CT18 update

J. Huston (for the CTEQ-TEA collaboration)

PDF4LHC meeting Nov. 17, 2023

…borrowing liberally from slides from P. Nadolsky, T. Hobbs, … especially from DIS talks

Some recent publications

1. Exploring the impact of high-precision top-quark pair production data on the structure of the proton at the LHC; A. Ablat, M. Guzzi, K. Xie, S. Dulat, T-J Hou; arXiv: 2307.11153
2. Quantifying the interplay of experimental constraints in analyses of parton distributions; ATLASpdf, CT and MMHT authors; *Phys.Rev.D* 108 (2023) 3, 034029
3. Precision studies of the post-CT18 LHC Drell-Yan data in the CTEQ-TEA global analysis; I. Sitiwaldi, K. Xie et al; Phys. Rev. D 108 (2023) 3, 034030
4. The persistent nonperturbative charm enigma, M. Guzzi, T. Hobbs et al; *Phys. Lett. B* 843 (2023), 13975
5. Parton distributions need representative sampling, A. Courtoy et al; Phys. Rev. D 107 (2023) 3, 034008
6. CT18 global PDF fit at leading order in QCD; M. Yan et al; *Phys. Rev. D* 107 (2023) 11, 116001
7. General heavy-flavor mass scheme for charged-current DIS at nnlo and beyond; J. Gao, T. Hobbs et al; *Phys. Rev D* 105 (2022) 1, L011503
8. Simultaneous CTEQ-TEA extraction of PDFs and SMEFT parameters from jet and ttbar data; J. Gao, T. Hobbs et al; arXiv:2211.01094
9. Parton distributions and lattice-QCD calculations: Towards 3D structure, A. Courtoy et al; *Prog. Part. Nucl. Phys.* 121 (2021) 103908

Since 2018, we have examined the impact of new LHC data, new parametrizations,joint PDF+EFT fits, as well as the impact of lattice constraints (especially on the strange quark).

CTEQ-TEA presentations at DIS'2023

Toward a new generation of CT202X PDFs

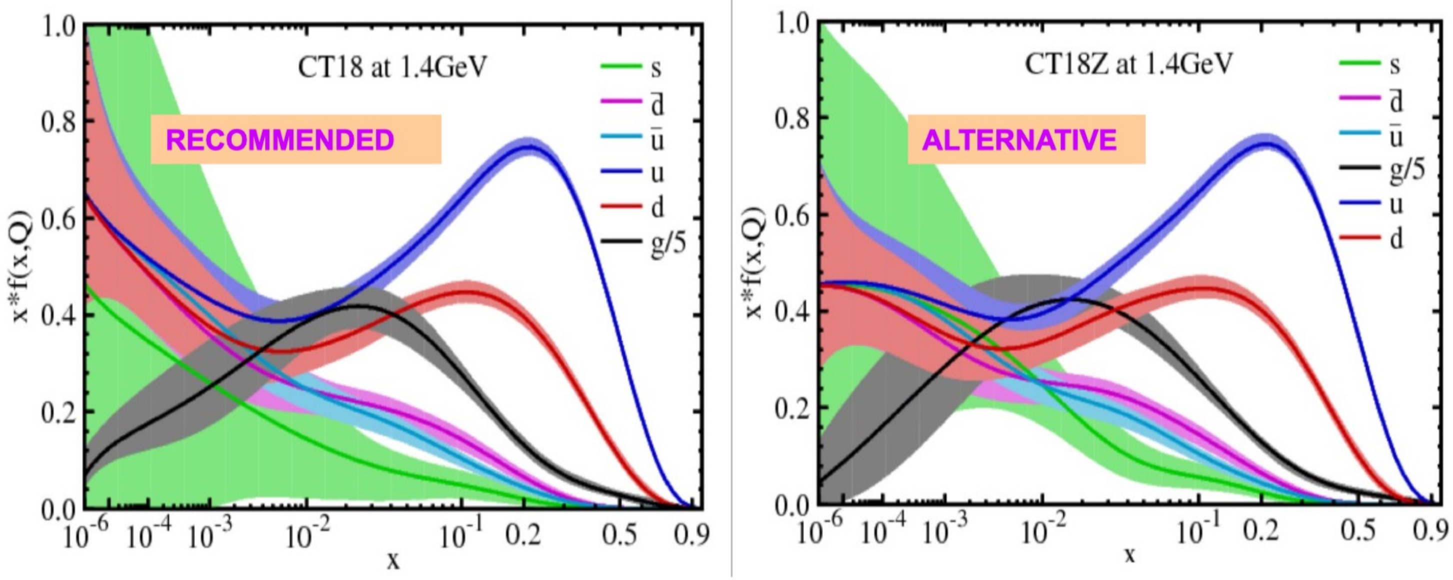
1.Impact of Drell-Yan data on post-CT18 global fits	**Keping Xie**	**WG3**
2. Constraints from $t\bar{t}$ production at LHC 13 TeV	**Marco Guzzi**	**WG1**
3. Epistemic uncertainty quantification in PDF fits	**P. Nadolsky**	**WG1**
4. CT18 NNLO fitted charm PDFs *[arXiv:2211.01387]*	**Tim Hobbs**	**WG1**
5. Prospects for using lattice-QCD constraints in the global PDF analysis	**T.-J. Hou**	**Plenary**
6. CTEQ-TEA NNLO predictions for high-energy neutrino cross sections	**Dan Stump**	**WG3**
7. Simultaneous CTEQ-TEA extraction of PDFs and SMEFT contributions	**Tim Hobbs**	**WG3**
8. Small-x dynamics in CTEQ-TEA fits and Forward Physics Facility	**Keping Xie**	**WG2**

- Impact of top/jet data->see talk of Marco Guzzi
- L2 sensitivity->see talk of Aurore Courtoy
- Replicability->see talk of Pavel Nadolsky

CT18 parton distributions

PRD 103 (2021) 014013

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



- The CT18 family of PDFs includes LHC data available up to 2018, i.e. mostly 7 and 8 TeV data
- CT18 is the primary PDF; CT18A includes the ATLAS 7 TeV W/Z data (excluded from CT18 due to very poor fit); CT18X includes scale to simulate effects of low x resummation for DIS; CT18Z includes both effects
- CT18As (new) allows a more flexible parametrization for strange
- CT18As_Lat (new) adds lattice constraint

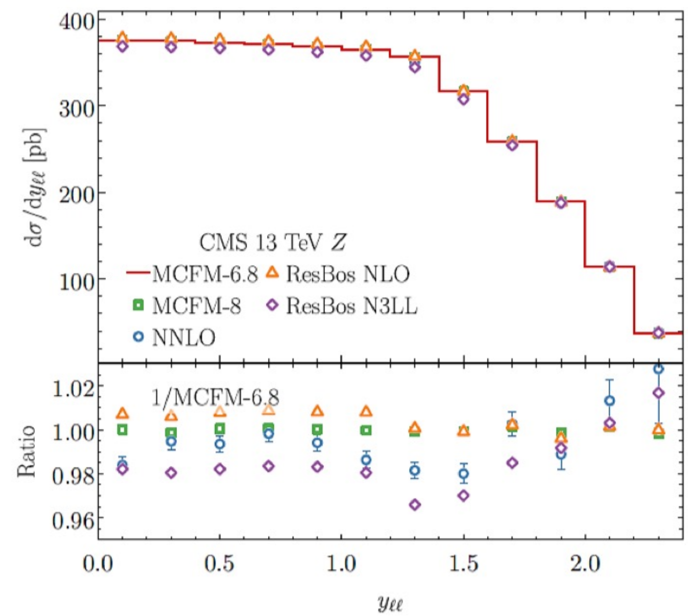
New CT 18 NNLO grids for precision calculations

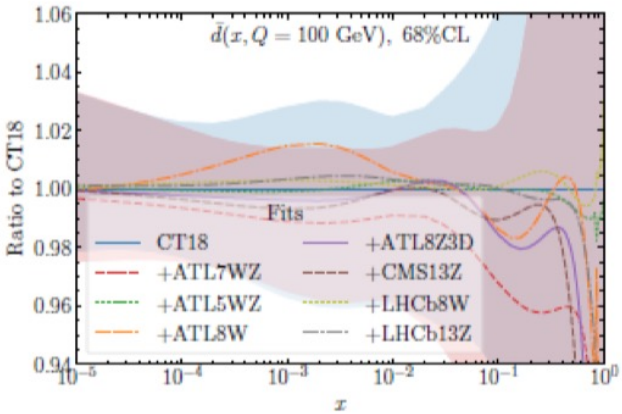
- Available on ct.hepforge.org
- Contain more x and Q points — improved interpolation at the expense of slightly slower evaluation
- Crossing of quark mass thresholds implemented with multiple Q grids. Complement the published (less dense) CT 18 grids on LHAPDF that remain sufficient for most applications

