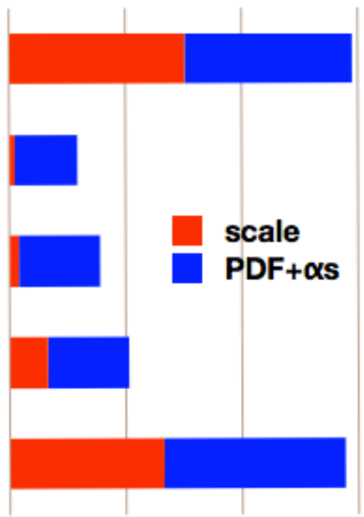
SM@LHC 2015, GGI ,Firenze

PDFs: a theory overview

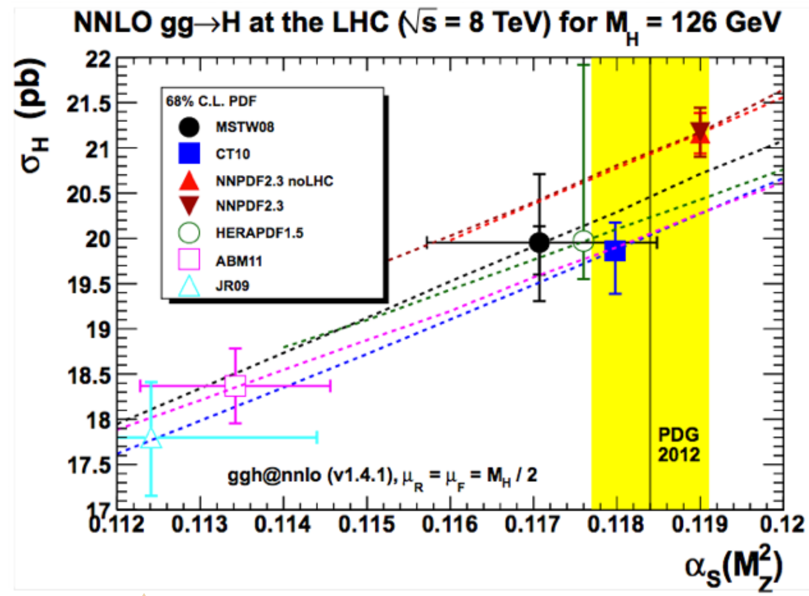
Maria Ubiali
University of Cambridge

PDFs: why bother?

	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
VBF	1.56 pb	2.9%
WH	0.70 pb	3.9%
ZH	0.39 pb	5.1%
ttH	0.13 pb	14.4%



J. Campbell, ICHEP 2012

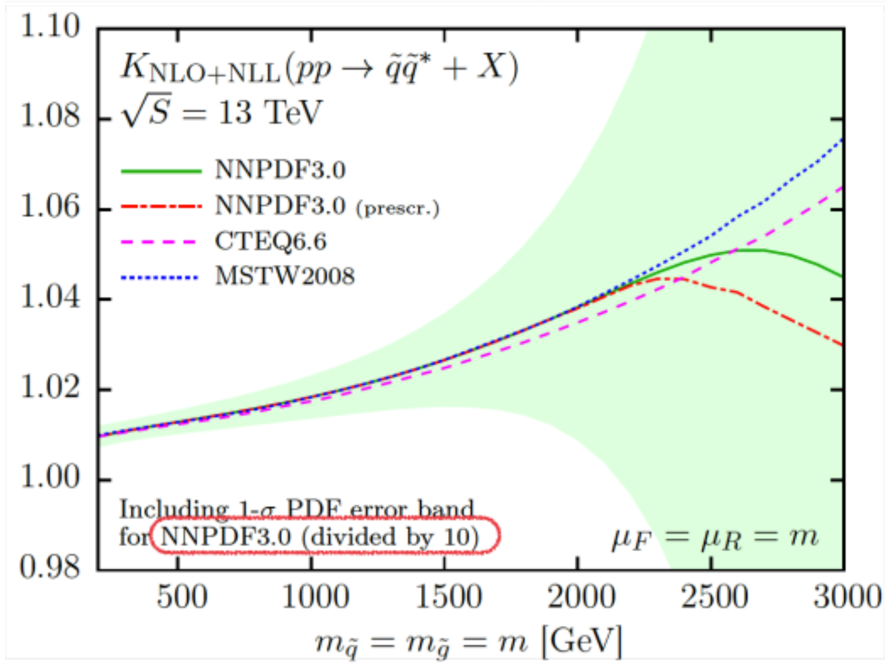


G. Watt, 2012

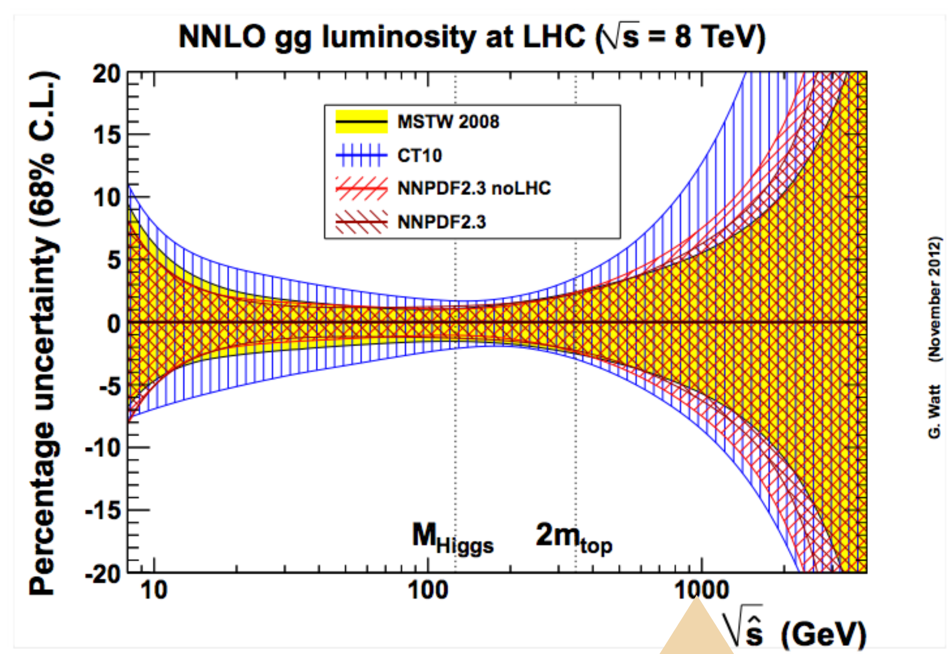
PDF uncertainties are a crucial input at the LHC, often being the limiting factor in the accuracy of theoretical predictions, both SM and BSM

- ☑ PDF uncertainty of each PDF set
- ☑ Value of $\alpha_S(M_Z)$
- ☑ Combination of different PDF sets

PDFs: why bother?



Courtesy of A. Kulesza



PDF uncertainties are a crucial input at the LHC, often being the limiting factor in the accuracy of theoretical predictions, both SM and BSM

- ☑ PDF uncertainty
- ☑ Lack of data
- ☑ Is theory precise enough?

Outline

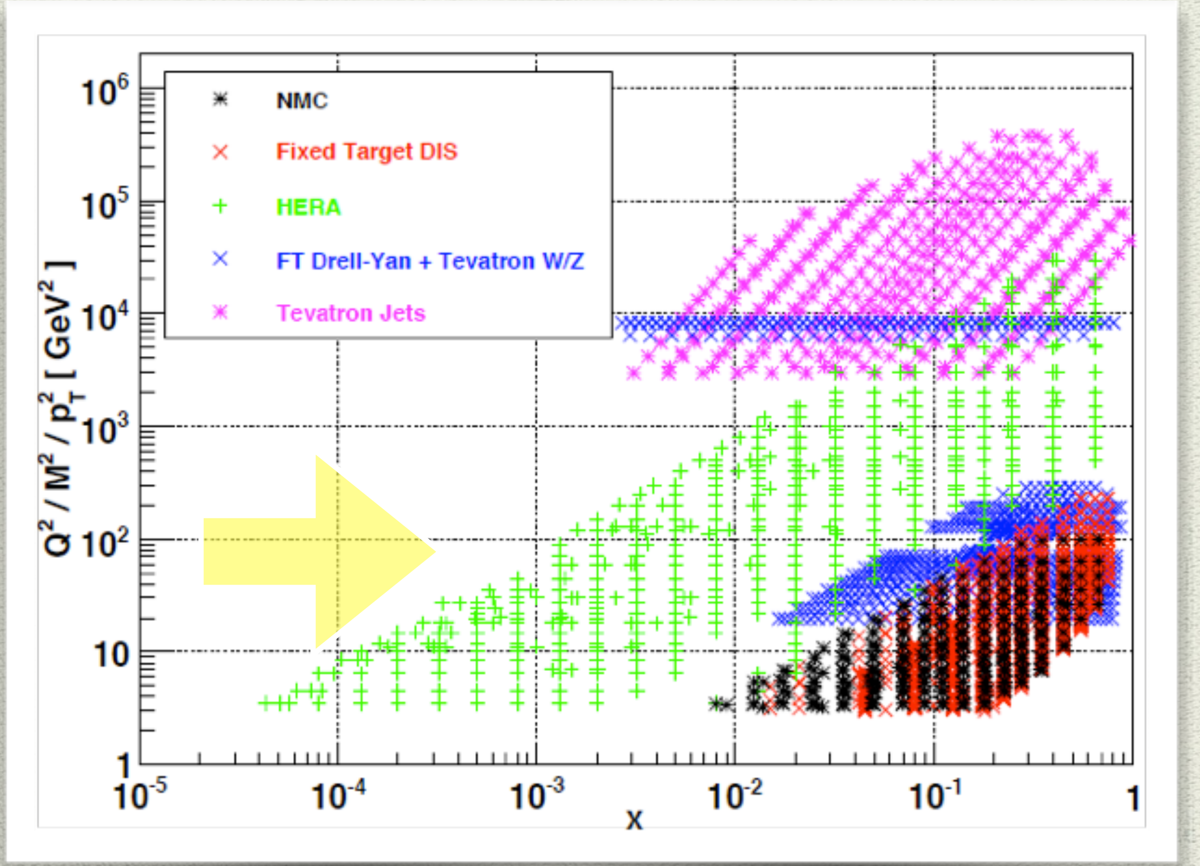
- Introduction
  - Parton Distribution Functions
  - The state of the art
- Progress and Frontiers
  - Theory
  - Data
  - Methodology
- Conclusions and Outlook

Parton Distribution Functions

Collinear factorisation theorem

$$\frac{d\sigma_H^{pp\to ab}}{dX} = \sum_{i,j=1}^{N_f} f_i(x_1,\mu_F)\, f_j(x_2,\mu_F)\, \frac{d\sigma_H^{ij\to ab}}{dX}(x_1 x_2 S_{\rm had}, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}^{2n}}{S_{\rm had}^n}\right)$$

- PDFs can be extracted from available experimental data and used as phenomenological input for theory predictions
- Different data constrain different parton combinations at different x



Progress in PDF determination

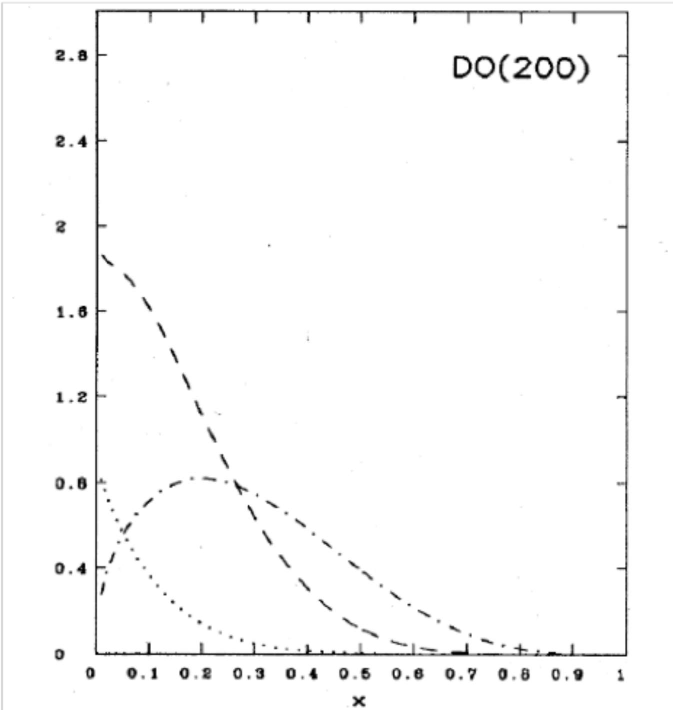
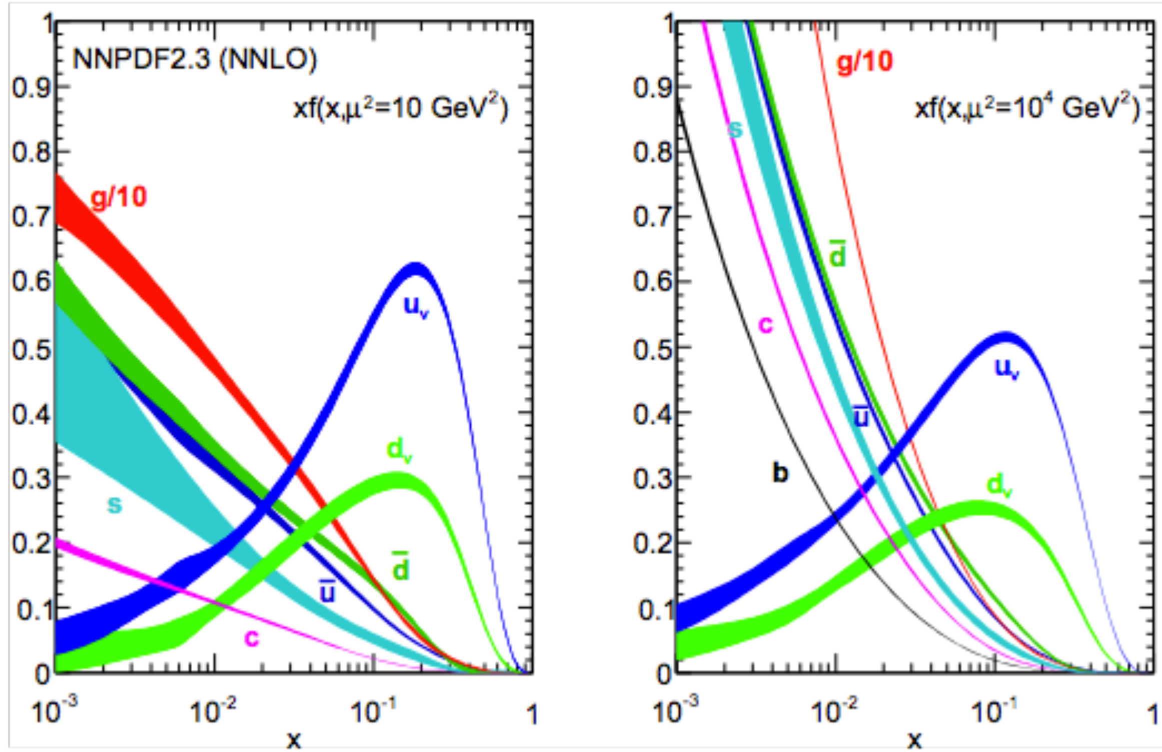


