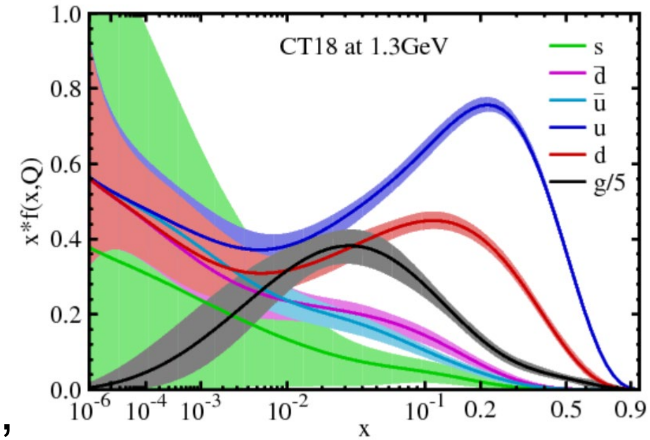
CTEQ-TEA parton distributions

Pavel Nadolsky

Southern Methodist University

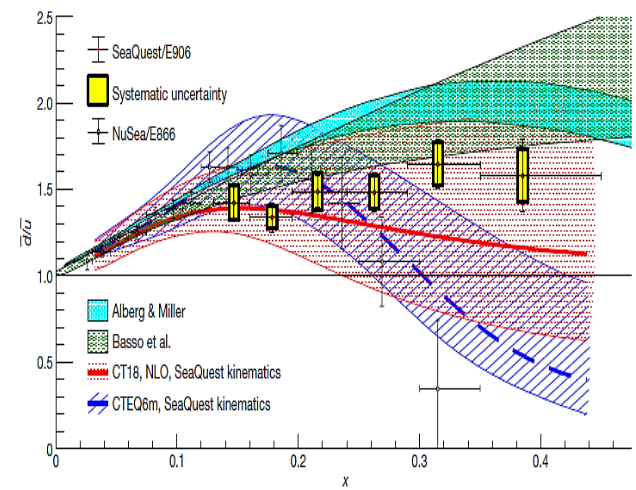


With CTEQ-TEA (Tung Et. Al.) working group

[S. Dulat, **T.J. Hobbs**, **T.-J. Hou**, J. Gao, **M. Guzzi**, J. Huston, D. Stump, C. Schmidt, I. Sitiwaldi, **K. Xie**, C.-P. Yuan]

and

A. Accardi, **A. Courtoy**, **X. Jing**, K. Kovarik, F. Olness, D. Soper



SMU

C T E Q

Talks by the CTEQ-TEA group at DIS'2021

1. Deuteron DIS in CJ and CT PDFs **(X. Jing, 04/13, SF WG)**
2. Large-x quark counting rules **(A. Courtoy, 04/14, SF WG)**
3. (Dis)connected sea partons in the CT analysis **(T.-J. Hou, 04/14, SF WG)**
4. Combined HERA charm data **(M. Guzzi, HF WG, flash talk)**
5. SACOT-MPS scheme for hadron-hadron scattering **(K. Xie, 04/14, HF WG)**
6. CT18QED PDFs **(K. Xie, 04/14, EW WG)**
7. CT PDFs at the EIC and LHeC **(T. Hobbs, 04/16, in a plenary talk)**

Large-x DIS

PDFs on lattice

Heavy flavors

QCD+QED PDFs

This talk:

- Implications of CT18 NNLO PDFs for experiments
- CT PDFs and SeaQuest
- CT18X PDFs and small-x saturation
- Strong goodness-of-fit criteria and other methodological developments [in the backup slides]

2020: main journal publications

1. Tie-Jiun Hou, Jun Gao, Tim Hobbs, Keping Xie, and others,

   New CTEQ global analysis of QCD with high-precision data from the LHC

   - *Phys.Rev.D* 103 (2021) 1, 014013 [arXiv:1912.10053]
   - Editors' Selection; 94 pages + 8 pages supplemental material

2. Karol Kovařík, Pavel Nadolsky, Dave Soper,

   Hadron structure in high-energy collisions

   - *Rev.Mod.Phys.* 92 (2020) 4, 045003 [arXiv: 1905.06957]
   - An introduction to theoretical and statistical aspects of modern PDF fits

The published journal versions (on arXiv) are expanded with additional material in response to peer reviews

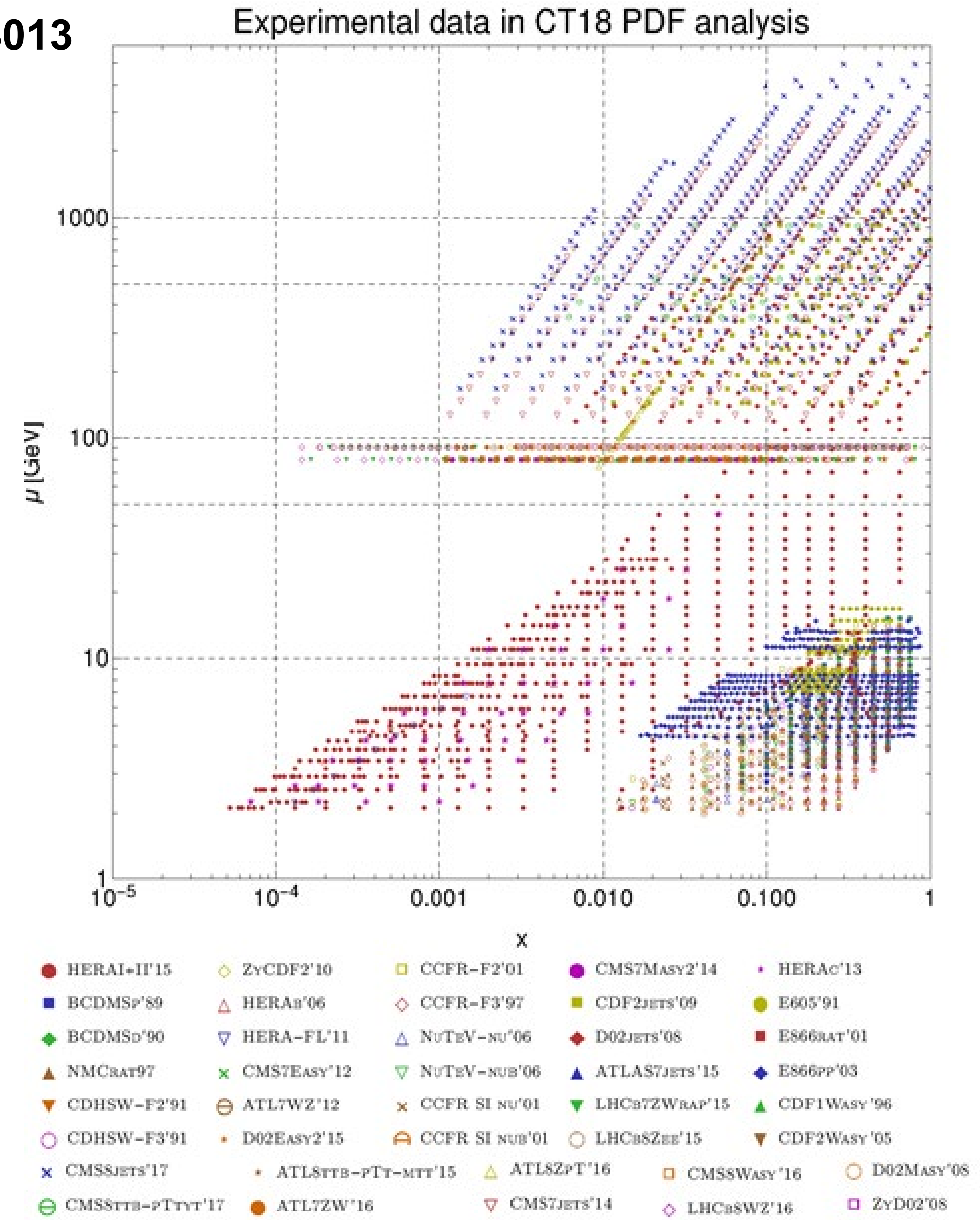
CT18 PDFs with LHC 7 and 8 TeV data

T.-J. Hou et al., Phys.Rev.D 103 (2021) 1, 014013

Included experiments:

- Combined HERA1+2 DIS
- LHCb 7 TeV Z, W muon rapidity dist.
- LHCb 8 TeV Z rapidity dist.
- ATLAS 7 TeV inclusive jet
- CMS 7 TeV inclusive jet
- ATLAS 7 TeV Z pT dist.
- LHCb 13 TeV Z rapidity dist.
- CMS 8 TeV Z pT and rapidity dist.
- CMS 8 TeV W, muon asymmetry dist.
- ATLAS 7 TeV W/Z, lepton(s) rapidity dist.
- CMS 7,8 TeV tT differential dist.
- ATLAS 7,8 TeV tT differential dist.

