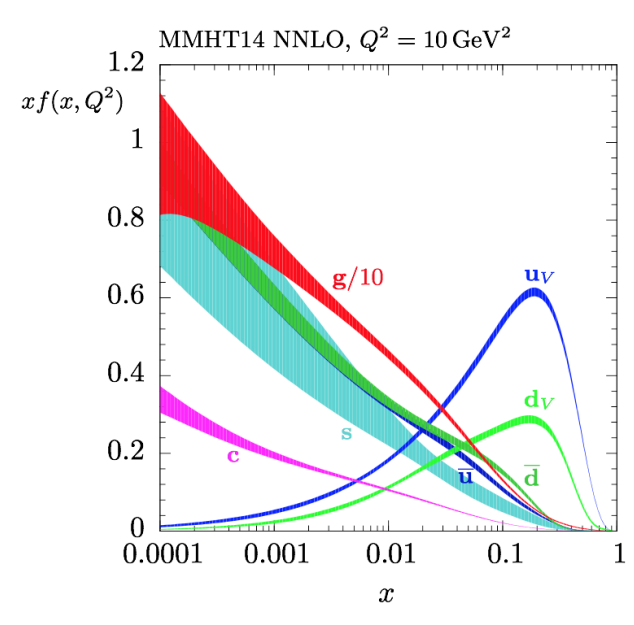
Developments in PDF4LHC

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
BUE, Cairo, Egypt

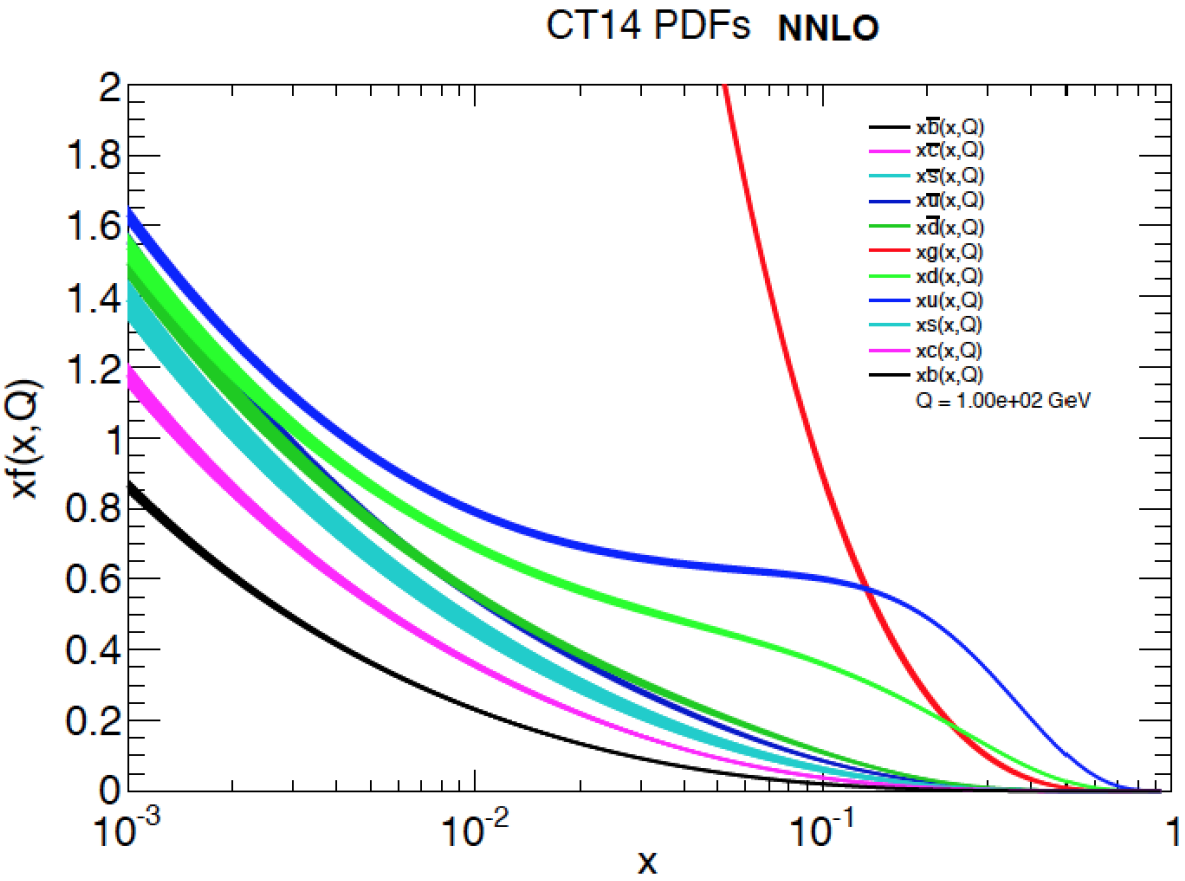
20th May 2015



History

- PDF4LHC originated from the HERA/LHC workshops organized in the period 2004-2008
- Forum for PDF discussions with all PDF groups and experiments
- First recommendation in 2010: arXiv:1101.0538 (under some duress of the Higgs cross section group ☺)
- This recommendation (see later) was a bit tedious: revised and being improved now…
- New recommendation being finalized, which should be a easier for the user, without (noticeable) loss of precision

New PDFs (2014/2015)



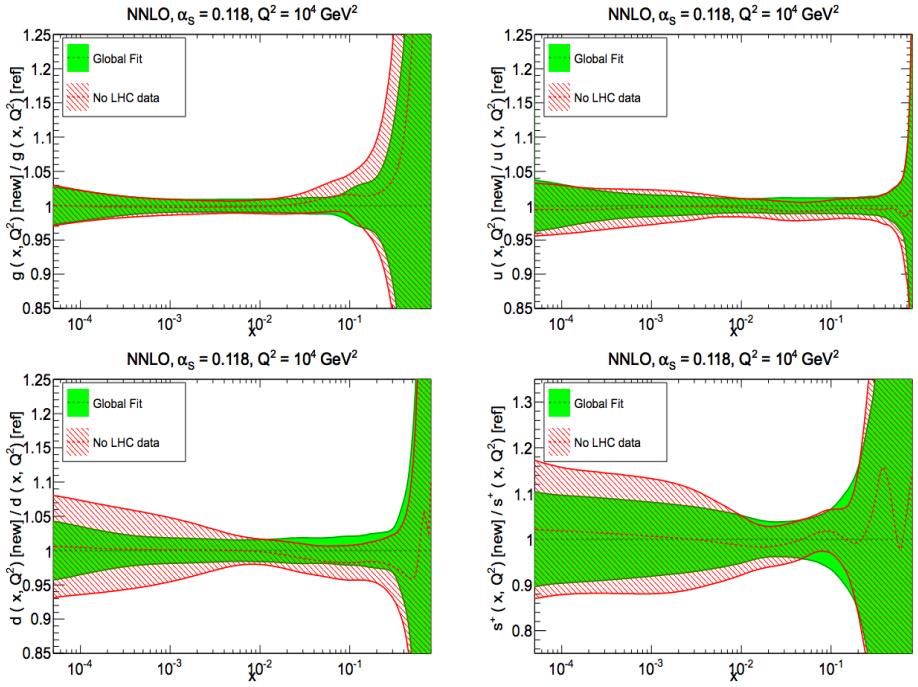
CT14 PDFs
To be released soon

Final combined HERA structure function data not yet released hence not included yet

- New release NNPDF3.0 arXiv:1410.8849
- New release MMHT arXiv:1412.3989 (formerly known as MSTW)
- HERAPDFs: data& fits ready, paper expected in a few weeks
- Other PDF updates of PDFs are older

LHC Data Plays an Increasing Role

arXiv:1410.8849: NNPDF Parton Distributions for the LHC Run-II



LHC data included

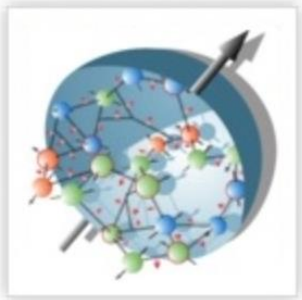
ATLAS							
	ATLAS W, Z 2010	[47]	M	full	i	30 (30/30)	
	ATLAS 7 TeV jets 2010	[50]	M	full	i,j	90 (90/9)	
	ATLAS 2.76 TeV jets	[63]	M	full	j	59 (59/3)	$20 \le p_T^{\rm jet} \le 200$ GeV $0 \le \lvert\eta^{\rm jet}\rvert \le 4.4$
	ATLAS high-mass DY	[56]	M	full		11 (5/5)	$116 \le M_{ll} \le 1500$ GeV
	ATLAS W p_T	[57]	M	full		11 (9/-)	$0 \le p_T^W \le 300$ GeV
CMS							
	CMS W electron asy	[48]	M	cov		11 (11/11)	
	CMS W muon asy	[58]	M	cov		11 (11/11)	$0 \le \lvert\eta_l\rvert \le 2.4$
	CMS jets 2011	[62]	M	full		133 (133/83)	$114 \le p_T^{\rm jet} \le 2116$ GeV $0 \le \lvert\eta^{\rm jet}\rvert \le 2.5$
	CMS $W + c$ total	[60]	M	cov		5 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$
	CMS $W + c$ ratio	[60]	M	cov		5 (5/5)	$0 \le \lvert\eta_l\rvert \le 2.1$
	CMS 2D DY 2011	[59]	M	cov		124 (88/110)	$20 \le M_{ll} \le 1200$ GeV $0 \le \lvert\eta_{ll}\rvert \le 2.4$
LHCb							
	LHCb W rapidity	[49]	M	cov		10 (10/10)	
	LHCb Z rapidity	[61]	M	cov		9 (9/9)	$2.0 \le \eta_l \le 4.5$
$\sigma(t\bar{t})$							
	ATLAS $\sigma(t\bar{t})$	[65–67]	M	none		3 (3/3)	-
	CMS $\sigma(t\bar{t})$	[68–70]	M	none		3 (3/3)	-

Plan for a discussion forum among the experiments for PDF sensitive measurements

Also, in preparation:

The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II

PDF Updates → Benasque Workshop



Parton Distributions for the LHC

2015, Feb 15 -- Feb 21

Organizers:
J. Rojo (CERN / University of Oxford)

Also summaries on recent PDF4LHC meeting (5/4/2014)

Monday, February 16

Morning session:

08:30h **Registration**

09:00h **Introduction to the workshop and logistics**
Juan Rojo

09:20h **CT plans**
Pavel Nadolsky

10:00h **MMHT plans**
Lucian Harland-Lang

11:00h **NNPDF plans**
Juan Rojo

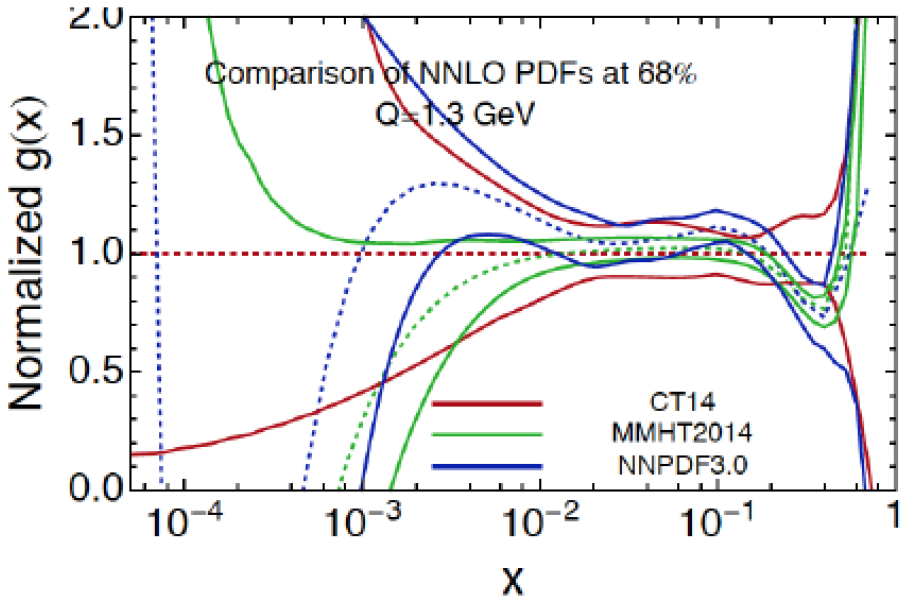
11:40h **HERAPDF plans**
Amanda Cooper-Sarkar

http://benasque.org/2015lhc/cgi-bin/talks/allprint.pl

PDF4BSM
Parton Distributions in the Higgs Boson Era

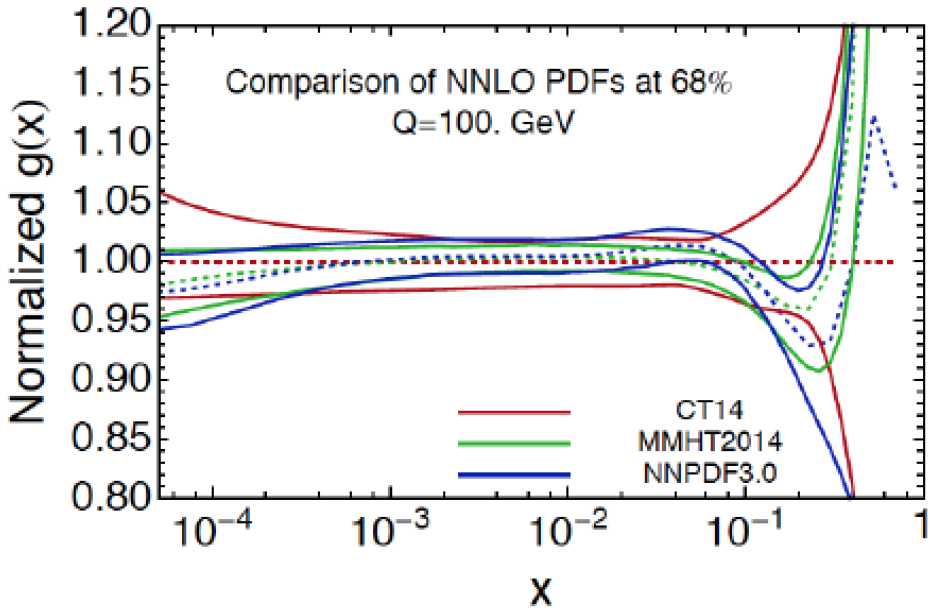
erc
European Research Council

Updated PDFs



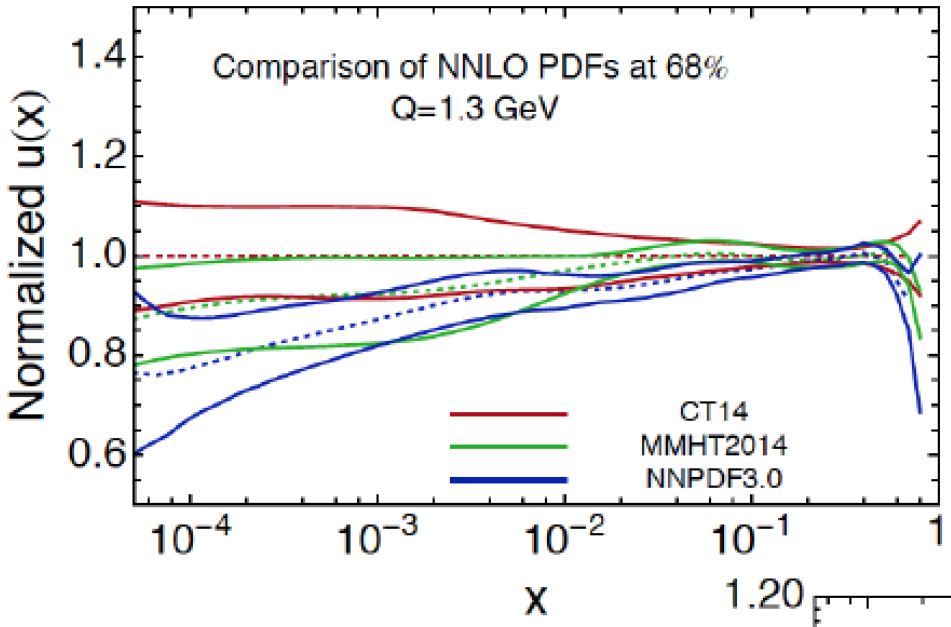
Slides from J. Huston
FNAL seminar last week

good agreement of CT14, MMHT14 and NNPDF3.0 within uncertainty bands

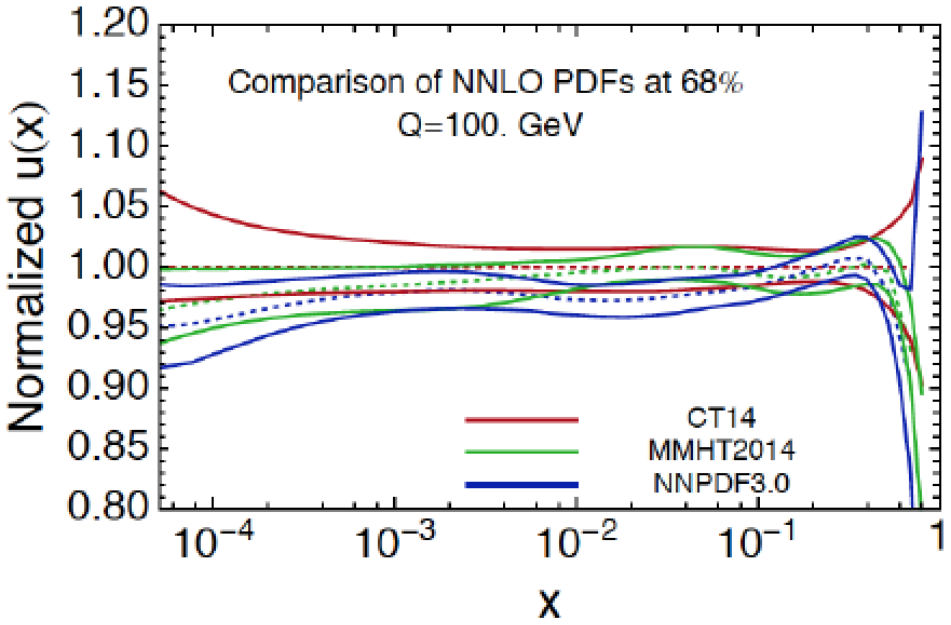


- New data added
- Partially new parameterization,
- Correcting some numerical problems in the global fit
- All sorts of improvements…

