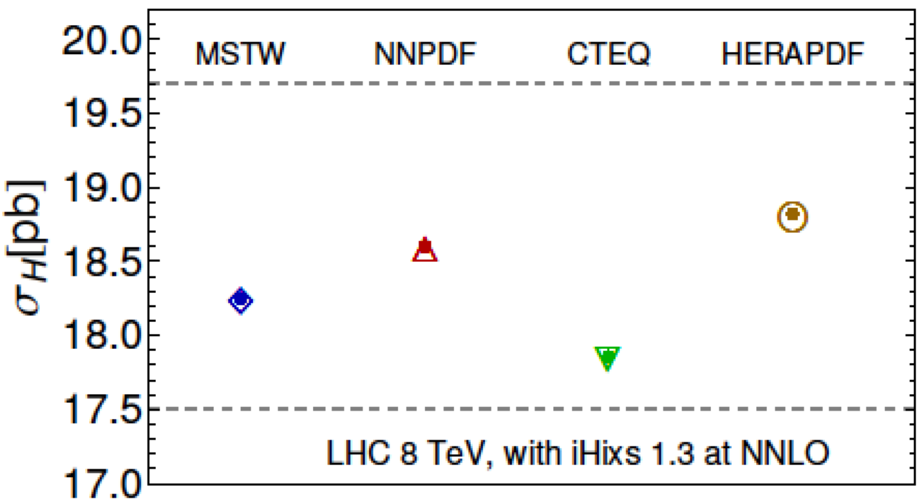


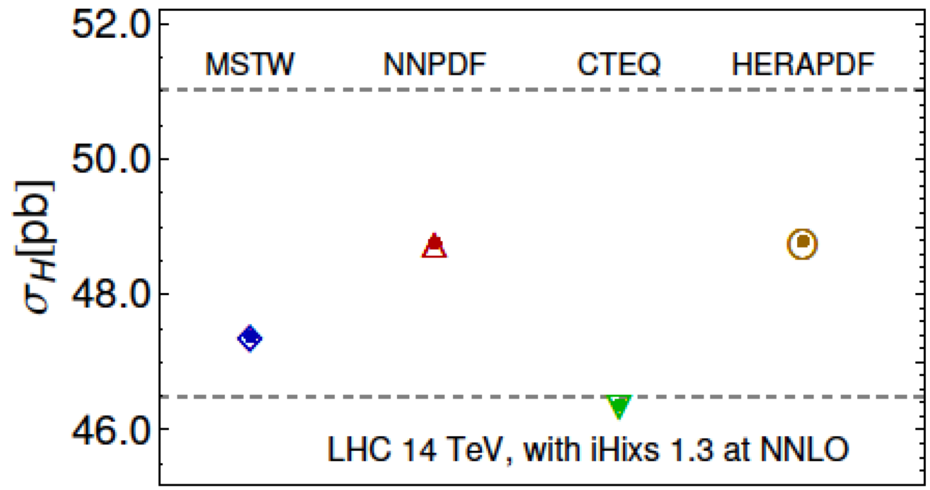


Results of fits to HERA1 only

- 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

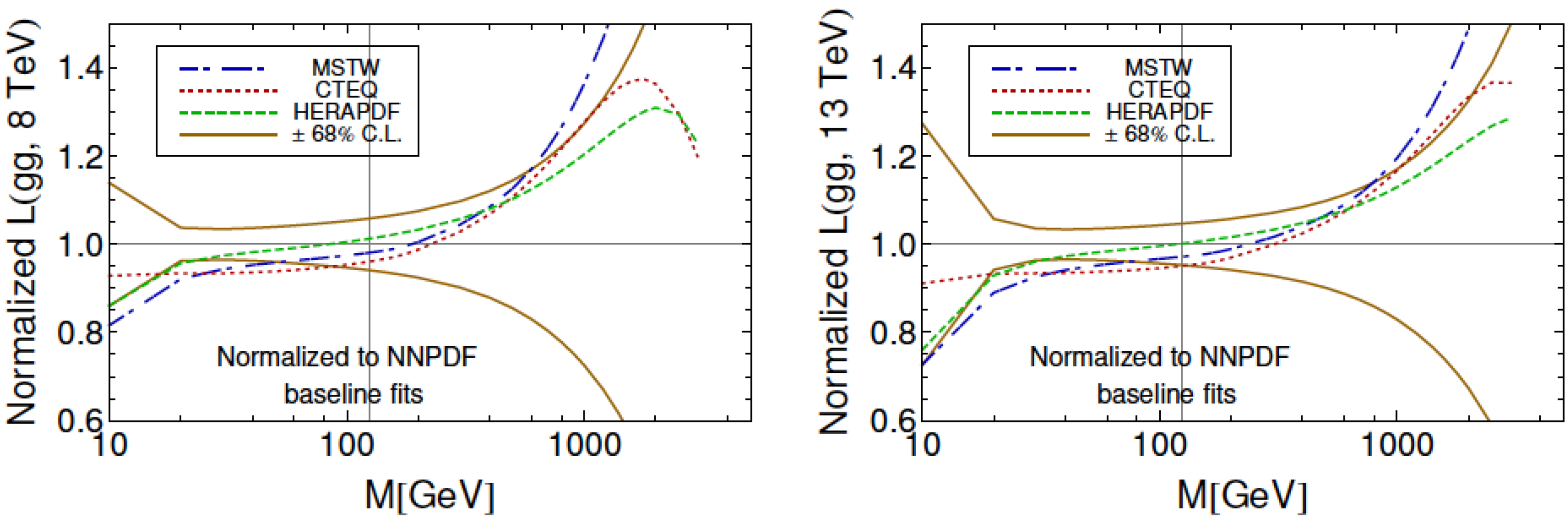


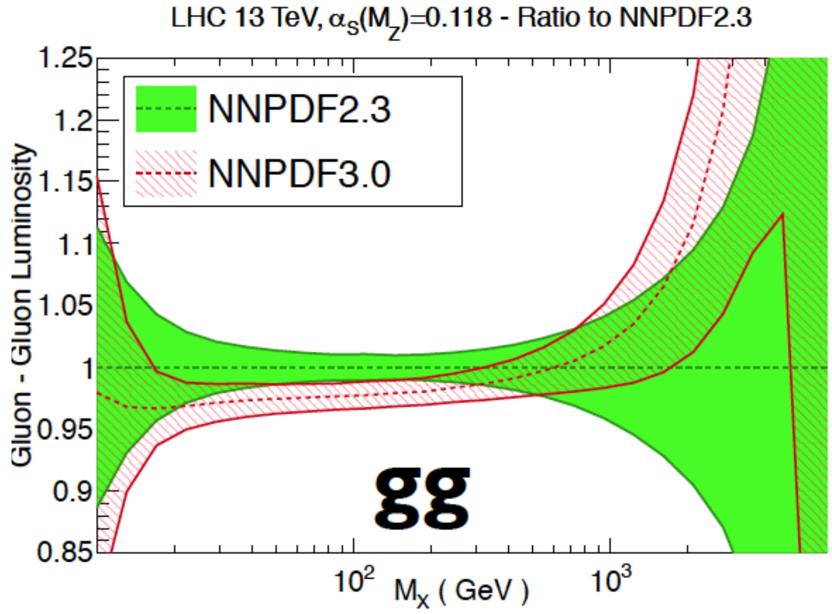
Fig. IV.14: Comparison of the gluon-gluon parton luminosity as a function of invariant mass at the LHC 8 and 13 TeV from the HERA-1-only NNLO fits, normalized to the NNPDF central prediction. The