- ATLAS 7 TeV W/Z production in CT18A and CT18Z, not in CT18

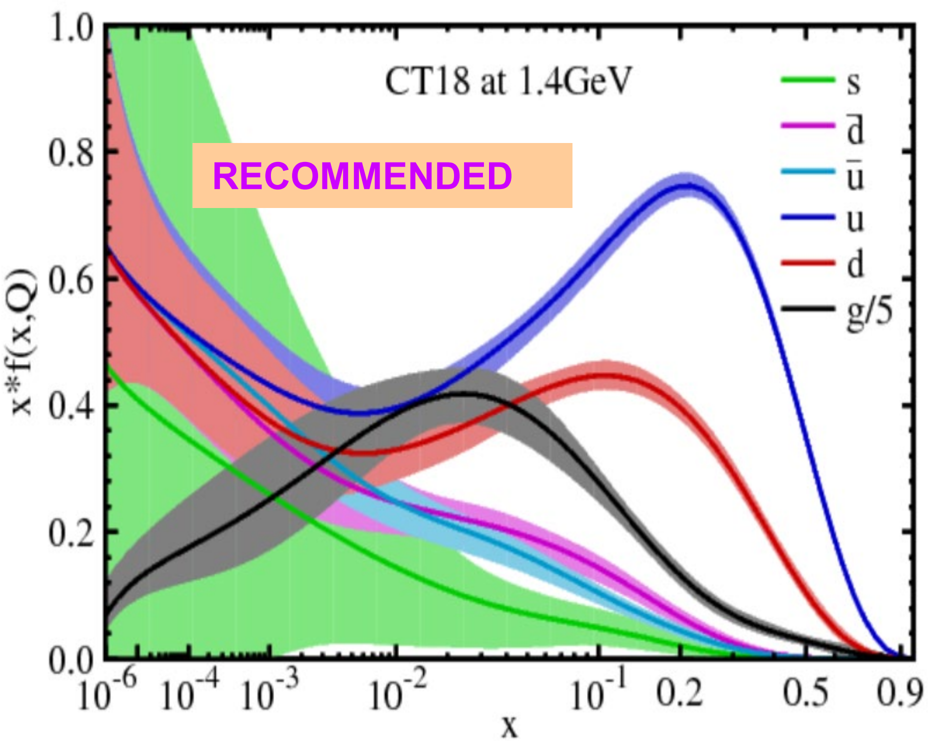


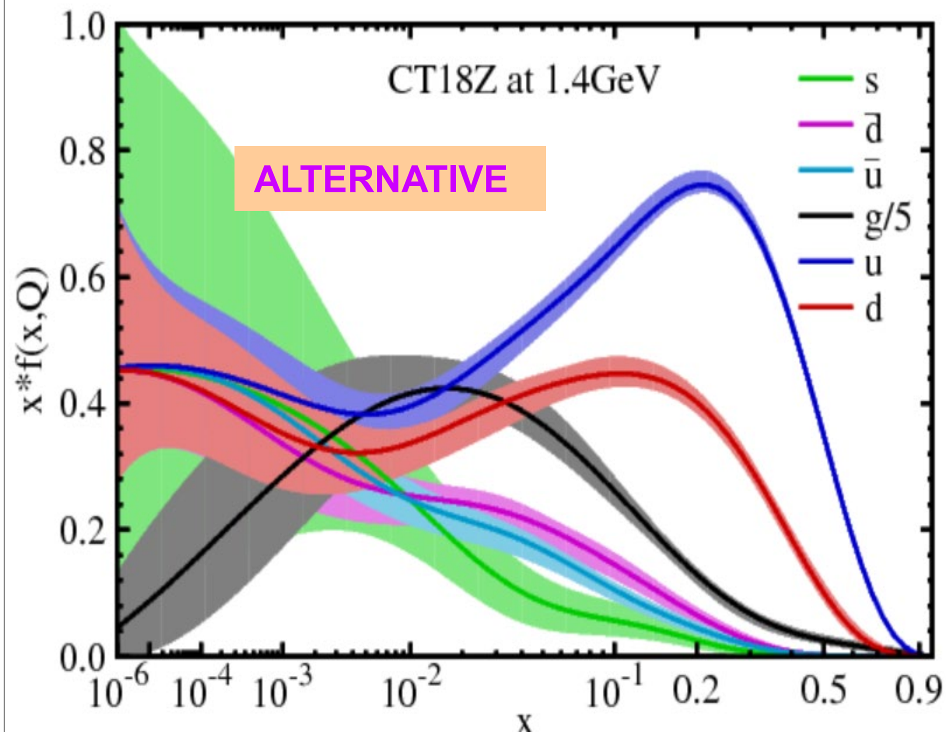
The CT18 study in a nutshell

- Identify and include LHC data sets (available by mid-2018) with highest sensitivity to PDFs, using fast Hessian techniques (**PDFSense** and **ePump**)
- **Benchmark predictions for newly implemented processes** using a combination of in-house ApplGrid/fastNLO grids and NNLO/NLO factor tables. Compare NNLO (FEWZ, VRAP,..) and NNLL/NNLO (ResBos 2) predictions for W/Z production.
- Examine **>250 PDF parameterization forms**; adjust the final uncertainty to cover the resulting spread in predictions
- Examine **QCD scale dependence** in key processes
- Validate the results using a **strong set of goodness-of-fit tests** *(Kovarik, PN, Soper,* arXiv:1905.06957*)*
- Examine agreement between experiments using diverse statistical techniques (**Lagrange Multiplier scans, Gaussian variables, PDFSense, ePump**)
- **Review phenomenological implications of CT18 PDFs**

CT18 parton distributions

Four PDF ensembles: CT18 (default), A, X, and Z

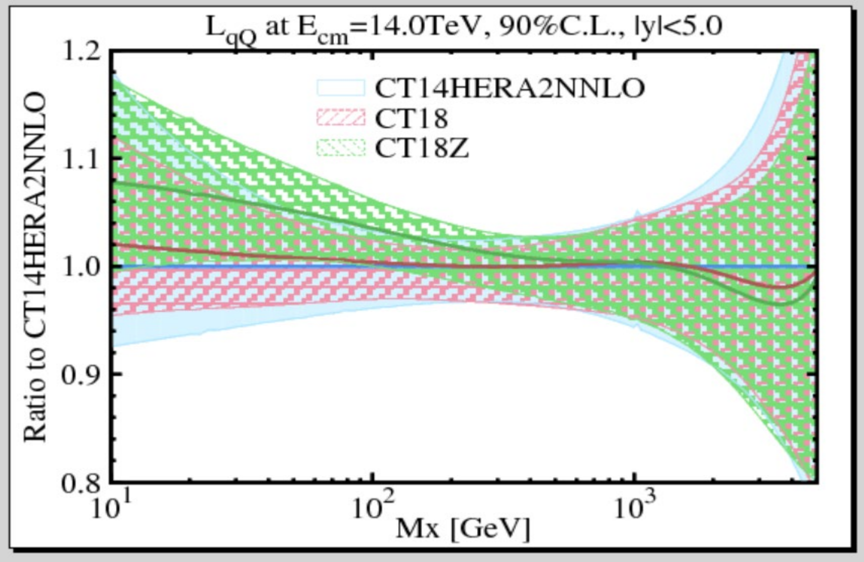


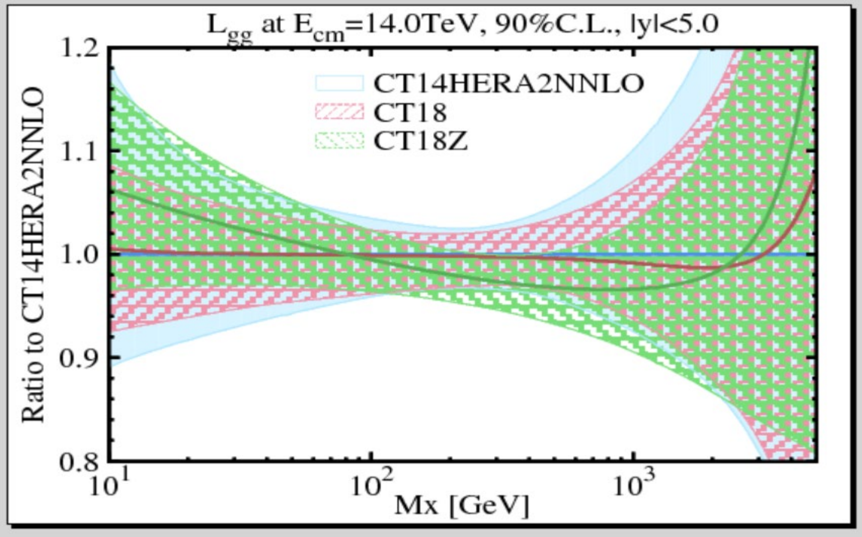


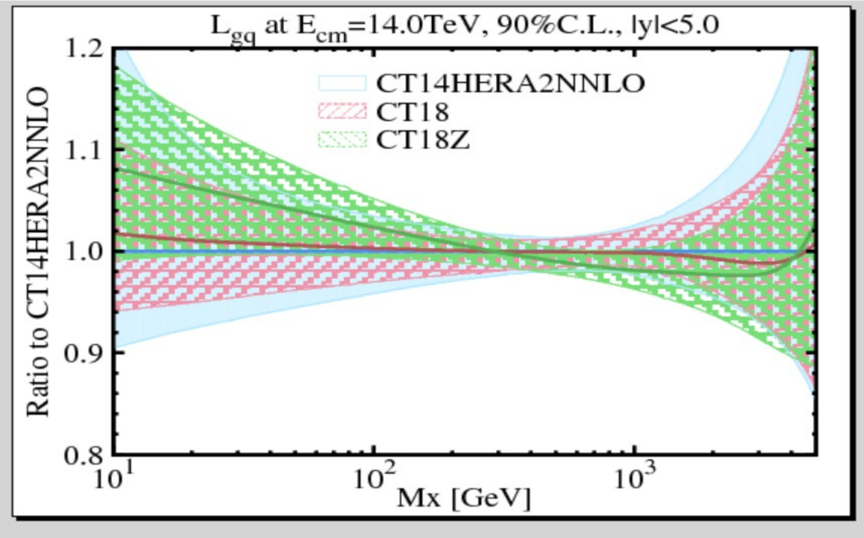
*** CT18 (N)NLO PDF set is recommended for the majority of LHC applications**

- CT18Z has enhanced gluon and strange PDFs at $x \sim 10^{-4}$, and reduced light-quark PDFs at $x < 10^{-2}$. The CT18Z maximizes the differences from CT18 PDFs, while preserving about the same goodness-of-fit as for CT18.
- CT18A and CT18X include some features of CT18Z, lie between CT18 and CT18Z

CT18/CT18Z parton luminosities







CT18 consistent with CT14

CT18Z has a somewhat different shape, especially at low invariant masses M_X

Note: parton luminosities are integrated over the accessible rapidity region $|y| < 5$

