Global PDF Analyses: Latest News

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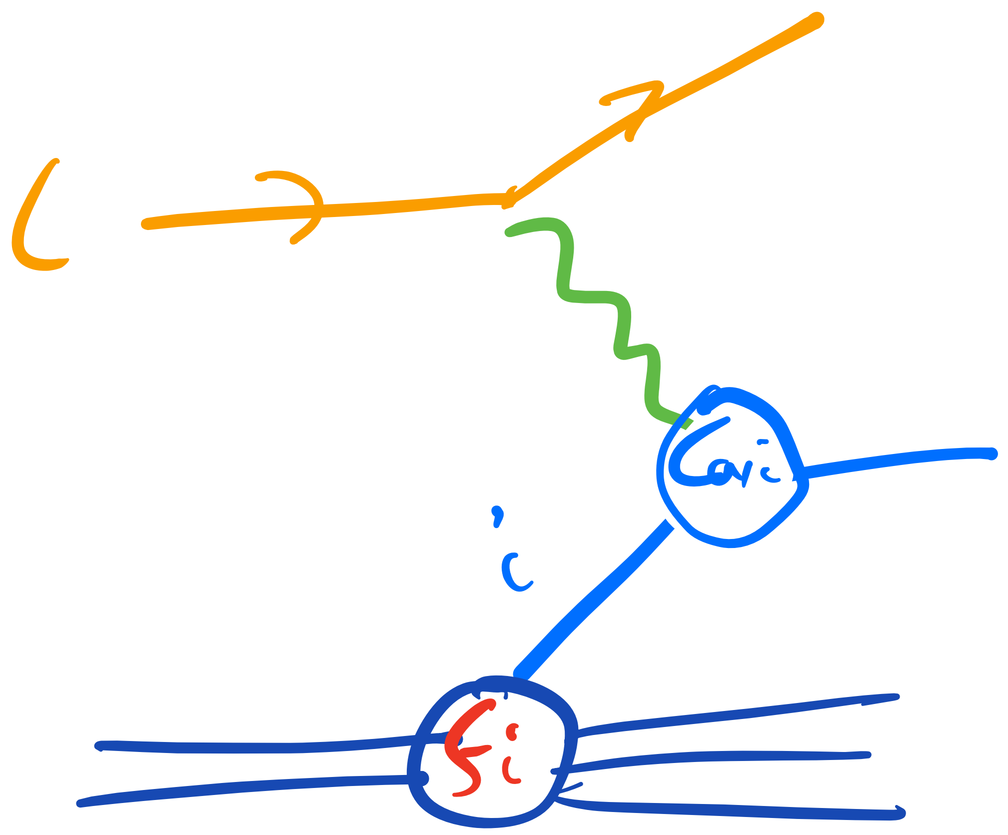
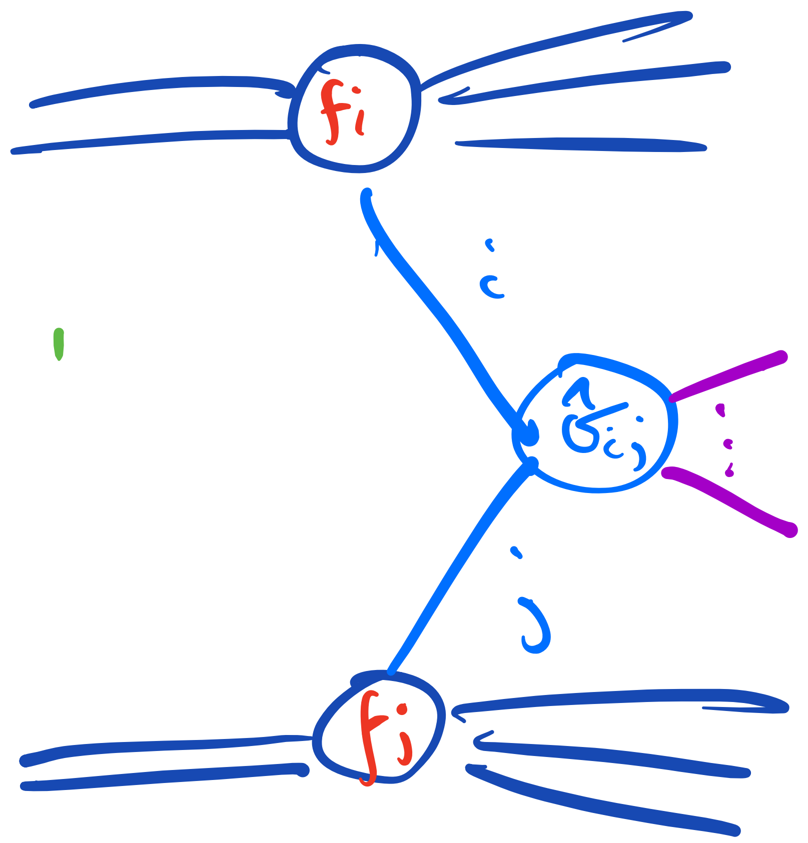
DIS 2024, Grenoble, 8th April 2024

UCL

Setting the Scene…

- Parton distribution functions (PDFs): a key ingredient in hadron collider physics!
- QCD factorization: perturbative physics separated from **universal** non-perturbative PDFs





$$F_a(x, Q^2) = \sum_{i=q,\bar{q},g} \int_0^1 \frac{dz}{z} f_i(z, Q^2) C_{a,i}\left(\frac{x}{z}, \alpha_S(Q^2)\right) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)$$

$$\sigma = \sum_{ij} \int_{x_{min}}^1 dx_1 dx_2\, f_i(x_1, \mu_f^2) f_j(x_2, \mu_f^2) \hat{\sigma}_{ij}(x_1 p_1, x_2 p_2, Q, \mu_F^2)$$

$$\text{Factorization} \Rightarrow f_i^{\text{DIS}}(x, Q^2) \equiv \{f_i^{\text{Collider}}(x, Q^2)\}$$ ← **Drell Yan, Jets, Higgs…**

- PDFs at different scales connected by DGLAP evolution $\frac{\partial f_q^{NS}(x, \mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dz}{z} f_q^{NS}(z, \mu^2) P_{qq}^{NS}(x/z)$ **etc…**

- Foundation of global PDF fits: use data at different scales and processes to extract PDFs.

Global PDF Fits

- Basic idea is simple: $\text{Data} = \text{PDF} \otimes \sigma_H$ but many ingredients enter! Three key areas:

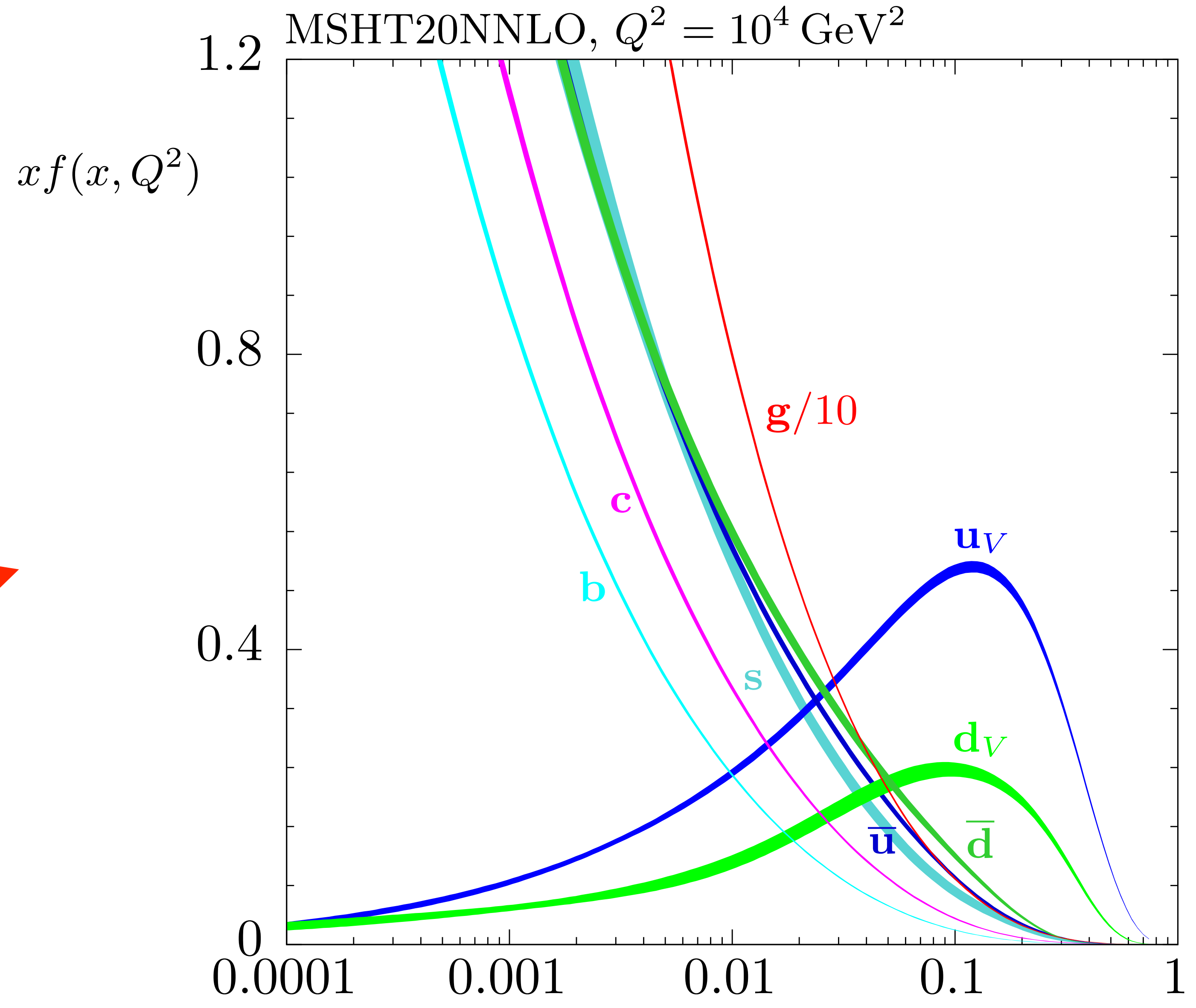
measure fit predict

Methodology

- PDF parameterisation, uncertainty prescription…

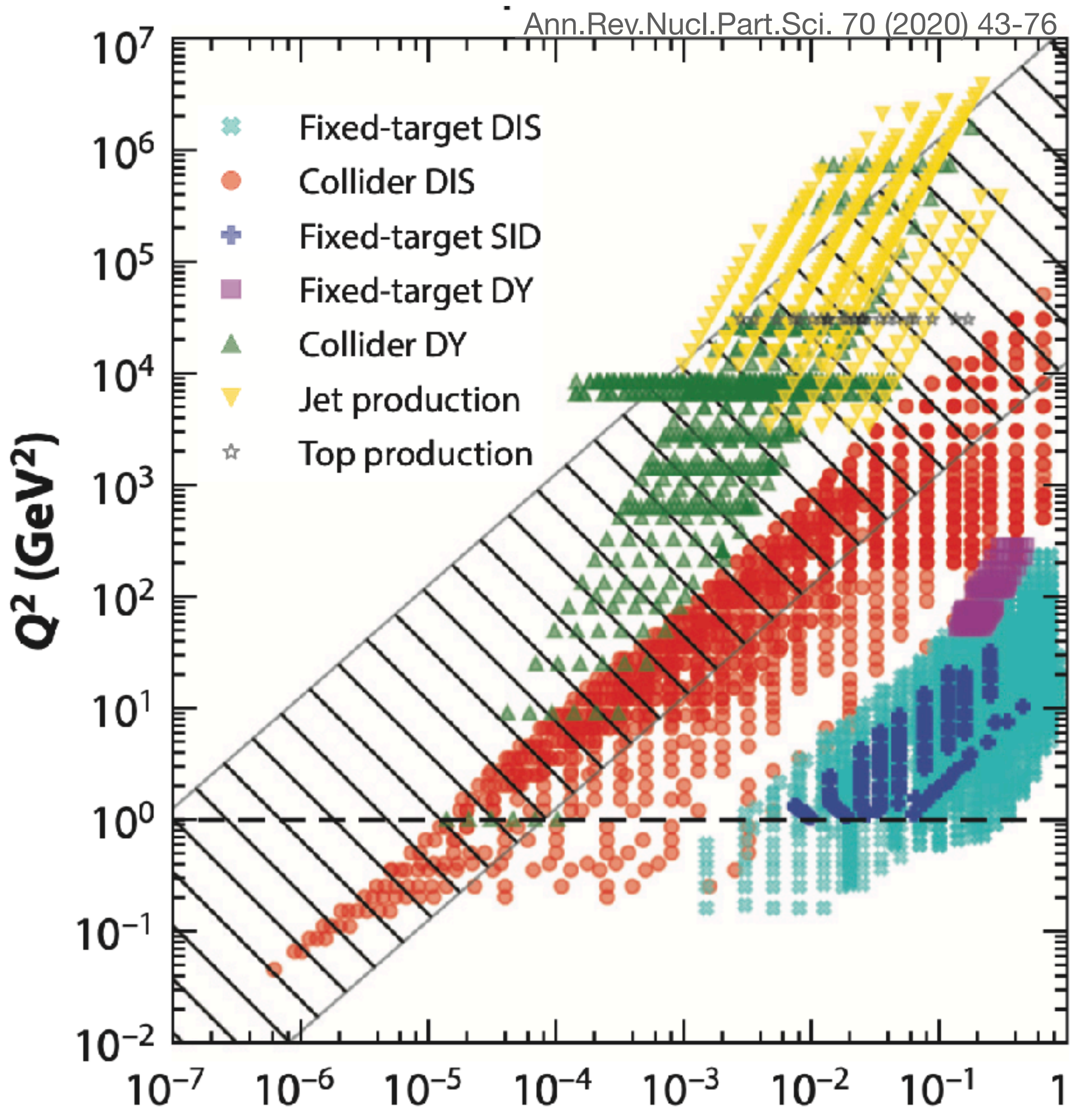
Theory

- High precision: NNLO QCD + NLO EW the standard



Data

- From fixed target, to HERA DIS and collider. LHC data increasingly important.



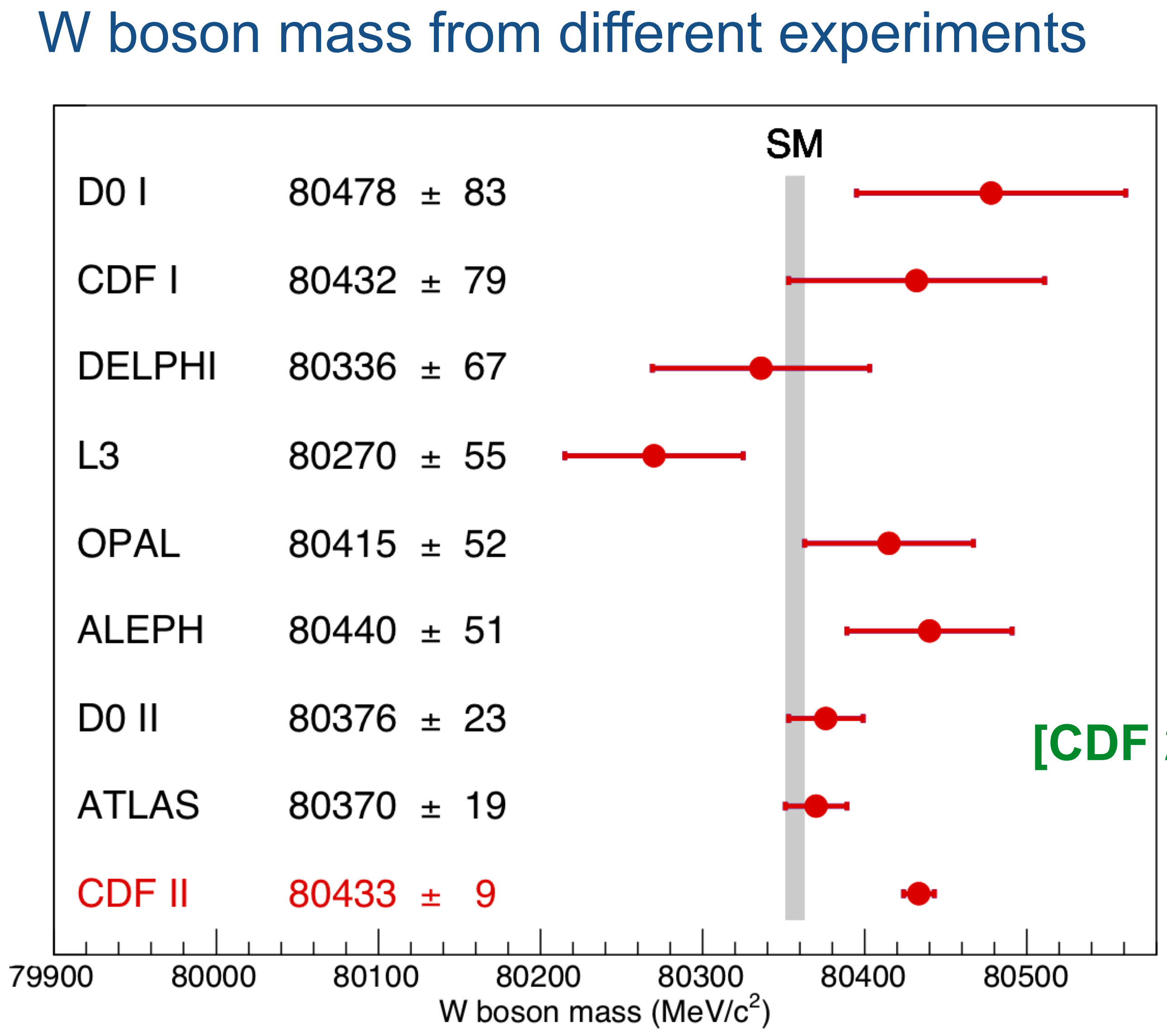
- Aim: high precison theory + wide range of data $\longrightarrow$ **precise** + **accurate** PDFs
- Alternative/complementary route: input from lattice.

See talk by H-W Lin

Why do we care about PDFs?

- The LHC is a Standard Model precision machine, and PDFs are a key ingredient in this. Increasingly a limiting factor:

W mass



[CDF 2022]

Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ (PDG 2020)

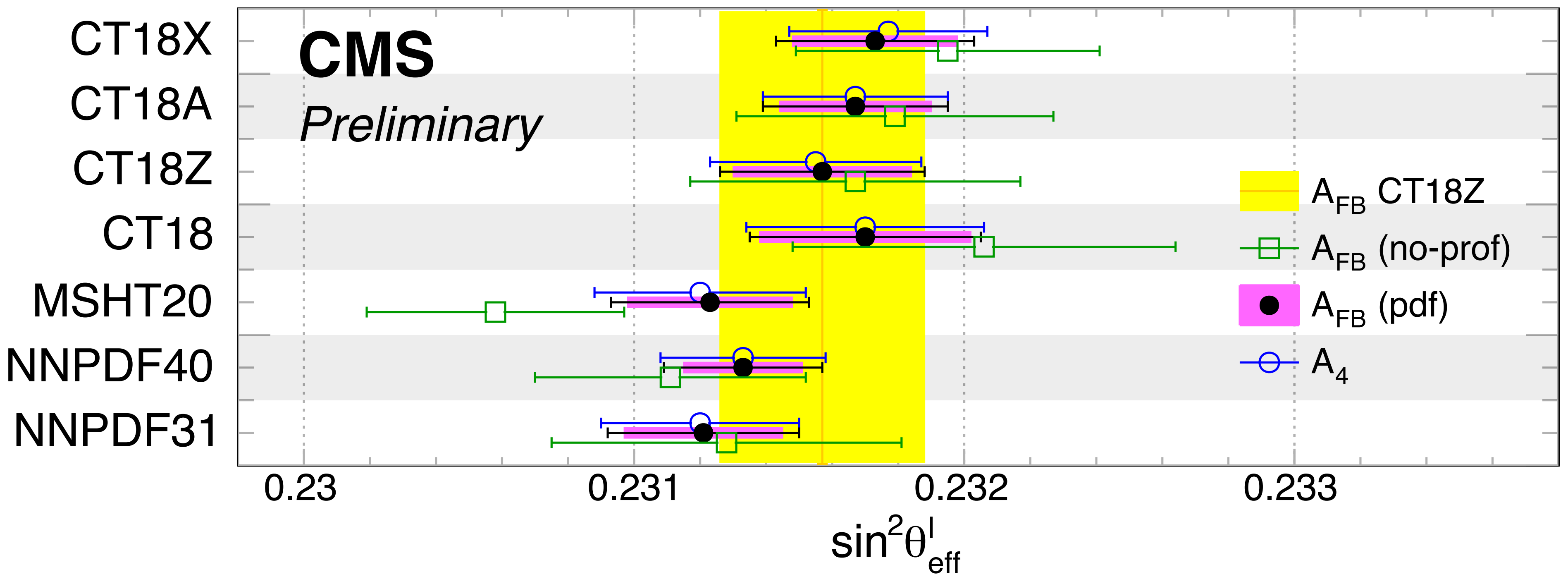
LHCb measurement : $M_W = 80{,}354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ *[JHEP* **2022,** 36 (2022)]

PDF unc. of CDF / ATLAS / LHCb: 3.9 / 8 / 9 MeV

$$\sigma_{\rm PDF} \sim \sigma_{\rm tot}/2$$

(up to)

$\sin^2 \theta^l_{\rm eff}$

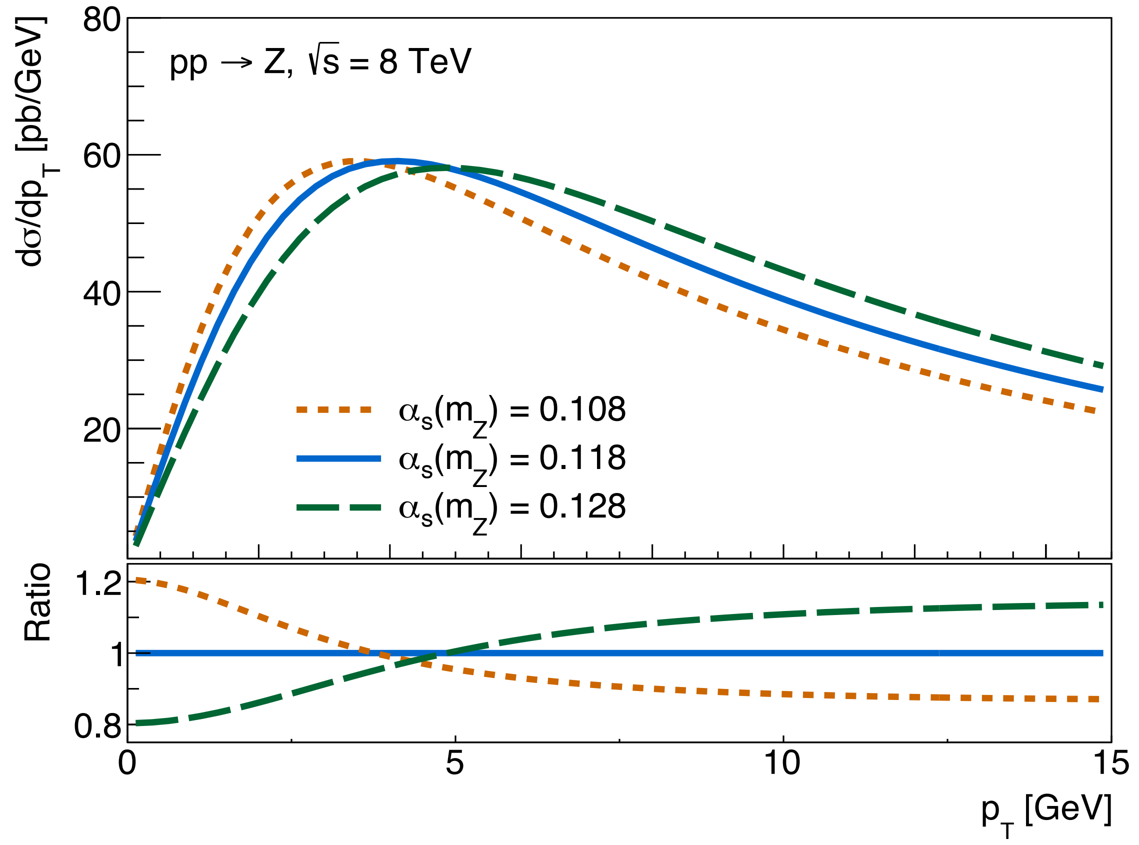


CMS PAS SMP-22-010

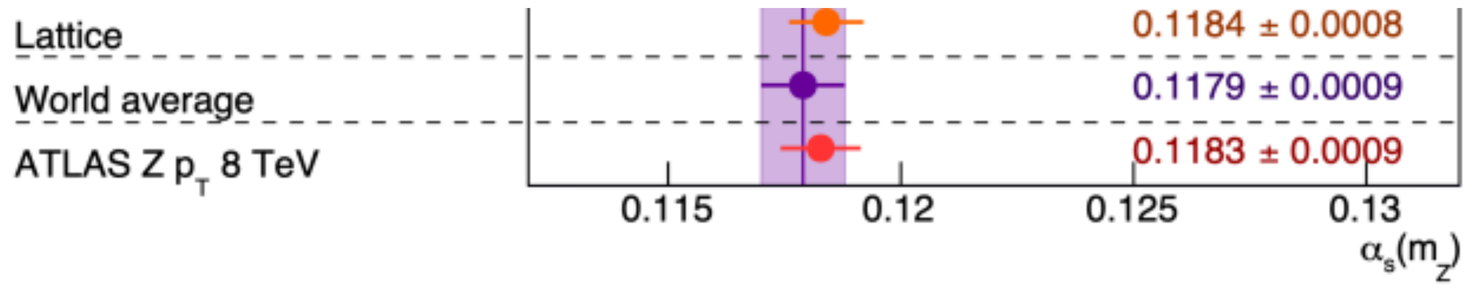
$$\sin^2\theta^\ell_{\rm eff} = 0.23157 \pm 0.00010({\rm stat}) \pm 0.00015({\rm syst}) \pm 0.00009({\rm theo}) \pm 0.00027({\rm PDF}),$$

$$\sigma_{\rm PDF} \sim \sigma_{\rm tot}$$

α_S



ATLAS, 2309.12986

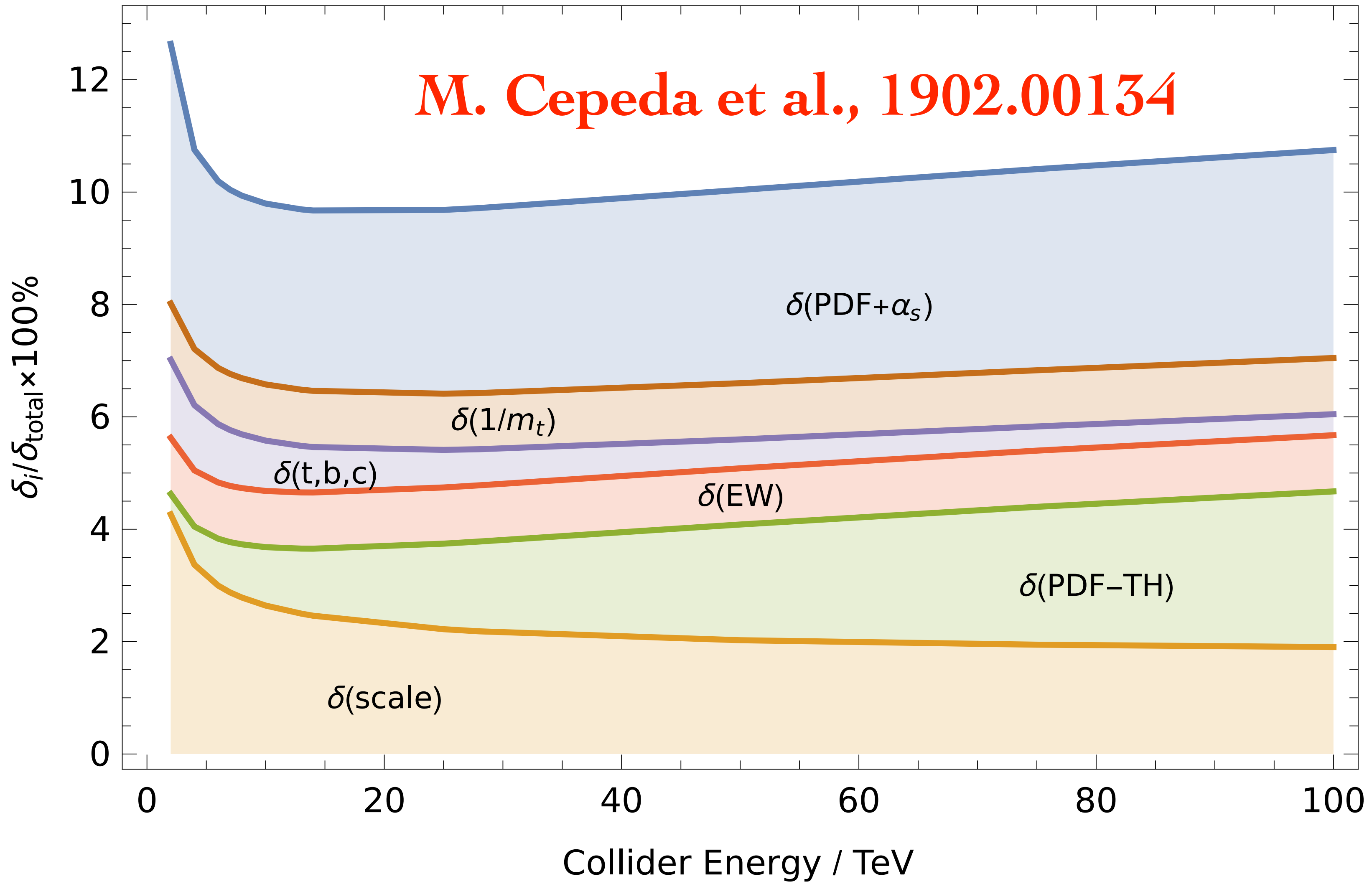


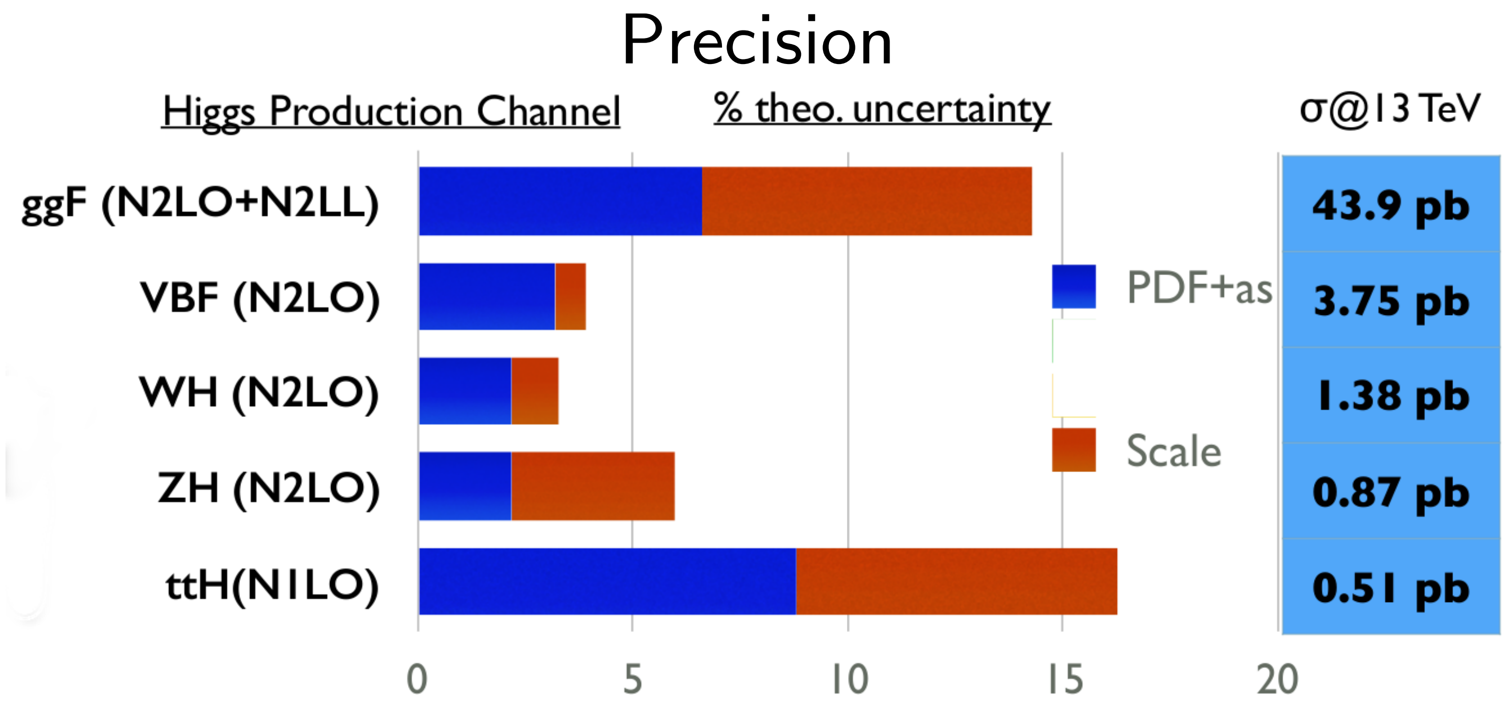
$$\sigma_{\rm PDF} \sim \sigma_{\rm tot}/2$$

