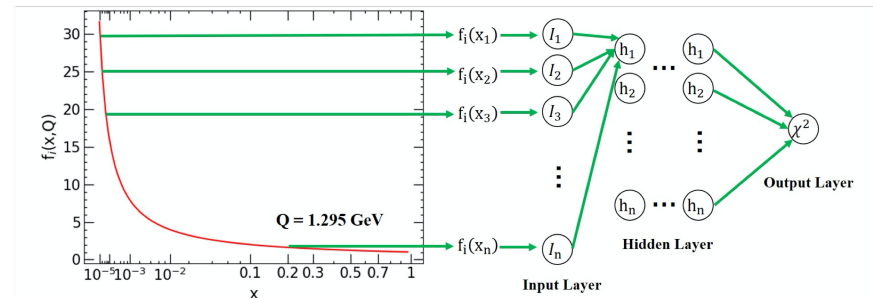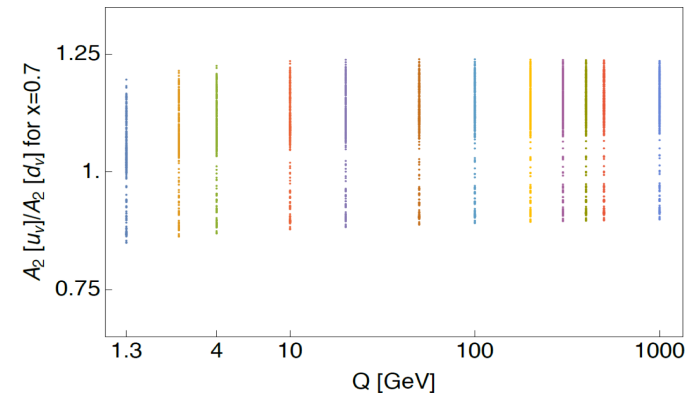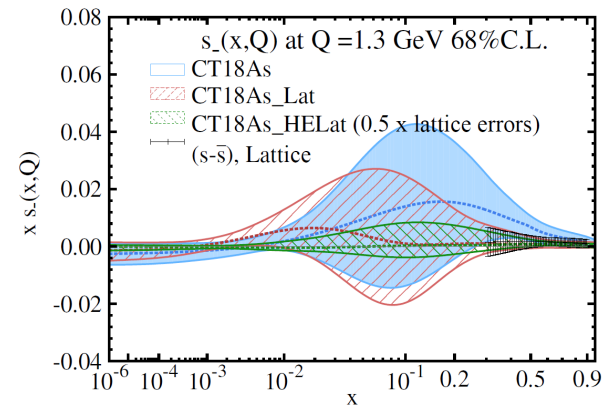# Update from CTEQ-TEA

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

CTEQ-TEA presentations at DIS'2022

1. **This talk**   **WG1**
   - Strangeness asymmetry and PDFs with lattice inputs
   - SeaQuest, Drell-Yan process
   - Large-x studies
   - Machine learning in CT18 framework

2. Toward precise and robust PDFs   **Aurore Courtoy**   **WG1**

3. PDFs at small x **Keping Xie**   **WG2**

4. CT18 photon PDF   **Keping Xie**
                                                                   WG3
5. NNLO CC DIS   **Tim Hobbs**

6. Forward charm production   **Marco Guzzi, K. Xie**
                                                                   WG4
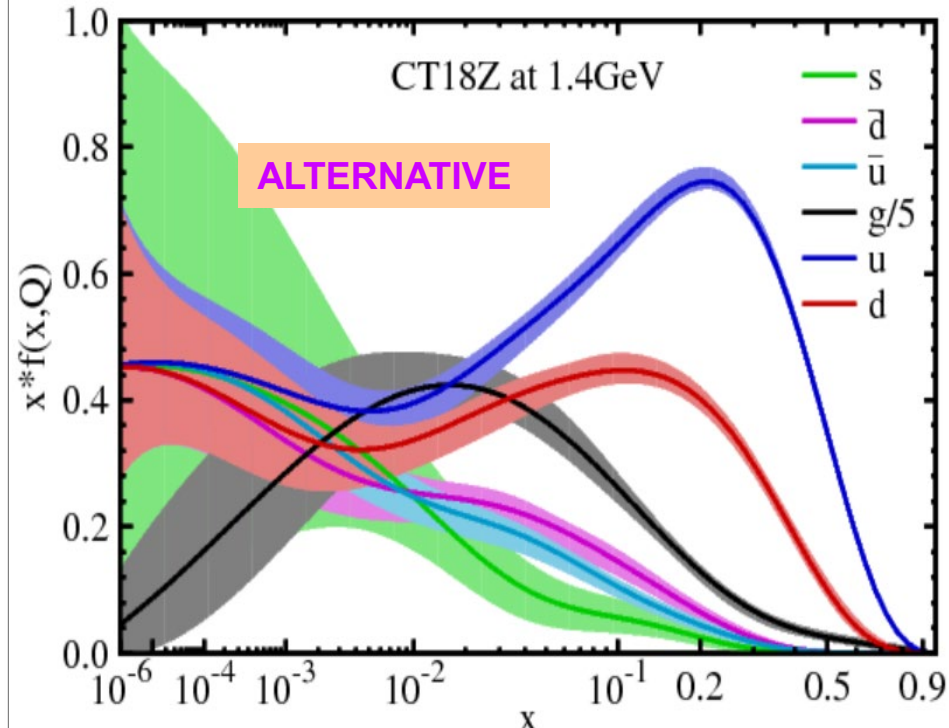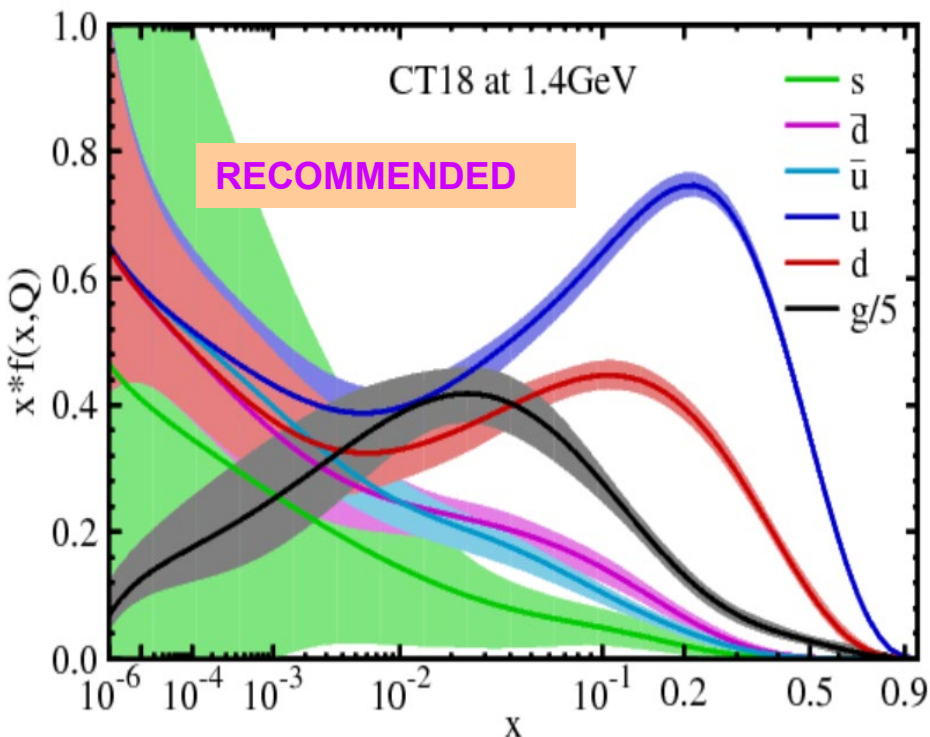7. Top-quark production and CT PDFs   **Marco Guzzi**

8. CT18 LO PDFs   **Mengshi Yan**   **Poster**

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.

3

CT18+CT18Z: robust PDF 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

- **CT18A:** include ATLAS 7 TeV W/Z data, enhanced s quark PDF
- **CT18X:** mimic small-x resummation, different g PDF
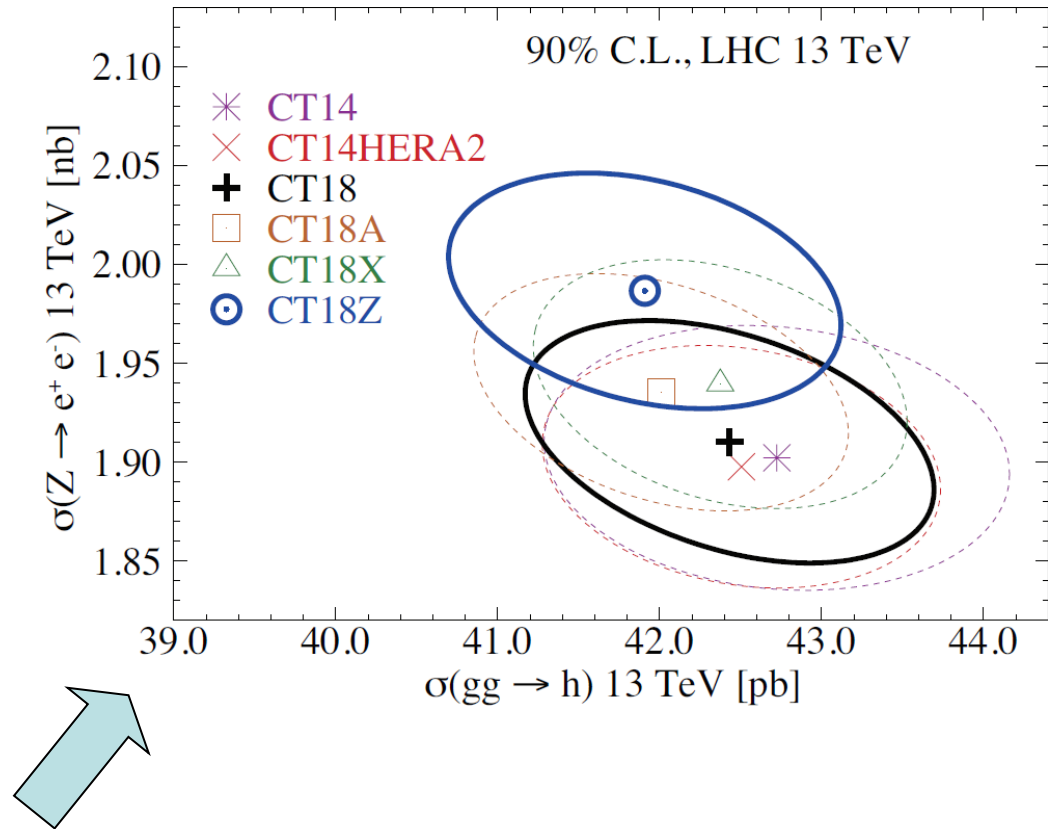
Taken together, CT18 and CT18Z render **robust PDF uncertainties**: they largely cover the spread of central predictions obtained with different assumptions and selections of experiments

New studies

- sea quarks
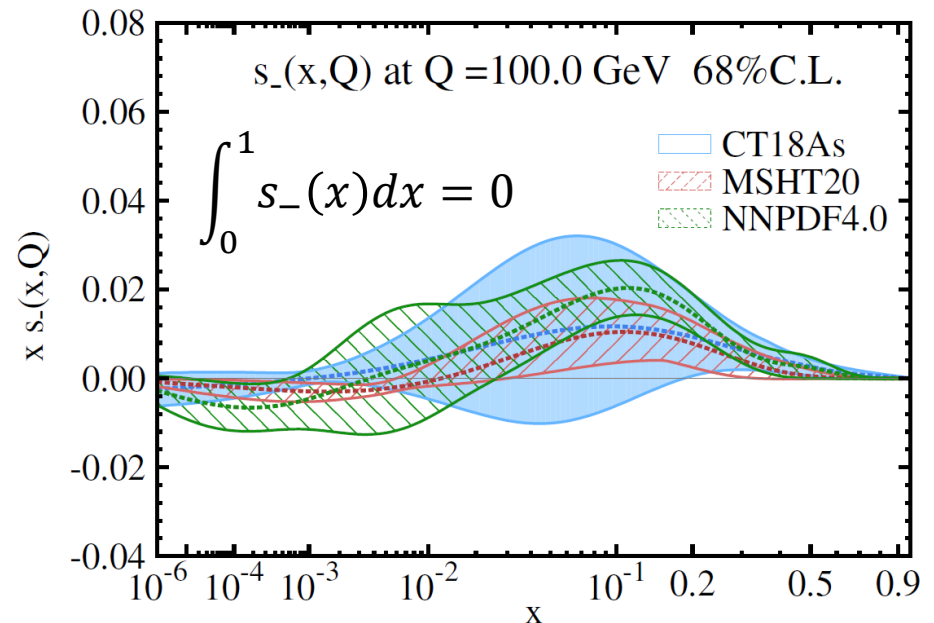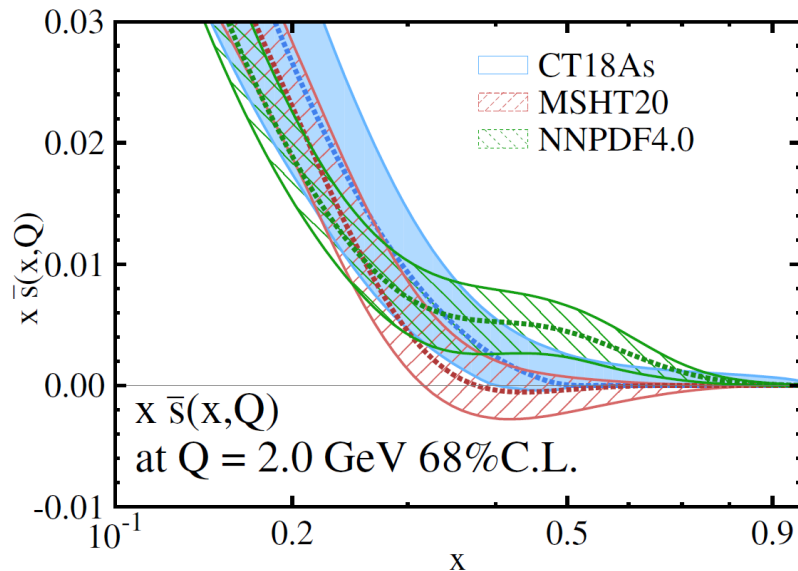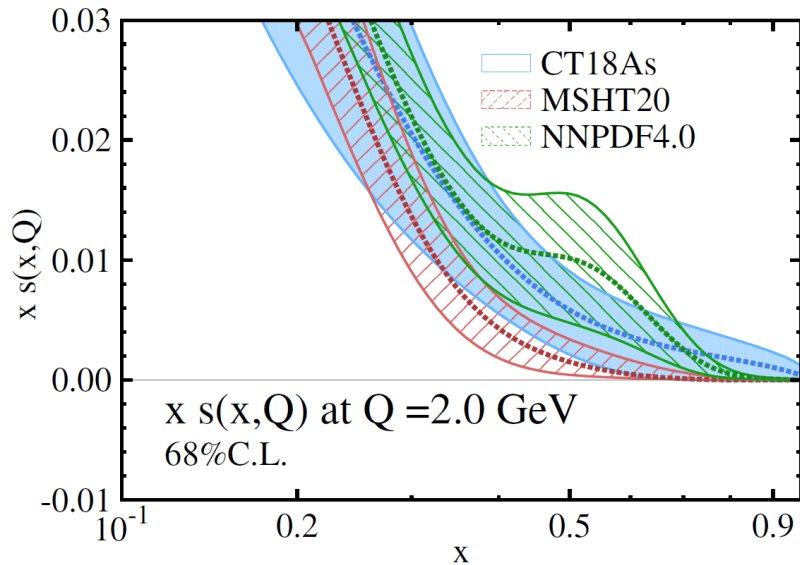- large-x PDFs
- deuteron and nuclear corrections
- …