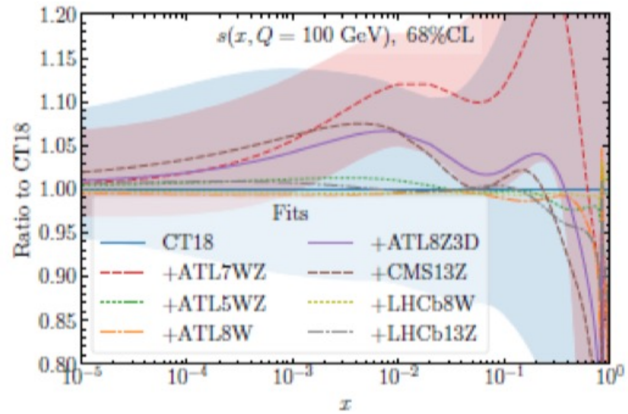
New post-CT18 LHC Drell-Yan data

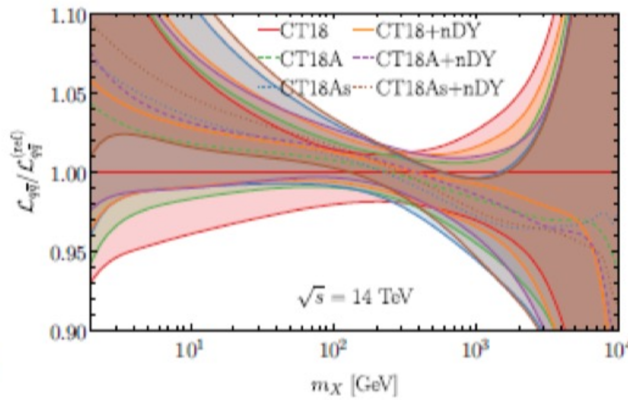
Boson	$\sqrt{s}$	Lumi	Observable	Ref.
ATLAS				
W, Z	2.76	$4.0\ \text{pb}^{-1}$	$\sigma^{\text{fid,tot}}$	1907.03567
W, Z	13	$81.0\ \text{pb}^{-1}$	σ^{fid}	1603.09222
W, Z	5.02	$25.0\ \text{pb}^{-1}$	$(\eta_\ell, y_{\ell\ell})$	1810.08424
Z	8	$20.2\ \text{fb}^{-1}$	$(m_{\ell\ell}, y_{\ell\ell})$	1710.05167
$W \to \mu\nu$	8	$20.2\ \text{fb}^{-1}$	η_μ	1904.05631
Z	13	$36.1\ \text{fb}^{-1}$	$p_T^{\ell\ell}$	1912.02844
CMS				
Z	13	$2.8\ \text{fb}^{-1}$	$m_{\ell\ell}$	1812.10529
Z	13	$35.9\ \text{fb}^{-1}$	(y, p_T, ϕ^*)	1909.04133
W	13	$35.9\ \text{fb}^{-1}$	σ^{fid}, $y_W, (\eta_\ell, p_T^\ell)$	2008.04174
LHCb				
$W \to e\nu$	8	$2.0\ \text{fb}^{-1}$	η_e	1608.01484
Z	13	$294\ \text{pb}^{-1}$	σ^{fid}, (y, p_T, ϕ^*)	1607.06495
$Z \to \mu\mu$	13	$5.1\ \text{fb}^{-1}$	σ^{fid}, (y, p_T, ϕ^*)	2112.07458

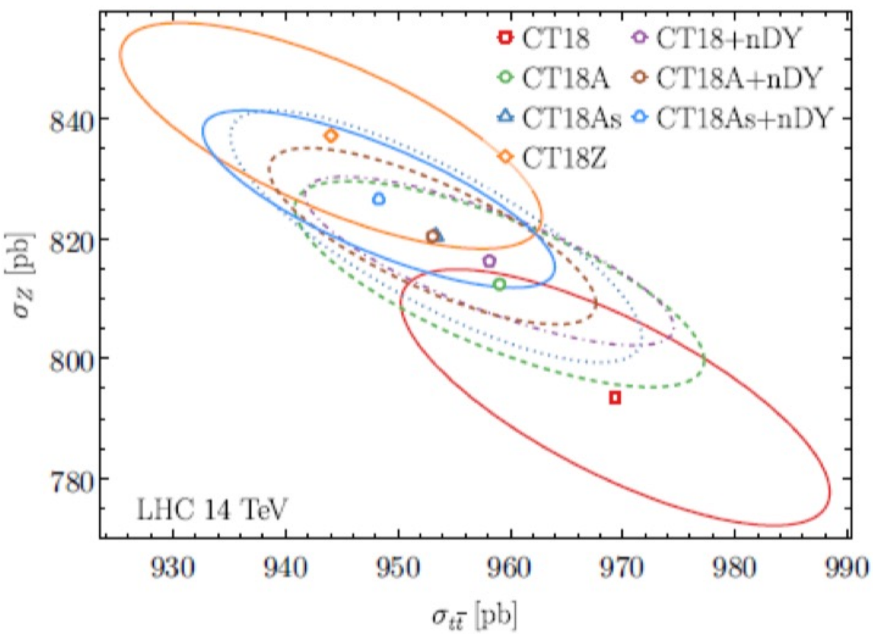
Multiple candidate fits to explore the impact of 8 and 13 TeV Drell-Yan data using NNLO and resummed N3LL-NNLO cross sections





