NNPDF3.0

Next generation PDFs for the LHC Run II

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Presented on behalf of the **NNPDF Collaboration:**
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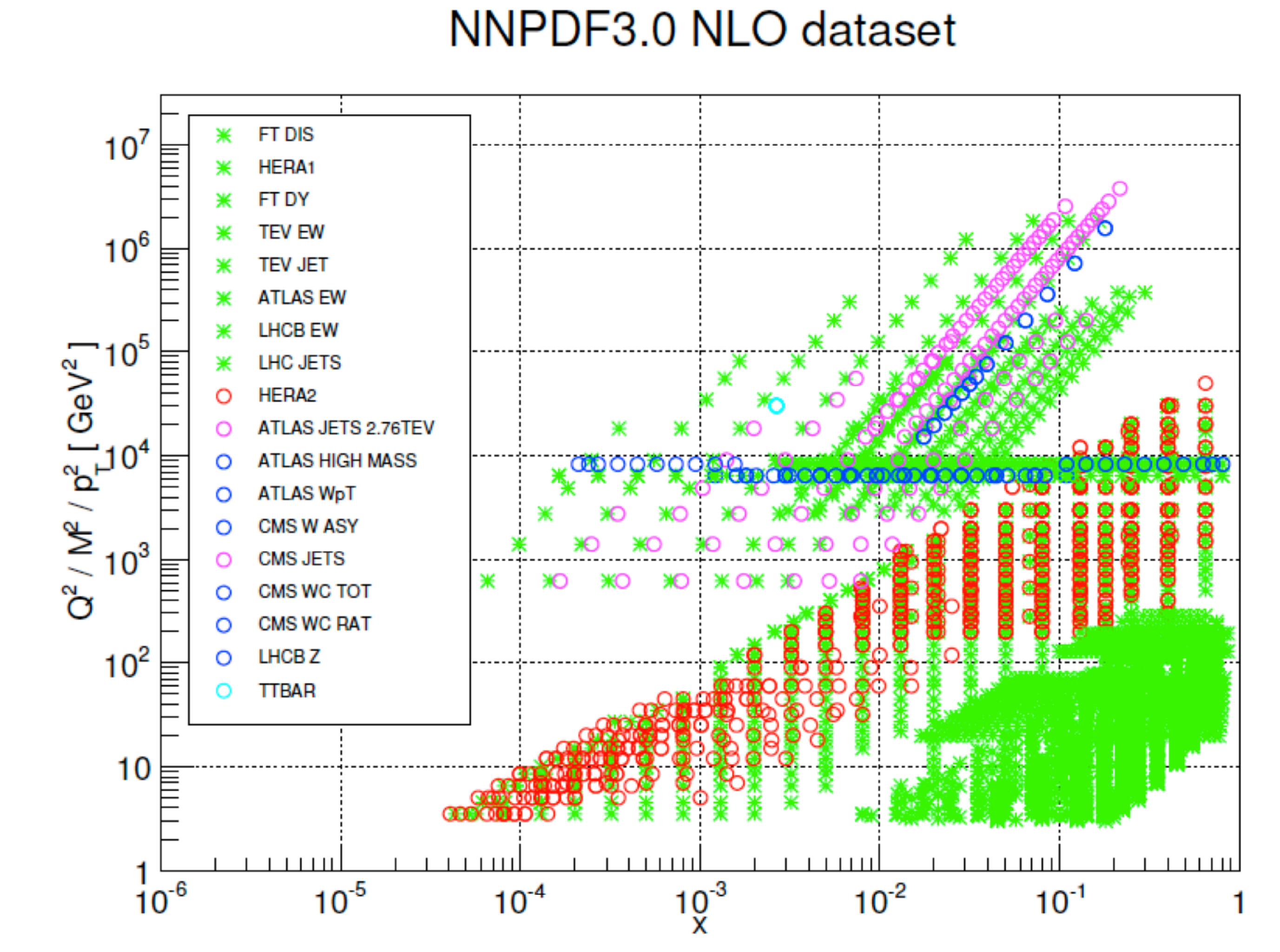
Parton Distributions for LHC Run II

- **PDFs** have been an essential ingredient for **Run I** phenomenology, and will be so even more at the upcoming **Run II at 13 TeV**
- Many crucial LHC analysis benefit from improved PDFs, from **precision Standard Model measurements**, like the W mass determination, and **Higgs boson characterization** to **BSM searches**
- **NNPDF3.0** is the new forthcoming PDF release from the NNPDF Collaboration, a major upgrade that accounts for recent progress in experimental constraints, theory calculations and methodological improvements. **To be released in the next few weeks**.
- In this talk I present **for the first time** the **final NNPDF3.0 sets,** including:
  - ☑ **New experimental data:** HERA-II structure functions, ATLAS and CMS jets, CMS W+charm, ATLAS and CMS Drell-Yan production, top quark production ....
  - ☑ **Improved theory calculations:** Approximate NNLO K-factors for jets, electroweak effects for Drell-Yan data, APPLgrid/FastNLO/aMCfast for all hadronic observables ...
  - ☑ **Fitting methodology:** C++ rewriting of the code, fitting strategy validated on closure tests, extended positivity, optimized Genetic Algorithms minimization ......
  - ☑ **Results** and **implications for LHC phenomenology**

New Experimental Data
LHC & HERA-II

New experimental data

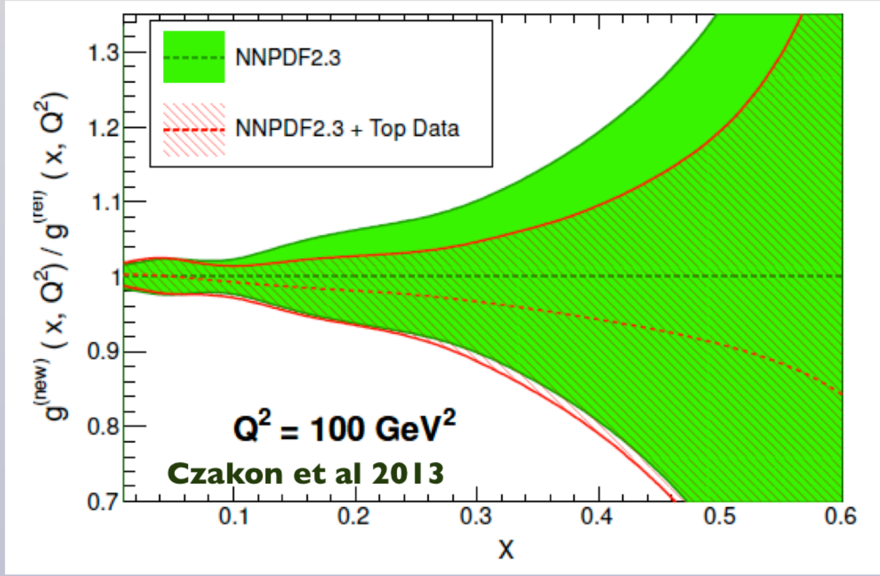
- More than **1000 new data points** from new HERA and LHC **data**
  - ☑ **HERA structure function data:** HERA-II structure functions from H1 and ZEUS, combined HERA F_{2c} cross-sections
  - ☑ **LHC jet data:** CMS **7 TeV inclusive jets** from 2011, ATLAS **2.76 TeV jets** including their correlation with the 7 TeV jet data
  - ☑ **LHC electroweak data:** CMS **muon asymmetries** from 2011, LHCb **Z rapidity distributions** from 2011, CMS **W+charm** production data, ATLAS and CMS **Drell-Yan production**, ATLAS **W** p_T distributions
  - ☑ **ATLAS and CMS top quark pair production data**

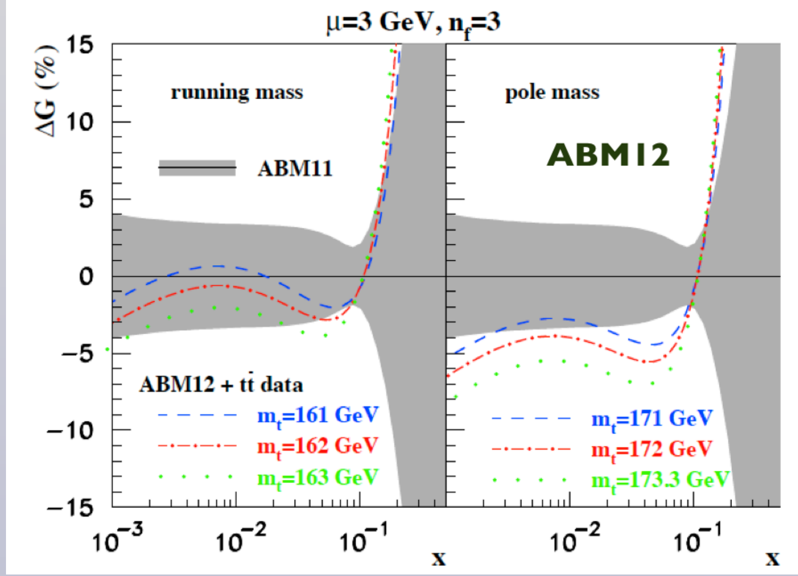


All these datasets **already reasonably well described by NNPDF2.3**

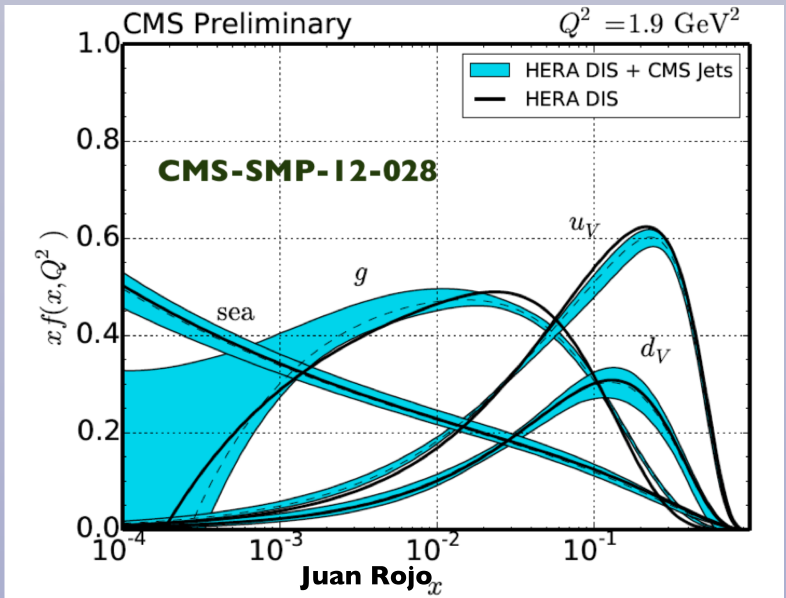
Motivation for new data

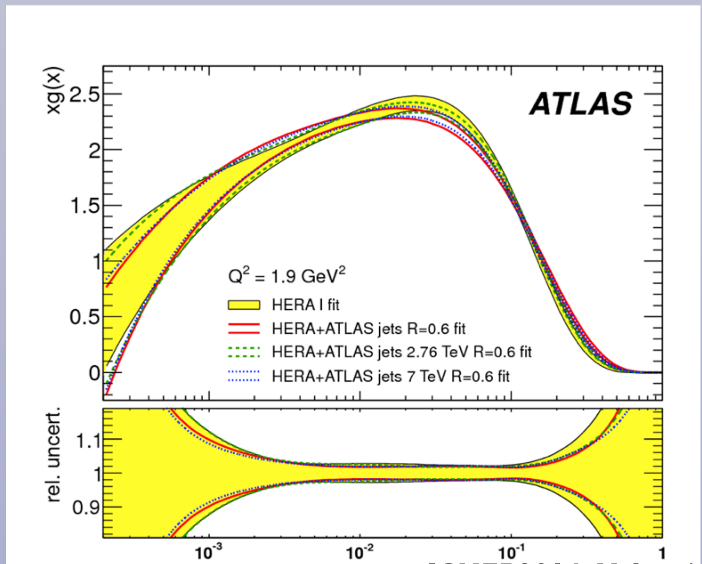
- **Top quark total cross-sections** allow to constrain the **large-x gluon PDF**





- **Jet cross-sections** pin down **medium and large-x gluon** and **large-x quarks**

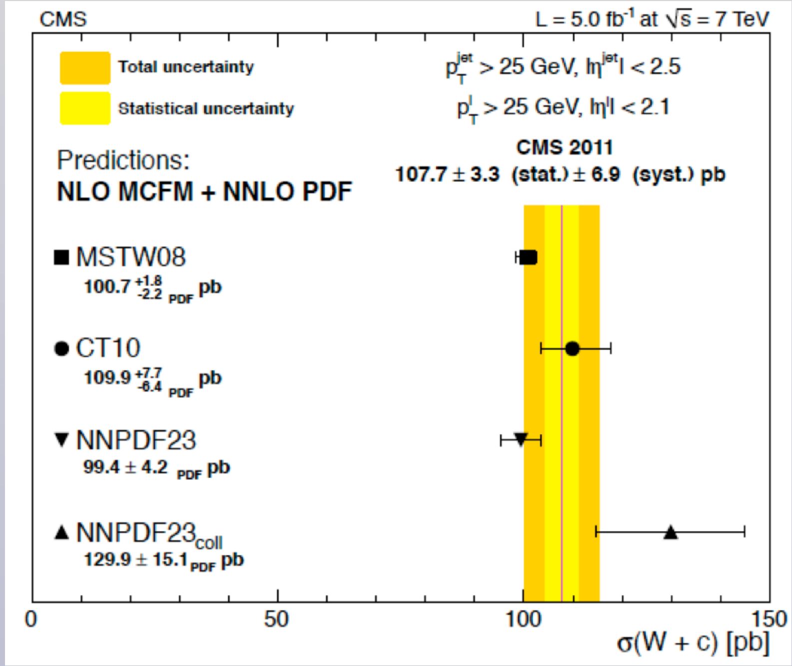


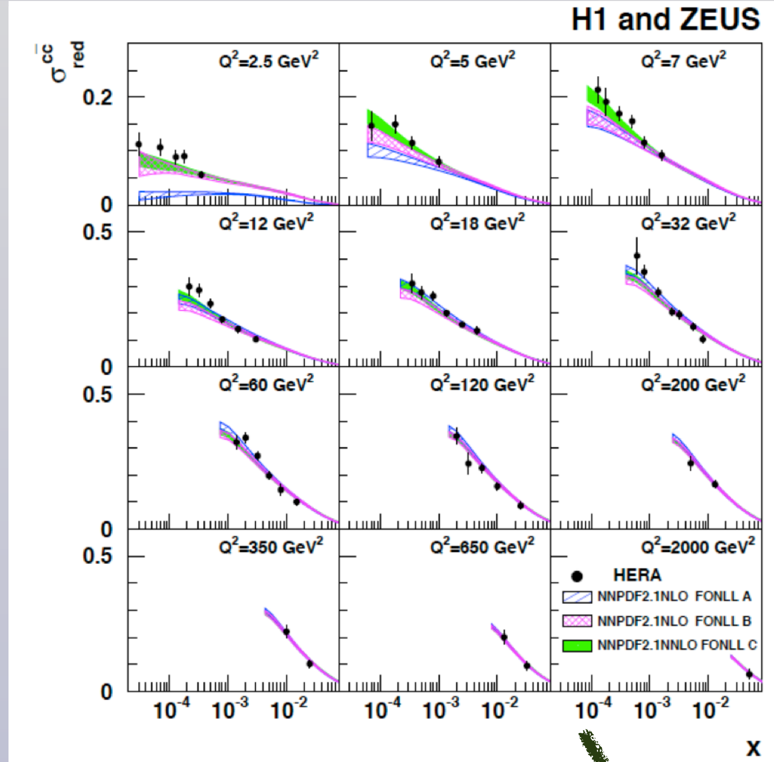


ATLAS data on the **ratio 7 TeV / 2.76 for jet production**, beautiful illustration of the PDF sensitivity of **cross-section ratios between different center-of-mass energies** (Mangano and JR 12)