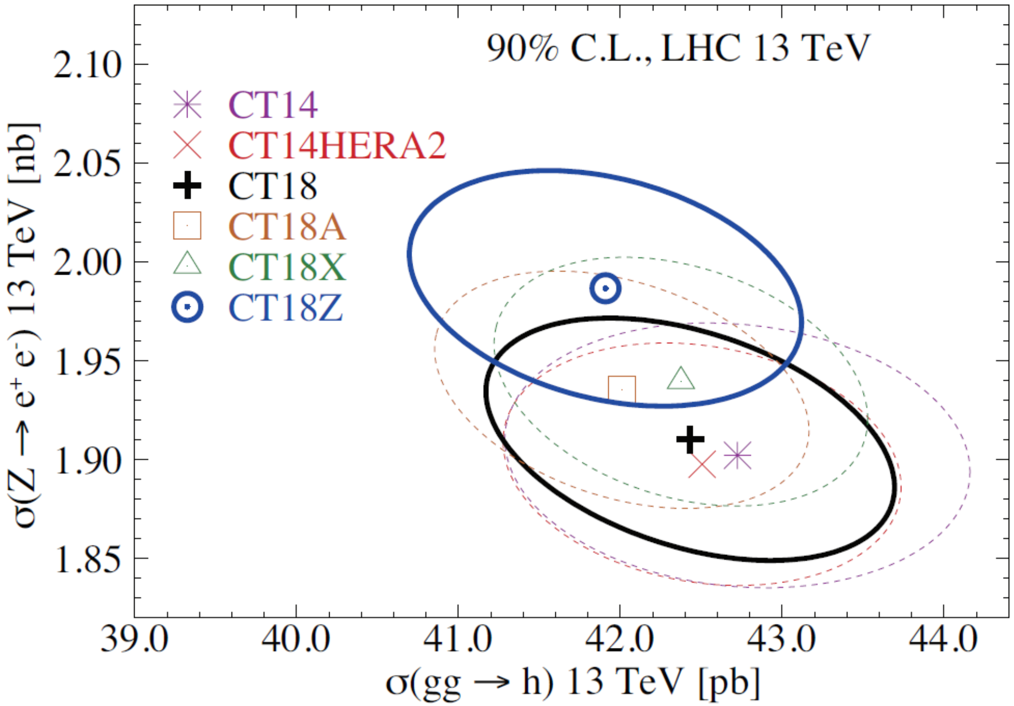
Alternative CT18 NNLO sets and CT18 uncertainties

PDF ensemble	Factorization scale in DIS	ATLAS 7 Z/W data included?	CDHSW $F_2^{p,d}$ data included?	Pole charm mass, GeV
CT18 default	$\mu_{F,DIS}^2 = Q^2$	No	Yes	1.3
CT18A	$\mu_{F,DIS}^2 = Q^2$	**Yes – affects R_s**	Yes	1.3
CT18X	$\mu_{F,DIS}^2 = 0.8^2 \left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}}\right)$ approximates small-x saturation	No	Yes	1.3
CT18Z	$\mu_{F,DIS}^2 = 0.8^2 \left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}}\right)$	**Yes**	No	1.4

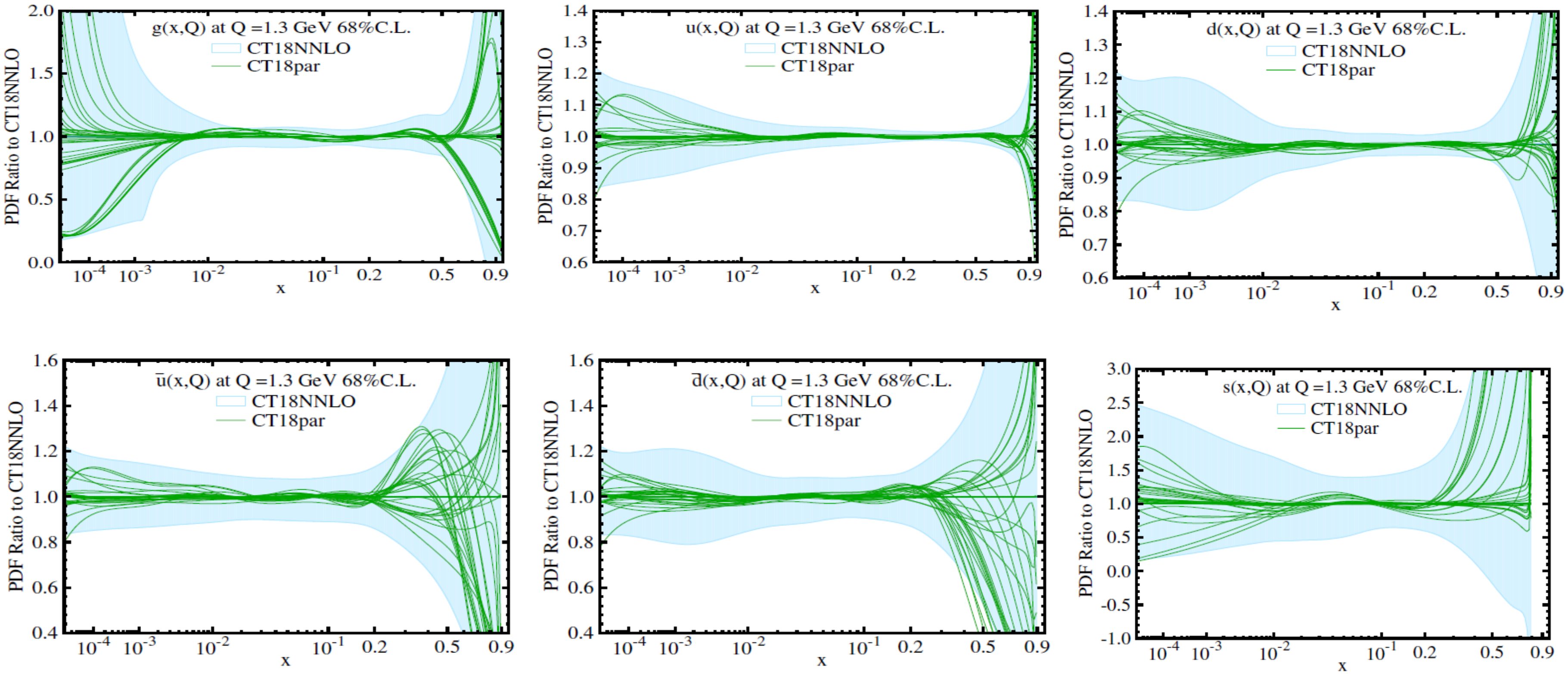
Alternative CT18 sets and CT18 uncertainties

The CT18 Hessian error PDFs account for a combination of **experimental**, **theoretical**, **parametrization**, and **methodological** uncertainties

As in CT14 NNLO, a combination of the global (**tier-1**) and dynamic (**tier-2**) tolerance is used



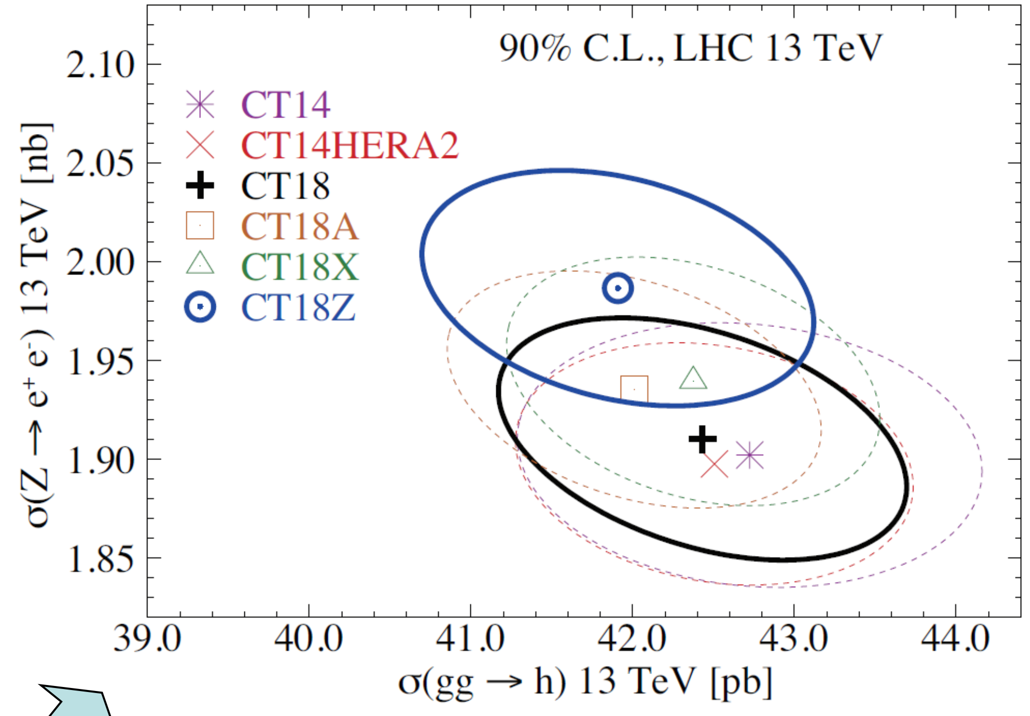
250+ candidate nonperturbative parametrization forms of CT18 PDFs



- CT18par – a sample of **some** non-perturbative parametrization forms tried in CT18
- The CT18 uncertainty covers most solutions with the same χ^2_{tot} based on alternative parametrization forms

Alternative CT18 sets and CT18 uncertainties

The CT18Z ensemble (obtained by combining effects in CT18A and X) quantifies displacements of central PDFs that fall out of the nominal 90% CL CT18 uncertainty bands



