

Update from CTEQ-TEA

Pavel Nadolsky

Southern Methodist University

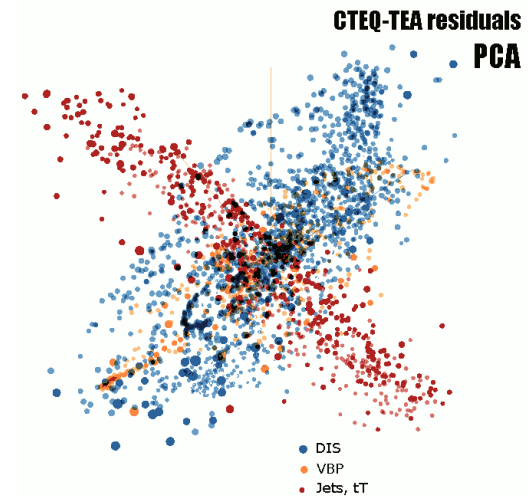
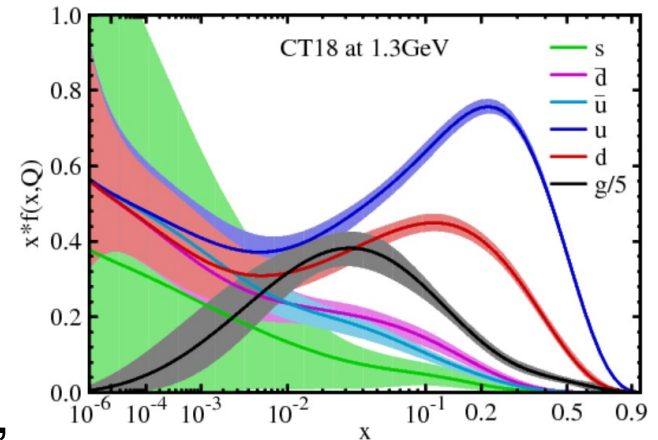
With CTEQ-TEA (Tung Et. Al.) working group

[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. Courtoy, X. Jing, K. Kovarik, F. Olness,

D. Soper



SMU

CTEQ

Many CTEQ-TEA efforts in 2020

CT18 post-publication studies

- Implications of CT18 NNLO PDFs for experiments
- CT18X PDFs and small- x saturation (in progress)
- Combined HERA charm data (in progress)
- CT18QED PDFs (in progress)
- Strong goodness-of-fit criteria and other methodological developments

In two talks on Tuesday:

- Deuteron DIS in CJ and CT PDFs; implications for LHC EW precision studies (A. Accardi, T. Hobbs, X. Jing, P.N., arXiv:[2102.01107](https://arxiv.org/abs/2102.01107))
- Impact of SeaQuest (Tim Hobbs)
- Large- x quark counting rules (A. Courtoy, PN, arXiv: [2011.10078](https://arxiv.org/abs/2011.10078))
- PDFs at the EIC and for lattice QCD (T. Hobbs, X. Jing, B.T. Wang,...)

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](https://arxiv.org/abs/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](https://arxiv.org/abs/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

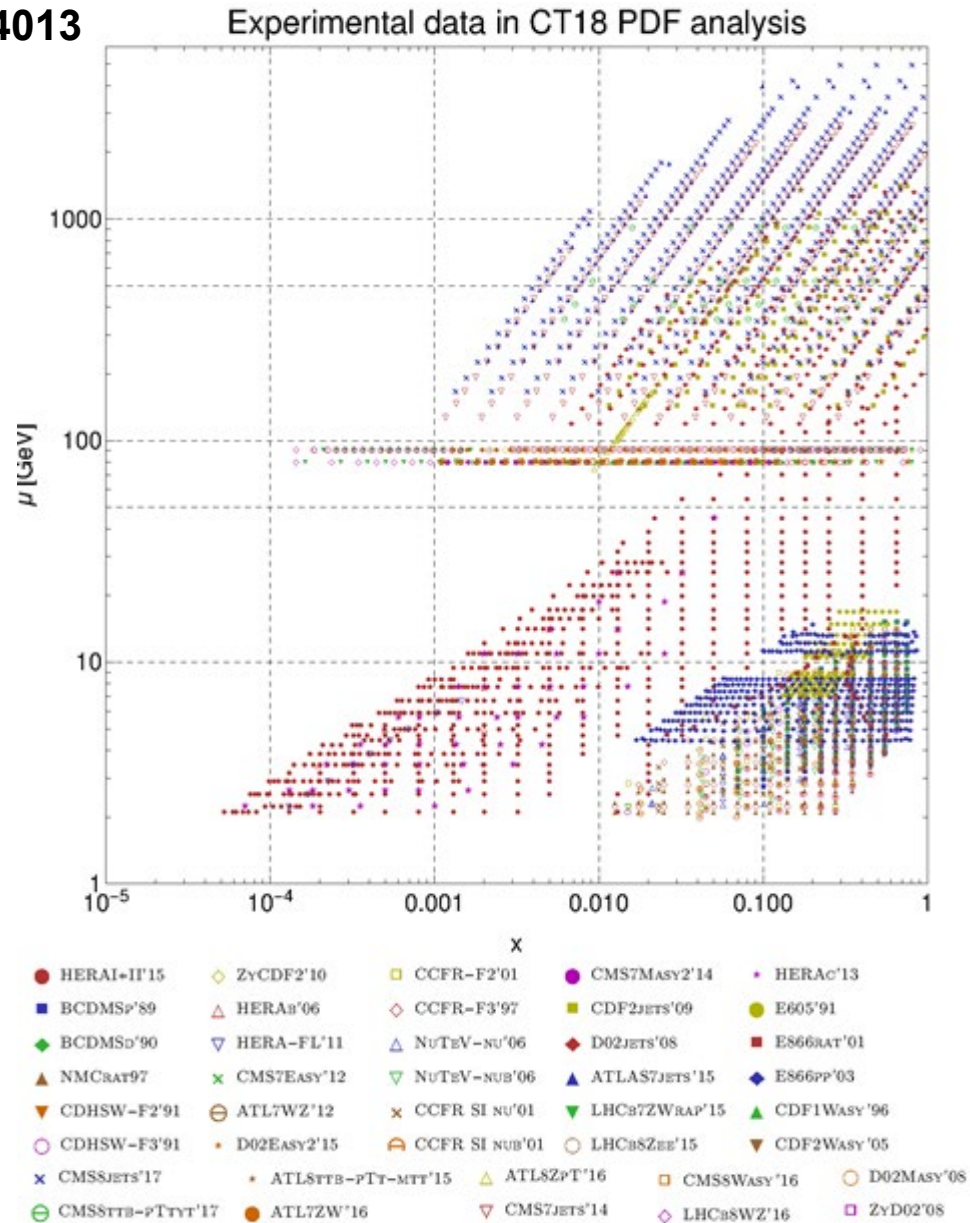
CT18 PDFs with LHC 7 and 8 TeV data

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

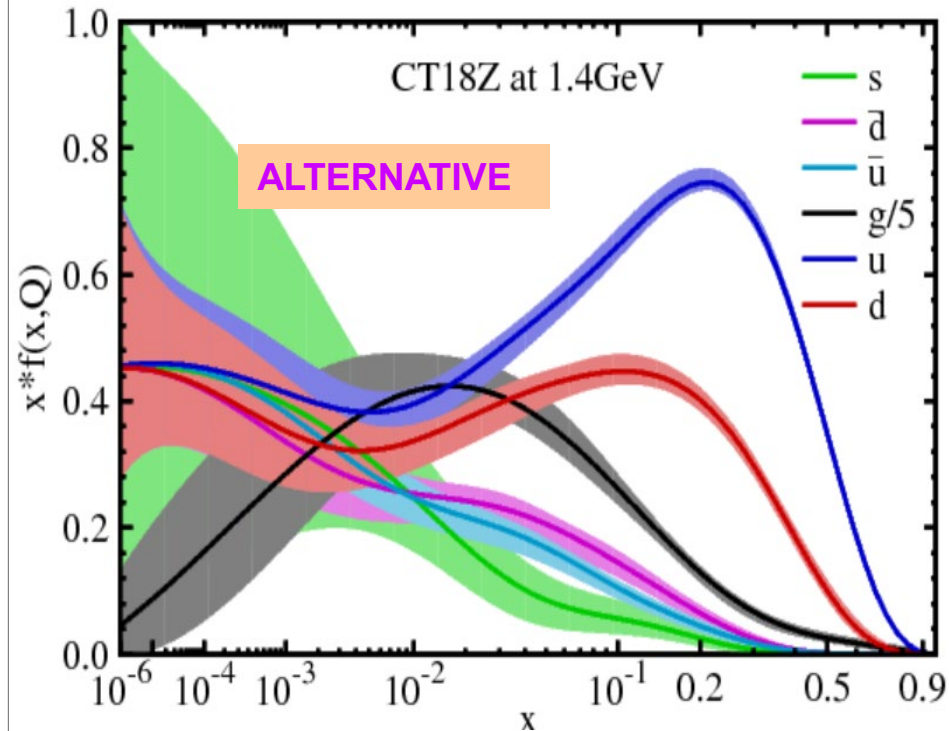
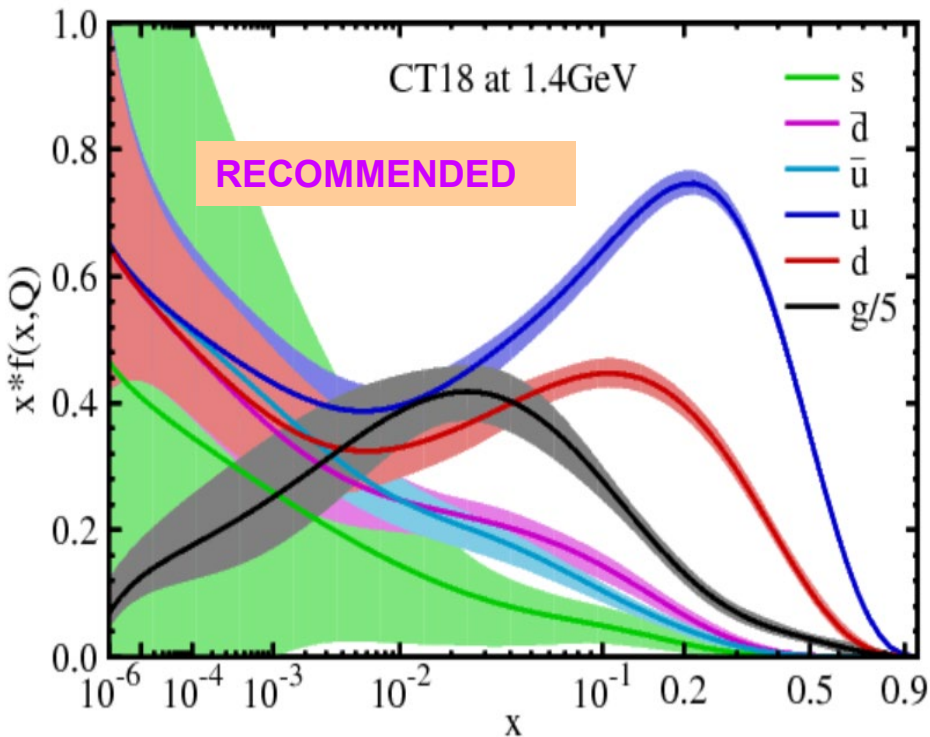