CT18As NNLO: Strangeness asymmetry with a lattice QCD constraint

New NNLO fits:

CT18As: CT18A with $s_- \equiv s - \bar{s} \neq 0$

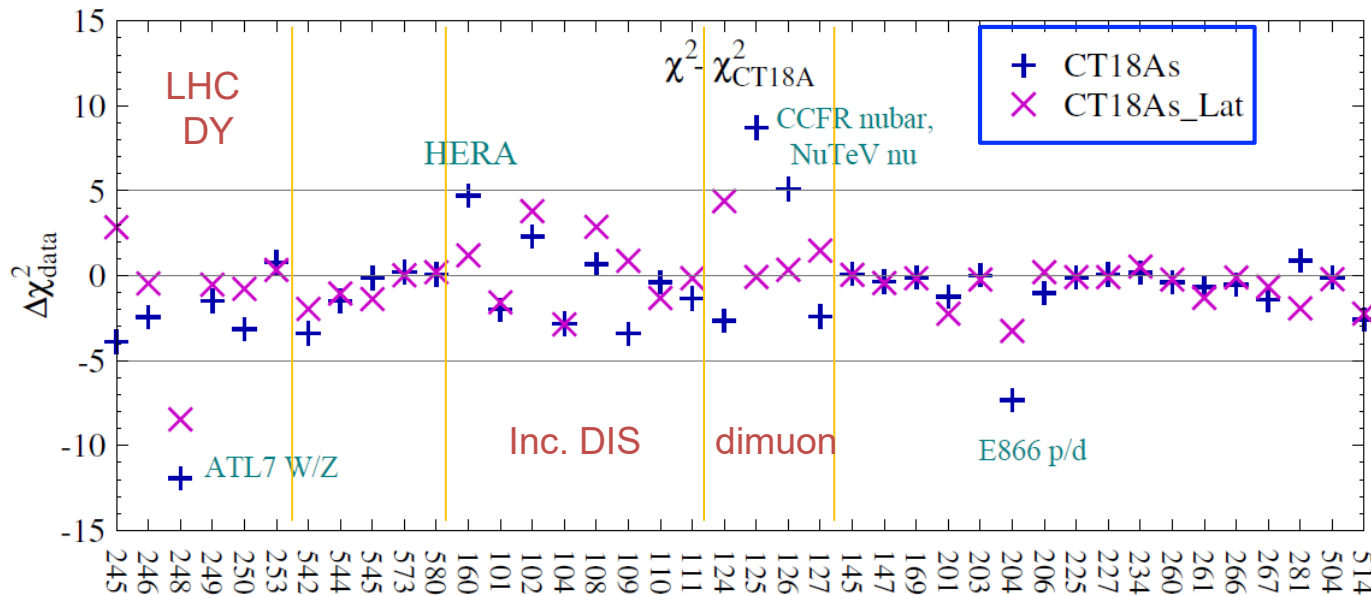**CT18AsLat:** CT18As with a lattice constraint on $s_-(x)$ at $0.3 \leq x \leq 0.8$
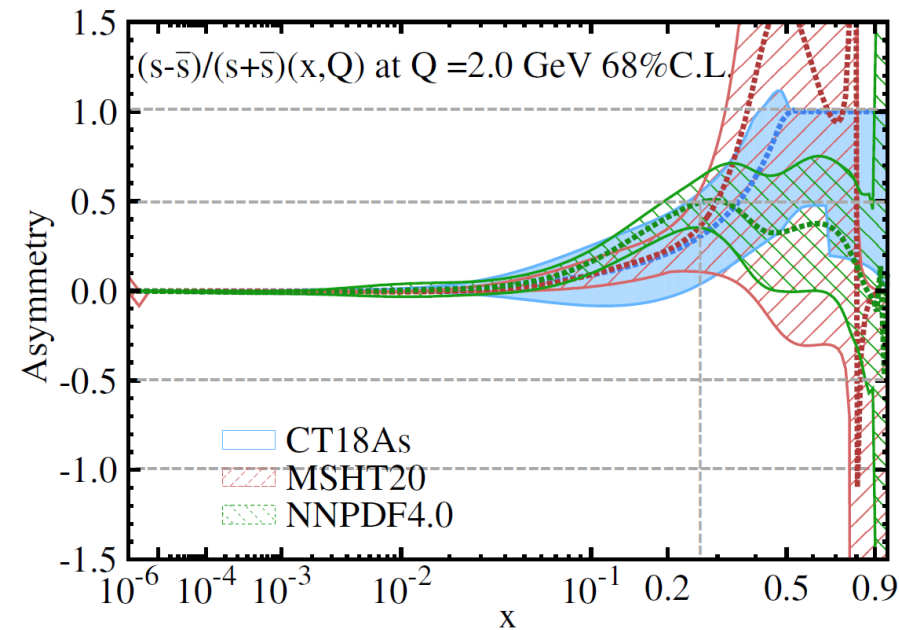
CT18As NNLO: Strangeness asymmetry with a lattice QCD constraint

$(s-\bar{s})/(s+\bar{s})(x,Q)$ at $Q = 2.0$ GeV 68%C.L.

Asymmetry (y-axis), x (x-axis)

Legend:
- CT18As
- MSHT20
- NNPDF4.0

T.-J. Hou et al., arXiv: 2204.07944

Asymmetry nominally reaches $\approx 50\%$ at $x \approx 0.25$ in three global fits. **Is there a dynamical mechanism to produce it at such x?**
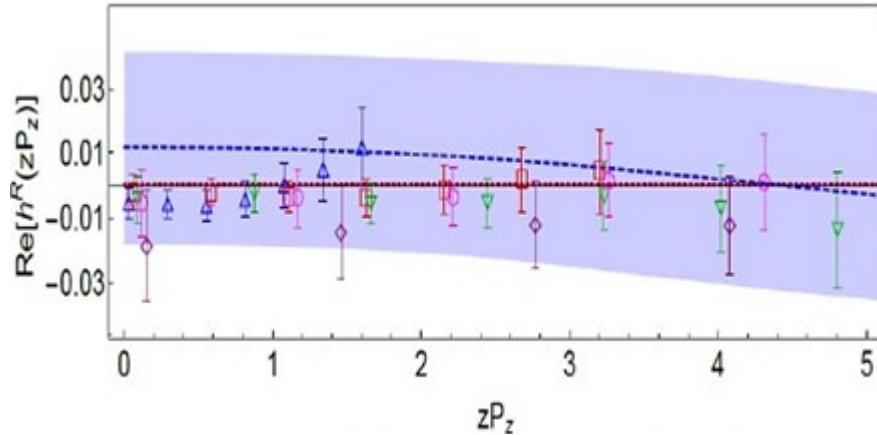
$$\chi^2(\text{CT18As}) - \chi^2(\text{CT18}) \approx -30$$

$\chi^2 - \chi^2_{CT18A}$

Legend:
- + CT18As
- × CT18As_Lat

Labels: LHC DY, HERA, CCFR nubar NuTeV nu, Inc. DIS, dimuon, E866 p/d, ATL7 W/Z

$s_- \neq 0$ is preferred by LHC Drell-Yan processes and E866 p/d ratio. DIS and dimuon SIDIS show less clear trends.

CT18AsLat NNLO

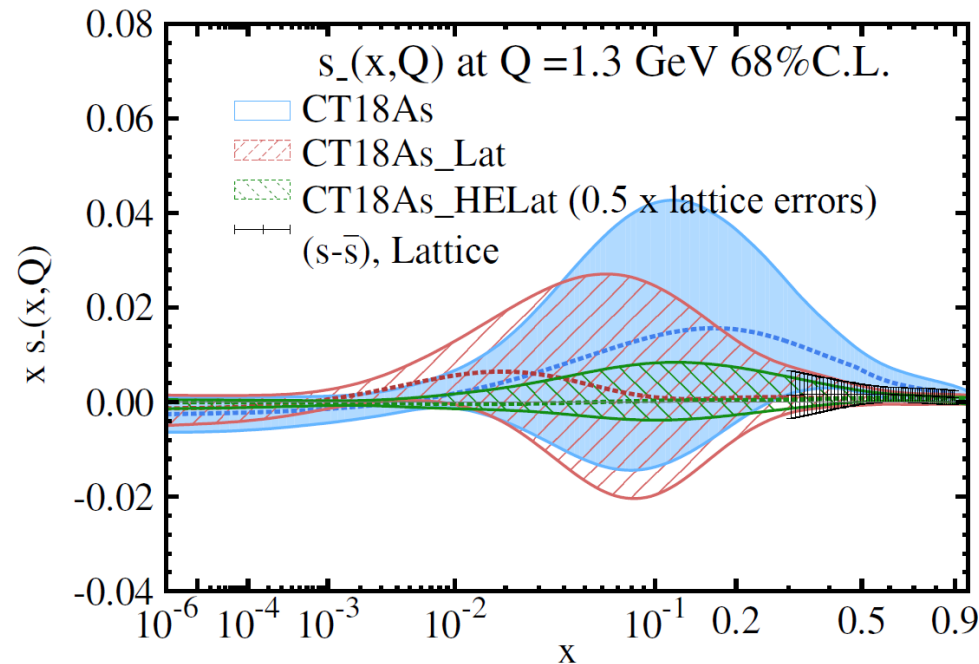$$\mathrm{Re}[h(z)] \propto \int dx (s(x) - \bar{s}(x)) \cos(xzP_z)$$

Include lattice data on s_- obtained by the MSULat/quasi-PDF method (2005.12015, Zhang, Lin, Yoon)

The lattice QCD prediction disfavors a large $s_-(x, Q)$ at $x > 0.3$

$\Rightarrow$ reduction in $s_-(x, Q)/s_+(x, Q)$ at $x < 0.3$ (depending on the parametrization form)

CT18As_HELat: PDFs if the lattice errors are reduced by 1/2

CT18CS: two-component sea (anti)quark PDFs

The Gottfried sum rule predicts

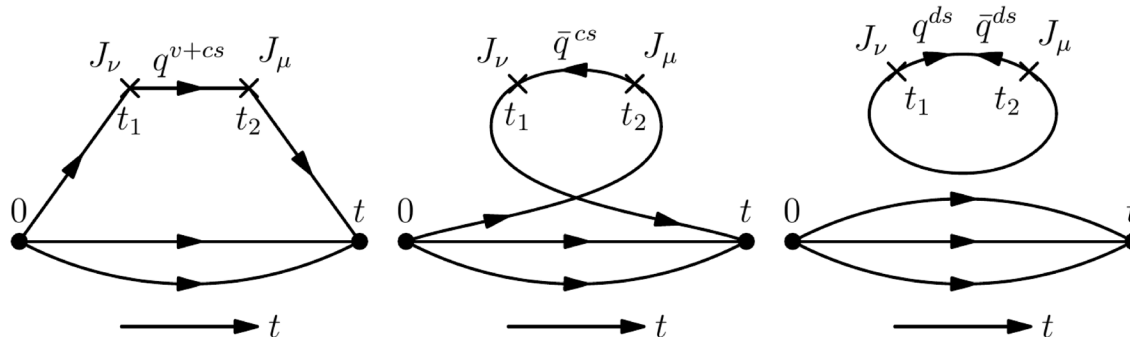$$S_G = \int_0^1 \frac{dx}{x} \left[F_2^p(x) - F_2^n(x) \right] = \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left(\bar{d}(x) - \bar{u}(x) \right) + O(\alpha_s^2)$$

$$= 0.235 \pm 0.026 \quad (Q = 2\,\text{GeV})$$

In lattice QCD:

$\bar{u}$ and $\bar{d}$ PDFs consist of connected (cs) and disconnected (ds) components.
$\int dx \left(\bar{d}(x) - \bar{u}(x) \right) \neq 0$ can be generated from connected 4-point
configurations in Euclidean path-integral formalism (K. F. Liu et al.).

