

# PDFs in 2016

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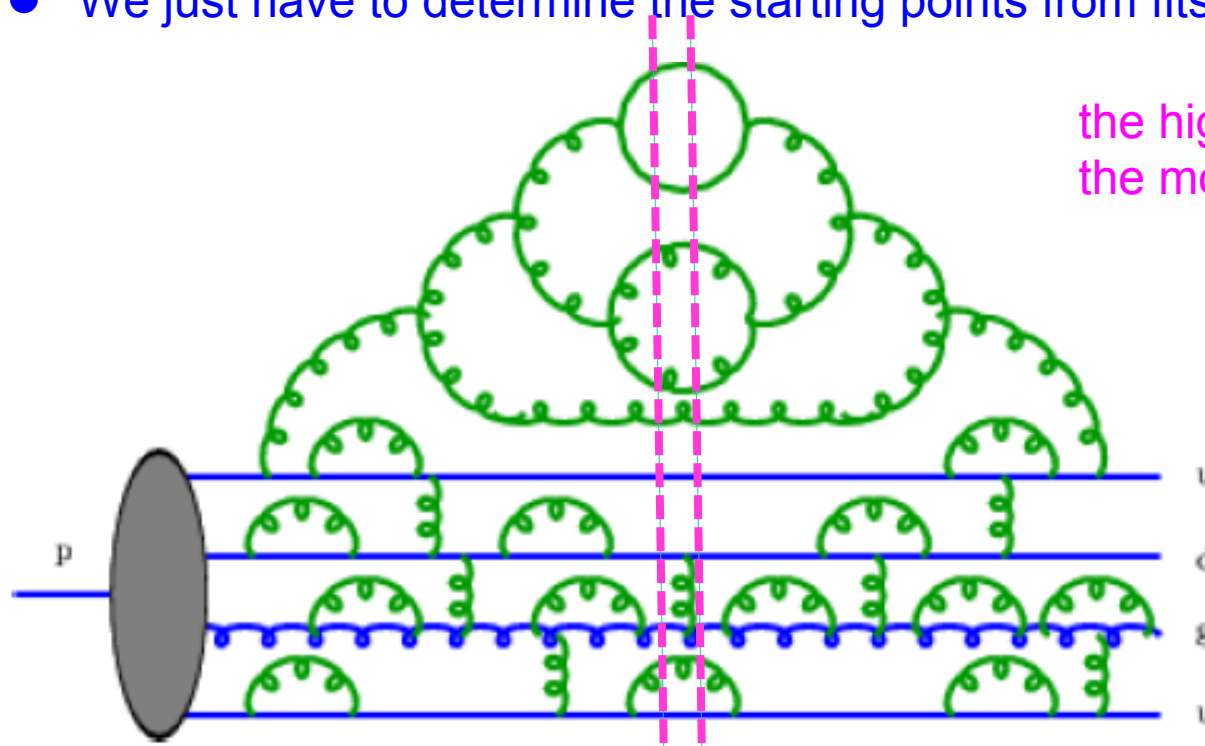




# Hadrons



- 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) (at LO, NLO, NNLO)
- We just have to determine the starting points from fits to data



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

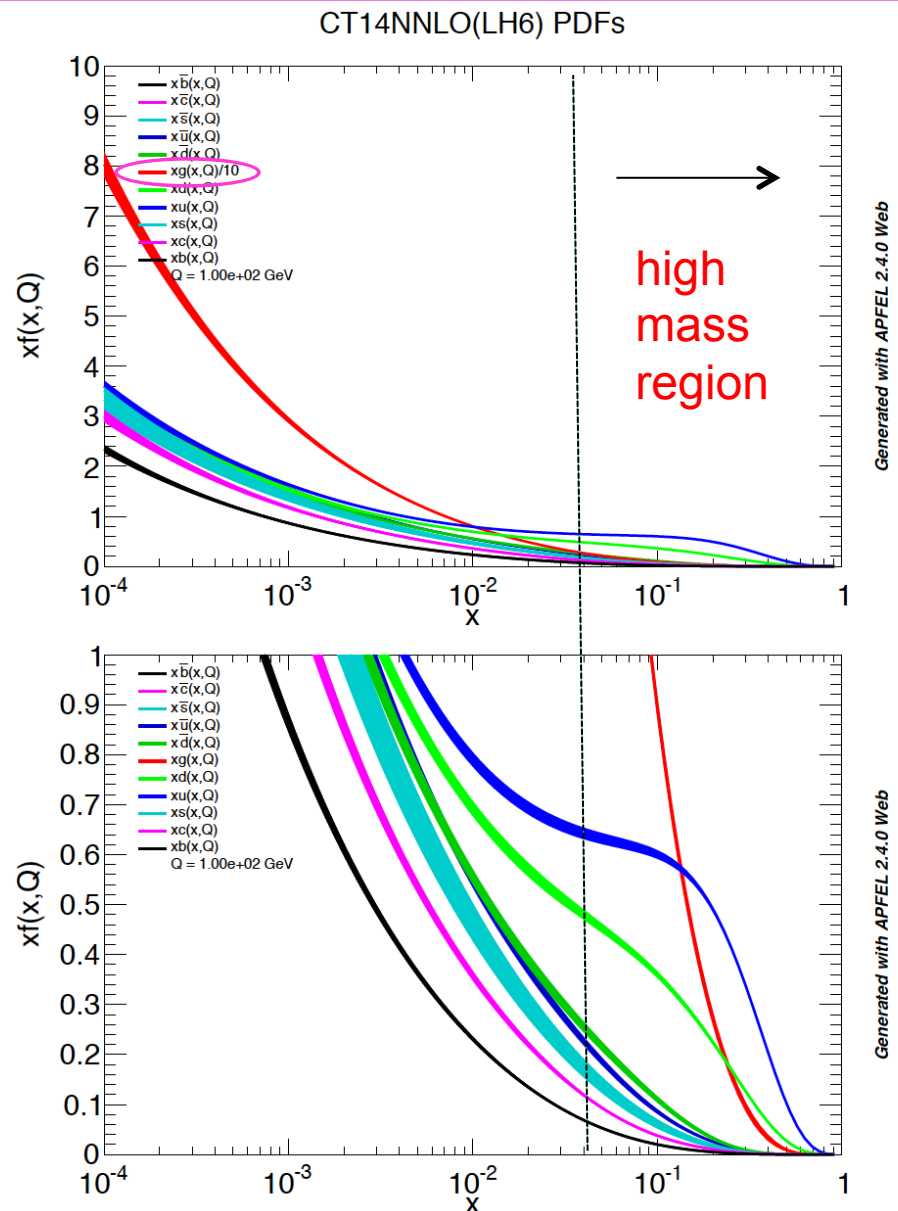
$f_i(x, Q^2)$  = number density of partons  $i$   
at momentum fraction  $x$  and probing scale  $Q^2$



# Parton distribution functions and global fits

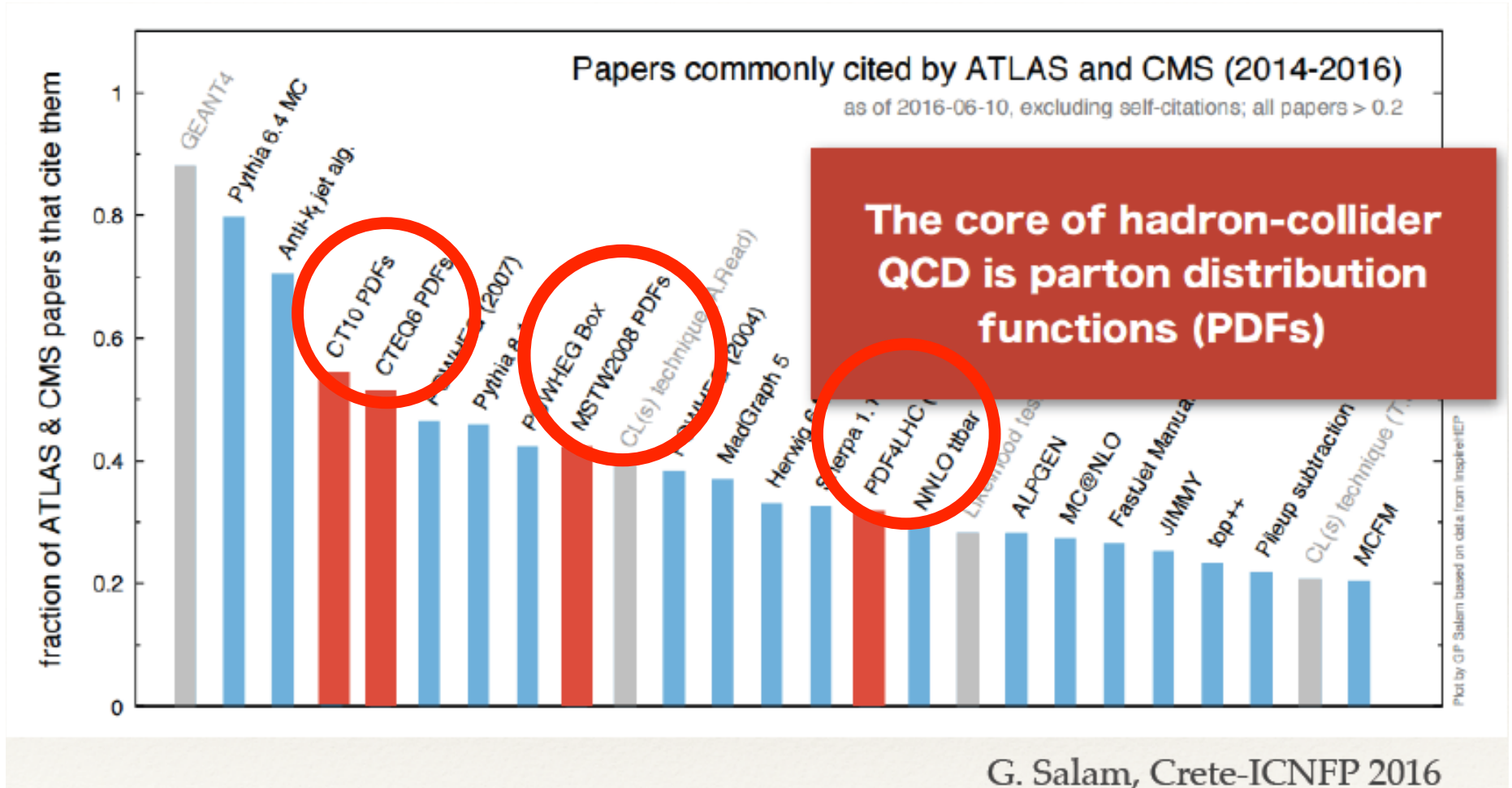


- Calculation of production cross sections at the LHC relies upon knowledge of PDF's in the relevant kinematic region
- PDFs are determined by global analyses of data from DIS, DY and jet production... now adding additional LHC processes such as  $t\bar{t}$  production, W/Z/photon +c, etc
- PDF fitting groups come out with new PDF sets as new data/technology warrants, at LO, NLO and NNLO
  - ◆ *ABM12*
  - ◆ *CT14*
  - ◆ *HERAPDF2.0*
  - ◆ *MMHT2014*
  - ◆ *NNPDF3.0*





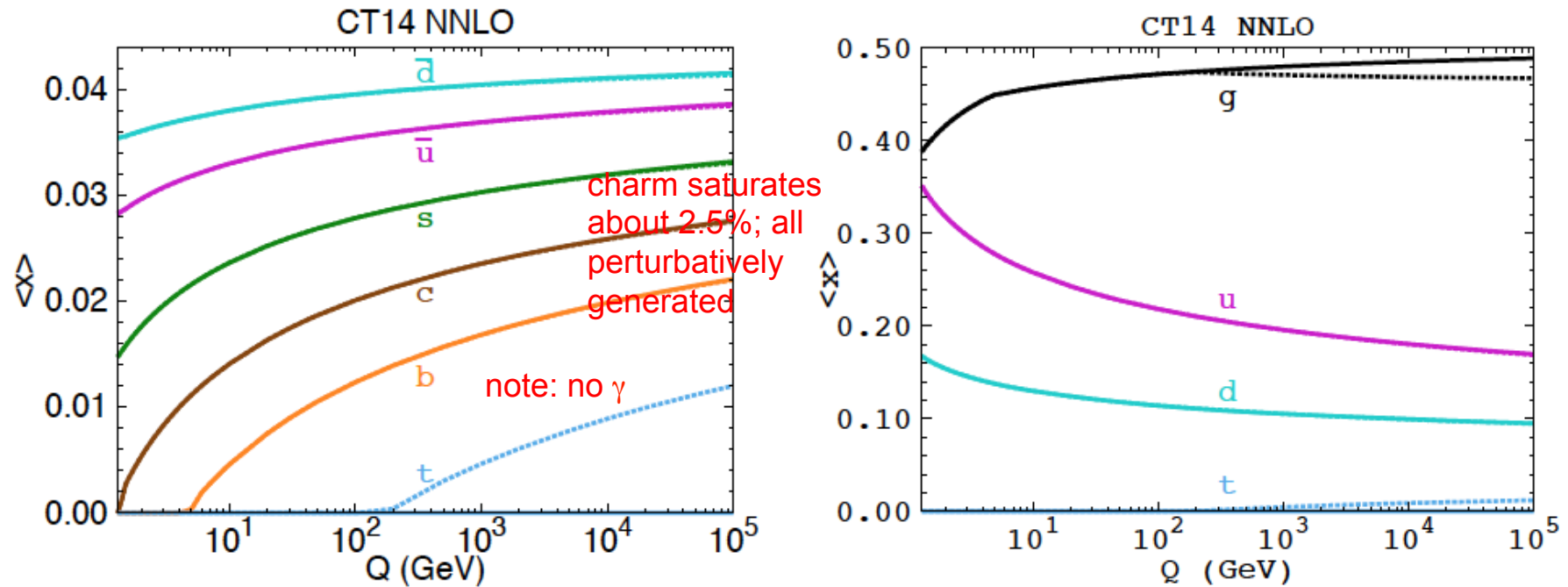
# PDFs are important



...at least to my citation index



# Momentum carried by partons



**Fig. 6.10** The momentum fractions carried by the CT14 NNLO quark and gluon distributions, as a function of  $Q$ . The gluon distribution in the right figure is shown without (with) the presence of a top quark PDF.

Don't usually define top quarks as initial state partons, but could. May be important for 100 TeV collider.

# LHC

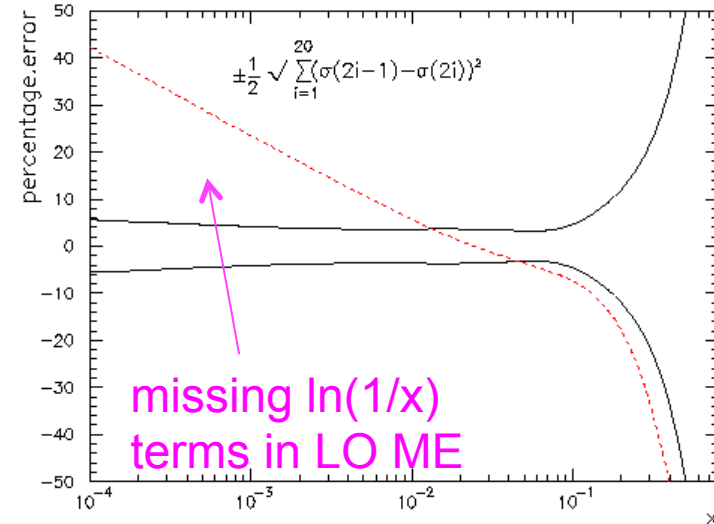
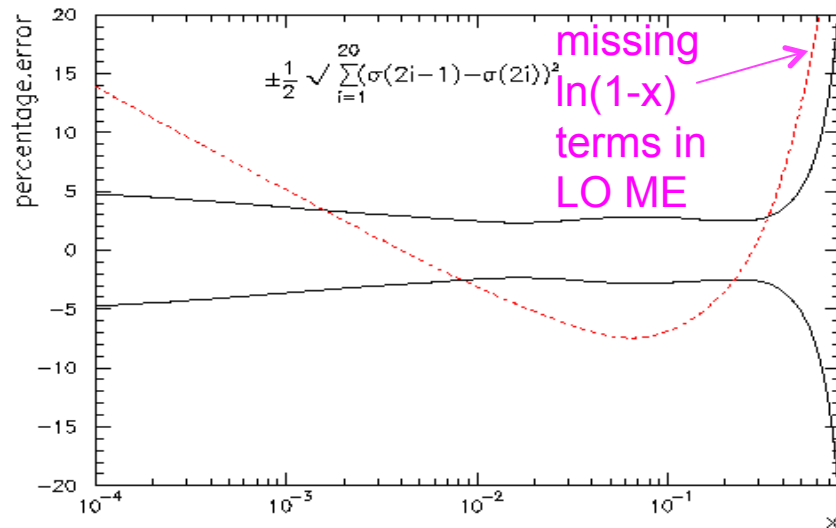
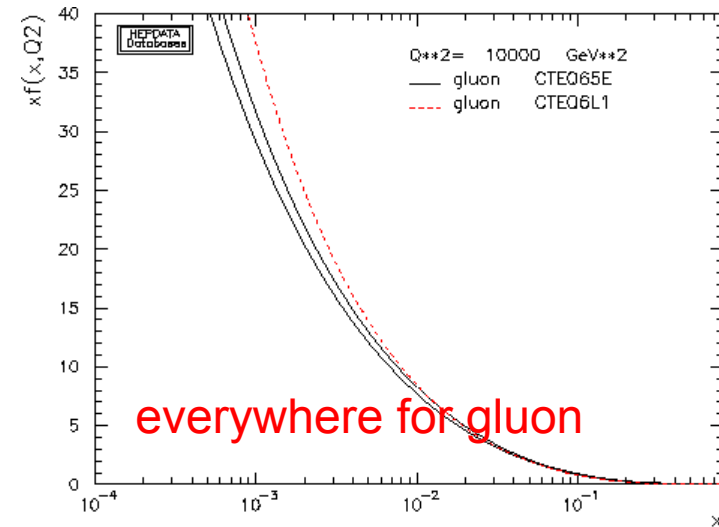
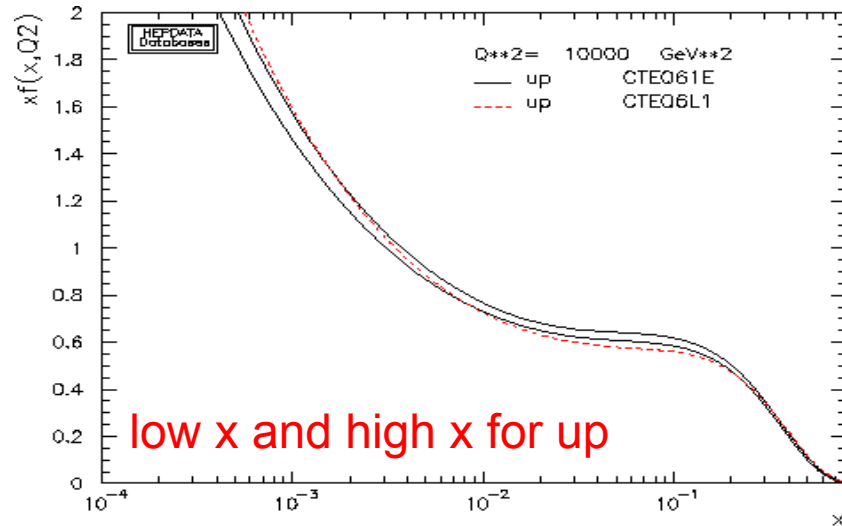
~

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

$$\sigma = \sum_{a,b} \int_0^1 dx_1 f_{a/A}(x_1, \mu_F^2) \int_0^1 dx_2 f_{b/B}(x_2, \mu_F^2) \left\{ \int d\hat{\sigma}_{ab}^{LO}(\alpha_s) \Theta_{\text{obs}}^{(m)} + \alpha_s(\mu_R^2) \left[ \int (d\hat{\sigma}_{ab}^V(\alpha_s, \mu_R^2) + d\hat{\sigma}_{ab}^C(\alpha_s, \mu_F^2)) \Theta_{\text{obs}}^{(m)} + \int d\hat{\sigma}_{ab}^R(\alpha_s) \Theta_{\text{obs}}^{(m+1)} \right] \right\} + \dots$$



# How non-reliable are LO PDFs?



Differences between NLO and NNLO PDFs typically much smaller.



# Lessons



- Don't believe in predictions using LO PDFs unless you have checked at NLO or NNLO
- (Don't believe)<sup>n</sup> \* LO PDF error sets

\*where n is a large number





# 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

$$\sigma = \sum_{a,b} \int_0^1 dx_1 f_{a/A}(x_1, \mu_F^2) \int_0^1 dx_2 f_{b/B}(x_2, \mu_F^2) \left\{ \int d\hat{\sigma}_{ab}^{LO}(\alpha_s) \Theta_{\text{obs}}^{(m)} + \alpha_s(\mu_R^2) \left[ \int (d\hat{\sigma}_{ab}^V(\alpha_s, \mu_R^2) + d\hat{\sigma}_{ab}^C(\alpha_s, \mu_F^2)) \Theta_{\text{obs}}^{(m)} + \int d\hat{\sigma}_{ab}^R(\alpha_s) \Theta_{\text{obs}}^{(m+1)} \right] \right\} + \dots$$

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

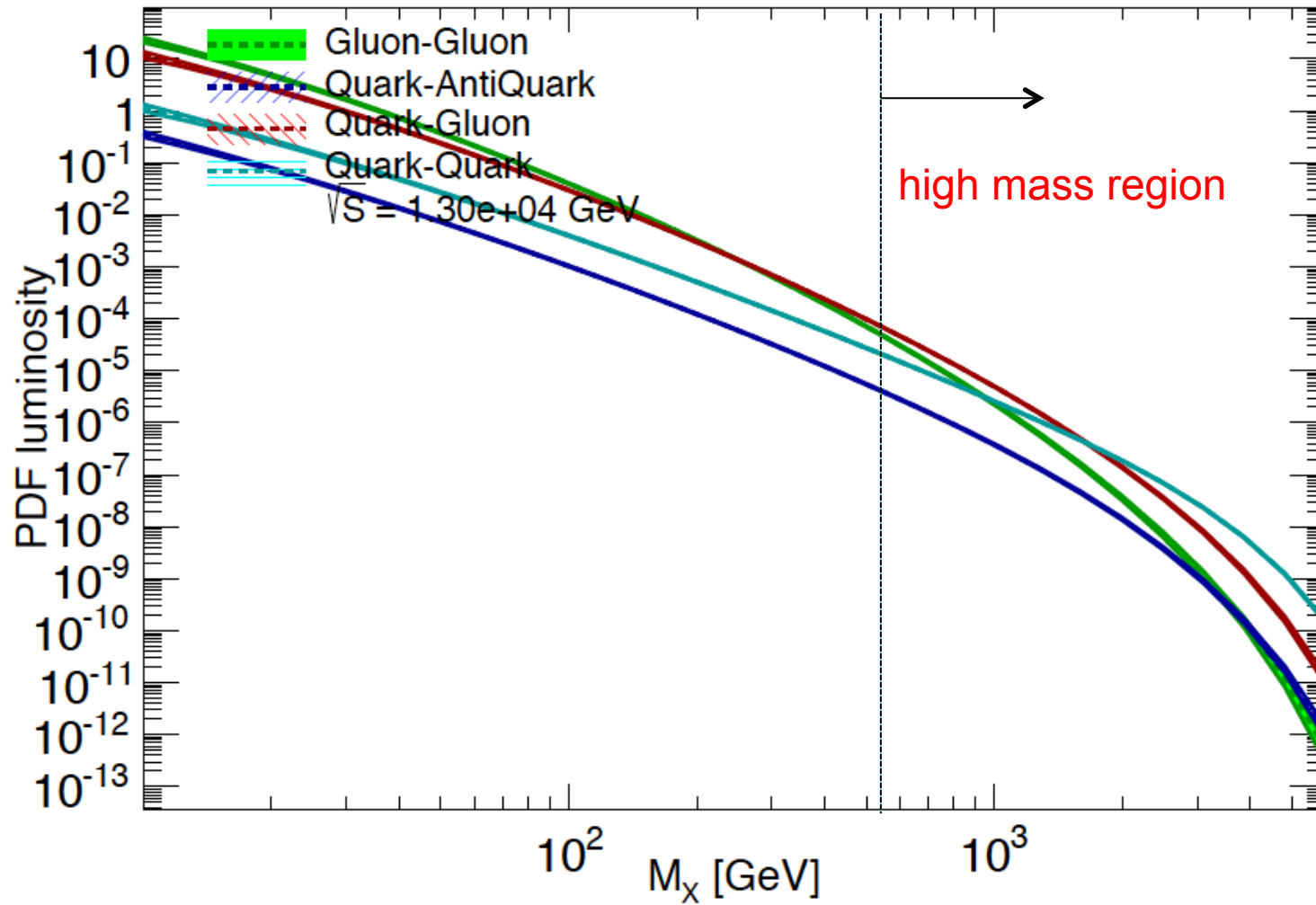
$$\frac{dL_{ij}}{d\hat{s} dy} = \frac{1}{s} \frac{1}{1 + \delta_{ij}} [f_i(x_1, \mu) f_j(x_2, \mu) + (1 \leftrightarrow 2)] . \text{ ...or integrated over } y$$



# PDF luminosities



## CT14 NNLO luminosities



Generated with APFEL 2.4.0 Web



# PDFs: pre-history



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

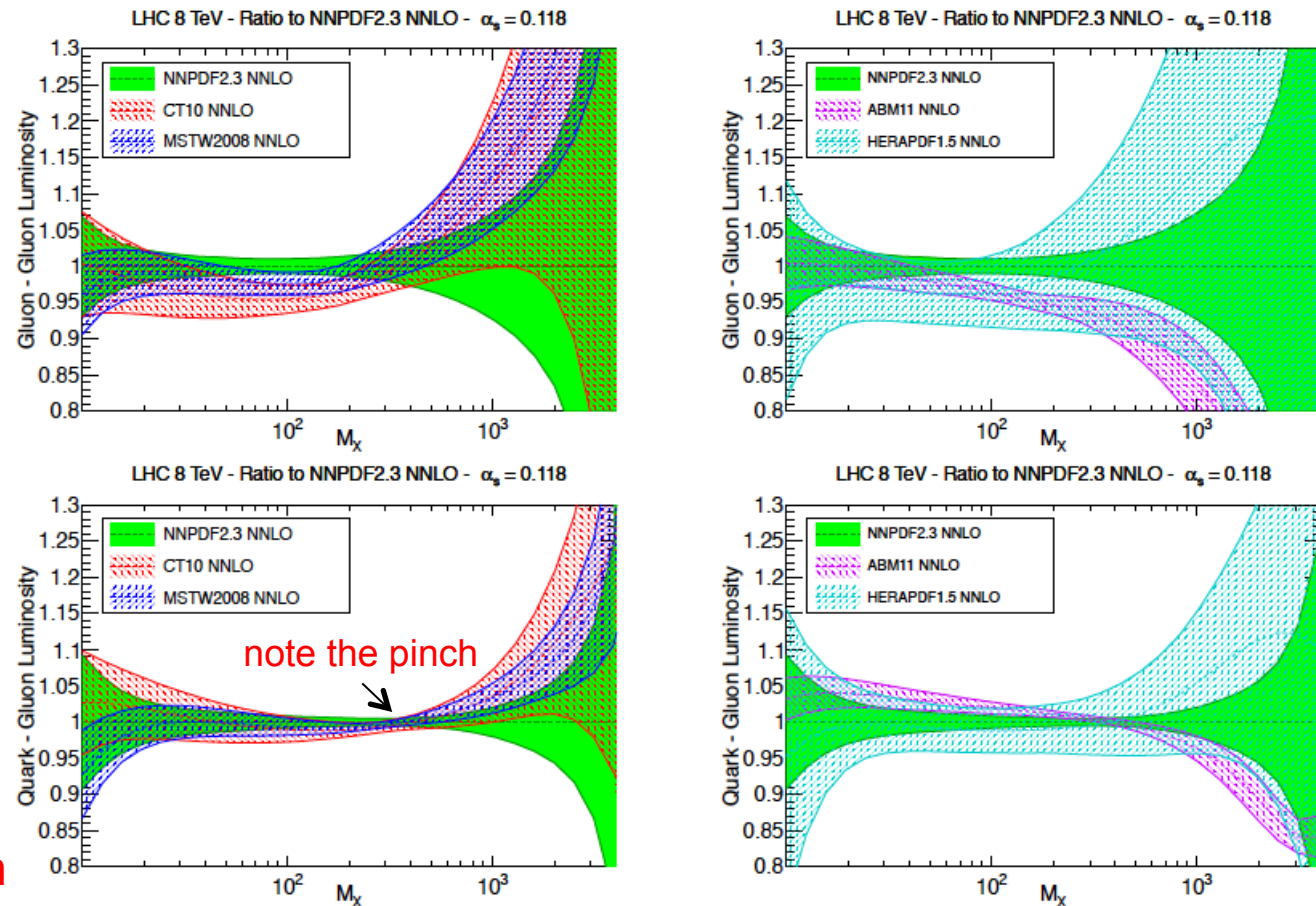


Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass  $M_X$  (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5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

