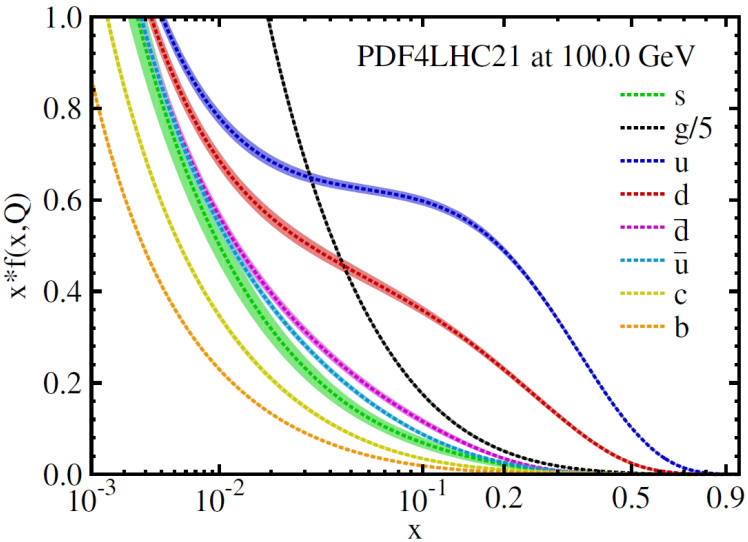
PDF developments for Run 3 and HL-LHC

Pavel Nadolsky
Southern Methodist University, USA



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

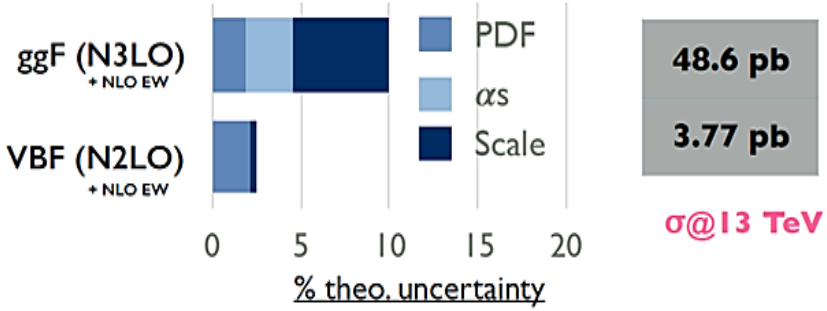
China: S. Dulat, J. Gao, T.-J. Hou, I. Sitiwaldi,
M. Yan, and collaborators

Mexico: A. Courtoy

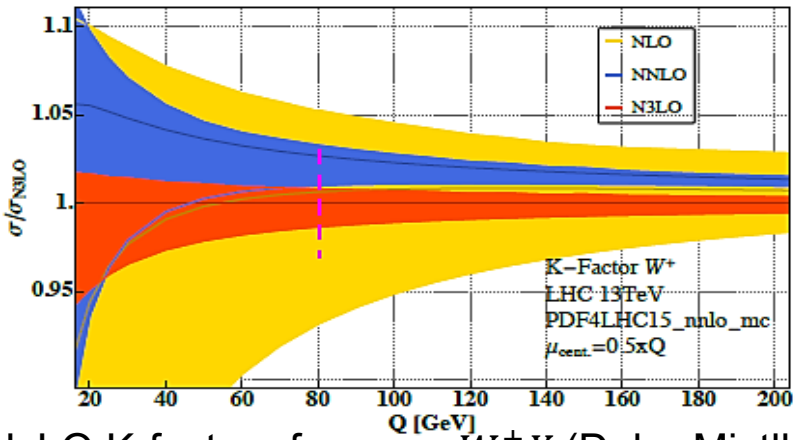
USA: A. Accardi, T.J. Hobbs, M. Guzzi, X. Jing,
J. Huston, H.-W. Lin, C. Schmidt, K. Xie, C.-P. Yuan

Reducing PDF and α_s uncertainties in EW/BSM physics at hadron colliders

Some key uncertainties in the (HL-)LHC Higgs physics are due to PDFs



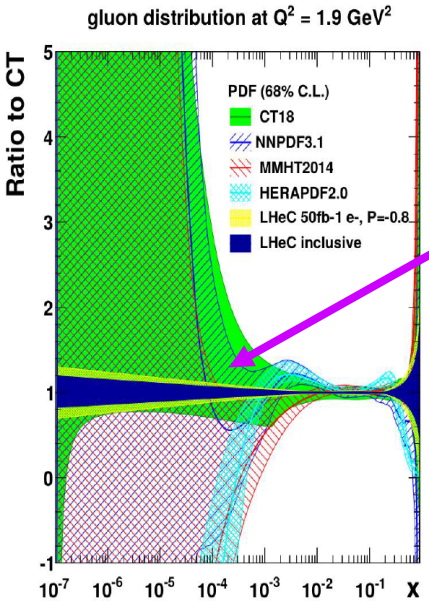
New N2LO/N3LO calculations precisely predict relevant PQCD cross sections



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

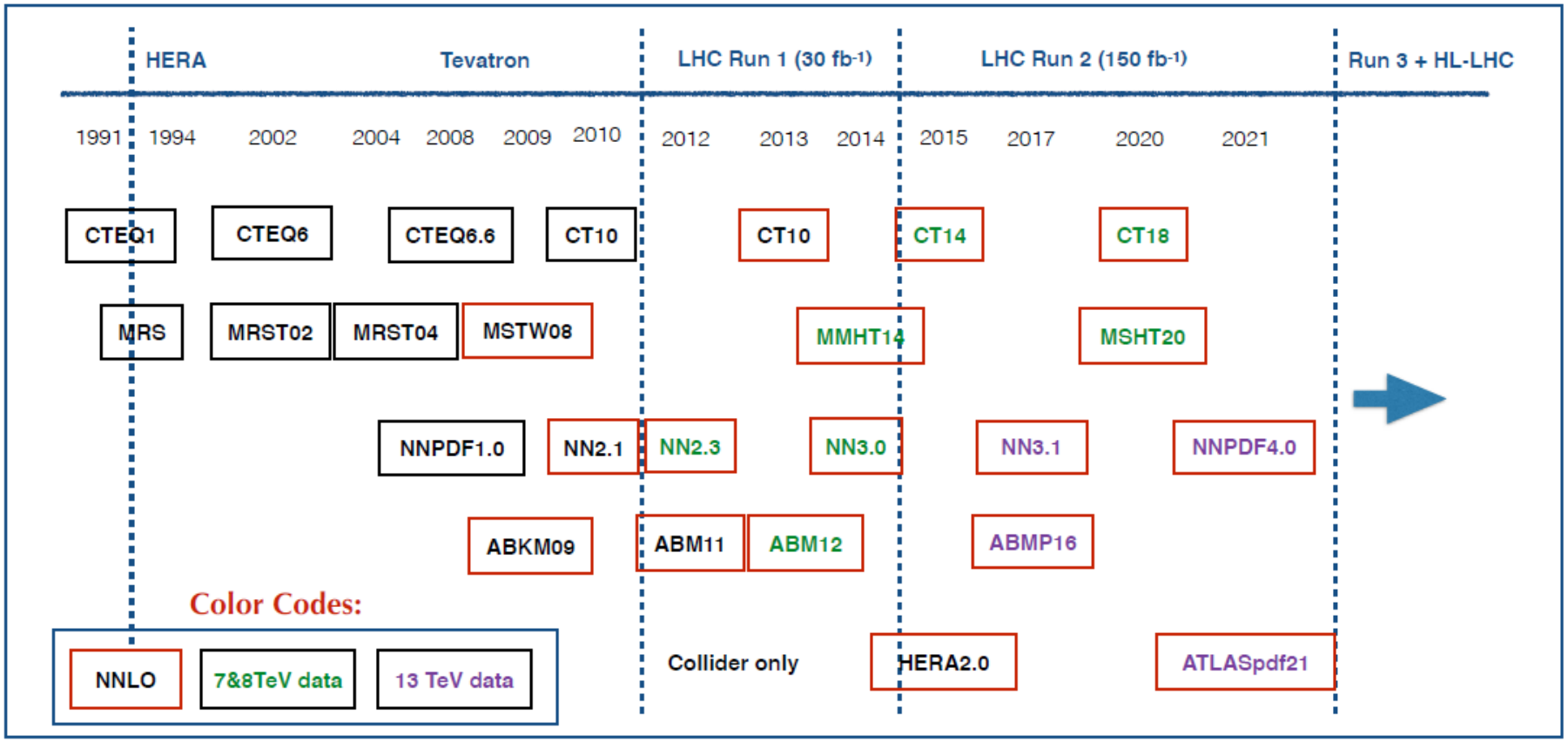
High-luminosity measurements at HL-LHC and planned DIS experiments (EIC, LHeC, Muon-Ion Colider,…) + the progress in PQCD hold the potential to dramatically increase the precision of PDFs.

This advancement critically depends on understanding various sources of **uncertainties in PDFs**



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

Progress in the PDF analyses



NNLO analyses as the precision standard. N3LO computations of DGLAP evolution kernels, DIS and DY short-distance cross sections are on a near-future horizon.

