PDF Update

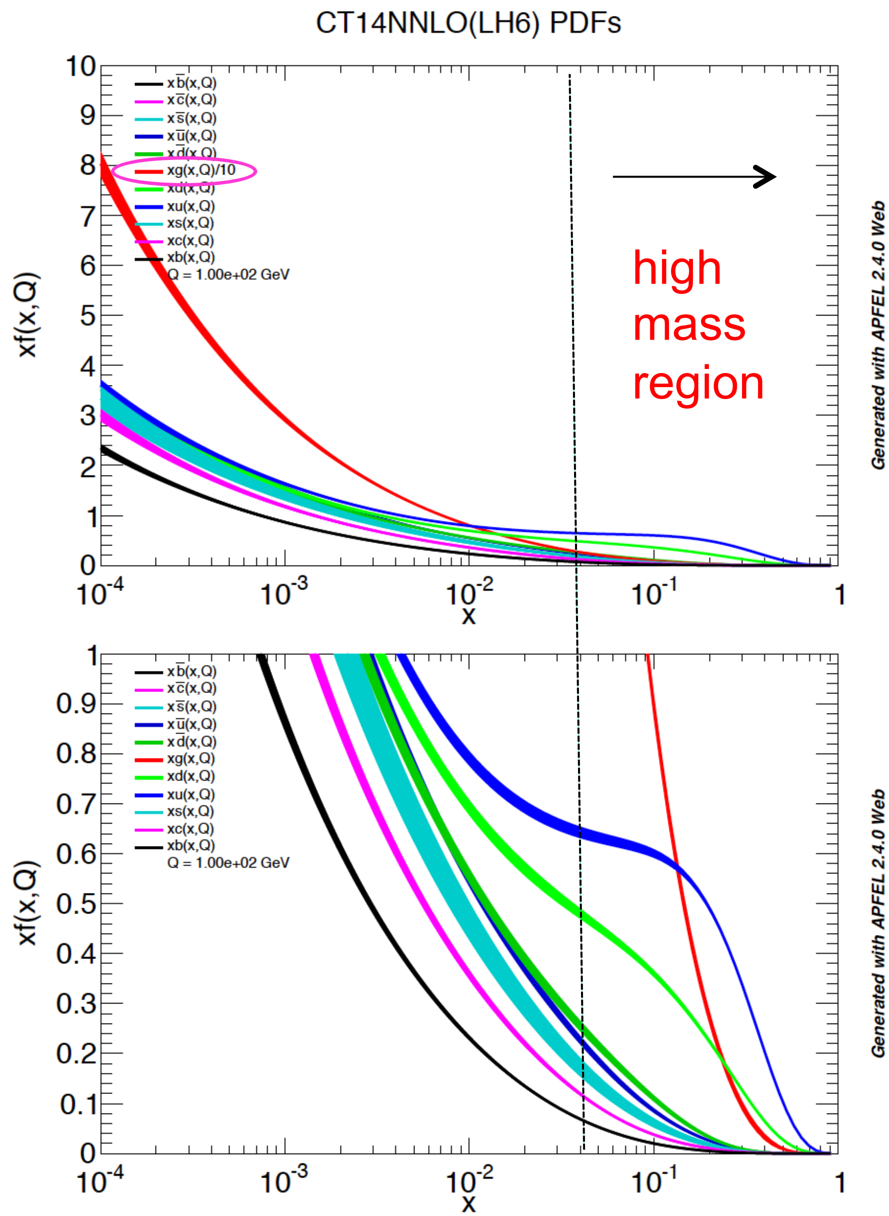
J. Huston
Michigan State University/
IPPP Durham

for PDF sub-group: JH, S. Forte,
R. Thorne

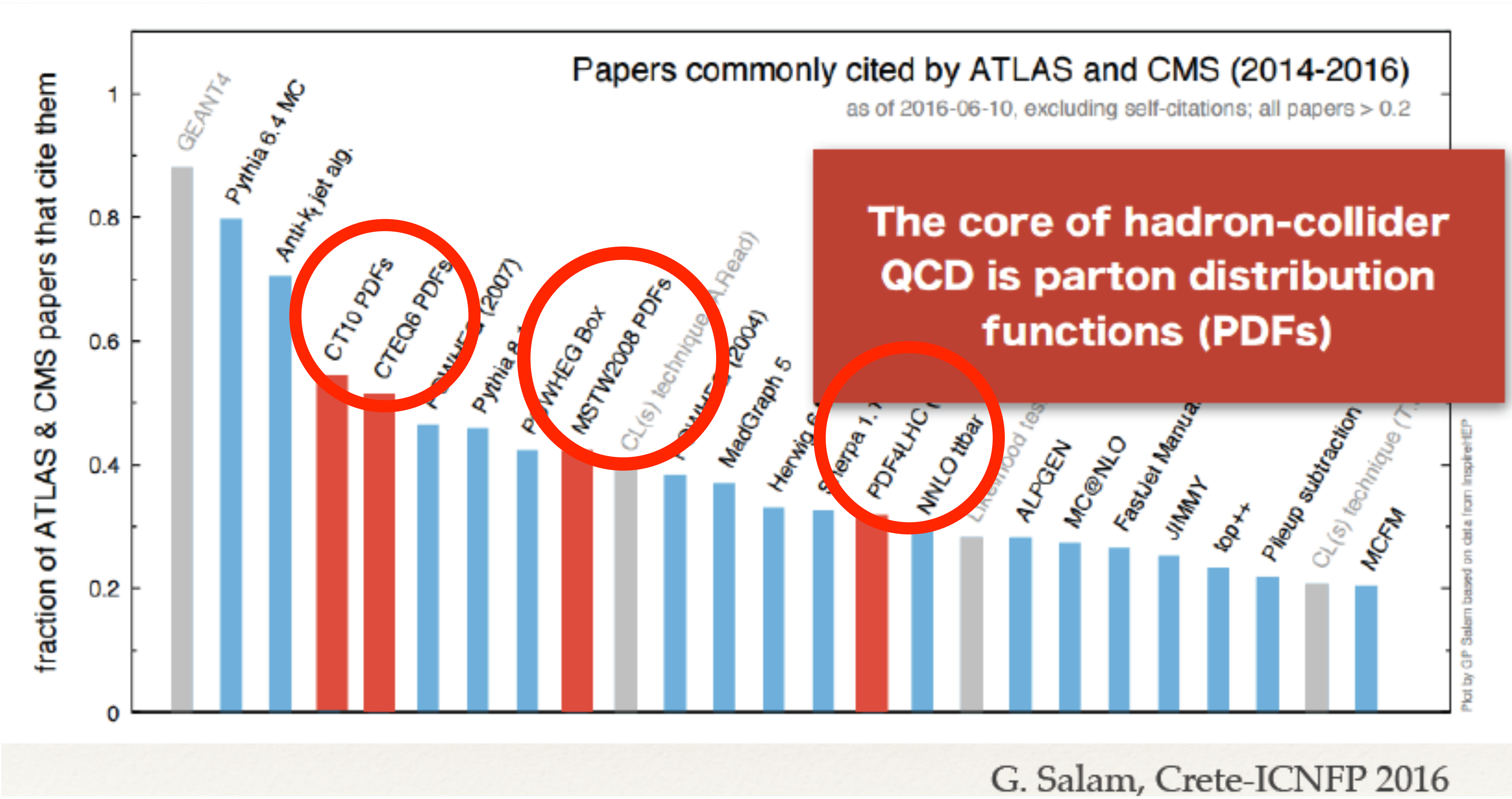
Alternate Title

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 ttbar 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

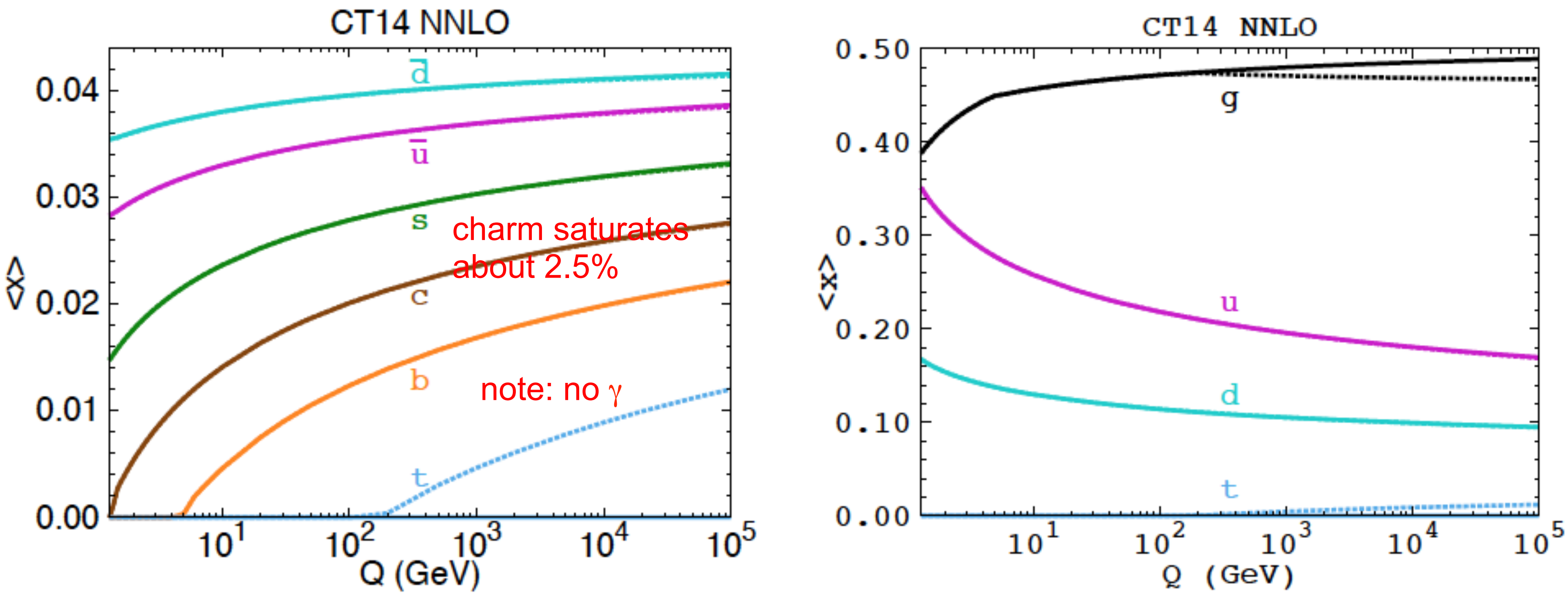


Fig. 6.10 The momentum fractions carried by the CT14 NNLO quark and gluon distributions, as a function of Q. The gluon distribution in the right figure is shown without (with) the presence of a top quark PDF.

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
- These PDFs are evaluated in the relevant expressions for the hard scattering cross sections we are interested .

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

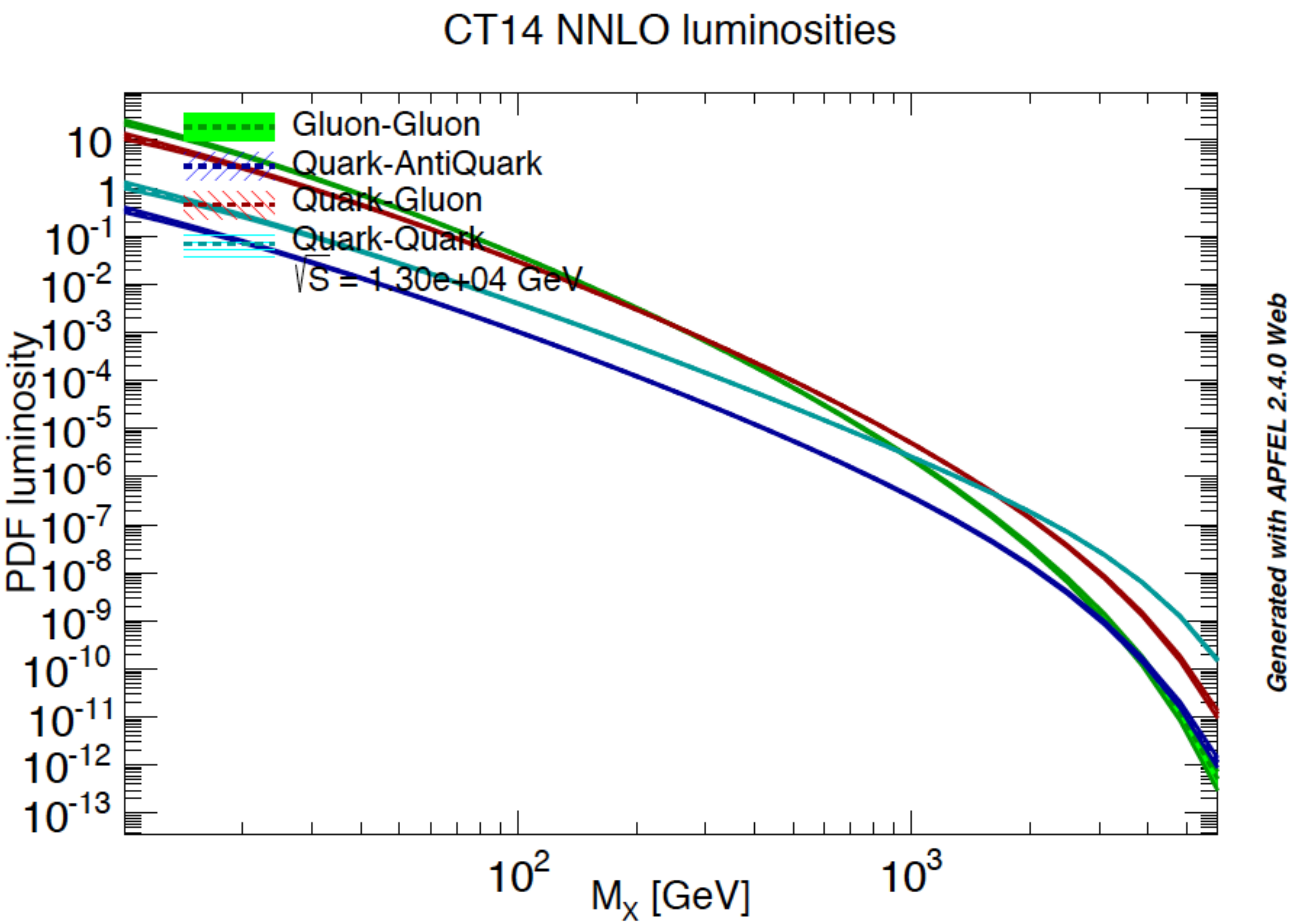
$$+ \alpha_s(\mu_R^2) \Big[\int \left(\mathrm{d}\hat{\sigma}_{ab}^{V} \, (\alpha_s,\mu_R^2) + \mathrm{d}\hat{\sigma}_{ab}^{C} \, (\alpha_s,\mu_F^2) \right) \Theta_{\rm obs}^{(m)} + \int \mathrm{d}\hat{\sigma}_{ab}^{R}(\alpha_s) \, \Theta_{\rm obs}^{(m+1)} \Big] \Big\} + \ldots$$

In addition to the PDFs themselves, it is also useful to define a PDF luminosity.