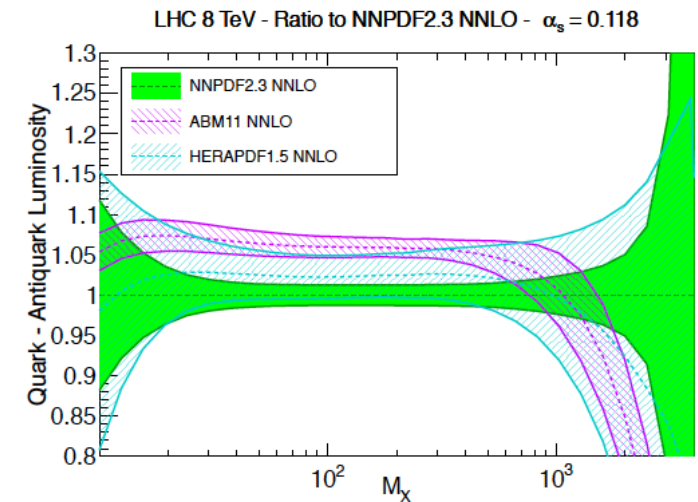
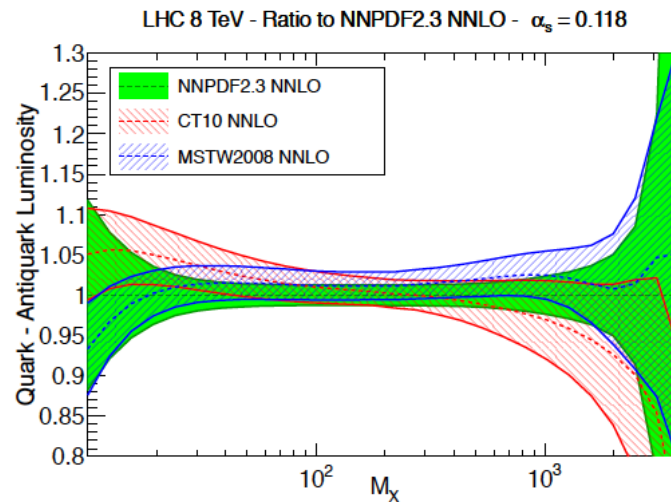


# PDF luminosities

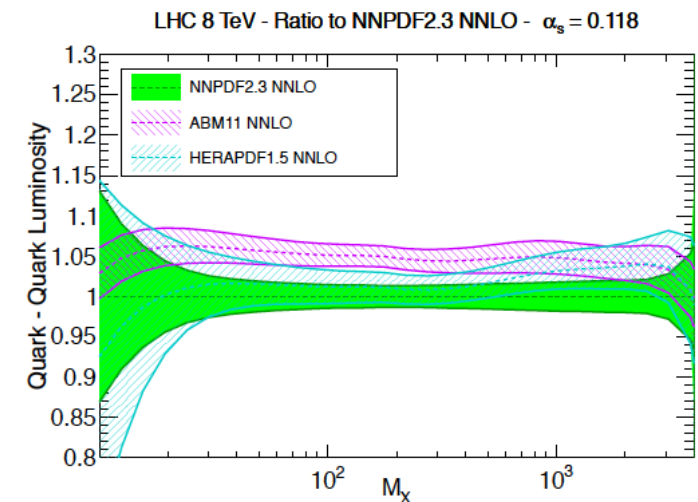
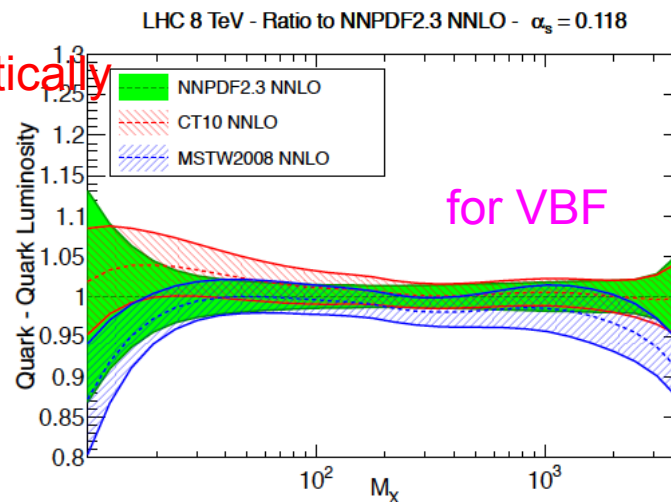


## quark-quark and quark-antiquark

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

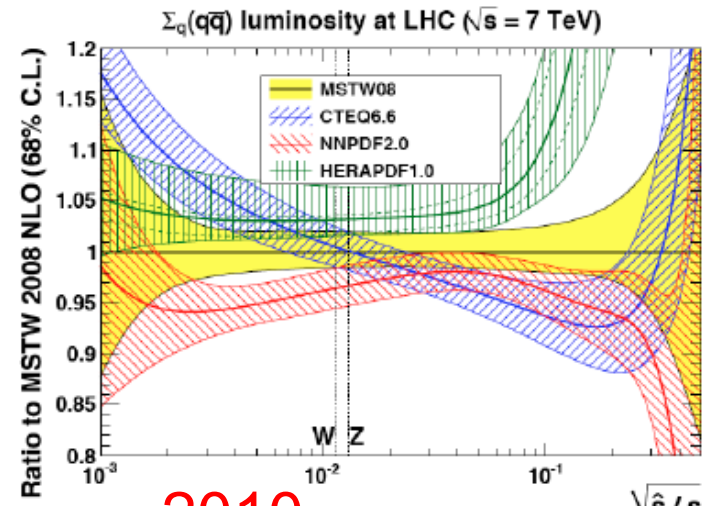




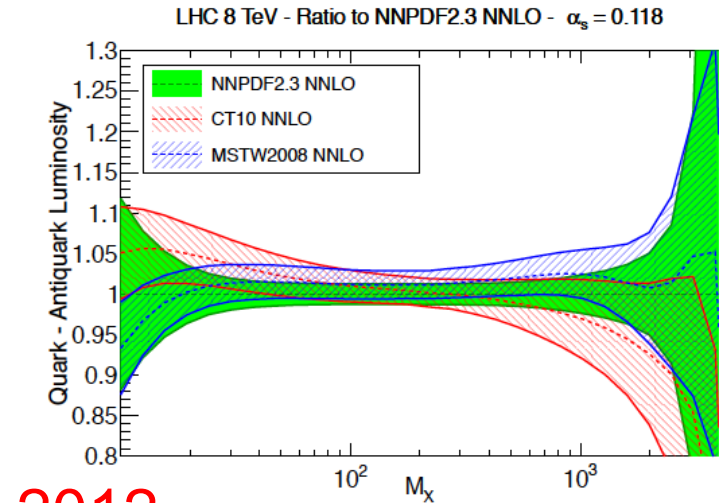
# Uncertainties had improved



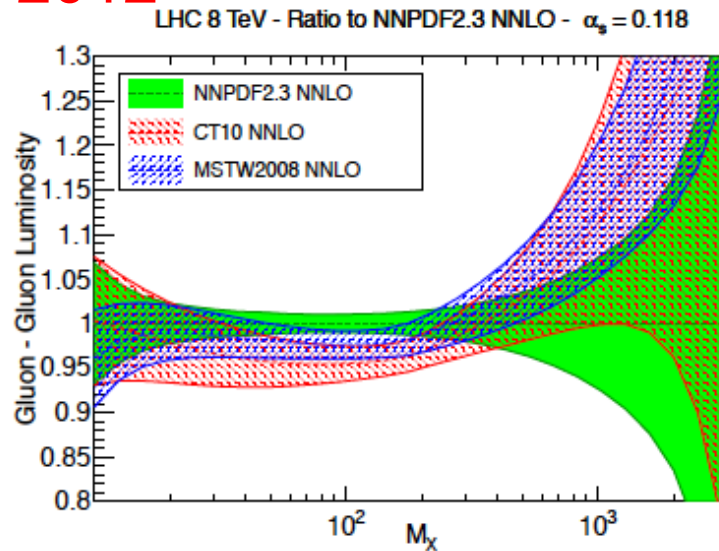
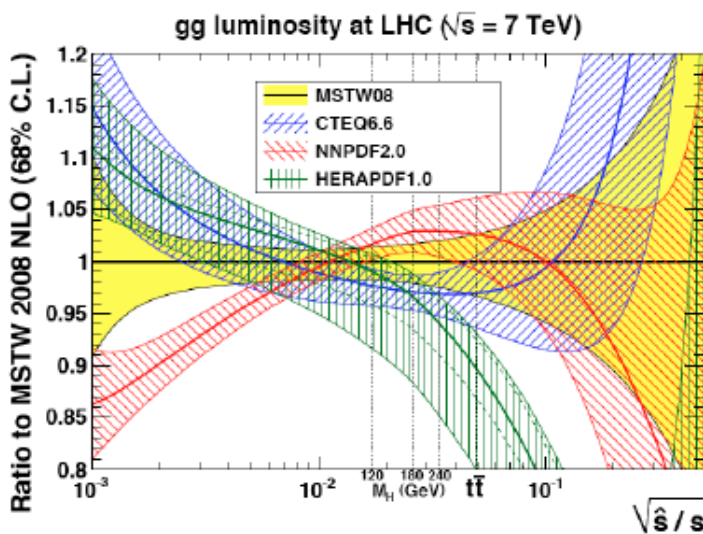
- ...with additional data and in going from NLO to NNLO



2010



2012

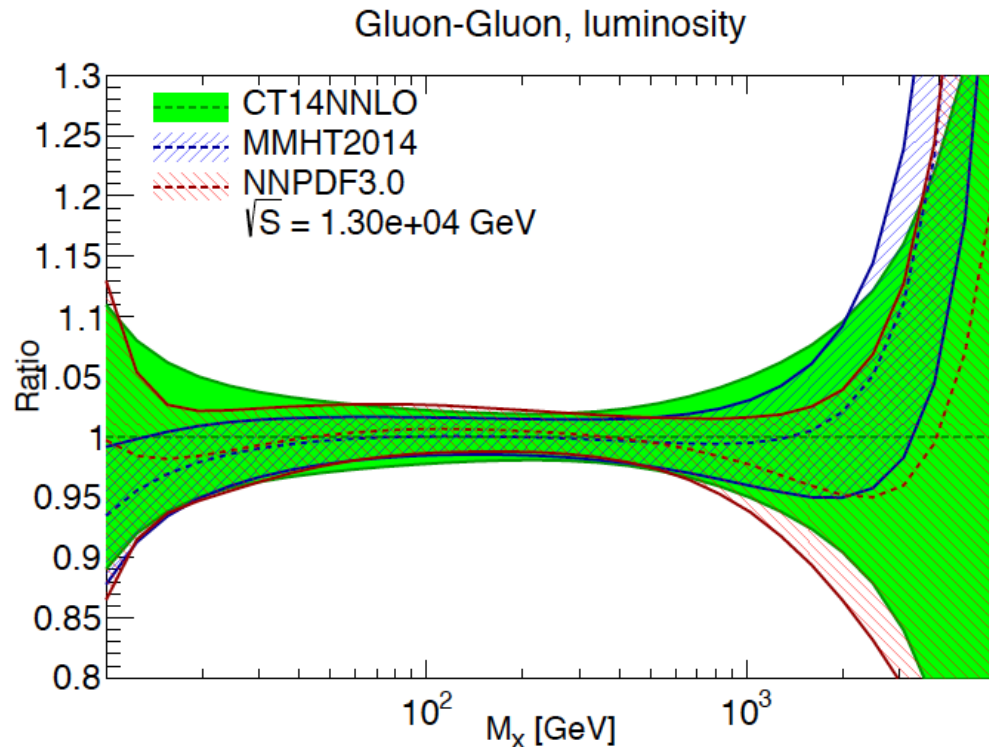




# PDFs: the next generation



- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (arXiv:1506.07443)
- HERAPDF2.0 (arXiv:1506.06042)
- The gg PDF luminosities for the first three PDFs are in good agreement with each other in the *precision physics* mass range, less so at very high mass



NNPDF down by 2-2.5%, CT14 up by ~1%,  
MMHT14 down by ~0.5%

partially data, partially corrections in  
fitting code, partially changes  
in fitting procedures

lead to new PDF4LHC recommendations

## PDF4LHC recommendations for LHC Run II

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# A comparison of ggF at NNLO

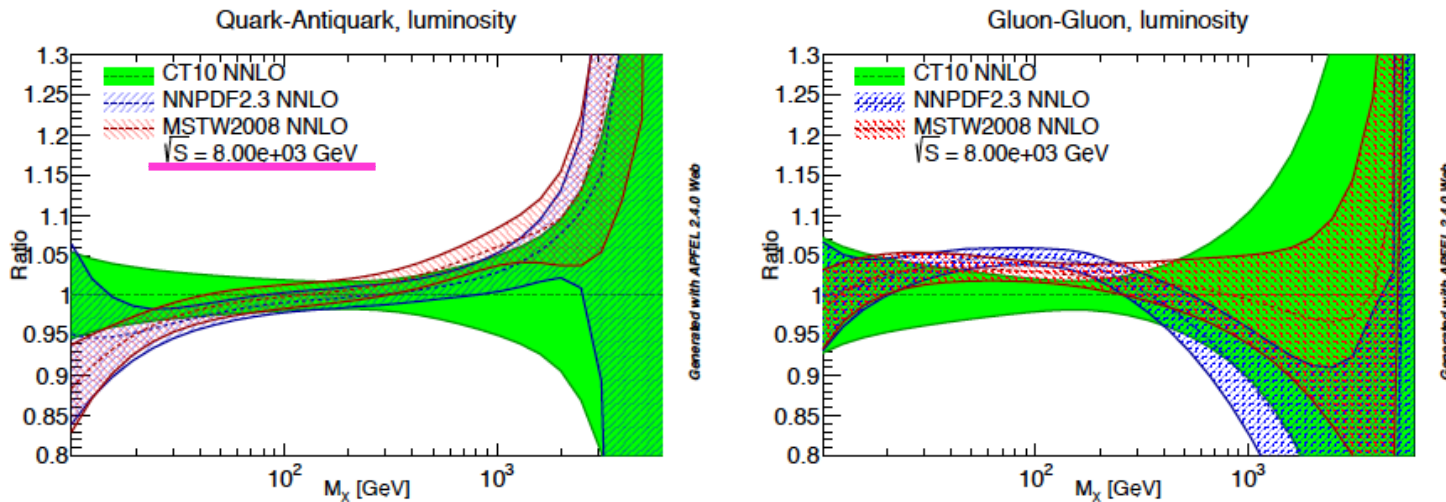
	CT14	MMHT2014	NNPDF3.0
<b>scale = <math>m_H</math></b>			
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

The PDF uncertainty using this new generation of PDFs (2-3%) is similar in size to the NNLO scale uncertainty and to the  $\alpha_s(m_Z)$  uncertainty.





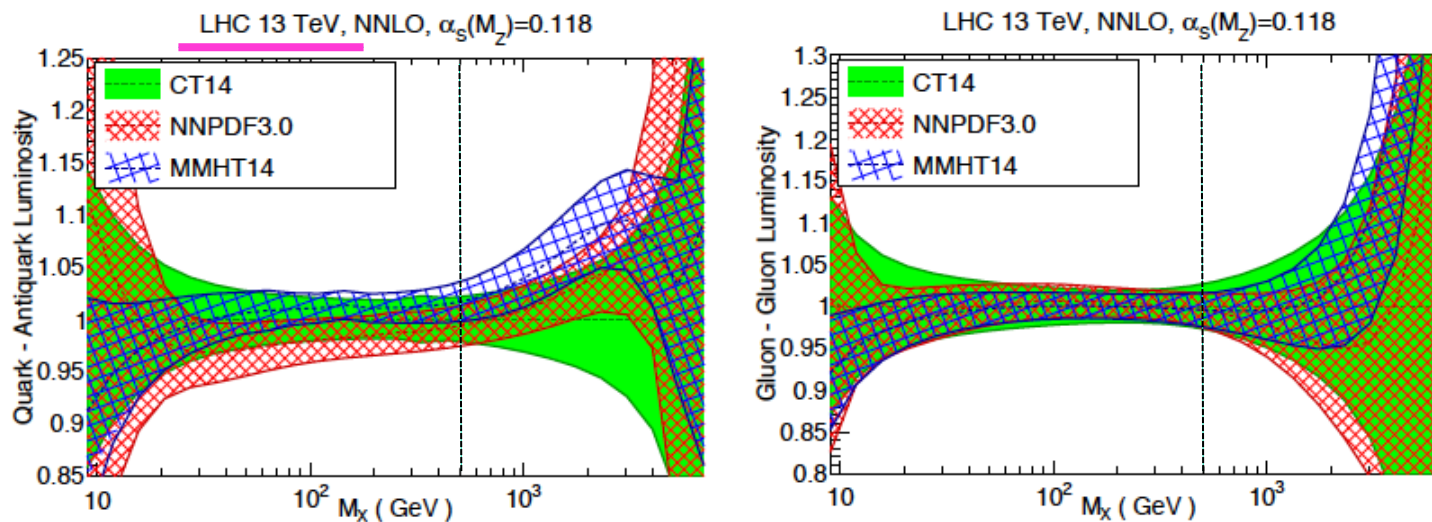
# Progress with recent PDFs



Note in particular the changes in the  $gg$  luminosity, especially important in the Higgs mass region

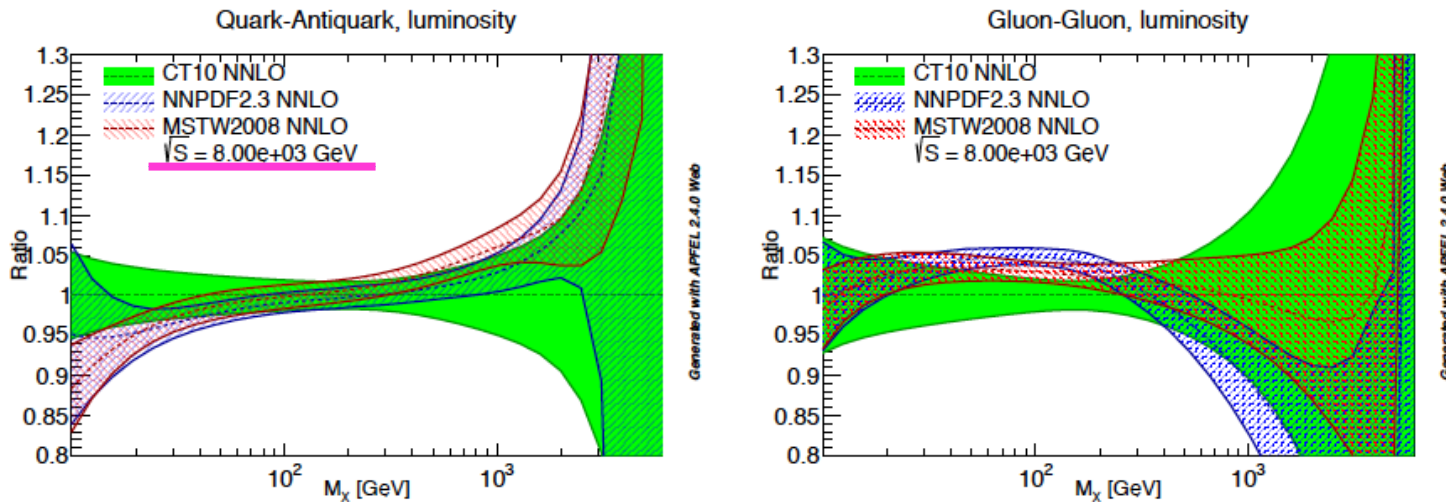
Figure 1: Comparison of the  $q\bar{q}$  (left) and  $gg$  (right) PDF luminosities at the LHC 8 TeV for CT10, MSTW2008 and NNPDF2.3. Results are shown normalized to the central value of CT10.

Note also differences remaining in high mass region





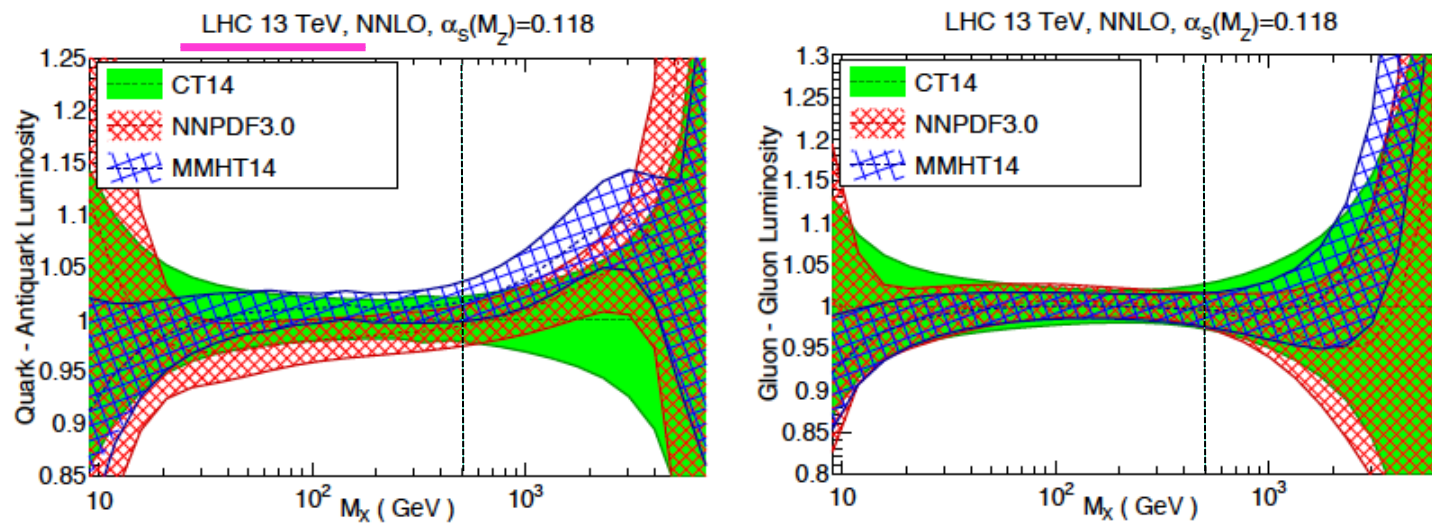
# Progress with recent PDFs



The gg precision has improved, but the qq has not.

We hope (and think) we are making progress, but next generation of PDFs could lead to somewhat different behavior, either data or formalism.

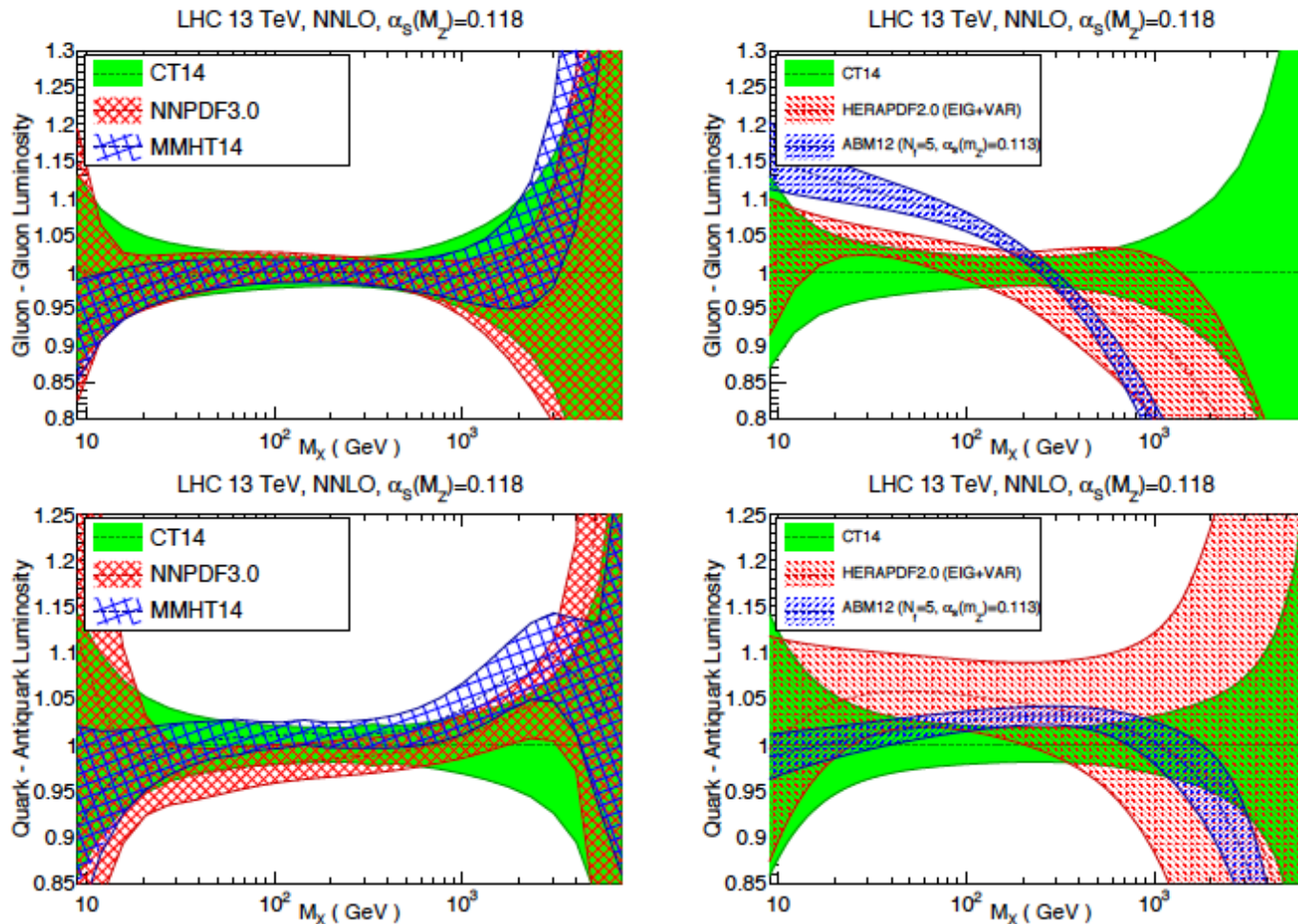
Figure 1: Comparison of the  $q\bar{q}$  (left) and  $gg$  (right) PDF luminosities at the LHC 8 TeV for CT10, MSTW2008 and NNPDF2.3. Results are shown normalized to the central value of CT10.



The variation from generation to generation is related to the accuracy of the PDF sets



# Other new sets out as well



behavior for  
HERAPDF2.0  
and ABM12  
somewhat  
different

HERAPDF2.0  
uncertainties  
tend to be  
larger

ABM12  
uncertainties  
tend to be smaller

Figure 5: Comparison of the gluon-gluon (upper plots) and quark-antiquark (lower plots) PDF luminosities from the CT14, MMHT14 and NNPDF3.0 NNLO sets (left plots) and from the NNPDF3.0, ABM12 and HERAPDF2.0 NNLO sets (right plots), for a center-of-mass energy of 13 TeV, as a function of the invariant mass of the final state  $M_X$ .