Figure: Jun Gao

Snowmass'21 whitepaper: Proton structrure at the precision frontier

arXiv:2203.13923 [hep-ph]

A summary of 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 app
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

A few examples of recent research based on the PDF whitepaper and CTEQ-TEA studies

Comparisons of the latest PDF sets…

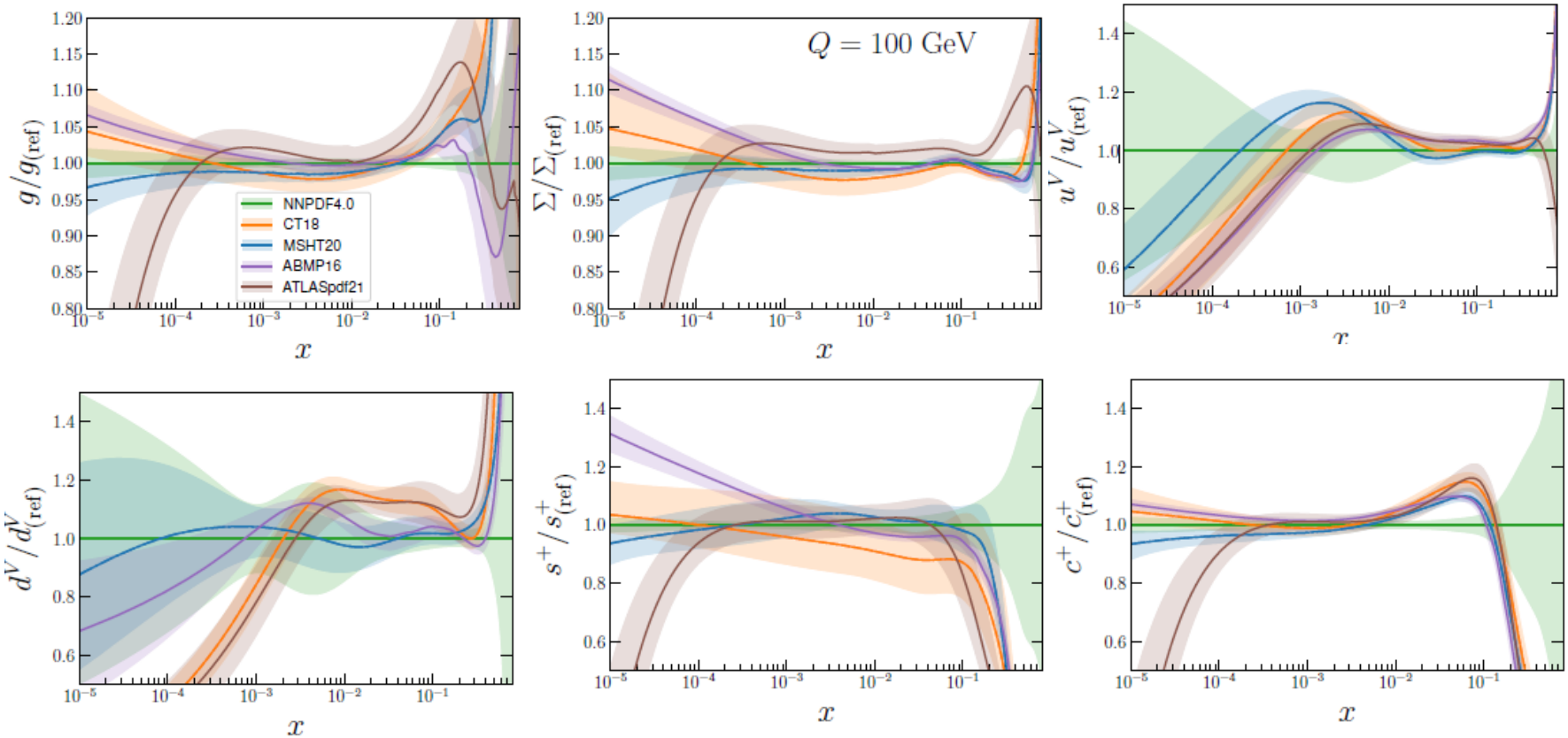


FIG. 2. Comparison of the PDFs at $Q = 100$ GeV. The PDFs shown are the N2LO sets of NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$, and ATLASpdf21. The ratio to the NNPDF4.0 central value and the relative 1σ uncertainty are shown for the gluon g, singlet Σ, total strangeness $s^+ = s +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

… PDF uncertainties…

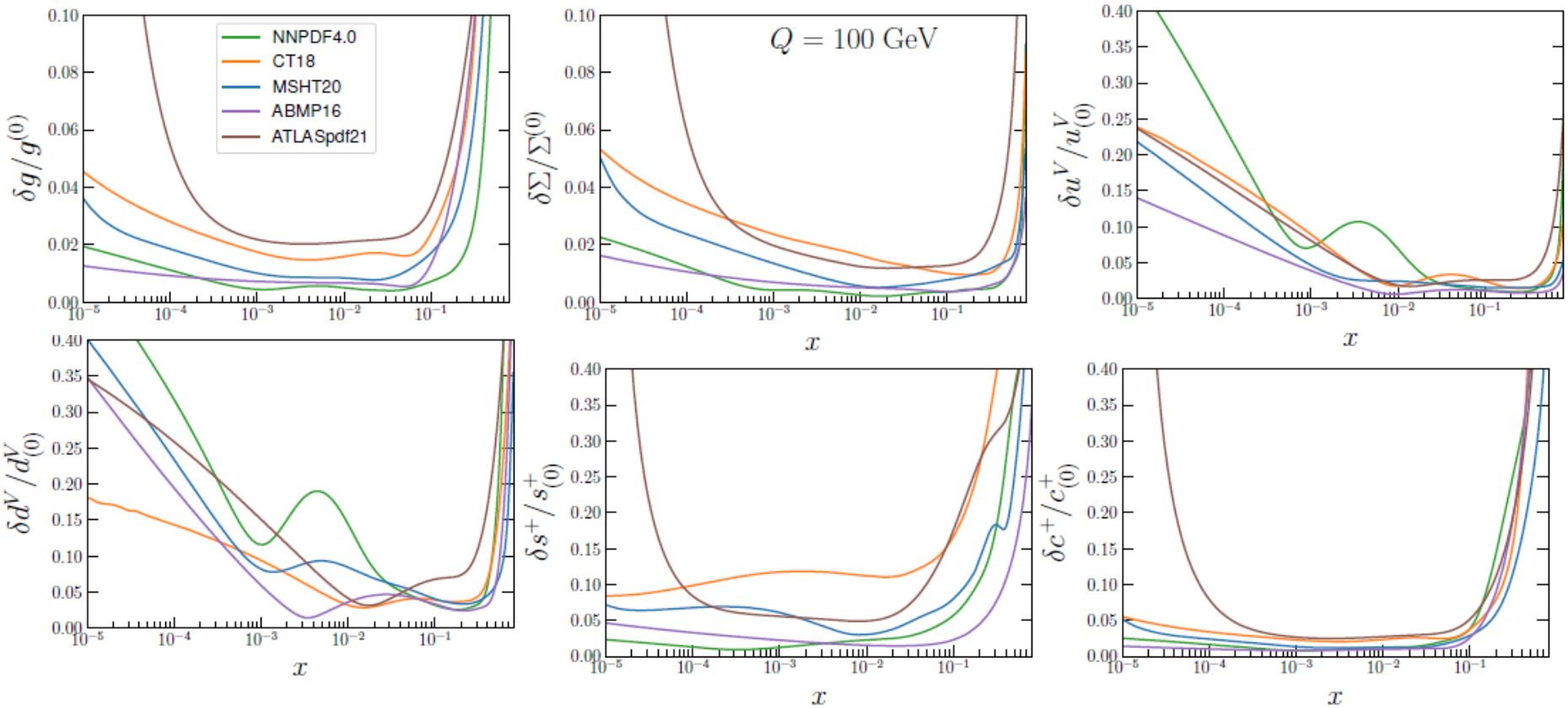


FIG. 3. Comparison of the symmetrized PDF uncertainties at $Q = 100$ GeV for the gluon g, singlet Σ, total strangeness $s^+ = s + \bar{s}$, total charm $c^+ = c + \bar{c}$, up valence u^V and down valence d^V PDFs. The PDF sets shown are the N2LO sets of NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z)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