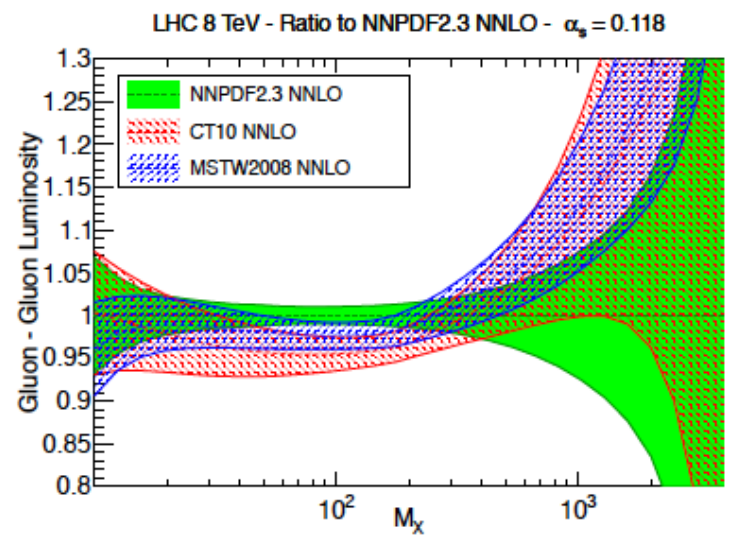
Summary (of study)

- 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
  - it looks like the newer sets will be available before we understand the differences in the older PDF sets
  - …and from what I've seen the gg PDF luminosity for NNPDF will come down
- Compare the impact of LHC data sensitive to the gluon PDF

…but

- There are some preliminary results from NNPDF3.0, which indicate that their gg PDF luminosity may decrease in the Higgs mass range
- So the agreement will be better

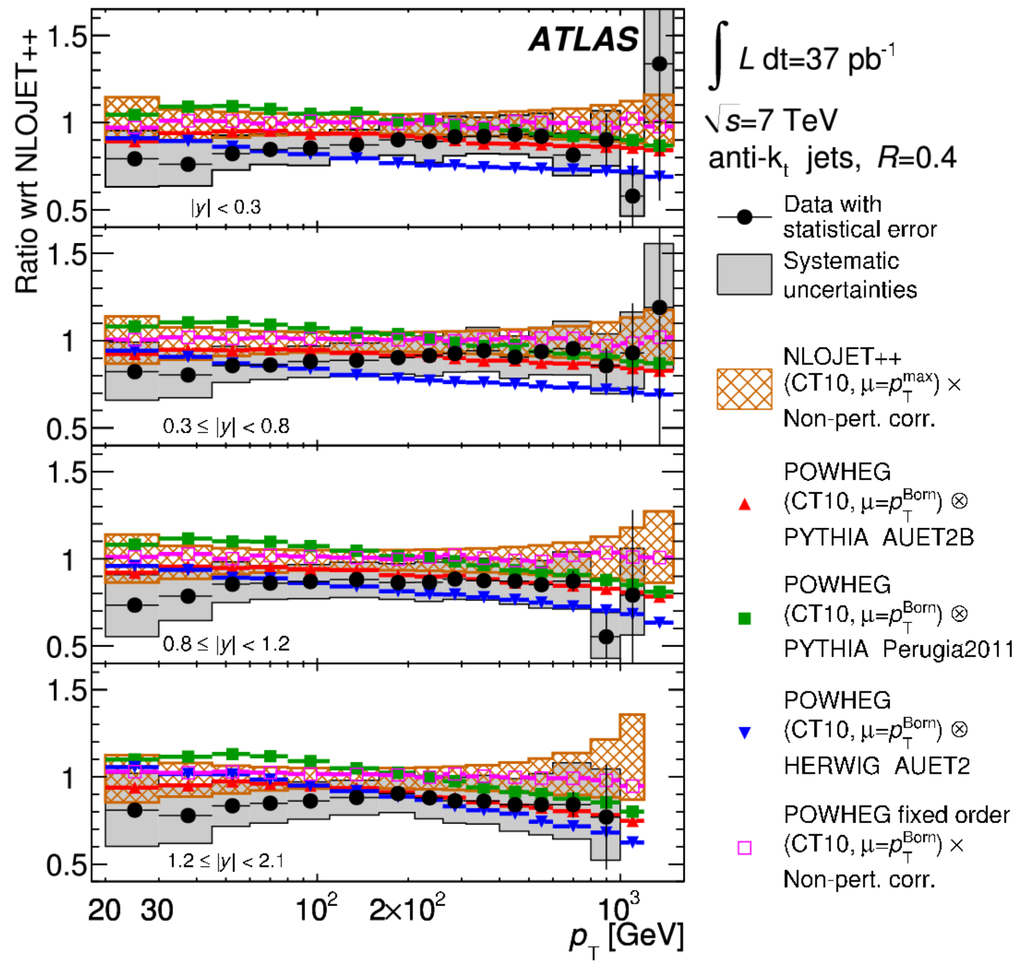




LHC data in global PDF fits

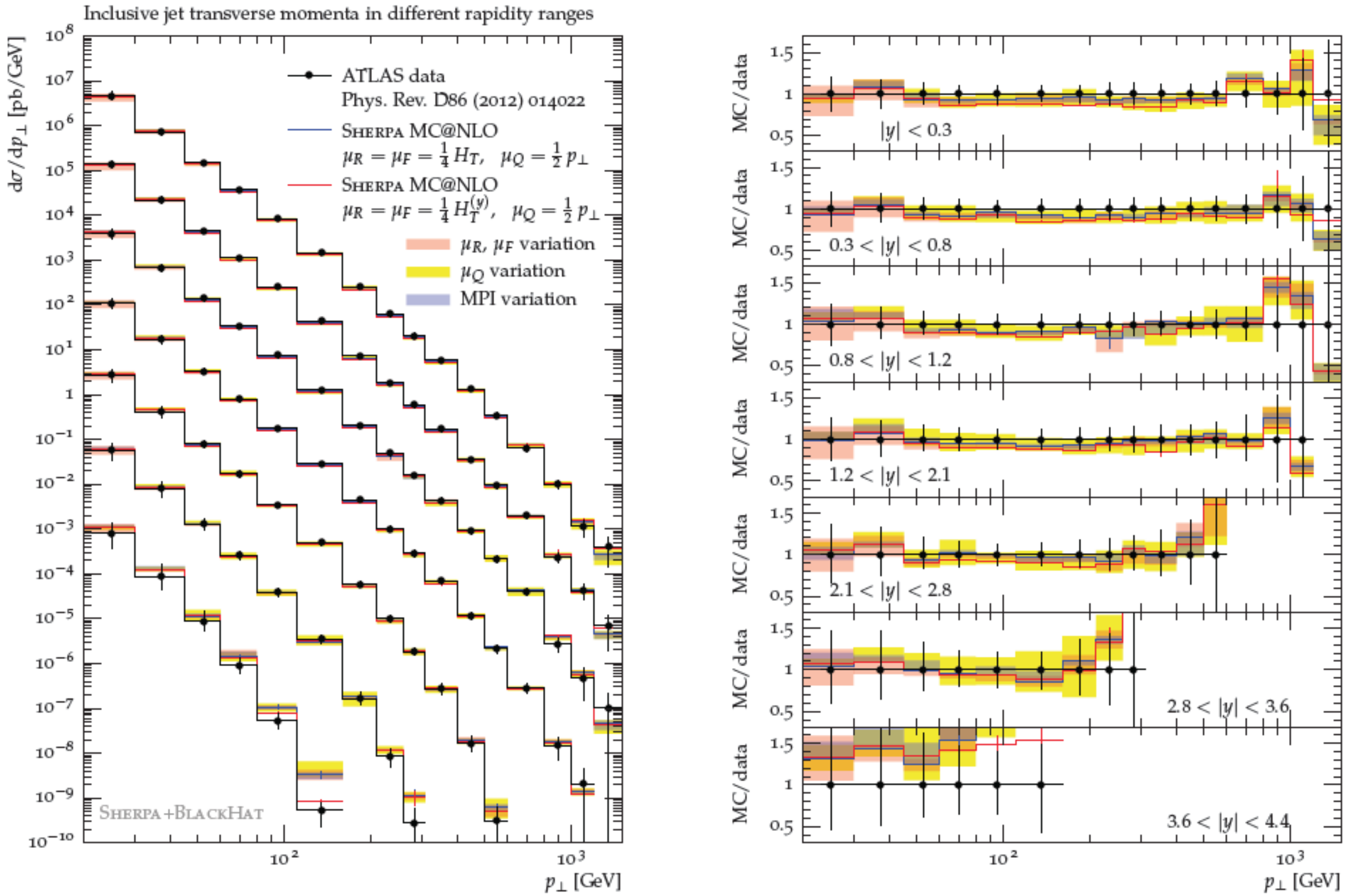
- LHC data will become increasingly important in global fits
- Not just inclusive jet data but for processes such as inclusive photon production, Drell-Yan, W/Z rapidity, ttbar mass and rapidity
- For any process to be used in a global PDF fit, correlated systematic errors must be provided
- 2010 inclusive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