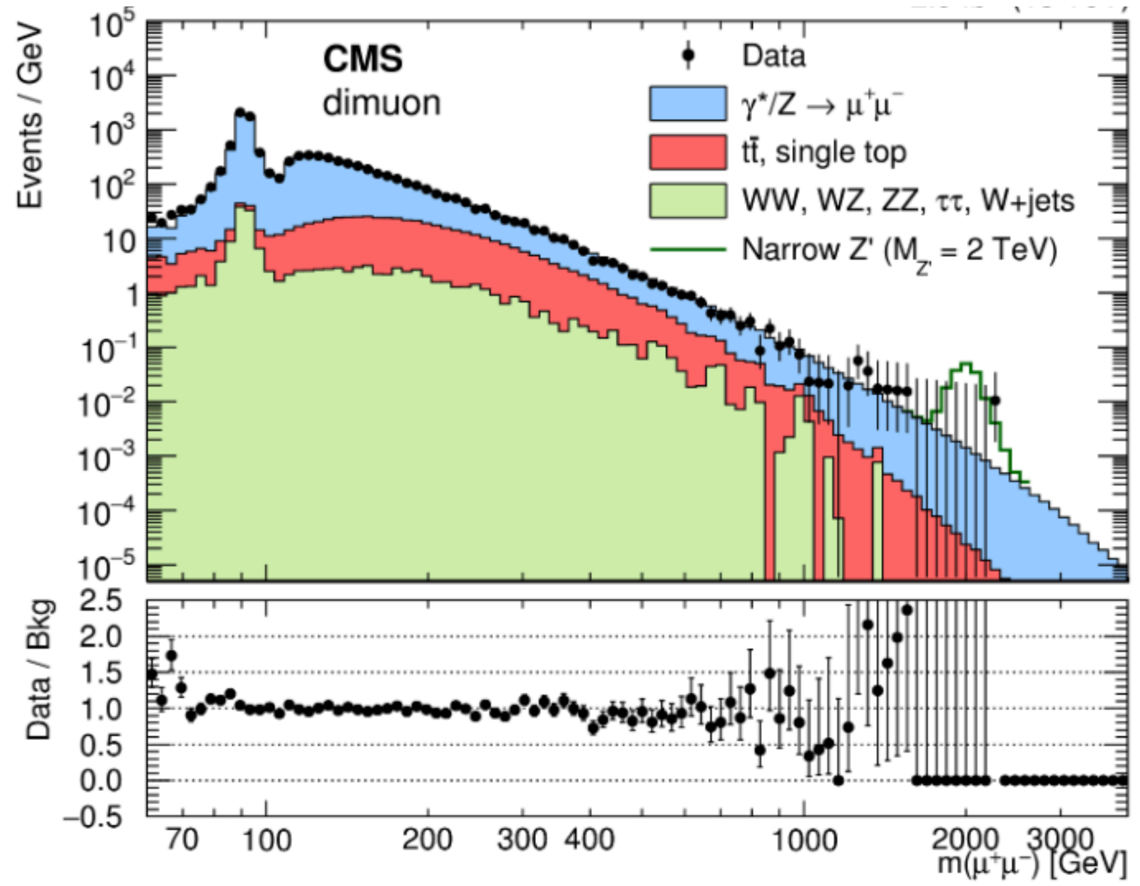
Disclaimer: will generally refer to papers by their arxiv number, even if published.

- The LHC is a **Higgs** factory: PDFs play a key role here.

Image Credit: Emanuele Nocera



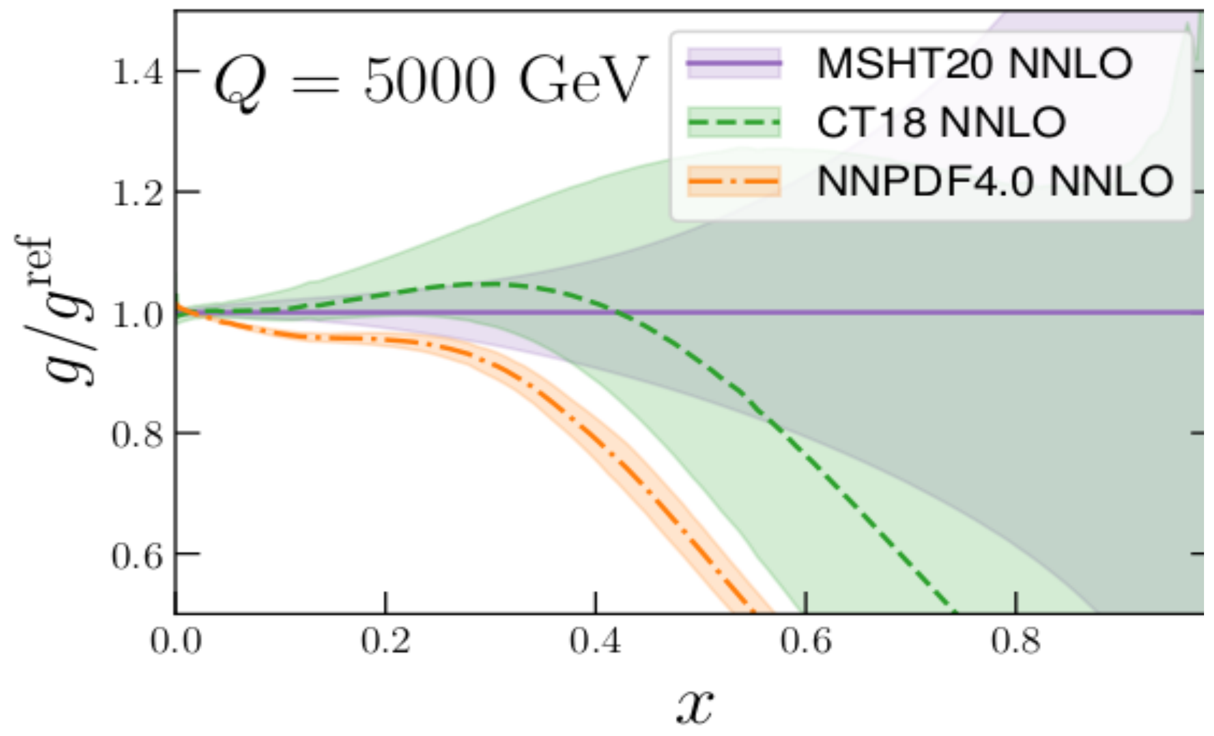




- The LHC is a **BSM** search machine. Often need PDFs here.

- High mass = high x , where PDFs are less well known. Key when looking for small/smooth deviations.

Image Credit: Tom Cridge



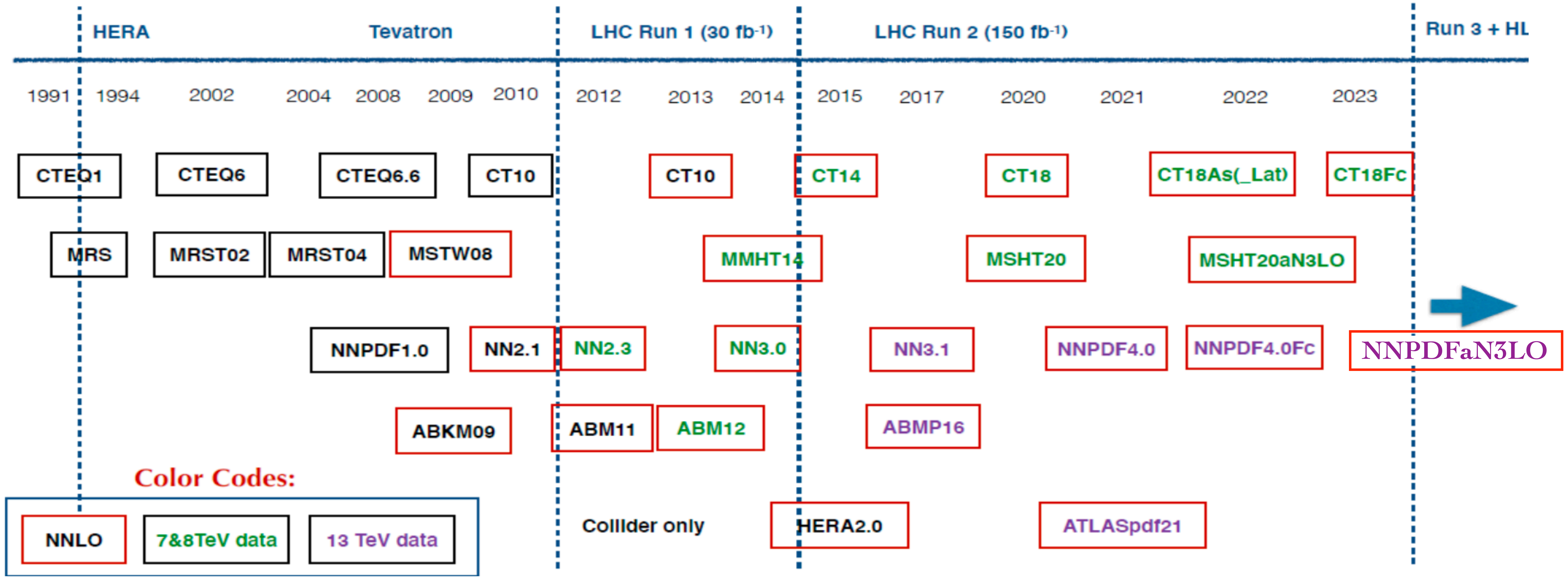
Major PDF Analyses

- Multiple PDF analyses, with different methodogies and datasets. Cannot cover these all here!
- Major releases from 3 global fitters (CT, MSHT, NNPDF) ~ 2 or more years ago. But they have been busy:

★ Major push to approximate N3LO + theoretical uncertainties

★ QED/EW corrections standard

★ Many dedicated studies



- These advances all build towards next generation of releases.

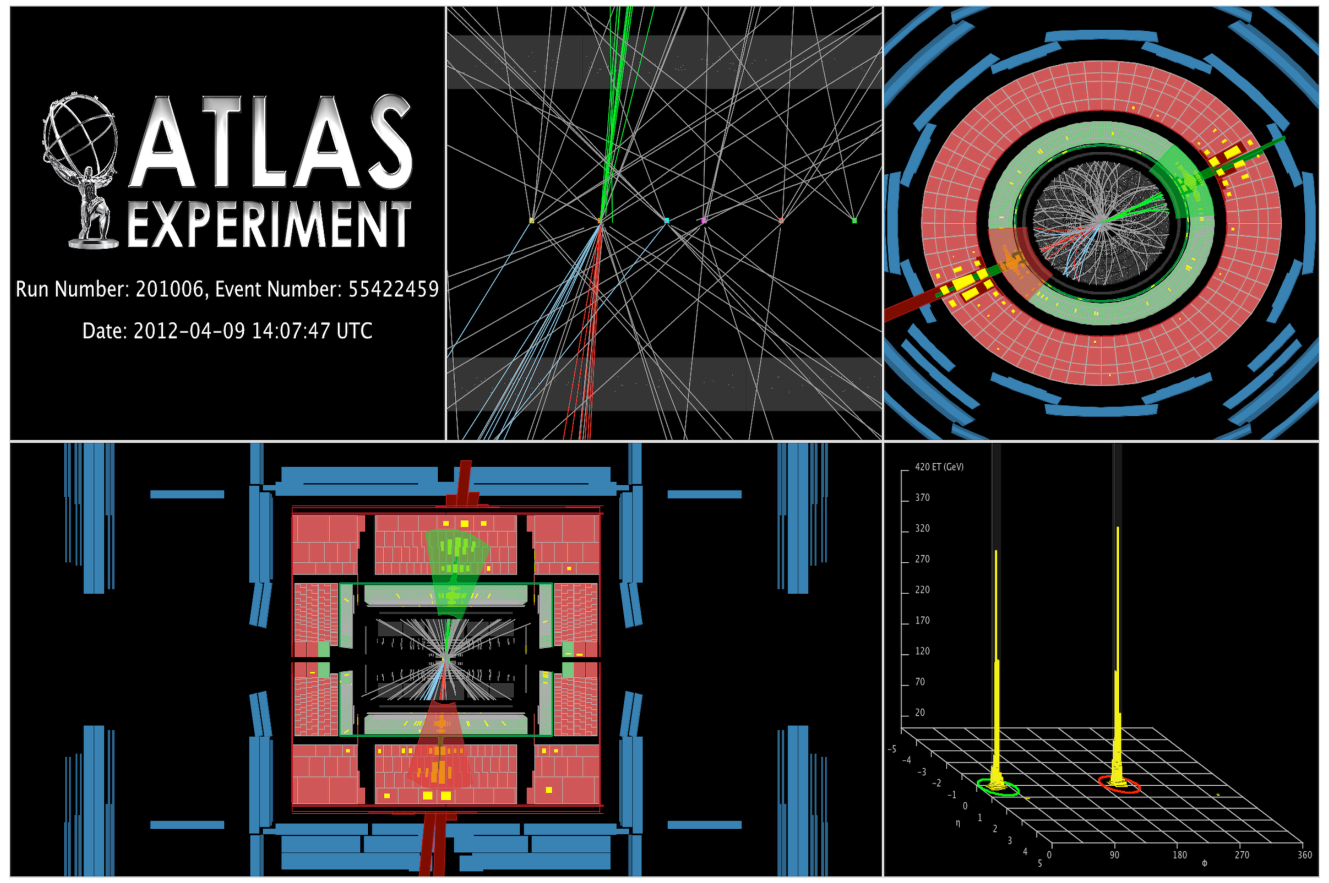
Image Credit: Jun Gao

LHC data!

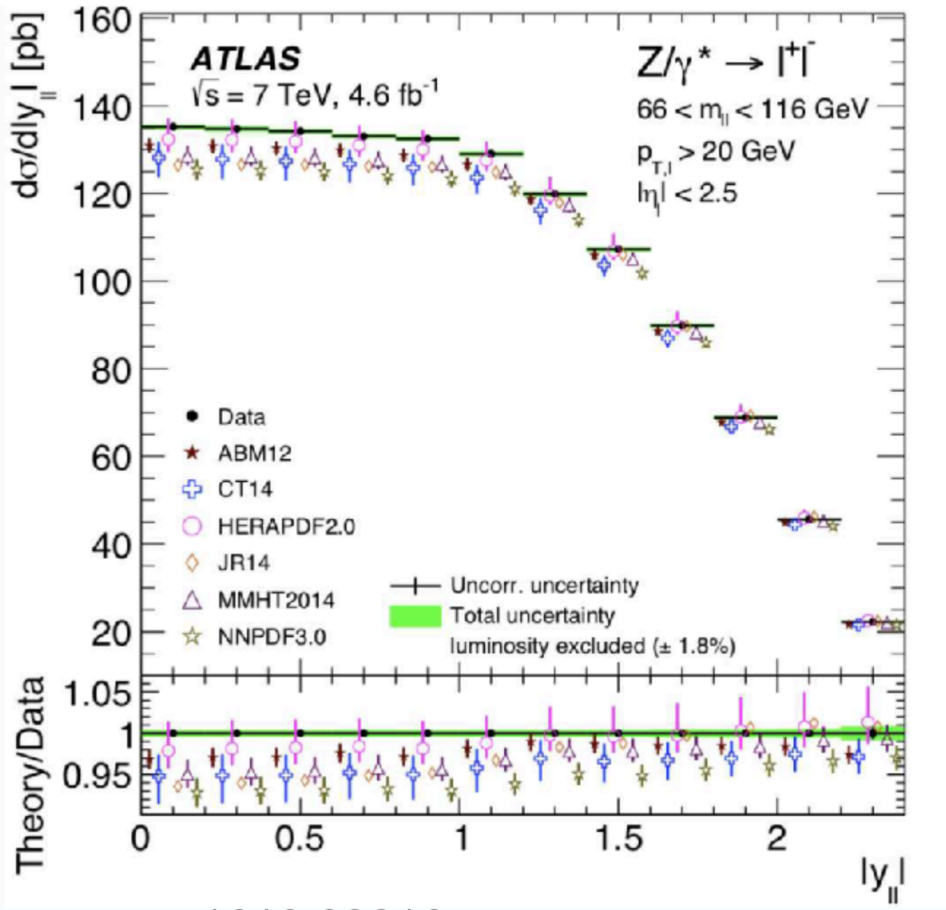
Maria Ubiali, ep/ea synergy workshop, CERN Feb 24

- A wealth of data from the **LHC**, playing a significant role in PDF fits:

★ **High energy** data - probing the high x region

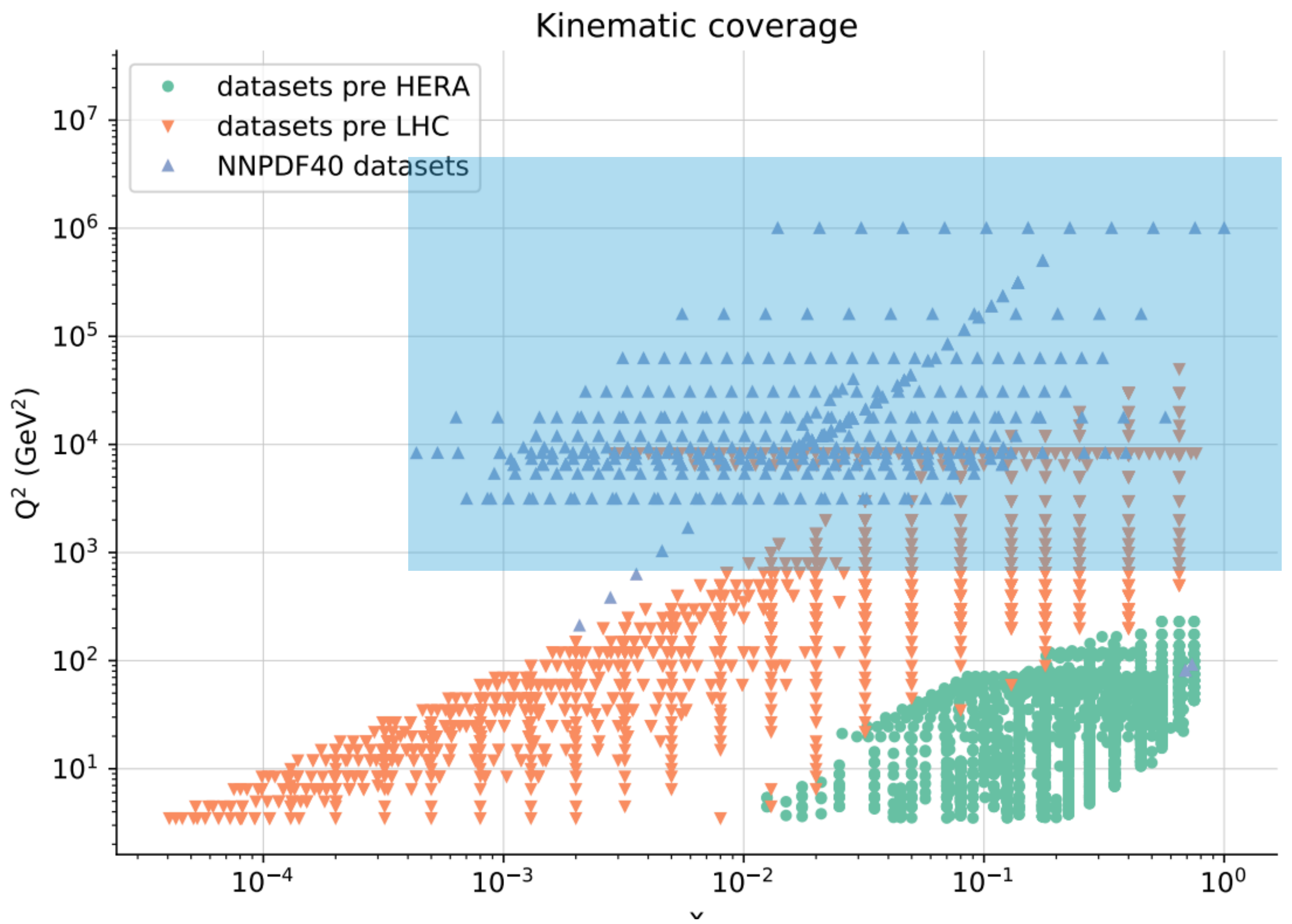


★ **High precision** data - DY and flavour structure



1612.03016

- Strong requirement for (at least?) NNLO theory.
- High precision data $\Rightarrow$ nowhere to hide: clear account of experimental, theoretical and methodological issues and differences essential.



NNPDF4.0: About 30% of input data are LHC data!

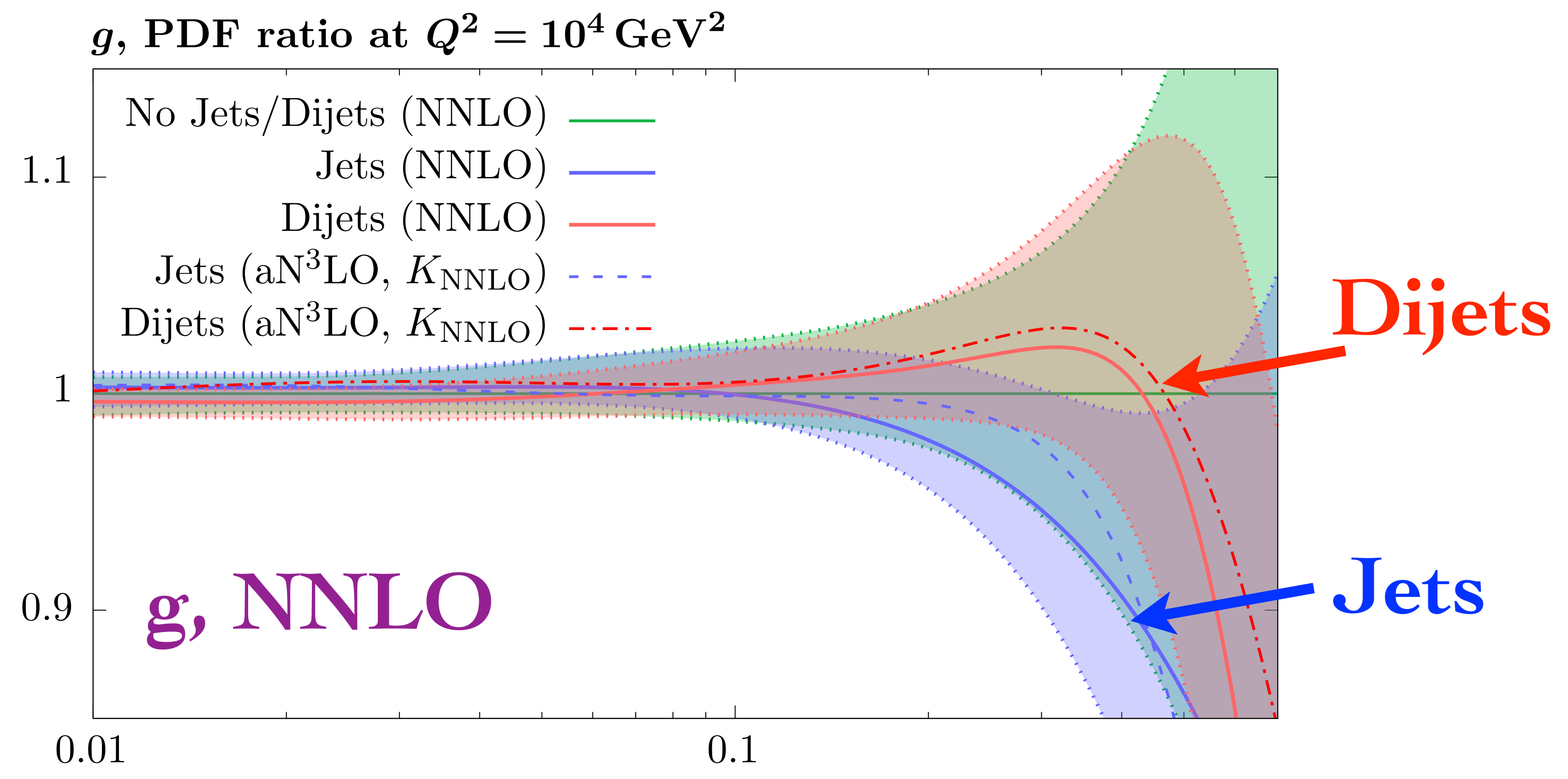
MSHT20

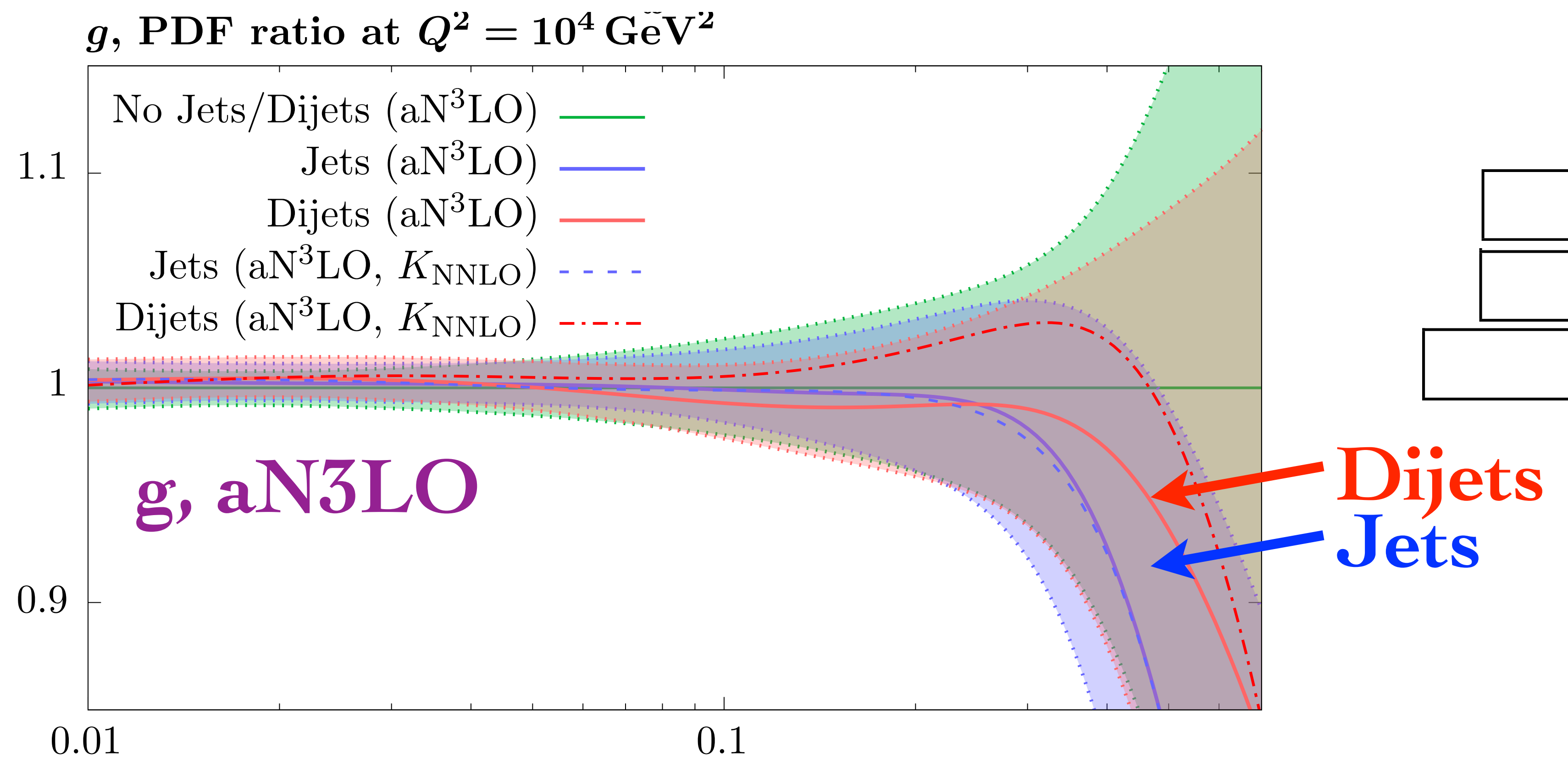
Data set	N_{pts}	NLO χ^2/N_{pts}	NNLO χ^2/N_{pts}
ATLAS 8 TeV s. diff $t\bar{t}$	25	1.56	0.98
CMS 8 TeV d. diff $t\bar{t}$	15	2.19	1.50
ATLAS 7 TeV W, Z	61	5.00	1.91
ATLAS 8 TeV W	22	3.85	2.61
ATLAS 8 TeV d. diff Z	59	2.67	1.45
ATLAS 8 TeV Z p_T	104	2.26	1.81
ATLAS 8 TeV W + jets	39	1.13	0.60
Total LHC data	1328	1.79	1.33
Total non-LHC data	3035	1.13	1.10
Total	4363	1.33	1.17

Image Credit: Tom Cridge

Impact of New Data

- Impact of newer (13 TeV) data being assessed, and older (7-8 TeV) data within new theory approaches:
  - ★ New study of impact of **jet** vs. **dijet** production at up to **aN3LO** order (more later).
  - ★ Preference for dijet data, and for aN3LO. PDF impact depends on order (NNLO vs aN3LO).