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).



PDG "Structure Functions"2013

- **< 2002:** sets without uncertainty
- **2003-2004:** first MRST, CTEQ, Alekhin sets with uncertainties
- **2004-now:** huge progress made in statistical and theoretical understand, new players

Progress…
A personal overview

PAST

THEORY

* Heavy quark scheme
* Parameters: α_S & m_Q
* (N)NLO corrections

DATA

* PDF uncertainty
* Treatment of correlated systematics

METH.

* Parametrisation bias
* Treatment of inconsistent data

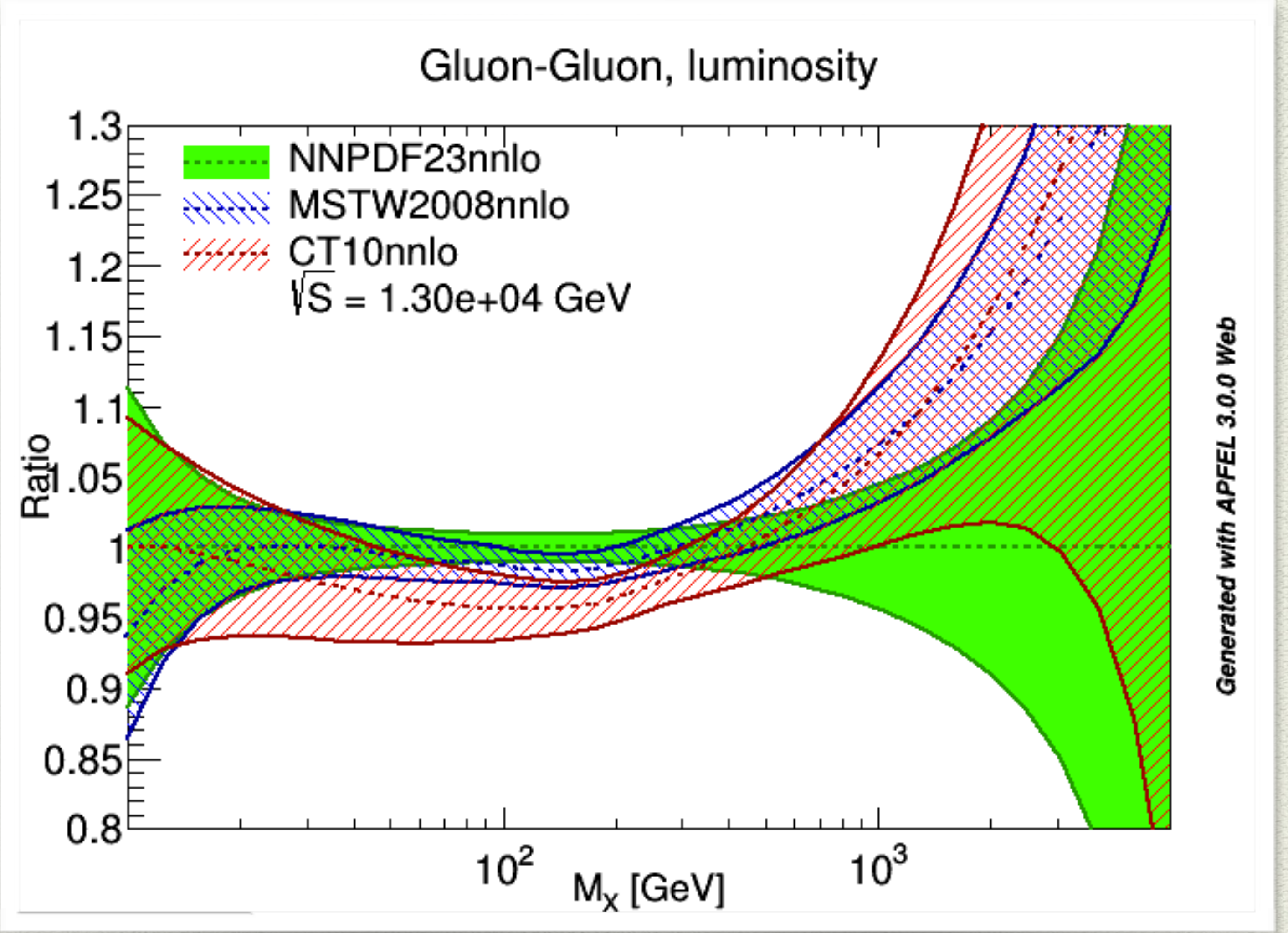
The state of the art

LHAPDF6.1.5 - https://lhapdf.hepforge.org

April 2015	Theory	Data	Methodology
CT14 preliminary	ACOT for HQ No LHC jets at NNLO APPLgrid/FastNLO Scale variation estimate	DIS Fixed Target DY Jets Top Quark LHC DY	Polynomial param (27 par.) Hessian eigenvectors Fixed Tolerance MC and Hessian Reweig.
MMHT arXiv:1410.3989	TR′ for HQ No LHC jets at NNLO APPLgrid/FastNLO EW corrections Deuteron corrections	DIS Fixed Target DY Jets Top Quark LHC DY	Chebyshev pol. (37 par.) Hessian eigenvectors Dynamic Tolerance MC and Hessian Reweig.
NNPDF3.0 arXiv:1410.8849	FONLL for HQ NNLO approx for jets APPLgrid/FastNLO EW corrections	DIS Fixed Target DY Jets Top Quark LHC DY	Neural Network param MC replicas Bayesian Reweighting Closure tests
ABM12 arXiv:1310.3059	FFN for DIS VFN for LHC DY Fitted αs	DIS Fixed Target DY LHC DY	Polynomial param (14 par.) Hessian eigenvectors No Tolerance
HERAPDF2.0 preliminary	TR′ for HQ plus other schemes implemented	HERA-I HERA-II	Hessian eigenvectors MC representation Model & param uncertainty

