Parton Distributions

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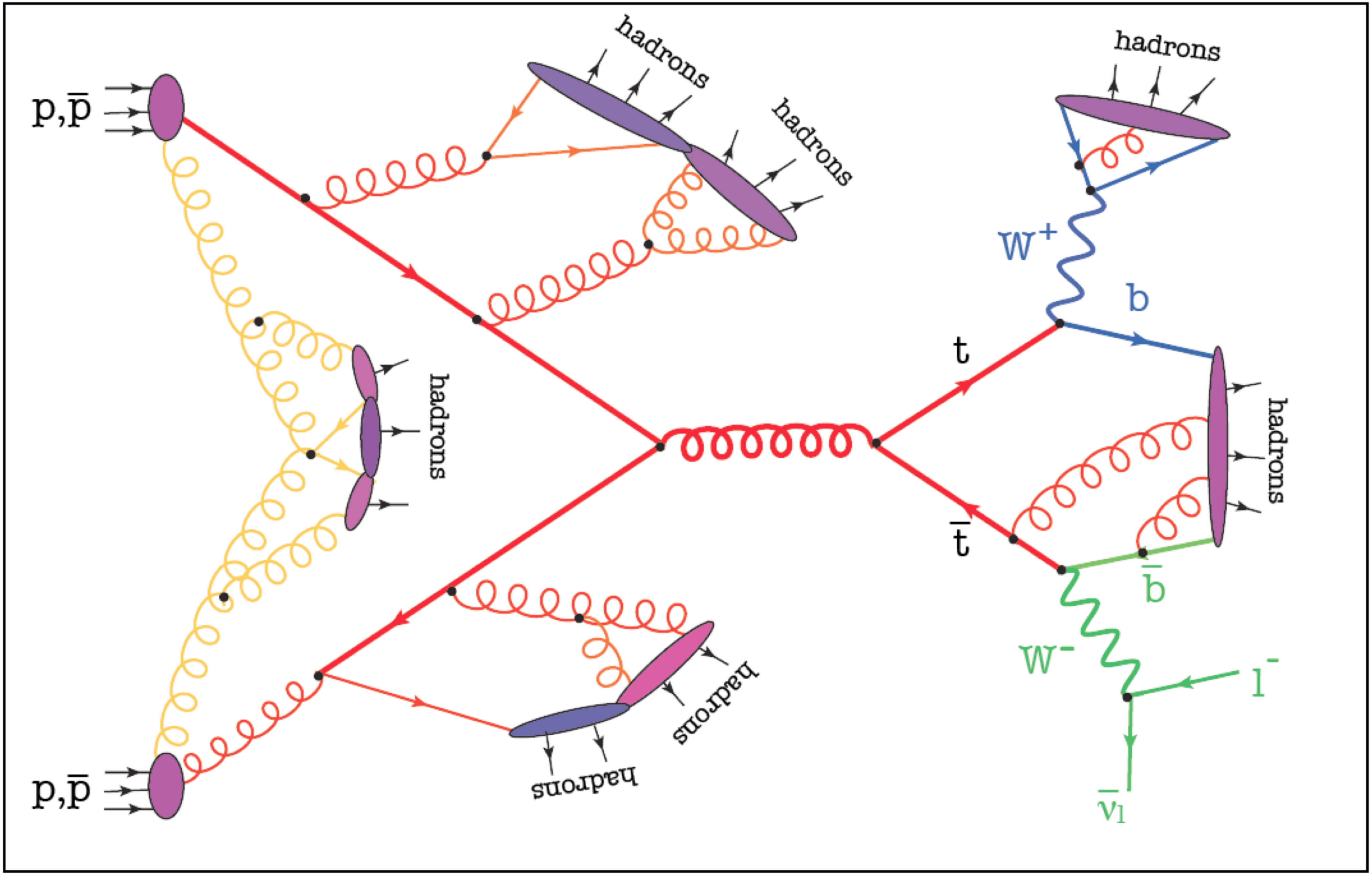
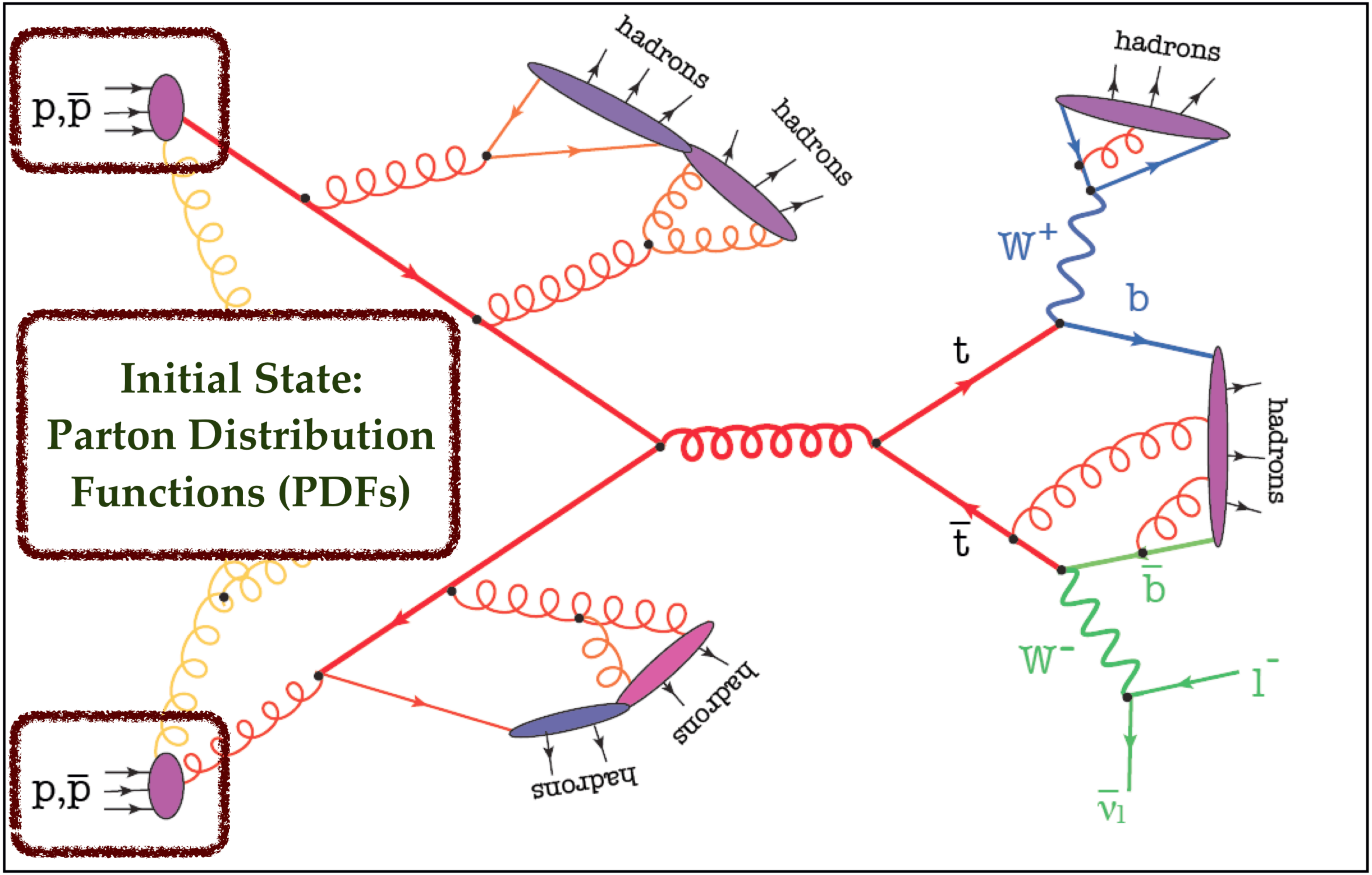
Standard Model at the LHC 2014
CIEMAT, Madrid, 09/04/2013

SM at the LHC in a nutshell



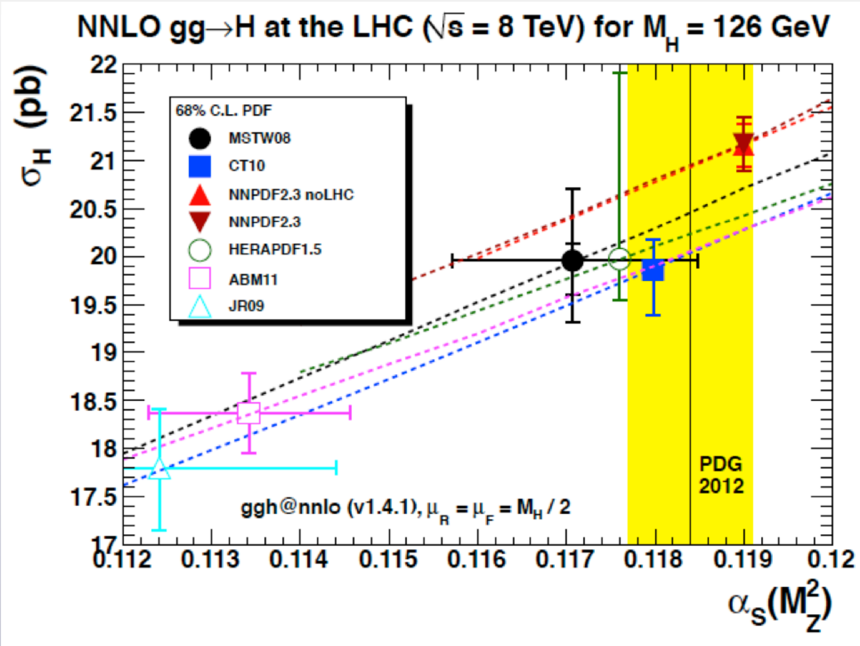
Drawing by K. Hamilton

SM at the LHC in a nutshell



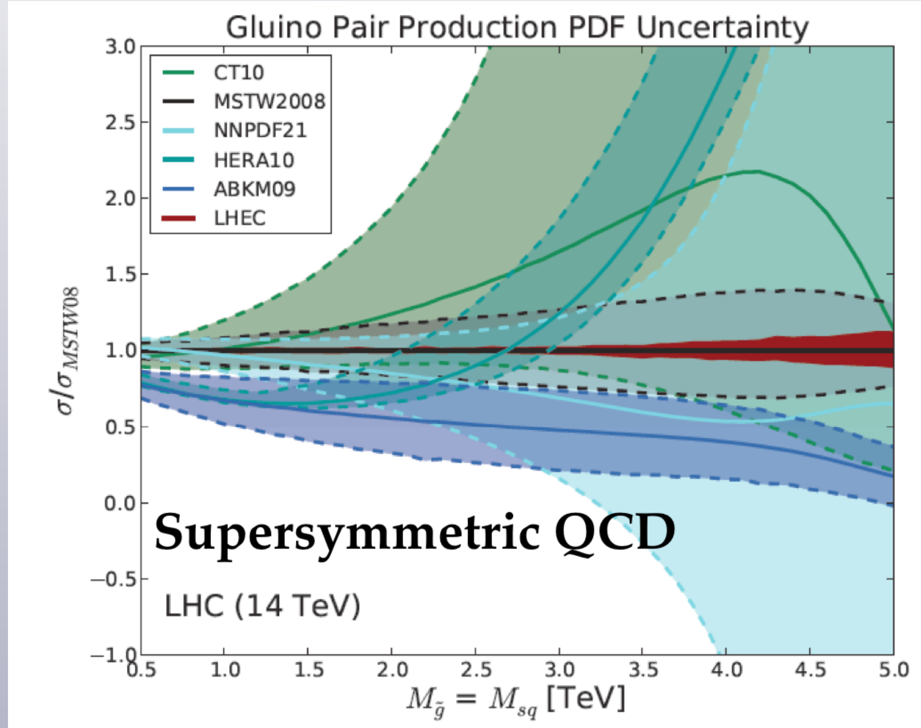
Drawing by K. Hamilton

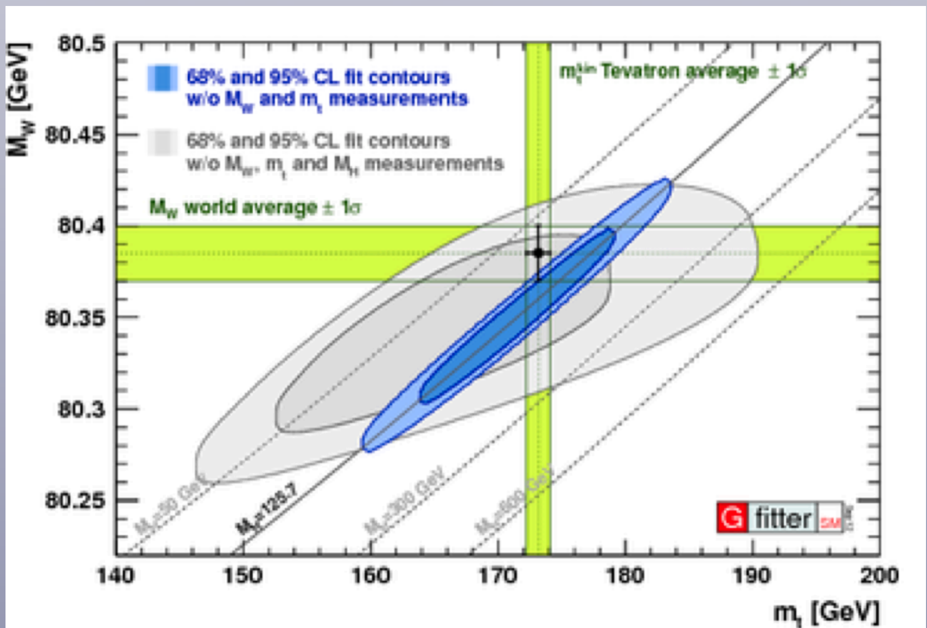
Parton Distributions and LHC phenomenology



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

2) Very large PDF uncertainties (>100%) for new heavy particle production





3) PDFs dominant systematic for precision measurements, like W boson mass, that test internal consistency of the Standard Model

Global PDF analyses

Theory

- ☑ NNLO corrections
- ☑ Jet data in global fits
- ☑ QED and electroweak evolution
- ☑ Heavy quark schemes

Data

- ☑ Inclusive jets and dijets, xsec ratios
- ☑ W+charm
- ☑ Drell-Yan production
- ☑ Top quark data
- ☑ HERAfitter analysis of LHC data

Tools and methodology

- ☑ PDF benchmarking exercises
- ☑ Meta-PDFs
- ☑ Fast interfaces to NLO and NLO+PS

Updates in PDF fits

- **ABM:** ABM12, inclusion of LHC data, ...
- **CT:** intrinsic charm, PDFs for Higgs physics, ...
- **MSTW**: impact of jet data, ...
- **NNPDF:** closure test fitting, NNPDF3.0 release, ...