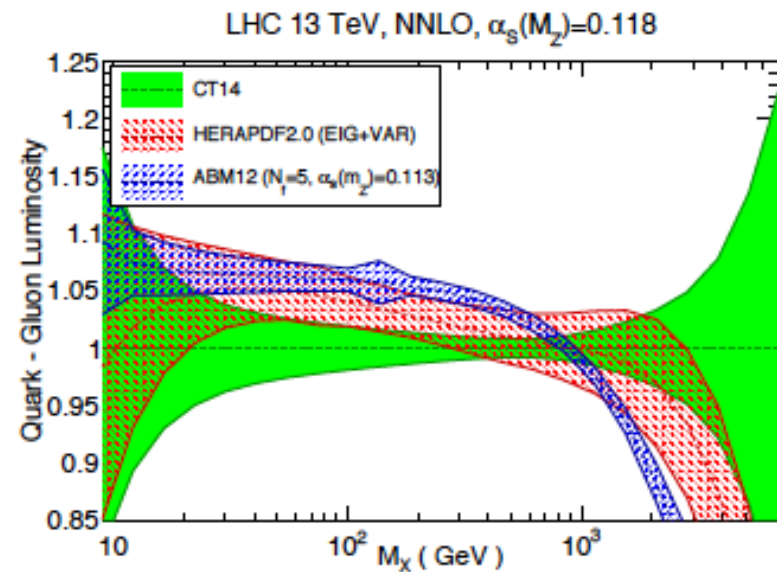
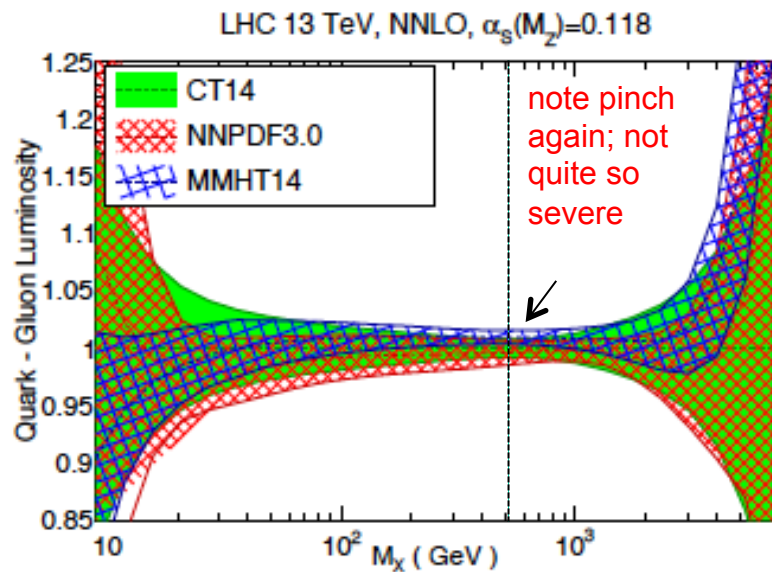
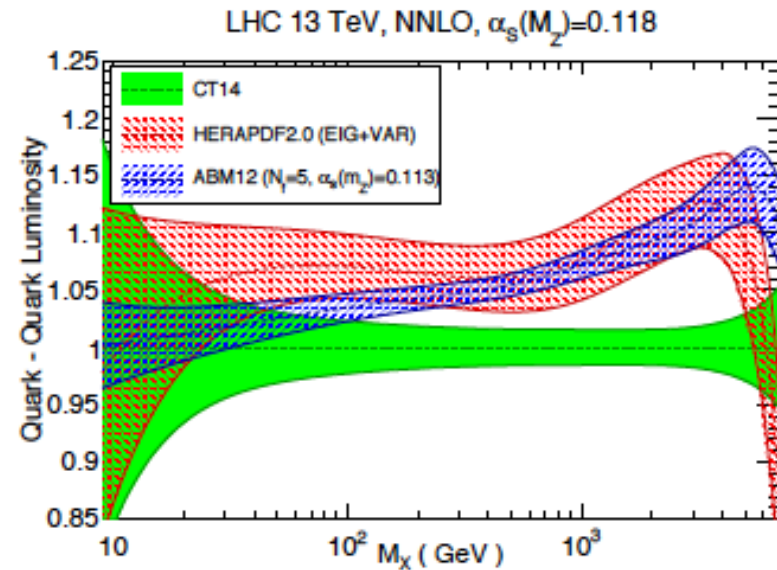
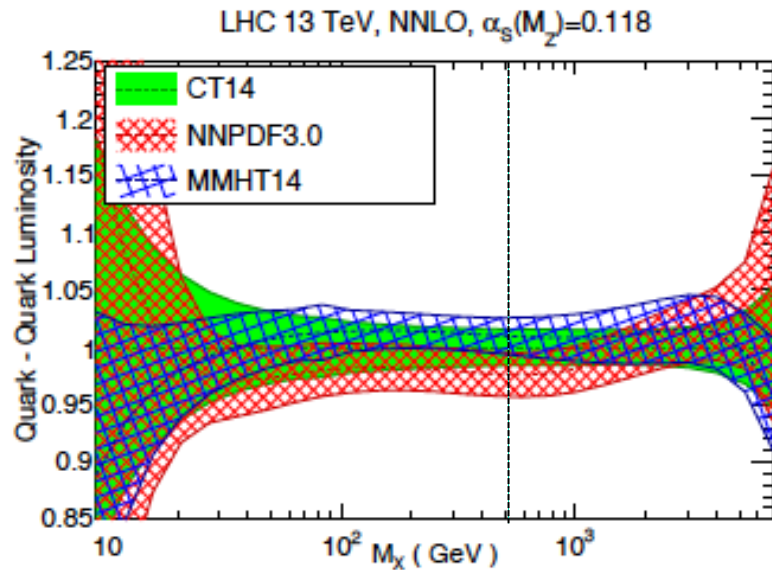


Figure 6: Same as Fig. 5 for the quark-quark (upper plots) and the quark-gluon (lower plots) PDF luminosities.



# Three main uses of PDFs at LHC



1. Assessment of the total uncertainty on a cross section based on the available knowledge of PDFs, *e.g.*, when computing the cross section for a process that has not been measured yet (such as supersymmetric particle production cross-sections), or for estimating acceptance corrections on a given observable. This is also the case of the measurements that aim to verify overall, but not detailed, consistency with Standard Model expectations, such as when comparing theory with Higgs measurements.
2. Assessment of the accuracy of the PDF sets themselves or of related Standard Model parameters, typically done by comparing theoretical predictions using individual PDF sets to the most precise data available.
3. Input to the Monte Carlo event generators used to generate large MC samples for LHC data analysis.

**For 2), use individual PDF sets.**

For 1), a more general uncertainty requires more than the use of 1 PDF set.

For 3), may want to use an average of PDF sets. This point seems to be confusing to some, i.e. you can use PDF4LHC15 PDFs for MC generation.



# What PDFs to use?

1. The PDF sets to be combined should be based on a global dataset, including a large number of datasets of diverse types (deep-inelastic scattering, vector boson and jet production, ...) from fixed-target and colliders experiments (HERA, LHC, Tevatron).
2. Theoretical hard cross sections for DIS and hadron collider processes should be evaluated up to two QCD loops in  $\alpha_s$ , in a general-mass variable-flavor number scheme with up to  $n_f^{\text{max}} = 5$  active quark flavors.<sup>1</sup> Evolution of  $\alpha_s$  and PDFs should be performed up to three loops, using public codes such as HOPPET [105] or QCDNUM [106], or a code benchmarked to these.
3. The central value of  $\alpha_s(m_Z^2)$  should be fixed at an agreed common value, consistent with the PDG world-average [107]. This value is currently chosen to be  $\alpha_s(m_Z^2) = 0.118$  at both NLO and NNLO.<sup>2</sup> For the computation of  $\alpha_s$  uncertainties, two additional PDF members corresponding to agreed upper and lower values of  $\alpha_s(m_Z^2)$  should also be provided. This uncertainty on  $\alpha_s(m_Z^2)$  is currently assumed to be  $\delta\alpha_s = 0.0015$ , again the same at NLO and NNLO.
4. All known experimental and procedural sources of uncertainty should be properly accounted for. Specifically, it is now recognized that the PDF uncertainty receives several contributions of comparable importance: the measurement uncertainty propagated from the experimental data, uncertainties associated with incompatibility of the fitted experiments, procedural uncertainties such as those related to the functional form of PDFs, the handling of systematic errors, etc. Sets entering the combination must account for these through suitable methods, such as separate estimates for additional model and parametrization components of the PDF uncertainty [9], tolerance [6, 10], or closure tests [11].



# Monte Carlo representation



- So based on the criteria on the previous slide, we use CT14, MMHT2014 and NNPDF3.0, with the option of adding additional sets in future upgrades if they satisfy the listed criteria
- In the previous recommendation, we used an envelope of 3 PDF sets; envelope determined by outliers
- Given the level of agreement of the 3 PDFs that will be used, try for a more relevant statistical approach
- Generate Monte Carlo replicas, equal numbers from error PDF sets of CT14, MMHT2014 and NNPDF3.0 using Thorne-Watt procedure
  - ◆ replicas generated from Hessian eigenvectors for CT14 and MMHT14 assuming a Gaussian probability distribution
  - ◆ this will lead to a more statistical representation of the uncertainty than the envelope procedure used previously



# Aside



...a different opinion, basically stating that all PDFs should be used for a general estimate of the total uncertainty

arXiv:1603.08906v2 [hep-ph] 8 Aug 2016

## A Critical Appraisal and Evaluation of Modern PDFs

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### Abstract:

We review the present status of the determination of parton distribution functions (PDFs) in the light of the precision requirements for the LHC in Run 2 and other future hadron colliders. We provide brief reviews of all currently available PDF sets and use them to compute cross sections for a number of benchmark processes, including Higgs boson production in gluon-gluon fusion at the LHC. We show that the differences in the predictions obtained with the various PDFs are due to particular theory assumptions made in the fits of those PDFs. We discuss PDF uncertainties in the kinematic region covered by the LHC and on averaging procedures for PDFs, such as advocated by the PDF4LHC15 sets, and provide recommendations for the usage of PDF sets for theory predictions at the LHC.





# The result



## Gluon-Fusion Higgs production, LHC 13 TeV

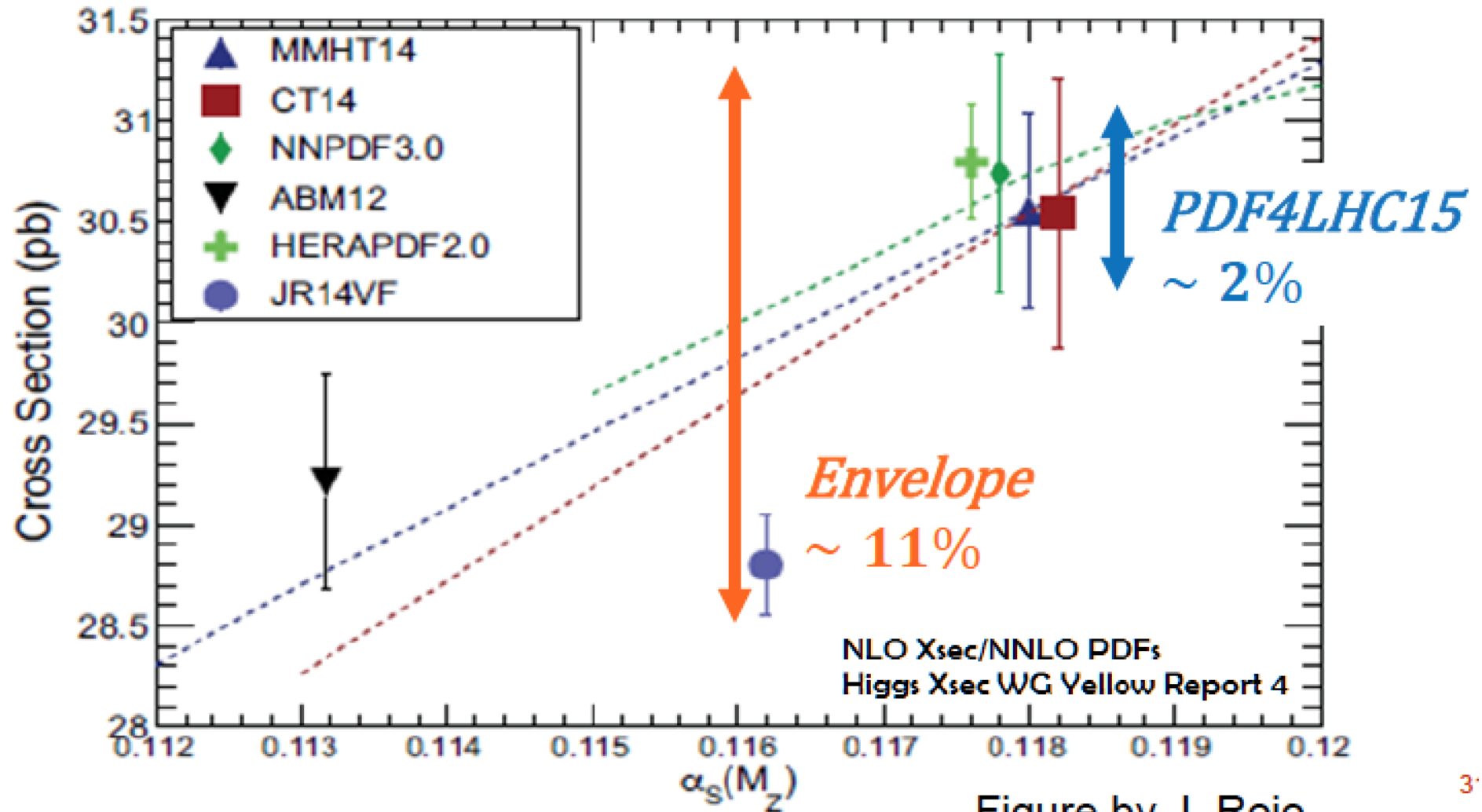
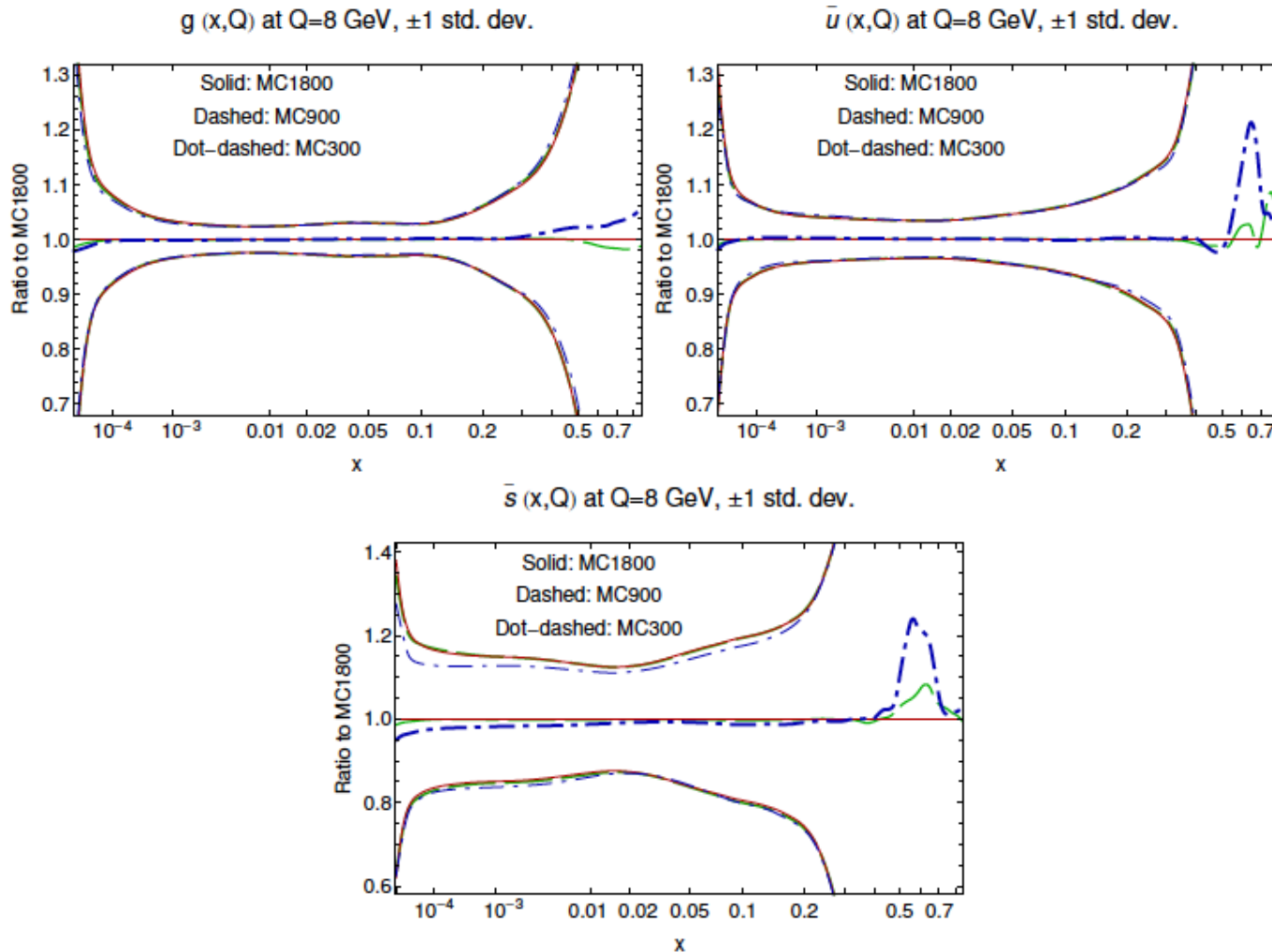


Figure by J. Rojo



# Monte Carlo replicas



900 replicas seems enough

->MC900 or PDF4LHC\_prior

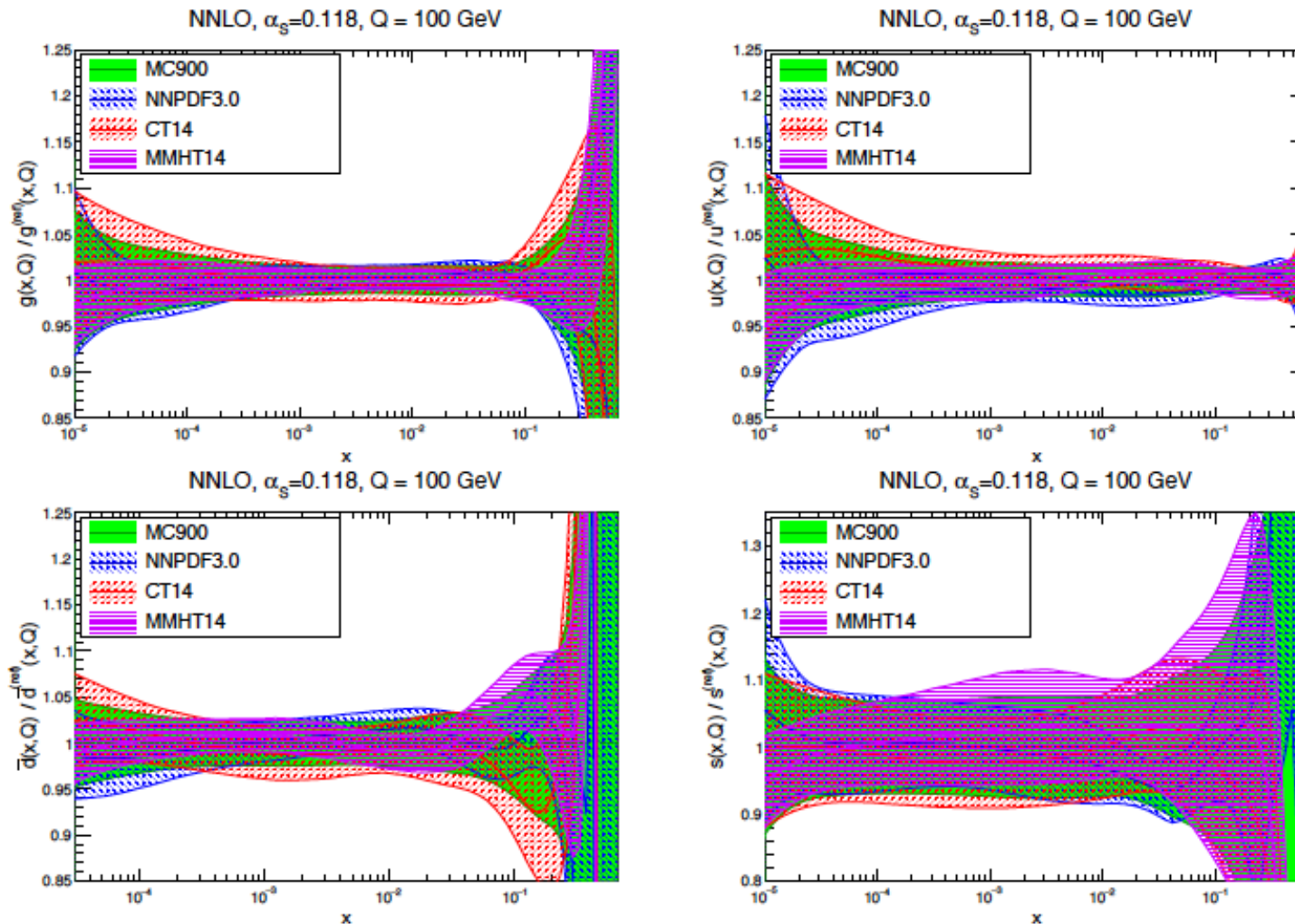
note that here we are trying for *precision*

the *accuracy* is another question. that is outside the realm of choosing a given number of replicas

Figure 7: Comparison of central values and uncertainties for the MC combination of CT14, MMHT14 and NNPDF3.0 for different values of  $N_{rep}$ , 300, 600 and 900, denoted by MC300, MC900 and MC1800 respectively.



# MC900



Note that MC900 is not the envelope of the 3 PDF error bands

The PDF error bands themselves are similar for the precision physics region, but not for low mass/high mass

Figure 8: Comparison of the MC900 PDFs with the sets that enter the combination: CT14, MMHT14 and NNP3.0 at NNLO. We show the gluon and the up, anti-down and strange quarks at  $Q = 100$  GeV. Results are normalized to the central value of MC900.



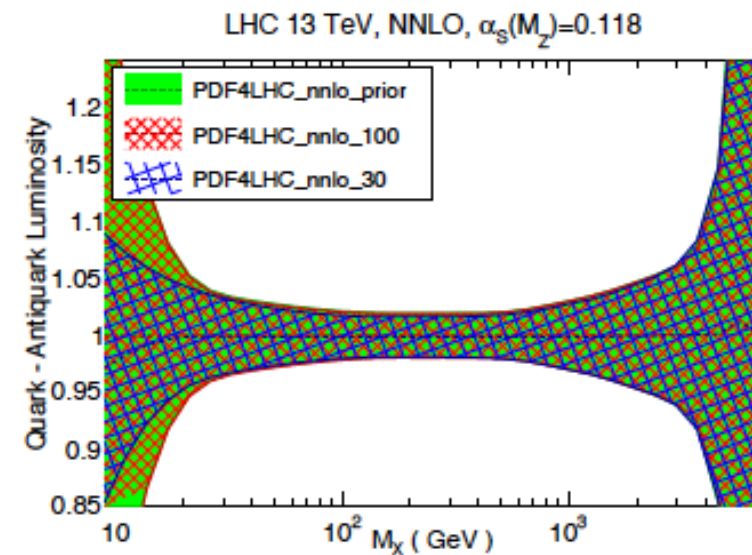
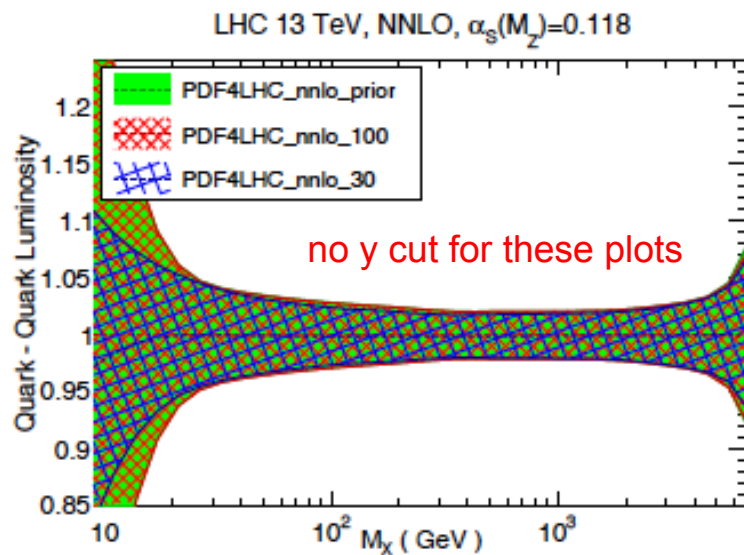
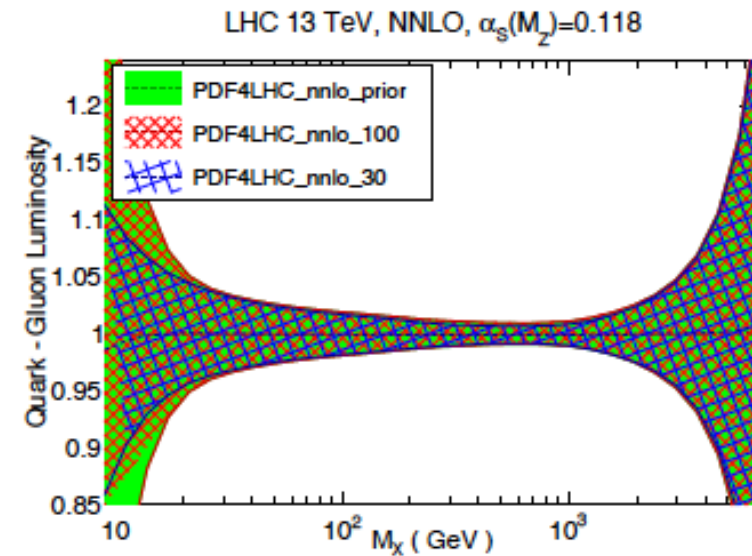
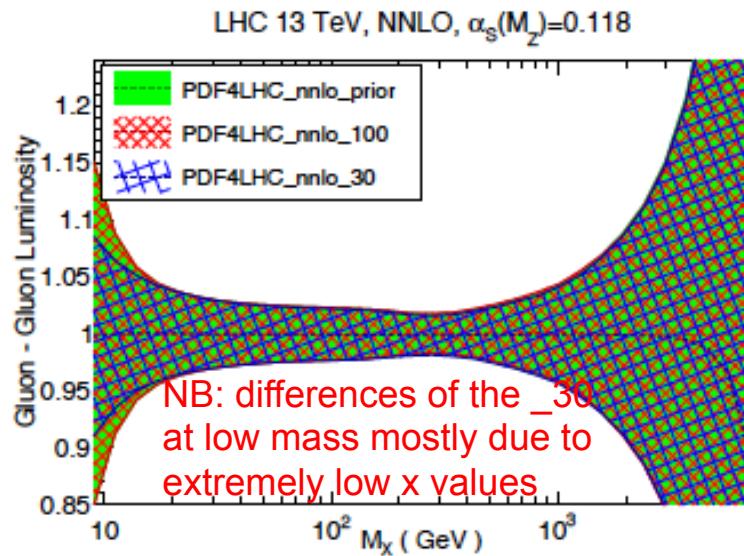
# Reduced sets



- 900 error PDFs are too much for general use
- We would like to reduce this number while still maintaining as much information on the uncertainties and on correlations between PDF uncertainties as possible
- We have settled on 3 techniques/outputs
  - ◆ Compressed Monte Carlo PDFs (PDF4LHC15\_nnlo(nlo)\_mc)
    - ▲ 100 PDF error sets; preserve non-Gaussian errors
  - ◆ META Hessian PDFs (PDF4LHC15\_nnlo(nlo)\_30)
    - ▲ 30 PDF error sets using METAPDF technique; Gaussian (symmetric) errors
  - ◆ MCH Hessian PDFs (PDF4lhc15\_nnlo(nlo)\_100)
    - ▲ 100 PDF error sets using MCH technique; Gaussian (symmetric errors)
- The META technique is able to more efficiently reproduce the uncertainties when using a limited number (30) of error PDFs
- The MCH technique best reproduces the uncertainties of the 900 MC set prior->**precision, not accuracy**



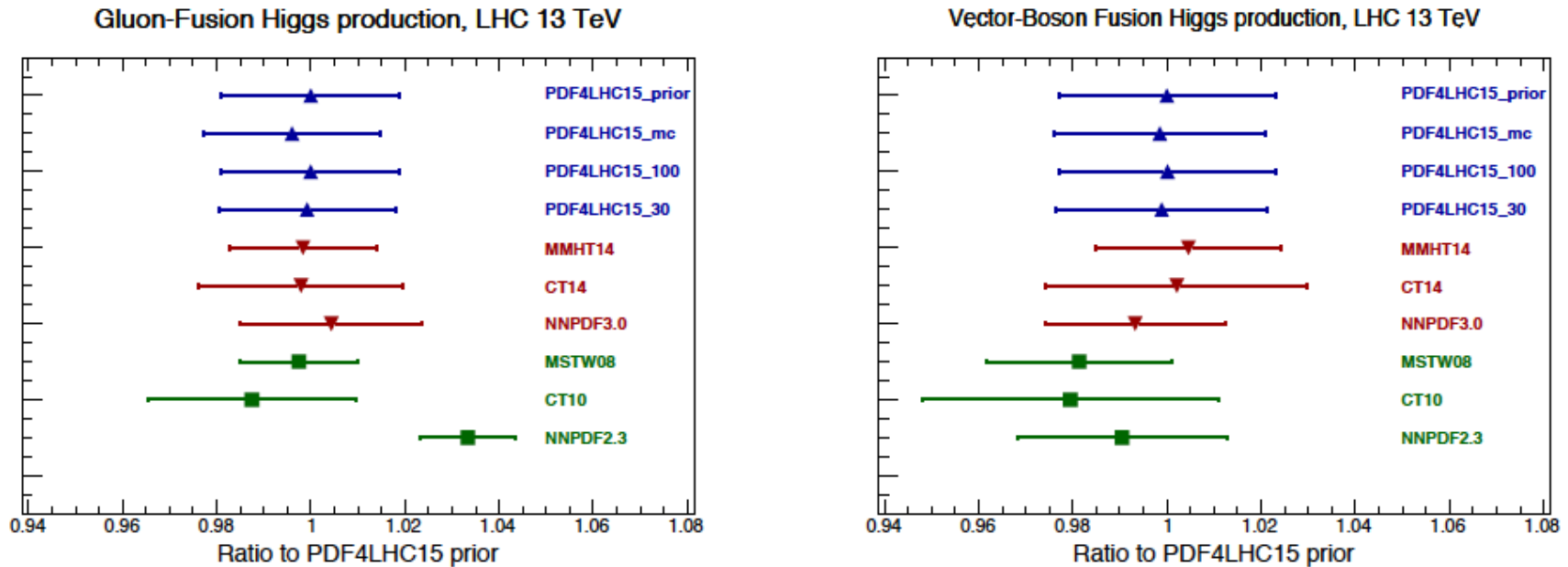
# Some comparisons: Hessian sets



...again, high mass uncertainty is smaller than envelope of 3 input PDFs



# Some comparisons for Higgs production

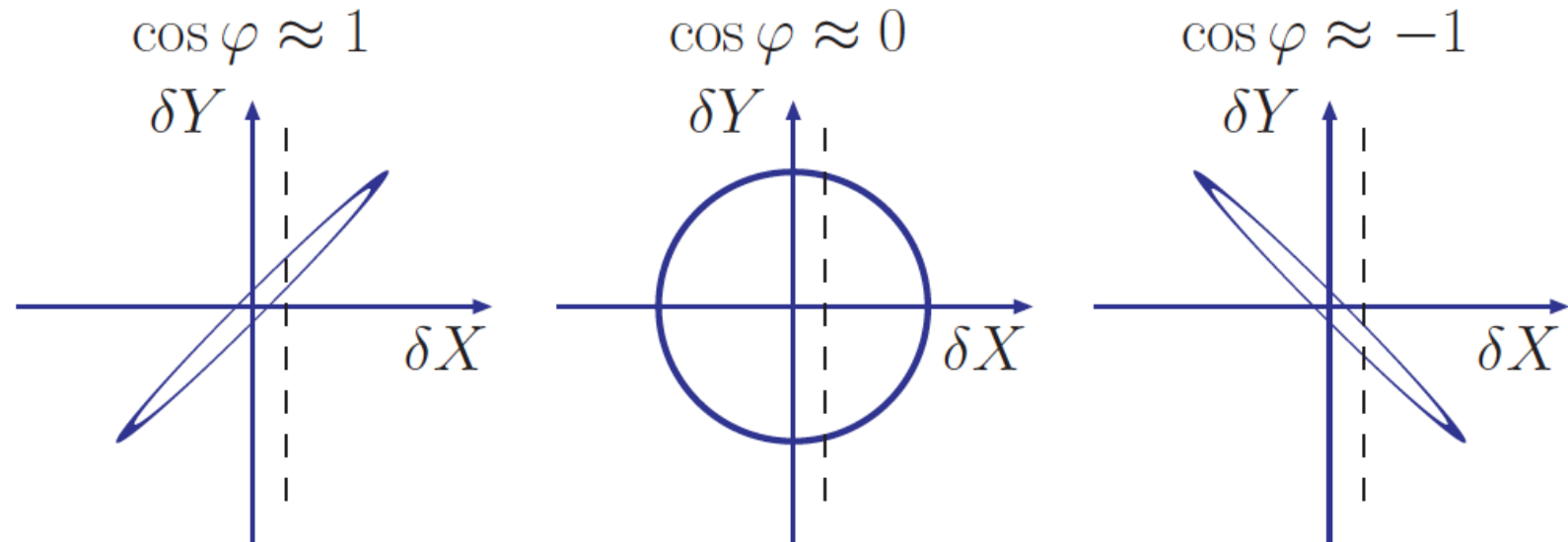


**Fig. 6.32** A comparison of the predictions for Higgs boson production through  $gg$  fusion (left) and vector boson fusion (right) is shown for a center-of-mass energy of 13 TeV,



# Correlations

- Useful to look at correlations of PDFs or of cross sections



**Fig. 6.23** Correlations ellipses for a strong correlation (left), no correlation (center) and a strong anti-correlation(right) [711].