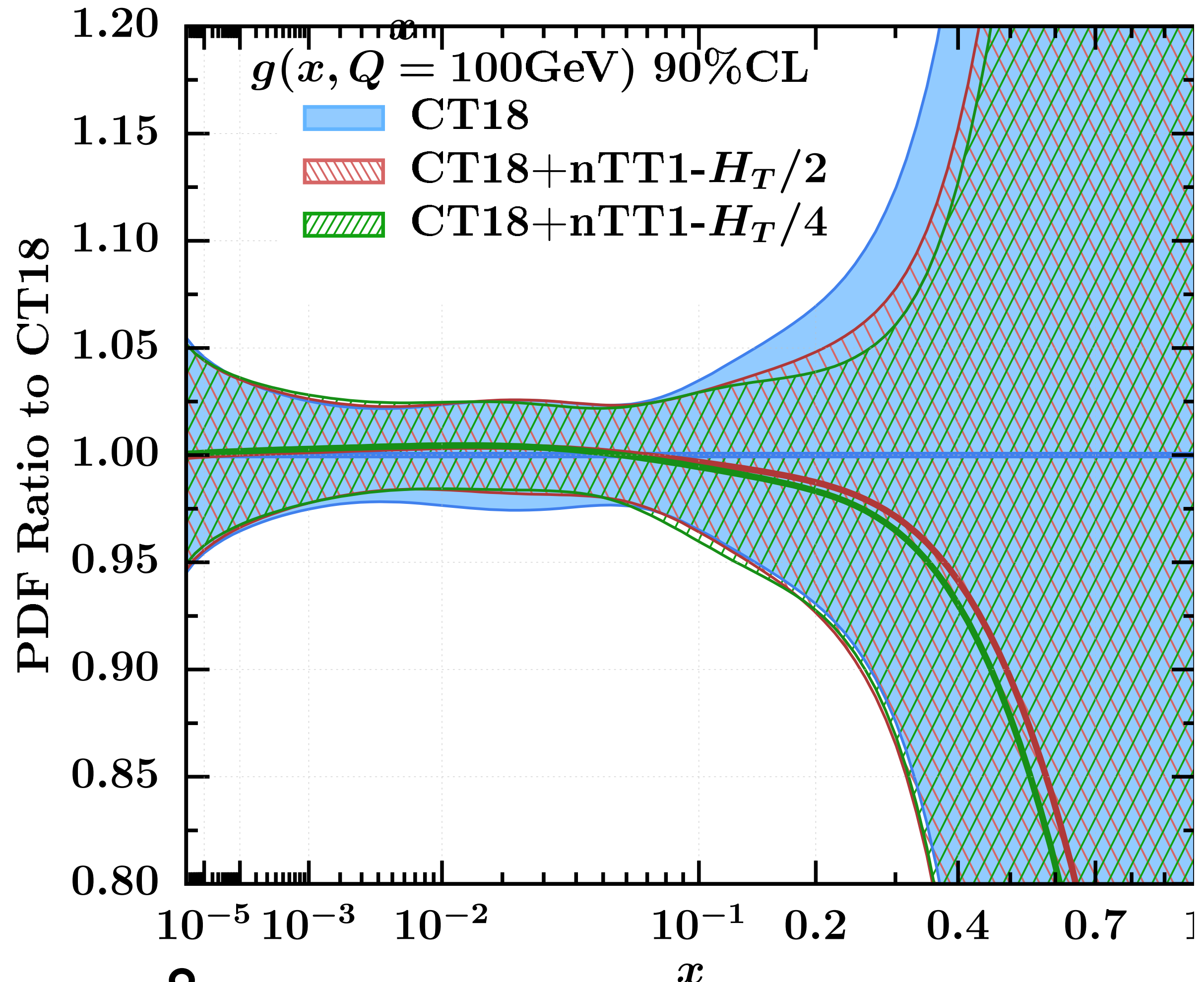
$\chi^2/N_{\rm pts}$

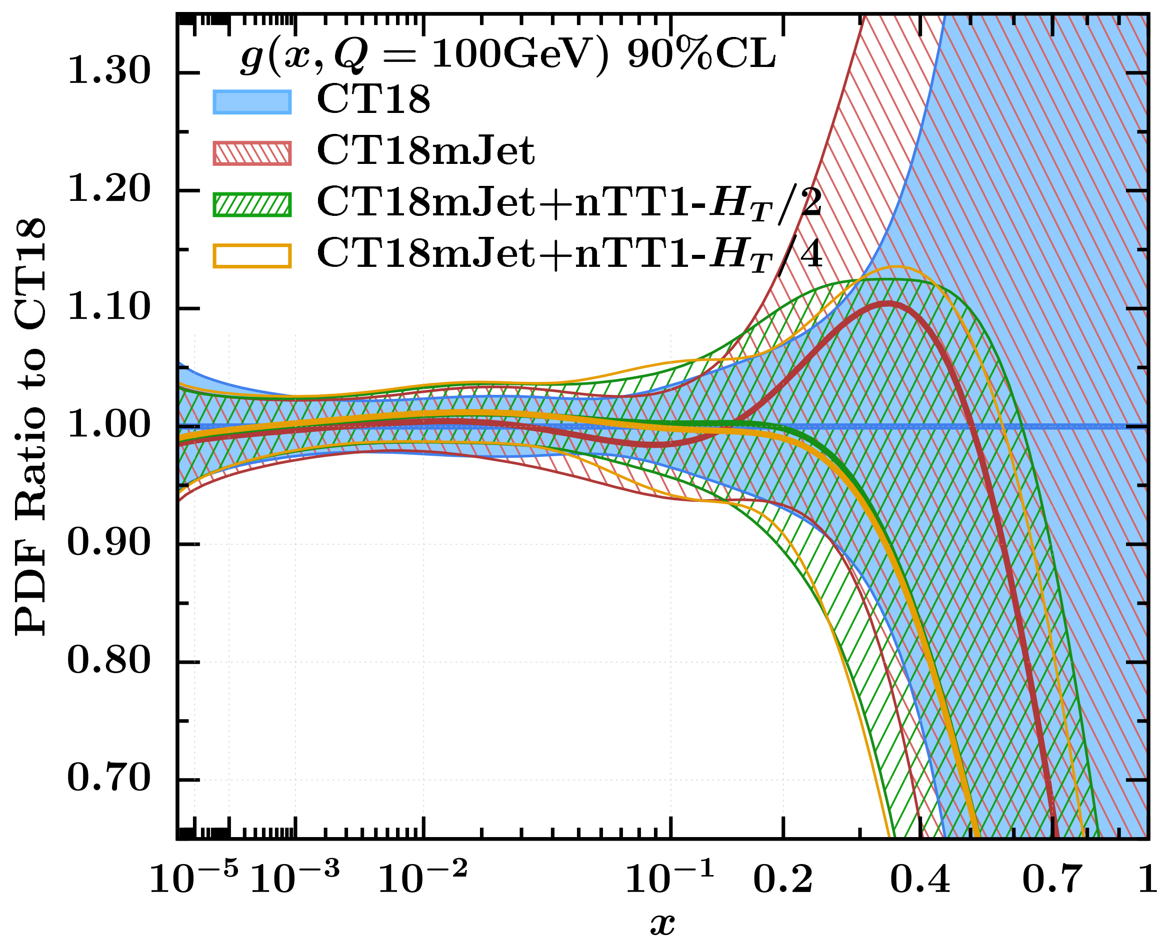
	$N_{\rm pts}$	NNLO	aN^{3}LO
Total Jets	643	1.67	1.63
Total Dijets	266	1.13	1.04

MSHT, arXiv:2312.12505

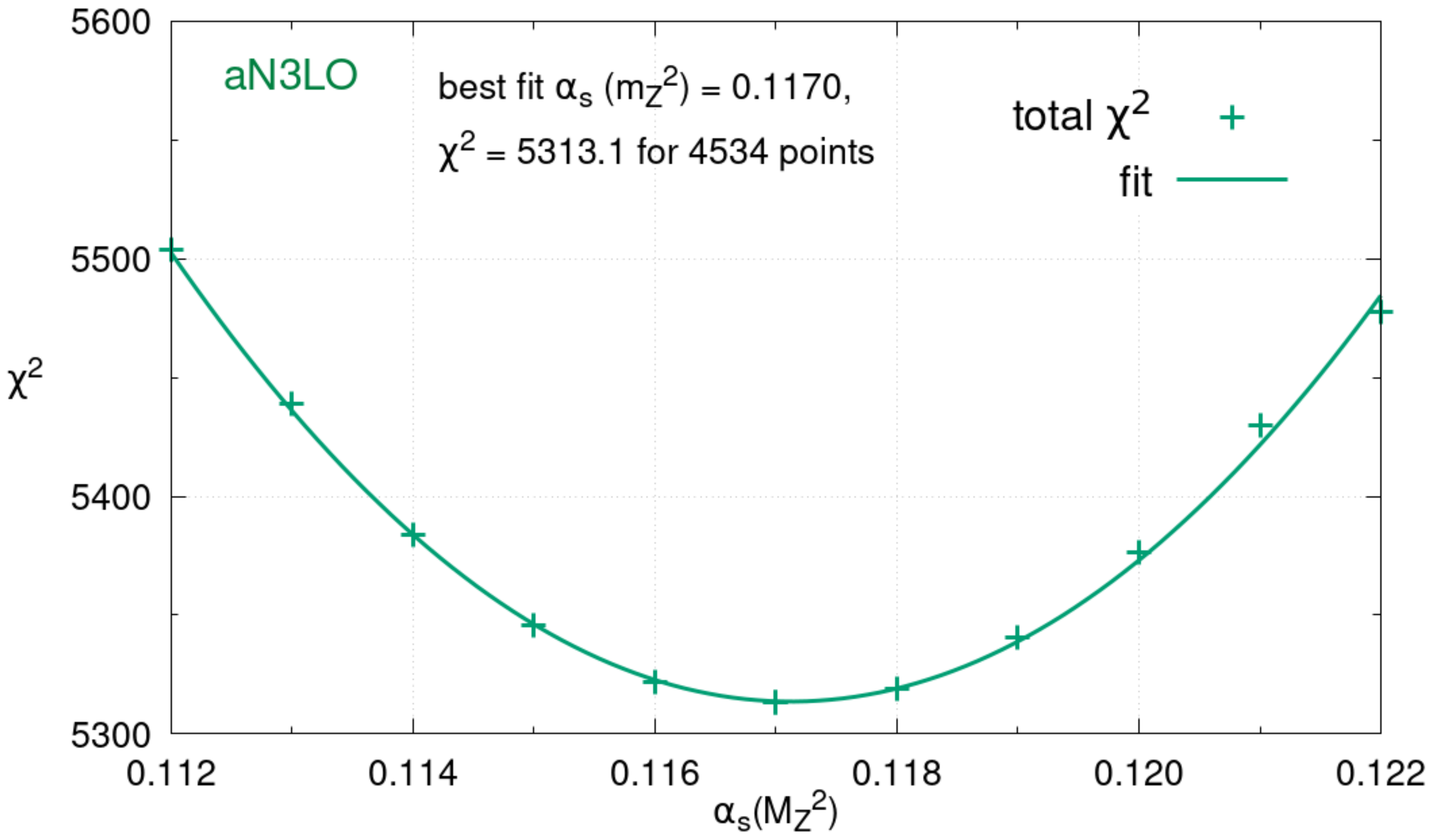
- ✦ 13 TeV $t\bar{t}$: study within **CT** global PDF fit.
- ✦ Impact moderate but non-negligible.
- ✦ Complementarity with LHC jet data highlighted.

A. Ablat et el., arXiv:2307.11153





★ First simultaneous α_S + global PDF extraction at aN3LO.



See talk by R. Thorne

MSHT, arXiv:2404.02964

$$\alpha_S(M_Z^2)(\text{NNLO}) = 0.1171 \pm 0.0014$$

$$\alpha_S(M_Z^2)(\text{aN}^3\text{LO}) = \underline{0.1170 \pm 0.0016}$$

★ Nice **convergence** from NNLO to aN3LO. Fully consistent with PDG.

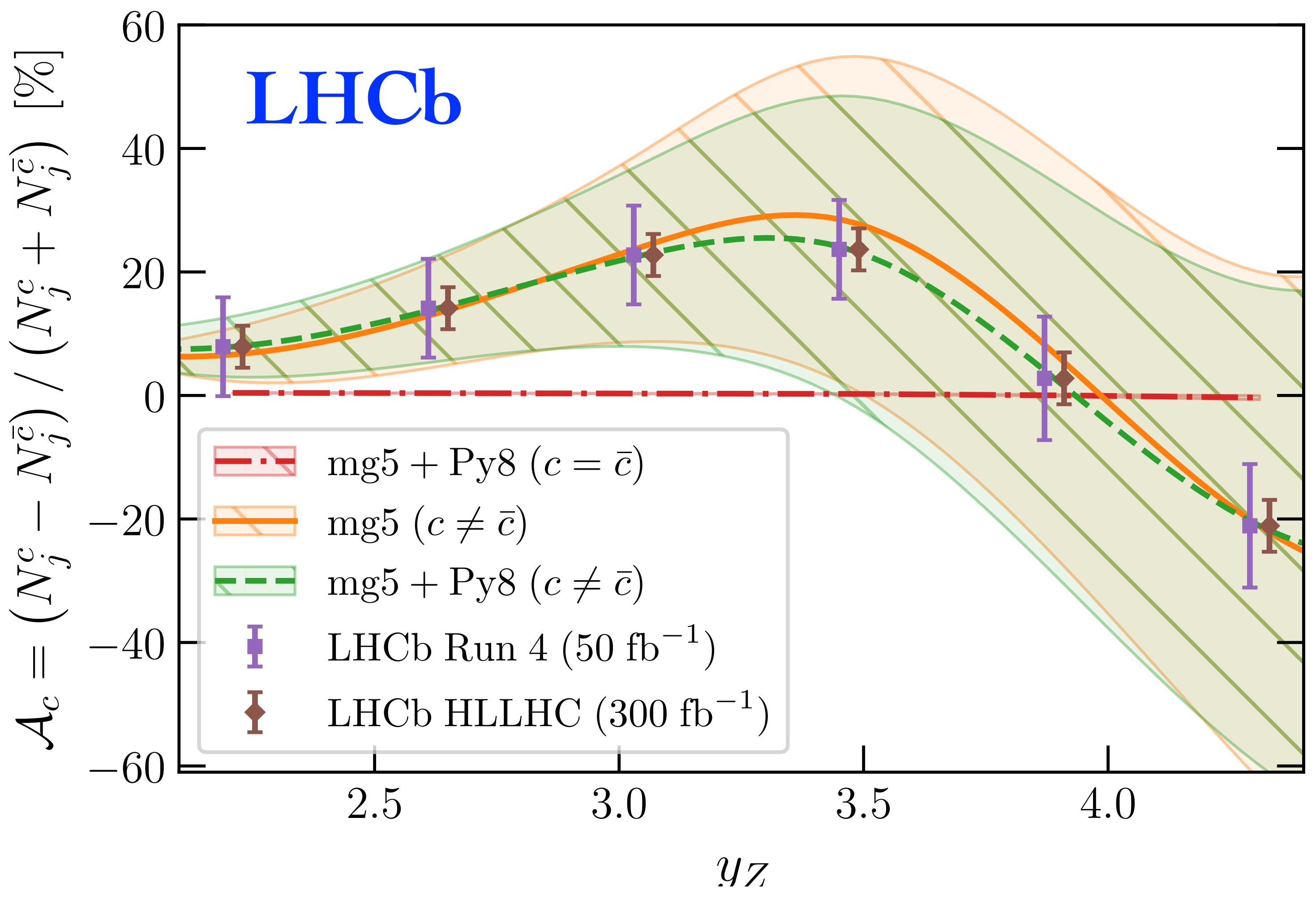
★ Errors slightly larger (more accurate) due to MHO uncertainty.

✦ New data - and theory - **valence charm** in proton. Evidence for non perturbatively generate charm and charm difference - \`instrinsic' charm.

✦ Evidence from global fit quality, but particular LHC (+ EIC) data sets can have further impact.

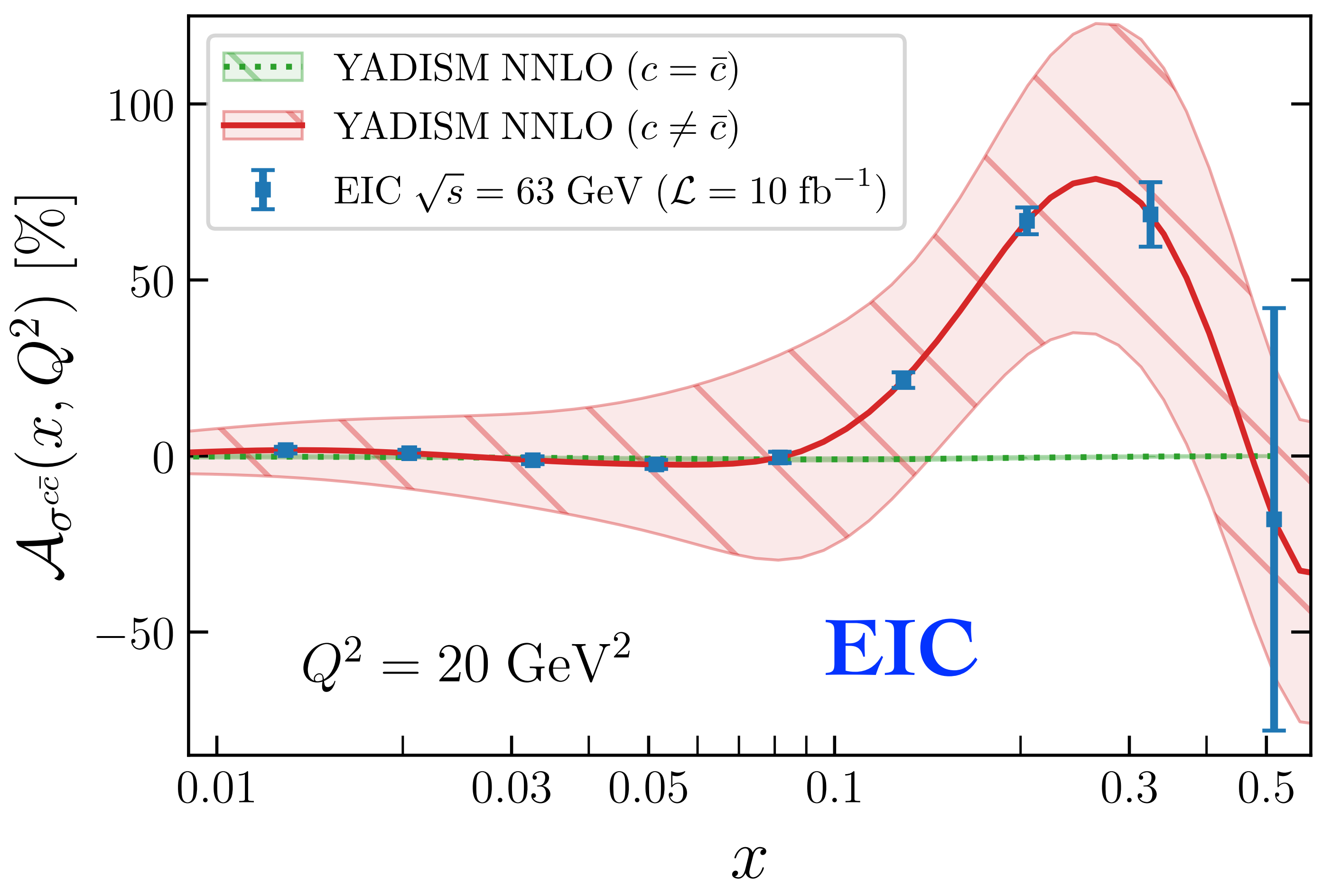
See talk by J. Rojo

R. Ball et al., arXiv:2311.00743



$$\mathcal{A}_c(y_Z) \equiv \frac{N_j^c(y_Z) - N_j^{\bar{c}}(y_Z)}{N_j^c(y_Z) + N_j^{\bar{c}}(y_Z)}$$

$$\mathcal{A}_{\sigma^{c\bar{c}}}(x, Q^2) \equiv \frac{\sigma^c_{\text{red}}(x, Q^2) - \sigma^{\bar{c}}_{\text{red}}(x, Q^2)}{\sigma^{c\bar{c}}_{\text{red}}(x, Q^2)}\,.$$

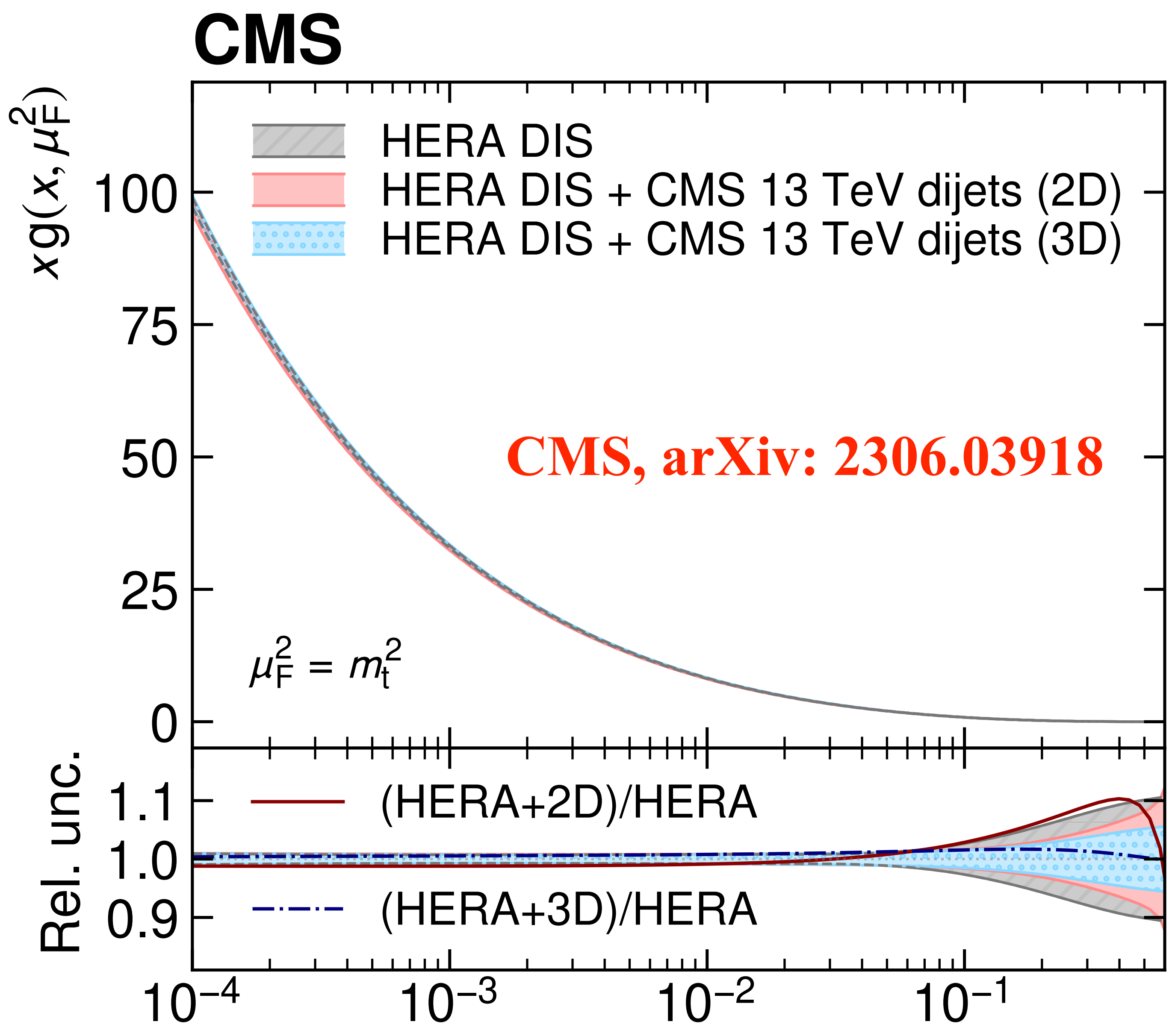


★ Not just global fitters - experimental collaborations also busily assessing impact of their data on PDFs.

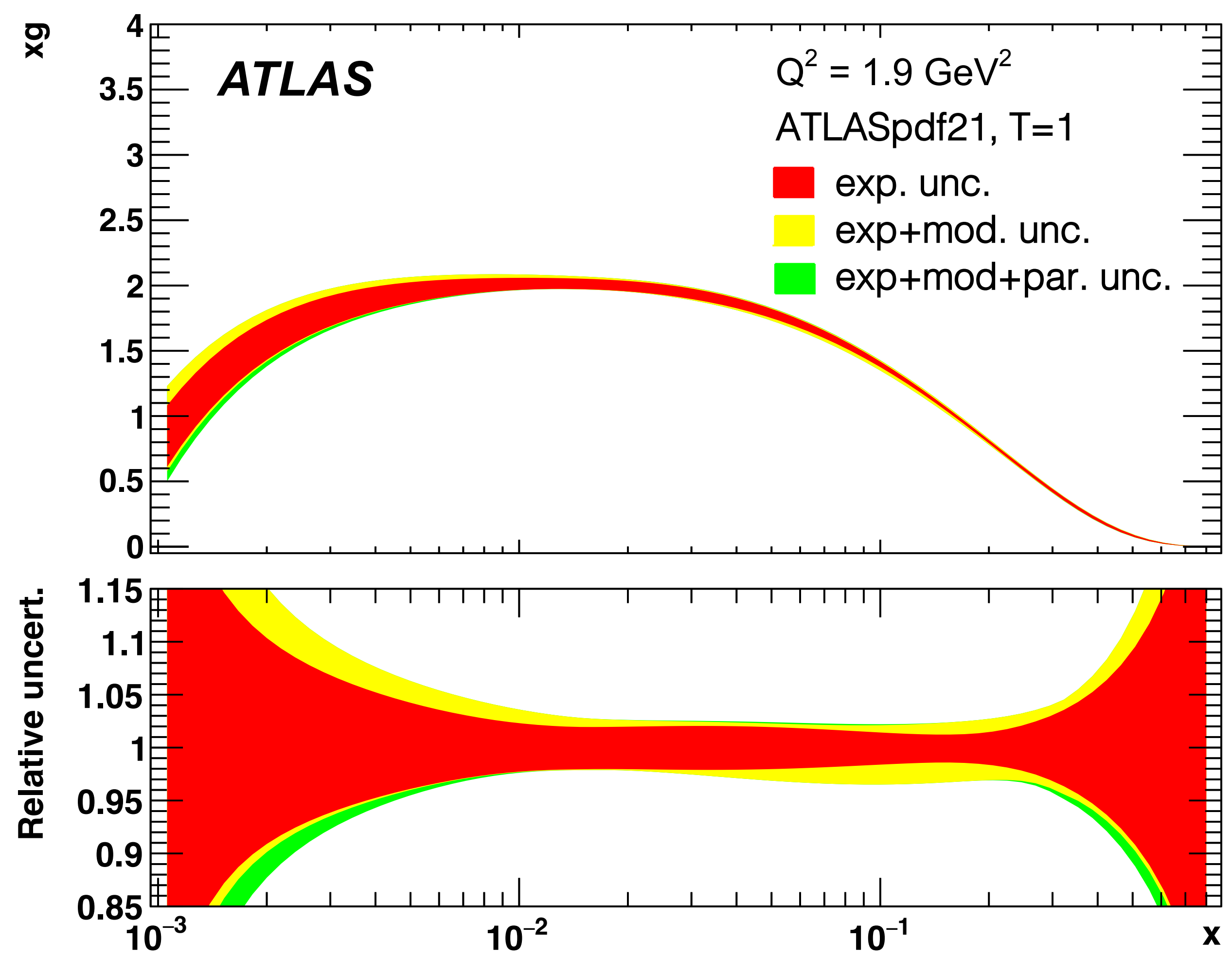
★ Though some caution often needed: impact not the same as in global fit.