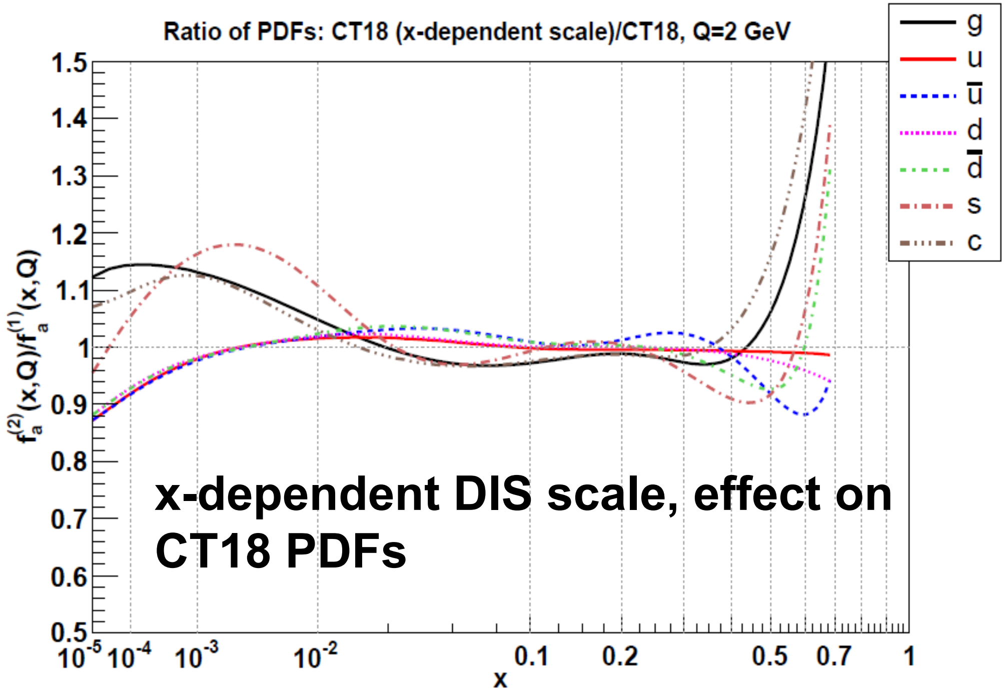
The CT18 uncertainties are **moderately conservative** and largely cover the spread of central predictions obtained with different assumptions and selections of experiments

CT18Z NNLO cross sections for $gg \to H$ production (Z production) lower by about 1% (higher by 4.9%) compared to CT14HERA2 NNLO

CT18X and Z: a special factorization scale in DIS

The CT18Z fits uses a $\mu_{DIS,X}$ scale that reproduces many features of NNLO-NLLx fits with $\ln(1/x)$ resummation by the NNPDF [arXiv:1710.05935] and xFitter [1802.0064] groups.

$$\mu^2_{DIS,X} = 0.8^2 \left(Q^2 + \frac{0.3\ GeV^2}{x^{0.3}} \right)$$

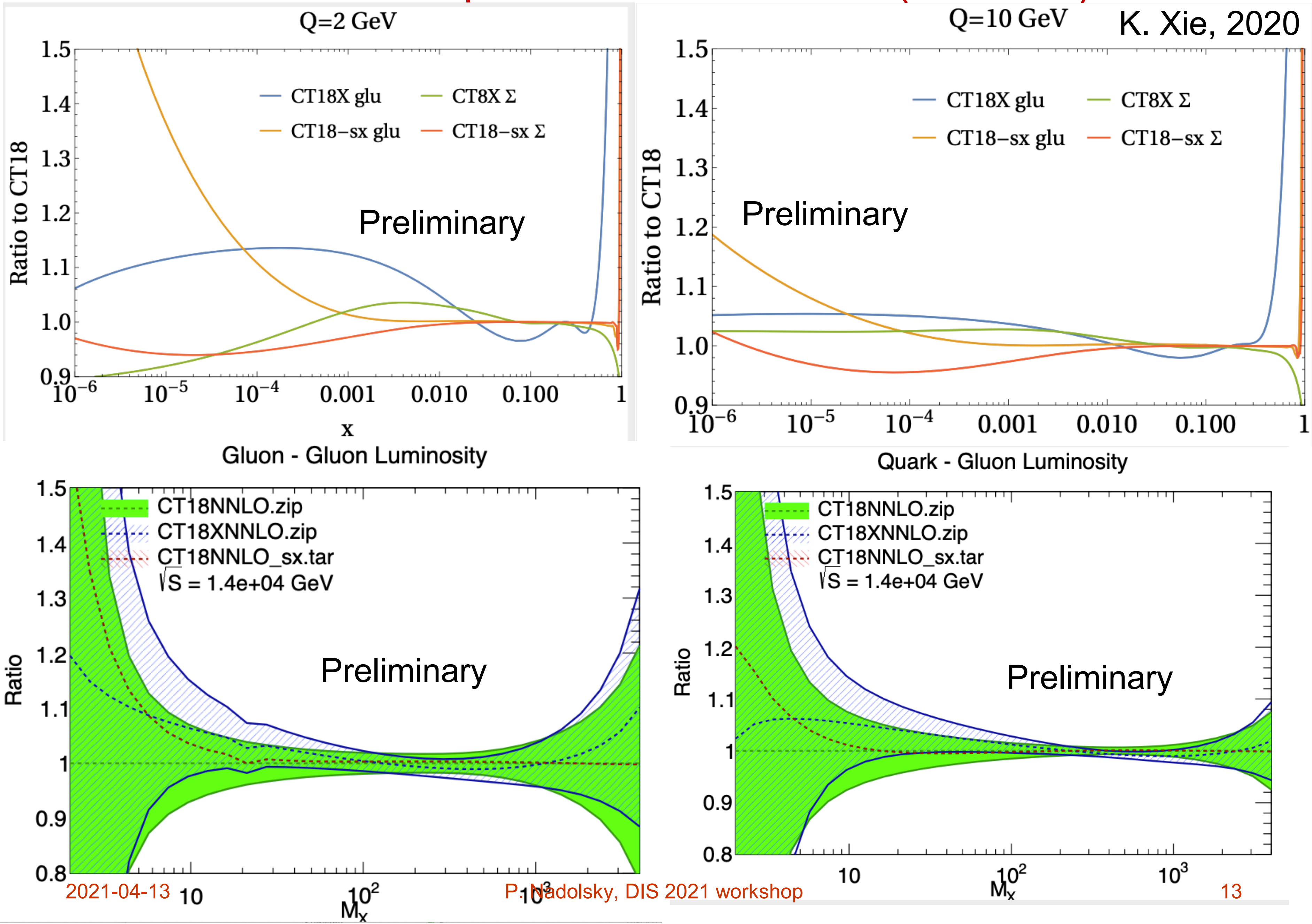


In the fitted region, the NNLO-NLLx fits and small-x scale fits are statistically indistinguishable.

We expect some differences between NNLO-NLLx predictions and fully saturated dynamics described by BK, JIMWLK equations at sufficiently small x

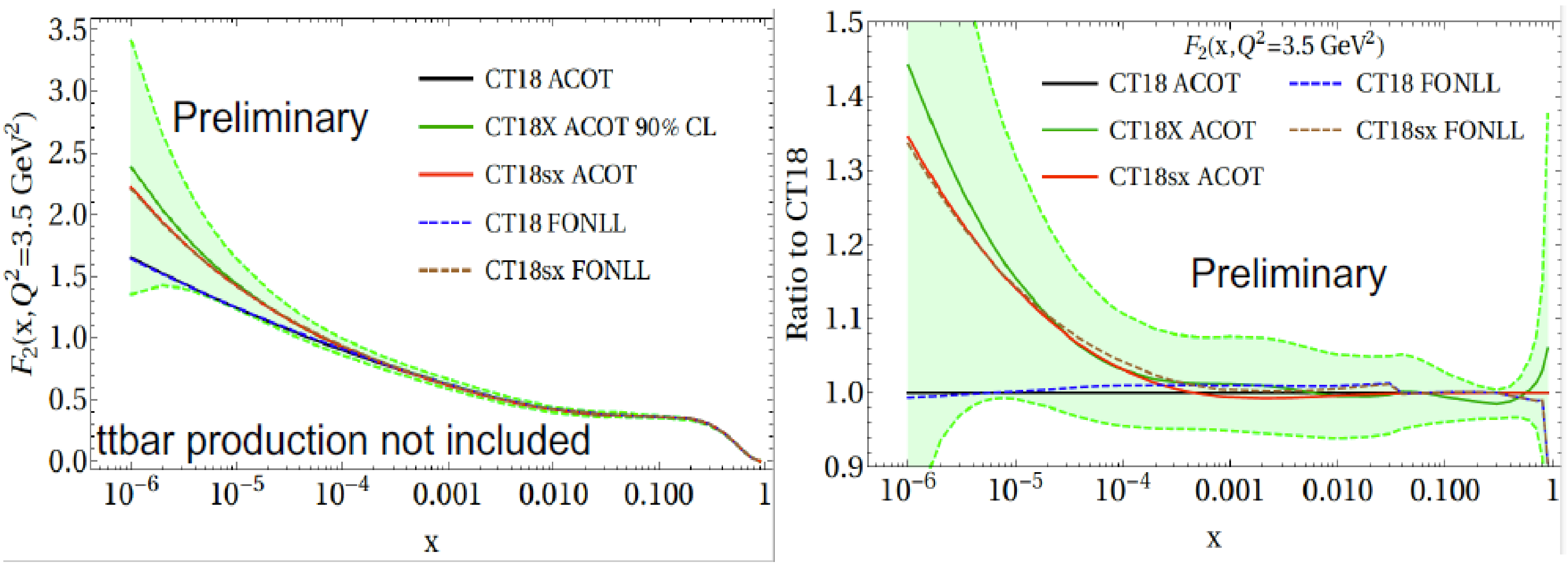
We compare predictions for for DIS $F_2(x,Q)$ and $F_L(x,Q)$ at NNLO-NLLx with CT18 PDFs using the HELL package and at NNLO with CT18X PDFs.