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

…or integrated over y

PDF luminosities



PDF luminosities: pre-history

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

HERAPDF1.5 uncertainties larger in general

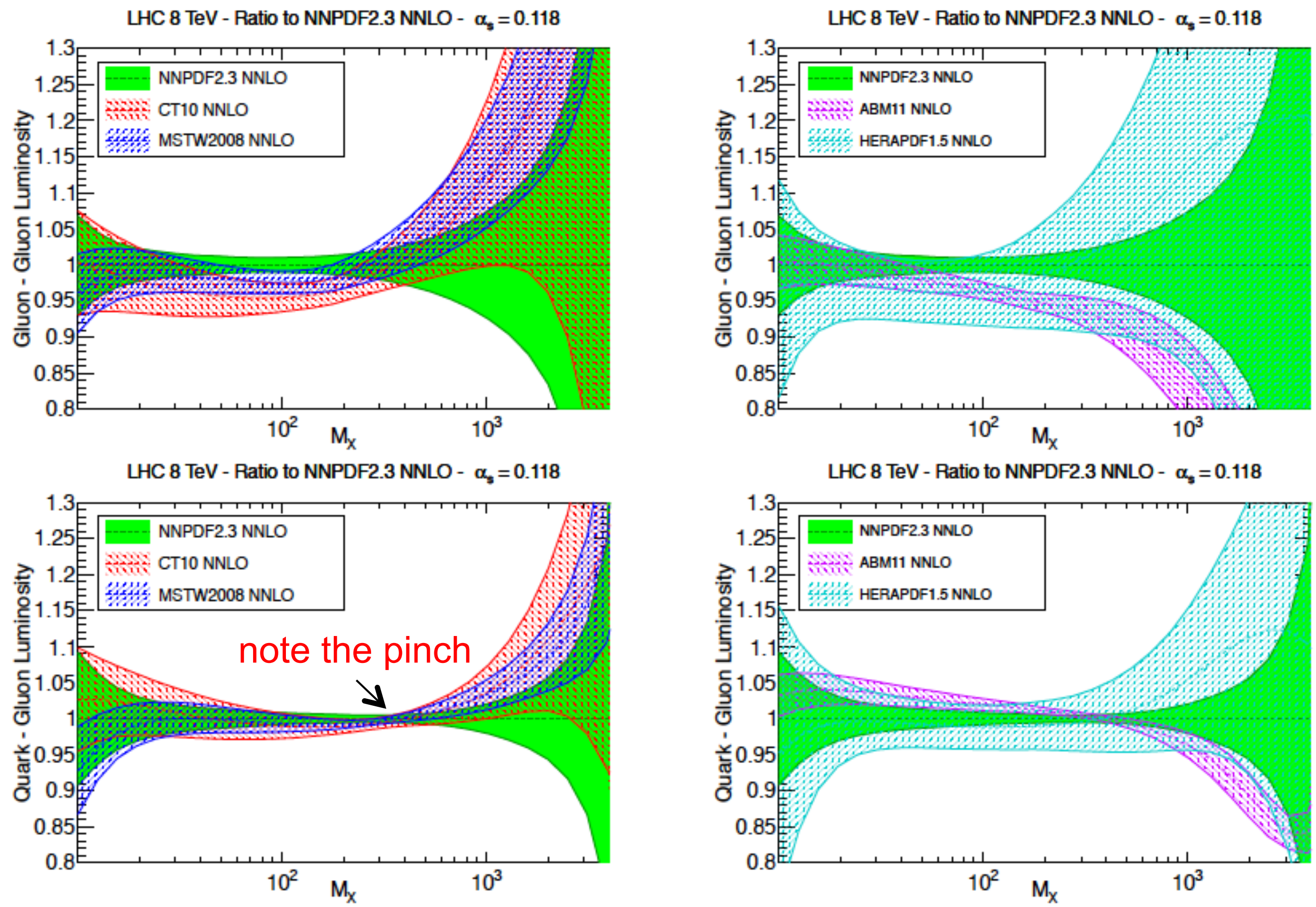


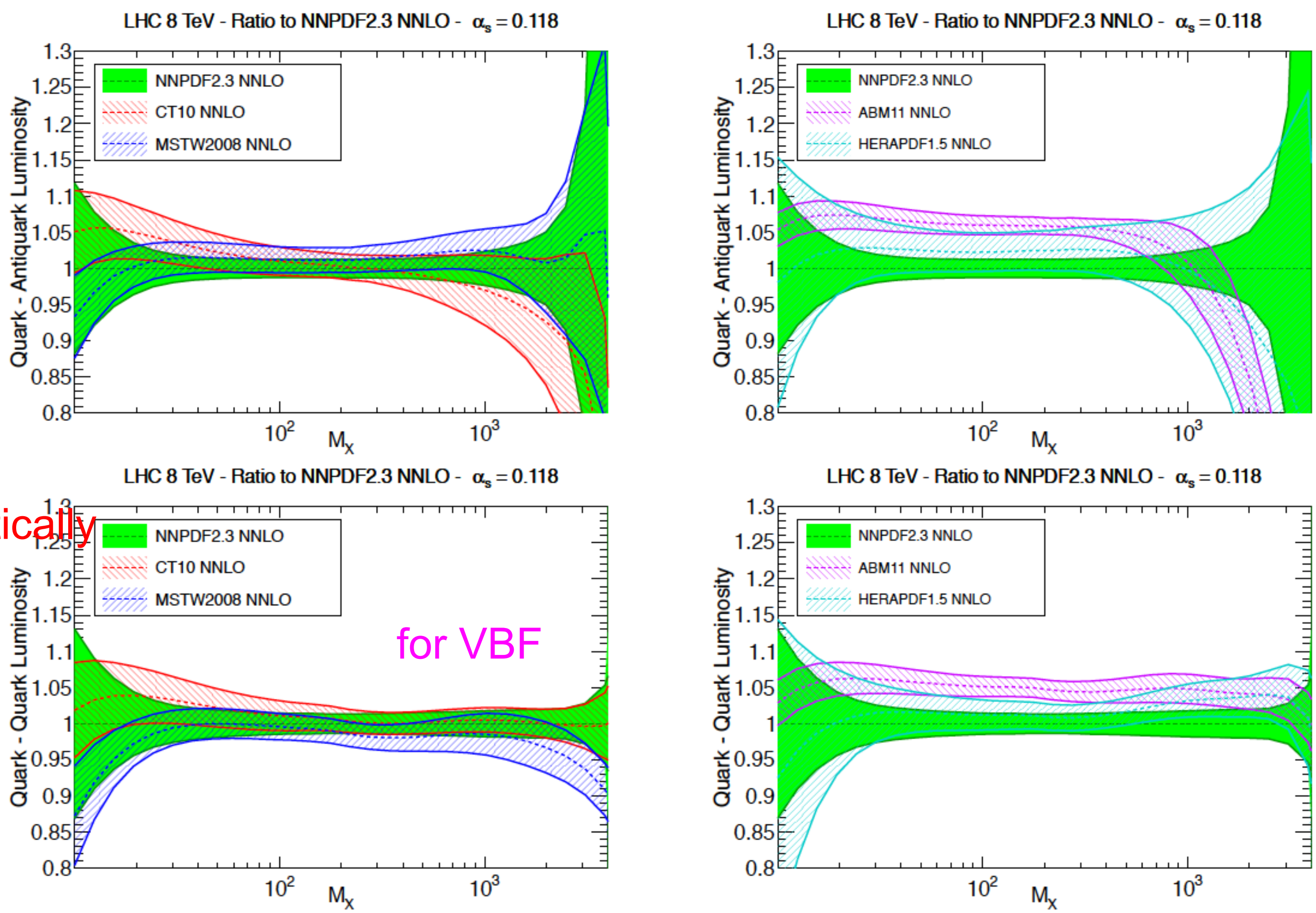
Figure 6: The gluon-gluon (upper plots) and quark-gluon (lower plots) luminosities, Eq. (2), for the production of a final state of invariant mass M_X (in GeV) at LHC 8 TeV. The left plots show the comparison between NNPDF2.3, CT10 and MSTW08, while in the right plots we compare NNPDF2.3, HERAPDF1.5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

PDF luminosities

quark-quark and quark-antiquark

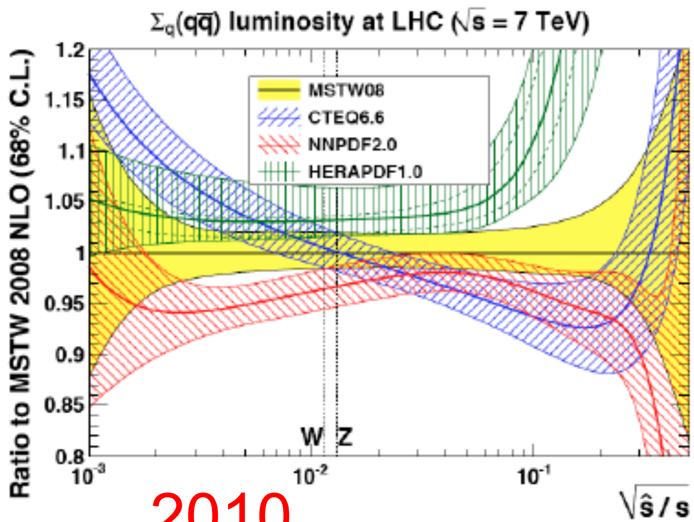
quark-antiquark luminosities for CT10, MSTW08 and NNPDF2.3 overlap almost 100% in W/Z range

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

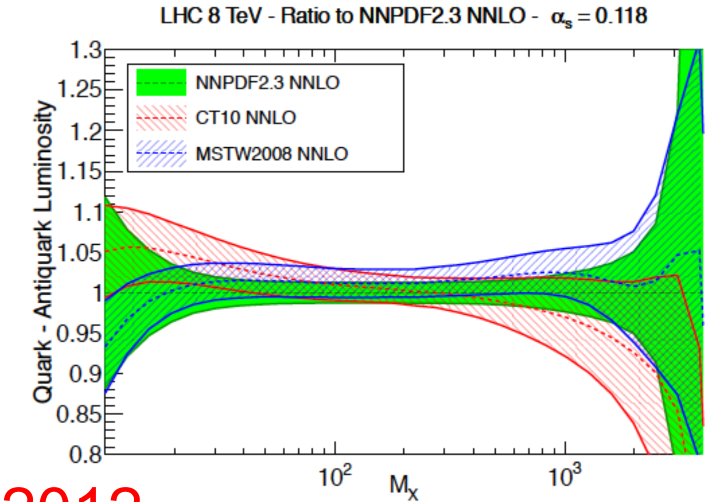


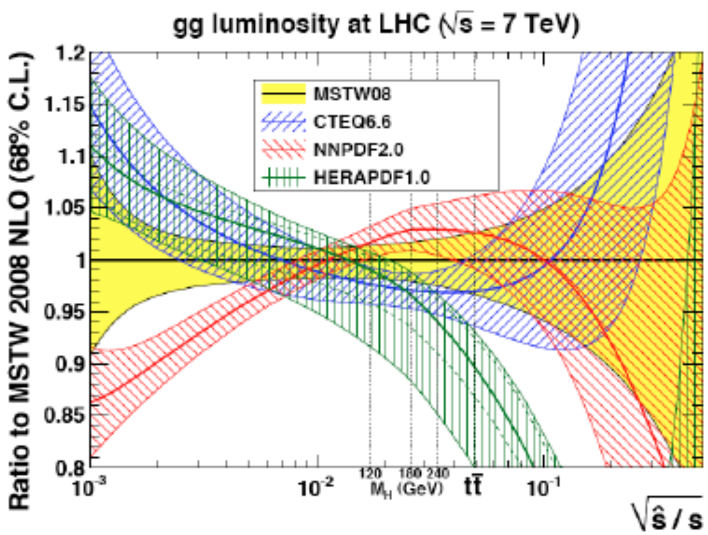
Uncertainties have improved

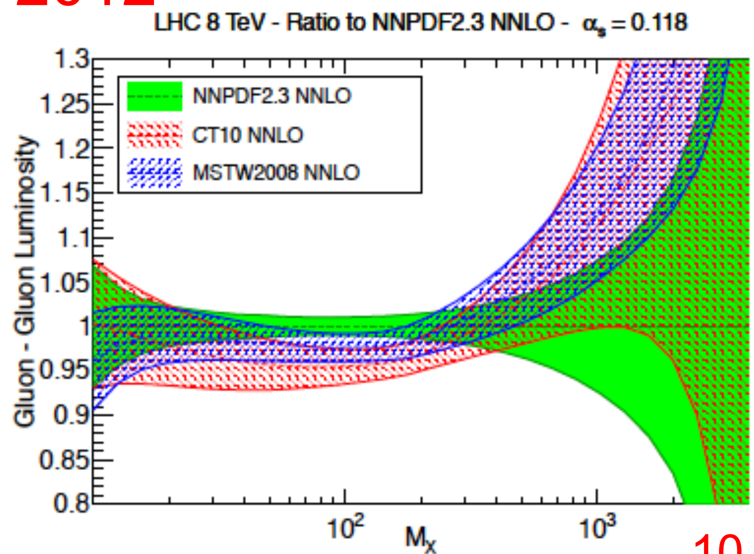
- …with additional data and in going from NLO to NNLO



2010 → 2012







A lot of *vetting* has taken place

Theoretical accuracy

A variety of comparisons was accomplished to benchmark NNLO theoretical calculations for key scattering processes

1. J. Gao et al., MEKS: a program for computation of inclusive jet cross sections at hadron colliders , arXiv:1207.0513

2. R. Ball et al., Parton Distribution benchmarking with LHC data, arXiv:1211.5142

3. S. Alekhin et al., ABM11 PDFs and the cross section benchmarks in NNLO, arXiv:1302.1516; The ABM parton distributions tuned to LHC data; arXiv:1310.3059

4. A.Cooper-Sarkar et al., PDF dependence of the Higgs production cross section in gluon fusion from HERA data, 2013 Les Houches Proceedings, arXiv:1405.1067, p. 37

5. S. Forte and J. Rojo, Dataset sensitivity of the gg->H cross-section in the NNPDF analysis, arXiv:1405.1067, p. 56

Verifying statistical methods

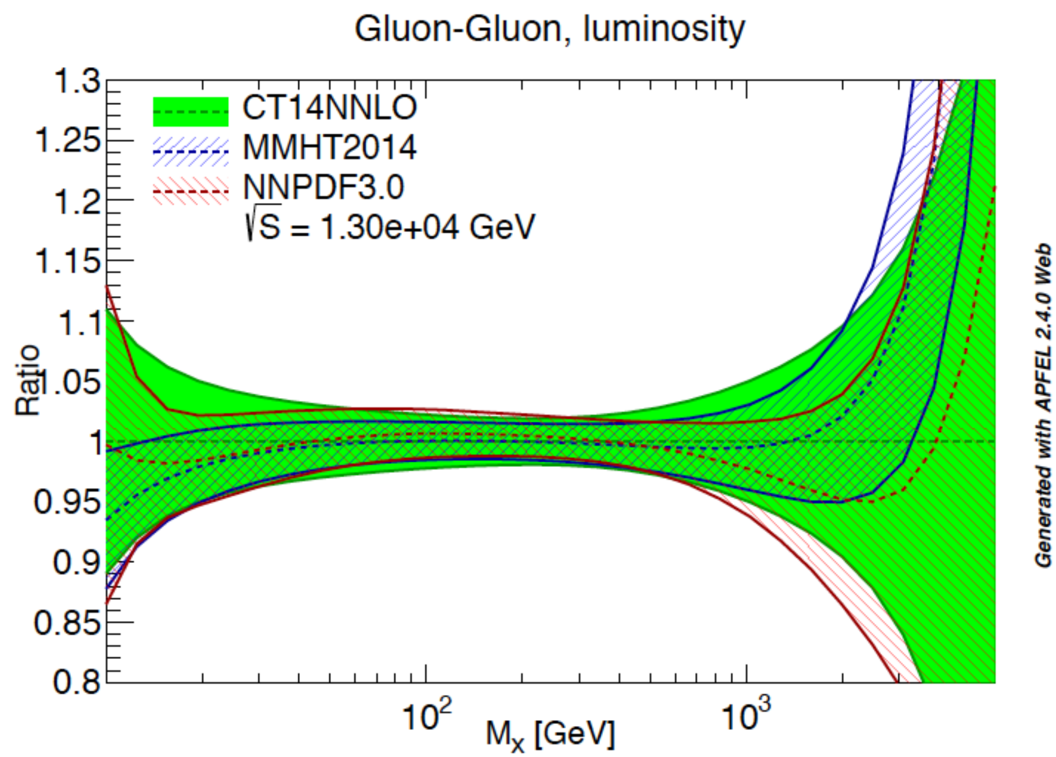
Parametric/Hessian methodology (CT, MMHT) and **nonparametric/Monte-Carlo methodology** (NNPDF) result in comparable global fits and PDF uncertainties

Advanced PDF parametrizations are employed by CT and MMHT for efficient, minimally biased, extraction of PDFs from global data

Hessian PDFs can be converted into MC PDFs, and back

PDFs: the next generation

- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (arXiv:1506.07443))
- HERAPDF2.0
- The gg PDF luminosities for the first three PDFs are in good agreement with each other in the Higgs mass range



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

A comparison of ggF at NNLO

	CT14	MMHT2014	NNPDF3.0
scale = m_H			
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 NNNLO scale uncertainty and to the $\alpha_s(m_Z)$ uncertainty.

OUTP-15-17P
SMU-HEP-15-12
TIF-UNIMI-2015-14
LCTS/2015-27

arXiv:submit/1375627 [hep-ph] 12 Oct 2015

PDF4LHC recommendations for LHC Run II

Jon Butterworth[1], Stefano Carrazza[2], Amanda Cooper-Sarkar[3], Albert De Roeck[4,5], Joël Feltesse[6], Stefano Forte[2], Jun Gao[7], Sasha Glazov[8], Joey Huston[9], Zahari Kassabov[2,10], Ronan McNulty[11], Andreas Morsch[4], Pavel Nadolsky[12], Voica Radescu[13], Juan Rojo[14] and Robert Thorne[1].