CT18CS: two-component sea (anti)quark PDFs

Starting from CT18 NNLO at $Q = 1.3$ GeV…

- Include a constraint from lattice (K.F. Liu):

$$\frac{1}{R} = \frac{\langle x \rangle_{s+\bar{s}}}{\langle x \rangle_{\bar{u}+\bar{d}}(DI)} = 0.822(69)(78)$$

- Parametrize quark PDFs as
  1. $u = u_v + \bar{u}, \quad \bar{u} = u^{cs} + q^{ds}$
  2. $d = d_v + \bar{d}, \quad \bar{d} = d^{cs} + q^{ds}$
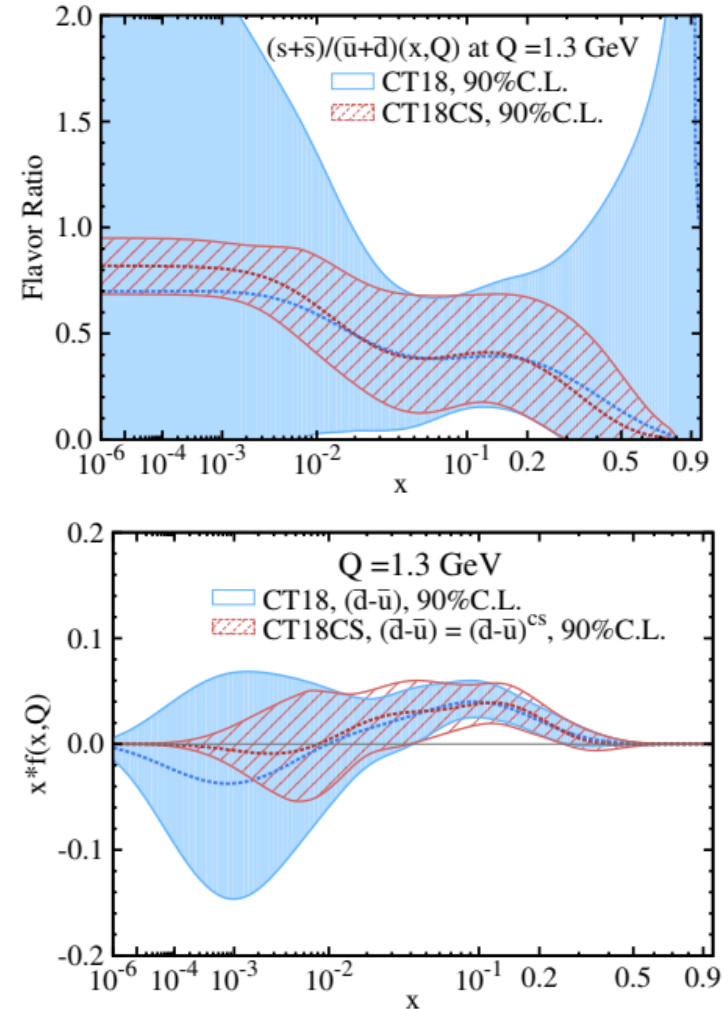 3. $s = \bar{s} = s^{ds} = q^{ds}/R$
  4. $x \to 0:$

  $\bar{d}/\bar{u} \to 1; \, q^{ds} \propto x^{-1}; \, a_1^{q^{ds}} = a_1^{q_v}$

  5. $x \to 1:$
  $d/u \to d/u$ of CT18
  $\bar{d}/\bar{u} \to \bar{d}/\bar{u}$ of CT18

CT18CS: two-component sea (anti)quark PDFs

T.-J. Hou et al., arXiv:2108.06768
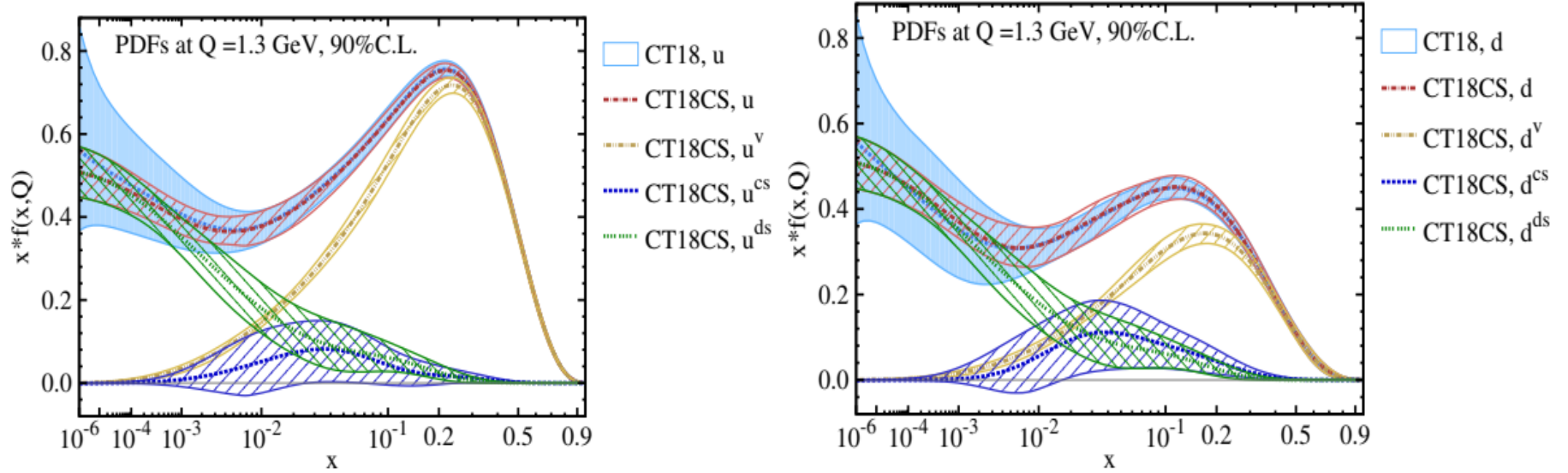

The CT18CS provide direct comparison between lattice calculations and global analysis for each parton degree of freedom.

| PDF	$<x>_{u^{v+cs}}$	$<x>_{d^{v+cs}}$	$<x>_{\bar{u}^{cs}}$	$<x>_{\bar{d}^{cs}}$	$<x>_{u^{ds}}$
CT18CS	0.335(7)	0.155(8)	0.0120(64)	0.0197(70)	0.0167(49)

Table 1: The second moment $\langle x \rangle$ of CT18CS at 1.3 GeV.

New Drell-Yan processes in the CTEQ-TEA global analysis

ID	Expt.	$N_{\rm pt}$	χ^2	$\chi^2/N_{\rm pt}$	S_E
	CT14HERA2 data				
201	E605DY	119	103.4(102.4)	0.9(0.9)	-1.0(-1.1)
203	E866 $\sigma_{pd}/(2\sigma_{pp})$	15	16.1(17.9)	1.1(1.2)	0.3(0.6)
204	E866 $Q^3{\rm d}^2\sigma_{pp}/({\rm d}Q{\rm d}x_F)$	184	244(240)	1.3(1.3)	2.9(2.7)
225	CDF1Z $A(e)$	11	9.0(9.3)	0.8(0.8)	-0.3(-0.2)
227	CDF2W $A(e)$	11	13.5(13.4)	1.2(1.2)	0.6(0.6)
234	D∅2W $A(\mu)$	9	9.1(9.0)	1.0(1.0)	0.2(0.1)
260	D∅2Z $y_{\ell\ell}$	28	16.9(18.7)	0.6(0.7)	-1.7(-1.3)
261	CDF2Z $y_{\ell\ell}$	29	48.7(61.1)	1.7(2.1)	2.2(3.3)
266	CMS7W $A(\mu)$	11	7.9(12.2)	0.7(1.1)	-0.6(0.4)
267	CSM7W $A(e)$	11	4.6(5.5)	0.4(0.5)	-1.6(-1.3)
268	ATL7WZ$_{(2012)}$	41	44.4(50.6)	1.1(1.2)	0.4(1.1)
281	D∅2W $A(e)$	13	22.8(20.5)	1.8(1.6)	1.7(1.4)
	New LHC data				
245	LHCb7WZ(μ)	33	53.8(39.9)	1.6(1.2)	2.2(0.9)
246	LHCb8Z(e)	17	17.7(18.0)	1.0(1.1)	0.2(0.3)
248	ATL7WZ$_{(2016)}$	34	287.3(88.7)	8.4(2.6)	13.7(4.8)
249	CMS8W $A(\mu)$	11	11.4(12.1)	1.0(1.1)	0.2(0.4)
250	LHCb8WZ(μ)	34	73.7(59.4)	2.1(1.7)	3.7(2.6)
253	ATL8ZpT	27	30.2(28.3)	1.1(1.0)	0.5(0.3)
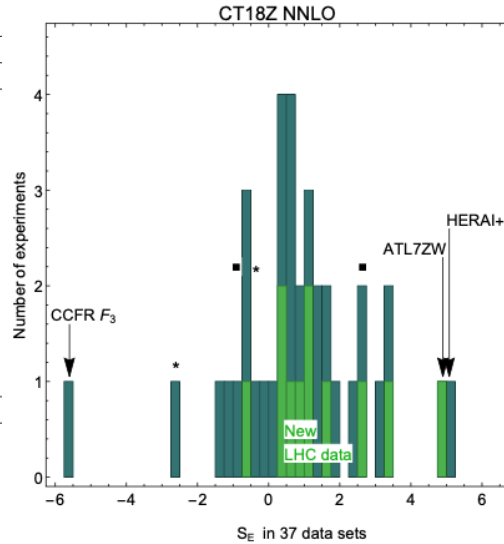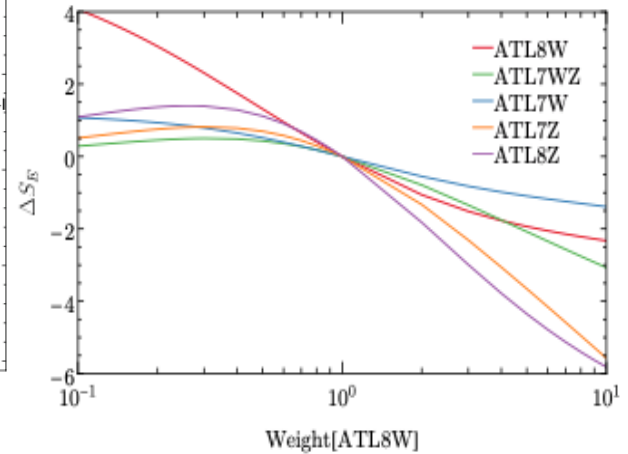
Drell-Yan data play an essential role in constraining (anti)quark sea

Most of the Drell-Yan data are fitted fairly.

ATLAS7 W/Z precision data are in tension with other data, especially HERA and NuTeV.

ATLAS 8 TeV W (Z) data are consistent with 7 TeV W (Z) data
ATLAS 7(8) TeV Z is in tension with W data.

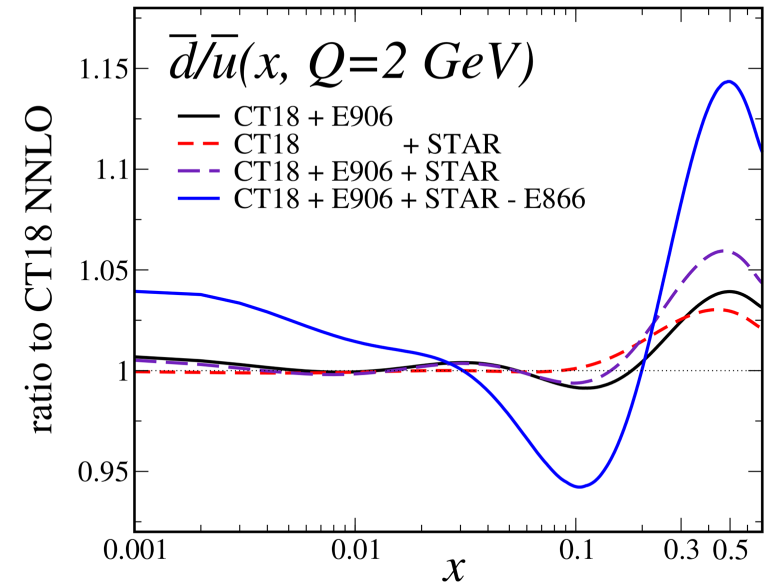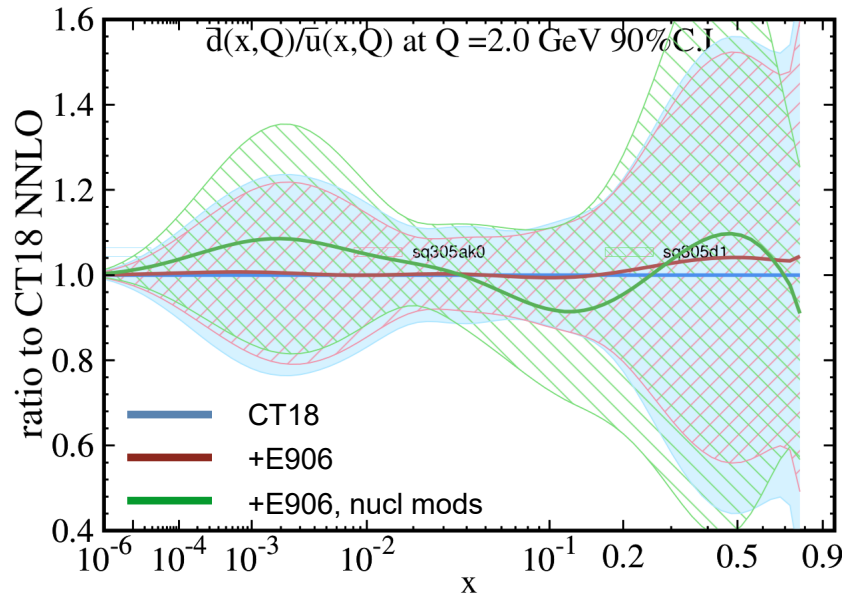Z data have strong impact on the strangeness.

