Top at the LHC and Preview of CT14

J. Huston

Michigan State University

What's new in CT14

New parameterization form

- In general

$$f_a(x) = x^{a_1}\,(1-x)^{a_2}\,P_a(x)$$

- In CT10

$$P(x) = \exp(a_0 + a_3\sqrt{x} + a_4 x + a_5 x^2)$$

  - exponential form conveniently enforces positive definite behavior
  - but power law behaviors from a_1 and a_2 may not dominate

- In CT14

$$P_a(x) = G_a(x)\,F_a(z)$$

  - where $G_a(x)$ is a smooth factor, and

    $$z = 1 - (1-\sqrt{x})^{a_3}$$

  - with a_3>0
  - preserves desired Regge-like behavior at low x and high x

- Express $F_a(z)$ as a linear combination of Bernstein polynomials

$$z^4,\ 4\,z^3\,(1-z),\ 6\,z^2\,(1-z)^2,\ 4\,z\,(1-z)^3,\ (1-z)^4$$

  - each basis polynomial has a single peak, with peaks at different values of z; reduces correlations among parameters

- $\alpha_s(m_Z)$=0.118, with 90%CL error = +/-0.002
- New data sets (in addition to those in CT10)
  - LHCb7 TeV W asymmetry
  - CMS W asymmetry, 4.7 fb^{-1}
  - ATLAS low mass/high mass DY
  - ATLAS inclusive jet 7 TeV R=0.6
  - CMS inclusive jet 7 TeV R=0.7
  - ATLAS jet ratio 2.76 TeV/7 TeV R=0.6
- Applgrid is used with ATLAS jet ratio data, and ATLAS low-mass and high-mass DY data sets
- fastNLO used with all other jet data sets
- Inclusive jet cross section not yet known to NNLO, so how to include in NNLO fit
- …especially if NNLO corrections for gg initial state appear to be large

…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 (know that corrections for qQ->gg <<5%)

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

so CT14 does not use threshold approximation for NNLO jets

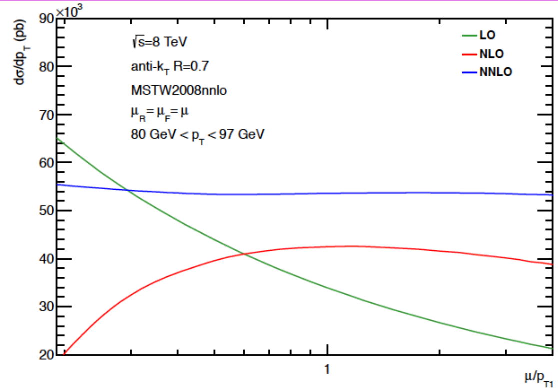


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

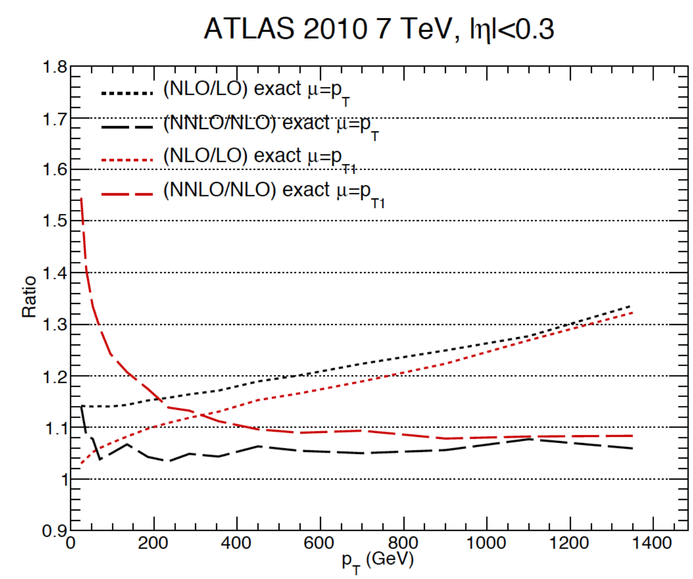
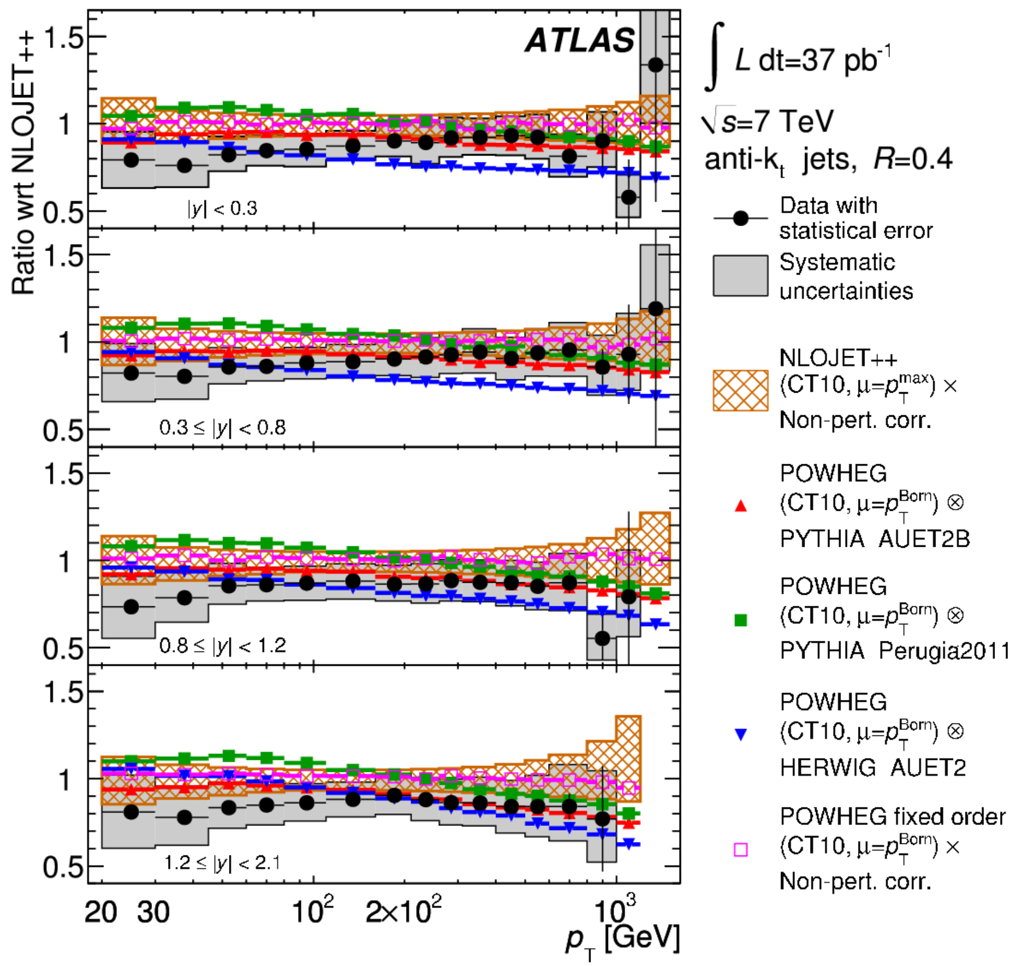


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

Jet data in global PDF fits

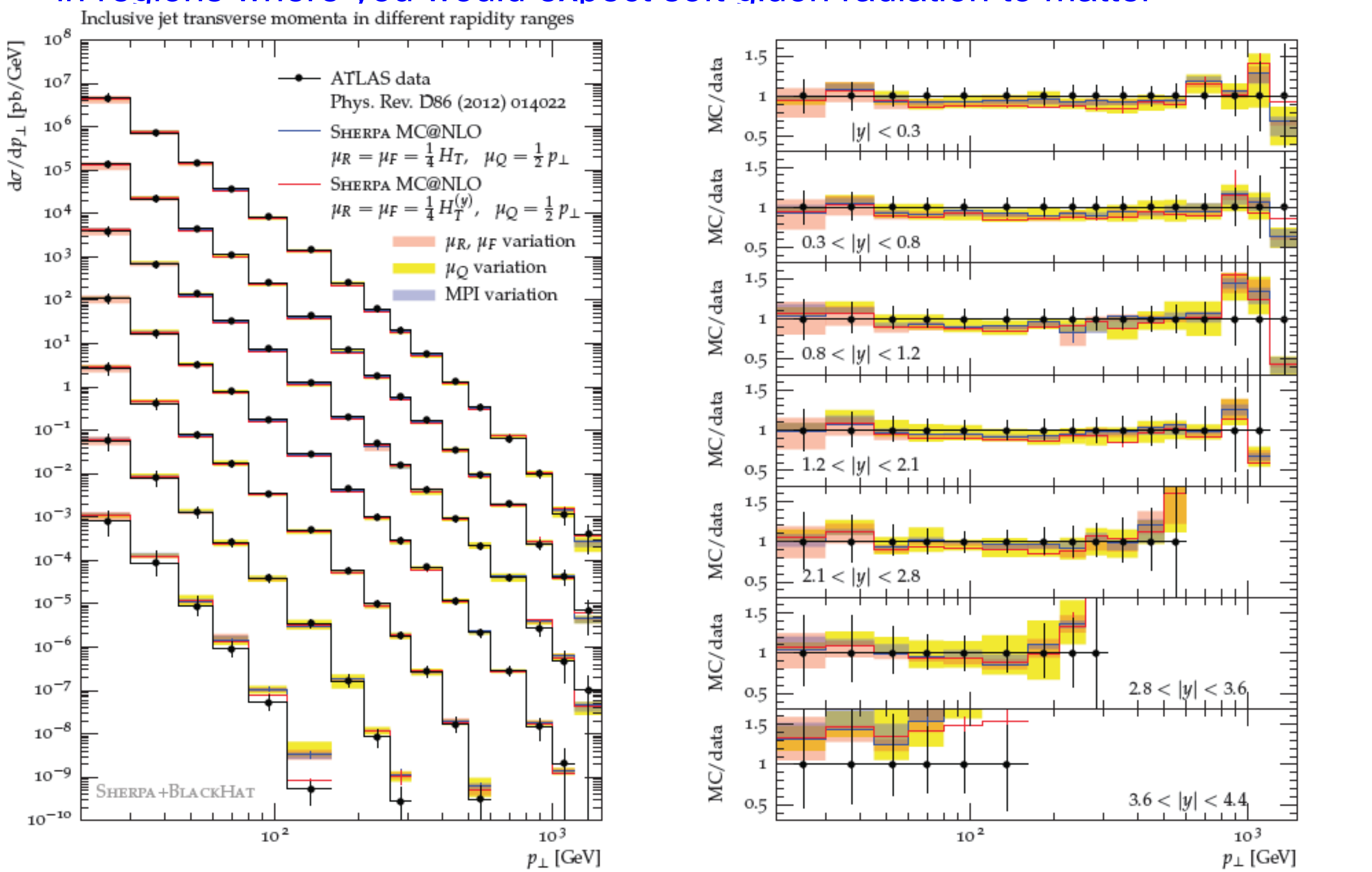
- The issue regarding jets at NNLO may be or may soon be resolved
- What about the impact of parton showers?
- So far that has been ignored by the PDF fitting community