[1] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK.*
[2] *TIF Lab, Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*
[3] *Particle Physics, Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK.*
[4] *PH Department, CERN, CH-1211 Geneva 23, Switzerland*
[5] *Antwerp University, B2610 Wilrijk, Belgium*
[6] *CEA, DSM/IRFU, CE-Saclay, Gif-sur-Yvette, France*
[7] *High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.*
[8] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany.*
[9] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824 U.S.A.*
[10] *Dipartimento di Fisica, Università di Torino and INFN, Sezione di Torino, Via Pietro Giuria 1, I-10125 Torino, Italy*
[11] *School of Physics, University College Dublin Science Centre North, UCD Belfeld, Dublin 4, Ireland*
[12] *Department of Physics, Southern Methodist University, Dallas, TX 75275-0181, U.S.A.*
[13] *Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany.*
[14] *Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, University of Oxford, OX1 3NP Oxford, UK*

Progress with recent PDFs

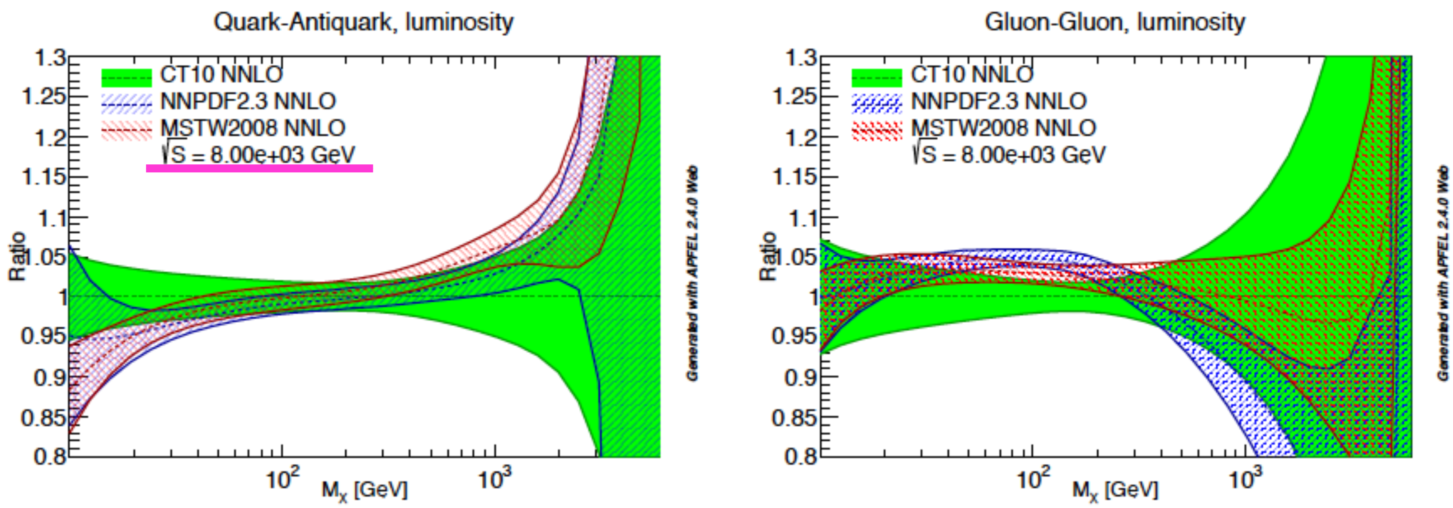
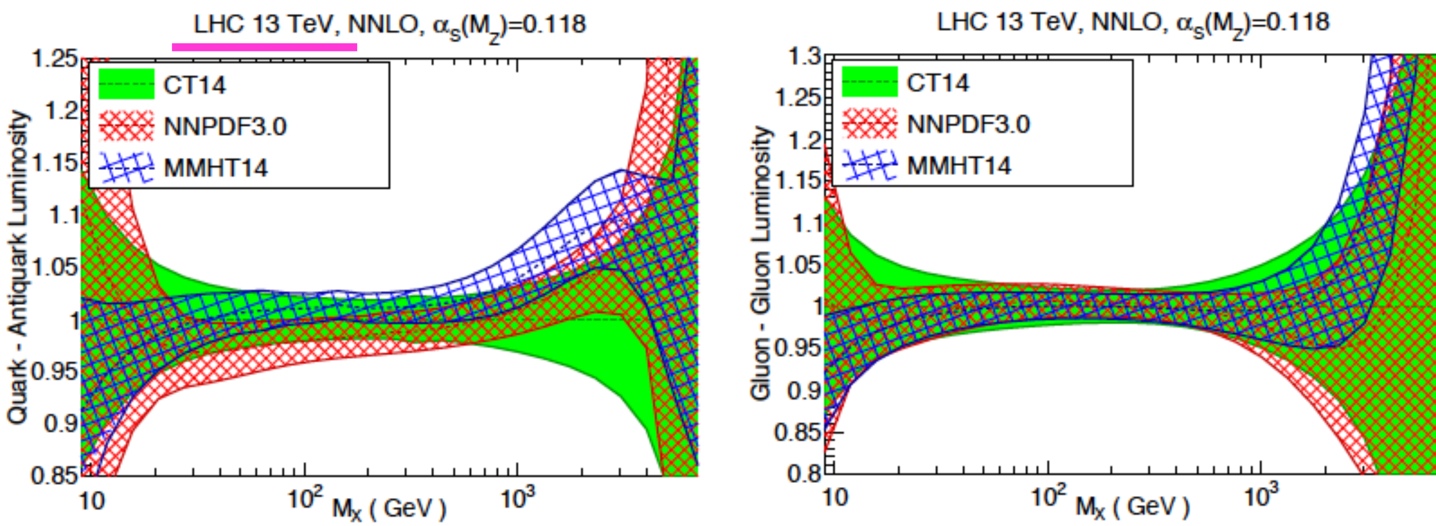


Figure 1: Comparison of the $q\bar{q}$ (left) and gg (right) PDF luminosities at the LHC 8 TeV for CT10, MSTW2008 and NNPDF2.3. Results are shown normalized to the central value of CT10.



The 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.

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

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**. it was always the intent of the PDF4LHC working group that the PDF4LHC15 PDFs can be used 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 α_s*, in a *general-mass variable-flavor number scheme* with up to $n_f^{\max} = 5$ active quark flavors.[1] Evolution of α_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.[2] For the computation of α_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

Aside

…a different approach, 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

A. Accardi[a,b], S. Alekhin[c,d], J. Blümlein[e], M.V. Garzelli[c], K. Lipka[f],
W. Melnitchouk[b], S. Moch[c], J.F. Owens[g], R. Plačakytė[f], E. Reya[h], N. Sato[b], A. Vogt[i]
and O. Zenaiev[f]

[a] *Hampton University, Hampton, VA 23668, USA*

[b] *Jefferson Lab, Newport News, VA 23606, USA*

[c] *II. Institut für Theoretische Physik, Universität Hamburg*
Luruper Chaussee 149, D–22761 Hamburg, Germany

[d] *Institute for High Energy Physics*
142281 Protvino, Moscow region, Russia

[e] *Deutsches Elektronensynchrotron DESY*
Platanenallee 6, D–15738 Zeuthen, Germany

[f] *Deutsches Elektronensynchrotron DESY*
Notkestraße 85, D–22607 Hamburg, Germany

[g] *Florida State University, Tallahassee, FL 32306, USA*

[h] *Institut für Physik, Technische Universität Dortmund*
D–44221 Dortmund, Germany

[i] *Department of Mathematical Sciences, University of Liverpool*
Liverpool L69 3BX, United Kingdom

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

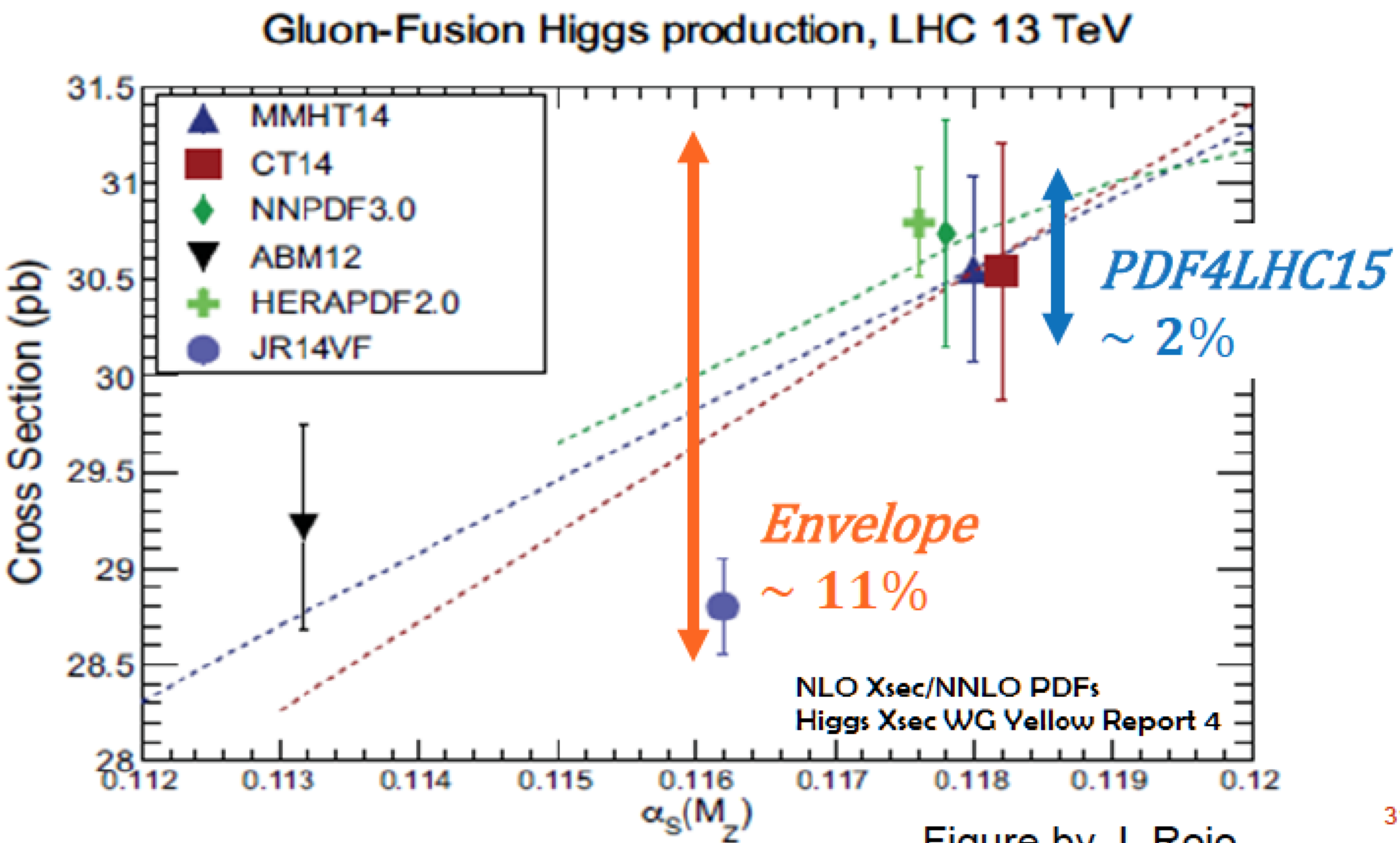


Figure by J. Rojo

Monte Carlo replicas

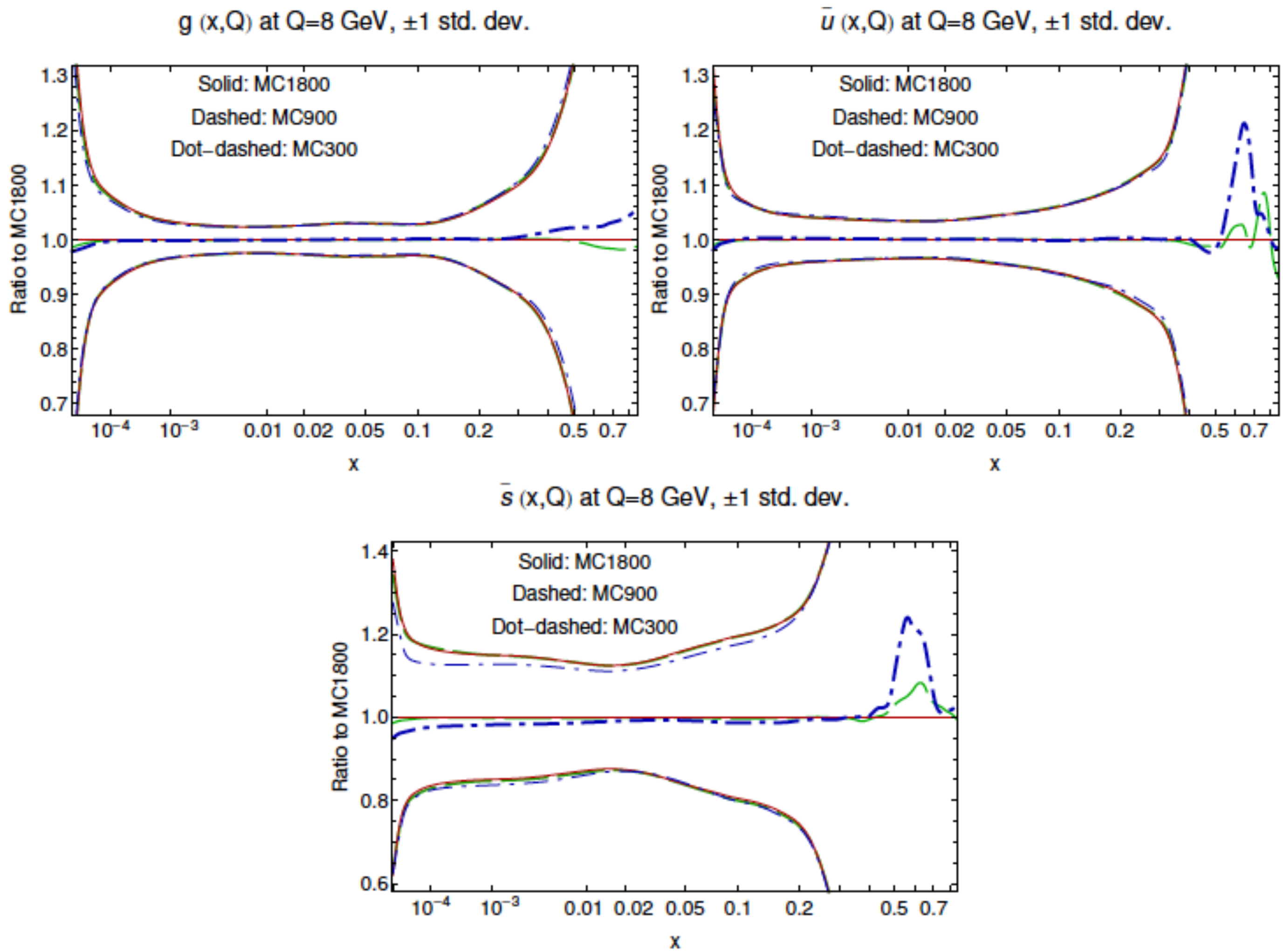


Figure 7: Comparison of central values and uncertainties for the MC combination of CT14, MMHT14 and NNPDF3.0 for different values of $N_{\rm rep}$, 300, 600 and 900, denoted by MC300, MC900 and MC1800 respectively.