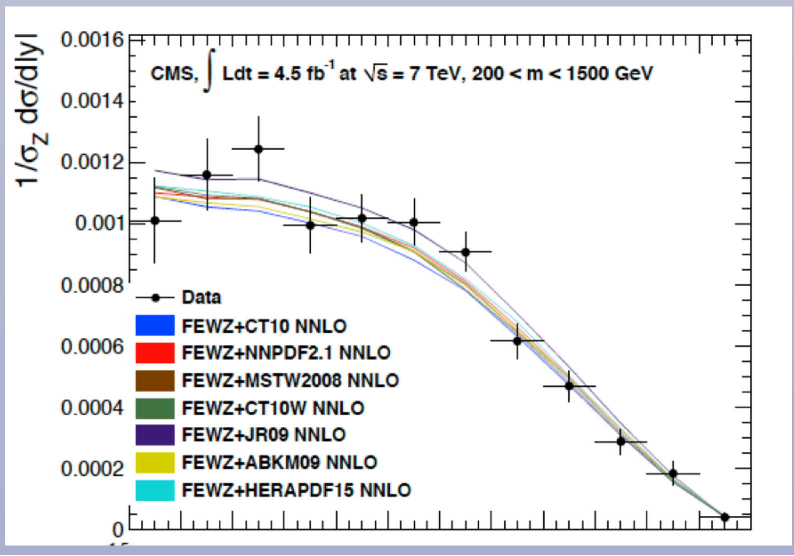
Motivation for new data

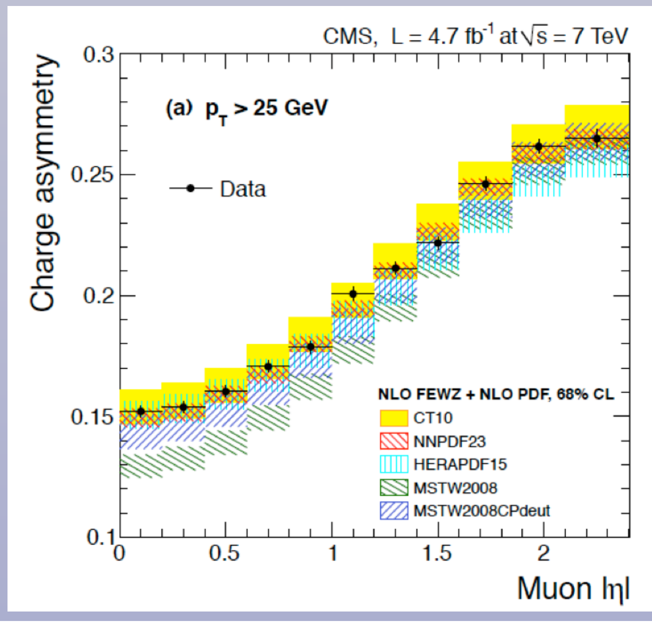
W+charm production data:
directly sensitive to the **strange PDF**





On-shell and off-shell **Drell-Yan data**:
Sensitive to **quark flavor separation**





HERA-II inclusive and charm data:
constrains on **medium and low-x quarks and gluons**

Theory & Tools

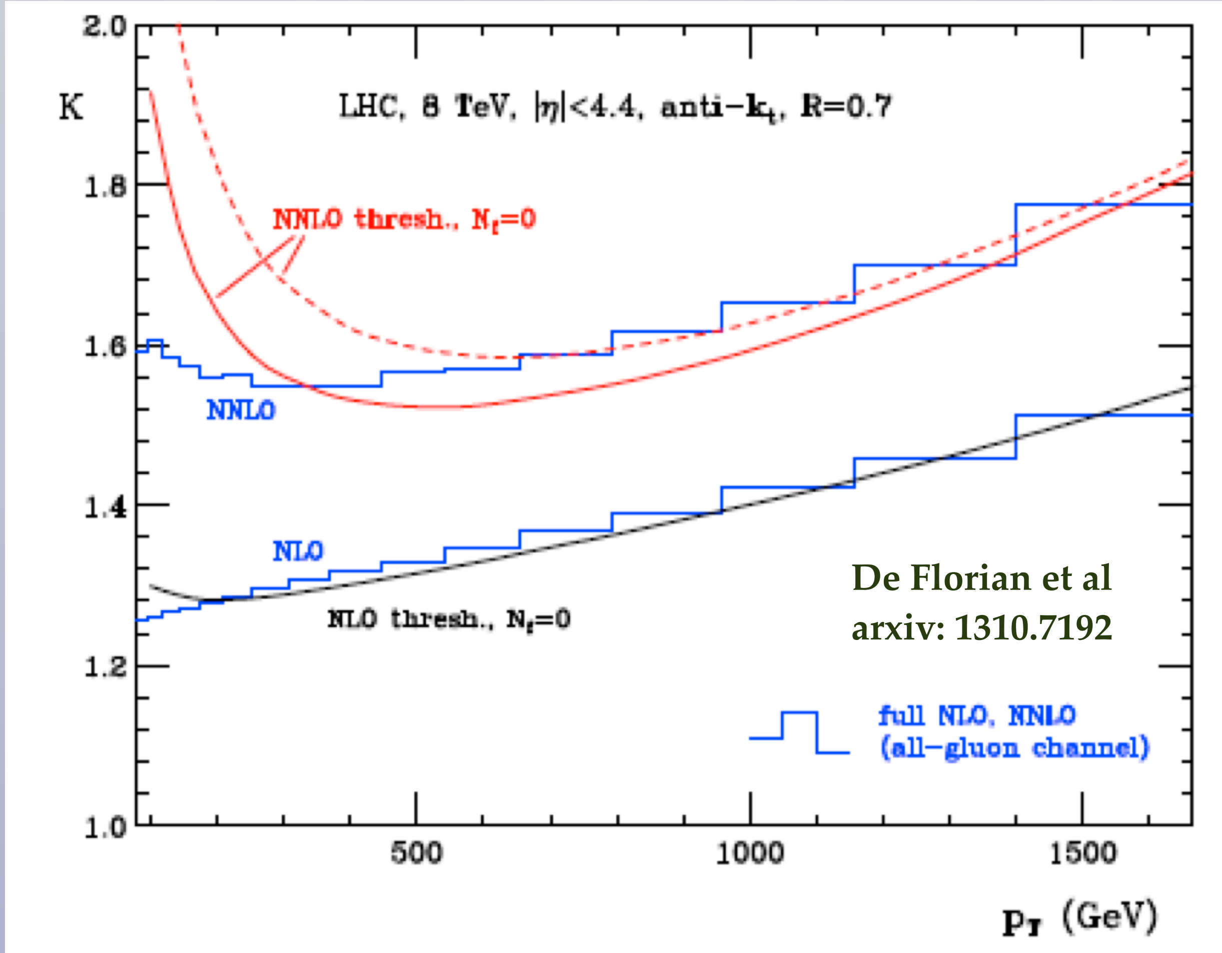
Fast interfaces for NLO calculations

- **(N)NLO QCD calculations** are too CPU-time intensive to be used directly into PDF analysis
- In the recent years, various approaches have been proposed to provide **fast interfaces to NLO calculations**, that can be used directly in PDF analysis, the main ones being:
  - **APPLgrid**: interface to **MCFM** and **NLOJet++** (arxiv:0911.2985)
  - **FastNLO**: interface to **NLOJet++** (arxiv:1109.1310)
  - **aMCfast:** interface to **Madgraph5_aMC@NLO** using the APPLgrid library (arxiv:1406.7693)
  - **FastKernel:** NNPDF internal (arxiv:1002.2312)
- In NNPDF3.0 we systematically use these **fast NLO calculations** for all collider data:
  - **NLOjet++/FastNLO:** CDF and CMS jet data
  - **NLOjet++/APPLgrid:** ATLAS jet data
  - **MCFM/APPLgrid:** ATLAS, CMS and LHCb electroweak gauge boson production, CMS W+charm production, ATLAS and CMS top quark data
  - **Madgraph5_aMC@NLO/aMCfast:** Higgs xsec in gluon fusion for positivity constraints
- For the **NNLO fits**, the NLO calculation are supplemented with **bin-by-bin C-factors** from the corresponding NNLO calculations: **top++** for top data, **FEWZ/DYNNLO** for Drell-Yan data,...

$$C_{\rm fact} = \frac{\hat{\sigma}^{\rm NNLO} \otimes \mathcal{L}^{\rm NNLO}}{\hat{\sigma}^{\rm NLO} \otimes \mathcal{L}^{\rm NNLO}}$$

Jets in NNLO global fits

- The recent calculation of the **gluon-gluon channel NNLO jet cross sections** (arxiv:1310.3993) is an important milestone for inclusion of jet data in NNLO 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
- 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**



Our strategy is the following:

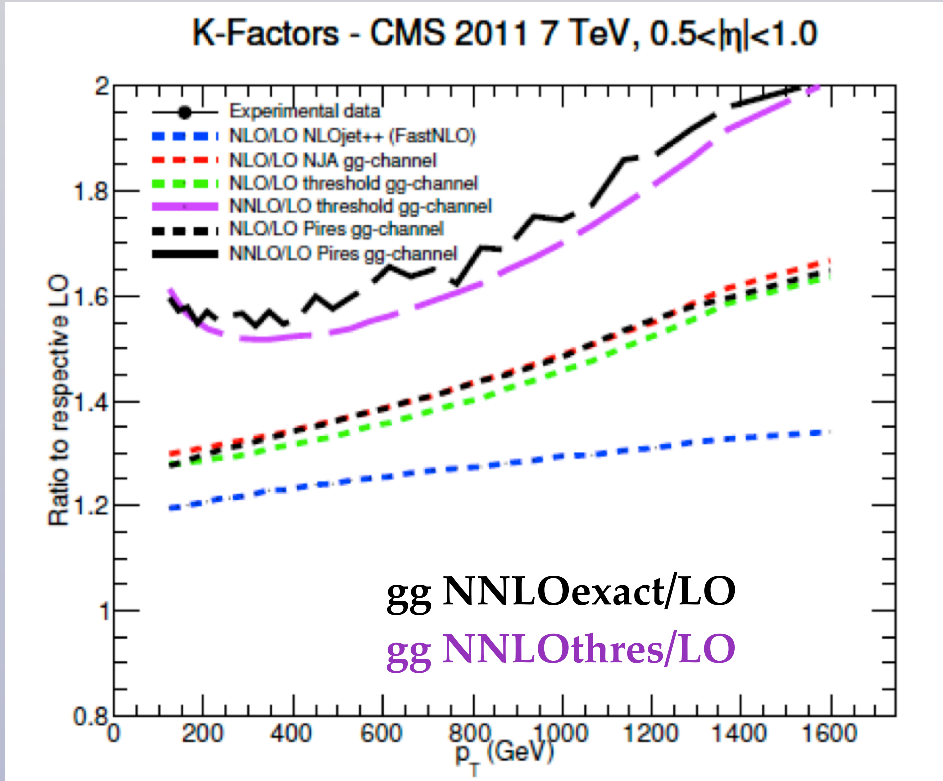
- Compute, for all jet data, the **NNLOexact** and **NNLOapprox** in the **gg channel**
- Use the exact calculation to determine the **range of validity** of the threshold calculation
- With this information, restrict the range of fitted jet data and use the **NNLOapprox calculation** accounting for all partonic channels
- To be **conservative**, we only include data points for which:

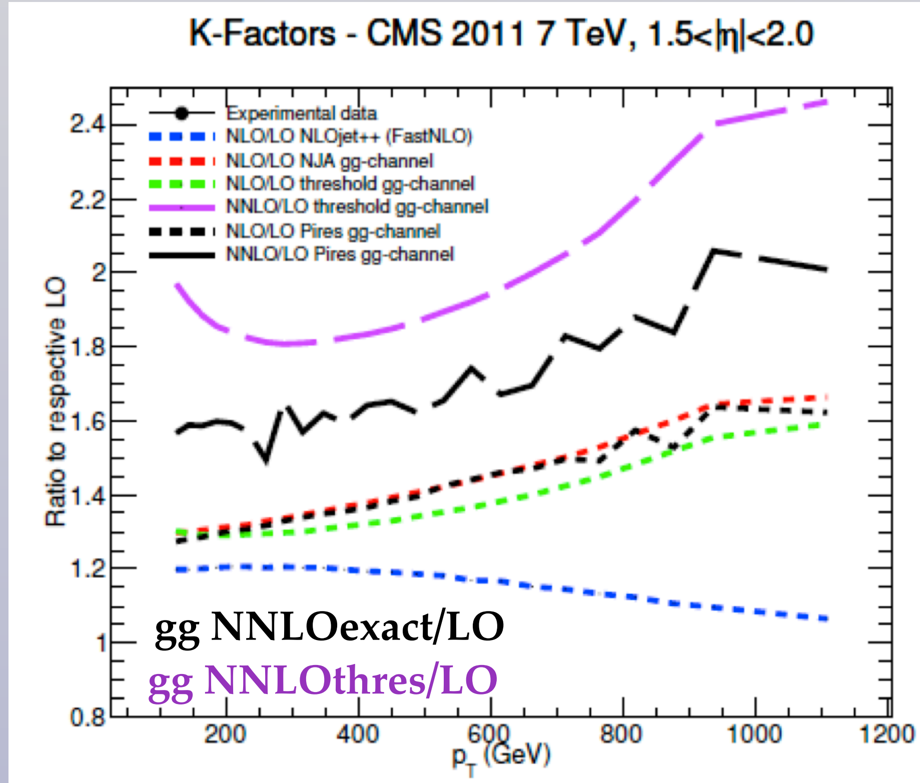
NNLOapprox < (**1.15** NLOexact)

Jets in NNLO global fits

- Therefore, **comparison with exact gg NNLO** can determine for which values of jet p_T and η the **NNLOthres** calculation can be trusted (assumption: NNLO K-factor similar in all channels)