The CT18 study in a nutshell

- 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 **350 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

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	$\mu_{F,DIS}^2 = 0.8^2 \left(Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$ approximates small-x saturation	No	Yes	1.3
CT18Z	$\mu_{F,DIS}^2 = 0.8^2 \left(Q^2 + \frac{0.3 \text{ GeV}^2}{x^{0.3}} \right)$	Yes	No	1.4

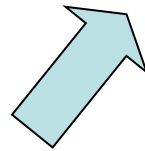
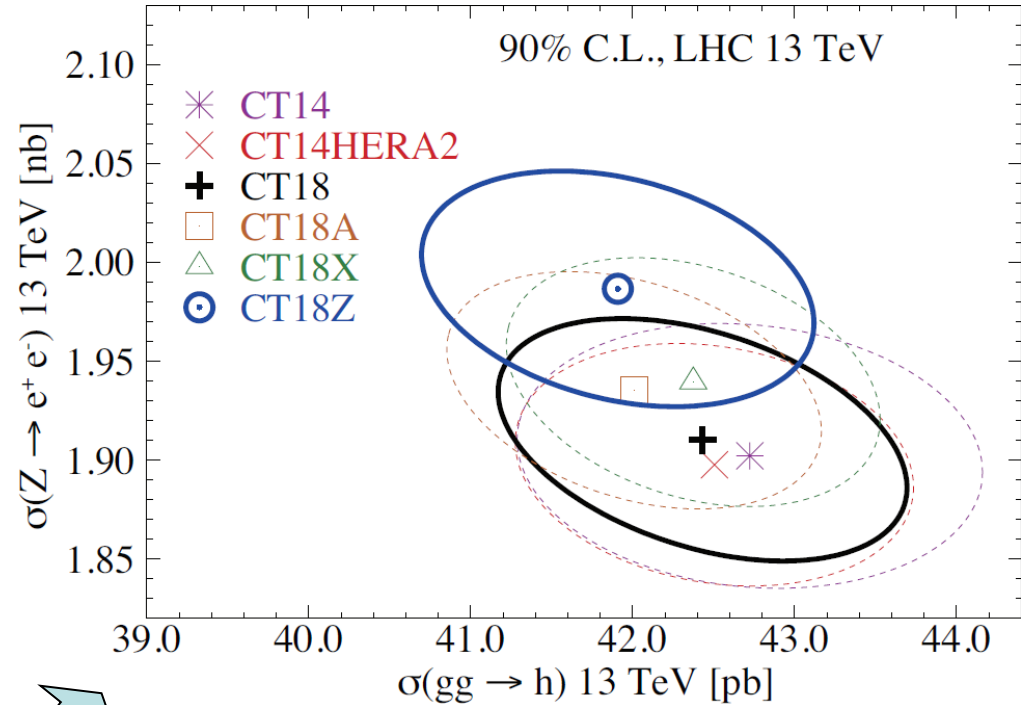
Alternative CT18 sets and CT18 uncertainties

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 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

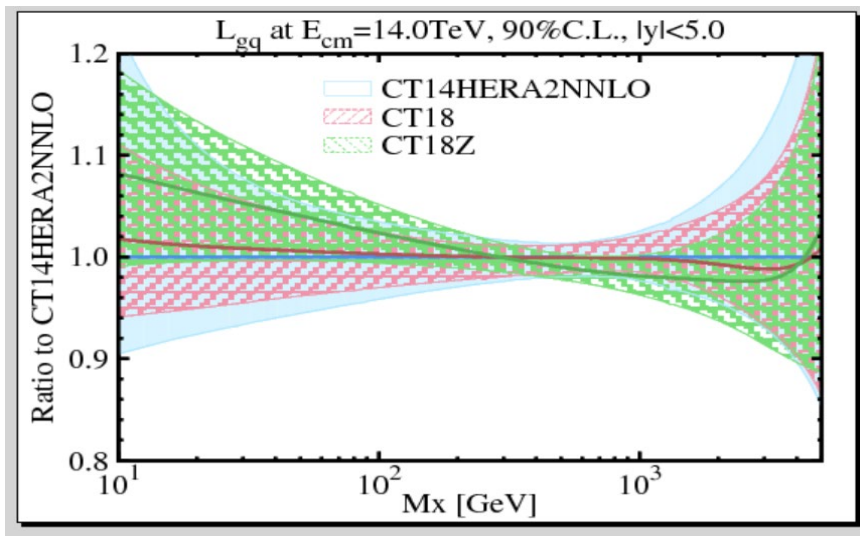
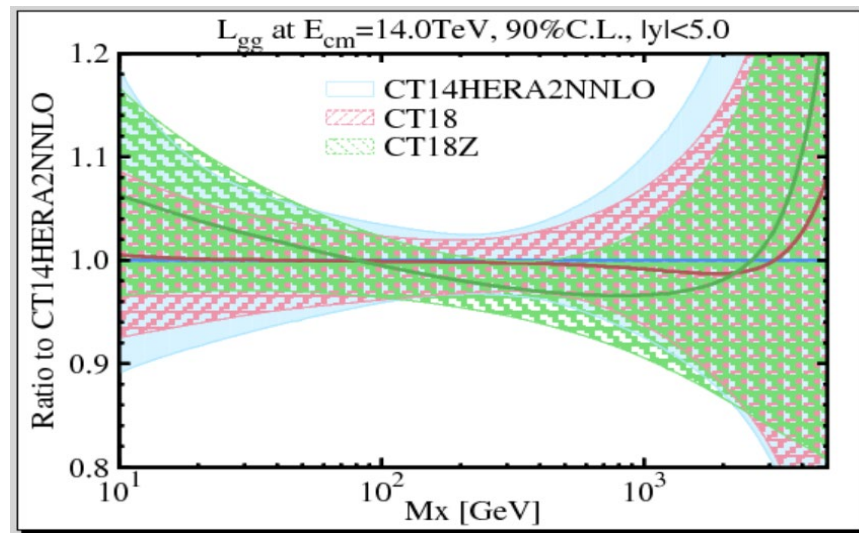
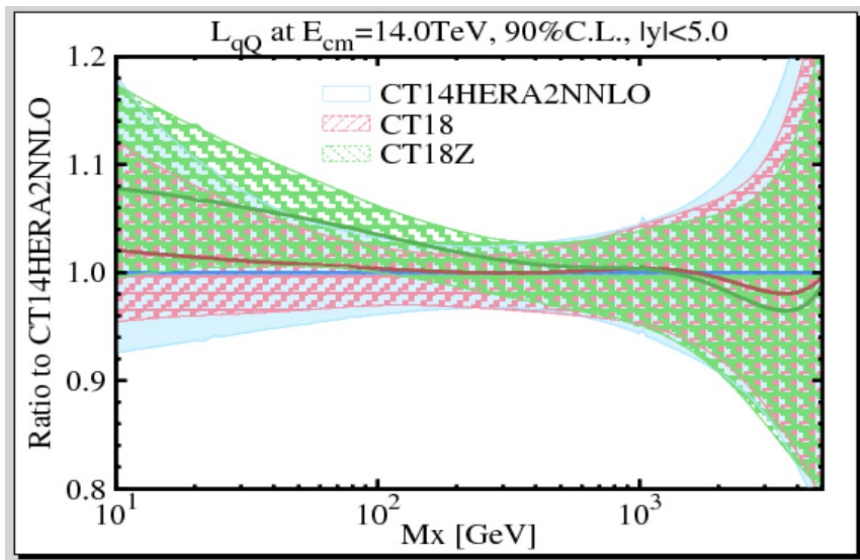
The CT18 uncertainties are **moderately conservative** and largely cover the spread of central predictions obtained with different assumptions and selections of experiments



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

← More on it later.