… parton luminosities…

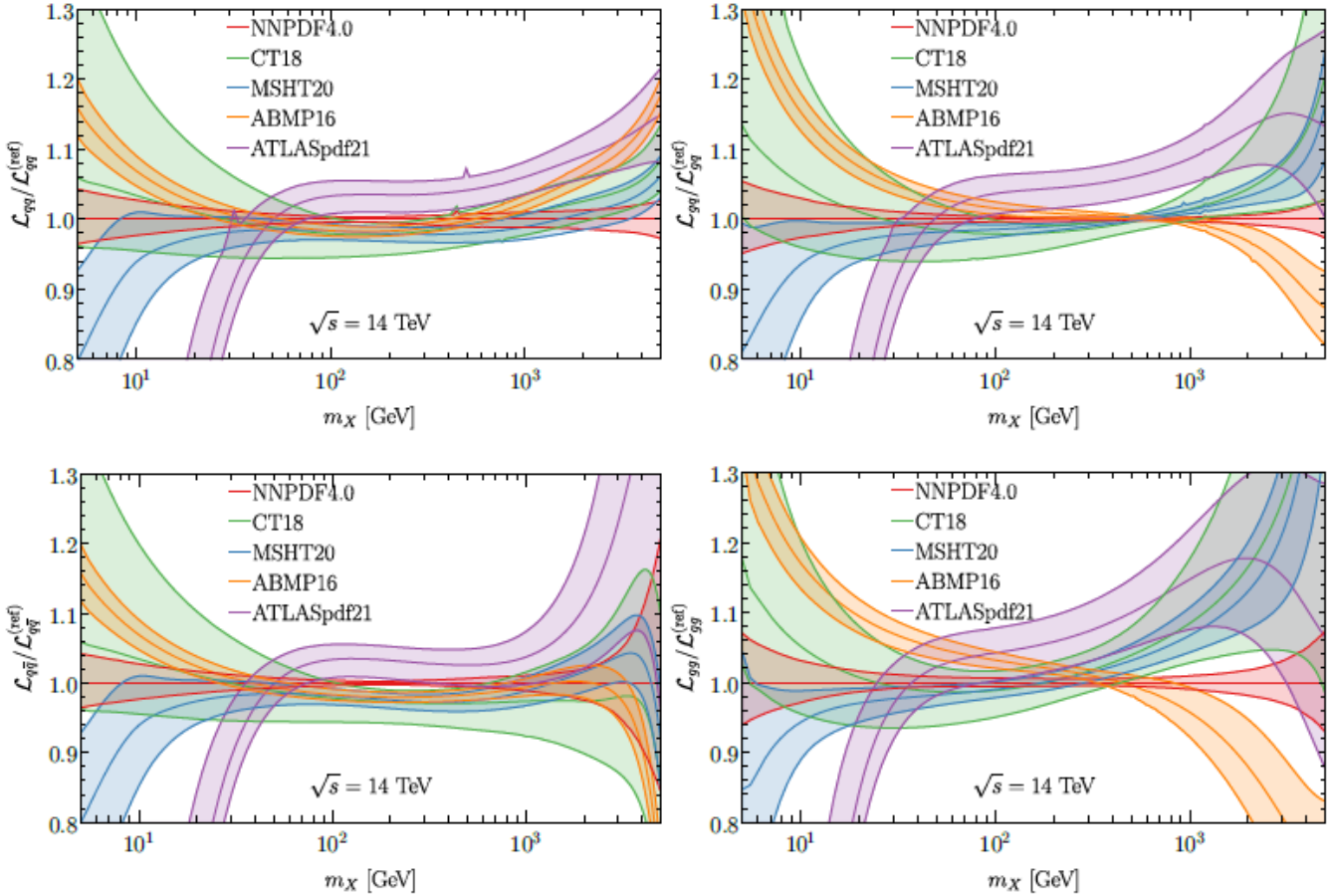
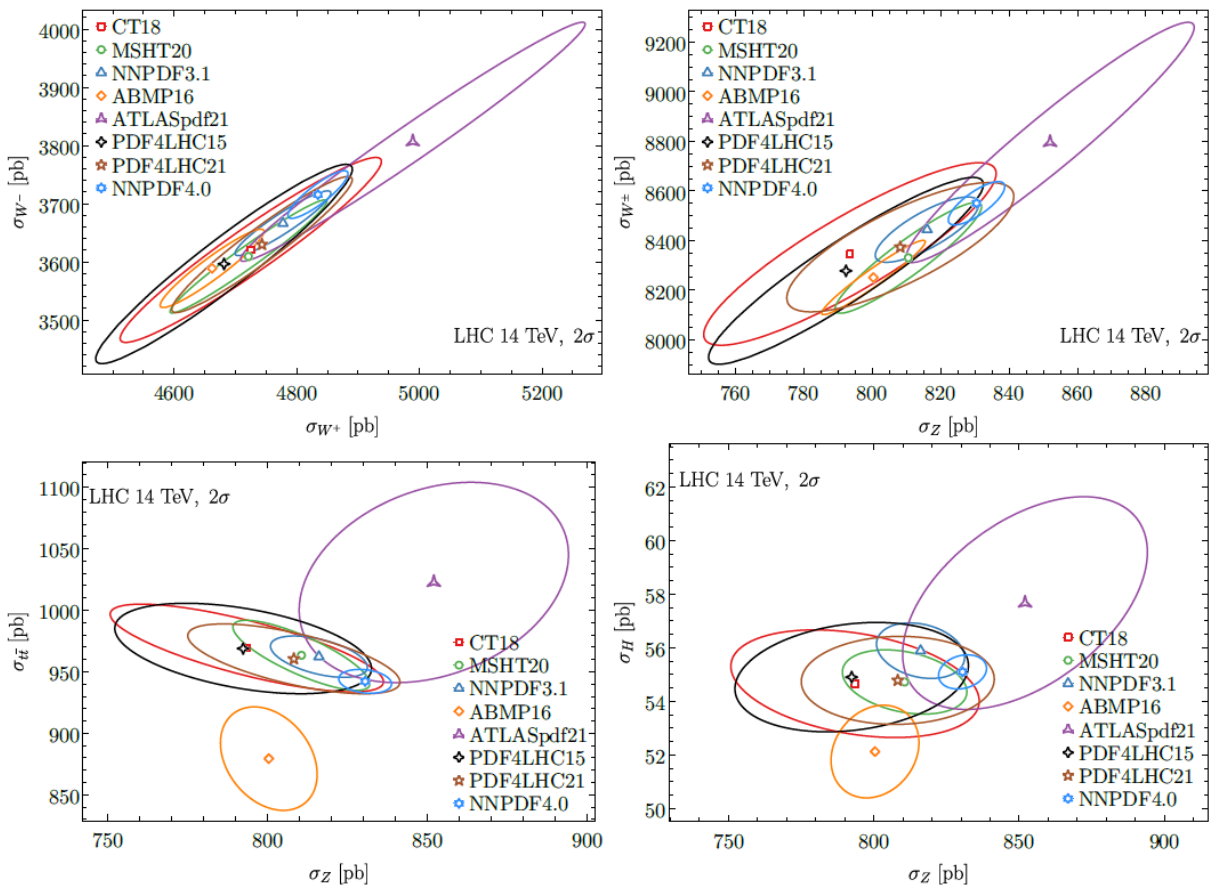


FIG. 4. Comparison, as a function of the invariant mass m_X, of the parton luminosities at $\sqrt{s} = 14$ TeV, computed using N2LO NNPDF4.0, CT18, MSHT20, ABMP16 with $\alpha_s(M_Z) = 0.118$, and ATLASpdf21. The ratio to the NNPDF4.0 central value and the relative 1σ uncertainty are shown for each parton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

… predictions for LHC benchmark cross sections

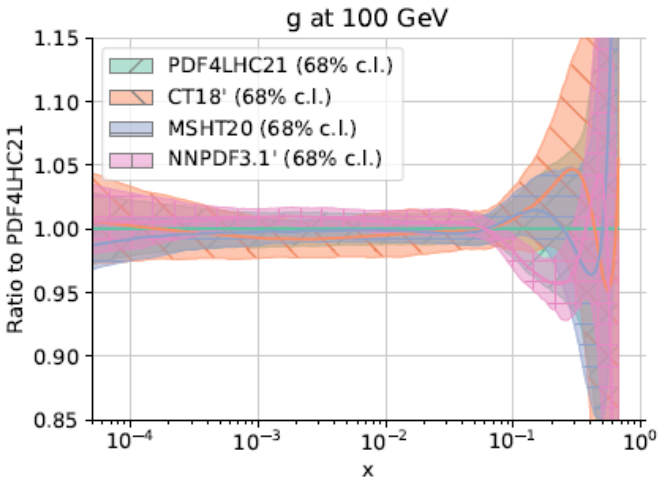


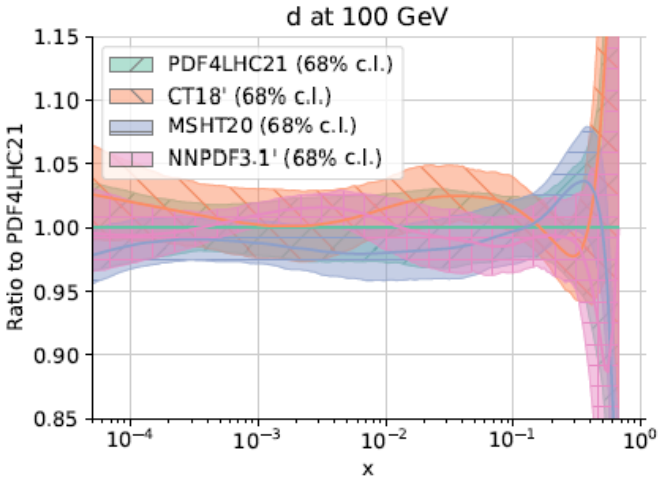
NNLO cross sections at the LHC and 95% CL PDF uncertainties predicted with recent PDF sets, including the latest NNPDF4.0, ATLAS21 analyses and predictions based on combined PDF4LHC21 PDF sets

PDF4LHC21 recommendation and combined PDFs

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 NNPDF3.1.1 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





PDF-related topics in Snowmass'13 [arXiv:1310.5189] and '21 studies

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

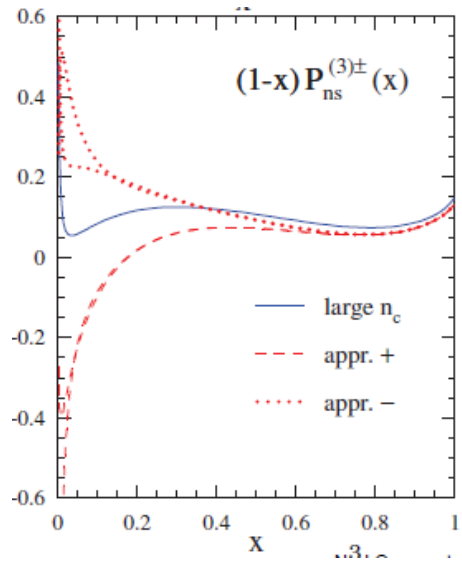
Progress toward N3LO theoretical calculations

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

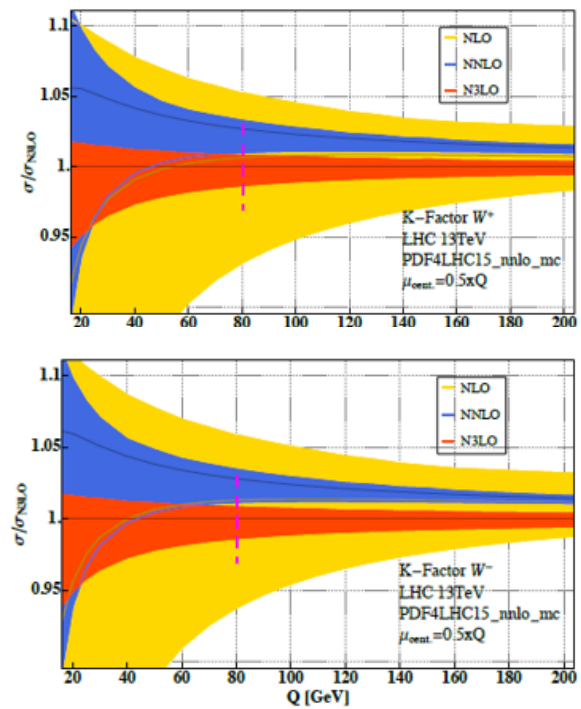
- In the fixed-target DIS region, the preliminary N3LO results are already stable.
- Steady progress in computing small-x and massive N3LO contributions