Sherpa at NLO

- With Sherpa NLO, the modifications to fixed-order predictions seem to be in regions where you would expect soft gluon radiation to matter

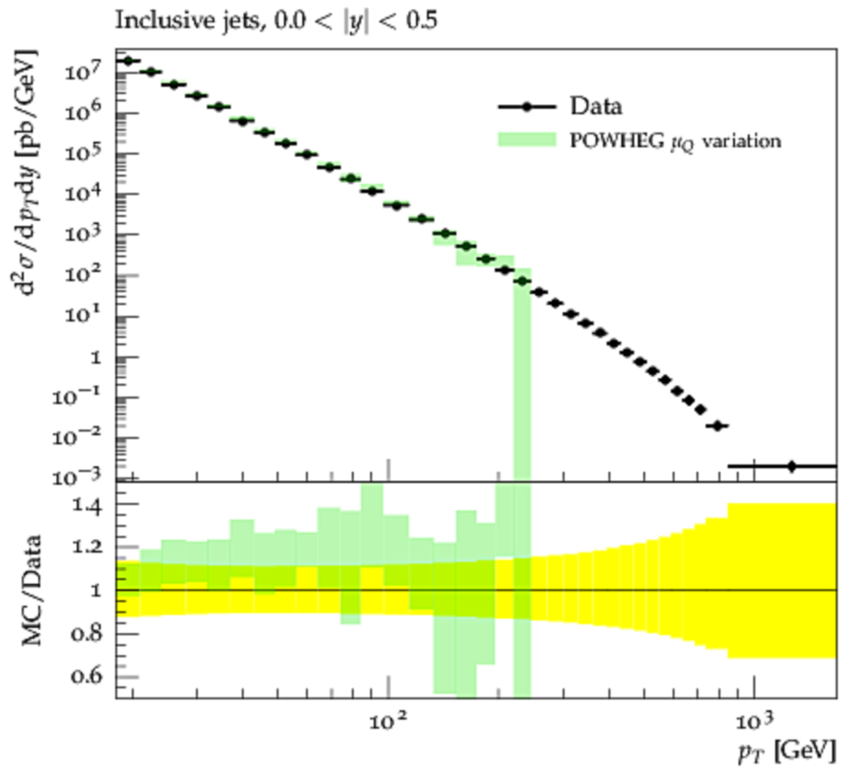


Powheg

- Maybe issue is with the scale at which the parton shower is started
- The green band to the right is the envelope of three Powheg-pT interpretations, i.e. three ways of defining the value pThard against which the pT of the emission is checked in order to decide on an emission veto:
  - 0 - pThard = SCALUP (of the LHA/LHEF standard)
  - 1 - the pT of the POWHEG emission is tested against all other incoming and outgoing partons, with the minimal value chosen
  - 2 - the pT of all final-state partons is tested against all other incoming and outgoing partons, with the minimal value chosen