S. Carrazza and J. Pires, in preparation





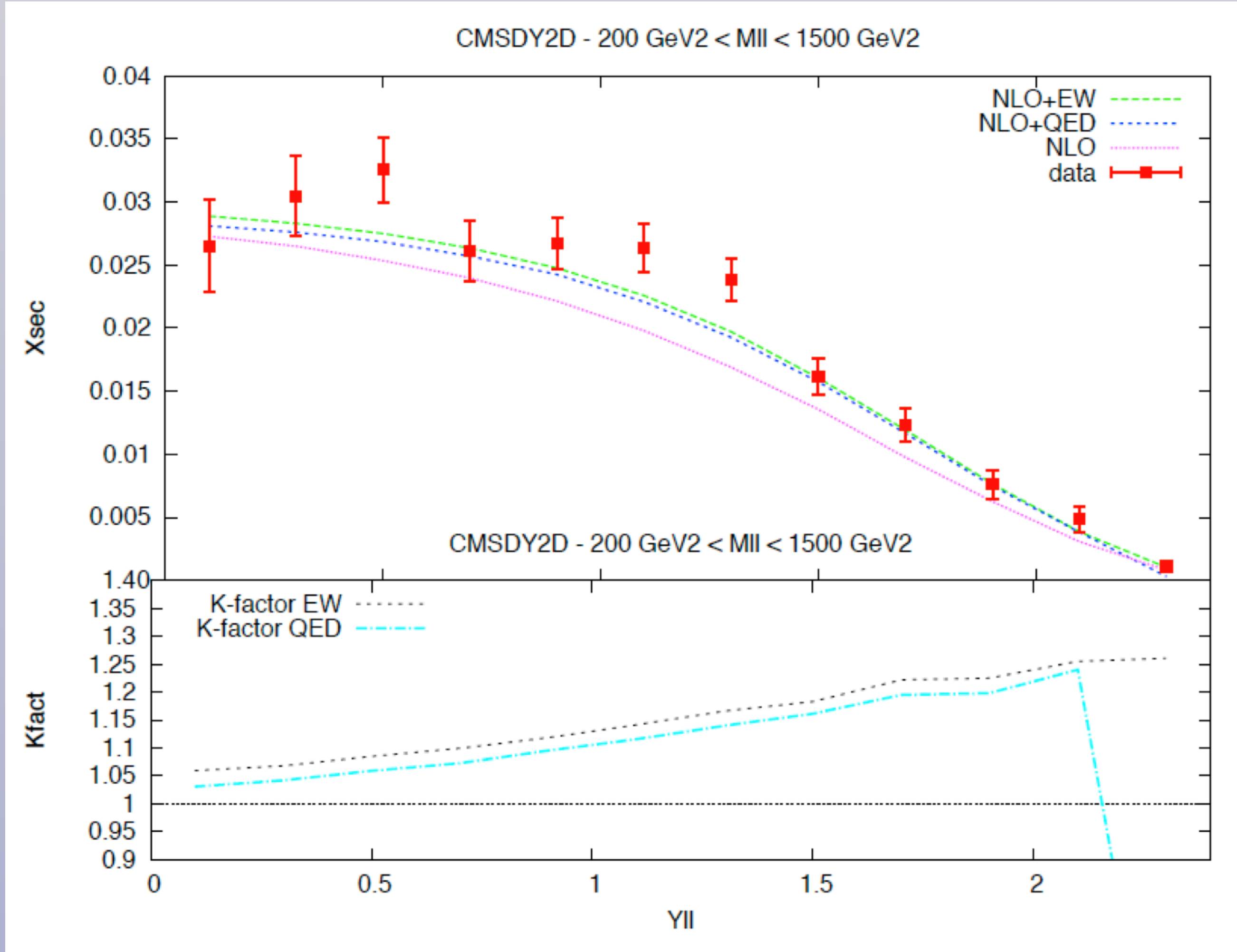
- We **discard jet data** in the kinematic range where the NNLO threshold calculation cannot be trusted
- This restriction will be superseded as soon as **full exact NNLO** results available
- This approximation allows to **keep a maximum of jet data in the NNLO fit**, without this data PDF uncertainties in the large-x gluon are much larger

Electroweak corrections

- Electroweak corrections are important for **W and Z** production specially at **large invariant masses and/or transverse momentum**

- In NNPDF3.0, full NLO electroweak corrections for all **neutral current Drell-Yan** datasets have been computed with **FEWZ3.1**

- As an illustration, **high-mass Drell-Yan** from CMS 7 TeV:



Electroweak corrections up to **25% at the highest dilepton masses**

QED corrections also large, but affected by the large uncertainties of **γ(x,Q)**

QED corrections not included in the NNPDF3.0 QCD-only fit (NNPDF3.0 QED to follow)

For 14 TeV, including EW corrections for most datasets will be mandatory

Methodology
&
Closure Testing

NNPDF3.0 is really NNPDF++

Completion of a major software development project: rewriting of most of the **NNPDF fitting framework** from **Fortran 77** to **C++** and **Python**

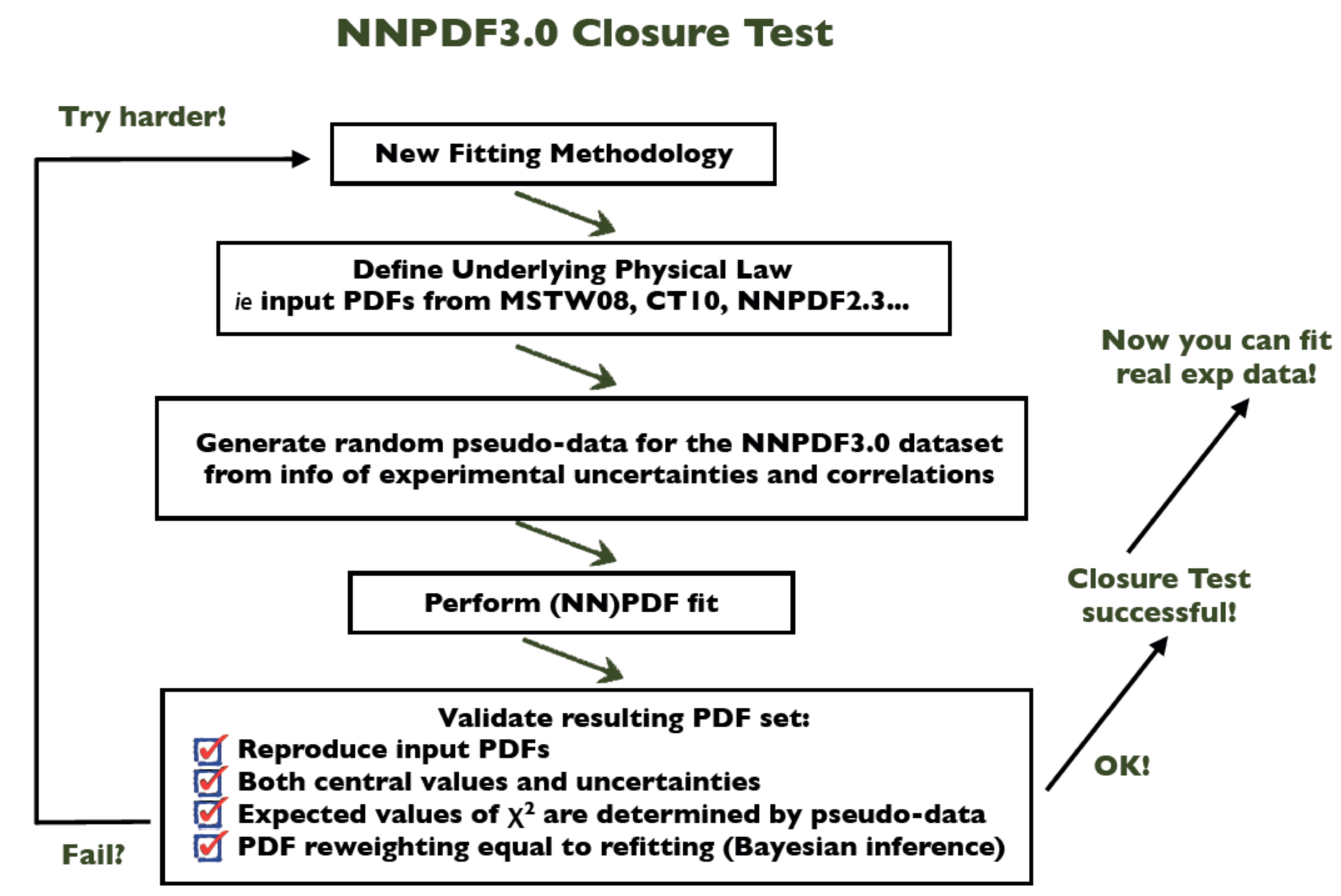
Lines of code by language in NNPDF3.0 fitting framework

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

- ☑ **Modular structure**: each dataset is an individual object, with the associated theory encapsulated in individual **FK tables:** easy to include new measurements and to upgrade theory for existing ones
- ☑ **Greatly improved fitting efficiency**: main bottleneck for PDF fits is convolution between input PDFs and theory, performed here with **assembly-like structure**
- ☑ Fits can now be easily parallelized to run in **clusters** and in **Graphical Processing Units**
- ☑ Guarantees **robustness and stability for NNPDF development** in the medium and long term

Closure Testing

Validation and optimization of fitting strategy performed on **closure test with known** underlying PDF set



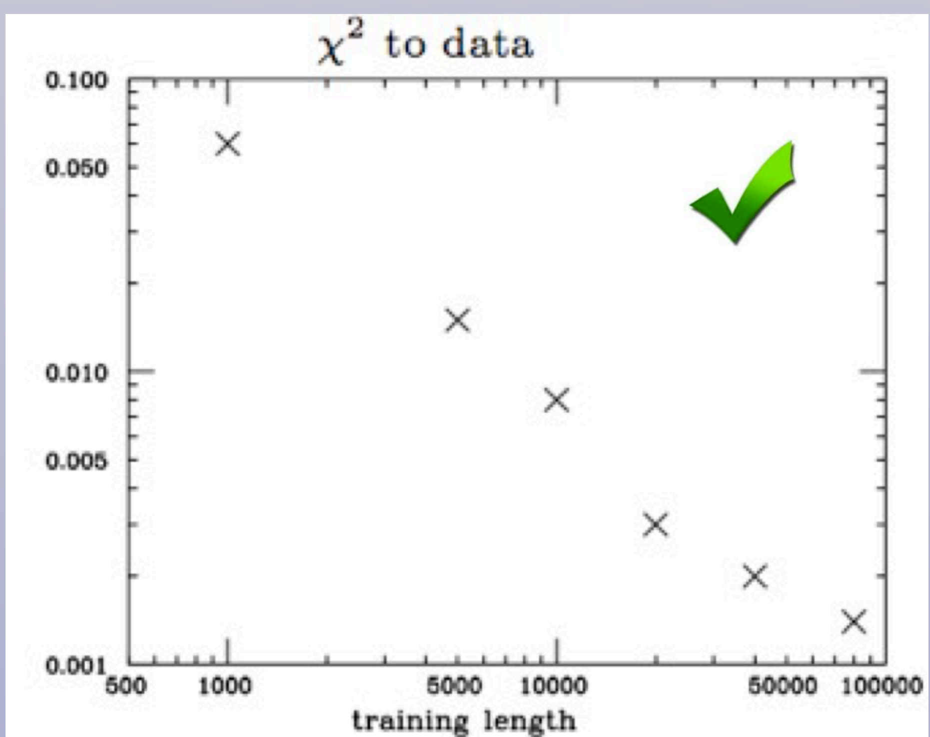
Closure Testing

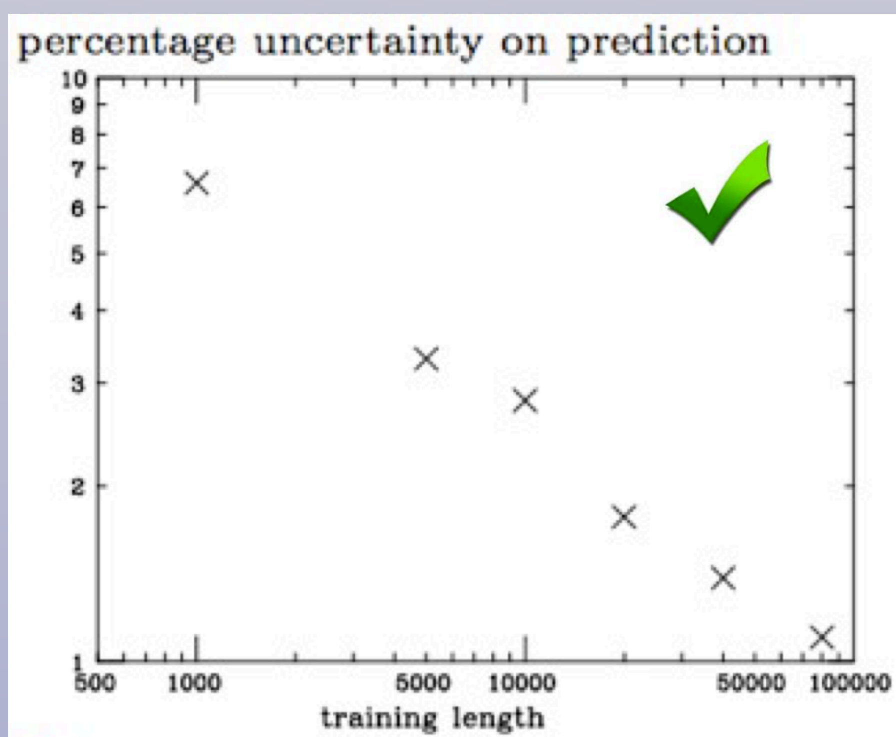
Validation and optimization of fitting strategy performed on **closure test** with **known** underlying PDFs

Three levels of closure tests:

- **Level 0:** no fluctuations on pseudo-data, no Monte Carlo replica generation
- **Level 1**: with fluctuations on pseudo-data, no Monte Carlo replica generation
- **Level 2**: with fluctuations on pseudo-data, with Monte Carlo replica generation

Example: **Level 0 closure tests -** Fit results successfully **converge towards underlying law**: central **χ^2 to pseudo-data tends to zero**, same for PDF uncertainties on predictions (all replicas converge on same underlying law)