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)



Understanding systematic uncertainties…

- from the experiment side

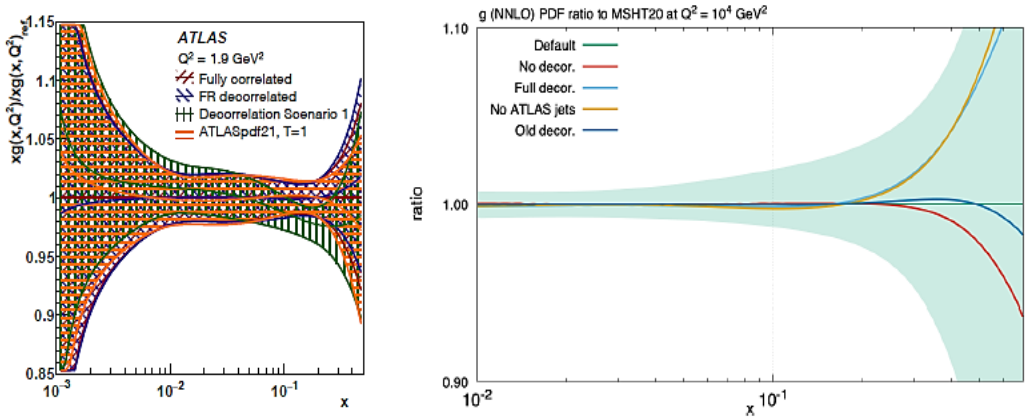


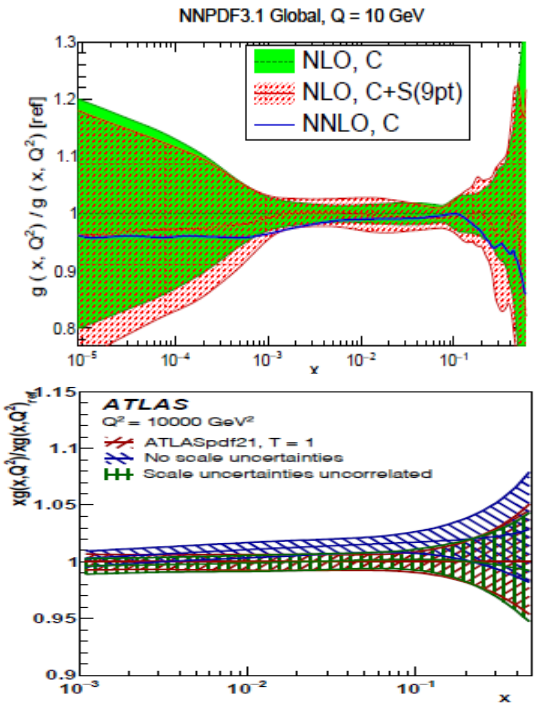
FIG. 9. Difference in the gluon PDF shown in ratio to the ATLASpdf21 (default) gluon(left). This default uses Decorrelation Scenario 2 and this is compared to the use of Full Correlation, Full decorrelation of the flavour response systematic and Decorrelation Scenario 1. The effect of no decorrelation,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

Strong dependence on the definition of corr. syst. errors would raise a general concern:

Overreliance on Gaussian distributions and covariance matrices for poorly understood effects may produce very wrong uncertainty estimates

[N. Taleb, Black Swan & Antifragile]

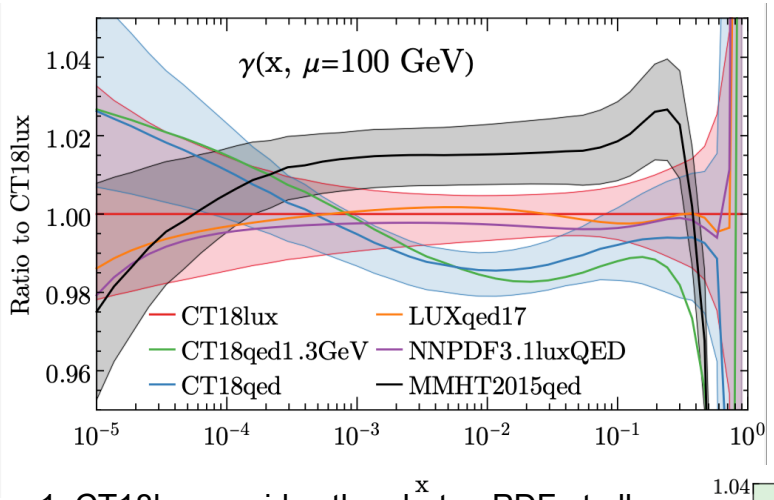
- from the theory side

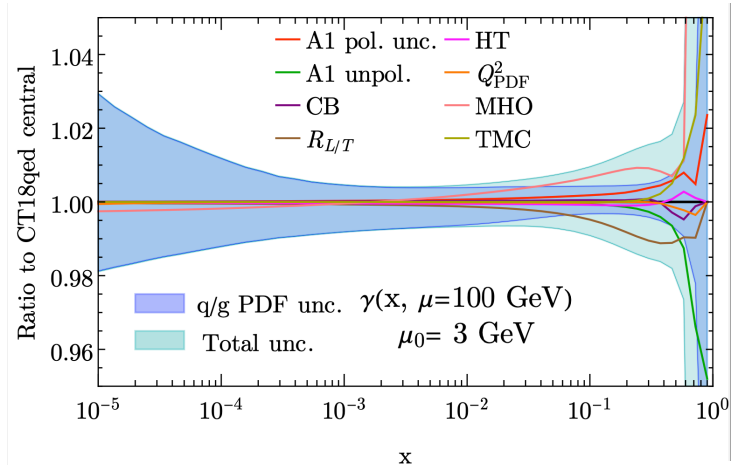


Examples:studies of theory uncertainties in the PDFs by NNPDF3.1 and ATLAS21

CT18QED: Photon PDF in the CTEQ-TEA global analysis

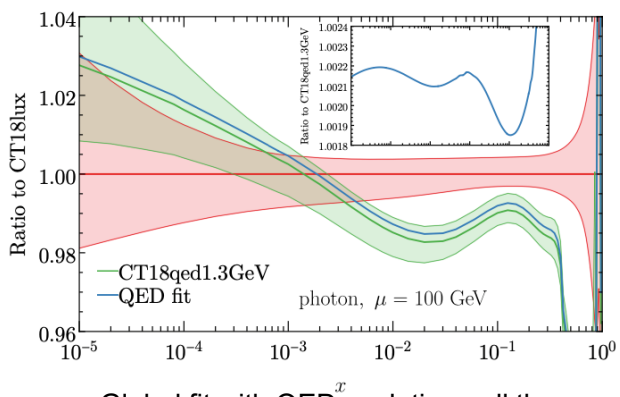
K. Xie et al., Phys.Rev.D 105 (2022) 5, 054006

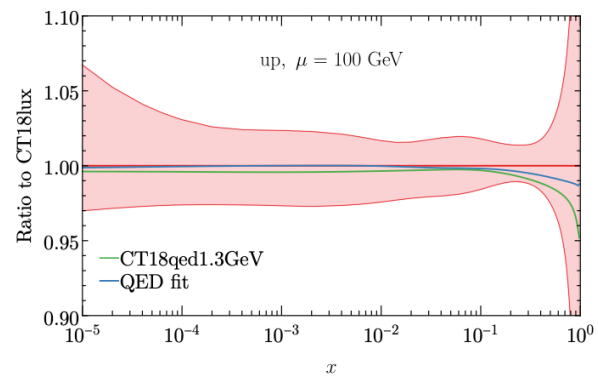




1. In the small-x region, the uncertainty mainly originates from the quark and gluon PDFs.
2. At large x, all nonperturbative sources contribute.

1. CT18lux provides the photon PDF at all scales, μ.
2. CT18qed initializes photon PDF at μ_0, and evolves to high scales.
3. CT18lux gives the photon in between LUXqed(17) and MMHT2015qed, while CT18qed gives smaller photon.



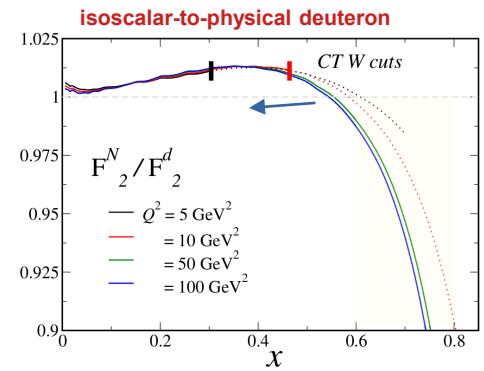


Global fit with QED evolution pull the quark PDFs back to the global minimum and therefore enahces photon slightly.