CT18/CT18Z parton luminosities

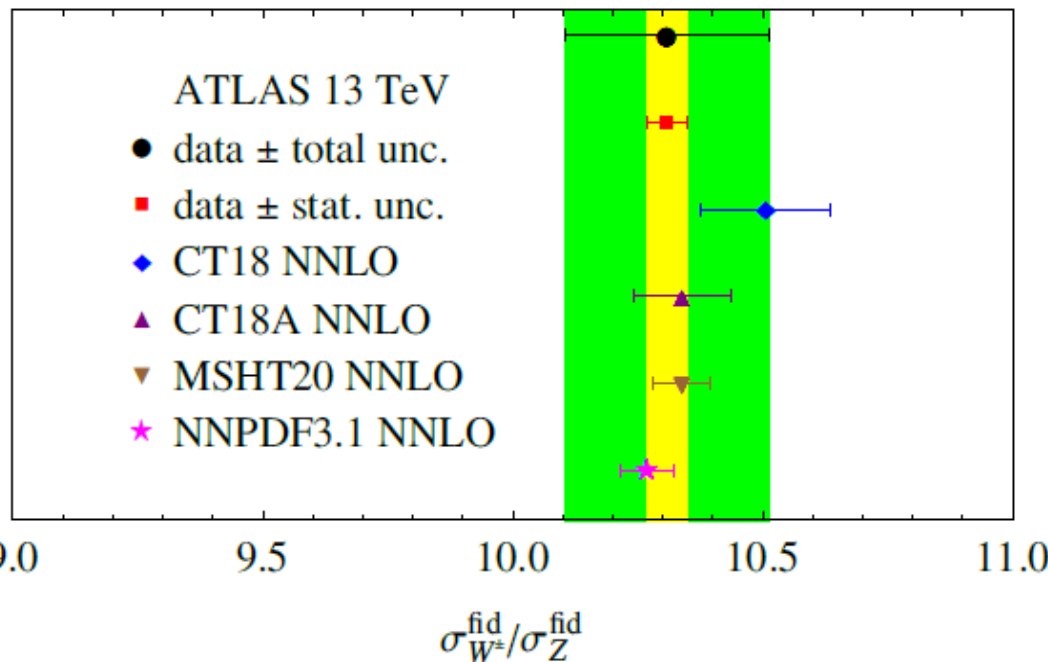
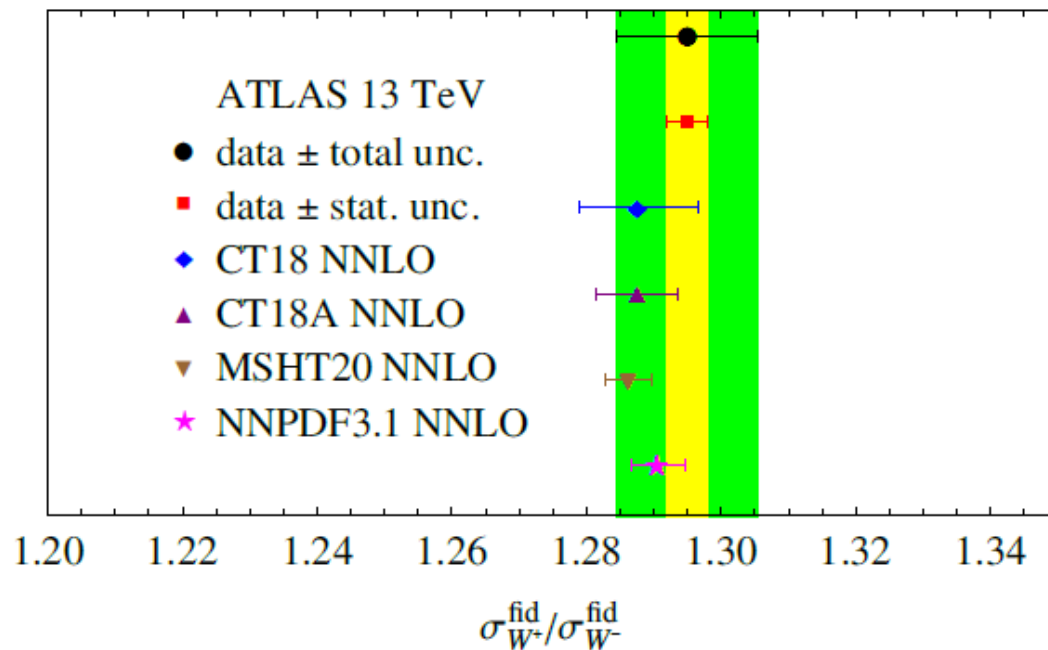


CT18 consistent with CT14

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

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

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

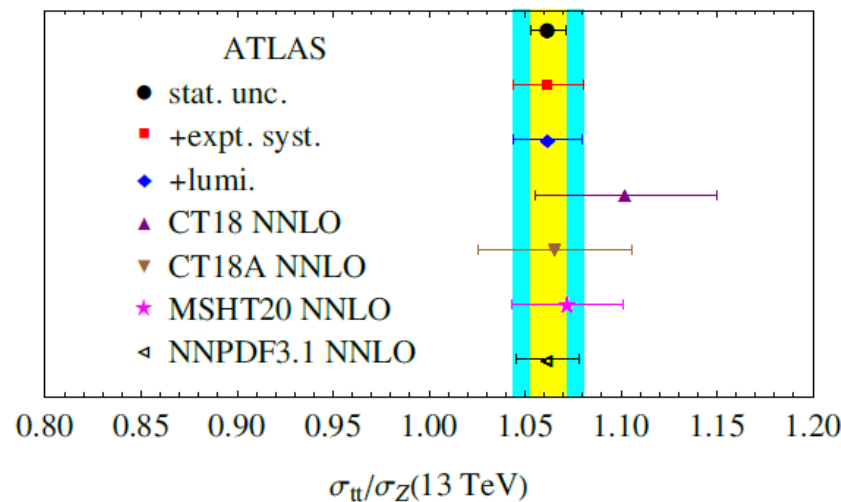
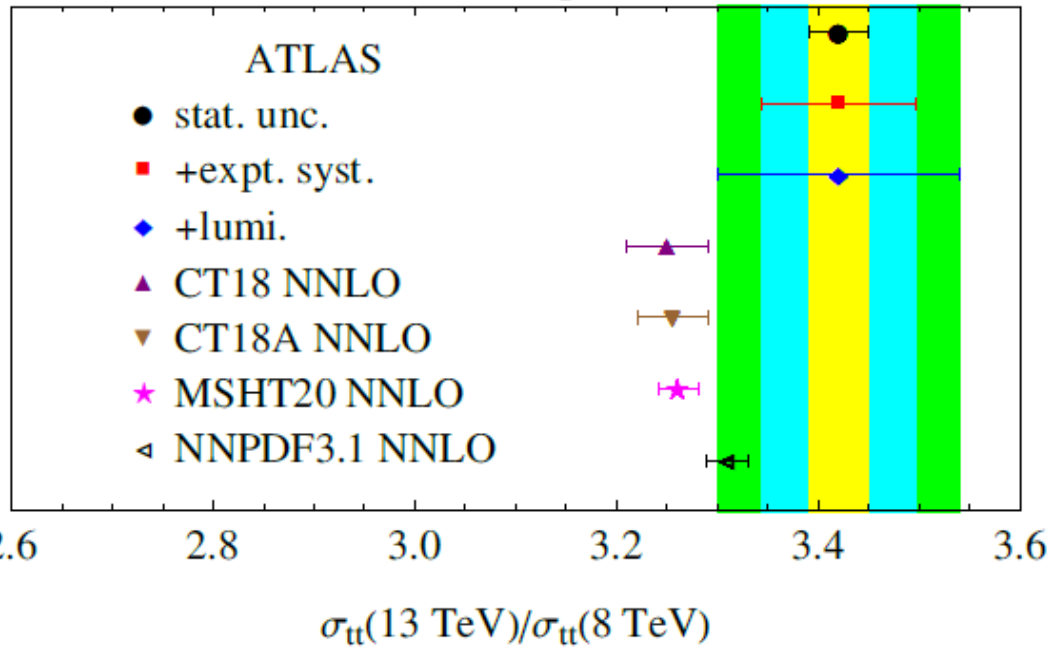
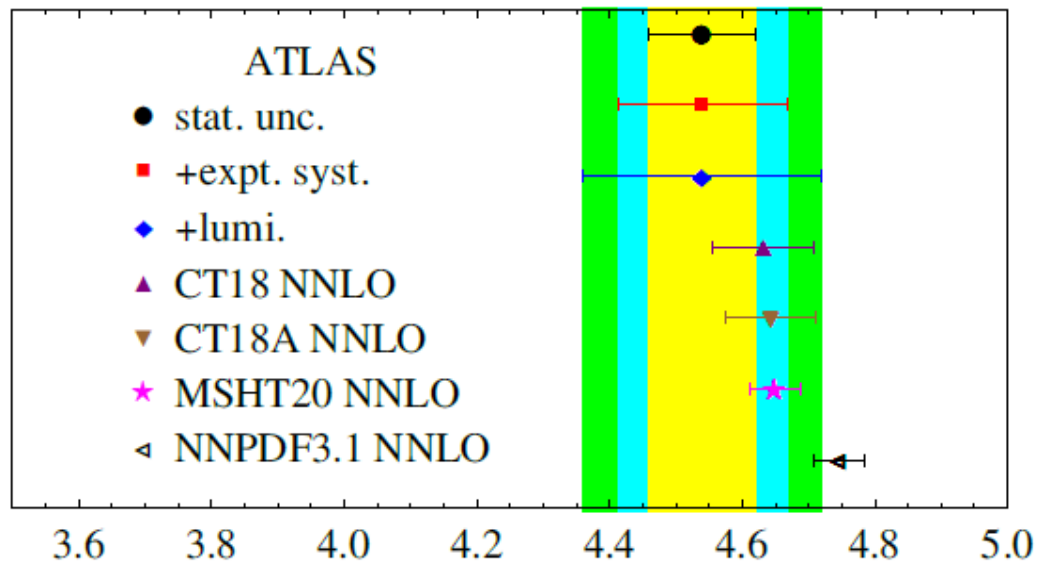


Slightly smaller uncertainties in CT18A than in CT18

More on it later.

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

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



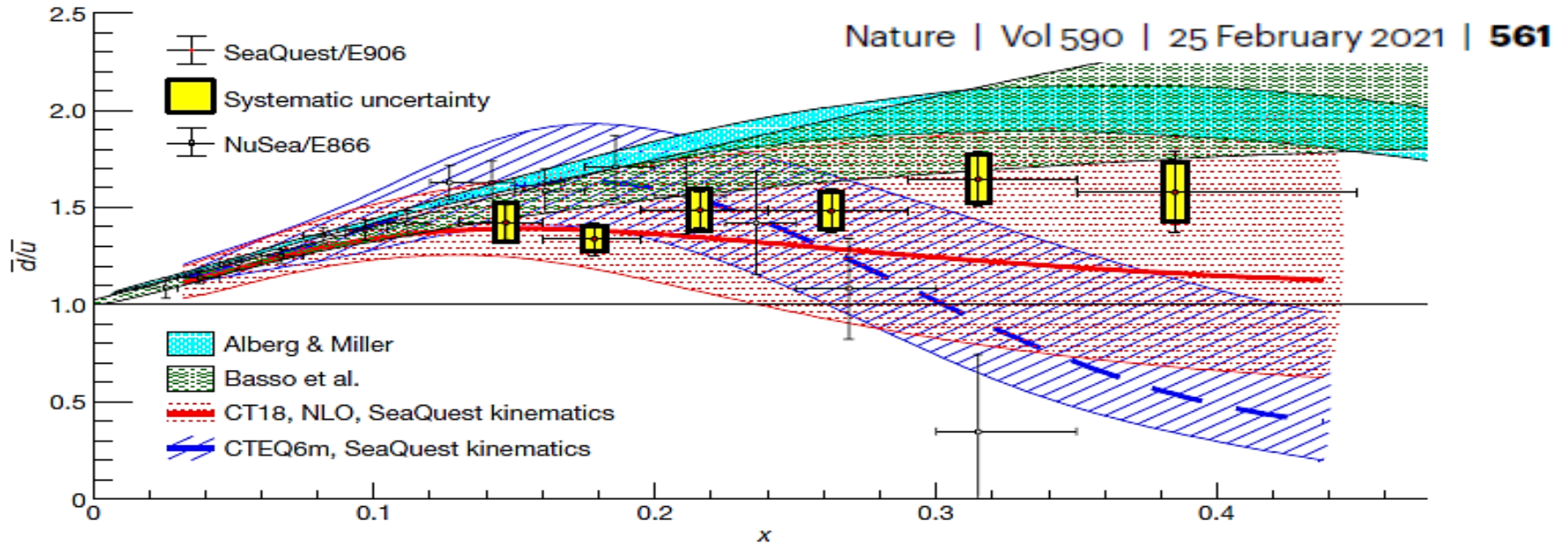
Some disagreement with $\sigma_{t\bar{t}}(8 \text{ TeV})$?