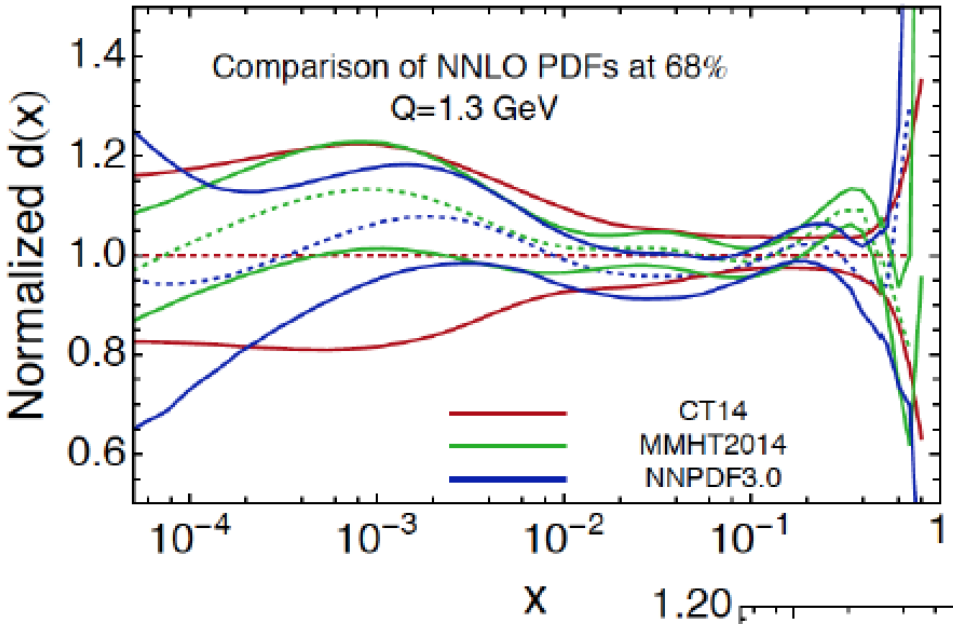
Updated PDFs

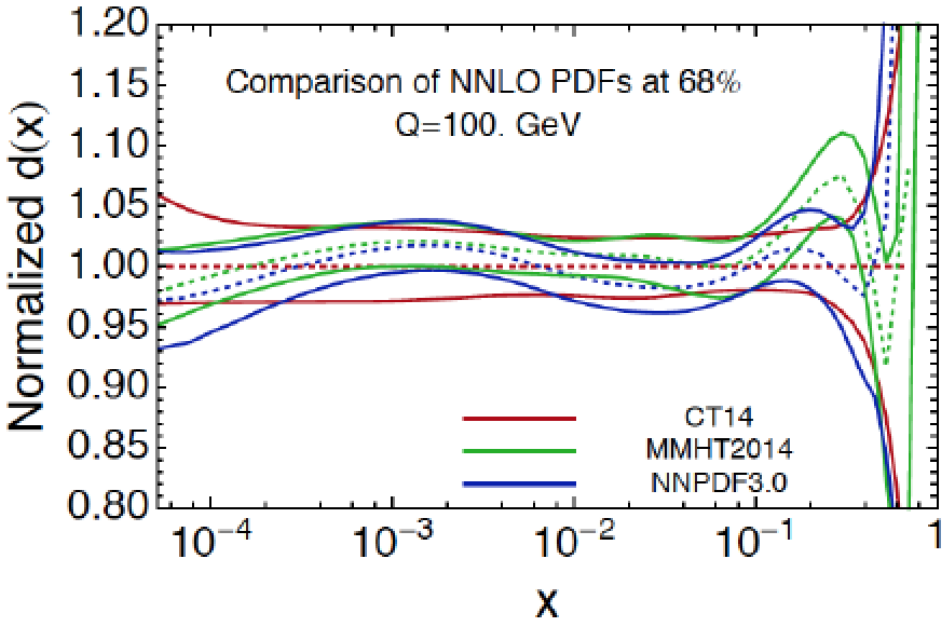


some differences showing up with NNPDF3.0 at low x

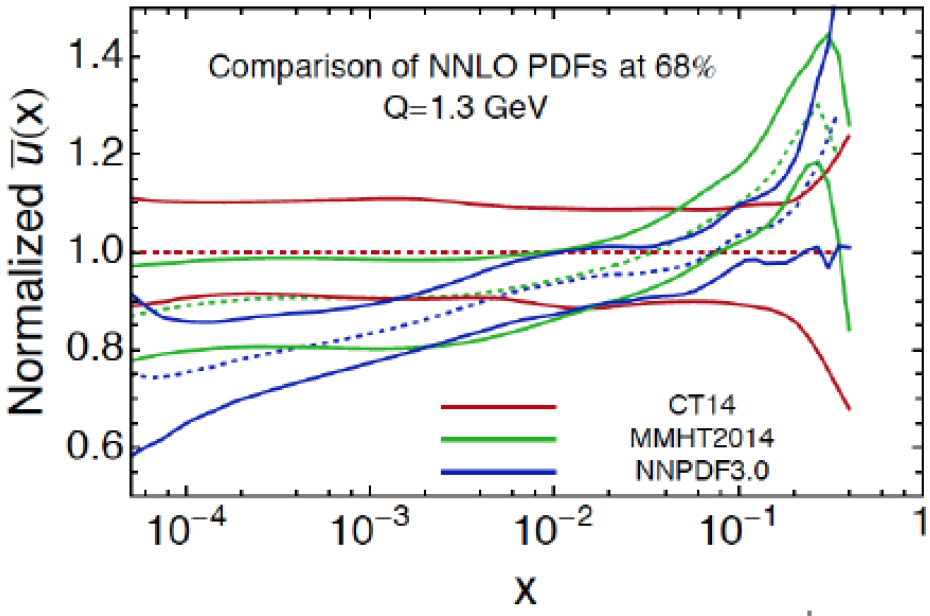


Updated PDFs

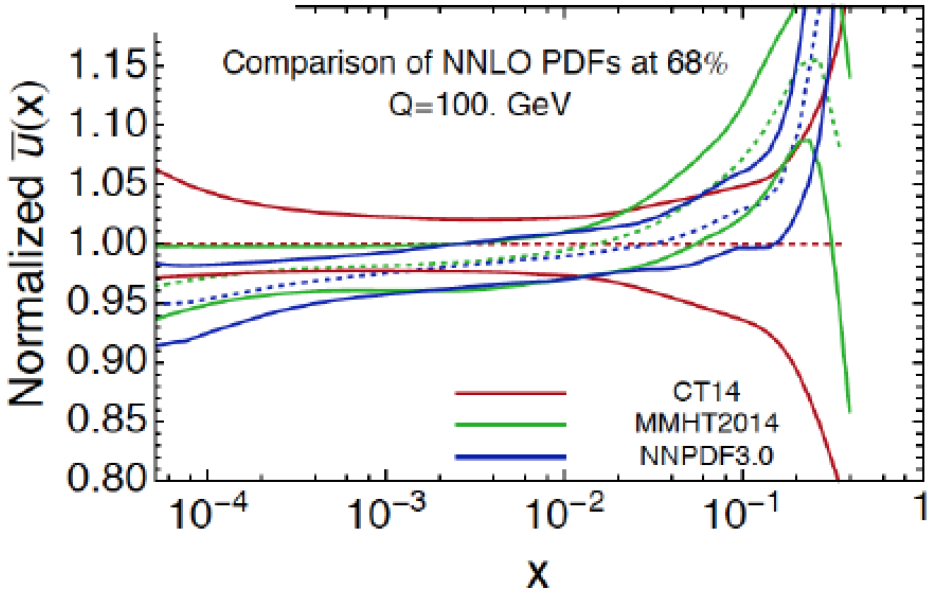




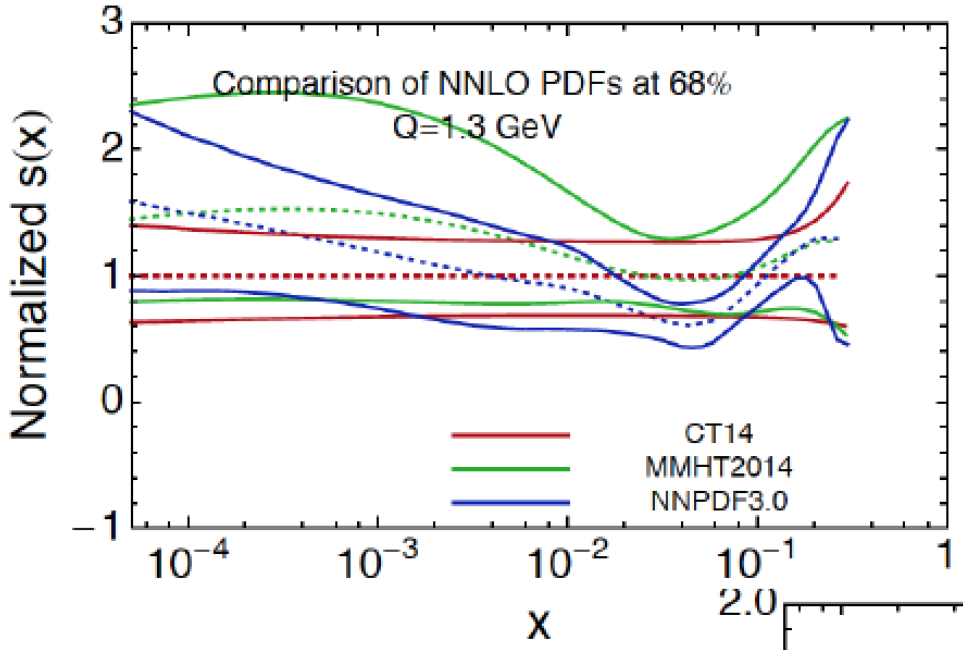
Updated PDFs



some differences at low x

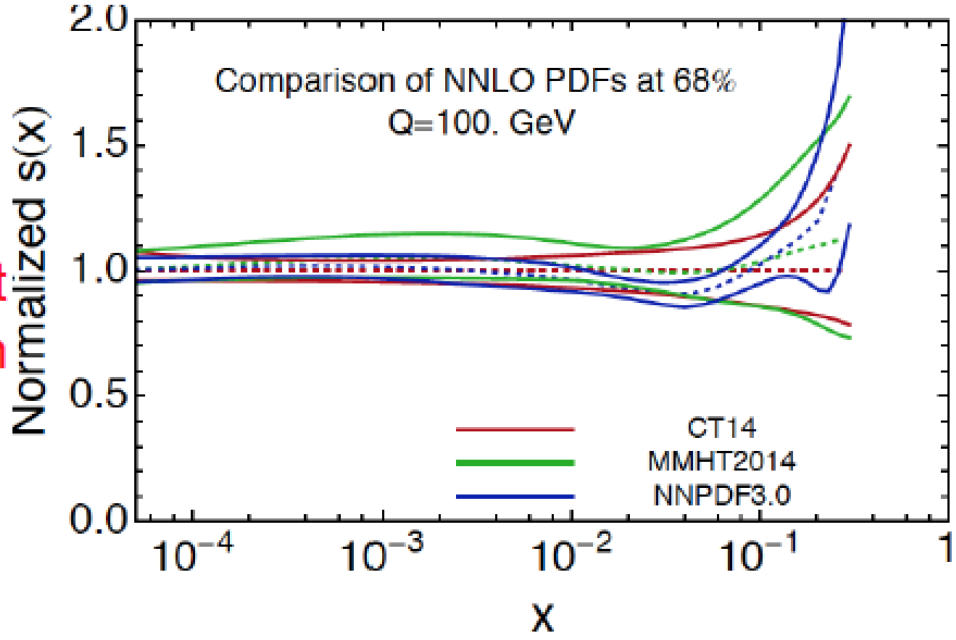


Updated PDFs

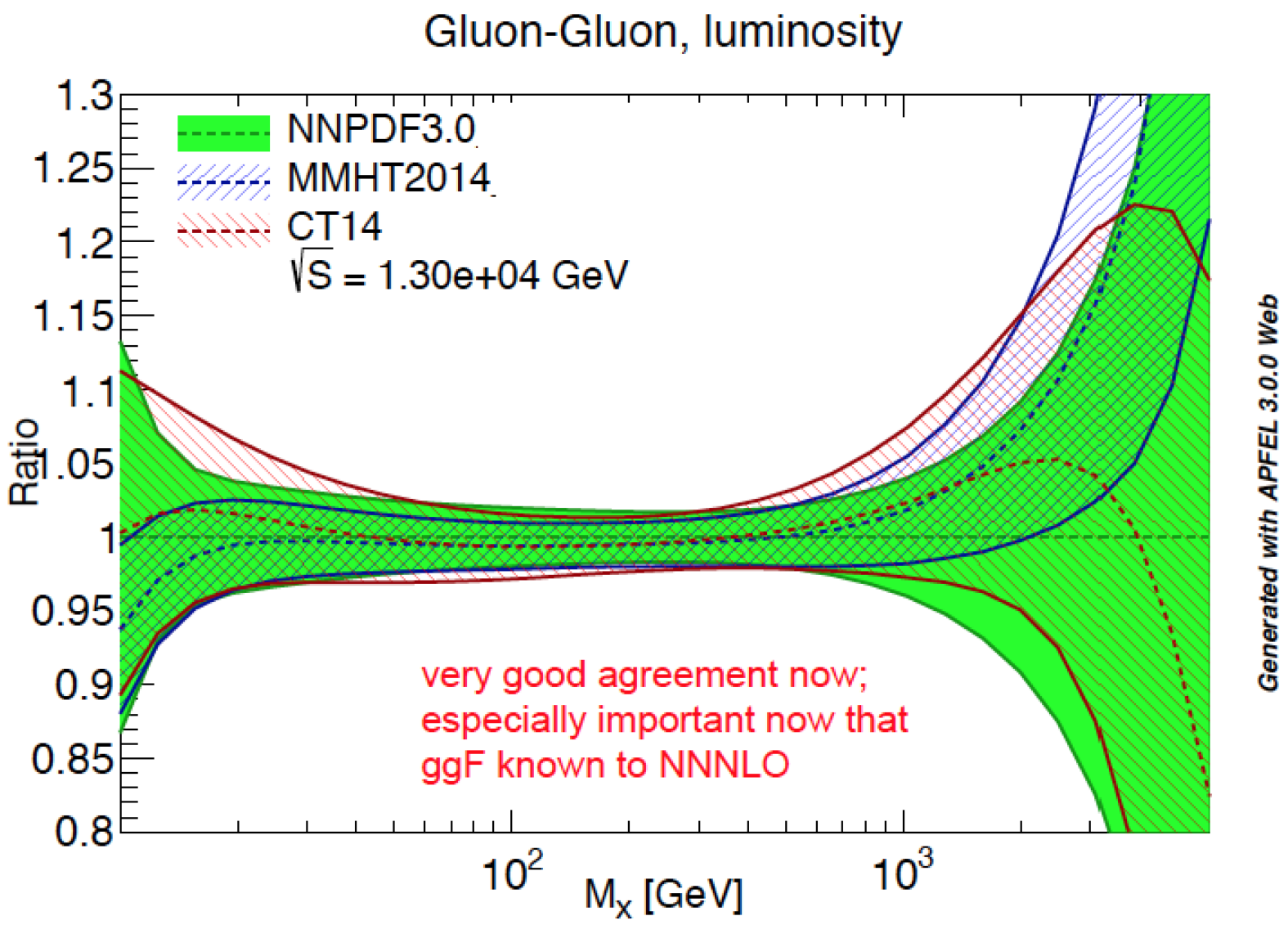


strange quark comparable to NNPDF3.0 at x~few X 10^{-2} at low Q

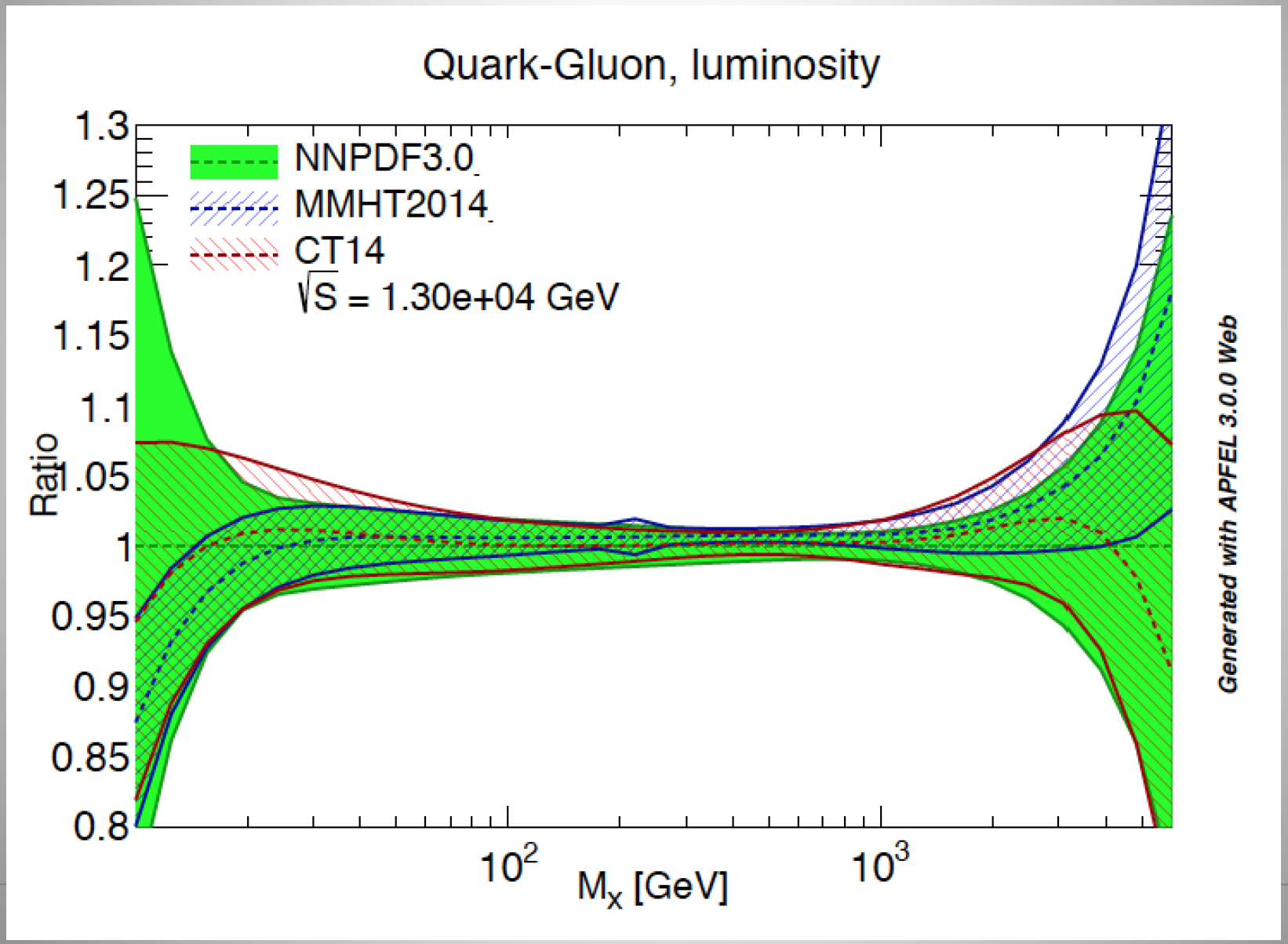