- 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

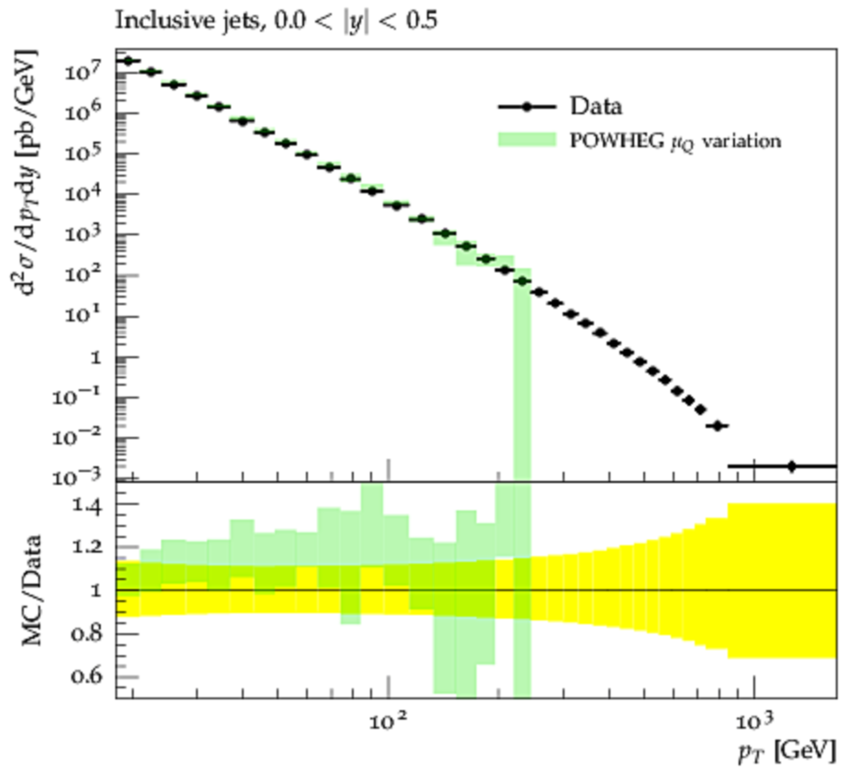


Powheg

- 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

Les Houches high precision wishlist

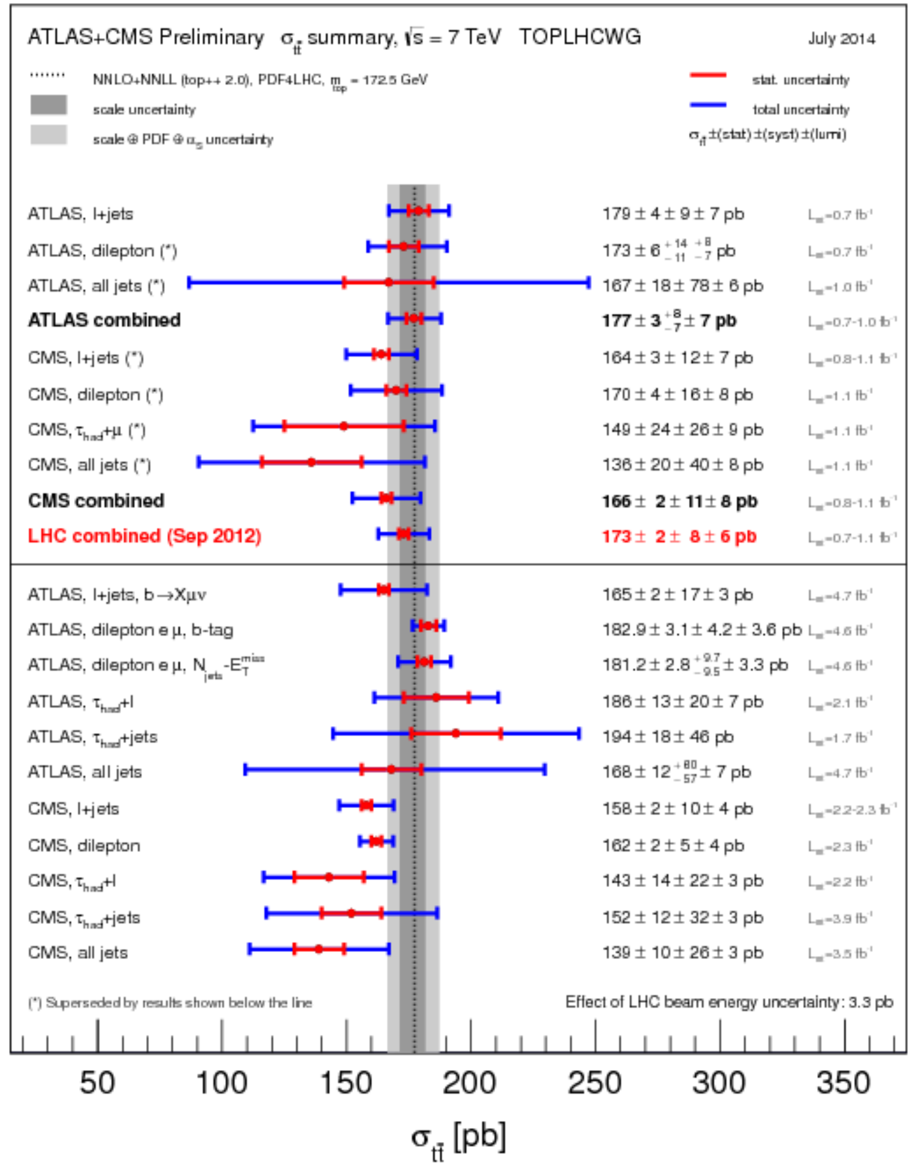
heavy quarks, photons, jets

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

Top pair production

- Top production is important both as a possible venue for new physics as well as for more mundane purposes such as the determination of the gluon PDF at high x
- Currently, the dilepton final state is known to an experimental uncertainty of 5% and the uncertainty for the leptons+jets final state should be of the same order in Run 2
  - a sizeable portion of that error is due to the luminosity uncertainty
- Currently know total top cross section to NNLO QCD and NLO EW
  - 4% uncertainties
- Need differential top cross section to NNLO QCD (with decays) including NLO EW effects