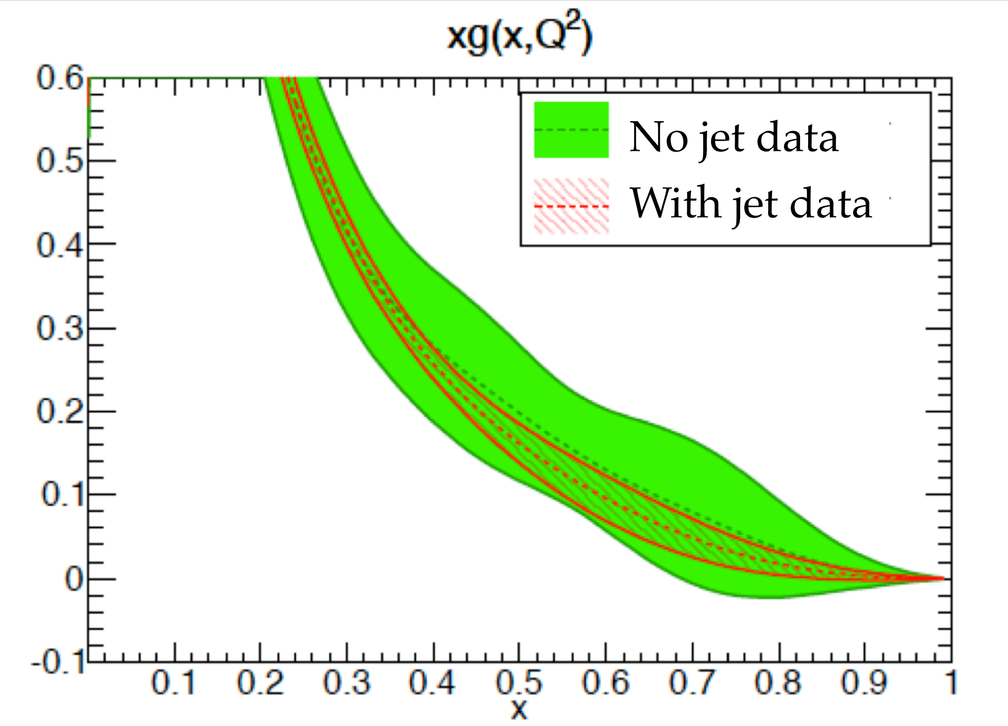




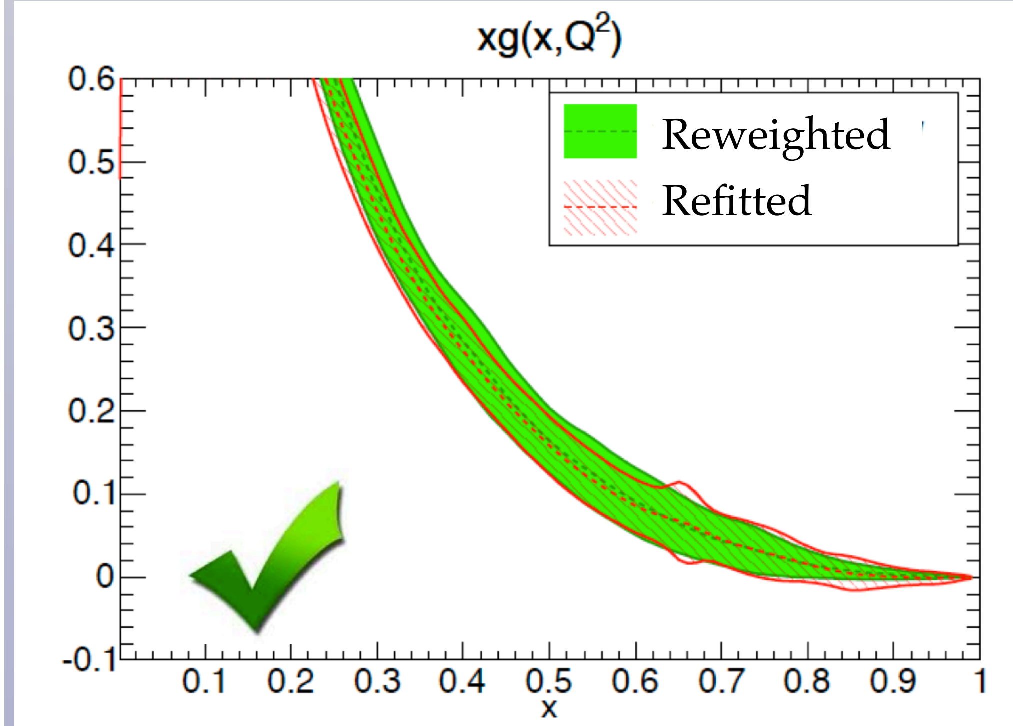
PDF reweighting

- **Statistically identical results** should be obtained when **refitting** or when **reweighting,** even more so in a **closure test**
- Thus **Bayesian inference** can be used as the **ultimate closure test**, sensitive to **all the moments** of the refitted / reweighting PDFs, not only central value and error
- As an illustration, compare effects of **CDF, D0 and ATLAS jet data** included by refitting and by reweighting. Compare both **NNPDF** and **Giele-Keller** prescriptions.

Fit wo jet data vs Fit with jet data



Fit with jet data vs RW with jet data



Note large uncertainties on gluon from missing jet data

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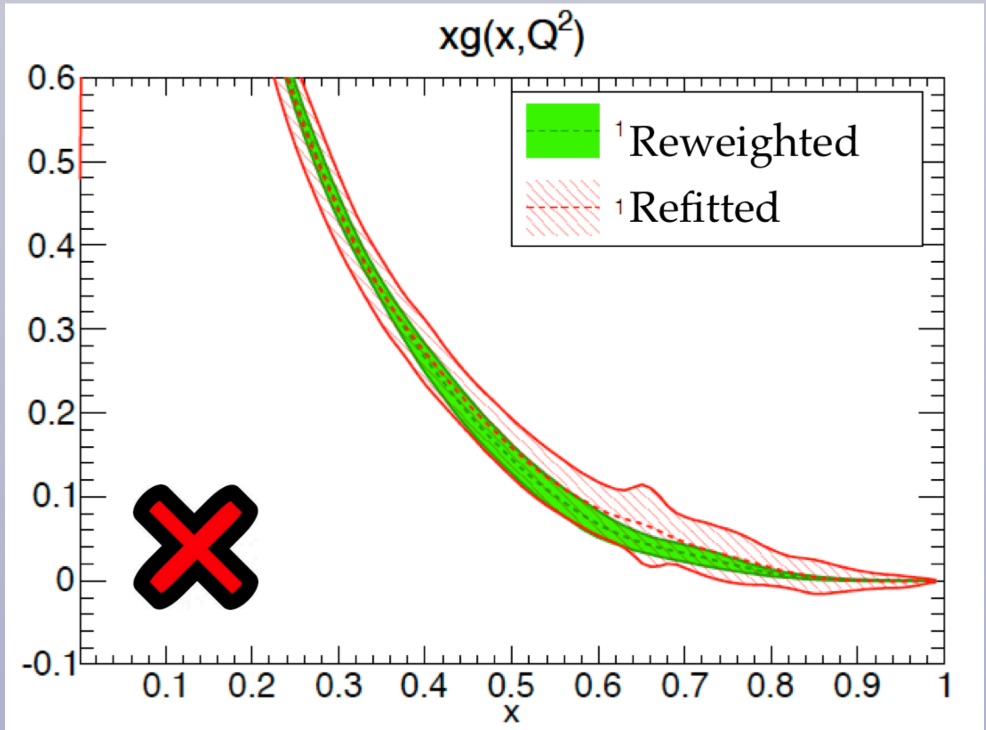
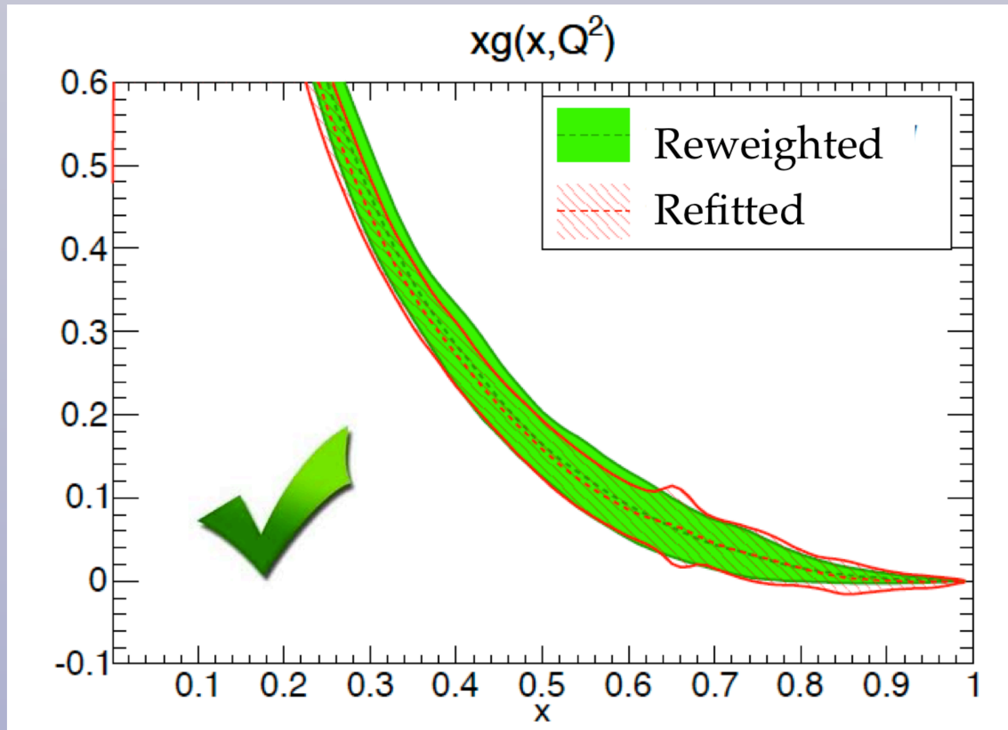
- As an illustration, compare effects of **CDF, D0 and ATLAS jet data** included by refitting and by reweighting. Compare both **NNPDF** and **Giele-Keller** prescriptions.

Giele-Keller $$w_k^G = \frac{e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^N e^{-\frac{1}{2}\chi_k^2}}.$$

NNPDF $$w_k = \frac{(\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}{\frac{1}{N}\sum_{k=1}^N (\chi_k^2)^{\frac{1}{2}(n-1)} e^{-\frac{1}{2}\chi_k^2}}$$

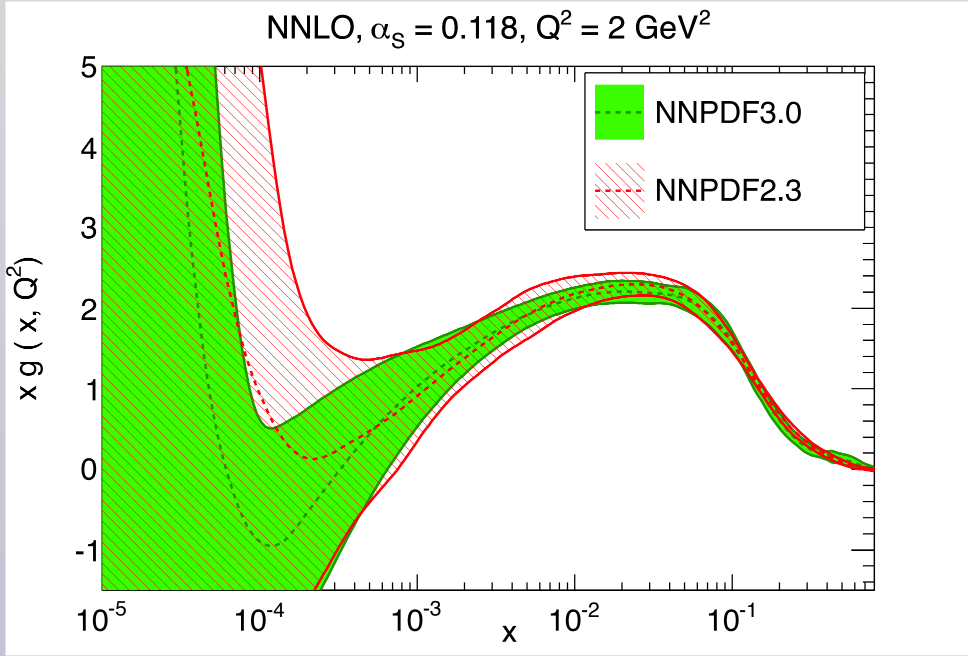




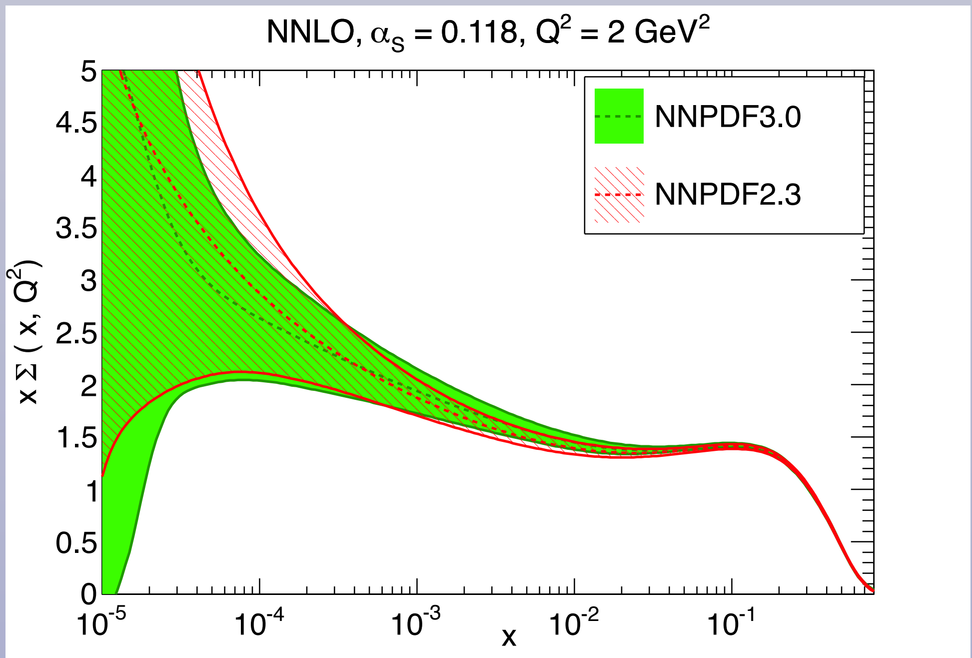
Refitted vs Reweighted

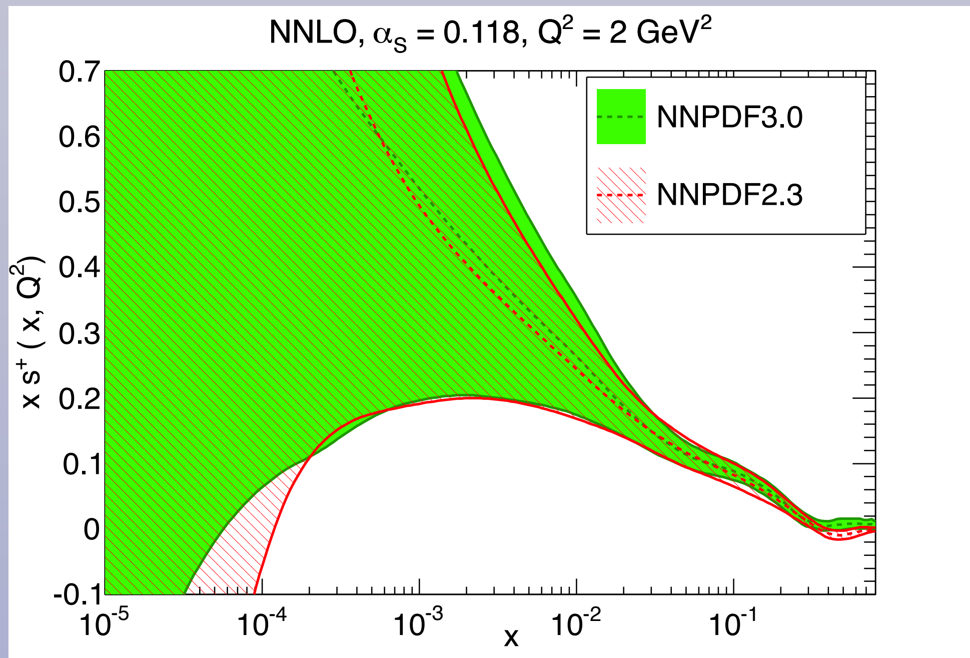
NNPDF3.0
Results &
Implications for the LHC

The NNPDF3.0 parton distributions

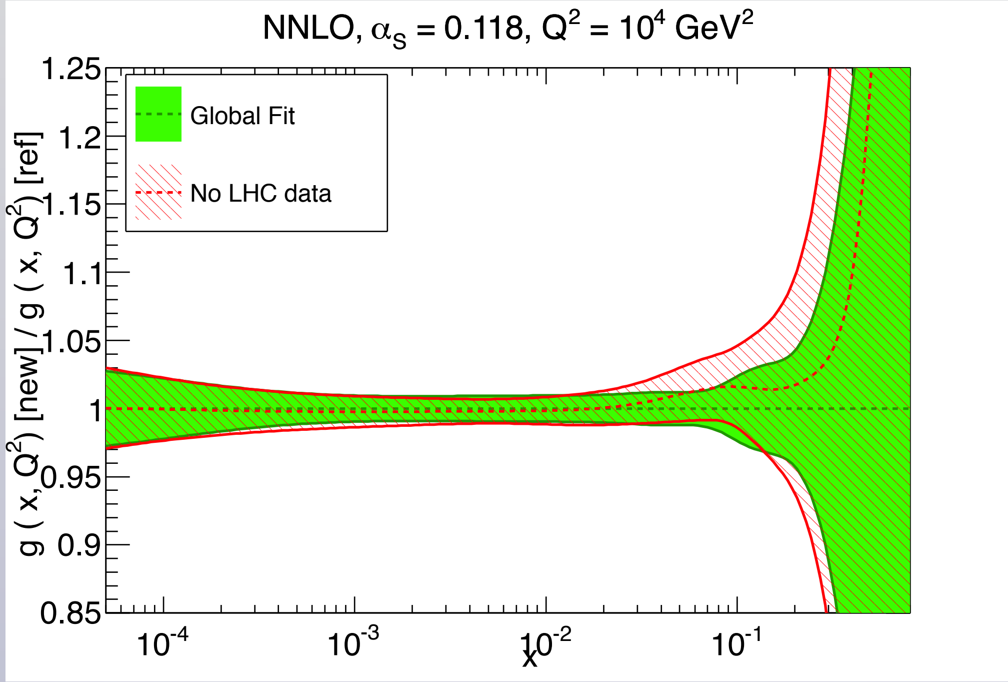


- Reasonable agreement between NNPDF2.3 and NNPDF3.0: as expected, since **all the new HERA and LHC data** already well described in NNPDF2.3
- Differences between PDFs at the 1-sigma level at most: impact of **new data** and of **updated theory and methodology**
- **PDF uncertainties are reduced** in many cases: small and large-x gluon, down quarks, strangeness...