Figures: K. Xie

The E906 SeaQuest experiment

CTEQ webinar, Paul Reimer (E906): March 24, 8:30AM CDT/9:30AM EDT/14h30 CERN
<https://youtu.be/GAdQDhvyl8w>

Impact on CT PDFs: T. Hobbs tomorrow



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.

Combined charm and bottom HERA SIDIS data (H1 and ZEUS Coll. 1804.01019) in the CT18 analysis

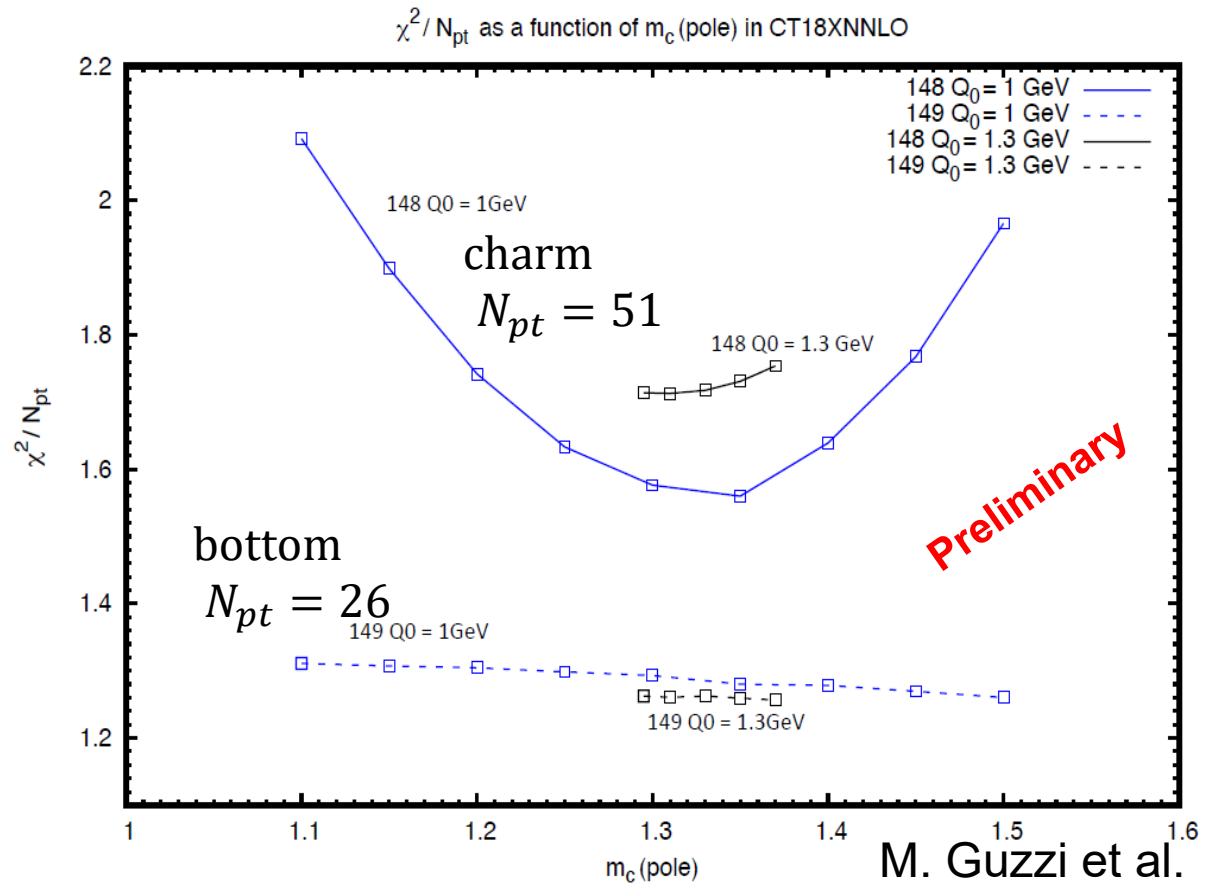


We fit these data using the SACOT- χ heavy-quark scheme at NNLO.

In all tried scenarios, we get χ^2/N_{pt} no less than 1.5, reached when the combined HERA HQ SIDIS data is included with a large statistical weight (100).

These data prefer a harder gluon at intermediate and small x .

Our χ^2 values are similar to those found by MSHT20 and to predictions from other groups reported in Table 4 of the HERA publication.



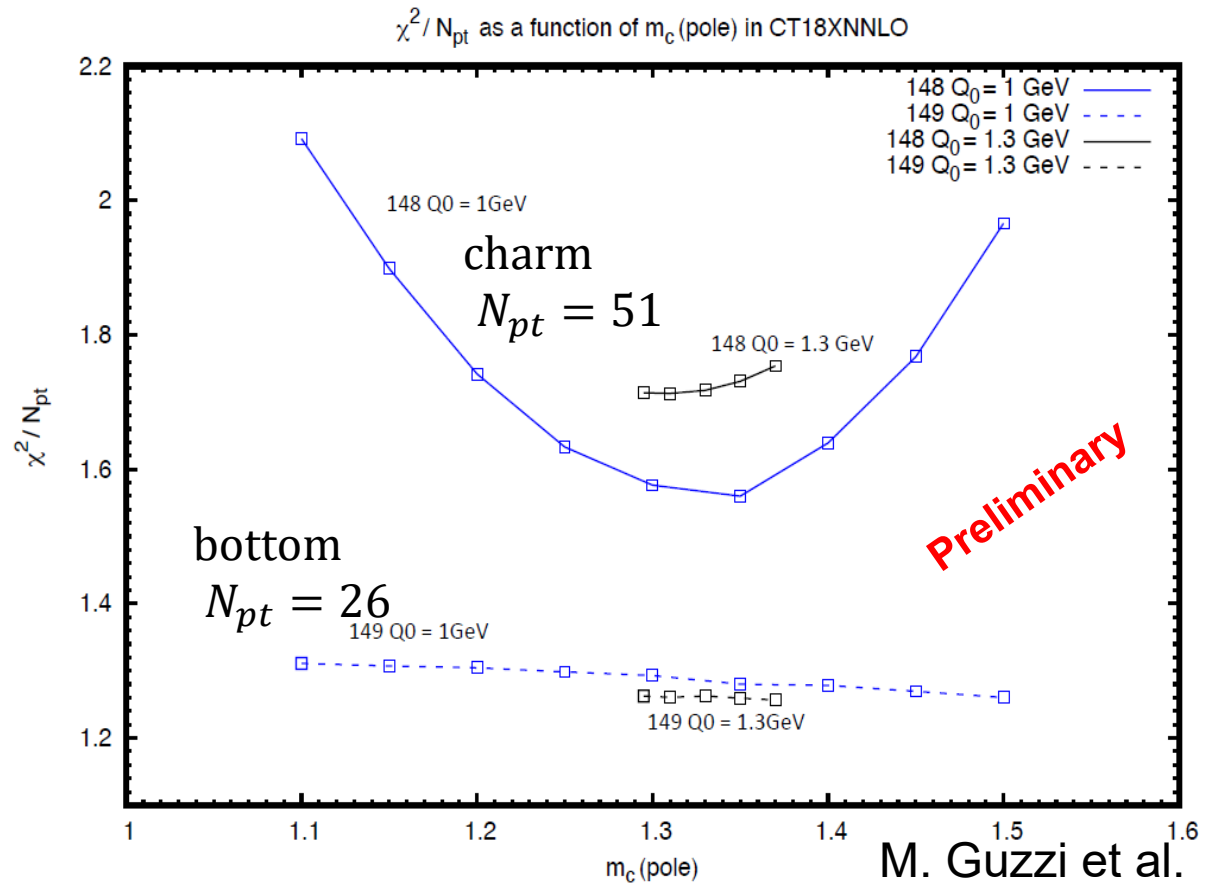
Combined charm and bottom HERA SIDIS data (H1 and ZEUS Coll. 1804.01019) in the CT18 analysis



We explored the following alternative settings in various combinations:

- Fits with increased weights of HERA HQ SIDIS data
- alternative parametrizations of the gluon
- varied $\overline{\text{MS}}$ and pole m_c
- varied initial scale Q_0
- varied parameters of the x -dependent DIS factorization scale
- varied S-ACOT- χ rescaling parameter

For large weights of the HERA c/b data, the opposing χ^2 pulls arise from LHCb 7 and 8 TeV W/Z Xsec, ATLAS 7 and CDF Run-2 incl. jets, CDF Run-2 Z rapidity and D0 Run-2 ele A_{ch} data.