★ Not just LHC data. Seaquest example of non-LHC dataset with important impact (high x flavour decomposition).

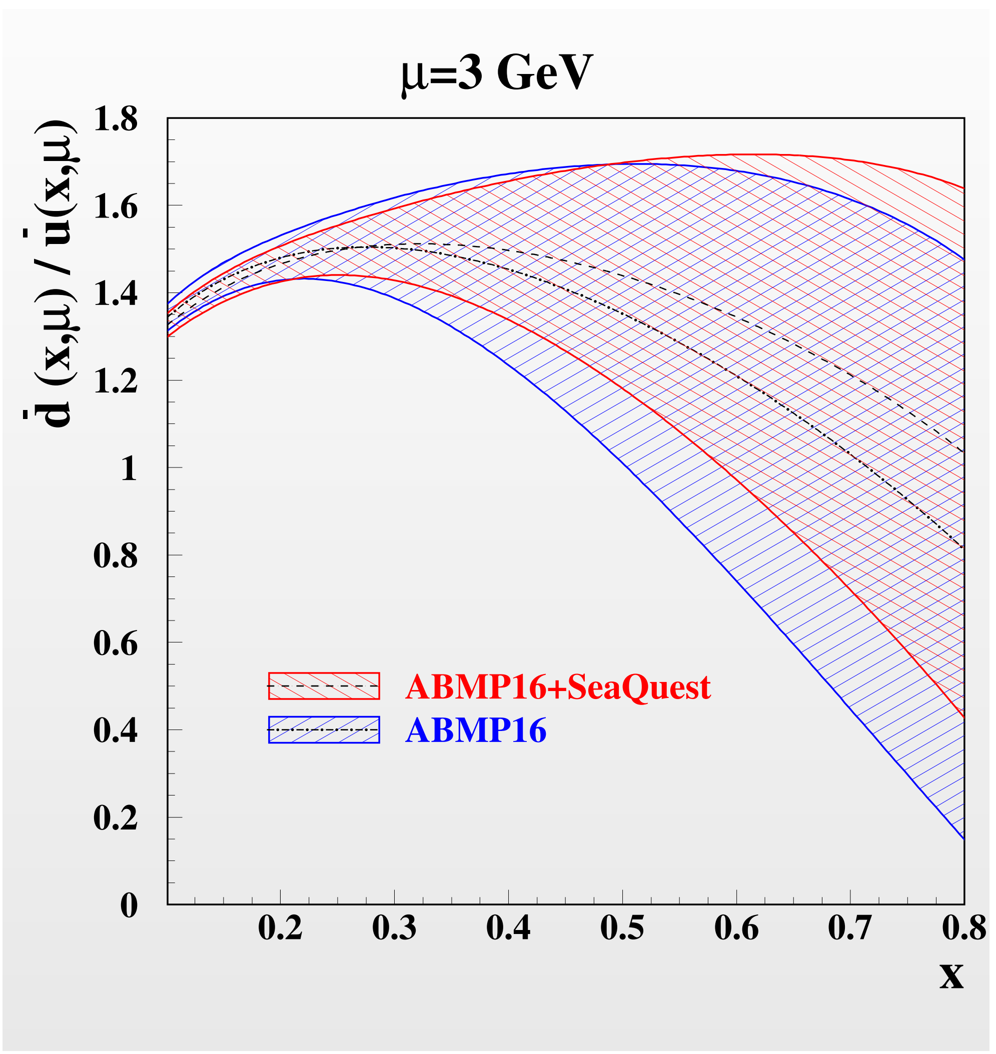
★ Though some tension with other (NuSea) data!

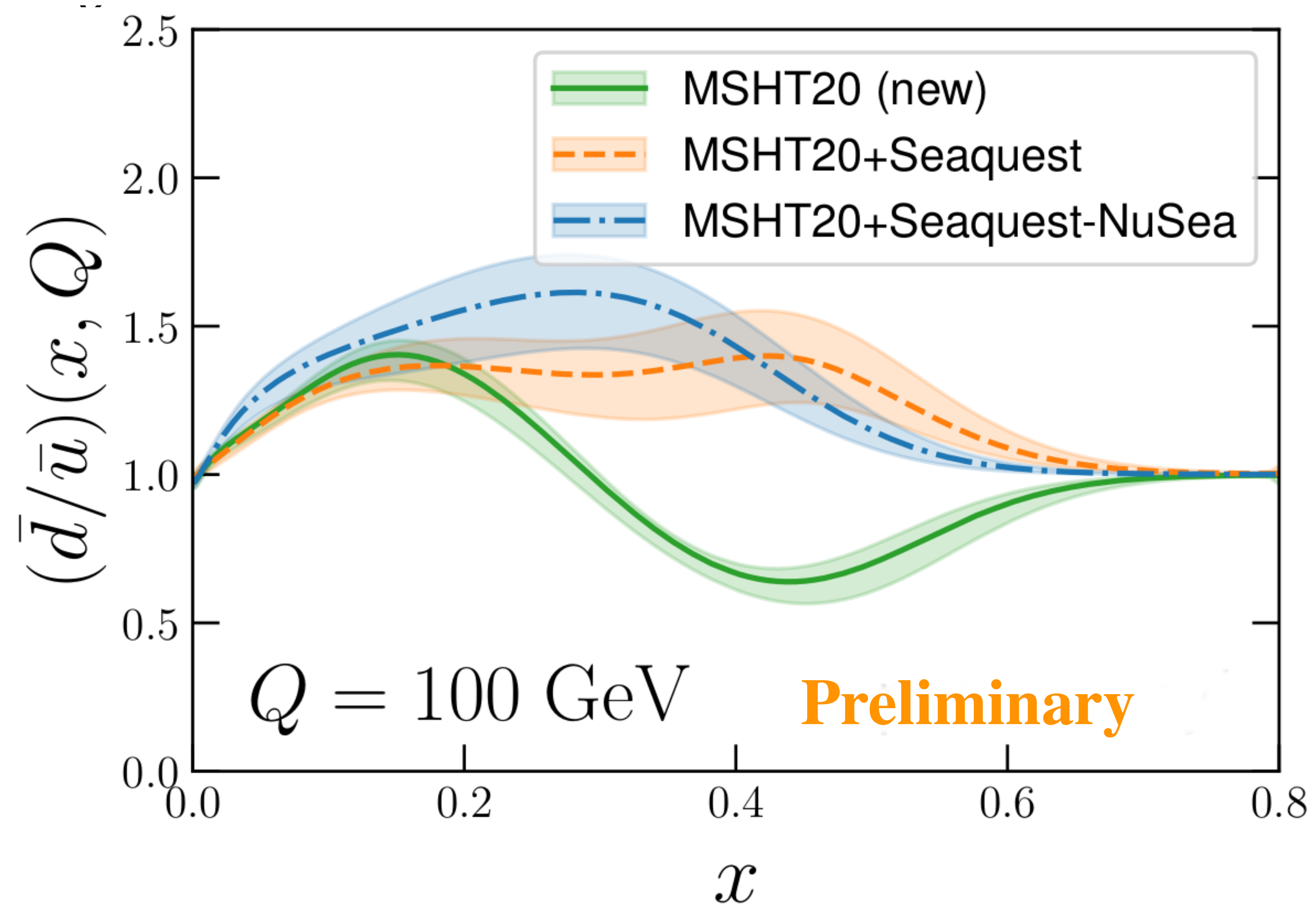


ATLAS, arXiv:2306.03918



ATLASpdf21





M. V. Garzeili, PDF4LHC23 meeting

New Developments : aN3LO and missing higher orders

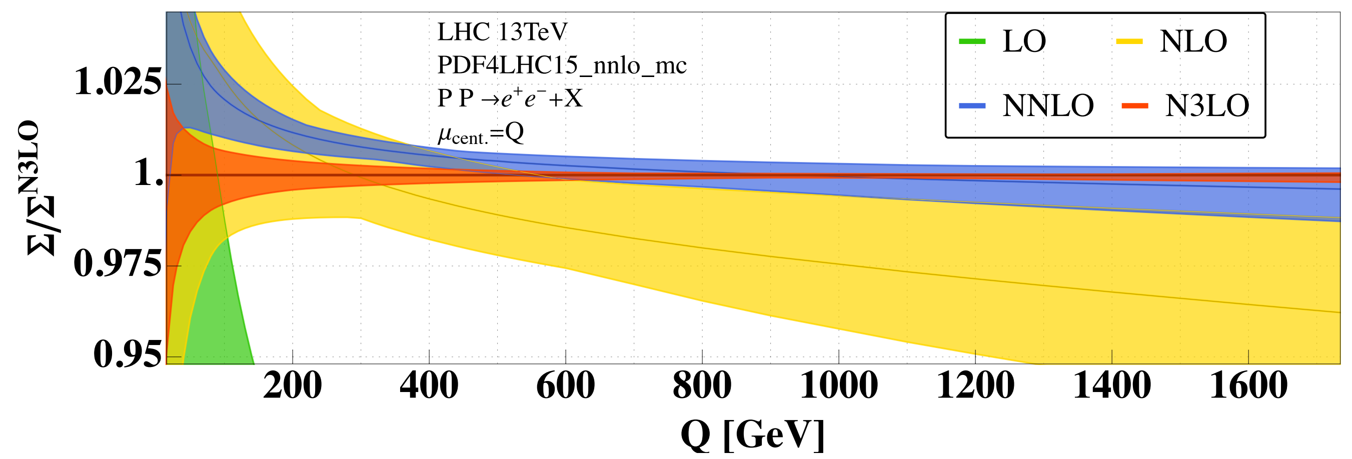
- **N3LO:**

  ⋆ State of the art is NNLO for PDF fits but a lot known at N3LO about DGLAP evolution and DIS (light + heavy flavours). Why not use this?

  ⋆ For hadron colliders less is known but already quite a bit

  - **Uncertainty** due to lack of N3LO PDFs a key factor $\Rightarrow$ need to - and can - go to N3LO!

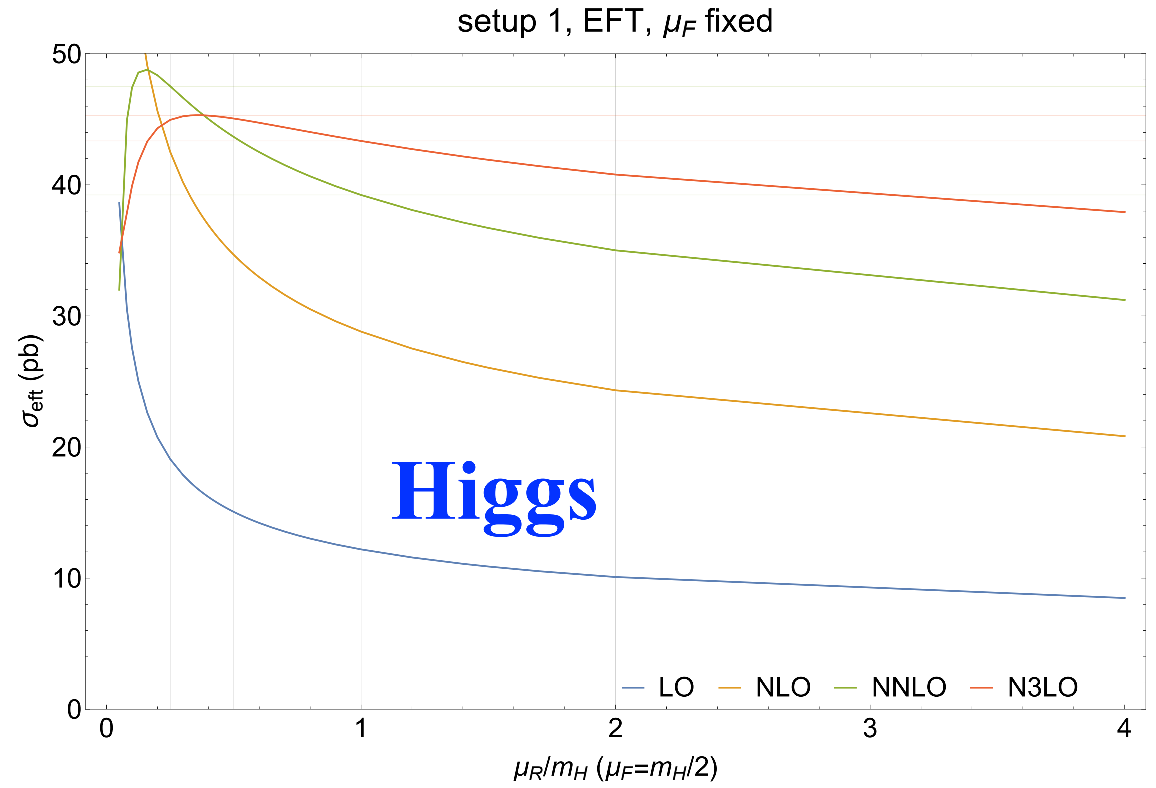
Drell Yan



C. Duhr and B. Mistleberger, arXiv:2111.10379

$$\delta(PDF-TH) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\mathrm{NNLO-PDFs}} - \sigma^{(2)}_{\mathrm{NLO-PDFs}}}{\sigma^{(2)}_{\mathrm{NNLO-PDFs}}}\right|$$

C. Anastasiou et al., arxiv:1602.00695



- **Missing higher orders:**

  ⋆ As (LHC) data becomes ever more precise sensitivity to any data/theory mismatch increases.

$$\chi^2 \sim \sum \frac{(D-T)^2}{\sigma^2_{\mathrm{exp}}} \qquad T_{\mathrm{N}^x\mathrm{LO}} \neq D \Rightarrow \chi^2 \to \infty \text{ as } \sigma_{\mathrm{exp}} \to 0$$

  ⋆ Need to account for this missing higher order uncertainty:

  - More precise PDF uncertainty.
  - Weight datasets correctly in fit (less well known $\Rightarrow$ larger uncertainty).

New Developments : aN3LO and missing higher orders

- Two approximate N3LO (aN3LO) global PDF sets available: **MSHTaN3LO** and **NNPDF4.0aN3LO**.

  - Approximate splitting functions built up from known information. Approximate $\neq$ poorly known. A lot of information available:

Splitting Functions

Singlet (P_{qq}, P_{gg}, P_{gq}, P_{qg})
– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]
– small-x limit [JHEP 06 (2018) 145]
– large-x limit [NPB 832 (2010) 152; JHEP 04 (2020) 018; JHEP 09 (2022) 155]
– 5 (10) lowest Mellin moments [PLB 825 (2022) 136853; ibid. 842 (2023) 137944; ibid. 846 (2023) 138215]

Non-singlet ($P_{NS,v}$, $P_{NS,+}$, $P_{NS,-}$)
– large-n_f limit [NPB 915 (2017) 335; arXiv:2308.07958]
– small-x limit [JHEP 08 (2022) 135]
– large-x limit [JHEP 10 (2017) 041]
– 8 lowest Mellin moments [JHEP 06 (2018) 073]

Emanuele Nocera, Forward Physics and QCD at the LHC and EIC, Bad Honnef 23

- And a great deal of progress recently!

G. Falcioni et al., arXiv:2307.04158

$$\begin{aligned}
\gamma_{qg}^{(3)}(N=2) &= -654.4627782\,n_f + 245.6106197\,n_f^2 - 0.924990969\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=4) &= 290.3110686\,n_f - 76.51672403\,n_f^2 - 4.911625629\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=6) &= 335.8008046\,n_f - 124.5710225\,n_f^2 - 4.193871425\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=8) &= 294.5876830\,n_f - 135.3767647\,n_f^2 - 3.609775642\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=10) &= 241.6153399\,n_f - 135.1874247\,n_f^2 - 3.189394834\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=12) &= 191.9712464\,n_f - 131.1631663\,n_f^2 - 2.877104430\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=14) &= 148.5682948\,n_f - 125.8231081\,n_f^2 - 2.635918561\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=16) &= 111.3404252\,n_f - 120.1681987\,n_f^2 - 2.443379039\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=18) &= 79.51561588\,n_f - 114.6171354\,n_f^2 - 2.285486861\,n_f^3\,,\\
\gamma_{qg}^{(3)}(N=20) &= 52.24329555\,n_f - 109.3424891\,n_f^2 - 2.153153725\,n_f^3\,.
\end{aligned}$$

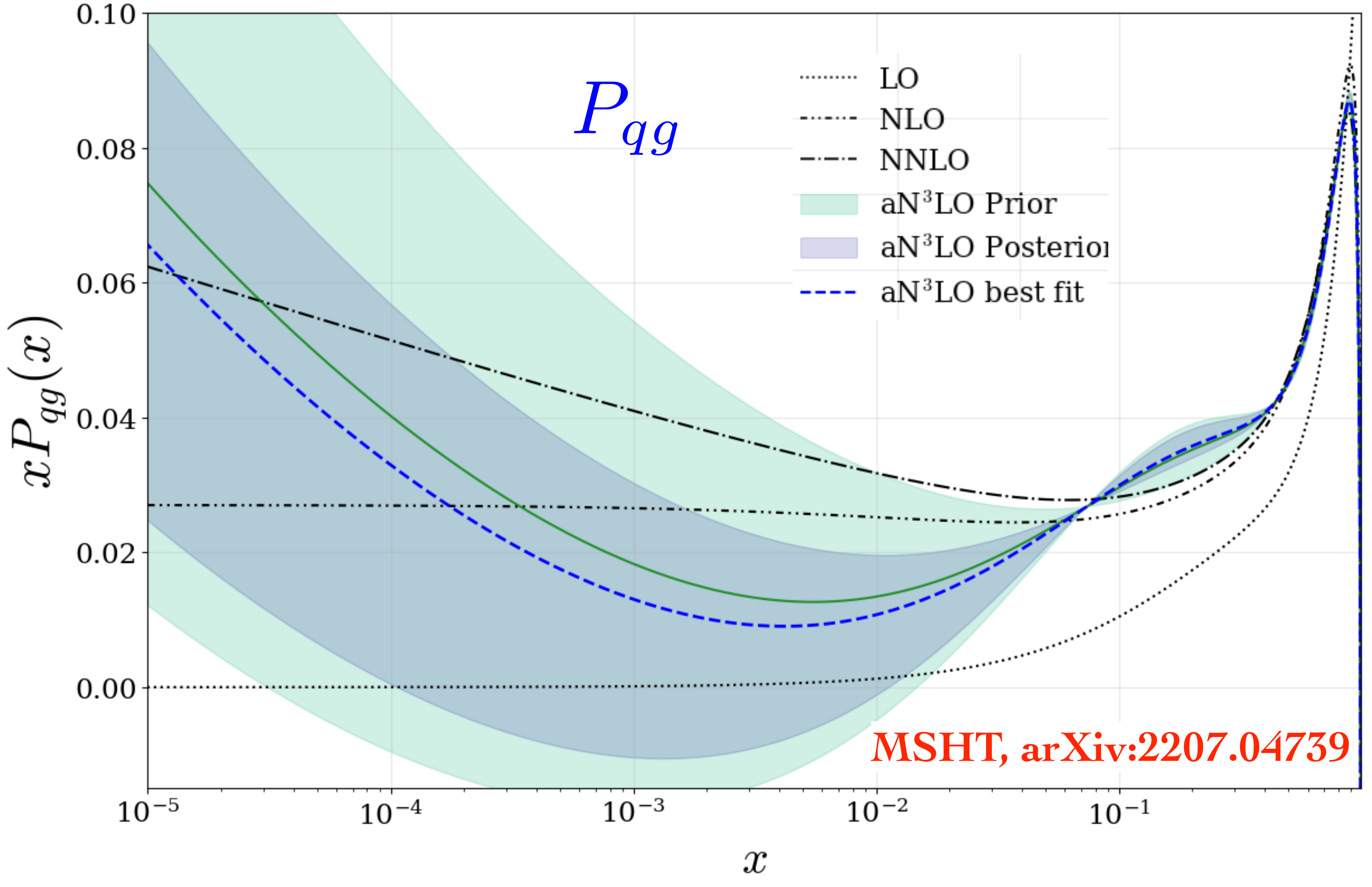
G. Falcioni et al., arXiv:2302.07593

$$\begin{aligned}
\gamma_{ps}^{(3)}(N=2) &= -691.5937093\,n_f + 84.77398149\,n_f^2 + 4.466956849\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=4) &= -109.3302335\,n_f + 8.776885259\,n_f^2 + 0.306077137\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=6) &= -46.03061374\,n_f + 4.744075766\,n_f^2 + 0.042548957\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=8) &= -24.01455020\,n_f + 3.235193483\,n_f^2 - 0.007889256\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=10) &= -13.73039387\,n_f + 2.375018759\,n_f^2 - 0.021029241\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=12) &= -8.152592251\,n_f + 1.819958178\,n_f^2 - 0.024330231\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=14) &= -4.840447180\,n_f + 1.438327380\,n_f^2 - 0.024479943\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=16) &= -2.751136330\,n_f + 1.164299642\,n_f^2 - 0.023546009\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=18) &= -1.375969240\,n_f + 0.960873318\,n_f^2 - 0.022264393\,n_f^3\,,\\
\gamma_{ps}^{(3)}(N=20) &= -0.442681568\,n_f + 0.805745333\,n_f^2 - 0.020918264\,n_f^3\,.
\end{aligned}$$

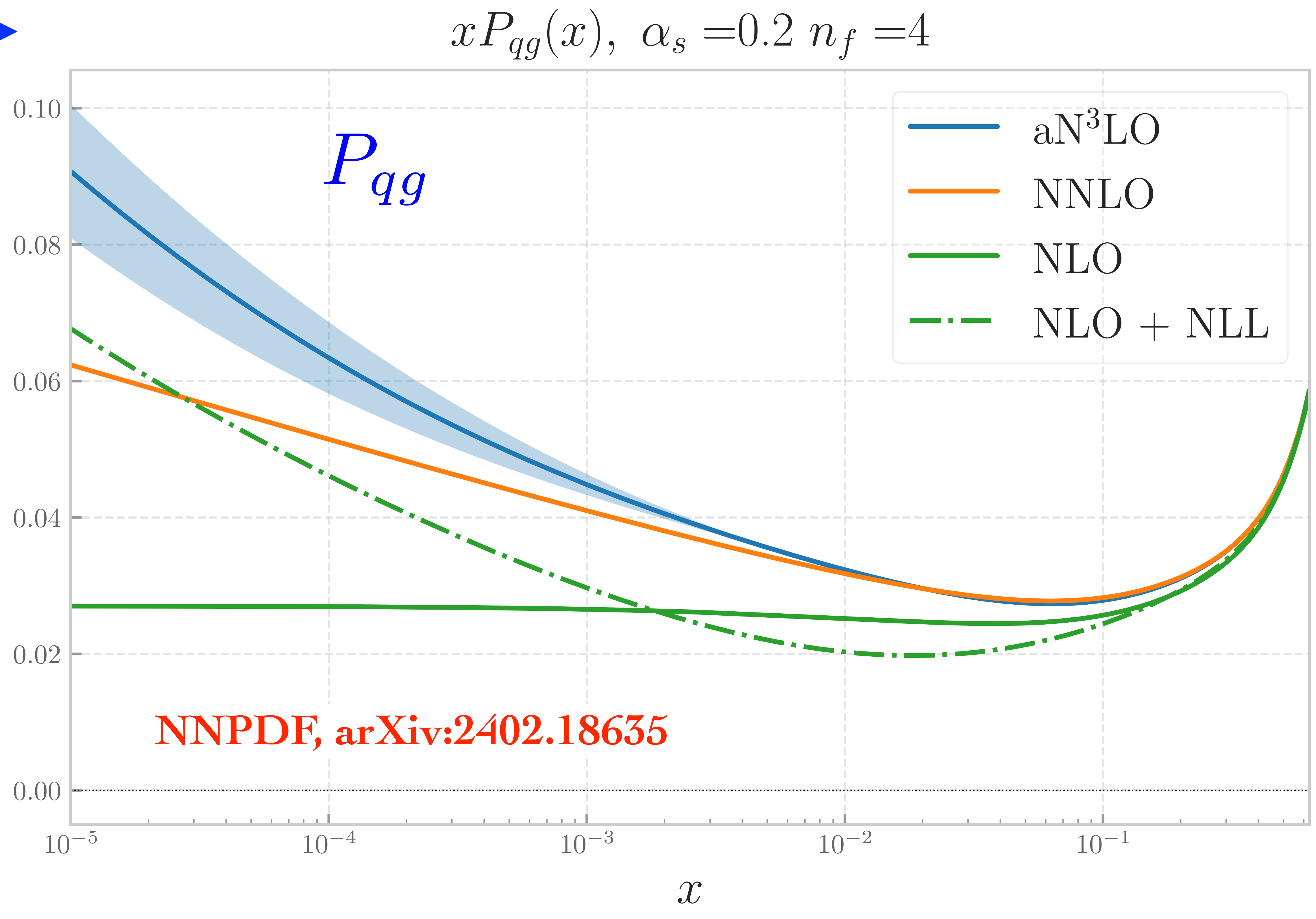
Up to $N = 20$ even moments in quark sector

See talks by G. Falcioni + T. Yang

- This information allows already sufficient determinations of splitting functions.
- Uncertainties from this now small, and limited to lower x region.
- Impact of recent progress clear, and further refinements can be added in.