strange quark distribution for CT14 lower than CT10 central value for x>0.01 but consistent with CT10 within uncertainties



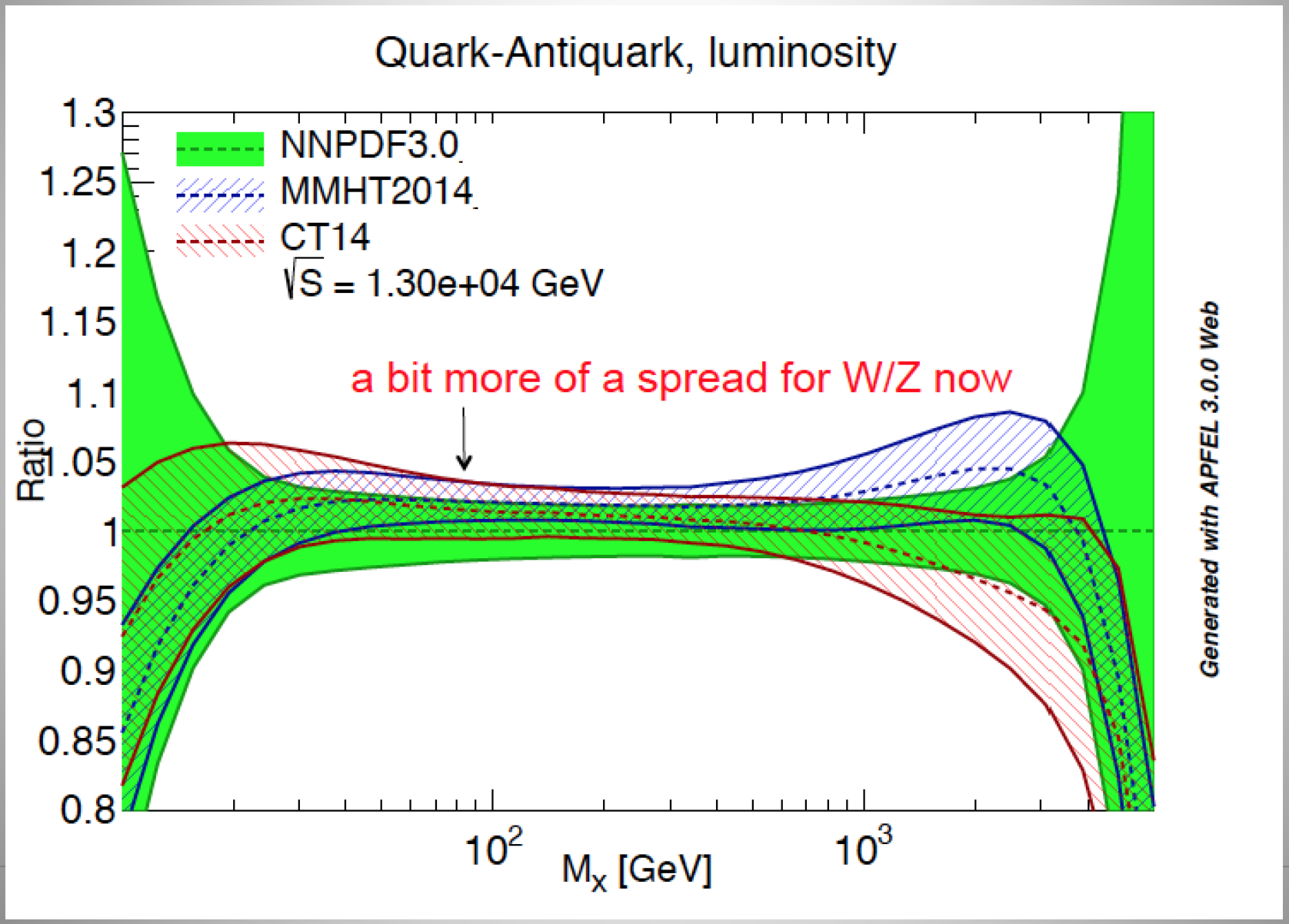
PDF Comparisons



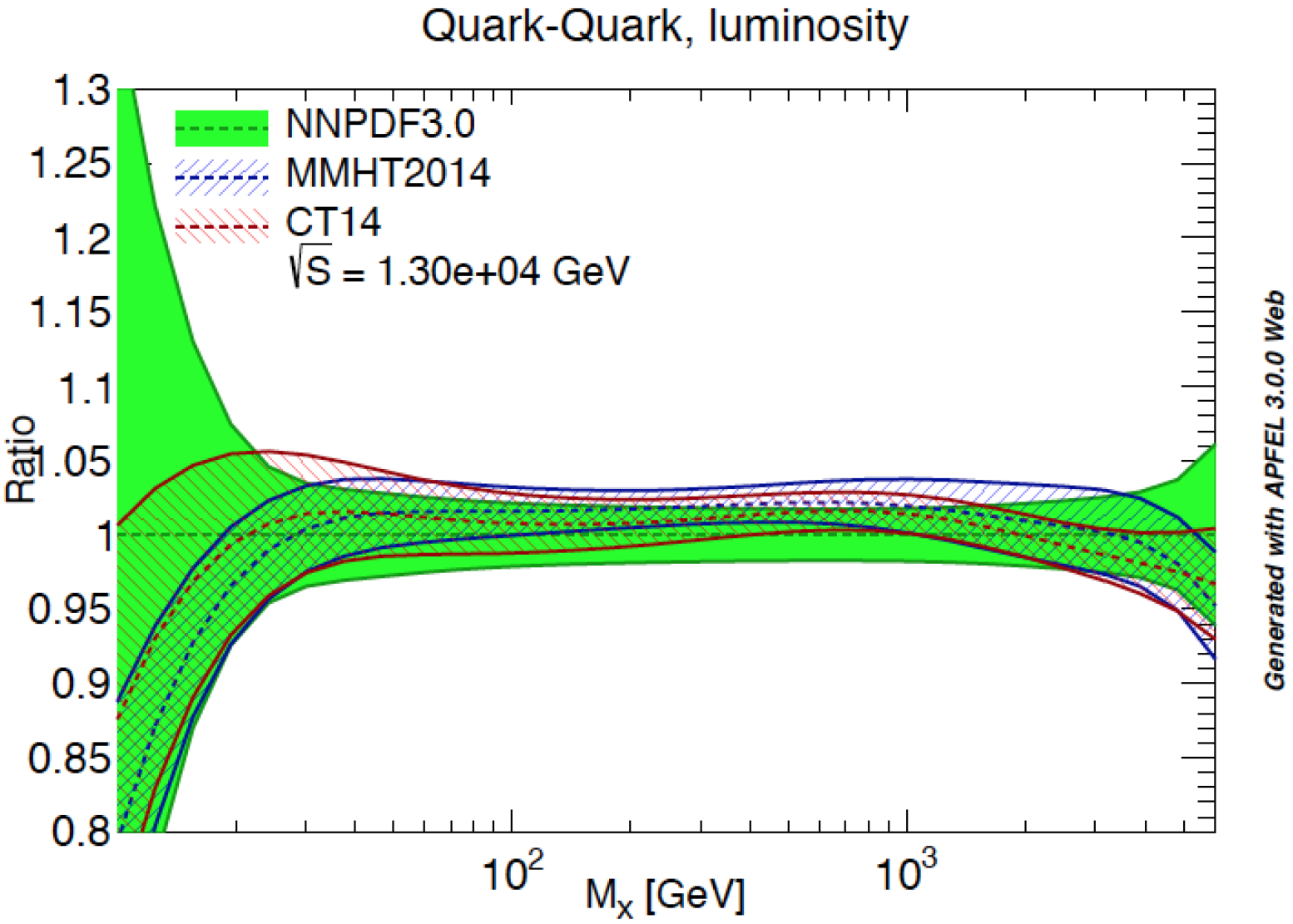
PDF Comparisons



PDF Comparisons



PDF Comparisons



NNLO ggF Higgs Cross Section

	CT14	MMHT2014	NNPDF3.0
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%

J.Huston, PDF4LHC, April 2015

- ALMOST PERFECT AGREEMENT BETWEEN GLOBAL PDF FITS
- PDF UNCERTAINTY REDUCED BY A FACTOR 2/3 W.R. TO PREVIOUS COMBINATION
- COMES OUT OF THE BOX, THANKS TO METHODOLOGICAL IMPROVEMENTS