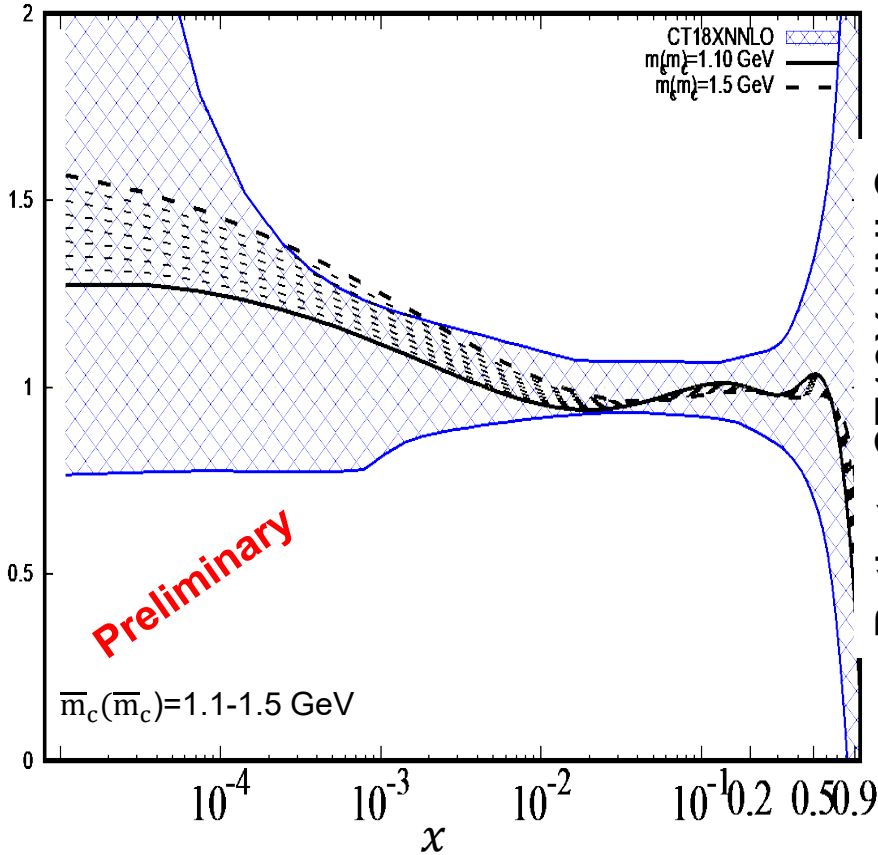


CT18XNNLO + combined HERA c/b DIS data set

Fits with varied $\bar{m}_c(\bar{m}_c)$

$Q_0 = 1 \text{ GeV}; g(x, Q = 2 \text{ GeV})$

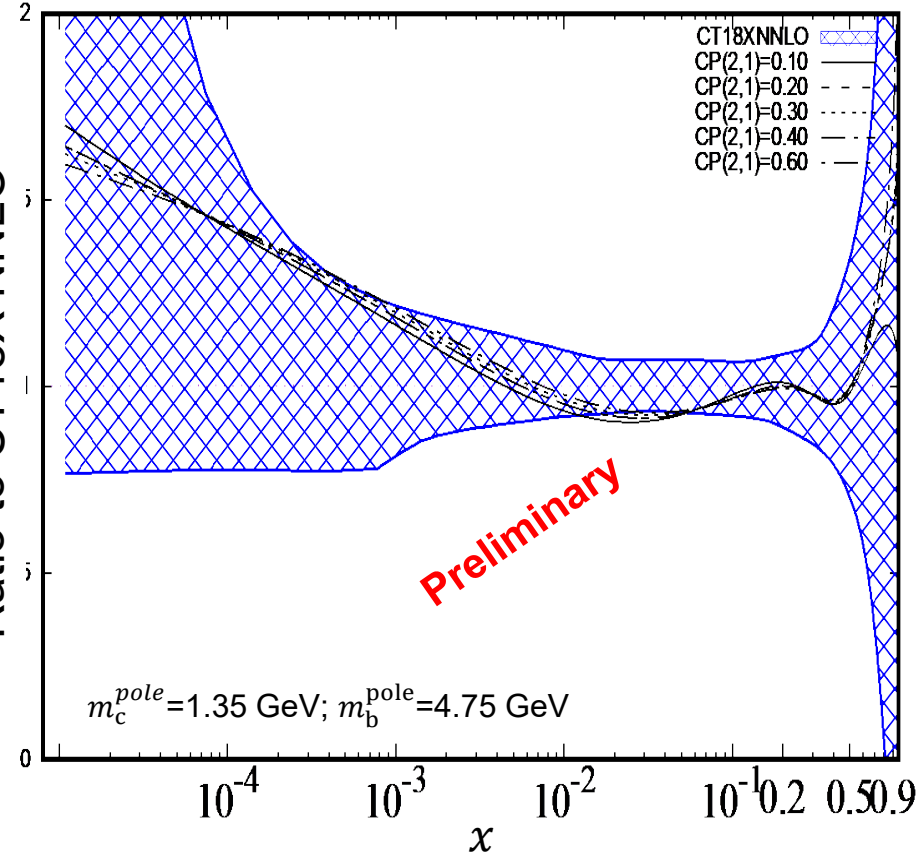
Ratio to CT18X NNLO



Fits with varied small-x scale

$Q_0 = 1 \text{ GeV}; g(x, Q = 2 \text{ GeV})$

Ratio to CT18X NNLO



This data set mildly prefers CT18XNNLO to CT18NNLO.

But χ^2/N_{pt} is never lower than 1.5 for all explored combinations

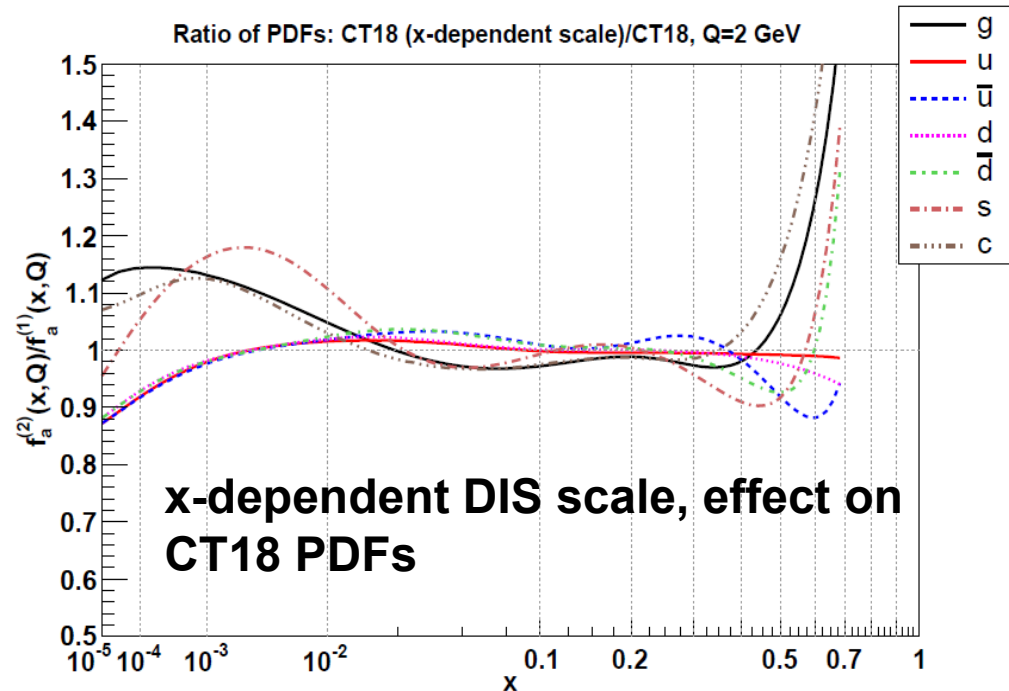
$$\mu_{DIS}(x) = A \sqrt{m_Q^2 + B^2/x^C}$$

Vary $B=CP(2,1)$, while keeping $A=0.5$ and $C=0.33$ fixed

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.