PDF Set	Correlation coefficient					
	$Z, W$	$Z, t\bar{t}$	$Z, ggh$	$Z, ht\bar{t}$	$Z, hW$	$Z, hZ$
PDF4LHC15_nlo_prior	0.90	-0.60	0.22	-0.64	0.55	0.74
PDF4LHC15_nlo_mc	0.92	-0.49	0.41	-0.58	0.61	0.77
PDF4LHC15_nlo_100	0.92	-0.60	0.23	-0.64	0.57	0.75
PDF4LHC15_nlo_30	0.90	-0.68	0.16	-0.71	0.55	0.76
PDF4LHC15_nnlo_prior	0.89	-0.49	0.08	-0.46	0.56	0.74
PDF4LHC15_nnlo_mc	0.90	-0.44	0.18	-0.42	0.62	0.80
PDF4LHC15_nnlo_100	0.91	-0.48	0.09	-0.46	0.59	0.74
PDF4LHC15_nnlo_30	0.88	-0.63	0.04	-0.61	0.56	0.72

Table 1: Correlation coefficient between the  $Z$  production cross-sections and the  $W$ ,  $t\bar{t}$ ,  $ggh$ ,  $ht\bar{t}$ ,  $hW$  and  $hZ$  production cross-sections. The PDF4LHC15 prior is compared to the Monte Carlo and the two Hessian reduced sets, both at NLO and at NNLO.

PDF Set	Correlation coefficient					
	$W, t\bar{t}$	$W, ggh$	$W, ht\bar{t}$	$W, hW$	$W, hZ$	$t\bar{t}, ggh$
PDF4LHC15_nlo_prior	-0.46	0.32	-0.51	0.77	0.78	0.27
PDF4LHC15_nlo_mc	-0.35	0.49	-0.46	0.81	0.80	0.27
PDF4LHC15_nlo_100	-0.47	0.32	-0.52	0.77	0.79	0.27
PDF4LHC15_nlo_30	-0.52	0.28	-0.56	0.79	0.81	0.32
PDF4LHC15_nnlo_prior	-0.40	0.20	-0.40	0.76	0.77	0.30
PDF4LHC15_nnlo_mc	-0.44	0.26	-0.42	0.81	0.82	0.32
PDF4LHC15_nnlo_100	-0.40	0.20	-0.40	0.76	0.77	0.30
PDF4LHC15_nnlo_30	-0.47	0.19	-0.47	0.77	0.76	0.31

Table 2: Same as Table 1 for the correlation coefficient of additional pairs of LHC inclusive cross-

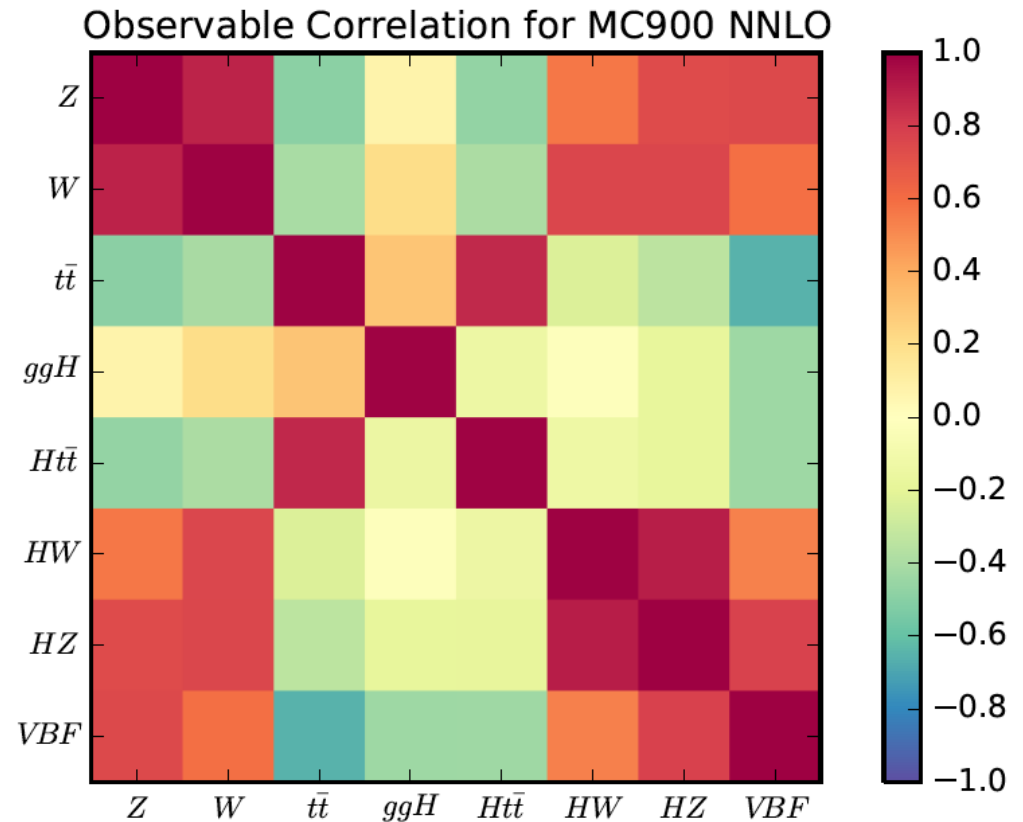
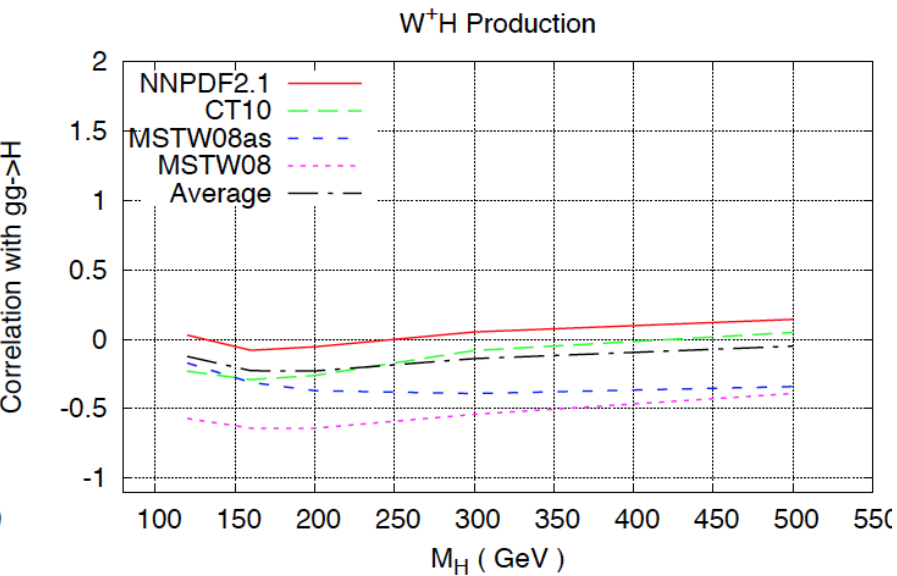




# Correlations



probably only 1 digit for the correlations is significant, so plot like on right is more relevant



→ correlations can differ significantly for example from the individual PDFs

from YR2



# (Relatively) New



## ● Photon PDFs

- ◆ the photon is a constituent of the proton just as quarks and gluons are
- ◆ it also evolves just as quarks and gluons do, but with Abelian splitting kernels
- ◆ it's much smaller than the other PDFs and there are fewer experimental handles to try to estimate its size
- ◆ but as it has implications for high mass physics, such as VV (or for a hypothetical particle at 750 GeV which could have been produced by a  $\gamma\gamma$  initial state), or EW corrections for just about any LHC final state, it's something we have to understand better

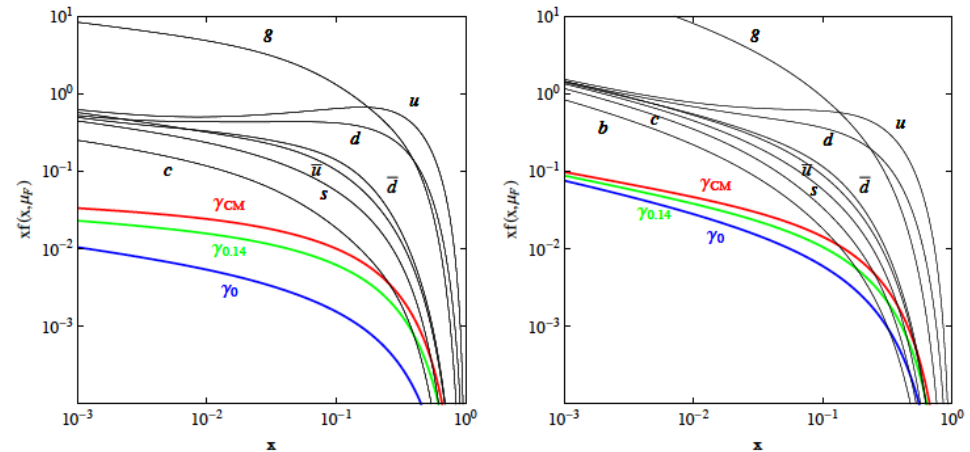
The evolution of the PDFs,  $f(x, \mu_F)$ , including QED contributions at leading order (LO) and QCD contributions at higher orders, is described by the equations:

$$\frac{df_{q_i}}{dt} = \frac{\alpha_s}{2\pi} \left( \sum_j (P_{q_i q_j} \circ f_{q_j} + P_{q_i g} \circ f_g) + P_{qg} \circ f_g \right) + \frac{\alpha}{2\pi} e_i^2 \left( \tilde{P}_{qq}^{(0)} \circ f_{q_i} + \tilde{P}_{q\gamma}^{(0)} \circ f_\gamma \right)$$

$$\frac{df_{\bar{q}_i}}{dt} = \frac{\alpha_s}{2\pi} \left( \sum_j (P_{\bar{q}_i \bar{q}_j} \circ f_{\bar{q}_j} + P_{\bar{q}_i g} \circ f_g) + P_{g\bar{q}} \circ f_g \right) + \frac{\alpha}{2\pi} e_i^2 \left( \tilde{P}_{q\bar{q}}^{(0)} \circ f_{\bar{q}_i} + \tilde{P}_{q\gamma}^{(0)} \circ f_\gamma \right)$$

$$\frac{df_g}{dt} = \frac{\alpha_s}{2\pi} \left( P_{gg} \circ f_g + \sum_i P_{gq} \circ (f_{q_i} + f_{\bar{q}_i}) \right) \quad (2)$$

$$\frac{df_\gamma}{dt} = \frac{\alpha}{2\pi} \left( \tilde{P}_{\gamma\gamma}^{(0)} \circ f_\gamma + \sum_i e_i^2 \tilde{P}_{\gamma q}^{(0)} \circ (f_{q_i} + f_{\bar{q}_i}) \right),$$



arXiv:1509.02905

FIG. 1: Plots of  $xf(x, \mu_F)$  for  $\mu_F = 3.2$  GeV (left) and  $\mu_F = 85$  GeV (right). Three representative photon PDFs are plotted: the “Current Mass” photon PDF ( $\gamma_{CM}$ , red), and photon PDFs with initial photon momenta fractions of  $p_0^\gamma = 0$  and 0.14% ( $\gamma_0$ , blue, and  $\gamma_{0.14}$ , green, respectively). The effect of the different initial photon PDFs on the quark and gluon PDFs is imperceptible in these plots.



# Photon PDFs



- MRST were the first
  - parametrize inelastic\* contribution to the photon at initial scale  $Q_0$  as

$$f_{\gamma/p}(x, Q_0) = \frac{\alpha}{2\pi} \left( A_u e_u^2 \tilde{P}_{\gamma q} \circ u^0(x) + A_d e_d^2 \tilde{P}_{\gamma q} \circ d^0(x) \right)$$

- $P_{\gamma q_0} f_0(x)$  is the convolution of the quark to photon splitting function with the primordial quark distribution
  - define  $A_i = \ln(Q^2/Q_i^2)$ , and setting  $Q_i$  to current quark masses; alternatively use constituent quark masses
- CT14qed followed a similar approach, but fitting to DIS data with isolated photons from ZEUS that allowed a constraint on the total photon momentum

- NNPDF2.3 used a more general photon parametrization, allowing photon to be fit to data (W,Z, Drell-Yan); this implicitly includes an elastic component as well

\*There is also an elastic component for the photon in which the proton remains intact. See, for example, arxiv:1607.04635.

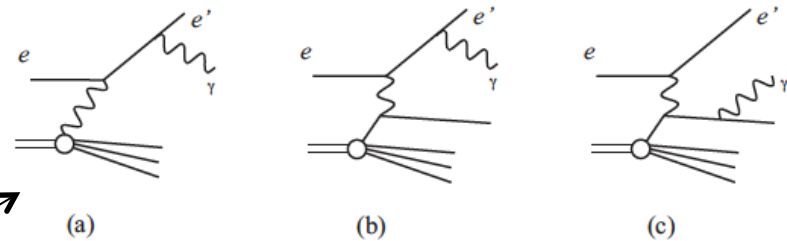
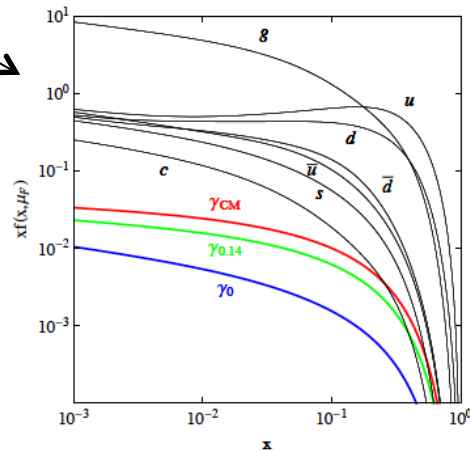


FIG. 3: Amplitudes for the process  $ep \rightarrow e\gamma + X$ . For each diagram shown there is an additional diagram where the photon is emitted off the initial-state lepton or quark.

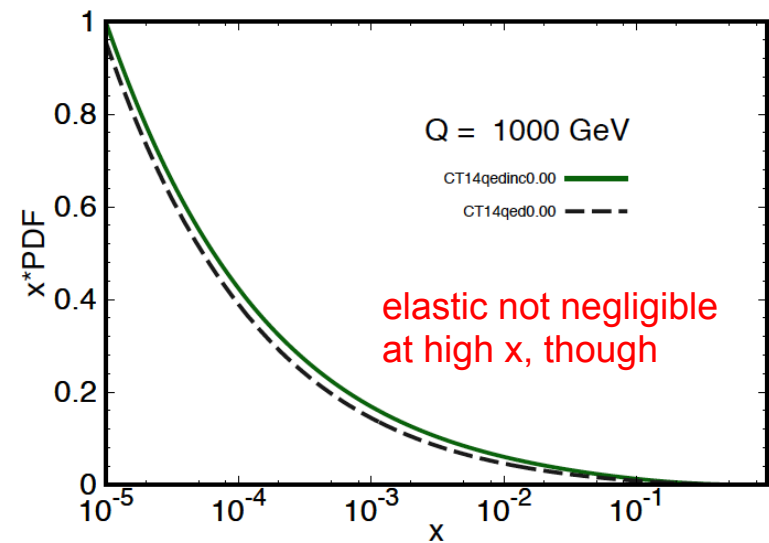
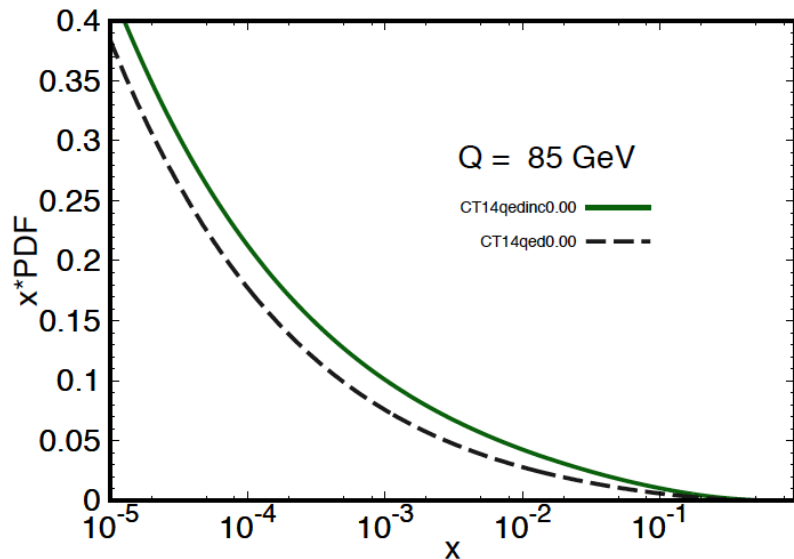
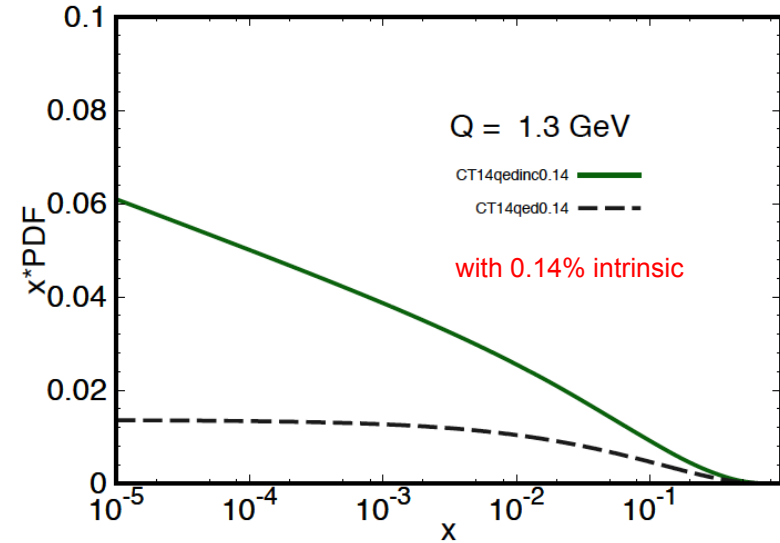
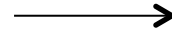
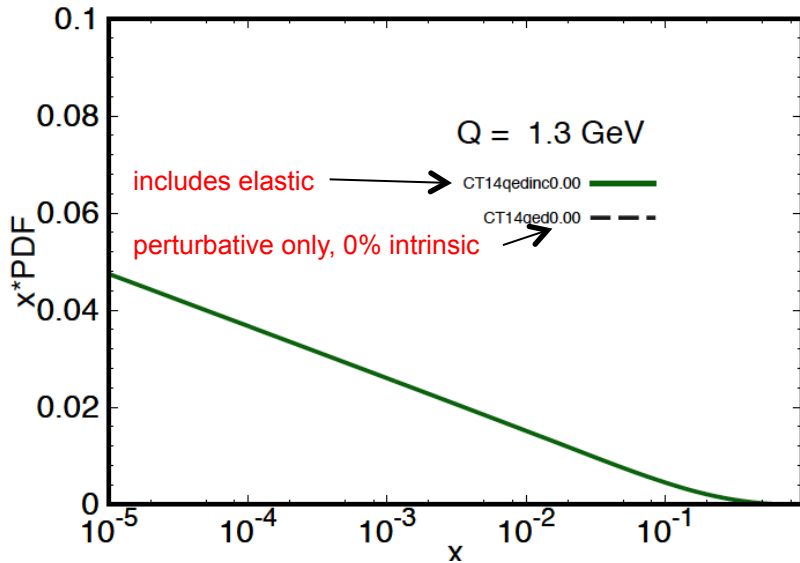


fit constrains the photon PDF;  $\gamma_{CM}$  doesn't fit the data; data fit well for current quark prescription with  $\gamma$  momentum fraction (at  $Q_0$ )=0.1%; 90%CL from 0 to 0.14%



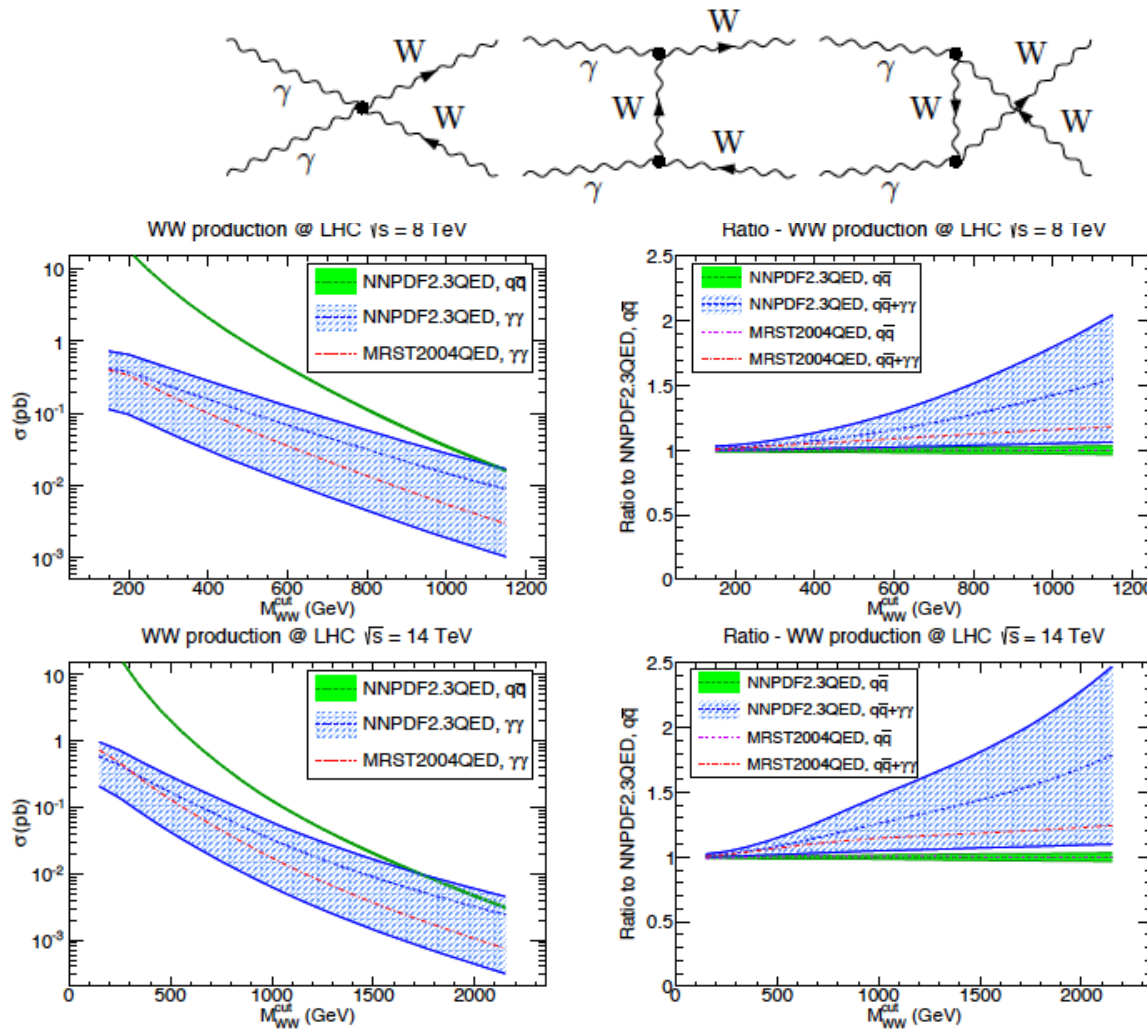
# Evolution of photon PDF

Elastic fraction of photon PDF shrinks as  $Q$  increases. Elastic does not evolve.