~ 2 years! → **G. Falcioni et al., arXiv:2307.04158**



New Developments : aN3LO and missing higher orders

- Massless **DIS** known, similar approx. to P_{ij} for massive (cross section + transition matrix elements).
- **Hadron-hadron**: much less known $\Rightarrow$ allow N3LO K-factor to be free in fit within reasonable prior. Built either on lower order results (MSHT) or on scale variations (NNPDF*)

$$K^{\mathrm{N^3LO/LO}} = K^{\mathrm{NNLO/LO}}\left(1 + a_1(K^{\mathrm{NLO/LO}} - 1) + a_2(K^{\mathrm{NNLO/NLO}} - 1)\right)$$

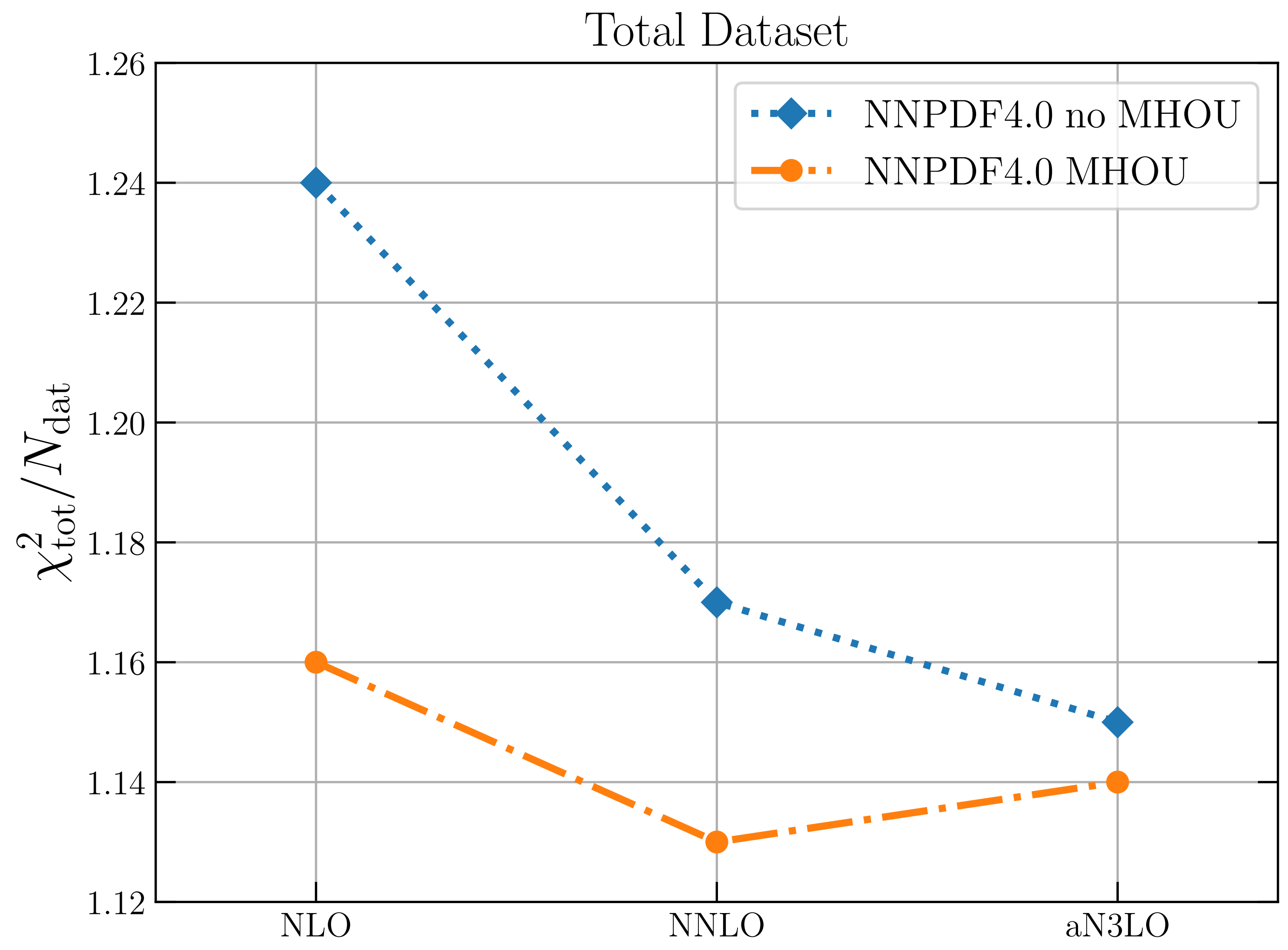
$$(\mathrm{cov_{th}})_{ij} = \frac{1}{N}\sum_k^N \Delta_i^{(k)}\Delta_j^{(k)};\ \Delta_i^{(k)} \equiv T_i^{(k)} - T_i$$

- Provides **missing higher order** (MHO) **uncertainty** in fit.
- Putting this all together find:

★ Improvement in fit quality, ~ driven by known N3LO

	LO	NLO	NNLO	$a\mathrm{N}^3\mathrm{LO}$
$\chi^2_{N_{pts}}$	2.57	1.33	1.17	1.14

MSHTaN3LO



NNPDF4.0aN3LO

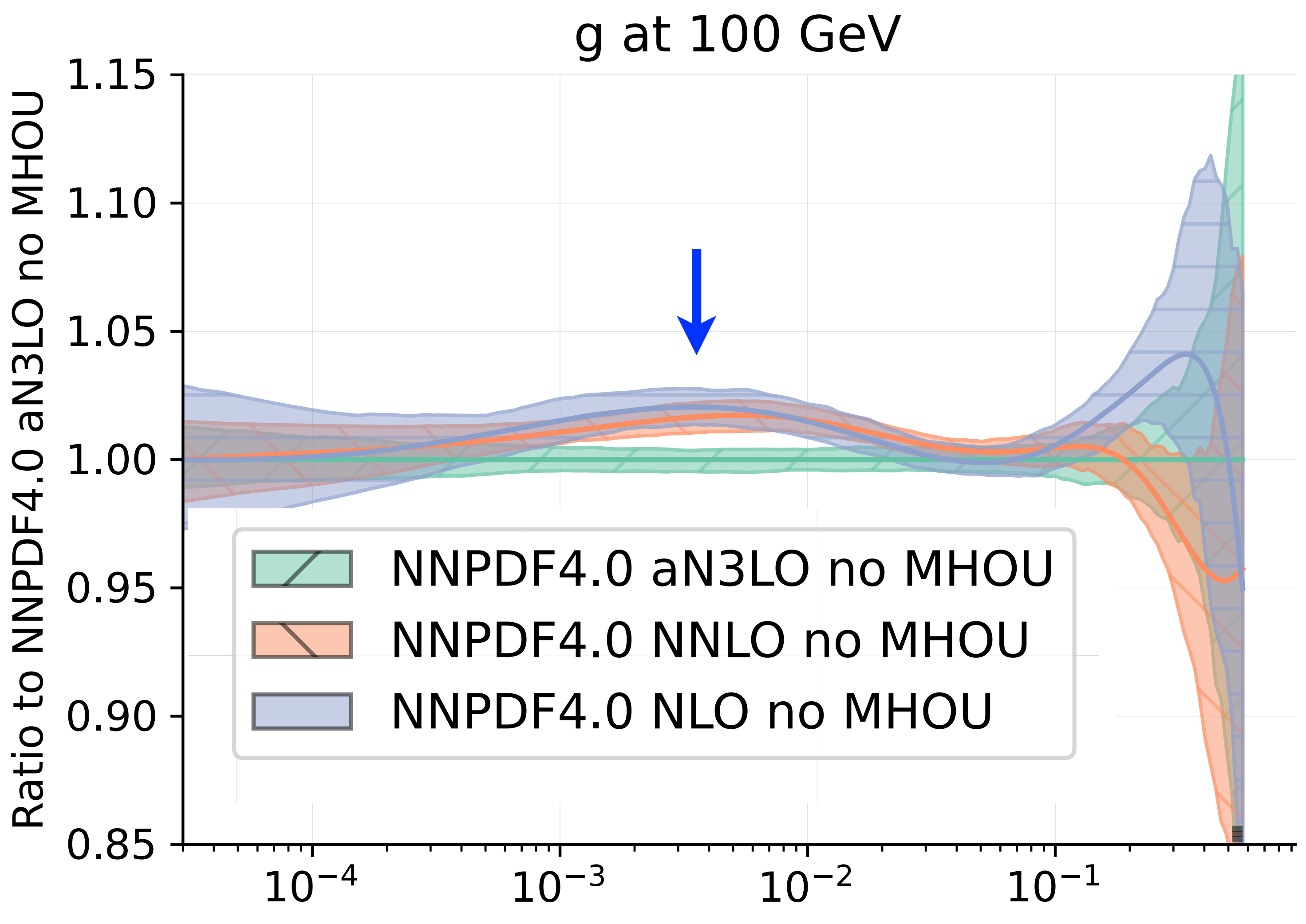
★ But NNPDF find this is stabilised once MHOU are included.

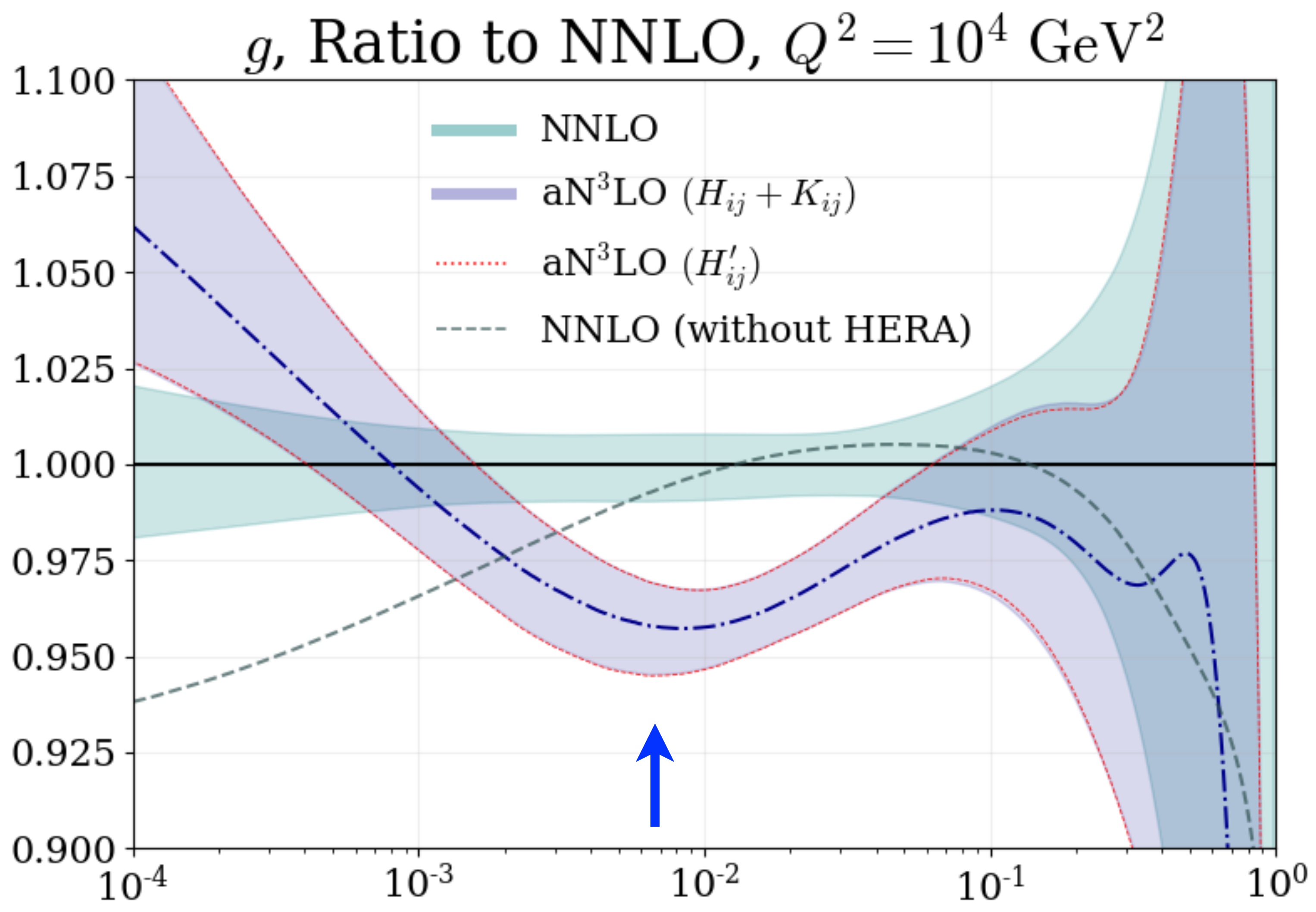
- What about PDFs?

*N.B. NNPDF include MHOUs more broadly: DIS and in evolution

New Developments : aN3LO and missing higher orders

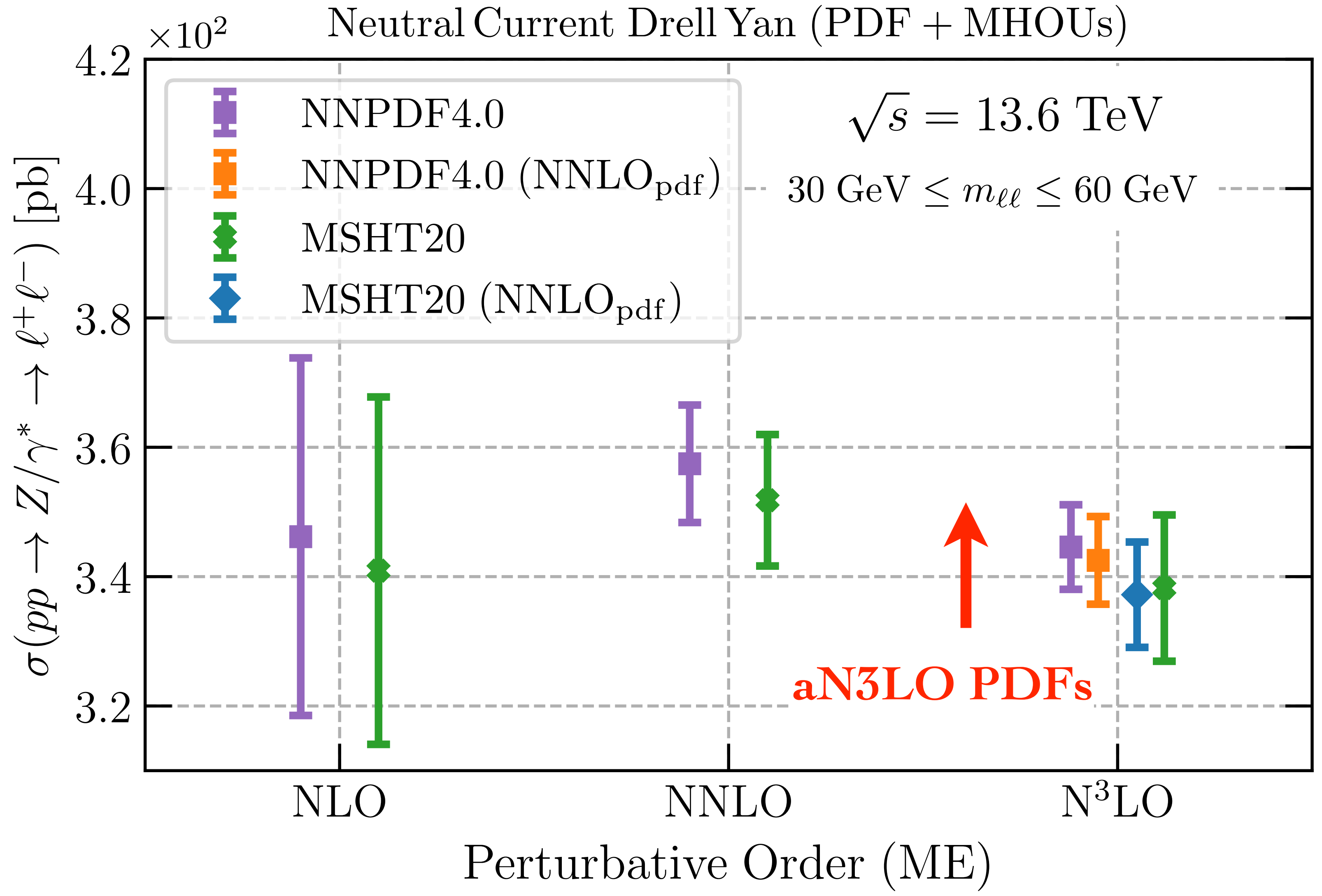
- PDF + pheno impact **moderate** but **non-negligible**:



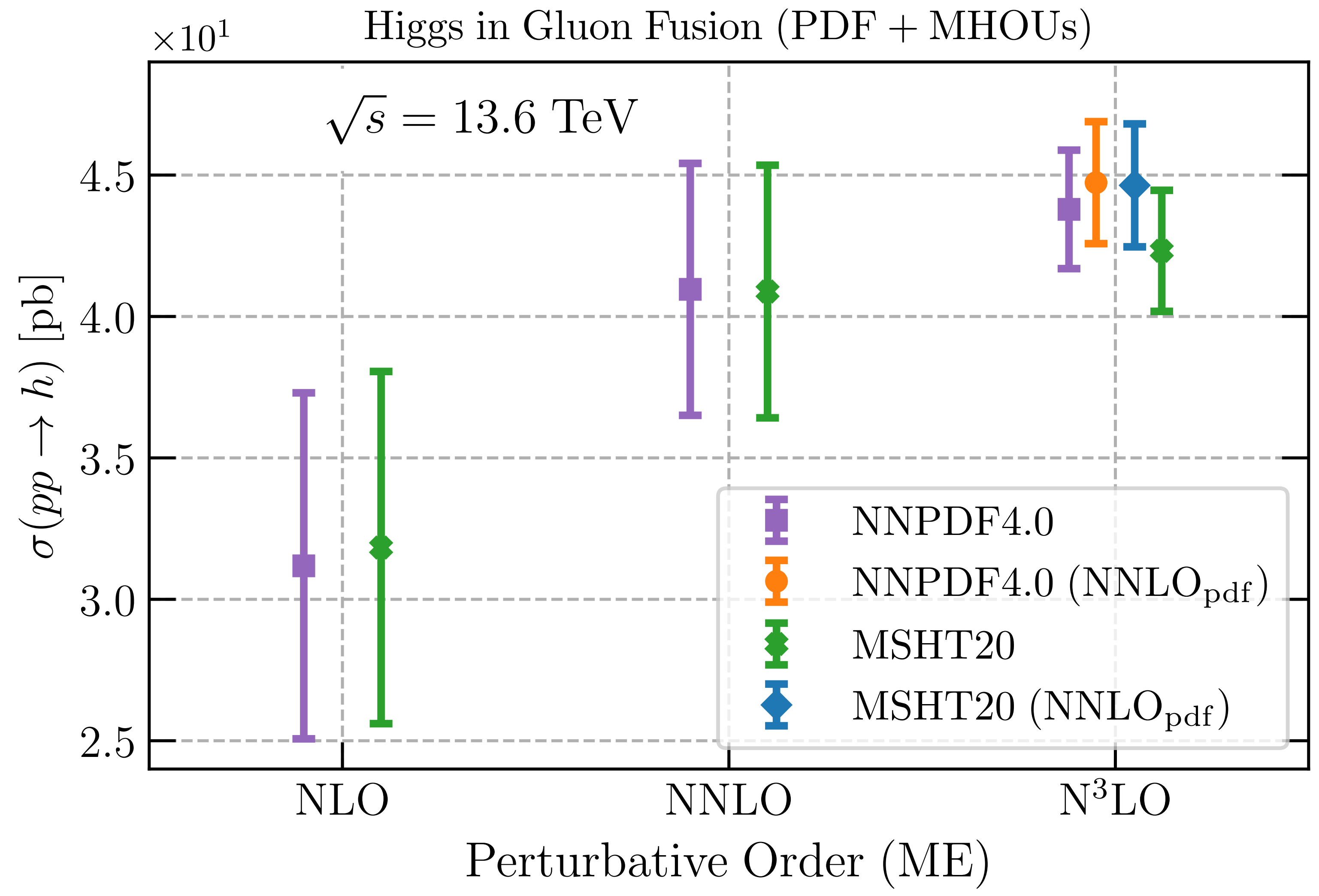


Note ratios reversed wrt MSHT - direction of change is consistent!

- **Drell Yan**: some evidence it improves stability of N3LO prediction



- **Higgs**: some difference between groups (in part due to newer theory)



- Comprehensive **benchmarking** study underway.

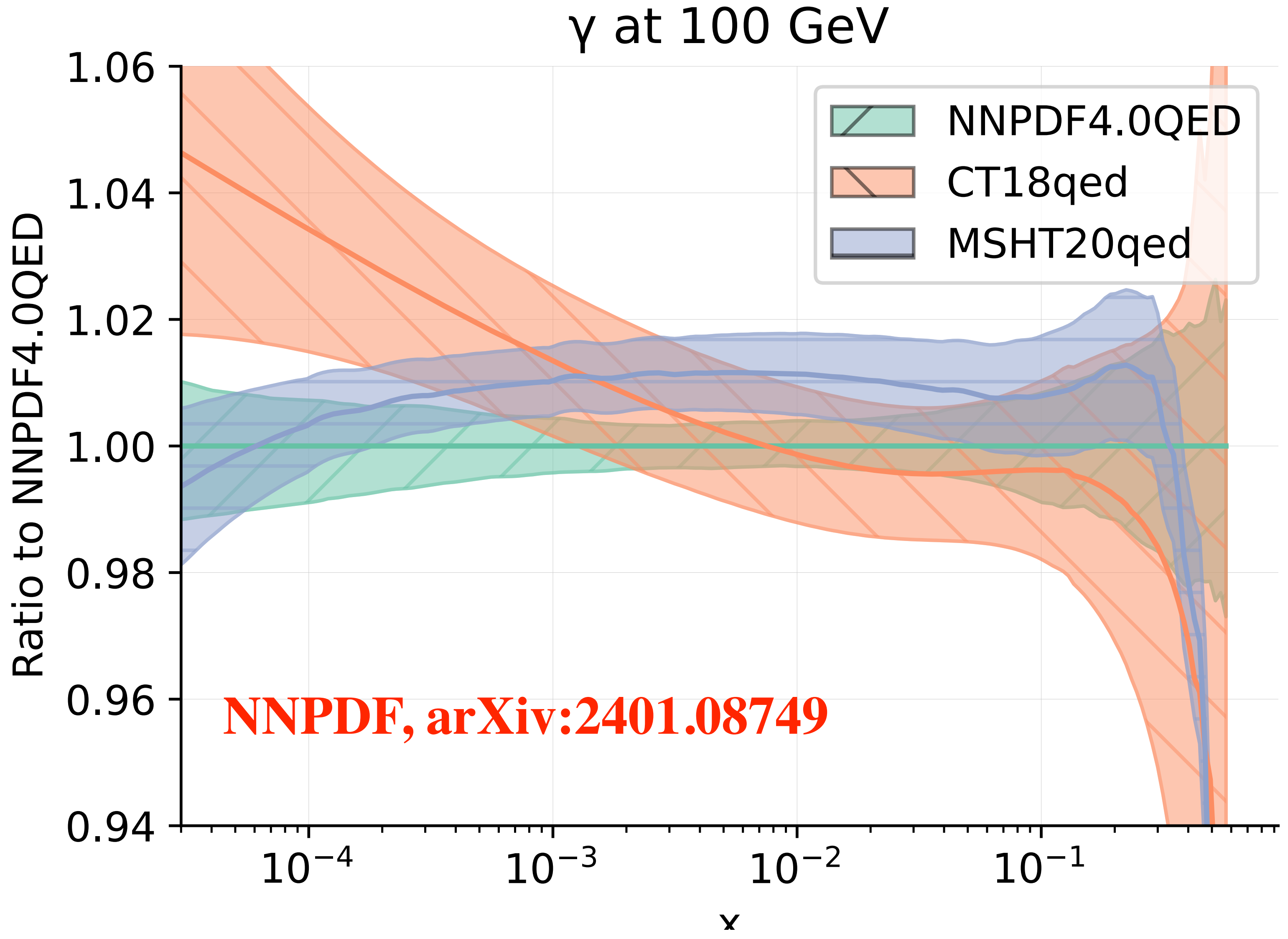
See talk by R. Thorne

New Developments : QED corrections

- QED corrections key part of PDF fit. Requires the **photon** be included as another parton of the proton: **LUXqed** breakthrough enables high precision. Some recent highlights:

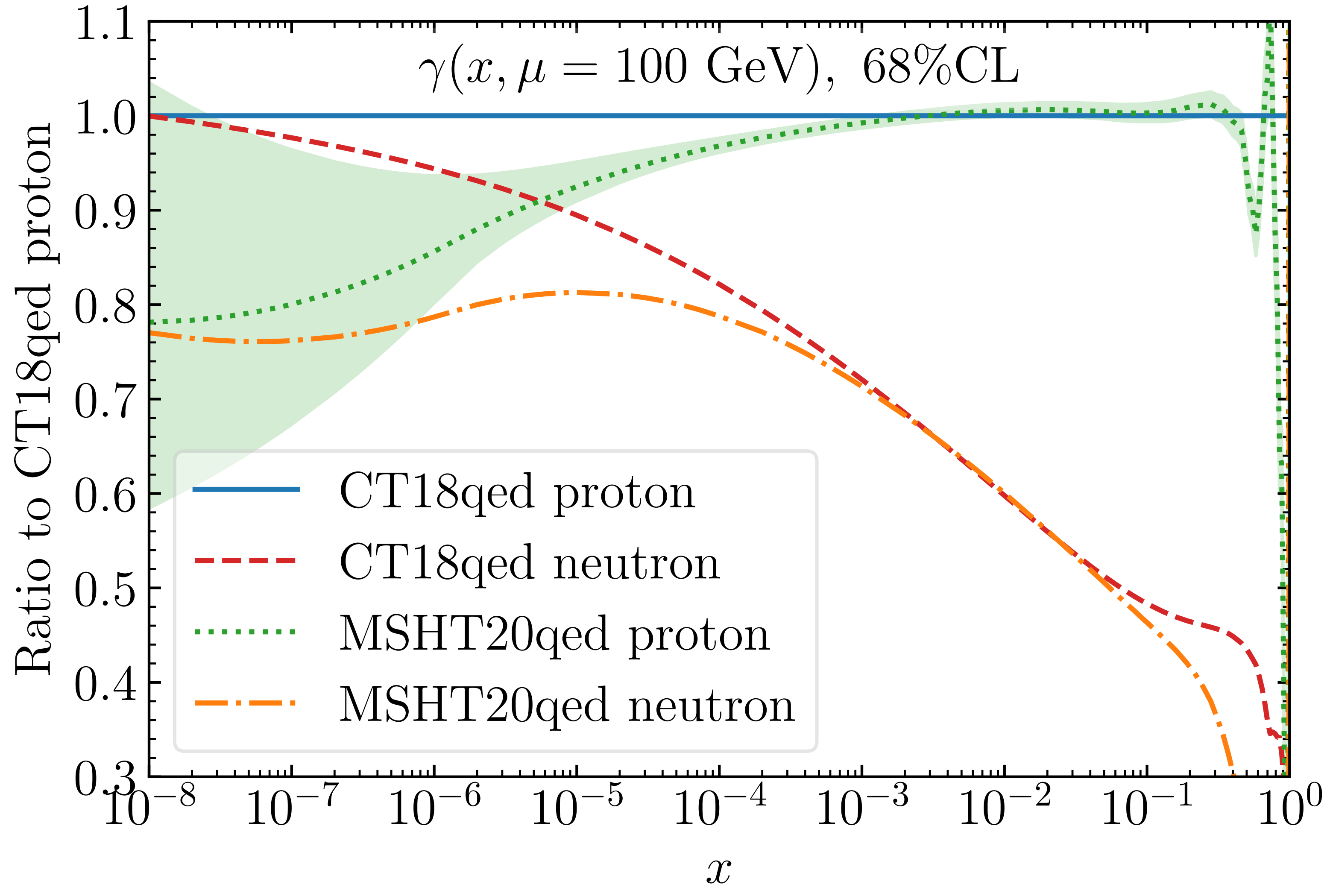
A. Manohar et al., JHEP 1712 (2017) 046

★ **NNPDF4.0QED**: latest addition to QED baseline sets



NNPDF, arXiv:2401.08749

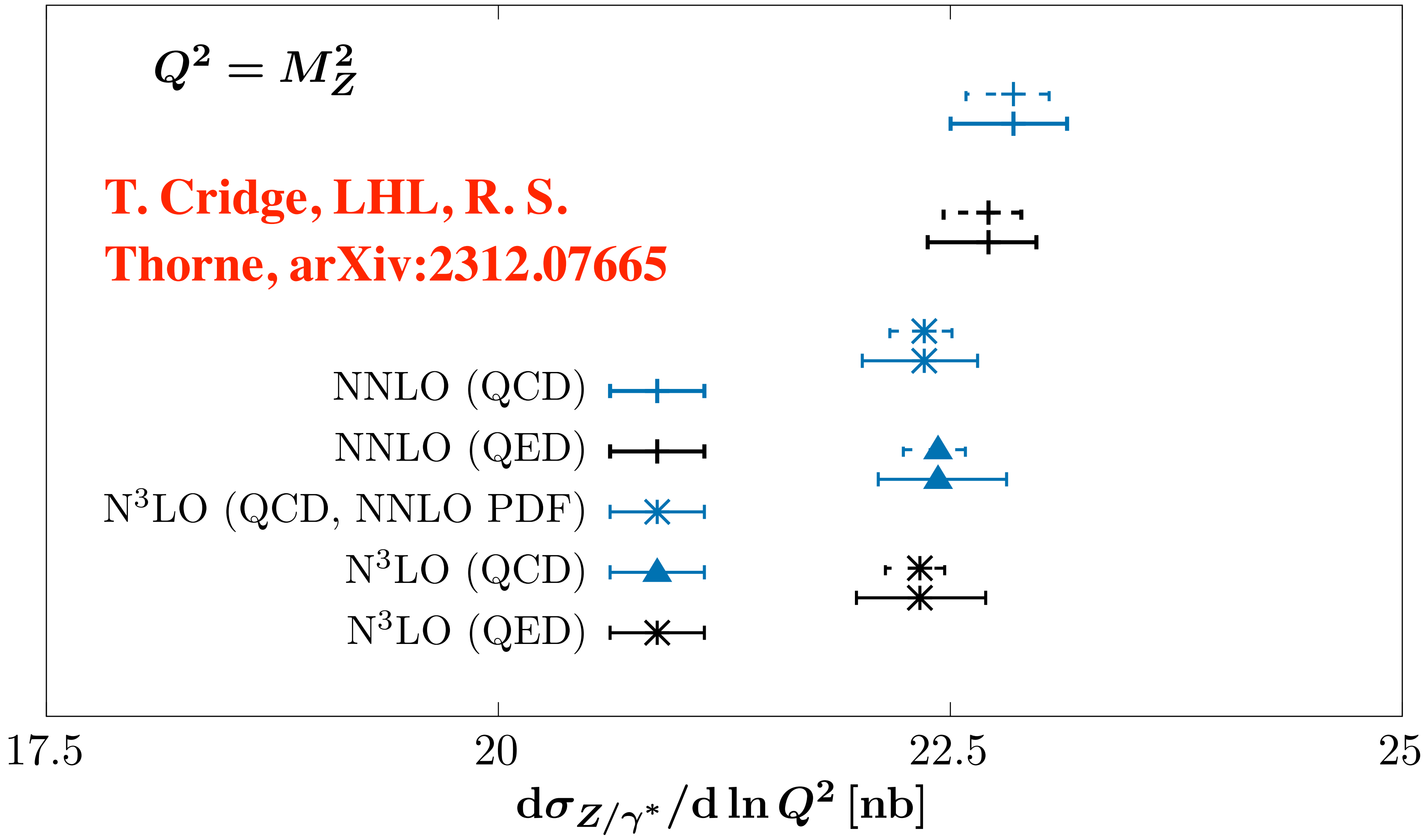
★ Not just the proton! Recent CT study on photon content of the **neutron**.



K. Xie, B. Zhou and T. Hobbs, arXiv:2305.10497

★ First combined **QED + aN3LO** set - **MSHT**. In future should/will be the standard.

★ QED on PDFs effects smaller then or ~ aN3LO. Need both!