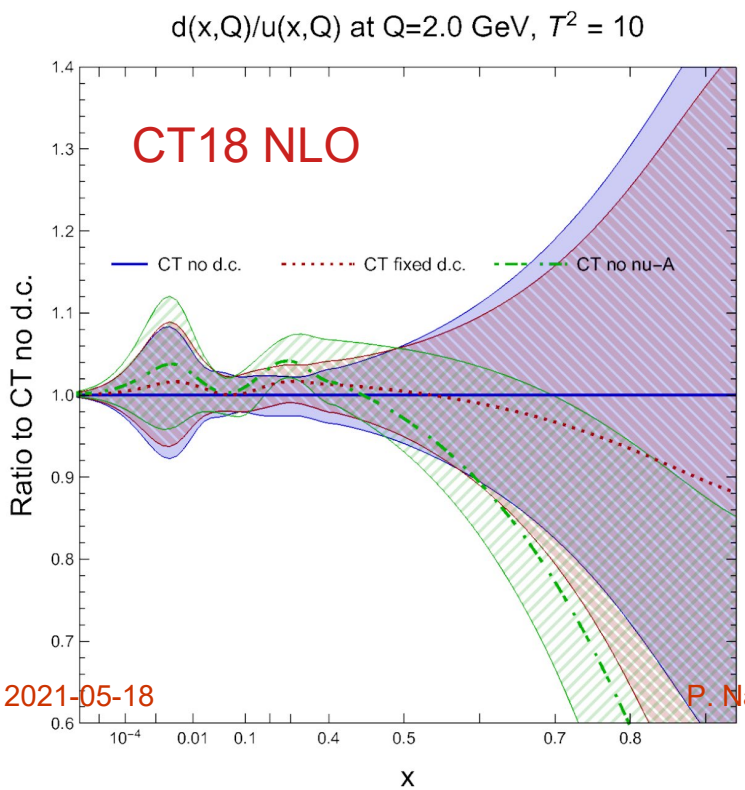
nuclear corrections of increasing importance with greater PDF precision

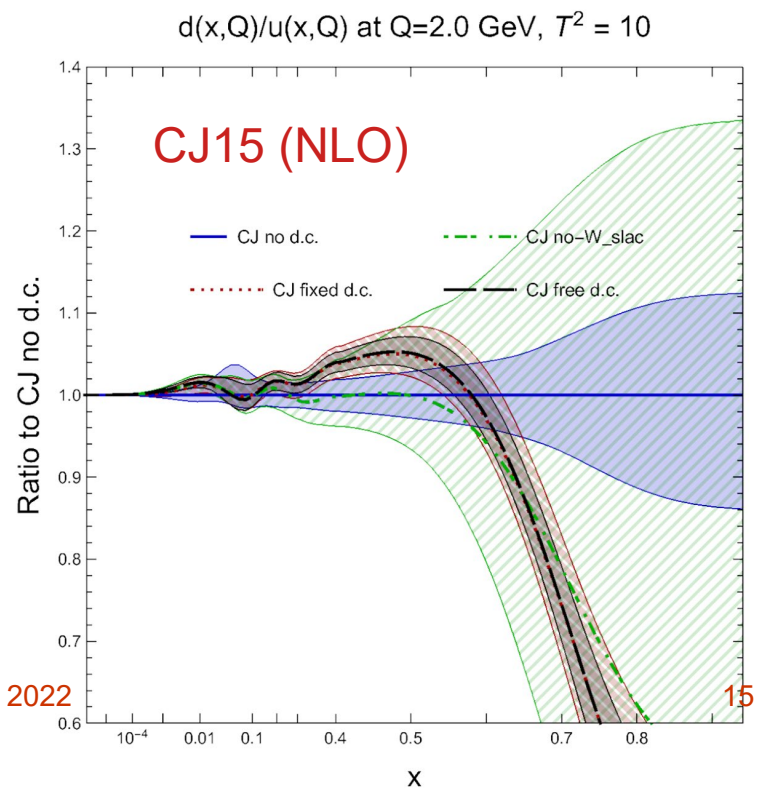
CJ-CT: Accardi, Hobbs, Jing, Nadolsky: EPJC**81** (2021) 7, 603

- light/heavy nuclear targets: valuable information, PDF flavor dependence (high-*x* *d*-quark; strangeness)
- example: nuclear effects in deuteron influence *d*-quark PDF (x>0.1)
- comparative L_2 analysis: additional correlations; lower-*x*, gluon impacts



- **subtle interplay with nuclear corrections in large-*A* targets**
  - → demands attention in future PDF studies

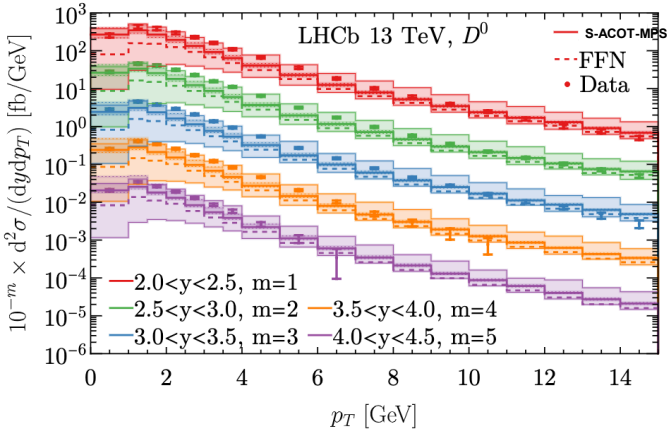




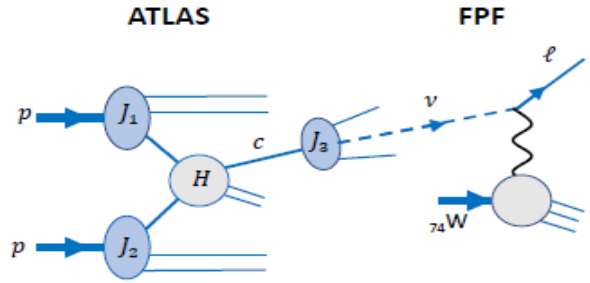
Charm and bottom production at central and forward rapidity
Forward Physics Facility (FPF)

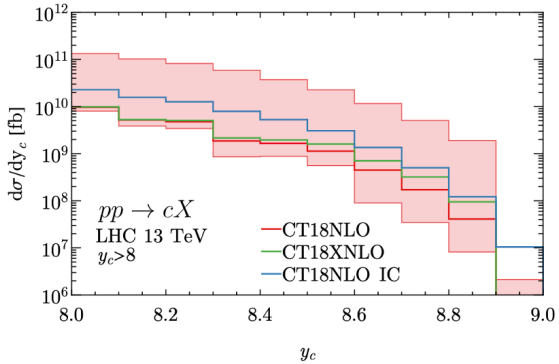
M. Guzzi, K. Xie, P.N.,
in *Phys.Rept.* 968 (2022) 1;
2203.05090

LHCb 13 TeV JHEP 03 (2016) 159

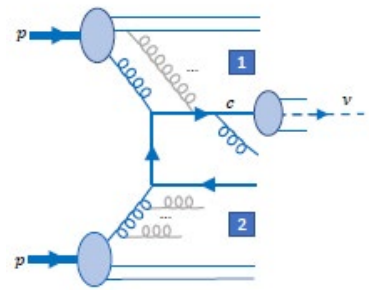


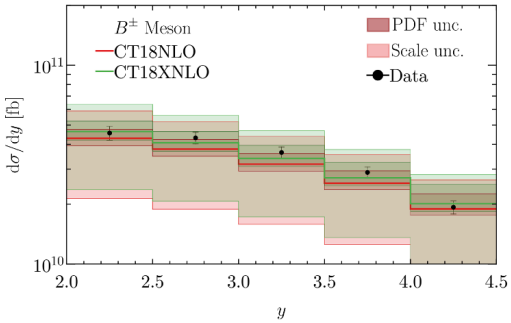
Charm pT at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties. 2108.03741



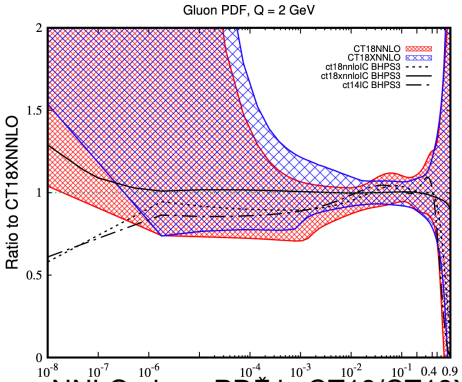


Charm rapidity at the LHC 13 TeV in the forward region $y_c > 8$.
FPF paper I, 2109.10905





B-meson production at LHCb 13 TeV
FPF paper II, 2203.05090



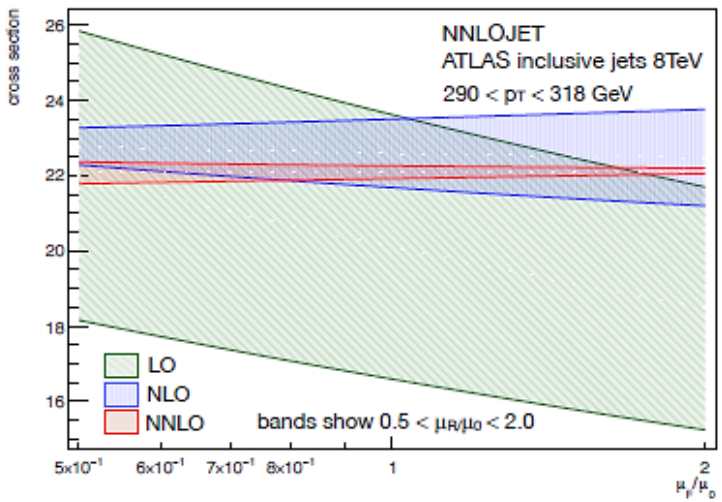
NNLO gluon PDF in CT18/CT18X with IC
Error PDFs at 90% C.L.. FPF paper I

Charm hadroproduction and Z + c production at the LHC can constrain the IC contributions. In CT14IC, we looked at Z+c at LHC 8 and 13 TeV. LHCb Z+c data deserve attention as they can potentially discriminate gluon functional forms at $x \geq 0.2$ and improve gluon accuracy.

For small x below 10^{-4}, higher-order QCD terms with $\ln(1/x)$ dependence grow quickly at factorization scales of order 1 GeV. An FPF like FASERν will access a novel kinematic regime where both large-x and small-x QCD effects contribute to charm hadroproduction rate.