PDF4LHC Recommendation 2010

- In 2010, we carried out an exercise to which all PDF groups were invited to participate
- A comparison of NLO predictions for benchmark cross sections at the LHC (7 TeV) using MCFM with prescribed input files
- Benchmarks included
  - W/Z production/rapidity distributions
  - ttbar production
  - Higgs production through gg fusion
    - masses of 120, 180 and 240 GeV
- PDFs used include CTEQ6.6, MSTW08, NNPDF2.0, HERAPDF1.0 ABKM09, GJR08
- Results summarized in Higgs YR1 and YR2

The PDF4LHC Working Group Interim Report

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

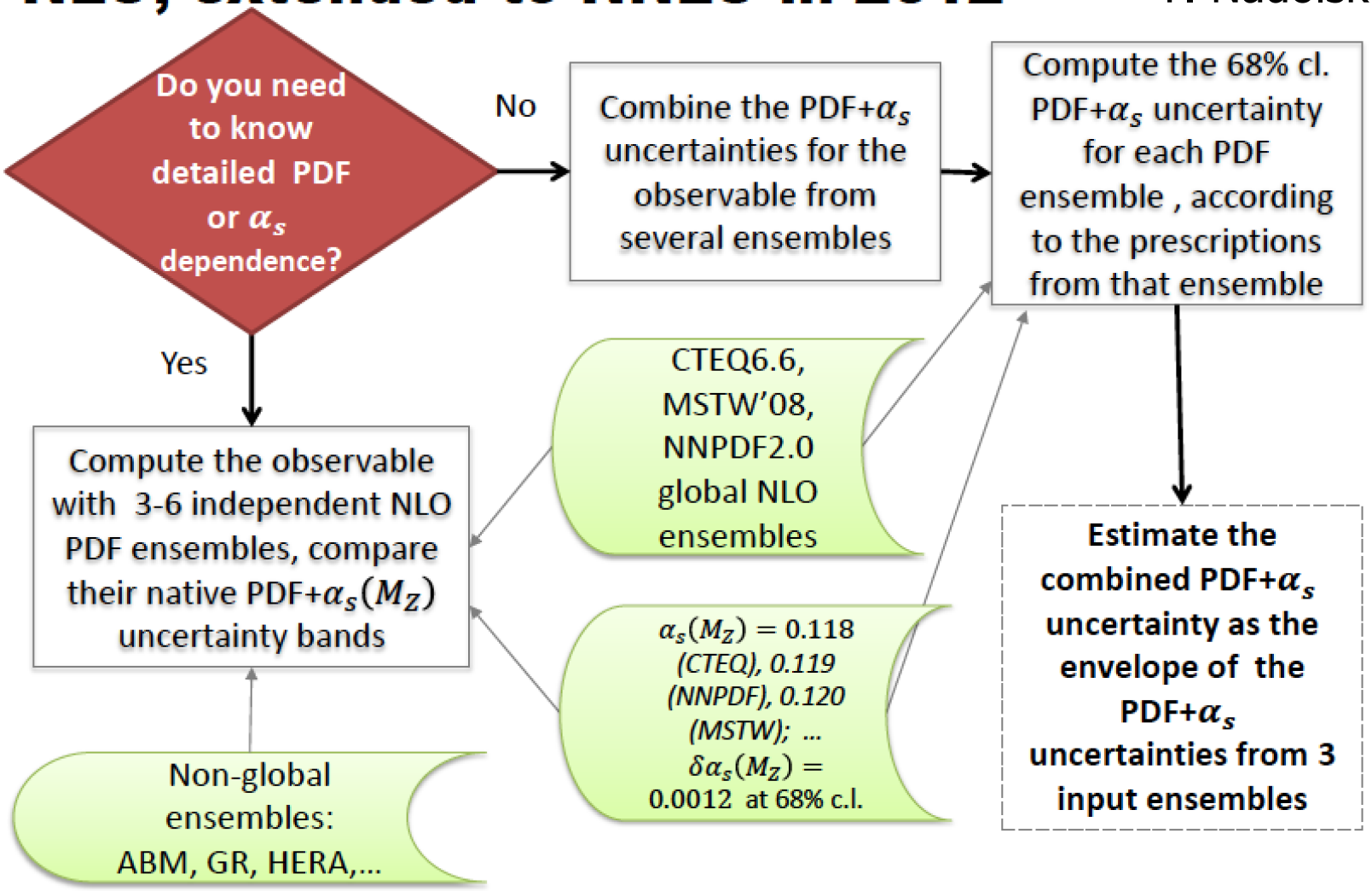
[1] Deutsches Elektronen-Synchrotron, DESY, Platanenallee 6, D-15738 Zeuthen, Germany
[2] Institute for High Energy Physics, IHEP, Pobeda 1, 142281 Protvino, Russia
[3] School of Physics and Astronomy, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland
[4] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg i. B., Germany
[5] NIKHEF, Science Park, Amsterdam, The Netherlands
[6] Department of Physics and Astronomy, University College, London, WC1E 6BT, UK
[7] Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
[8] Department of Physics, Oxford University, Denys Wilkinson Bldg, Keble Rd, Oxford, OX1 3RH, UK
[9] CERN, CH-1211 Genève 23, Switzerland; Antwerp University, B-2610 Wilrijk, Belgium; University of California Davis, CA, USA
[10] CEA, DSM/IRFU, CE-Saclay, Gif-sur-Yvette, France
[11] Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy
[12] Deutsches Elektronensynchrotron DESY Notkestraße 85 D–22607 Hamburg, Germany
[13] Physics and Astronomy Department, Michigan State University, East Lansing, MI 48824, USA
[14] Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland
[15] Taipei Municipal University of Education, Taipei, Taiwan
[16] School of Physics, University College Dublin Science Centre North, UCD Belfield, Dublin 4, Ireland
[17] Department of Physics, Southern Methodist University, Dallas, TX 75275-0175, USA
[18] Physikalisches Institut, Universität Heidelberg Philosophenweg 12, D–69120 Heidelberg, Germany
[19] Department of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, S-223 62 Lund, Sweden
[20] Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
[21] Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany
[22] Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

All of the benchmark processes were to be calculated with the following settings:

1. at NLO in the $\overline{MS}$ scheme
2. all calculation done in a the 5-flavor quark ZM-VFNS scheme, though each group uses a different treatment of heavy quarks
3. at a center-of-mass energy of 7 TeV
4. for the central value predictions, and for $\pm 68\%$ and $\pm 90\%$ c.l. PDF uncertainties
5. with and without the α_s uncertainties, with the prescription for combining the PDF and α_s errors to be specified
6. repeating the calculation with a central value of $\alpha_s(m_Z)$ of 0.119.

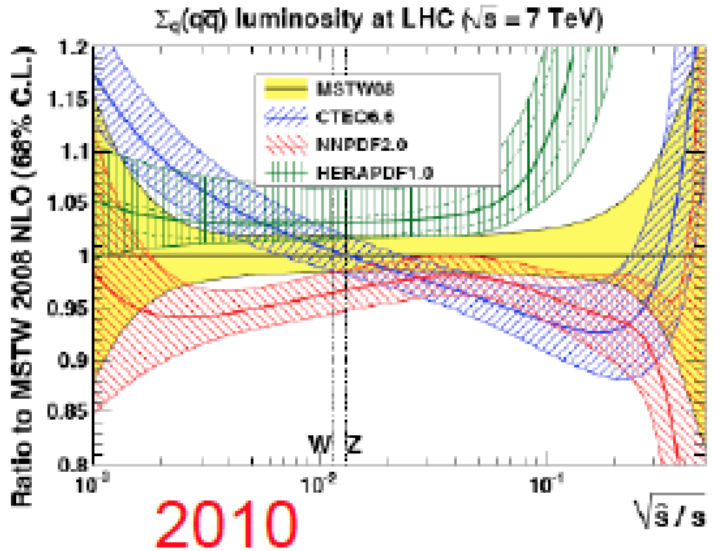
Use CTEQ6.6, MSTW, MSTW08 for PDF uncertainty calculations

PDF4LHC Recommendation 2010

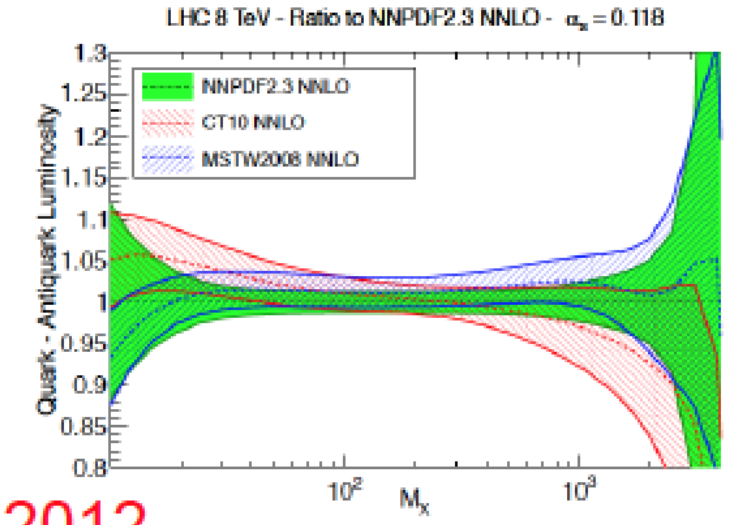


PDF Evolution

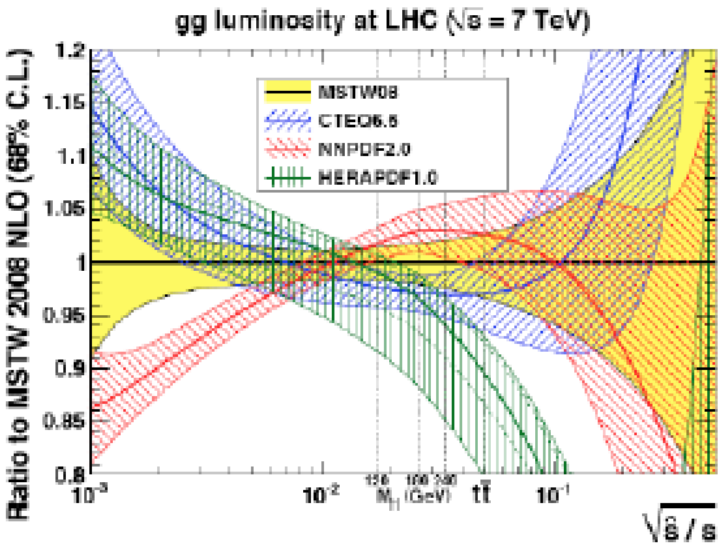
- …with additional data and in going from NLO to NNLO (and other theory improvements)