Global PDF analyses

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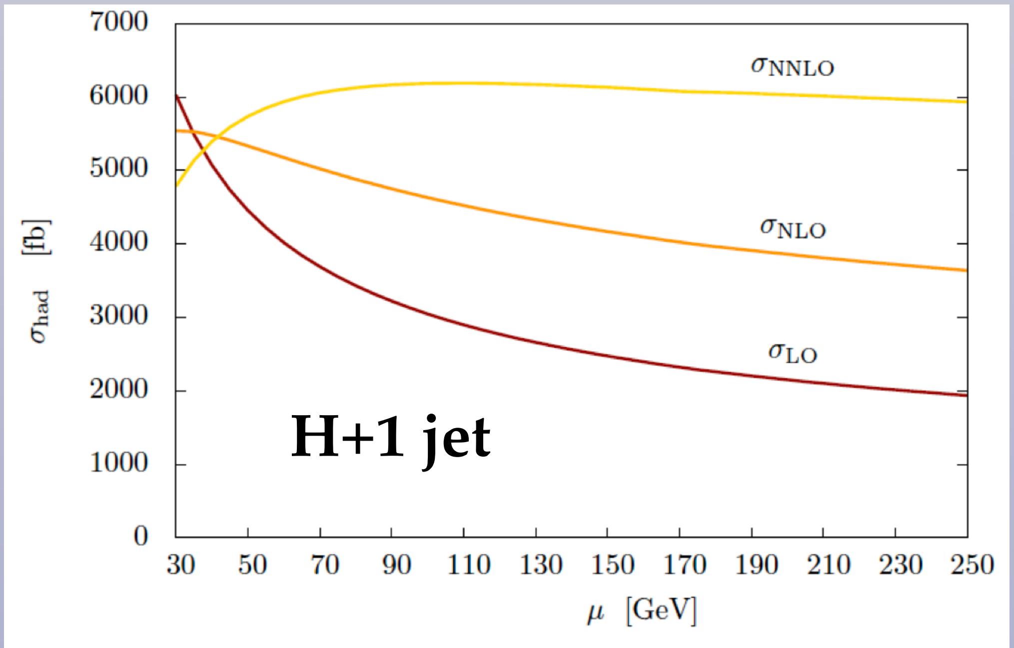
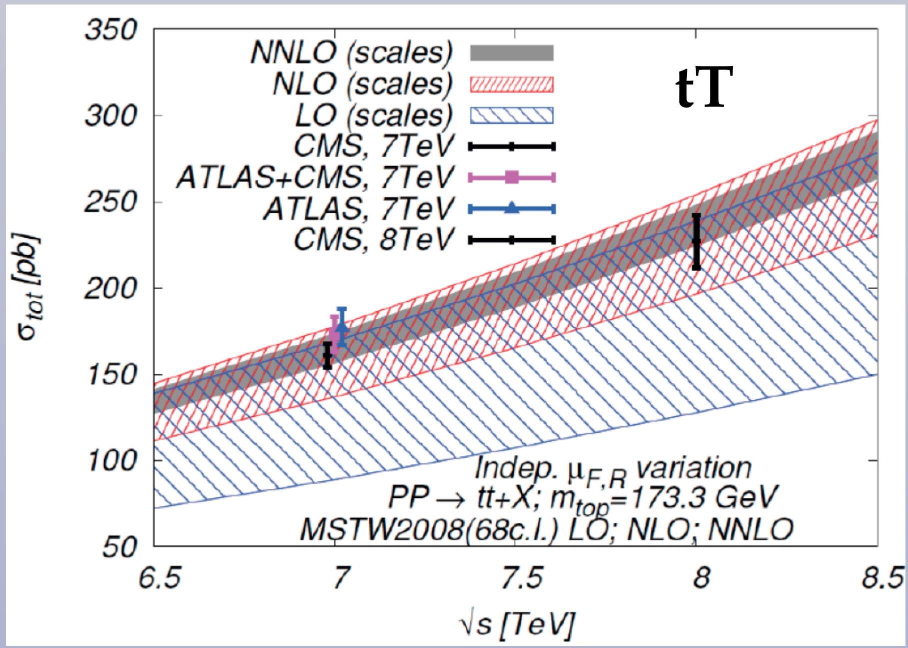
Theory

Higher order calculations

- NNLO calculations are essential to **reduce theoretical uncertainties** in PDF analysis
- Up to last year, only small number of **processes relevant for PDFs** available at **NNLO**
- Recent important progress was made on some **key processes** (see Nigel's talk):
  - **NNLO inclusive jet production** in the gluon-gluon channel has been completed (arxiv:1310.3993), jet data essential in PDF fits for **gluons and large-x quarks**
  - The full **NNLO top quark production cross section** is also available (**top++2.0**), **differential distributions** to follow this year (arxiv:1303.6254), allows to pin down **large-x gluon**
  - **Higgs + 1 jet** also available now at **NNLO** (arxiv:1302.6216), important milestone towards the closely related **Z + 1 jet** and **W + 1 jet**, important for **gluon constraints** and **quark flavor separation**

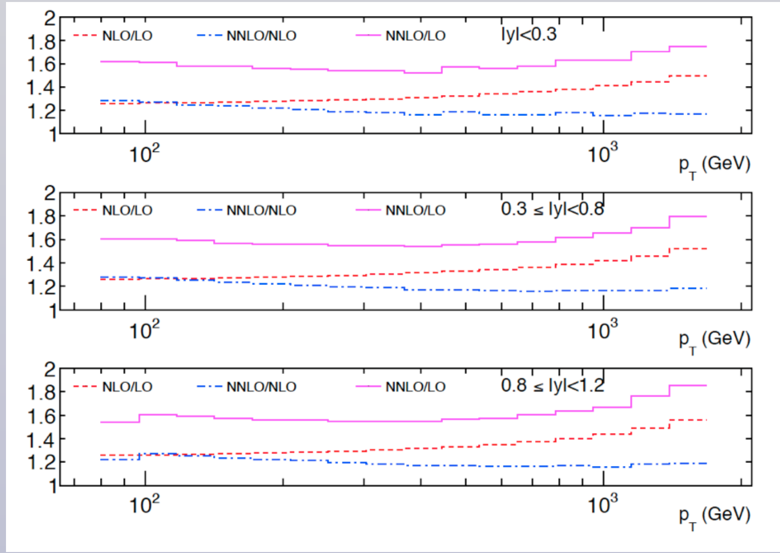


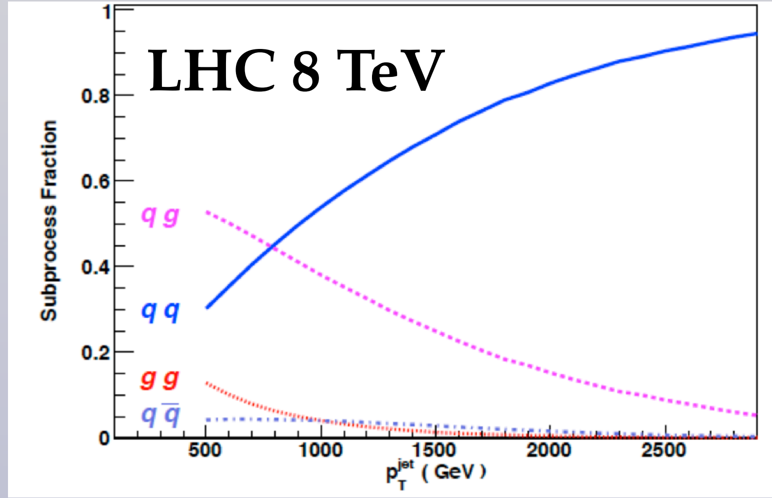


Theory

Jets in NNLO global fits

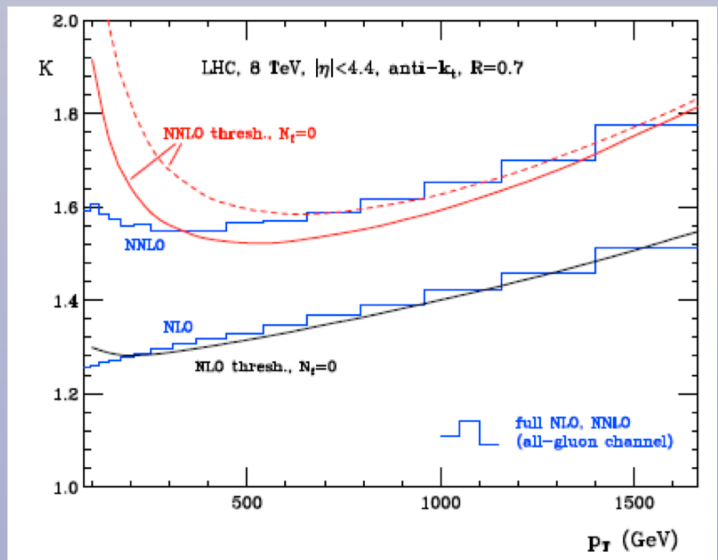
- The recent calculation of the **gluon-gluon channel NNLO jet cross sections** is an important milestone towards the exact inclusion of jet data in NNLO PDF fits: **O(20-25%) enhancements wrt NLO results**
- On the other hand, the **gg channel is small** at medium and large p_T at the LHC energies





arxiv:1310.3993
and Nigel's talk

- While full NNLO result becomes available, **approximate NNLO** results can be derived from the **improved threshold calculation**: reasonable approximation to exact at large p_T, **breaks down at small p_T**



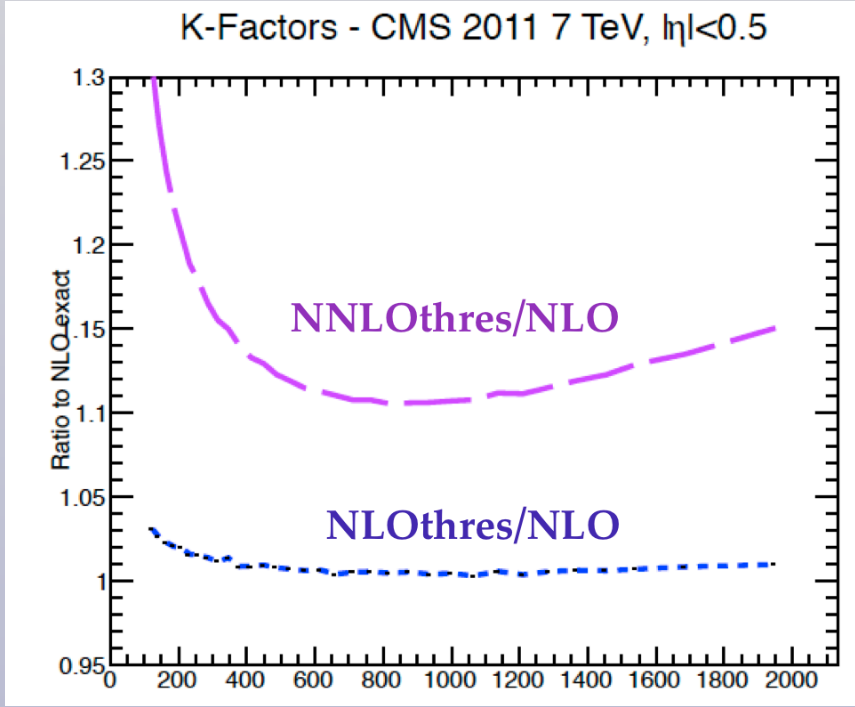
D. De Florian et al
arxiv: 1310.7192

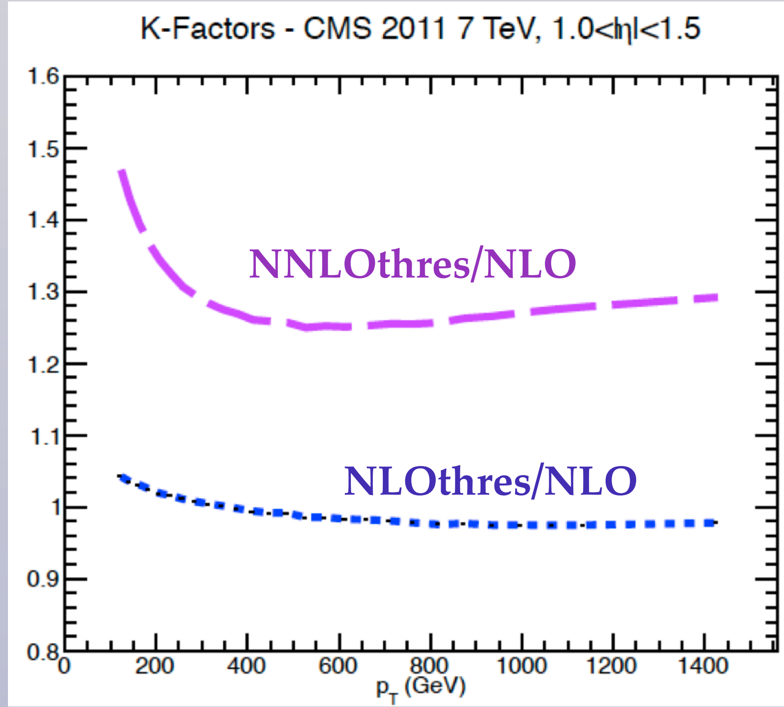
Theory

Jets in NNLO global fits

- We can therefore compute **approximate NNLO K-factors** using the **threshold approximation**
- **Comparison with exact gg NNLO** can determine for which values of jet p_T and η the **NNLOthres** calculation can be trusted (assume NNLO K-factor similar in all channels)

Plots by S. Carrazza and J. Pires





- Until **exact NNLO available**, jet data at small jet p_T and large η **should be excluded from NNLO fit**, since NNLOthres not suitable there
- Small impact for Tevatron jets (where NNLOthres works in a wider range) and ATLAS 2010 jet data (substantial uncertainties), but important for the **ATLAS and CMS jet data from the 2011 and 2012 runs**

Theory

Jets in NNLO global fits

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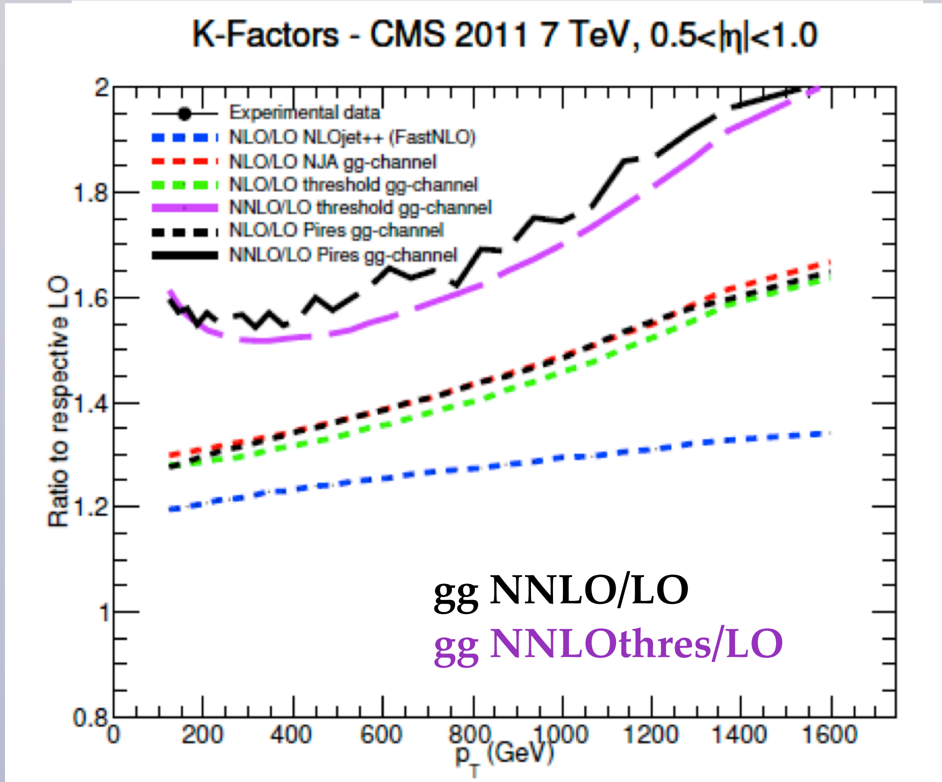