Both 7 and 8 TeV data have too large χ^2, which is moderately (not completely) by using a more flexible (CT18As-like) parametrization.

12
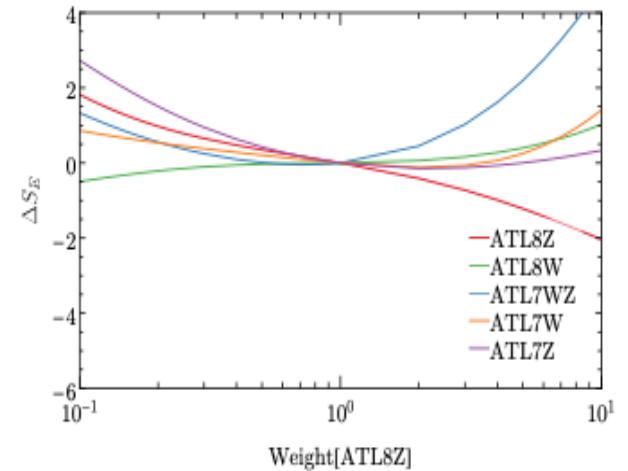
# sea-quark asymmetries at high x: SeaQuest (E906) and STAR Drell-Yan data

- recently-released SeaQuest data have moderate sensitivity to dbar > ubar at high x:

- SeaQuest prefers larger values of dbar/ubar at $x > 0.2$; may somewhat reduce strange-PDF uncertainty

- subtle interplays with: treatment of nucl. data (left); inclusion of STAR W-prod., E866 expts. (right)
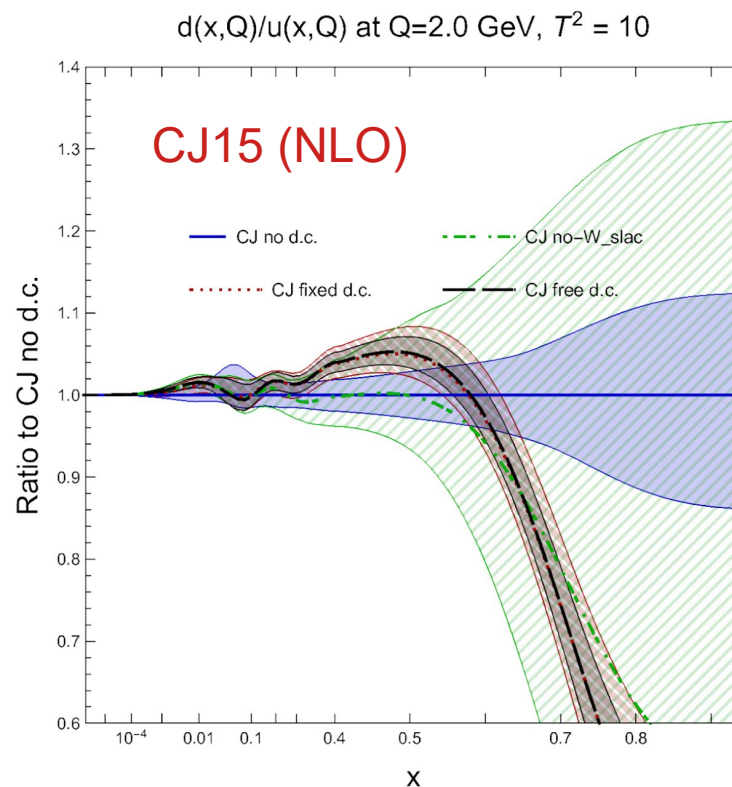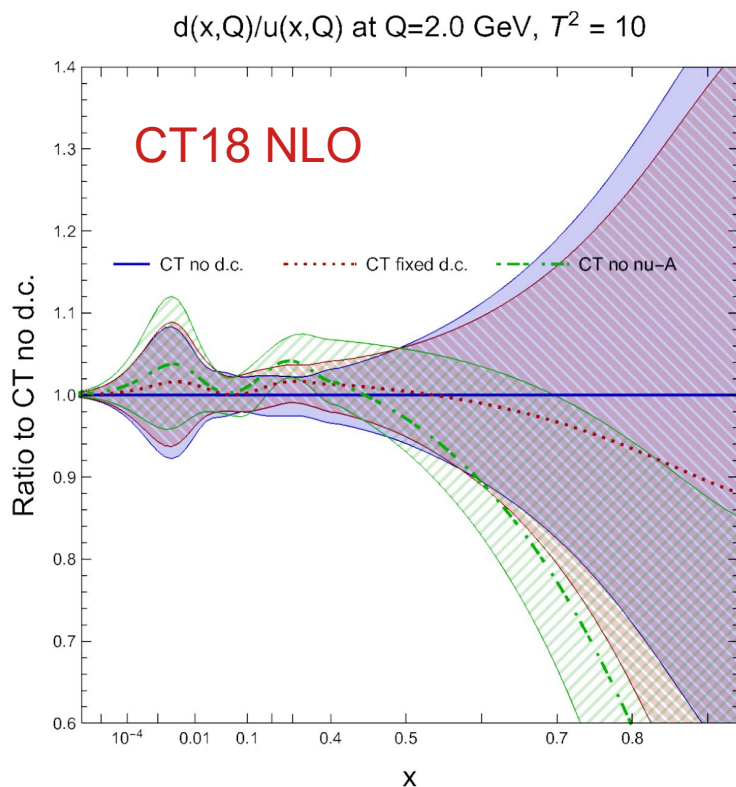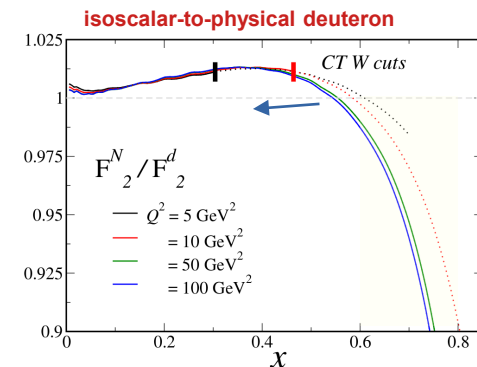
  $\rightarrow$ E906, STAR constructively enhance dbar/ubar; removing E866 augments this effect

- L_2 sensitivities: excluding E866, minimal tensions between E906, other sets

- forthcoming study: exploration of PDF pulls in post-E906 fits

13
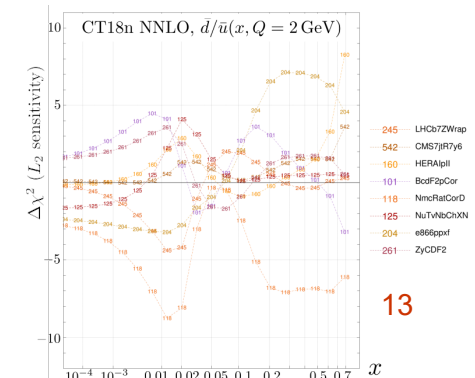
nuclear corrections of increasing importance with greater PDF precision

- 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

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

- **subtle interplay with nuclear corrections in large-A targets**

  - $\rightarrow$ demands attention in future PDF studies

isoscalar-to-physical deuteron

F_2^N/F_2^d

CT W cuts

$Q^2 = 5$ GeV^2
$= 10$ GeV^2
$= 50$ GeV^2
$= 100$ GeV^2

$d(x,Q)/u(x,Q)$ at Q=2.0 GeV, $T^2 = 10$

CT18 NLO

Ratio to CT no d.c.

CT no d.c.   CT fixed d.c.   CT no nu–A

$d(x,Q)/u(x,Q)$ at Q=2.0 GeV, $T^2 = 10$

CJ15 (NLO)

Ratio to CJ no d.c.

CJ no d.c.   CJ no–W_slac
CJ fixed d.c.   CJ free d.c.

Large-x PDFs

PDFs at large x are (to be) tested in experiments at low Q (e.g. MARATHON, BONuS) and high Q (e.g. ZEUS, EIC)

Their shape may reveal QCD dynamics at low energies

We analyze the quark counting rules for CT18NNLO, i.e. the fall-off power A_2 for $f_a(x) \propto (1-x)^{A_2}$ at $x \to 1$

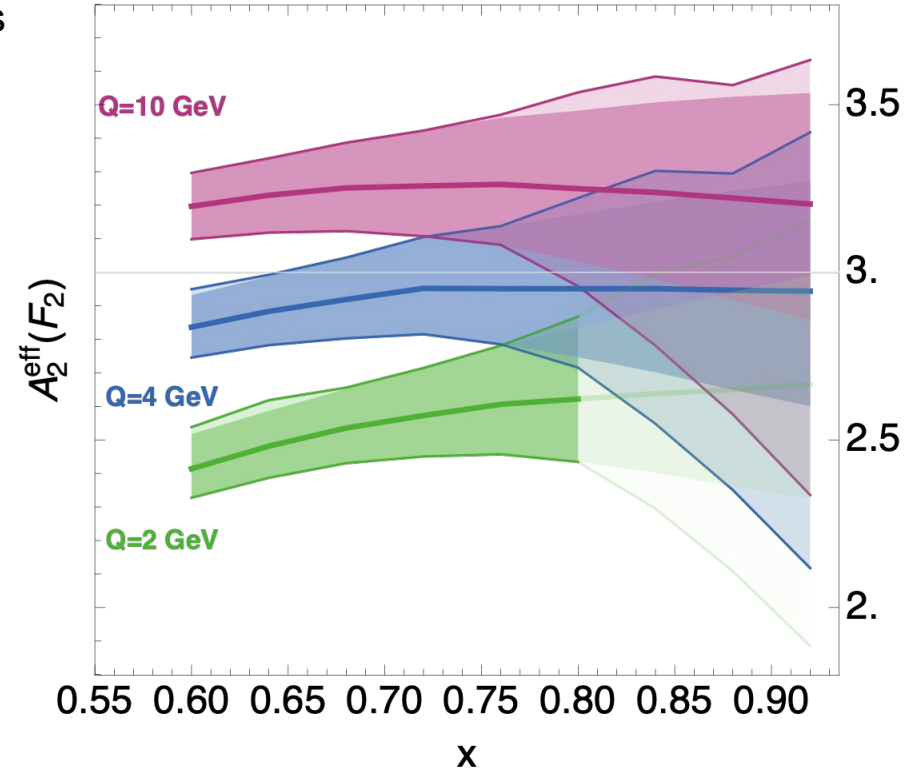**Mimicry** prevents finding the primordial A_2 from discrete data.

Instead, an **effective exponent**
$$A_2^{\text{eff}}(F(x)) \equiv \partial(\ln(F))/\partial(\ln(1-x))$$
can be derived from the fit and compared against nonpert. QCD predictions

CT18 NNLO, parametrization dependence

$A_2^{eff}(x)$ for $F_2(x,Q)$ predicted by the CT18 NNLO fit is consistent with 3 within the uncertainty

Effective PDF exponents at $x > 0.7$

Since non-singlet DGLAP evolution is known precisely, constraints on A_2^{eff} at $x > 0.7$ at high Q can be confidently evolved to low Q and even higher x
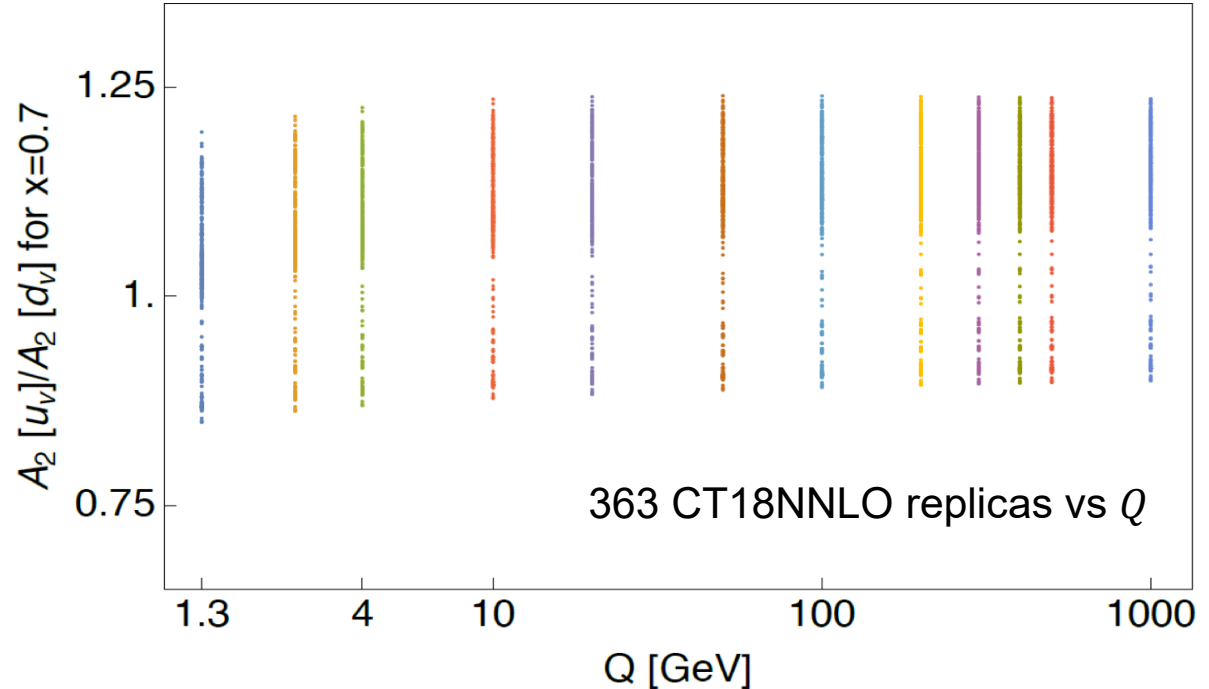

In this region, **ZEUS data at $x > 0.7$** [Abt et al., PRD101] can constrain $A_2^{eff}(F_2)$ precisely.