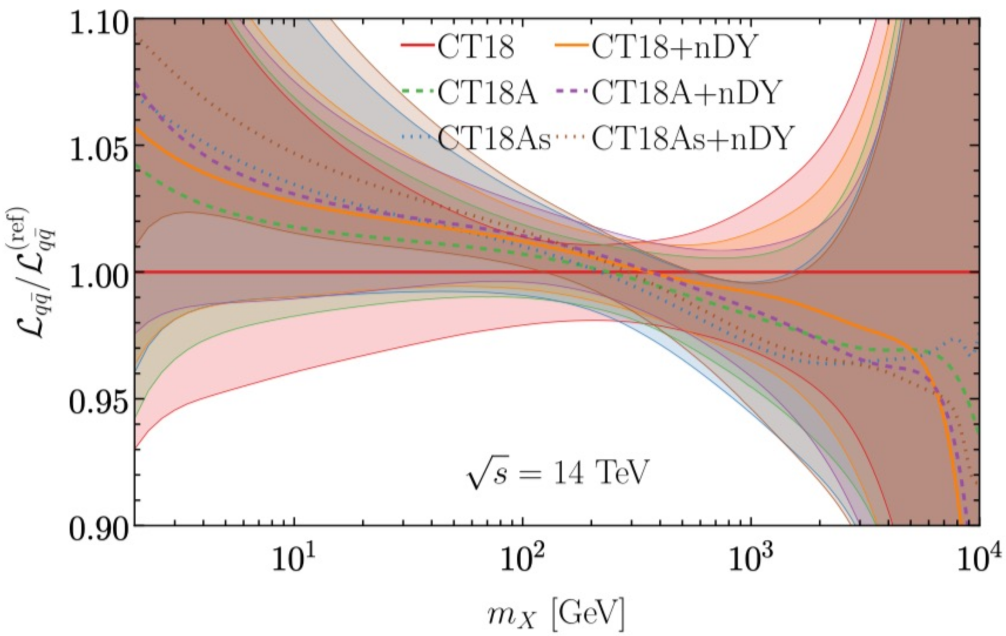


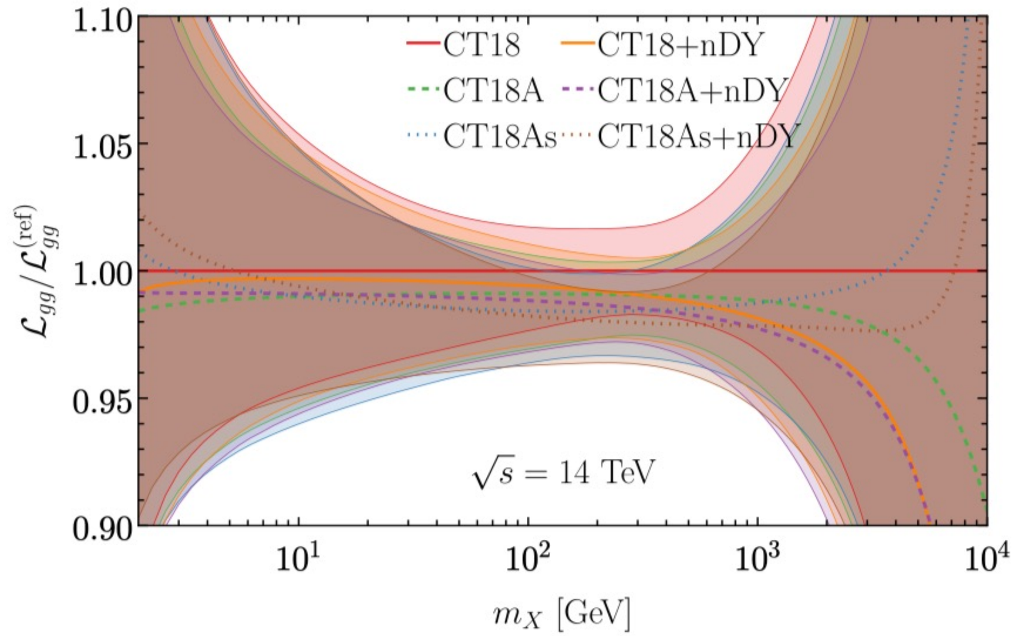


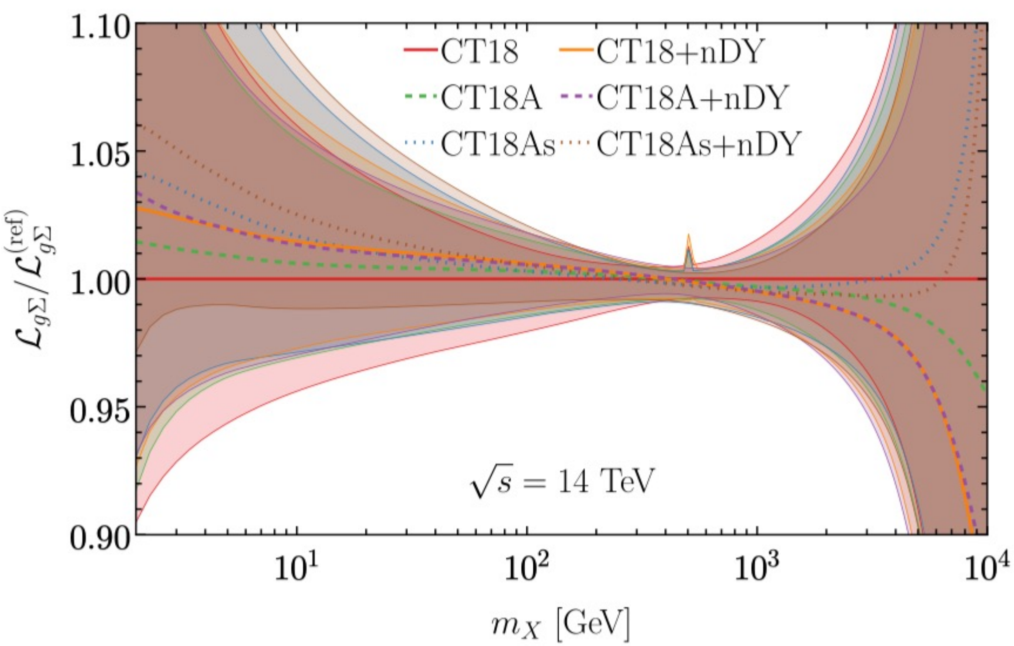


- Most of the post-CT18 LHC Drell-Yan data are consistent with the ATLAS 7 TeV W, Z precision measurement, which enhance the strangeness (CT18A).
- Exceptions for ATLAS and LHCb 8 TeV W data, which push the $d(\bar{d})$ PDFs to the opposite direction.
- The post-CT18 LHC Drell-Yan data shrink the error bands.
- The joint impact of these new data sets pull the PDFs and predictions from CT18 to CT18Z direction.

Parton Luminosities

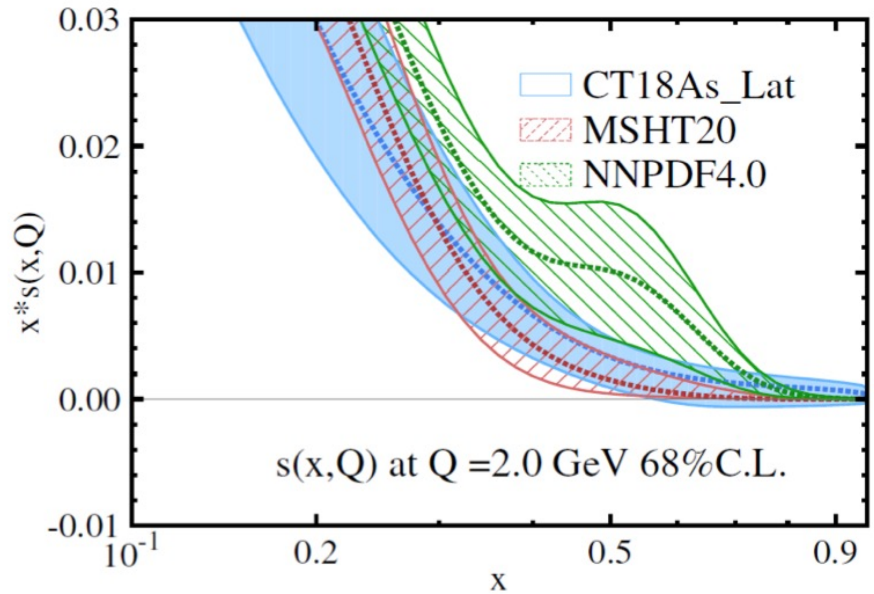






- The new Drell-Yan data increases (decreases) the quark-related luminosity at low (high) invariant mass
- …with a reduction in the size of the error bands
- The more flexible strangeness parameterization in CT18As can enlarge the uncertainty bands for quark-related parton luminosities

CT18As_Lat NNLO: Strangeness asymmetry with a lattice QCD constraint

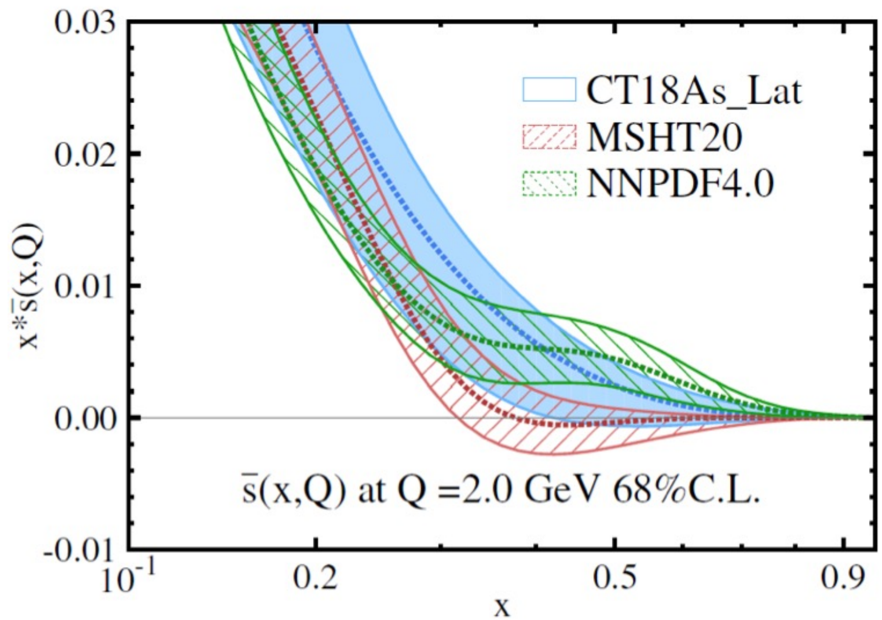


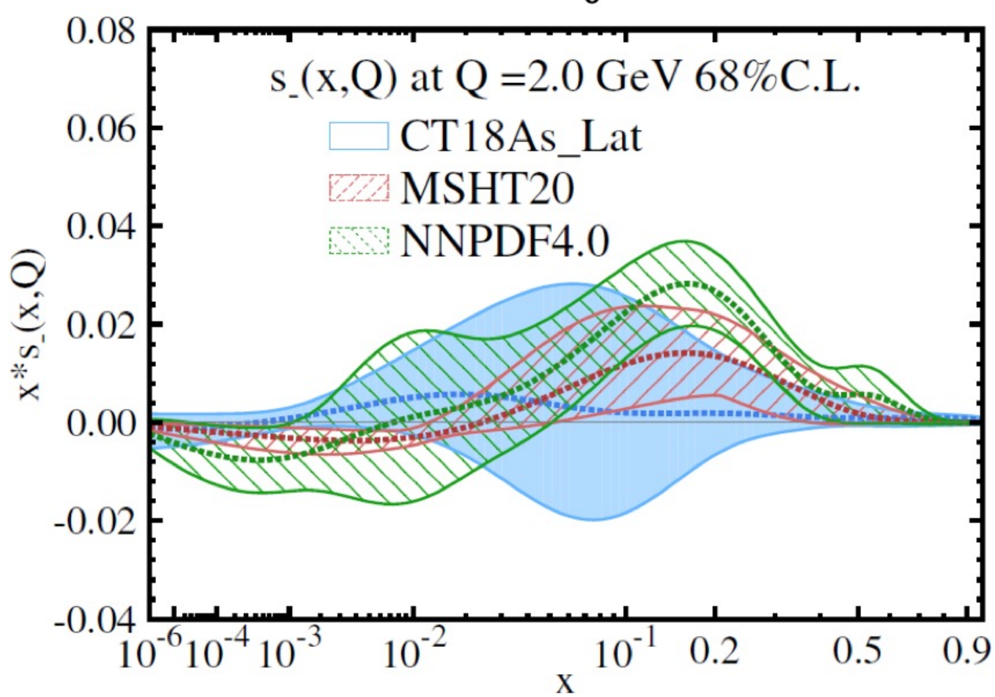
T.-J. Hou et al., arXiv: 2211.11064

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

CT18As_Lat: CT18As with a lattice constraint on $s_(x)$ at $0.3 \leq x \leq 0.8$.