New Developments : New Physics + PDFs

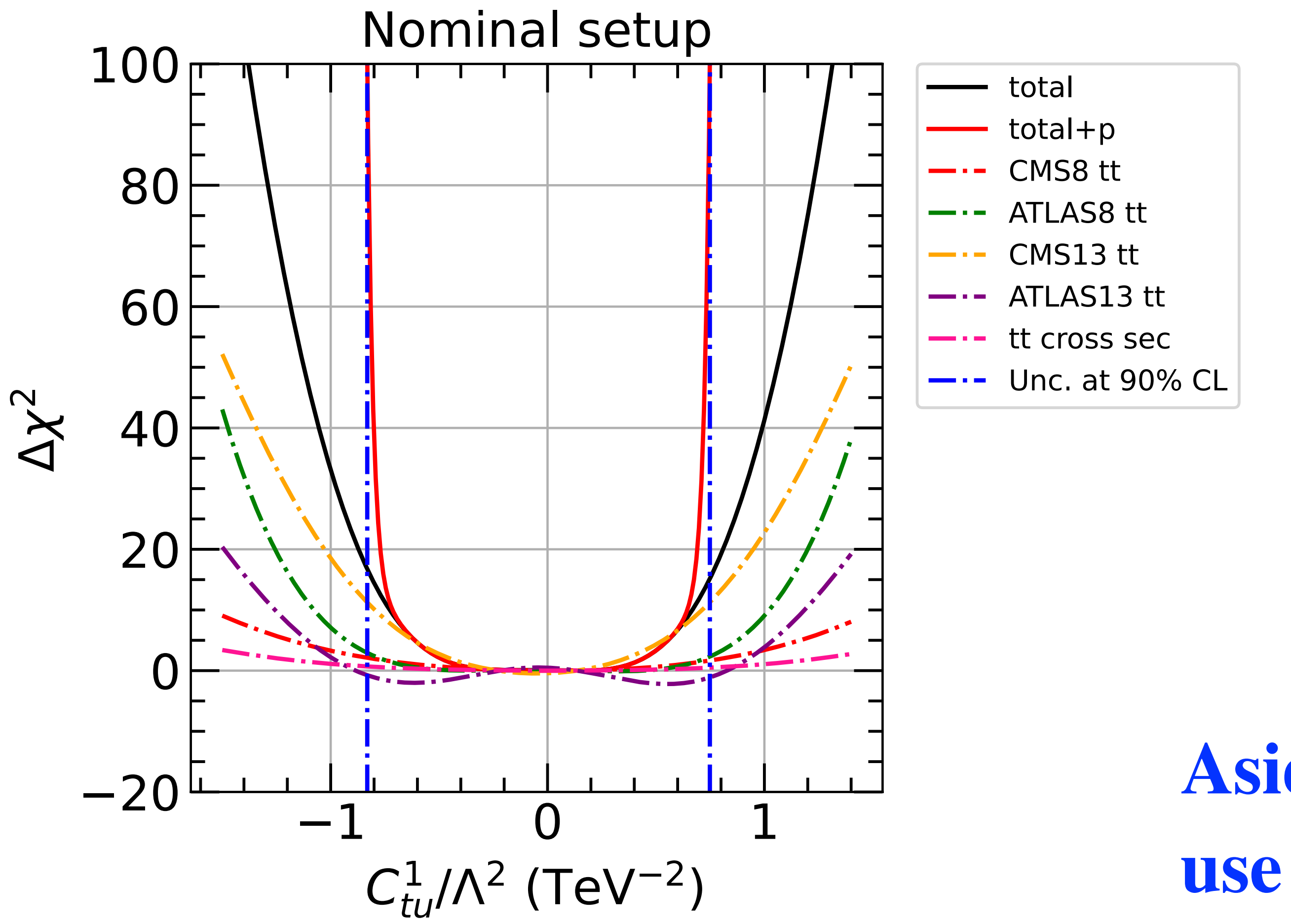
- Key element of LHC precision physics: looking for indirect signs of new physics in high energy data. Parameterise in **SMEFT**:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \ldots,$$

- When constraining BSM with **SMEFT** fits, in principle need to account for interplay with **PDF** fit.

★ CT study - joint fit to SMEFT + PDF parameters.

★ For current LHC data PDF - SMEFT correlation small (safely fit SMEFT with fixed PDFs).



J. Gao et al., arXiv:2211.020194

Aside: both of these studies rely on use of Neural Networks!

`Physics Beyond the Standard Proton'

✦ NNPDF (**PBSP**) study: similar conclusion for current data, but what about the HL-LHC?

✦ HL-LHC pseudodata study: could new physics might be absorbed in PDF fit, and if so what to do?

E. Hammou et al., arXiv:2307.10370

'Reality'

- Predictions are formed from **TRUE** PDFs, and **TRUE** New Physics parameters:

$$\sigma = \hat{\sigma}_{\rm SM+NP} \otimes f_{\rm true}$$

Result of fit

- Predictions are formed from **CONTAMINATED** PDFs, and **NO** New Physics parameters:

$$\sigma = \hat{\sigma}_{\rm SM} \otimes f_{\rm cont}$$

See also A. Anataichuk et al., arXiv:2310.19638

New Developments : New Physics + PDFs

★ HL-LHC pseudodata study: could **new physics** might be **absorbed** in PDF fit?

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \ldots,$$

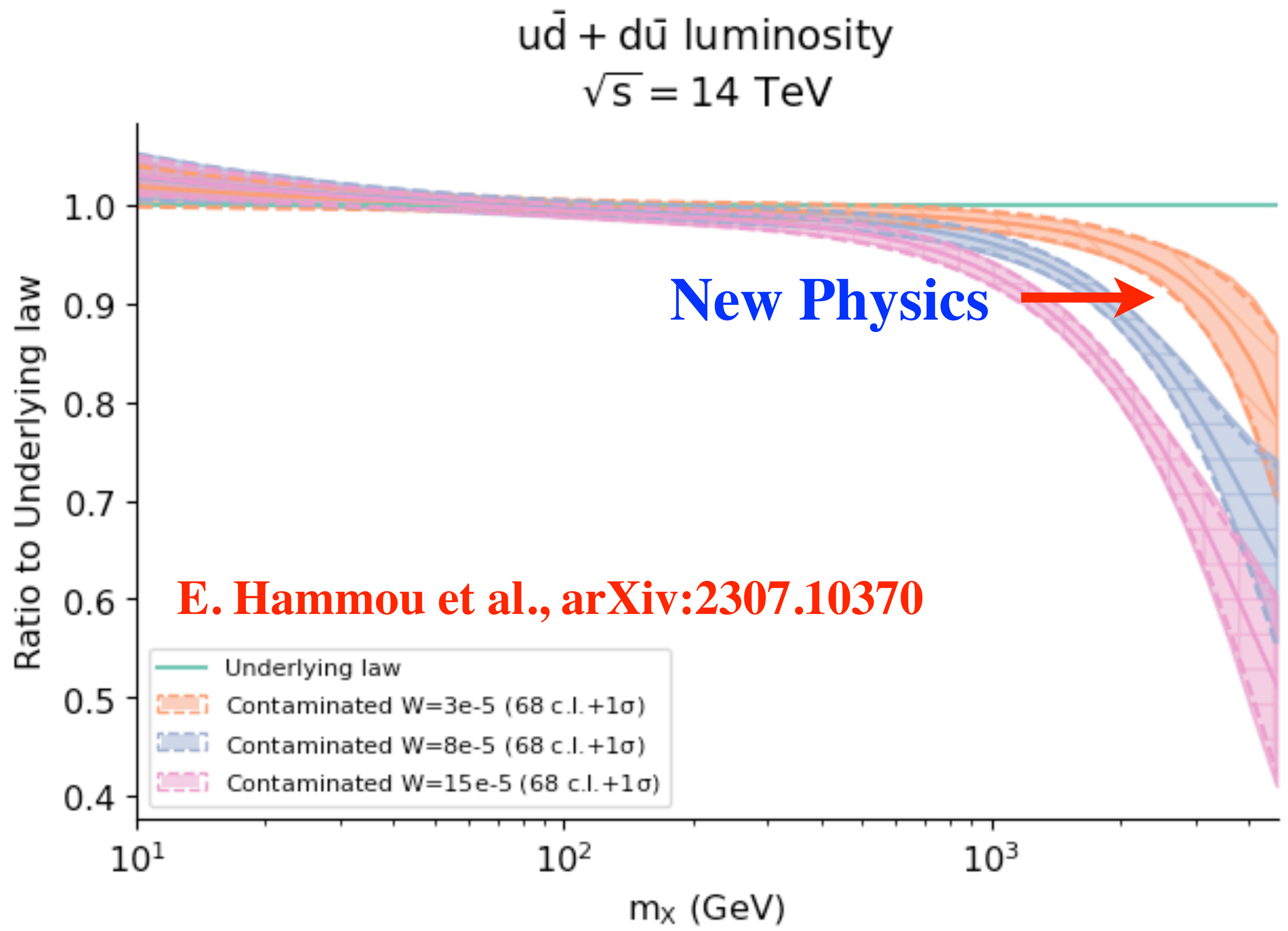
- For certain models **it can**. New physics in high mass DY absorbed into PDFs, with still reasonable fit quality.

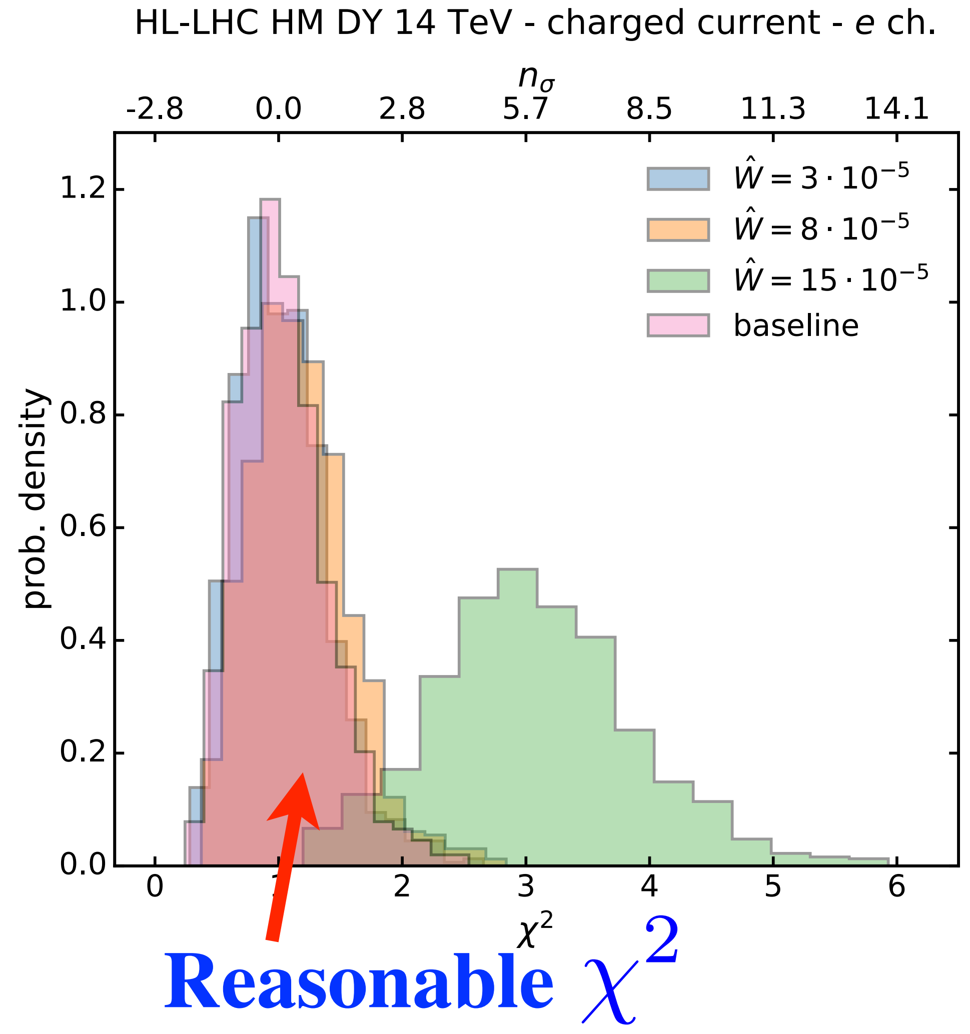
Public `SIMUnet' tool for this:

https://hep-pbsp.github.io/SIMUnet

PBSB collab., arXiv:2402.03308

- Solutions?





✦ Limit PDF fits to lower mass? **Too Naive**: if high mass deviation seen, first place would look is PDFs. Suitable choice of observables, e.g. cross section ratios better.

✦ **LHC(b)** forward data: yes, less clear for high x antiquarks $\Rightarrow$ Low energy data from future experiments (**EIC**)

✦ More broadly highlights benefit of **global fit**: different data constraints can limit above effect. Of course relies on a good understanding of PDF absent BSM…

New Challenges

MSHTaN3LO

	LO	NLO	NNLO	N^3LO
$\chi^2_{N_{pts}}$	2.57	1.33	1.17	1.14

- PDF fitting is a **challenging** environment.

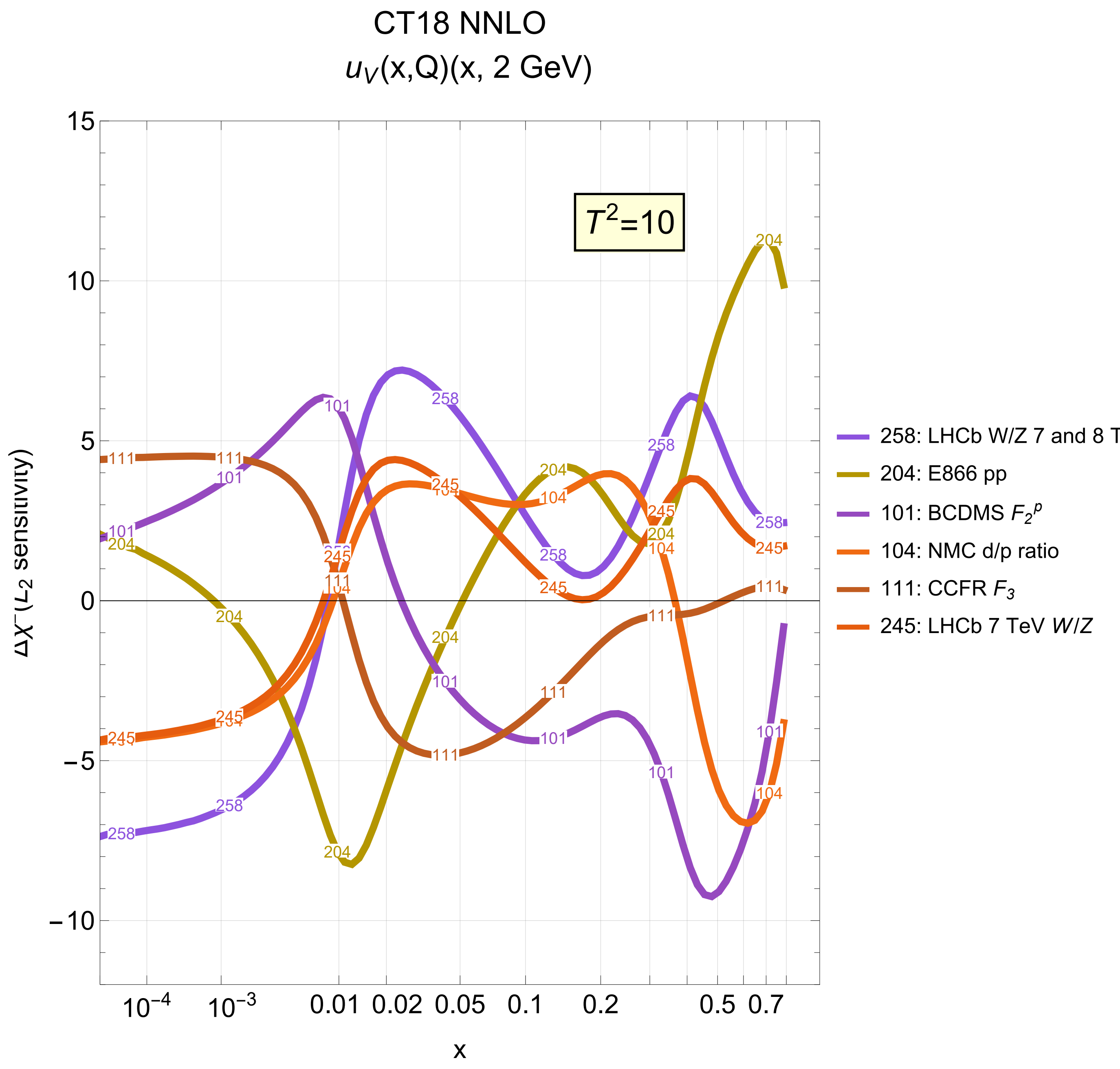
$$\frac{\chi^2}{N_{\rm pts}} \gg 1 + \sigma(N_{\rm pts}) \sim 1.02$$

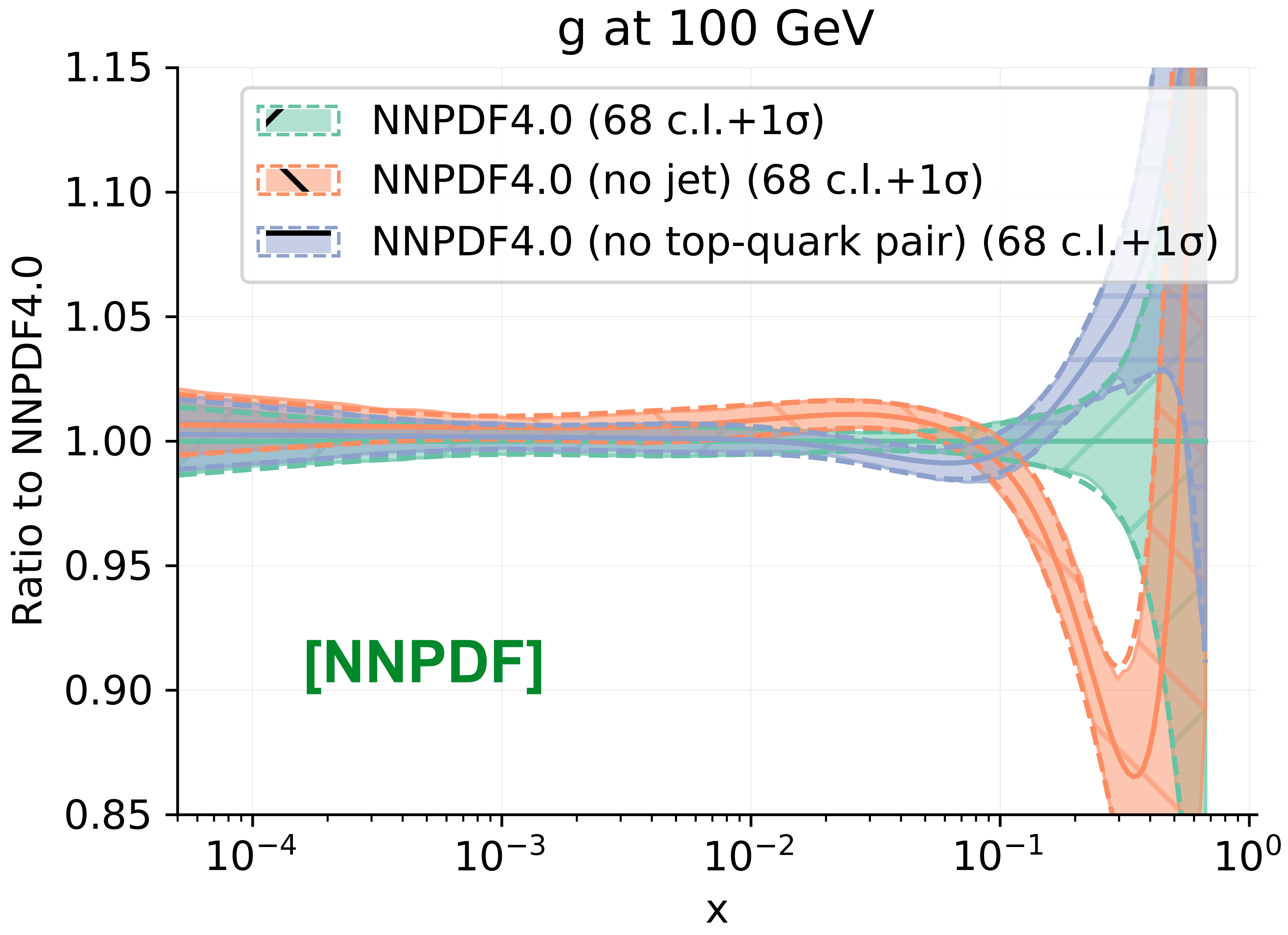
  - Global PDF **fit qualities** not good by textbook definition. Many reasons for this:

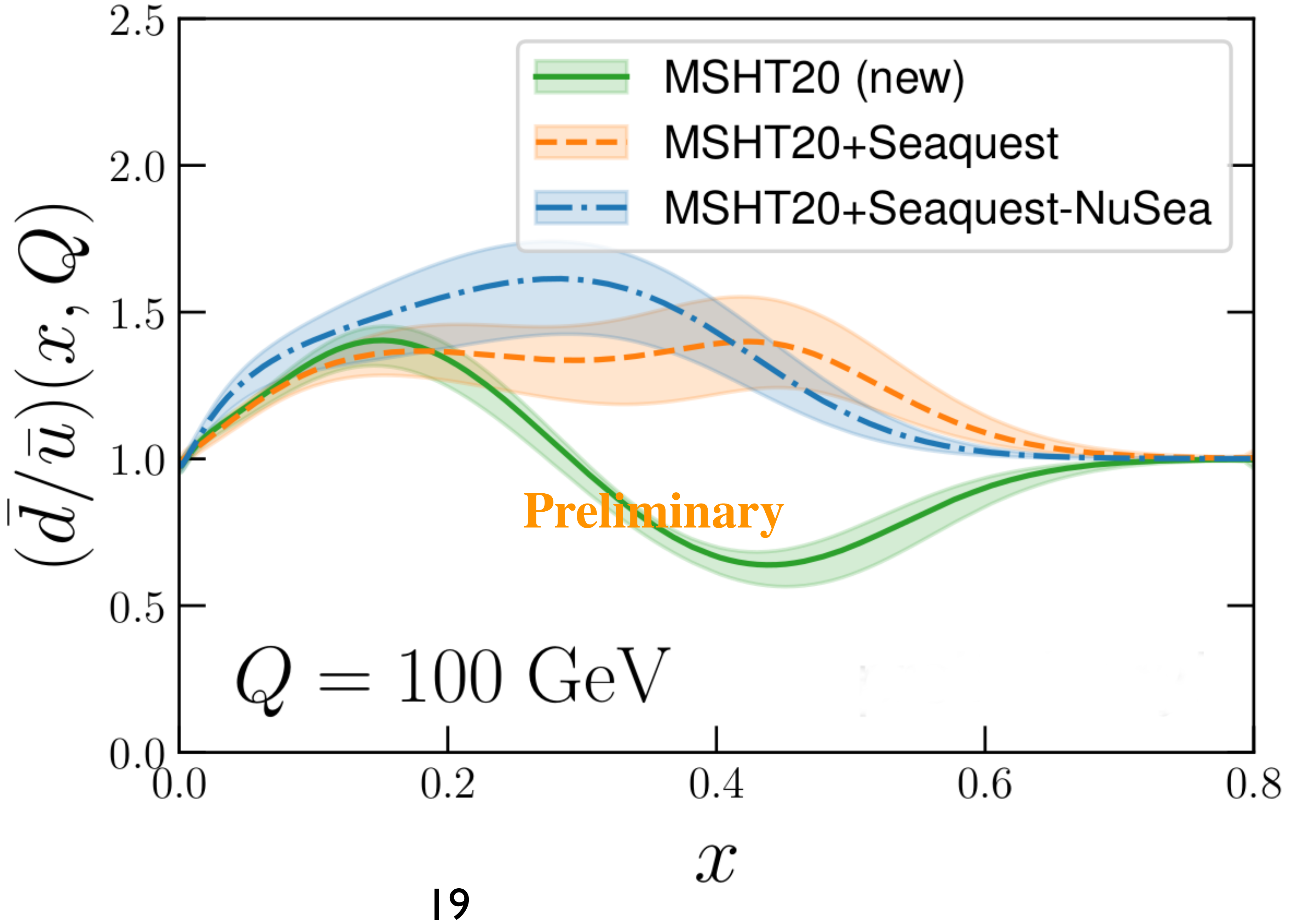
And similar for other fits!

X. Jing et al., arXiv:2306.03918

★ Global fits adversarial - different datasets pull in different directions and **tensions** exist. See recent study on `L2' sensitivity

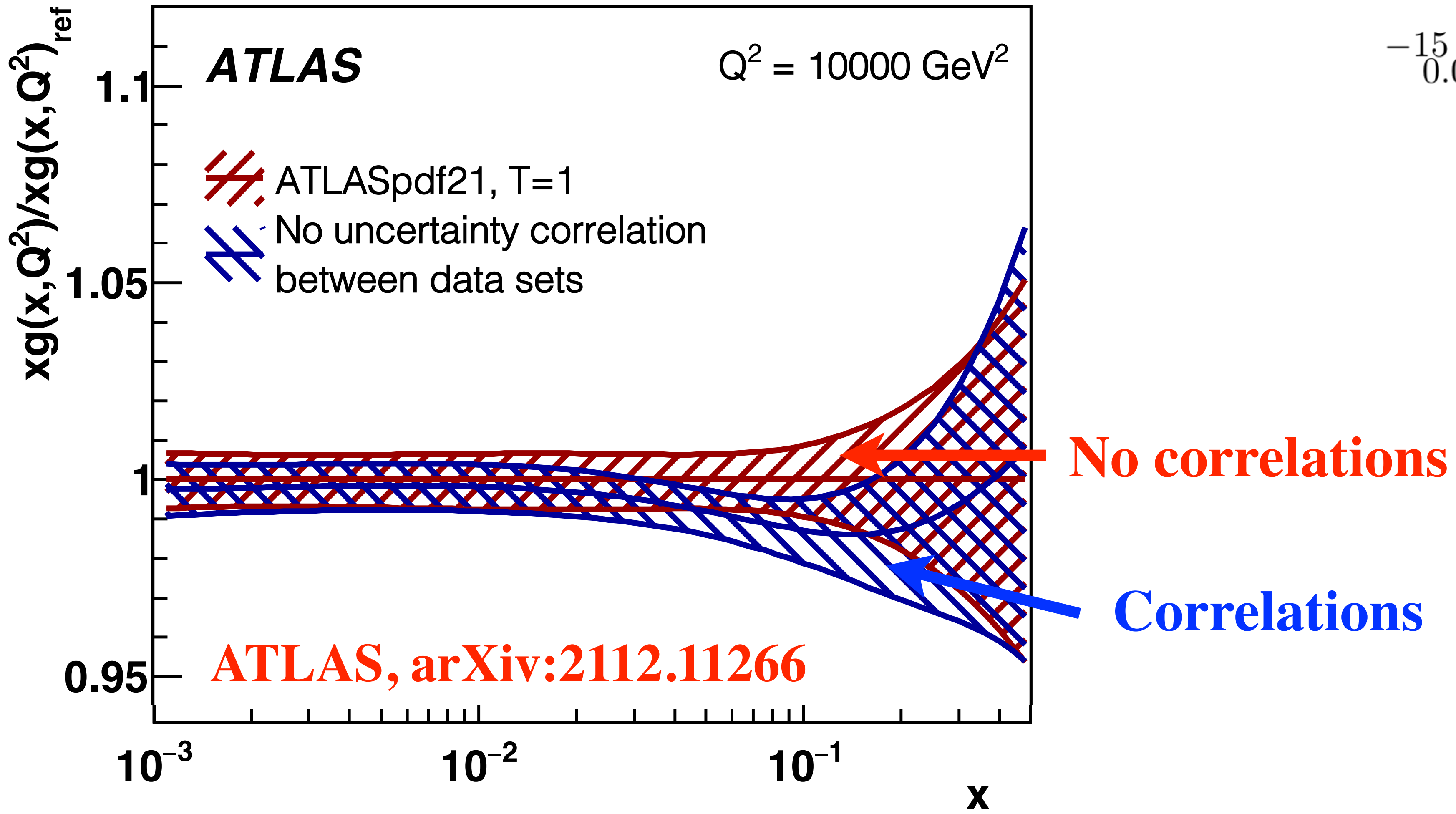


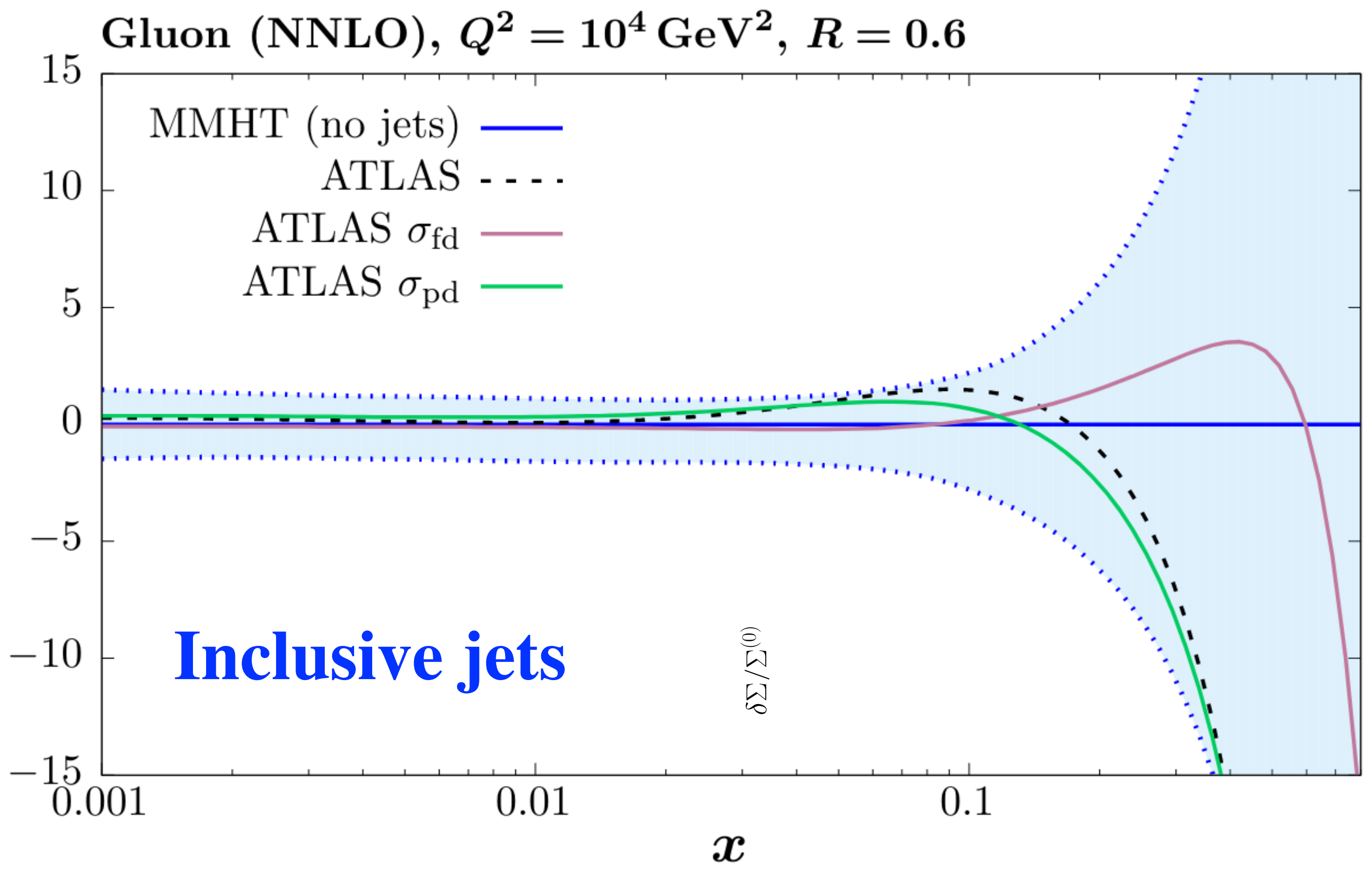




★ As LHC datasets become increasingly **systematics** dominated, sensitive to precise treatment of these, and their correlations…