The ratio of effective exponents for valence PDFs is approximately independent of Q. It can be determine from future (SI)DIS/DY measurements.
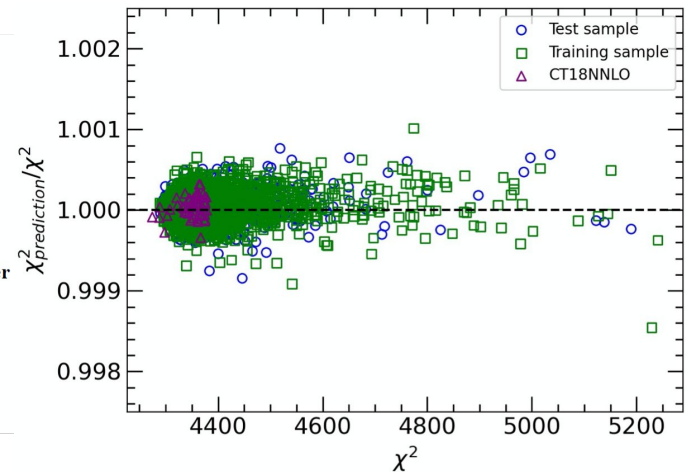
Machine Learning in CTEQ-TEA analysis

[D. Y. Liu, C. L. Sun, Jun Gao 2201.06586]

✦ We developed an efficient framework employing a neural network that learns the dependence of log-likelihood function (χ^2) or cross sections on PDFs; computational efficiency is improved by orders of magnitudes comparing to the full fit

sketch of NN architecture
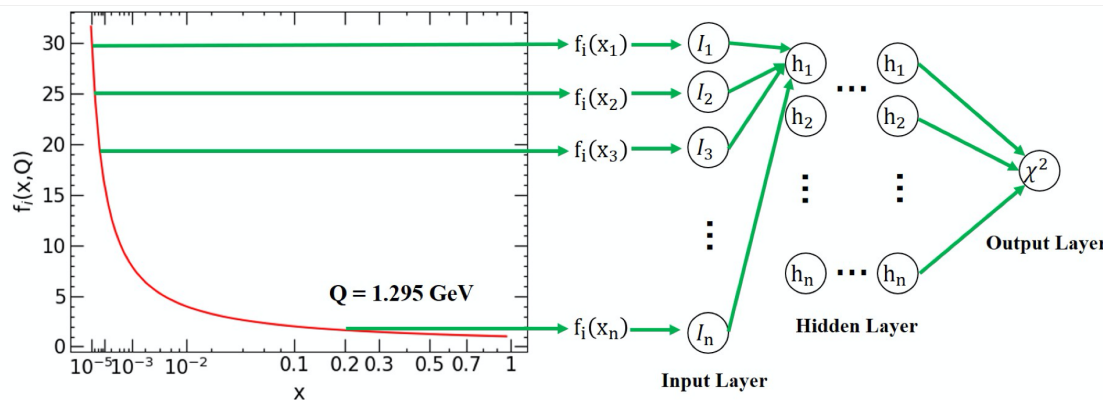
modeling accuracy

❖ **multi-layer NNs with discretized PDFs as input; trained with a large sample from CT18 MC PDFs**

❖ **Reproduce the χ^2 from the full CT18 fit to better than one per mille**

❖ **Very fast! An alternative to the PDF reweighting [1806.07950] and L_2 sensititivity Hessian methods**

computing efficiency per parameter point

cost \ target method	χ^2	σ	$f(x, Q)$
NNs	0.70 ms	0.41 ms	0.37 ms
traditional	$10^7(300)$ ms	$10^6(30)$ ms	20(2) ms

Machine Learning in CTEQ-TEA analysis

[D. Y. Liu, C. L. Sun, Jun Gao 2201.06586]

✦ The new ML approach ensures efficient scans over the full PDF parameter space, especially the Lagrange Multiplier scans of χ^2, as demonstrated for a study on impact of NOMAD data and a study on the constraint of SMEFT couplings
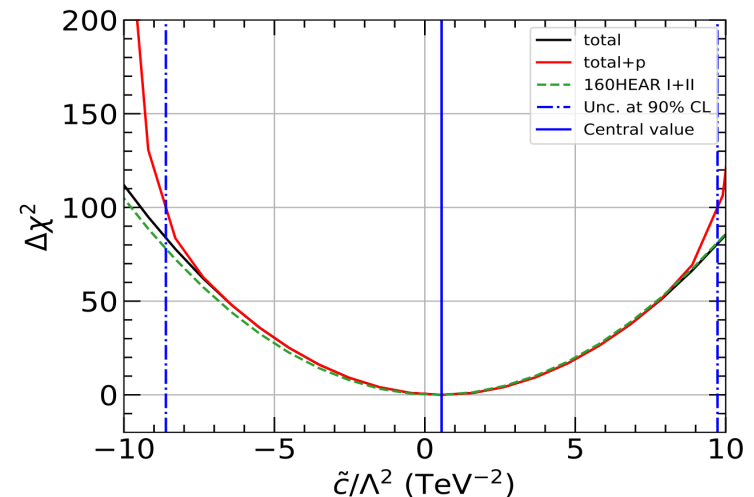
LM scans on Rs

$R_s(x=0.023, Q=1.5\text{GeV})$

lepton-quark contact interactions

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i,j} \frac{c_{ij}}{\Lambda^2}(\bar{q}_i\gamma_\mu q_i)(\bar{l}_j\gamma^\mu l_j)$$
$$= \mathcal{L}_{\text{SM}} + \frac{\tilde{c}}{\Lambda^2}\sum_{i,j} e_{q_i} e_{l_j}(\bar{q}_i\gamma_\mu q_i)(\bar{l}_j\gamma^\mu l_j)$$

LM scans on EFT couplings

$\tilde{c}/\Lambda^2$ (TeV^{-2})
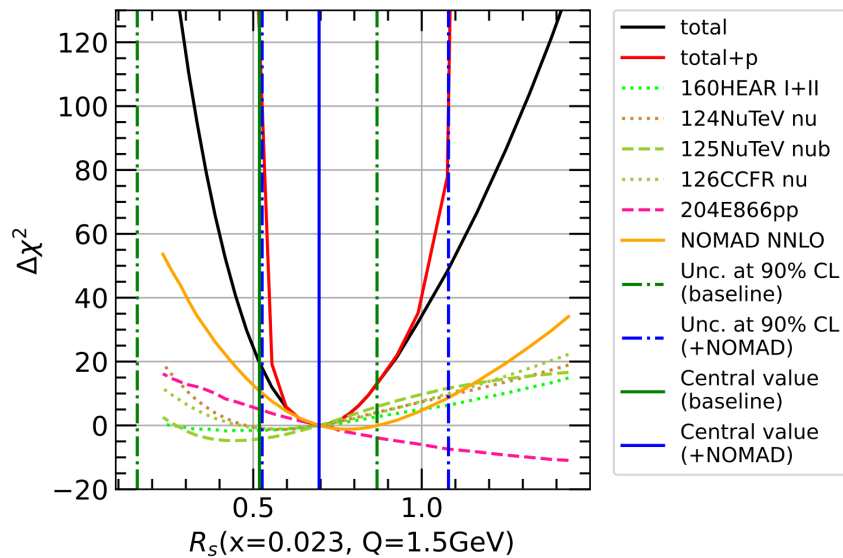
❖**NOMAD prefers a larger s-PDF than NuTeV and CCFR dimuon data; prefers an increase in R_s from 0.5 to 0.7**

❖**reduction of PDF uncertainty by more than 30%**

The tolerance puzzle

**Why do groups fitting the same data
obtain different PDF uncertainties?**

Legend:
- CT18
- MSHT20
- NNPDF3.1
- ABMP16
- ATLASpdf21
- PDF4LHC15
- PDF4LHC21
- NNPDF4.0

Tevatron 1.96 TeV, 2σ
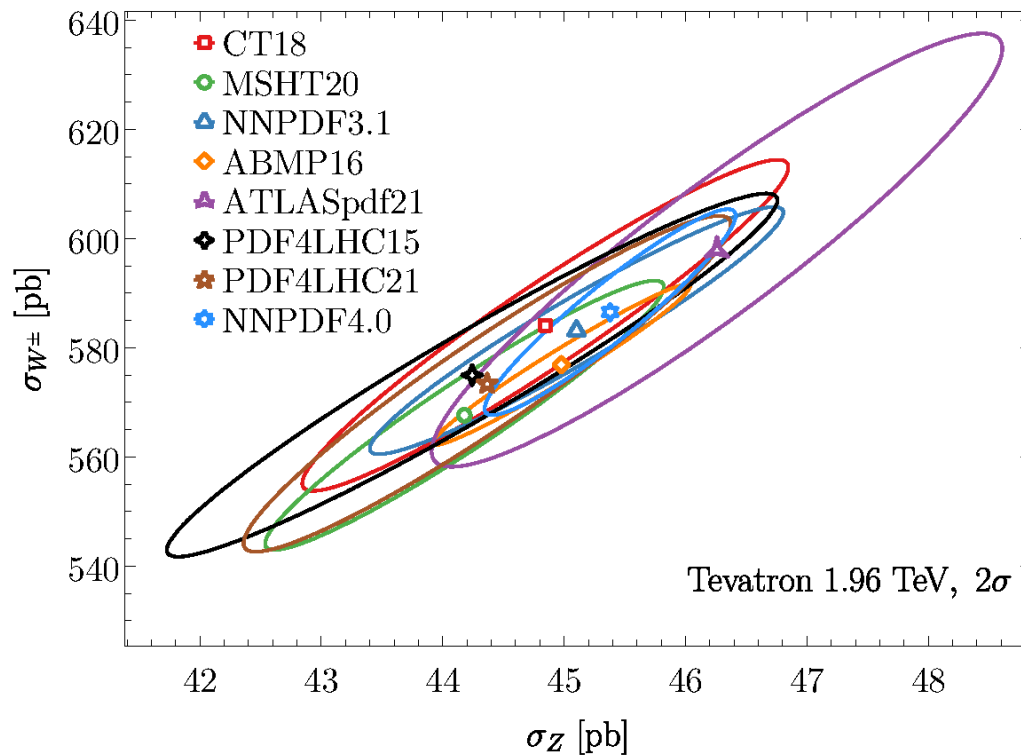
W and Z correlation ellipses for the Tevatron
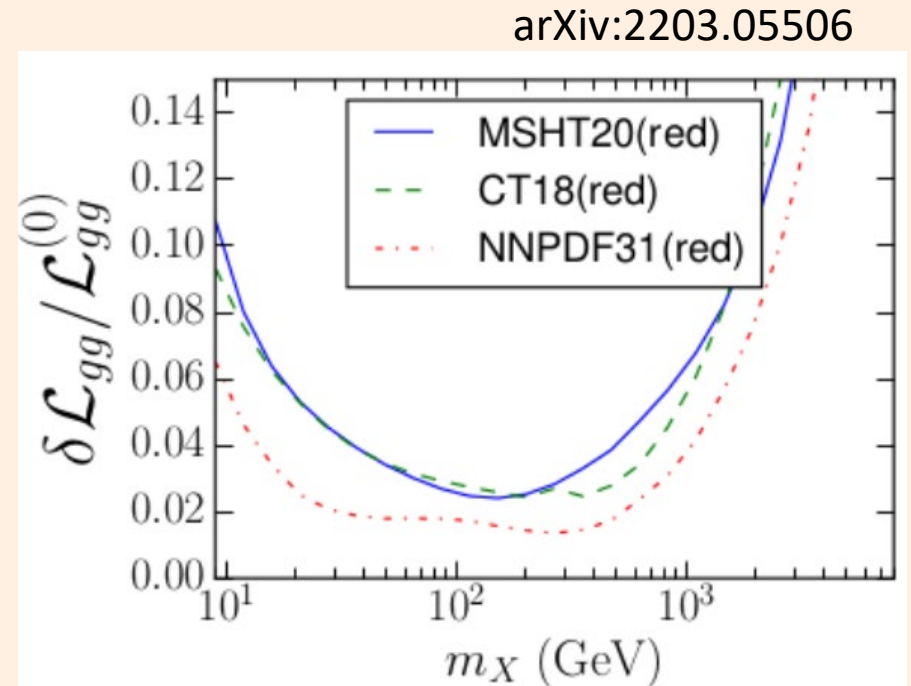Run-2 (by K. Xie)

PDF experts must solve
this puzzle.