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



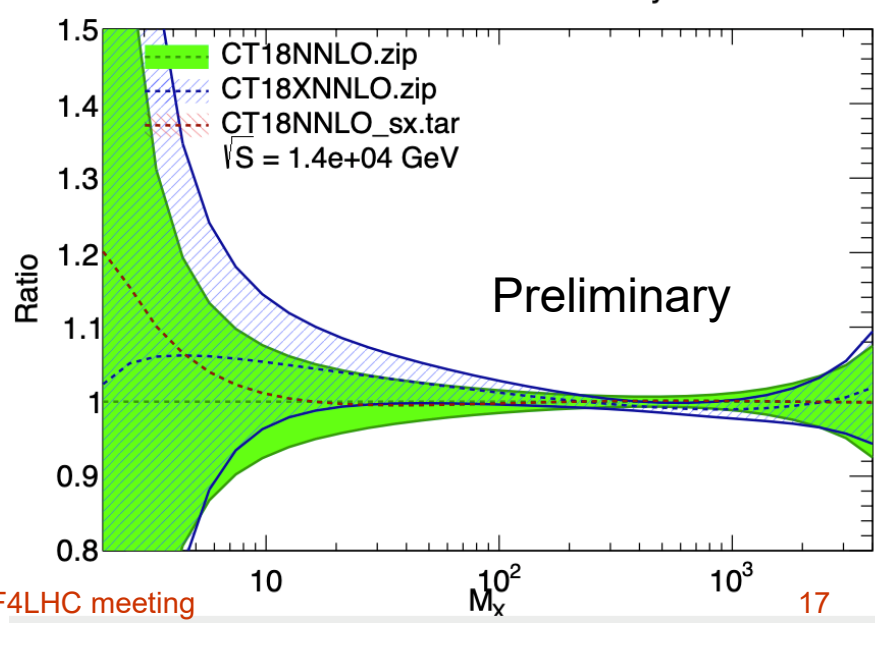
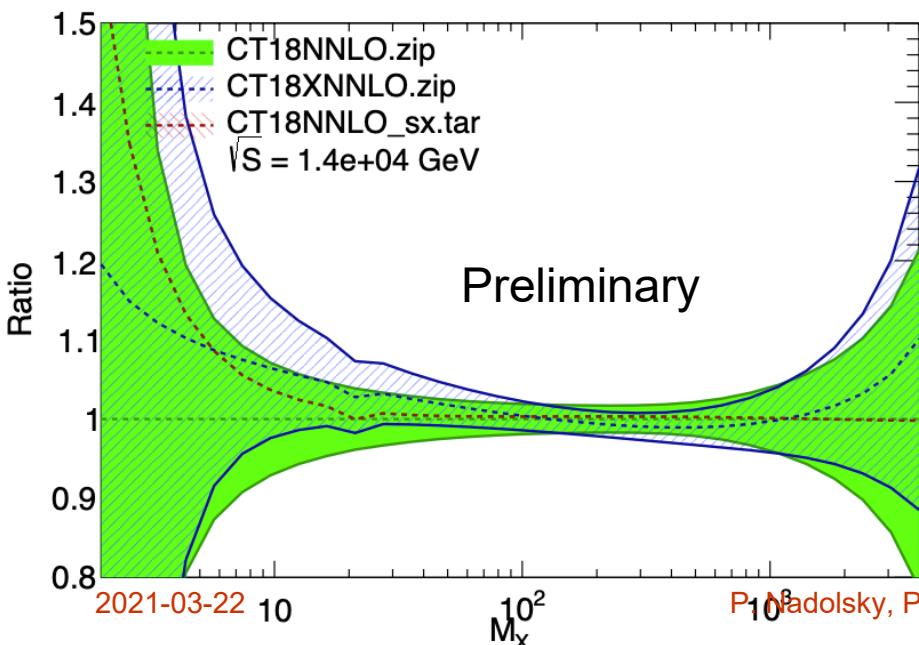
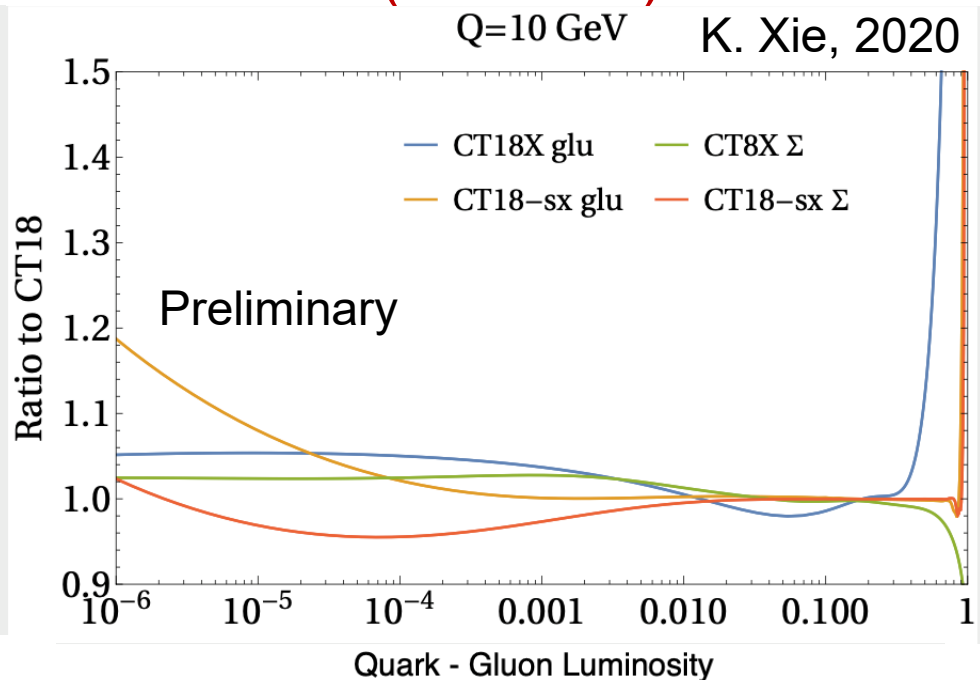
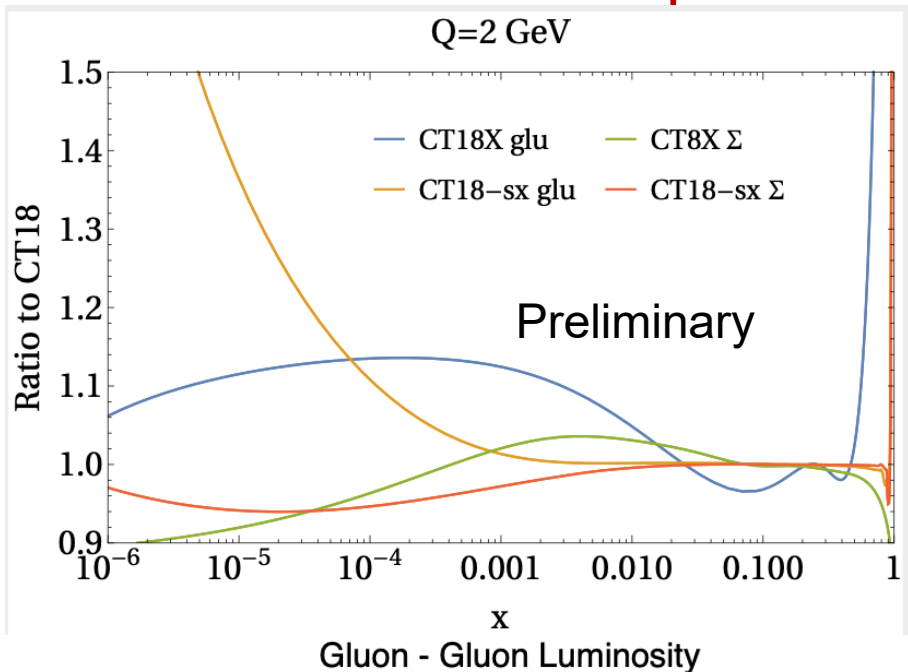
In the fitted region, the NNLO-NLLx fits and small- x scale fits are statistically indistinguishable.

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.

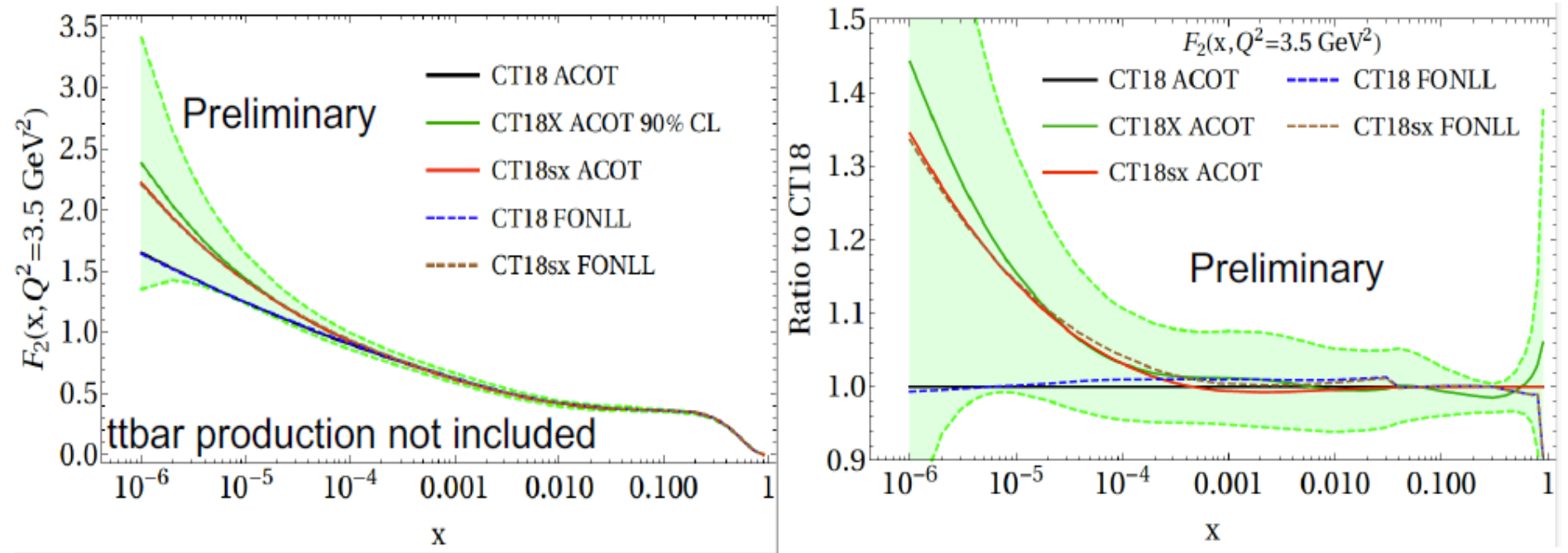
CT18X NNLO compared to NLLx-NNLO (CT18-sx) PDFs

K. Xie, 2020



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

K. Xie, 2020



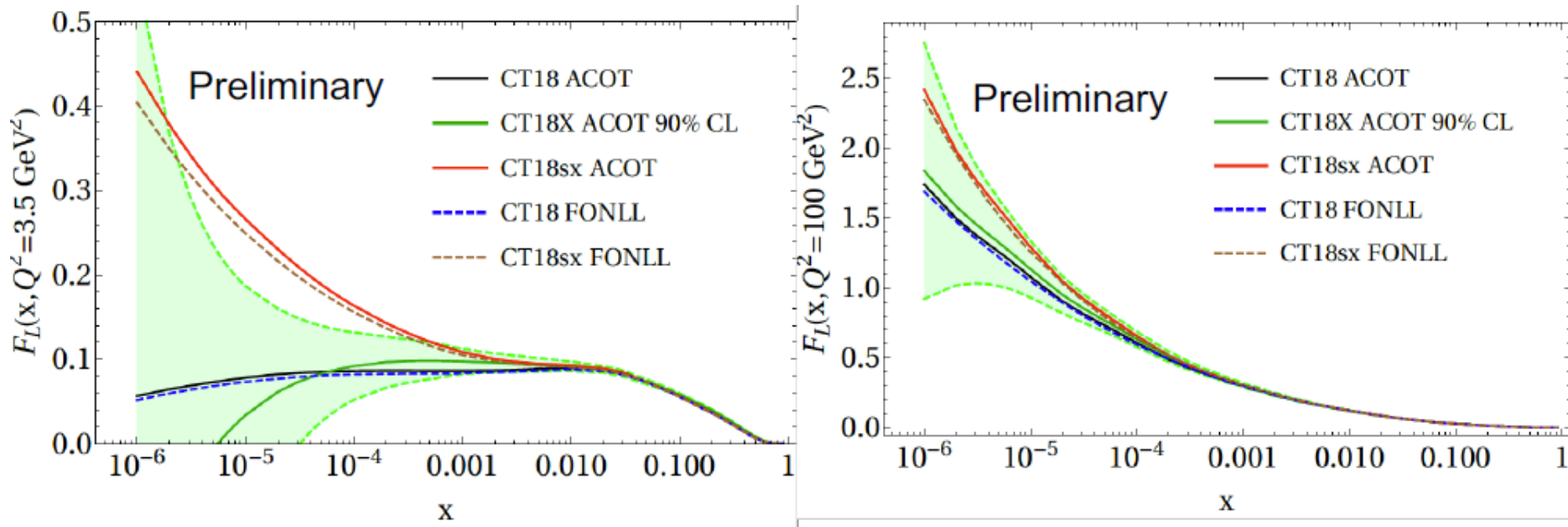
- CT utilizes the SACOT- χ scheme, which is close to the NNPDF's FONLL scheme.
- The CT18 SACOT small x (sx) resummed F_2 is obtained with the K-factor approach

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

- 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.