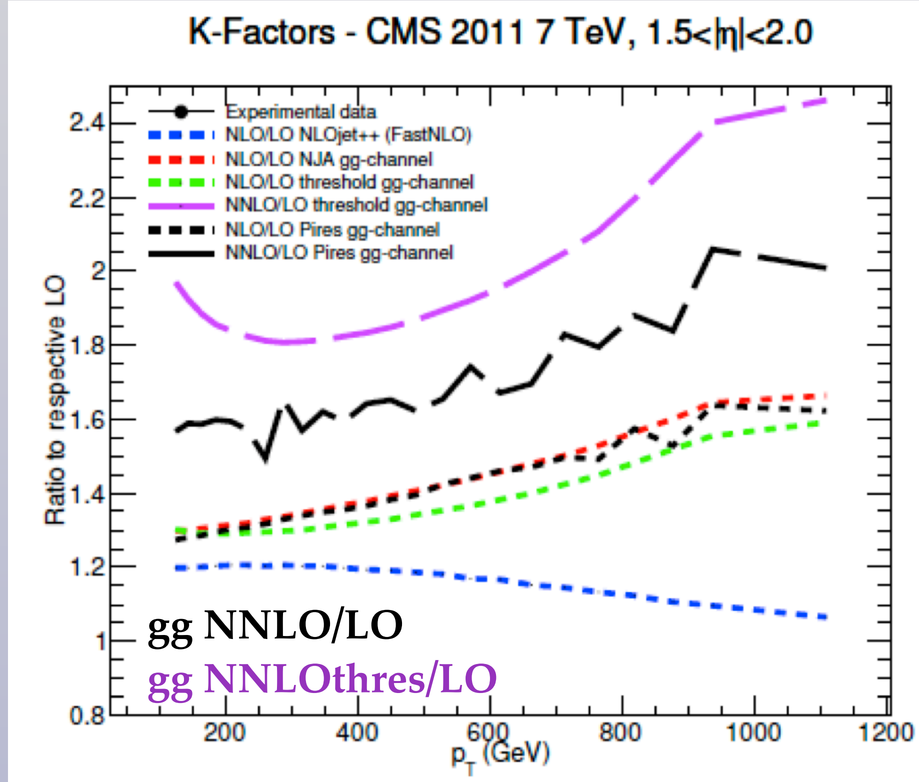

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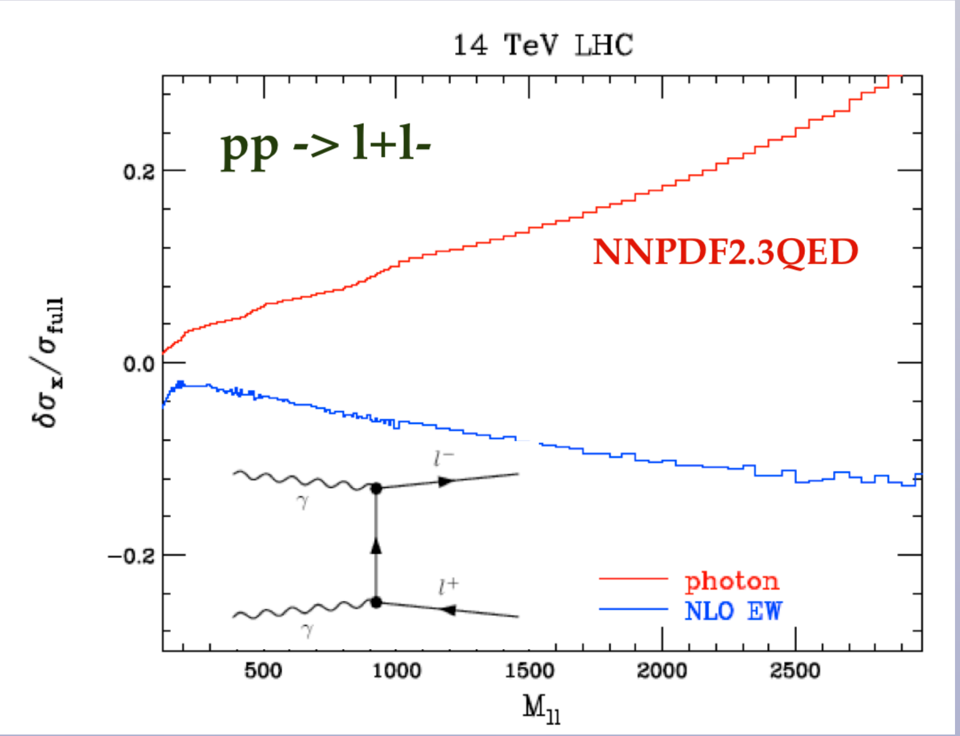
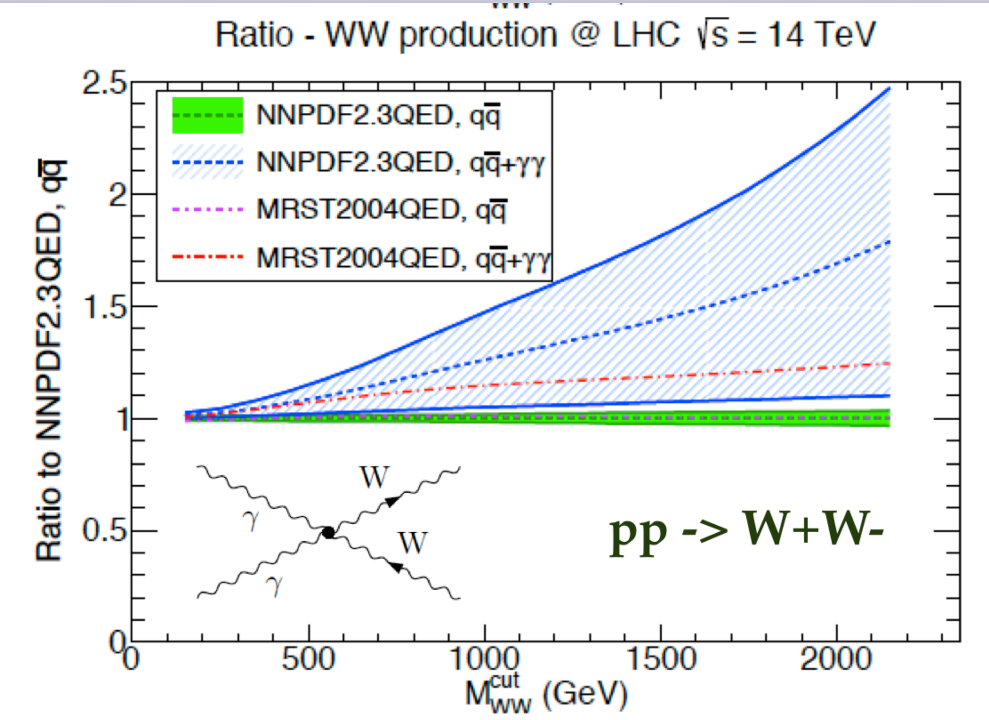
Theory

QED corrections

- **Photon-initiated diagrams** are required for consistent electroweak calculations (See also Tobias' talk)
- The **DGLAP QCD equations** can be modified with **QED corrections,** introducing a **photon PDF**
- **NNPDF2.3 QED set** is the only available **QCD+QED PDF set** with an independent determination of the photon PDF **from DIS and LHC data** (arxiv:1308.0598)
- Important for electroweak LHC phenomenology: **W', Z' searches**, **M_W** fits, **WW production**, ...
- New public **QCD+QED PDF evolution** code available: **APFEL** (Bertone, Carrazza, JR, arxiv:1310.1394)



Boughezal et al, arxiv:1312.3972



NNPDF, arxiv:1308.0598

Theory

Electroweak corrections

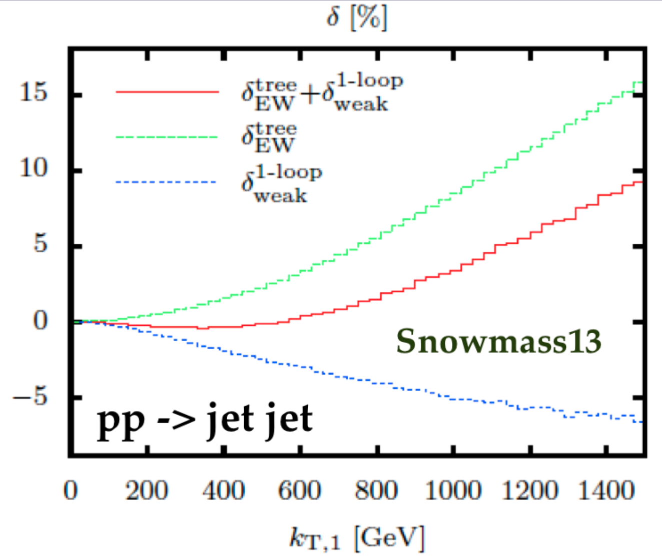
- At present level of precision in QCD calculations, **electroweak corrections** become **comparable if not larger**
- **Electroweak Sudakov logarithms** grow with energy, more important at **LHC 13 TeV**

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1$ TeV:

$$\delta_{\mathrm{LL}}^{1-\mathrm{loop}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2} \ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta_{\mathrm{NLL}}^{1-\mathrm{loop}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2} \ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

- Electroweak corrections affect the **TeV scale phenomenology**, both for **New Physics searches** in the high-mass tails, **Higgs characterization** and **precision SM measurements**, such as PDF fits

Electroweak corrections to high-pT jets @ LHC8



see also Markus' talk

TABLE V: Are we in the Sudakov zone yet?

Process	$\sqrt{s} = 8$ TeV	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33, 100$ TeV
Inclusive jet, dijet	Yes	Yes	Yes
Inclusive W/Z tail	∼ Yes	Yes	Yes
Wγ, Zγ tail ($\ell\nu\gamma, \ell\ell\gamma$)	No	∼ Yes	Yes
W/Z+jets tail	∼ Yes	Yes	Yes
WW leptonic	Close	∼ Yes	Yes
WZ, ZZ leptonic	No	No	Yes
WW, WZ, ZZ semileptonic	∼ Yes	Yes	Yes

- Therefore, **including high-Et data into global PDF fits** requires inclusion of electroweak corrections
- More importantly, for consistency this requires also **PDFs with electroweak corrections in the DGLAP evolution,** that is, complement QCD and QED splitting functions with pure weak splittings and the **W and Z PDFs** in the proton
- Non trivial task: **structure of EWK evolution equations** very different from the QCD/QED ones **(Ciafaloni, Comelli 05)**

$$-\frac{\partial}{\partial t} \underset{g}{\mathcal{F}}_{AB} = \frac{\alpha_W}{2\pi} \left\{ C_g \underset{g}{\mathcal{F}}_{AB} \otimes P_{gg}^V + (T_V^C \underset{g}{\mathcal{F}} T_V^C)_{AB} \otimes P_{gg}^R + \left(\sum_L \mathrm{Tr}\left[t^B \underset{L}{\mathcal{F}} {}^t t^A \right] + \sum_{\bar{L}} \mathrm{Tr}\left[t^A \underset{\bar{L}}{\mathcal{F}} t^B \right] \right) \otimes P_{fg}^R + \mathrm{Tr}\left[T_L^B \underset{\phi}{\mathcal{F}} {}^t T_L^A \right] \otimes P_{\phi g}^R \right\}$$

Global PDF analyses

Data

- ☑ Inclusive jets and dijets, xsec ratios
- ☑ W+charm
- ☑ Drell-Yan production
- ☑ Top quark data
- ☑ HERAfitter analysis of LHC data

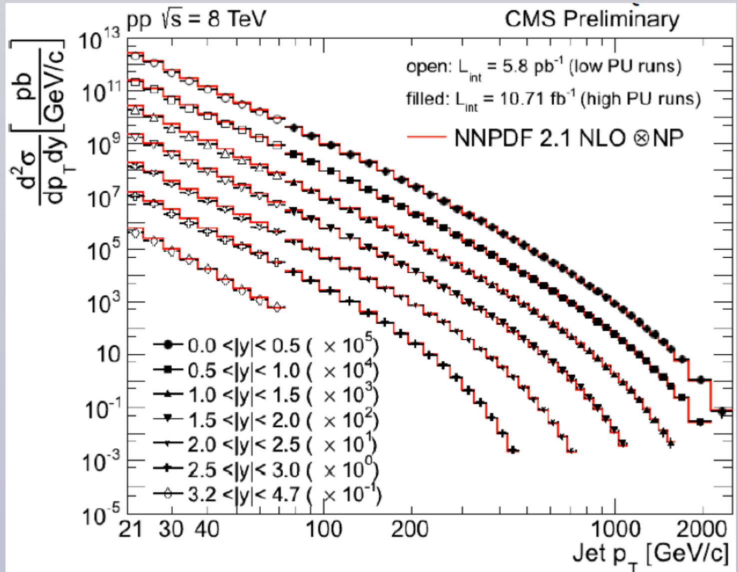
Data

Experimental constraints - I

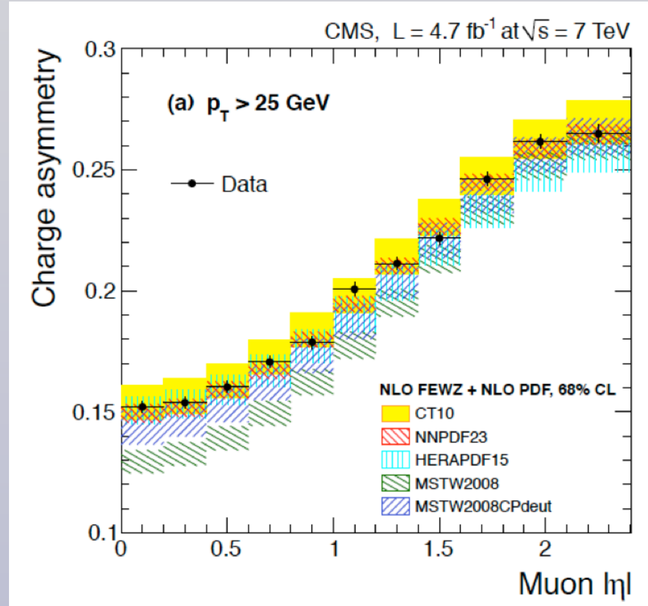
Traditional processes for **PDF fits at hadron colliders** are **jet/dijet, Drell Yan and inclusive W,Z** production

The LHC is providing an **impressive wealth of data** here, already included in various PDF fits

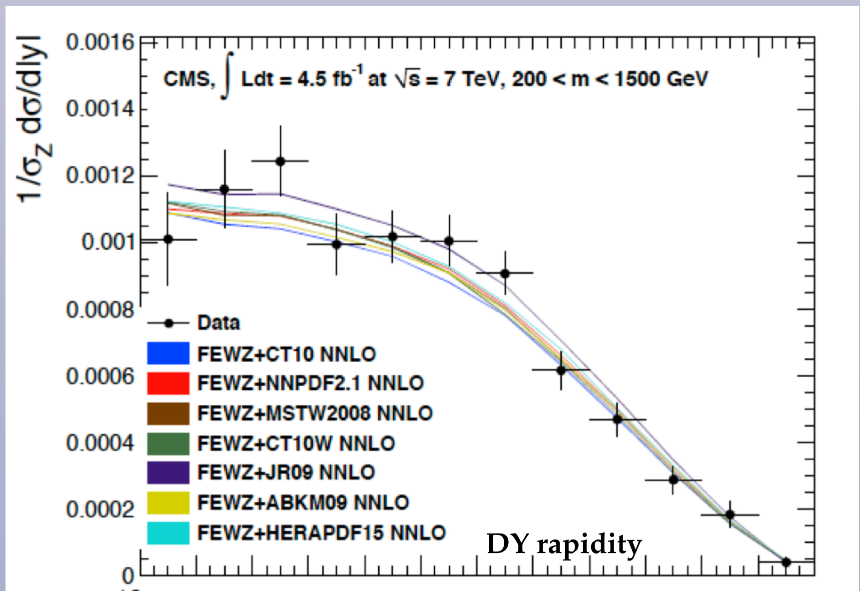
☑ **Inclusive jet production** (ATLAS, CMS)