$\Rightarrow$ Talk by A. Courtoy,
WG 1

The tolerance puzzle

NNLO Z^0 and $gg \to H^0$ cross sections at the LHC, and 95% CL PDF uncertainties predicted with recent PDF sets.
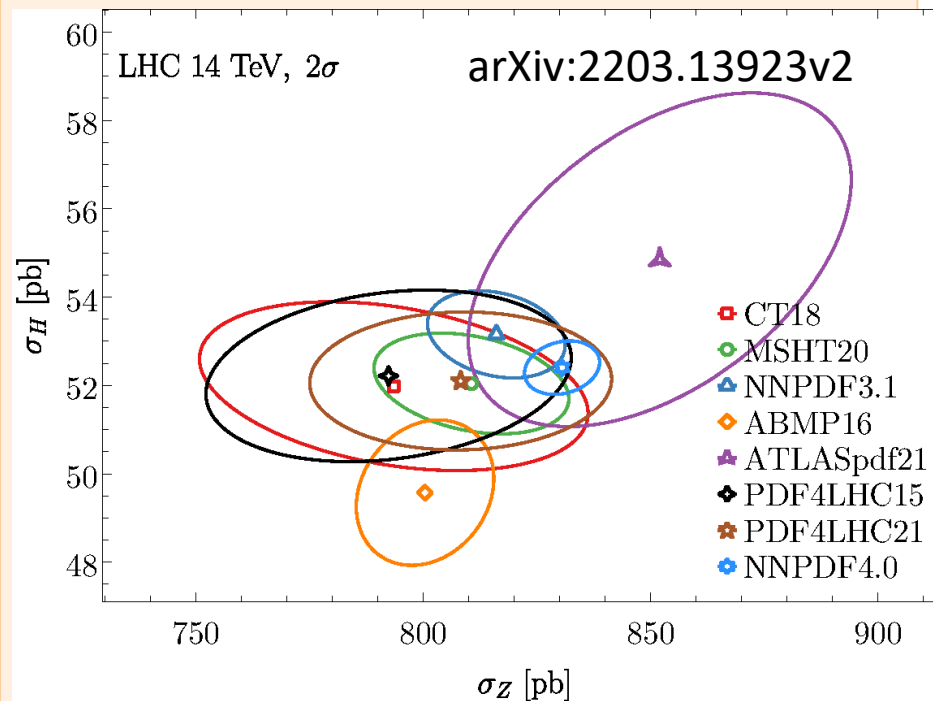
Relative PDF uncertainties on the gg luminosity at 14 TeV in three PDF4LHC21 fits to the **identical** reduced global data set

arXiv:2203.13923v2

arXiv:2203.05506

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.

CT18 LO PDFs

M. Yan, T.-J. Hou, P. N., C.-P. Yuan, on arXiv

Leading-order (LO) PDFs are still used by event generators, though the predictive power of LO QCD is limited in view of today's precise measurements. In this work [1], we present a global fit of CT18 LO PDFs by adopting the framework of CT18 NNLO and NLO studies.
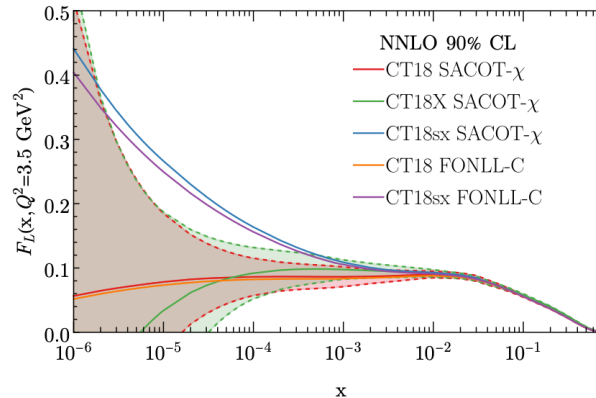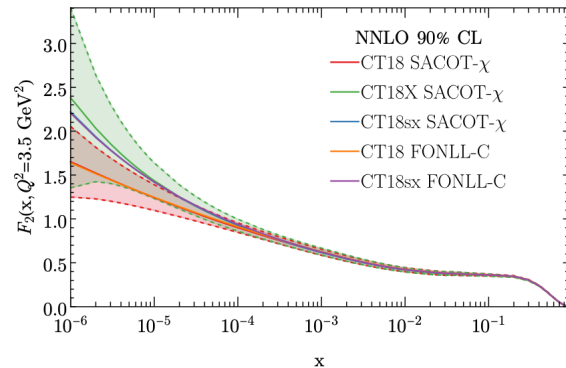
Details in the poster session
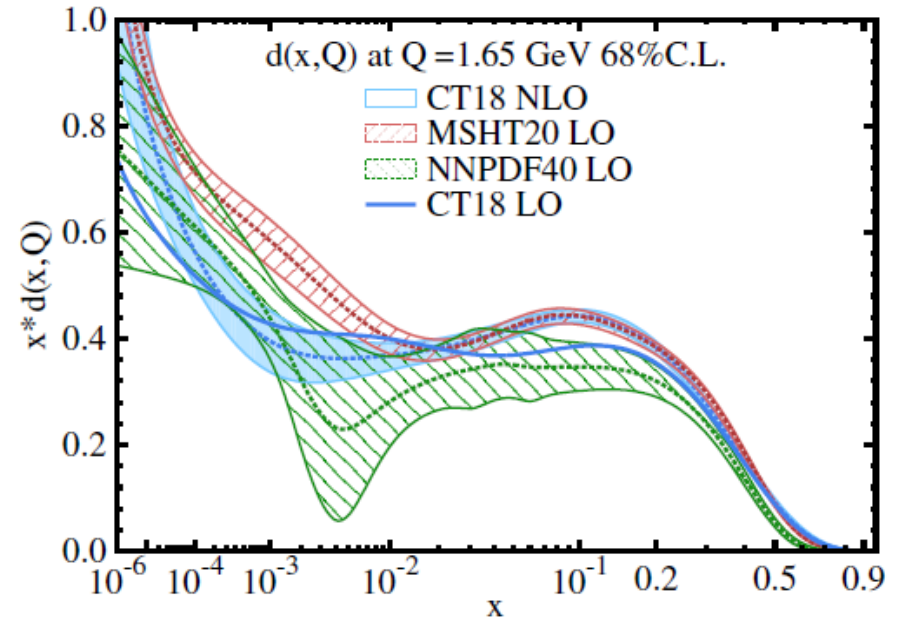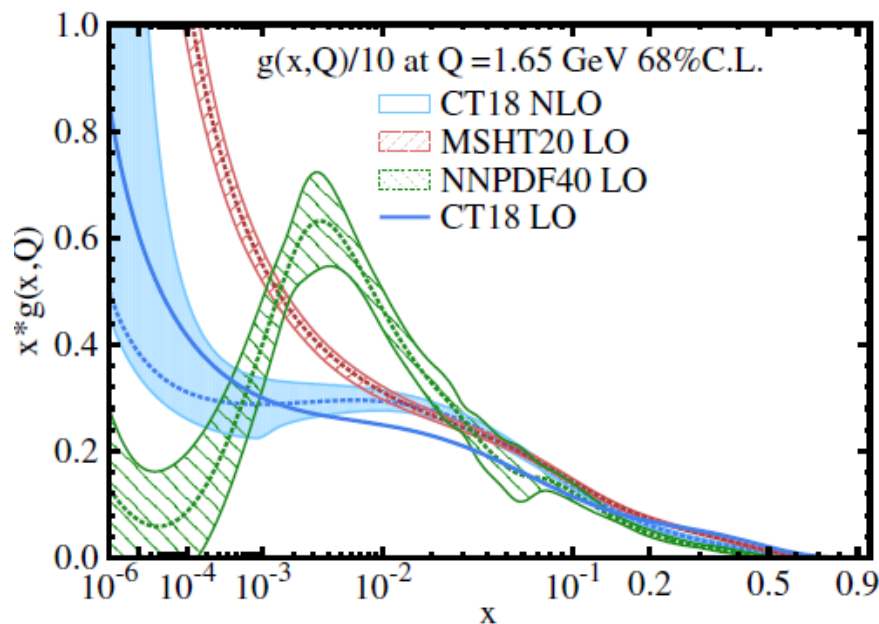
PDFs at small x: resummation or saturation?

See talk by K. Xie, WG2, 3 May
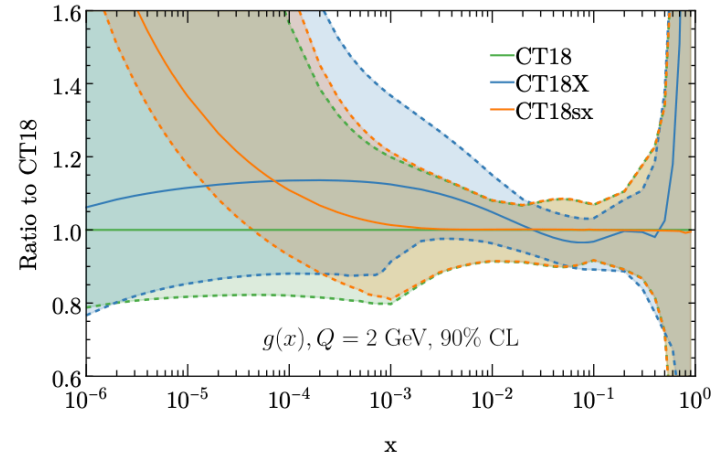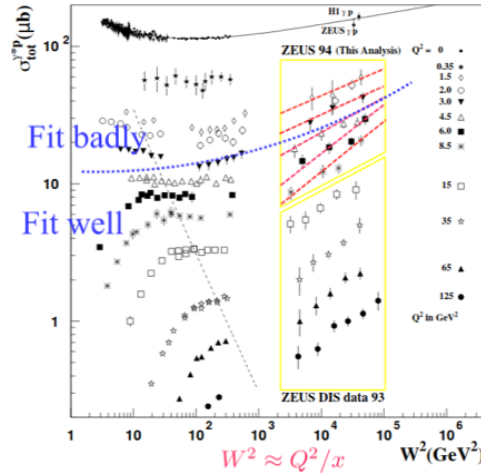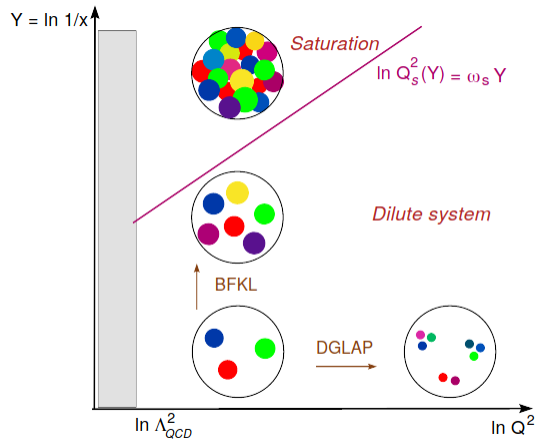
In the small-x and small-Q^2 region, PDFs enter the BFKL regime and

DIS data in this region are fitted badly

NNPDF and xFitter adopts BFKL to resum small-x logs.
CT adopt a saturation DIS scale and obtain similar quality of description of data.
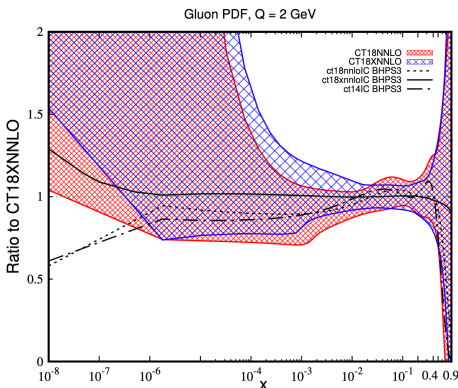
Both small-x resummation and saturation scale enhance F_2, which improves the fits.
Small-x resummation enhances F_L while saturation reduces it – this can be tested in future experiments