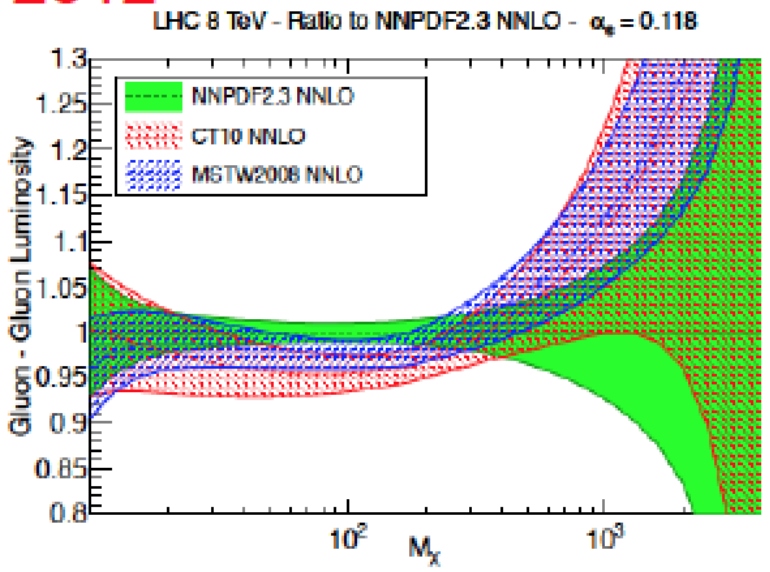


2010



2012





Adapted Recommendation (2013)

On PDF4LHC web page: http://www.hep.ucl.ac.uk/pdf4lhc/

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

Updated Recommendation

- Criticism: use of only 3 PDF (motivated in arXiv:1101.0538)
- Criticism: complicated for the user, having to make the envelope for each observable. Some signal programs are not adapted well to do that in an efficient way.
- Criticism: not statistically rigorous/robust
- Response: Use the transition from Run-I to Run-II for a more statistically rigorous procedure. Ideas developed in o.a. Forte arXiv:1011.5247, G Watt PDF4LHC meeting 4/2013
- Idea: create a “combined-PDF” set based on N input PDFs with its uncertainty band, using the MC replica method. This is what the user can use directly. Correlations between the PDFs should be kept. The user should have a simple procedure.
- Compress the set to reduce the number of replicas

Updated Recommendation

- In principle N can be larger than 3, ie it can allow for more PDFs that the 3 sets used before to enter in such a ‘combination’
- In practice one has to study this carefully. So far we have used only the ‘global fitted’ PDFs from the previous envelope. When new sets are included that do not contain all available experimental data in the fits, we will (likely) have to use some weighting procedure in the combination.
- Hence we start the first set of these ‘Combined-PDFs’ including CT, MMTH and NNPDF. HERAPDF could be next to be included.
- Minimum requirements for PDFs to be considered in the combination, see https://indico.cern.ch/event/377812

Basic inputs for the Combination

- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (preliminary) To be released soon
- HERAPDF2.0 (preliminary) Not yet included
- Except for HERAPDF, all include data from the LHC, such as
  - inclusive jet->need full cross section at NNLO but corrections look to be small if scale of p_T^{jet} used
  - Drell-Yan
  - tT cross sections->need differential cross sections at NNLO (and EW corrections) to make full use of data
- HERAPDF2.0 includes the HERA2 combined data (not available for the other PDFs yet)
- Typically other improvements as well, such as in parametrizations

Combining Procedures

Two methods for combination of PDFs were extensively compared, with promising results:

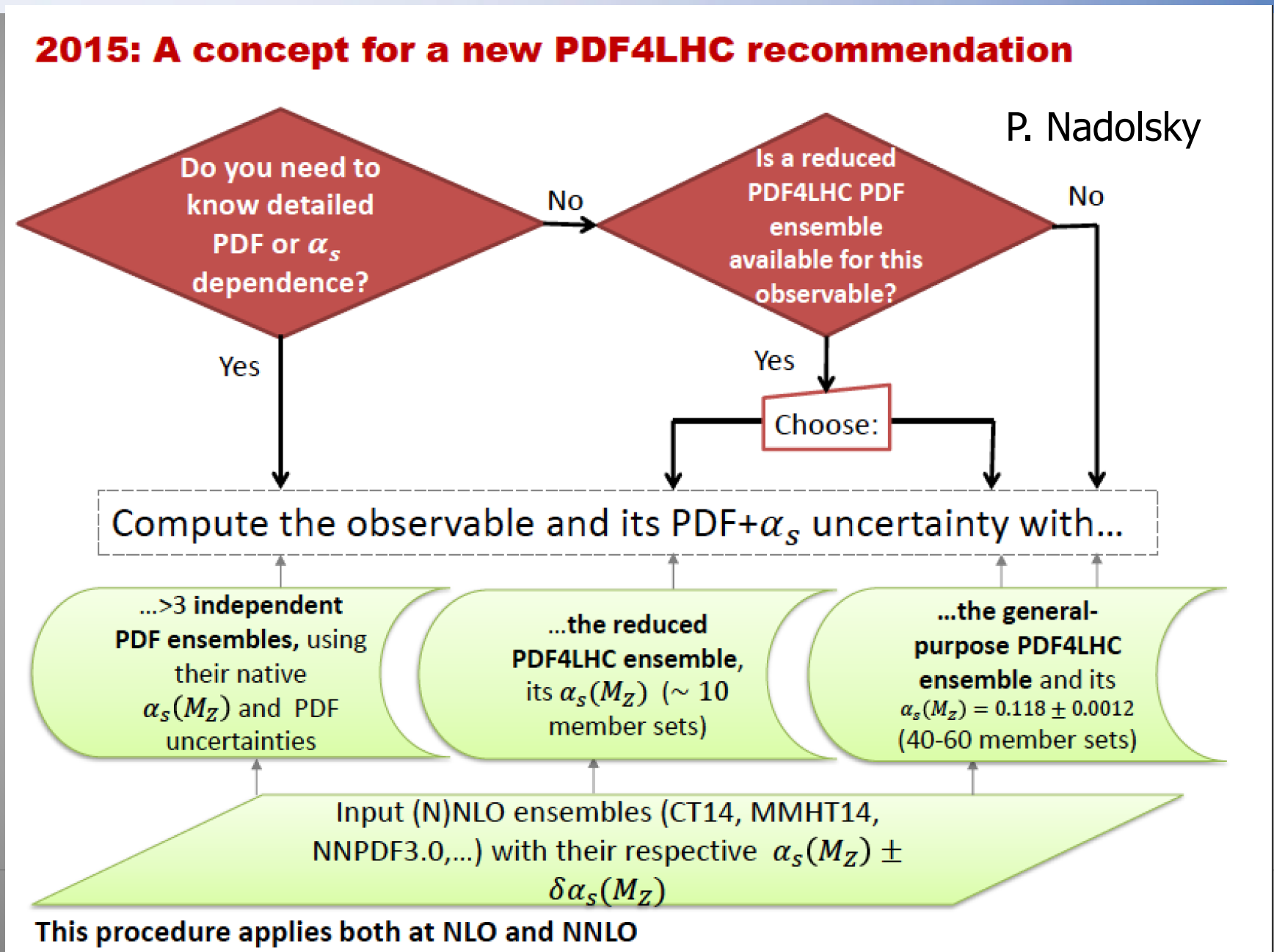
1. **Meta-parametrizations + MC replicas + Hessian data set diagonalization** (J. Gao, J. Huston, P. Nadolsky, 1401.0013)

2. Compression of Monte-Carlo replicas (Carazza, Latorre, Rojo, Watt, 1504:06469)

Both procedures start by creating a combined ensemble of MC replicas from all input ensembles (G. Watt, R. Thorne, 1205.4024; S. Forte, G. Watt, 1301.6754). They differ at the second step of reducing a large number of input MC replicas (~300) to a smaller number for practical applications (13-100 in the META approach; 40 in the CMC approach). The core question is how much input information to retain in the reduced replicas in each Bjorken-x region.

- See for example the presentation and discussion from PDF4LHC meeting
  - https://indico.cern.ch/event/355287/other-view?view=standard
- …and Pavel Nadolsky's talk at DIS2015
  - https://indico.cern.ch/event/341292/session/11/contribution/265

Updated Recommendation



Meta-PDFs

META1.0 PDFs: A working example of a meta-analysis
See arXiv:1401.0013 for details

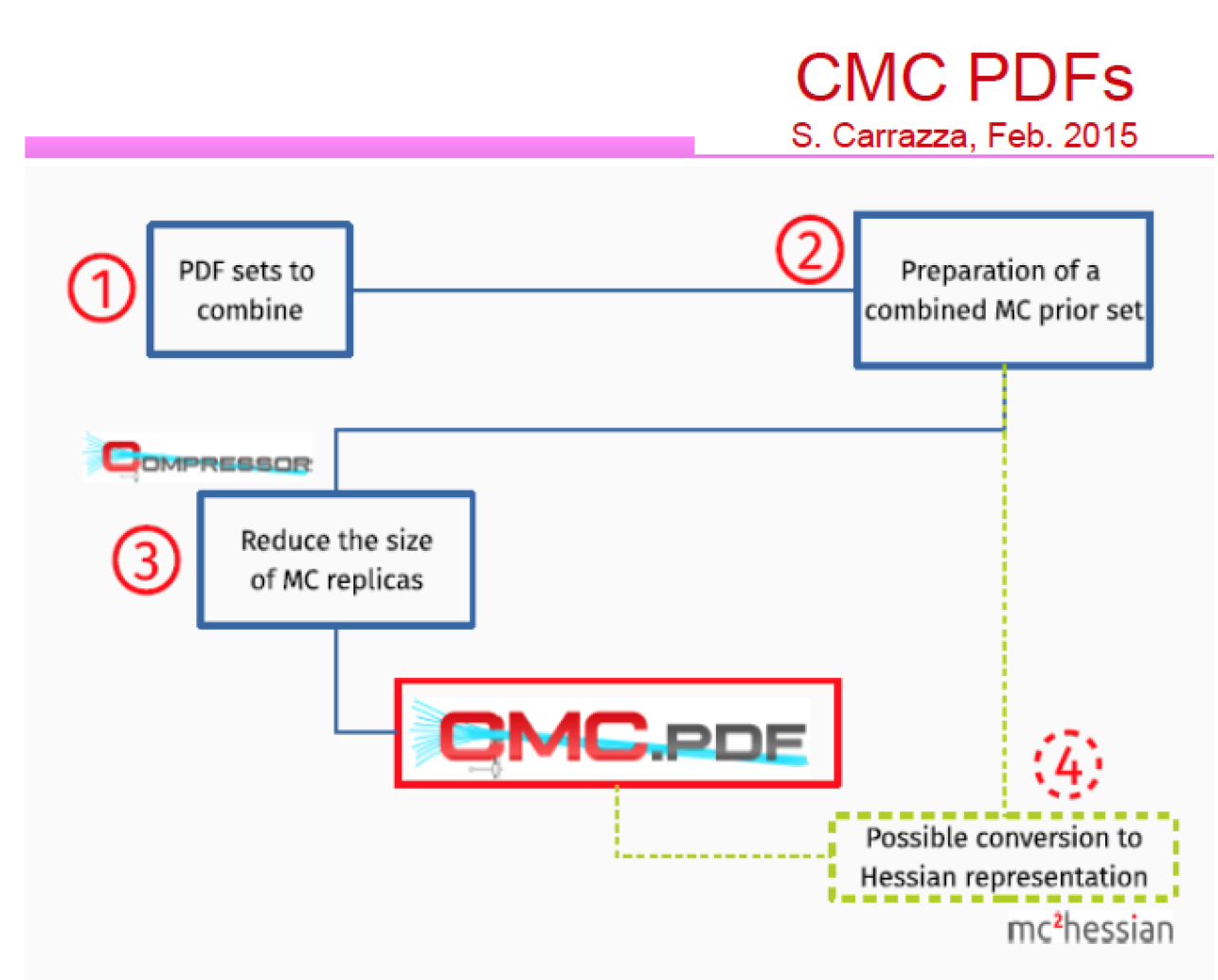
1. Select the input PDF ensembles (CT, MSTW, NNPDF…)
2. Fit each PDF error set in the input ensembles by a common functional form ("**a meta-parametrization**")
3. Generate many Monte-Carlo replicas from meta-parametrizations of each set to investigate the probability distribution on the ensemble of all meta-parametrizations (as in Thorne, Watt, 1205.4024)
4. Construct a final ensemble of 68% c.l. **Hessian eigenvector sets** to propagate the PDF uncertainty from the combined ensemble of replicated meta-parametrizations into LHC predictions.