CT18X NNLO compared to NLLx-NNLO (CT18-sx) PDFs



Structure function $F_2(x, Q^2)$

K. Xie, 2020



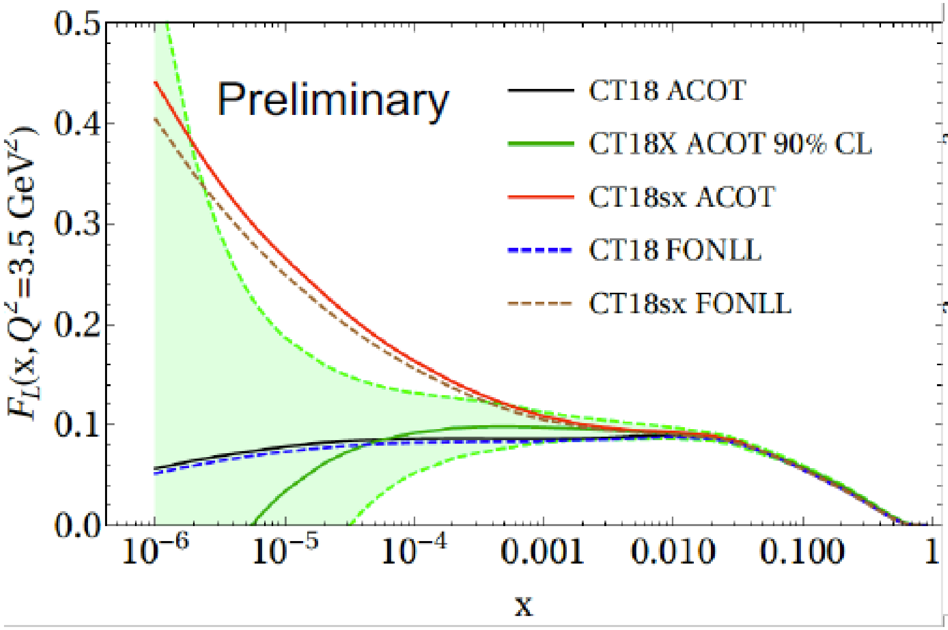
- CT utilizes the SACOT-χ scheme, which is close to the NNPDF's FONLL scheme.
- The CT18 SACOT small x (sx) resummed F_2 is obtained with the K-factor approach

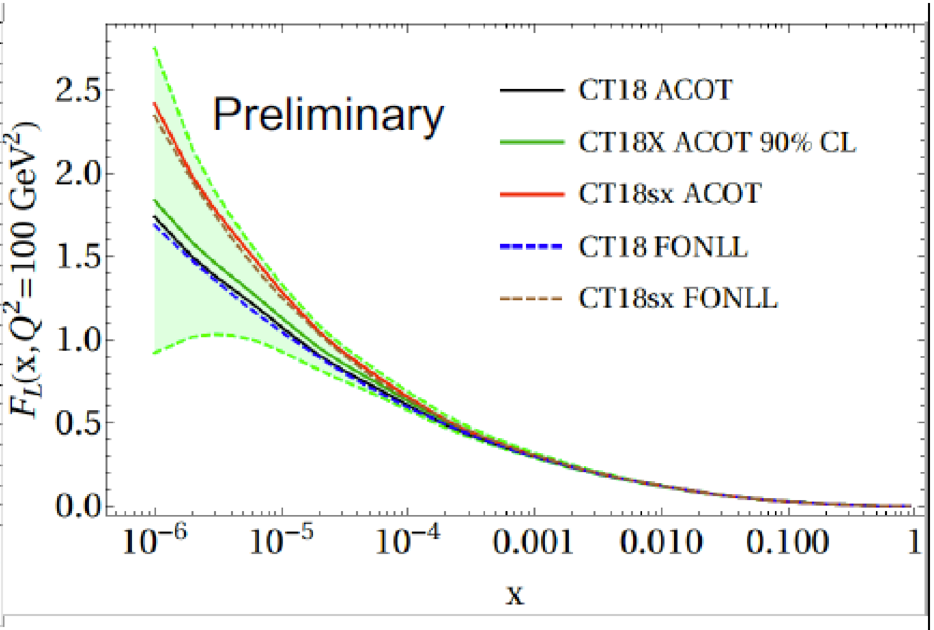
$$\text{CT18sx ACOT} = \text{CT18 ACOT}\ \frac{\text{FONLL}\ sx}{\text{FONLL}}$$

- For F_2, the NNLO CT18X and NNLO-NLLx CT18 are indistinguishable down to $x \sim 10^{-5}$.
- At $Q > 10$ GeV, give the same prediction as the standard DGLAP one (CT18).

Structure function $F_L(x, Q^2)$

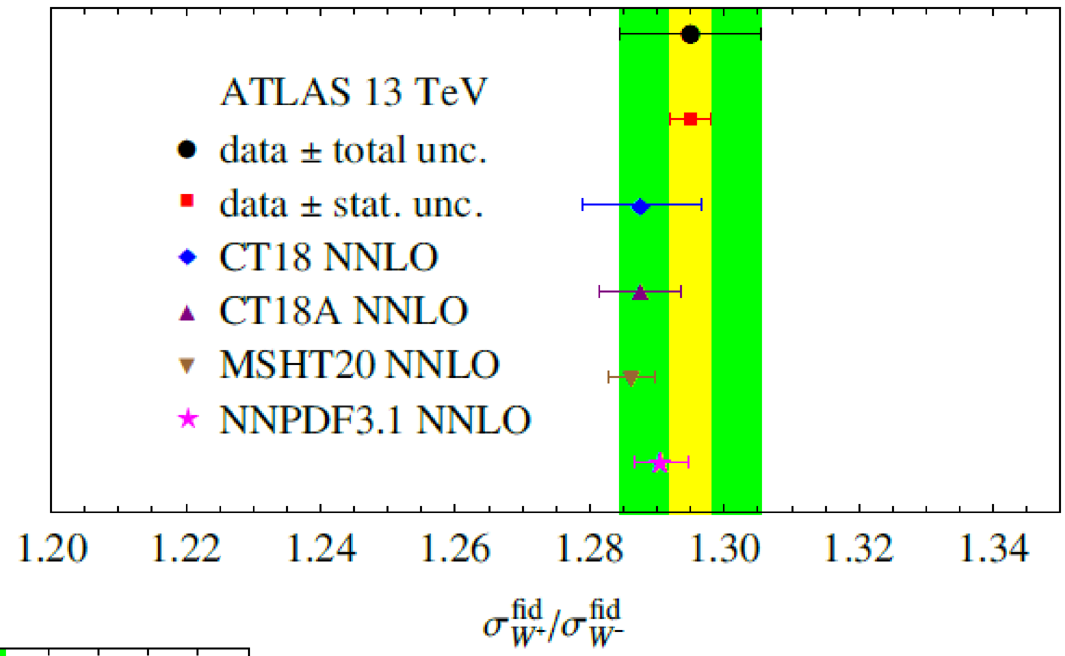
K. Xie, 2020

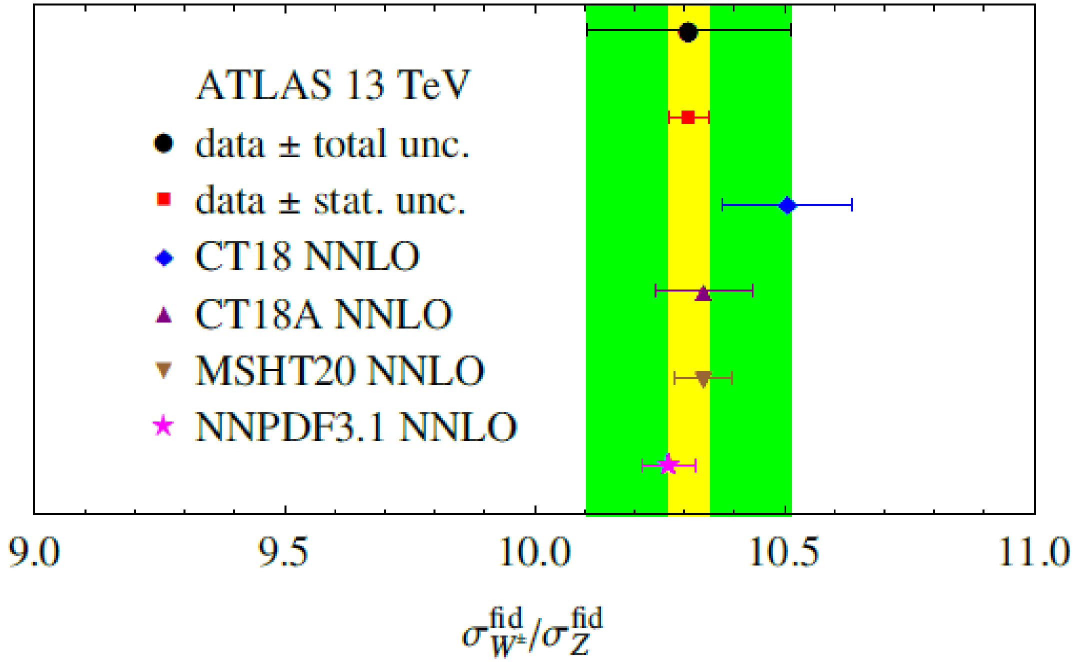




- At low Q and $x < 10^{-5}$, CT18X reduces F_L, while the small-x resummation enhances it.
- At high Q, both enhance F_L, while the CT18X prescription is smaller.
- It would be very interesting to see which behavior is preferred by data.