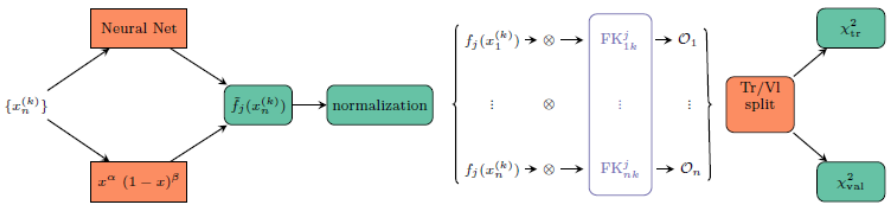
New public computer programs for the global QCD analysis

ApplFast, PineAppl fast interfaces

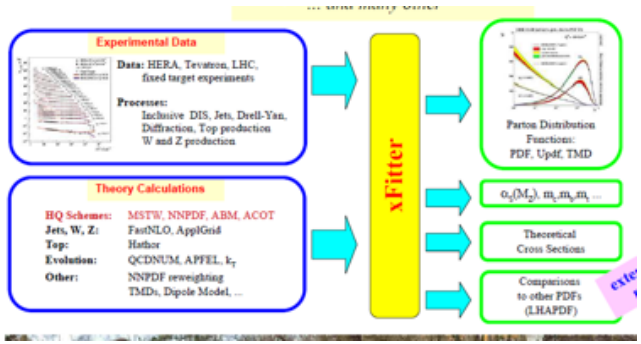


Fast interfaces allow quick evaluation of NLO and NNLO cross sections in the PDF fits, including QCD scale dependence

NNPDF4.0 fitting code



xFitter

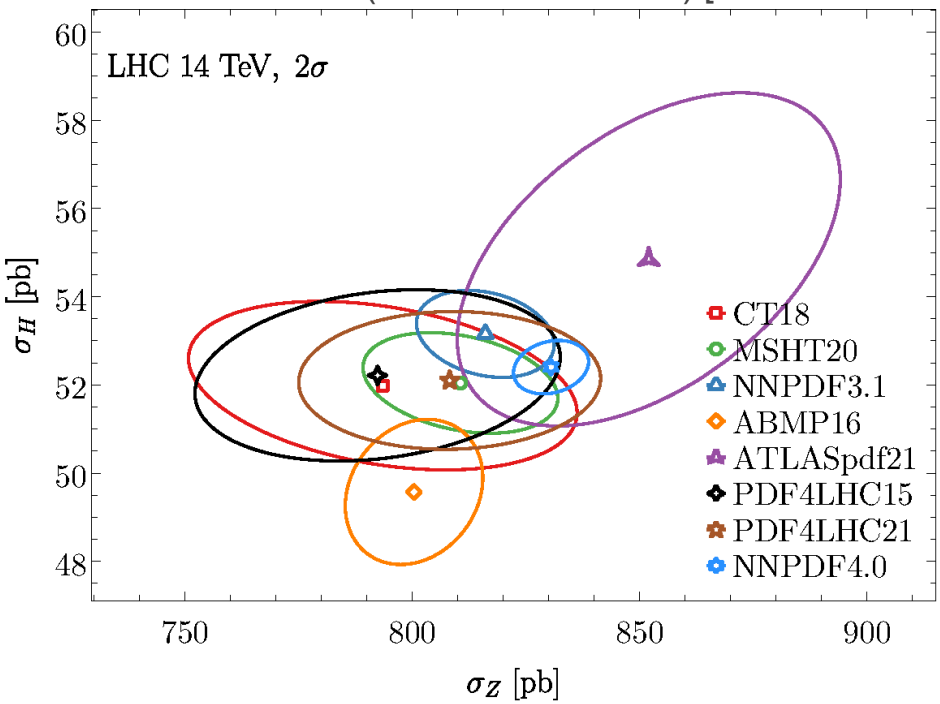


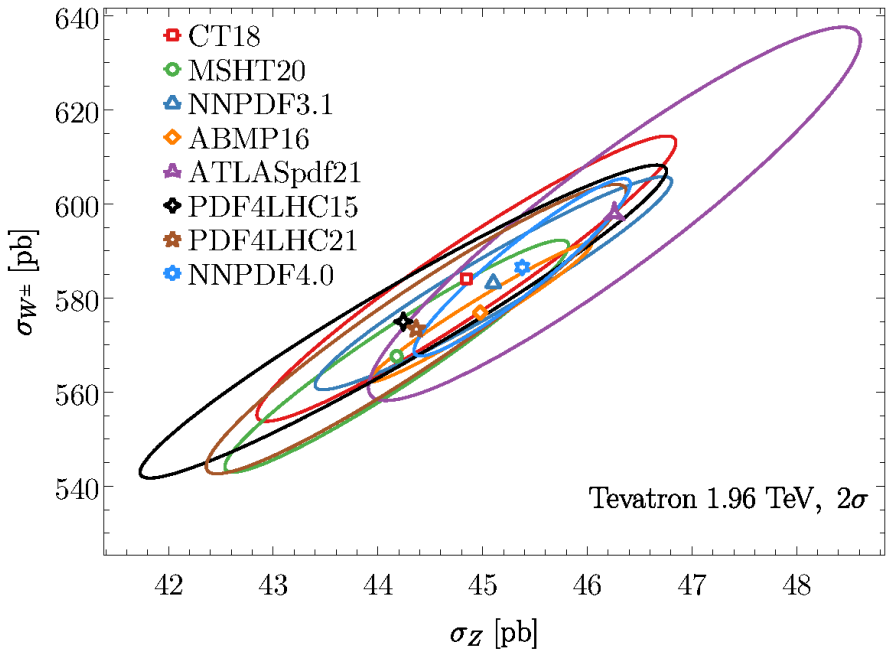
The tolerance puzzle

Why do groups fitting similar data sets obtain different PDF uncertainties?

Courtoy, Huston, Nadolsky, Xie, Yan, Yuan, SMU-HEP-22-03

Precision PDFs (Snowmass 21 WP) [2203.13923v2]





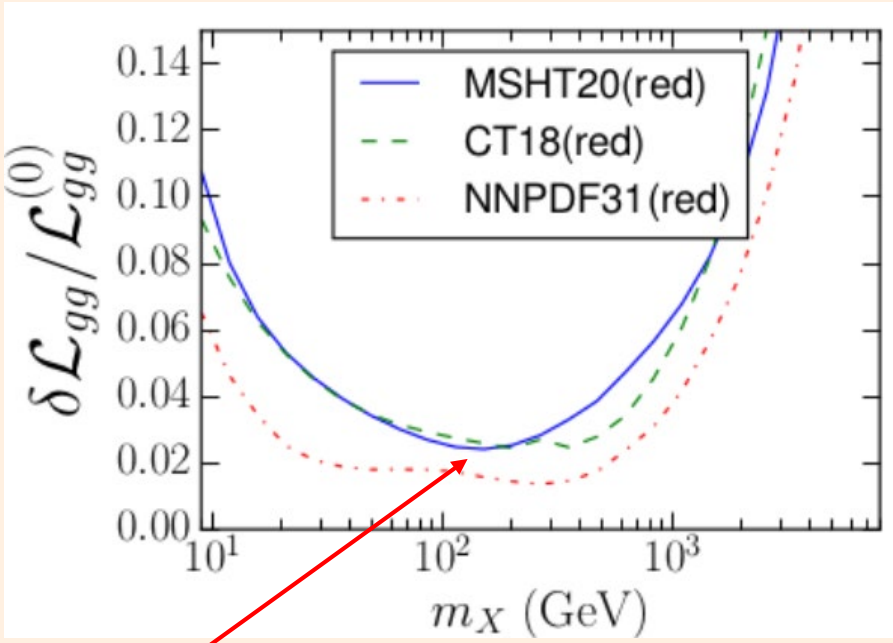
The answer has direct implications for high-stake experiments such as W boson mass measurement

The tolerance puzzle

While the fitted data sets are identical or similar in several such analyses, the resulting PDF sets may differ because of methodological choices adopted by the PDF fitting groups.

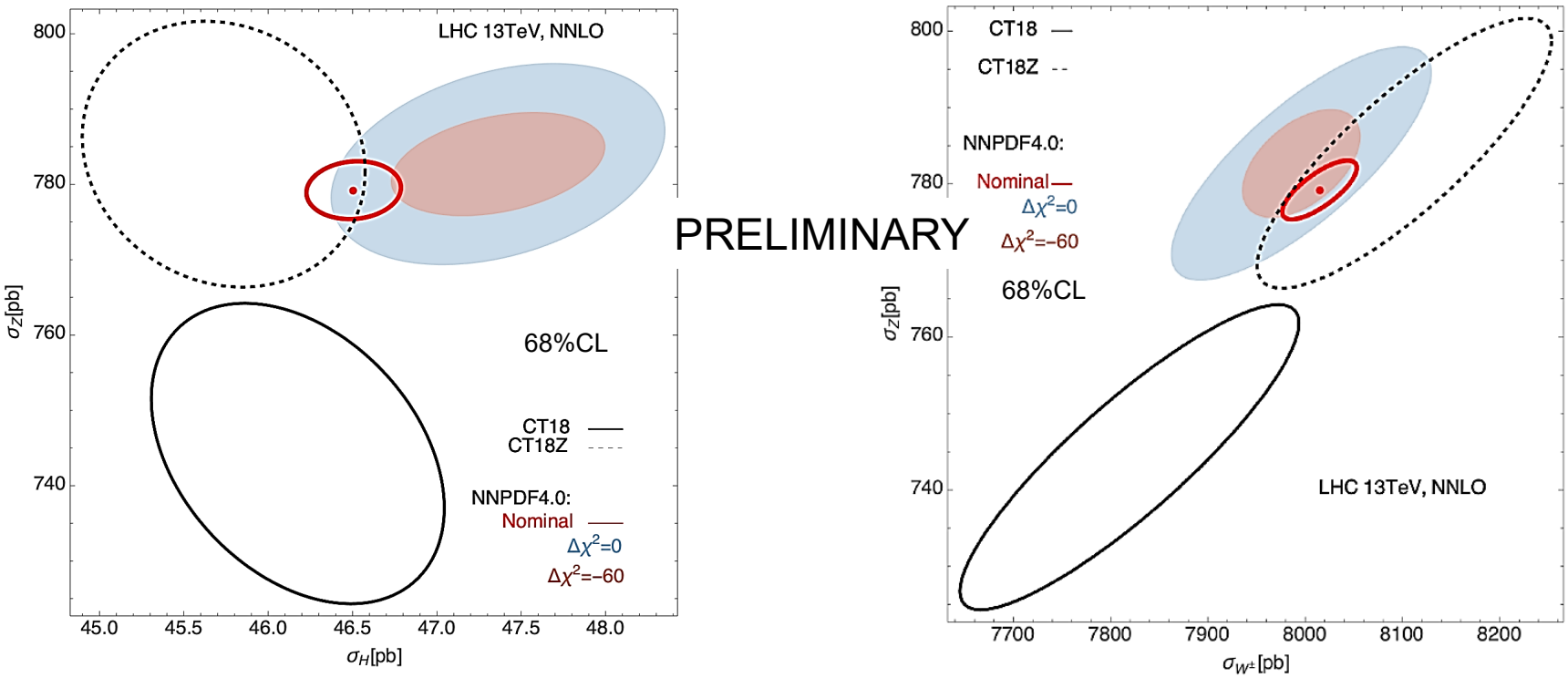
Relative PDF uncertainties on the gg luminosity at 14 TeV in three PDF4LHC21 fits to the **identical** reduced global data set