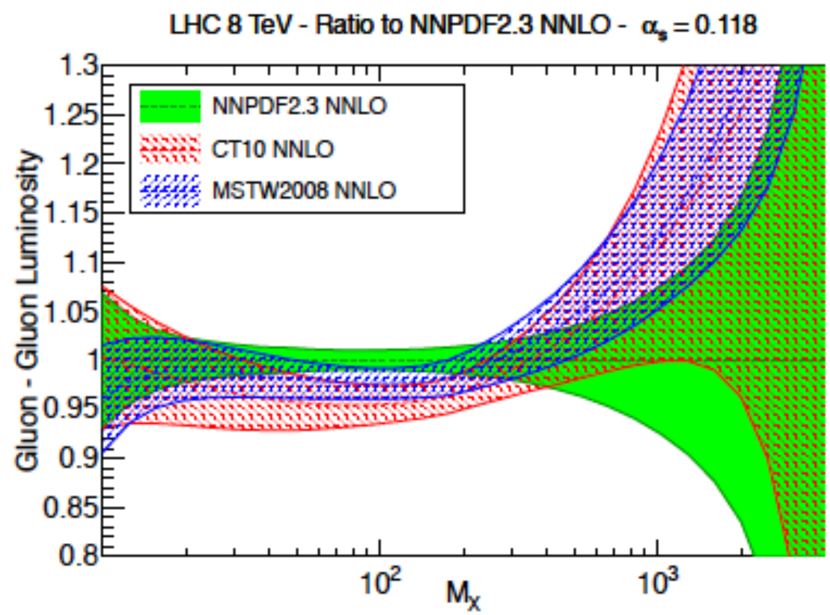


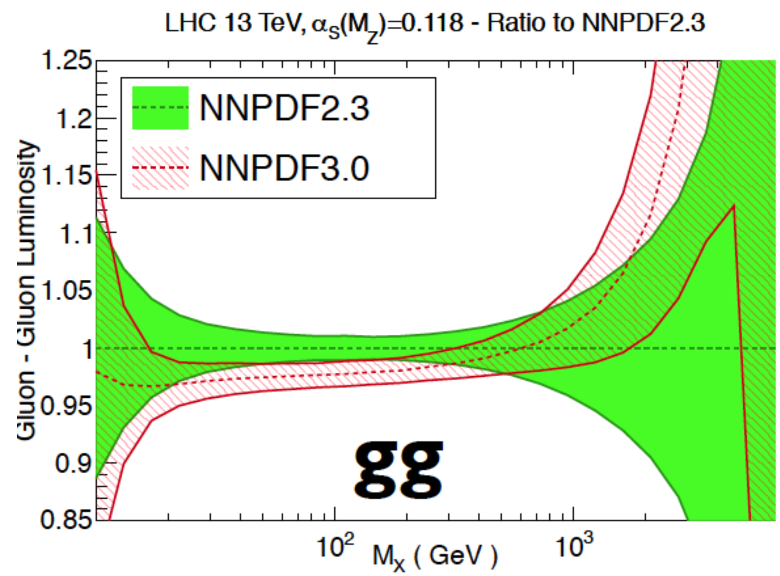
Now to CT14 gluon distribution

- Reminder: CT10 gg luminosity forms lower bound for LHC combination, for m< 400 GeV
  - NNPDF3.0 decreases by 2-3% compared to NNPDF2.3
- CT14 predictions for Higgs cross sections at 8, 14 TeV will increase by 1-1.5%, thus further reducing the size of the envelope (assuming MTXX14 doesn't move much)
  - parameterization, new data
- Top cross sections will increase by roughly 2%

	CT10	CT14
7 TeV	172.5 pb	176.1 pb
8 TeV	246.3 pb	251.3 pb
13 TeV	805.7 pb	819.6 pb

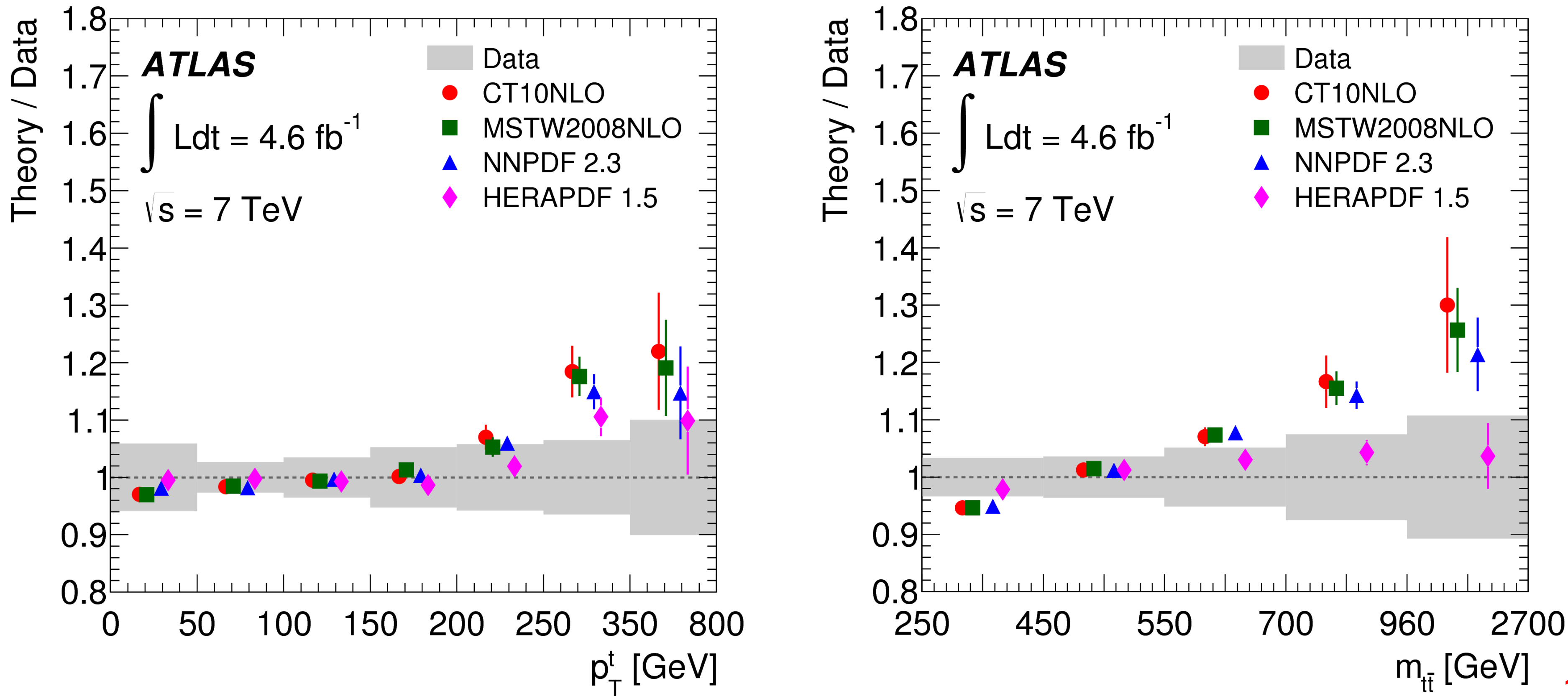
J. Gao top++ m_{top}=173.3 GeV





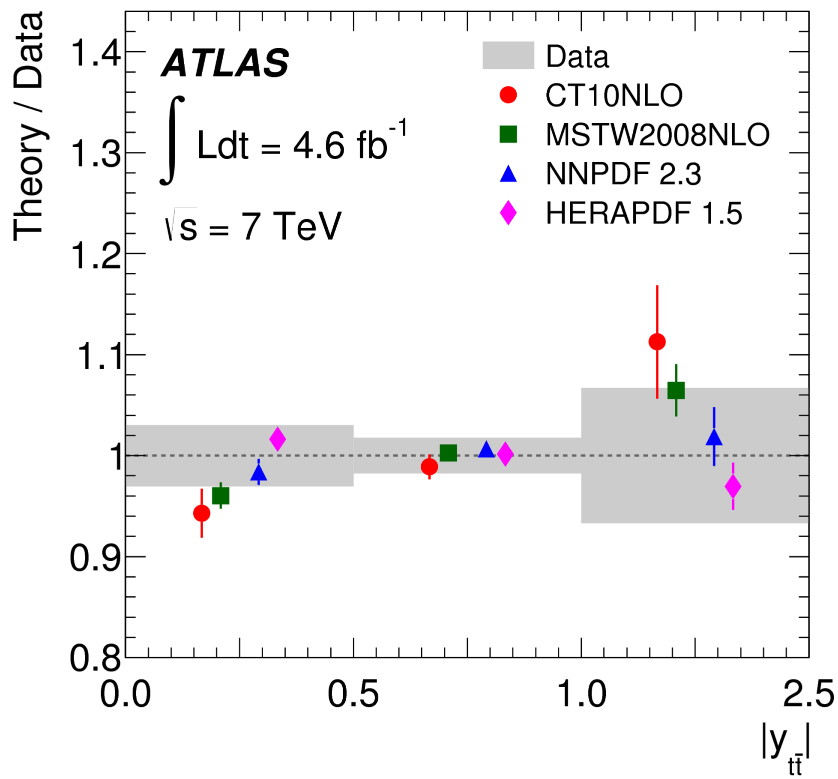
Mass and rapidity distributions

- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution
- Note that tT differential distributions prefer weaker high x gluon than does the jet data
  - impact of NNLO corrections (and of EW)