CT18/CT18A ratios of NNLO $W^{\pm}$and Z^{0}cross sections



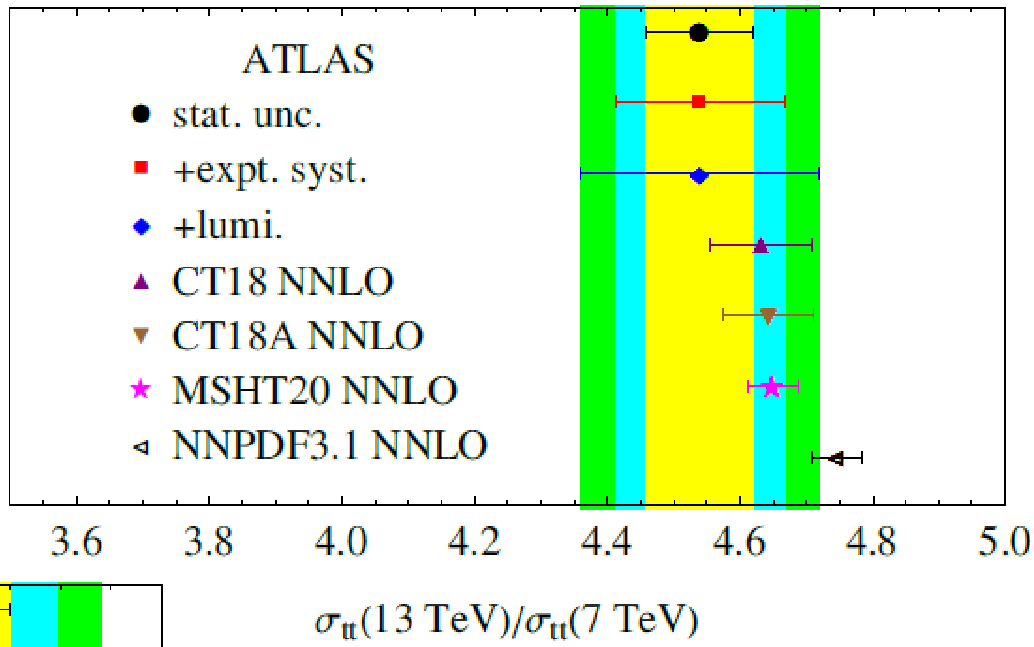


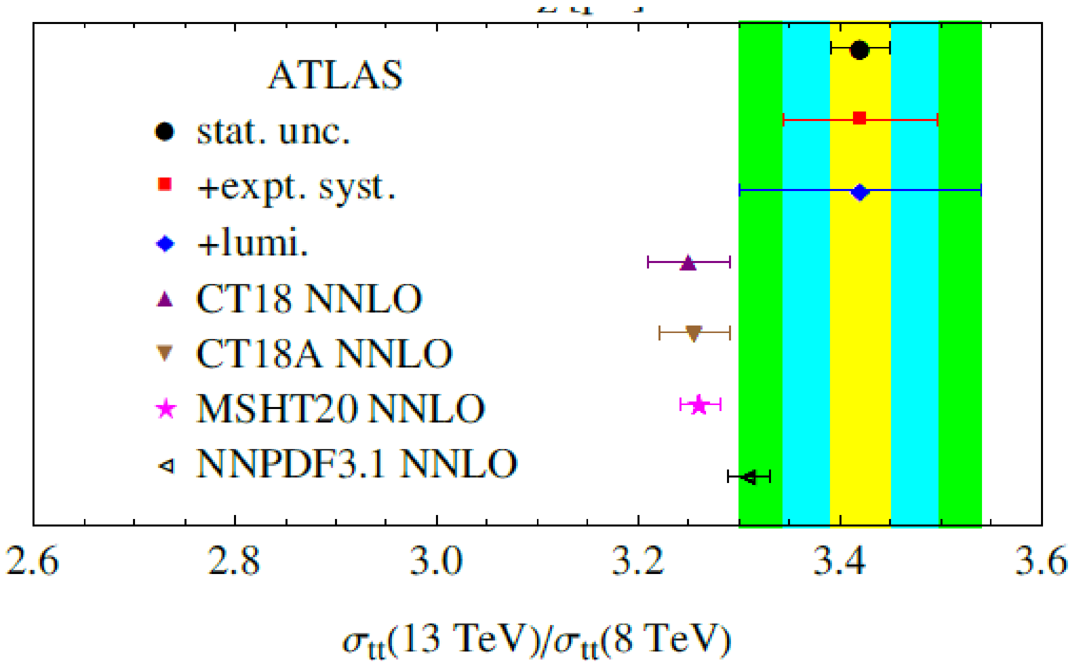
Slightly smaller uncertainties in CT18A than in CT18

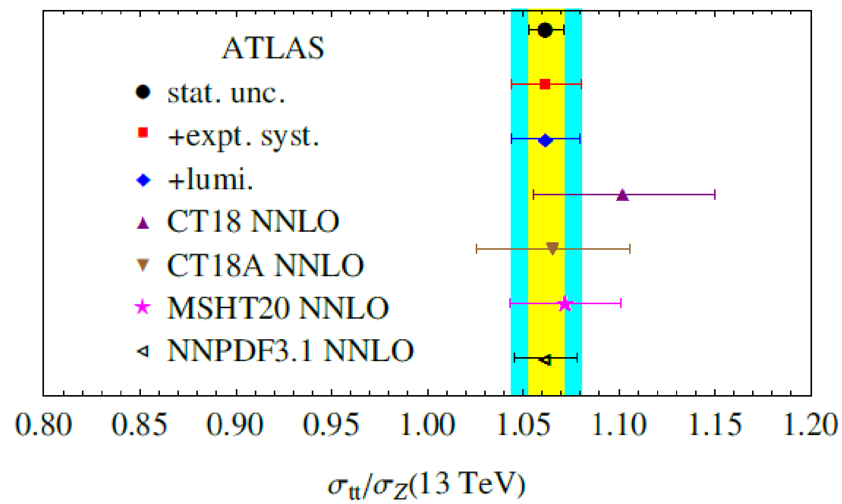
More on it later.

Figures: K. Xie, MCFM @ NNLO Comparisons of different DY codes in CT18 paper, appendix F

CT18/CT18A ratios of NNLO $t\bar{t}$ and Z^0 cross sections





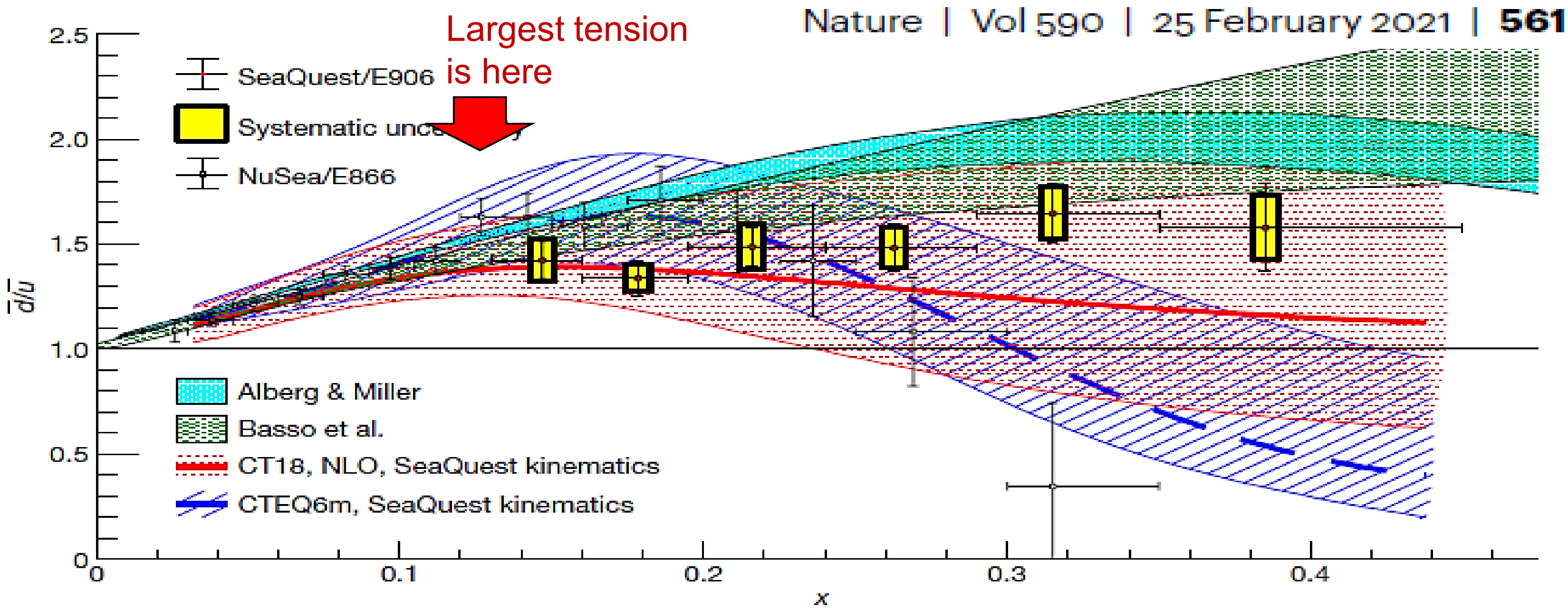


Some disagreement with $\sigma_{t\bar{t}}(8\ \mathrm{TeV})$?