# NNPDF2.3qed



appreciable  
fraction of WW cross  
section at large  
mass due to  $\gamma\gamma$   
initial state

arxiv:1308.0598

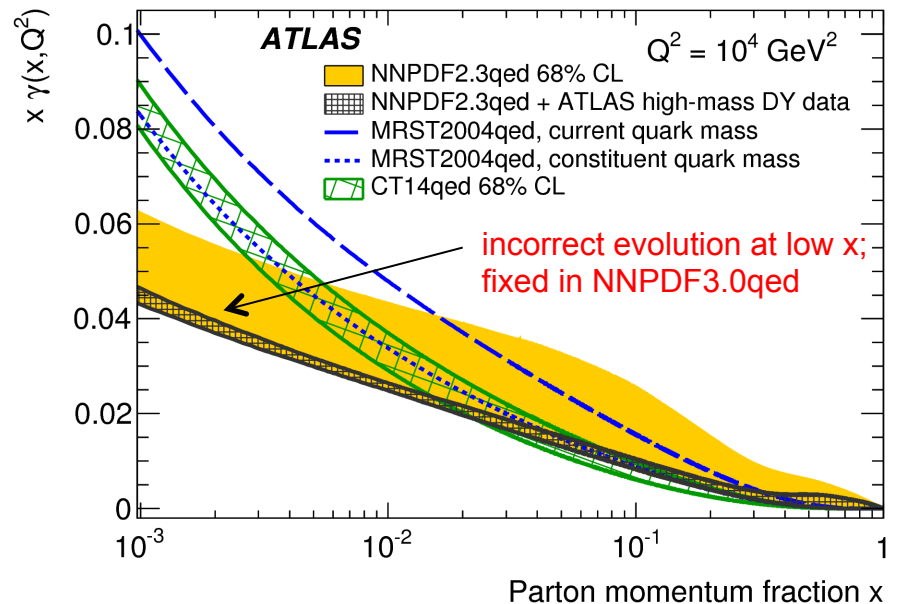
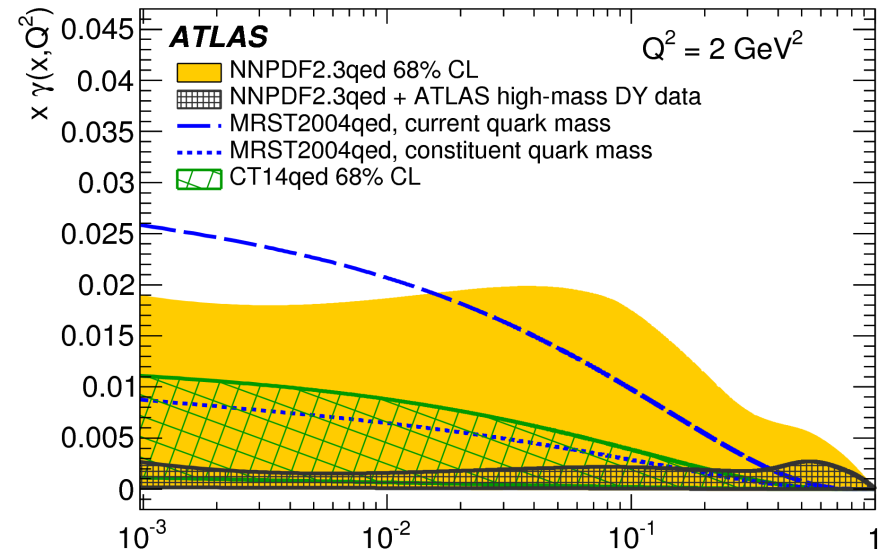
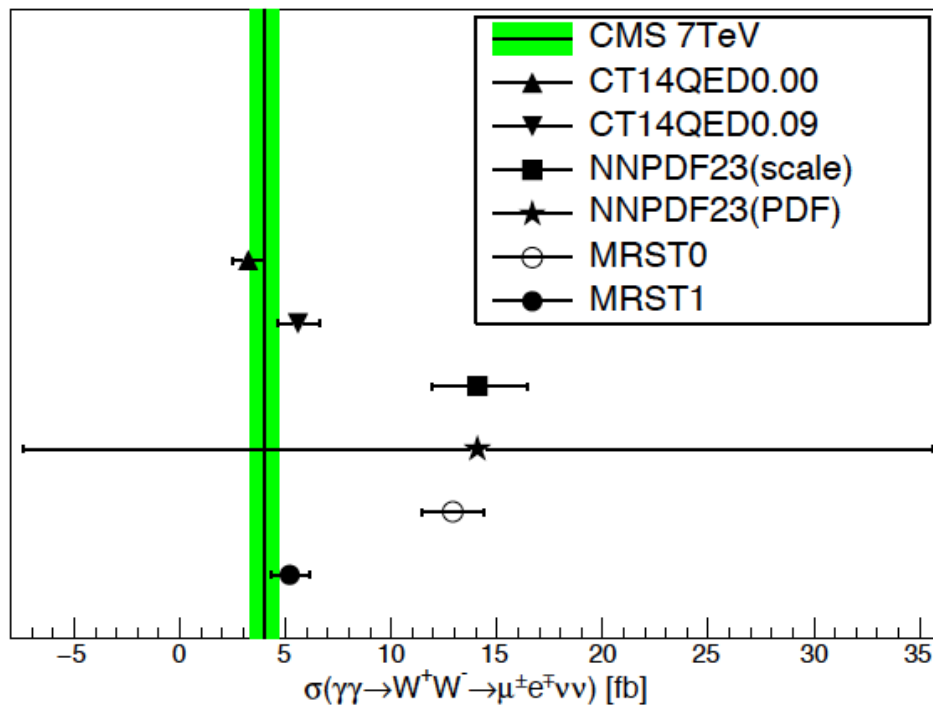
Figure 25: Photon-induced and quark-induced Born-level contributions to the production of a  $W$  pair with mass  $M_{WW} > M_{WW}^{\text{cut}}$  plotted as a function of  $M_{WW}^{\text{cut}}$  at the LHC 8 TeV (top) and LHC 14 TeV (bottom), computed with the code of Ref. [64] and NNPDF2.3QED NLO and MRST2004QED PDFs.



...but



- ATLAS fit to higher statistics Drell-Yan data prefers photon distribution at lower end of NNPDF2.3qed uncertainty band, << central value
- Also, arXiv:1603.04874

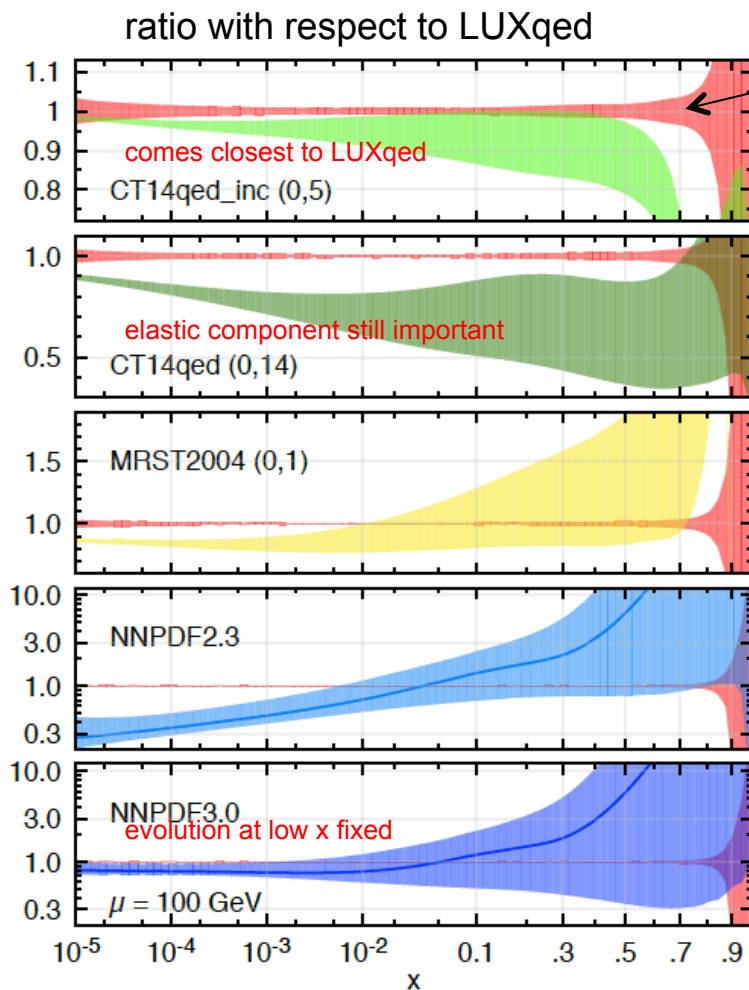




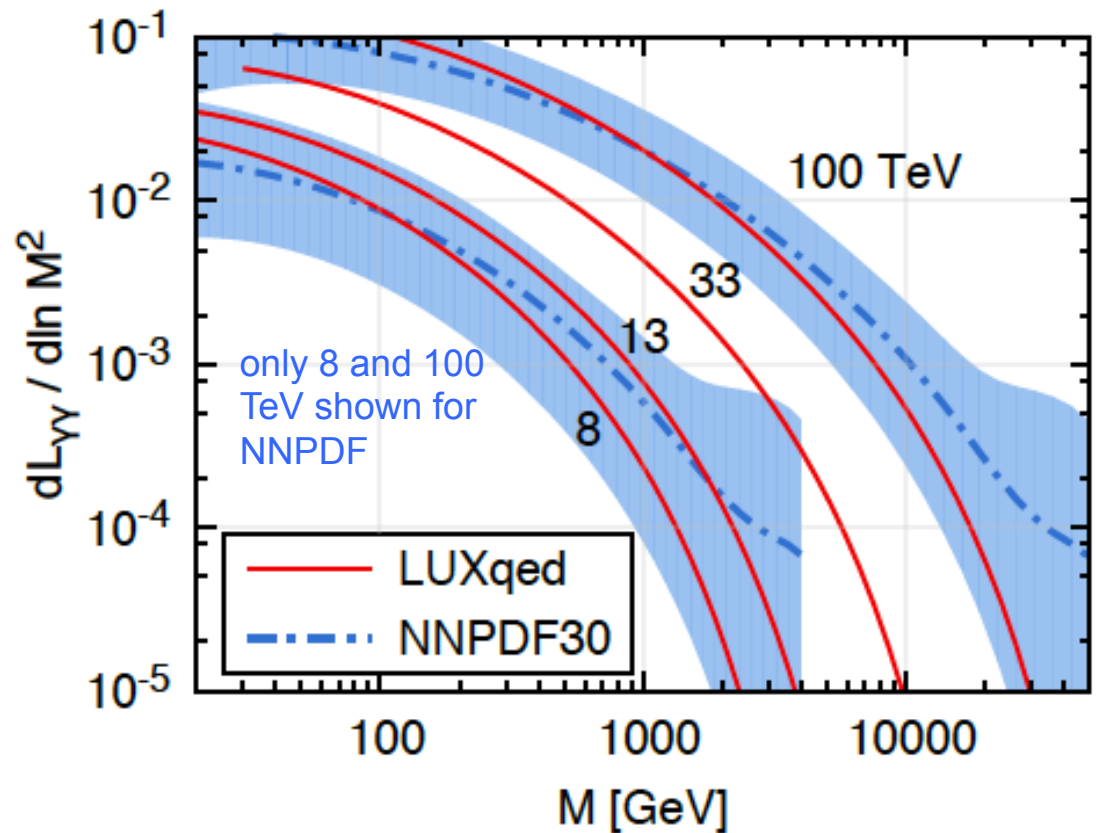
# How bright is the photon?: arXiv:1607.04266



Can define the MS photon PDF in terms of proton structure functions, resulting in a constraint of the photon PDF at the level of 1-2% over a broad range of  $x$ .



LUXqed

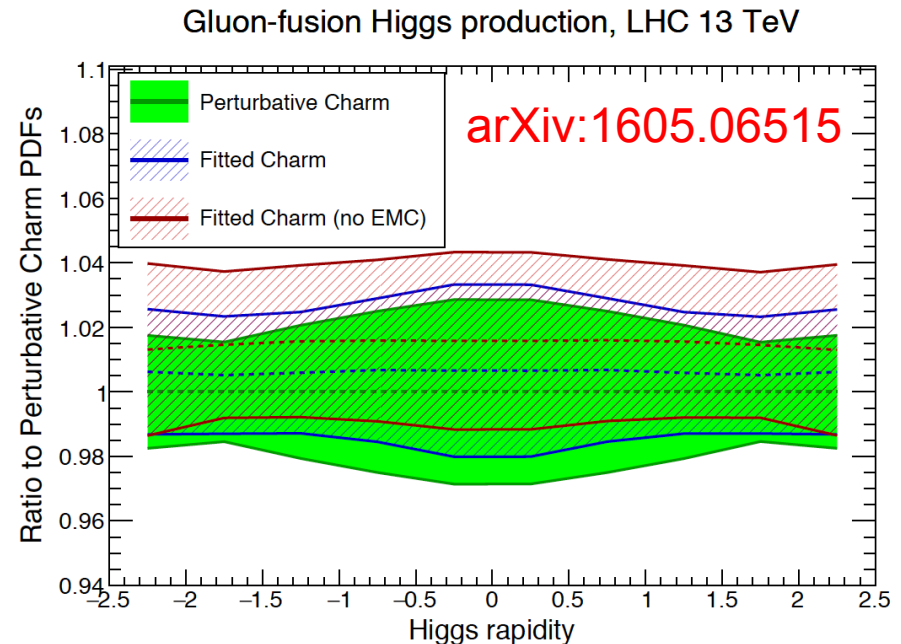




# Impacts of fitted charm at LHC



- Can you fit charm with the same freedom as up, down, gluon, etc?
- Suffers from lack of data to constrain it (similar to the photon case)
- Impacts for any charm-related cross section but also for cross sections like Higgs ggF
- Noticeable change in central value and envelope, especially for fitted charm with no EMC data
- If true, this would reflect on the *accuracy* of the previous error band
- NNPDF3.1 plans to use fitted charm as part of their baseline formalism
- CTEQ PDF fits have traditionally found a modest improvement in  $\chi^2$  by inclusion of intrinsic charm



...see extra slides for details

So uncertainty for ggF would change for next PDF4LHC update (unless other factors/data bring it down again for NNPDF)





# Further investigations

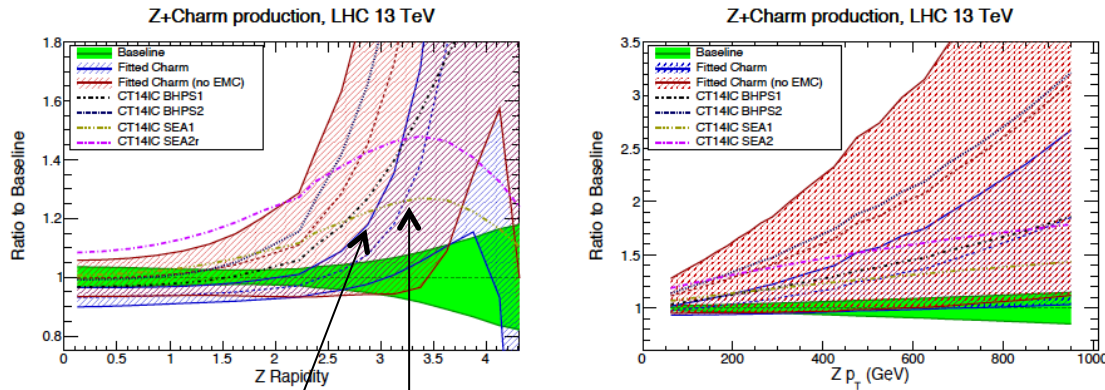
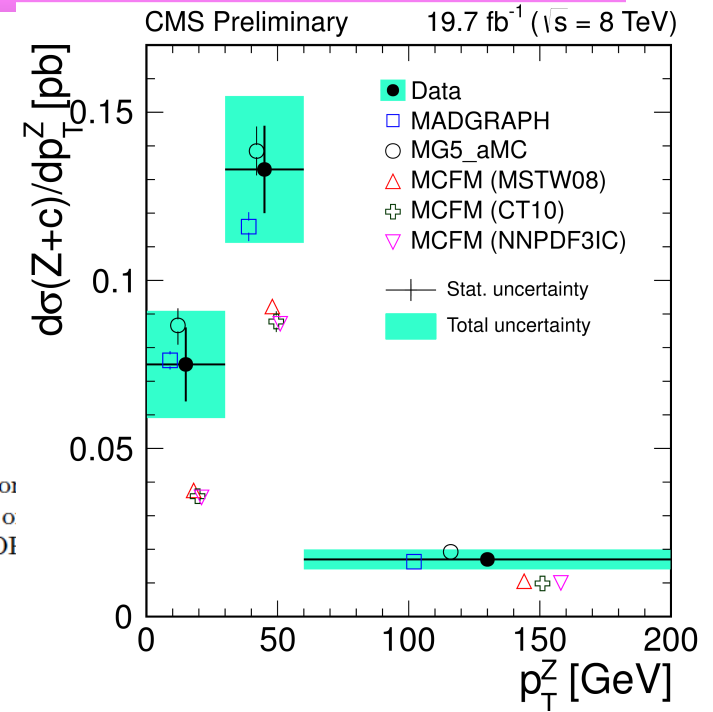


Figure 27: The  $Z$  boson rapidity (left) and transverse momentum (right) distributions for  $Z$  production in association with charm at the LHC 13 TeV, computed using the NNPDF sets with perturbative or fitted charm, and the CT14 IC PDFs shown in Fig. 16. Results are shown as a ratio to the NNPDF1 perturbative charm set.

fitted charm      BHPS1

no discrimination  
in LHC data so far,  
nor in Tevatron



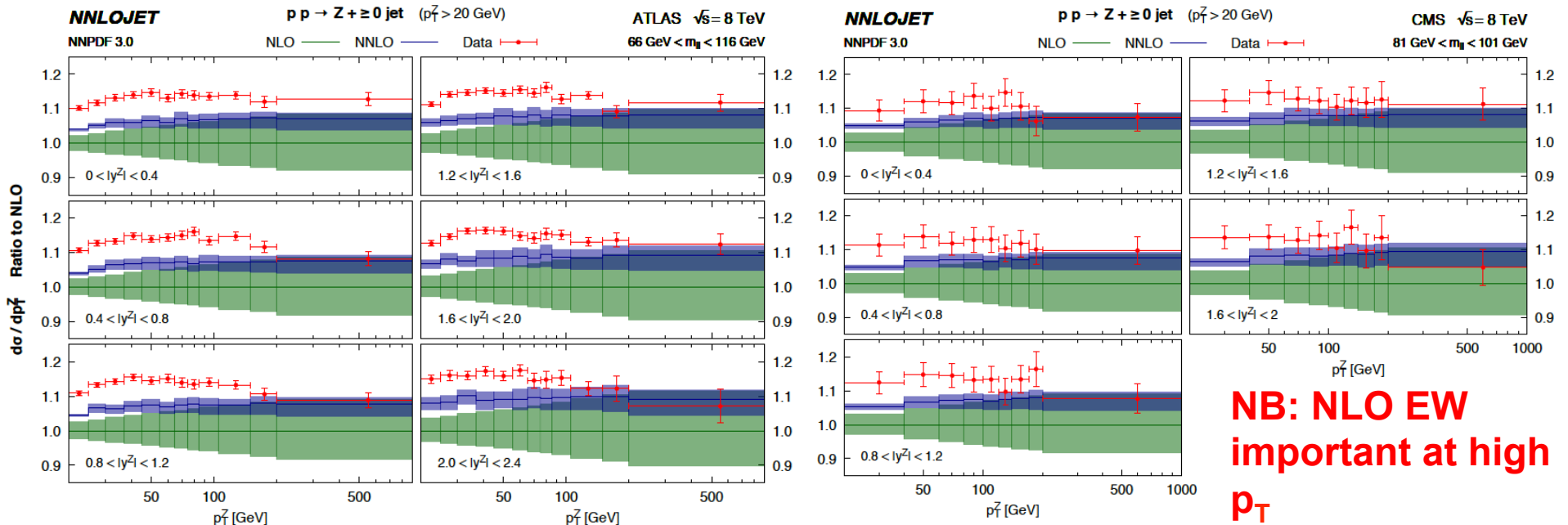
- I'm working with J. Winter, F. Siegert and J. Krause on inclusion of photon+charm at NLO into Sherpa
  - ◆ need Sherpa-like framework since fixed-order is not sufficient
  - ◆ data from 2016 should be enough to discriminate



# Z $p_T$ (arXiv:1605.04295)



- ATLAS, CMS Z  $p_T$  data seem to be above NNLO prediction
  - ◆ better agreement if normalize to the Z cross section
- These distributions are very precise at both the experimental and theoretical levels
- The data will be included in the next round of global PDF fits
- The impact may be to increase the quark/gluon distributions at moderate x values, so may possibly have an impact on ggF Higgs cross section





# Dijets



- 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
  - ◆ now it 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
- We also need a better understanding of the impact of parton showers on the fixed order cross section

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

IPPP/16/110, MPP

NNLO QCD predictions for single jet inclusive production at the LHC

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<sup>b</sup> Max-Planck-Institut für Physik, Föhringer Ring 6 D-80805 Munich, Germany

We report the first calculation of fully differential jet production in all partonic channels at next-to-next-to leading order (NNLO) in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their associated scale variation across a wide range in jet transverse momentum,  $p_T$ , and rapidity,  $y$ . We find significant effects, especially at low  $p_T$ , and discuss the possible implications for Parton Distribution Function fits.

topic for Les Houches

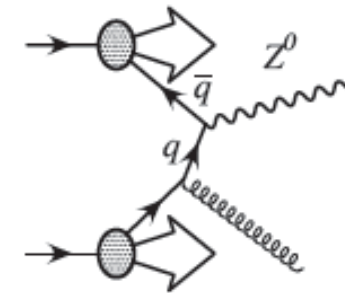


# NNLO

- How to distribute the calculation?
- For calculations like  $W/Z + n$  jets, Higgs +  $n$  jets, all at NLO, use ROOT ntuples
- Processes at NNLO, such as  $H + \text{jet}$ , and  $W/Z + \text{jet}$ , use MCFM?
- Inclusive jet production not amenable to above techniques, so may use applgrid/fastNLO grids
- Such an approach needed for global PDF fits

## NNLOJET (and APPLfast)

- Semi-automated calculation of cross sections at NNLO from the IPPP, Zurich, ETH and others
  - Gehrmann-De Ridder *et al* [arXiv: 1607.01749](https://arxiv.org/abs/1607.01749)
  - See talk from **Alex Huss** tomorrow
- APPLfast-NNLO
  - Developers from **NNLOJET**, **APPLgrid** and **fastNLO**
  - A single, combined interface for NNLOJET with both APPLgrid and fastNLO



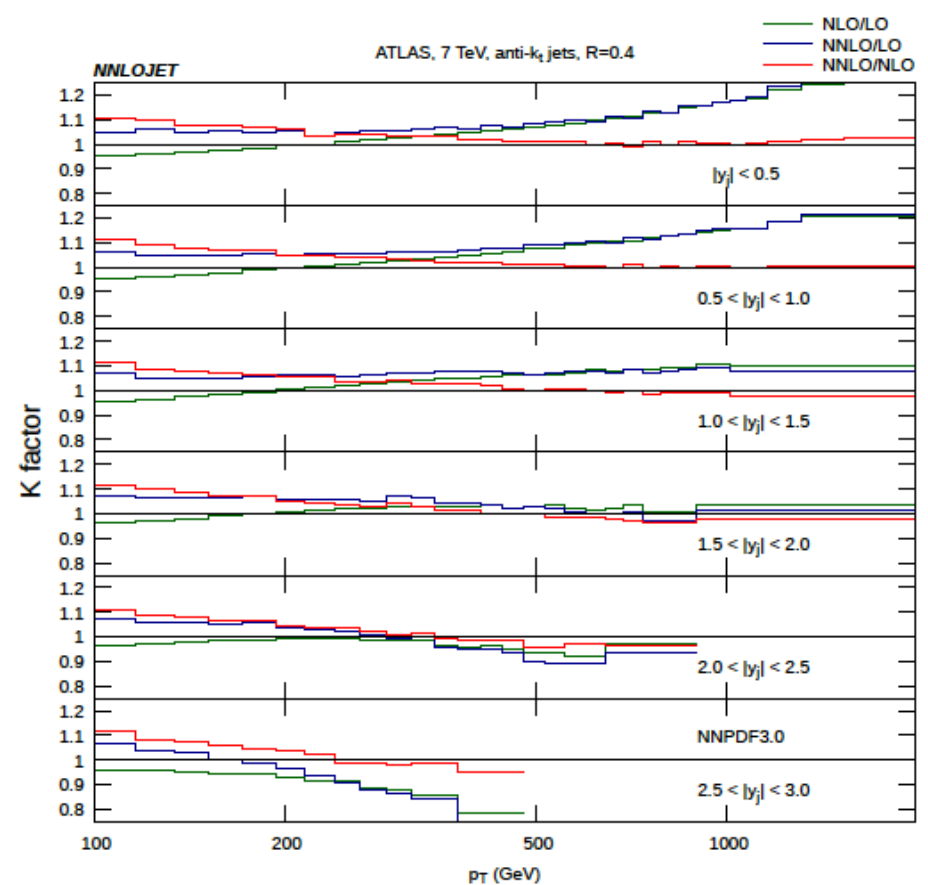
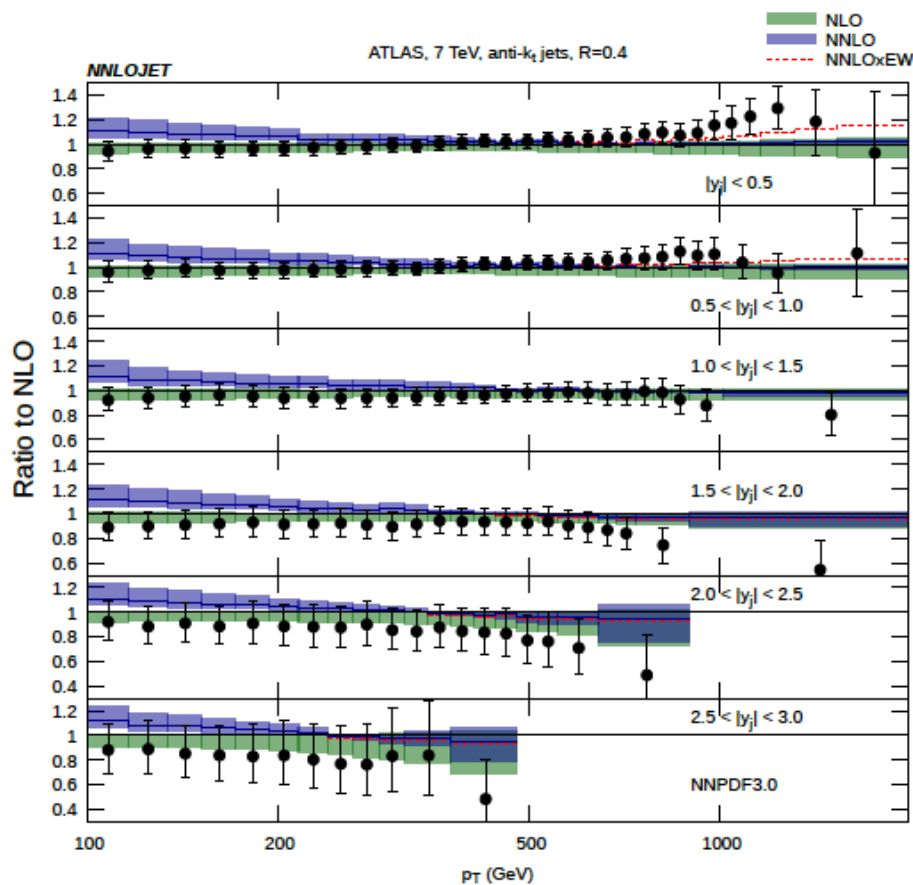
- Many processes implemented in NNLOJET
  - Developing a generic interface for **all available** processes
  - Concentrating on  $Z + \text{jets}$  at NNLO for the initial development and proof-of-concept



# NNLO



- NNLO corrections appear to be small, scale dependence reduced, except for low  $p_T$



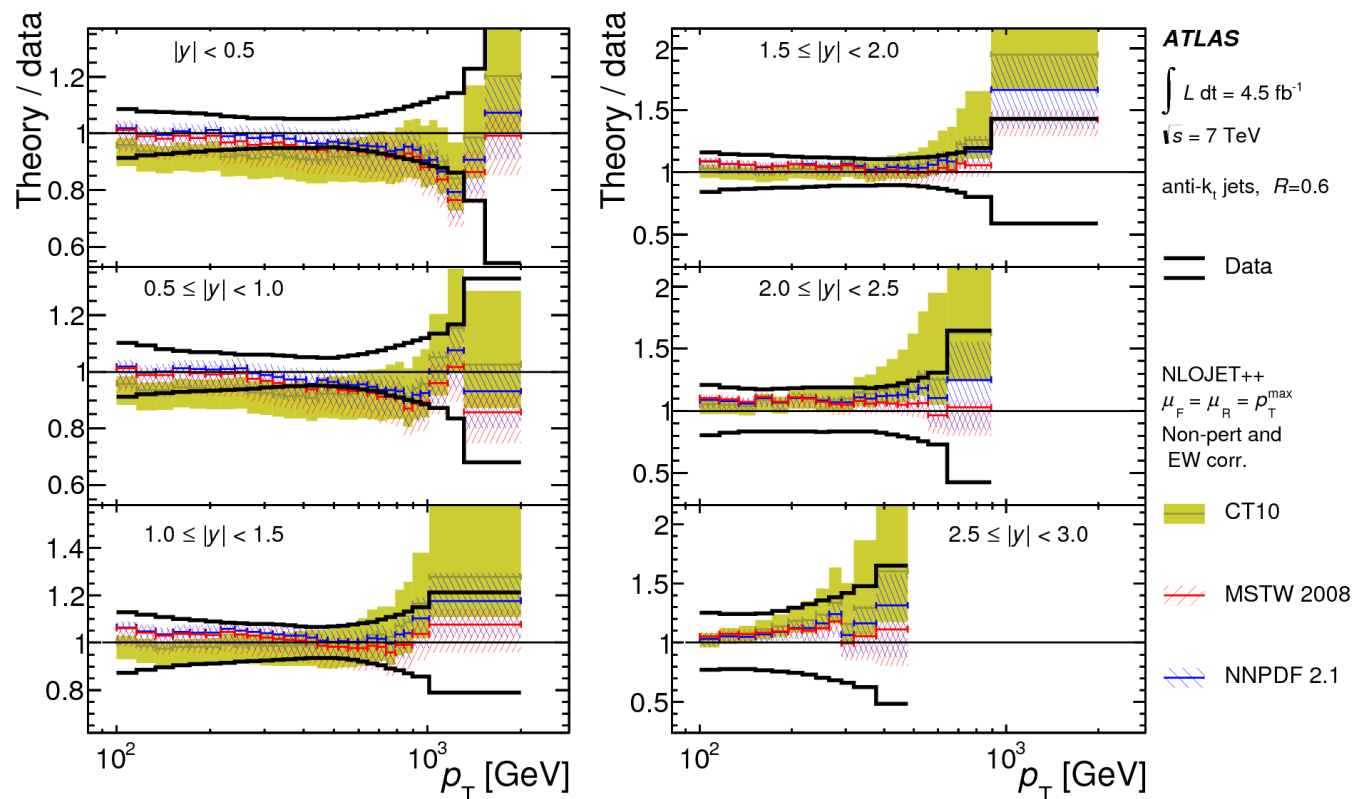
Issue: scale choice; these predictions use the scale of the highest  $p_T$  jet; PDF fits typically use scale of inclusive jet, and  $R=0.6 \rightarrow$  little difference between NLO and NNLO