Two PDF sets: CT18lux vs CT18qed

K. Xie, T. Hobbs, T. J. Hou, C. Schmidt, M. Yan, C.-P. Yuan, in progress

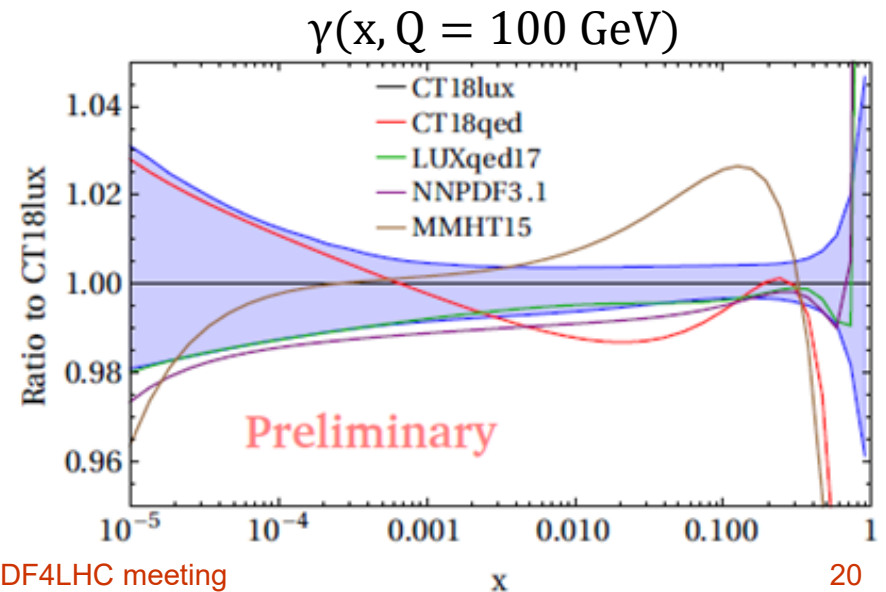
- CT18lux: directly calculate the photon PDF with the LUX formalism

[1607.04266,1708.01256]

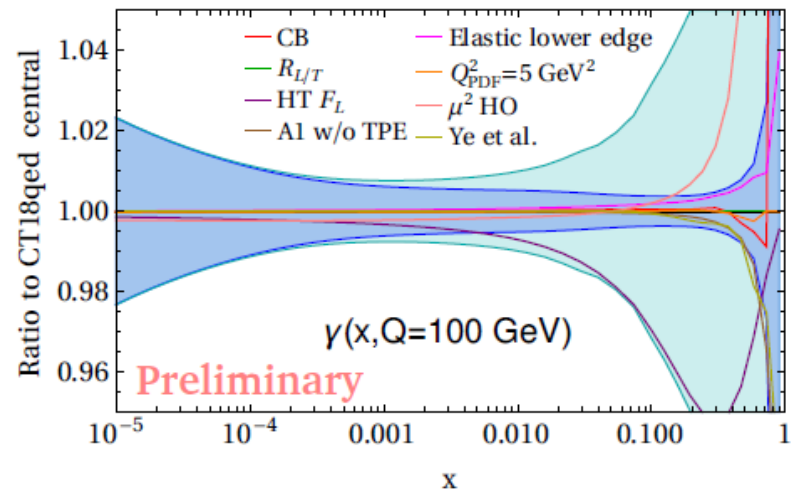
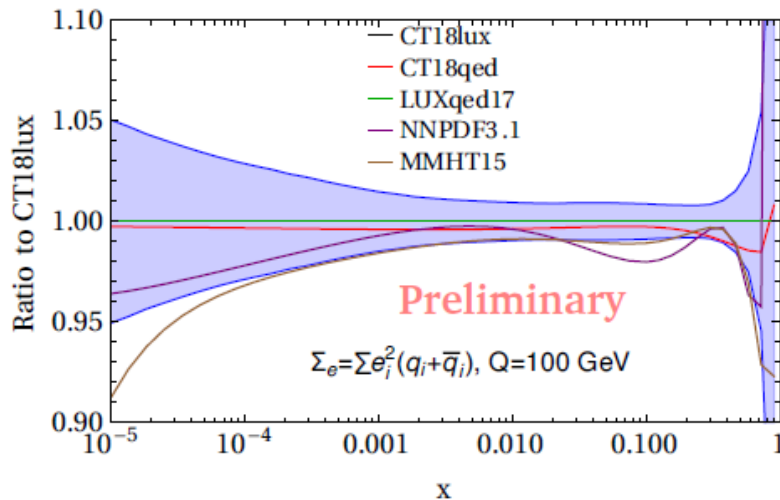
$$x\gamma(x, \mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(zp_{\gamma q}(z) + \frac{2x^2 m_q^2}{Q^2} \right) \times \right. \right. \\ \left. \left. F_2(x/z, Q^2) - z^2 F_L(x/z, Q^2) \right] - \alpha^2(\mu^2) z^2 F_2(x/z, \mu^2) \right\}.$$

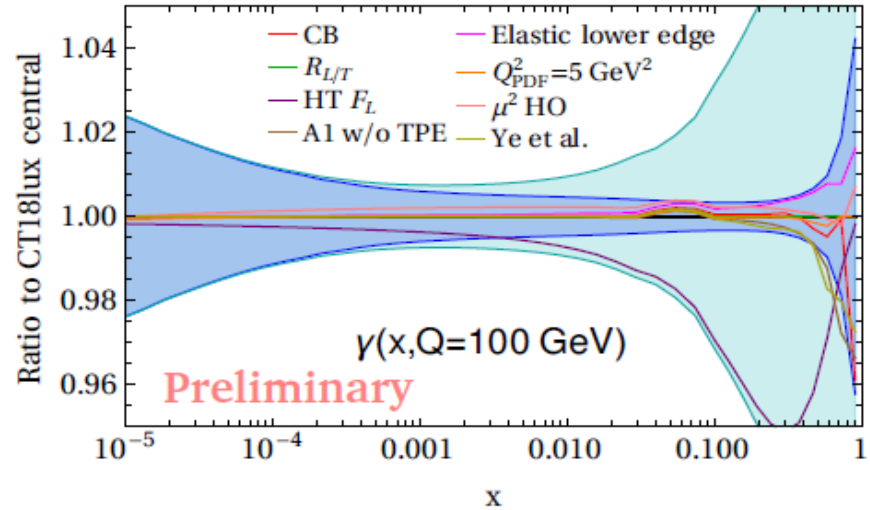
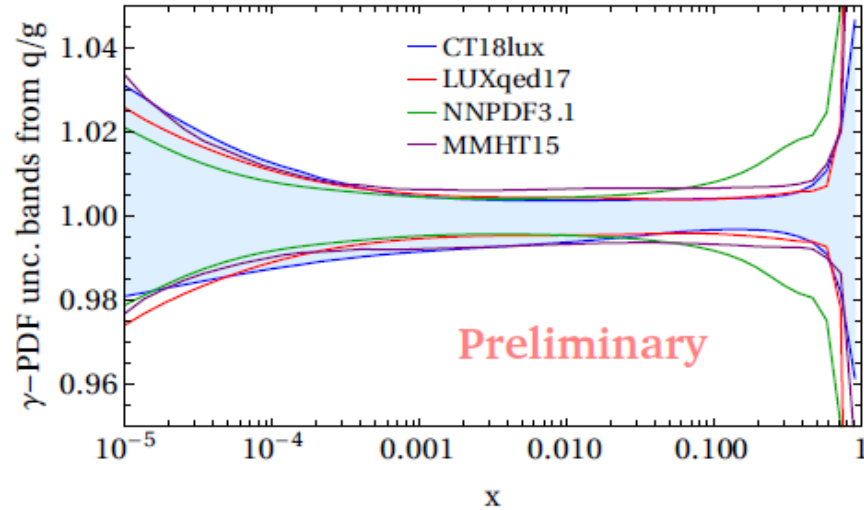
- CT18qed: initialize the photon PDF with the LUX formalism at $Q_0 = 2$ GeV, and evolve the $\text{QED}_{\text{NLO}} \otimes \text{QCD}_{\text{NNLO}}$ DGLAP equations up to high scales.