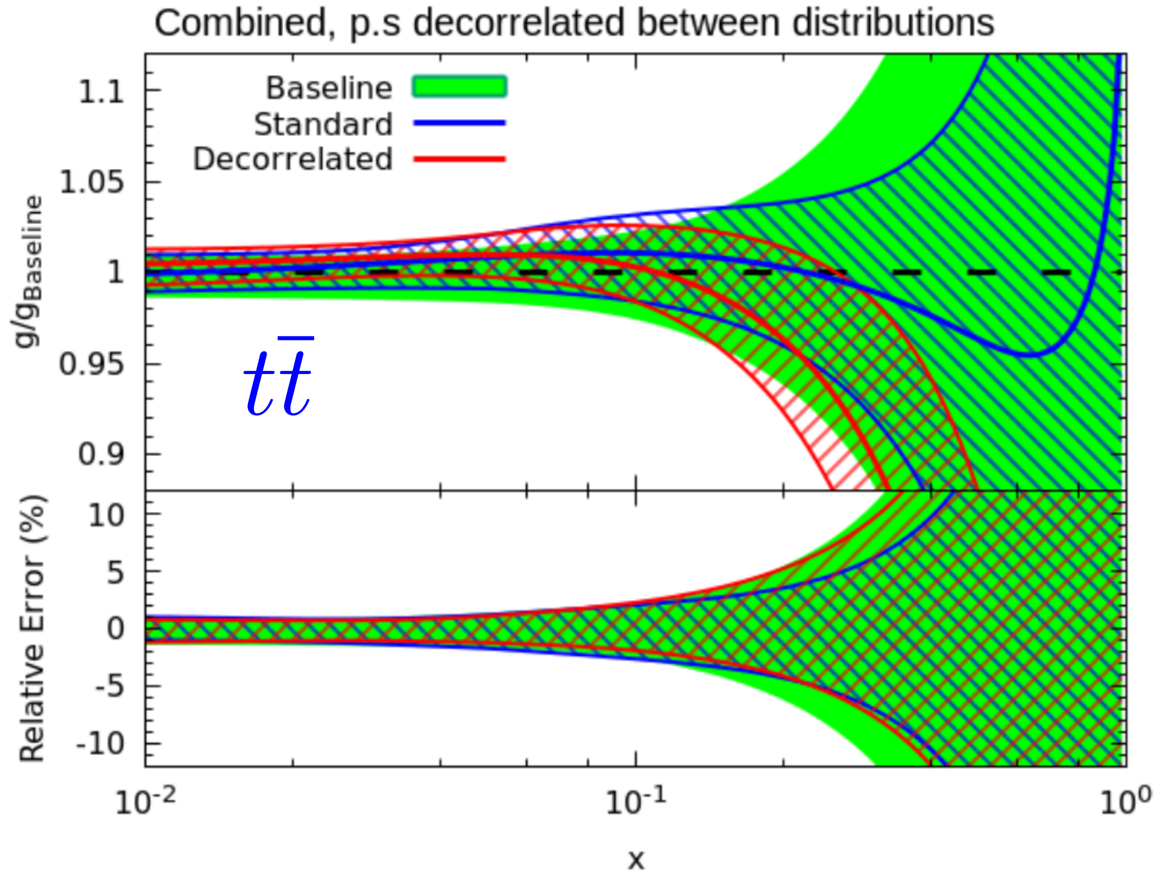
★ …as well as correlations between datasets!





S. Bailey et al., arXiv:2012.04684

$n_{\rm dat}$	default	part. decorr.	full decorr.
140	1.89	1.28	0.83



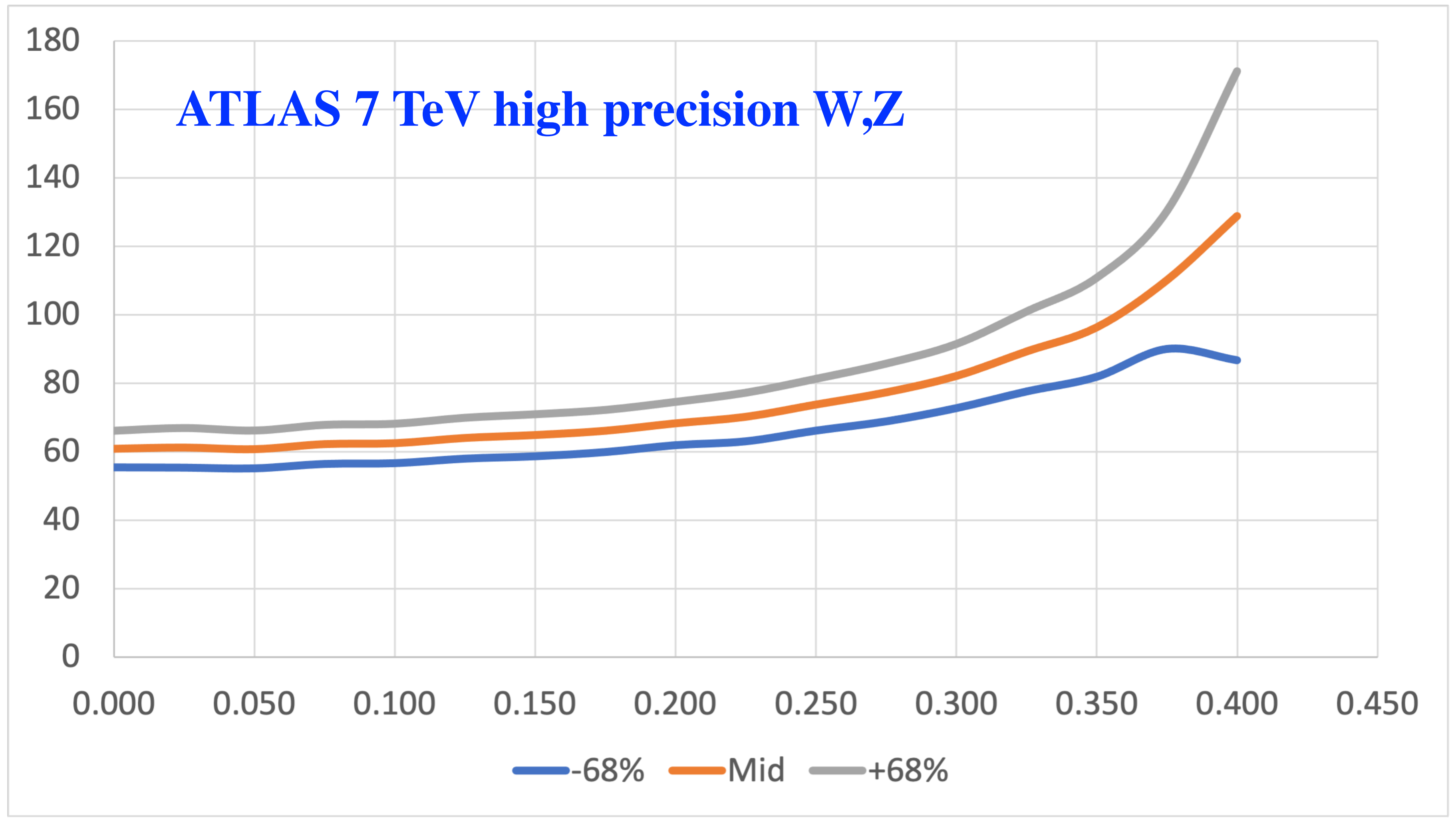
S. Bailey and LHL, arXiv:1909.10541

$n_{\rm dat}$	default	stat. uncorr.	p.s. uncorr
25	7.00	3.28	1.80

★ Could be that a more systematic approach is needed here: include errors on the errors fit quality.

★ Monitor what size of error is needed to match observed χ^2 for high precision datasets. Feeds into expected tolerance.

$$L(\mu,\theta,\sigma^2_{u_i}) = P(y|\mu,\theta)\prod_{i=1}^{N}\frac{1}{\sqrt{2\pi}\sigma_{u_i}}e^{-(u_i-\theta_i)^2/2\sigma^2_{u_i}}\frac{\beta_i^{\alpha_i}}{\Gamma(\alpha_i)}v_i^{\alpha_i-1}e^{-\beta_i v_i}$$



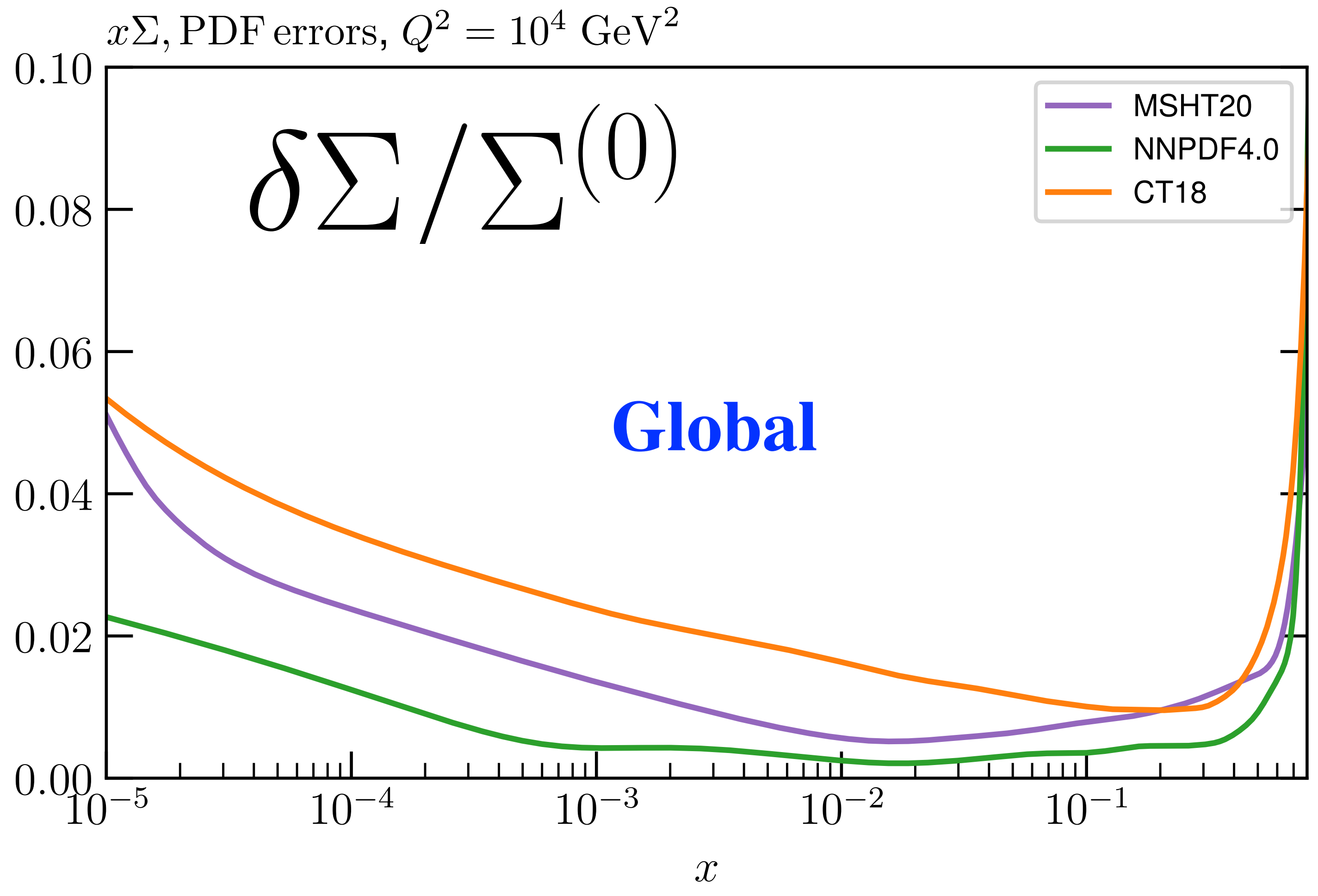
See talk by M Reader

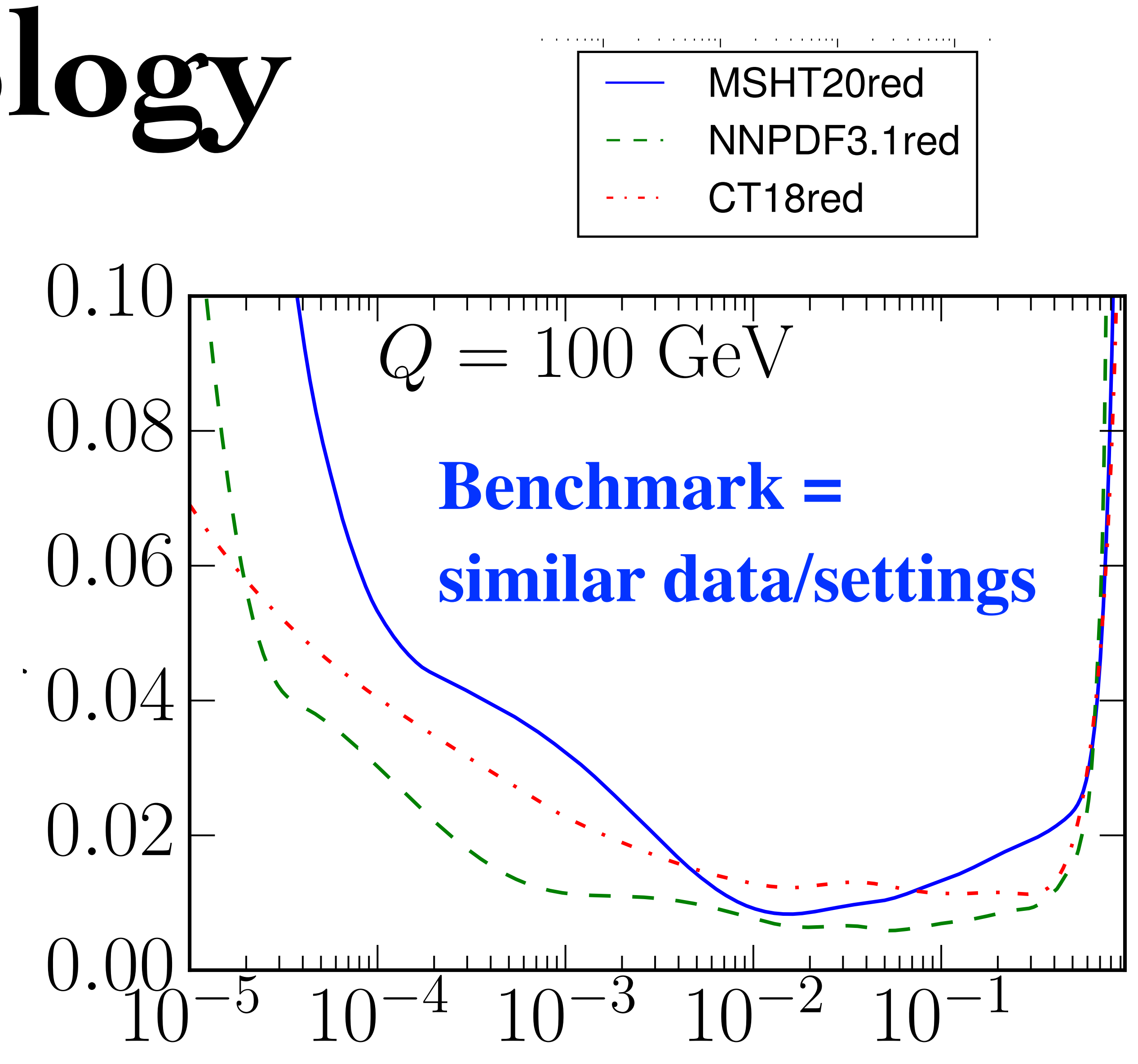
Understanding the Fitting Methodology

- Comparing uncertainties of global PDF fits, find increasingly different results. Not just due to different data, but to **methodology**.

$f_i(x, Q_0): \; A_f x^{a_f}(1-x)^{b_f} \times$ → $\sum_{i=1}^{n} \alpha_{f,i} P_i(y(x))$, **CT, MSHT…**

↘ $\mathrm{NN}_i(x)$ **NNPDF**

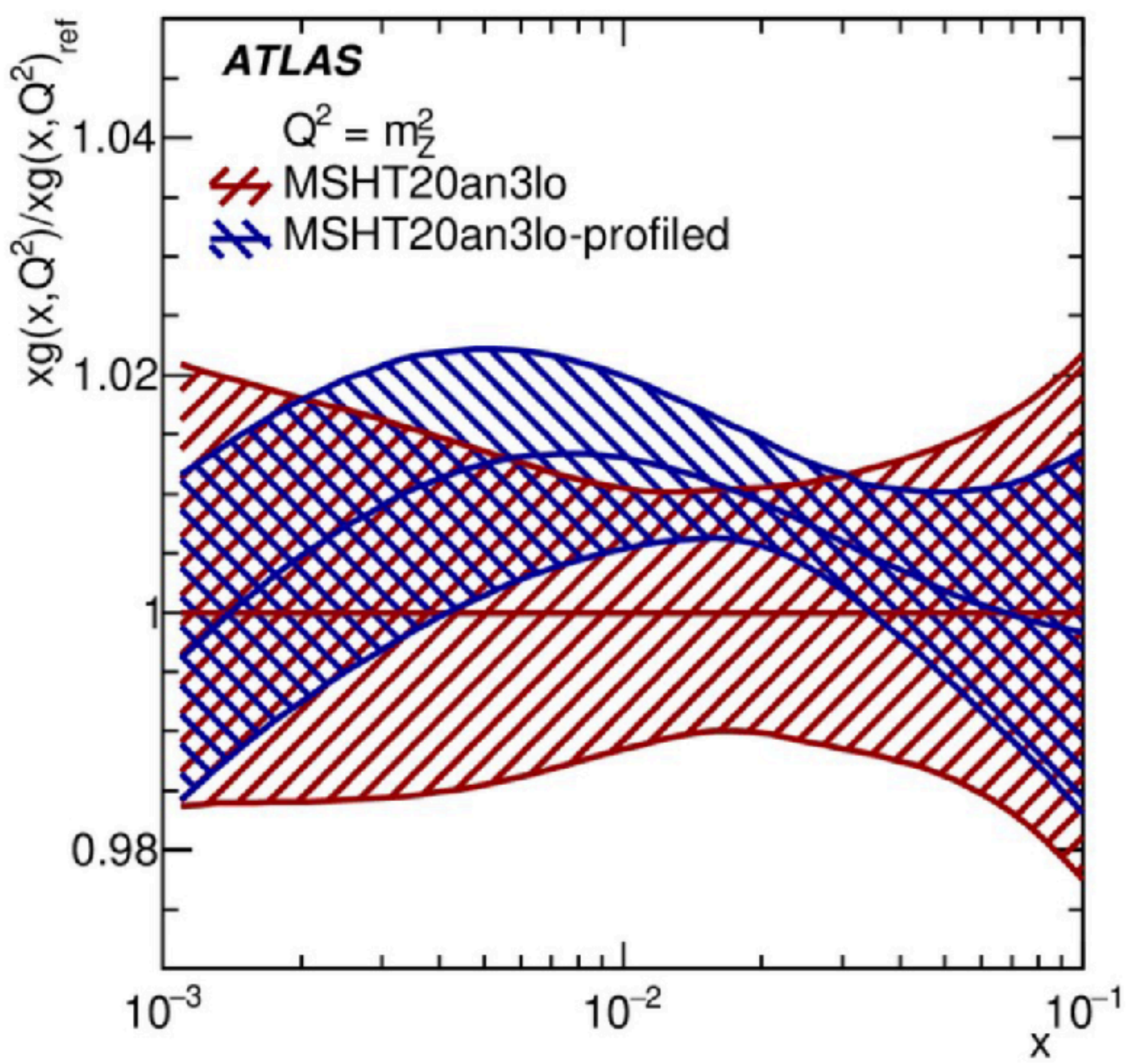




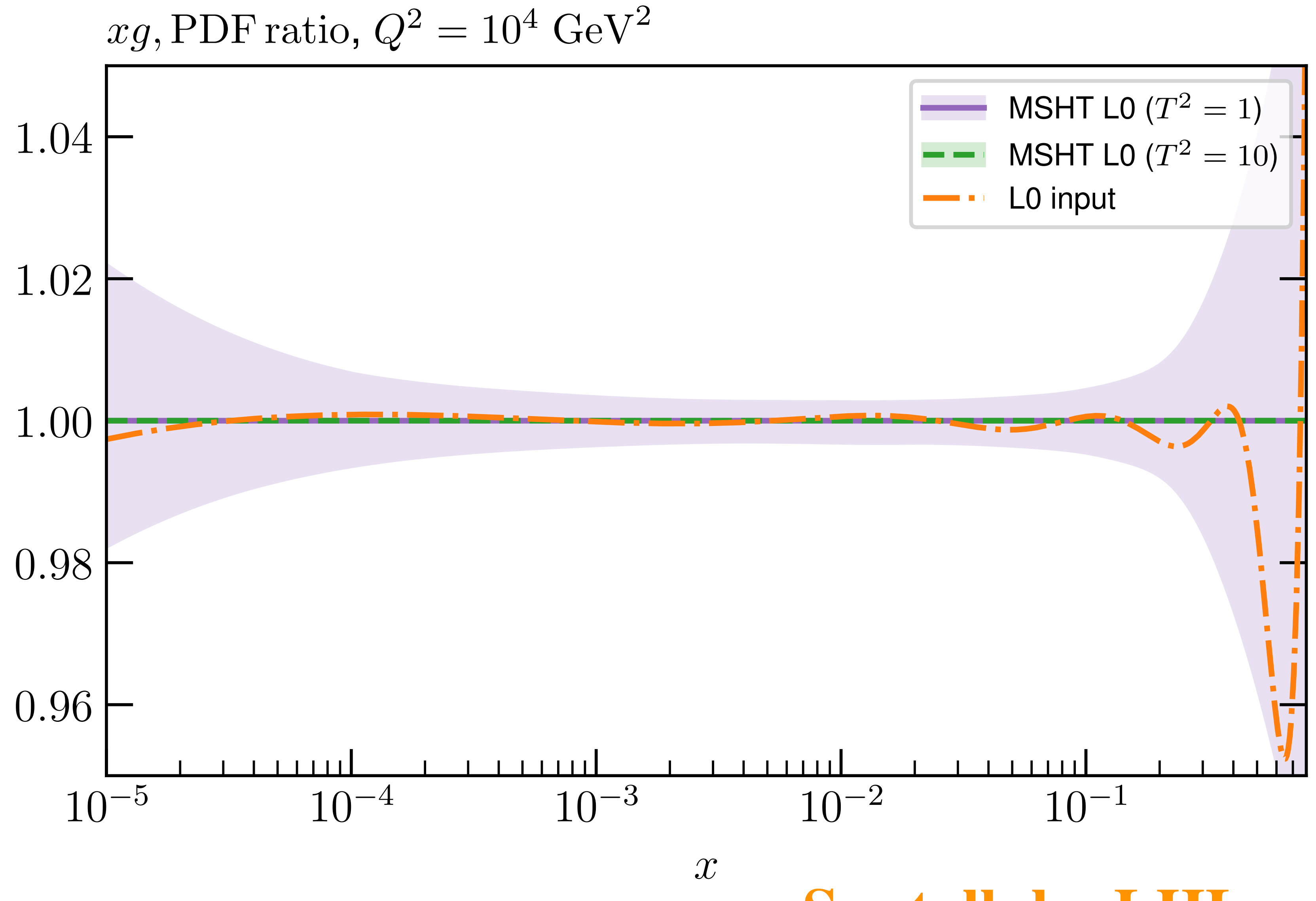
PDF4LHC21, arXiv:2203.05506

- Two fitting techniques - **Neural Nets** (NNPDF) or **Explicit Parameterisation** (CT, MSHT). Different approaches to PDF error definition - include explicit `**tolerance**' or not to account for tensions/inconsistencies in fit or not, and if so how to do it.
- All lead to different results. **Better understanding**/comparison **needed**.
- Note this question also highly relevant for experimental analyses when placing `**in-situ**' constraints. PDF impact here not necessarily = impact in global fit.
- Role of tolerance also important here - if omitted will overweight profiled data.

2309.12986



- One (very) recent attempt - first global **closure test** of explicit parameterisation (**MSHT**) fit and direct comparison to the NN approach.
- Passes closure test well - output PDFs agree with input well within $T^2 = 1$ uncertainties, i.e. suggests parameterisation inflexibility not dominant issue (c.f. tolerance) in data region.
- Performs well in full global fit with NNPDF dataset/theory.



See talk by LHL

- Another way to shed light on this could be to consider other approaches to PDF fitting/uncertainty estimation.

★ Some recent development in **Bayesian** approach to PDF uncertainty evaluation. In principle allows us to move beyond standard χ^2 approach and Gaussian error assumptions.

F. Capel et al., arXiv:2401.17729

Posterior of model given the data

Prior on the model

$$p(f|D) = \frac{p(D|f)p(f)}{p(D)}$$

T. Giani, CERN TH seminar

★ Can even allow alternative PDF 'parameterisation' via probability distribution PDF values at given x_i points.

See talks by F. Capel, T. Giani and others

$$\mathbf{f} = \begin{pmatrix} f(x_1) \\ \vdots \\ f(x_N) \end{pmatrix}$$

Parameters: stochastic variables representing values of the PDF on a grid of points

- Notable how many talks on **PDF uncertainty/alternative approaches** this year. No time to discuss more here - but please go and listen!

A critical assessment of uncertainty propagation methodologies in PDF fitting

10 Apr 2024, 09:10
20m
Maison MINATEC, Grenoble, FR

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Mark N. Costantini (University of Cambri...

PartonDensity.jl: a novel parton density determination code

10 Apr 2024, 16:20
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Allen Caldwell (Max Planck Institut...

Fantômas4QCD: pion PDFs with epistemic uncertainties

10 Apr 2024, 14:50
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

eaker

urore Courtoy

A Markov chain Monte Carlo determination of Proton PDF uncertainties at NNLO

10 Apr 2024, 10:10
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Peter Risse (University of Münst...

Partonic collinear structure by quantum computing

10 Apr 2024, 16:00
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Hongxi Xing (South China Normal...

A study of systematic uncertainties within the MSHT PDF framework.

10 Apr 2024, 09:30
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Bayesian Inference and Gaussian Processes for PDF determination

10 Apr 2024, 09:50
20m
Maison MINATEC, Grenoble, FRANCE

Regular parallel talk | WG1: Structure Fun... | WG1

Speaker

Tommaso Giani (Nikhef)

PDF uncertainties: a critical examination

10 Apr 2024, 08:50
20m
Maison MINATEC, Grenoble, FRANCE

Speaker

Lucian Harland-Lang (University College L...