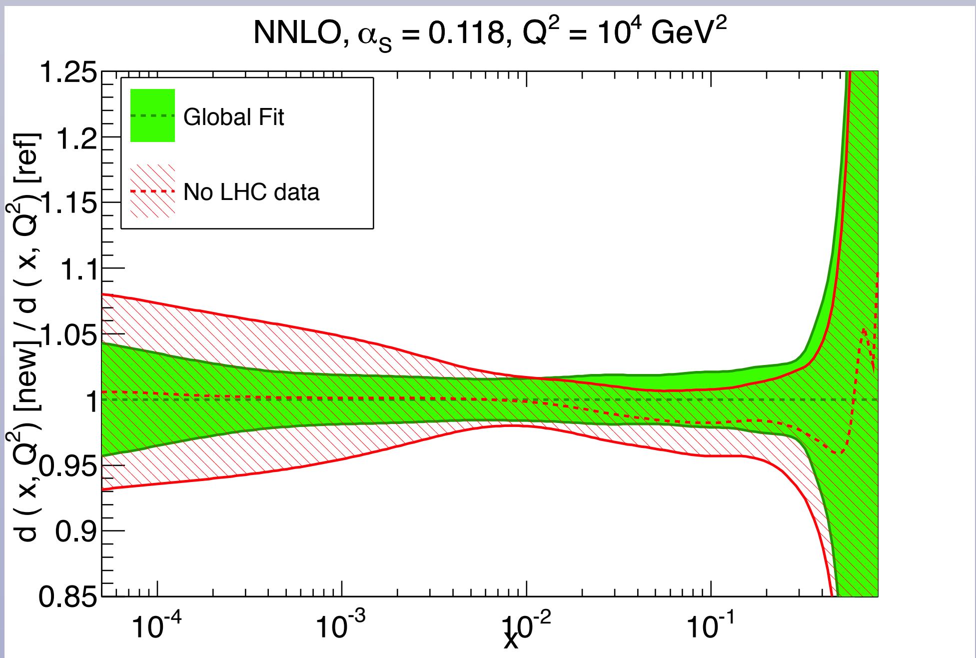


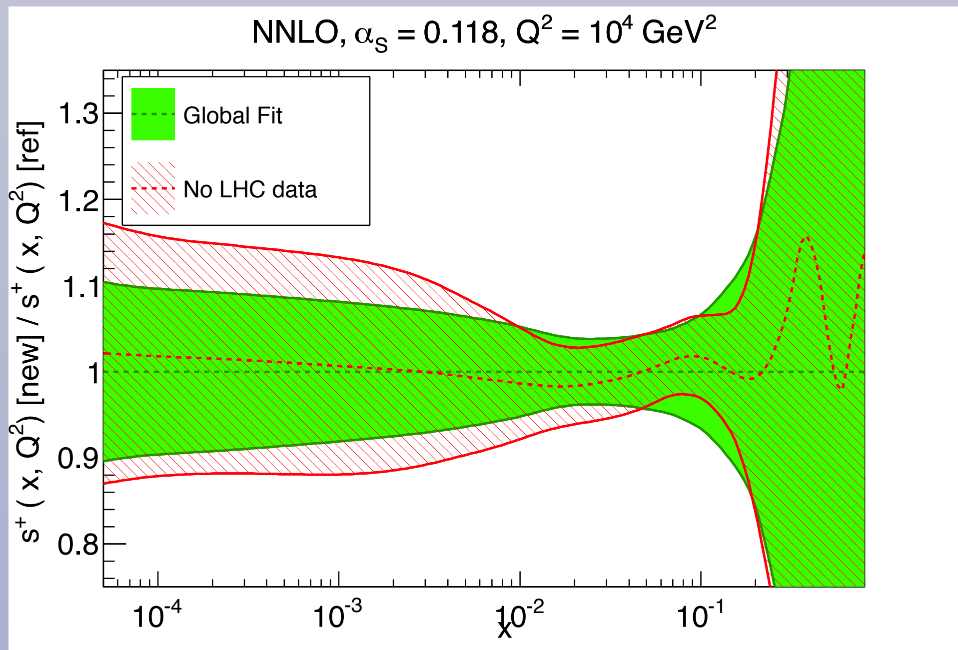


Impact of LHC data

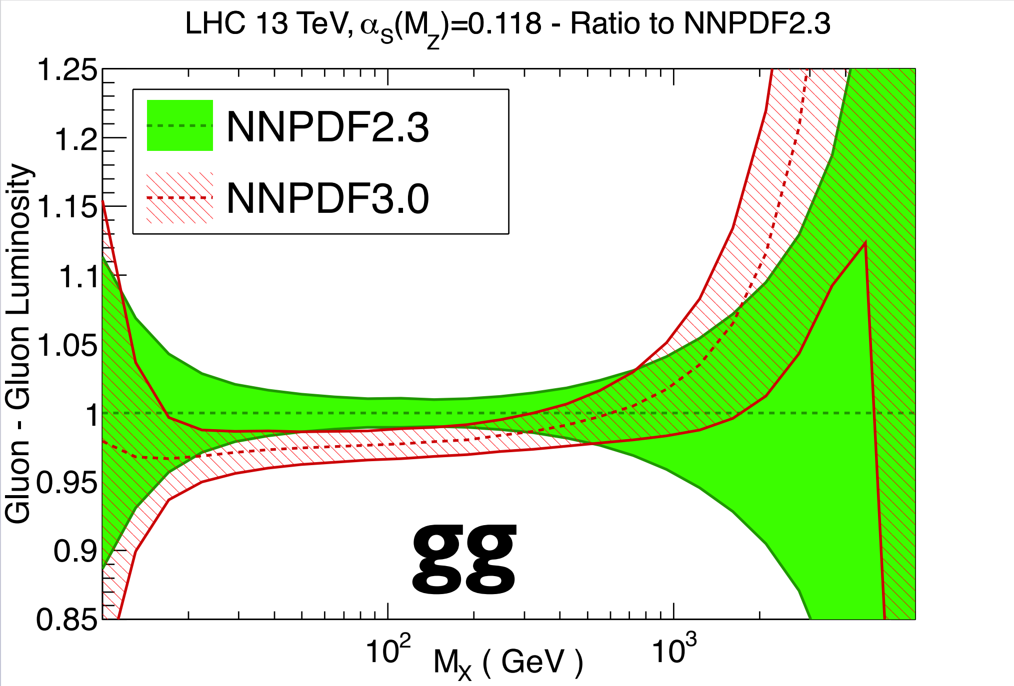


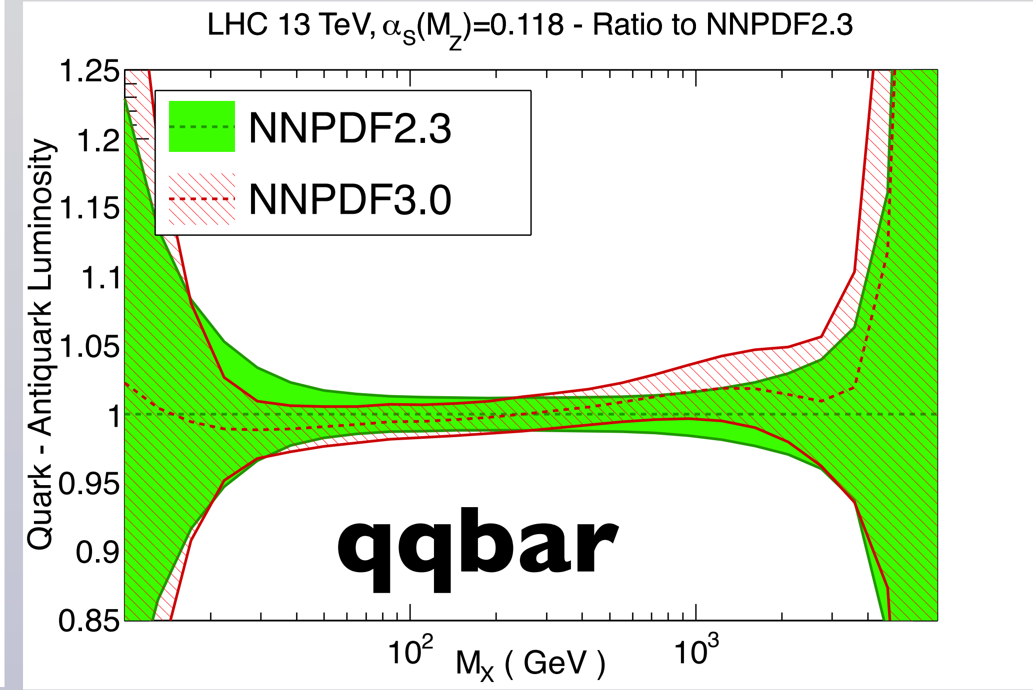
- Compare global NNPDF3.0 fit with a fit **without LHC data**
- PDF uncertainties on **large-x gluon** reduced due to **top quark and jet data**
- PDF uncertainties on **light quarks** reduced from the **Drell-Yan** and **W+charm data**
- The **description of all new LHC data**, already good in NNPDF2.3, is further improved in NNPDF3.0

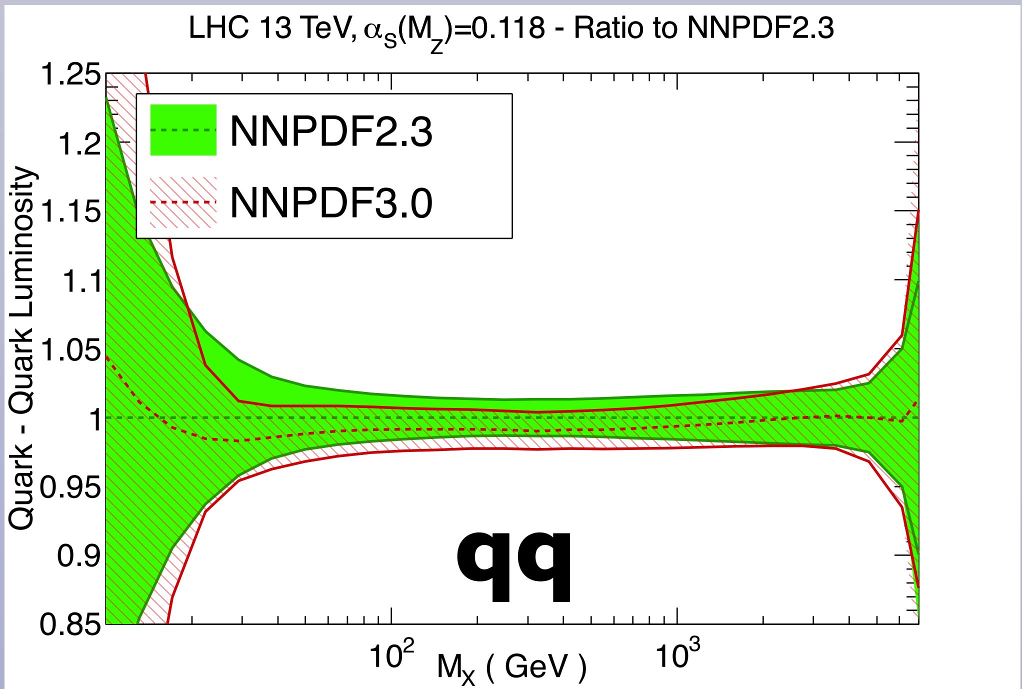




PDF luminosities

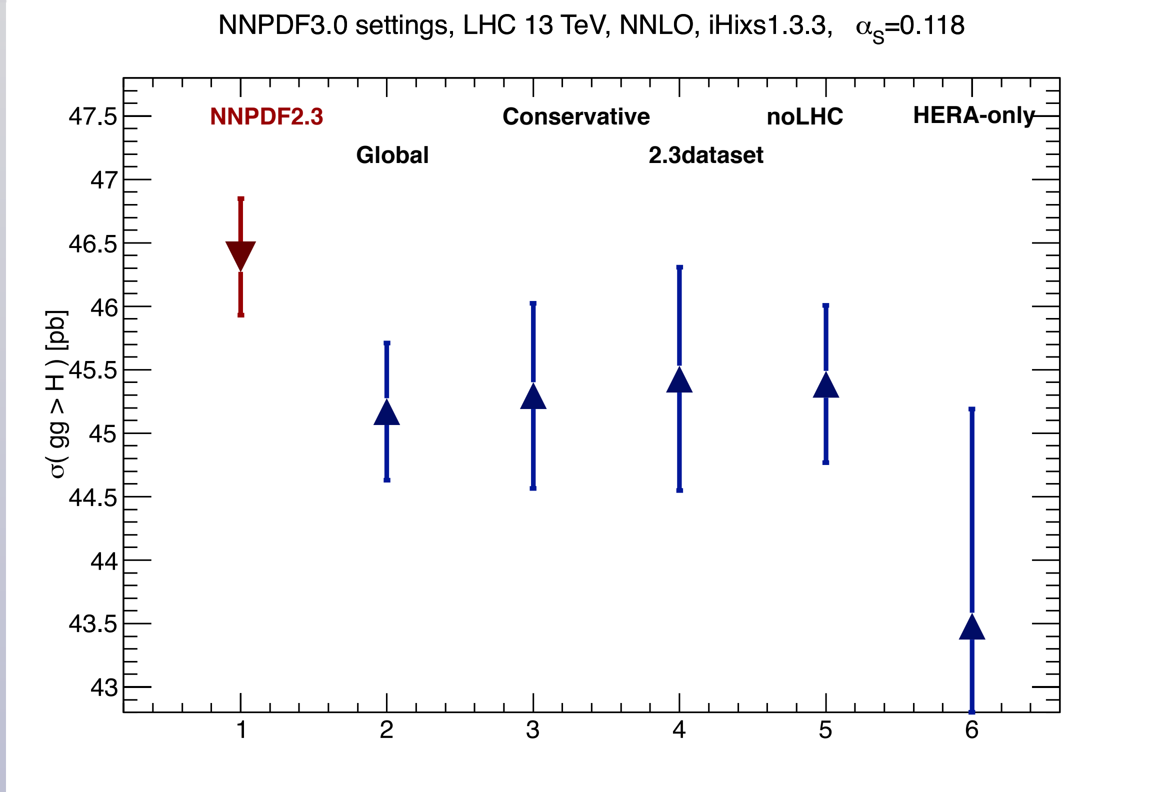






- **PDF luminosities** are useful to translate differences in PDFs into differences in LHC cross-sections
- For **quarks,** luminosities are similar between 2.3 and 3.0. **Antiquarks** in 3.0 at large masses are harder than in 2.3
- More differences for the **gluon-gluon luminosity**. NNPDF3.0 softer by about 1-sigma wrt NNPDF2.3 for M< 500 GeV: **implications for Higgs production**