Mass and rapidity distributions

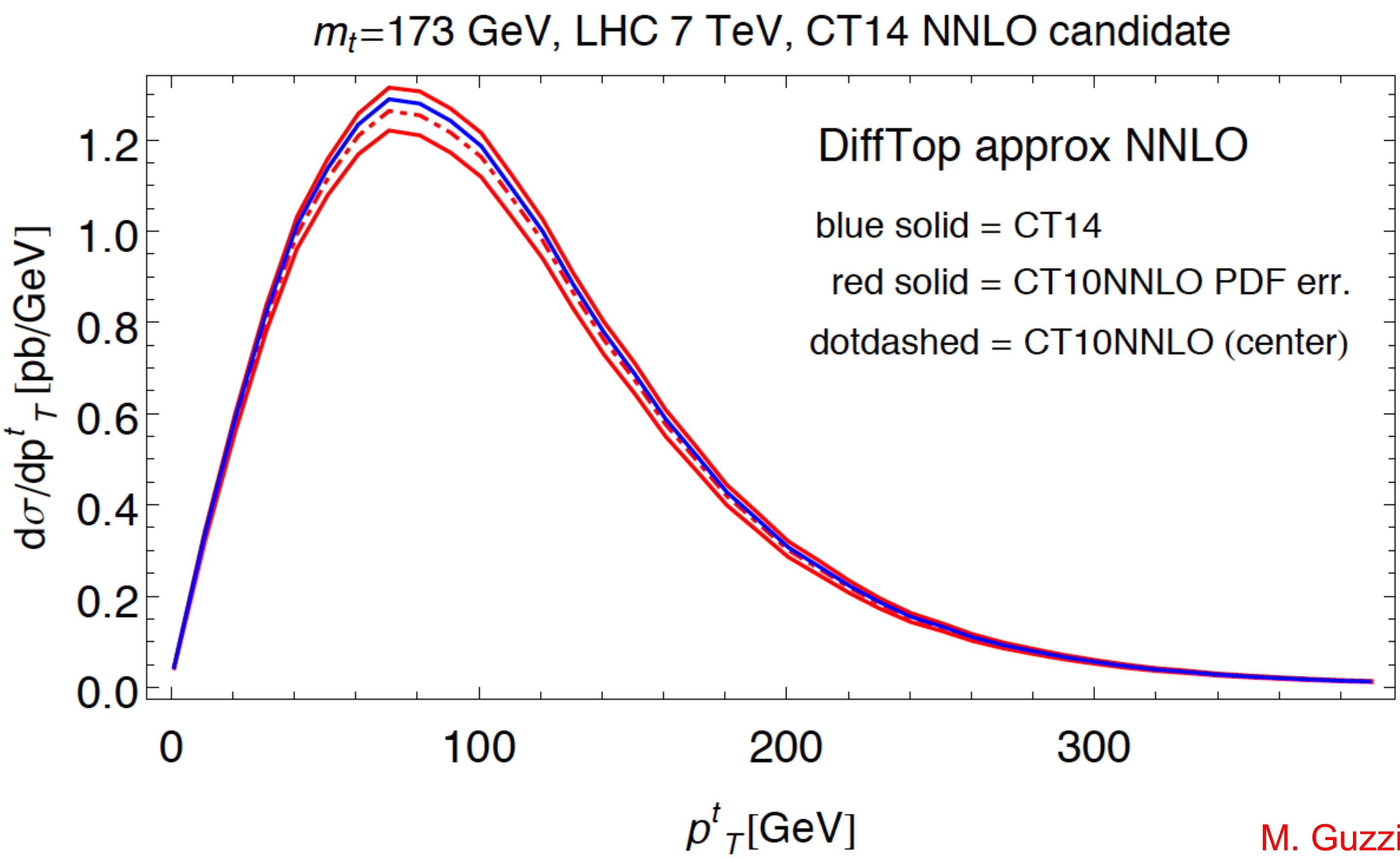
- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution
- Note that tT differential distributions prefer weaker high x gluon than does the jet data
  - impact of NNLO corrections (and of EW); however both known only at NLO



some potential shape information here; would like finer differential distributions (more data?)

Top differential distributions

- So again, CT14NNLO a few percent higher than CT10NNLO for differential distributions
- NB: DiffTop in general gives a result 2-3% higher than NNLO