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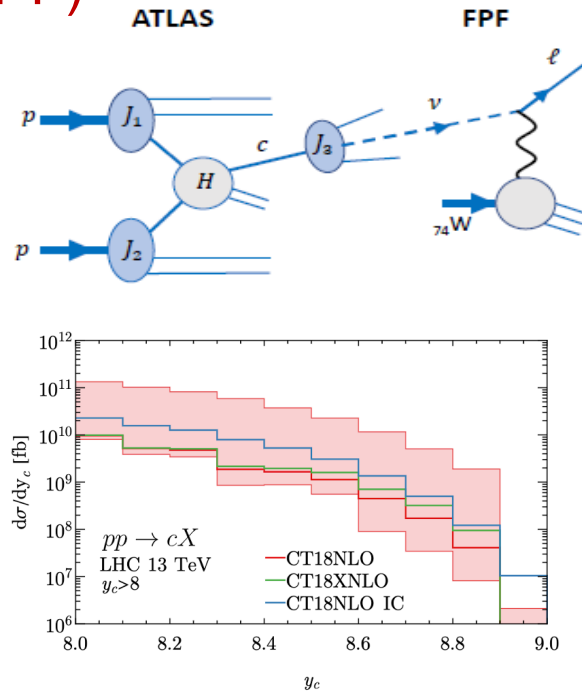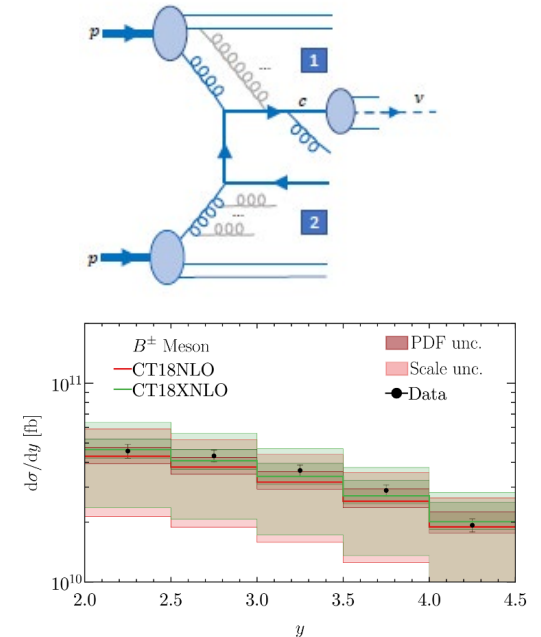# Forward Physics Facility (FPF)

ATLAS   **FPF**

LHCb 13 TeV JHEP 03 (2016) 159
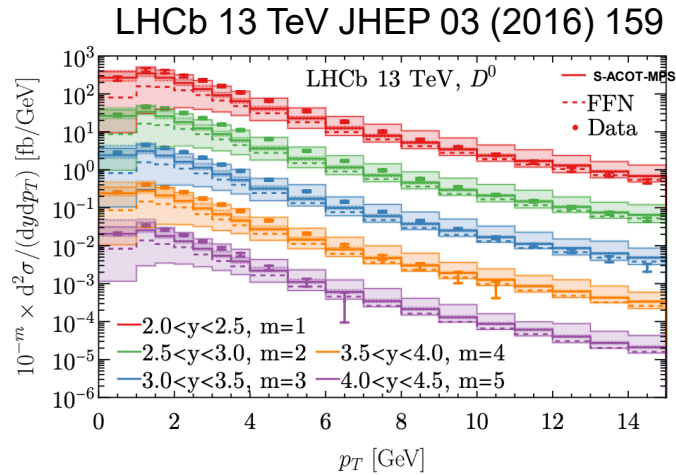
Charm pT at central rapidity at LHCb 13TeV.
Error bands are scale uncertainties. 2108.03741

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.

charge-current DIS: higher perturbative accuracy at **NNLO and beyond**
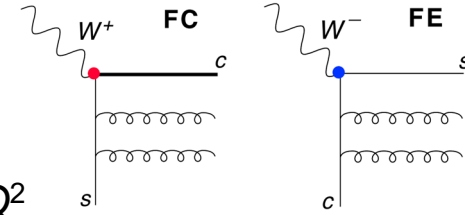
- CC DIS data cover wide range of scales; can provide strong flavor separation

- higher pQCD accuracy needed to stabilize PDF extractions

- general-mass (GM) HQ scheme, comprehensive description over low-to-high Q^2

  Gao, Hobbs, Nadolsky, Sun, Yuan: Phys. Rev. D**105** (2022) 1, L011503

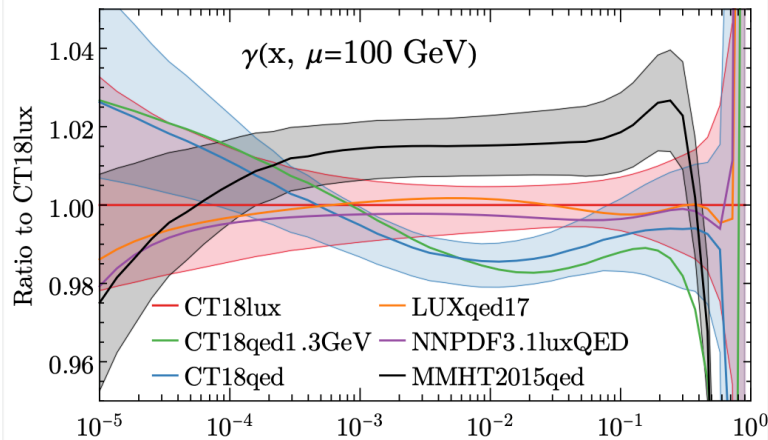 → S-ACOT-χ implementation: requires careful treatment of HQ flow at the diagram level

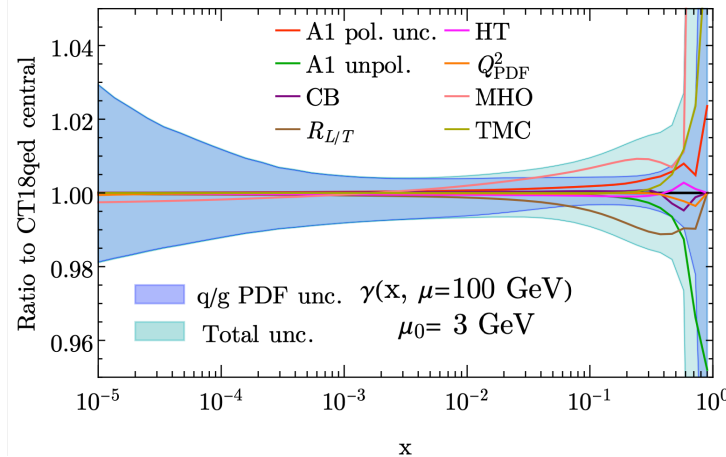- GM NNLO, approx. N³LO (N3LO') stabilize scale uncertainties for vDIS (left), EIC red. X-sect (right)
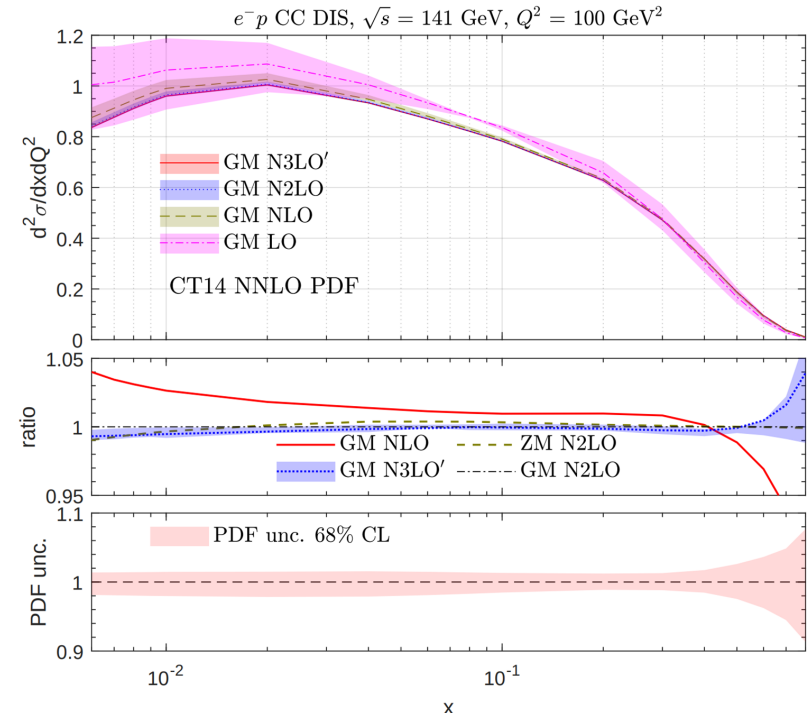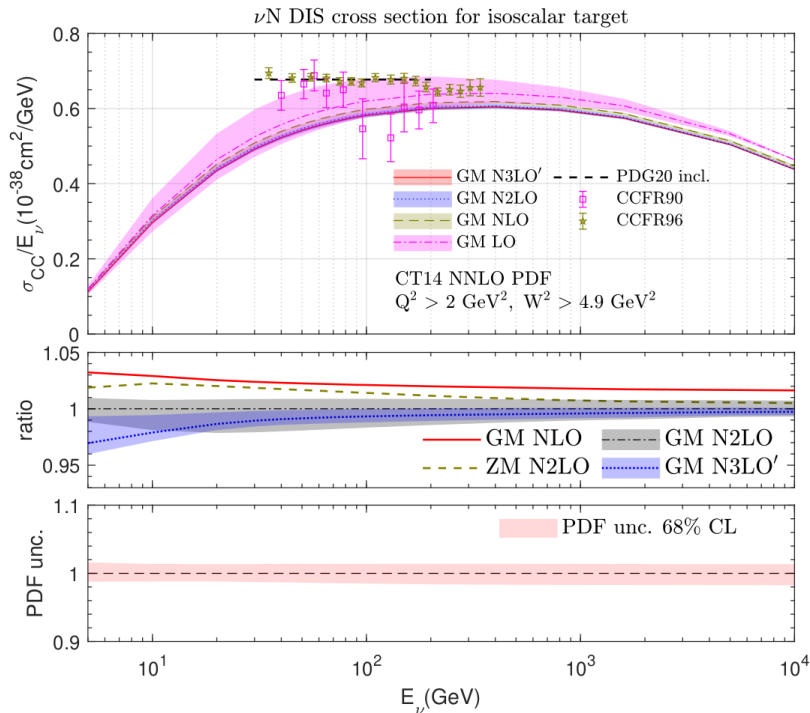
CT18QED: Photon PDF in the CTEQ-TEA global analysis

Phys.Rev.D 105 (2022) 5,

1. In the small-x region, the uncertainty mainly originates from the quark and gluon PDFs.
2. At large x, all nonperturbative sources contribute.
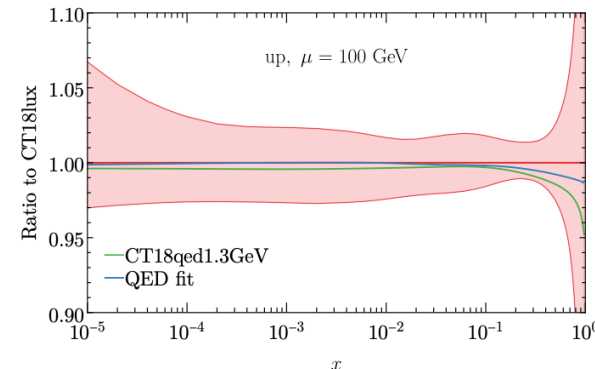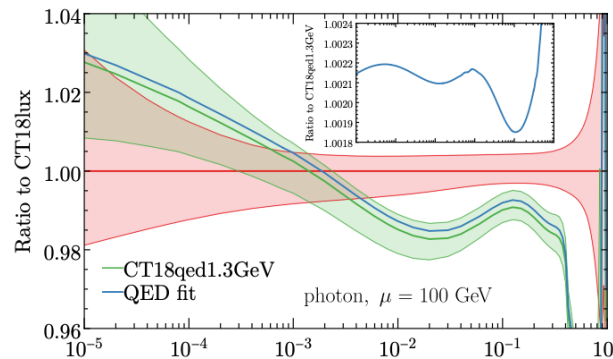
1. CT18lux provides the photon PDF at all scales, μ.
2. CT18qed initializes photon PDF at μ_0, and evolves to high scales.
3. CT18lux gives the photon in between LUXqed(17) and MMHT2015qed, while CT18qed gives smaller photon.

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

# $t\bar{t}$ production at 13 TeV in CT18NNLO

Add diff. cross section measurements from CMS and ATLAS at $\sqrt{S} = 13$ TeV to the CT18 fit

CMS: $t\bar{t}$ 1D diff. Xsec at 13 TeV; 2 lepton channel; 35.9 fb^{-1} (**1811.06625**)
ATL: $t\bar{t}$ 1D diff. Xsec at 13 TeV; all-hadronic channel; 36.1 fb^{-1} (**2006.09274**)

* Gluon impacted at large x [0.04:0.4] as expected
* Pulls from ATLAS and CMS found to be in the same direction
* Compatibility and complementarity with jet data explored
* m_t dependence explored
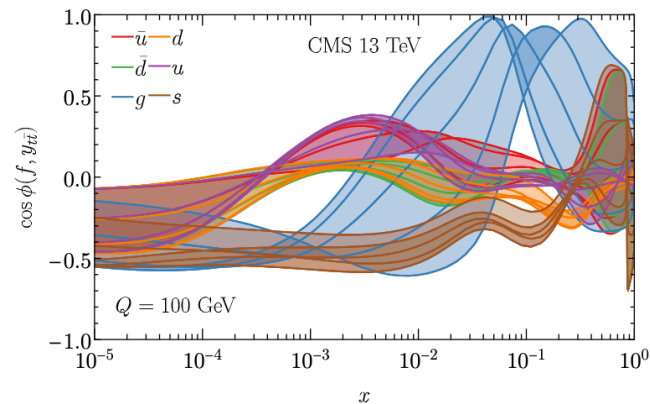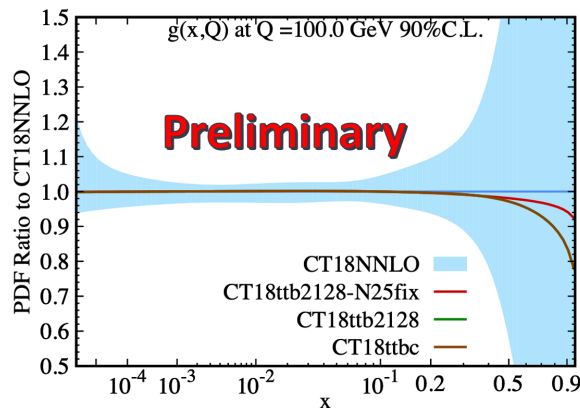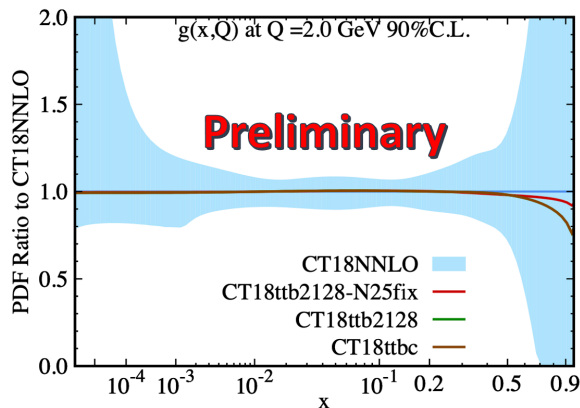
A. Ablat, S. Dulat, M.Guzzi., T.-J. Hou, I. Sitiwaldi, K. Xie, and C.-P. Yuan, in preparation

Thank you for your attention!