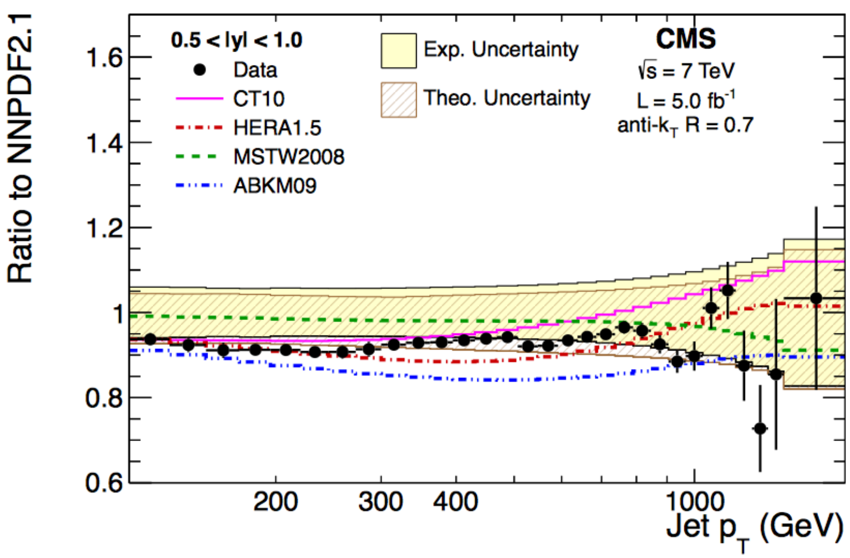
default

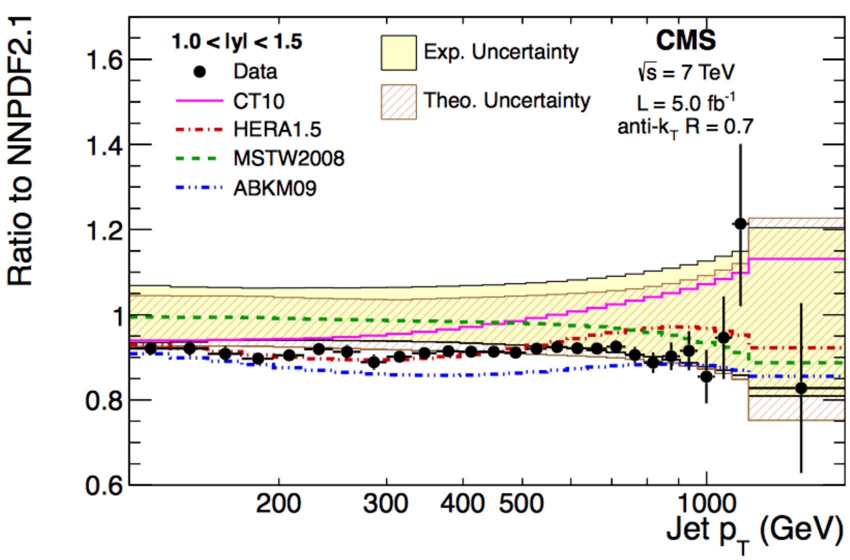
Stefan Prestel

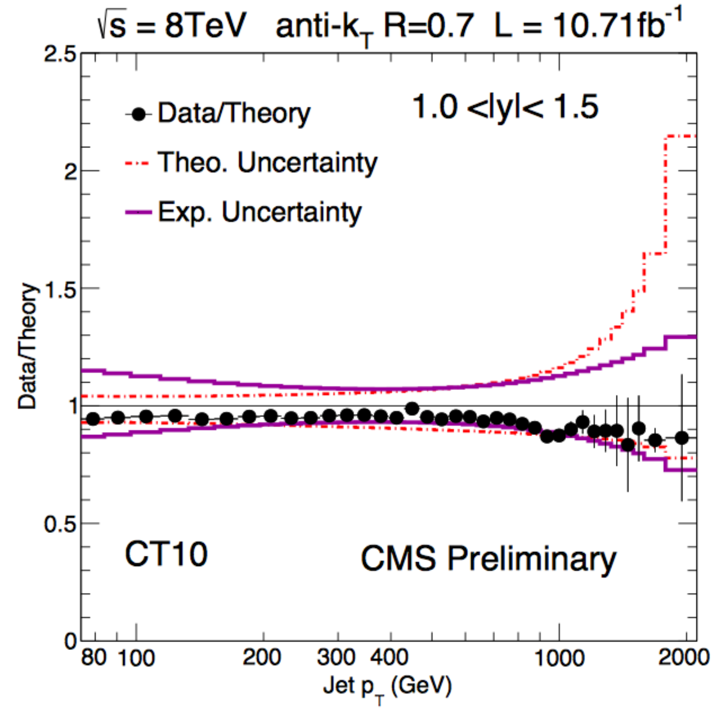


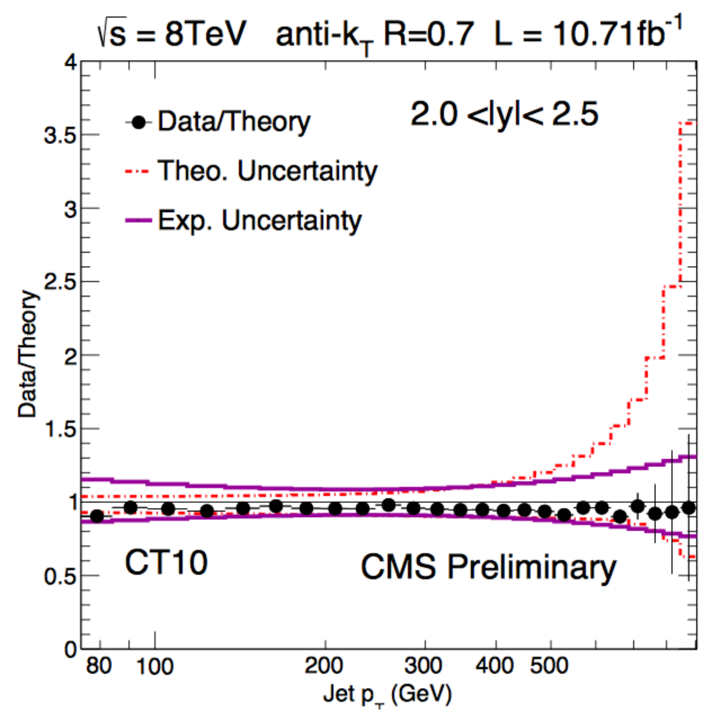
see arXiv:1303.3922, + use a vetoed shower

Compare CMS 7 to 8 TeV data









NNLO QCD + NLO EWK wishlist

- One of key processes for perturbative QCD
  - covers largest kinematic range with jets produced in the multi-TeV range
  - EW effects very important in this range
- Only process currently included in global fits not known at NNLO
  - gg channel has been calculated
- Current experimental precision on the order of 5-10% for jets from 200 GeV/c to 1 TeV/c
- Would like better precision for theory
  - so need NNLO QCD and NLO EW
- <u>We also need a better understanding of the impact of parton showers on the fixed order cross section</u>

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

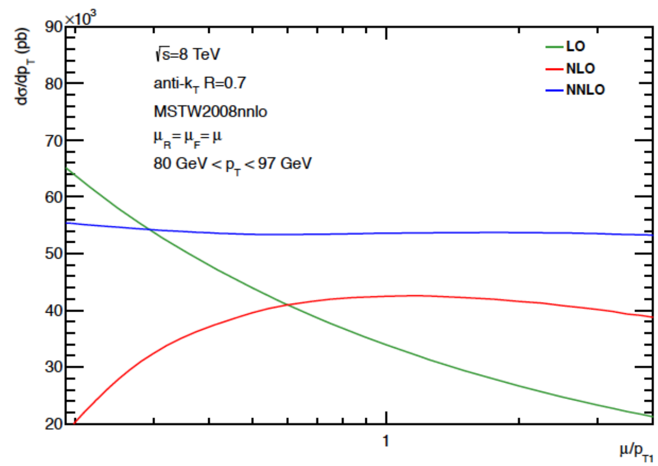


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

…but, arXiv:1407.7031

- NNLO/NLO corrections smaller (on the order of 5%) and flat as a function of jet p_T if scale of inclusive jet pT is used rather than p_T of the lead jet
- …which is what should be used in any case
- expect corrections for other subprocesses to be of similar order

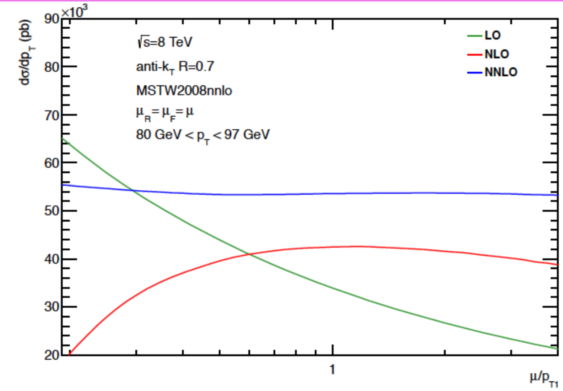


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

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

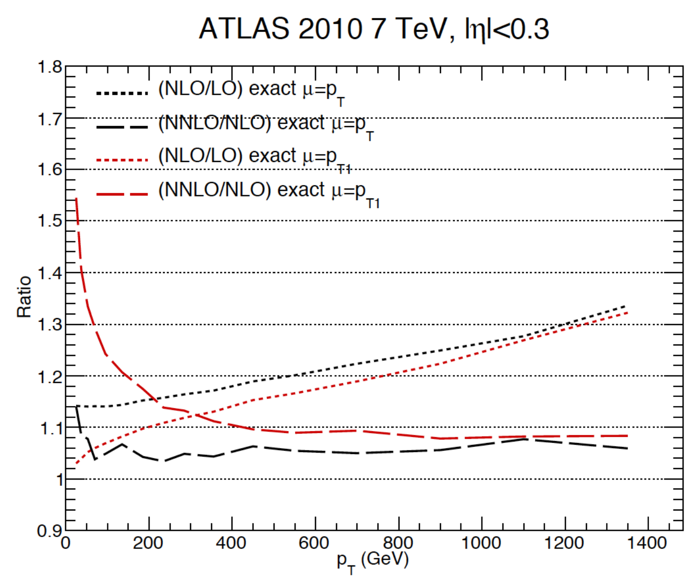
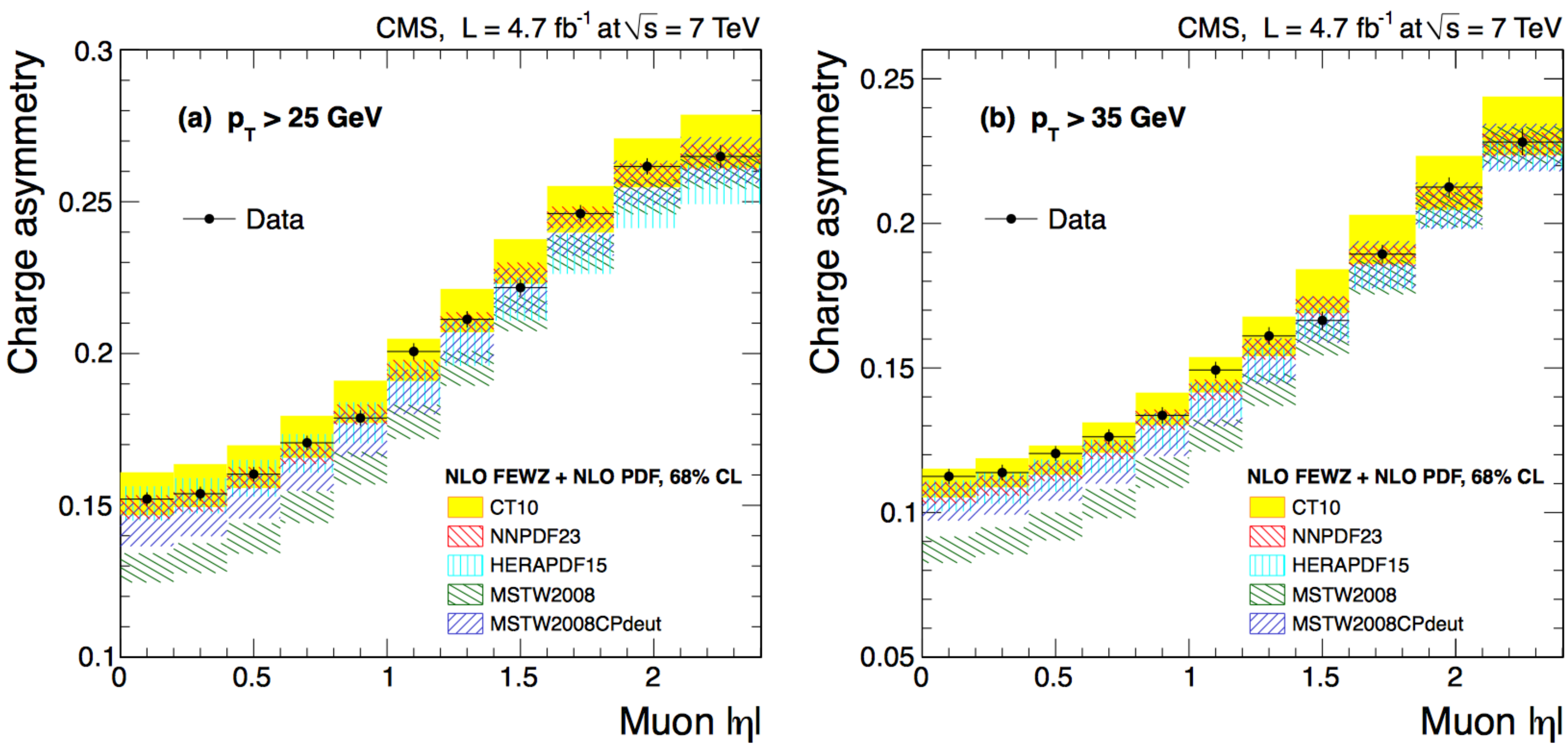