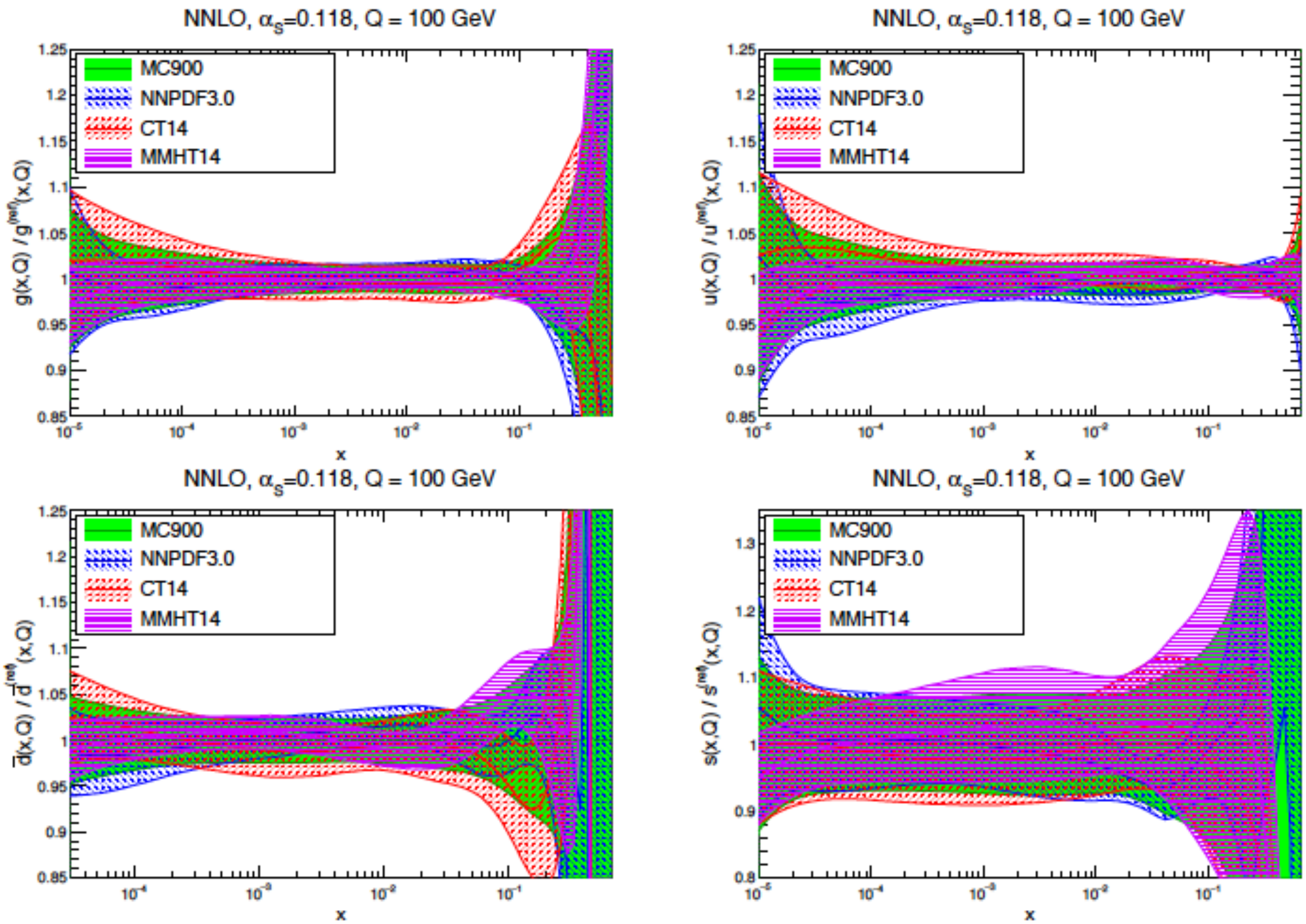
900 replicas seems enough

->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

MC900



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

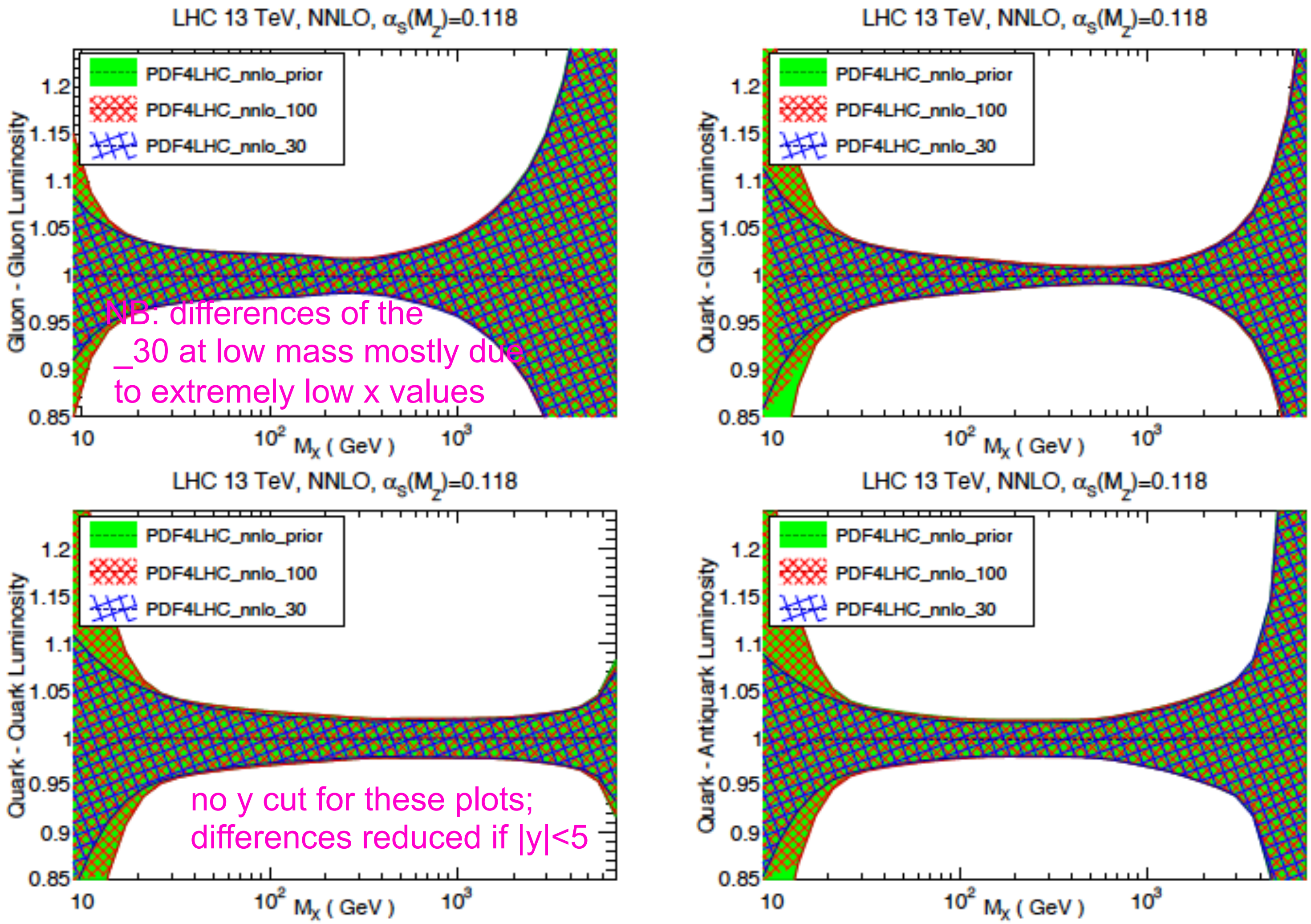
The PDF error bands themselves are similar for the precision physics region, but not for low mass/high mass

Figure 8: Comparison of the MC900 PDFs with the sets that enter the combination: CT14, MMHT14 and NNPDF3.0 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



in large uncertainty regions, prior itself will change depending on the conversion procedure of CT14 and MMHT to MC replicas; see arXiv: 1607.06066

The differences between each band and the _prior band represents the precision with which each reproduces the prior. **It does not say anything about the accuracy of the prior.**

Some comparisons for Higgs production

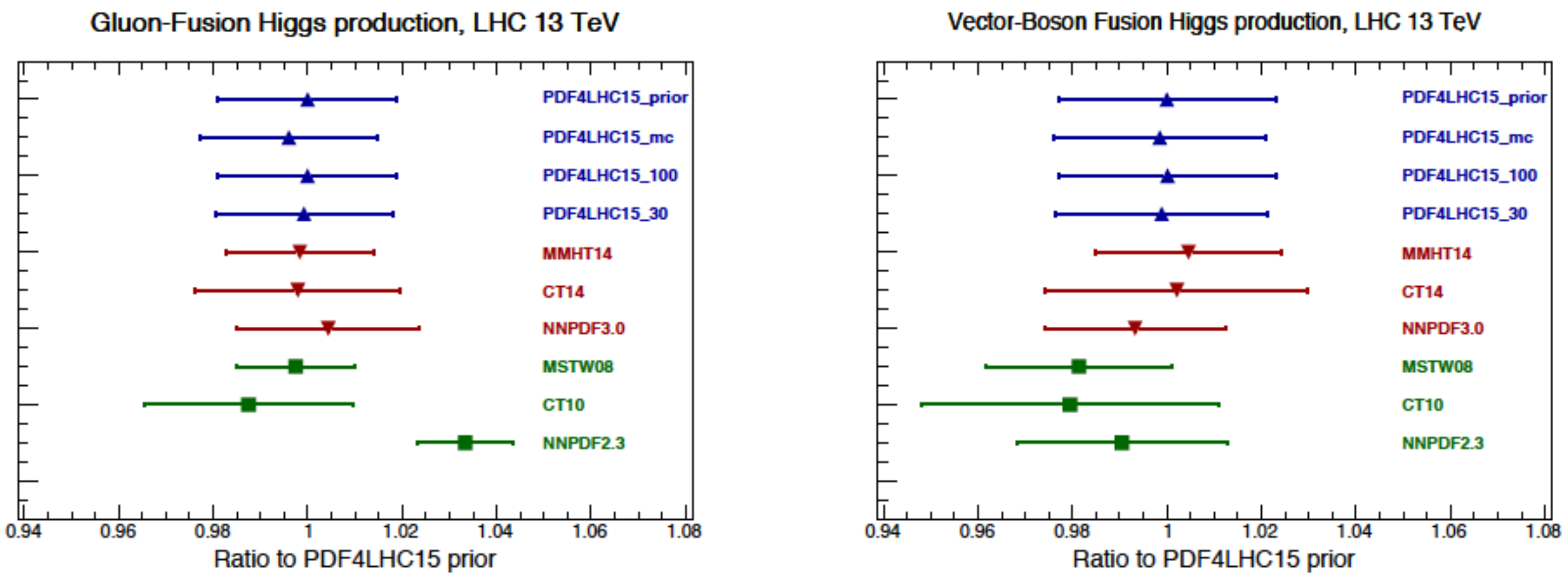
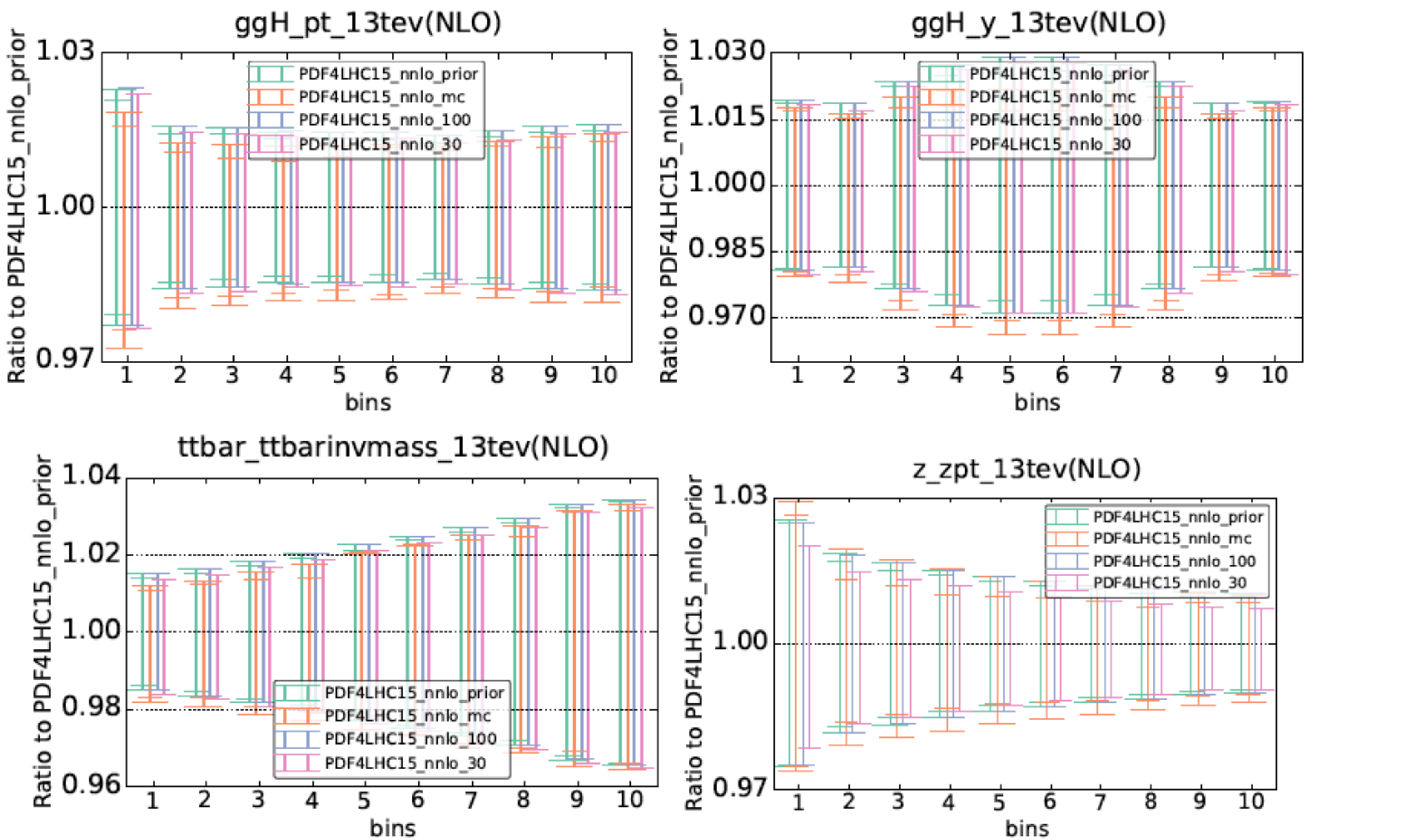


Fig. 6.32 A comparison of the predictions for Higgs boson production through gg fusion (left) and vector boson fusion (right) is shown for a center-of-mass energy of 13 TeV,

Application to cross sections



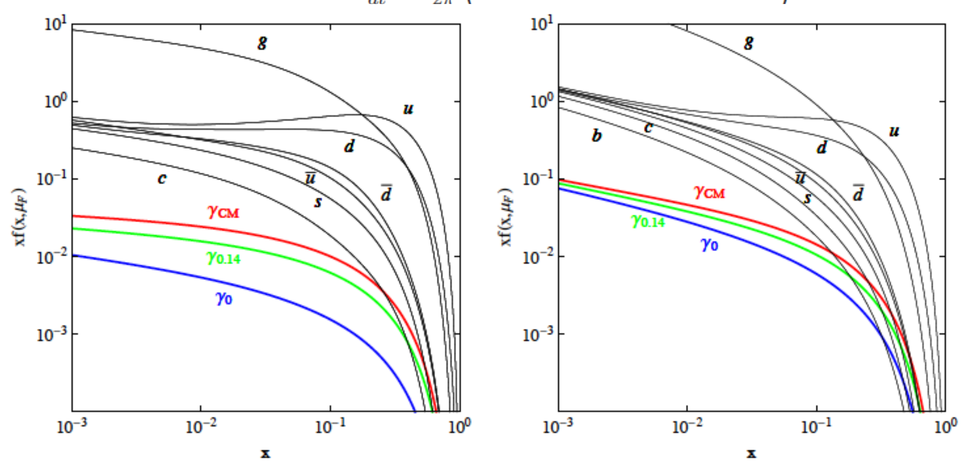
For more comparisons, see for example https://smu.box.com/s/p2ob0lpbzpq4mggu0f7lcryajgm4zj8v

(Relatively) New PDF Developments

- 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 may be produced by a γγ initial state), or for WH production, 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:

$$\begin{aligned}
\frac{df_{q_i}}{dt} &= \frac{\alpha_s}{2\pi}\left(\sum_j \left(P_{q_i q_j} \circ f_{q_j} + P_{q_i \bar{q}_j} \circ f_{\bar{q}_j}\right) + P_{qg} \circ f_g\right) \\
&\quad + \frac{\alpha}{2\pi} e_i^2 \left(\tilde{P}^{(0)}_{qq} \circ f_{q_i} + \tilde{P}^{(0)}_{q\gamma} \circ f_\gamma\right) \\
\frac{df_{\bar{q}_i}}{dt} &= \frac{\alpha_s}{2\pi}\left(\sum_j \left(P_{\bar{q}_i \bar{q}_j} \circ f_{\bar{q}_j} + P_{\bar{q}_i q_j} \circ f_{q_j}\right) + P_{qg} \circ f_g\right) \\
&\quad + \frac{\alpha}{2\pi} e_i^2 \left(\tilde{P}^{(0)}_{qq} \circ f_{\bar{q}_i} + \tilde{P}^{(0)}_{q\gamma} \circ f_\gamma\right) \\
\frac{df_g}{dt} &= \frac{\alpha_s}{2\pi}\left(P_{gg} \circ f_g + \sum_i P_{gq} \circ \left(f_{q_i} + f_{\bar{q}_i}\right)\right) \\
\frac{df_\gamma}{dt} &= \frac{\alpha}{2\pi}\left(\tilde{P}^{(0)}_{\gamma\gamma} \circ f_\gamma + \sum e_i^2 \tilde{P}^{(0)}_{\gamma q} \circ \left(f_{q_i} + f_{\bar{q}_i}\right)\right) ,
\end{aligned} \tag{2}$$



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 ($\gamma_{\rm CM}$, red), and photon PDFs with initial photon momenta fractions of $p_0^\gamma = 0$ and 0.14% (γ_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_o as

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

  - $P_{\gamma q o} f_o(x)$ 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 constitutent 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.