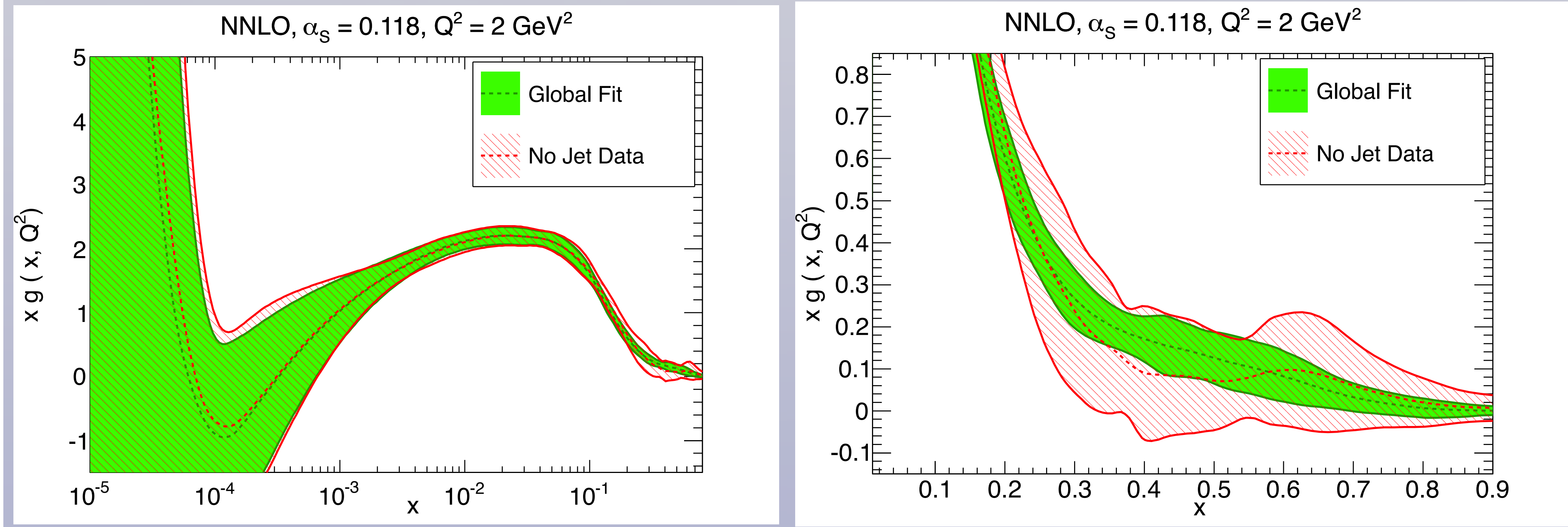
Higgs production in gluon fusion



- The softer gg luminosity in NNPDF3.0 leads to a **decrease in the ggH xsec** at the LHC 13 TeV
- This effect arises from the combination of the **improved methodology**, based on closure tests, and the **new HERA-II and LHC data**
- Remarkable **stability of the NNPDF3.0 predictions** with respect to the fitted dataset
- Interesting to compare with predictions of the **upcoming updates** from CT, HERAPDF and MSTW.
- In the pipeline: systematic comparison of NNPDF2.3 and NNPDF3.0 for a **wide range of LHC observables** using **MadGraph5_aMC@NLO**

Impact of jet data

- **Removing all jet data** from the NNLO global fit (until exact NNLO available) is not an option: substantial increase in **large-x gluon PDF uncertainties**
- Using the **NNLO threshold calculation**, benchmarked with the **exact NNLO results the gg channel**, allows to make the most of the **Tevatron and LHC jet data** until full NNLO result available
- Remarkably, in **NNPDF3.0 the central value for g(x) in jetless fit** is within 1-sigma of the global fit result: **consistency** between jet data and all other datasets



Summary & Outlook

Summary and outlook

NNPDF3.0 is the new upcoming release from the NNPDF collaboration.

It represents a **substantial improvement over NNPDF2.3** both in terms of data, theory and methodology:

- ☑ **Data:** all available **H1 and ZEUS HERA-II data included**, and many new **LHC** measurements from **ATLAS, CMS, LHCb** including W asymmetry, W+charm, inclusive jets, high and low mass Drell-Yan, top quark production, ...
- ☑ **Theory:** Improved **approximate NNLO K-factors for jet data** based on the partial exact NNLO results, **electroweak corrections** included for all relevant data, FONLL-B for NLO sets
- ☑ **Methodology:** fitting strategy validated using **closure tests,** optimized Genetic Algorithms, extended positivity, fast Bayesian regularization, PDF fitting basis independence ....

LO, NLO and NNLO sets for a range of α_S **values** will become available in **LHAPDF6**

Also PDF sets based on **different datasets,** PDFs sets in **different VFN schemes,** ...

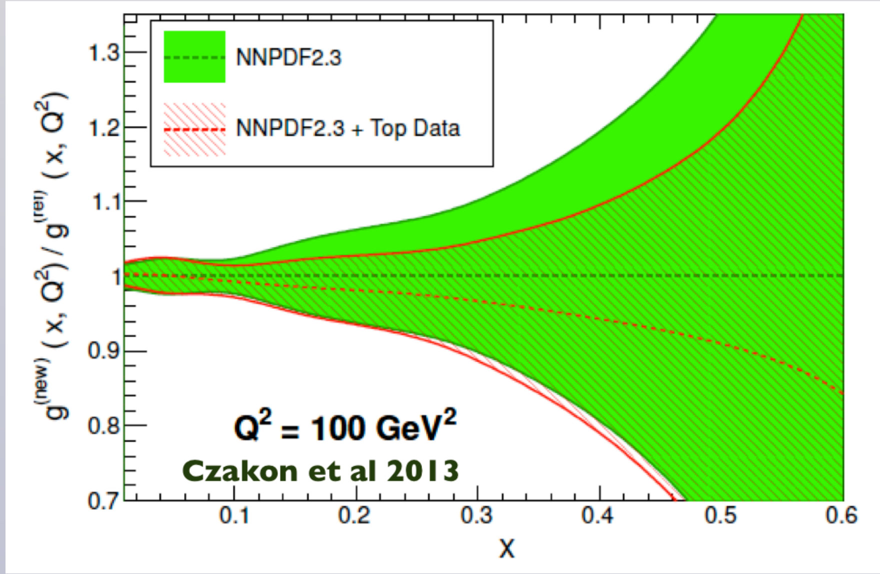
In the medium and long term, **NNPDF development plans**:

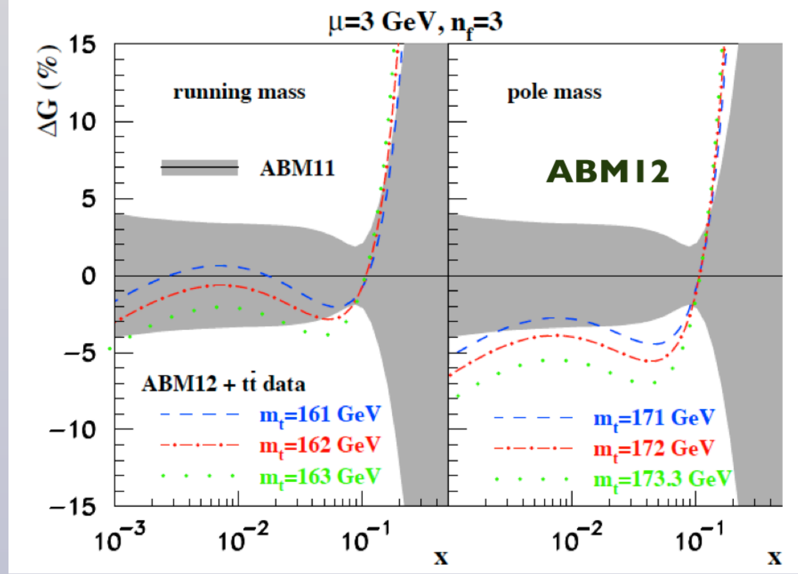
- Include all relevant **LHC Run I data**: Complete set of 8 TeV measurements, high pT Z+jets, direct photon production. Then from 2015 also add **LHC Run II data**
- **Upgrade theory calculations** as they become available: NNLO for top quark differential distributions, exact NNLO for jets and for Z+jets
- Produce NNPDF3.0 sets with **QED corrections**, **intrinsic charm**, threshold and high-energy **resummation,** as well as PDF sets specific for NLO **Monte Carlo event generators**

Extra Material

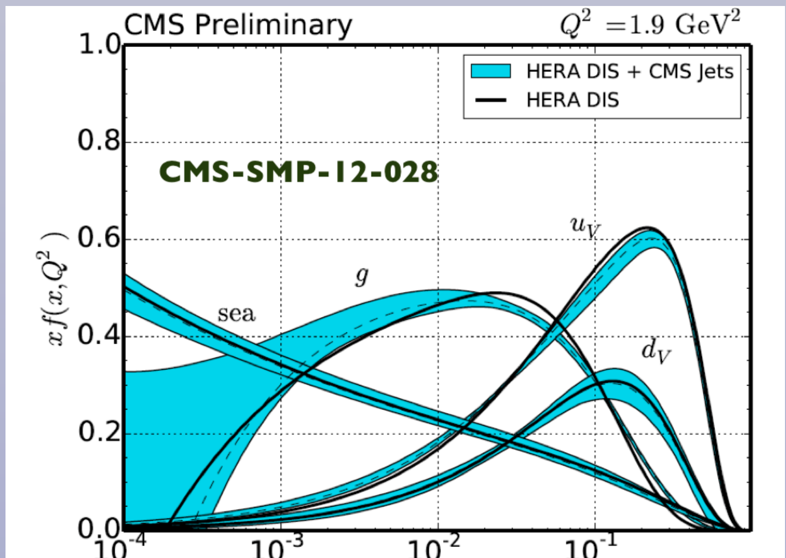
Motivation for new data in NNPDF3.0

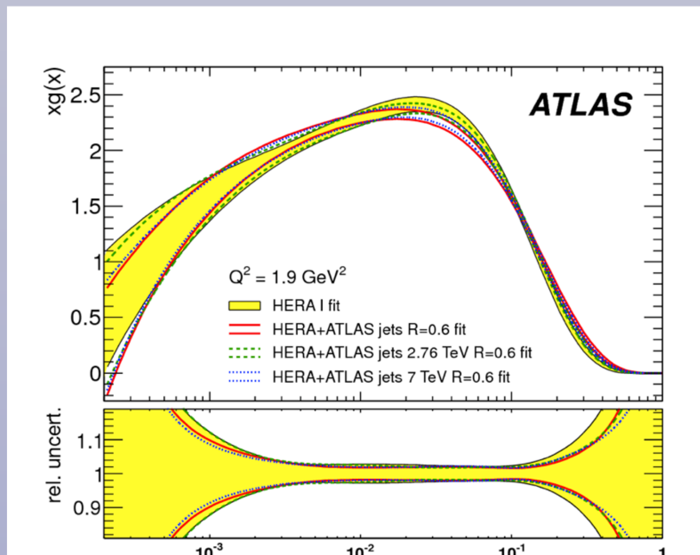
- **Top quark total cross-sections** allow to constrain the **large-x gluon PDF** (NNLO for differential distributions will be available soon, should be able to include as well differential top production measurements)





- **Jet cross-sections** pin down **medium and large-x gluon** and **large-x quarks** (important to include properly information on NNLO corrections, see later)



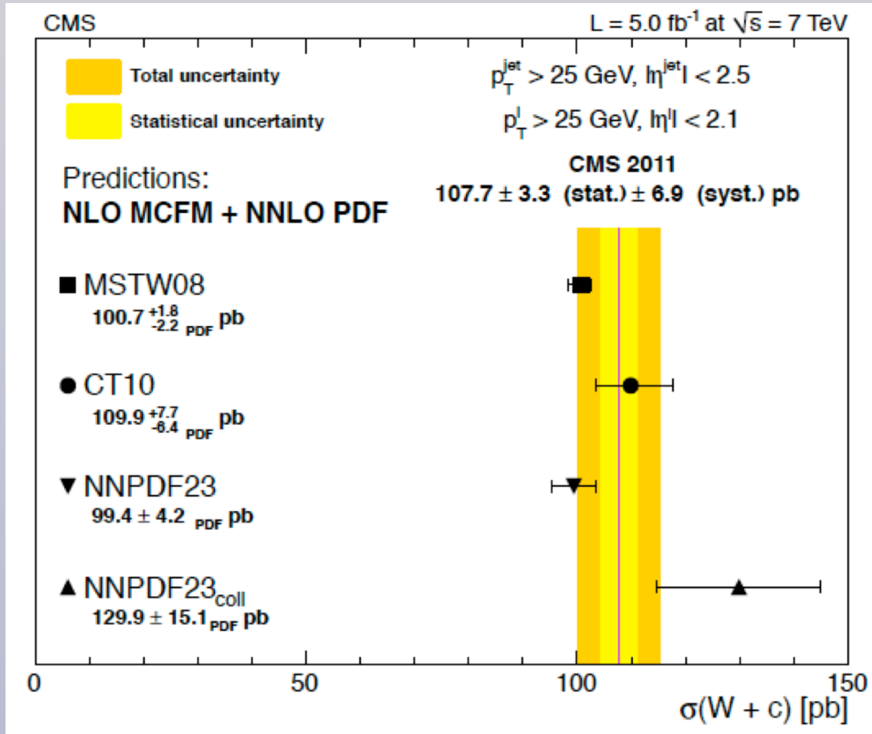


ATLAS data on the **ratio 7 TeV / 2.76 for jet production**, beautiful illustration of the PDF sensitivity of **cross-section ratios between different center-of-mass energies** (Mangano and JR 12)