STAY TUNED FOR NEW RESULTS

Backup slides
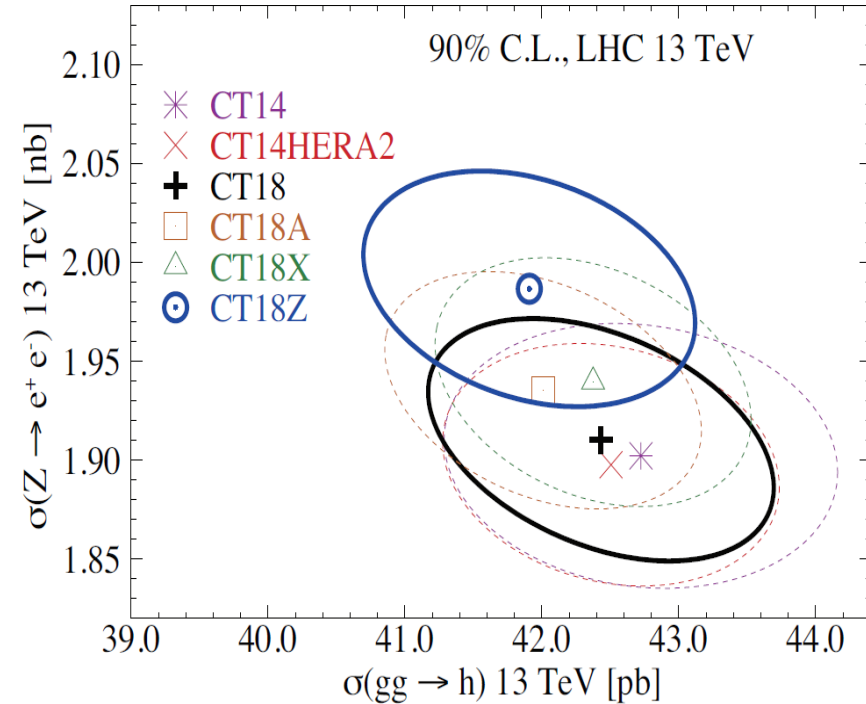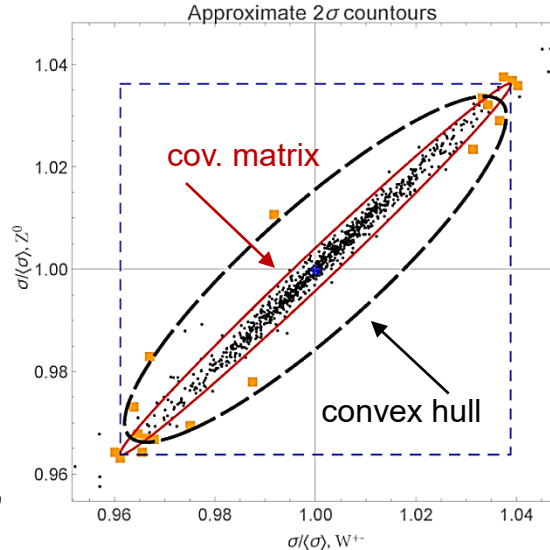
Toward **robust** PDF uncertainties

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]

Approximate 2σ countours

cov. matrix

convex hull

90% C.L., LHC 13 TeV

* CT14
× CT14HERA2
+ CT18
□ CT18A
△ CT18X
⊙ CT18Z

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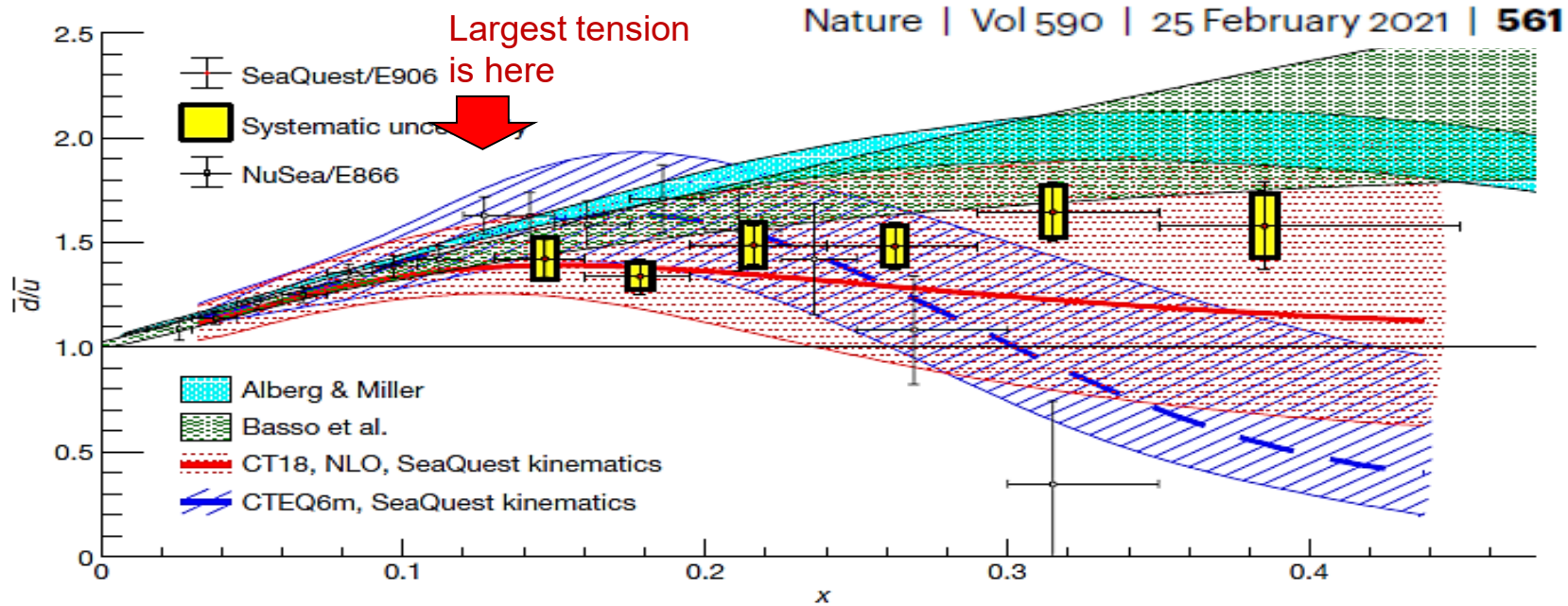
The Fermilab E906 muon pair production experiment suggests there are more $\bar{d}$ than $\bar{u}$ antiquarks at large momentum fractions. It disagrees with the E866 experiment suggesting a suppressed $\bar{d}/\bar{u}$ ratio at $x > 0.3$.

The CT18 PDFs agree well with the E906 data at all accessed x values.
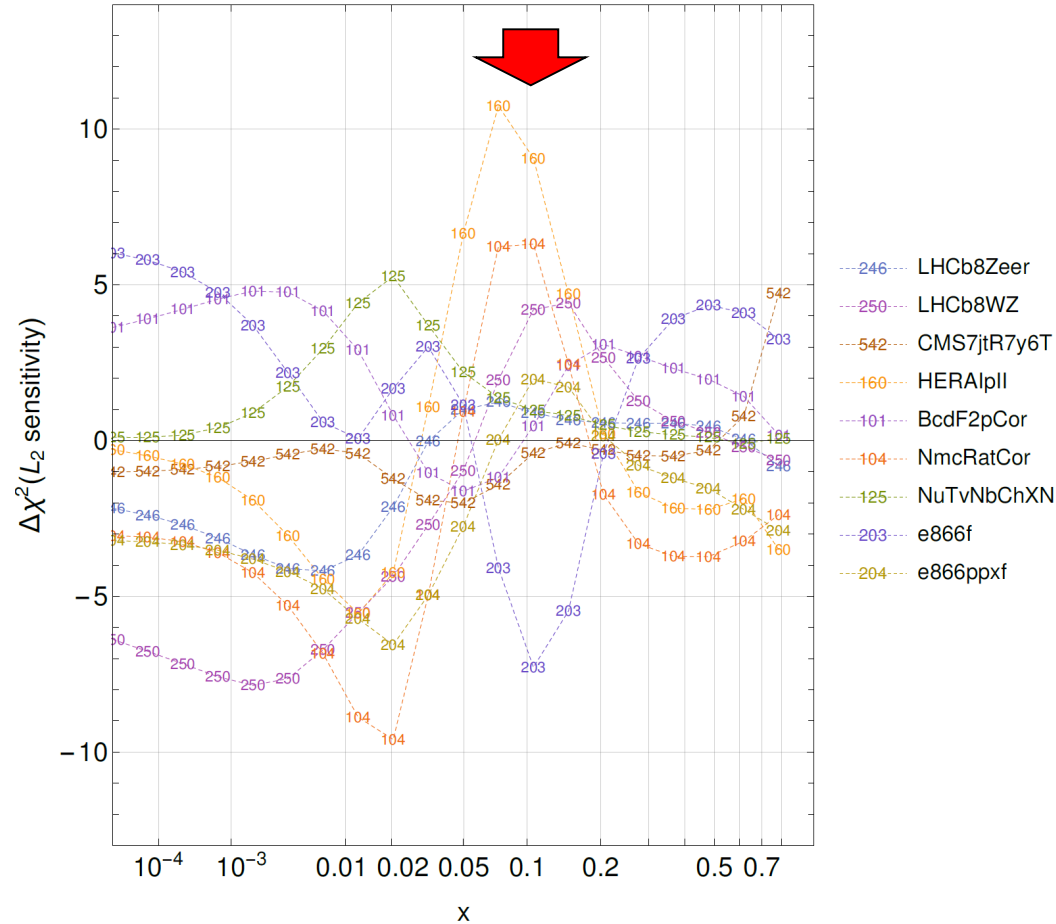
The CT18 PDFs provide the most comprehensive uncertainty estimate among the shown bands (resulting in larger uncertainties).

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

CT18 NNLO, $\bar{d}(x,Q)/\bar{u}(x,Q)(x, 2\text{ GeV})$

https://ct.hepforge.org/PDFs/ct18/figures/L2Sensitivity/
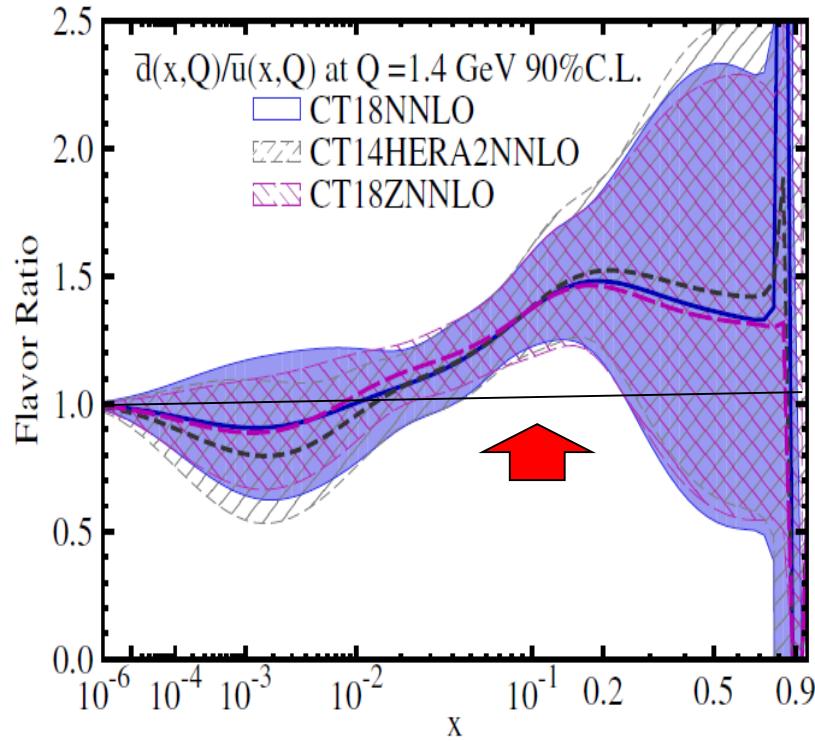
Data are consistent with either sign of $\bar{d} - \bar{u}$ except at $x \sim 0.1$, where the strong upward pull of E866 ratio (203) opposes the downward pulls of HERA (160), NMC d/p (104), and LHCb 8 W/Z (250) experiments