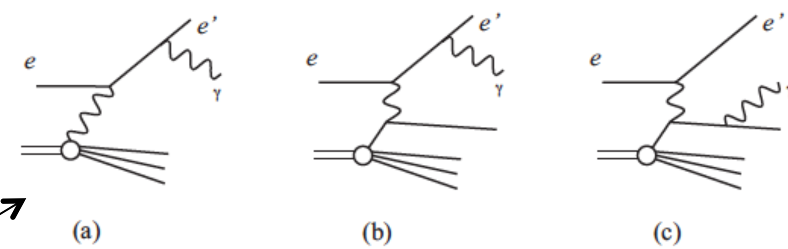
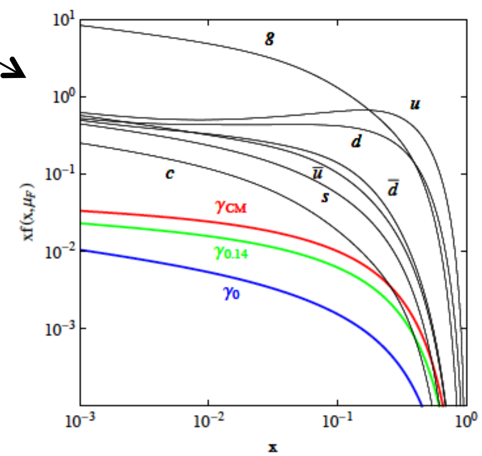


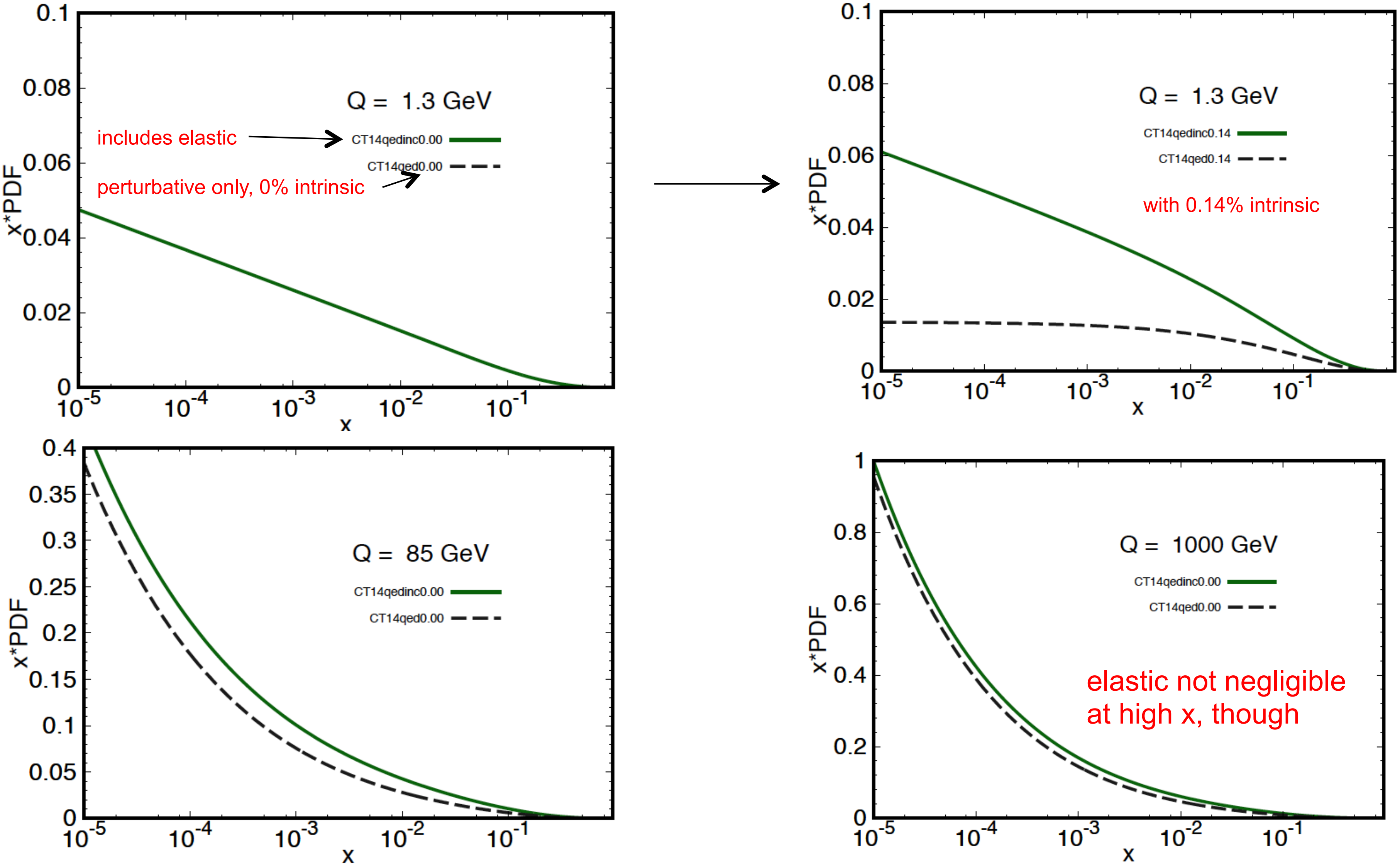
FIG. 3: Amplitudes for the process $ep \to e\gamma + X$. For each diagram shown there is an additional diagram where the photon is emitted off the initial-state lepton or quark.



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

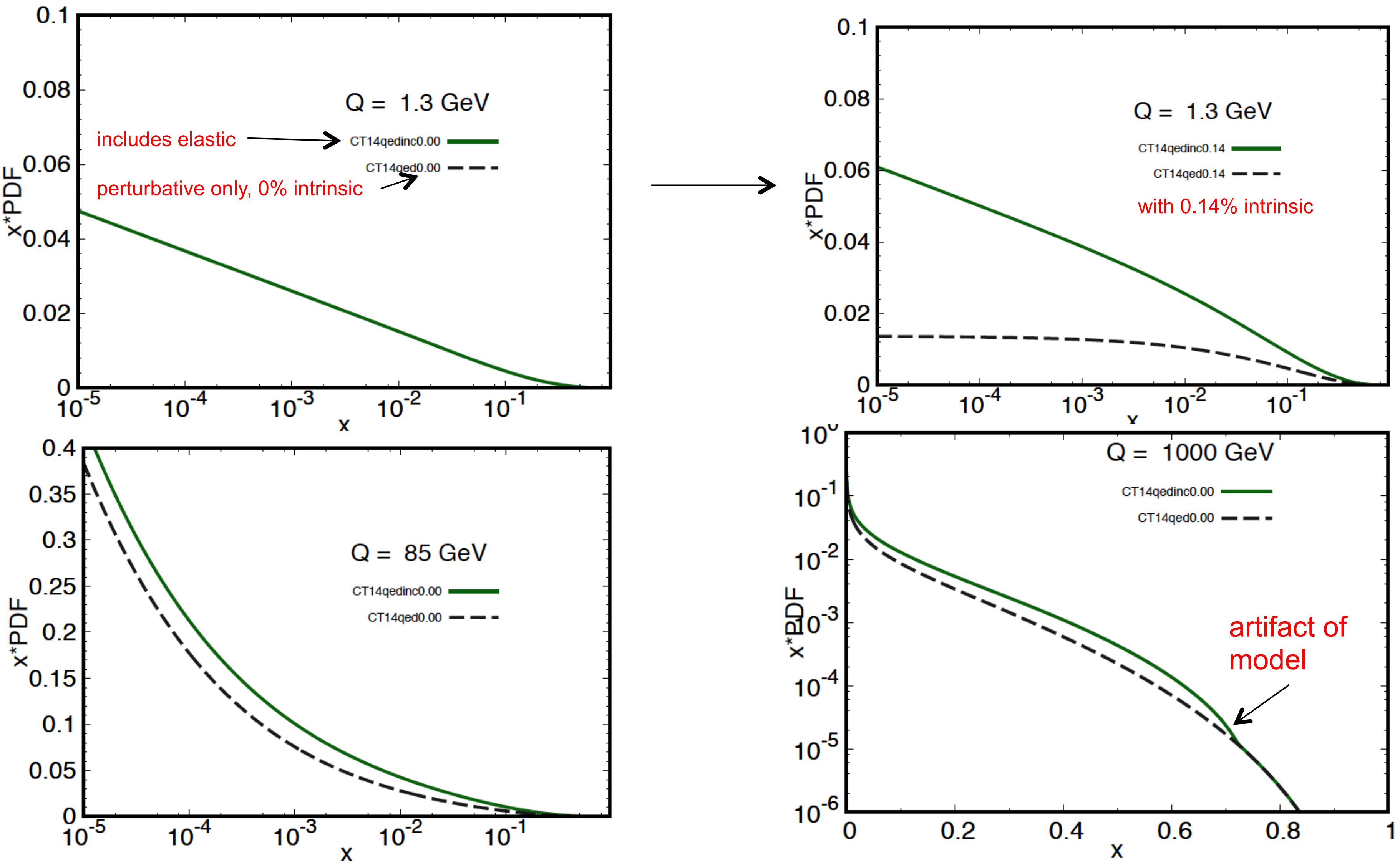
Evolution of photon PDF

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



Evolution of photon PDF

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



NNPDF2.3qed

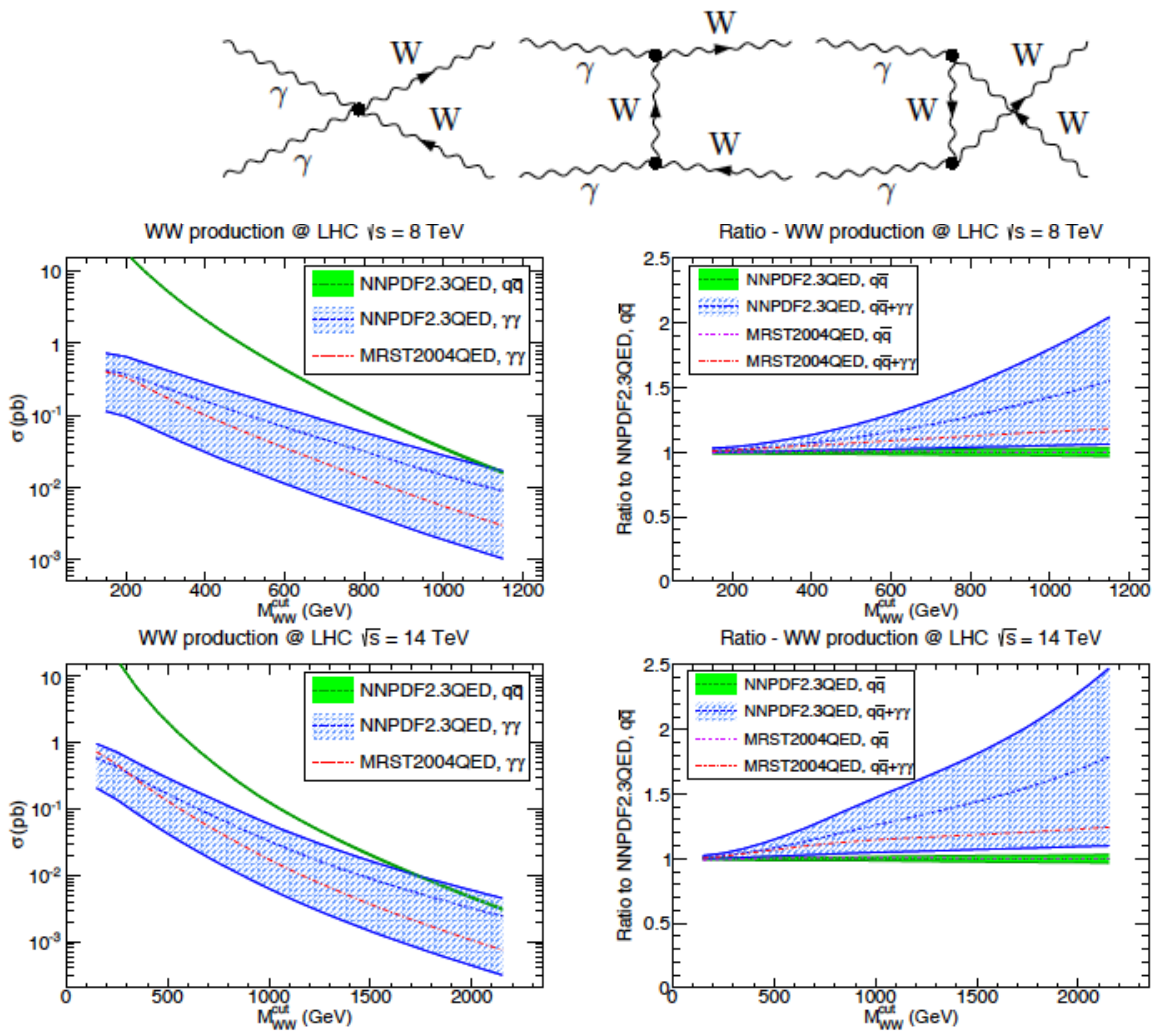


Figure 25: Photon-induced and quark-induced Born-level contributions to the production of a W pair with mass $M_{WW} > M_{WW}^{\rm cut}$ plotted as a function of $M_{WW}^{\rm cut}$ at the LHC 8 TeV (top) and LHC 14 TeV (bottom), computed with the code of Ref. [64] and NNPDF2.3QED NLO and MRST2004QED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

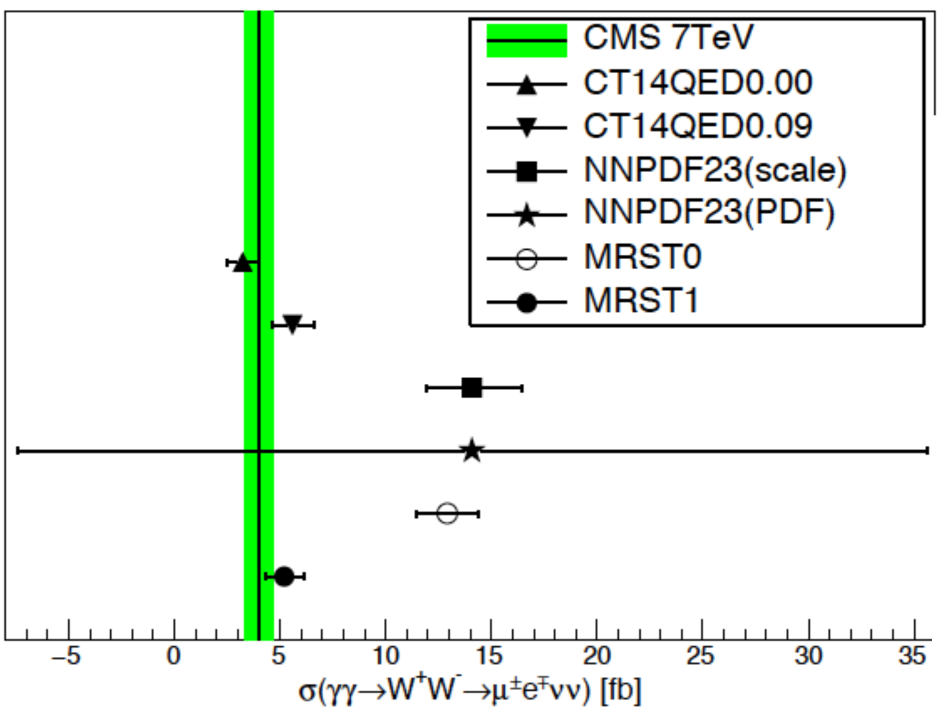
arxiv:1308.0598

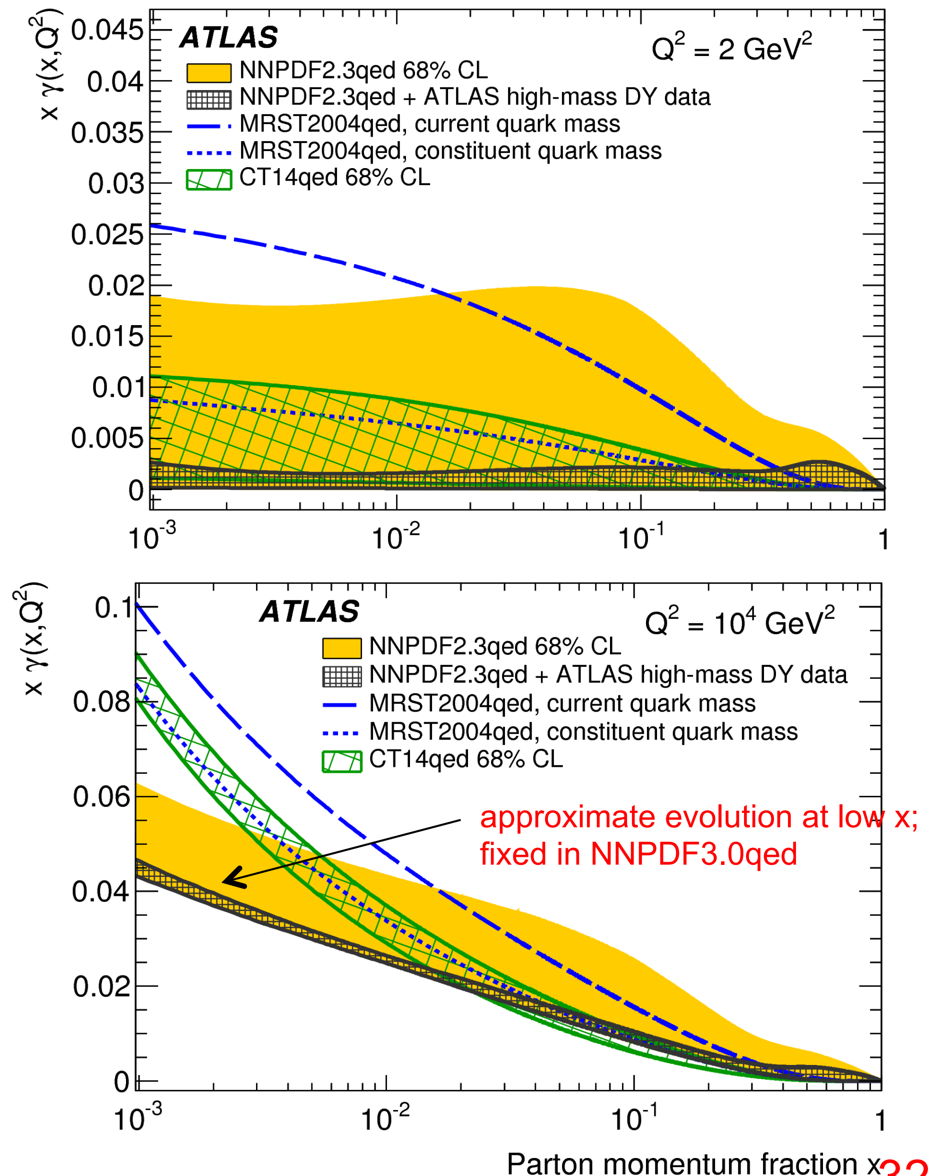
appreciable fraction of WW cross section at large mass