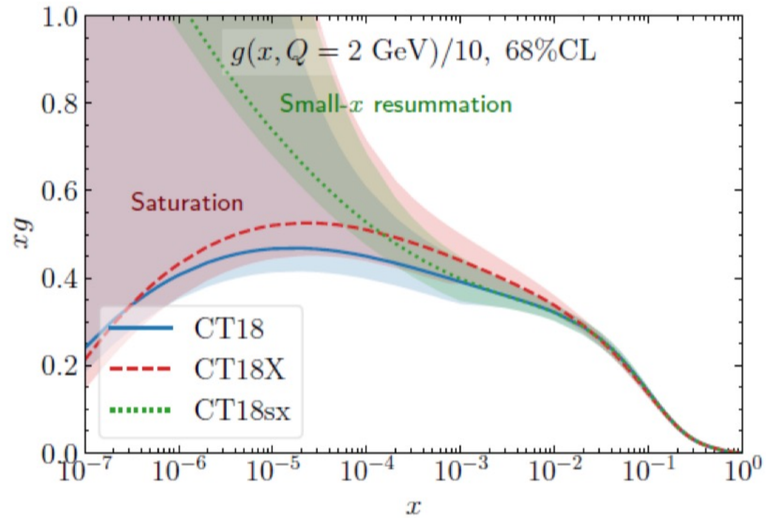
$$\int_0^1 s_-(x)dx = 0$$

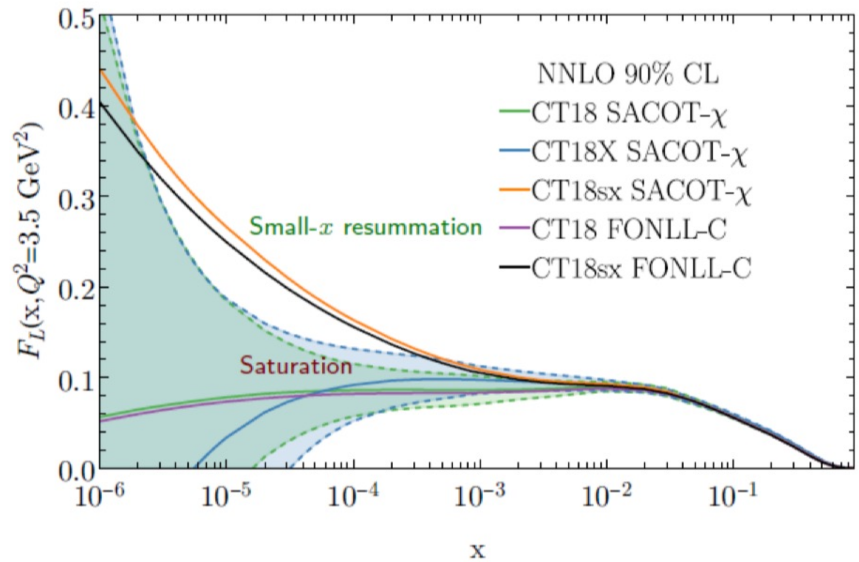


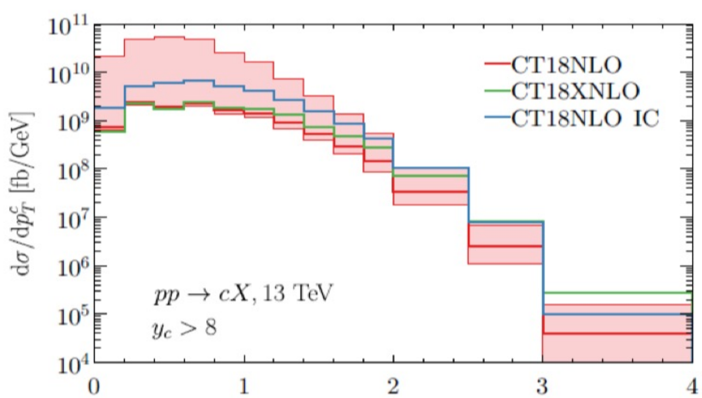


Small−x dynamics in CTEQ-TEA PDFs

K. Xie, WG2







- Both the BFKL resummation (CT18sx) and saturation (CT18X) models improve the description of HERA DIS data, which enhances gluon PDF at small x and low Q^2.
- F_L at $x \to 0$ is enhanced (stays ≈ constant) with resummation (saturation) models.
- Forward charm production at CERN FPF gets large uncertainty from small-x dynamics.

New CT18 Fitted Charm analysis

T. Hobbs, WG1

moments of the FC PDFs often used to characterize magnitude, asymmetry

$$\langle x^n \rangle_{c^\pm} = \int_0^1 dx\, x^n (c \pm \bar{c})[x, Q]$$

$$\langle x \rangle_{\mathrm{FC}} \equiv \langle x \rangle_{c^+}[Q_0 = 1.27\,\mathrm{GeV}]$$ ...at NNLO.

$$= 0.0048\,^{+0.0063}_{-0.0043}\,\left(^{+0.0090}_{-0.0048}\right),\ \mathrm{CT18\ (BHPS3)}$$

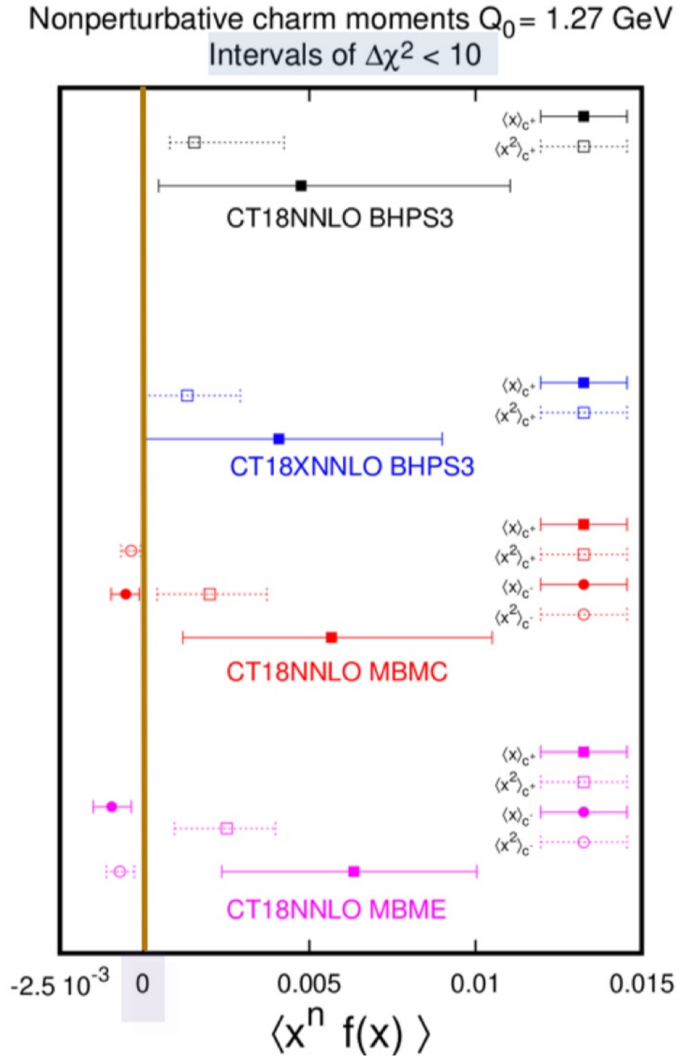
$$= 0.0041\,^{+0.0049}_{-0.0041}\,\left(^{+0.0091}_{-0.0041}\right),\ \mathrm{CT18X\ (BHPS3)}$$

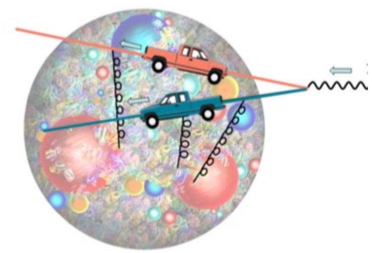
$$= 0.0057\,^{+0.0048}_{-0.0045}\,\left(^{+0.0084}_{-0.0057}\right),\ \mathrm{CT18\ (MBMC)}$$

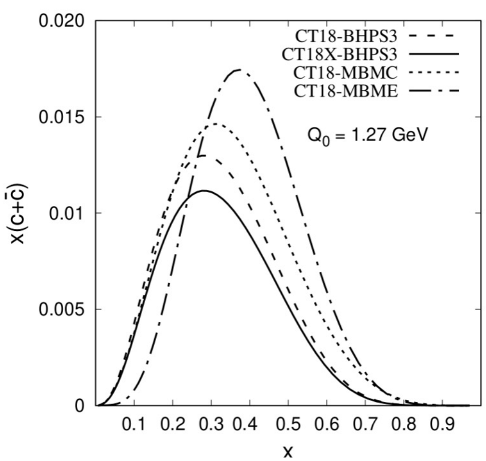
$$= 0.0061\,^{+0.0030}_{-0.0038}\,\left(^{+0.0064}_{-0.0061}\right),\ \mathrm{CT18\ (MBME)}$$