- CT18lux photon PDF is in between the LUXqed (similar to NNPDF3.1luxQED [1712.07053]) and MMHT2015qed [1907.02750]



- At low x , CT18lux photon is smaller than the CT18qed one, because of the higher orders included in the structure functions
- At large x , the LUX approach gives significantly larger PDF than the DGLAP one, because of the upper integration limit $\frac{\mu^2}{1-x}$, which is quantified as higher order (HO) uncertainty (pink line)
- The difference between CT18qed and MMHT2015qed is due to the charge-weighted singlet PDF
- The smaller CT18qed weighted singlet is due to the radiation $q \rightarrow q\gamma$

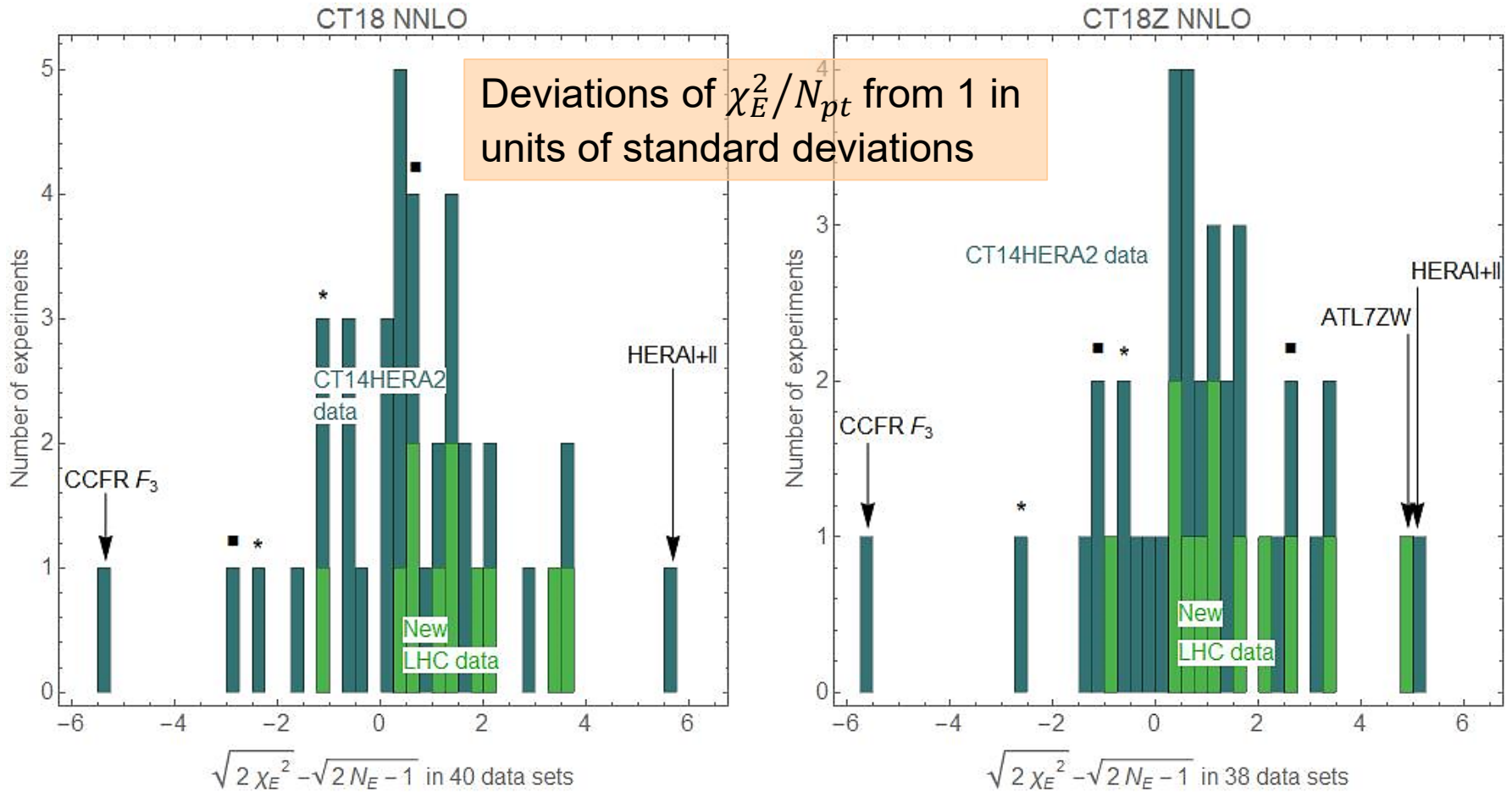




- The q/g uncertainty contributing to the structure functions in high Q^2 region
- CB: Changing the SF in the resonance region from CLAS to Christy-Bosted fit
[0712.3731]
- Variations of $R_{L/T} = \sigma_L/\sigma_T$
- HT F_L : Adding higher-twist contribution to F_L
- A1 w/o TPE: The A1 fit of elastic form factor without two photon exchange
- Elastic lower edge: statistic and systematic uncertainty in the A1 w/ TPE fit
- $Q_{\text{PDF}}^2 = 9 \rightarrow 5 \text{ GeV}^2$: matching scale
- μ^2 HO: changing the upper integration limit of Q^2 as $\frac{\mu^2}{1-z} \rightarrow \mu^2$
- Ye et al.: Changing the elastic form factor to Ye et al.

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?



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. ...

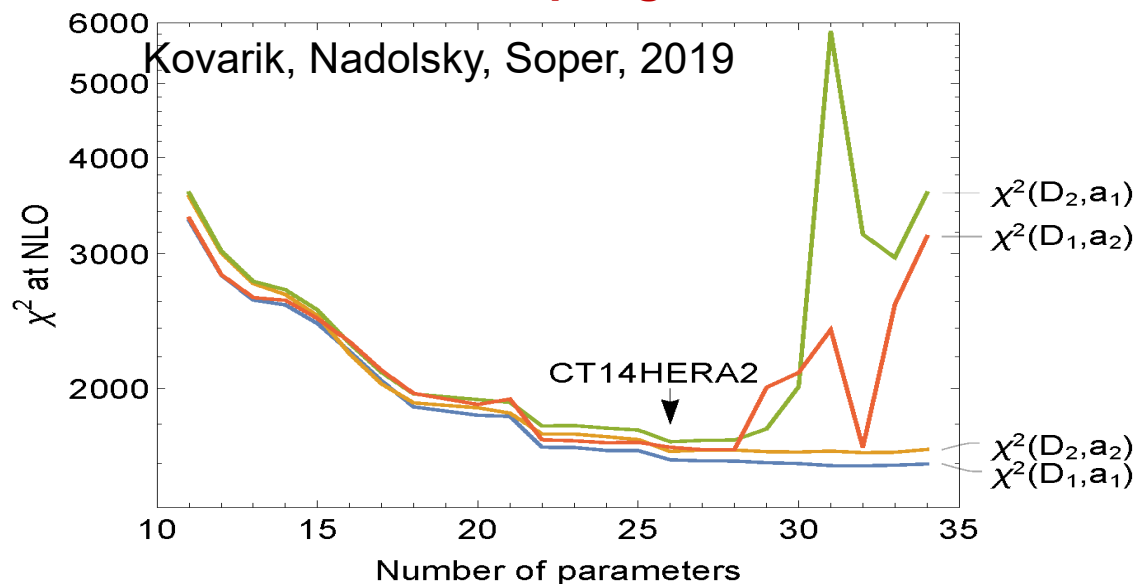
The resampling test of CT PDFs indicates that 25-30 parameters (26 in CT14HERA2) is optimal for neither underfitting nor overfitting the CT data.

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:

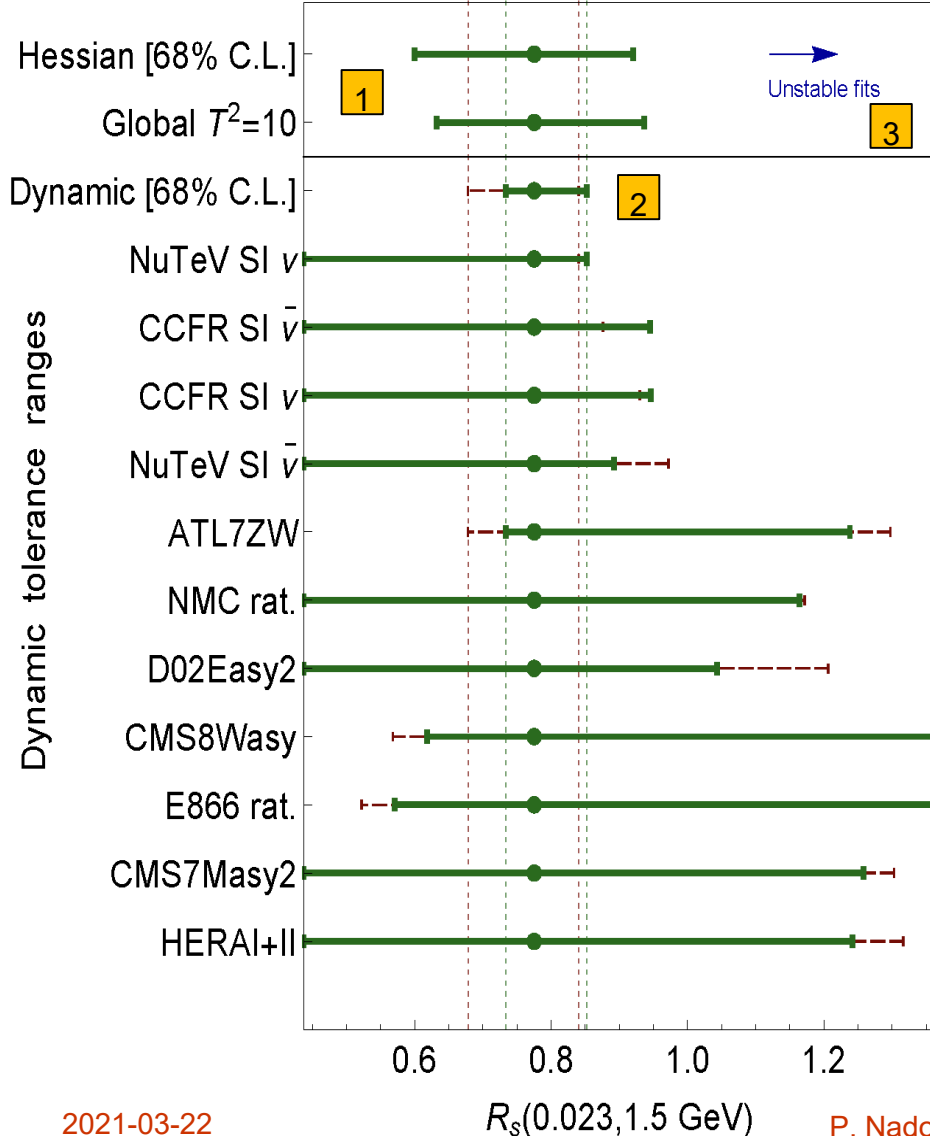
- a unique global fit may not exist, or χ^2 minimization may destabilize
- iterative diagonalization of the Hessian matrix may fail
- in underconstrained directions, the Hessian errors and in particular the dynamic tolerance with disagreeing experiments sometimes underestimate the uncertainty; this is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

CT14HERA2 resampling test



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

CT18A NNLO, LM scan uncertainties



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 after CT18 publication

- 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
- Goodness-of-fit criteria
 - To include disagreeing experiments or not?
 - What is the right tolerance?
- Deuteron DIS in CJ and CT PDFs (Tuesday)
- Impact of SeaQuest (Tuesday)
- CTEQ-TEA PDFs at large x (Tuesday)