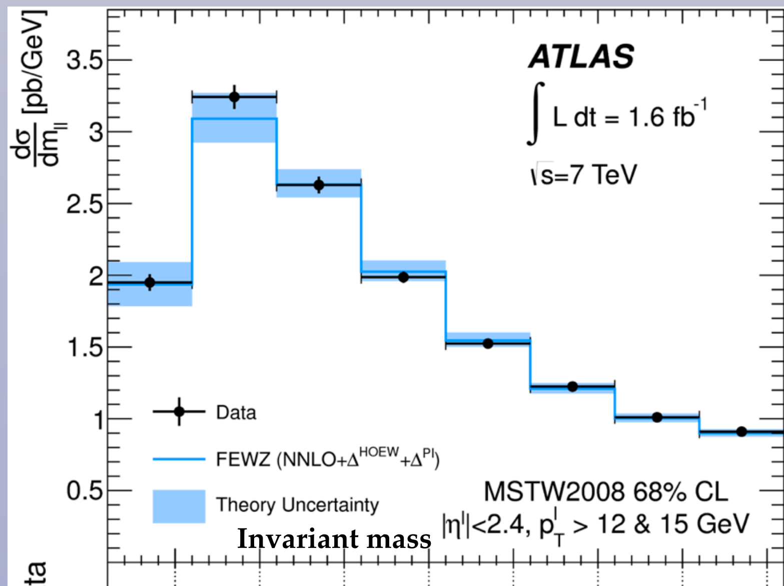
☑ **W lepton asymmetry** (ATLAS, CMS, LHCb)



☑ **High mass Drell-Yan** (ATLAS, CMS)



☑ **Low mass Drell-Yan** (ATLAS, CMS, LHCb):

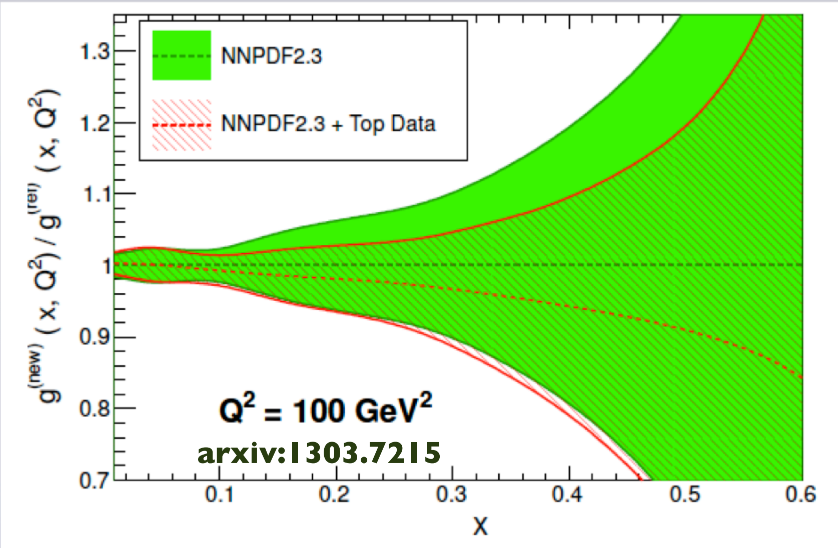


Data

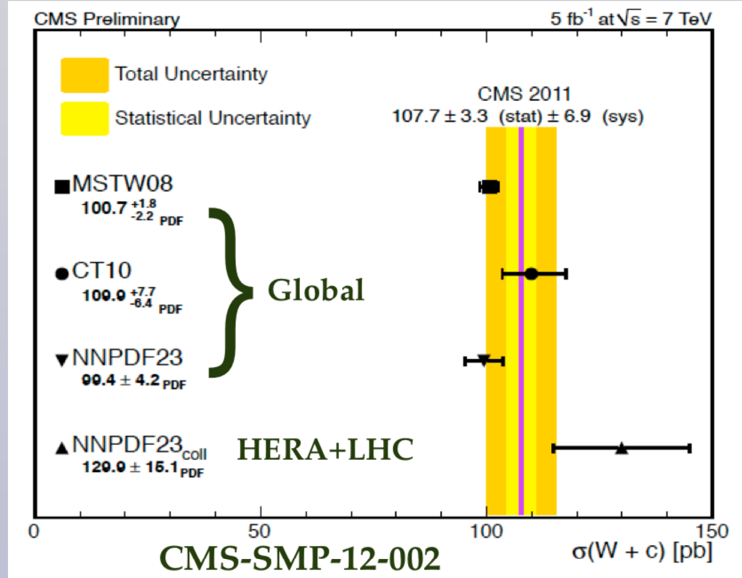
Experimental constraints - II

On top of traditional processes, like **jets** and **W, Z production**, a **wide range of new processes** that provide PDF information is now available at the **LHC**

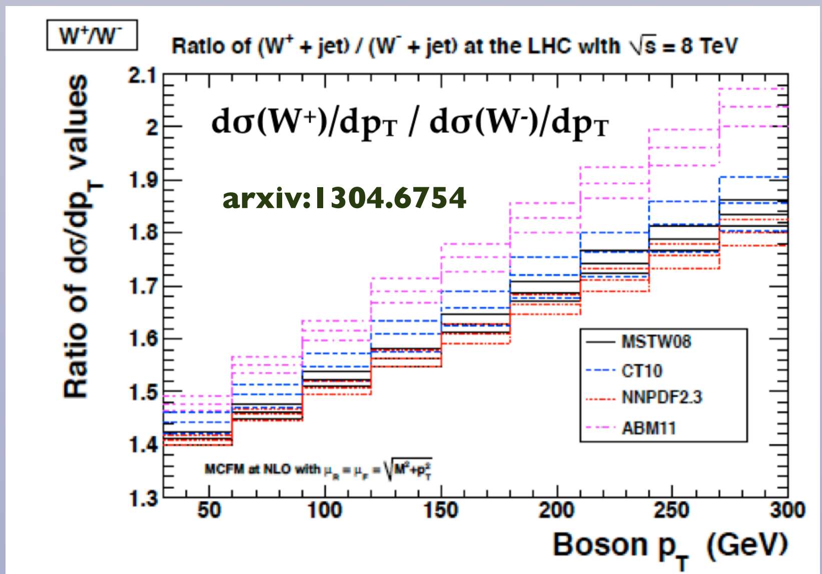
- **Top quarks:** constrain **large-x gluon**



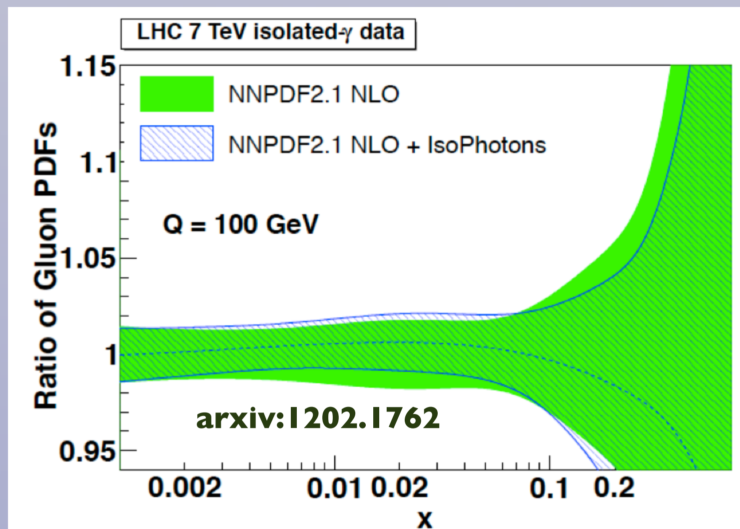
- **W+charm**: sensitivity to **strangeness**



- **high p_T W and Z: gluon** and on **d/u ratio**



- **Isolated photons**: complementary probe of the **gluon,** same x-range as for gg Higgs production

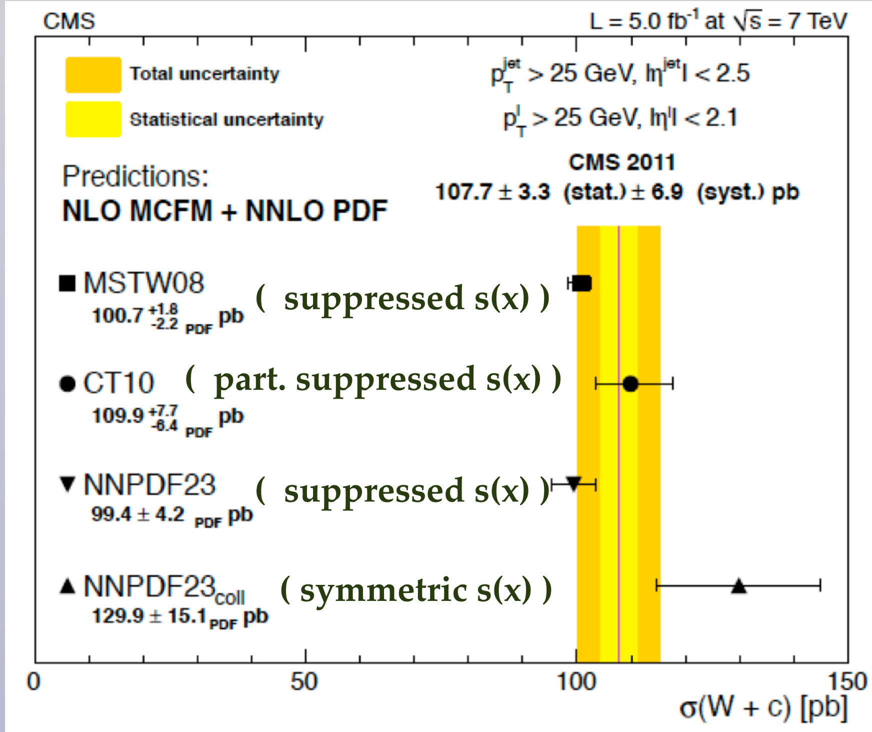


Data

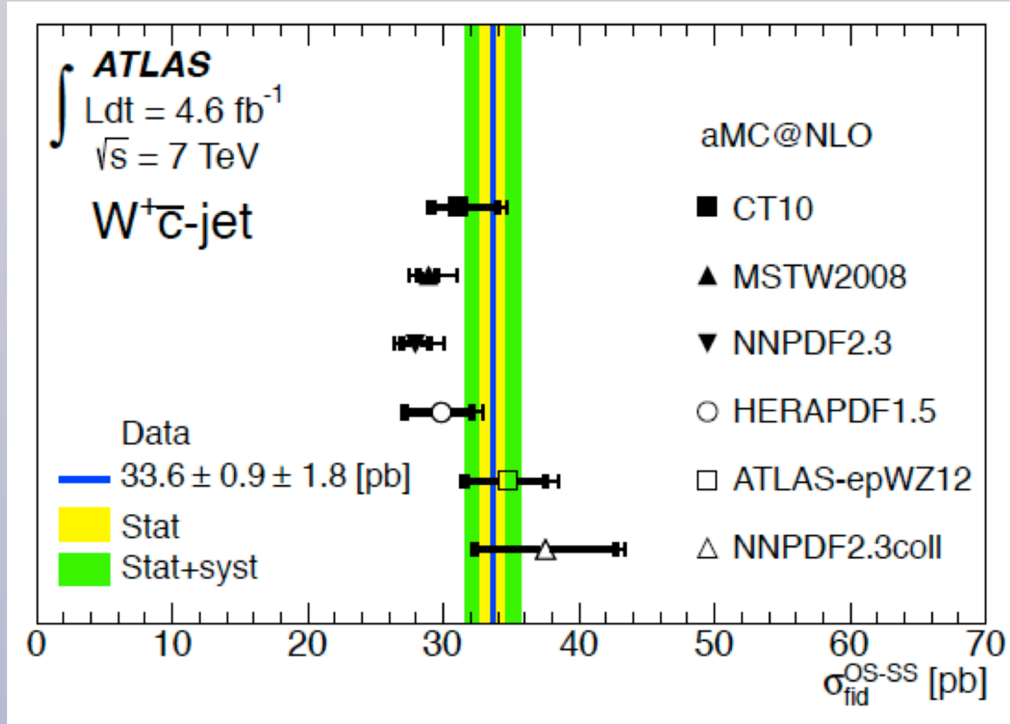
The strangeness conundrum

- In pre-LHC PDF fits, strangeness **s(x,Q)** mostly constrained from **DIS neutrino data**
- W production in association with charm quarks provide a clean probe of the **strange PDF at the LHC**
- Measured by ATLAS (arxiv:1402.6263) and CMS (arxiv:13101138) with somewhat opposite (?) conclusions

CMS: strange suppression in agreement with DIS data



ATLAS: light quark sea symmetric preferred



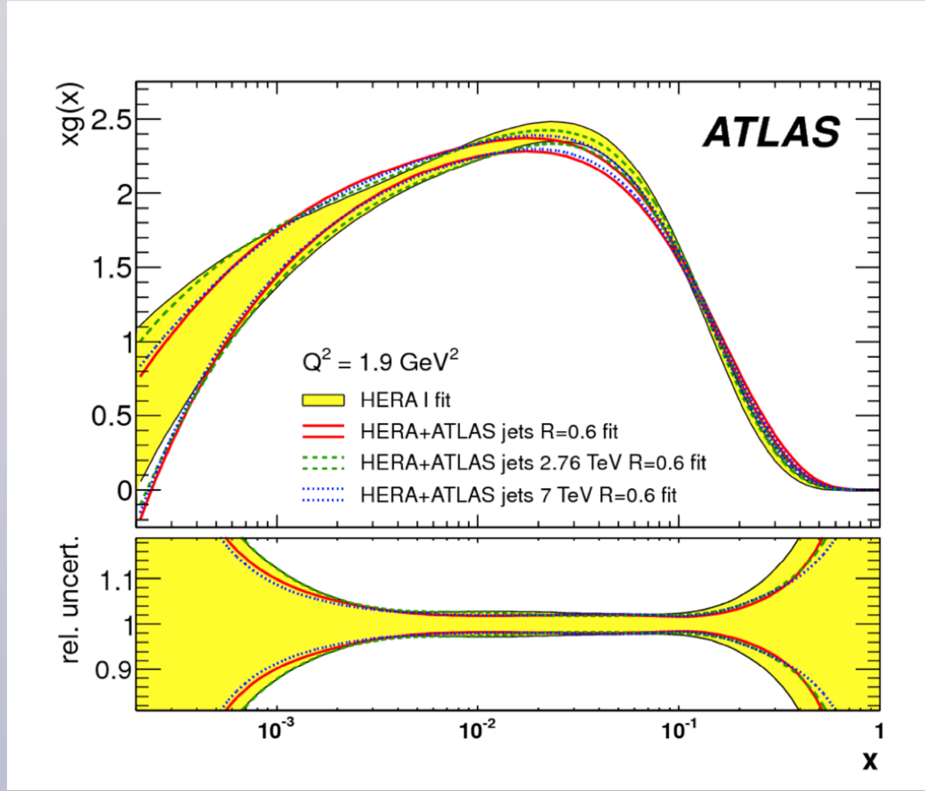
- But: **different analysis techniques**, kinematical cuts, selections, theory predictions used...
- Full differential distributions with covariance matrix
- Only meaningful comparison the results is provided by **including both datasets in a global PDF analysis** and determine the value of **strange PDF** which maximizes agreement with the two datasets
- All technical tools to carry this exercise available, see later in the talk