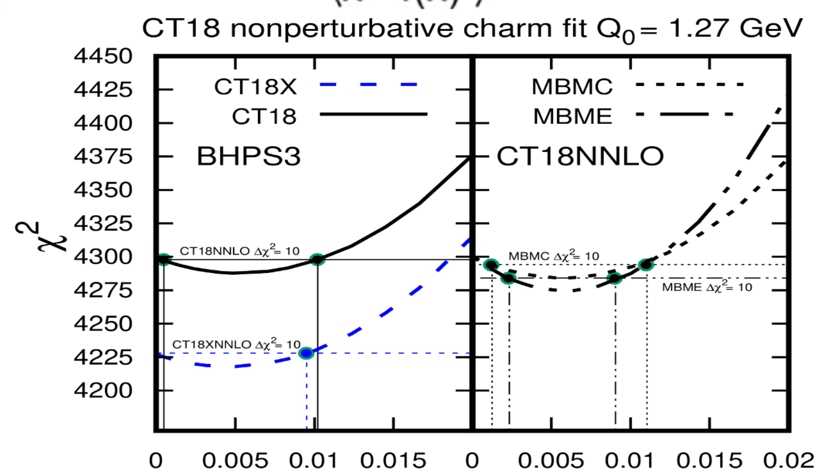
$\Delta\chi^2 \leq 10$ (restrictive tolerance)

$\Delta\chi^2 \leq 30$ (~CT standard tolerance)









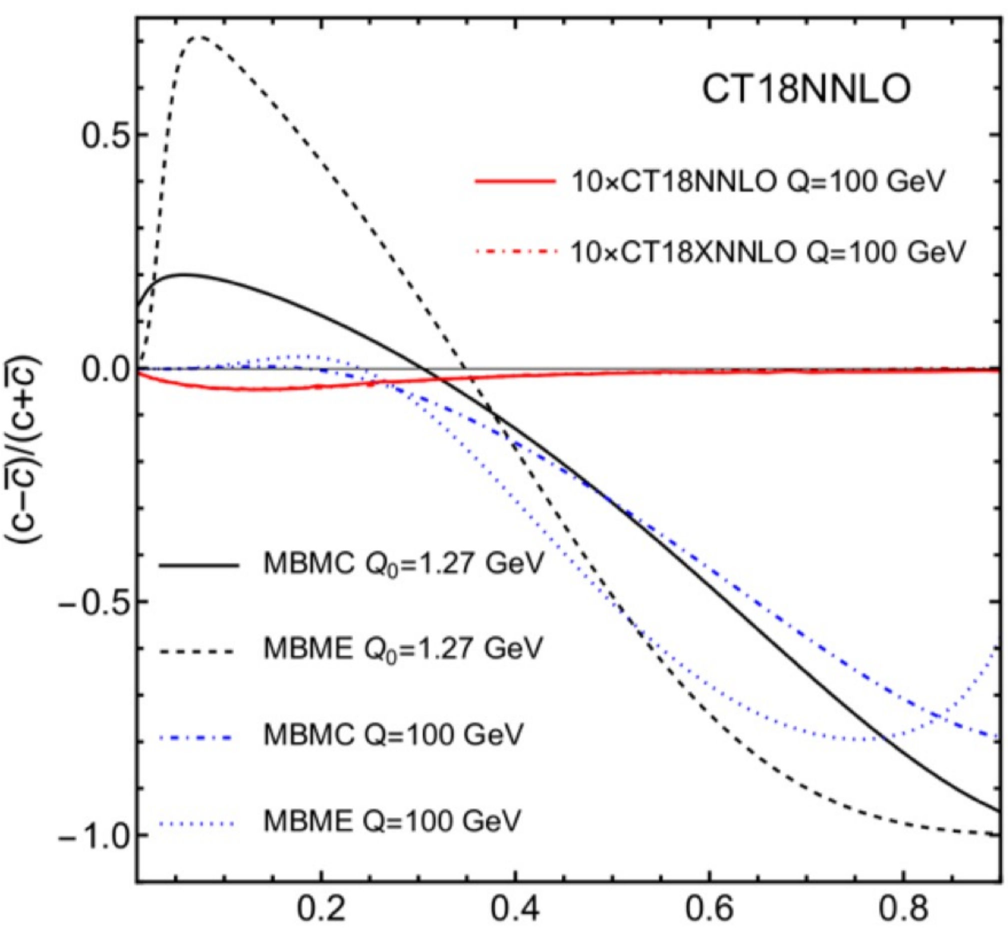
possible charm-anticharm asymmetries

CT18FC first modern PDF fit to break c=cbar

pQCD only very weakly breaks $c = \bar{c}$ through HO corrections

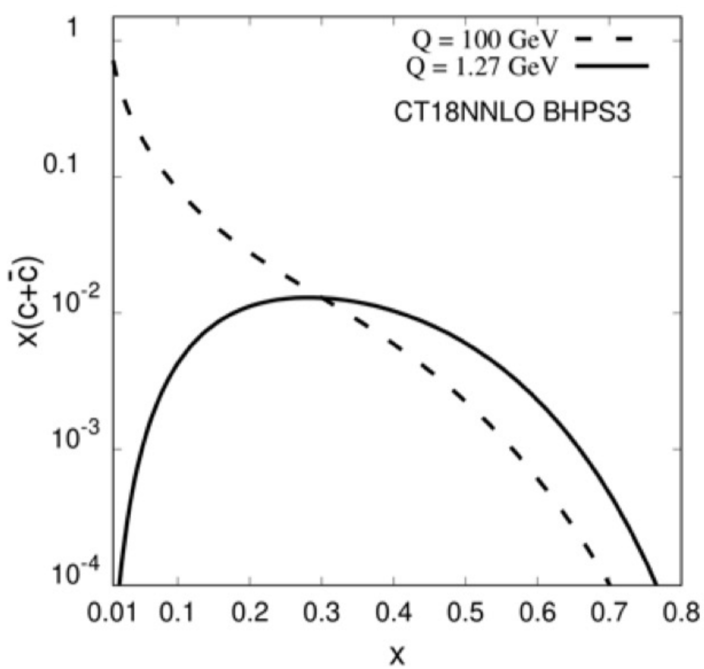
→ large(r) charm asymmetry would signal nonpert dynamics, IC

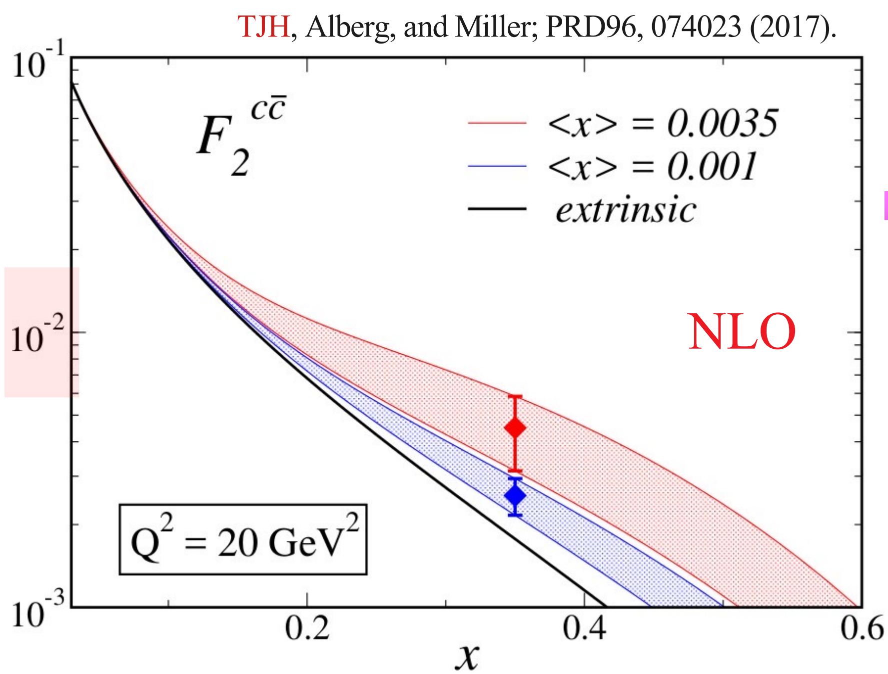
→ MBM breaks $c = \bar{c}$ through hadronic interactions



consider two MBM models as ***examples*** (not predictions)

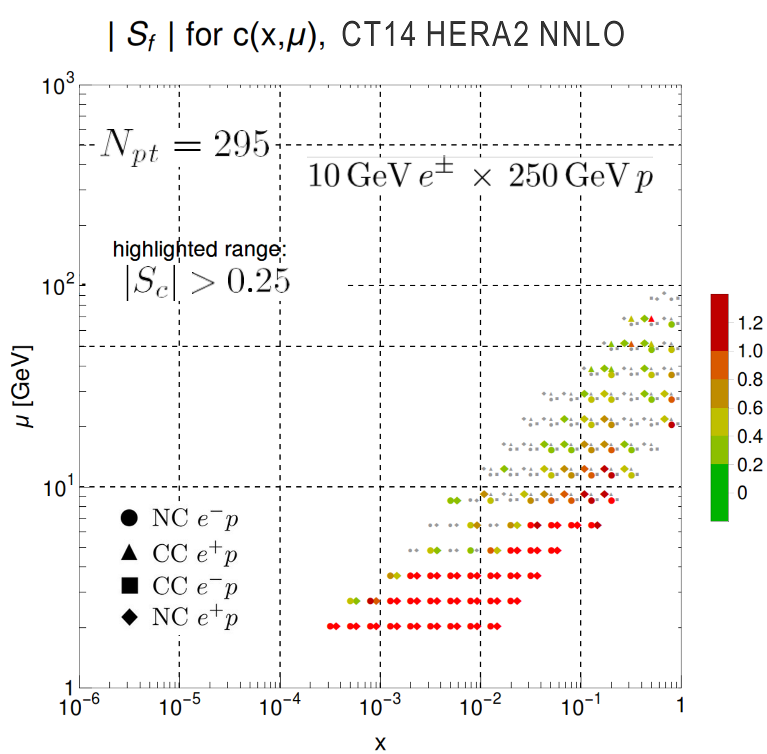
→ asym. small but ratio (left) can be bigger; will be hard to extract from data