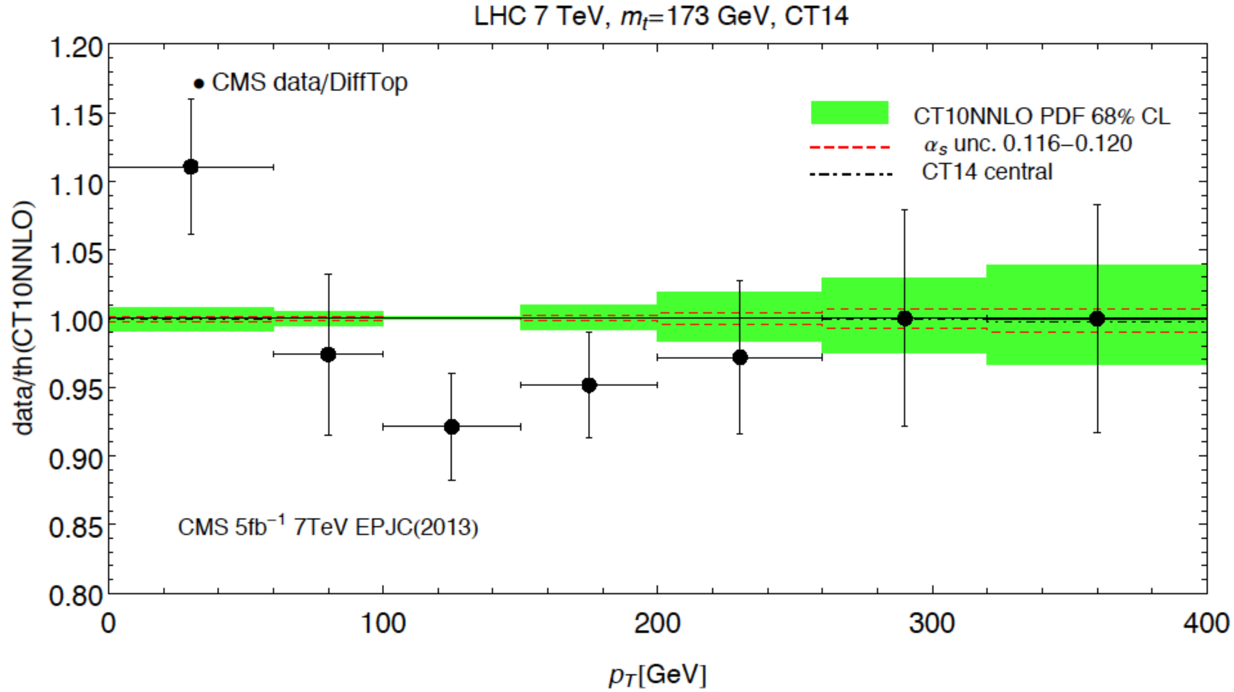


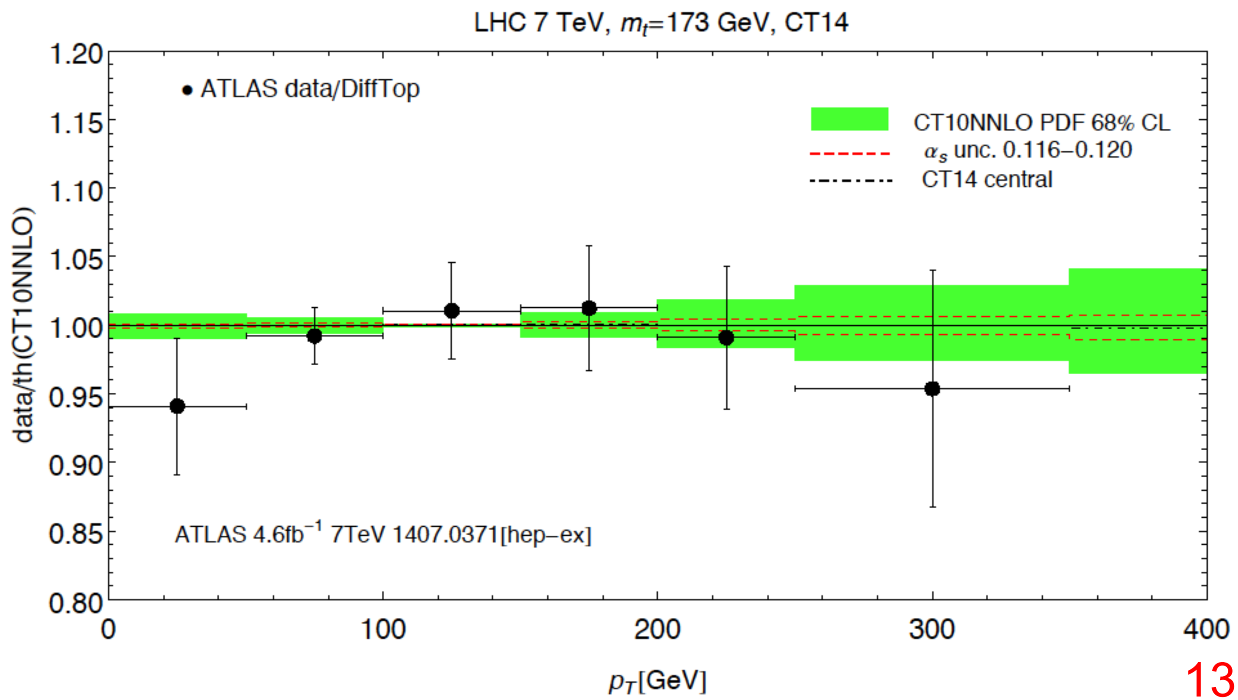
M. Guzzi

normalized cross sections

again not much shape change from CT10 to CT14

normalization taken out in this comparison



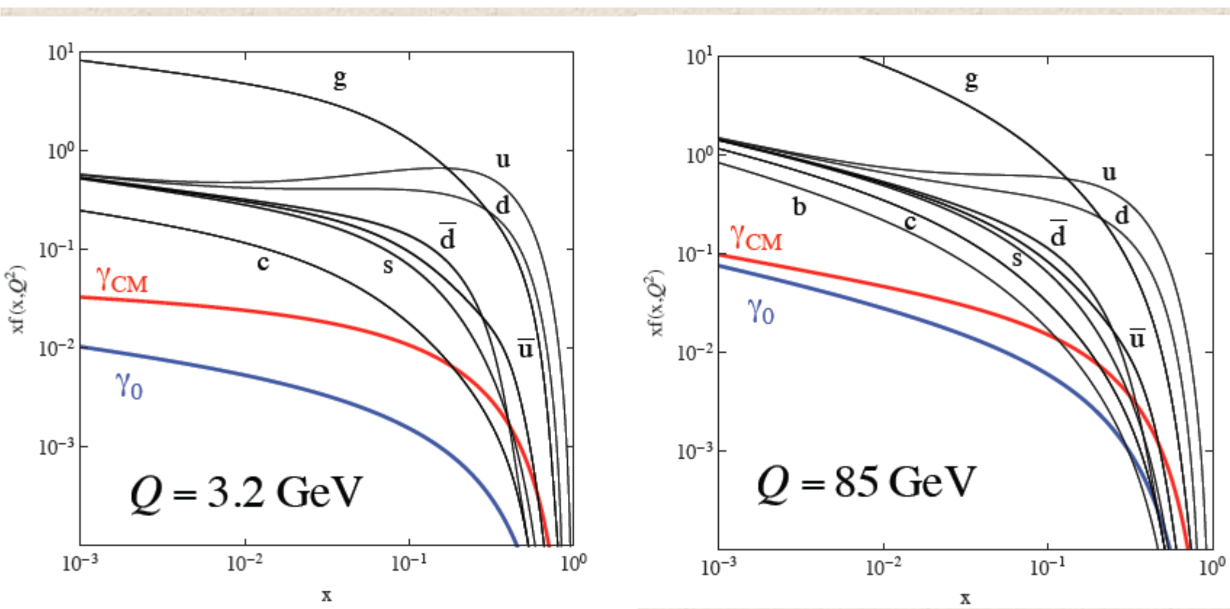


Next steps

- Finalize parameterization form
- Generate error PDF sets
- …and not necessarily for CT14 (depending on timing)
- add 2011 7 TeV ATLAS jet data
- add 2011 7 TeV CMS jet data (after revision of errors)
  - hopefully 8 TeV analysis will have public errors soon after
- add 2011 CMS Drell-Yan data
- add HERA2 combined data once it comes out
- use differential top data from ATLAS and CMS once NNLO differential top calculations available

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
- CT14 release will include photon PDFs for first time
  - fitting to photon production in DIS
- See talk of C. Schmidt at DIS2014



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

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)

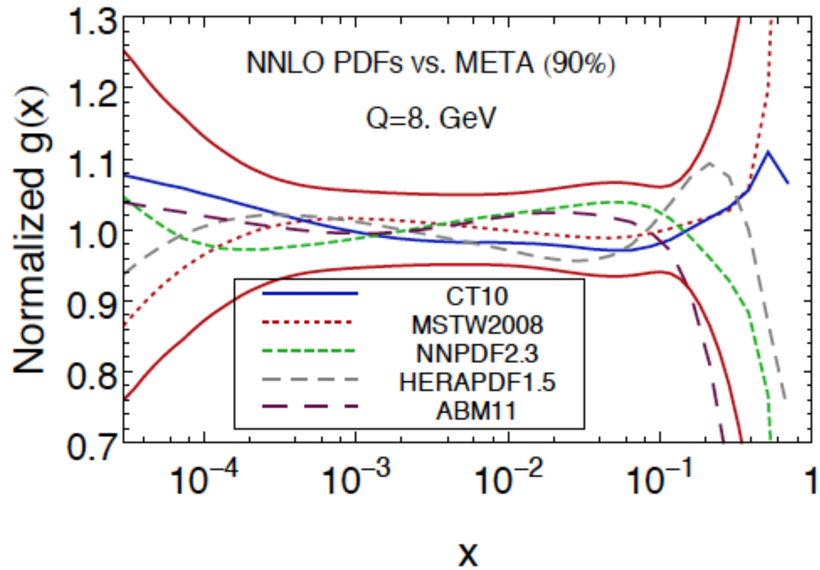
$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i \geq 4} a_i \left[T_{i-3}(y(x)) - 1\right]}$$