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

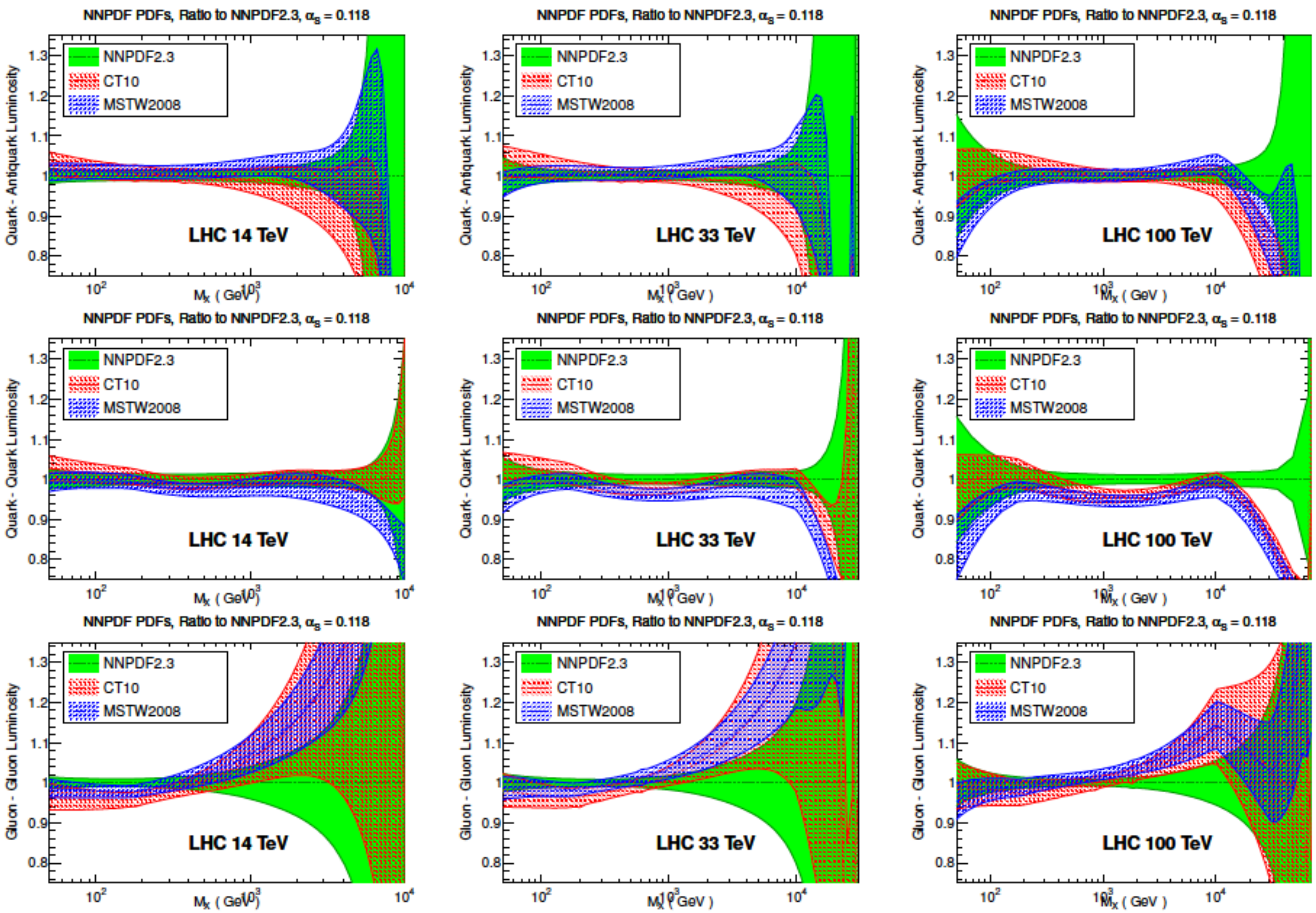
One example of a dataset that will be constraining

…because this is a ratio, where the systematic errors are very small, and because it covers a relatively wide kinematic range