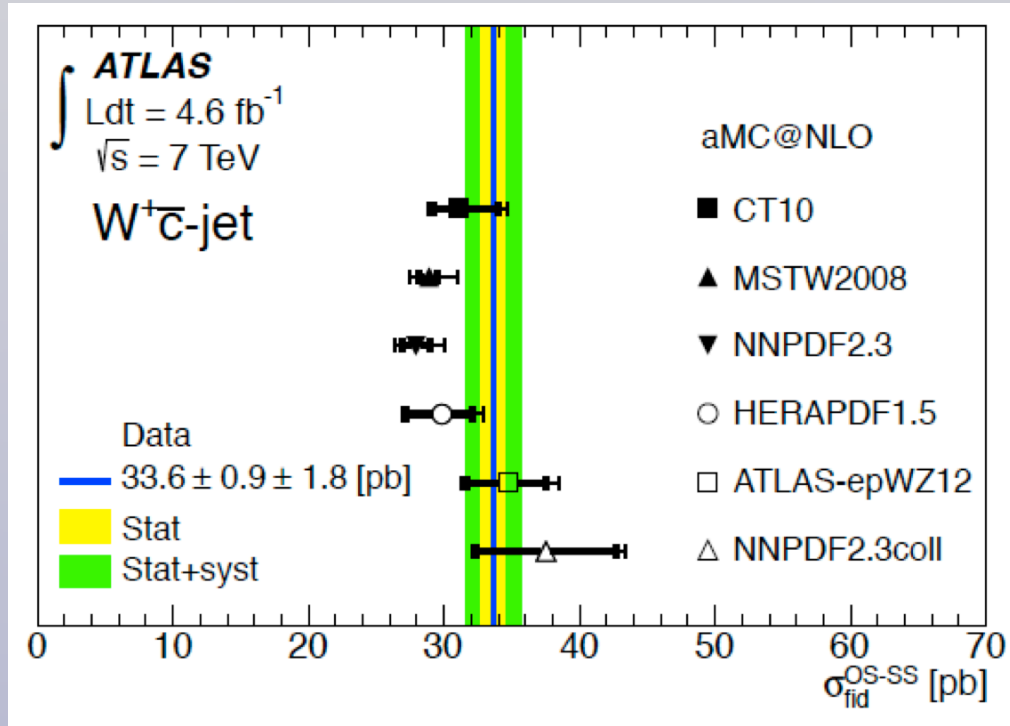
Motivation for new data in NNPDF3.0

- **W+charm** production data directly sensitive to the strange PDF
- Measured by ATLAS (arxiv:1402.6263) and CMS (arxiv:13101138) with somewhat opposite (?) conclusions

CMS: strange suppression in agreement with DIS data



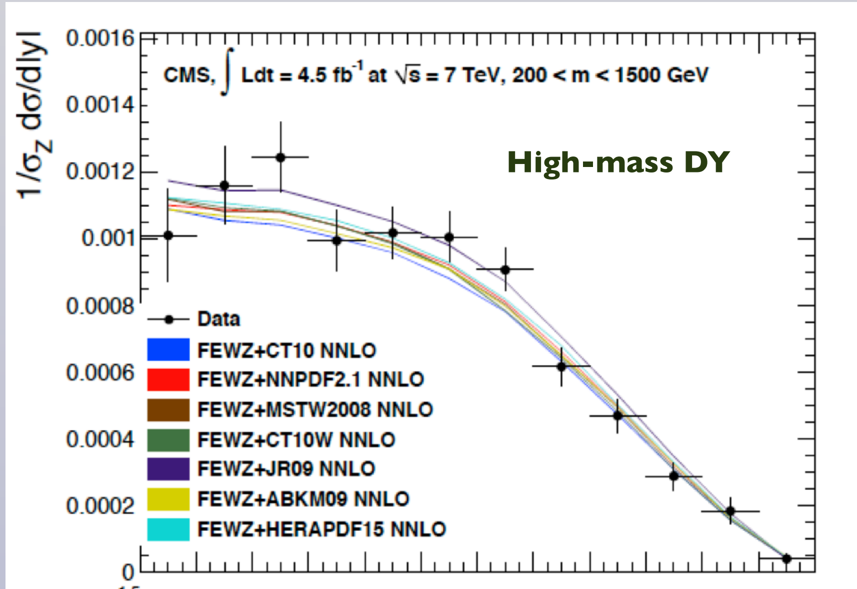
ATLAS: light quark sea symmetric preferred

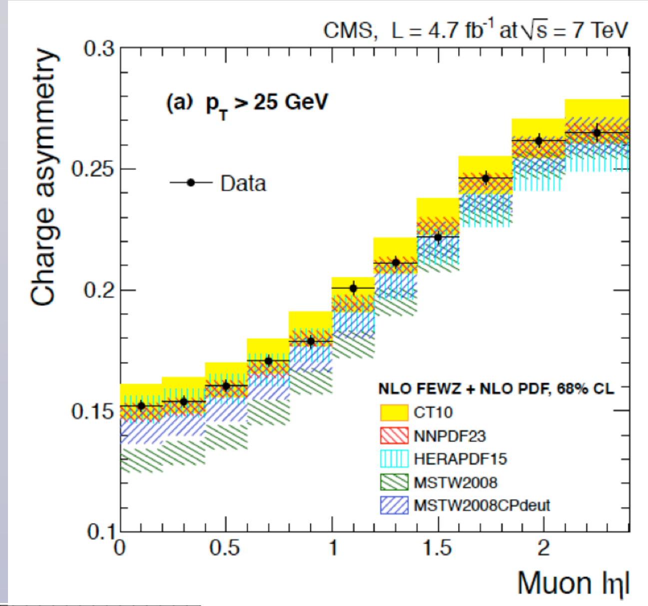


- However, only in the context of a **global fit** the **optimal** value for strangeness can be determined
- A recent analysis in the **ABM framework** (arxiv:1404.6469) suggest that **fits with symmetric strangeness** cannot describe properly fixed target DIS and Drell-Yan data (see also R. Thorne in past PDF4LHC) and that one can fit ATLAS data with still a suppressed strangeness (same as found in NNPDF2.3 for **incl W,Z**)
- The **NNPDF3.0** will perform a similar analysis, with the advantage of using a **completely flexible parametrization for s(x,Q)**, which in other analysis uses a very restrictive functional form

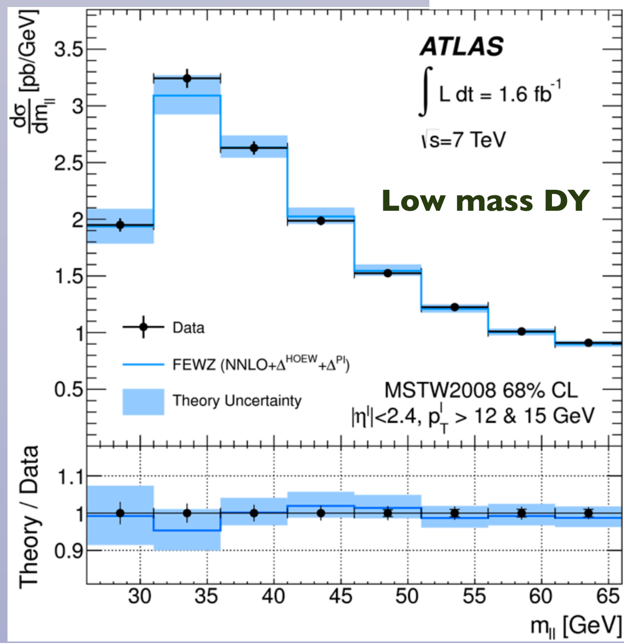
Motivation for new data in NNPDF3.0

- **Electroweak gauge boson production** is an essential measurement for **quark flavor separation**
- The relevance of LHC W,Z production is even greater in **collider-only fits**
- Data on the **Drell-Yan process** at **low and high masses** allow to extend the kinematical coverage in Bjorken-x





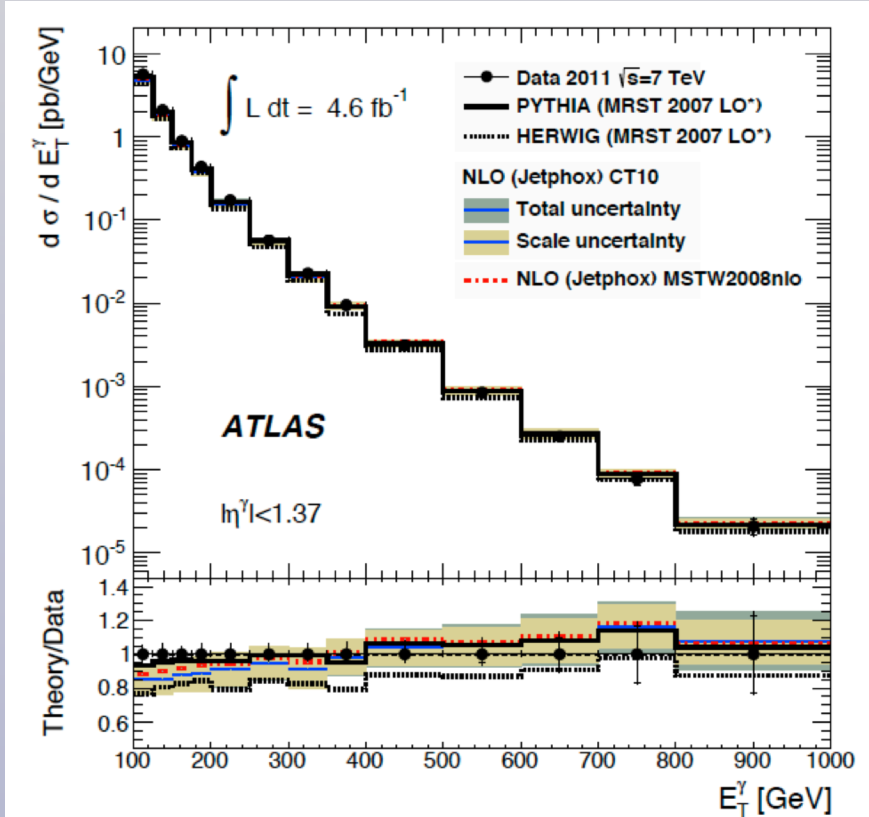
W asymmetry



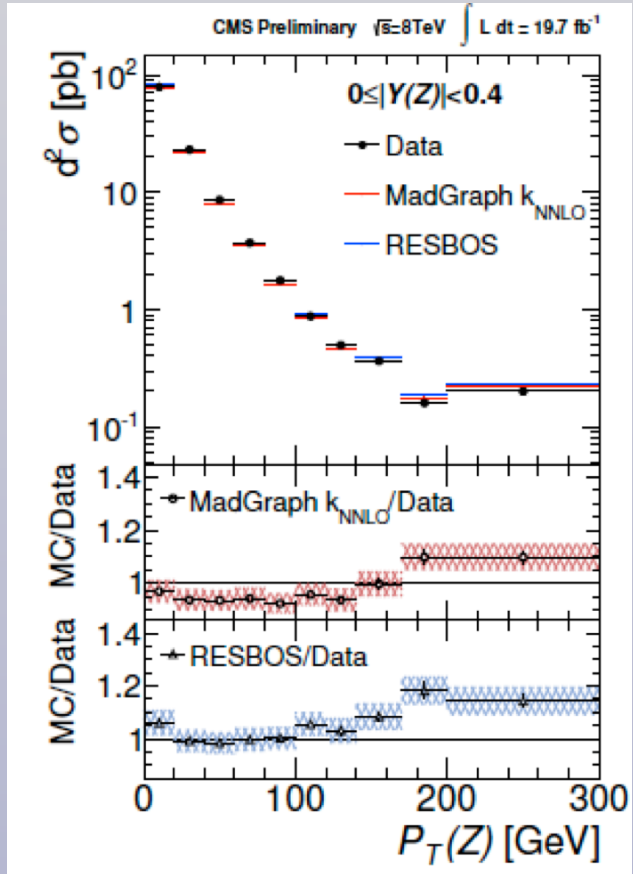
Given the data precision, NNLO corrections are essential, and also **electroweak corrections** at high masses

More data in the pipeline

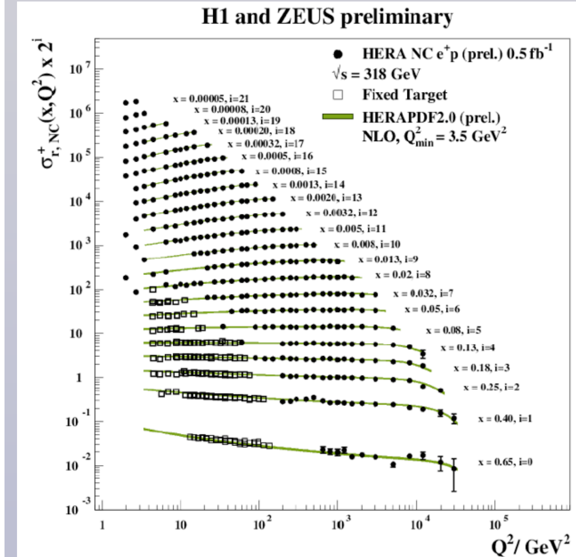
- **The plethora of new LHC data** that is becoming available for PDF fitting makes any PDF fit somewhat outdated shortly after it has been released
- At some point we need to put a **cut-off** about the data to include in NNPDF3.0
- Some **important measurements** that we might try to add in time for NNPDF3.0 include



ATLAS direct photon data from 2011 run
But need APPLgrids and K-factors, already available for the ATLAS analysis



CMS-SMP-13-013
Measurement of the Z pt spectrum at high pt
But data still preliminary
(see Markus's talk)



Combined HERA-II data
To supersede the separated H1 and ZEUS HERA-II data already included in 3.0

Independence of PDF fitting basis

- **Predictions for physical observables** should be independent of the specific choice of PDF fitting basis
- We have explored in **closure tests** that thanks to the **improved NNPDF3.0 methodology**, we achieve almost statistically equivalent fits using **two very different basis**

NNPDF2.3 basis

$$
\begin{aligned}
\Sigma(x,Q_0^2) &= \sum_{i=1}^{3}(q_i+\bar{q}_i)(x,Q_0^2) \\
T_3(x,Q_0^2) &= \left(u+\bar{u}-d-\bar{d}\right)(x,Q_0^2) \\
\Delta_S(x,Q_0^2) &= \left(\bar{d}-\bar{u}\right)(x,Q_0^2) \\
s^+(x,Q_0^2) &= (s+\bar{s})(x,Q_0^2) \\
V(x,Q_0^2) &= \sum_{i=1}^{3}(q_i-\bar{q}_i)(x,Q_0^2) \\
s^-(x,Q_0^2) &= (s-\bar{s})(x,Q_0^2)
\end{aligned}
$$

NNPDF3.0 basis

$$
\begin{aligned}
\Sigma(x,Q_0^2) &= \sum_{i=1}^{3}(q_i+\bar{q}_i)(x,Q_0^2) \\
T_3(x,Q_0^2) &= \left(u+\bar{u}-d-\bar{d}\right)(x,Q_0^2) \\
T_8(x,Q_0^2) &= \left(u+\bar{u}+d+\bar{d}-2s-2\bar{s}\right)(x,Q_0^2) \\
V(x,Q_0^2) &= \sum_{i=1}^{3}(q_i-\bar{q}_i)(x,Q_0^2) \\
V_3(x,Q_0^2) &= \left(u-\bar{u}-d+\bar{d}\right)(x,Q_0^2) \\
V_8(x,Q_0^2) &= \left(u-\bar{u}+d-\bar{d}-2s+2\bar{s}\right)(x,Q_0^2)
\end{aligned}
$$