arXiv:2203.05506



$\times\ 1.5 - 2$ difference

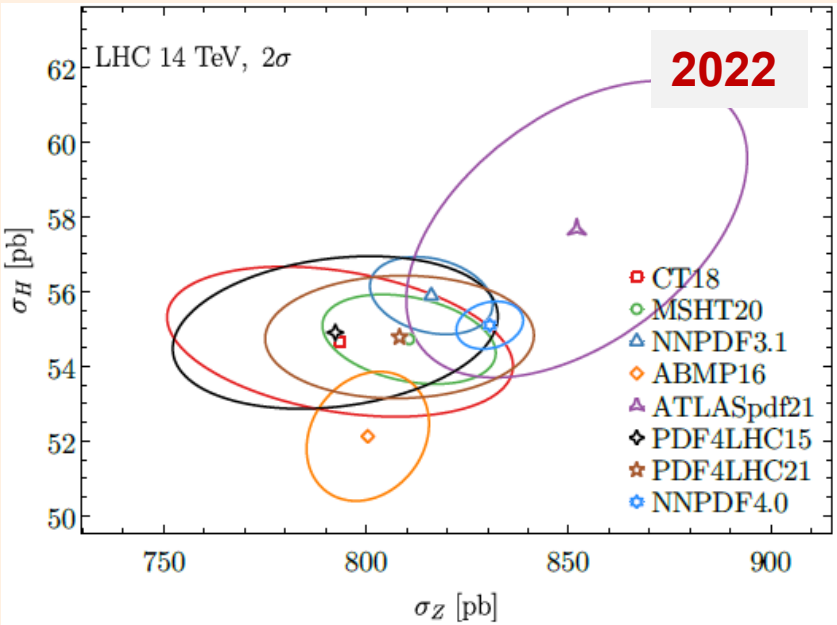
Monte-Carlo sampling of PDF parametrizations



PDF uncertainties for Monte-Carlo error sets can be sensitive to the sampling procedure. Using the public NNPDF4.0 fitting code, we find multiple acceptable PDF solutions to the NN4.0 fit that have better χ^2 (by as much as 80 units) than the published replica 0. The figures show approximate regions of the LHC cross sections corresponding to such alternative solutions with $\Delta\chi^2 < -60$ ($\Delta\chi^2 < 0$) w.r.t. to the NN4.0 replica 0. Red ellipses are the nominal NN4.0 uncertainties. Including the solutions in the brown and blue regions shifts the central NN4.0 predictions and enlarges the NN4.0 uncertainties.

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

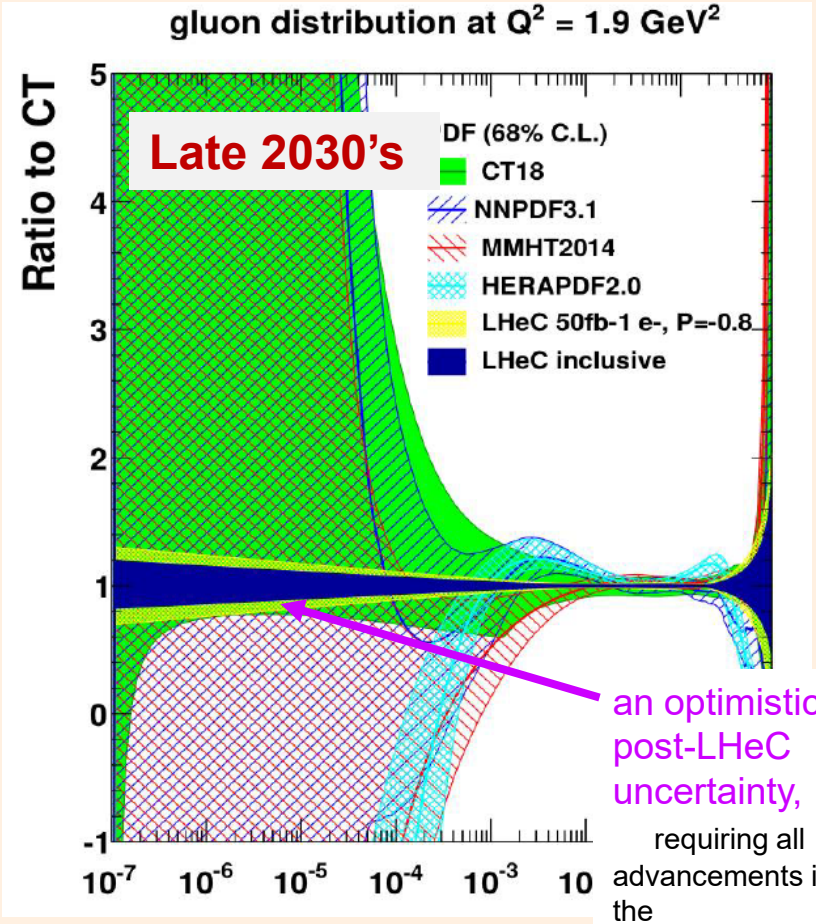
How do we get from here…



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

PDF fits have lots of work ahead!

STAY TUNED FOR NEW RESULTS

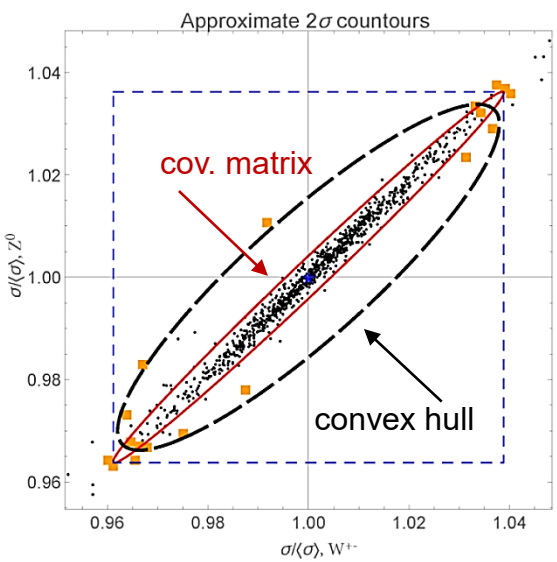
Backup slides

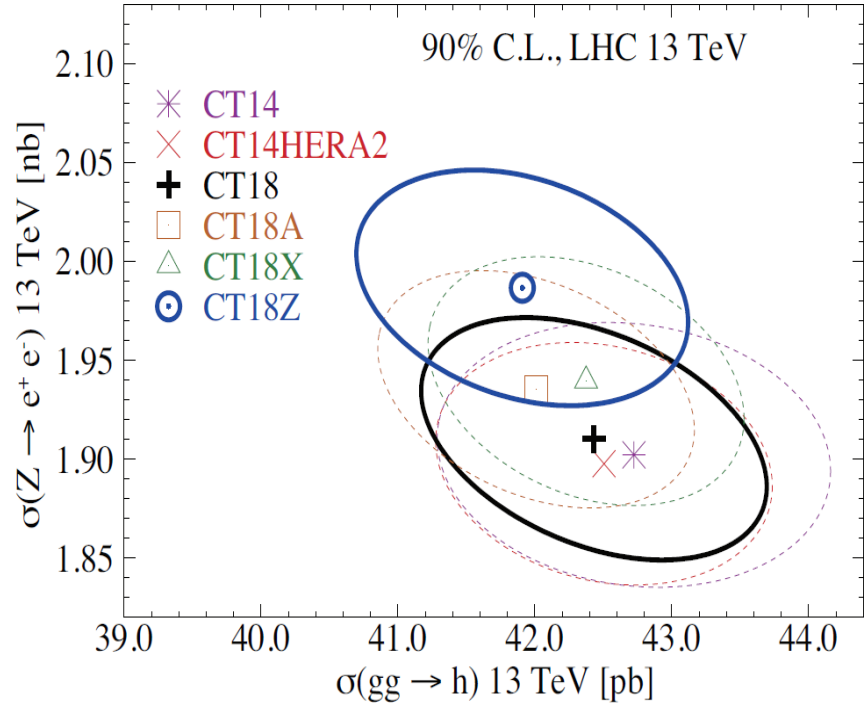
Toward **robust** PDF uncertainties

Strong dependence on the definition of corr. syst. errors would raise a general concern:

Overreliance on Gaussian distributions and covariance matrices for poorly understood effects may produce very wrong uncertainty estimates
[N. Taleb, Black Swan & Antifragile]

For instance, the cov. matrix may overestimate the correlation among discrete data points, resulting in a too aggressive error estimate
[Anwar, Hamilton, P.N., arXiv:1905.05111]

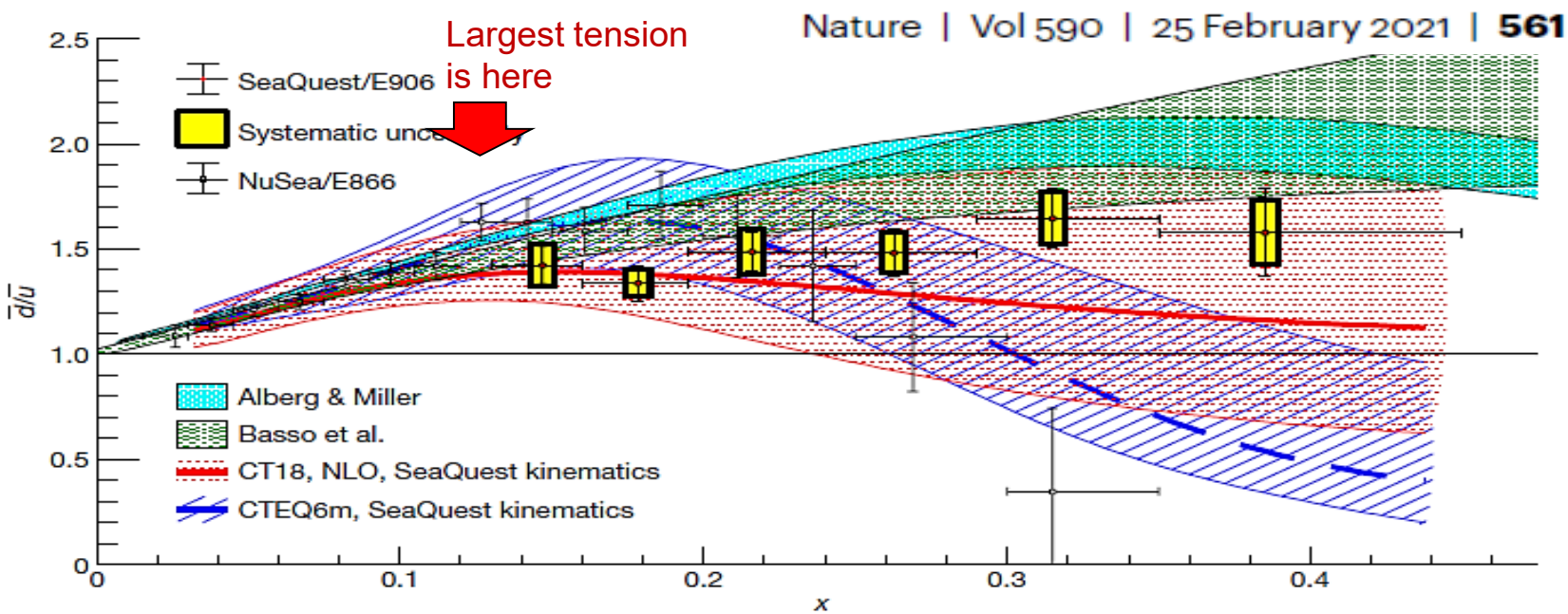




The CT18 uncertainties aim to be **robust**: they largely cover the spread of central predictions obtained with different selections of experiments and assumptions about systematic uncertainties

The E906 SeaQuest experiment

NEW

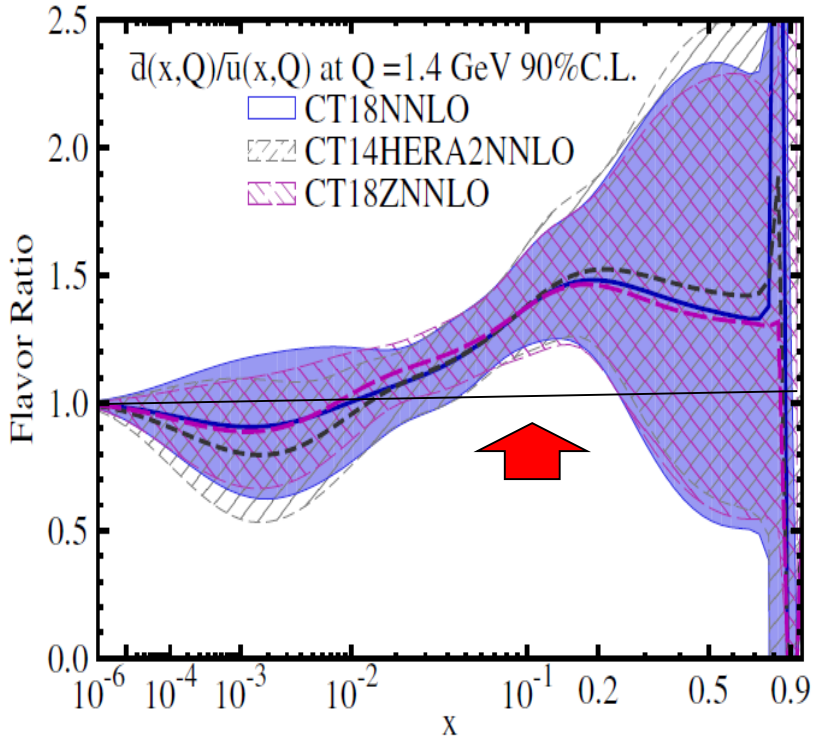


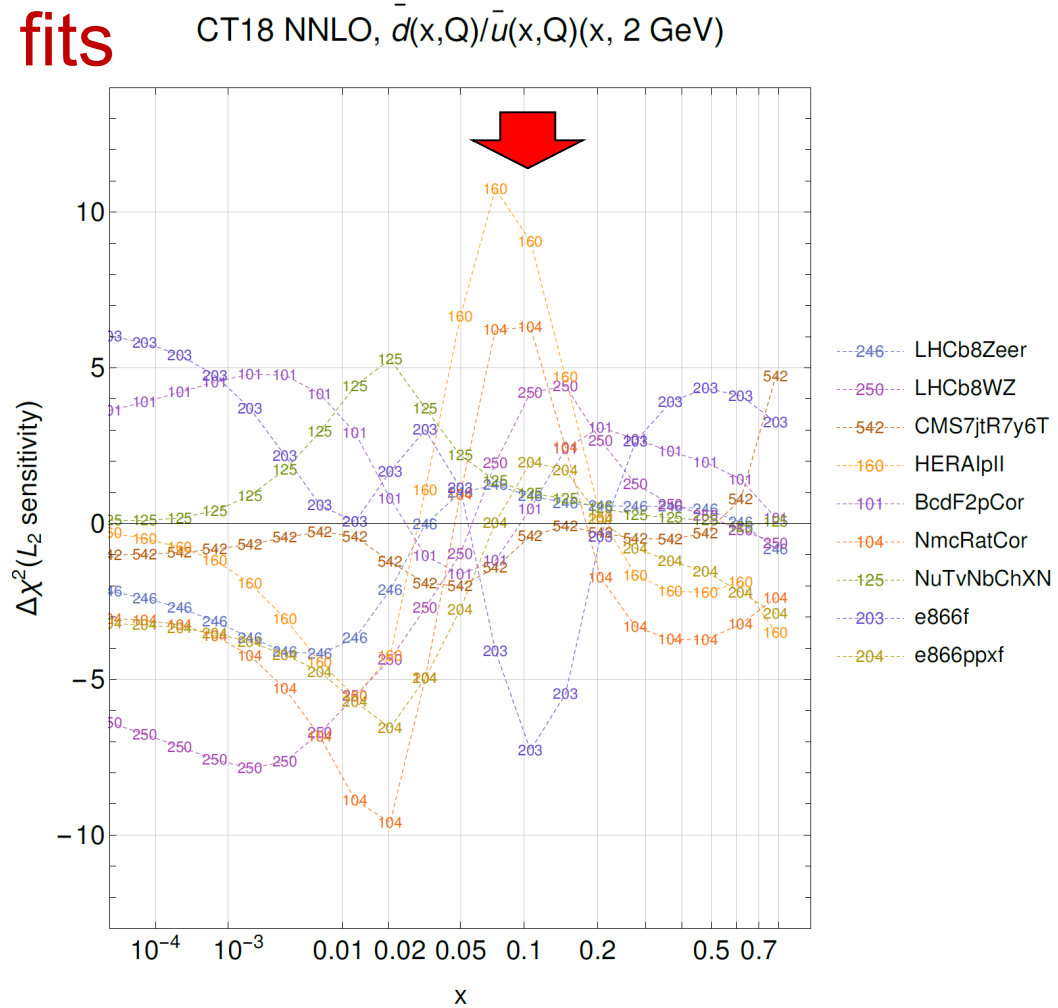
The Fermilab E906 muon pair production experiment suggests there are more $\bar{d}$ than $\bar{u}$ antiquarks at large momentum fractions. It disagrees with the E866 experiment suggesting a suppressed $\bar{d}/\bar{u}$ ratio at $x > 0.3$.

The CT18 PDFs agree well with the E906 data at all accessed x values.

The CT18 PDFs provide the most comprehensive uncertainty estimate among the shown bands (resulting in larger uncertainties).

$\bar{d}/\bar{u}$ in the CT18/CT18Z fits





https://ct.hepforge.org/PDFs/ct18/figures/L2Sensitivity/

Data are consistent with either sign of $\bar{d} - \bar{u}$ except at $x \sim 0.1$, where the strong upward pull of E866 ratio (203) opposes the downward pulls of HERA (160), NMC d/p (104), and LHCb 8 W/Z (250) experiments