- 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

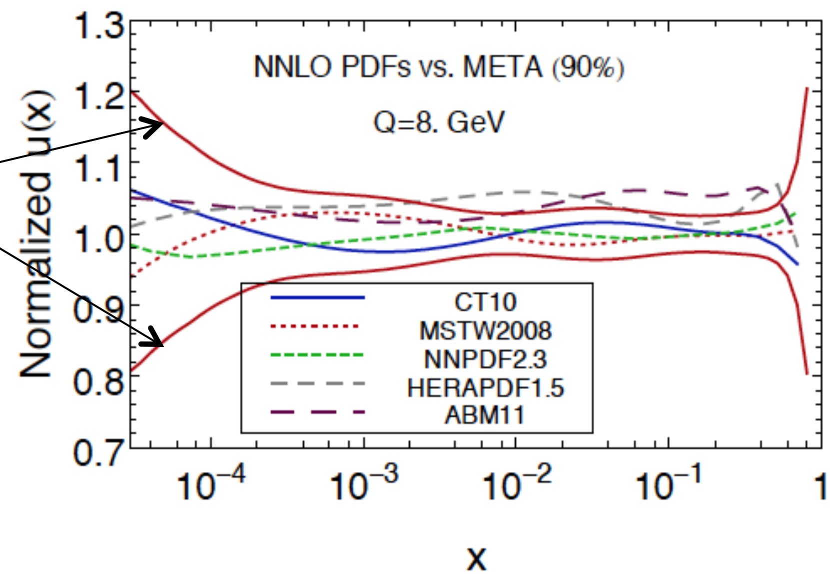
J. Gao, P. Nadolsky

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



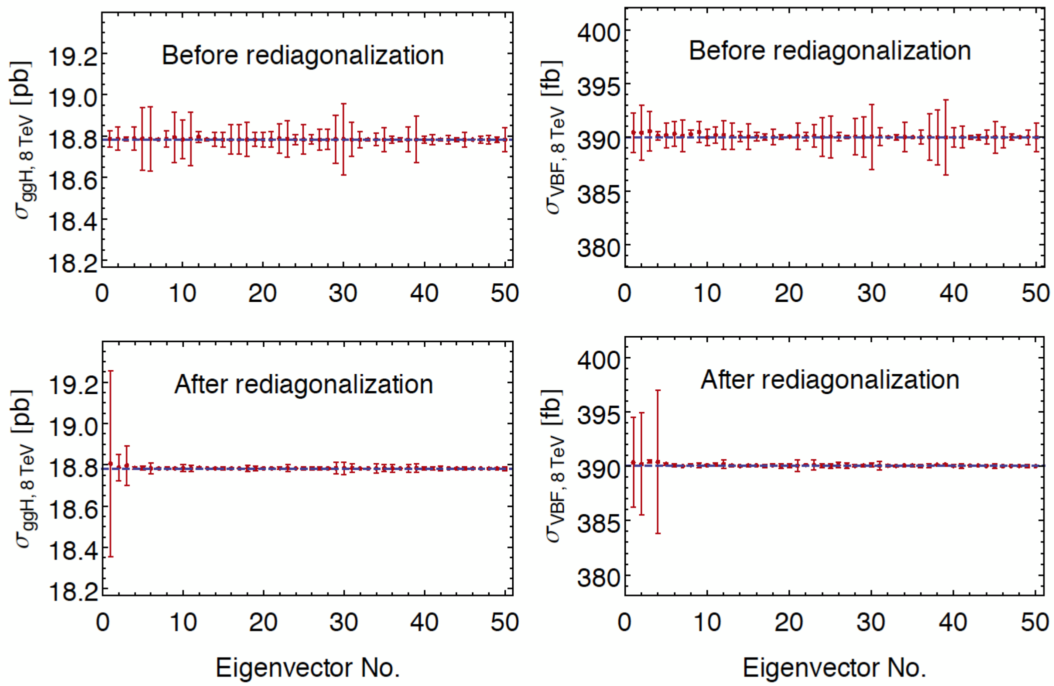
Higgs observables

- 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

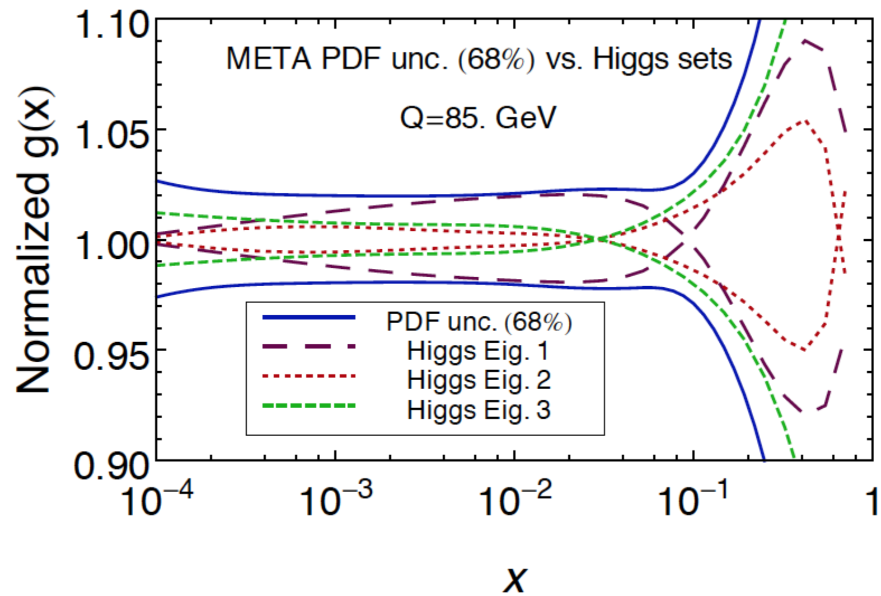


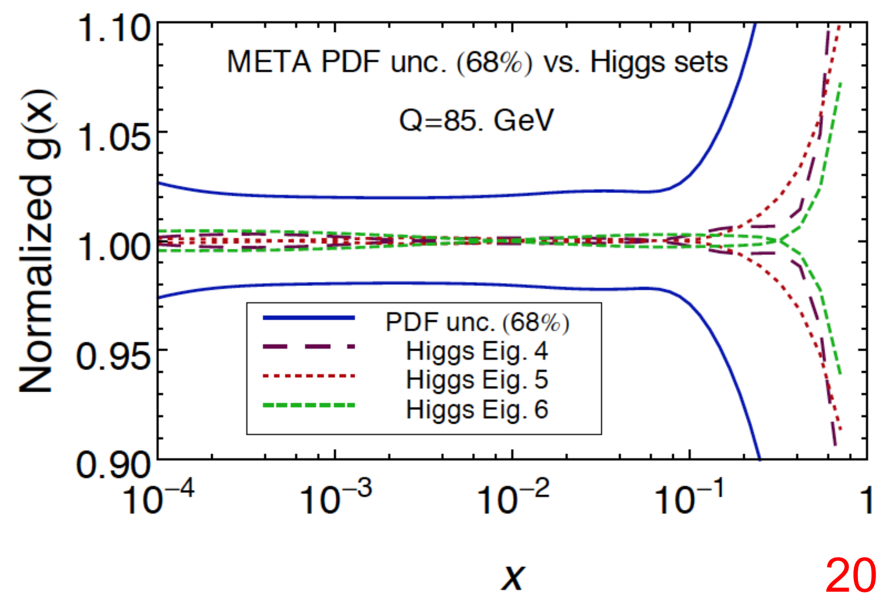
J. Gao,
J. Huston
P. Nadolsky
(in progress)

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

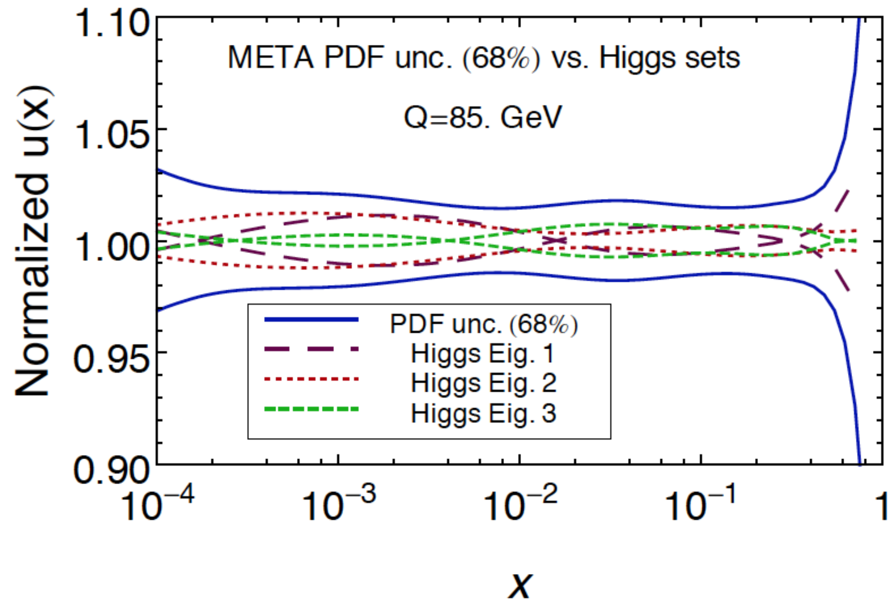
- Eigenvectors 1-3 cover the gluon uncertainty
- Note that eigenvector 1 saturates the uncertainty for most of the gg->Higgs range
- In fact eigenvector 1 covers much of the range for tT production, especially at 13 TeV
  - although would want to include 2 and 3 to get best accuracy