Data

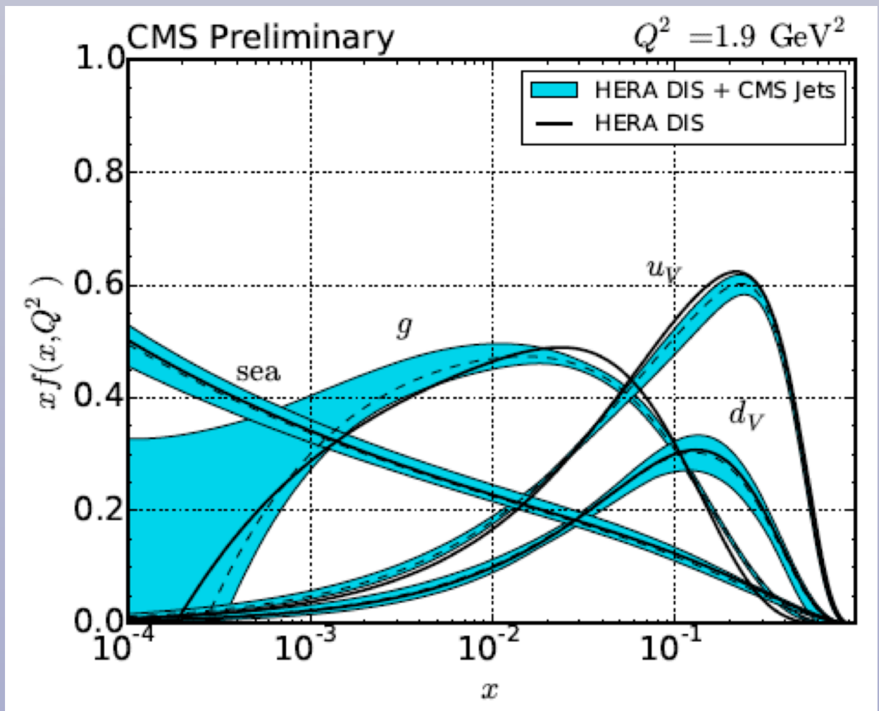
PDF studies from ATLAS and CMS

- In addition of **providing the data**, ATLAS and CMS also perform their **own PDF studies** using the **HERAfitter** framework
- Very important as **quantitative estimates of the PDF constraints from individual datasets**, and internal cross-check of the **estimation of systematic errors** (but not meant to be used as *replacements* to global fits)
- Recent results as well in the determination of related SM parameters, like in particular α_S
- More in **Fred's** and **Claudia's** talks

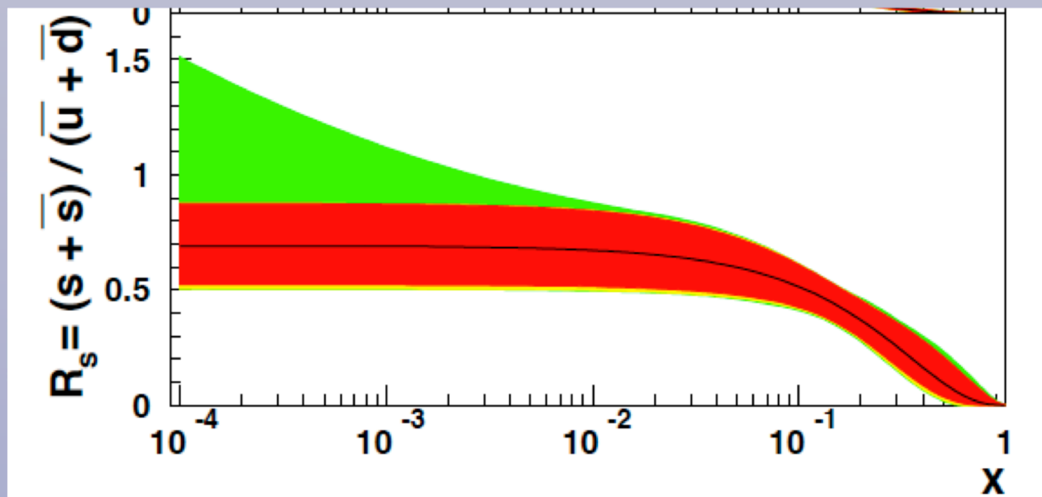
ATLAS: gluon PDF from 7 TeV/2.76 TeV jet xsec ratio



CMS: gluon and quark PDFs from 2011 inclusive jets



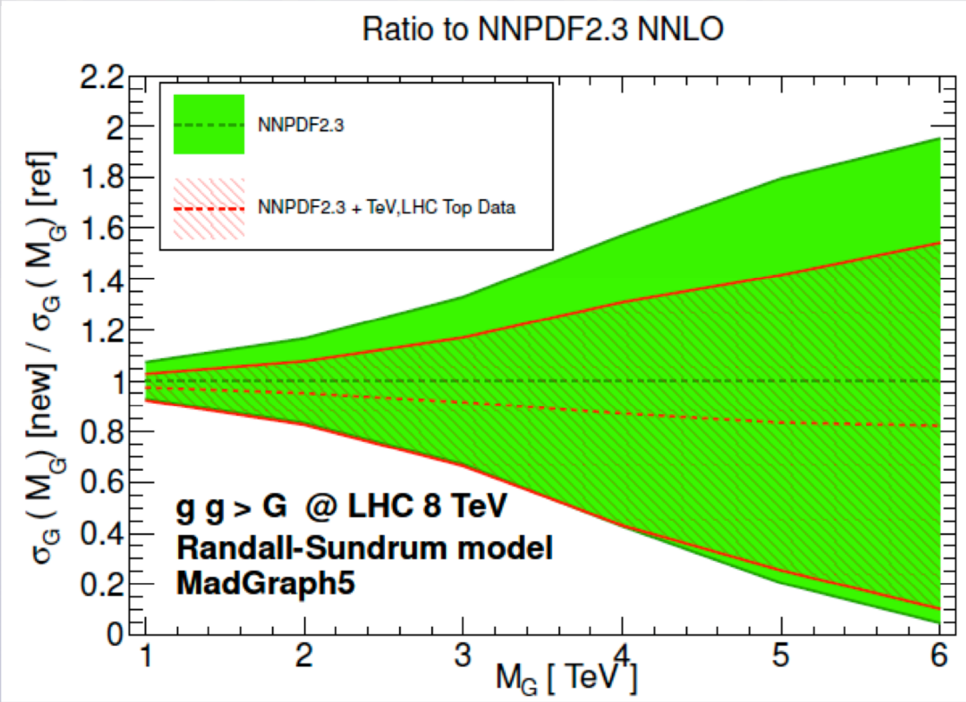
CMS: strangeness from W+c production



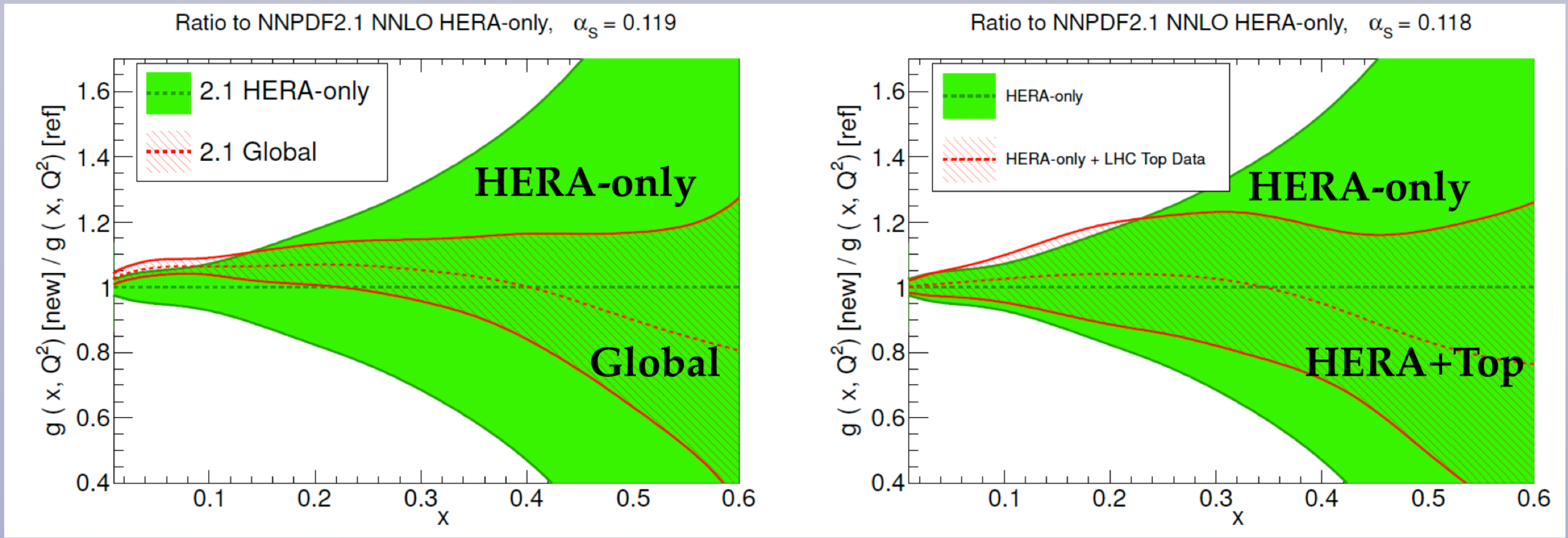
Data

Top quarks as gluon luminometers

- The **full NNLO calculation** implies that top quark production is the **only hadron collider observable directly sensitive to the gluon** which can be consistently **included in a NNLO PDF fit** without any approximation
- Important implications for **high mass gluon initiated BSM processes**
- The gluon PDF in a fit with **HERA+top data** is remarkably similar at large-x to the gluon of the **global PDF fit**, driven by jet data
- Improved constraints from **NNLO diff distributions**



Czakon, ManganoMitov, JR, arxiv:1303.7215



Global PDF analyses

Updates in PDF fits

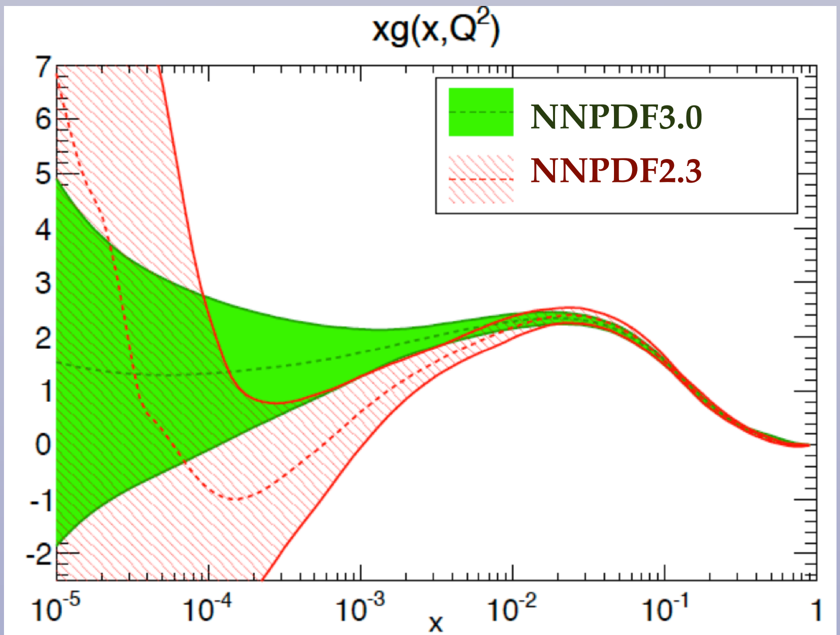
- **ABM:** ABM12, inclusion of LHC data, ...
- **CT:** intrinsic charm, PDFs for Higgs physics, ...
- **MSTW**: impact of jet data, ...
- **NNPDF:** closure test fitting, NNPDF3.0 release, ...

NNPDF updates

- Next release will be **NNPDF3.0**, based on a complete rewriting of the NNPDF framework in **C++** (more than **70K** lines of code)

Language	files	blank	comment	code
C++	106	6993	6048	26551
Fortran 77	113	115	10161	20872
C/C++ Header	134	1183	857	3920
make	34	792	447	1699
ASP.Net	1	511	0	1390
Bourne Shell	23	261	202	802
Python	8	187	168	565
Fortran 90	1	32	43	117
Bourne Again Shell	3	7	11	34
SUM:	423	10081	17937	55950

- More than **1000 new data points** from **HERA-II and the LHC**, including jet cross-sections, W+charm production, top quark data, low and high mass Drell-Yan, W lepton asymmetries.....

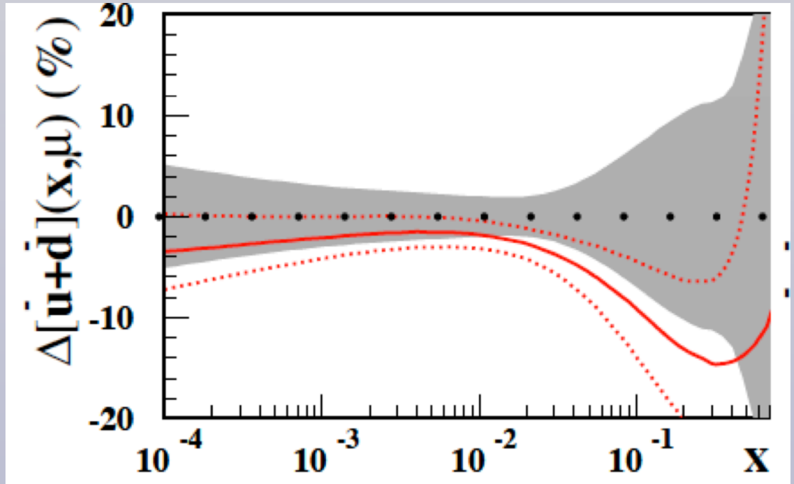


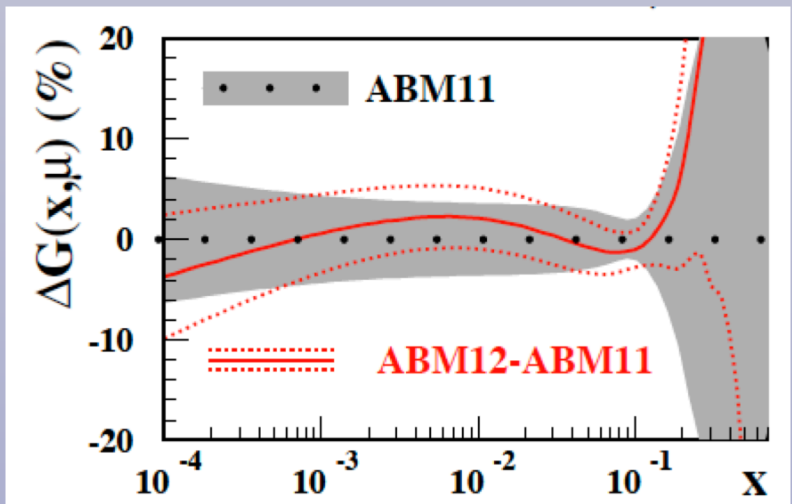
- Completely redesigned fitting methodology based on **closure tests** with known underlying physical laws **(S. Forte, PDF4LHC, 12/2014)**
- Substantially improved **Genetic Algorithms minimization** with new **Weight Penalty method** for fitting (iterative Bayesian regularization)