# ATLAS 7 TeV jet data



- Impossible to get a good  $\chi^2$  when fitting all rapidity intervals simultaneously, although each rapidity interval by itself gives a good  $\chi^2$  -> correlations? 8 TeV data has the same problem
- If only one y interval is chosen, which one? Do the other rapidity intervals provide the same constraint? If not, then how can the data be used?
- In general, ATLAS jet data prefers a weaker gluon at high x

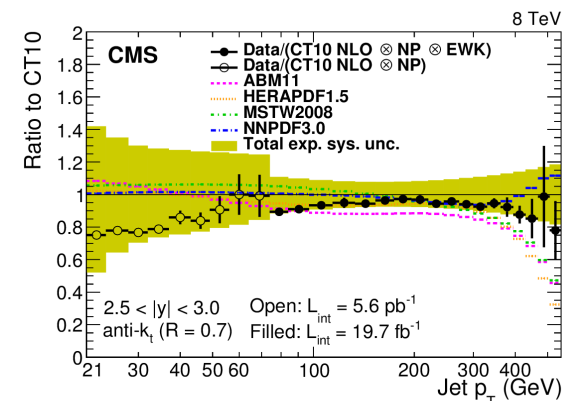
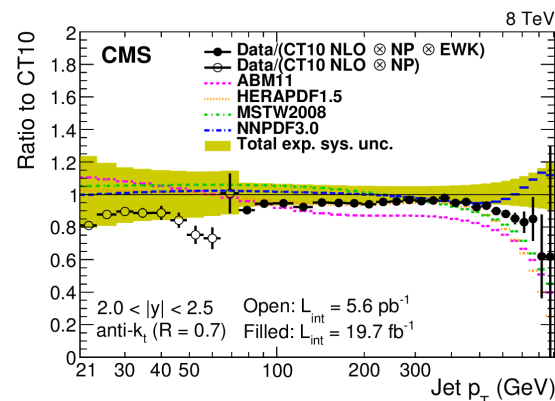
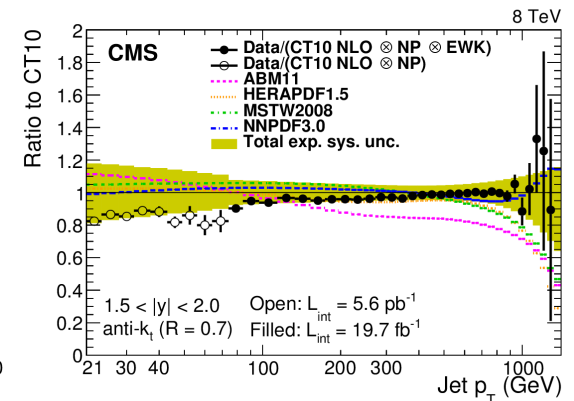
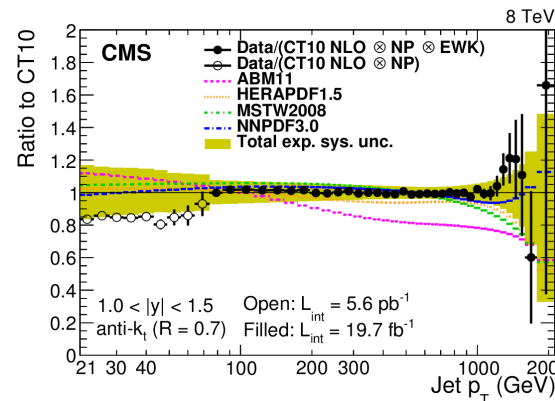
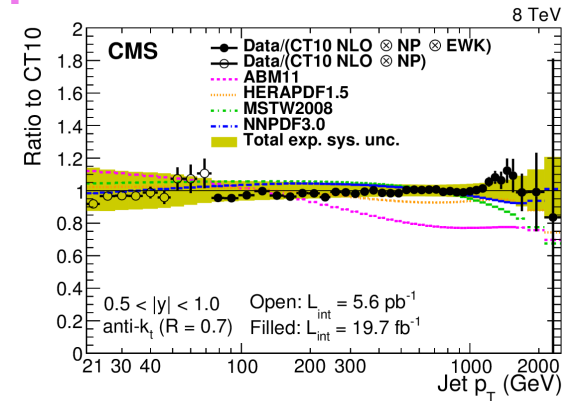
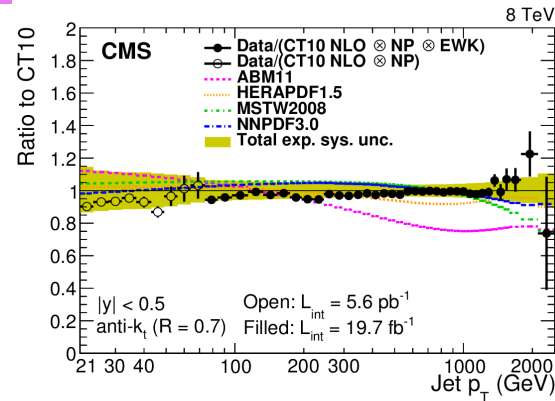




# CMS 8 TeV jet data



- CT10 has a harder gluon than CT14
- CMS data seems happy with that
- I'm happy with that
- ...but may point out a tension between the ATLAS and CMS jet data sets; if so, high  $x$  gluon uncertainty may not be reduced by these data sets
- CMS 8 TeV jet information public within next few weeks?

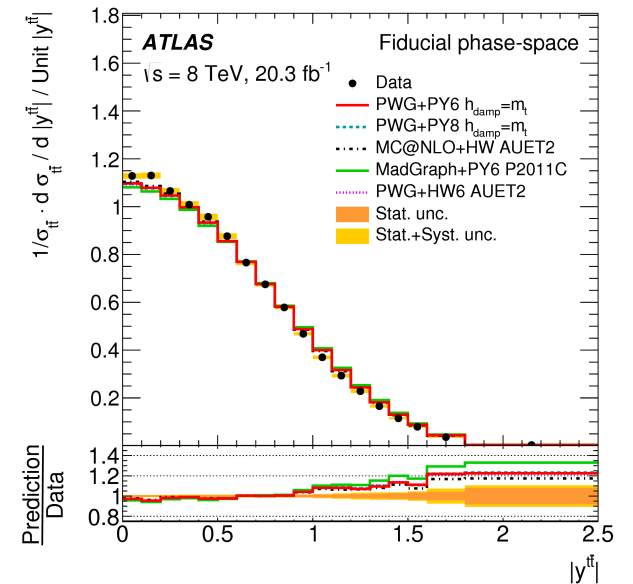
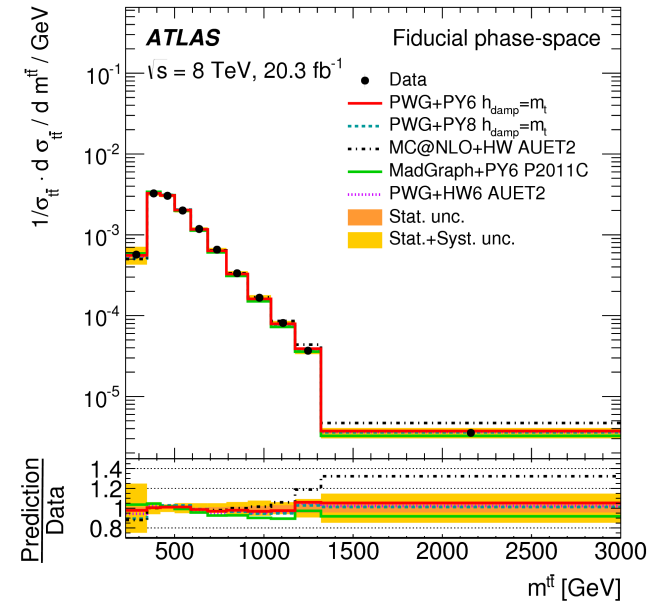
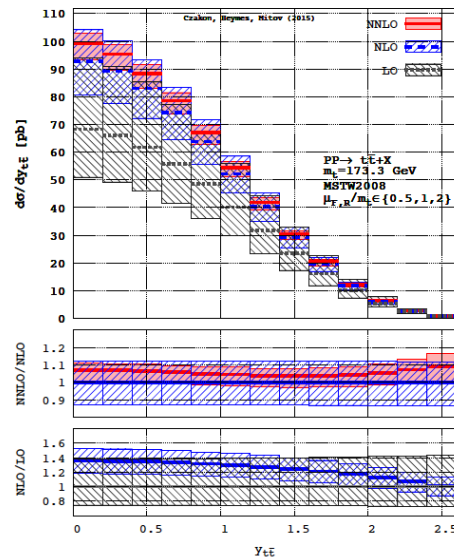
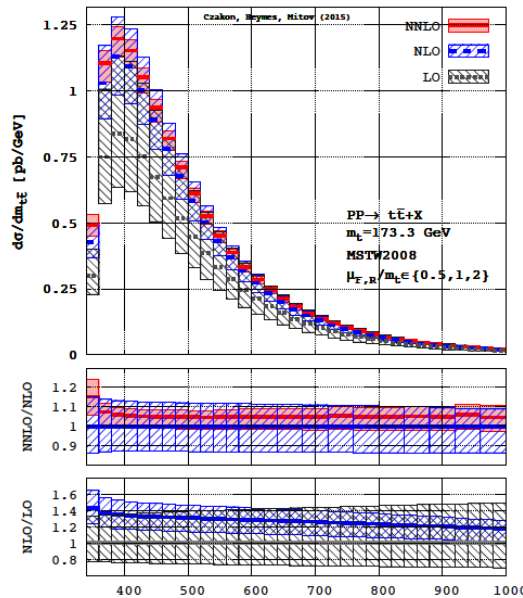




# tT differential data



- tT differential cross sections provide a great handle on the high x gluon distribution
  - may settle the struggle between ATLAS and CMS jet data
- Recent calculation by Czakon, Heyes and Mitov; arXiv:1511.00549
- Rant for the ATLAS plots: How can the predictions differ by so much at high mass, rapidity? If it's the PDFs, then this should be clearly labelled
- if it's because of the parton shower/matching, how can that be?







# Top distributions



- There are several distributions measured by ATLAS and CMS that have information on the high  $x$  gluon
  - ◆  $m_{tT}$ ,  $y_{tT}$  directly
  - ◆  $y_{t,T}$ ,  $p_T^{tT}$  indirectly
- Only one distribution should be used, unless a correlation model can be developed
  - ◆ which one?
  - ◆ do they give the same answer? if not, do we understand why? how can you claim a decrease in uncertainty if you pick and choose the variables that give the answer (and constraints) you want?
- ATLAS and CMS have different trends; in this case, ATLAS favors harder gluon (than NNPDF3.0) at high  $x$ , CMS weaker gluon
- In general, the ATLAS and CMS top results are in tension internally, and with each other (the latter more so in the case of normalized distributions where the experimental errors are smaller)
- This is similar to the tension that exists between the ATLAS and CMS jet data, although there the tension is in the opposite direction
- If tension, then gluon PDF uncertainty may not decrease and may even increase

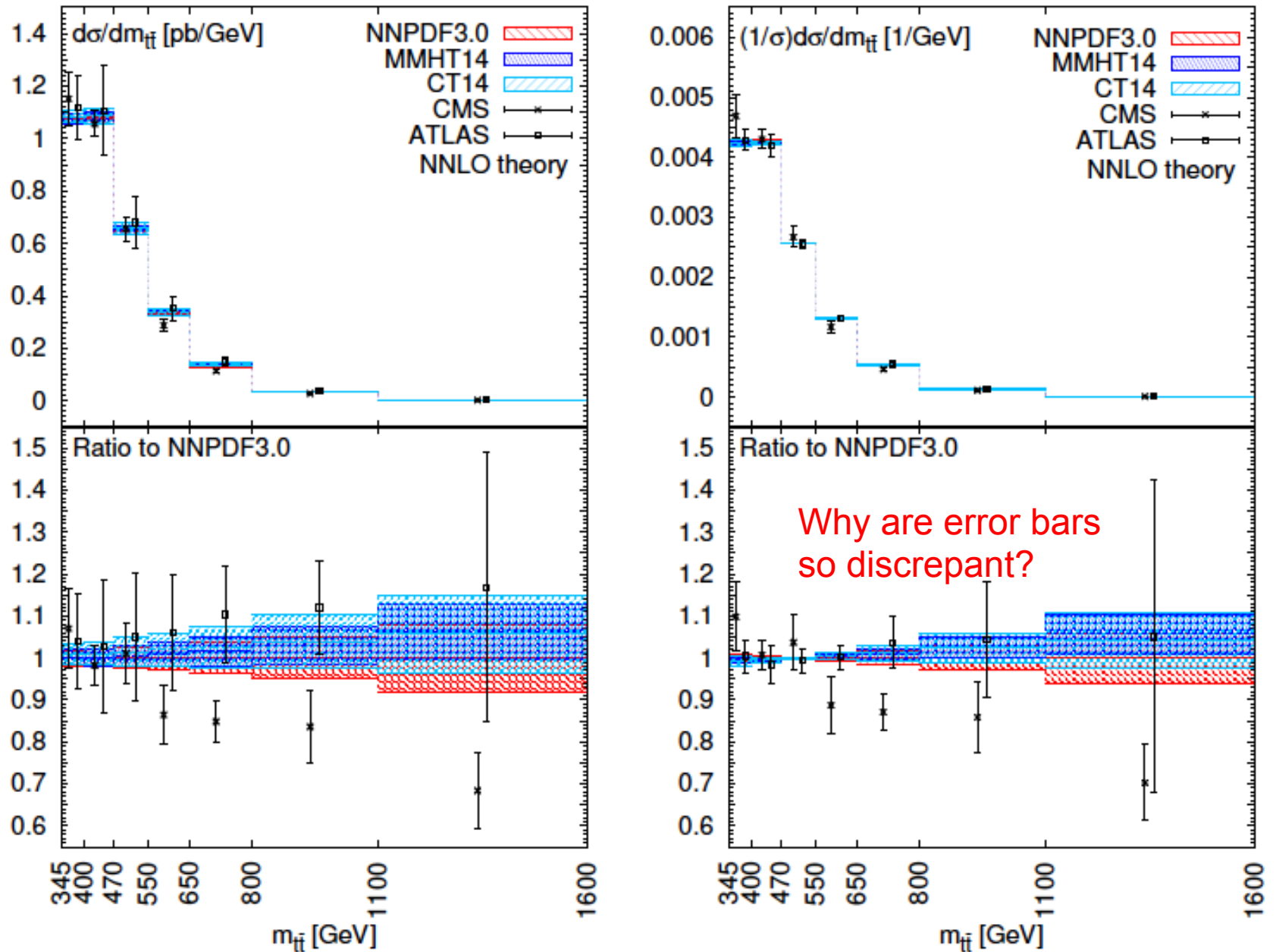


Figure 10: Same as Fig. 4 for the invariant mass distribution of the top-antitop pair,  $m_{\bar{t}t}$ .



dataset	Fit ID									
	1	2	3	4	5	6	7	8	9	10
ATLAS $d\sigma/dp_T^t$	2.37	2.30	<b>1.99</b>	2.36	2.24	2.23	2.09	2.18	2.34	2.24
ATLAS $d\sigma/dy_t$	0.93	0.80	0.74	<b>1.09</b>	0.76	0.76	0.86	0.69	0.76	0.66
ATLAS $d\sigma/dy_{t\bar{t}}$	2.44	2.03	1.96	2.59	<b>1.32</b>	2.32	2.11	1.74	1.26	1.80
ATLAS $d\sigma/dm_{t\bar{t}}$	4.27	4.47	4.68	4.14	4.92	<b>4.02</b>	4.34	4.79	4.98	4.99
ATLAS $(1/\sigma)d\sigma/dp_T^t$	2.93	3.97	3.29	4.36	5.22	4.35	<b>2.96</b>	4.26	4.92	5.68
ATLAS $(1/\sigma)d\sigma/dy_t$	5.00	3.17	2.47	6.36	1.55	2.93	3.94	<b>1.68</b>	<b>1.45</b>	1.10
ATLAS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	9.69	5.59	5.89	8.95	2.68	5.73	6.73	3.57	<b>2.17</b>	3.73
ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	2.30	2.80	3.31	2.67	3.96	4.21	3.09	3.68	3.77	<b>2.98</b>
ATLAS $\sigma_{t\bar{t}}$	0.12	<b>0.10</b>	0.21	0.10	0.10	0.12	<b>0.36</b>	<b>0.29</b>	<b>0.26</b>	0.10
CMS $d\sigma/dp_T^t$	3.50	3.46	<b>2.60</b>	3.50	3.03	3.00	2.85	3.11	3.24	2.92
CMS $d\sigma/dy_t$	3.48	3.71	4.05	<b>2.66</b>	4.18	3.49	3.38	4.23	4.43	4.99
CMS $d\sigma/dy_{t\bar{t}}$	1.36	1.13	1.00	1.32	<b>0.89</b>	0.86	1.00	1.01	1.04	1.24
CMS $d\sigma/dm_{t\bar{t}}$	7.07	6.27	5.79	6.33	5.09	<b>5.11</b>	6.00	5.57	5.21	4.31
CMS $(1/\sigma)d\sigma/dp_T^t$	4.31	4.00	3.39	4.28	3.65	3.59	<b>3.56</b>	3.57	3.73	3.48
CMS $(1/\sigma)d\sigma/dy_t$	3.66	4.10	4.45	3.10	4.98	4.06	3.65	<b>4.76</b>	5.13	6.09
CMS $(1/\sigma)d\sigma/dy_{t\bar{t}}$	1.59	1.20	1.06	1.73	0.94	1.01	1.20	0.99	<b>1.05</b>	1.32
CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	12.0	10.8	9.81	11.1	8.72	8.72	10.3	9.15	9.27	<b>7.27</b>
CMS $\sigma_{t\bar{t}}$	0.10	<b>0.35</b>	0.26	0.19	0.32	0.21	0.11	<b>0.10</b>	<b>0.15</b>	<b>0.35</b>

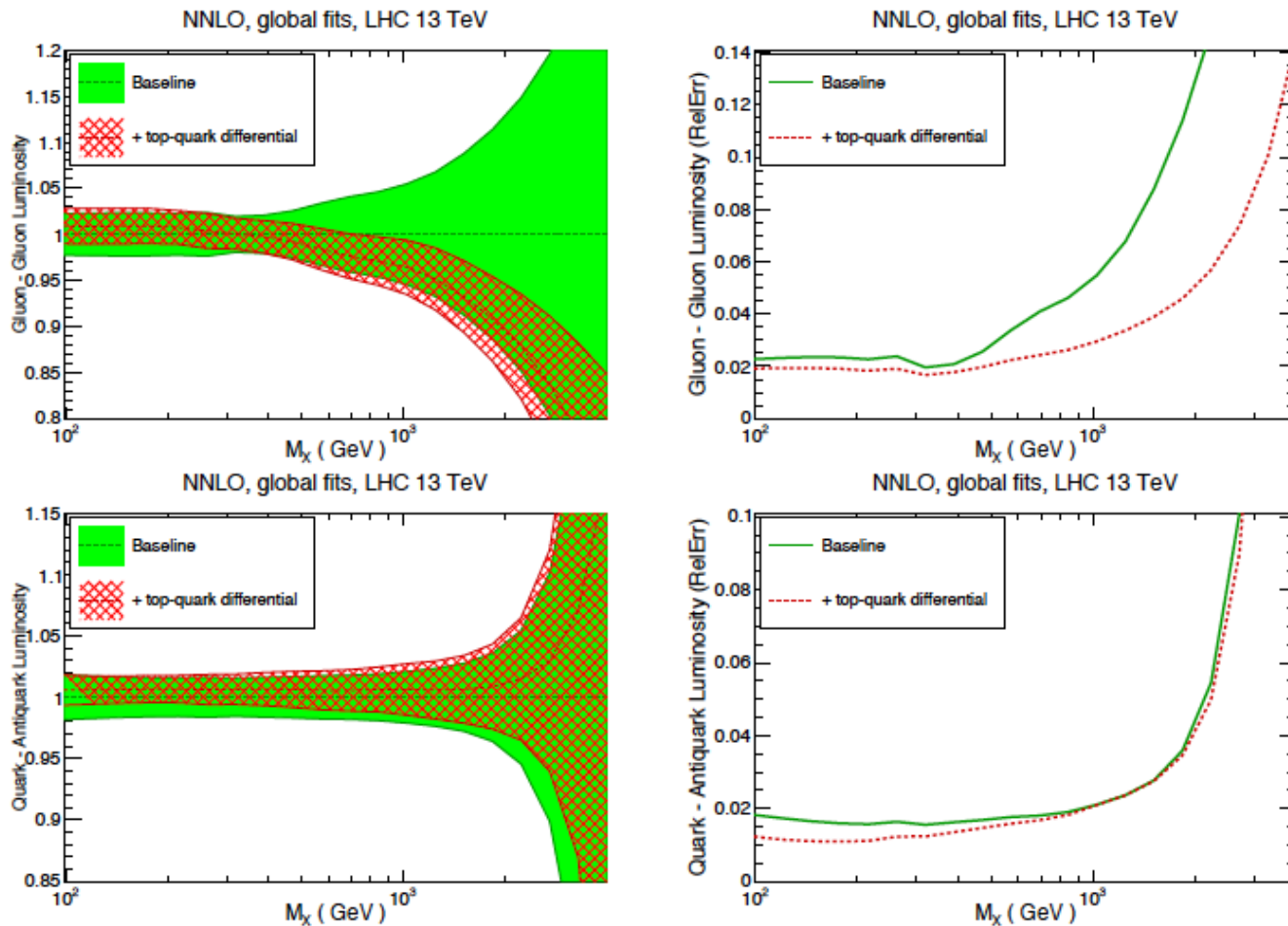
final fit includes only these cross sections

...and not these (for example)

Table 7: Same as Table 6 for the global fits.



# Resultant fit



I think more detailed studies investigating the degree of compatibility between the different observables in ATLAS and CMS is needed before any strong conclusion can be determined

Figure 15: The gluon-gluon (upper) and quark-antiquark (lower) NNLO luminosities (left) and their relative  $1\text{-}\sigma$  PDF uncertainties (right) at the LHC with  $\sqrt{s} = 13$  TeV. We compare the global baseline fit with the fit including the optimal combination of LHC top-quark pair differential data.



# 8 is enough



- PDF4LHC15\_30 is a general purpose LHC set
- Can re-diagonalize eigenvector set to look for directions most sensitive to a particular class of physics, for example Higgs physics
- In that case, 8 PDFs are sufficient
- Could also do the same for any cross section

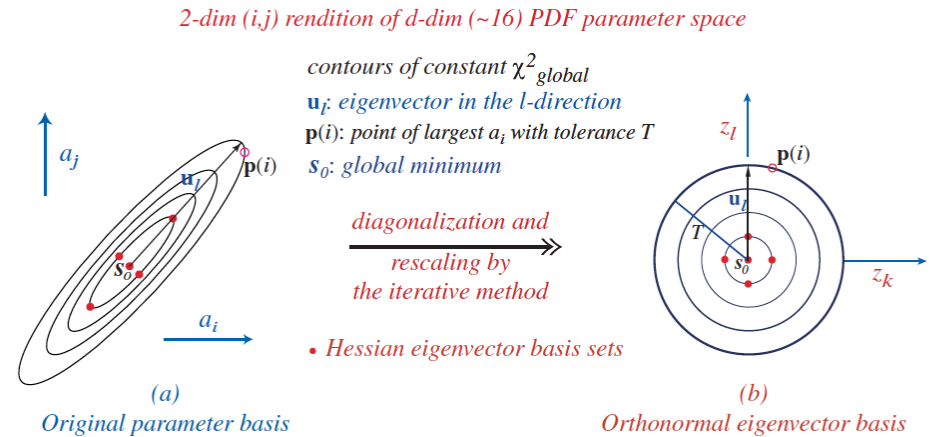


Fig. 6.13 A schematic representation of the transformation from the pdf parameter basis to the orthonormal eigenvector basis.

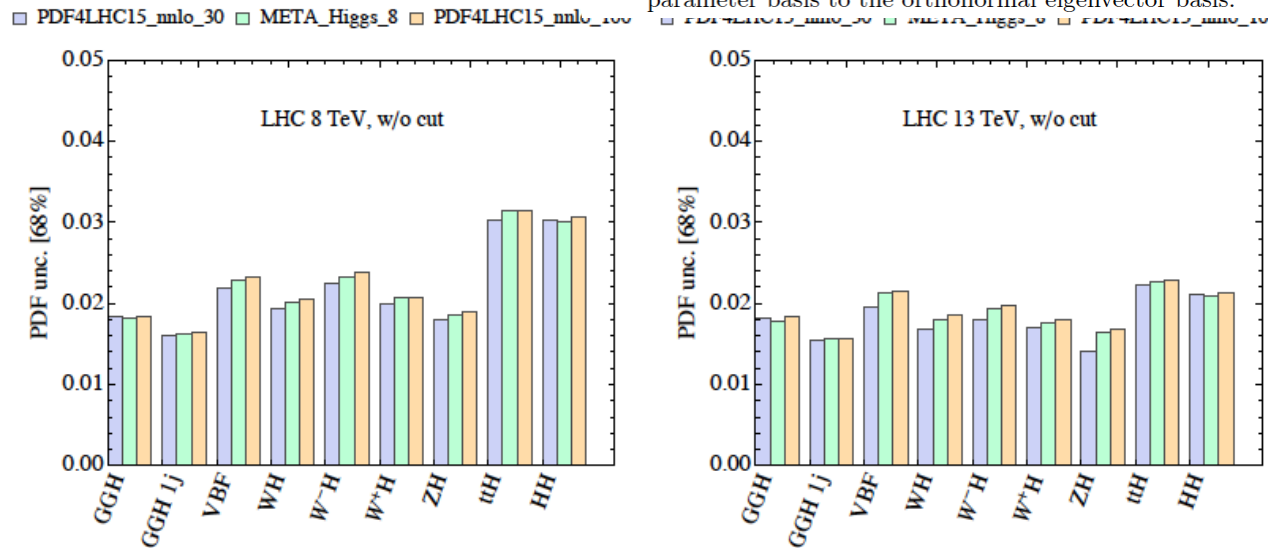


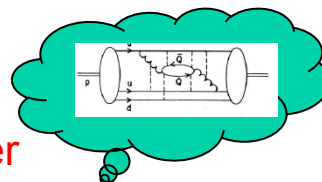
FIG. 1: Predictions on the total PDF uncertainties comparing NNLO PDFs of PDF4LHC15 30 set, reduced set (with 8 eigenvectors), and PDF4LHC15 100 set.