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

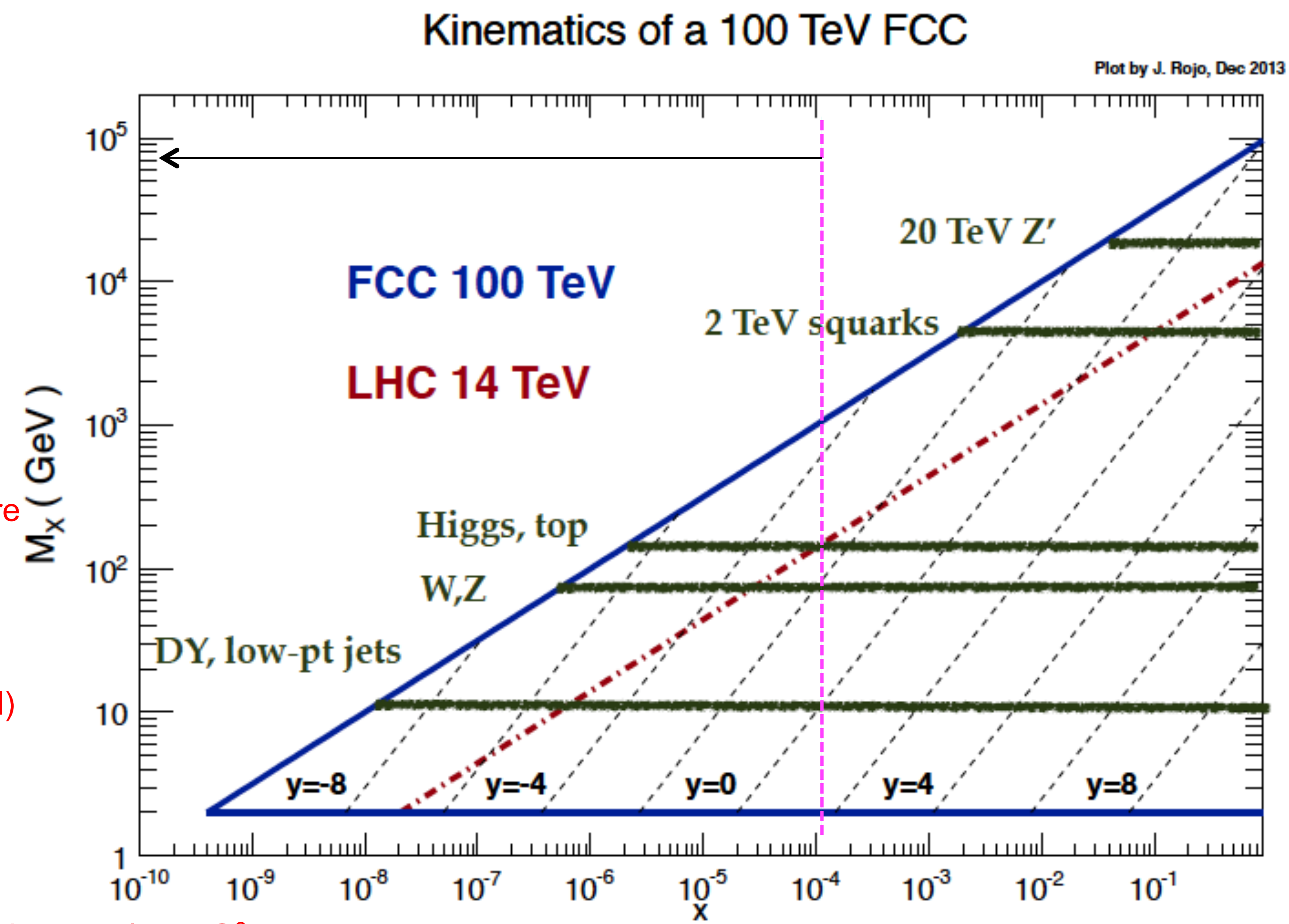
will access smaller x, larger Q^2

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

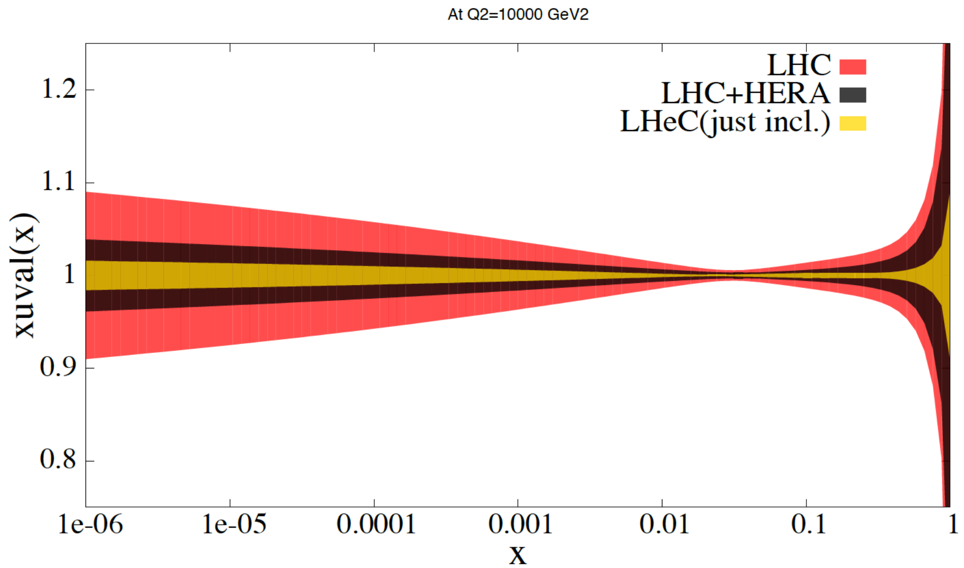
poor constaints (still) as well for high x PDFs

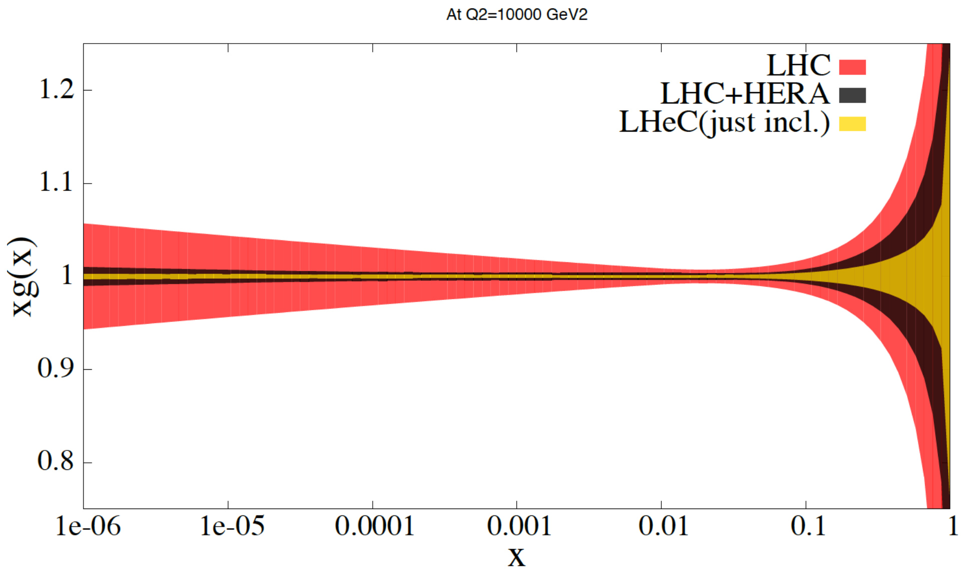
at high masses (Q^2), rely on DLAP evolution; we know at large Q^2, EW effects also become important



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)





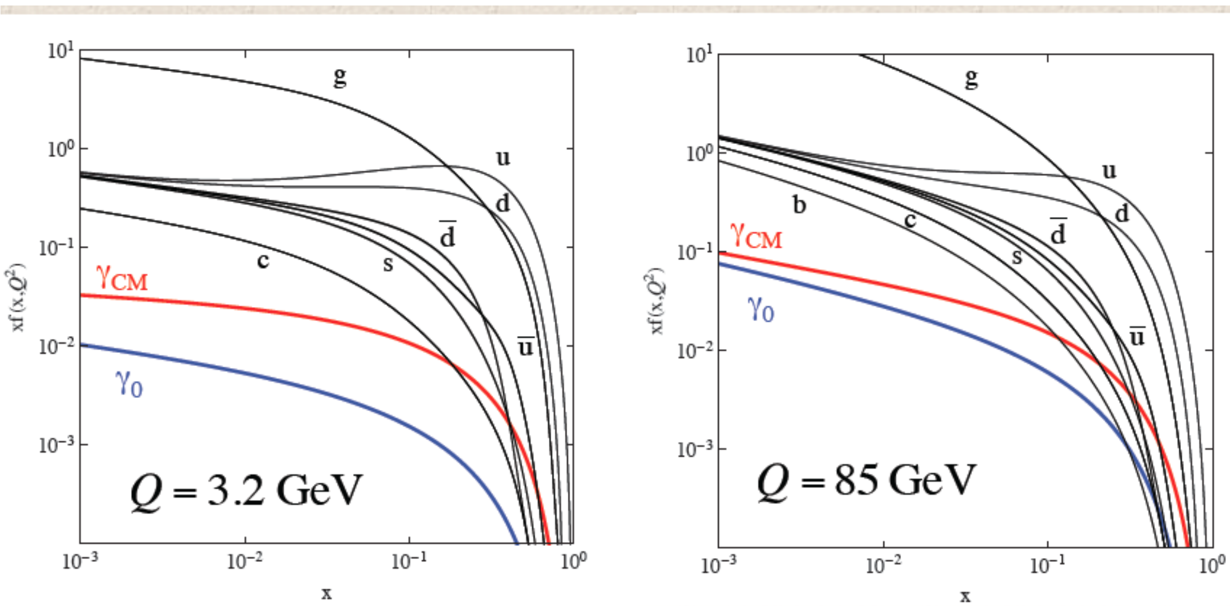
New PDF4LHC exercise

- 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, discussed at PDF4LHC meeting in May

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

Photon PDFs

- Photon PDFs: photon PDFs can be larger than antiquark distributions at high x; the LHC is a $\gamma\gamma$ 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