Experiment	Dataset	DOF
NMC		356
	NMCPD	132
	NMC	224
SLAC		74
	SLACP	37
	SLACD	37
BCDMS		581
	BCDMSP	333
	BCDMSD	248
CHORUS		862
	CHORUSNU	431
	CHORUSNB	431
NTVDMN		79
	NTVNUDMN	41
	NTVNBDMN	38
HERA1AV		592
	HERA1NCEP	379
	HERA1NCEM	145
	HERA1CCEP	34
	HERA1CCEM	34
ZEUSHERA2		252
	Z06NC	90
	Z06CC	37
	ZEUSHERA2NCP	90
	ZEUSHERA2CCP	35
H1HERA2		511
	H1HERA2NCEM	139
	H1HERA2NCEP	138
	H1HERA2CCEM	29
	H1HERA2CCEP	29
	H1HERA2LOWQ2	124
	H1HERA2HGHY	52
HERAF2CHARM		47
DYE886		199
	DYE886R	15
	DYE886P	184
DYE605		119
CDF		105
	CDFZRAP	29
	CDFR2KT	76
D0		138
	D0ZRAP	28
	D0R2CON	110
ATLAS		179
	ATLASWZRAP36PB	30
	ATLASR04JETS36PB	90
	ATLASR04JETS2P76TEV	59
CMS		95
	CMSWEASY840PB	11
	CMSWMASY47FB	11
	CMSJETS11	63
	CMSWCHARMTOT	5
	CMSWCHARMRAT	5
	CMSDY2D11	132
LHCB		19
	LHCBW36PB	10
	LHCBZ940PB	9
TOP		6
Total (exps)		4214

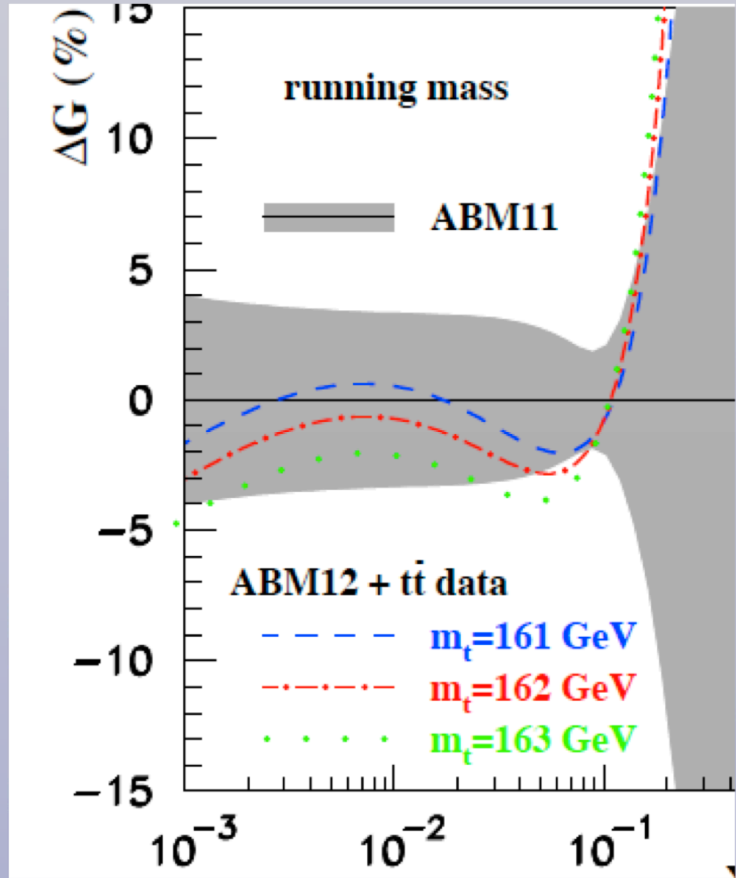
ABM updates

- **ABM12**: New release of the ABM family (arxiv:1310.3059)
- Includes **W and Z production data from the LHC**, and studies constraints from **top quark production data** (but not included in public fit)
- Main impact of new LHC data is on **quark flavor separation**, gluon PDF more stable
- Substantial impact of **top quark data**, central value of gluon can shift by > 1-sigma





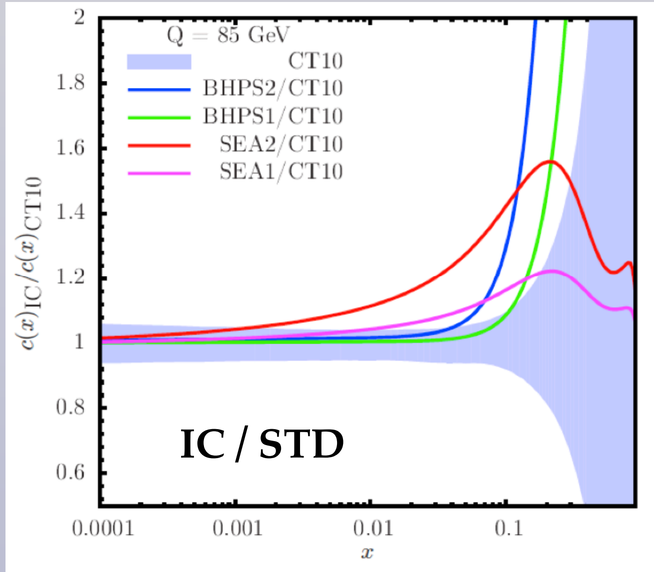
Impact of top quark data in ABM11



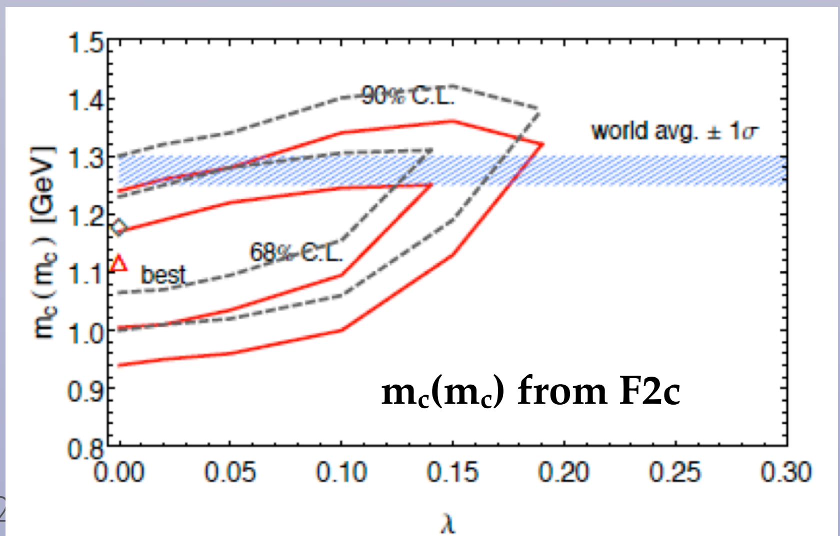
PDF updates

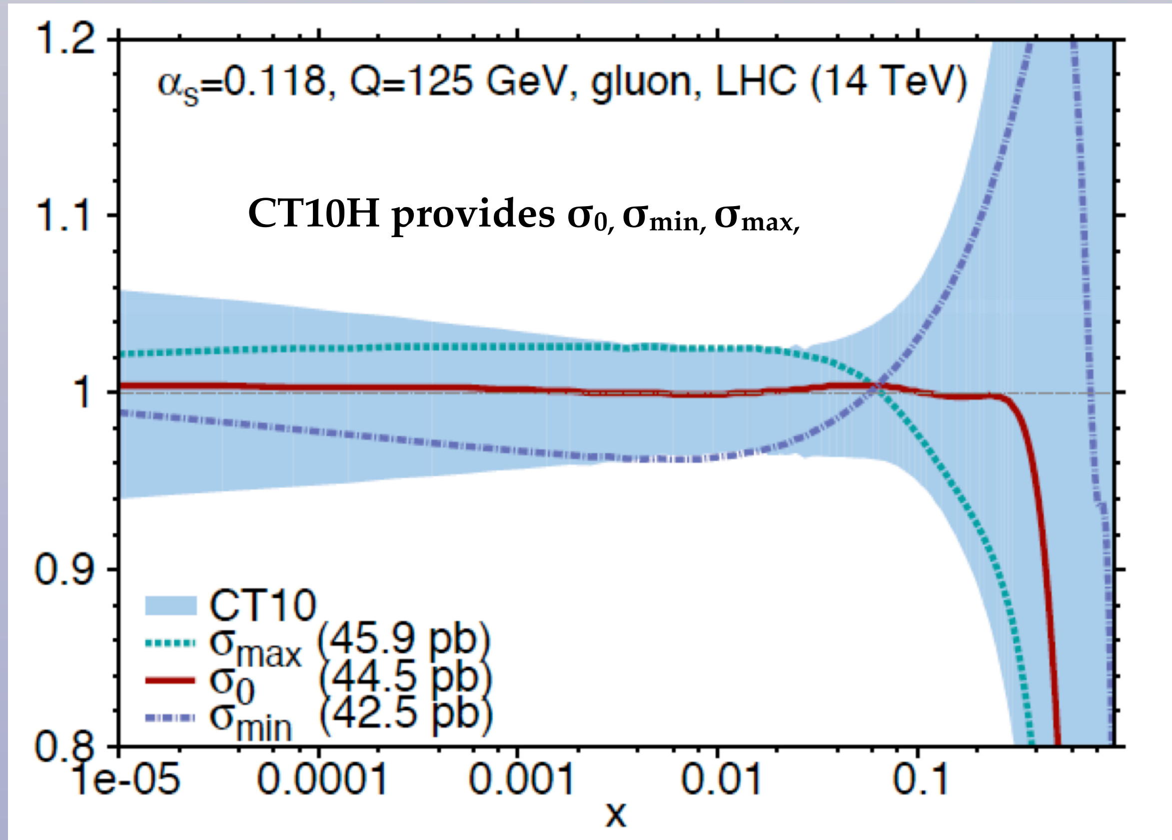
CT updates

- Various phenomenological studies, based on the **CT10NNLO** **(arxiv:1302.6246)**
- Determination of the **running charm mass $m_c(m_c)$** from the combined HERA F2c data **(arxiv:1304.3494)**
- Studies of the **dataset dependence of the gg Higgs cross-section**, and PDF sets specific for Higgs cross-section calculations **(arxiv:1310.7601)**
- Updated determination of the **intrinsic charm** component of the proton **(arxiv:1309.0025)**



Understanding **dataset dependence** of Higgs cross-section in PDF fits is crucial task **(more in Les Houches 2014 proceedings)**



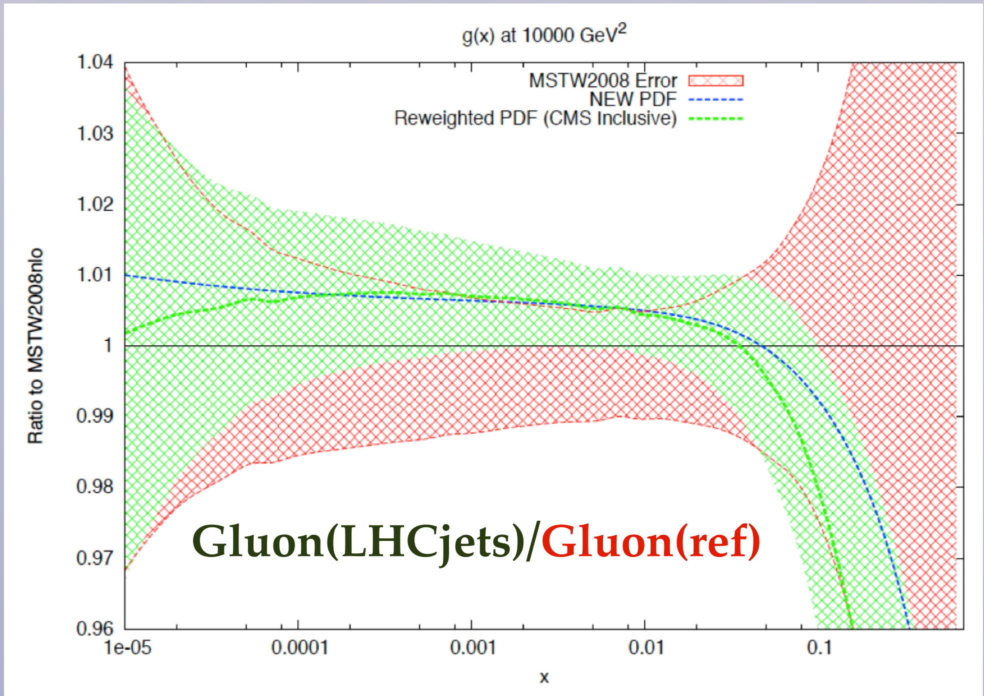


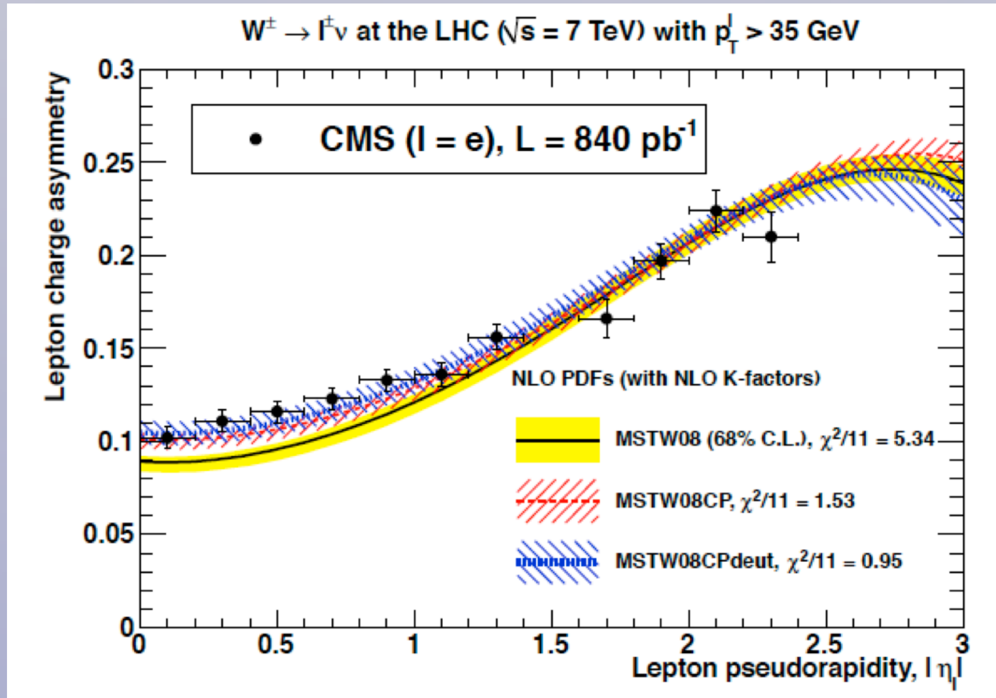
MSTW updates

- MSTW08 provided a **poor description of LHC W asymmetry data**. Agreement improved if a **more flexible PDF parametrization**, based on Chebyshev polynomials, introduced (arxiv:1211.1215)
- Illustration that LHC i) **improves agreement of PDF fits** and ii) **requires improved PDF methodologies**
- Detailed study of impact of all **available jet data** on the MSTW PDFs (restricted to NLO) in arxiv:1311.5703
- Good consistency with **ATLAS10** and **CMS11** inclusive jets found, with CMS being the more constraining dataset for the **gluon PDF**
- Troubles in fitting **LHC dijet data**, and strong dependence on scale choice. NNLO required here?