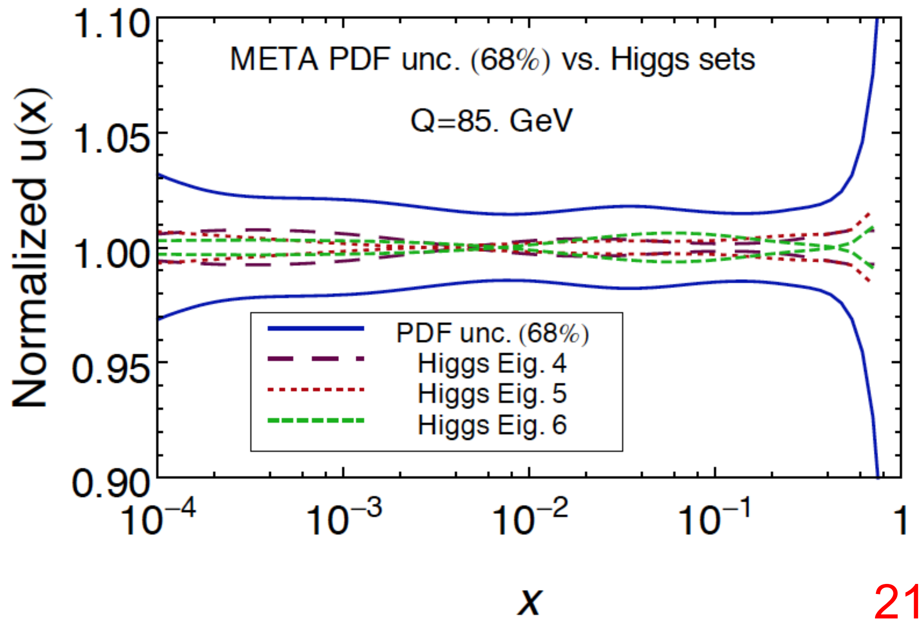




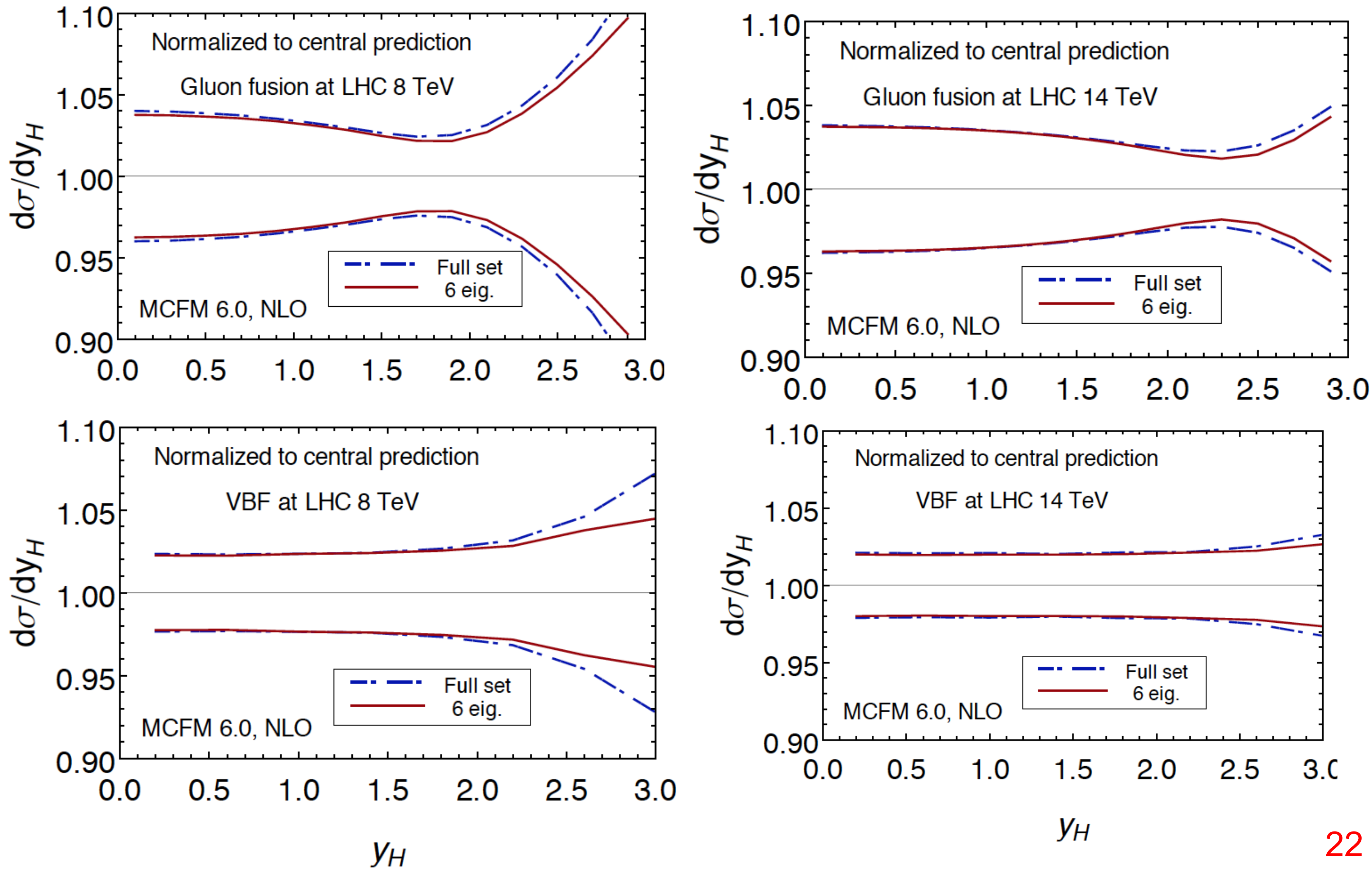
Re-diagonalized eigenvectors

- Up quark uncertainties a bit more distributed



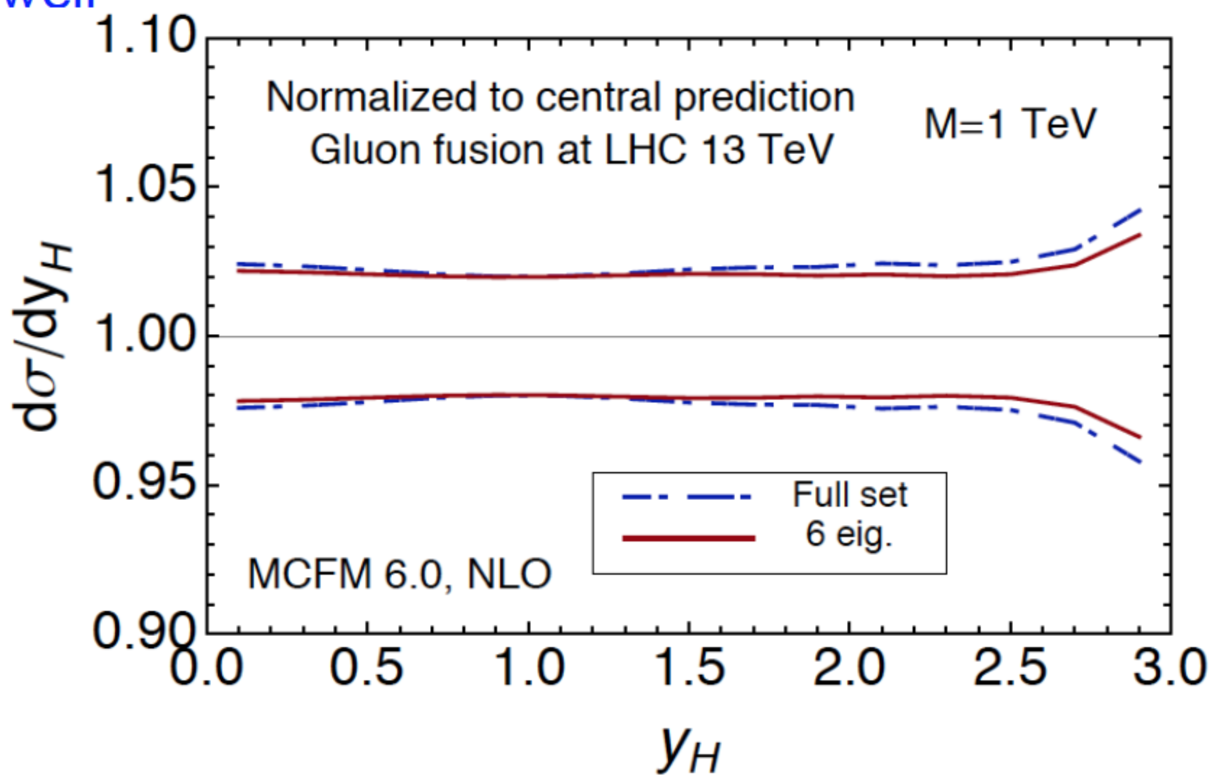


Some comparisons



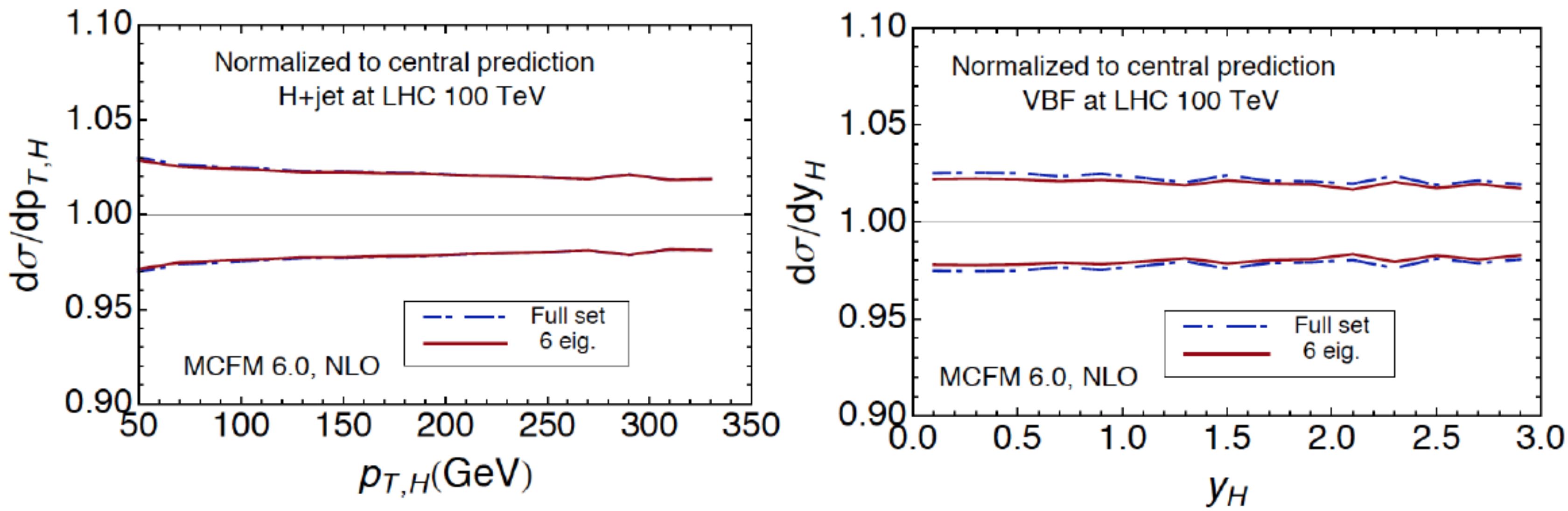
Try other distributions

- Look at rapidity distribution for production of a 1 TeV mass state through gg fusion
- This was not an input to the re-diagonalization, but still works fairly well



Look at 100 TeV

- Again, these cross sections were not used in the re-diagonalization



Other cross sections

- Cross sections at 8 and 13 TeV
- Bottom 8 processes not used in re-diagonalization, but have agreement for central prediction (by construction) and for PDF errors
- Looking at differential distributions

process	$\sigma_{cen.}$	δ_{Full}	$\delta_{Diag.}$	$\sigma^{\alpha_s}_{0.116}$	$\sigma^{\alpha_s}_{0.120}$
$gg \to H$ [pb]	18.77	$^{+0.48}_{-0.46}$	$^{+0.48}_{-0.44}$	18.11	19.46
	43.12	$^{+1.13}_{-1.07}$	$^{+1.13}_{-1.04}$	41.68	44.61
VBF [fb]	302.5	$^{+7.8}_{-6.7}$	$^{+7.6}_{-6.7}$	303.1	301.4
	878.2	$^{+19.7}_{-17.9}$	$^{+19.2}_{-17.3}$	877.3	878.4
HZ [fb]	396.3	$^{+8.4}_{-7.3}$	$^{+8.1}_{-7.4}$	393.0	399.7
	814.3	$^{+14.8}_{-13.2}$	$^{+13.8}_{-13.0}$	806.5	823.3
$HW^{\pm}$ [fb]	703.0	$^{+14.4}_{-14.4}$	$^{+14.3}_{-14.1}$	697.4	708.9
	1381	$^{+28}_{-22}$	$^{+26}_{-22}$	1368	1398
HH [fb]	7.81	$^{+0.33}_{-0.30}$	$^{+0.33}_{-0.30}$	7.50	8.10
	27.35	$^{+0.78}_{-0.72}$	$^{+0.78}_{-0.68}$	26.48	28.22
$t\bar{t}$ [pb]	248.4	$^{+9.1}_{-8.2}$	$^{+9.2}_{-8.1}$	237.1	259.5
	816.9	$^{+21.4}_{-19.6}$	$^{+21.4}_{-18.4}$	785.5	848.1
$Z/\gamma^*(l^+l^-)$ [nb]	1.129	$^{+0.025}_{-0.023}$	$^{+0.024}_{-0.023}$	1.113	1.147
	1.925	$^{+0.043}_{-0.041}$	$^{+0.040}_{-0.037}$	1.897	1.959
$W^+(l^+\nu)$ [nb]	7.13	$^{+0.14}_{-0.14}$	$^{+0.14}_{-0.13}$	7.03	7.25
	11.64	$^{+0.24}_{-0.23}$	$^{+0.22}_{-0.21}$	11.46	11.84
$W^-(l^-\bar{\nu})$ [nb]	4.99	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	4.92	5.08
	8.59	$^{+0.21}_{-0.20}$	$^{+0.19}_{-0.18}$	8.46	8.74
W^+W^- [pb]	4.14	$^{+0.08}_{-0.08}$	$^{+0.08}_{-0.07}$	4.04	4.20
	7.54	$^{+0.15}_{-0.14}$	$^{+0.14}_{-0.12}$	7.39	7.57
ZZ [pb]	0.703	$^{+0.016}_{-0.014}$	$^{+0.015}_{-0.014}$	0.695	0.713
	1.261	$^{+0.026}_{-0.024}$	$^{+0.024}_{-0.022}$	1.256	1.277
W^+Z [pb]	1.045	$^{+0.019}_{-0.018}$	$^{+0.019}_{-0.017}$	1.039	1.068
	1.871	$^{+0.033}_{-0.031}$	$^{+0.029}_{-0.027}$	1.850	1.898
W^-Z [pb]	0.788	$^{+0.020}_{-0.019}$	$^{+0.019}_{-0.018}$	0.780	0.795
	1.522	$^{+0.034}_{-0.032}$	$^{+0.033}_{-0.031}$	1.509	1.549