Only in the META set

CMC-PDFs

Compressed Monte Carlo PDFs (a la NNPDF)

arXiv:1504.06469



Compression Strategy

THE COMPRESSION STRATEGY

CMC PDFs

S. Carrazza, Feb. 2015

https://indico.cern.ch/event/377812

We define **statistical estimators** for the MC prior set:

1. **moments:** central value, variance, skewness and kurtosis
2. **statistical distances:** the Kolmogorov distance
3. **correlations:** between flavors at multiple x points

These estimators are them **compared** to subsets of replicas **interactively** driven by an *error function*, i.e.

$$\mathrm{ERF}_{\mathrm{tot}} = \sum_n \frac{1}{N_n} \sum_i \left(\frac{C_i^{(n)} - O_i^{(n)}}{O_i^{(n)}} \right)^2$$

where n runs over the number of statistical estimators and

- N_i is a normalization factor extracted from random realizations
- $O_i^{(n)}$ is the value of the estimator for the prior
- $C_i^{(n)}$ is the corresponding value for the compressed set

Comparisons

Benchmark comparisons of CMC and META PDFs

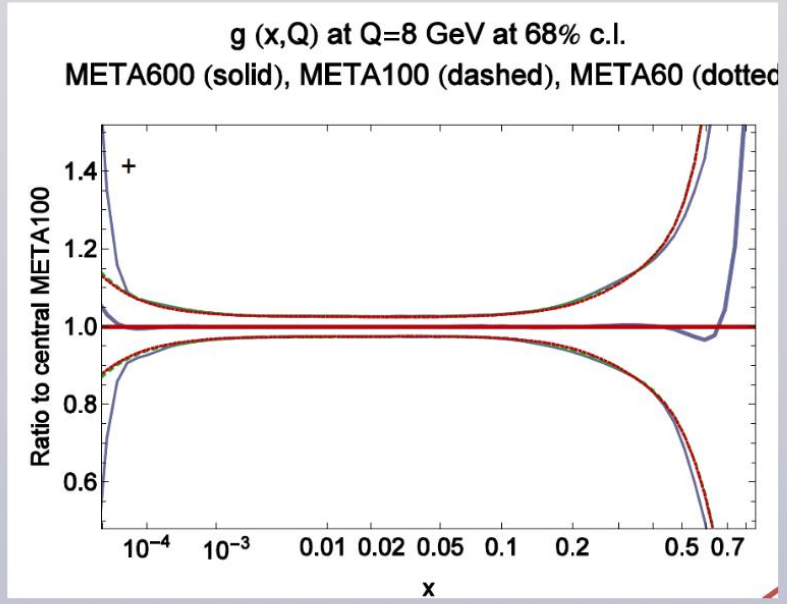
CMC ensembles with 40 replicas and META ensembles with 40-100 replicas are compared with the full ensembles of 300-600 MC replicas.

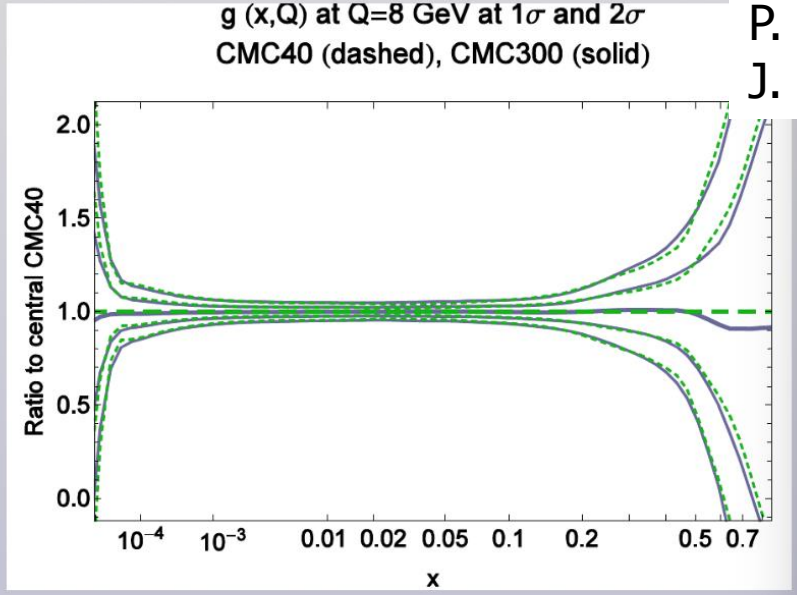
Accuracy of both combination procedures is already competitive with the 2010 PDF4LHC procedure, can be further fine-tuned by adjusting the final number of replicas.

Error bands:

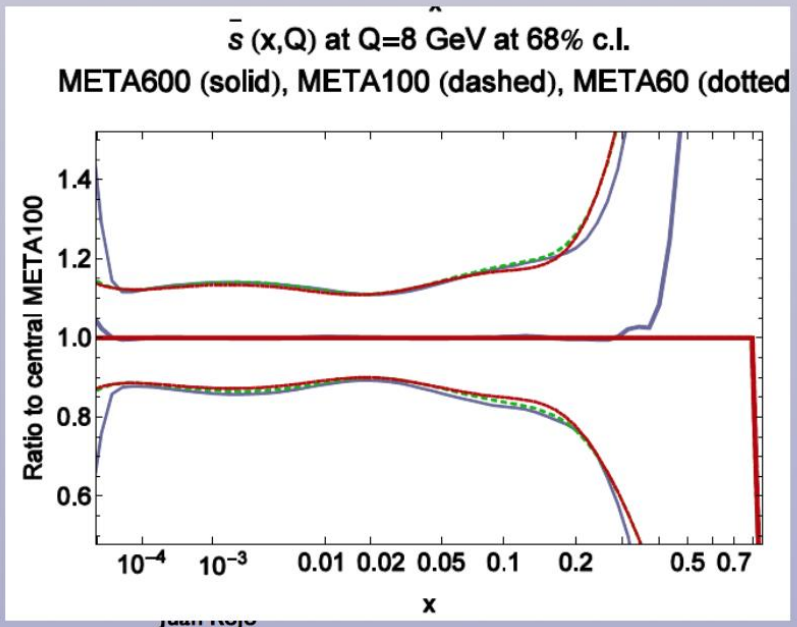
In the (x, Q) regions covered by the data, the agreement of 68%, 95% c.l. intervals is excellent. The definition of the central PDFs and c.l. intervals is ambiguous in extrapolation regions, can differ even within one approach. E.g., differences between mean, median, mode “central values”.

