News from the CTEQ-TEA group

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With the CTEQ-TEA (Tung Et. Al.) working group

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National Science Foundation

Higgs Xsec WG, June 26, 2024

Importance of high-order perturbative calculations

Latest developments in precision QFT and applications to hard-scattering calculations are crucial to bring PDF analyses to the next level of accuracy and precision for an improved understanding of experimental data.

Improved PDFs → Improved theory predictions to be compared to data

- Compatible high-precision experimental data
- Developments in loop calculations for DGLAP evolution (**N3LO on the way**) and hard scatterings
- **Fast calculations (critical for global QCD analyses)**
- Improvements in current understanding of uncertainties

Necessary components of an N3LO PDF analysis

Component		Availability
Splitting functions		Partial N3LO
Hard cross sections	• DIS, light flavors	Full N3LO
	• NC DIS, heavy flavors	Full N3LO (Blümlein et al.), not yet in fitting codes
	• Vector boson production	Full N3LO for some processes, fixed N3LO/NLO K-factor tables
	• CC DIS, jet, $t\bar{t}$ production	N2LO
	• $pp \to W + c$, $pp \to Z + b$, $\mathrm{pp} \to b$	NLO (massive); NNLO (ZM)

Looking forward to including all components **exactly and fully** to reduce the QCD scale uncertainty and guarantee the N3LO accuracy in the near future.

CTEQ-TEA and other groups include some N3LO contributions in their fitting codes: remarkable progress of MSHT and NNPDF in aN3LO fits

These extended (N2LO+, or aN3LO) calculations agree with N2LO within their scale dependence

For $gg \to H^0$ production, the aN3LO-N2LO difference is comparable to other effects due to the remaining scale dependence, selection of experiments, treatment of systematic uncertainties

2012→2015: Agreement between NNLO PDFs greatly improved

2015

1510.03865

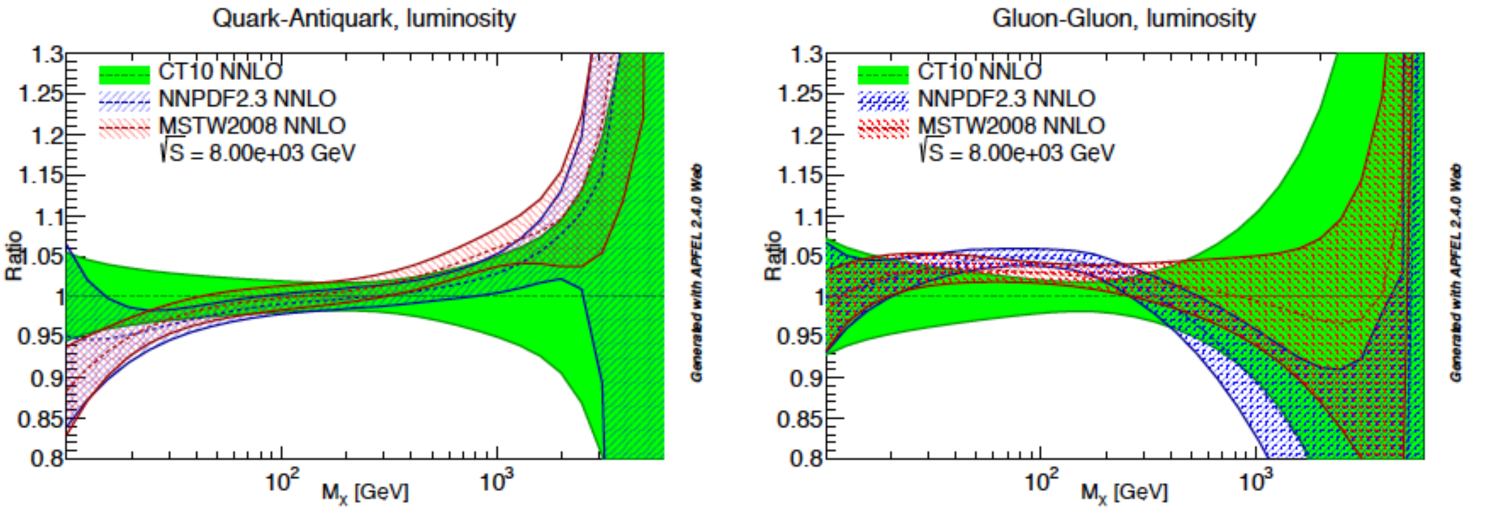
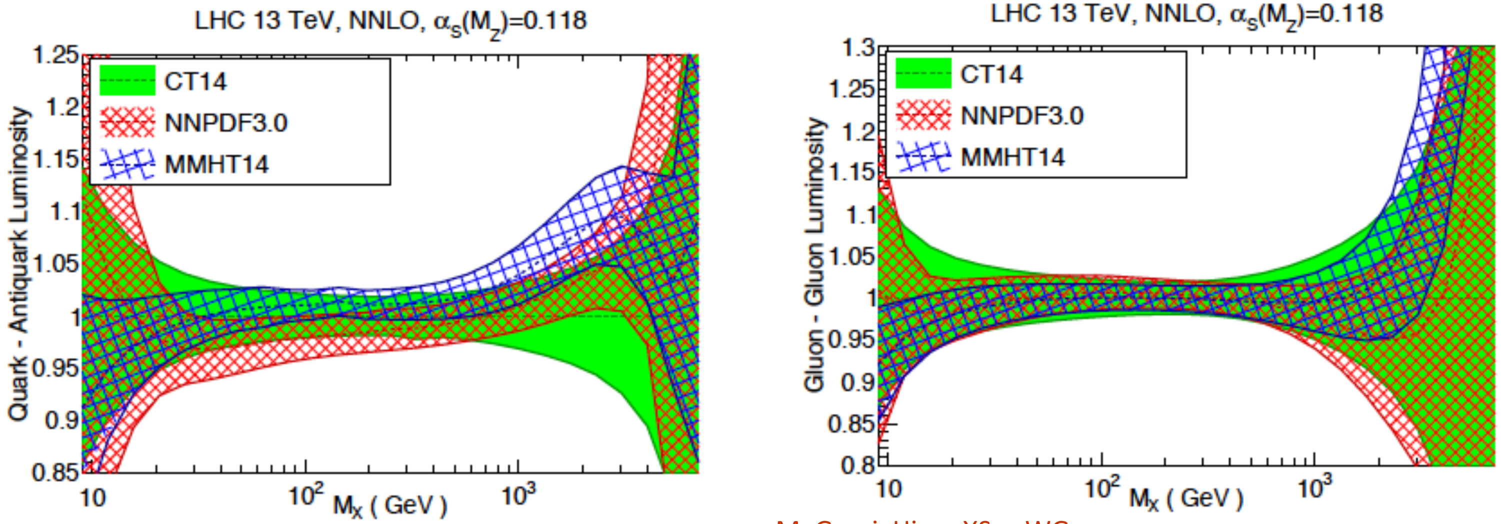


Figure 1: Comparison of the $q\bar{q}$ (left) and gg (right) PDF luminosities at the LHC 8 TeV for CT10, MSTW2008 and NNPDF2.3. Results are shown normalized to the central value of CT10.



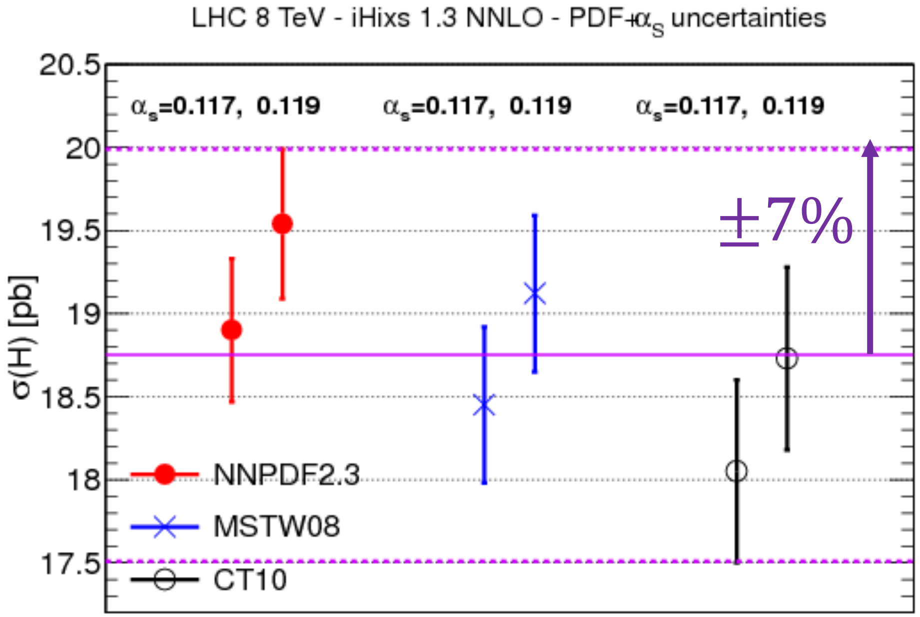
Note in particular the changes in the gg luminosity, especially important in the Higgs mass region

LHC data has been added for all 3 new PDFs, but most of change is due to changes in formalisms

PDF4LHC15 benchmarking of codes reduced the PDF error on Higgs cross sections

2015

$2012: \delta_{PDF} \approx 7\%$



R. Ball et al., **arXiv:1211.5142**

Disagreement in central values

$2015: \delta_{PDF} \approx 2-3\%$

$\sigma(gg \to H^0)$ at NNLO

	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

Good agreement of central values

N3LO scale dependence on σ_H is <3%

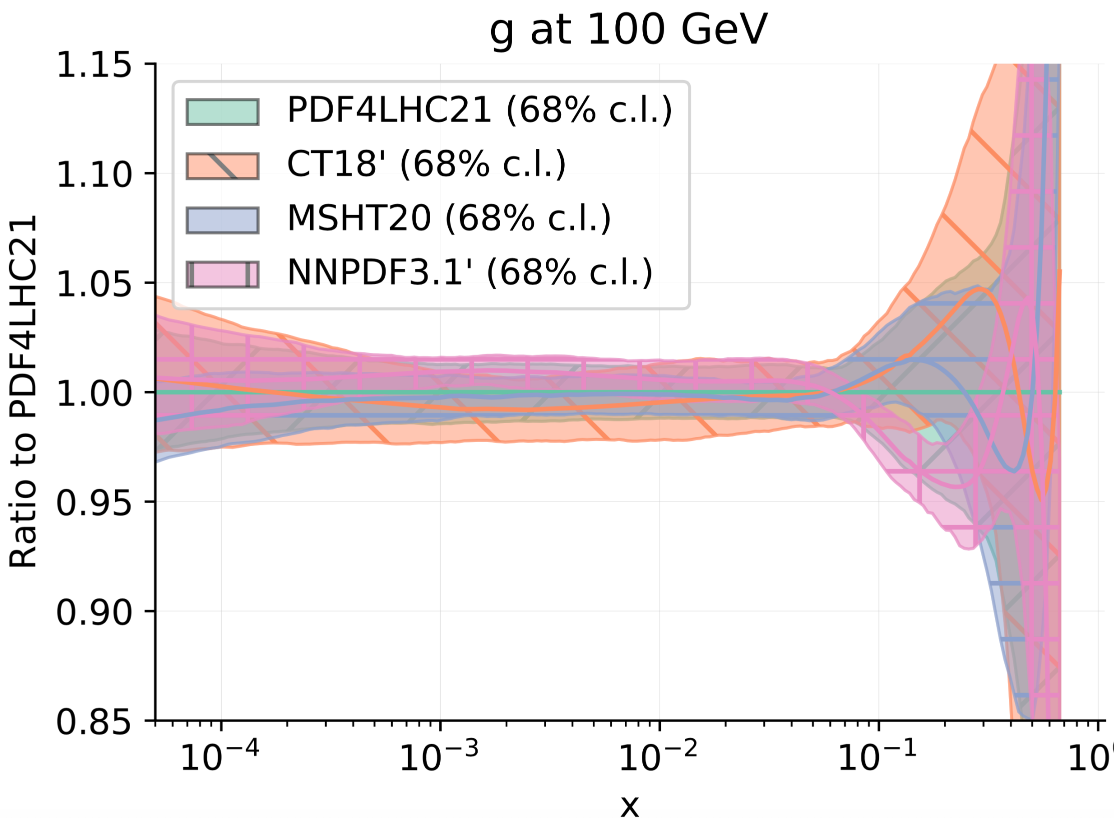
Similar agreement for $t\bar{t}$ cross sections

PDF4LHC21 recommendation and combined PDFs

2022

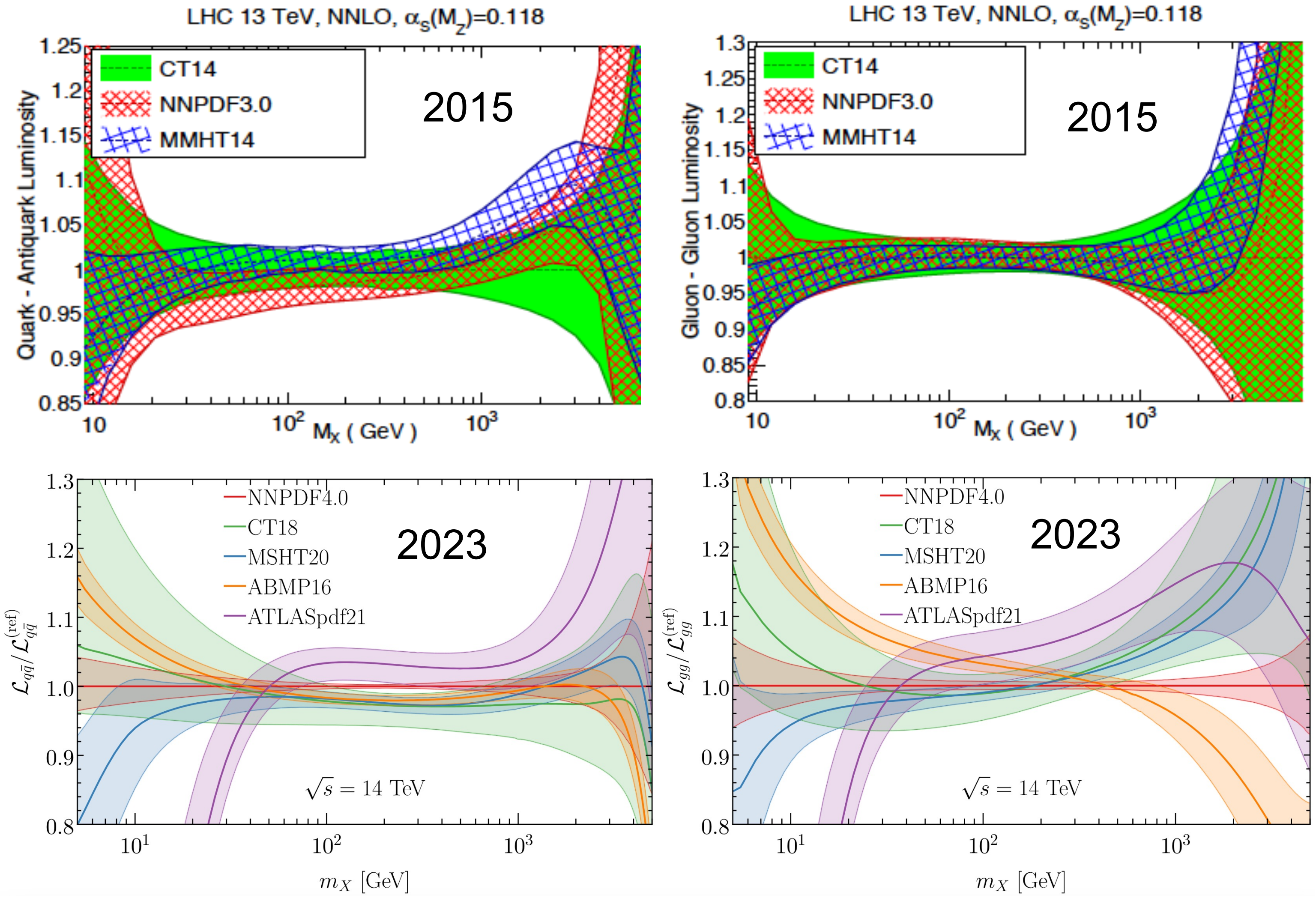
arXiv:2203.05506

- A comprehensive recommendation for usage of PDFs at the LHC
- Replaces the PDF4LHC15 recommendation
- A detailed benchmarking comparison of global fits by three main groups
- Combined PDF4LHC21 NNLO PDFs based on CT18', MSHT'20, and NNPDF3.1' ensembles for BSM searches, measurements of moderate precision, theory predictions
- Provided as 40-member Hessian PDFs and 100-member Monte-Carlo PDFs of comparable accuracy



2015→2023: The agreement of NNLO proton PDFs challenged by several effects

2023



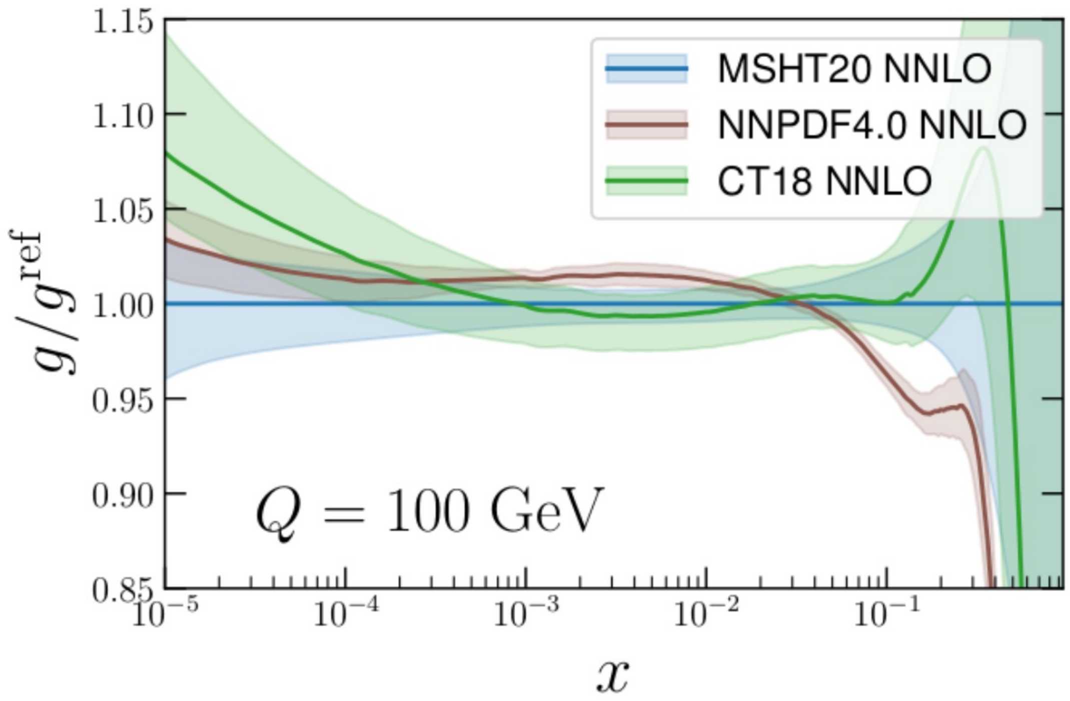
S. Amoroso et al., 2203.13923

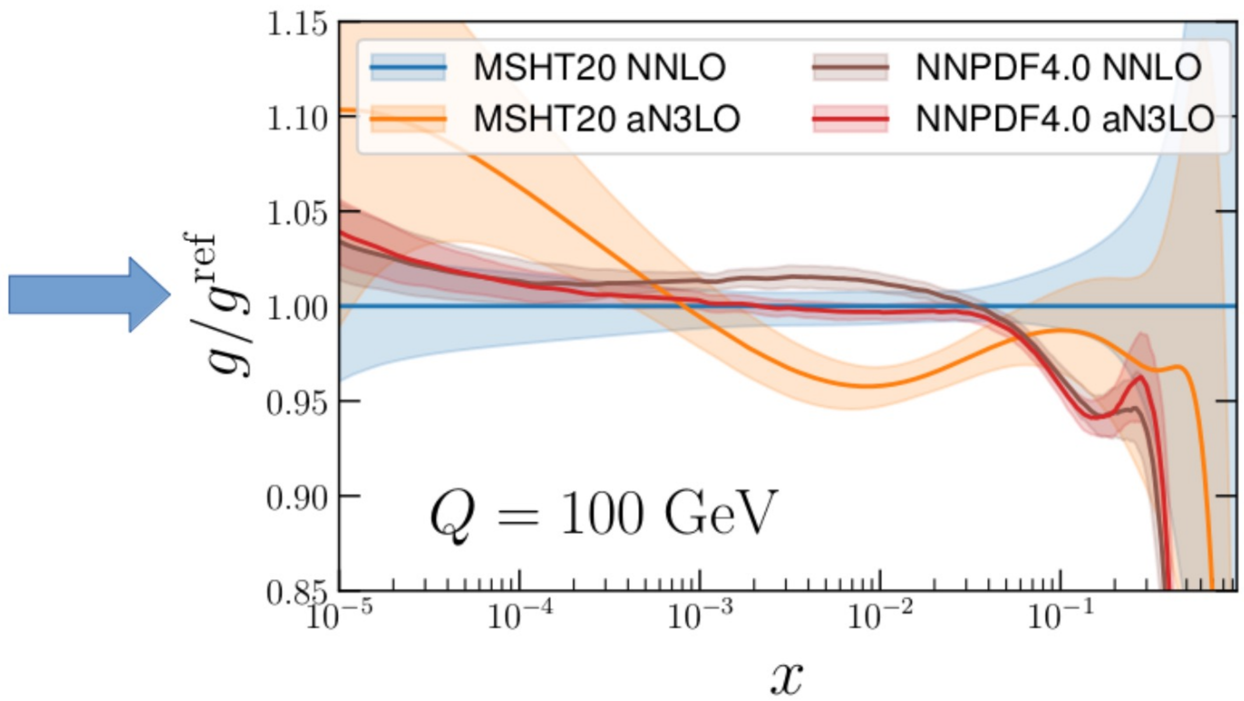
The fitting groups and PDF4LHC21 study identified some possible reasons:

1. insufficient agreement between the fitted experiments **(systematic uncertainties)**
2. differences in the fitting methodologies **(tolerance)**
3. **more fundamental reasons**

Recent progress toward N3LO global analyses

T. Cridge, LoopFest 2024

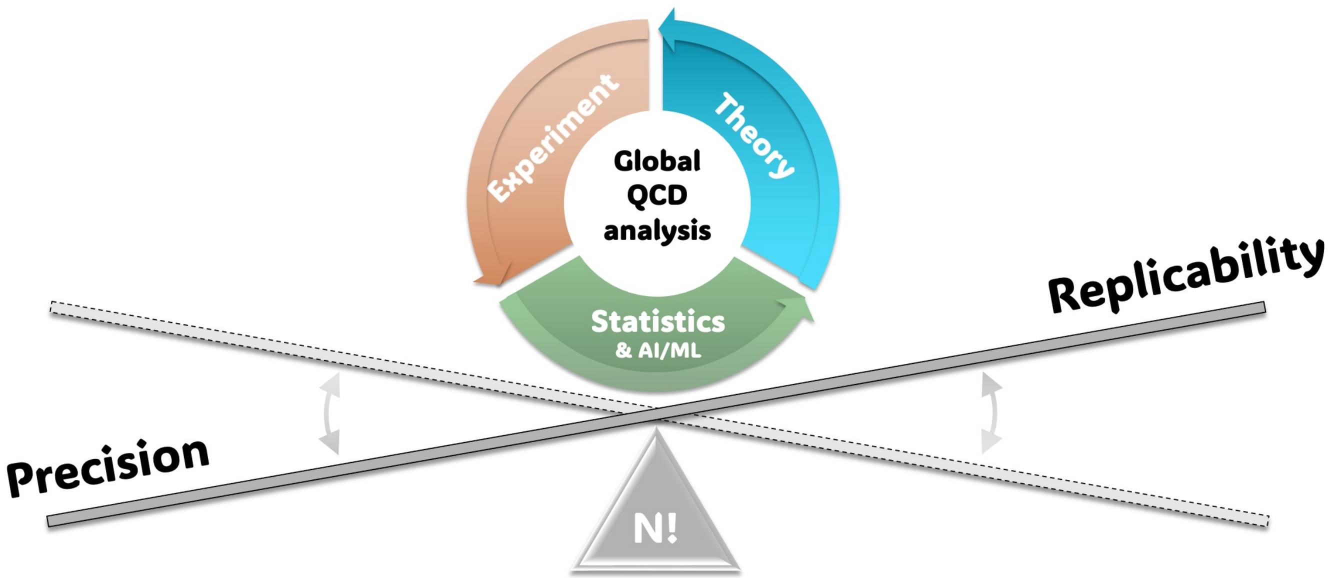


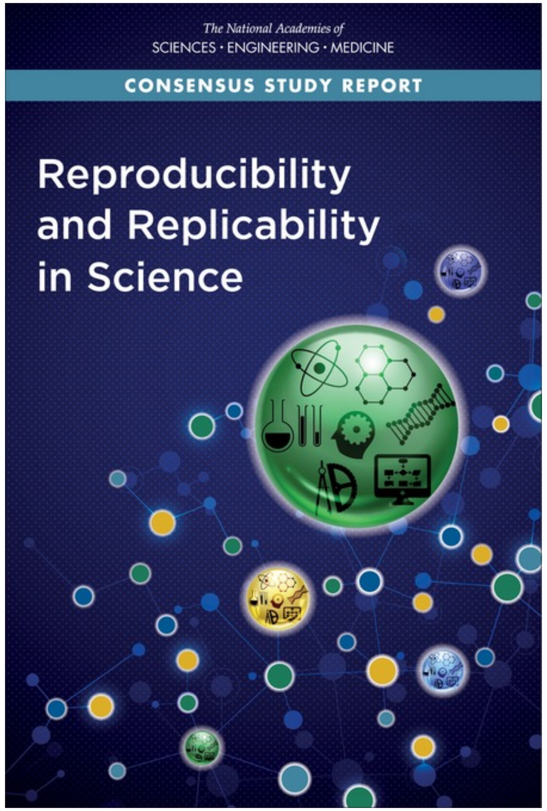


- What is the accuracy we wish to achieve?
- It's natural to guess that once all the ingredients of DGLAP evol. @ N3LO and more N3LO Xsecs will be made available, there will be several benchmark exercises to improve PDF quality.
- What are the necessary steps to be taken to make N3LO PDFs the new standard?

Balancing precision and replicability in PDF uncertainty quantification

Ongoing work





US National Academy of Sciences, Engineering, and Medicine, 2019, https://doi.org/10.17226/25303

Replicability challenges for precision QCD

Replicability is a requirement of obtaining consistent results across studies aimed at answering the same scientific question, each of which has its own analysis strategy or data.

Nearly all complex STEM fields encounter replicability challenges.

Modern Particle Physics is not an exception.

Uncertainties in N3LO global analyses dominated by:

- missing pieces in N3LO DGLAP
- treatment of N3LO light flavors in DIS, and heavy-flavor contributions
- missing HOU, scale choices
- agreement between experiments
- methodological choices
- ….

Epistemic PDF uncertainty…

…reflects **methodological choices** such as PDF functional forms, NN architecture and hyperparameters, or model for systematic uncertainties

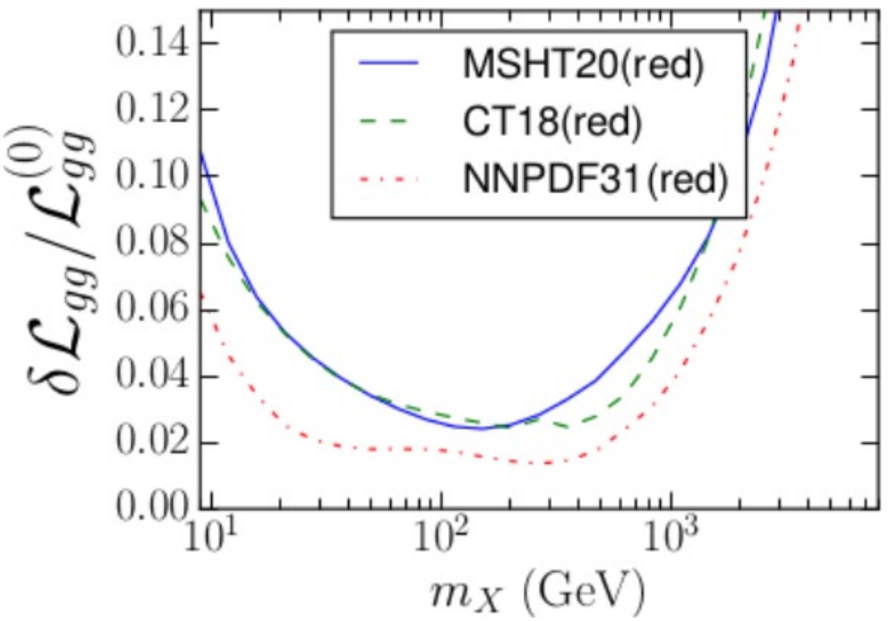
… can dominate the full uncertainty when experimental and theoretical uncertainties are small.

…is associated with the **prior probability**.

… can be estimated by **representative sampling** of the PDF solutions obtained with acceptable methodologies.

⇒ sampling over choices of experiments, PDF/NN functional space, models of correlated uncertainties…

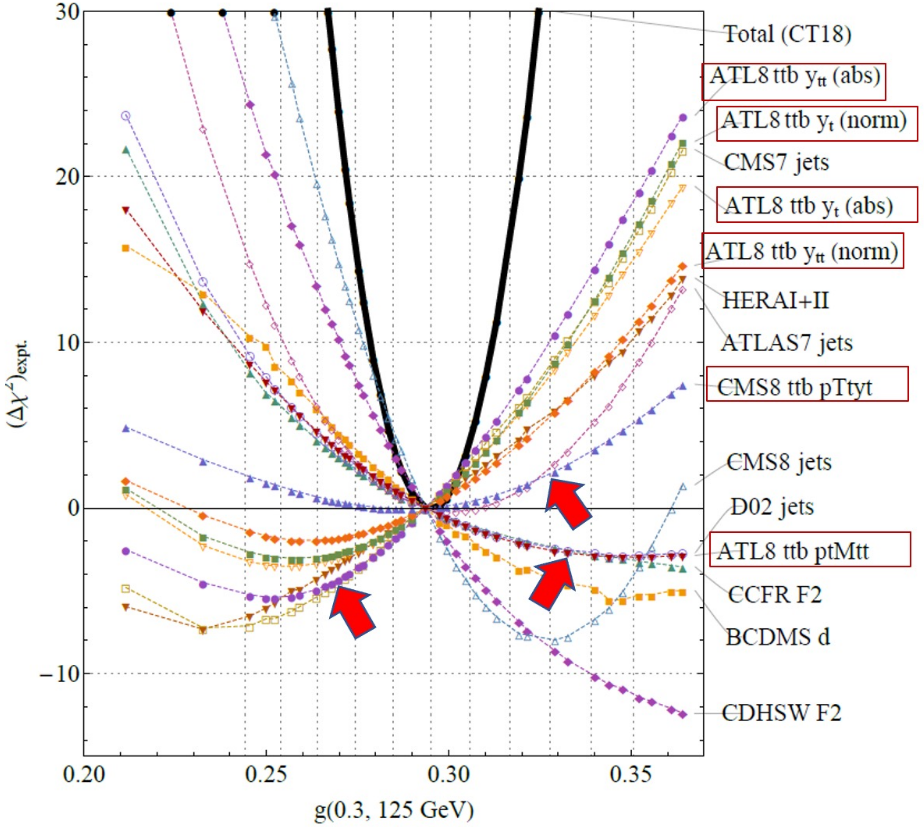
⇒ in addition to sampling over data fluctuations



Epistemic uncertainties explain many of the differences among the sizes of PDF uncertainties by CT, MSHT, and NNPDF global fits to the same or similar data

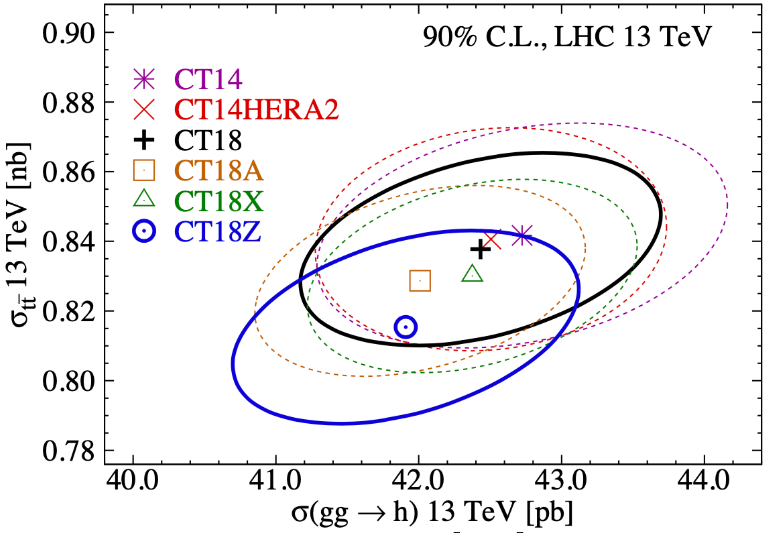
Details in arXiv:2203.05506, arXiv:2205.10444

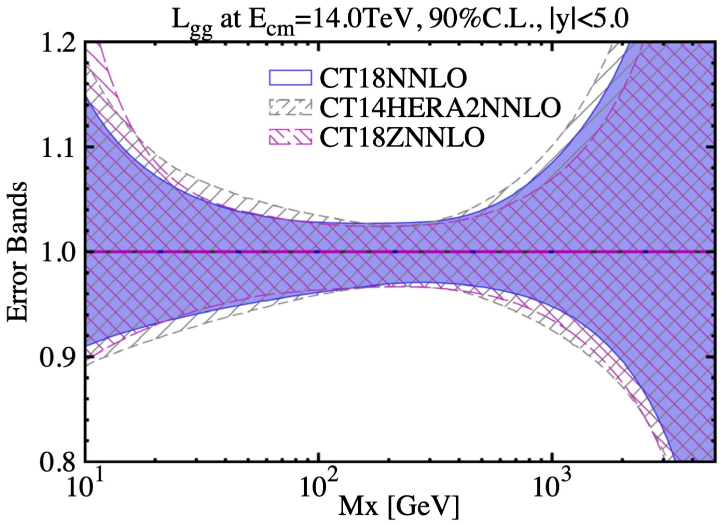
The CT18 gluon PDF and the Higgs cross section



PDF error estimates must account for:

- multiple PDF functional forms
- disagreements between measurements



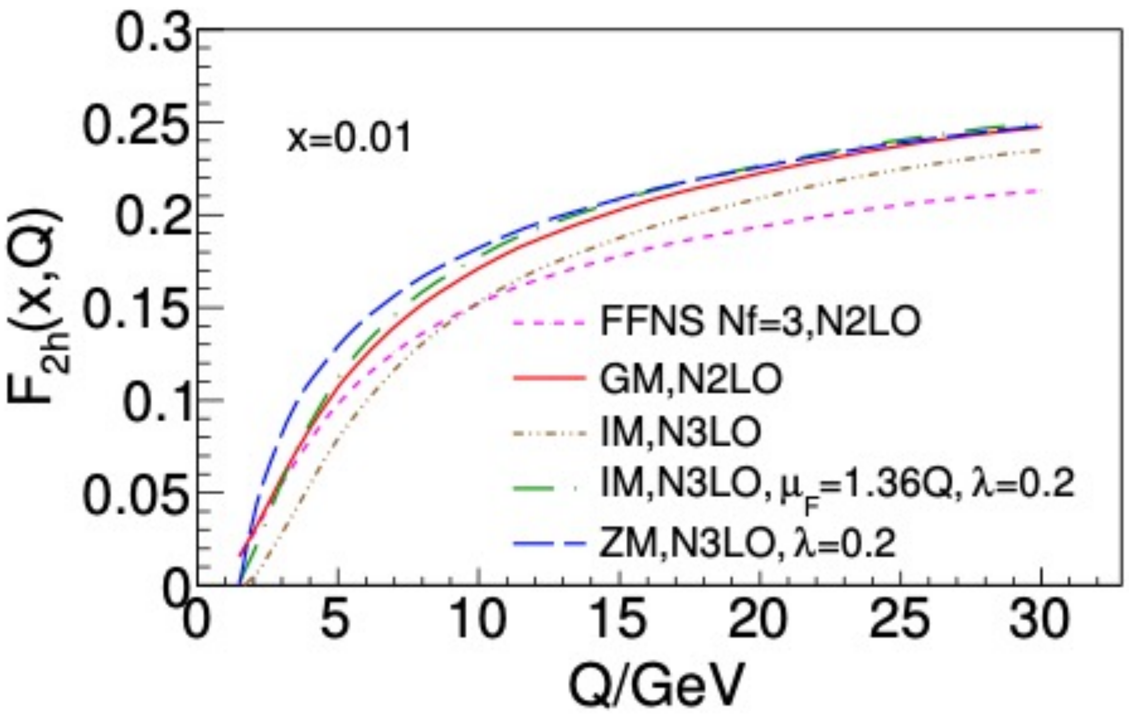


Many processes contribute to constraining the Higgs Xsec.
Realistic N3LO is not likely to be available
(let alone consistently fitted) for all of them any time soon.

Partial inclusion of HO corrections for some, but not other, data sets might worsen some of the tensions that are already evident here

QCD cross sections @N3LO

Work in progress



- **DIS:** The CTEQ-TEA code implements complete flavor decompositions of DIS SFs at N3LO using approximate zero-mass Wilson coefficients with a rescaling variable (the **Intermediate-Mass VFN scheme**, cf. the figure)

Boting Wang's and Keping Xie's Theses, SMU

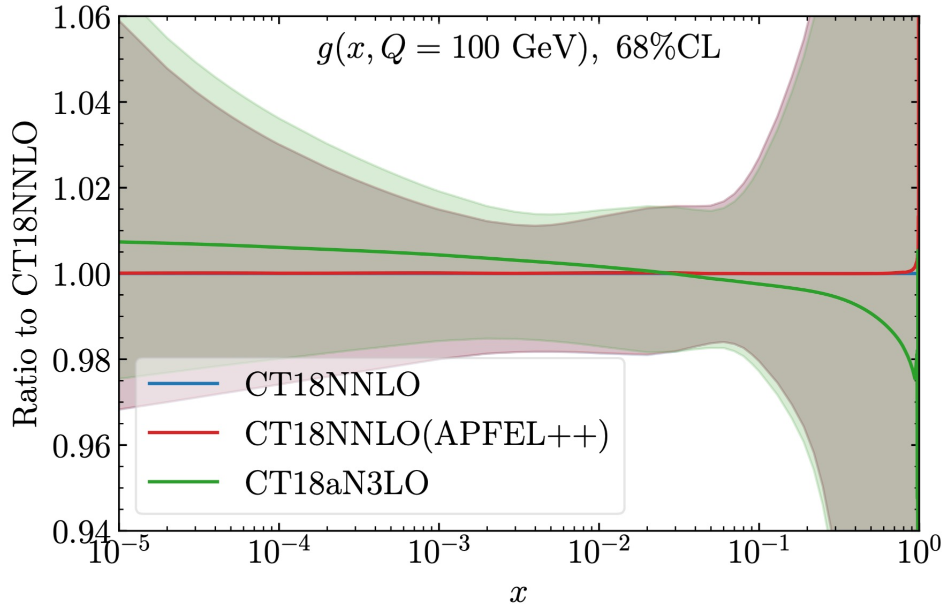
- **Working on the implementation of** massive N3LO heavy-quark coefficients to obtain N3LO DIS cross sections in **the SACOT-MPS General-Mass VFN scheme**

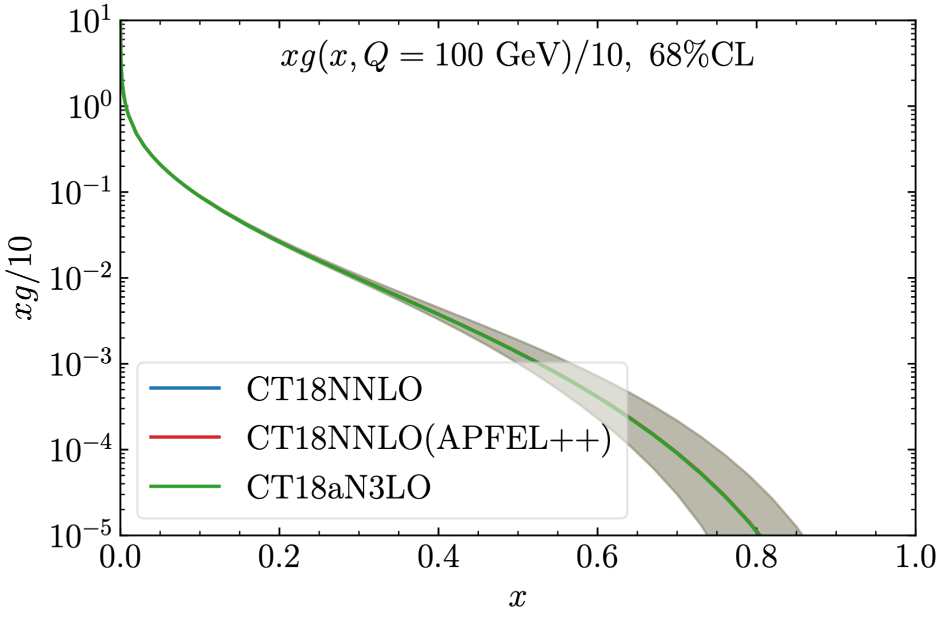
Factorization schemes	Mass dependence in the FC terms	Mass dependence of the FE and subtraction terms	Introduce heavy-quark PDFs at large Q
FFN	Exact	N/A	no
ZM	None	None	yes
IM	Approximate	Approximate	yes
GM	Exact	Approximate	yes

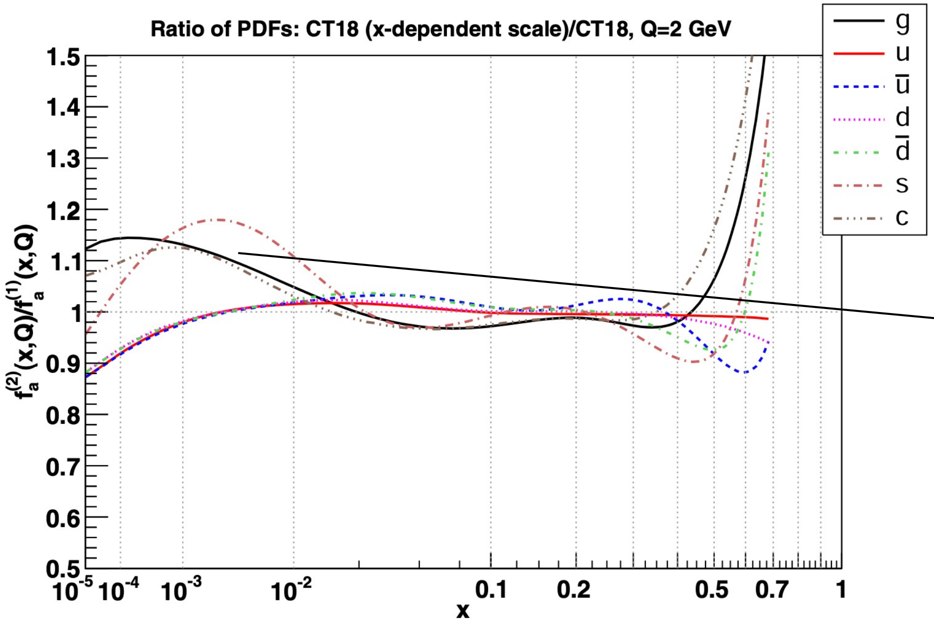
- **DGLAP evolution** is performed at N3LO with APFEL/APFEL++.
- **Drell-Yan:** Ongoing work to include N3LO DY effects using NNLO ApplFast + N3LO/N2LO K-factor tables

CT18aN3LO gluon

Work in progress



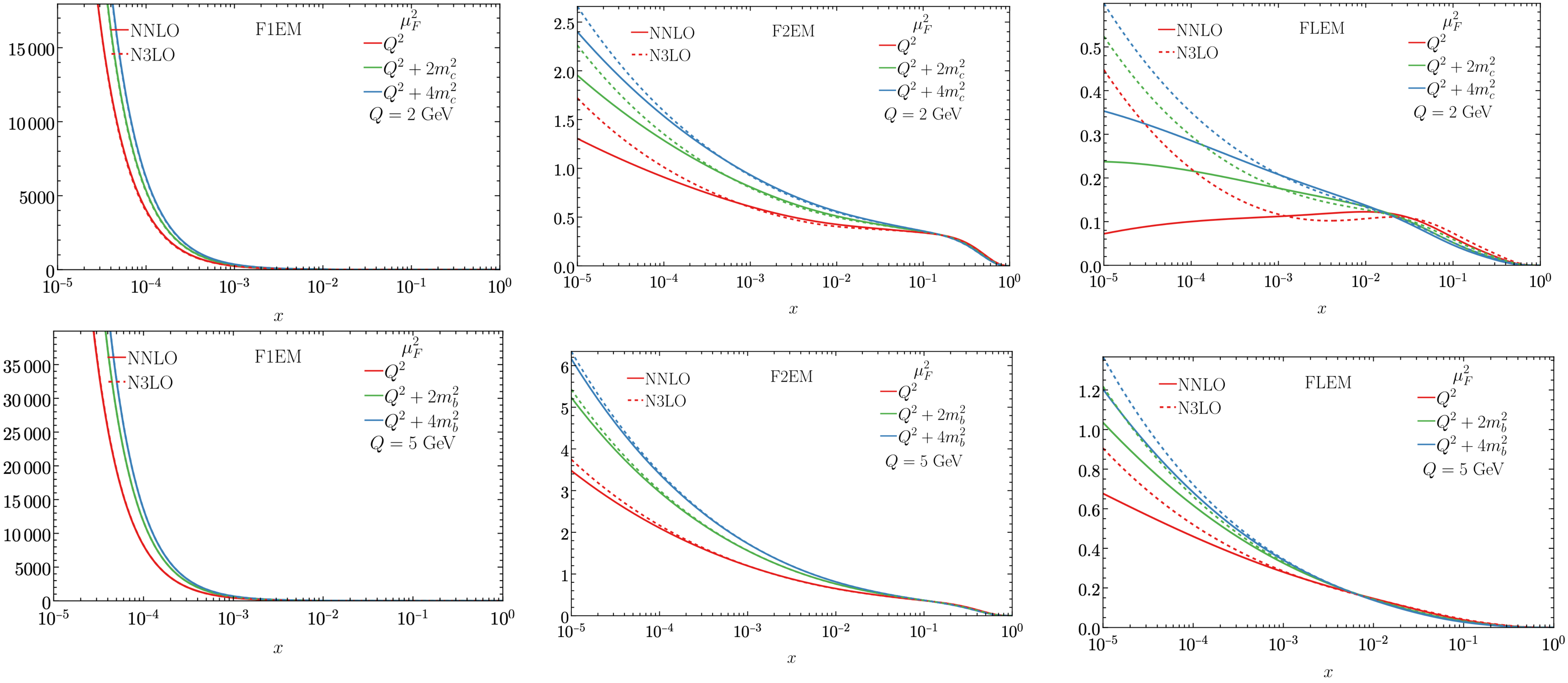




Some of the aN3LO gluon features reproduced by suitable scale choice in DIS NNLO
(cfr. CT18X)

ZM Structure Functions: scale variation

Work in progress



NO refitting here

NNLO fits with new data at 8 and 13 TeV

Example

χ^2/N_{pt} for CT18+new data (CT18 in parentheses) NNLO fits; 68% CL

ID	Exp	N_{pt}	χ^2/N_{pt}
	Drell-Yan		
215	ATLAS 5.02 TeV W,Z	27	$0.82^{+0.55}_{-0.16}$ ($1.15^{+1.22}_{-0.43}$)
211	ATLAS 8 TeV W	22	$2.42^{+2.49}_{-1.51}$ ($4.25^{+6.39}_{-3.34}$)
214	ATLAS 8 TeV Z3D	188	$1.12^{+0.46}_{-0.02}$ ($1.99^{+5.10}_{-1.85}$)
212	CMS 13 TeV Z	12	$2.48^{+4.76}_{-0.88}$ ($12.03^{+38.04}_{-21.84}$)
217	LHCb 8 TeV W	14	$1.35^{+0.59}_{-0.61}$ ($1.35^{+0.72}_{-0.64}$)
218	LHCb 13 TeV Z	16	$1.18^{+1.42}_{-0.60}$ ($1.49^{+1.74}_{-0.89}$)
	13 TeV $t\bar{t}$		
521	ATLAS all-hadronic $y_{t\bar{t}}$	12	$1.06^{+0.14}_{-0.09}$ ($1.05^{+0.21}_{-0.10}$)
528	CMS dilep $y_{t\bar{t}}$	10	$1.10^{+1.08}_{-0.68}$ ($1.03^{+1.60}_{-0.74}$)
587	ATLAS lep+Jet $m_{t\bar{t}} + y_{t\bar{t}} + y^B_{t\bar{t}} + H^{t\bar{t}}_T$	34	$0.92^{+0.32}_{-0.14}$ ($0.94^{+0.59}_{-0.16}$)
581	CMS lep+jet $m_{t\bar{t}}$	15	$1.44^{+1.18}_{-0.73}$ ($1.37^{+1.86}_{-0.82}$)
	Inclusive Jet		
553	ATLAS 8 IncJet	171	$1.76^{+0.20}_{-0.12}$ ($1.80^{+0.33}_{-0.16}$)
554	ATLAS 13 IncJet	177	$1.38^{+0.13}_{-0.10}$ ($1.39^{+0.20}_{-0.11}$)
555	CMS 13 IncJet	78	$1.10^{+0.24}_{-0.17}$ ($1.11^{+0.30}_{-0.16}$)

nDY

nTT

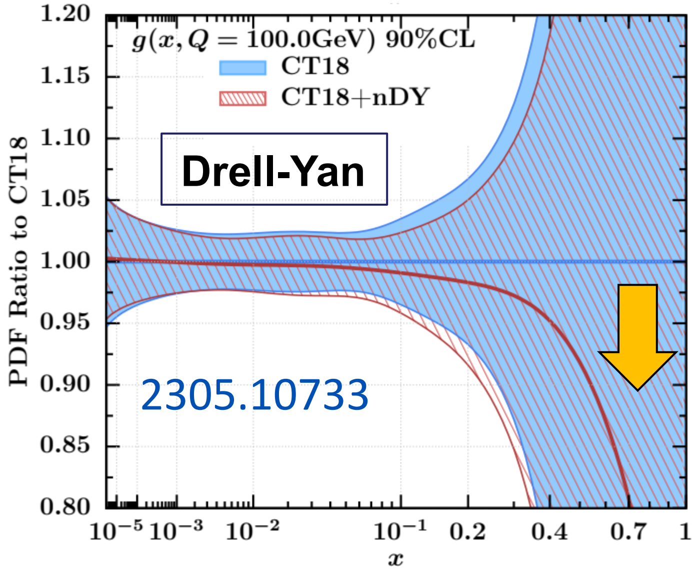
nIncJet

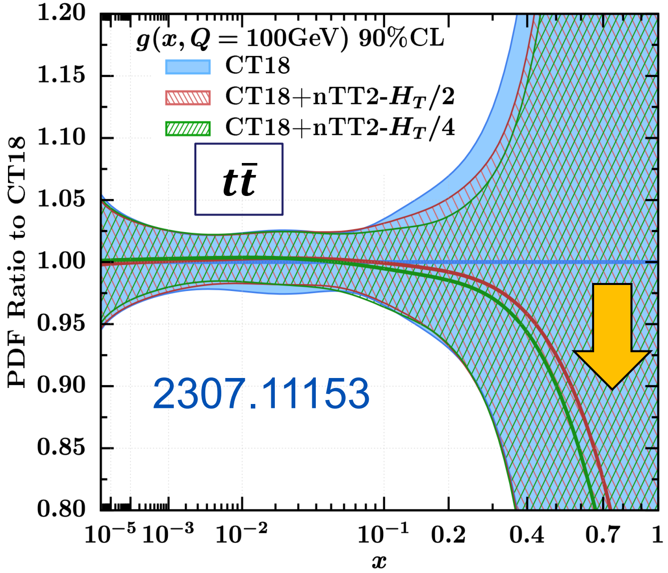
nDYTTIncJet

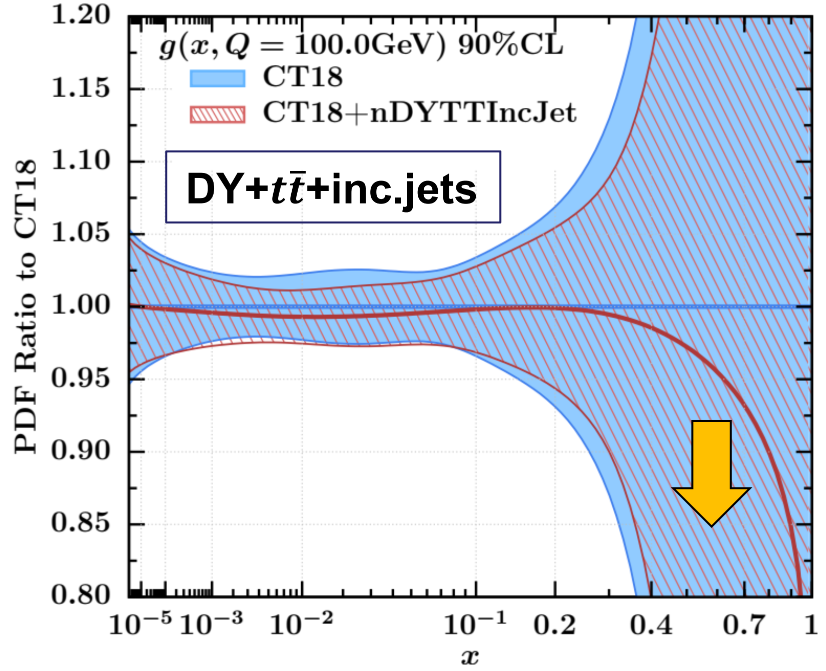
Fits with 1 type of new data

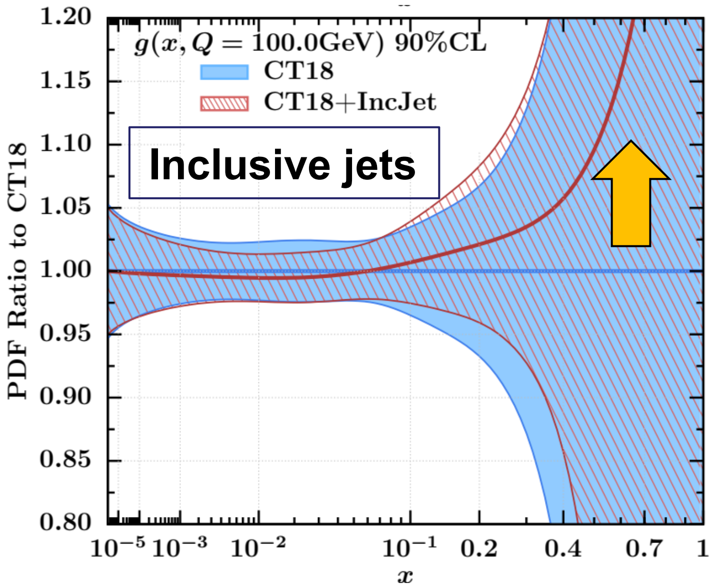
A fit with all 3 types

Pulls on the gluon PDF by the new data type



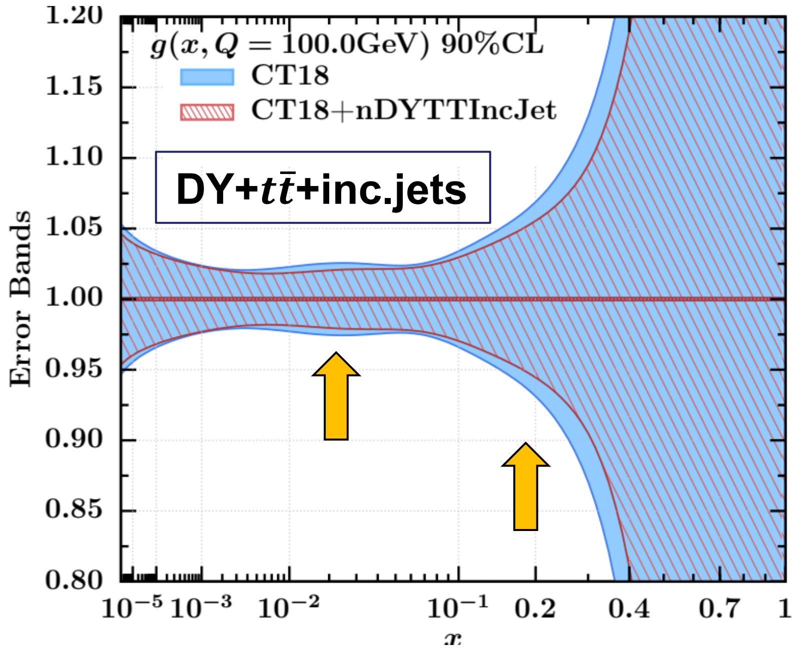






After including DY, $t\bar{t}$, and inc. jet data simultaneously, we get a softer gluon. Note that new DY and $t\bar{t}$ data favor a softer gluon, new inc. jet data prefer a harder gluon.

Mild changes in the gluon uncertainty



PRELIMINARY

Conclusions

- More and more N3LO contributions will soon be available for PDF analyses

- True extent of N3LO in global PDF analyses not fully known until all components are included

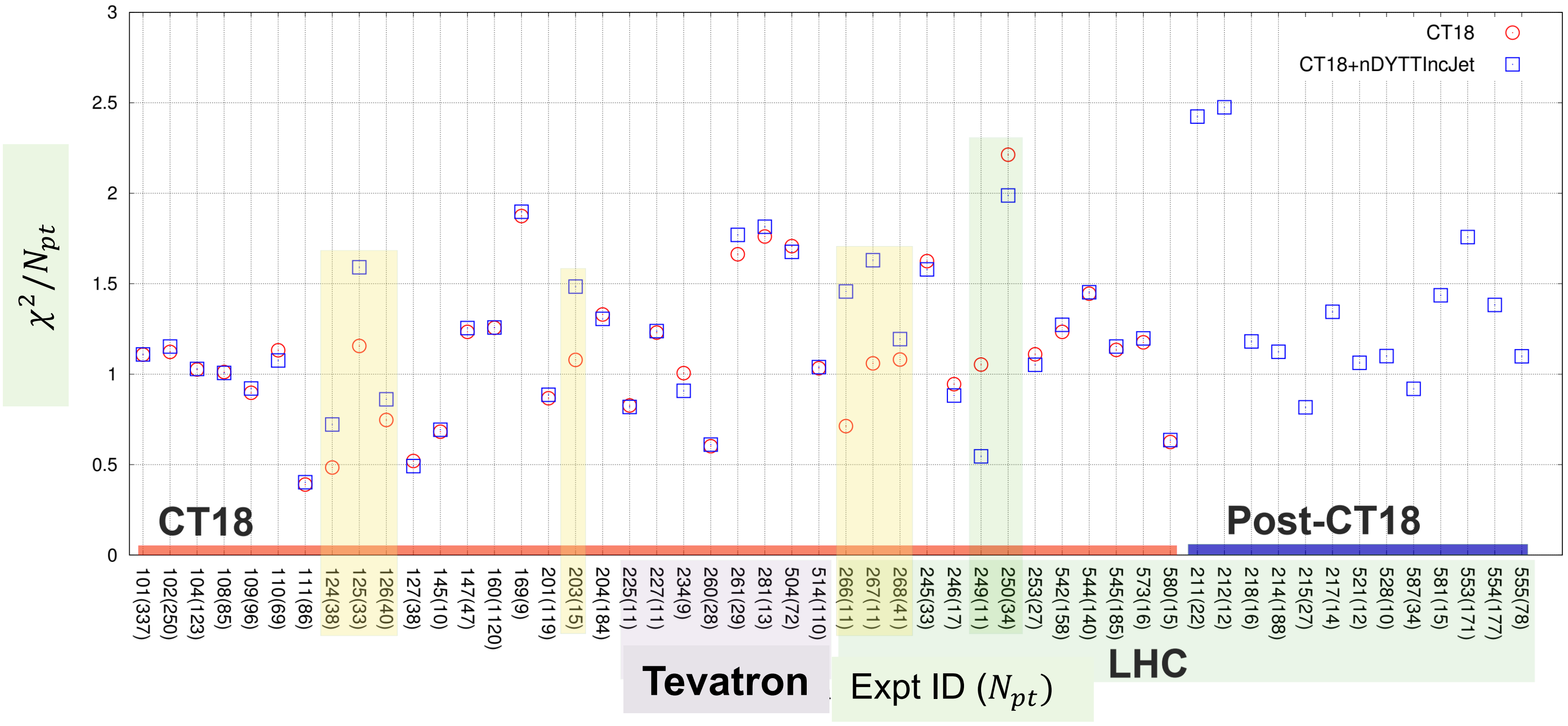
- CTEQ-TEA works on implementing N3LO and other comparable factors, and on exploring the impact of new data in CT202X global analyses

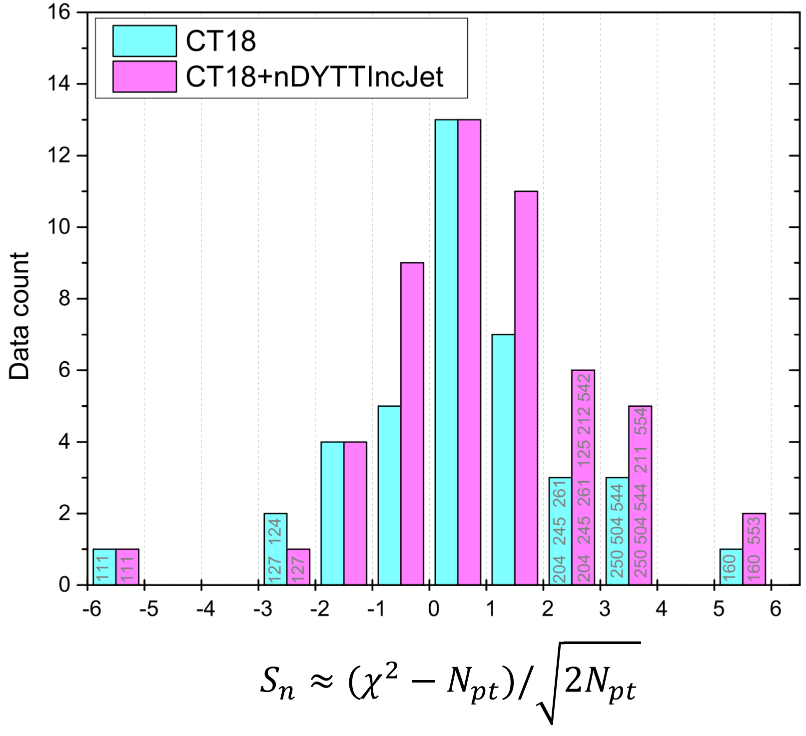
- N3LO uncertainties dominated by current missing pieces in N3LO DGLAP, N3LO DIS, missing HOU, scale choices, agreement between experiments, methodologies, … These are likely to pose challenges to replicability

BACK UP SLIDES

PRELIMINARY

A 3-data-type fit (CT18+nDYTTIncJet)





The most precise new experiments tend to have an elevated χ^2/N_{pt}, in the same pattern as observed for CT18

χ^2/N_{pt} increases for experiments 124 and 125 (NuTeV), 126 and 127 (CCFR) and 203 (E866 DY), 266 and 267 (CMS 7TeV Ach), 268 (ATLAS 7TeV W, Ach).

χ^2/N_{pt} decreases for experiments 249 (CMS 8 TeV Ach), 250 (LHCb 8 TeV W/Z)