META PDFs and top cross sections

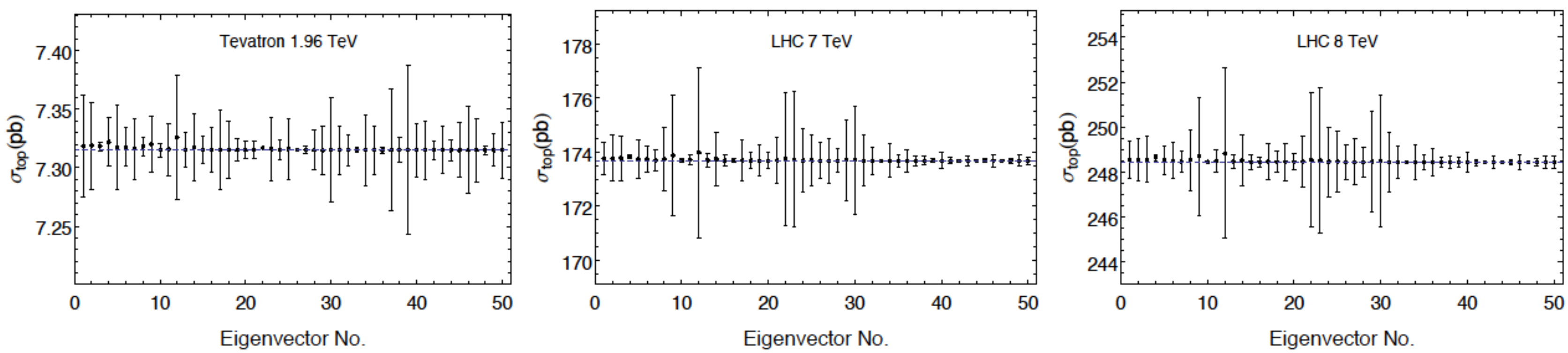


FIG. 8: NNLO+NNLL predictions for the inclusive rate of top quark pair production at the Tevatron and LHC 7, 8 TeV from all the error sets of the META PDFs. Each error bar corresponds to the two error sets of one eigenvector direction. The horizontal line represents the central predictions.

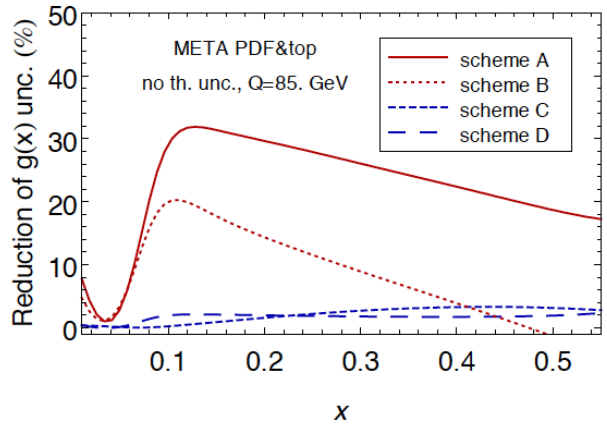
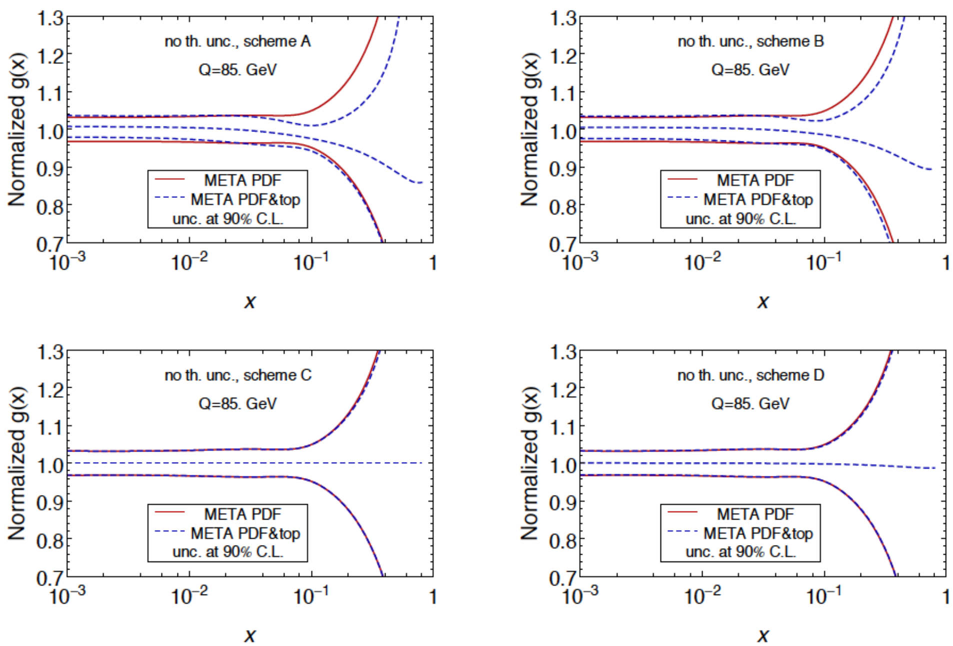


FIG. 12: Reduction of the relative PDF uncertainty of gluon at $Q = 85\,\text{GeV}$ after including the top quark measurements under different reweighting schemes. Only experimental errors are considered in the χ^2 function of the top quark data.



C and D have larger tolerances and are intended to mimic global fits from MSTW and CT

FIG. 11: Comparison of the gluon PDF at $Q = 85\,\text{GeV}$ before and after including the top quark measurements under different reweighting schemes. Only experimental errors are considered in the χ^2 function of the top quark data.

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%

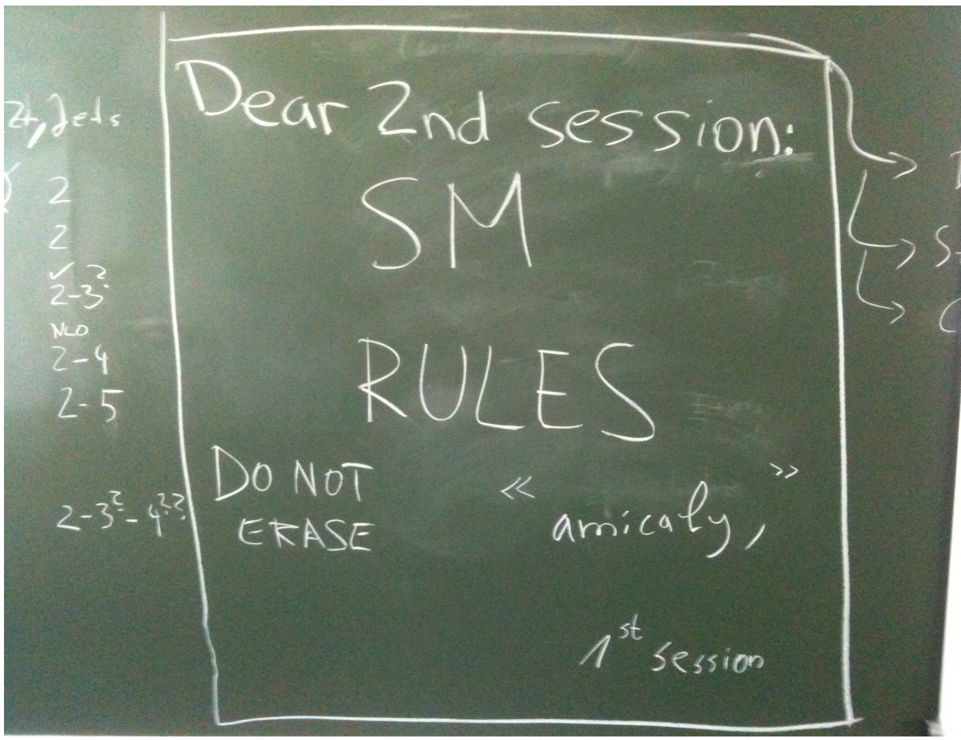
❖ using PDF α_s series of the META PDFs

Although these were intended to describe full PDF uncertainty only of Higgs cross sections, they also do a reasonable job of describing the full PDF uncertainty of a great many processes at the LHC; so it may be possible to make them more 'universal' by adding a few more eigenvectors

In any case, the next PDF4LHC recommendation for PDF uncertainties will be in the framework of META PDFs

Finally, tT asymmetry

It would have been nice to have had a BSM explanation, but …



Daniel de Florian's words

Daniel de Florian's t-shirt