# Summary



- First, let me summarize what I didn't talk about
  - ◆ the combined HERA1+2 data set was released after this last generation of PDF sets
  - ◆ all PDF groups have included the data in a new round of (private) fits, and find that it doesn't change the results obtained with using HERA1 data alone
- ...and this
  - ◆ sometimes data is included in PDF fits not directly, but by re-weighting; I think this is typically not done correctly, and over-estimates the effect of the data->work in progress
- It appears that the photon PDF is fairly-well constrained now, and fairly small
- The idea of a large *intrinsic/fitted* charm component still needs more study, both theoretical and experimental
  - ◆ LHC data should be able to tell us
  - ◆ Stan may have to keep dreaming for a bit longer
- PDF fitting continues to grow in sophistication and in the amount of LHC data included in the fits
  - ◆ still hard to fight the precision of the DIS data
  - ◆ ATLAS, CMS, LHCb data have to agree in order to reduce the current size of PDF uncertainties
  - ◆ some PDFs, such as charm, strange, photon, and the high  $x$  gluon still have large uncertainties, but with further data/improvements, should improve





# Summary



- There's a wealth of new data from the LHC along with new calculations at NNLO that should allow more detailed knowledge of PDFs and of cross sections at the LHC
- One problem is the use of such calculations in global PDF fits where thousands of iterations are required
  - ◆ for CT, we are using a combination of applgrid and fastNLO for the NLO matrix elements, with NNLO/NLO K-factors, along with parallelization of the computations
  - ◆ it may be possible to directly use applgrid/fastNLO such as what NNLOJET is working on
- In any case, the impact of the LHC data on global PDF fits requires a great deal of study and interaction with the experimenters, especially in cases where the experiments disagree and where different observables (or even rapidity regions) within the the same experiment disagree
- Next PDF4LHC meeting March 7, 2017 at CERN
  - ◆ updates of PDF fits, data sets
  - ◆ discussion of incorporation of scale uncertainties in PDF fits
  - ◆ correlations among data sets
  - ◆ ...



We don't have the 750 GeV any more,  but we still have ...



Because you know it's all about that  
Higgs, 'Bout that Higgs, no SUSY

REGAN





~~Winter~~ Les Houches is coming 



Les Houches 2017 June 5-23



The topics in this talk, and many others, will be investigated.

<https://phystev.cnrs.fr>  
registration now open



...meanwhile, the book



The screenshot shows a PDF viewer window titled "book.pdf". The toolbar includes a "Create" dropdown, a folder icon, a save icon, a print icon, an email icon, a settings gear, a comment bubble, a search icon, a refresh icon, a back icon, and a forward icon. The page navigation bar shows "1 / 752" with a red circle around the "752". The zoom level is set to "100%". The main content area displays the title page of the book:

**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  
*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

F. Krauss  
*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*



# Ciaran Williams presents his vision of British HEP after Brexit





# Joey Huston presents his vision of US HEP after Trump





Meanwhile, the book... 

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# Extras





# Some pre-history: PDF4LHC



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

## The PDF4LHC Working Group Interim Report

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

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<sup>8</sup> Department of Physics, Oxford University, Denys Wilkinson Bldg, Keble Rd, Oxford, OX1 3RH, UK  
<sup>9</sup> CERN, CH-1211 Genève 23, Switzerland; Antwerp University, B-2610 Wilrijk, Belgium; University of California Davis, CA, USA

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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  $\alpha_s$  uncertainties, with the prescription for combining the PDF and  $\alpha_s$  errors to be specified
6. repeating the calculation with a central value of  $\alpha_s(m_Z)$  of 0.119.



## PDF4LHC recommendations(arXiv:1101.0538)



So the prescription for NLO is as follows:

- For the calculation of uncertainties at the LHC, use the envelope provided by the central values and PDF+ $\alpha_s$  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  $\alpha_s$  variation suggested is consistent with this. Note that the CTEQ6.6 set has uncertainties and  $\alpha_s$  variations provided only at 90% c.l. and thus their uncertainties should be reduced by a factor of 1.645 for 68% c.l.. Within the quadratic approximation, this procedure is completely correct.

So the prescription at NNLO is:

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

So basically, this is a factor of 2.

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





# More benchmarking



2 studies in 2011 Les Houches proceedings(1203.6803)

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



# Higgs Yellow Reports



CERN-2011-002  
17 February 2011

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

**Handbook of LHC Higgs cross sections:  
1. Inclusive observables**

**Report of the LHC Higgs Cross Section Working Group**

**Handbook of LHC Higgs cross sections:  
2. Differential Distributions**

**Report of the LHC Higgs Cross Section Working Group**

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

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

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

paralleled 2010 PDF4LHC  
report

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

more extensive use of PDF and cross  
section correlations



# Followup



- Study of NNLO PDFs from 5 PDF groups (no new updates for JR)
  - ◆ drawing from what Graeme Watt had done at NNLO, but now including CT10 NNLO, and NNPDF2.3 NNLO
    - ▲ HERAPDF has upgraded to HERAPDF1.5; ABM09->ABM11
  - ◆ using a common values of  $\alpha_s$  (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 were utilized in a subsequent PDF4LHC document(s)
- ...and are in YR3



# Now on LHAPDF



LHAPDF6 grid	Pert order	ErrorType	$N_{\text{mem}}$	$\alpha_s(m_Z^2)$
PDF4LHC15_nnlo_mc	NNLO	replicas	100	0.118
PDF4LHC15_nnlo_100	NNLO	symmhessian	100	0.118
PDF4LHC15_nnlo_30	NNLO	symmhessian	30	0.118
PDF4LHC15_nnlo_mc_pdfas	NNLO	replicas+as	102	mem 0:100 $\rightarrow$ 0.118 mem 101 $\rightarrow$ 0.1165 mem 102 $\rightarrow$ 0.1195
PDF4LHC15_nnlo_100_pdfas	NNLO	symmhessian+as	102	mem 0:100 $\rightarrow$ 0.118 mem 101 $\rightarrow$ 0.1165 mem 102 $\rightarrow$ 0.1195
PDF4LHC15_nnlo_30_pdfas	NNLO	symmhessian+as	32	mem 0:30 $\rightarrow$ 0.118 mem 31 $\rightarrow$ 0.1165 mem 32 $\rightarrow$ 0.1195
PDF4LHC15_nnlo_asvar	NNLO	-	1	mem 0 $\rightarrow$ 0.1165 mem 1 $\rightarrow$ 0.1195

Table 5: Summary of the combined NNLO PDF4LHC15 sets with  $n_f^{\text{max}} = 5$  that are available from LHAPDF6. The corresponding NLO sets are also available. Members 0 and 1 of PDF4LHC15\_nnlo\_asvar coincide with members 101 and 102 (31 and 32) of PDF4LHC15\_nnlo\_mc\_pdfas and PDF4LHC15\_nnlo\_100\_pdfas (PDF4LHC15\_nnlo\_30\_pdfas). Recall that in LHAPDF6 there is always a zeroth member, so that the total number of PDF members in a given set is always  $N_{\text{mem}} + 1$ . See text for more details.



# Recommendations



## 1. Comparisons between data and theory for Standard Model measurements

**Recommendations:** Use *individual PDF sets*, and, in particular, as many of the modern PDF sets [5–11] as possible.

**Rationale:** Measurements such as jet production, vector-boson single and pair production, or top-quark pair production, have the power to constraining PDFs, and this is best utilized and illustrated by comparing with many individual sets.

As a rule of thumb, *any measurement that potentially can be included in PDF fits* falls in this category.

The same recommendation applies to the *extraction of precision SM parameters*, such as the strong coupling  $\alpha_s(m_Z^2)$  [75,124], the  $W$  mass  $M_W$  [125], and the top quark mass  $m_t$  [126] which are directly correlated to the PDFs used in the extraction.

## 2. Searches for Beyond the Standard Model phenomena

**Recommendations:** Use the PDF4LHC15\_mc sets.

**Rationale:** BSM searches, in particular for *new massive particles in the TeV scale*, often require the knowledge of PDFs in regions where available experimental constraints are limited, notably close to the hadronic threshold where  $x \rightarrow 1$  [127]. In these extreme kinematical regions the PDF uncertainties are large, the *Monte Carlo combination of PDF sets is likely to be non-Gaussian*. *c.f.* Figs. 10 and 11.



3. Calculation of PDF uncertainties in situations when computational speed is needed, or a more limited number of error PDFs may be desirable

**Recommendations:** Use the PDF4LHC15\_30 sets.

**Rationale:** In many situations, PDF uncertainties may affect the extraction of physics parameters. From the point of view of the statistical analysis, it might be useful in some cases to *limit the number of error PDFs* that need to be included in such analyses. In these cases, use of the PDF4LHC15\_30 sets may be most suitable.

In addition, the calculation of *acceptances, efficiencies or extrapolation factors* are affected by the corresponding PDF uncertainty. These quantities are only a moderate correction to the measured cross-section, and thus a mild loss of accuracy in the determination of PDF uncertainties in these corrections is acceptable, while computational speed can be an issue. In these cases, use of the PDF4LHC15\_30 sets is most suitable.

However, in the cases when PDF uncertainties turn out to be substantial, we recommend to cross-check the PDF estimate by comparing with the results of the PDF4LHC15\_100 sets.

4. Calculation of PDF uncertainties in precision observables

**Recommendation:** Use the PDF4LHC15\_100 sets.

**Rationale:** For several LHC phenomenological applications, the highest accuracy is sought for, with, in some cases, the need to *control PDF uncertainties to the percent level*, as currently allowed by the development of high-order computational techniques in the QCD and electroweak sectors of the Standard Model.

Whenever the highest accuracy is desired, the PDF4LHC15\_100 set is most suitable.



Pedagogical text about their use has been added



## 6.2 Formulae for the calculation of PDF and PDF+ $\alpha_s$ uncertainties

For completeness, we also collect in this report the explicit formulae for the calculation of PDF and combined PDF+ $\alpha_s$  uncertainties in LHC cross-sections when using the PDF4LHC15 combined sets. Let us assume that we wish to estimate the PDF+ $\alpha_s$  uncertainty of given cross-section  $\sigma$ , which could be a total inclusive cross-section or any bin of a differential distribution.

First of all, to compute the PDF uncertainty, one has to evaluate this cross-section  $N_{\text{mem}} + 1$  times, where  $N_{\text{mem}}$  is the number of error sets (either symmetric eigenvectors or MC replicas) of the specific combined set,

$$\sigma^{(k)}, \quad k = 0, \dots, N_{\text{mem}}, \quad (19)$$

so in particular  $N_{\text{mem}} = 30$  in PDF4LHC15\_30 and  $N_{\text{mem}} = 100$  in PDF4LHC15\_100 and PDF4LHC15\_mc.

**PDF uncertainties for Hessian sets.** In the case of the Hessian sets, PDF4LHC15\_30 and PDF4LHC15\_100, the master formula to evaluate the PDF uncertainty is given by

$$\delta^{\text{pdf}} \sigma = \sqrt{\sum_{k=1}^{N_{\text{mem}}} (\sigma^{(k)} - \sigma^{(0)})^2}, \quad (20)$$

This uncertainty is to be understood as a 68% confidence level. From this expression it is also easy to determine the contribution of each eigenvector  $k$  to the total Hessian PDF uncertainty. **...continues with discussion of MC PDFs**



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

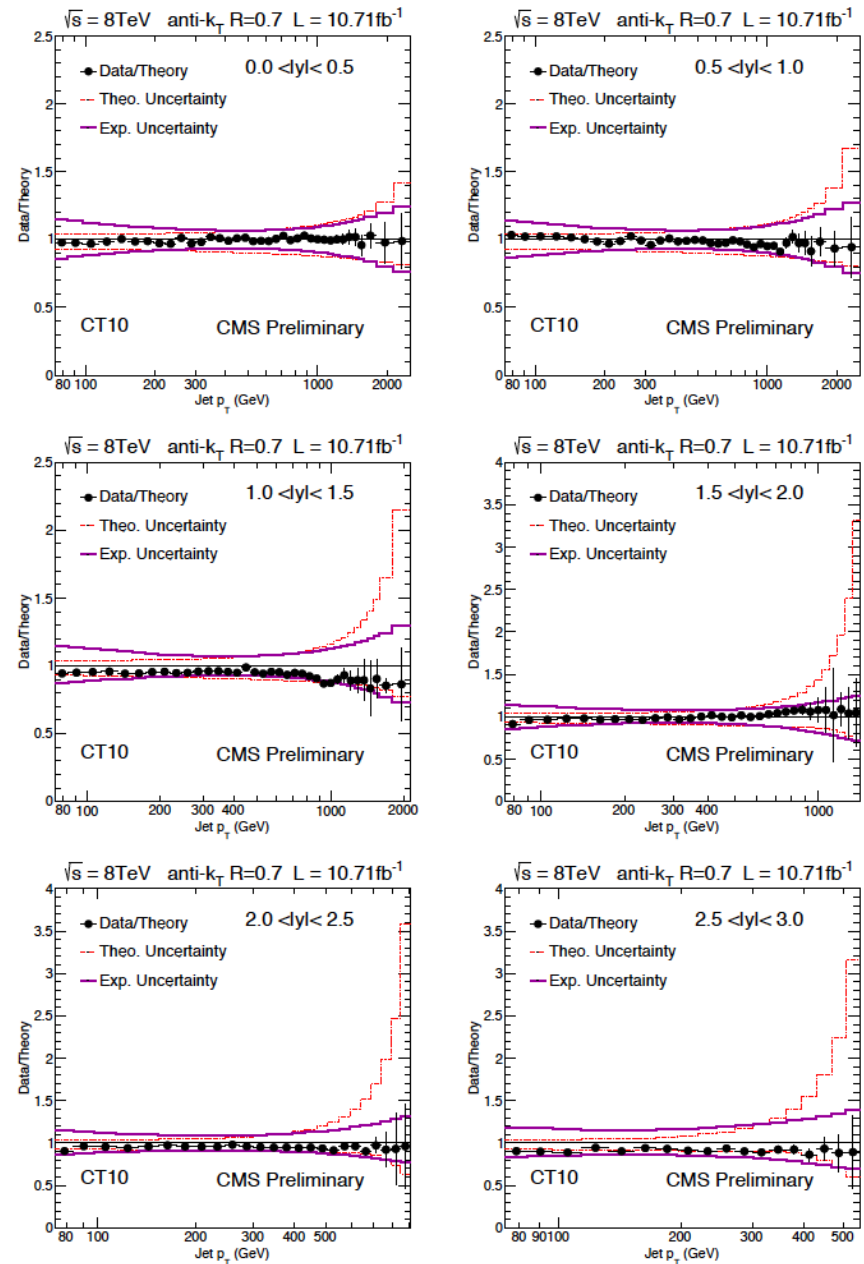
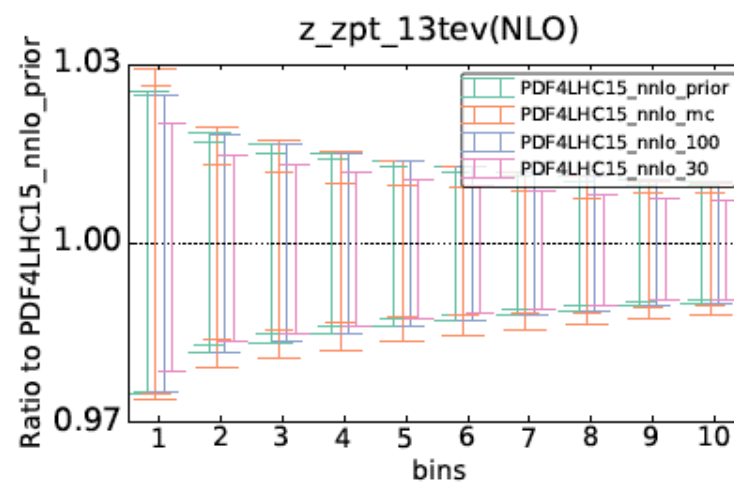
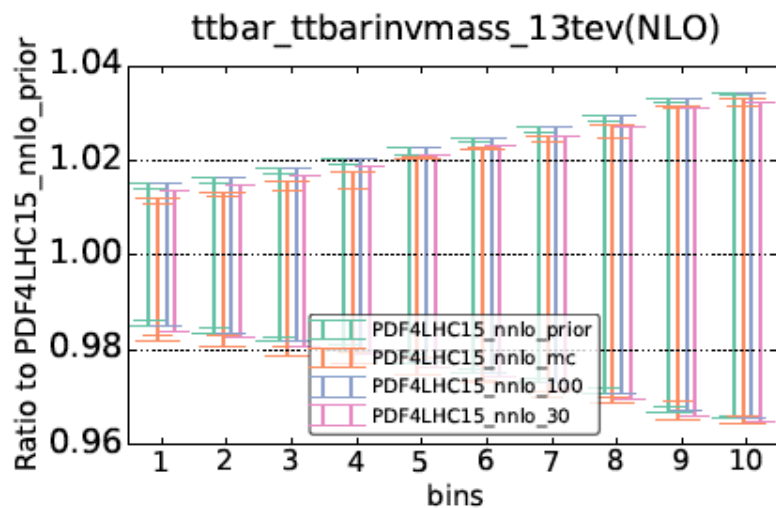
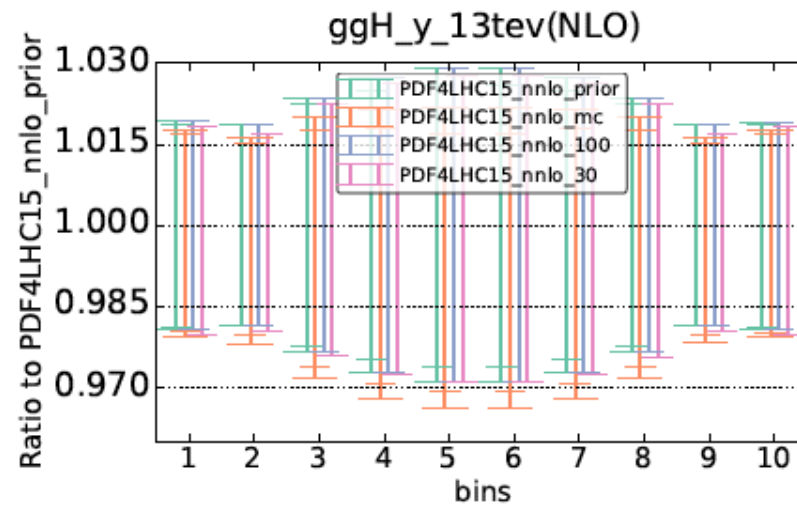
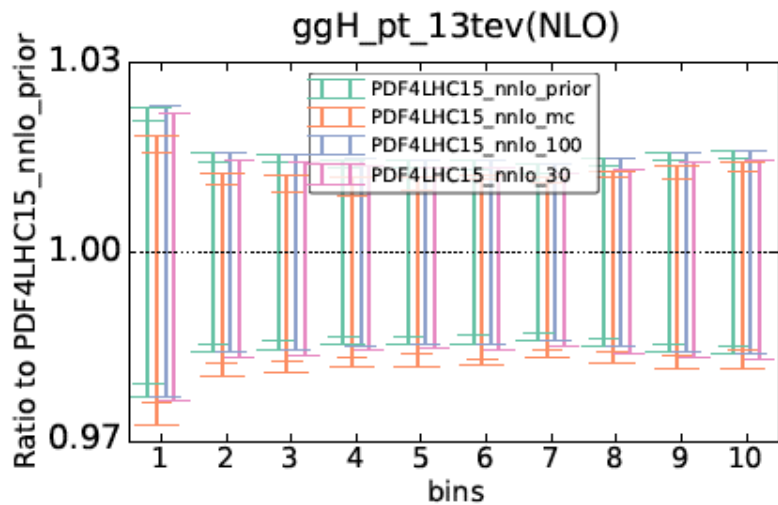


Figure 3: Ratio of data over theory at NLO times NP correction for the CT10 PDF set. For comparison the total theoretical (band enclosed by dashed red lines) and the total experimental systematic uncertainty (band enclosed by full magenta lines) are shown as well. The error bars correspond to the statistical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





# Application to cross sections



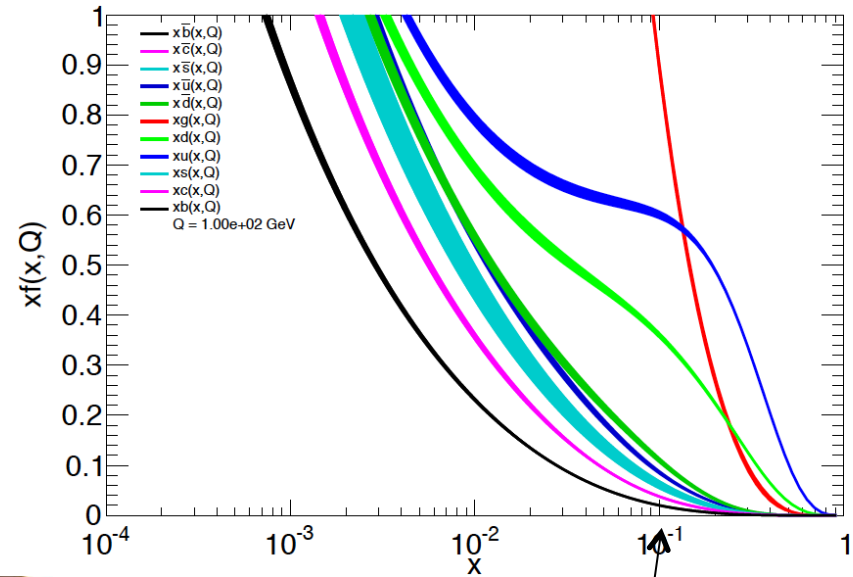
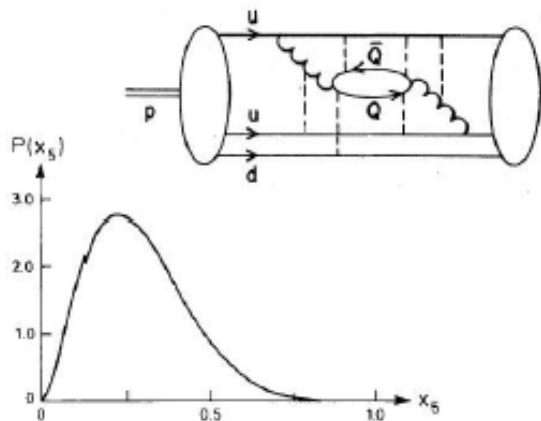


# Charm

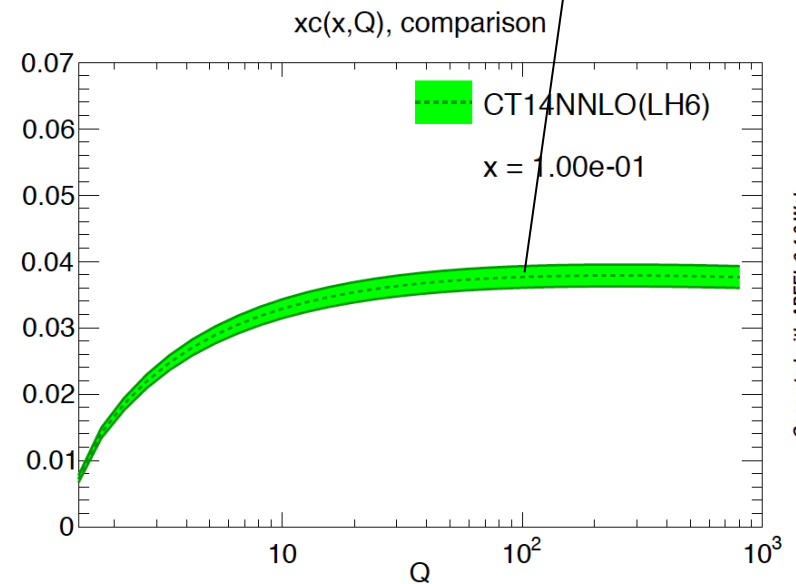


- The charm quark distribution is generated perturbatively through gluon splitting
- So normally no charm below  $c\bar{c}$  threshold
- But what if there is an intrinsic charm present in the proton at low  $Q$
- This has been Stan Brodsky's dream for some time

BHPS PLB93B (1980) 451  
 Brodsky et al: arXiv:1504.06287



Generated with APFEL 2.4.0 Web



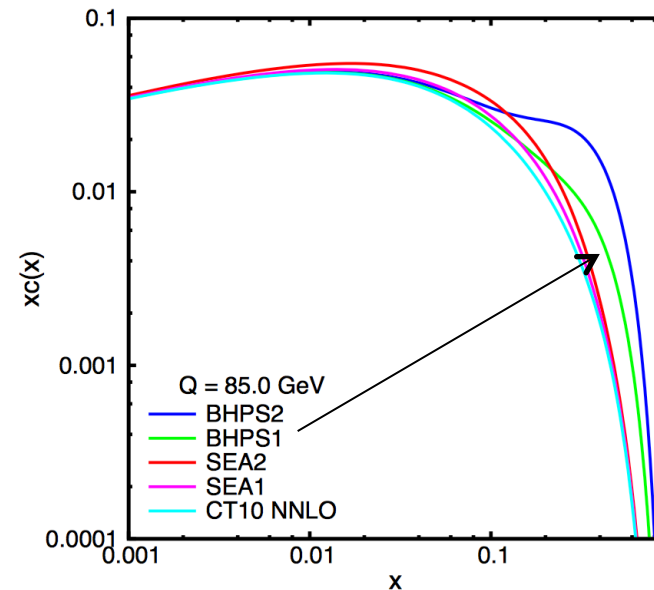
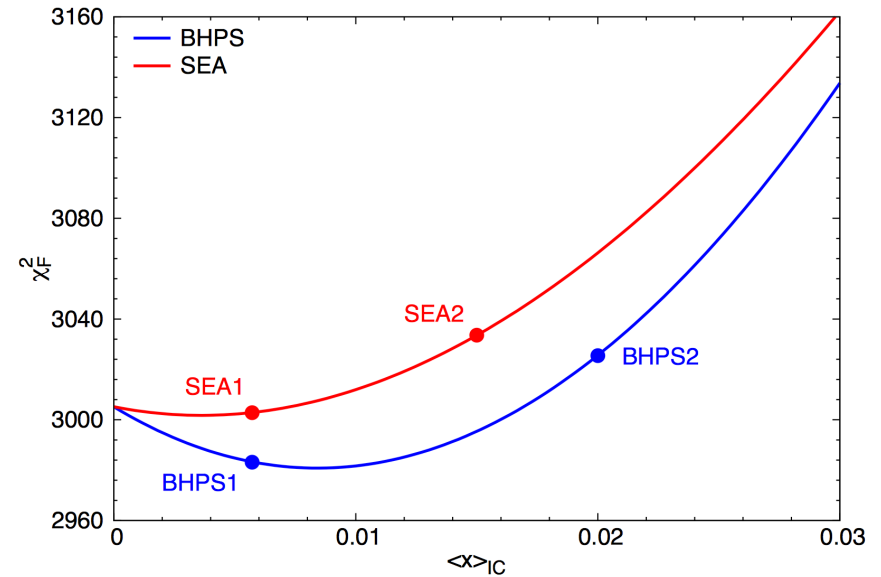
Generated with APFEL 2.4.0 Web



# Intrinsic charm



- ...and has been studied by CTEQ in, for example, arXiv: 1309.0025 and in proceedings of DIS2014
  - ◆ these analyses carried out at NNLO
- Two types of models: Brodsky-like (valence-like) or Sea-quark like
- One Brodsky-like model, BHPS1 actually leads to a modest reduction in  $\chi^2$ , but as we said in the paper, it's interesting, but not enough to claim the discovery of intrinsic charm