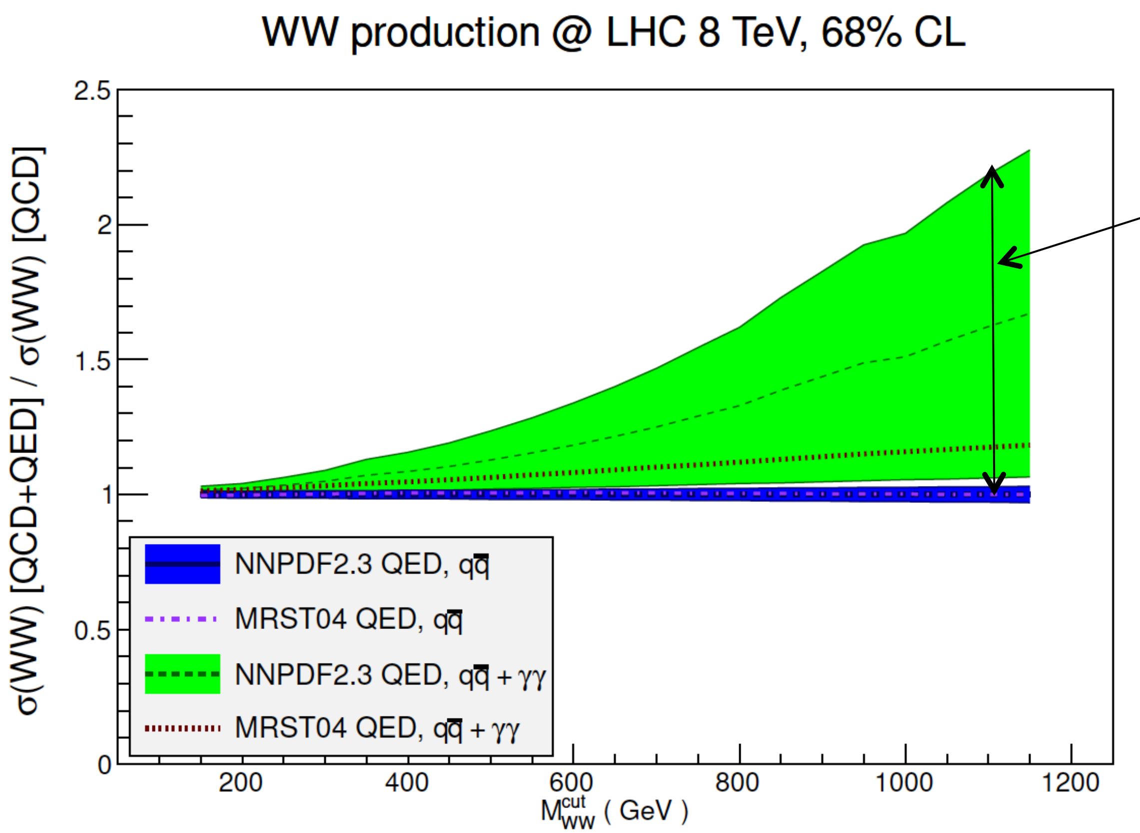
γ momentum fraction:

$p^{\gamma}(Q)$	$\gamma(x,Q_0)=0$	$\gamma(x,Q_0)_{CM}$
$Q = 3.2$ 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)

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

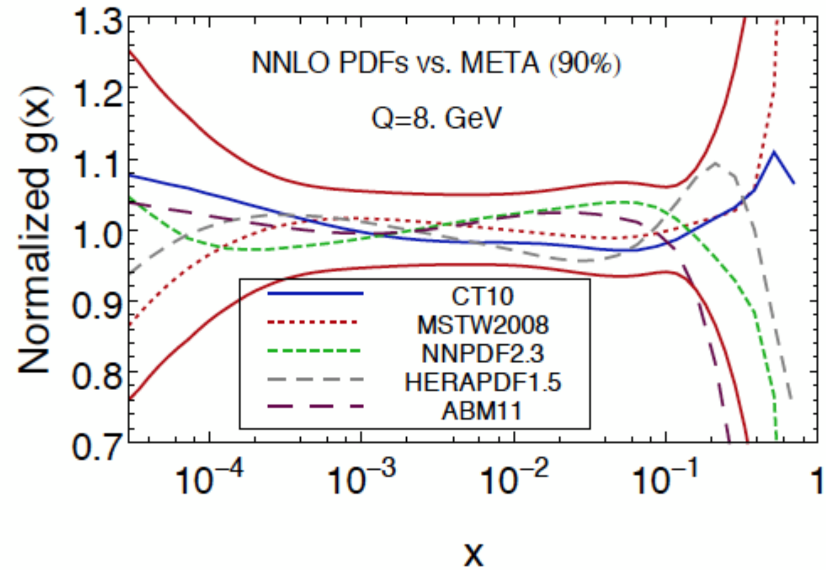
- Generate MC replicas for all 3 groups and merge with equal weights, finding meta parameters for each of the replicas by fitting PDFs in x ranges probed at LHC
- Construct 50 eigenvectors using Hessian method
- These 50 eigenvectors provide a very good representation of the PDF uncertainties for all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

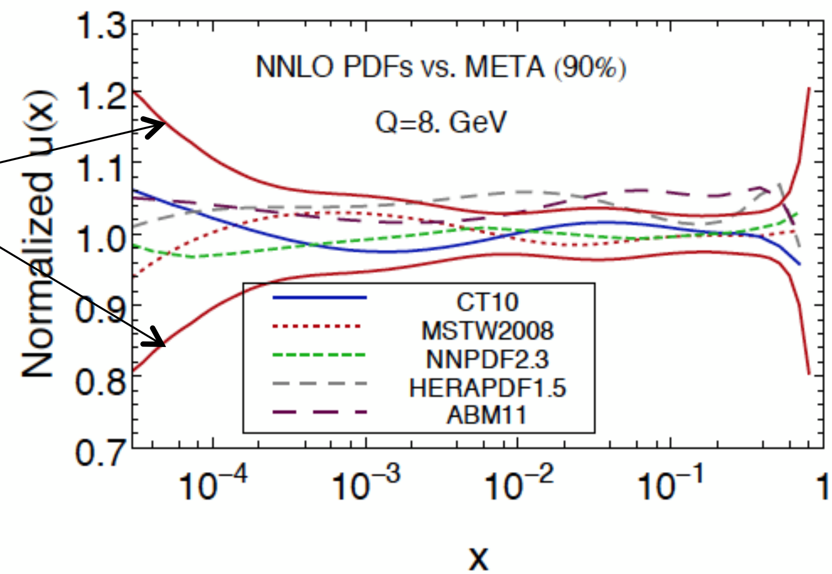
J. Gao, P. Nadolsky

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





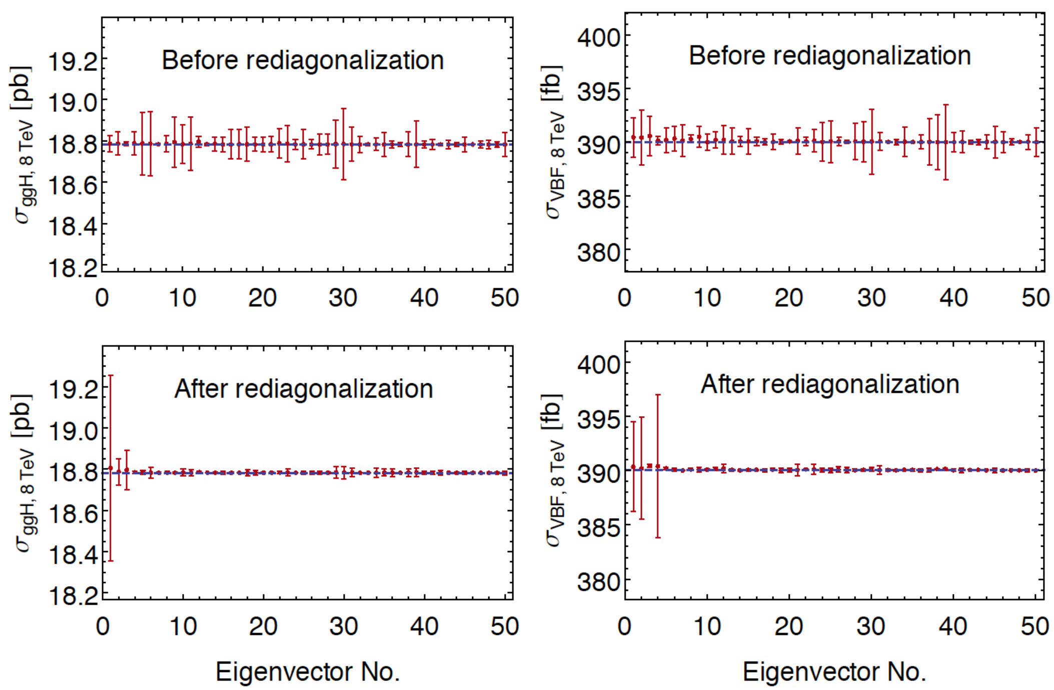
Higgs observables

- 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	$\sigma(inc.)$	$\sigma(\lvert y_H \rvert > 1)$	$\sigma(p_{T,H} > m_H)$	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