Natural basis from the point of view of physical observables

Natural basis from point of view of PDF evolution equations

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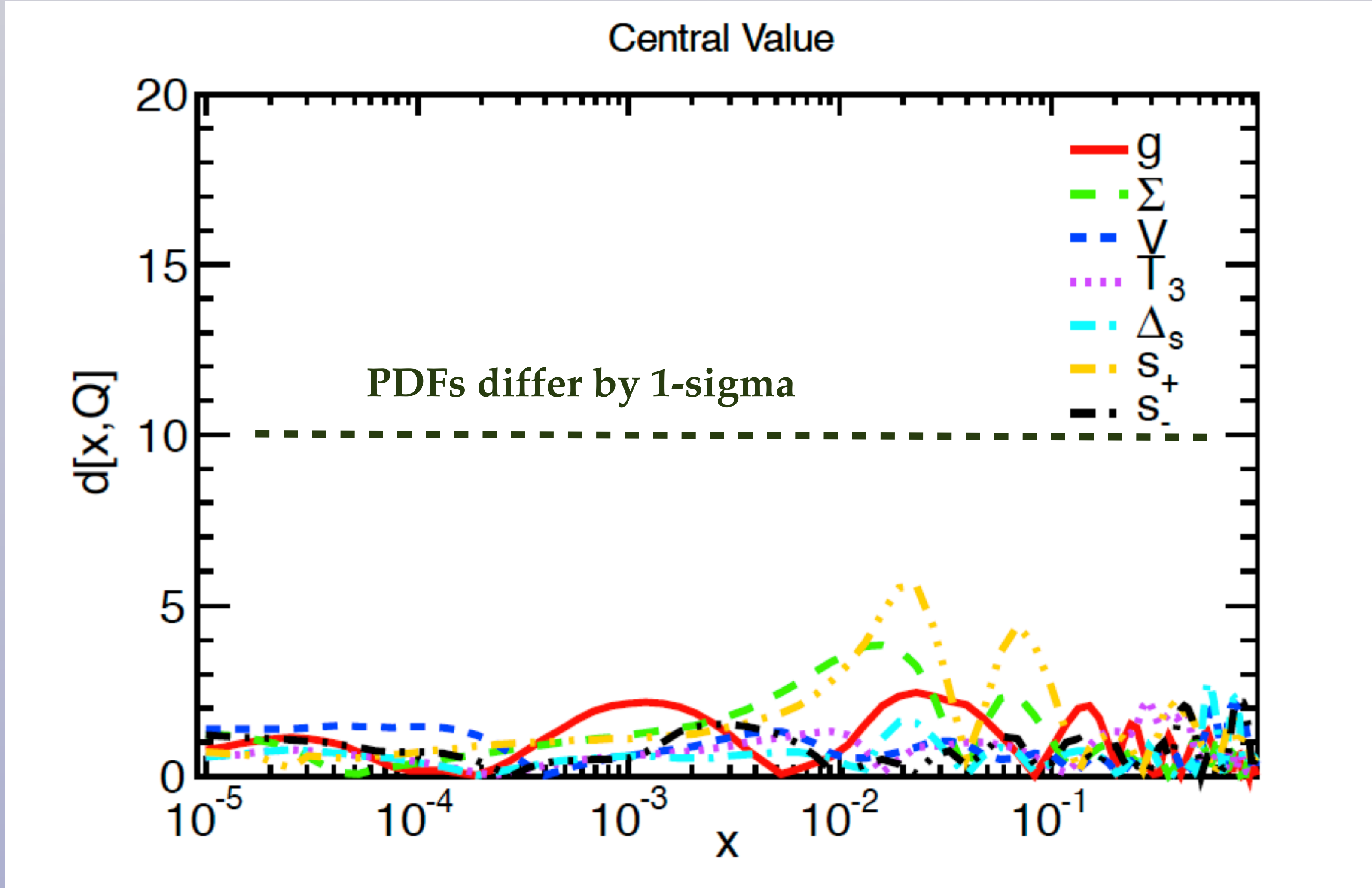
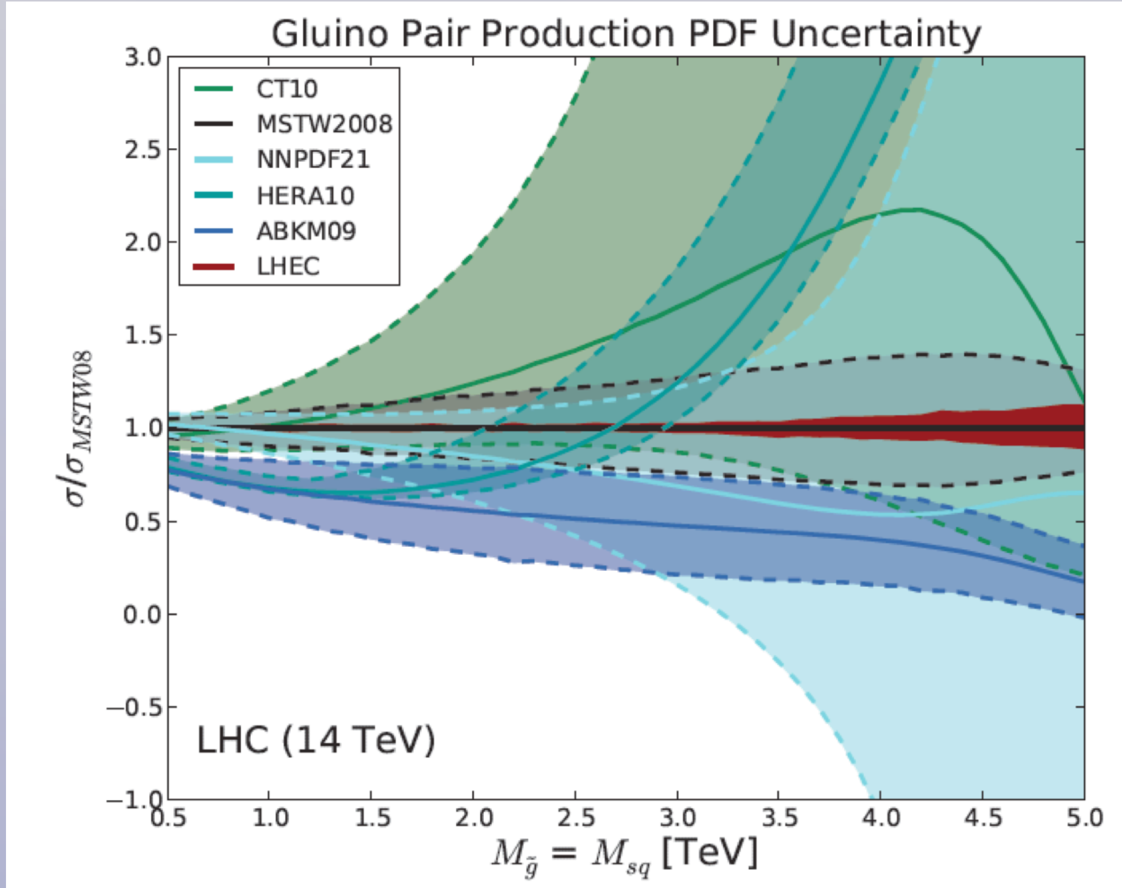
Fit in NNPDF2.3 basis vs Fit in NNPDF3.0 basis



Positivity of physical cross-sections

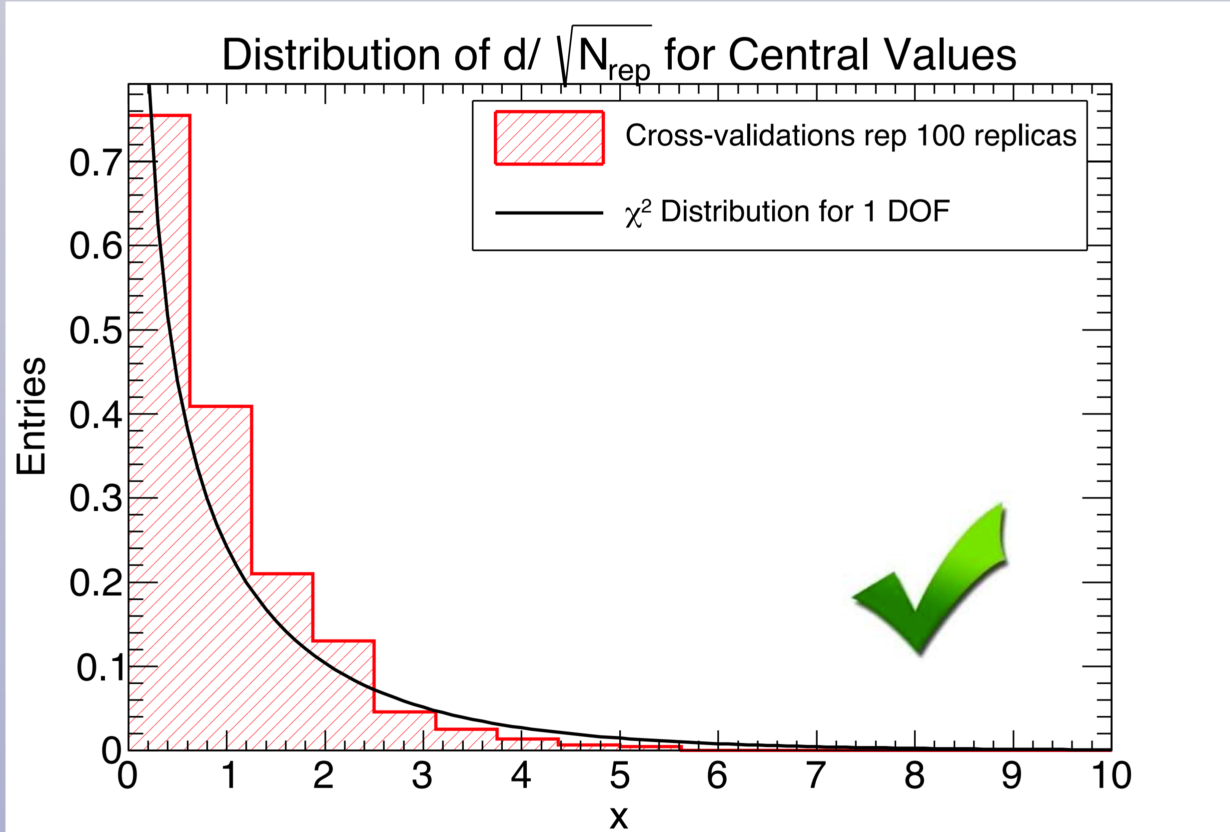
- While PDFs are not **positive definite beyond LO**, **physical cross-sections** should always be positive
- Implementing this condition, **without overconstraining PDFs with a too restrictive parametrization**, is essential for a reliable estimate of PDF uncertainties
- This is particularly crucial in the **large-x region,** production of BSM high-mass particles



PDF reweighting

- **Statistically identical results** should be obtained when **refitting** or when **reweighting,** even more so in a **closure test**
- Thus **Bayesian inference** can be used as the **ultimate closure test**, sensitive to all the higher moments of the refitted/reweighting PDFs
- As an illustration, compare effects of **CDF, D0 and ATLAS jet data** included by refitting and by reweighting. Compare also **NNPDF** and **Giele-Keller** prescriptions.

Distribution of distances between refit and RW



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Quark positivity

Anti-Quark positivity

Gluon positivity

$$\begin{aligned}
F_2^u(x,Q^2) &\propto x\left(u(x,Q^2)+\bar{u}(x,Q^2)\right)+\mathcal{O}(\alpha_s)\\
F_2^d(x,Q^2) &\propto x\left(d(x,Q^2)+\bar{d}(x,Q^2)\right)+\mathcal{O}(\alpha_s)\\
F_2^s(x,Q^2) &\propto x\left(s(x,Q^2)+\bar{s}(x,Q^2)\right)+\mathcal{O}(\alpha_s)\\
\frac{d^2\sigma^{\mathrm{DY,u}}}{dM^2\,dy} &\propto u(x_1,Q^2)\bar{u}(x_3,Q^2)+\mathcal{O}(\alpha_s)\\
\frac{d^2\sigma^{\mathrm{DY,d}}}{dM^2\,dy} &\propto d(x_1,Q^2)\bar{d}(x_2,Q^2)+\mathcal{O}(\alpha_s)\\
\frac{d^2\sigma^{\mathrm{DY,s}}}{dM^2\,dy} &\propto s(x_1,Q^2)\bar{s}(x_2,Q^2)+\mathcal{O}(\alpha_s)\\
F_L(x,Q^2) &\propto C_g\otimes g(x,Q^2)+C_q\otimes q(x,Q^2)+\mathcal{O}(\alpha_s^2)\\
\frac{d\sigma^{\mathrm{higgs}}}{dy_H} &\propto g(x_1,M_H^2)g(x_2,M_H^2)+\mathcal{O}(\alpha_s^3)\qquad M_H\equiv Q_{\mathrm{pos}}
\end{aligned}$$

Positivity of physical cross sections imposed at a **low scale ~ 2 GeV**, then maintained by evolution

Preprocessing exponents

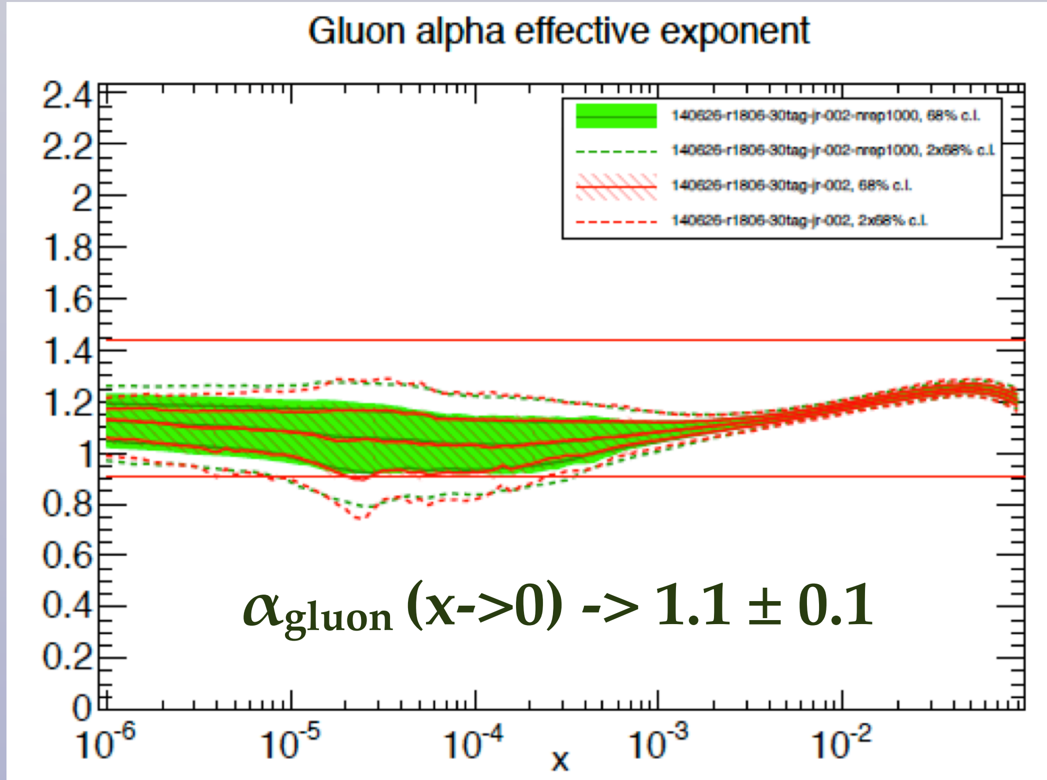
- In our PDF parametrization, the **neural networks** are complemented by **polynomial prefactors** whose goal is to s**peed-up the NN minimization**: preprocessing analysis, standard in **machine learning**

$$f_i(x,Q) = A_i\, x^{-\alpha_i}(1-x)^{\beta_i}\,\mathrm{NN}_i(x)$$

- These exponents are selected at **random for each replica**, in a wide range determined dynamically by iterating the determination of the **effective preprocessing exponents**

$$\alpha_{\mathrm{eff},i}(x) = -\frac{|f_i(x)|}{\log(x)}$$

$$\beta_{\mathrm{eff},i}(x) = \frac{|f_i(x)|}{\log(1-x)}$$



These effective exponents are also useful to validate different **models of non-perturbative QCD**