Figures: K. Xie

The E906 SeaQuest experiment

NEW

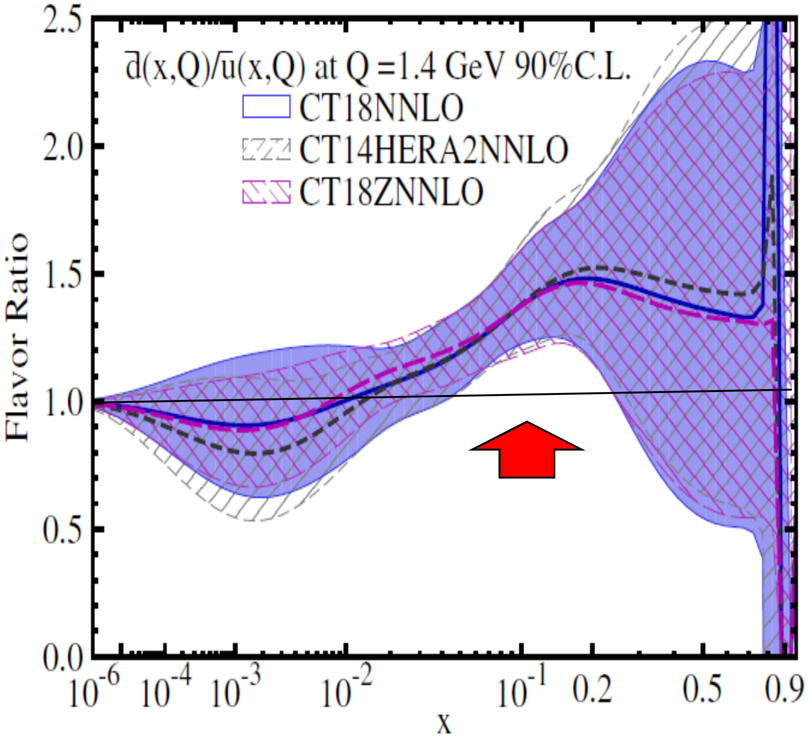


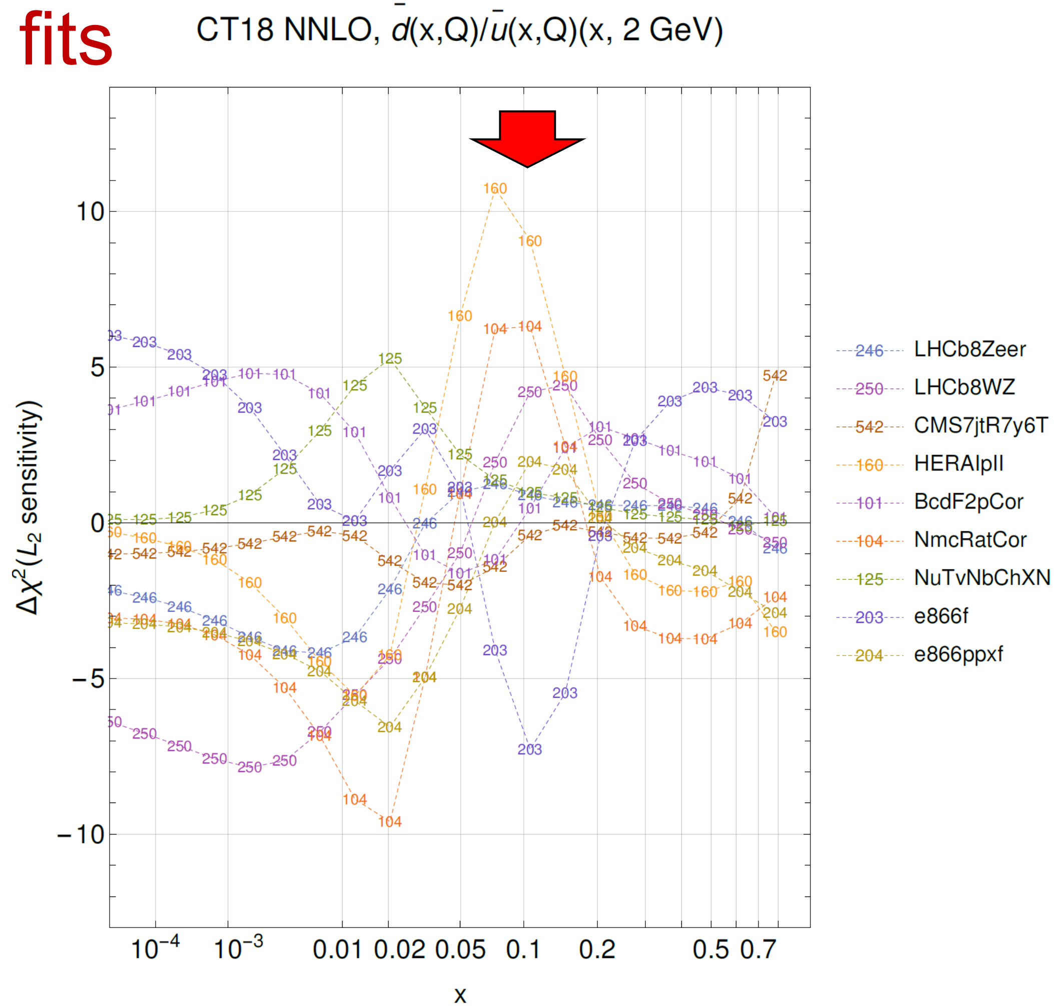
The Fermilab E906 muon pair production experiment suggests there are more $\bar{d}$ than $\bar{u}$ antiquarks at large momentum fractions. It disagrees with the E866 experiment suggesting a suppressed $\bar{d}/\bar{u}$ ratio at $x > 0.3$.

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





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

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

Do the LHC experiments agree among themselves and with other experiments in the CT18 data set?

A **consistent** answer emerges from a powerful combination of four methods:

1. Effective Gaussian variables [H.-L. Lai et al., arXiv:1007.2241]
2. Lagrange multiplier scans
3. PDFSense and L_2 sensitivity **[Talk by X. Jing]**
4. ePump [Schmidt, Pumplin, Yuan, PRD 98, 094005]

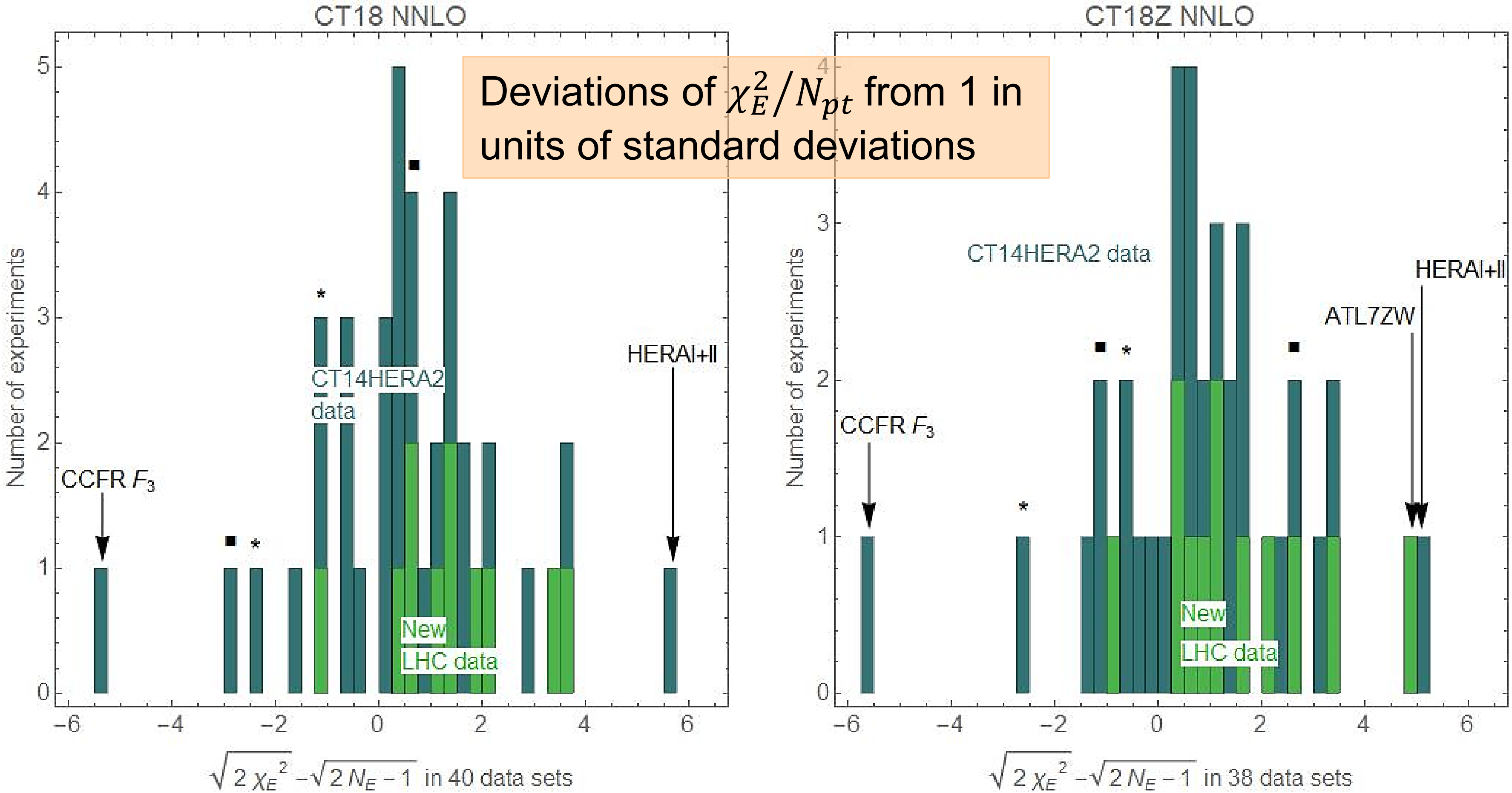
} slow, most accurate (methods 1–2)

} Fast approximations (methods 3–4)

To include disagreeing experiments or not?

Several LHC experiments have elevated χ_n^2/N_{pt} (about the same as for other groups). What does it mean as we advance to 1% PDF uncertainties?

Deviations of χ_E^2/N_{pt} from 1 in units of standard deviations



An excellent fit…

…has a global $\chi^2 \lesssim N_{pt} + \kappa\sqrt{2N_{pt}}$, with κ of order 1

…is stable with respect to different selections of experiments

…is stable numerically (e.g., there are no multiple minima or flat directions in the PDF parameter space)