χ^2 to CMS dijet data:

	$0.5 * p_T^{av}$	$1.0 * p_T^{av}$	$2.0 * p_T^{av}$
MSTW2008 NLO	2.76	1.97	2.18





Global PDF analyses

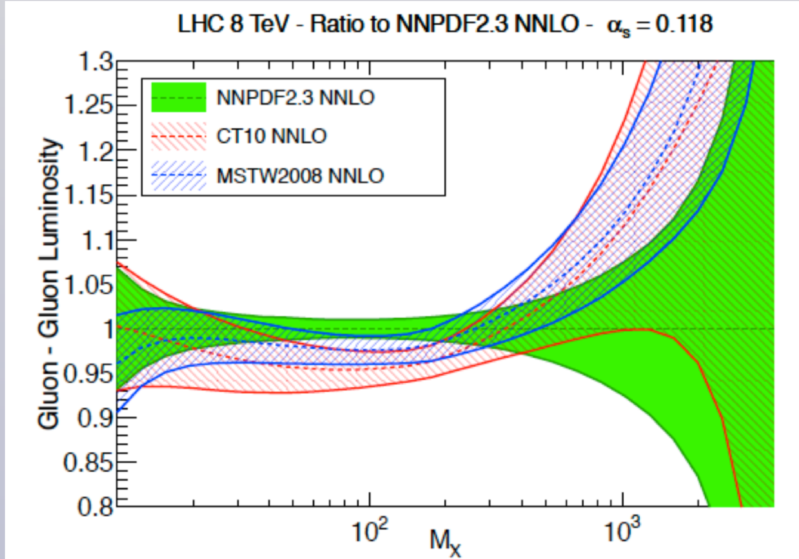
Tools and methodology

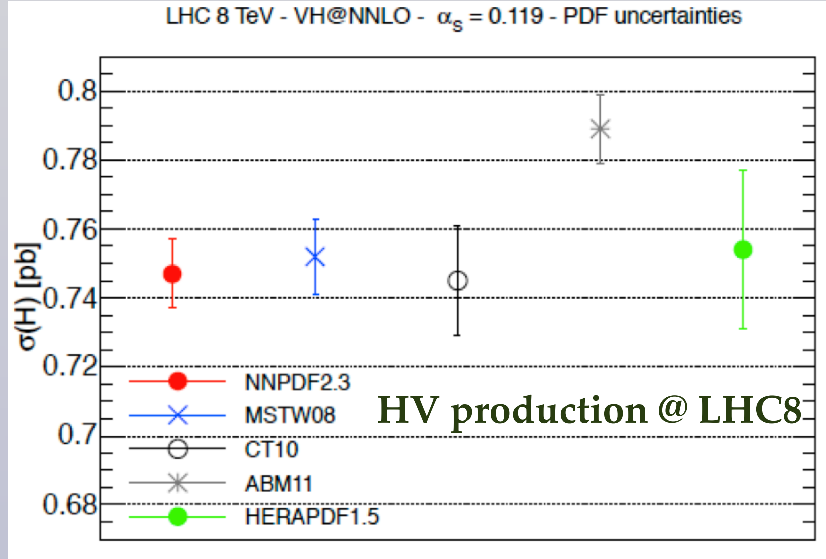
- ☑ PDF benchmarking exercises
- ☑ Meta-PDFs
- ☑ Fast interfaces to NLO and NLO+PS

Tools

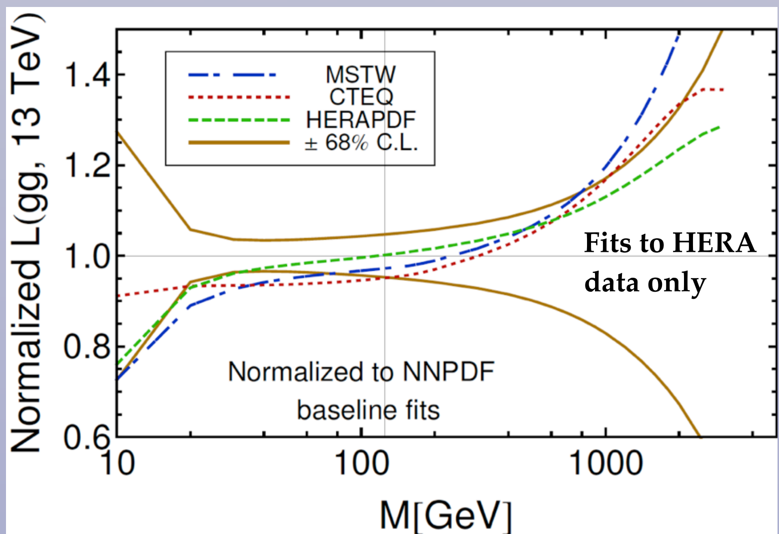
PDF benchmarking

- Careful comparison of the outputs from **different fitting codes** is an essential ingredient to understand and improve the differences between PDF sets: DGLAP evolution, heavy quark schemes, collider cross-section ....
- Most recent benchmark comparison **with LHC data as discriminator** from CT, MSTW and NNPDF **(arxiv:1211.5142)**

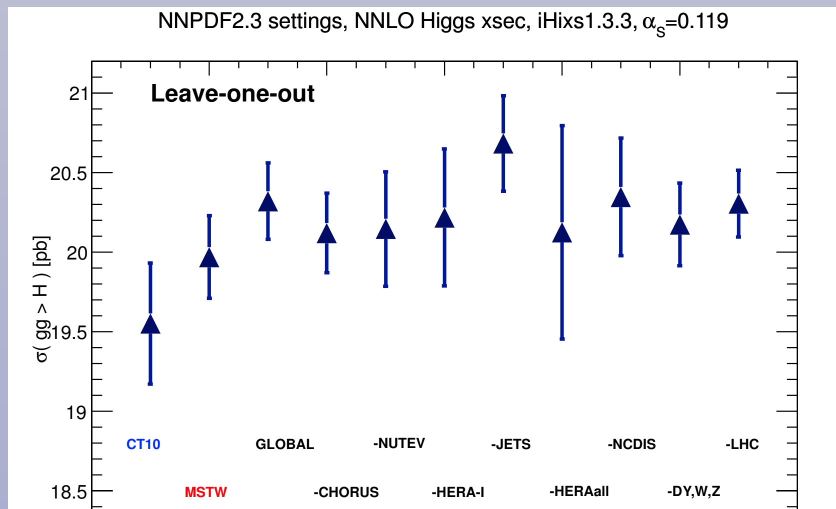




- In the upcoming **Les Houches 2014 proceedings**, first steps towards **understanding dataset dependence of Higgs production cross-sections** from PDF fits (see also **Stefano's talk**) : good agreement for gg Higgs from HERA only fits



Remove 1 exp at time in NNPDF2.3



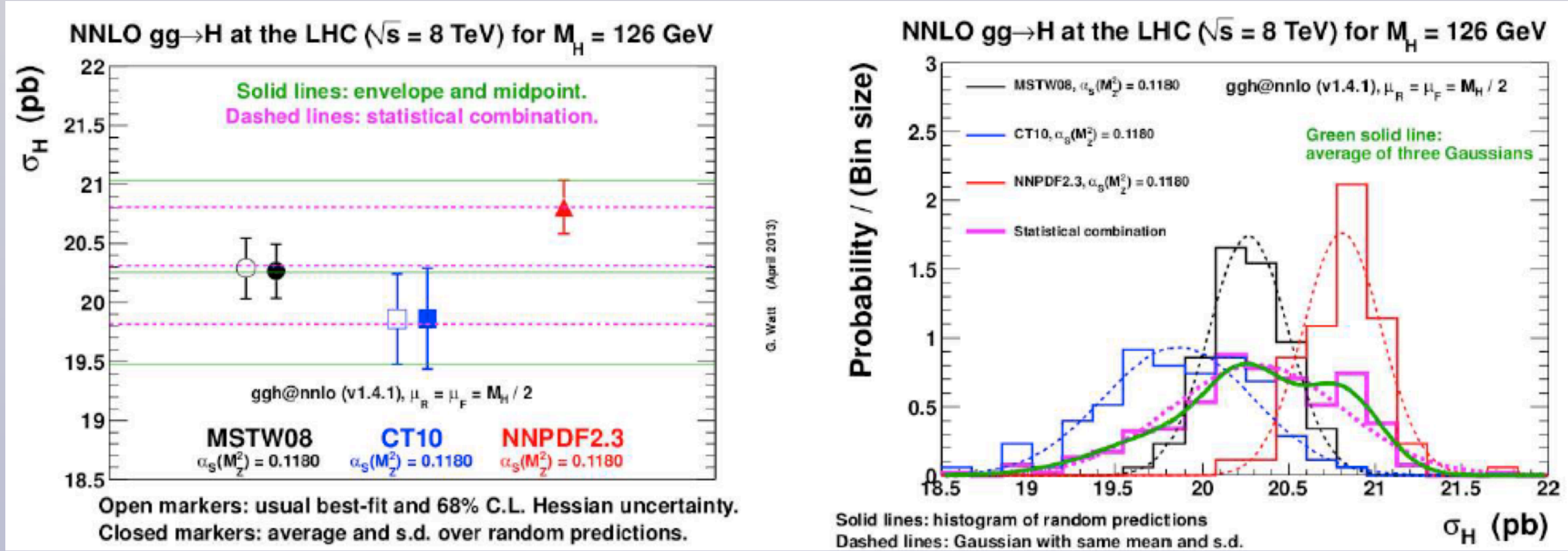
Forte and JR LH14 procs

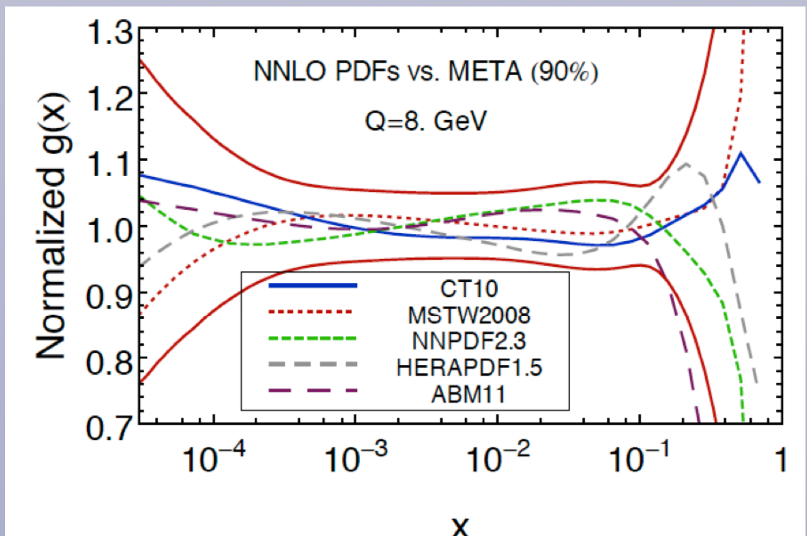
4

Tools

Combining different PDF sets

- Reliably estimate of PDF errors in LHC cross-sections can arise only **combining predictions from different sets**
- **PDF4LHC official prescription:** PDF+α_S uncertainty defined from **envelope** of the predictions from **CT, MSTW and NNPDF**, each at their default α_S
- Statistically more robust combination: generate Monte Carlo sets for CT and MSTW, then combine (with NNPDF) the three probably distributions into a joint one **(G. Watt 13)**





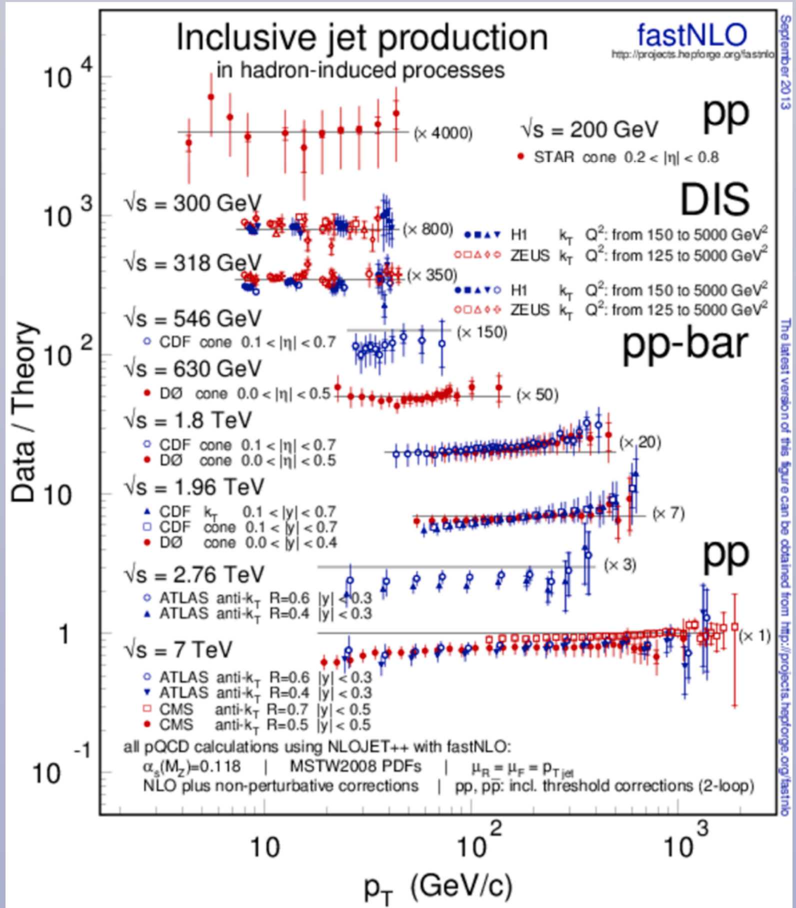
- Another alternative is to construct **Meta-PDFs** from fitting with an input functional form the CT, MSTW and NNPDF input PDF shapes and then combine them into a unique consistent PDF set **(Gao, Nadolsky 14)**

- In all cases, **major bottleneck** is how to determine the **optimal value of α_S** and its uncertainty in the combination procedure: crucial input from **theory and LHC data** needed (**talks by Nigel and Fred**)

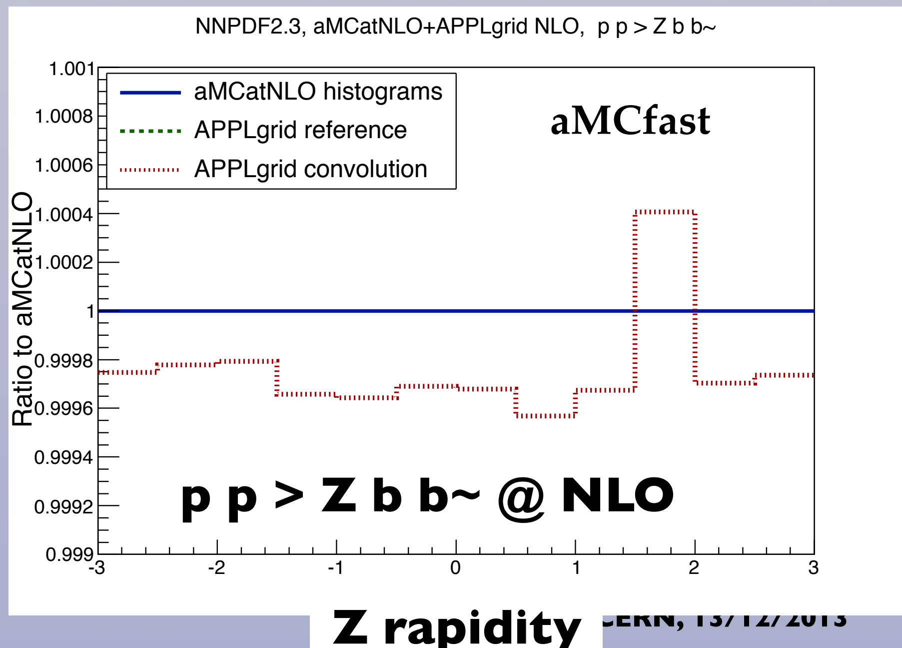
Tools

Fast NLO calculations in PDF analyses

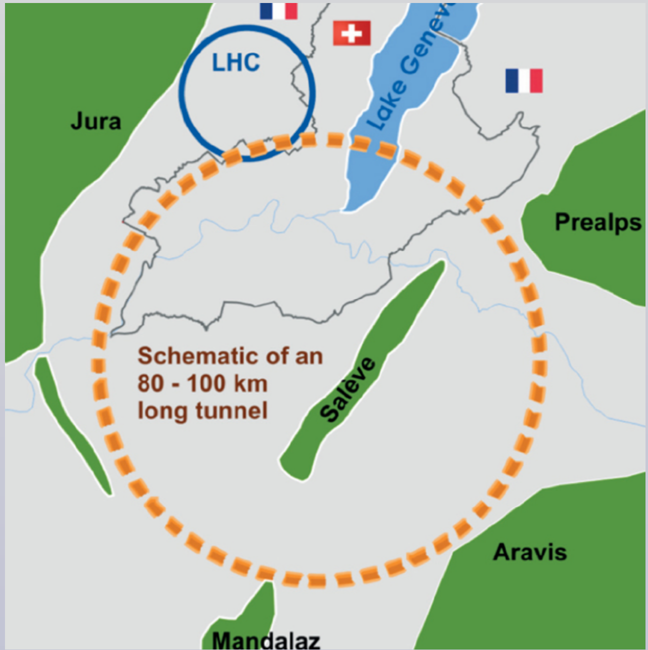
- **(N)NLO QCD calculations** are too CPU-time intensive to be used directly into PDF analysis
- Various approaches provide **fast interfaces to NLO calculations** for global PDF fits:
  - ☑ **APPLgrid**: interfaced to **MCFM, NLOJet++** and **DYNNLO**
  - ☑ **FastNLO**: interfaced to **NLOJet++**
- Basic strategy: **interpolate PDFs** in a suitable basis, and **precompute the partonic cross-section** into a set of grids, reconstructing the final distributions via a fast convolution -> **Essential tools for PDF fitting!**
- Limitations of present tools: need to be built on a **process-by-process basis**, they are restricted to **NLO QCD** and they do not account for **parton shower effects**