…photon PDF fit to 7 TeV ATLAS high mass Drell-Yan data

…but

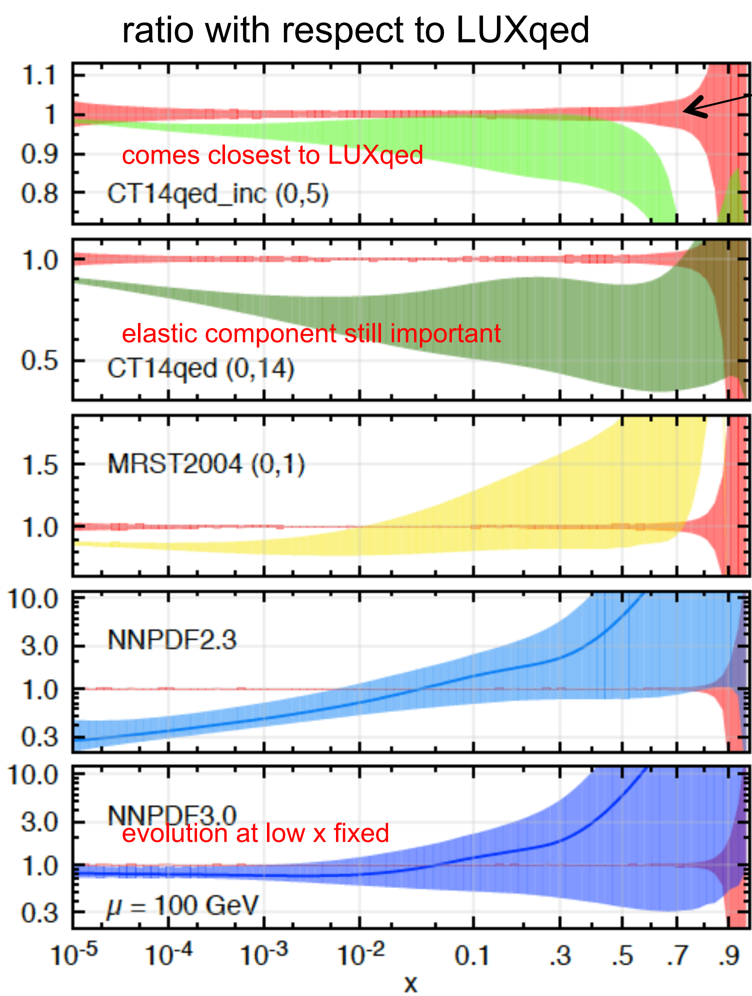
- ATLAS fit to 8 TeV Drell-Yan data prefers photon distribution at lower end of NNPDF2.3qed uncertainty band, << central value
- Also, arXiv:1603.04874





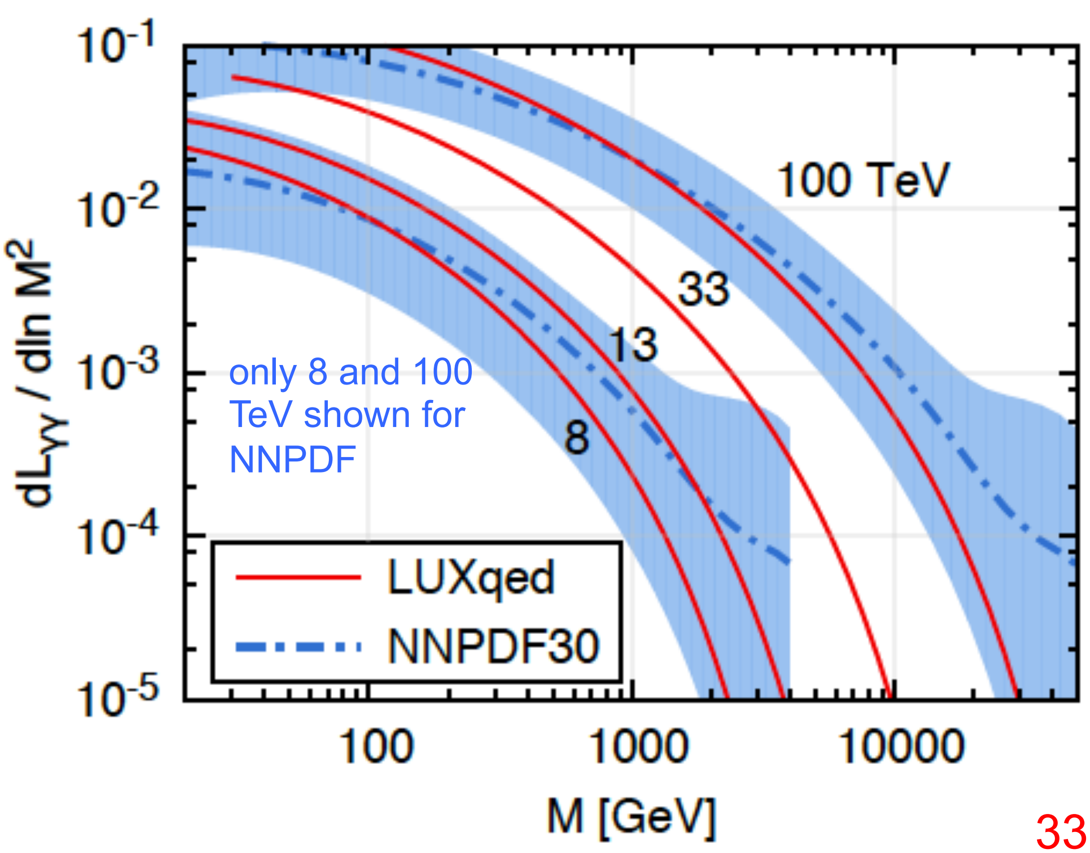
How bright is the photon?: arXiv:1607.04266

Can define the $\overline{MS}$ 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

LUXqed approach with further constraints?



As a reminder

- Non-negligible contribution (and uncertainty) to WH from photon-induced processes (YR4)
- Calculated using median of MRST2004qed (set 1) and NNPDF2.3qed PDFs replicas
  - contribution (and uncertainty) can now be reduced

Table 27: Total $W^+(\to l^+\nu_l)H$ cross sections including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_H = 125$ GeV.

$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{PDF/\alpha_s/PDF\oplus\alpha_s}$[%]	$\sigma^{DY}_{NNLOQCD}$[fb]	$\sigma_{t\text{-loop}}$[fb]	δ_{EW}[%]	σ_γ[fb]
7	40.99	$^{+0.7}_{-0.9}$	$\pm1.9/\pm0.7/\pm2.0$	42.78	0.42	-7.2	$0.88^{+1.10}_{-0.10}$
8	49.52	$^{+0.6}_{-0.9}$	$\pm1.8/\pm0.8/\pm2.0$	51.56	0.53	-7.3	$1.18^{+1.38}_{-0.14}$
13	94.26	$^{+0.5}_{-0.7}$	$\pm1.6/\pm0.9/\pm1.8$	97.18	1.20	-7.4	$3.09^{+3.33}_{-0.37}$
14	103.63	$^{+0.3}_{-0.8}$	$\pm1.5/\pm0.9/\pm1.8$	106.65	1.36	-7.4	$3.55^{+3.72}_{-0.43}$

Table 28: Total $W^-(\to l^-\bar{\nu}_l)H$ cross sections including QCD and EW corrections and their uncertainties for different proton–proton collision energies $\sqrt{s}$ for a Higgs-boson mass $M_H = 125$ GeV.

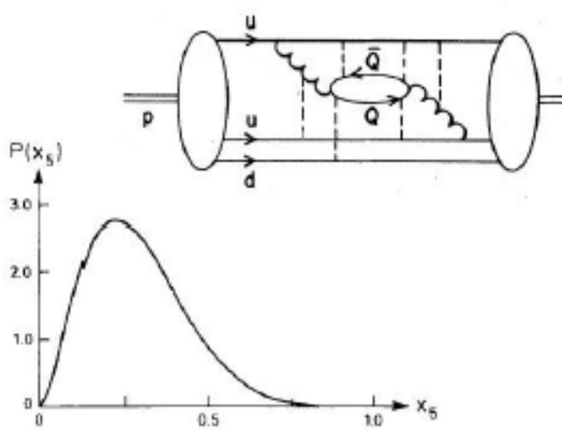
$\sqrt{s}$[GeV]	σ[fb]	Δ_{scale}[%]	$\Delta_{PDF/\alpha_s/PDF\oplus\alpha_s}$[%]	$\sigma^{DY}_{NNLOQCD}$[fb]	$\sigma_{t\text{-loop}}$[fb]	δ_{EW}[%]	σ_γ[fb]
7	23.04	$^{+0.6}_{-0.8}$	$\pm2.2/\pm0.6/\pm2.3$	23.98	0.24	-7.0	$0.51^{+0.69}_{-0.05}$
8	28.62	$^{+0.6}_{-0.8}$	$\pm2.1/\pm0.6/\pm2.1$	29.71	0.31	-7.1	$0.70^{+0.94}_{-0.07}$
13	59.83	$^{+0.4}_{-0.7}$	$\pm1.8/\pm0.8/\pm2.0$	61.51	0.78	-7.3	$2.00^{+2.34}_{-0.22}$
14	66.49	$^{+0.5}_{-0.6}$	$\pm1.7/\pm0.9/\pm1.9$	68.24	0.89	-7.3	$2.32^{+2.65}_{-0.26}$

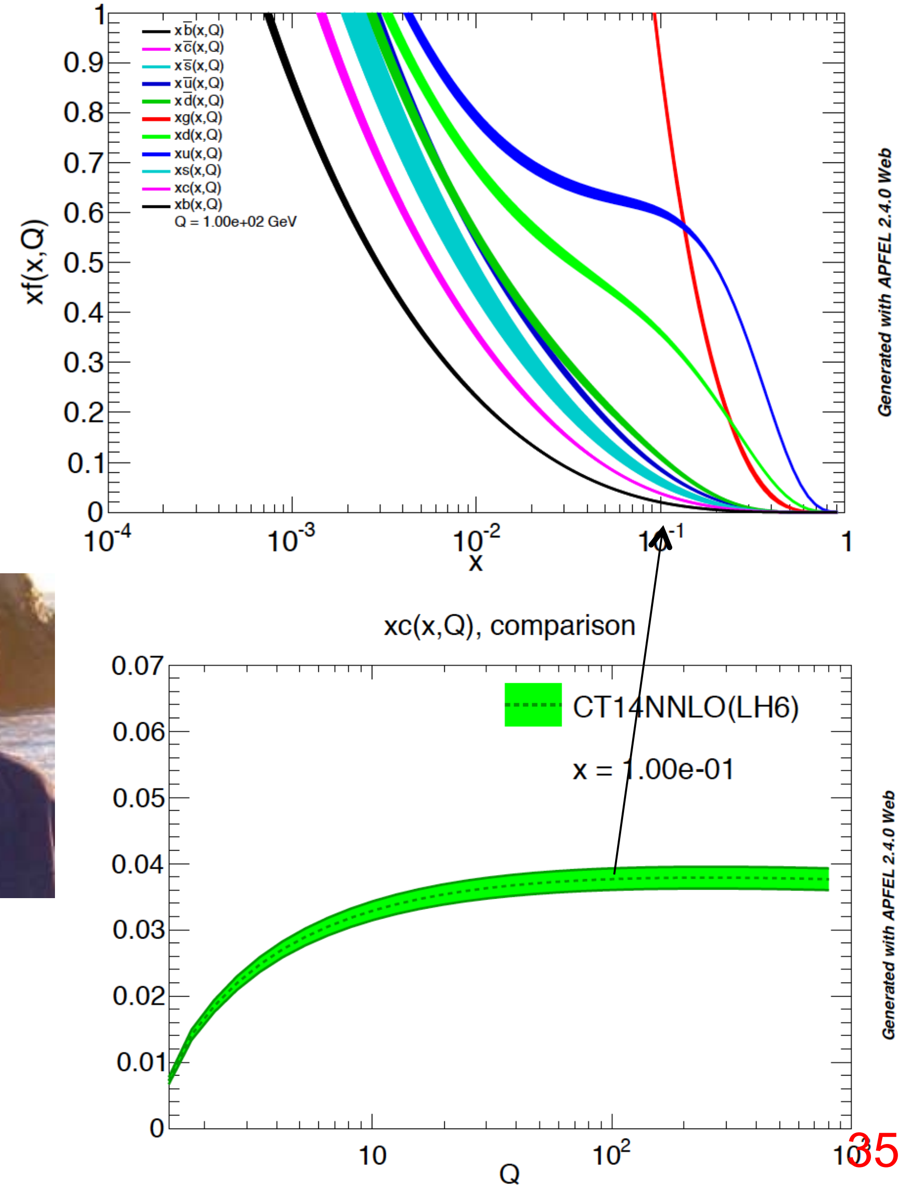
Charm

- The charm quark distribution is generated perturbatively through gluon splitting
- So normally no charm below ccbar 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

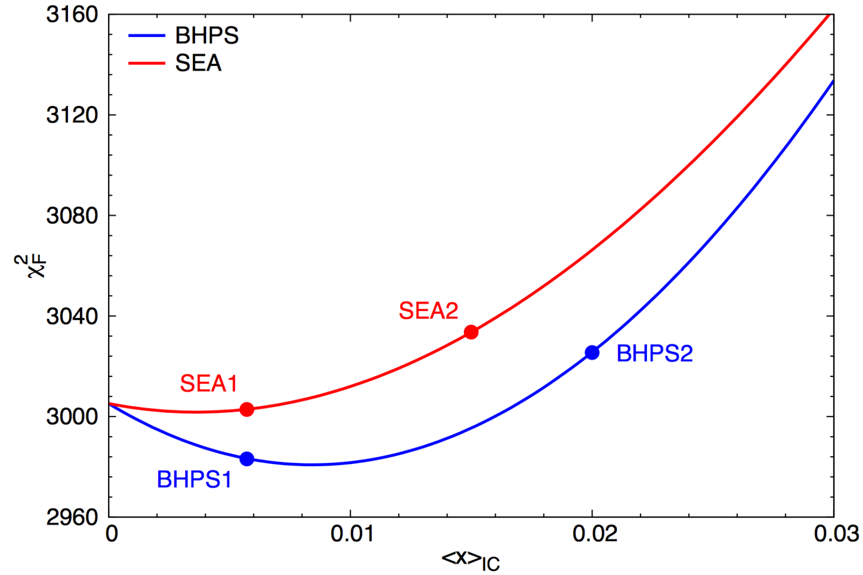
Brodsky et al: arXiv:1504.06287

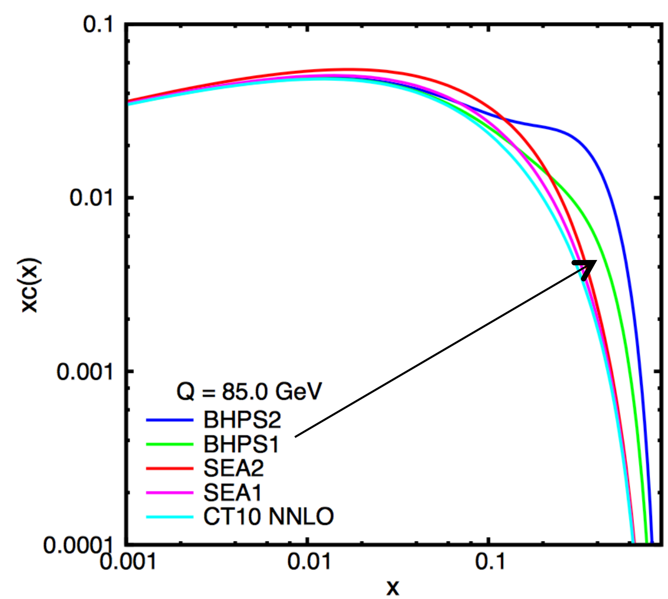




Intrinsic charm

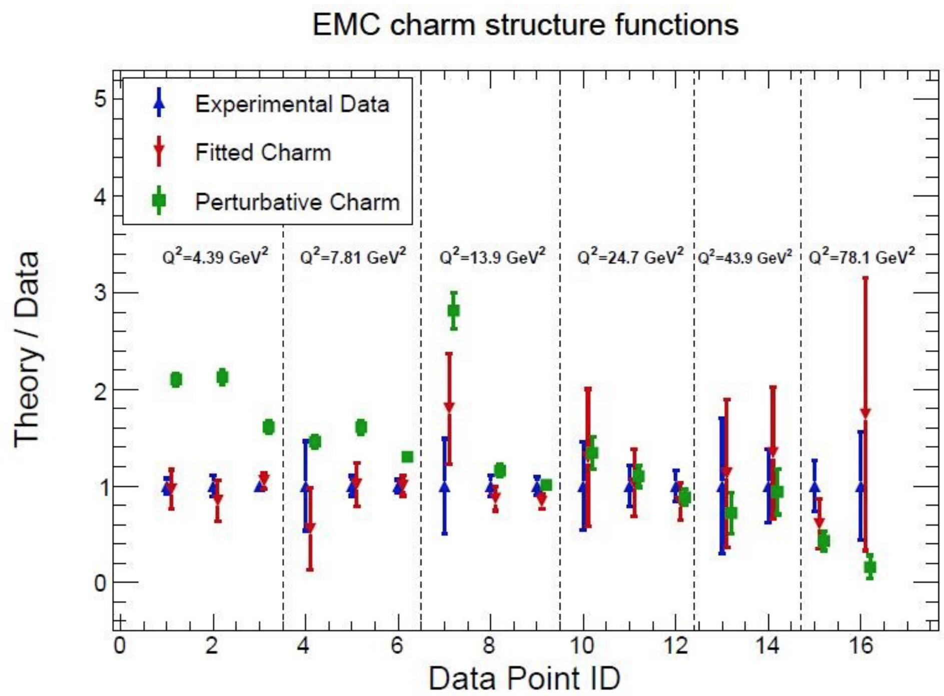
- …and has been studied by CTEQ in, for example, arXiv: 1309.0025 and in proceedings of DIS2014
  - these analyses carried out at NNLO
- Two types of models: Brodsky-like (valence-like) or Sea-quark like
- One Brodsky-like model, BHPS1 actually leads to a modest reduction in χ^2, but as we said in the 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 can be dangerous for a PDF that's poorly constrained, as we saw for the photon
  - this analysis carried out at NLO
- Use EMC charm structure function data in global fit
  - inclusive EMC data has not been used in PDF fits for several decades due to known problems with the data (tracking)
    - what about charm data?
    - calorimeter-based
  - NNPDF argument is that data is precise enough to provide information on charm
  - enchanced charm without the EMC data, but with much larger uncertainty
  - reduction in global χ^2 with inclusion of fitted charm