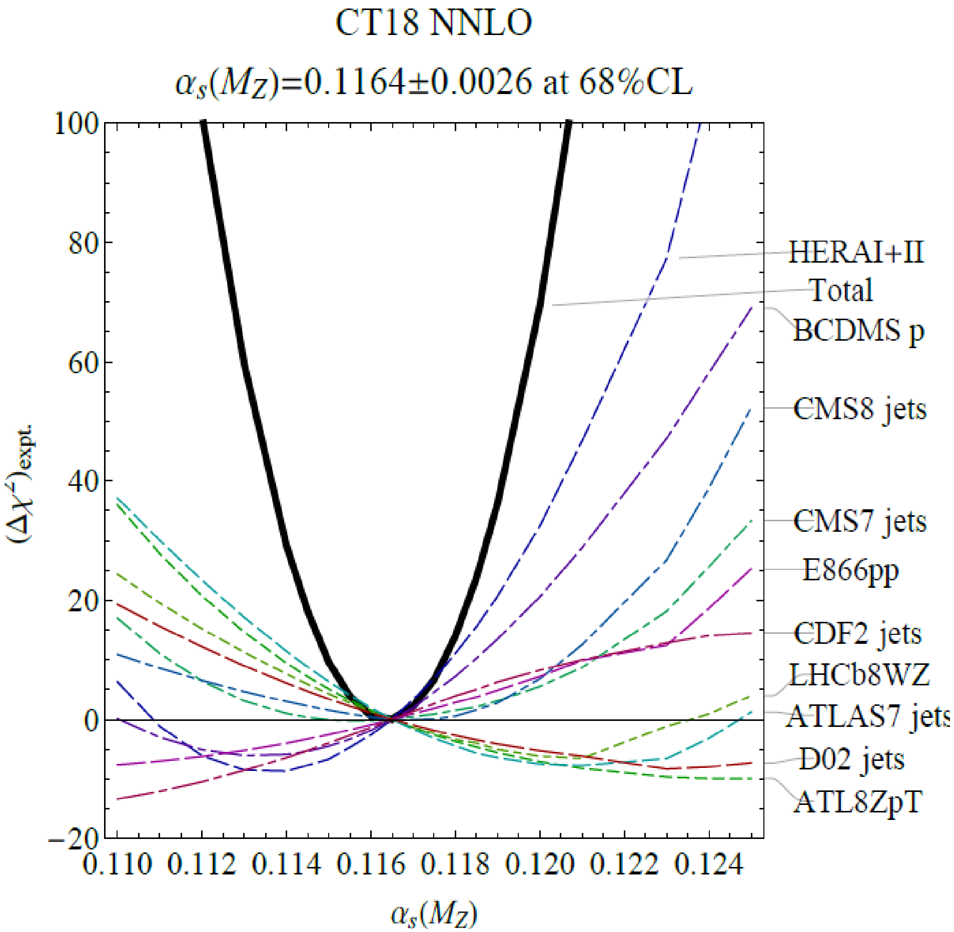
…passes a number of other quality tests

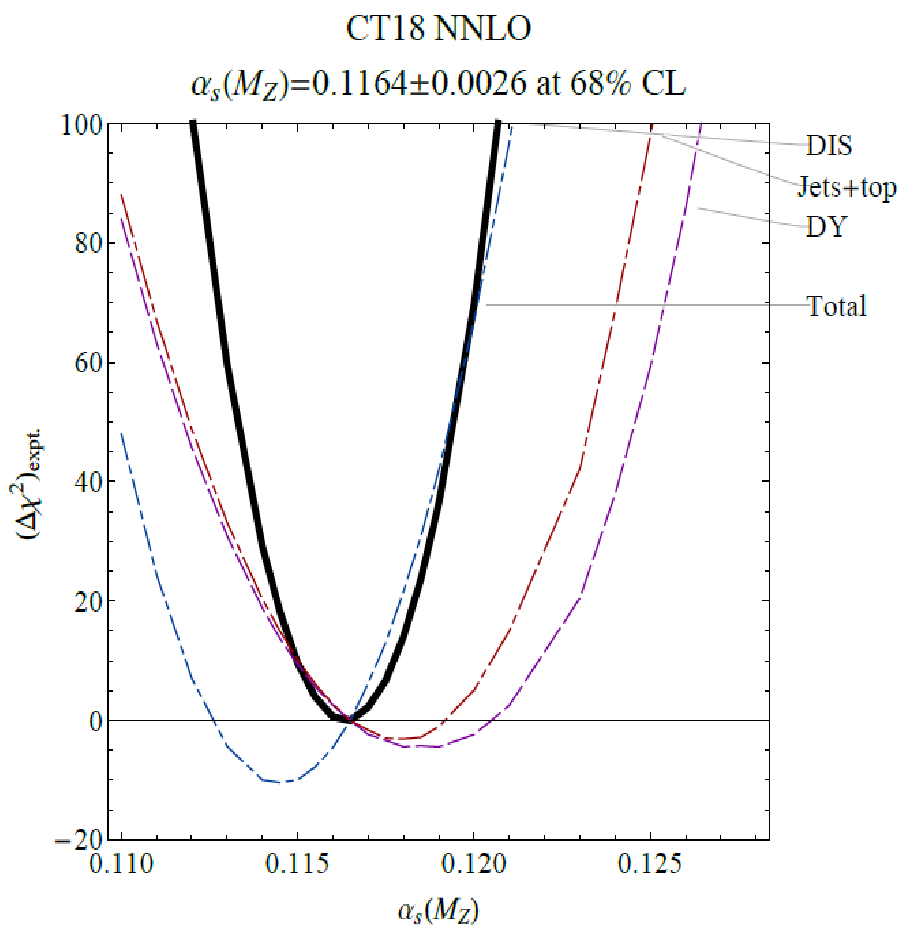
Together, these conditions comprise the **strong set of goodness-of-fit criteria** [Kovarik, PN, Soper, *RMP* 92 (2020) 4, 045003]

Satisfying these conditions is difficult when there are disagreements among (or within) experiments.

CT18/CT18X are somewhat closer to satisfying these conditions then CT18A/CT18Z.

A scan on $\alpha_s(M_Z)$ in the CT18 fit

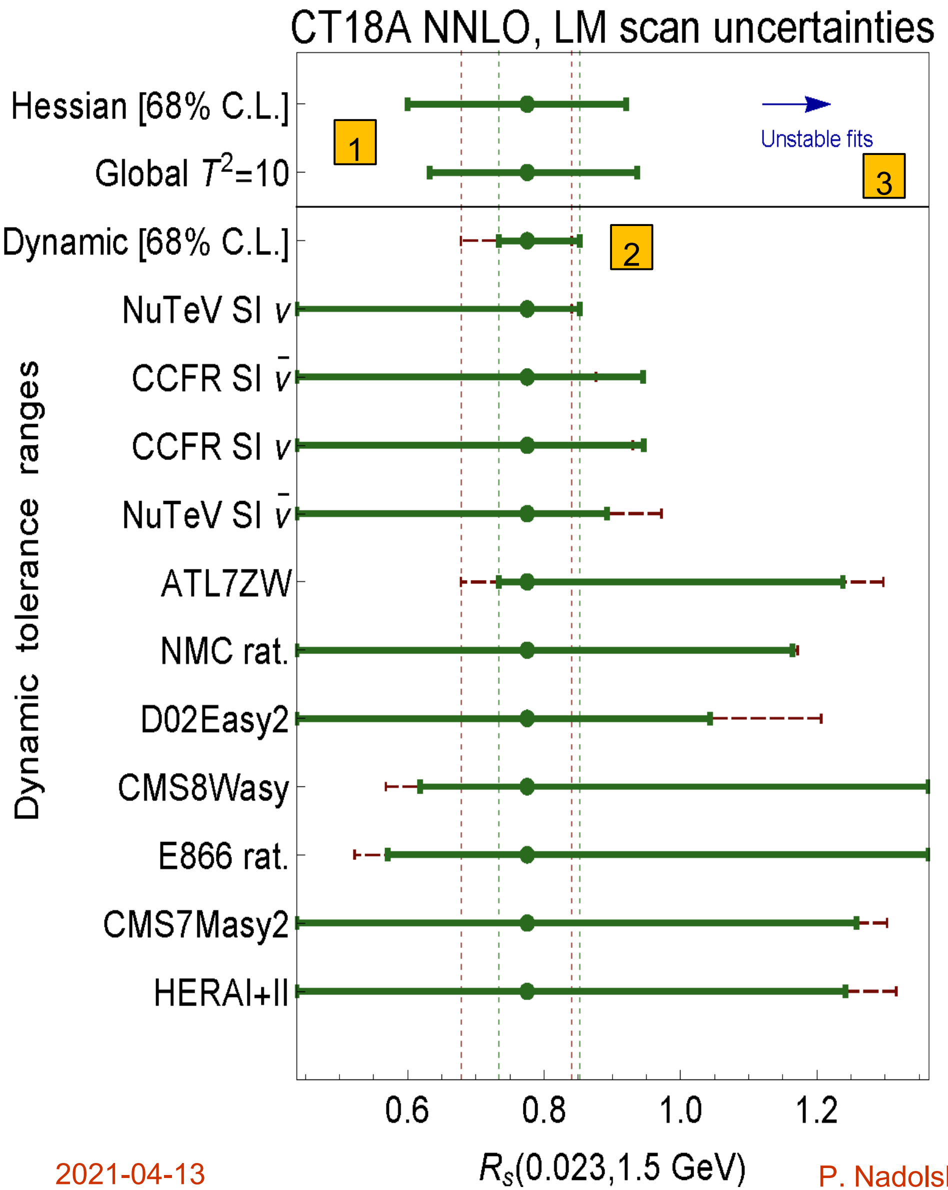




Note the opposing pulls of DIS and jet+top production experiments (affected by the NNLO uncertainty) that significantly exceed the $\Delta\chi^2 \sim 1$ variation implied by the simplest statistical framework

Example: uncertainty estimates on $R_s = (s + \bar{s})/(\bar{u} + \bar{d})$ from a LM scan

PRD 103 (2021) 014013



The LM scan reveals details not captured by other methods

1 **Nonlinearities:** the probability intervals may not obey the Gaussian distribution

2 **Tension between NuTeV+HERA and ATLAS 7TeV W/Z production:** in the affected direction(s), the global tolerance and **especially dynamic tolerance** underestimate the true PDF error.

3 **χ^2 instabilities:** Neither the "global T^2" nor "dynamic T^2" reflect multiple solutions when experiments disagree (resulting in the instability of CT18A/Z fit at $R_s > 1$)

Conclusion: CTEQ-TEA studies in progress

- Implications of CT18 NNLO PDFs for experiments
- CT18X PDFs for small x
- Combined HERA charm+bottom data
  - Can experimentalists recommend how to fit these data?
- CT18QED PDFs
- Lattice inputs for PDF fits
- Goodness-of-fit criteria
  - To include disagreeing experiments or not?
  - What is the right tolerance?
- Deuteron DIS in CJ and CT PDFs
- Impact of SeaQuest
- CTEQ-TEA PDFs at large x

STAY TUNED!

An excellent fit requires more than a good global χ^2

It passes a number of quality tests, called together the **strong set of goodness-of-fit criteria** [Kovarik, PN, Soper, *RMP* 92 (2020) 4, 045003]

1. Each possible partition n of the global data set has a good χ^2
   – differences between theory and data for this partition are indistinguishable from random fluctuations
   – experimental data sets are in mutual agreement
   – $P(\{\chi_n^2\}) \geq 0.68$ for the distribution of χ_n^2 over N_{part} partitions
2. Best-fit systematic nuisance parameters obey the expected probability distribution
3. **Resampling test:** the data are neither underfitted nor overfitted
4. A **closure test** is passed, like the one used in NNPDF 3.x
5. …

The resampling test of CT PDFs indicates that 25-30 parameters (26 in CT14HERA2) is optimal for neither underfitting nor overfitting the CT data.

With 29 eigenvector directions in CT18, the diagonalization of the Hessian matrix by MINUIT is close to the convergence limit.

A large disagreement between experiments, e.g. between NuTeV+HERA and ATLAS 7 TeV W/Z production, leads to numerical problems in our studies:

- a unique global fit may not exist, or χ^2 minimization may destabilize
- iterative diagonalization of the Hessian matrix may fail
- in underconstrained directions, the Hessian errors and in particular the dynamic tolerance with disagreeing experiments sometimes underestimate the uncertainty;

this is revealed by LM scans

CT14HERA2 resampling test