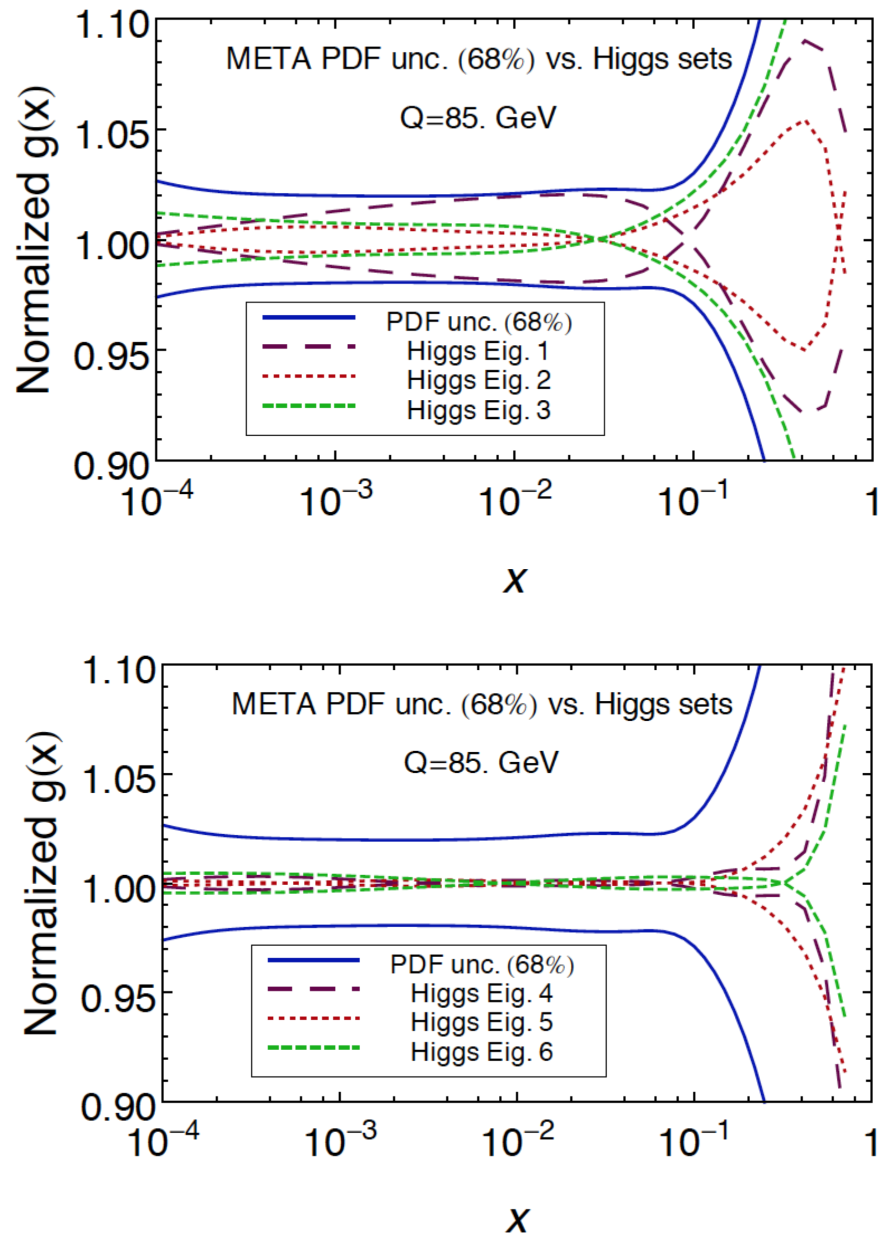


J. Gao,
J. Huston
P. Nadolsky
(in progress)

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

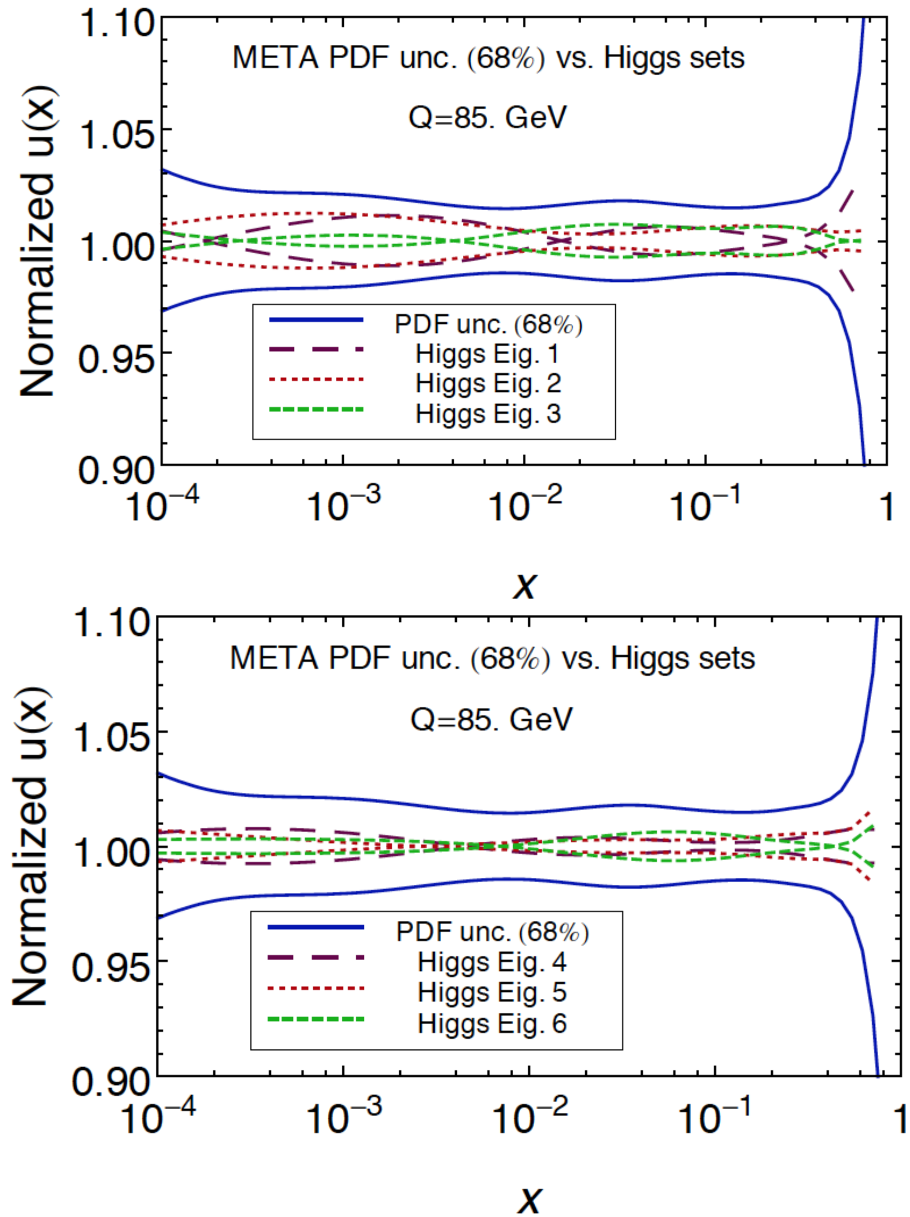
Re-diagonalized eigenvectors

- Eigenvectors 1-3 cover the gluon uncertainty
- Note that eigenvector 1 saturates the uncertainty for most of the gg->Higgs range



Re-diagonalized eigenvectors

- Up quark uncertainties a bit more distributed



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

Summary

- In general, good agreement among global PDF sets for LHC predictions
- gg initial states not as good, though
- The PDF4LHC prescription has been updated to reflect newer generations of PDFs, and new prescription for α_s
- Global PDF sets all planning new releases in near future which will include both HERA2 data and LHC data
- META PDFs are a technique of summarizing the PDF(+α_s) uncertainties for a range of physics processes in a range of center-of-mass energies with just a few eigenvectors
- ATLAS is considering their use for Run 2 MC production
- What about CMS?

Coming in the near future

The Black Book of Quantum Chromodynamics

A QCD primer for the LHC era

J. M. Campbell

Theoretical Physics Department, Fermilab, P.O.Box 500, Batavia, IL 60510, USA

J. W. Huston

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