conclusion: require more data/input to resolve FC

EIC + lattice QCD will constrain FC scenarios



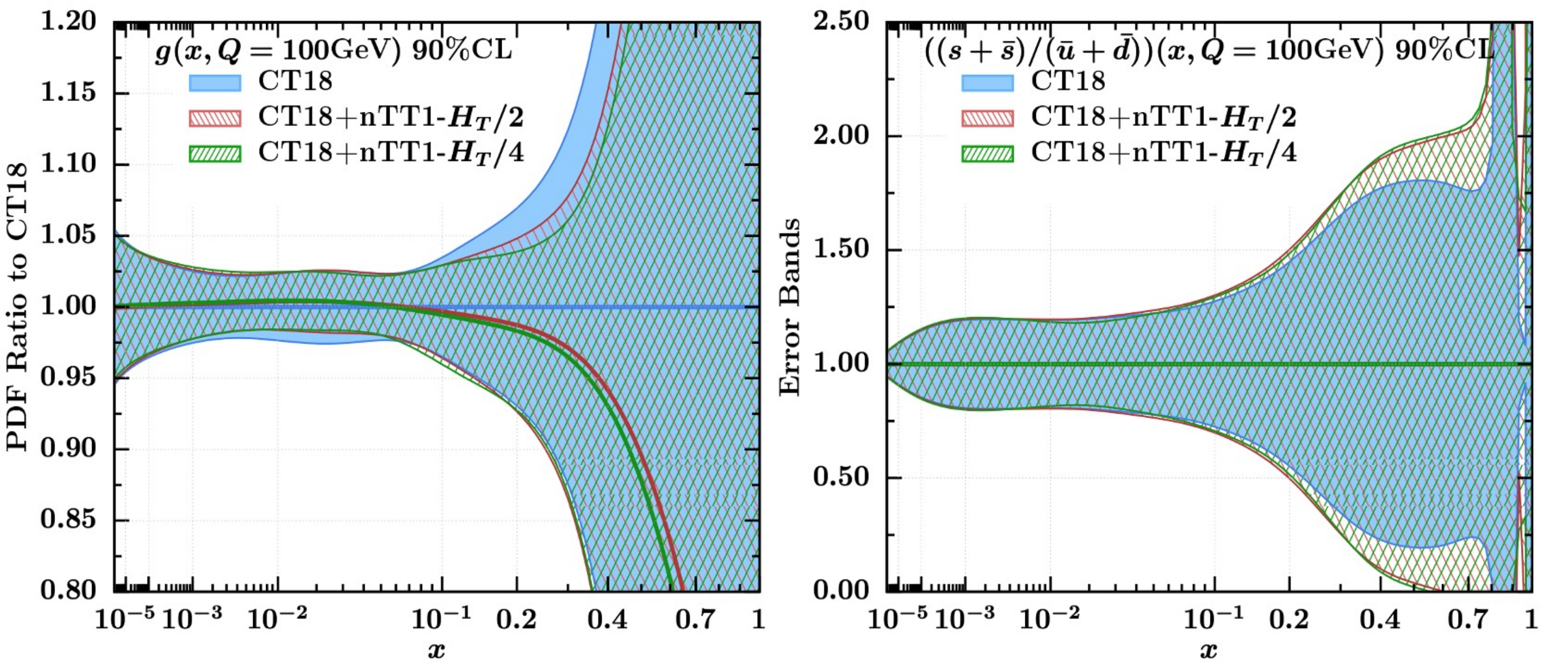
enhanced FC momentum implied by EMC data → small high-x effects in structure function; need high precision

- essential complementary input from LHC; CERN FPF

EIC will measure precisely in the few-GeV, high-x region where FC signals are to be expected

One slide on ttbar

Global fit: impact from new baseline with $t\bar{t}$@13 TeV



Theory predictions:

- MATRIX (Catani, Grazzini et al. PRD 2019)
- FastNNLO (Czakon, et al. 1704.08551)

Blue band: CT18NNLO 90% C.L.
Hatched bands: CT18+new-data
Green: $\mu_R = \mu_F = H_T/2$
Red: $\mu_R = \mu_F = H_T/4$

Differences related to different scale choices are well within the CT18 PDF error band.

Optimal baselines consists of combinations of 1D absolute Xsec from

- ATLAS all hadronic, ytt
- ATLAS lepton + jets, ytt and stat. comb. {ytt, Mtt, yBtt, HTtt} have very similar impact
- CMS dilepton, ytt
- CMS lepton + jets, Mtt

0

Reduction in scale uncertainty for gg observed in ggF Higgs region

Simultaneous CTEQ-TEA extraction of PDFs and SMEFT parameters from jet and $t\bar{t}$ data

T.J. Hobbs DIS

motivation

arXiv:2211.01094

- strong recent interest: model-independent BSM analyses

  EFT-based parametrizations: *e.g.*, SM effective field theory (SMEFT)

- EFT global analyses often assumed *fixed* SM calculations

  → PDFs not actively fitted alongside SMEFT parameters

  → could potentially bias resulting SMEFT analysis

- some recent studies: preliminary attempts at joint SMEFT/PDF fits

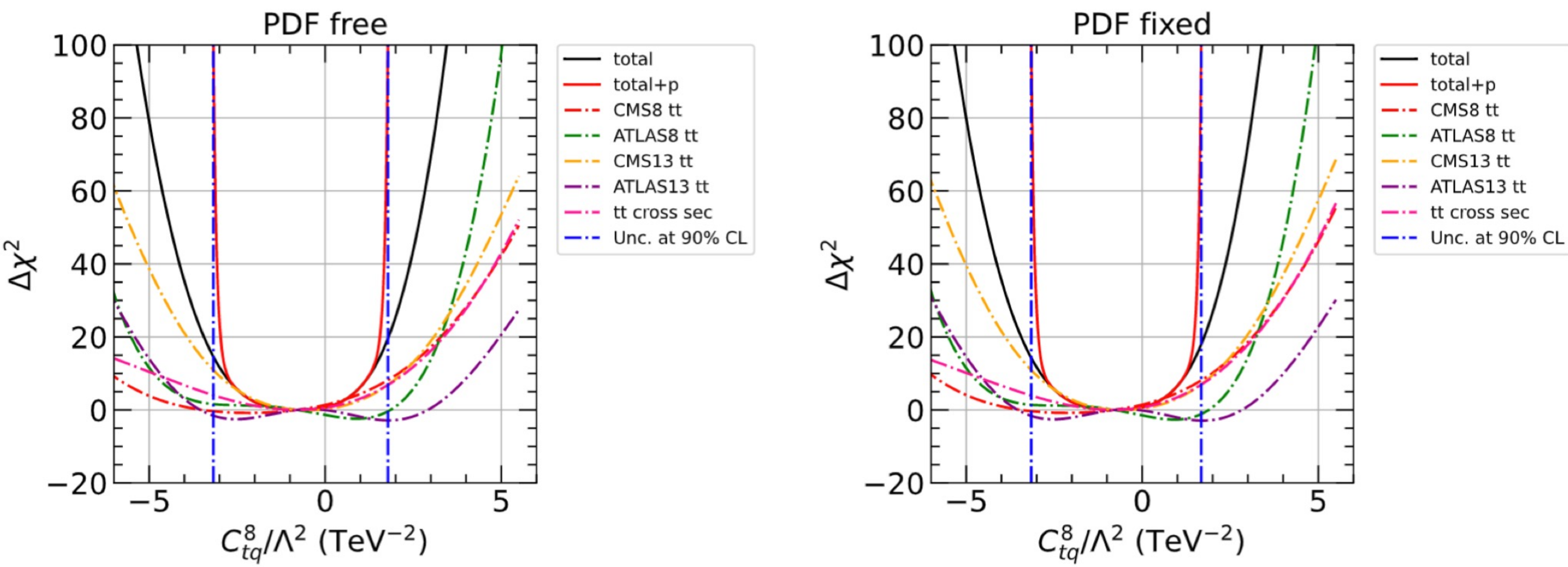
  → this work: explore in context of CTEQ-TEA (CT) framework

  → demonstration study focusing on select data: jet, $t\bar{t}$ production

  → examine possible PDF-SMEFT correlations

examine SMEFT uncertainties in joint PDF fit

- quantify SMEFT uncert. through Lagrange Multiplier (LM) scans:



→ constraints to top-associated Wilson coefficient, C^8_{tq}/Λ^2

- modest increase in uncertainty when co-fitted with PDFs
- predominantly *quartic* shapes for $\Delta\chi^2$ reflect pure SMEFT contributions $\sim\dfrac{1}{\Lambda^4}$

- growing interest in EFT global fits, joint analyses with PDFs
- completed first simultaneous PDF-SMEFT fit within CT framework