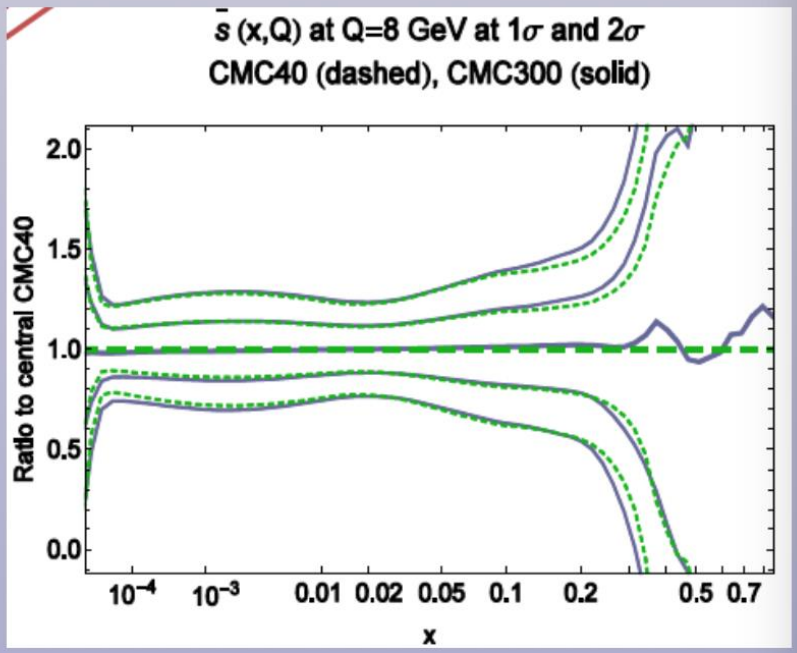
Compressions



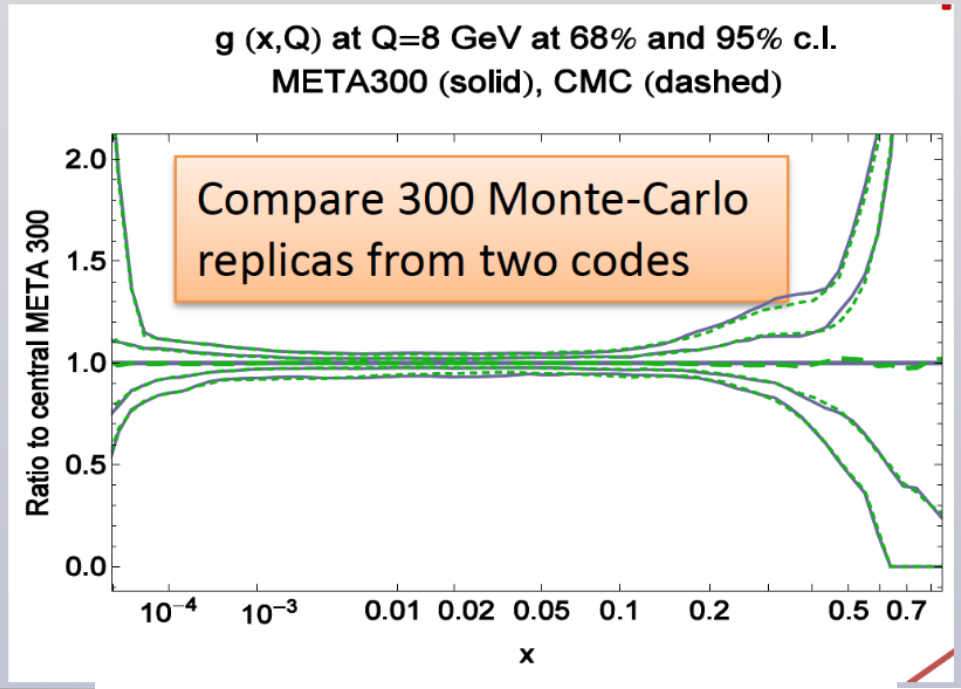


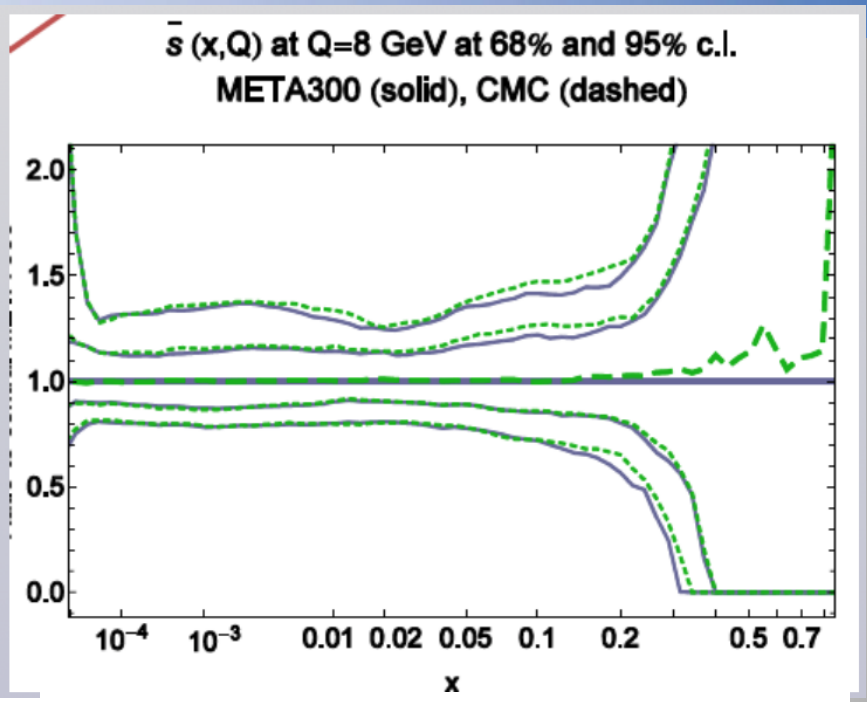
P. Nadolsky,
J. Rojo et al.

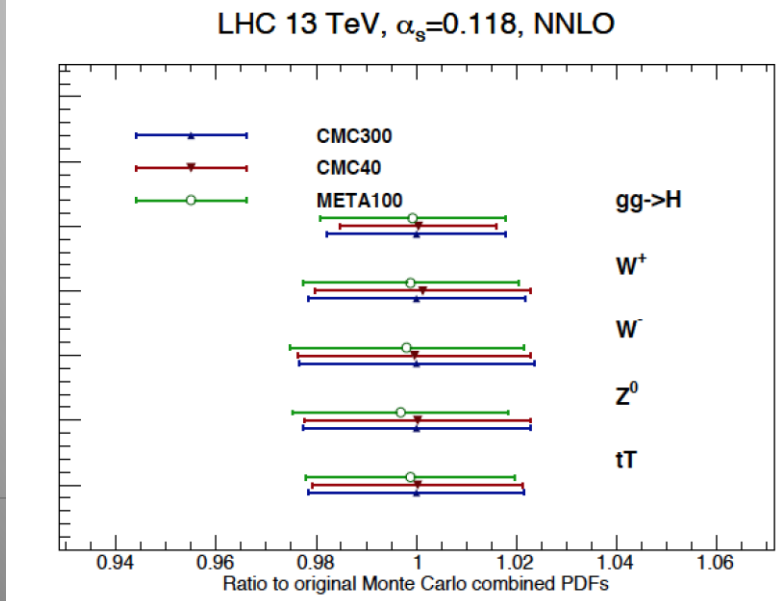


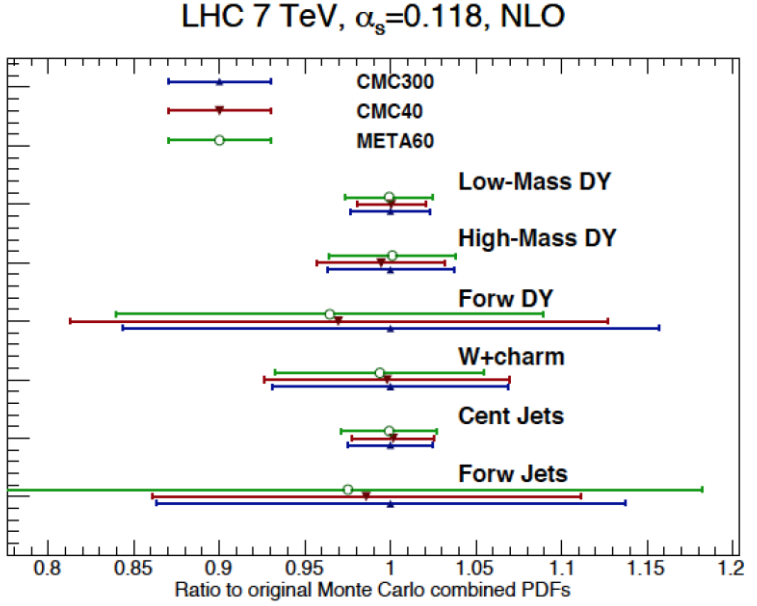


Comparisons







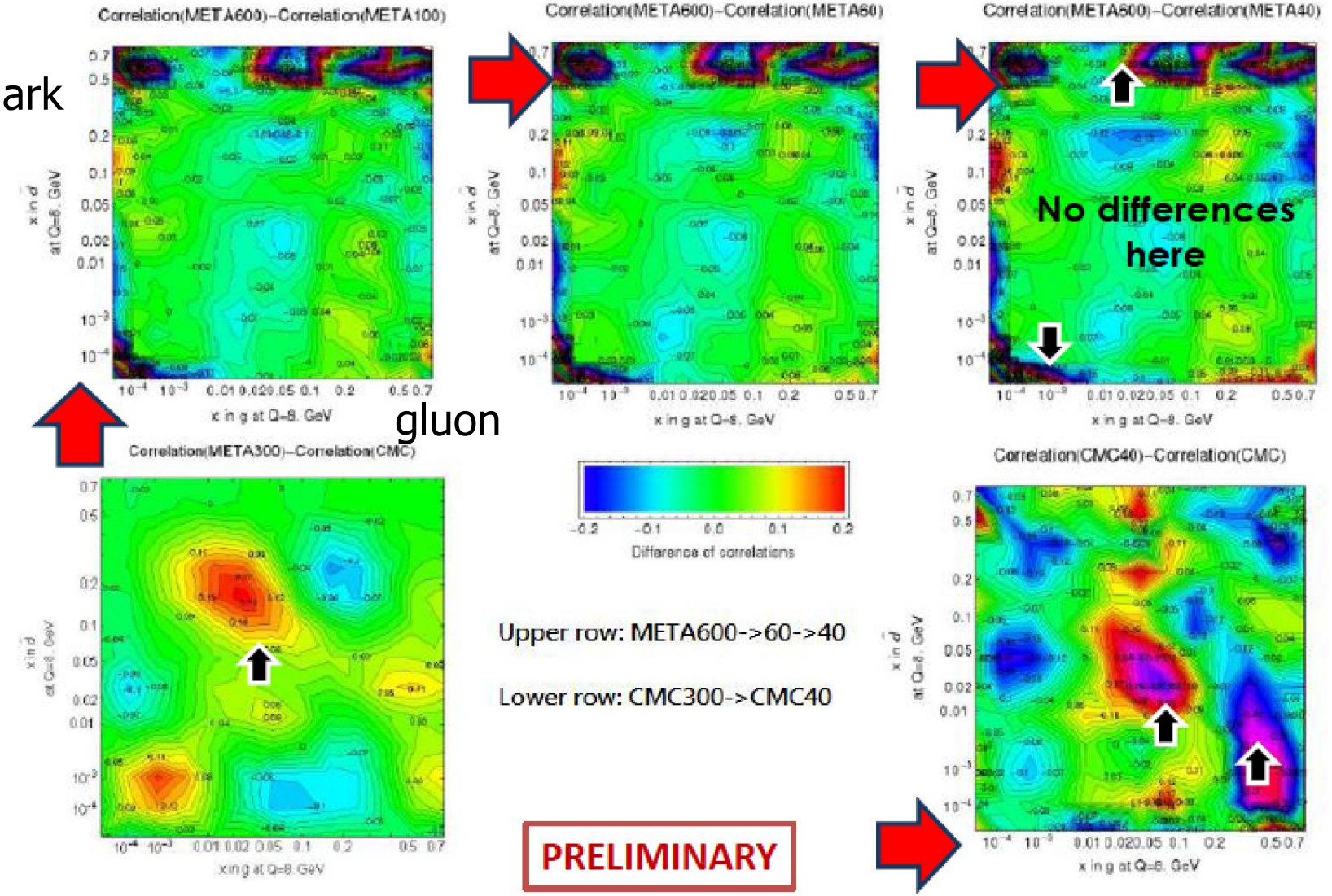


PDF-PDF Correlations

P. Nadolsky DIS2015

PDF-PDF correlation, example: $\bar{d}(x,Q)$ vs $g(x,Q)$ at $Q = 8\ GeV$

Anti d-quark



Documentation (in prep.)

preprint numbers

PDF4LHC recommendations for Run 2

Author list

Author affiliation list

Abstract:

A new generation of PDFs has been recently developed, including for the first time, in many cases, data from Run 1 at the LHC. With the advent of Run 2, and of the data at higher energies/luminosities, it is important to re-visit the PDF4LHC recommendations for PDF+$\alpha_s(m_Z)$ uncertainties, taking into account this new generation of PDFs. This document presents the updated recommendations in standard form, and in the newly developed META- and CMC-PDF formats.

Expected in June/July

The PDF4LHC report on PDFs and LHC data: Results from Run I and preparation for Run II

The PDF4LHC Working Group: Juan Rojo[1], Albert de Roeck (eds.), Richard D. Ball, Amanda Cooper-Sarkar[2], Stephen Farry, Joey Huston, Maxime Gouzevitch[3], Claire Gwenlan[2], Katerina Lipka, Pavel Nadolsky, Robert Thorne, ...

[1] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
[2] *Particle Physics, Department of Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
[3] *Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

Abstract

The accurate determination of the Parton Distribution Functions (PDFs) of the proton is an essential ingredient of the Large Hadron Collider (LHC) program. PDF uncertainties impact a wide range of processes, from Higgs boson characterization and precision Standard Model measurements, to New Physics searches. A major development in modern PDF fits has been the inclusion of a wealth of measurements from the LHC. In this report we summarise the information that PDF-sensitive measurements at the LHC Run I have provided, and then we review the prospects for the corresponding measurements at Run II. We also present an overview of those studies that have quantified the information on PDFs provided by LHC data. This document should provide useful input to the LHC collaborations to prioritize their PDF-sensitive measurements at Run II, and will also provide a comprehensive set of references for the PDF fitting collaborations.

Selection of PDF ensembles for the 2015 CMC and META PDFs

Draft, by PDF4LHC group

The PDF4LHC group provides a recommendation on how to combine PDF ensembles that are publicly available in LHAPDF6, are based only on published data, and are accompanied by a published paper that summarizes the details of the construction of this PDF fit. This note summarizes some of the conditions that simplify inclusion of the PDF ensembles into the PDF4LHC combination.

Summary/Plan

- Status: Two methods available, using different methodology. Eg one can be the baseline, the other used as a cross check. Both will be made available.
- Finalizing tests and discussions still ongoing within the group
- Note is in preparation (plan to circulate in the PDF groups of the experiment for further feedback)
- Plan to release these combined PDFs for use end of June or in July
- Further studies will continue after that eg more thorough study on theoretical errors.
- New sets will be made available as needed by new PDFs added or improved inputs in future

The PDF Landscape

Panorama of PDF representations: