Snowmass 2021 whitepaper: Proton structure at the precision frontier

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arXiv:2203.13923 [hep-ph]
submission under discussion

Keping Xie
University of Pittsburgh

Mainly contribute to
EF06: hadron structure, forward QCD, and hadron spectroscopy

P. Nadolsky's talk in
Energy Frontier Workshop and
Community Meeting

Recent trends in the global analysis of proton PDFs

1. Status of modern NNLO PDFs and their applications
2. Future experiments to constrain PDFs
3. Theory of PDF analysis at N2LO and N3LO
4. New methodological advancements
   - Experimental systematic uncertainties in PDF fits
   - Theoretical uncertainties in PDF fits
   - Machine learning/AI connections
5. Delivery of PDFs; PDF ensemble correlations in critical applications
6. PDFs and QCD coupling strength on the lattice
7. Nuclear, meson, transverse-momentum dependent PDFs
8. Public PDF fitting codes
9. Fast (N)NLO interfaces
10. PDF4LHC21 recommendation and PDF4LHC21 PDFs for the LHC analyses

PDF-focused topics explored in Snowmass

Topic	Status, 2013	Status, 2022
Achieved accuracy of PDFs	N2LO for evolution, DIS and vector boson produciton	N2LO for all key processes; N3LO for some processes
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	LuXQED and other photon PDFs from several groups; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Small-x and threshold resummations implemented in several PDF sets
Available LHC processes to determine nucleon PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production at 7 and 8 TeV	+ $t\bar{t}$, single-top, dijet, $\gamma/W/Z$ +jet, low-Q Drell Yan pairs, … at 7, 8, 13 TeV
Near-future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …
Benchmarking of PDFs for the LHC	PDF4LHC'2015 recommendation in preparation	PDF4LHC'21 recommendation issued
Precision analysis of specialized PDFs		Nuclear, meson, transverse-momentum dependent PDFs

NEW TASKS in the HL-LHC ERA:

Obtain complete N2LO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast N2LO interfaces	Estimate N2LO theory uncertainties	New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications

Comparisons of the latest PDF sets

New

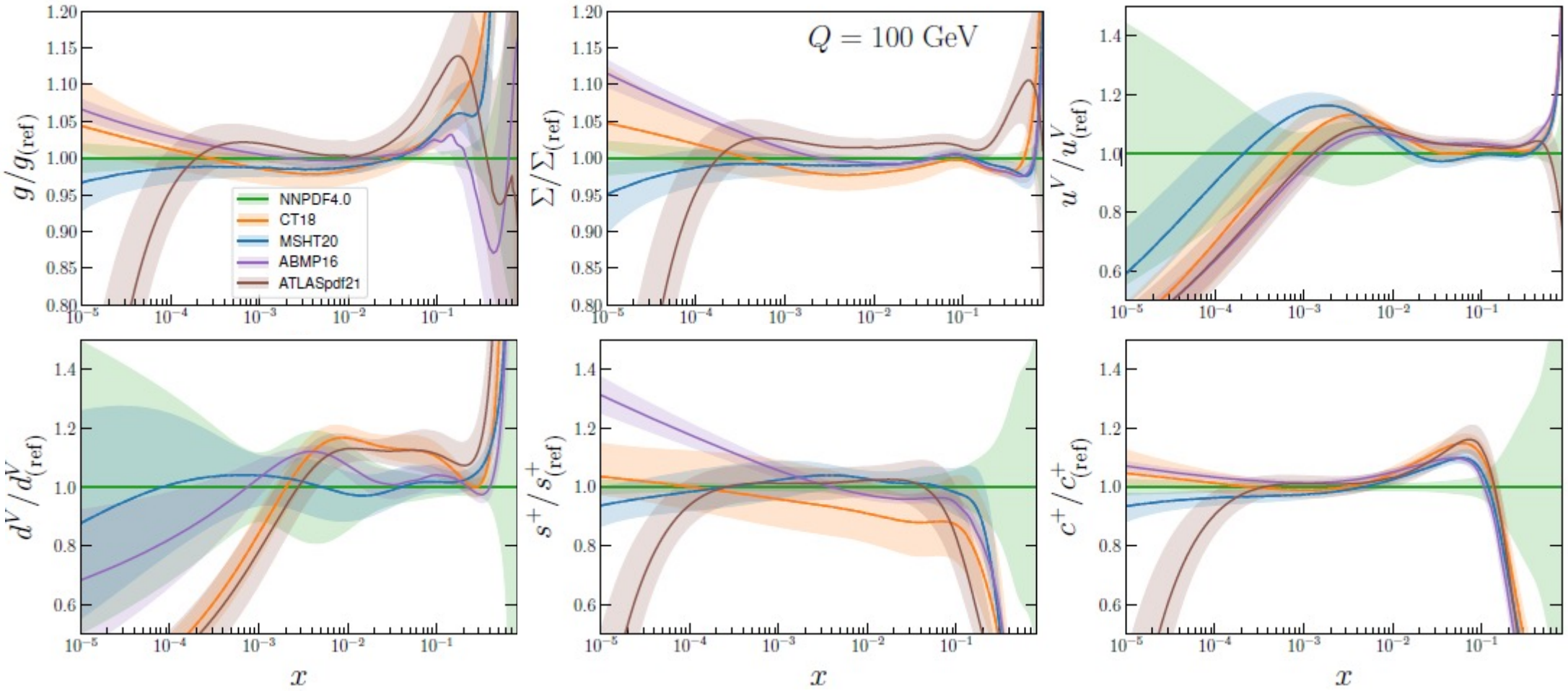


FIG. 2. Comparison of the PDFs at $Q = 100$ GeV. The PDFs shown are the N2LO sets of NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$, and ATLASpdf21. The ratio to the NNPDF4.0 central value and the relative 1σ uncertainty are shown for the gluon g, singlet Σ, total strangeness $s^+ = s + \bar{s}$, total charm $c^+ = c + \bar{c}$, up valence u^V and down valence d^V PDFs.

PDF uncertainties

New

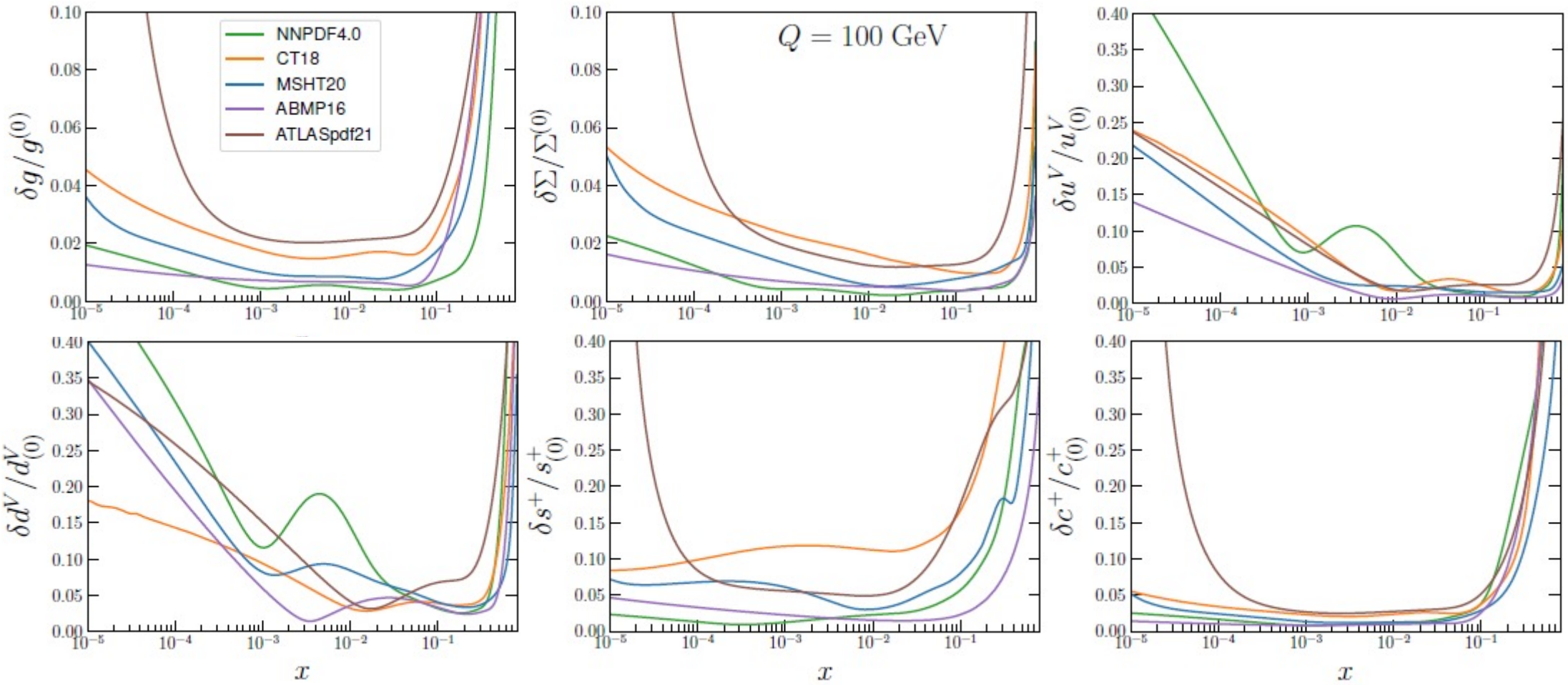


FIG. 3. Comparison of the symmetrized PDF uncertainties at $Q = 100$ GeV for the gluon g, singlet Σ, total strangeness $s^+ = s + \bar{s}$, total charm $c^+ = c + \bar{c}$, up valence u^V and down valence d^V PDFs. The PDF sets shown are the N2LO sets of NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$ and ATLASpdf21.

Parton luminosities

New

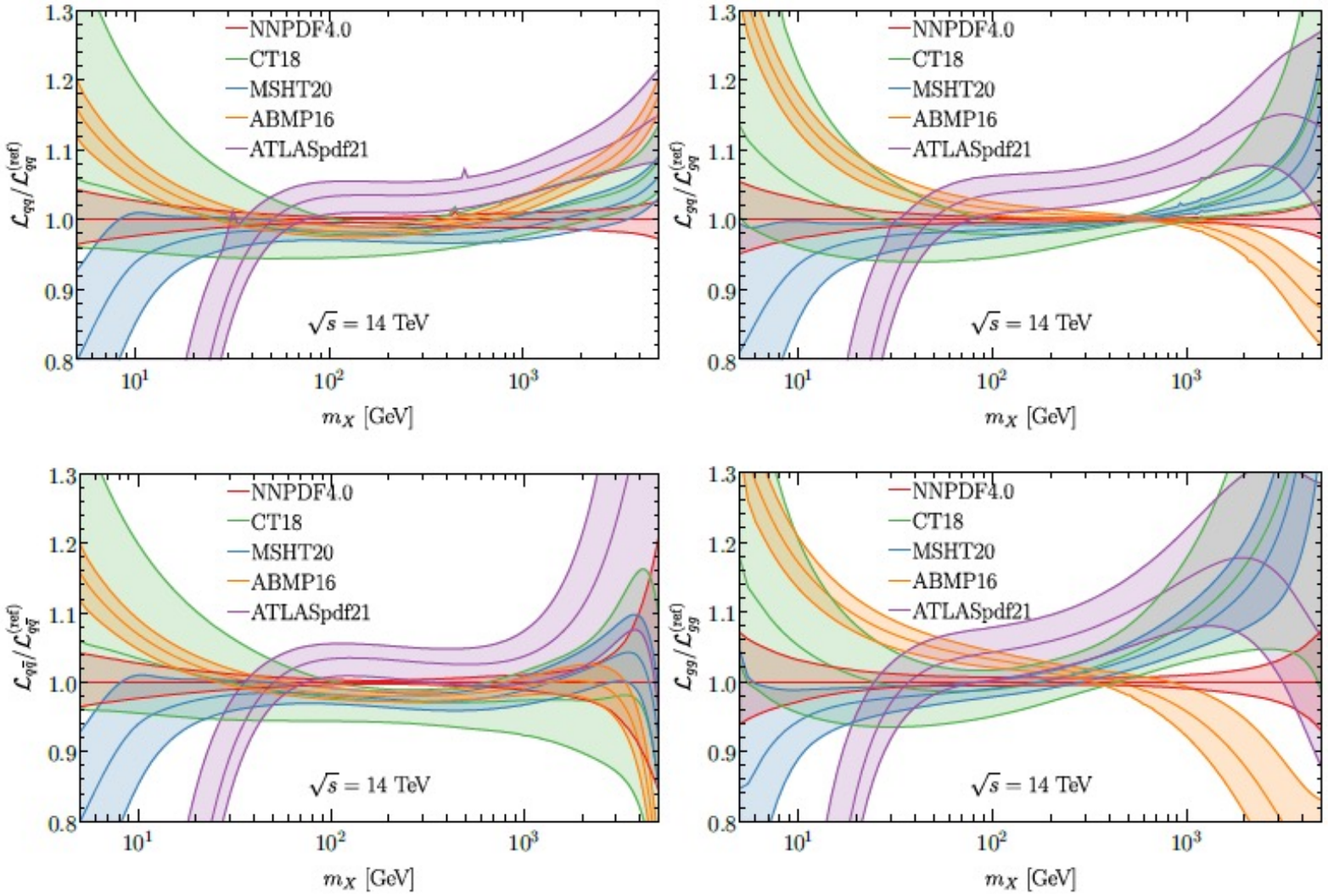
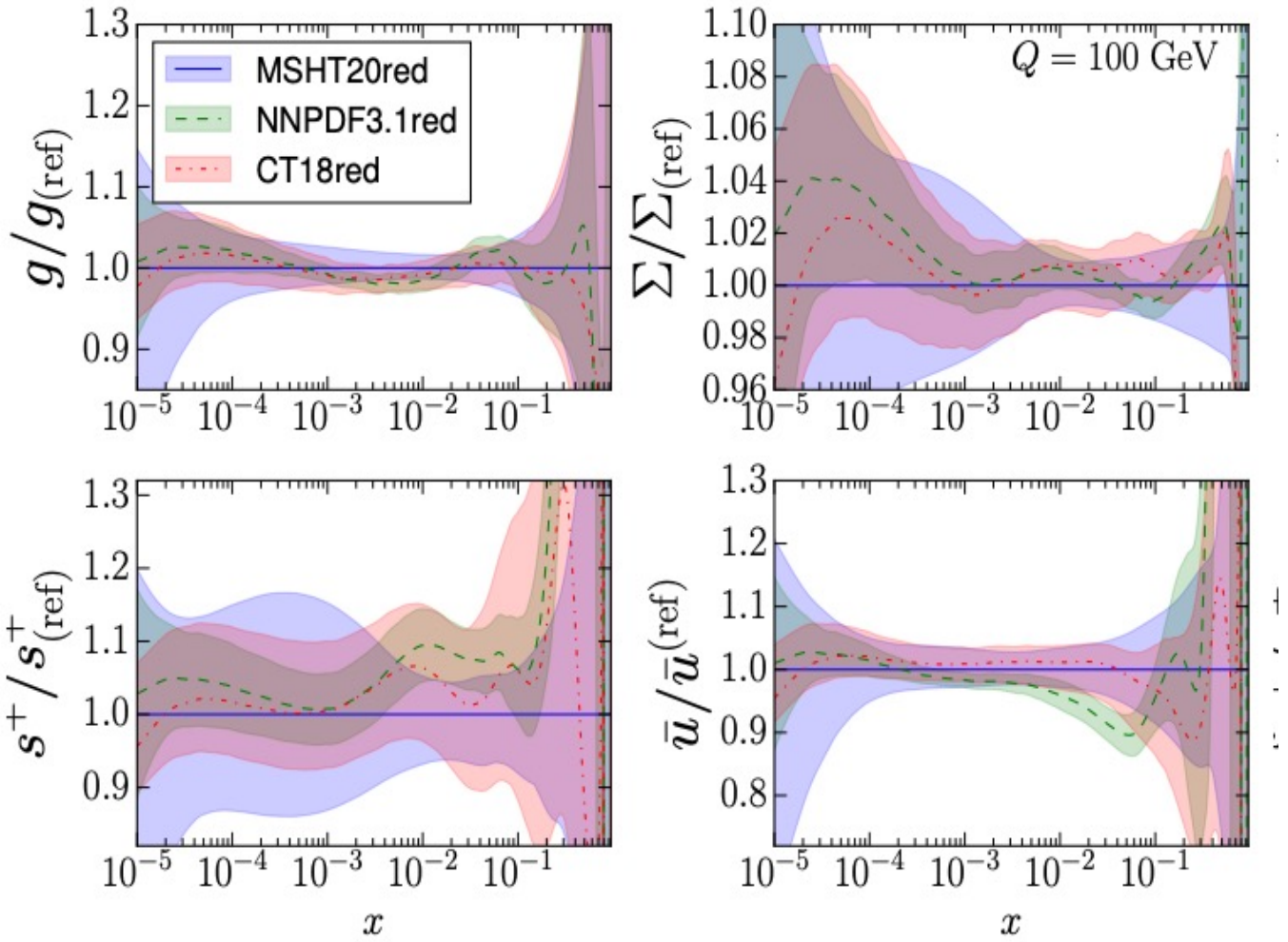
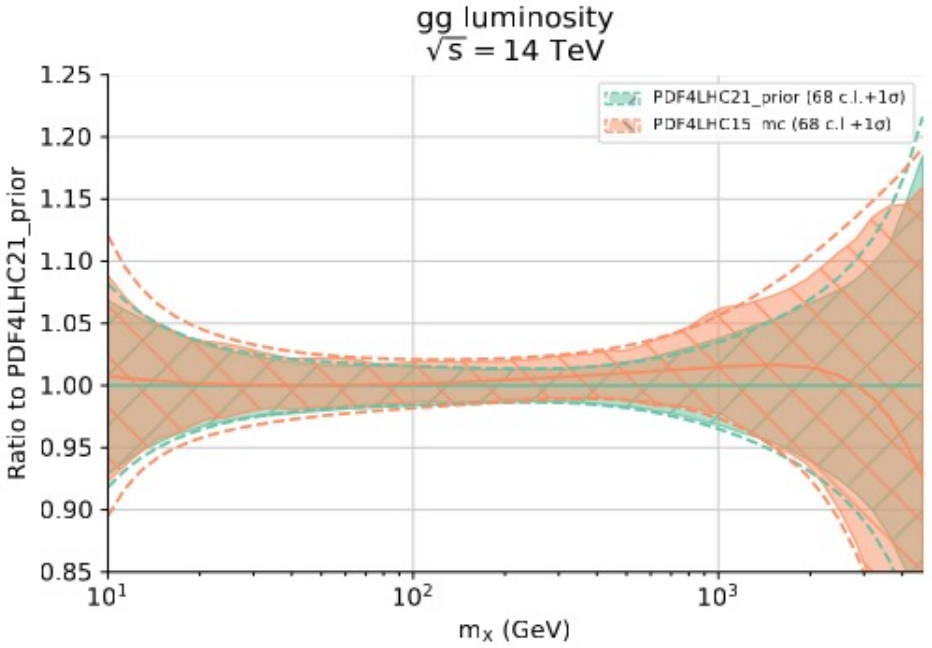
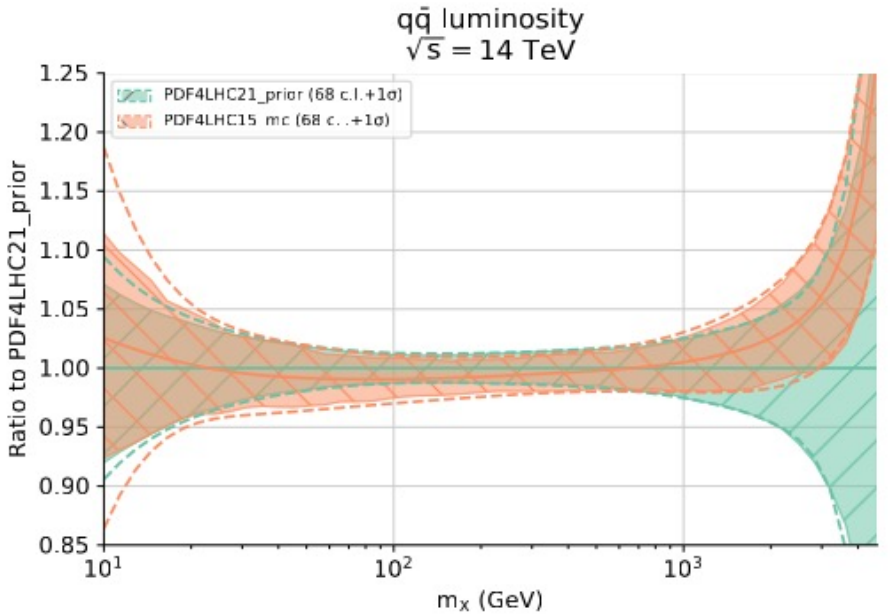


FIG. 4. Comparison, as a function of the invariant mass m_X, of the parton luminosities at $\sqrt{s} = 14$ TeV, computed using N2LO NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$, and ATLASpdf21. The ratio to the NNPDF4.0 central value and the relative 1σ uncertainty are shown for each parton combination.

PDF4LHC21 benchmarking study

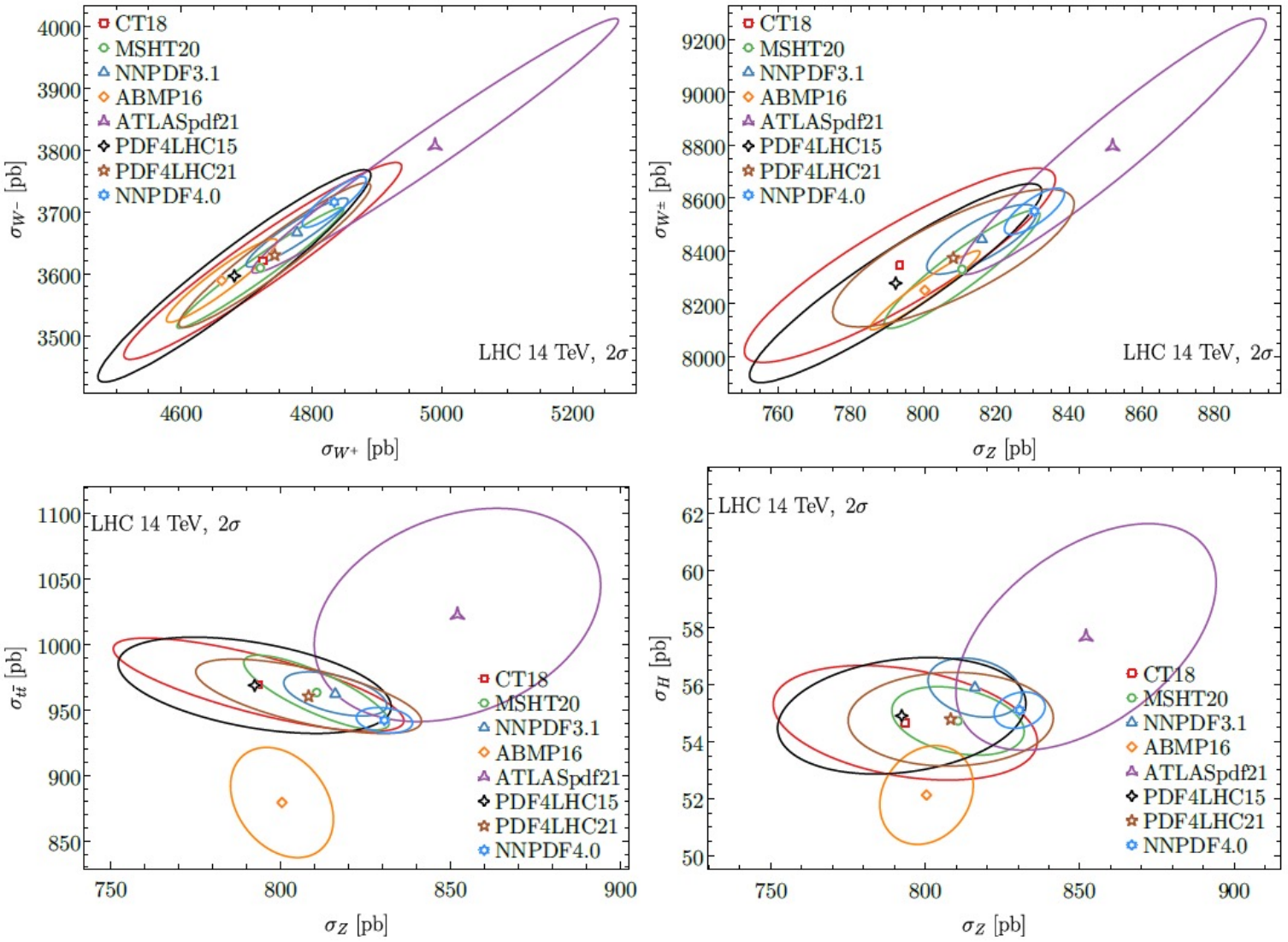






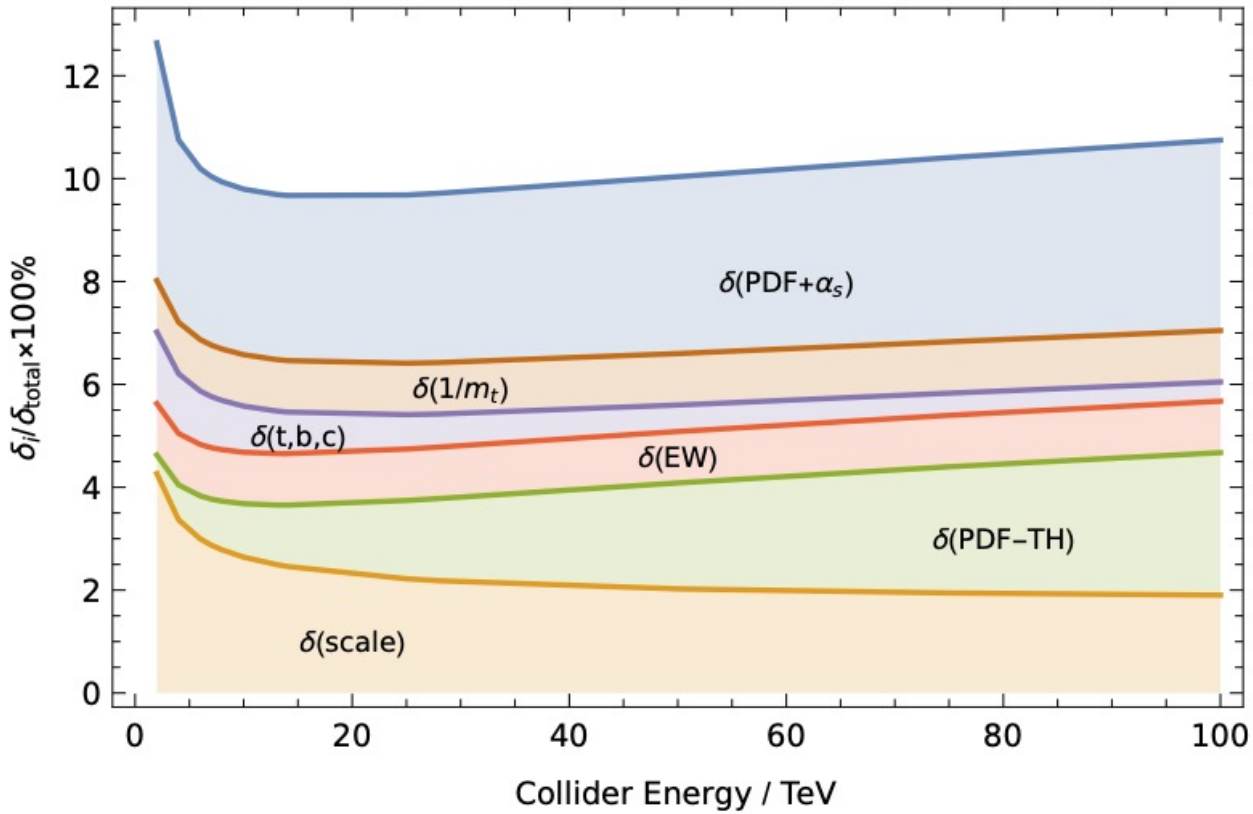
Predictions for LHC benchmark cross sections

New

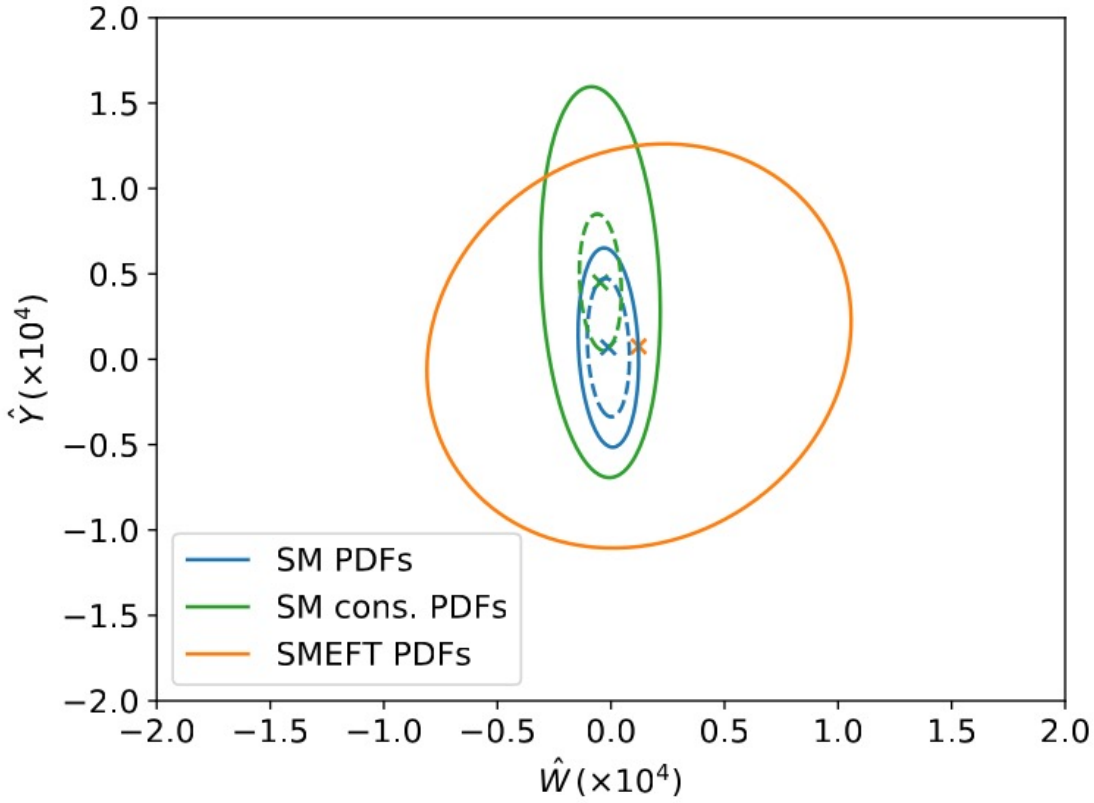


NNLO cross sections at the LHC and 95% CL PDF uncertainties predicted with recent PDF sets, including the latest NNPDF4.0, ATLAS21 analyses and predictions based on combined PDF4LHC21 PDF sets

Applications to Higgs physics, BSM, and SMEFT



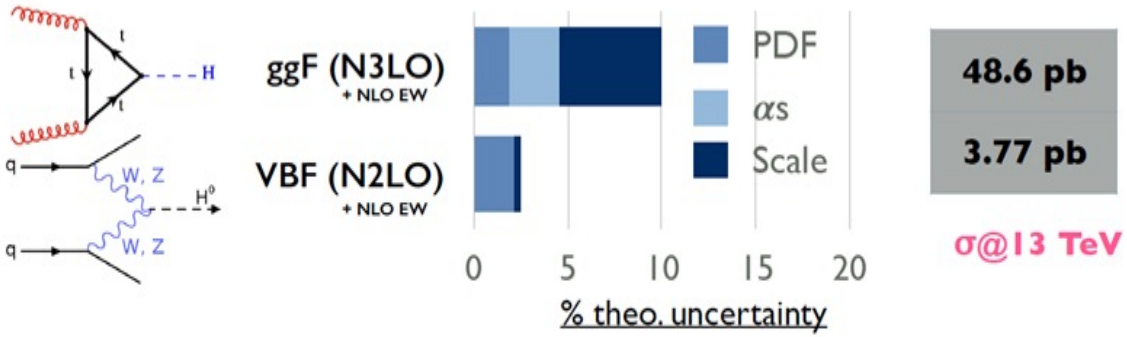
arXiv:1902.00134 [hep-ph]



arXiv:2104.02723 [hep-ph]

PDFs and α_s introduce leading uncertainties in EW/BSM physics at hadron colliders

For example, in Higgs production at the HL-LHC and HE-LHC

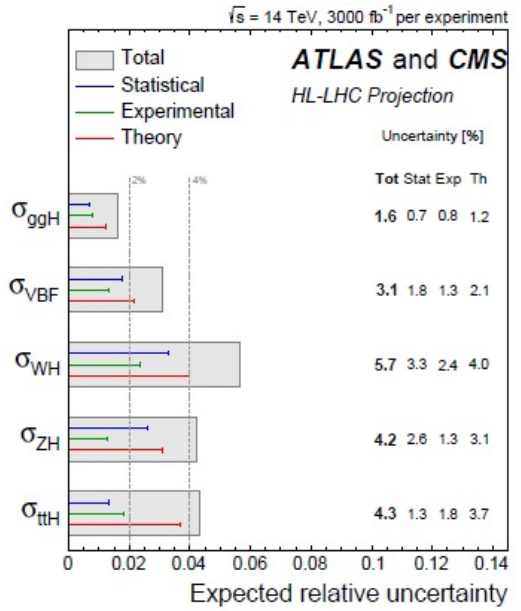


Reaching the targeted accuracy of PDFs at the HL-LHC/HE-LHC is not automatic:

Which advancements in QCD theory & PDF determination will be required, as well as new measurements at the LHC and other facilities?

How to tackle the growing complexity of the PDF analysis on the path to 1% uncertainties?

MW measurement, $\sin(\theta_{eff})$, etc.



M. Cepeda et al., arXiv:1902.00134

Understanding systematic uncertainties

- from the experiment side

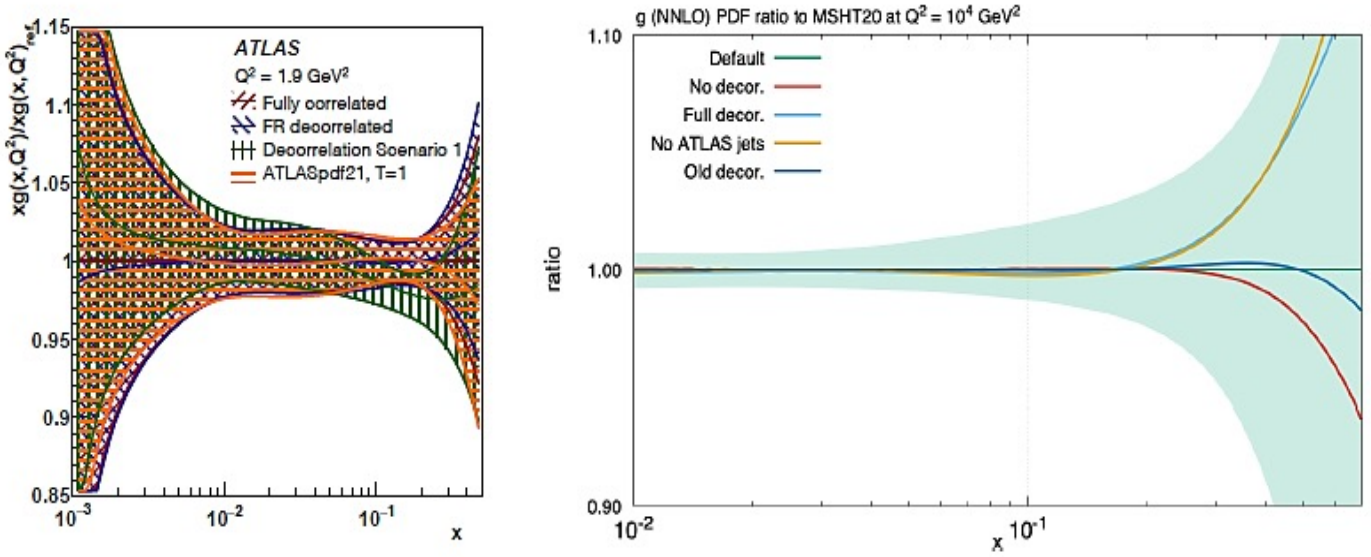
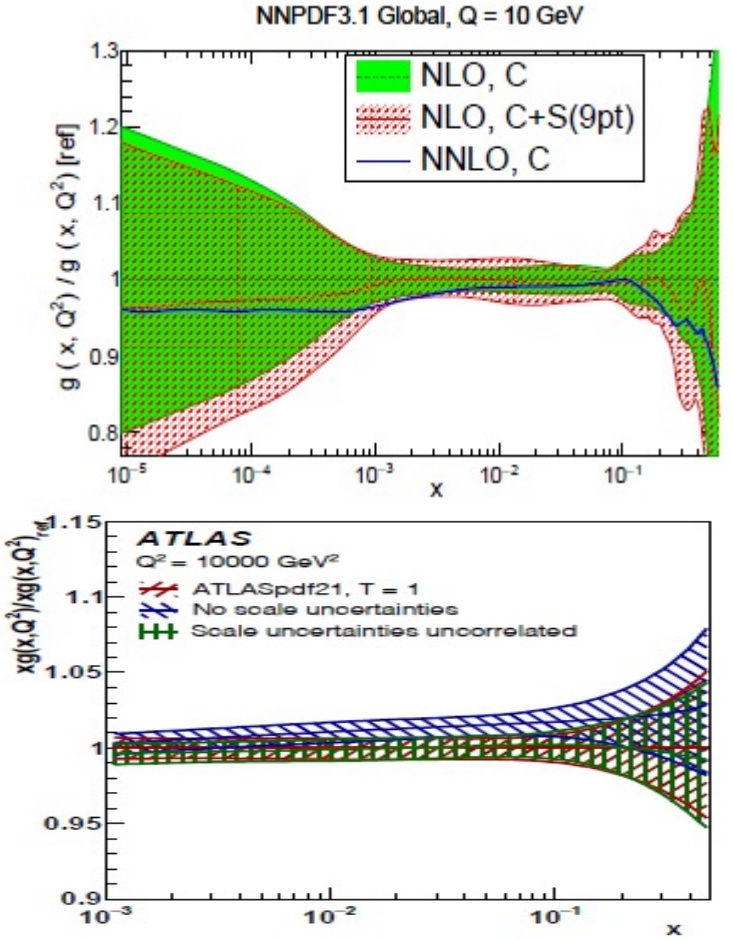


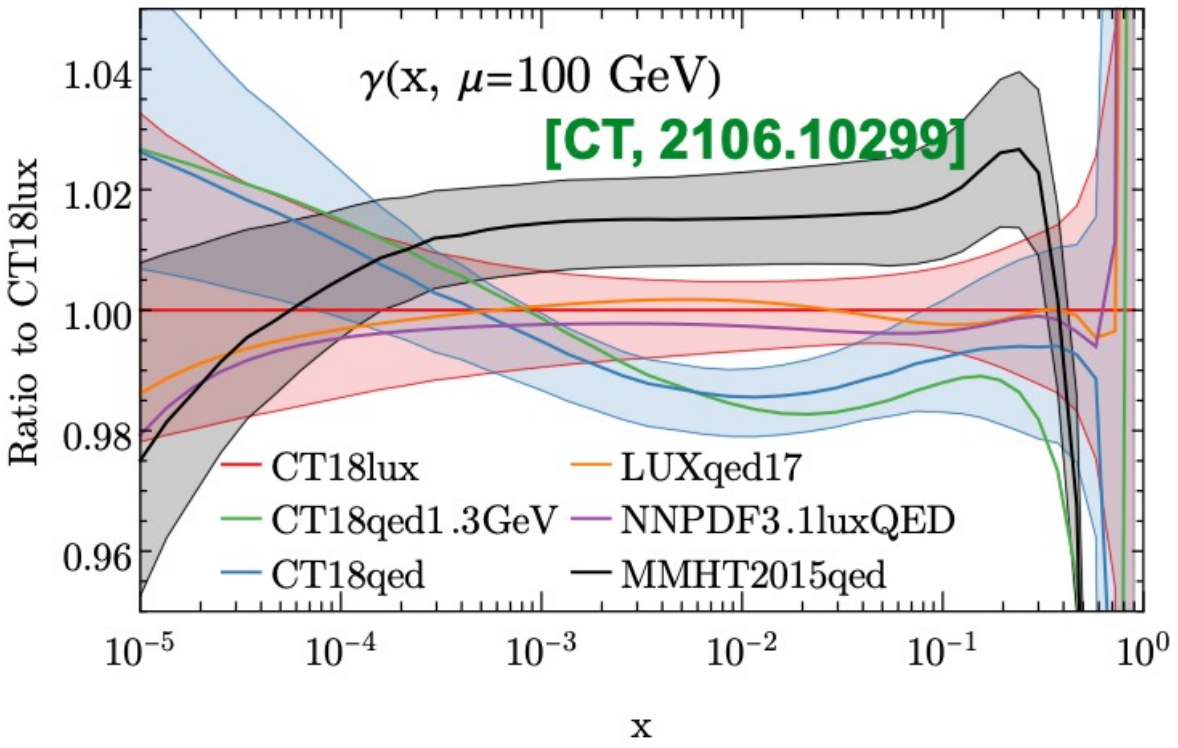
FIG. 9. Difference in the gluon PDF shown in ratio to the ATLASpdf21 (default) gluon(left). This default uses Decorrelation Scenario 2 and this is compared to the use of Full Correlation, Full decorrelation of the flavour response systematic and Decorrelation Scenario 1. The effect of no decorrelation, the default correlation of [9], the decorrelation in [362], and full decorrelation for the MSHT20 gluon (right).

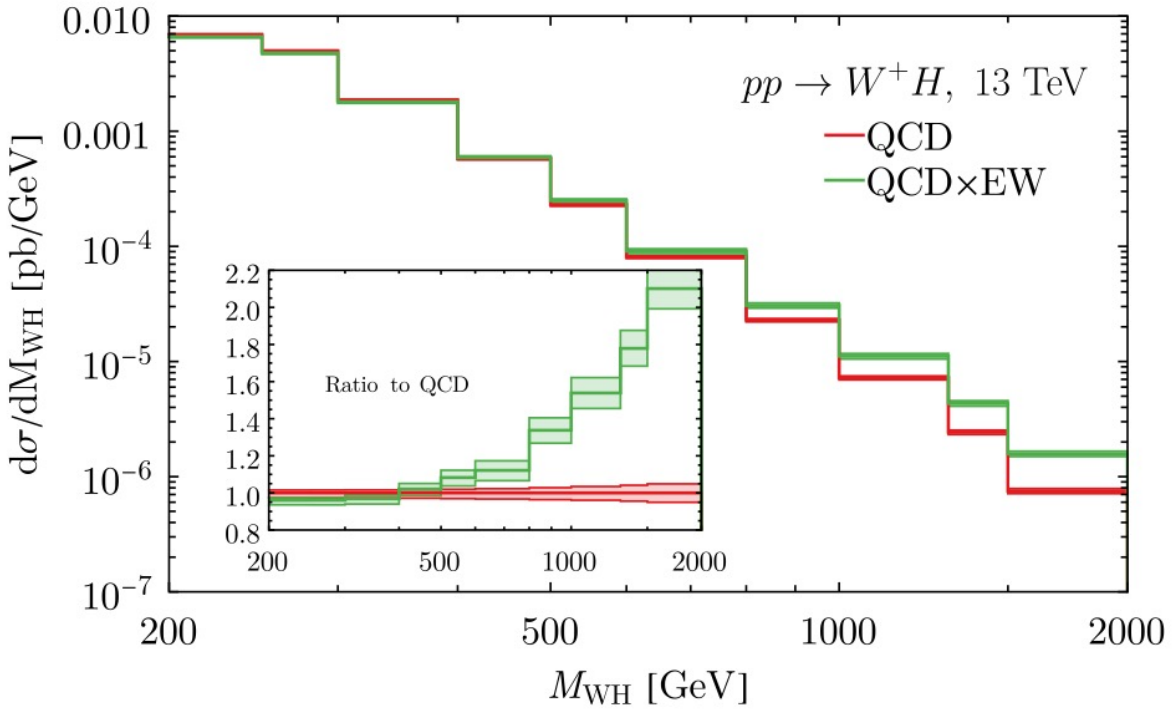
- from the theory side



Examples:studies of theory uncertainties in the PDFs by NNPDF3.1 and ATLAS21

EW corrections





All three groups have taken the LUXqed formalism to constrain the photon PDF and reach percent level uncertainty.
MMHT2015qed is superseded by MSHT20qed [**2111.05357**], in a good agreement with agrees with CT18qed and NNPDF3.1luxqed.

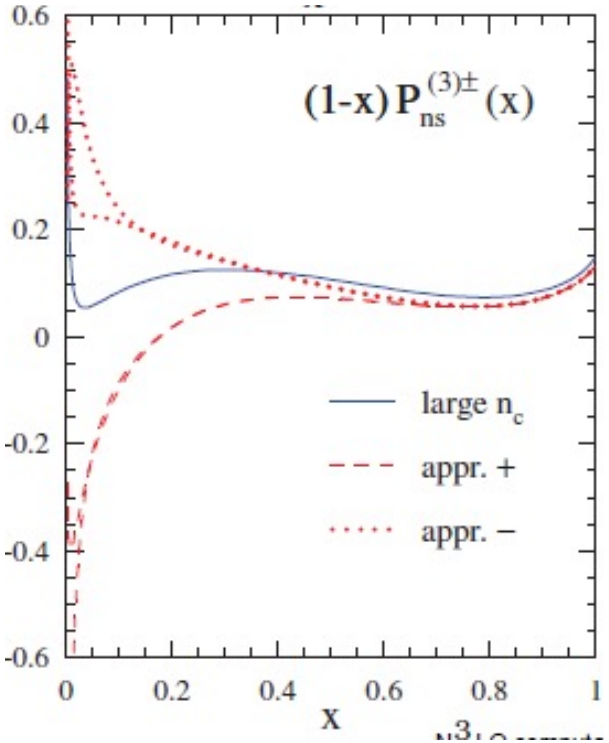
Progress toward N3LO theoretical calculations

A section by S.-O. Moch, B. Mistlberger, G. Magni, J. Blümlein

DIS and DGLAP evolution: we are getting close to having full N3LO predictions

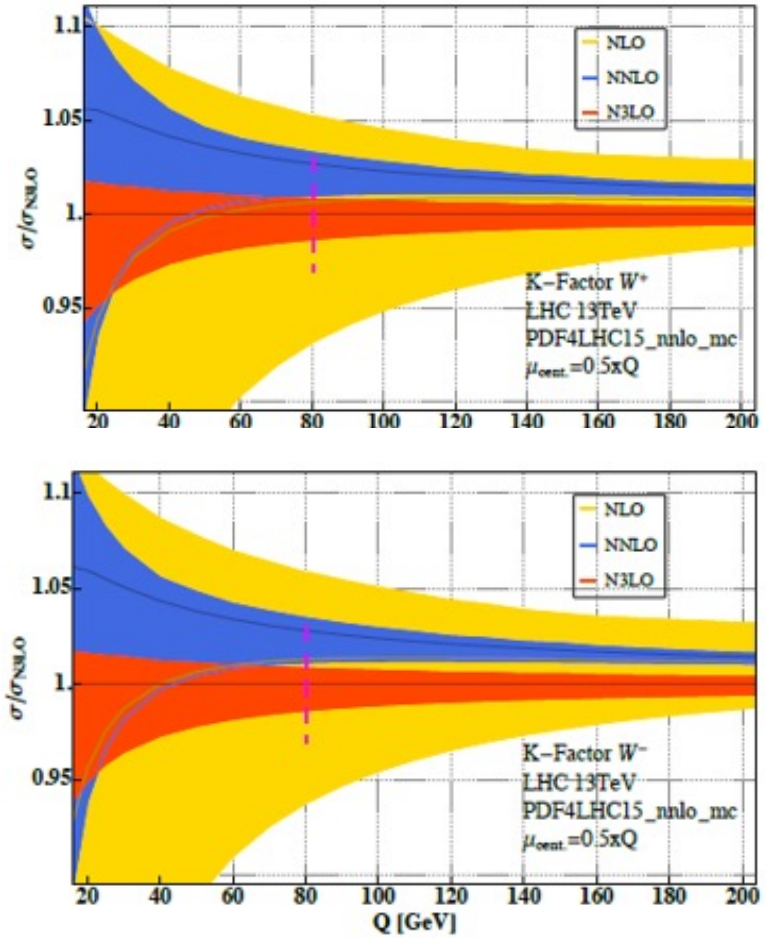
- In the fixed-target DIS region, the preliminary N3LO results are already stable.
- Steady progress in computing small-x and massive N3LO contributions

four-loop $P_{\rm ns}^{(3)\pm}(x)$ and uncertainty bands beyond large-n_c limit with $n_f = 4$



Vector boson production: first N3LO predictions are available

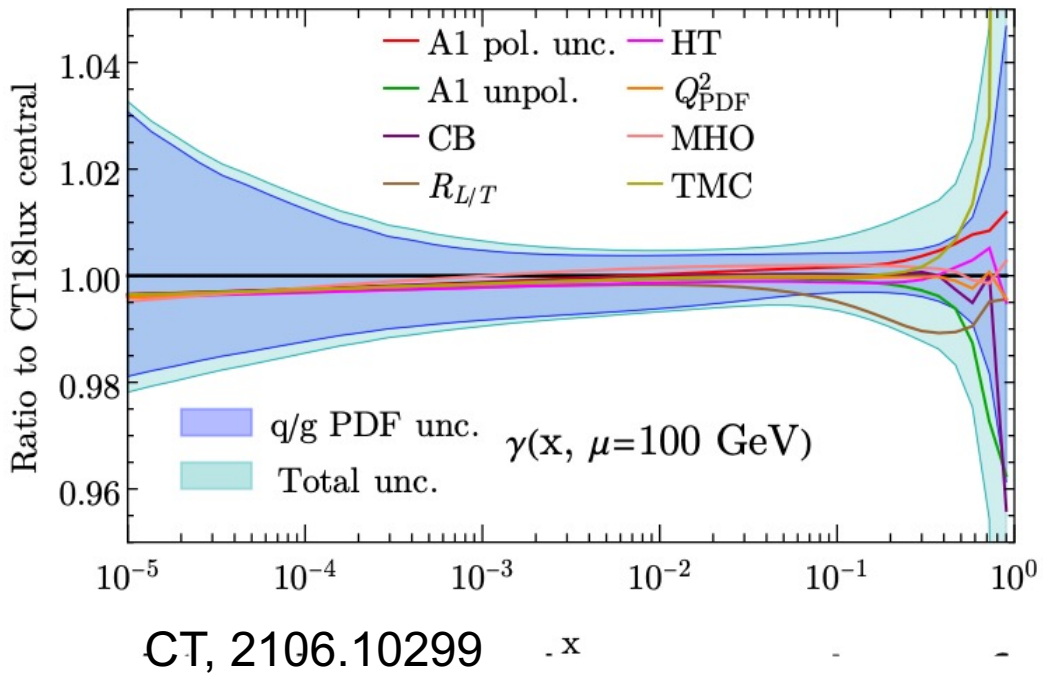
NxLO K-factors for $pp \to W^+X$ (Duhr, Mistlberger)



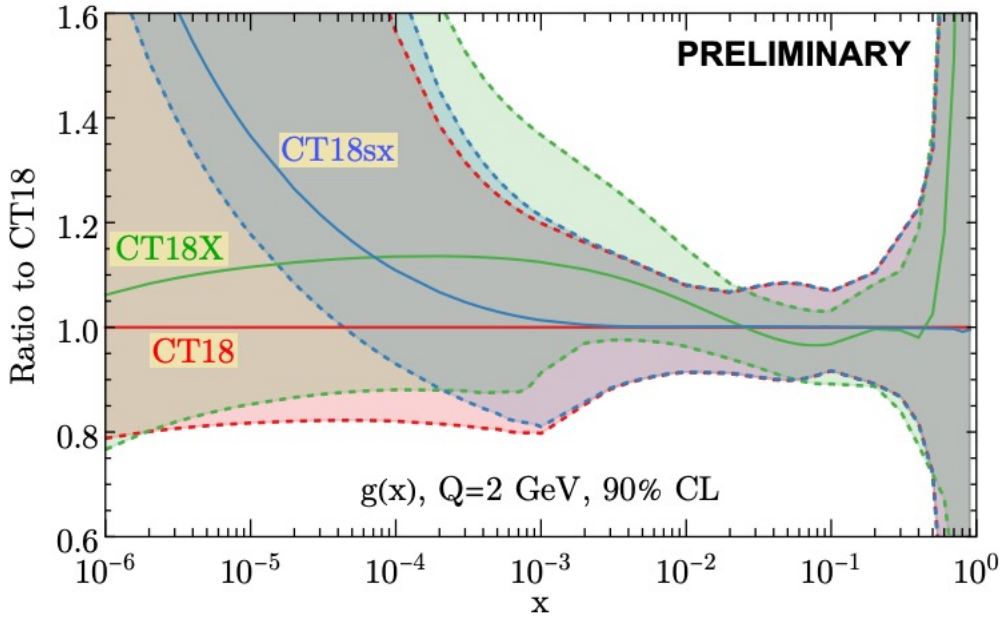
Approximated N3LO PDFs, MSHT20aN3LO [2207.04739], come out.

Other theoretical developments

- Large x: many non-perturbative uncertainty, nuclear, target mass, higher twist, threshold resummation, etc
- Small x: BFKL resummation, saturation, etc [see Mark's talk]



CT, 2106.10299



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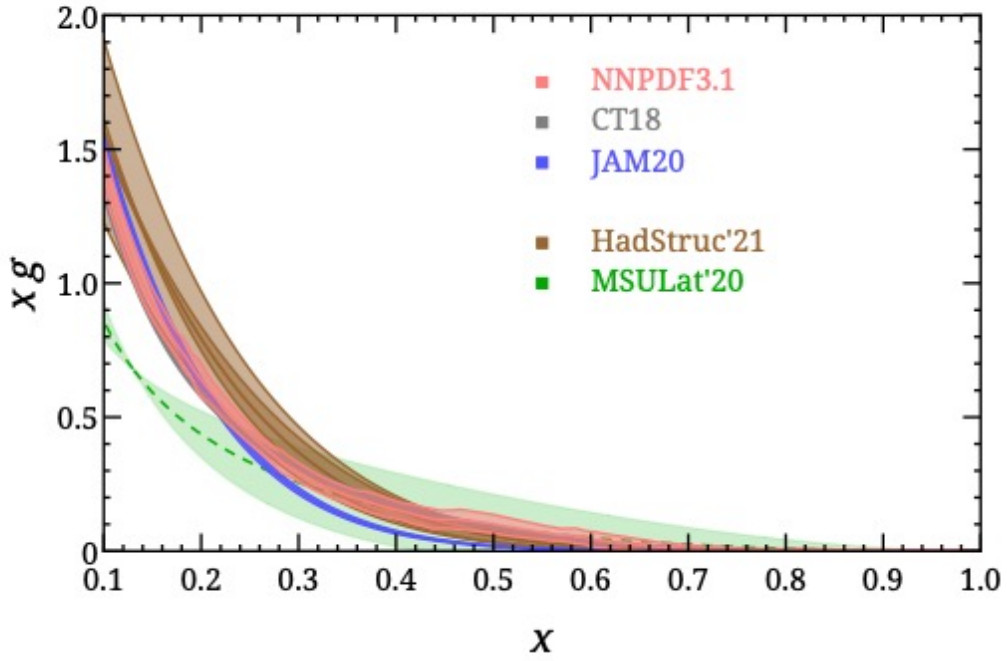
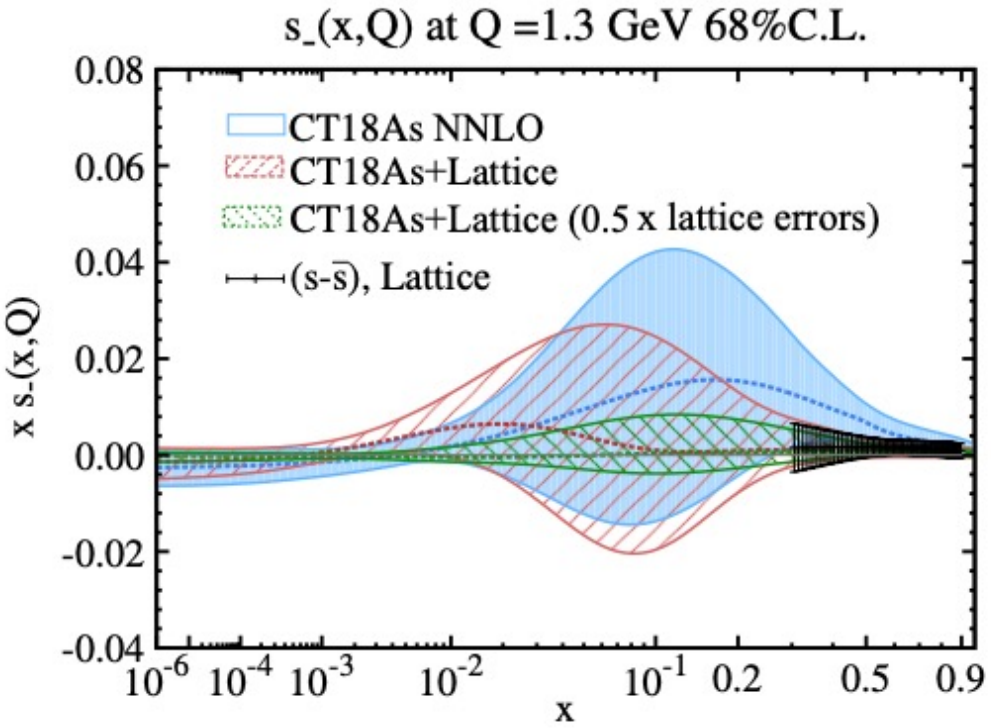
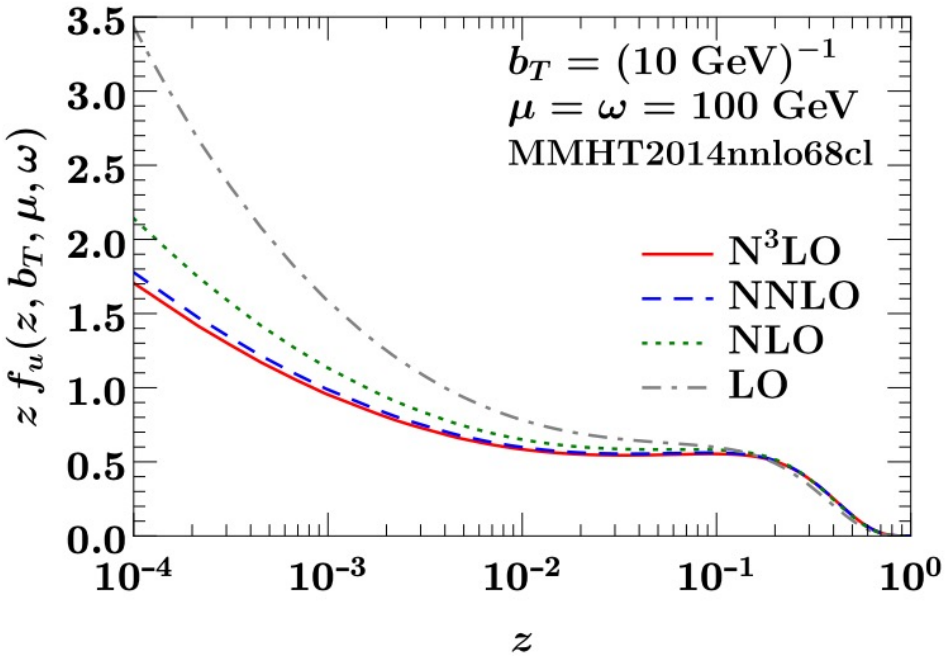
Lattice calculations of PDFs

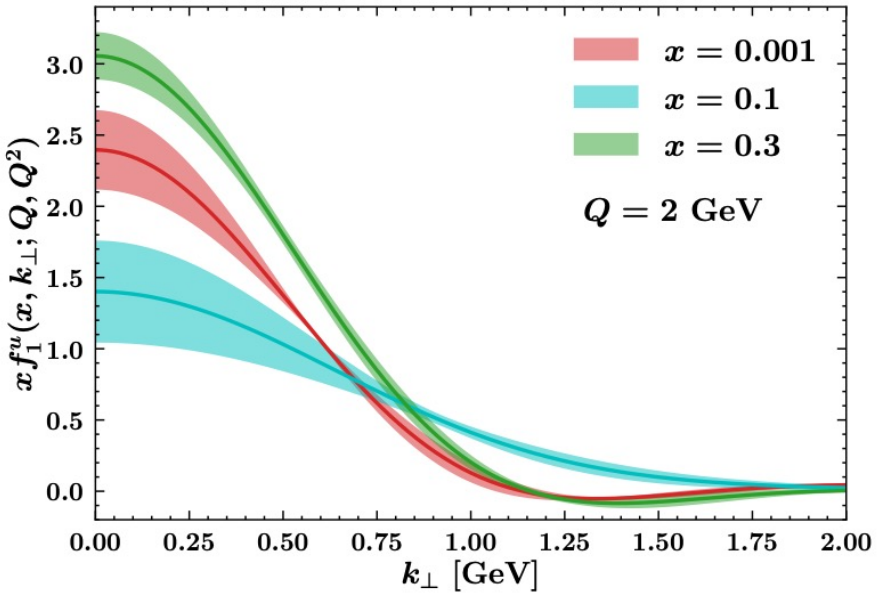




Large Momentum Effective Theory (quasi-PDF) can well determine the momentum $\langle x^{n-1} \rangle_q = \int_{-1}^{1} dx\, x^{n-1} q(x)$
All momentum recover the true distribution.
This approach can give good information of the large-x PDFs.

Transverse-momentum dependent (TMD) and general parton distributions (GPD)





pT observables require TMD factorization

We need TMD evolution and match to the colliear PDFs

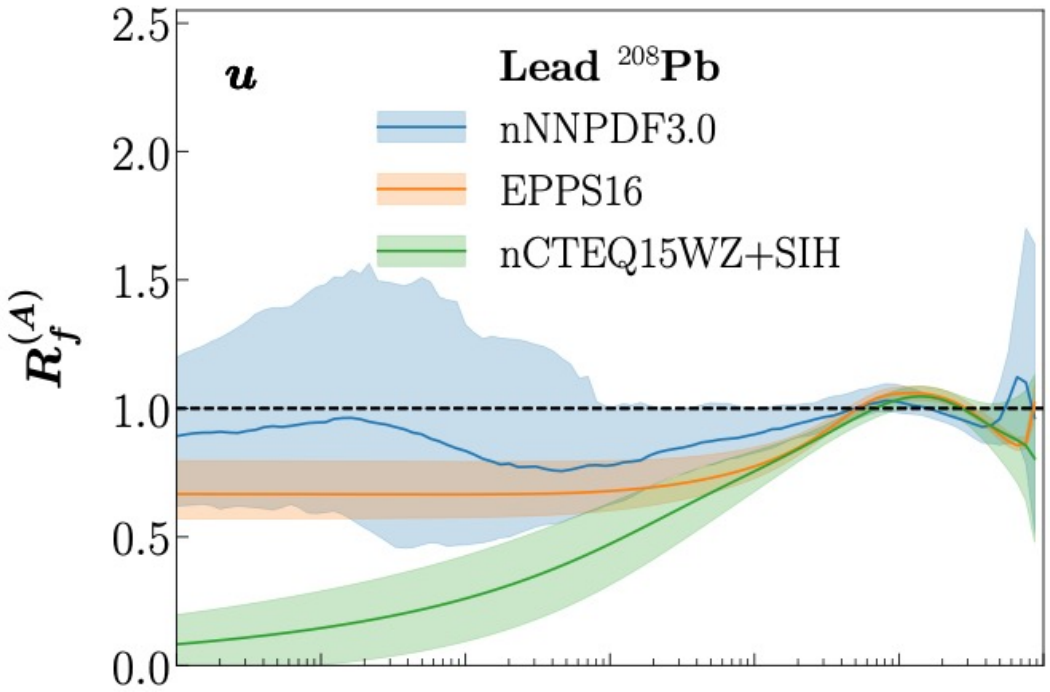
Non-perturbative parameters can be extracted from data (CDF's MW measurement)

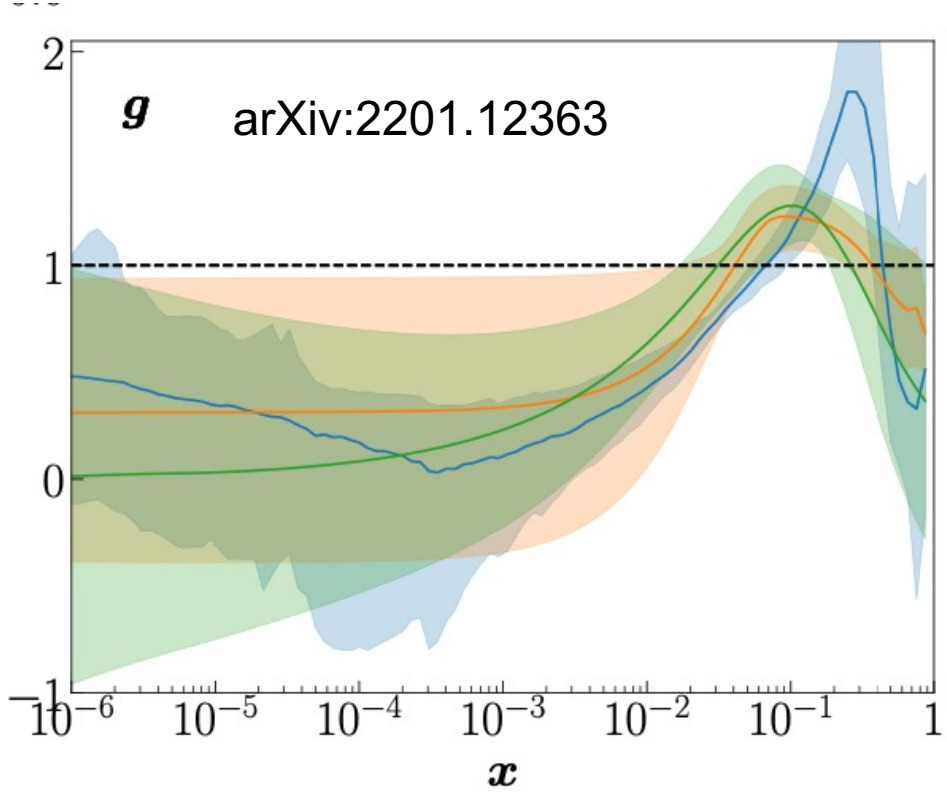
Nuclear PDFs

- Parton distributions inside of nuclei receive nuclear correction.
- Free proton and neutron with isospin symmetry

$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q), \quad d_V(n) = u_V(p) \text{ and } u_V(n) = d_V(p)$$

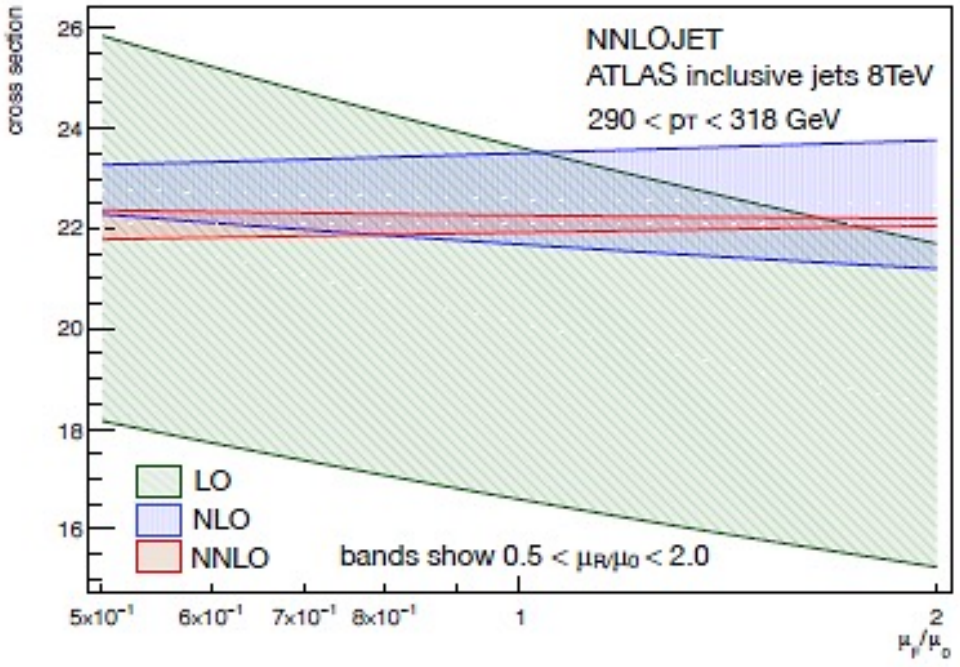
- A-dependent in general





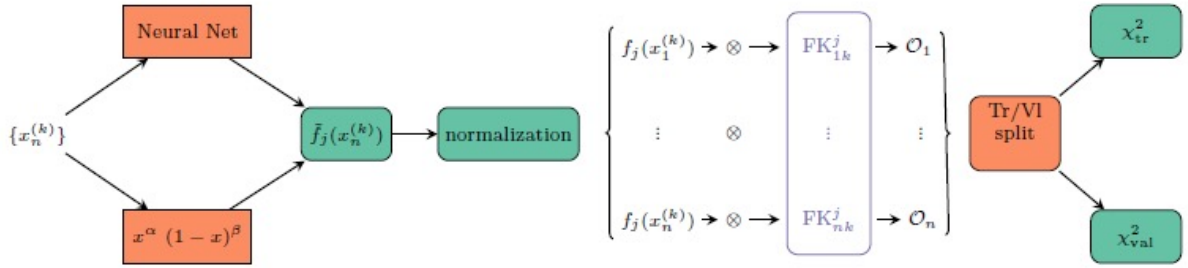
New public computer programs for the global QCD analysis

ApplFast, PineAppl fast interfaces

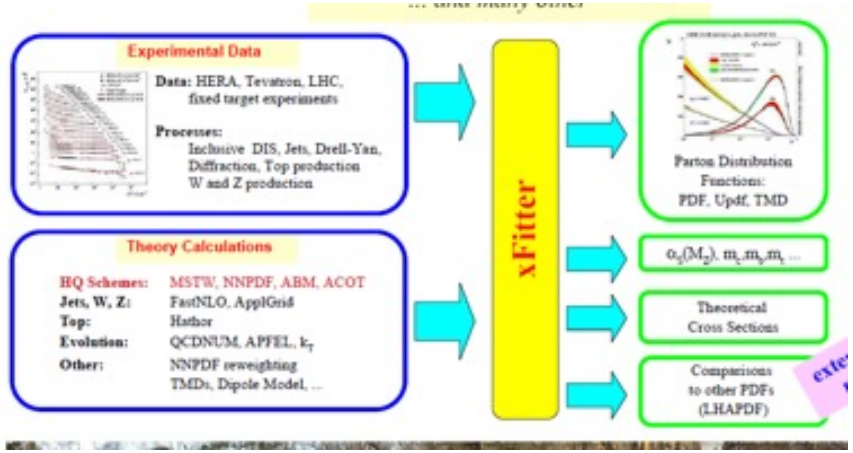


Fast interfaces allow quick evaluation of NLO and NNLO cross sections in the PDF fits, including QCD scale dependence