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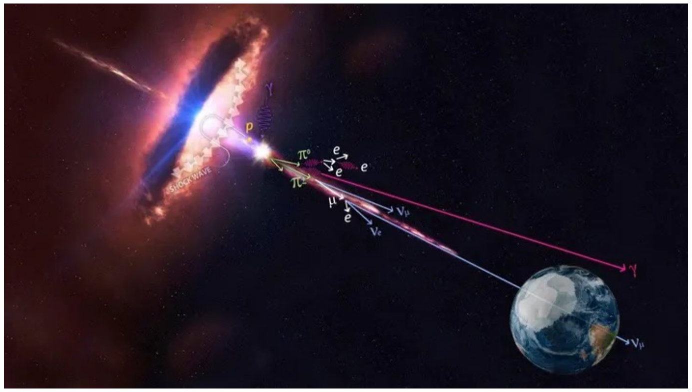
- explore jet and $t\bar{t}$ data as a demonstration study; examine correlations
  - → relatively weak PDF-SMEFT correlations
  - → evidence of correlation between high-x gluon, contact interaction
  - → these will increase with growing expt precision; e.g., at HL-LHC
  - → need further theory development; more operator combinations, …

- ML-based framework; scalable to larger SMEFT parameter space

UHE neutrinos: probe matter at extreme scales, BSM sensitivity

- relevant energies are those attained at *neutrino telescopes*, *e.g.*, IceCube



'high energy': $10^3 < E_\nu < 10^8 \text{ GeV}$

'ultra-high energy' (UHE): $E_\nu > 10^8 \text{ GeV}$

- far exceed energy scales achievable at terrestrial facilities (e.g., the LHC)
  - → potentially probe saturation physics at extremely low x
  - → test BSM scenarios: leptoquarks, hidden extra dimensions, …
  - → provide information on 6 of 9 flavor oscillation channels
  - → yield insights into astrophysics ('multi-messenger' astronomy)

- bridge between HEP-NP research areas

CT18 NNLO high-energy neutrino DIS cross sections from 10^2 to 10^7 GeV

K. Xie et al., arXiv:2303.13607

D. Stump, WG3

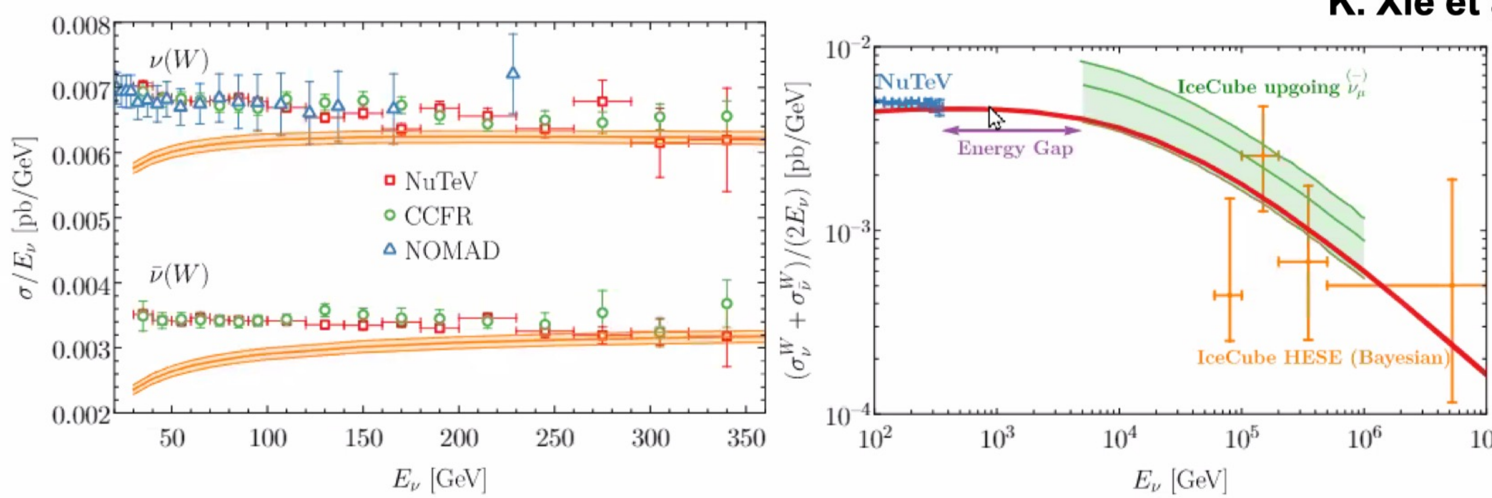
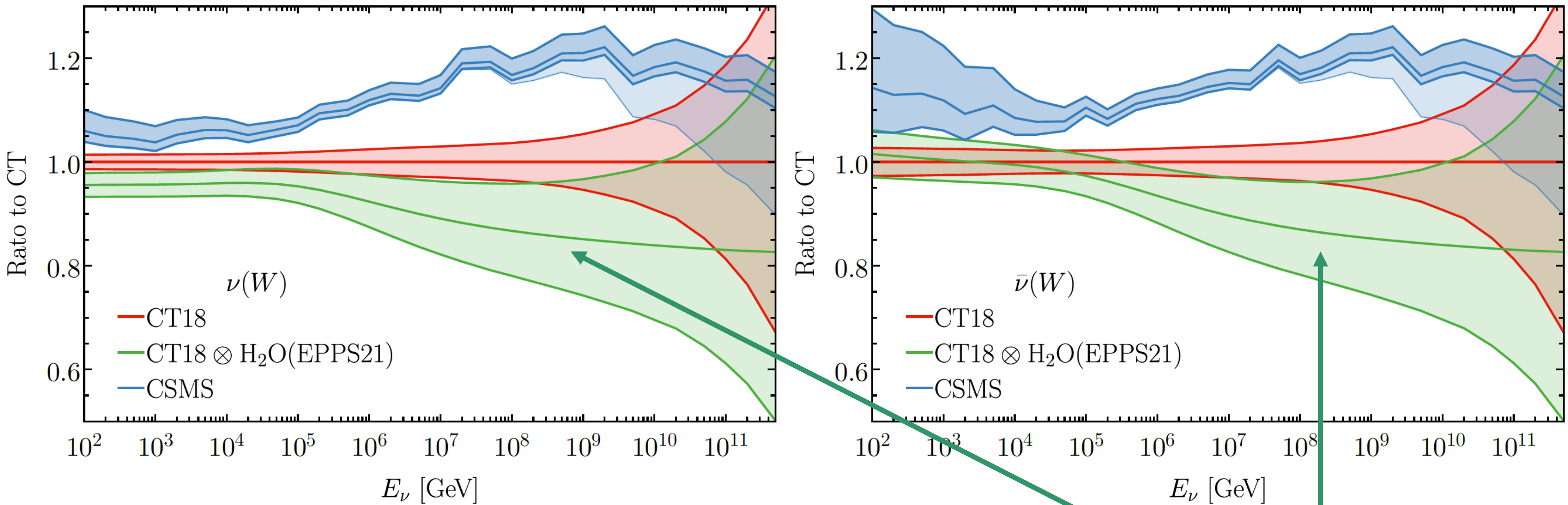


FIG. 20. Left: The CT18 predictions for the neutrino-isoscalar charged-current cross sections divided by the (anti)neutrino energy, σ/E_ν, in comparison with data measured at accelerator-based experiments [88–90]. Right: The CT18 prediction of the averaged neutrino-isoscalar charged-current cross sections divided by neutrino energy in the energy gap (360 GeV $\lesssim E_\nu \lesssim$ 6 TeV), which can be measured by the FASER and other FPFs at the LHC [15, 16]. We included cross sections below 360 GeV measured by NuTeV [88] and above 6.3 (60) TeV by IceCube upgoing $\overset{(-)}{\nu}_\mu$ [9] (HESE Bayesian [10]) analyzes.

QCD uncertainties remain challenging at high energies



- ❑ combined CT18 and EPPS21 uncertainties represent a more aggressive scenario

  → nCTEQ15-based predictions enlarge high-energy uncertainties further

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- ❑ many additional model considerations: heavy-quark mass effects; extrapolations, …

  → compelling arena to test QCD across HEP-NP!

arXiv: 2303.13607

e.g., nuclear models in saturation regime could strengthen BSM sensitivity…

Low-x (n)PDF and theory uncertainties form a limitation to accuracy at very high energies

Toward a new generation of CT202X PDFs

1. **Identify sensitive, mutually consistent new experimental data sets** using preliminary fits and fast techniques (L_2 sensitivities and $ePump$)
2. Implement N3LO QCD and NLO EW contributions as they become available. N3LO accuracy is reached only when N3LO terms are **fully** implemented.
3. Meanwhile, "**NNLO+" PDFs**: e.g., include theoretical uncertainty due to QCD scale dependence for key processes as has been done in CT18/CT18X NNLO PDFs
4. Explore quark sea flavor dependence: $s - \bar{s}$ (CT18As), fitted charm (CT18FC),…
5. Include lattice QCD constraints (CT18As_Lat)
6. Next-generation PDF uncertainty quantification: META PDFs, Bézier curves, MC sampling, ML stress-testing, multi-Gaussian approaches, …

↓ Krieste, Hobbs—forthcoming study

↓ see arXiv:2311.08447 on archive yesterday

Exploratory effort on ~n3lo PDFs at the moment, but more will come in the future

Extras

ChatGPT 3.5

HU **You**

write a joke about Donald trump that has to do with high energy physics

ChatGPT

Why did Donald Trump apply for a job at the Large Hadron Collider?