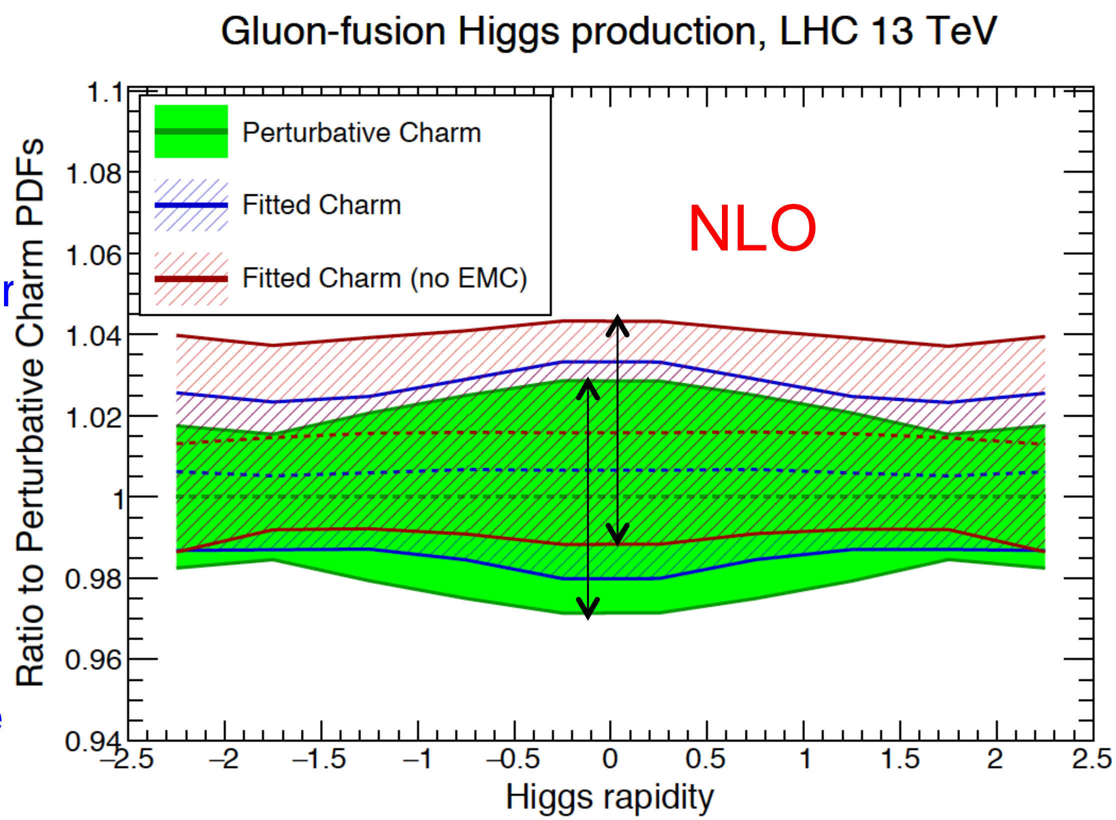


arXiv:1605.06515 + Richard Ball at LoopFest

all done at NLO; fitted charm would implicitly include some NNLO effects since it is fit to data

Higgs impacts at LHC

- Impacts for any charm-related cross section but also (indirectly) for cross sections like Higgs ggF
- Noticeable change in central value and envelope, especially for fitted charm with no EMC
- NNPDF3.1 plans to use intrinsic/ fitted charm as part of their baseline formalism
- If this were the only change among the PDF groups, the uncertainty for ggF would change for next PDF4LHC update
  - NB: other new data sets may affect the uncertainty band/ central prediction in the opposite direction



this reflects on the **accuracy**, i.e. new data/assumptions can change the central PDF and the uncertainty band

Further investigations

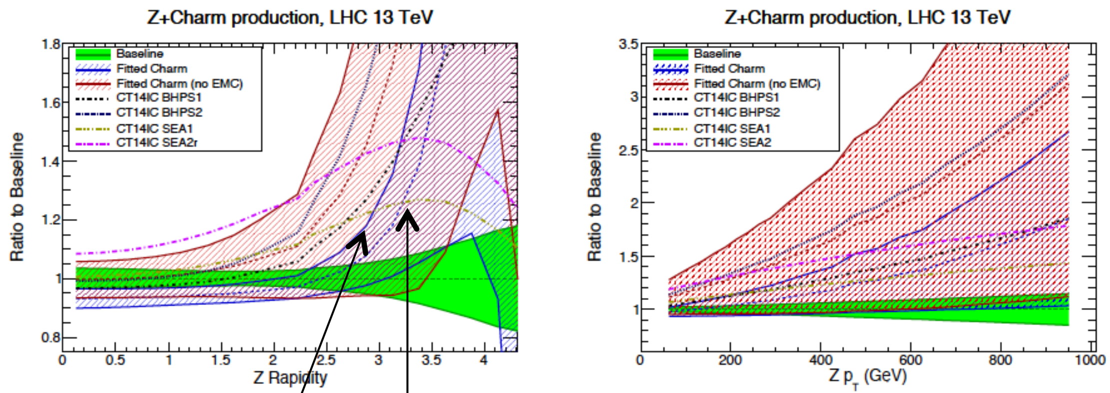
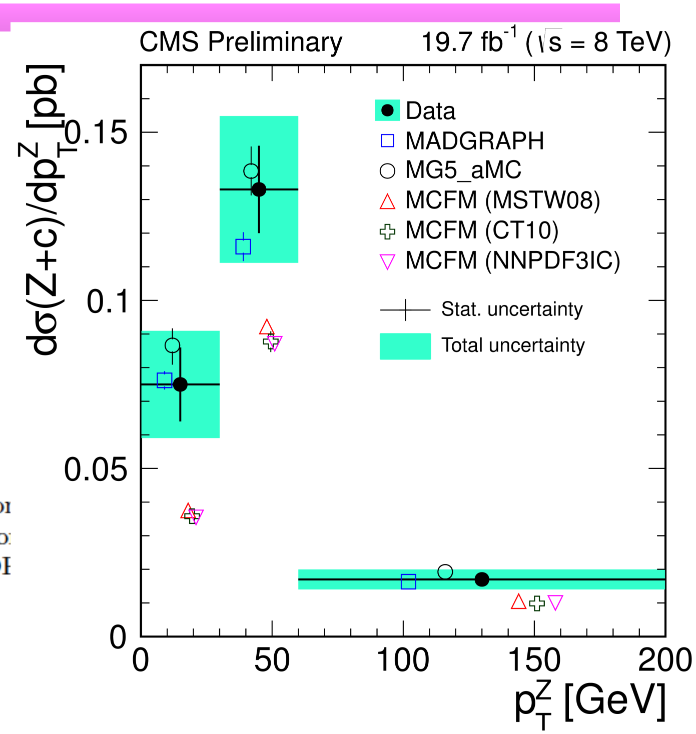


Figure 27: The Z boson rapidity (left) and transverse momentum (right) distributions for Z production in association with charm at the LHC 13 TeV, computed using the NNPDF sets with perturbative or fitted charm, and the CT14 IC PDFs shown in Fig. 16. Results are shown as a ratio to the NNPDF perturbative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

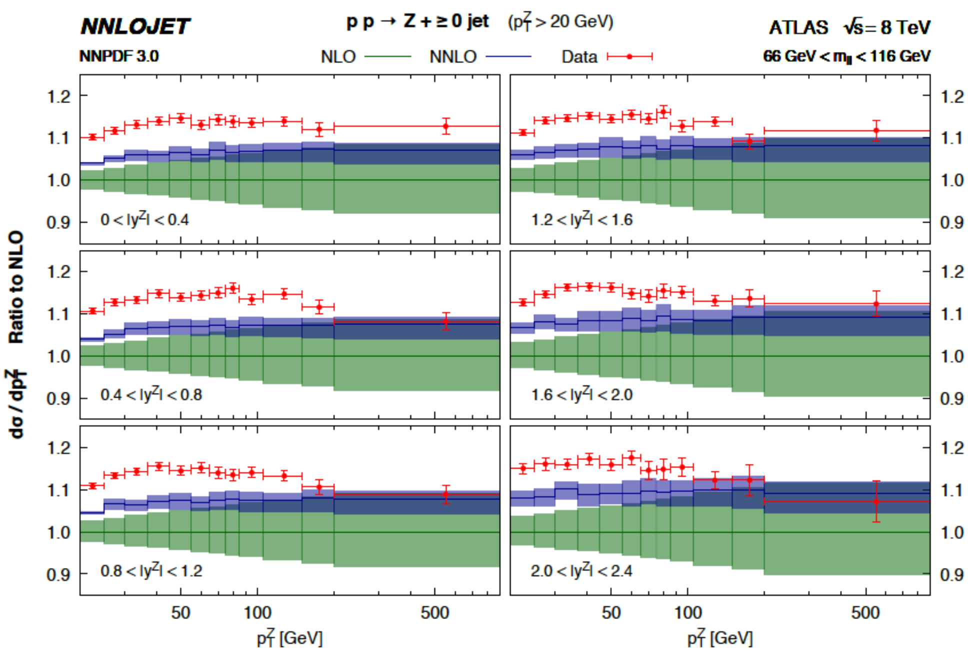
fitted charm BHPS1

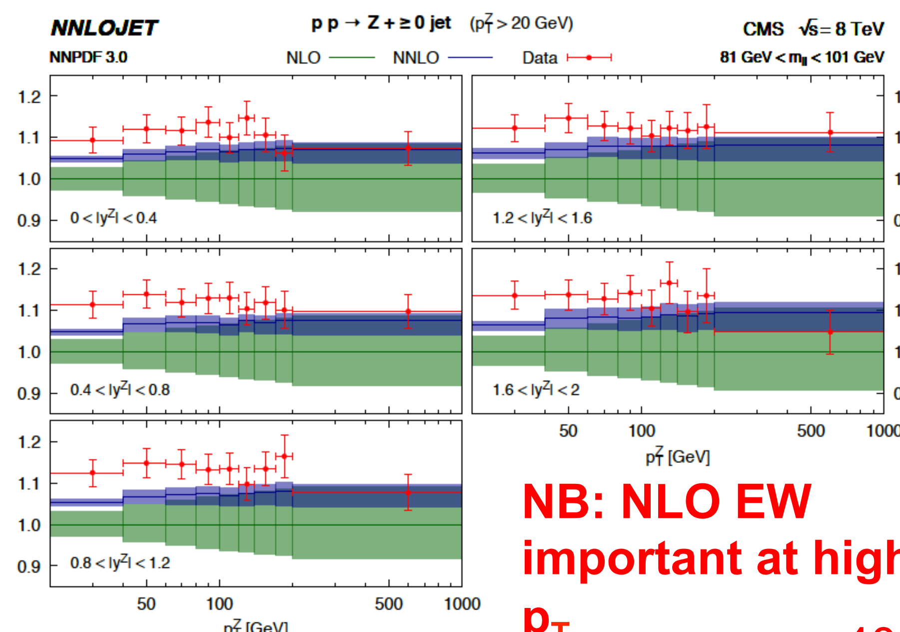


no discrimination
in LHC data so far,
nor in Tevatron; higher
statistics/further reach
for distributions such as Z+c
may help the discrimination

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

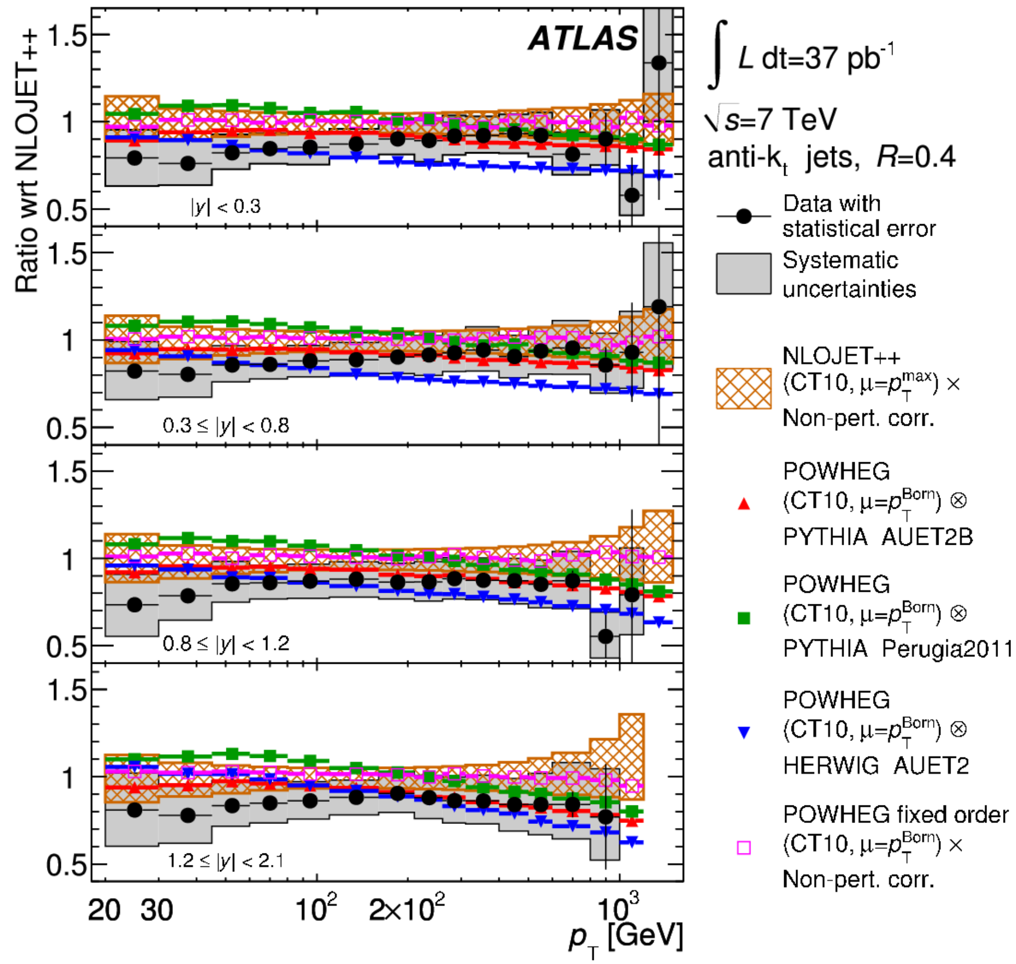




NB: NLO EW important at high p_T

LHC jet data

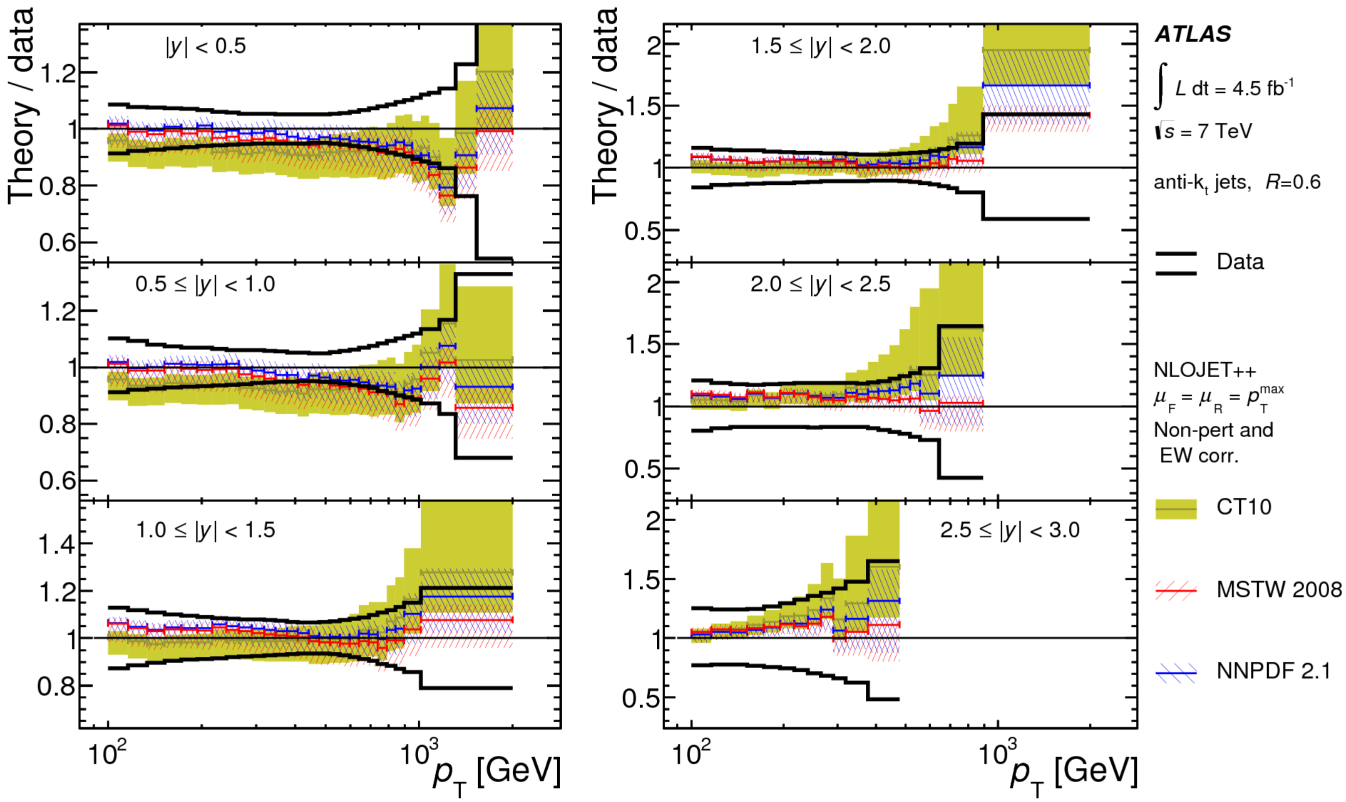
- In global PDF fits, we assume that fixed order (with non-perturbative predictions) is sufficient to describe the data, as long as the cross sections are sufficiently inclusive, such as the inclusive jet cross section
- There seems to be some difference between Powheg+parton shower and Powheg+fixed order
- This is not seen, for example, 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**