NNPDF4.0 fitting code

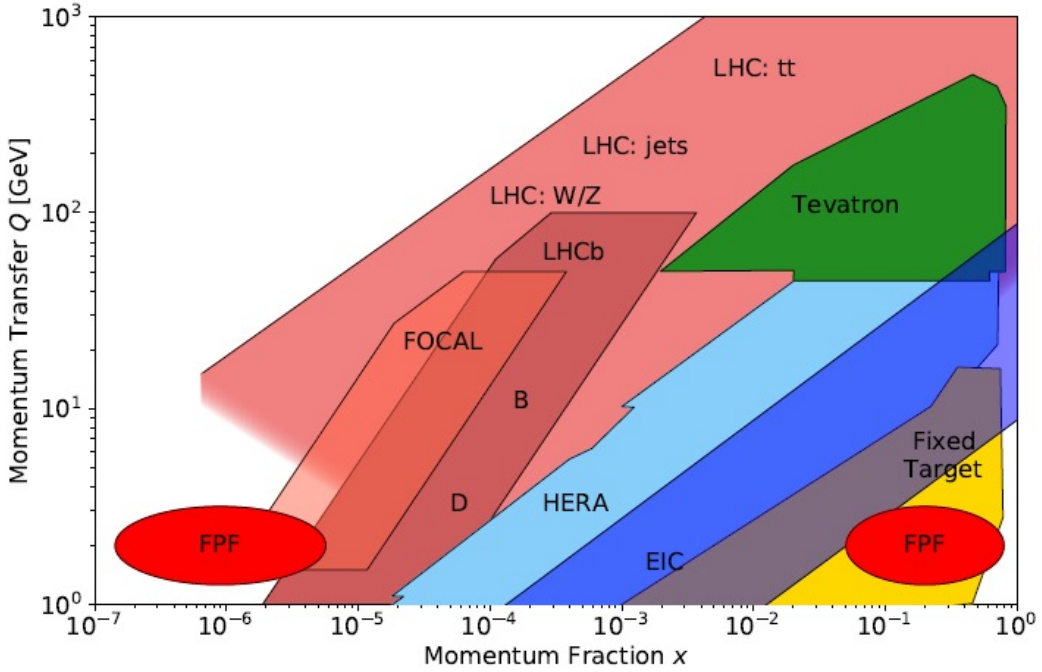


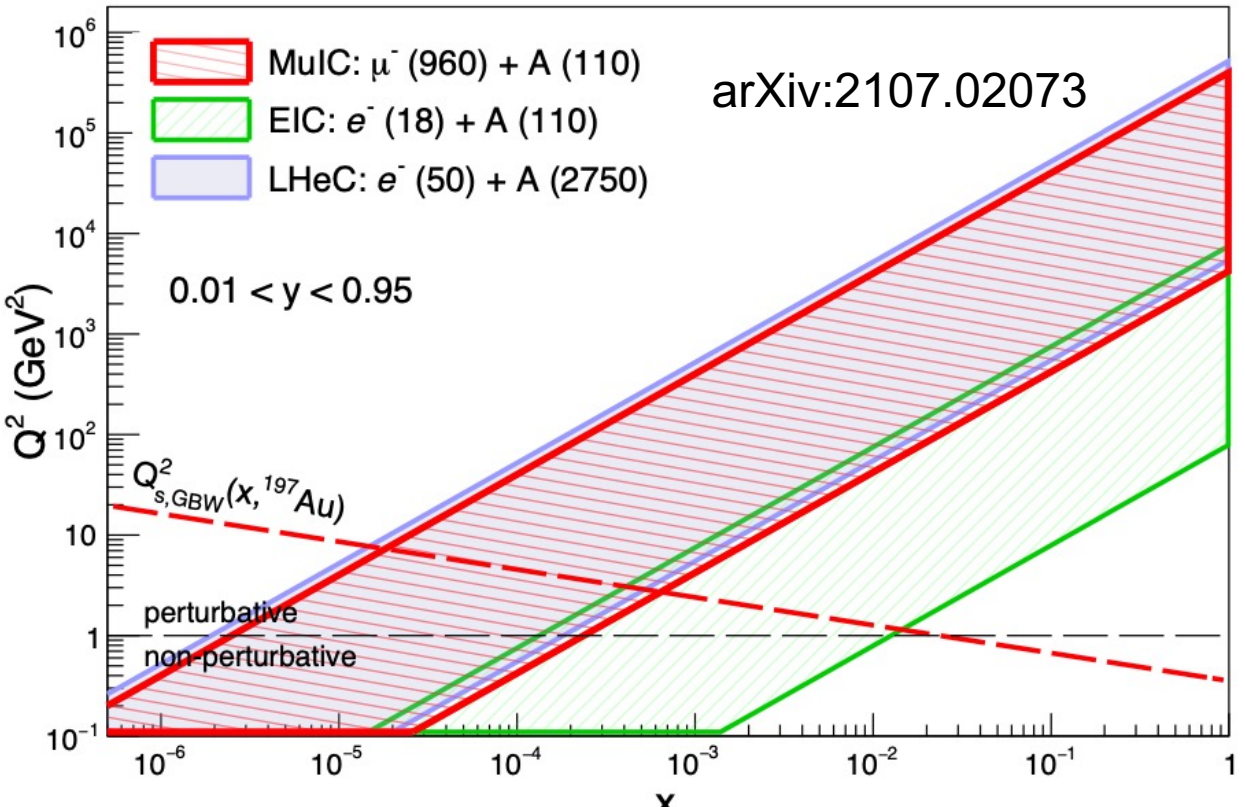
xFitter



Ongoing and future experiments

- (HL-)LHC: Inclusive W/Z, inclusive jet/di-jet, W/Z+jets, ttbar, direct photon, W+c, Z+c, high-pT W/Z, Open charm/bottom, FPF
- EIC: polarization and nuclear exploration
- LHeC and MuIC

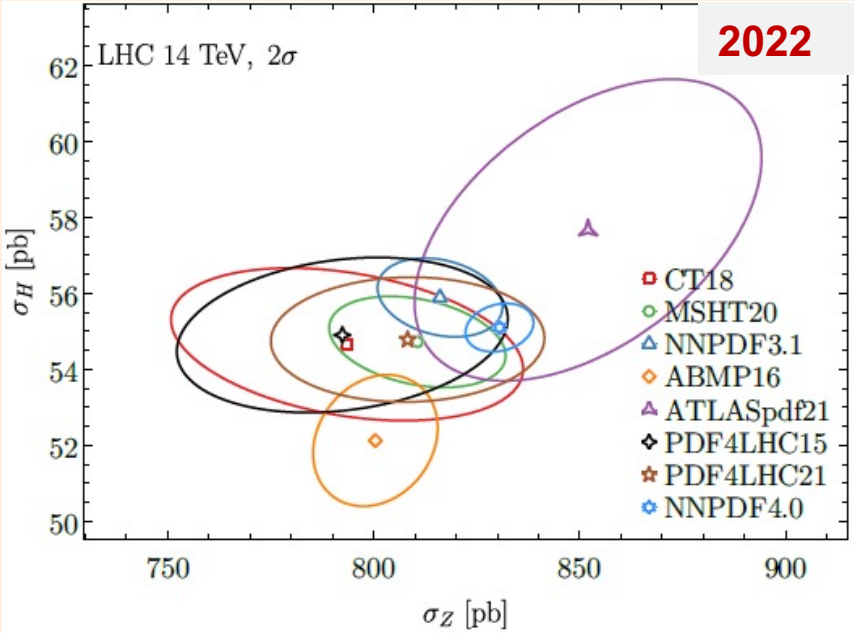




A $10,000,000 question for the precision PDF analysis

"Proton structure at the precision frontier" whitepaper

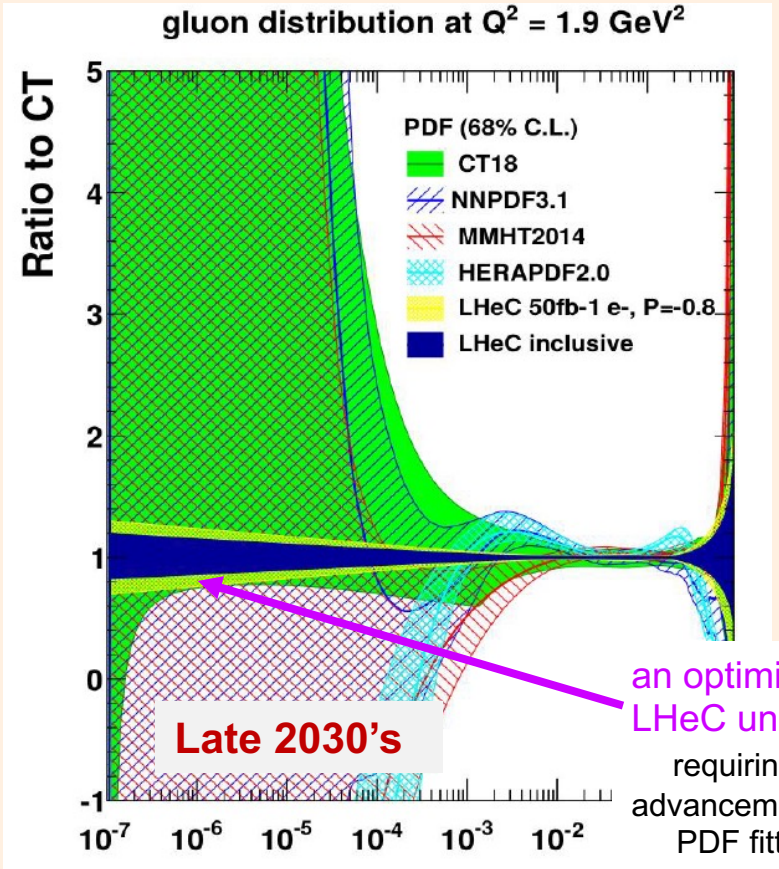
How do we get from here…



NNLO Z^0 and $gg \to H^0$ cross sections at the LHC, and 95% CL PDF uncertainties predicted with recent PDF sets.

While the fitted data sets are similar in several of these analyses, the observed differences reflect to substantial degree the different methodological choices adopted by the PDF fitting groups.

…to here?



an optimistic post-LHeC uncertainty, requiring all advancements in the PDF fitting methodology