Because he heard they were looking for someone with "tremendous energy" to lead the charge in particle politics!

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ChatGPT

Why did Donald Trump enroll in a physics class?

Because he wanted to learn the art of "alternative dimensions" where everything is relative, especially when it comes to polls!

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…as I was quoted in this week's Higgs XSWG meeting (re:aN3LO PDFs), chatGPT jokes about Donald Trump and physics are "informative but not definitive"

selecting dominant SMEFT operators

- this study: dim-6 operators only

  → dim-8 contributions small (may be relevant for future precision)

  → consider several SMEFT operators associated with jet, $t\bar{t}$

jet production: contact interaction

$$O_1 = 2\pi \left(\sum_{i=1}^{3} \bar{q}_{Li} \gamma_\mu q_{Li} \right) \left(\sum_{j=1}^{3} \bar{q}_{Lj} \gamma^\mu q_{Lj} \right)$$

Warsaw operator basis

top production

$$O^1_{tu} = \sum_{i=1}^{2} (\bar{t}\gamma_\mu t)(\bar{u}_i \gamma^\mu u_i) ,$$

$$O^1_{td} = \sum_{i=1}^{3} (\bar{t}\gamma^\mu t)(\bar{d}_i \gamma_\mu d_i) ,$$

$$O_{tG} = i g_s (\bar{Q}_{L,3} \tau^{\mu\nu} T^A t) \tilde{\varphi} G^A_{\mu\nu} + \text{h.c.} ,$$

$$O^8_{tq} = \sum_{i=1}^{2} (\bar{Q}_i \gamma_\mu T^A Q_i)(\bar{t}\gamma^\mu T^A t) ,$$

- have imposed multiple symmetries on SMEFT space

explore SMEFT constraints from range of LHC expts

- included on top of default CT18 fitted experiments

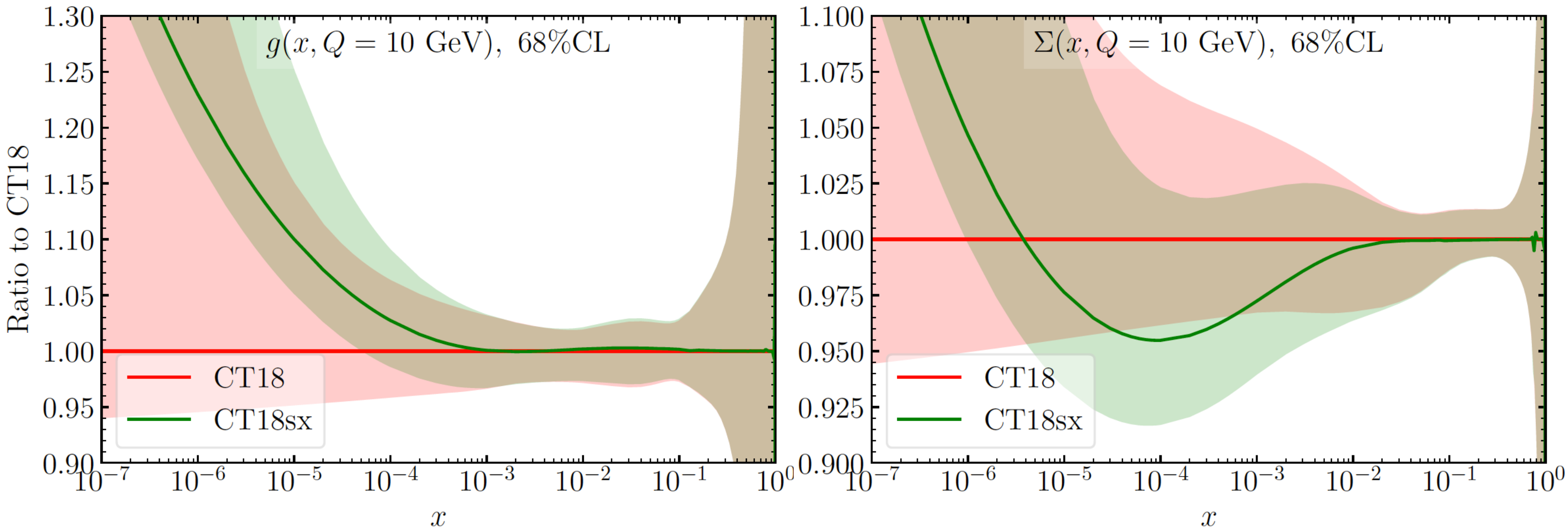
  → nominally fit ~112 fb^{-1} of top data; ~67 fb^{-1} for jet production

Experiments	$\sqrt{s}$(TeV)	$\mathcal{L}(fb^{-1})$	observable	N_{pt}
*† LHC(Tevatron)	7/8/13(1.96)	—	$t\bar{t}$ total cross section	8
*† ATLAS $t\bar{t}$	8	20.3	1D dis. in $p_{T,t}$ or $m_{t\bar{t}}$	15
*† CMS $t\bar{t}$	8	19.7	2D dis. in $p_{T,t}$ and y_t	16
CMS $t\bar{t}$	8	19.7	1D dis. in $m_{t\bar{t}}$	7
*† ATLAS $t\bar{t}$	13	36	1D dis. in $m_{t\bar{t}}$	7
*† CMS $t\bar{t}$	13	35.9	1D dis. in $m_{t\bar{t}}$	7
*† CDF II inc. jet	1.96	1.13	2D dis. in p_T and y	72
*† D0 II inc. jet	1.96	0.7	2D dis. in p_T and y	110
*† ATLAS inc. jet	7	4.5	2D dis. in p_T and y	140
*† CMS inc. jet	7	5	2D dis. in p_T and y	158
* CMS inc. jet	8	19.7	2D dis. in p_T and y	185
† CMS dijet	8	19.7	3D dis. in $p_T^{ave.}$, y_b and y^*	122
† CMS inc. jet	13	36.3	2D dis. in p_T and y	78

*(in nominal top fits); †(in nominal jet fits)

cross sections sensitive to proton PDF extrapolation region

- gluon and singlet PDF uncertainties become poorly controlled below $x \lesssim 10^{-5} - 10^{-4}$



- parametrization, low-x resummation and related effects become significant

Error ellipses for new PDFs

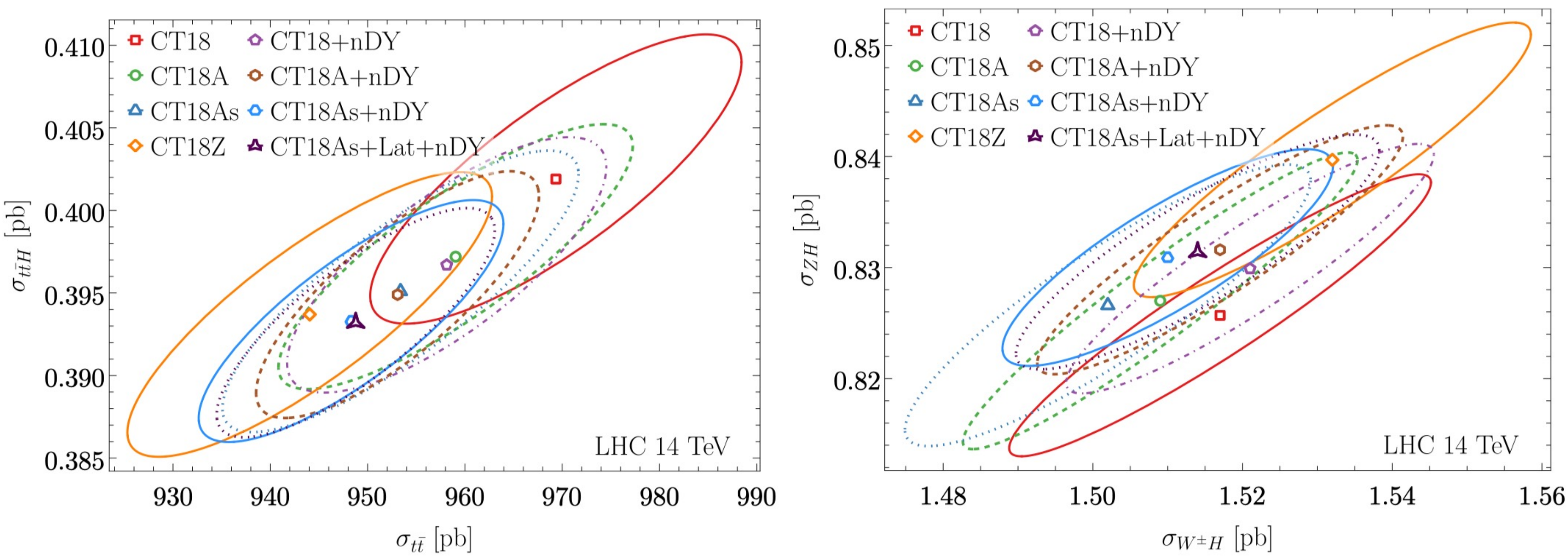


Figure 3: The correlation ellipses in the 68% confidence level between the inclusive $t\bar{t}$ and $t\bar{t}H$, $W^{\pm}H$ and ZH production at the 14 TeV LHC.