- Similar study planned for inclusive jets at 2017 Les Houches

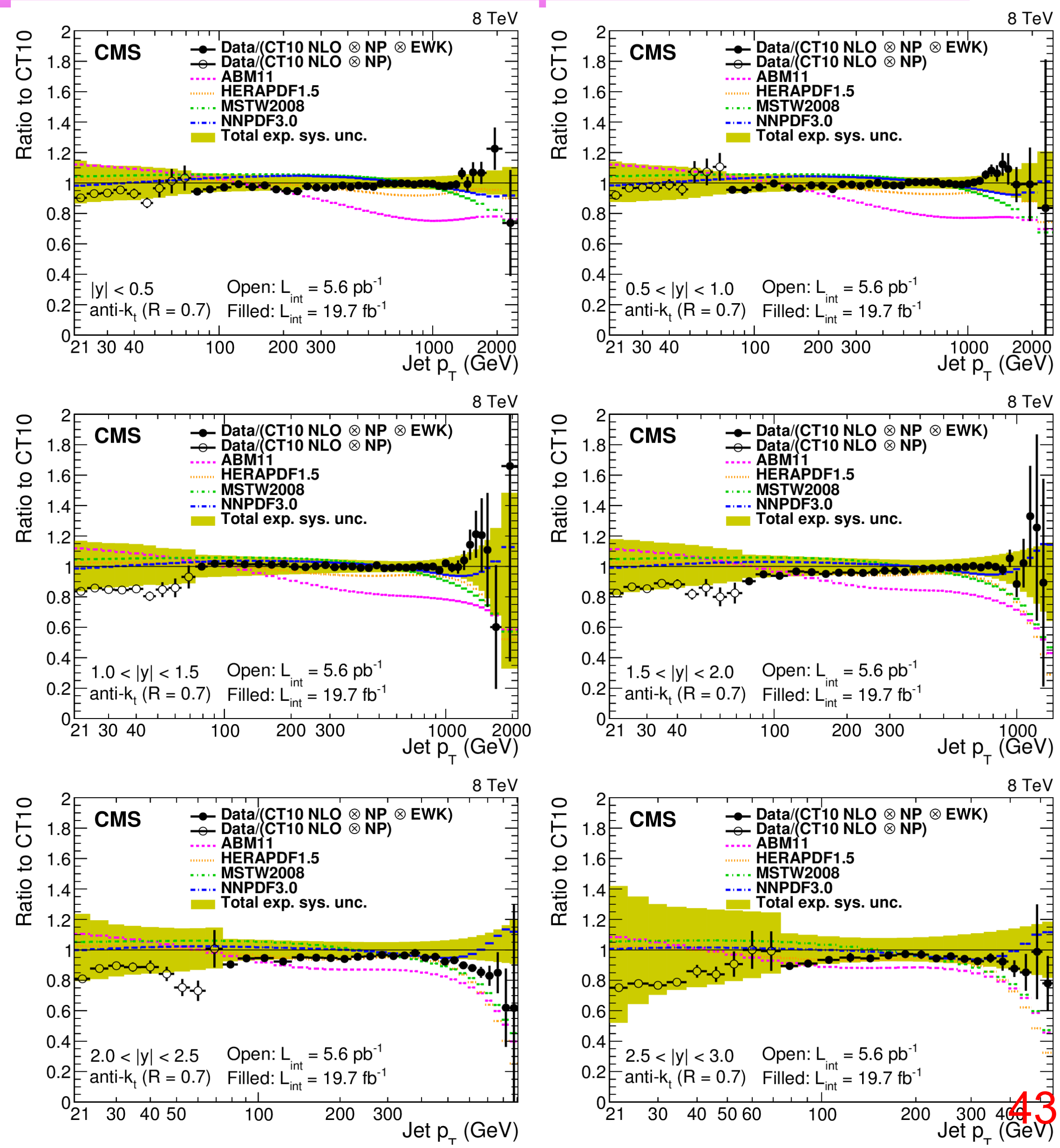
ATLAS 7 TeV jet data

- Impossible to get a good χ^2 when fitting all rapidity intervals simultaneously, although each rapidity interval by itself gives a good χ^2 ->correlations?
- If only one y interval is chosen, which one? Do the other rapidity intervals provide the same constraint?
- 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

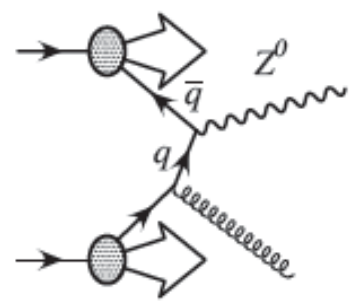


NNLO

- Inclusive jet production is a critical component of any PDF fit
- In most cases, it is the only NLO prediction in a NNLO fit
- We are all eagerly awaiting the publication of the full NNLO inclusive jet predictions
  - Nigel says the fun will begin in just a few weeks
- So far we've seen that NNLO corrections have been mild (using p_T as the renormalization/ factorization scale)
- One of the problems is the delivery of the calculation
- Too big for ntuples? Use applgrid/ fastNLO

NNLOJET (and APPLfas

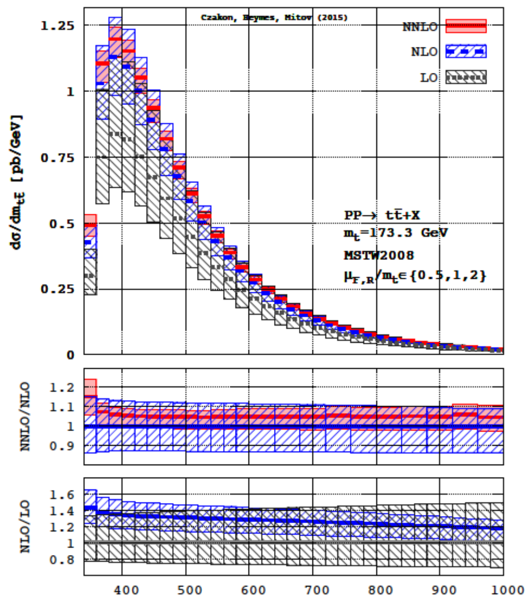
- Semi-automated calculation of cross sections at NNLO from the IPPP, Zurich, ETH and others
  - Gehrmann-De Ridder *et al* **arXiv: 1607.01749**
  - See talk from **Alex Huss** tomorrow
- APPLfast-NNLO
  - Developers from **NNLOJET**, **APPLgrid** and **fastNLO**
  - A single, combined interface for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

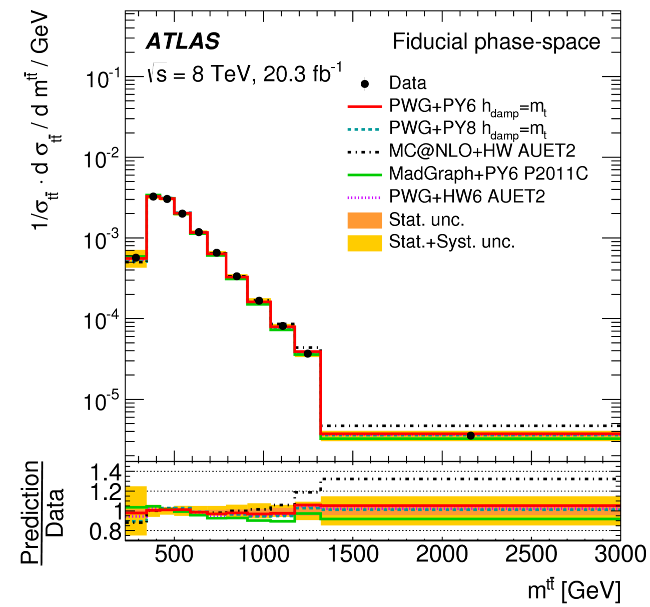


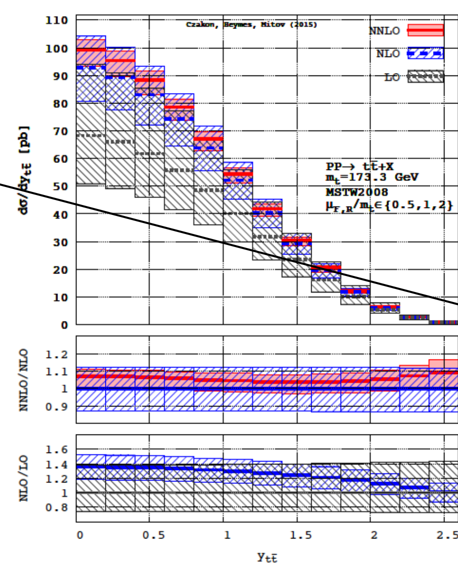
- Many processes implemented in NNLOJET
  - Developing a generic interface for **all available** processes
  - Concentrating on Z + jets at NNLO for the initial development and proof-of-concept

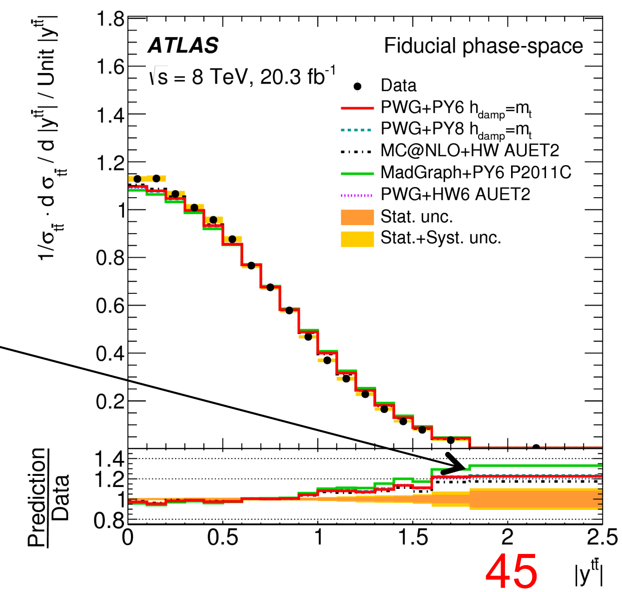
tT differential data

- tT differential cross sections provide a great handle on the high x gluon distribution
  - provides additional information on gluon than inclusive jet
- Recent calculation by Czakon, Heyes and Mitov; arXiv:1511.00549
- Aside: how can the predictions differ by so much at high mass, rapidity? These are predictions for which fixed order (NLO and NNLO) should provide valid predictions



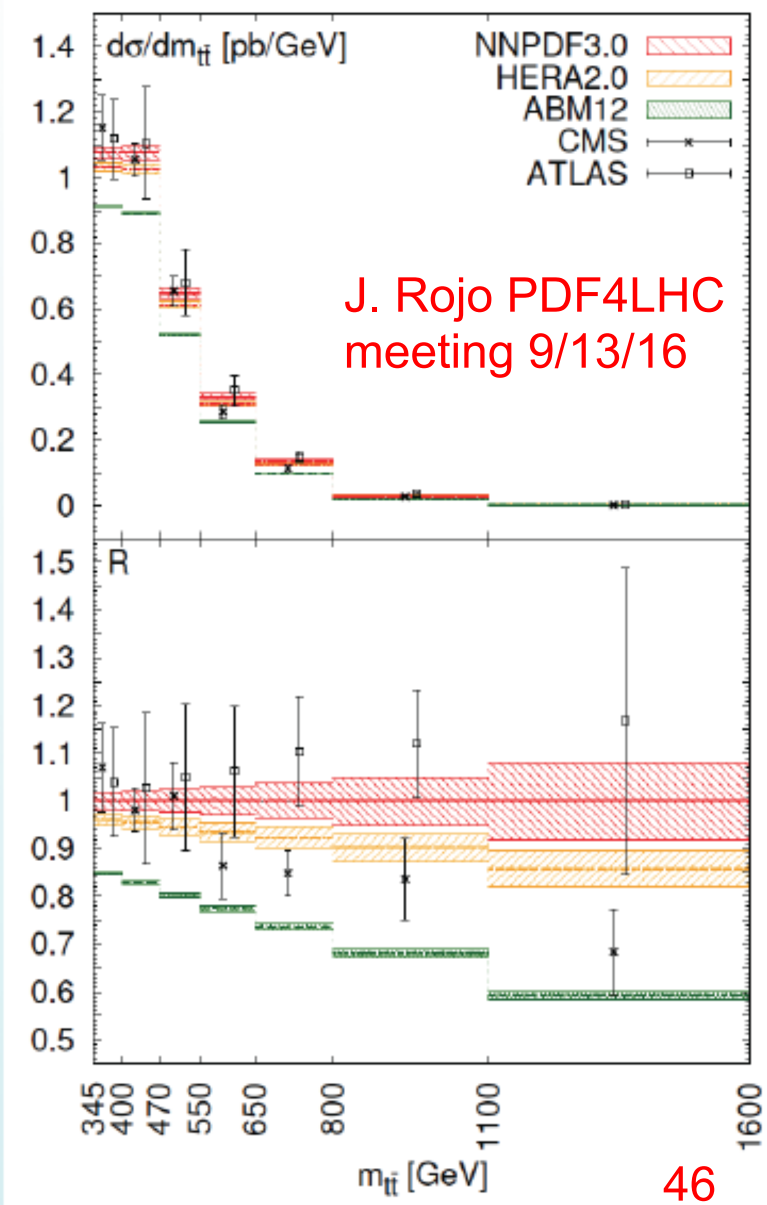






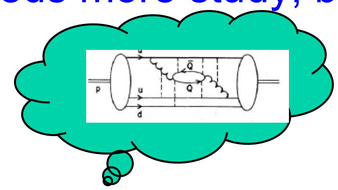
Top distributions

- 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?
- ATLAS and CMS have different trends; in this case, ATLAS favors harder gluon (than NNPDF3.0)at high x, CMS weaker gluon



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 fits, and find that it doesn't change the results obtained with using HERA1 data alone
- It appears that the photon PDF is fairly-well constrained now, and fairly small
- The idea of a large (*intrinsic)* charm component still needs more study, both theoretical and experimental
  - Stan may have to keep dreaming for a bit longer
  - LHC data should be able to tell us (eventually)
  - starting with NNPDF3.1, their framework will be based on fitted charm, so PDFs may change



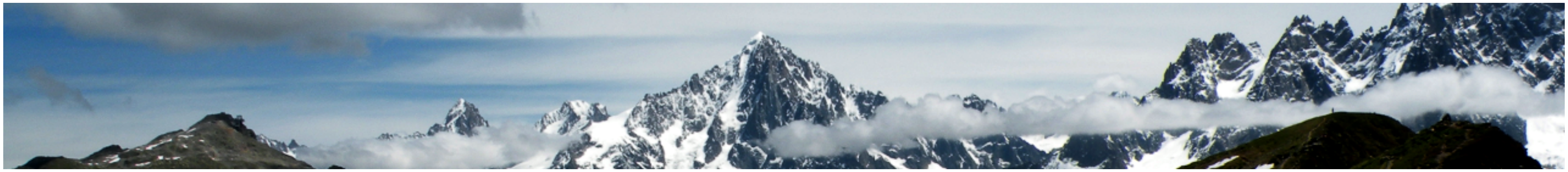
- PDF fitting continues to grow in sophistication and in the amount of LHC data included in the fits
  - still hard to fight the precision of the DIS data, but LHC high statistics DY data are trying (which will also require control of theory systematics to sub-percent level)
  - ATLAS, CMS, LHCb data 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 LHC data, should improve

Summary, continued

- PDF4LHC recommendations have tended to come every 3 years: 2012 ,2015. 2018 is likely for next update unless there's a driving reason to have it sooner.
- We have been working towards a standardization of parameters
  - $\alpha_s(m_Z)$ set to a world-average-like value of 0.118
  - uncertainty equal to +/-0.0015
  - (Remember α_s and PDF uncertainties are uncorrelated)
- Next step may be a common value of m_c, m_b

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

~~Winter~~ Les Houches is coming



Les Houches 2017 June 5-23

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