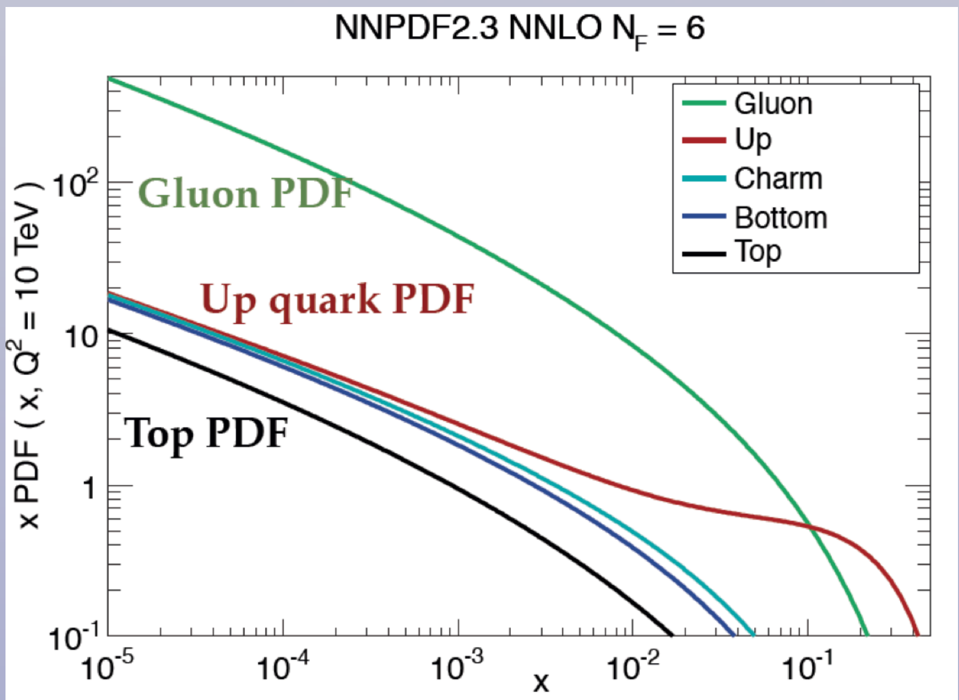
- **aMCfast** is a fast interface to **MadGraph_aMC@NLO** based on APPLgrid, which provides the complete automation of fast NLO QCD interfaces for PDF fits **(Bertone, Frederix, Frixione, JR, Sutton, preliminary)**
- **MCgrid** is a fast interface to **SHERPA/Rivet** also based on APPLgrid, suitable for any MC generator with **HepMC** output **(Del Debbio, Hartland, Schumann 13)**

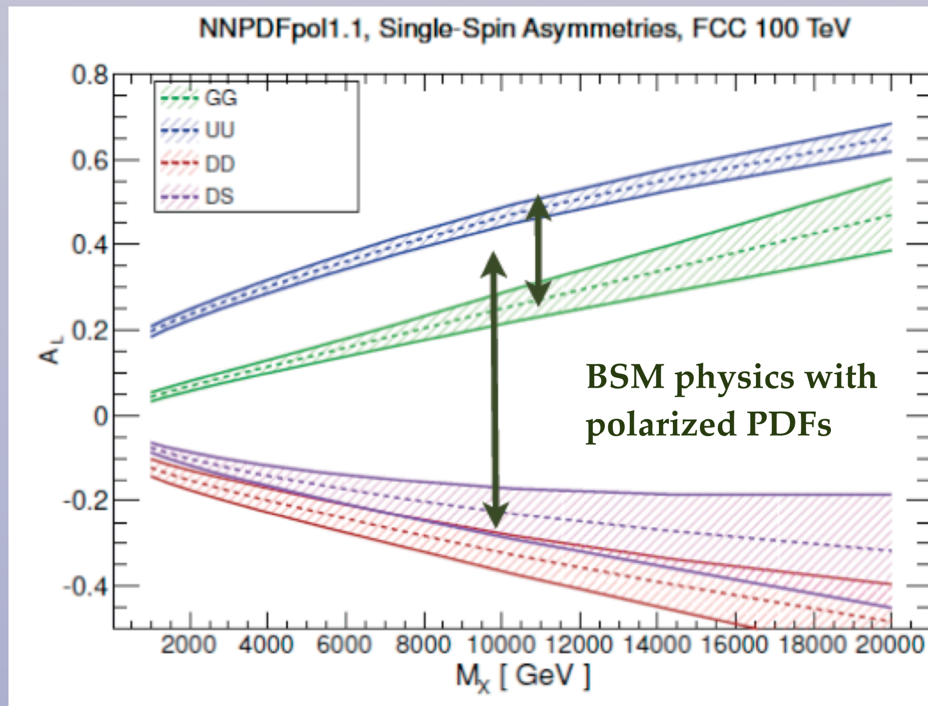


Going Beyond: PDFs at a 100 TeV collider



- Growing consensus that the next big machine more suitable to **explore the energy frontier** should be a **100 TeV hadron collider**, possibly with also **e+e-** and **ep** operation modes
- The **phenomenology of PDFs** at such extreme energies is very rich: **top quark PDFs**, electroweak effects on PDFs and **W/Z boson PDFs**, ultra-low-x physics, **BFKL dynamics**, BSM physics with polarized PDFs, ..., **lots of fun**!
- First studies being now performed in the context of the **CERN FCC working group**





Summary & outlook

- **Parton Distributions** are an **essential ingredient** of the LHC physics program
- **Precision PDFs** are required for most LHC analysis, from **Higgs boson characterization**, **searches for new massive particles** to **self-consistency tests of the Standard Model**
- A huge amount of work devoted in the last year to provide an **improved QCD/QED/EW calculations**, study the constraints from the **wealth of new experimental data** and adopt a **robust methodology** in **PDF analysis**
- Despite all this progress, many **theoretical open issues** need to be tackled to match requirements of LHC data:
  - How can we reduce the **PDF+ α_S uncertainty** in all Higgs production channels? Which is the optimal value of α_S to adopt? What about its uncertainty?
  - Do we need **PDFs at (approximate) N3LO?** Perhaps not for Higgs in gluon fusion, but yes for top quark production, what about other processes? What is the best way to construct such approximation?
  - Some of the best known cross sections at LHC (Higgs, top) available at **NNLO+NNLL**. Do we need **PDF sets with fixed order plus threshold resumation**? Are all the tools needed available?
  - What about PDFs with **high-energy and BFKL resummation?** Hints in small-x HERA data that this might be required for an improved description
  - How can we implement **EW corrections in PDF evolution**? What are the phenomenological implications for LHC 14 TeV? And at higher energy colliders?
  - NLO event generators are state-of-the-art at LHC. Do we need specific **PDFs for NLO event generators**? Can we simultaneously fit hard-scattering and semi-hard data with a single PDF set?
  - Can we imagine **new avenues to use global PDF fits for New Physics searches**? What about including BSM dynamics in DGLAP evolution? **Full potential largely unexplored!**

Parton Distributions for the LHC workshop

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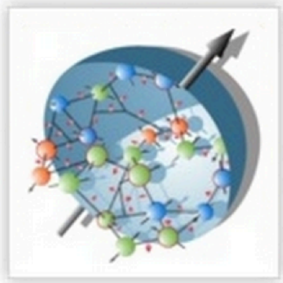

Parton Distributions for the LHC

2015, Feb 15 -- Feb 21

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

Benasque Center for Science, Spain

With the recent discovery of a Higgs-like particle at the Large Hadron Collider (LHC), high-energy physics has entered a new era that emphasizes detailed studies of the properties of this new particle and exploration of the energy frontier in search for Beyond the Standard Model (BSM) dynamics. To fully exploit the LHC potential, theoretical predictions for many process must be provided with unprecedented accuracy. A crucial ingredient of these theoretical prediction are the Parton Distributions of the proton (PDFs). While much progress has been achieved in the last years towards improved determinations of PDFs, the requirements for the upcoming 13 TeV Run II at the LHC require to further development of the existing directions in PDF physics, as well as the exploration of completely new avenues, such as PDFs with electroweak effects or PDFs for NLO Monte Carlo event generators. In addition, exploiting the full power of PDF physics to improve BSM prospects requires a direct interaction between PDF and BSM phenomenology.

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CONFERENCE DATA

Application deadline for this conference is November 30.

- APPLICATION FORM
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- ACCOMMODATION RATES
- LIST OF PARTICIPANTS

Parton Distributions for the LHC workshop

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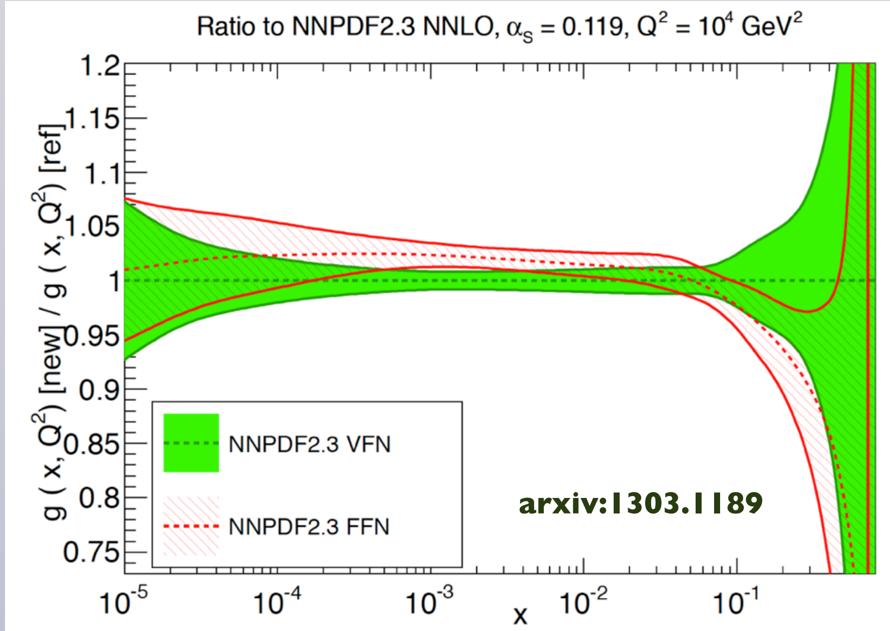
Thanks for your attention!

Extra Material

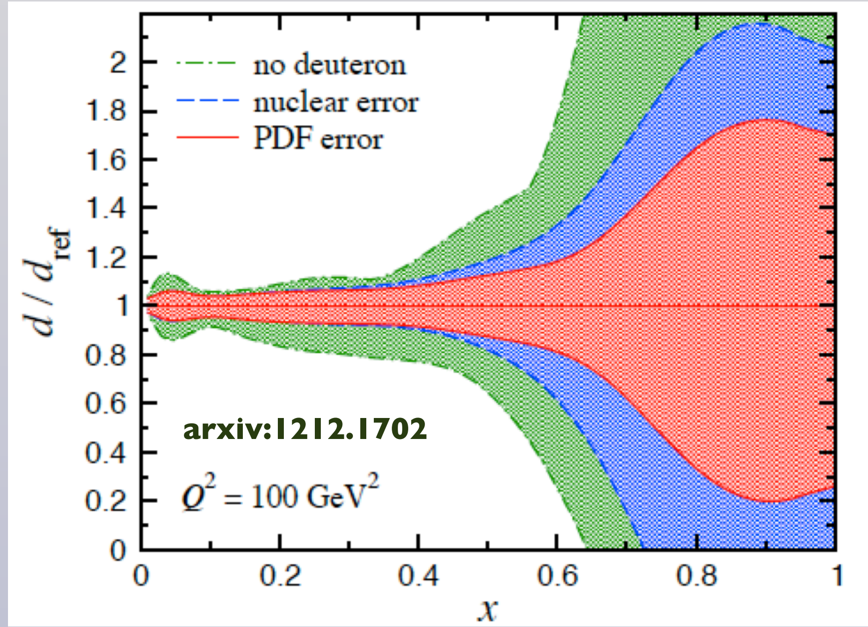
Theory

Theoretical uncertainties on PDFs

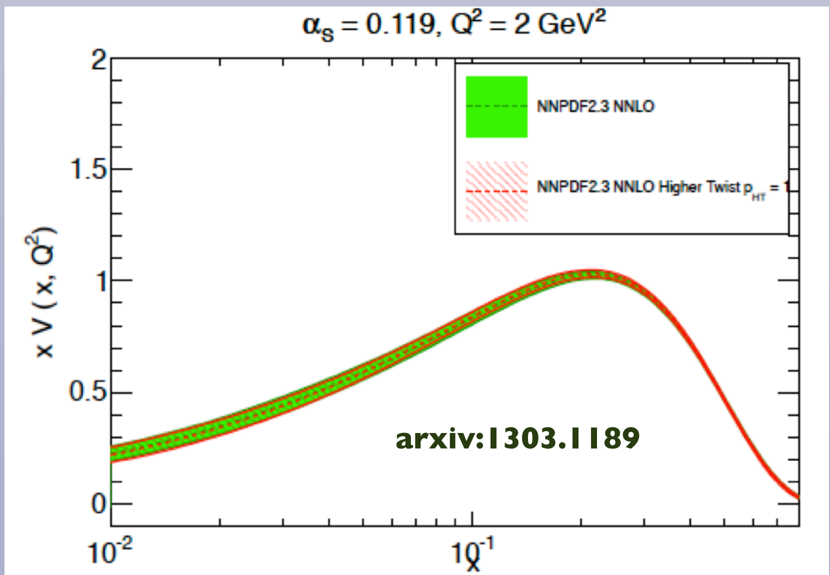
Impact of **VFN vs FFN** (**NNPDF, Thorne**): FFN leads to softer large-x gluon and harder quarks.



Impact of **deuteron corrections** on PDFs and the **d/u ratio at large-x** (**CJ12, NNPDF, MSTW**)



PDFs and alphas **stable** against **higher twists** for standard W^2 cuts (**ABM, MSTW, NNPDF**)



Sensitivity to value of **charm mass**, determinations of **running mass from HERA** (**ABM, HERAPDF, CT**)