News for LHC@13 TeV

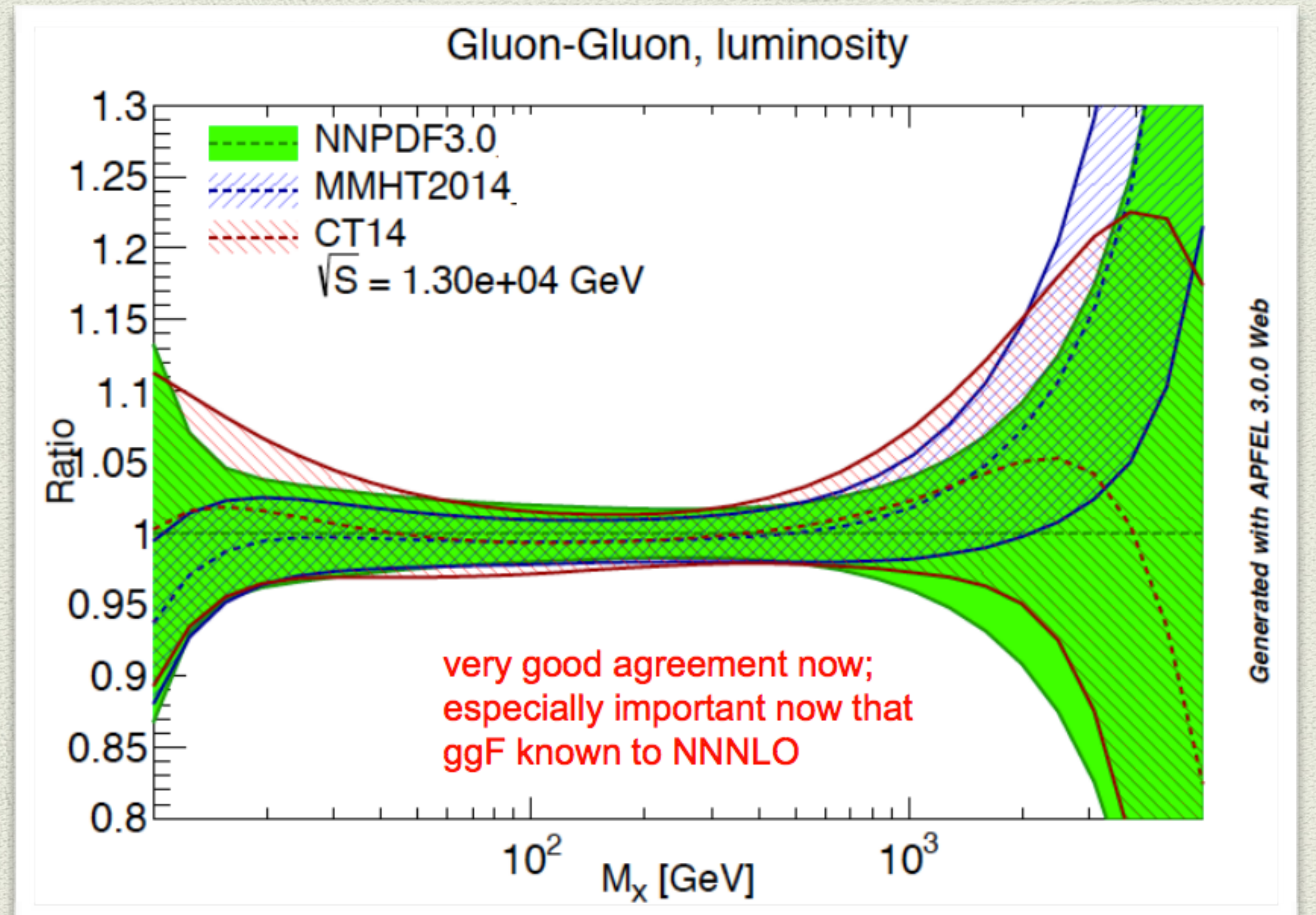
Gluon luminosity



2014

News for LHC@13 TeV

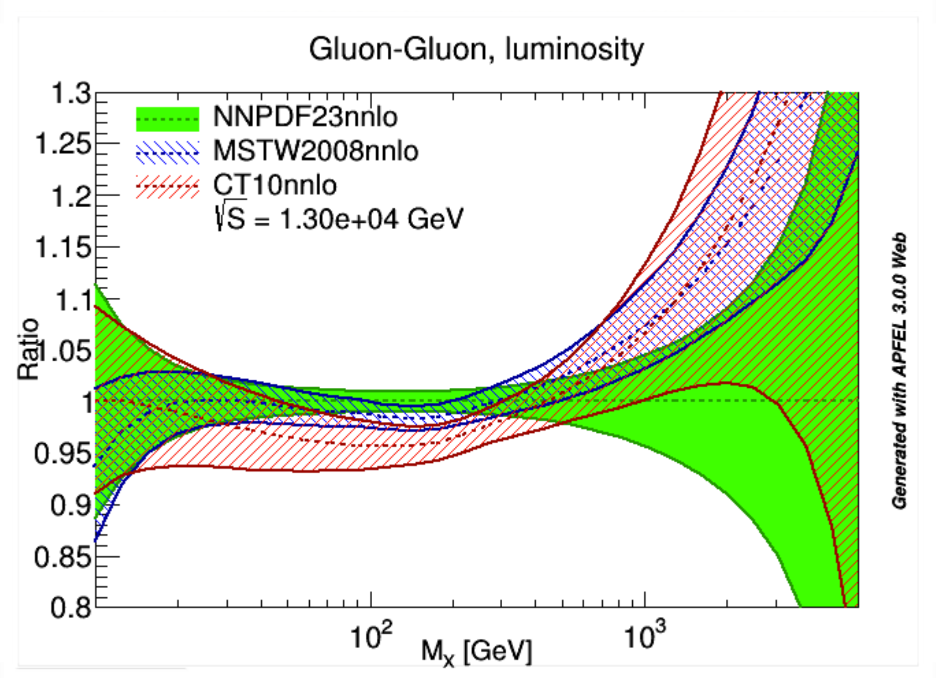
Gluon luminosity

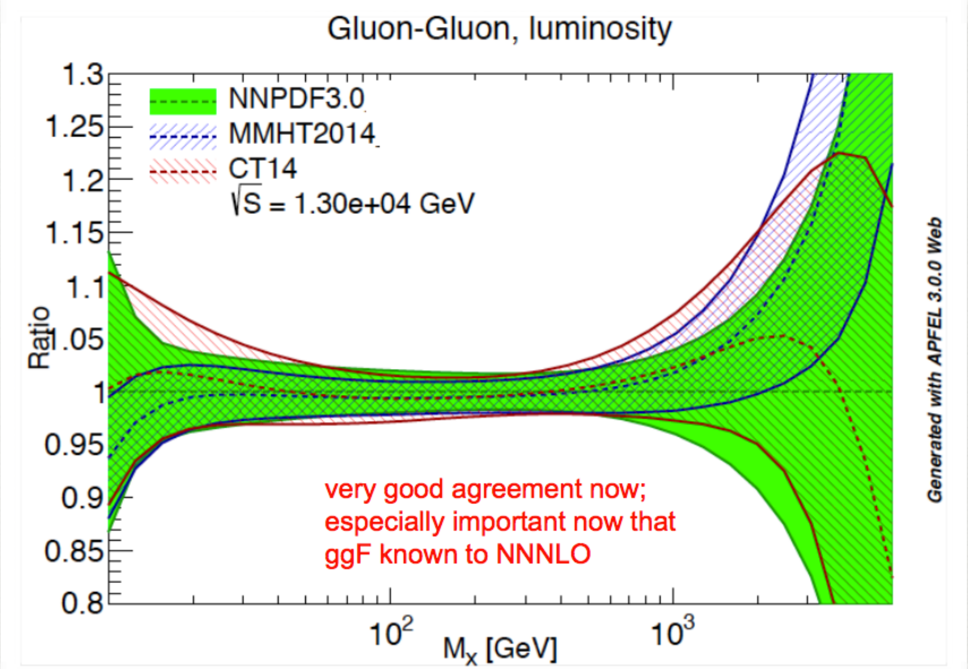


2015

J. Houston, PDF4LHC April 2014

News for LHC@13 TeV
Gluon luminosity and Higgs production





J. Houston, PDF4LHC April 2014

ggF @ NNLO (pb)	CT14	NNPDF3.0	MMHT2014
8 TeV	18.66	18.77	18.65
13 TeV	42.68	42.97	42.70

Progress and frontiers

A personal overview

	PAST	PRESENT
THEORY	* Heavy quark scheme * Parameters: α_S & m_Q * (N)NLO corrections	* NNLO corrections * QED/EW corrections * Resummations
DATA	* PDF uncertainty * Treatment of correlated systematics	* LHC data, combinations from HERA, Tevatron, data from Nomad, CHORUS
METH.	* Parametrisation bias * Treatment of inconsistent data	* Closure Tests * Combination of different PDF sets

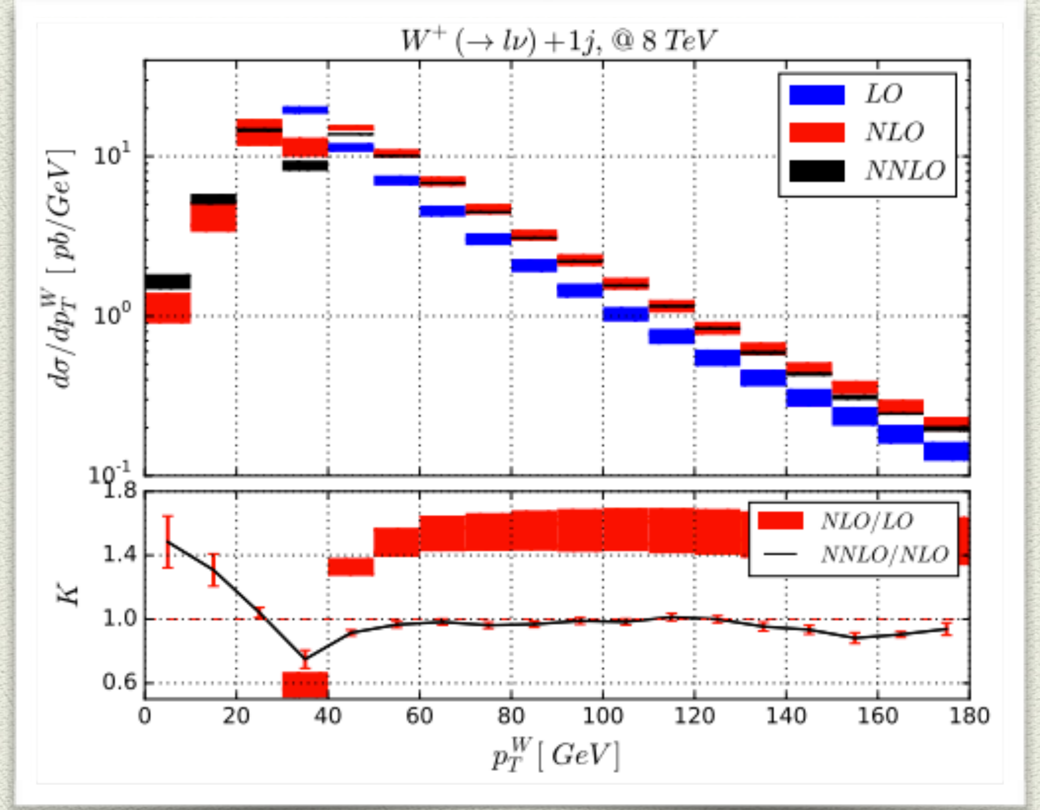
Theory
The NNLO revolution

- NNLO calculations are essential to reduce theoretical uncertainties in PDF analyses
- Recently important progress has been made on some key processes

✓ Full NNLO top quark production cross section is available (TOP++2.0) and differential distributions are expected soon → gluon at large x

✓ W+1j also available now at NNLO, soon Z+1j → gluon & quark separation

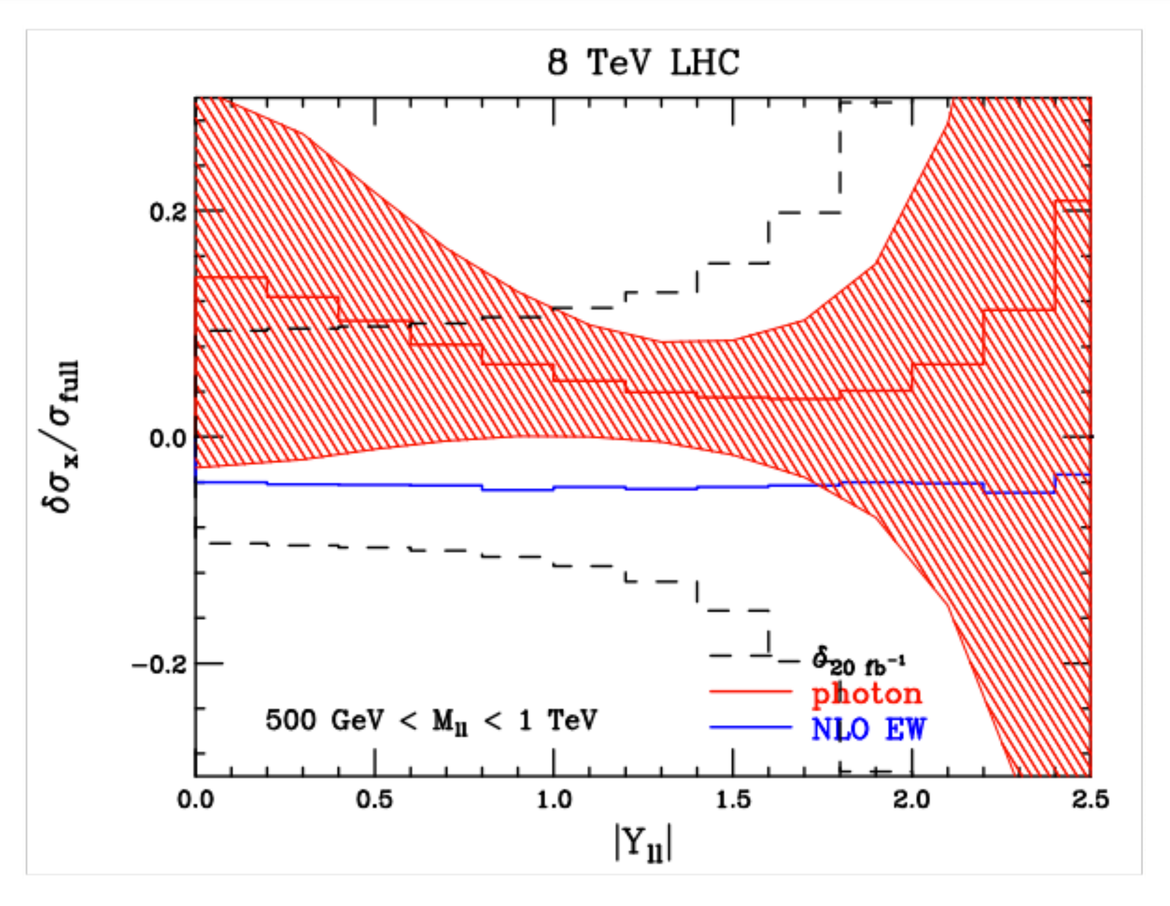
✓ NNLO inclusive jet production in the gluon gluon channel has been completed → gluon and quarks at large x



Czakon, Fiedler, Mitov PRL 110 (2013) 25
Boughezal et al, 1504.02131
Gehrmann-De Ridder et al, Phys.Rev.Lett. 110 (2013) 16

Theory
QED and EW corrections

- EW corrections become relevant at the current precision level
- Several tools to compute them along with QCD correction [FEWZ3.1, Phys.Rev. D86 (2012) 094034]
- EW corrections can be sizeable especially at large invariant mass
- QED corrections affected by large uncertainty induced from uncertainty on photon PDF

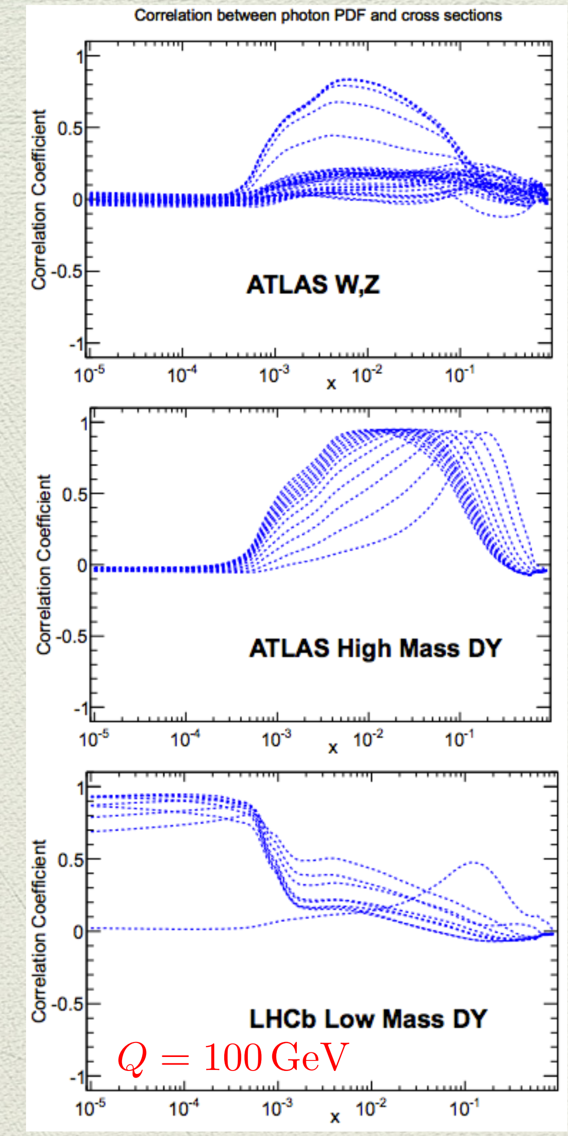


Boughezal, Li, Petriello, Phys.Rev. D89 (2014) 3, 034030

Theory

The photon PDF

- The inclusion of EW corrections requires PDF with QED effects
- **NNPDF23QED** is a recent PDF set with uncertainties which incorporates (N)NLO QCD + LO QED effects. MMHT QED set and CT14 sets expected soon
- Photon PDF fitted from DIS and DY data (on-shell W,Z production and low/high mass DY)
- Photon PDF is poorly determined from DIS data. Need hadron collider processes where photon contributes at LO!



Ball et al, Nucl.Phys. B877 (2013) 290-320

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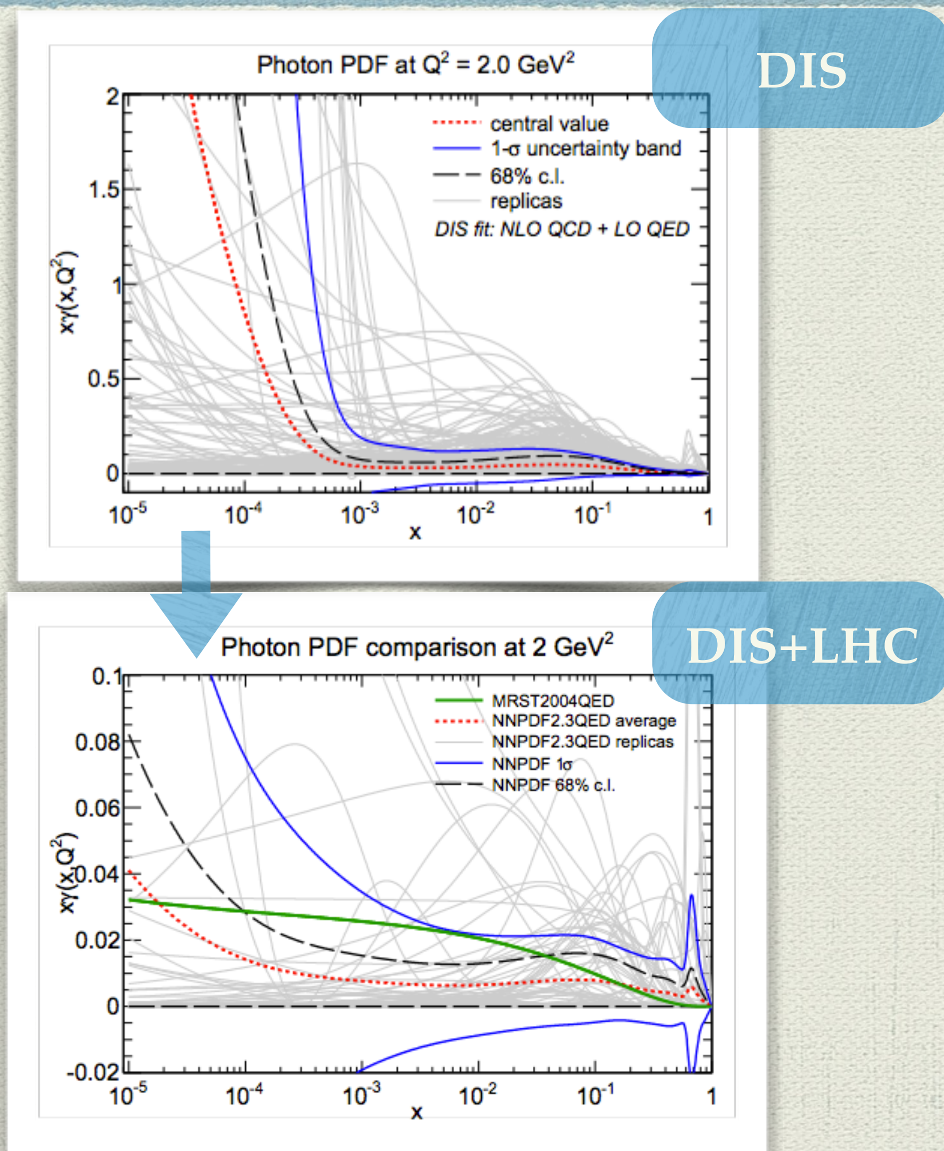
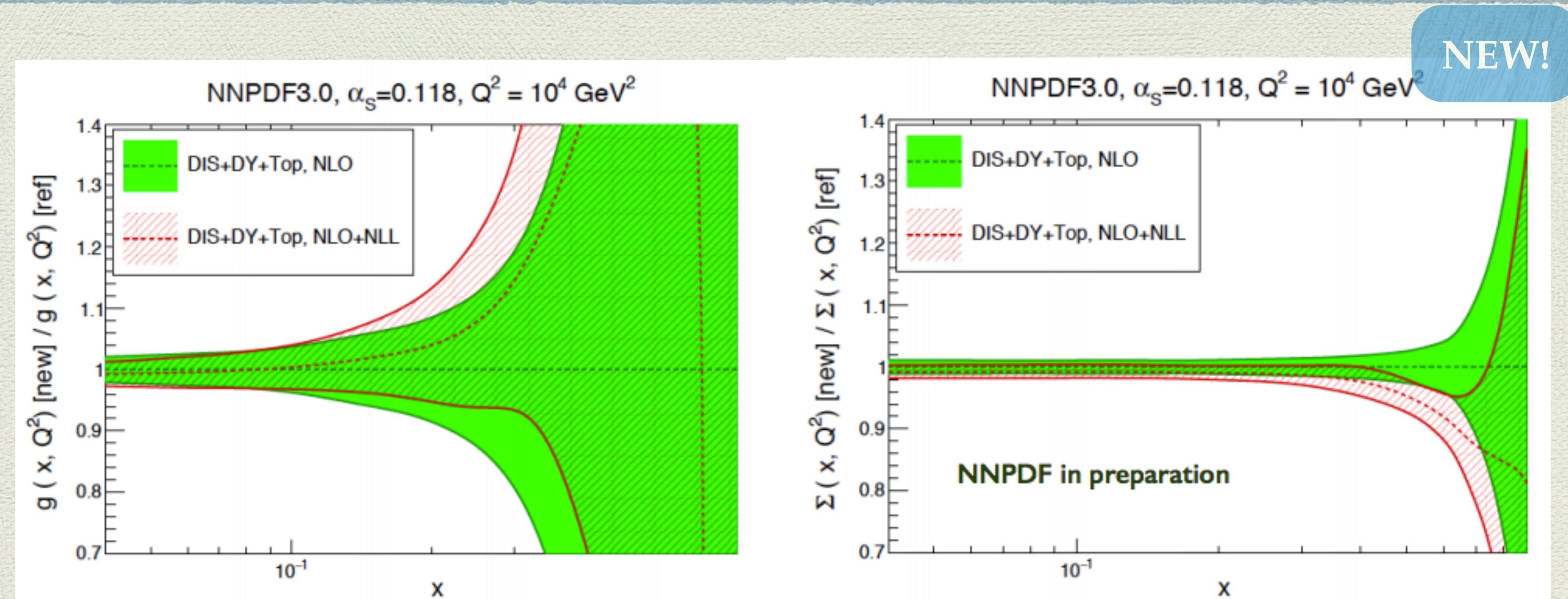


Ball et al, Nucl.Phys. B877 (2013) 290-320

Theory
Threshold resummation



NNPDF coll., in progress

- Resummation included for the first time in PDF fit using public codes **ReDY** (Bonvini et al.), **TROLL** (successor of ResHiggs) and **TOP++** (Czakon et al.),
- In a NLO+NLL fit, effects can be large. Up to -20% for quark and +40% for gluons.
- Work in progress also to include Parton Shower resummation using aMCfast (Bertone et al.) and small-x resummation in PDF fits

Data

Inclusion of LHC data

GLUON

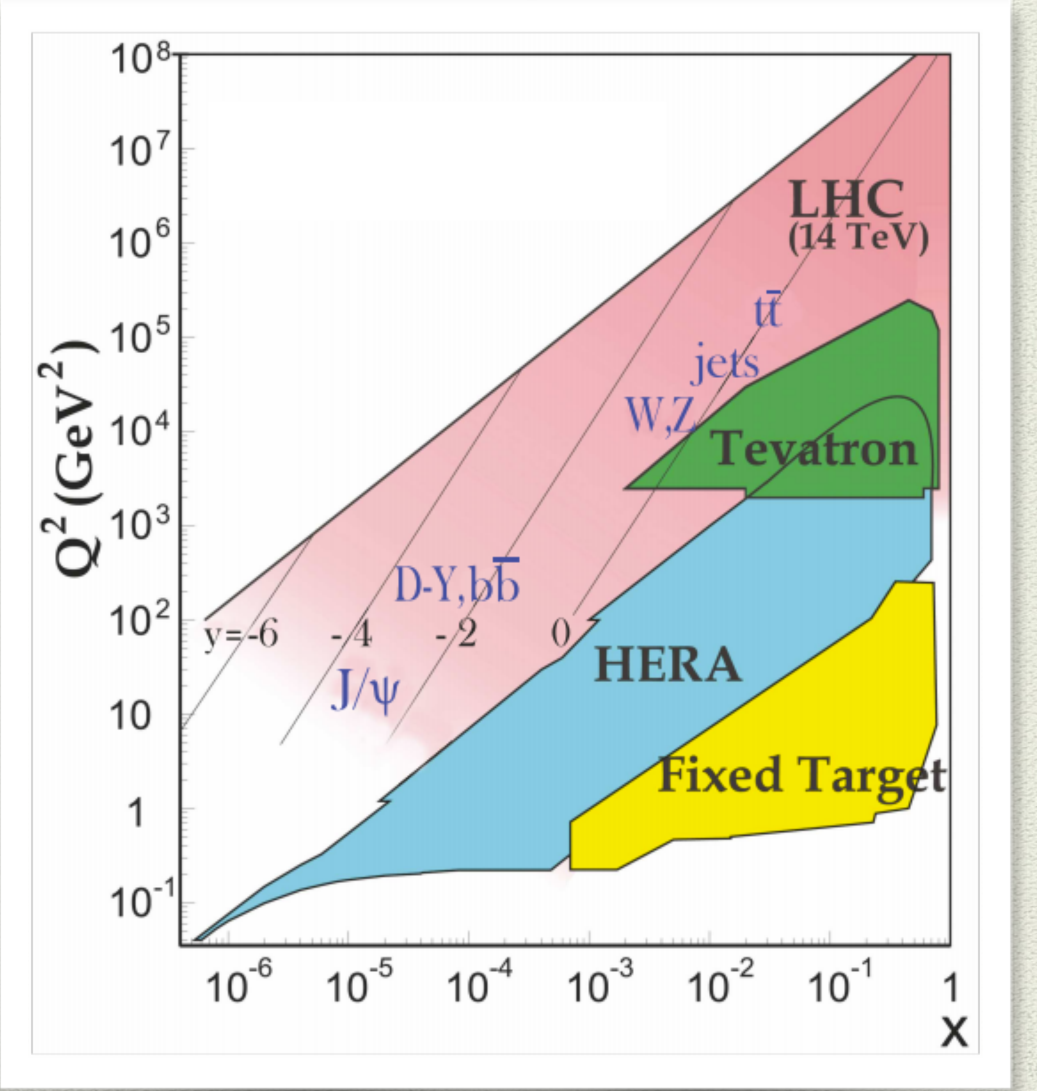
Inclusive jets and dijets
(medium/large x)
Isolated photon and γ+jets
(medium/large x)
Top pair production **(large x)**
High p_T Z(+jets) distribution
(small/medium x)

QUARKS

High p_T W(+jets) ratios
(medium/large x)
W and Z production
(medium x)
Low and high mass Drell-Yan
(small and large x)
Wc **(strangeness at medium x)**

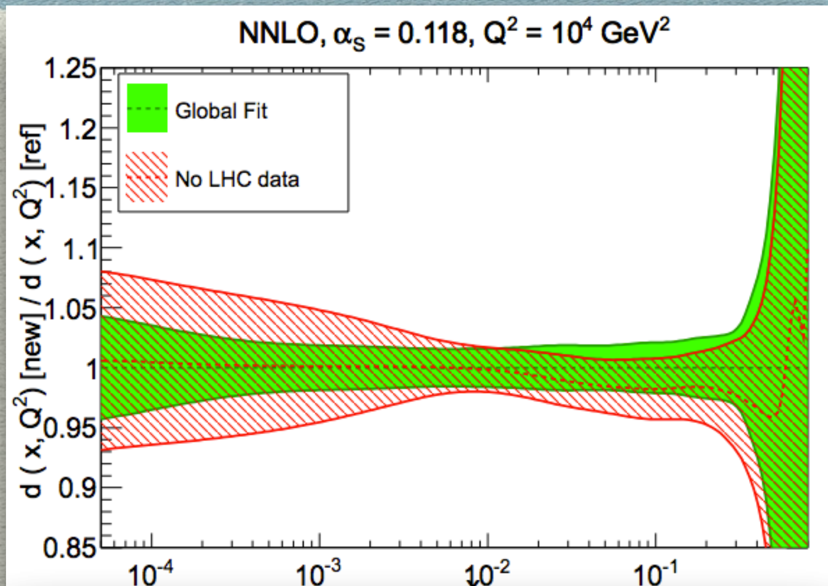
PHOTON

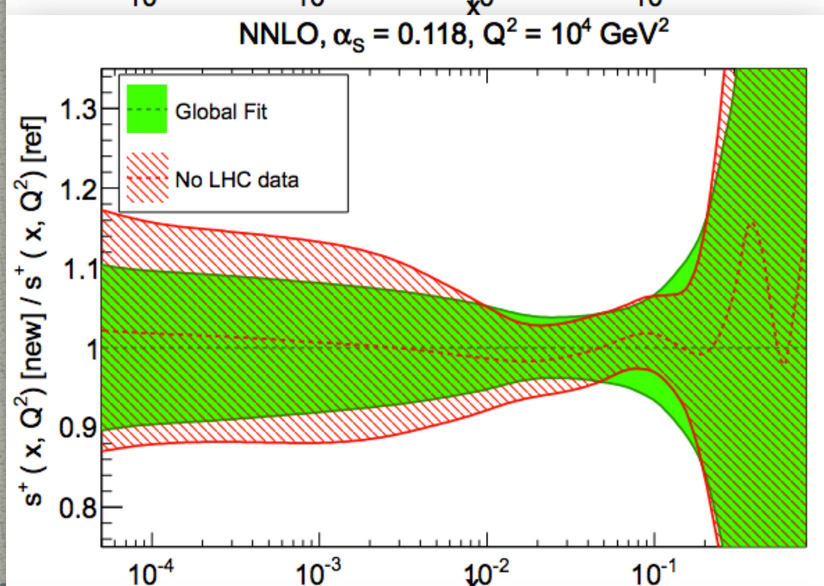
Low and high mass Drell-Yan
WW production

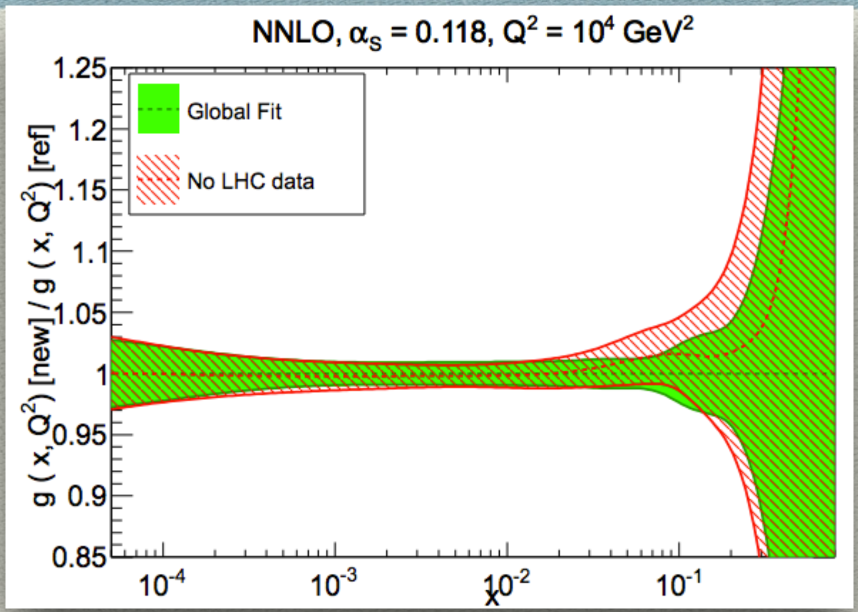


Data

Inclusion of LHC data





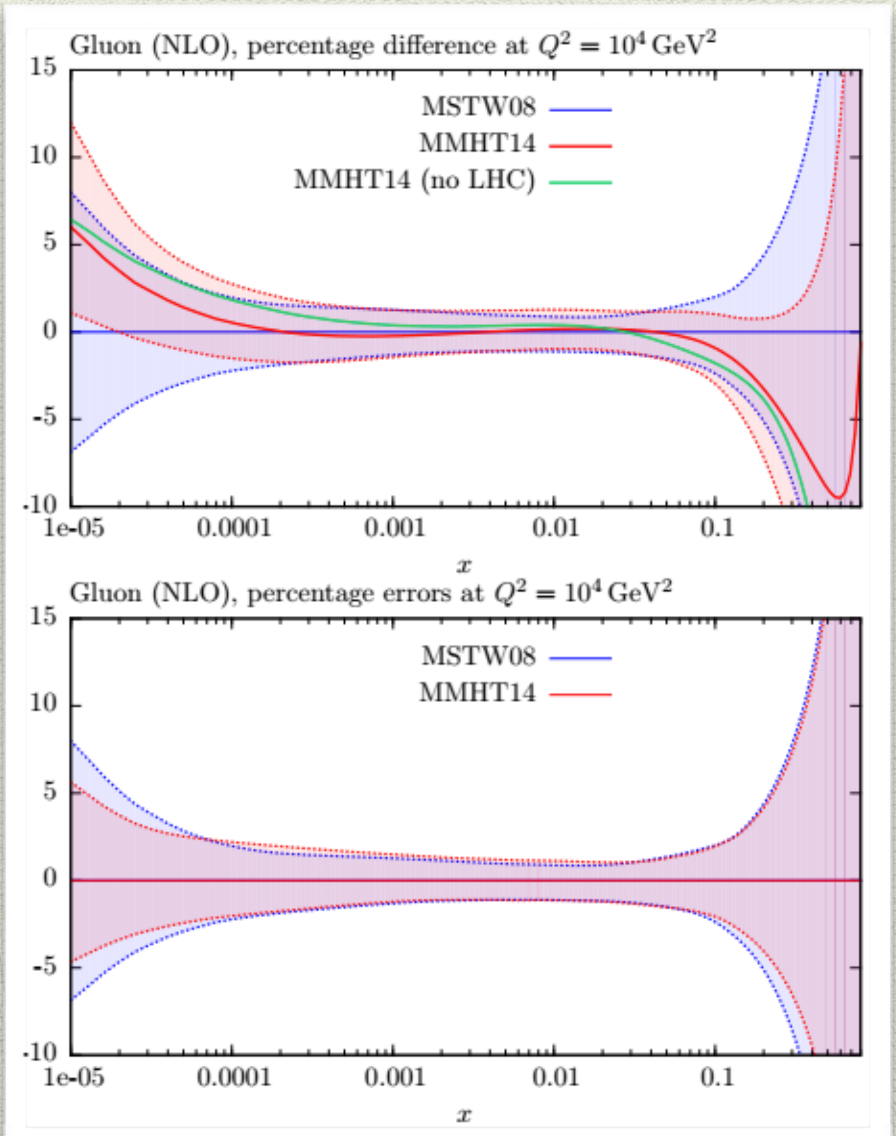


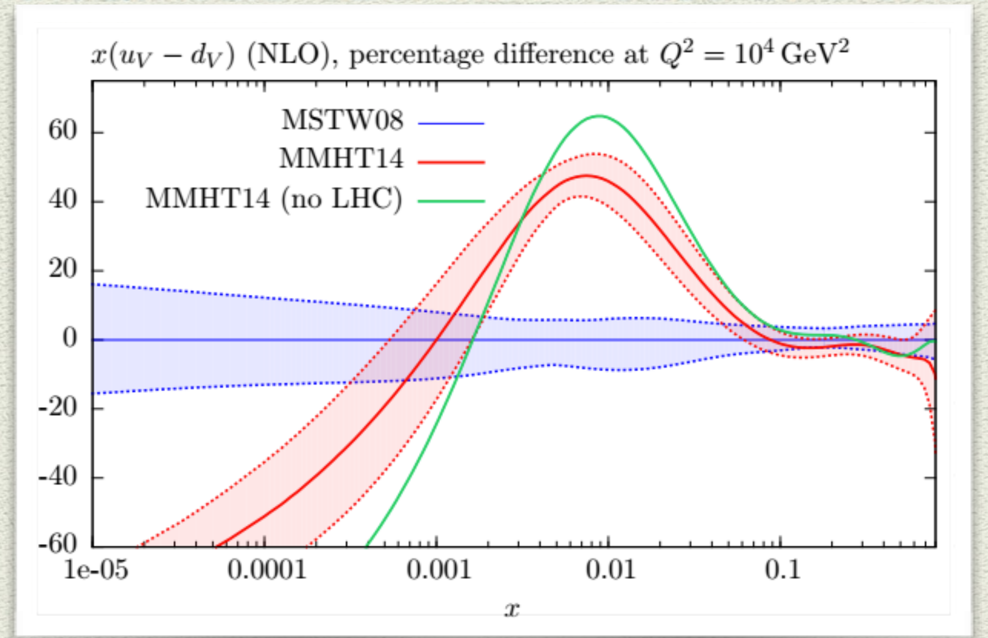
NNPDF collaboration, JHEP04(2015)040

- PDF uncertainty of large-x gluon reduced by inclusion of jet and top data
- Uncertainty of light quarks at small x reduced by DY data and W+c

Data

Inclusion of LHC data





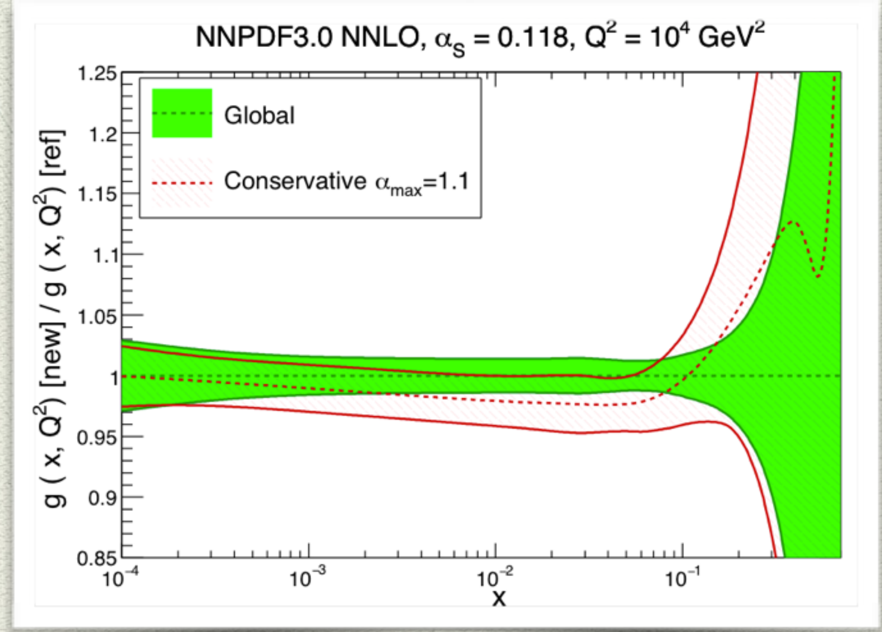
MMHT, arXiv:1412.3989

- Large effect on quark flavour decomposition
- Important to disentangle changes due to methodology (parametrisation and fitting) from effect of LHC data
- More studies from ex.collaborations

Data/Methodology
Conservative partons

Q: As more data at higher energy will be released, how can we make sure that we will not absorb new physics in the PDFs?

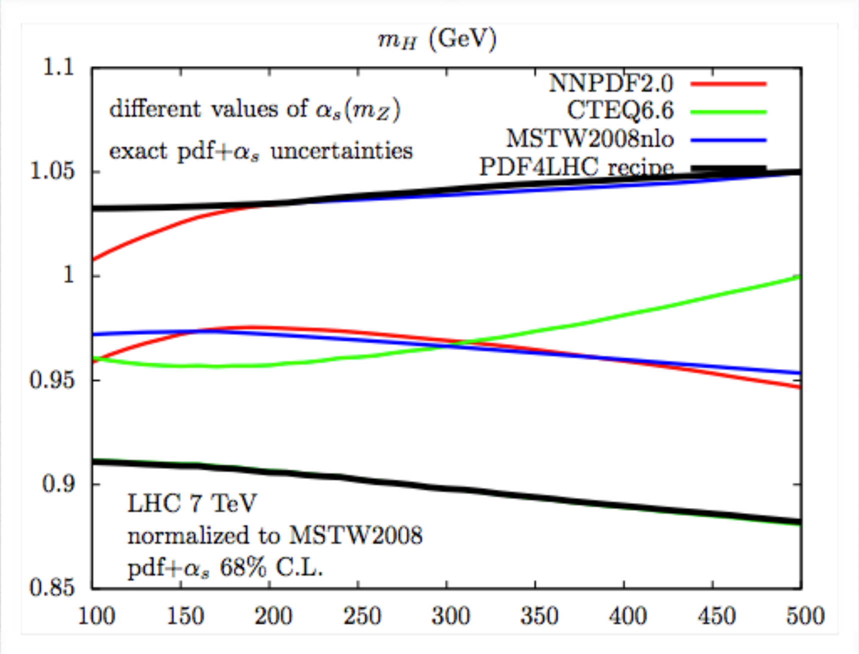
- Inconsistencies between data that enter a global PDF analysis can distort statistical interpretation of PDF uncertainties
- Inconsistency of any individual dataset with the bulk of global fit may suggest that its understanding (theory or experiment) is incomplete
- Set of **conservative partons** based on measure of consistency are crucial to systematically study inclusion of new data



NNPDF collaboration, JHEP04(2015)040

Methodology

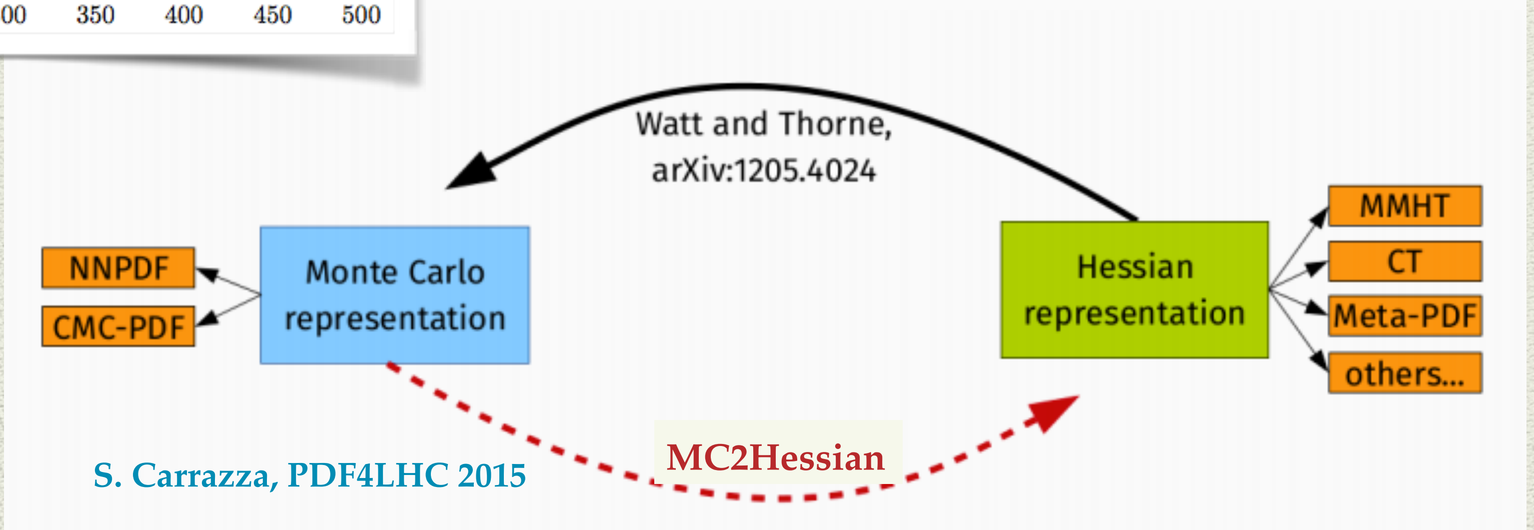
Towards a new PDF4LHC prescription



Moving forward from PDF4LHC envelope (2010):

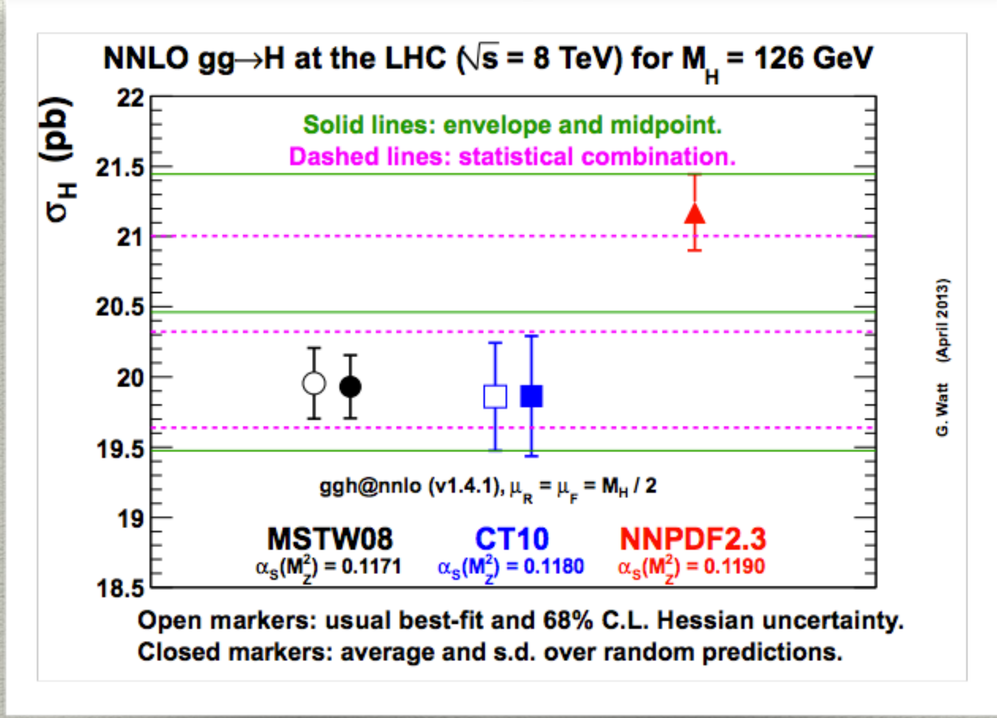
➡ Statistical combination from different PDF groups generating MC sets

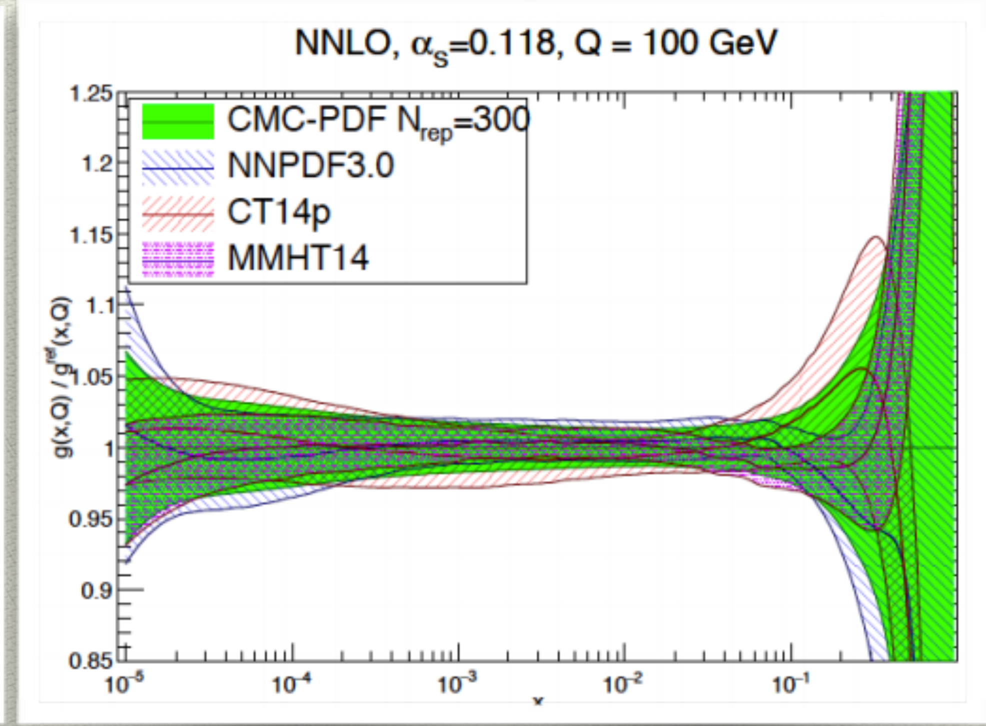
➡ Meta-PDFs: fit with input functional form the CT, MMHT and NNPDF shapes and combine in a unique consistent set



Methodology

Combined MC set

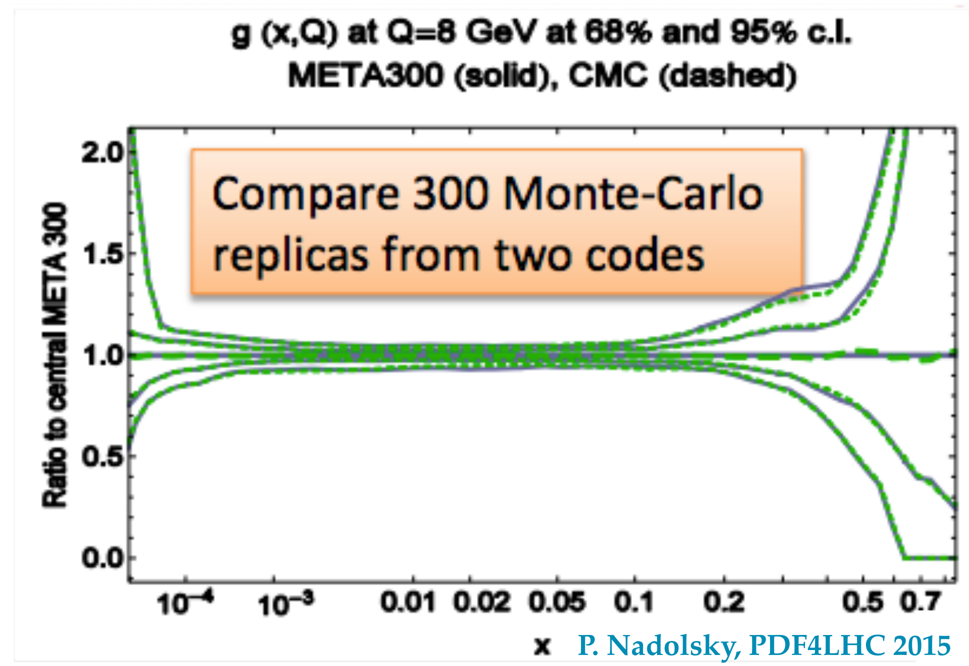




- Monte Carlo combination of most recent global PDF sets **[Forte, Watt]**
- Each replica receives the same weight: uncertainty smaller than in the envelope, as in the latter outliers are given a larger weight
- New compression studies: N=40 replicas are virtually identical to the original 300 replicas from the point of view of correlation, standard deviation, observables **[Carrazza et al.]**

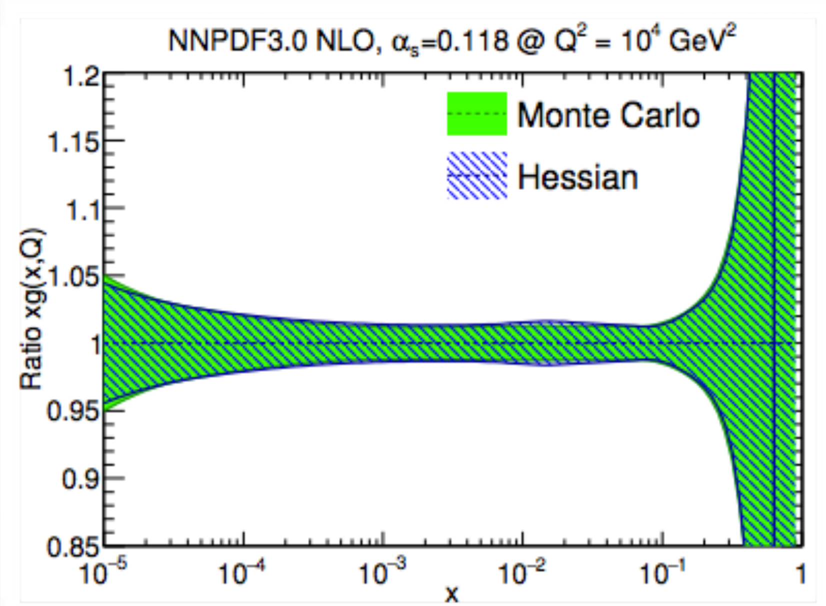
Methodology
Hessian representation

- Ongoing benchmark between compressed set of Monte Carlo replicas and meta-parametrisation



P. Nadolsky, PDF4LHC 2015

- Preliminary: 60-100 Meta PDFs and 40 CMC replica sets broadly agree



- Ongoing work on MC2Hessian (Carrazza et al.) using MC replicas as basis of the linear representation to avoid parametrisation bias

Conclusions and Outlook

- PDF uncertainties are still limiting factor in achieving precise predictions
- Fast progress in recent months, new PDF sets, inclusion of new data, more solid theory and methodology
- No time to mention closure test to validate fitting procedure in PDF fits
- Still a lot of work ahead

**
* Fast interface to NNLO observables
* N(N)LO+NLO EW fits with initial photon
* Effect of parton shower resummation in PDF fits
* Small-x resummation
* Definition of theoretical uncertainties in PDF fits
**

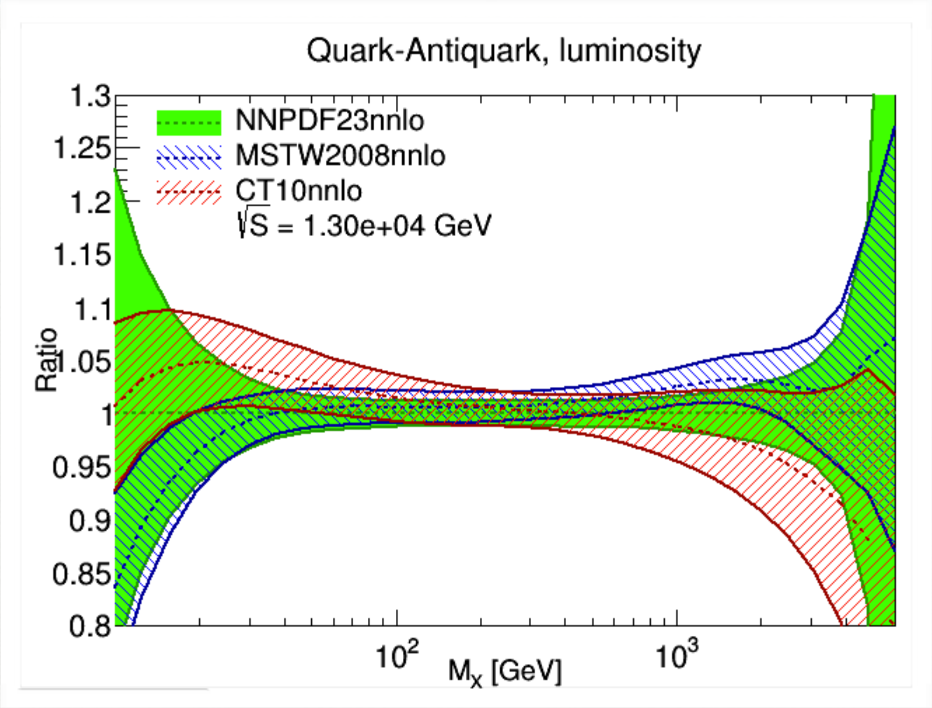
**
* HERA I+II combination
* Loads of new data from LHC and new observables to be investigated
**

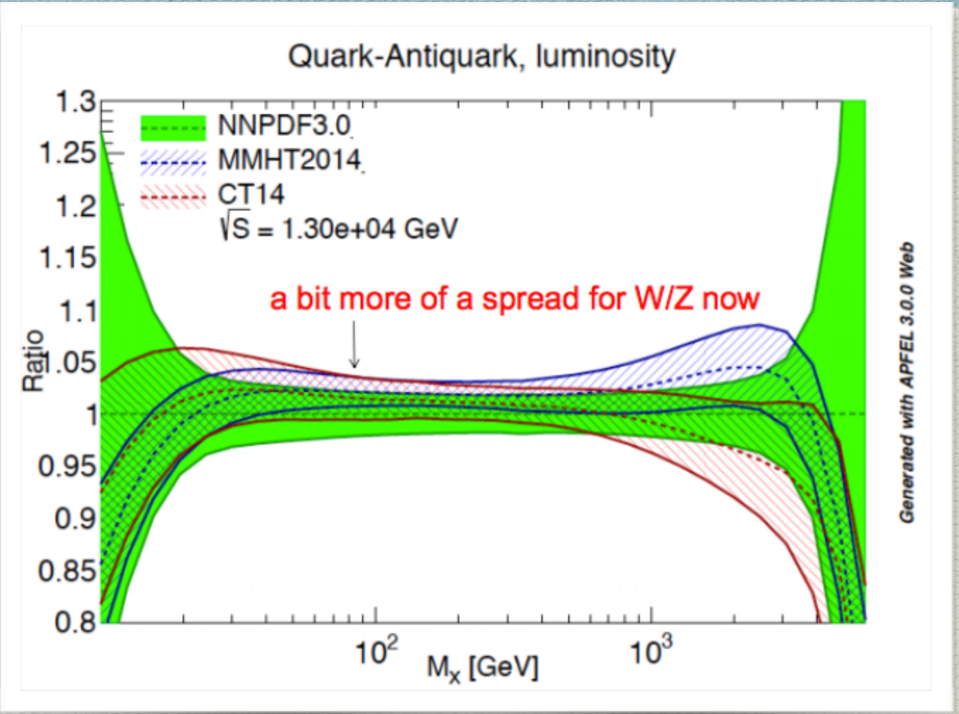
**
* Statistically-sound PDF combination
* Closure tests and measure of data consistency
**

Back up

News for LHC@13 TeV

Quark-Antiquark luminosity





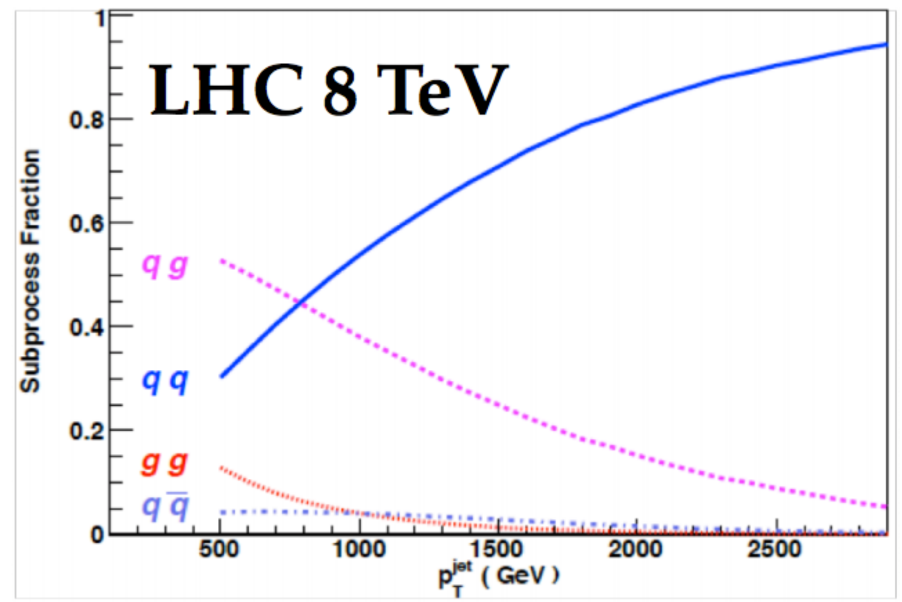
J. Houston, PDF4LHC April 2014

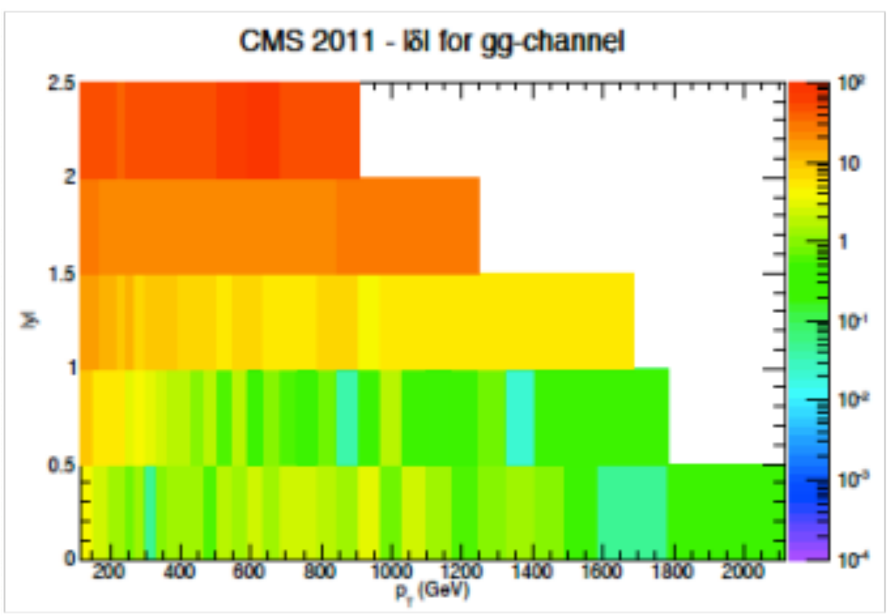
Theory

Inclusion of jet observables in NNLO fits

• At the LHC gluon-gluon channel is small at medium-large pT
• Approximate NNLO results can be derived from improved threshold calculation, reasonable at large pT and expected to break down at small pT

[De Florian et al, Phys.Rev.Lett. 112 (2014) 082001]



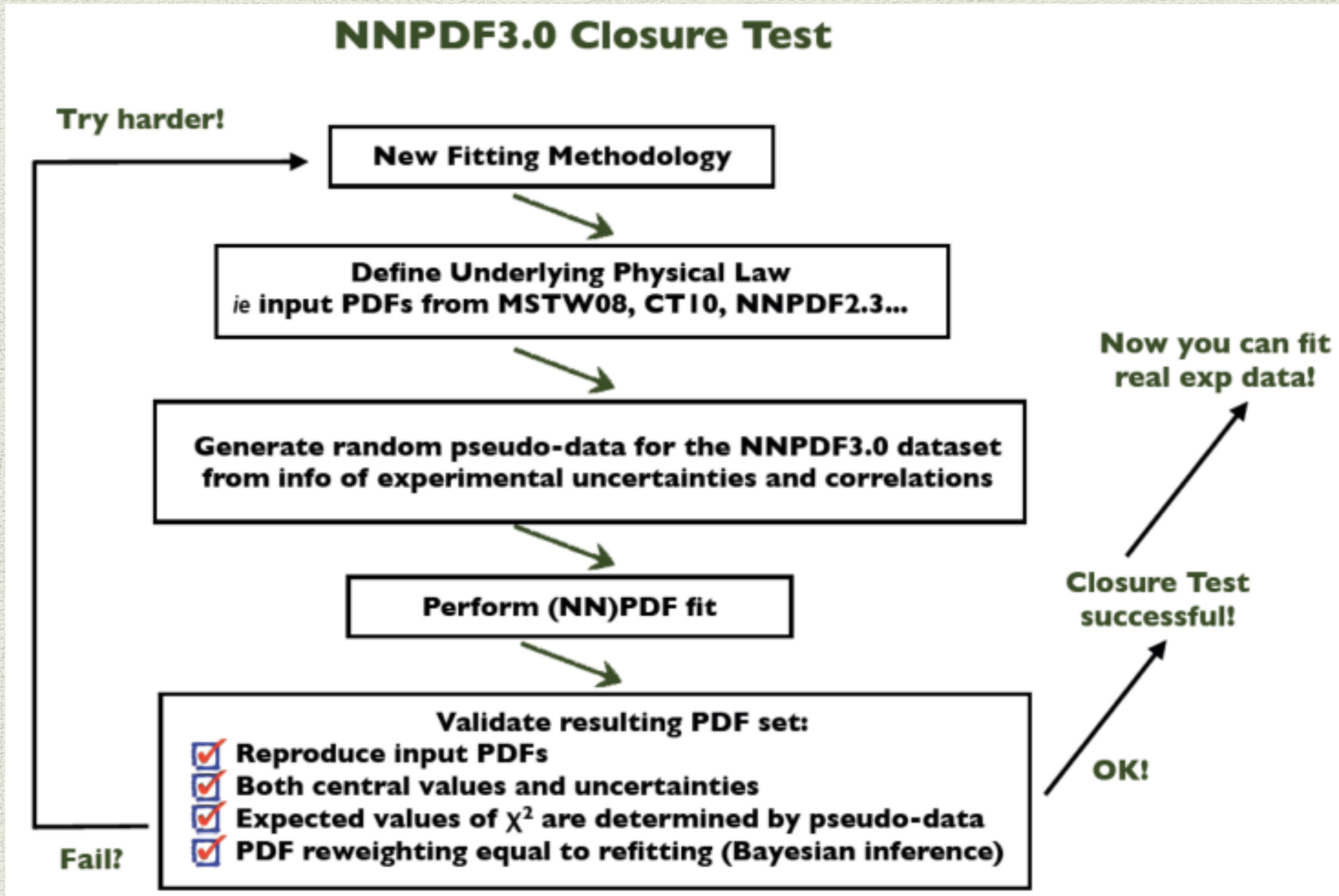


• Comparison between NNLO approximation and full NNLO in the gg channel can determine for which value of pT and η NNLO approximation can be trusted
• This assumes NNLO K-factors similar in all channels

S. Carrazza, J. Pires, JHEP 1410 (2014) 145

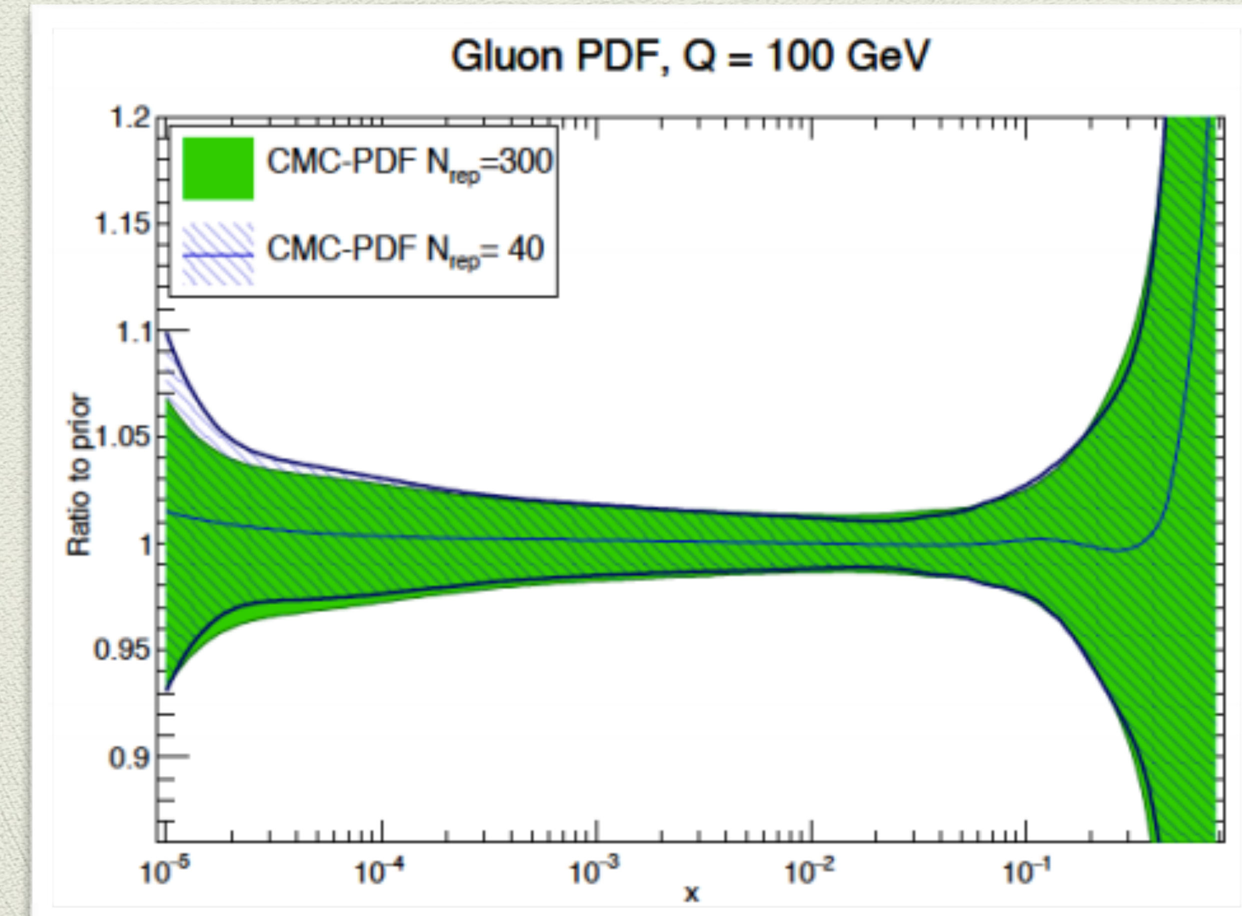
Methodology

Closure tests



Methodology
Compressed MC set

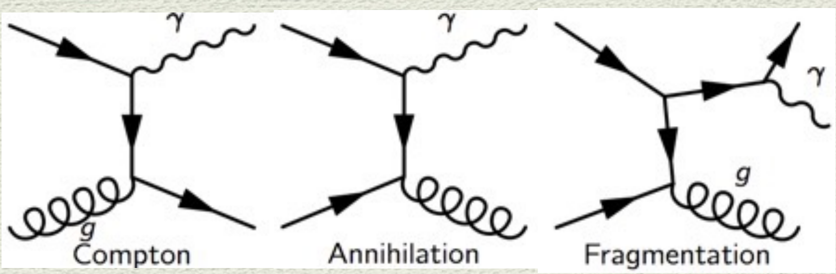
Good news: 40 reps as good as 300 replicas!

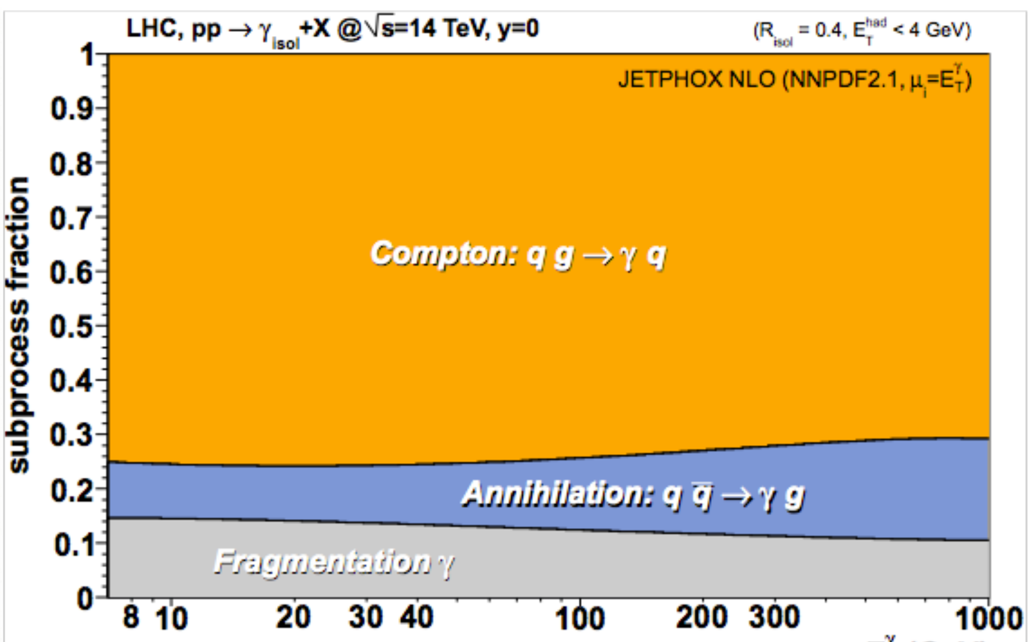


Gluons

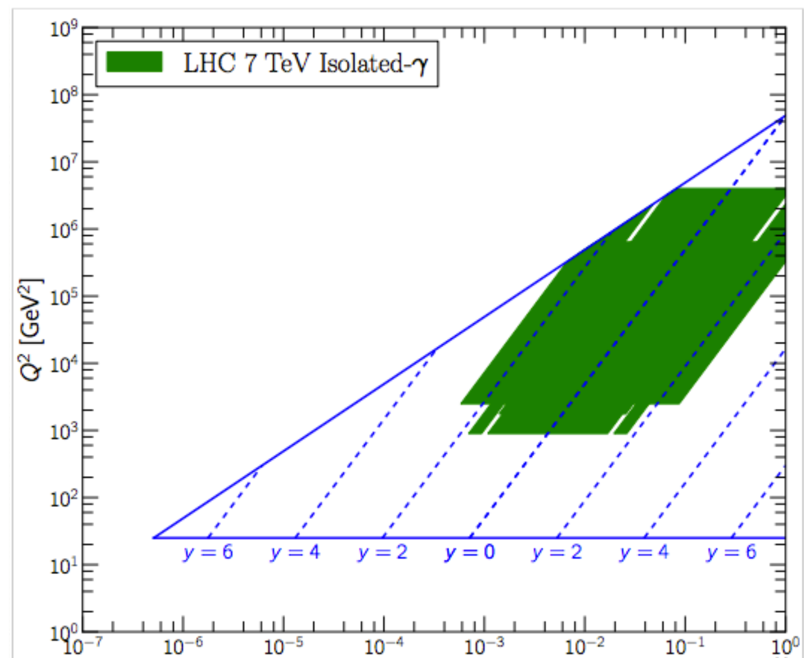
Prompt photon production: data

- Prompt photon production directly sensitive to the gluon-quark luminosity via Compton scattering
- Isolated prompt photon data well described by NLO QCD theory
- ATLAS and CMS measurements at 7 TeV constrain medium-x region





D'Enterria, Rojo, Nucl. Phys. B860 (2012), 311



S. Farry, QCD@LHC 2013

Gluons

Prompt photon production: impact of data

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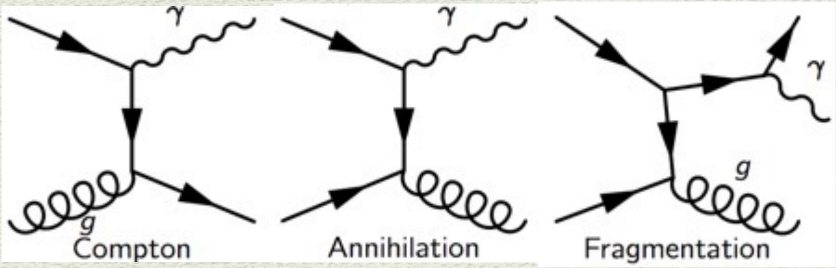
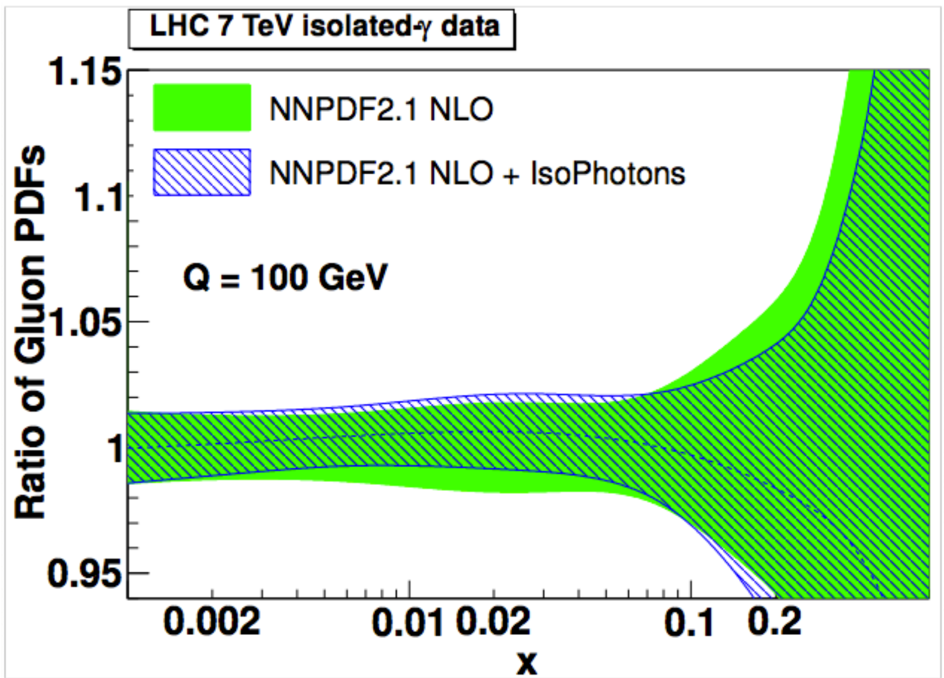


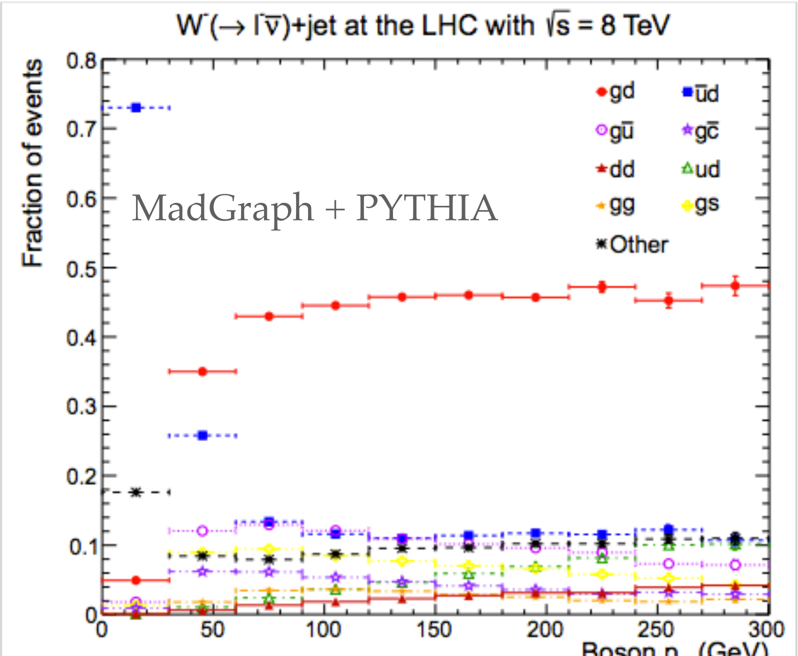


D'Enterria, Rojo, Nucl. Phys. B860 (2012), 311

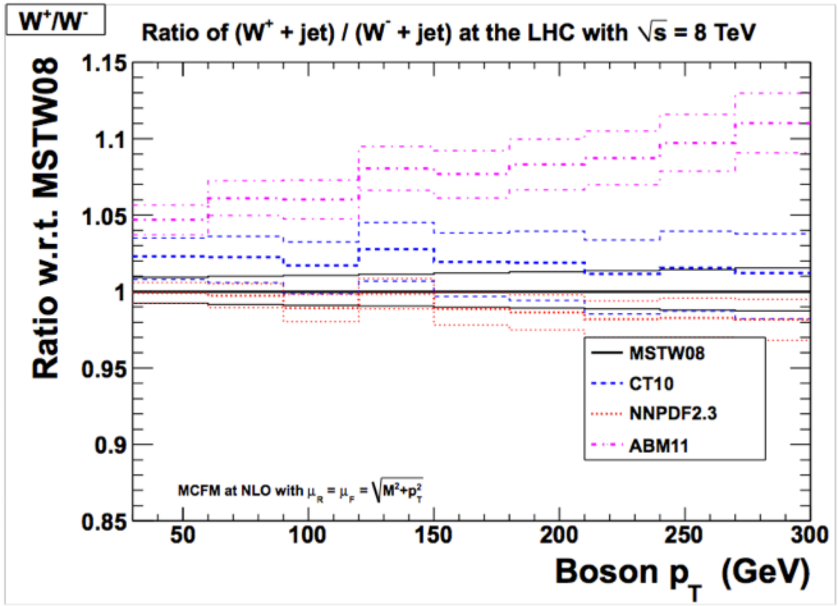
- Included ATLAS 880 nb^{-1}, and 35 pb^{-1}, CMS 1.9^{-1} and 36 pb^{-1}
- Moderate uncertainty reduction in the region which affects and reduce uncertainties for Higgs gluon fusion predictions by 20%
- Issue: there is not yet a public fast interface available for JETPHOX [P. Aurenche et al] in PDF fits but it is likely to be available shortly

Gluons
High pT vector boson production

- In global fits, medium/large x gluon is mainly constrained by jet data.
- W/Z boson at large p_T (associated with jets) would provide a complementary constraint in x region which enters gg>H production
- At large pT, gluon up (for Z and W^+) or gluon down (for W^-) scattering dominate: can exploit these observables to constrain gluon and u/d ratio



Malik,Watt ArXiv: 1304.2424



- pT spectra affected by possibly large theoretical uncertainties, soft resummation and EW corrections at small/large pT.
- Need NNLO, hopefully not too far after calculation of H+j at NNLO [Boughezal et al]
- Exploit ratios to cancel theoretical uncertainties

Photon
More constraints from LHC

Ball et al, 1308.0598

- WW production is phenomenologically relevant as a background for BSM searches
- At high M_{WW}, photon-induced contribution becomes relevant
- The large uncertainty at large M_{WW} comes from the large uncertainty of photon PDF for $x > 0.1$
- New LHC data give unique opportunity of constraining the photon in that region