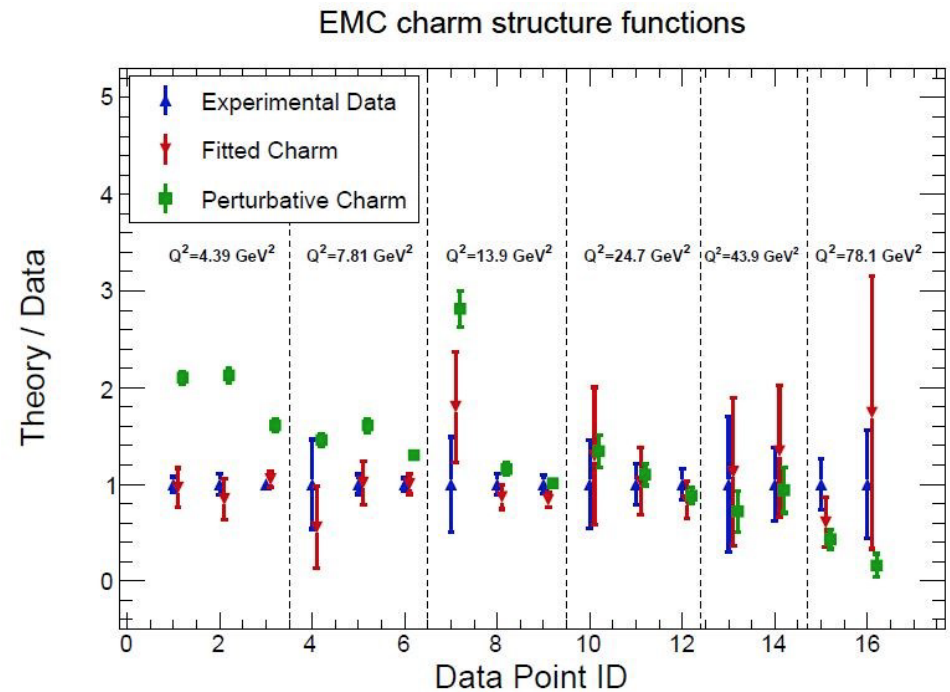




# New NNPDF paper



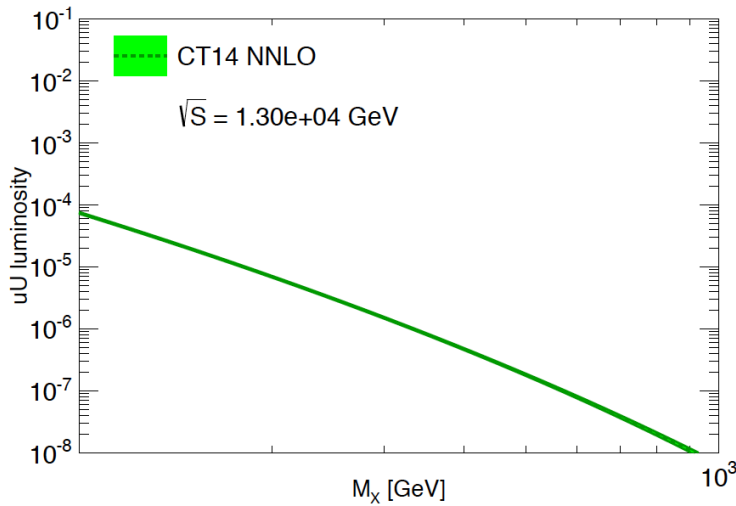
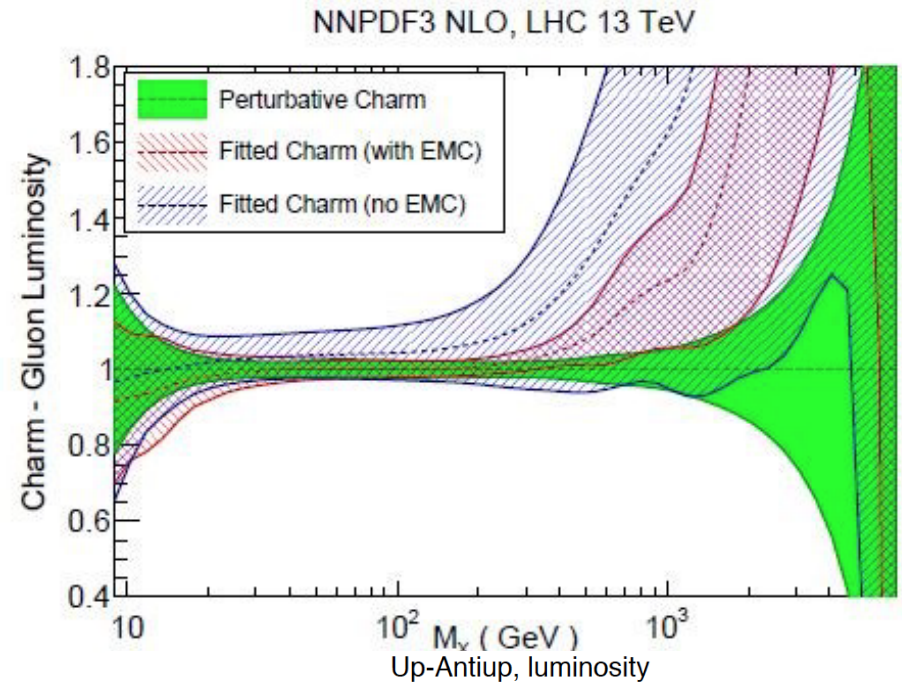
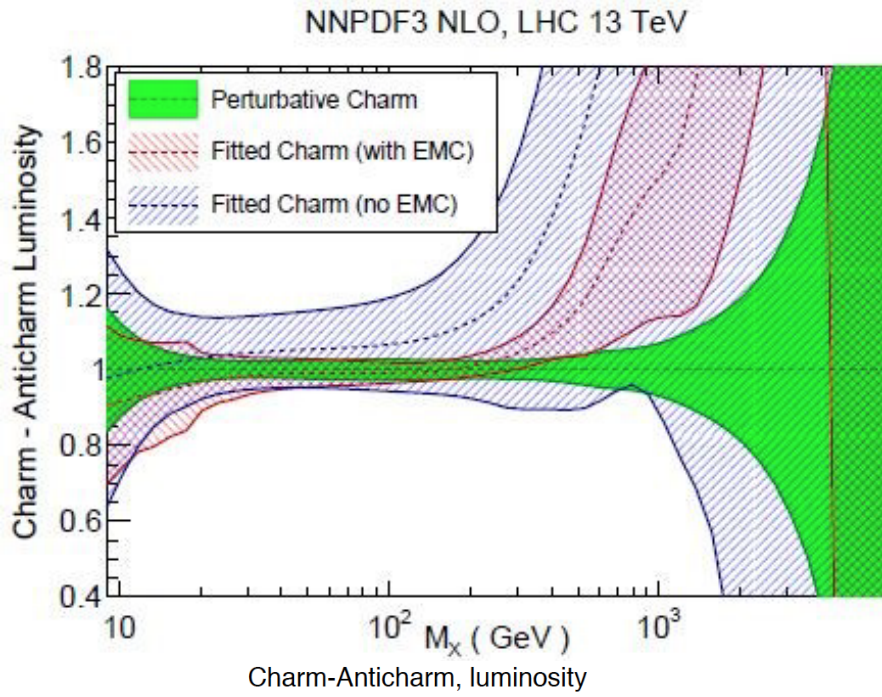
- Fit charm with flexibility present in other PDFs
  - ◆ this analysis carried out at NLO
  - ◆ this can be dangerous for a PDF that's poorly constrained, as we saw for the photon
- Use EMC charm structure function data in global fit
  - ◆ EMC data has not been used in PDF fits for several decades due to known problems with the data
    - ▲ pointed out by the experimenters themselves
  - ◆ NNPDF argument is that data is precise enough to provide evidence of intrinsic charm
  - ◆ enhanced charm without the EMC data, but with much larger uncertainty
  - ◆ reduction in global  $\chi^2$  with inclusion of fitted charm



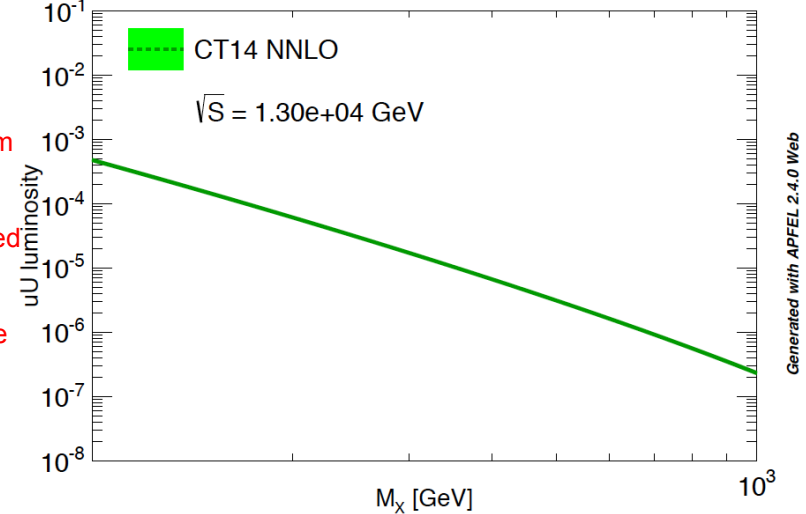
arXiv:1605.06515 + Richard Ball  
at LoopFest



# LHC Impact



even if intrinsic charm present at NNPDF level, cC final state will still be suppressed at high mass with respect to uU, but contribution would be noticeable

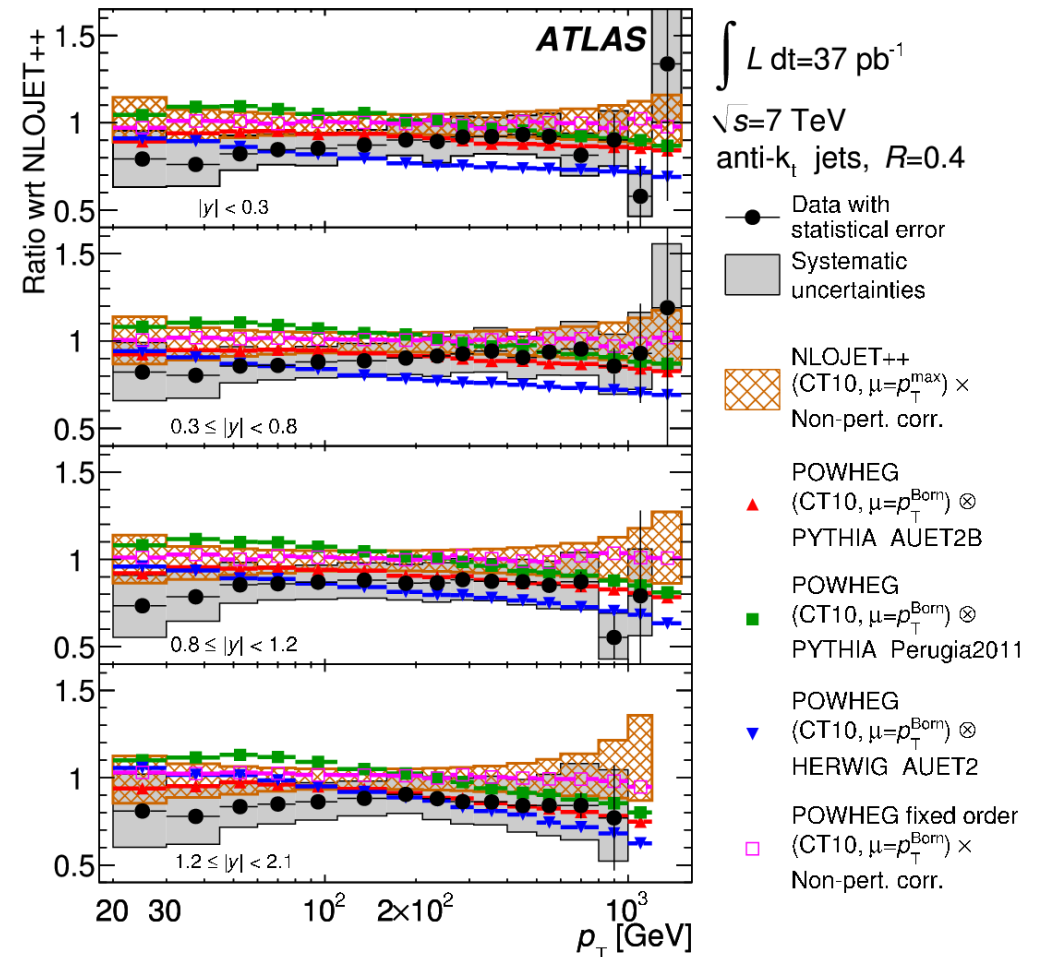




# LHC jet data



- In global PDF fits, we assume that fixed order (with non-perturbative predictions) is sufficient to describe the data, as long as the cross sections are sufficiently inclusive, such as the inclusive jet cross section
- There seems to be some difference between Powheg+parton shower and Powheg+fixed order
- This is not seen with Sherpa
- ...and needs to be better understood
- In Les Houches 2015 study for Higgs +jets observables, all ME+PS programs *devolve* to underlying fixed order predictions in non-Sudakov regions, i.e. the parton showers have little effect on either the normalization or shape of these cross sections
- I'd like to extend this study to inclusive jet production in LH2017





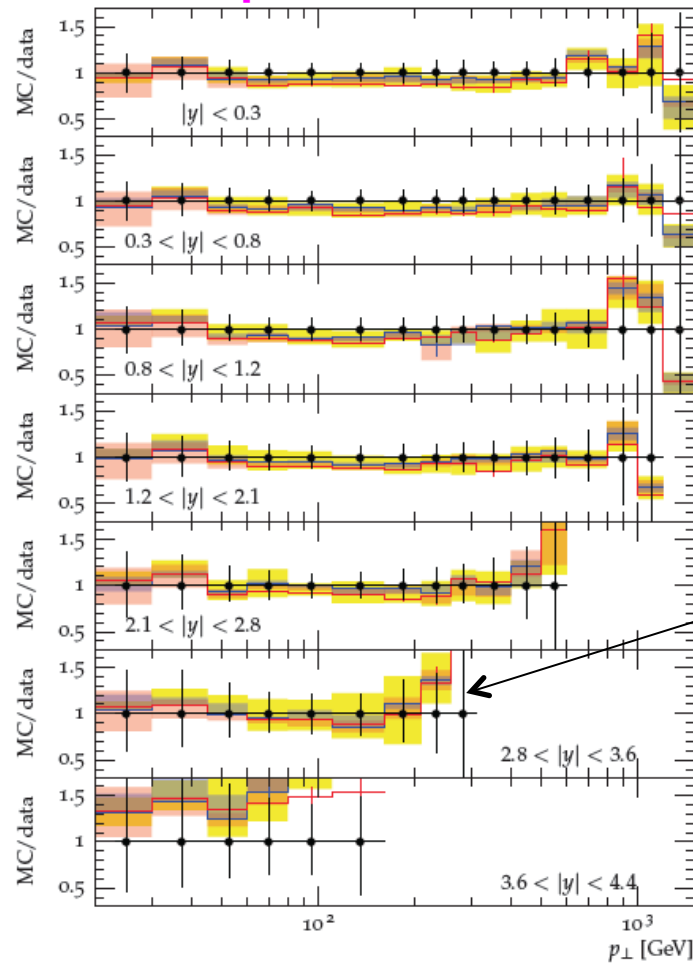
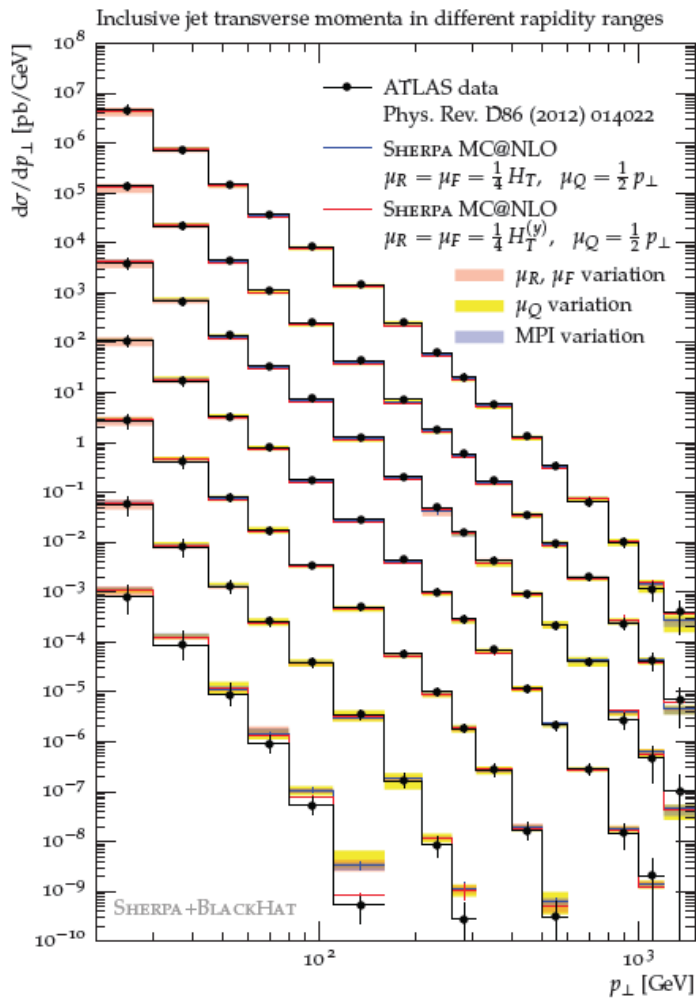
# Inclusive jet production



- We also need a better understanding of the impact of parton showers on the fixed order cross section

Sherpa MC@NLO seems to do a good job in describing ATLAS data (but PDF dependent statement)

Compare to fixed order with same PDF



resummation scale uncertainties seem small except at extremes of phase space (as expected)



# Photons



- One of key processes at hadron colliders
- Has not been used in global PDF fits since 90's
  - ◆ relatively large scale uncertainty at NLO
  - ◆ worry about isolation
  - ◆ kT effects (fixed target)
- As of Wed, now calculated at NNLO
  - ◆ using n-jettiness subtraction

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

## Direct photon production at next-to-next-to-leading order

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<sup>2</sup>Institute for Particle Physics Phenomenology, Department of Physics, University of Durham, Durham, DH1 3LE, UK

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(Dated: December 14, 2016)

We present the first calculation of direct photon production at next-to-next-to leading order (NNLO) accuracy in QCD. For this process, although the final state cuts mandate only the presence of a single electroweak boson, the underlying kinematics resembles that of a generic vector boson plus jet topology. In order to regulate the infrared singularities present at this order we use the  $N$ -jettiness slicing procedure, applied for the first time to a final state that at Born level includes colored partons but no required jet. We compare our predictions to ATLAS 8 TeV data and find that the inclusion of the NNLO terms in the perturbative expansion, supplemented by electroweak corrections, provides an excellent description of the data with greatly reduced theoretical uncertainties.

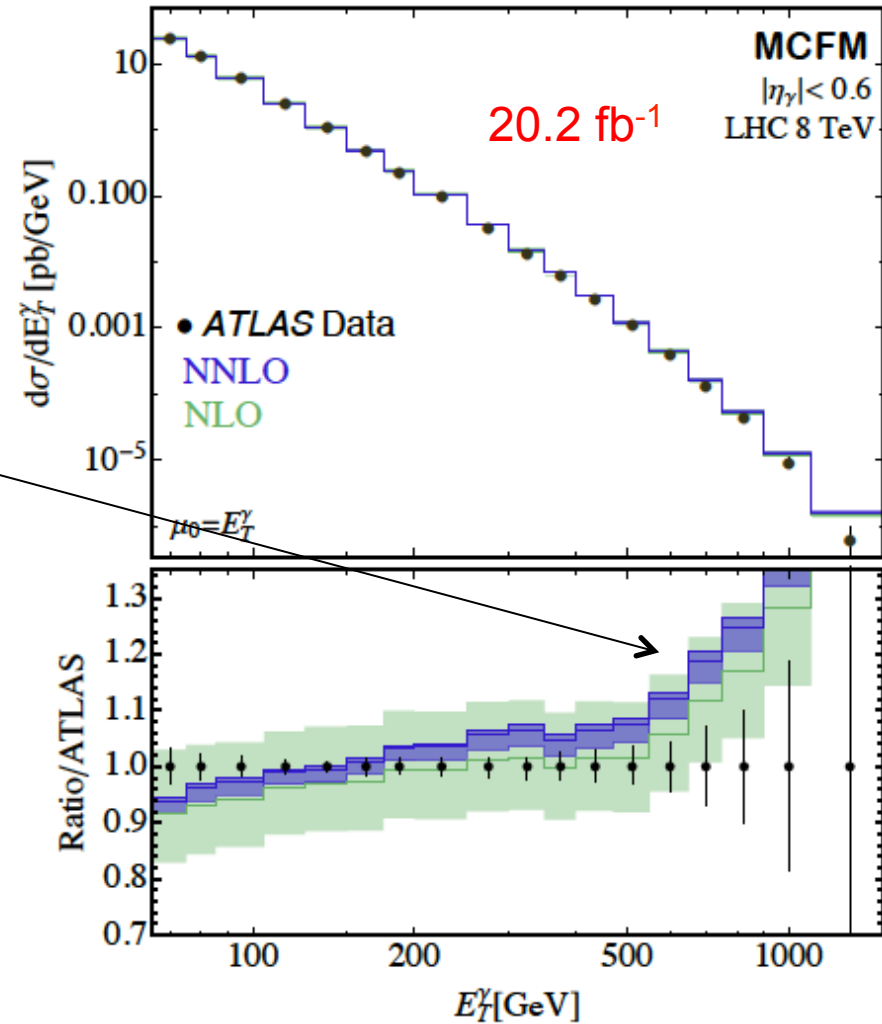




# Photon at NNLO



- Scale uncertainty much smaller
- Still some disagreement with data, especially at high  $E_T$



Frixione isolation applied to theory

$$\sum E_T^{\text{had}}(R) < \epsilon_\gamma E_T^\gamma \left( \frac{1 - \cos R}{1 - \cos R_0} \right)^n$$

eliminates fragmentation contribution

$n=2, \epsilon_\gamma=0.1$  and  $R_0=0.4$  matches impact of experimental isolation cuts

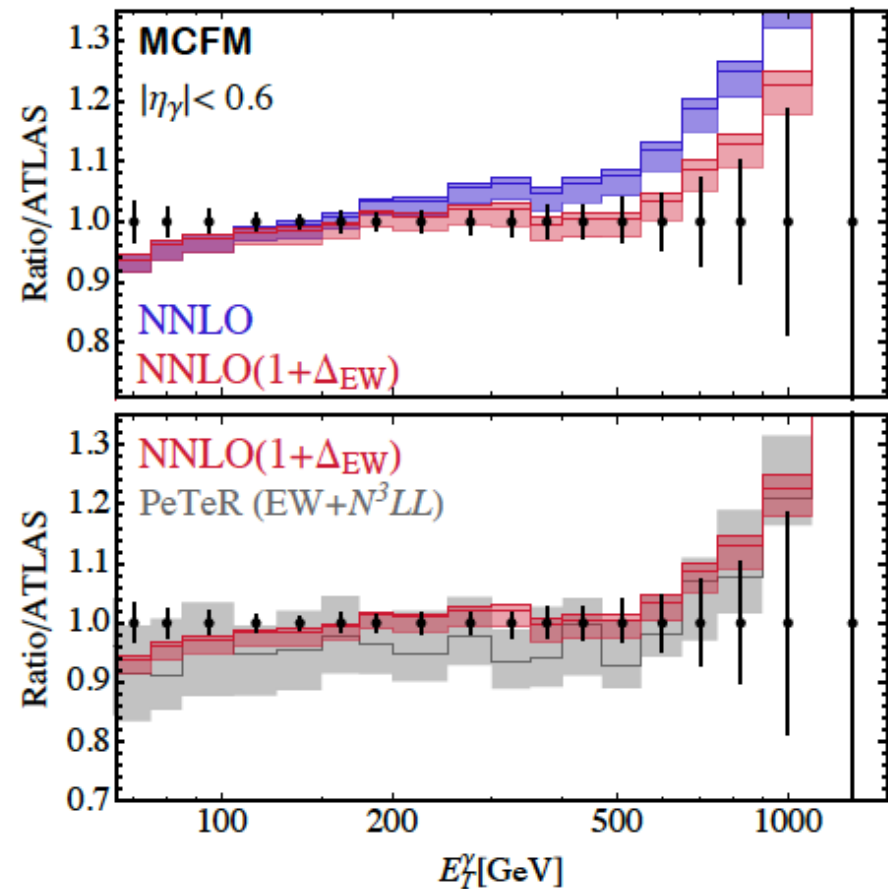
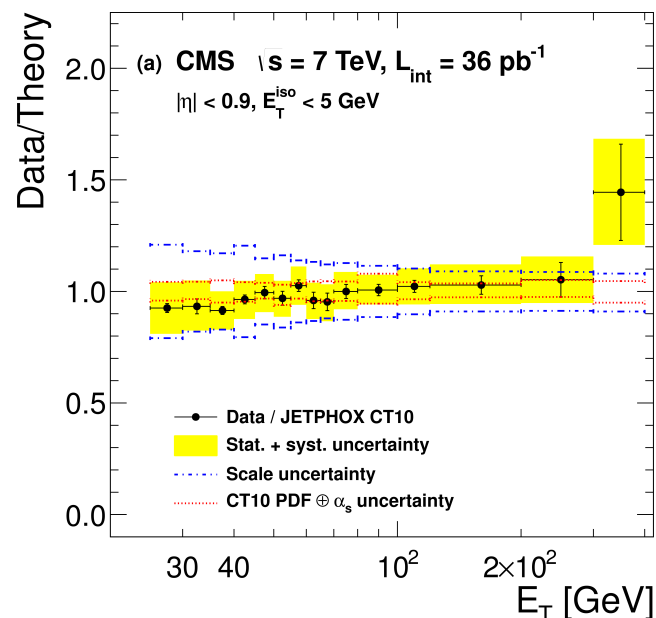
Note use  $\alpha=1/128$



# Photons at NNLO



- EW corrections very important at high  $E_T$ 
  - ◆ leading log Sudakov corrections applied
- Could higher order EW contribute as well?
- CMS qualitatively the same, but only low statistics for inclusive cross section





# A few last words



- Modern technology for ME+PS programs allows the underlying event to be calculated (and tuned) using one PDF and the matrix element evaluation and parton showering to be done with another
  - ◆ can think of it as an effective factorization
- That UE PDF can even be LO...in fact usually better/easier if it's LO
- Thus, a lot of work that is carried out by LHC experiments on creating tunes for new versions of PDFs can be avoided, IMHO



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

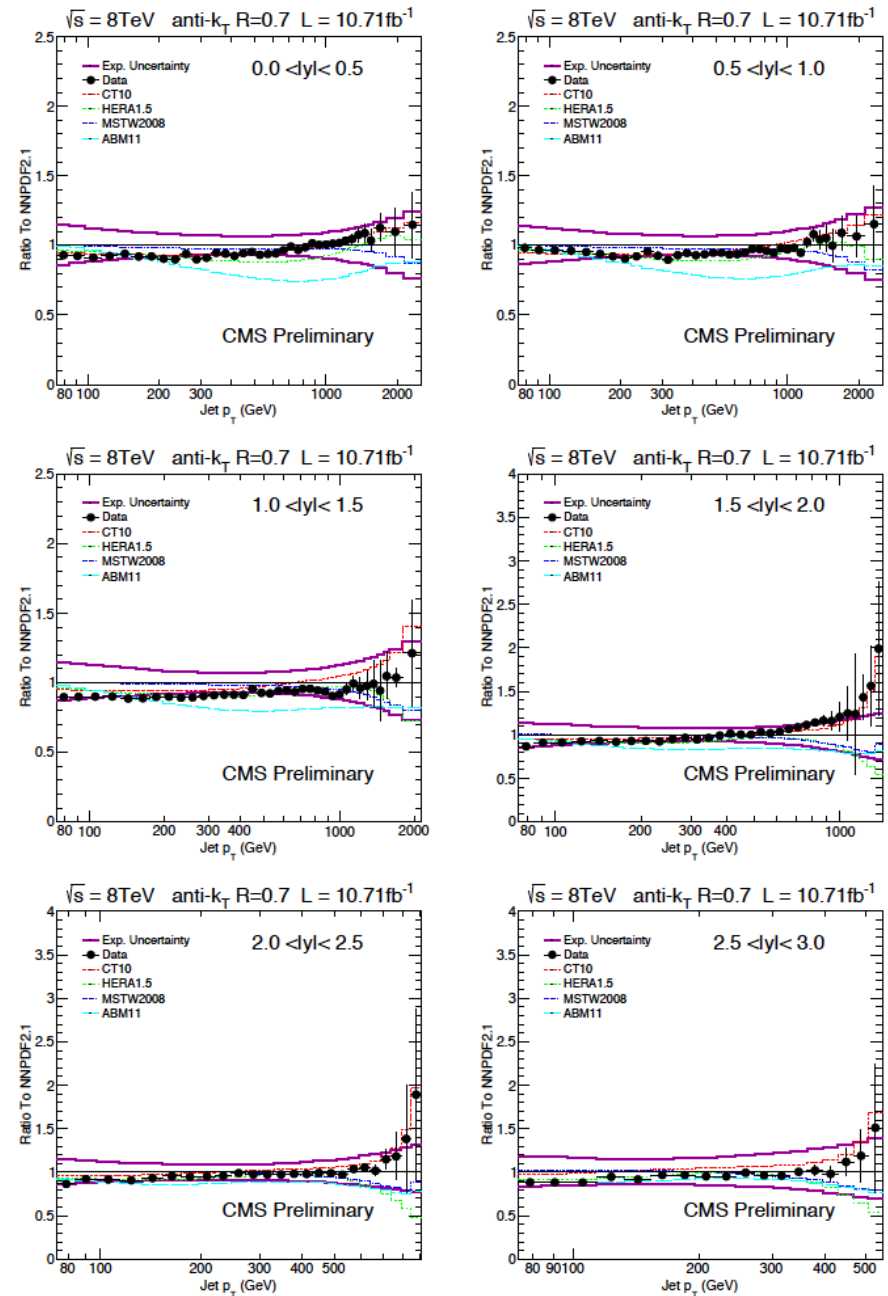


Figure 7: Ratio of data over theory at NLO times NP correction for the NNPDF2.1 PDF set. For comparison predictions employing four other PDF sets are shown in addition to the total experimental systematic uncertainty (band enclosed by full magenta lines). The error bars correspond to the statistical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