Analytic Solutions of the DGLAP Evolution and Theoretical Uncertainties

10 Apr 2024, 16:40
20m
Maison MINATEC, Grenoble, FRANCE

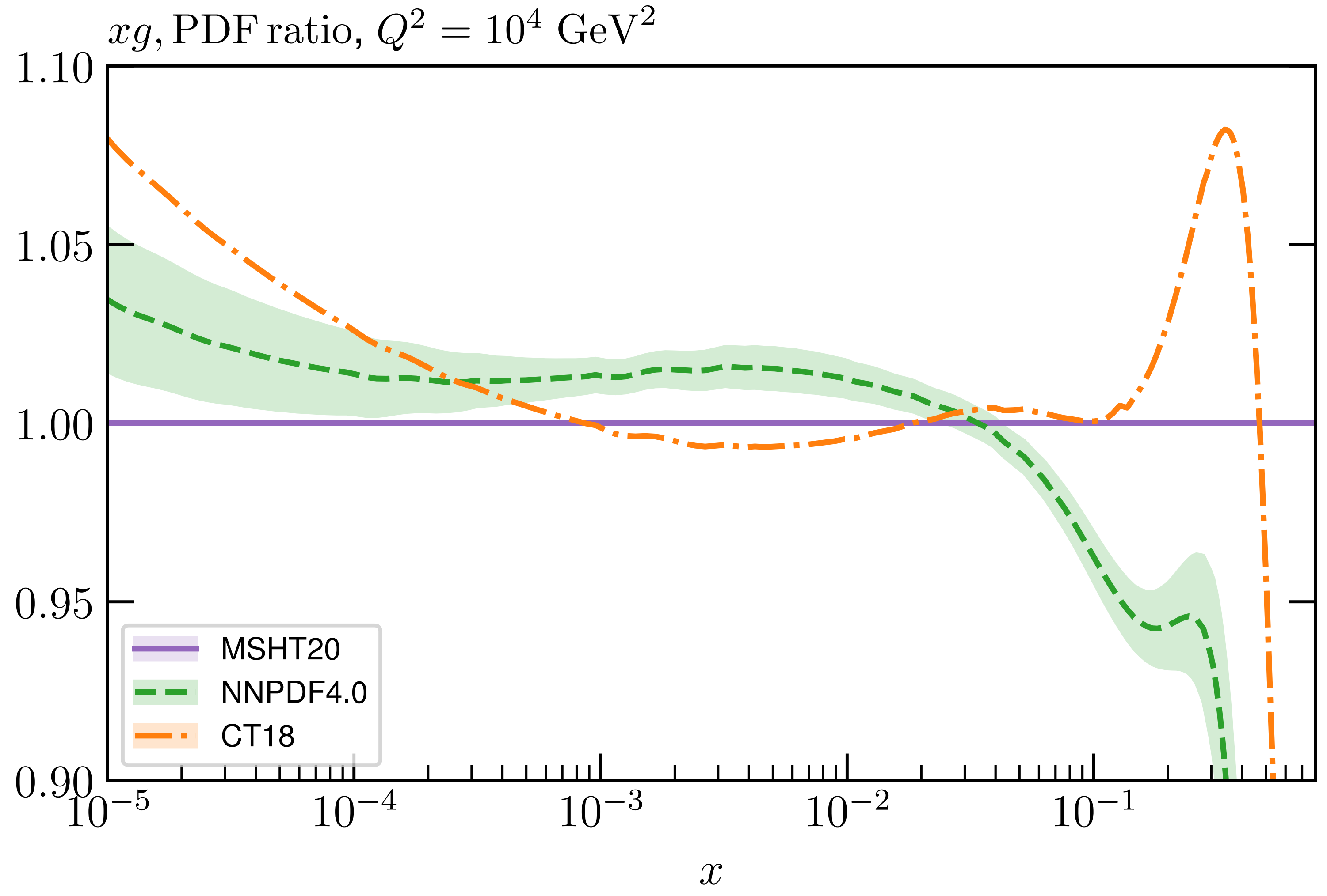
Regular parallel talk | WG1: Structure Fun... | WG1

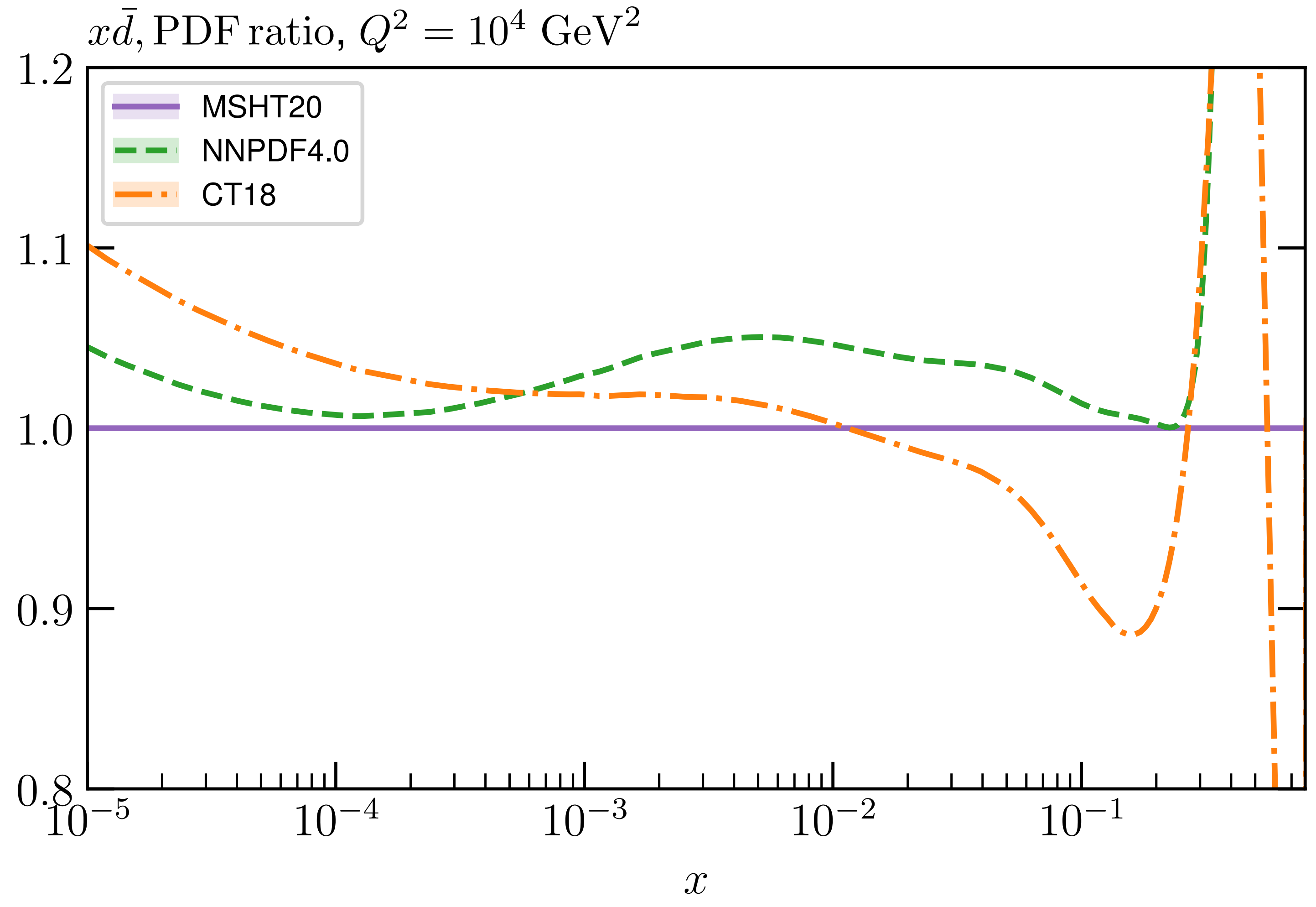
Speaker

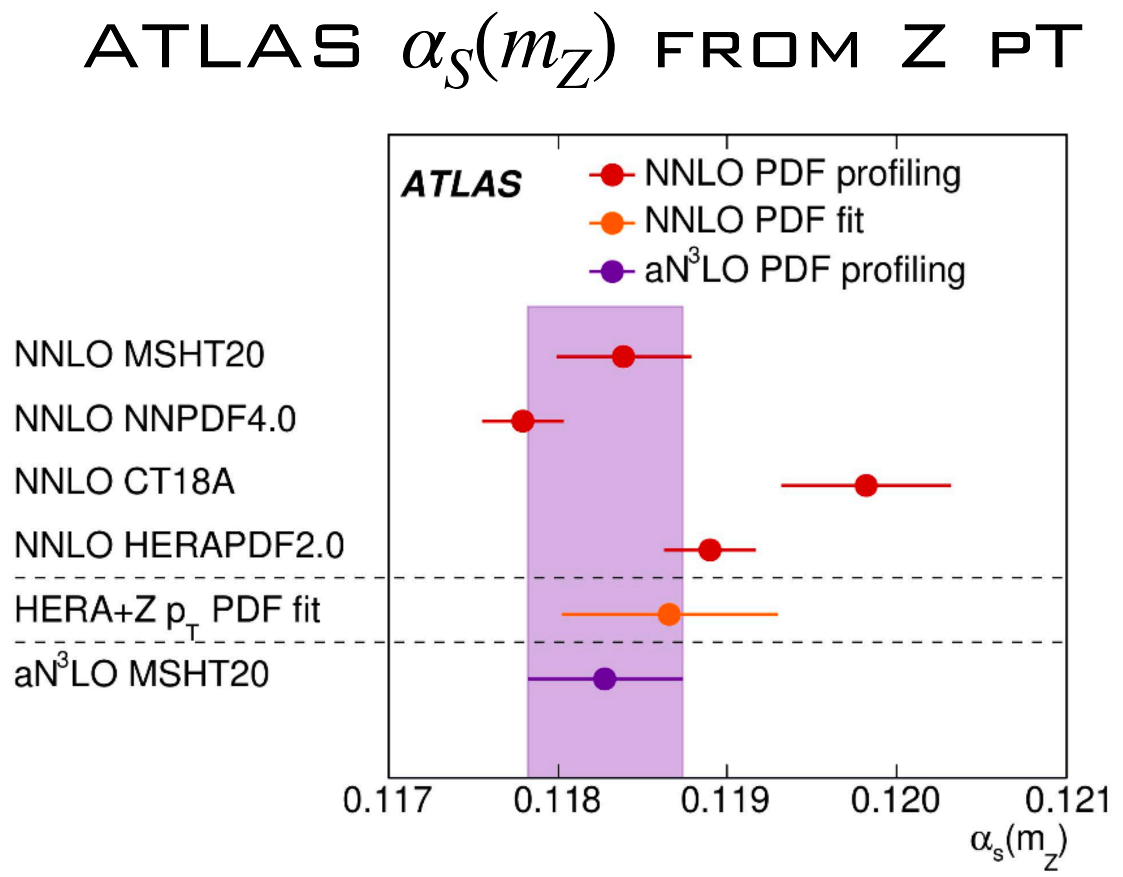
Andrea Simonelli (Old Dominion Unive...

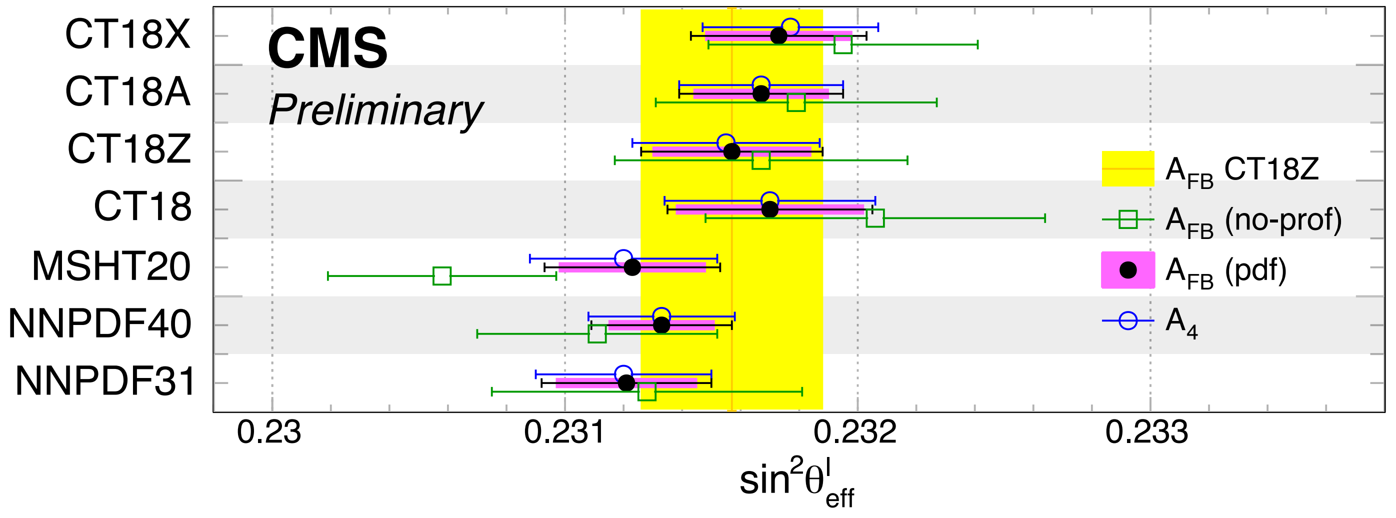
Where do we stand? Where might we go?

- New (LHC) data in fits has clear impact - PDF uncertainties continue to reduce - and theoretical precision continues increase, up to now aN3LO order.
- But agreement between sets not always good - **bottleneck** for precision physics.









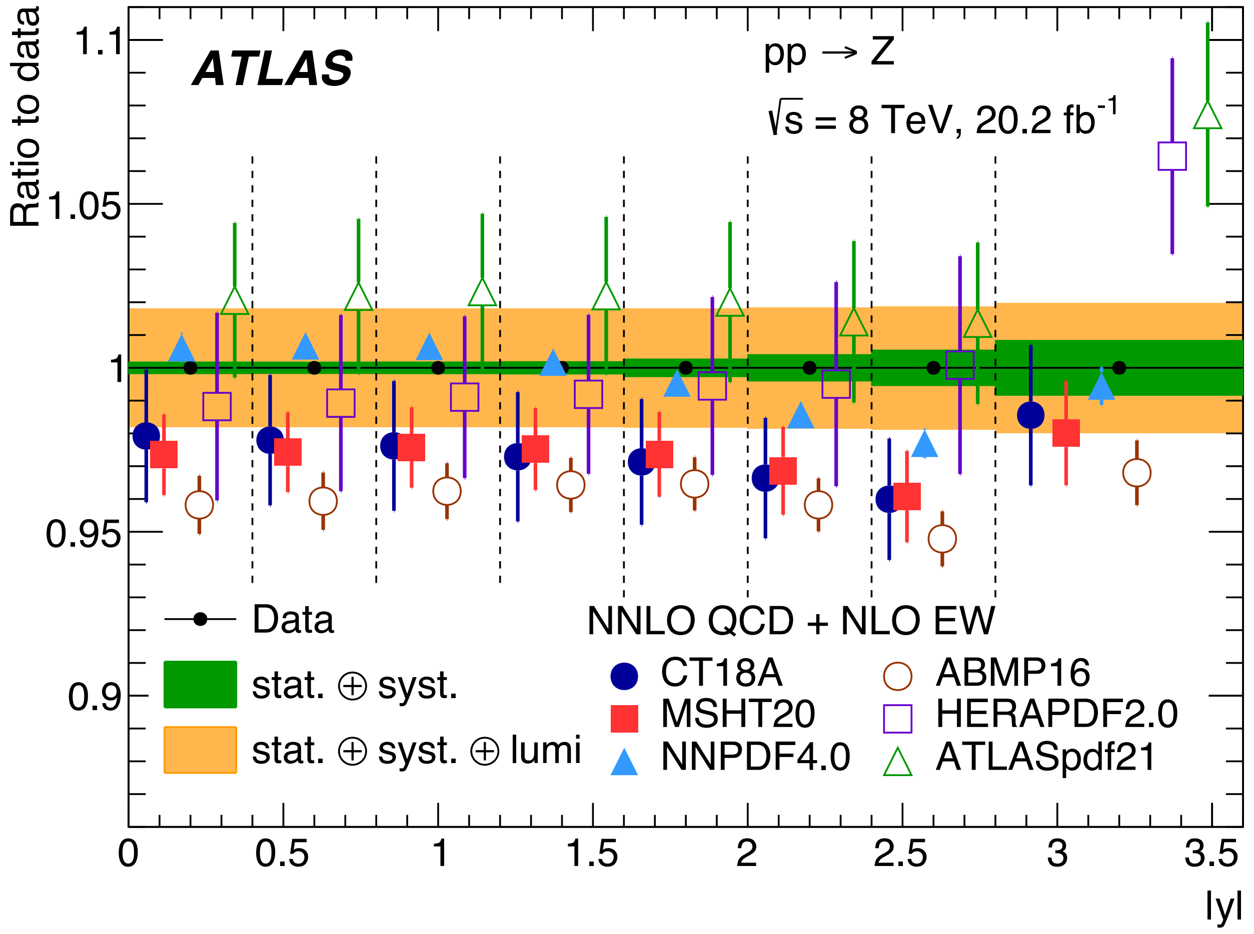
- New ideas/comparisons will be needed.
- But future data also will be the determining factor: how well do PDFs describe data not currently in fit?

See talk by J. Cruz-Martinez

Precision continues!

- Plenty of data yet to be included in global fits - more information to come and comparisons to make.

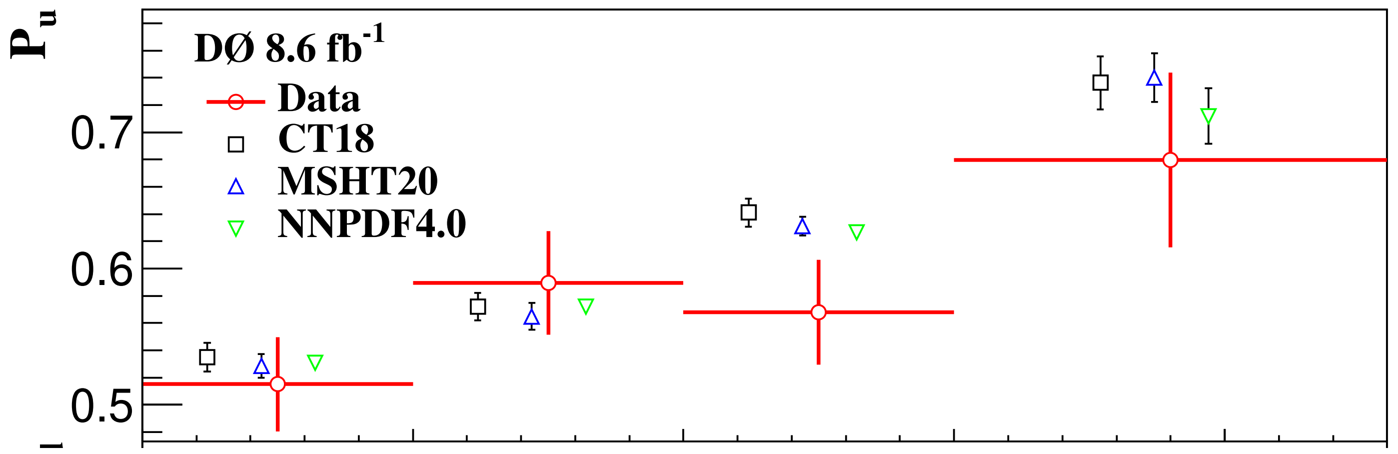
★ **New observables:** l^+l^- corrected to full phase space. Angular coefficients - limit extrapolation uncertainty.

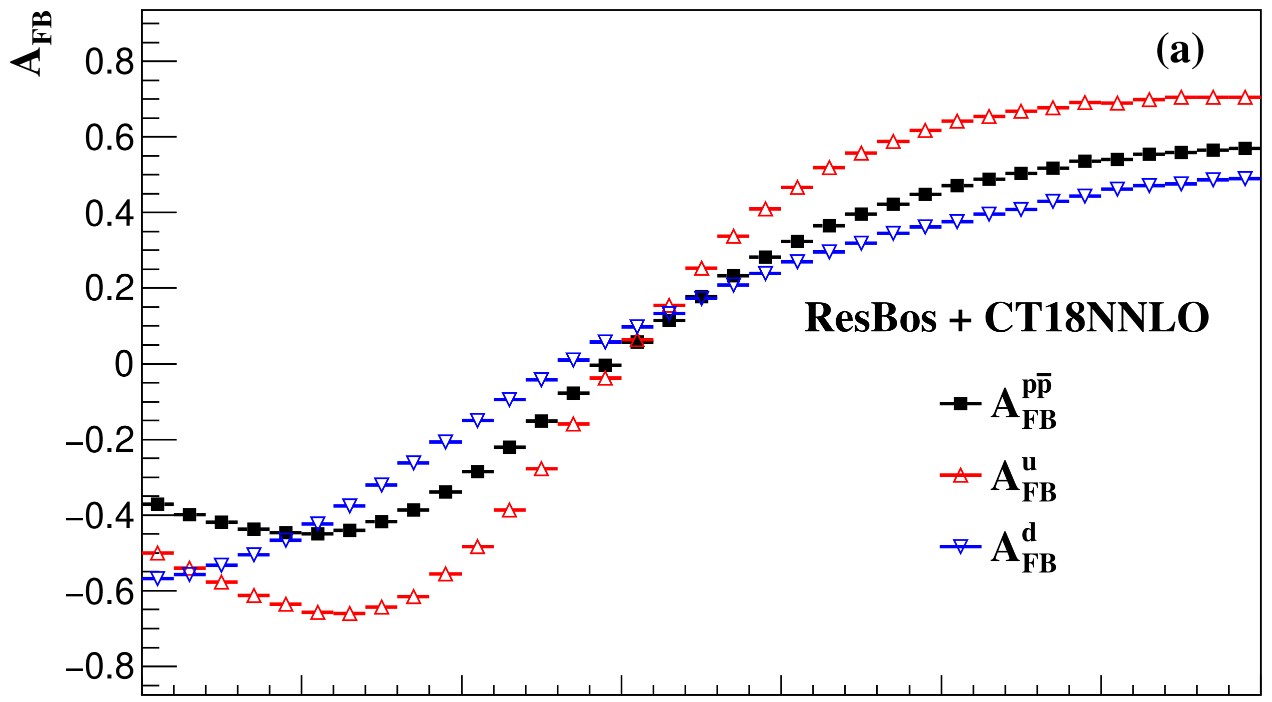


PDF set	Total χ^2 / d.o.f.	χ^2 p-value	Pull on luminosity
MSHT20aN^{3}LO [58]	13/8	0.11	1.2 ± 0.6
CT18A [59]	12/8	0.17	0.9 ± 0.7
MSHT20 [60]	10/8	0.26	0.9 ± 0.6
NNPDF4.0 [61]	30/8	0.0002	0.0 ± 0.2
ABMP16 [62, 63]	30/8	0.0002	1.8 ± 0.4
HERAPDF2.0 [64]	22/8	0.005	−1.3 ± 0.8
ATLASpdf21 [65]	20/8	0.01	−1.1 ± 0.8

ATLAS, arXiv:2309.09318

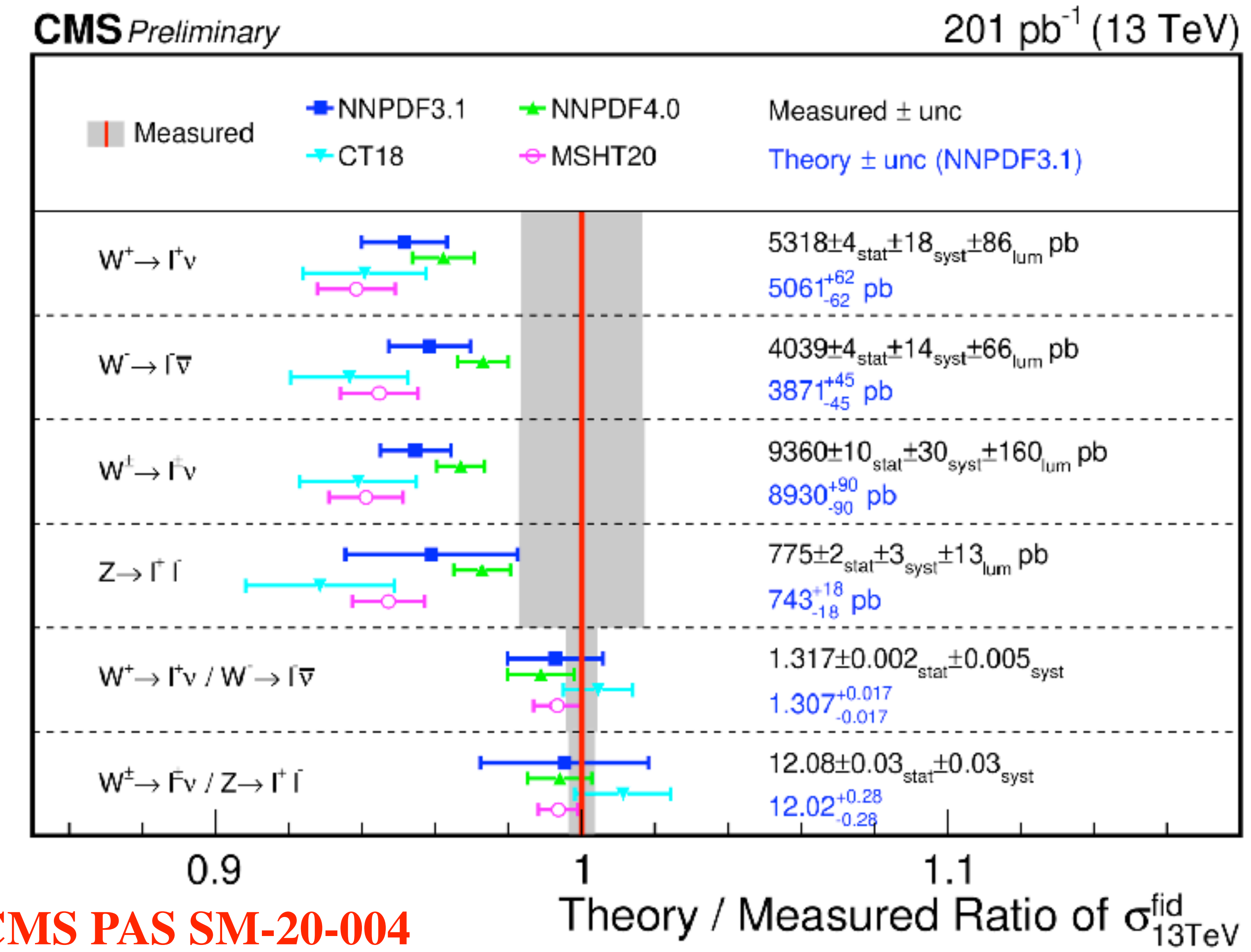
★ **New data:** Not just the LHC. Recent **D0** measurement of dilepton AFB. Sensitivity to high x flavour structure.





★ **New ratios:** low lumi runs. Ratios at different energies increase PDF sensitivity.

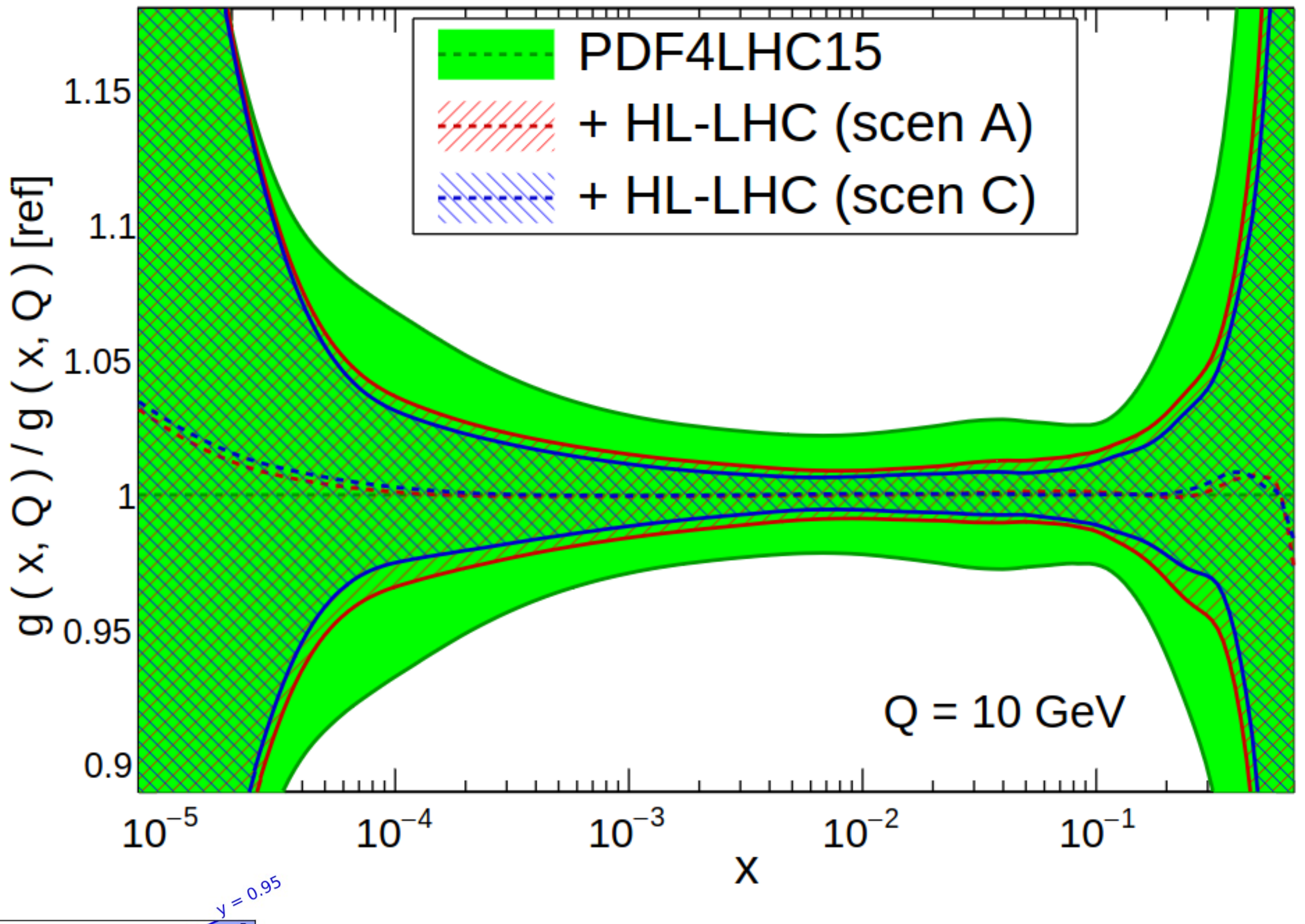
- And much more not shown here.

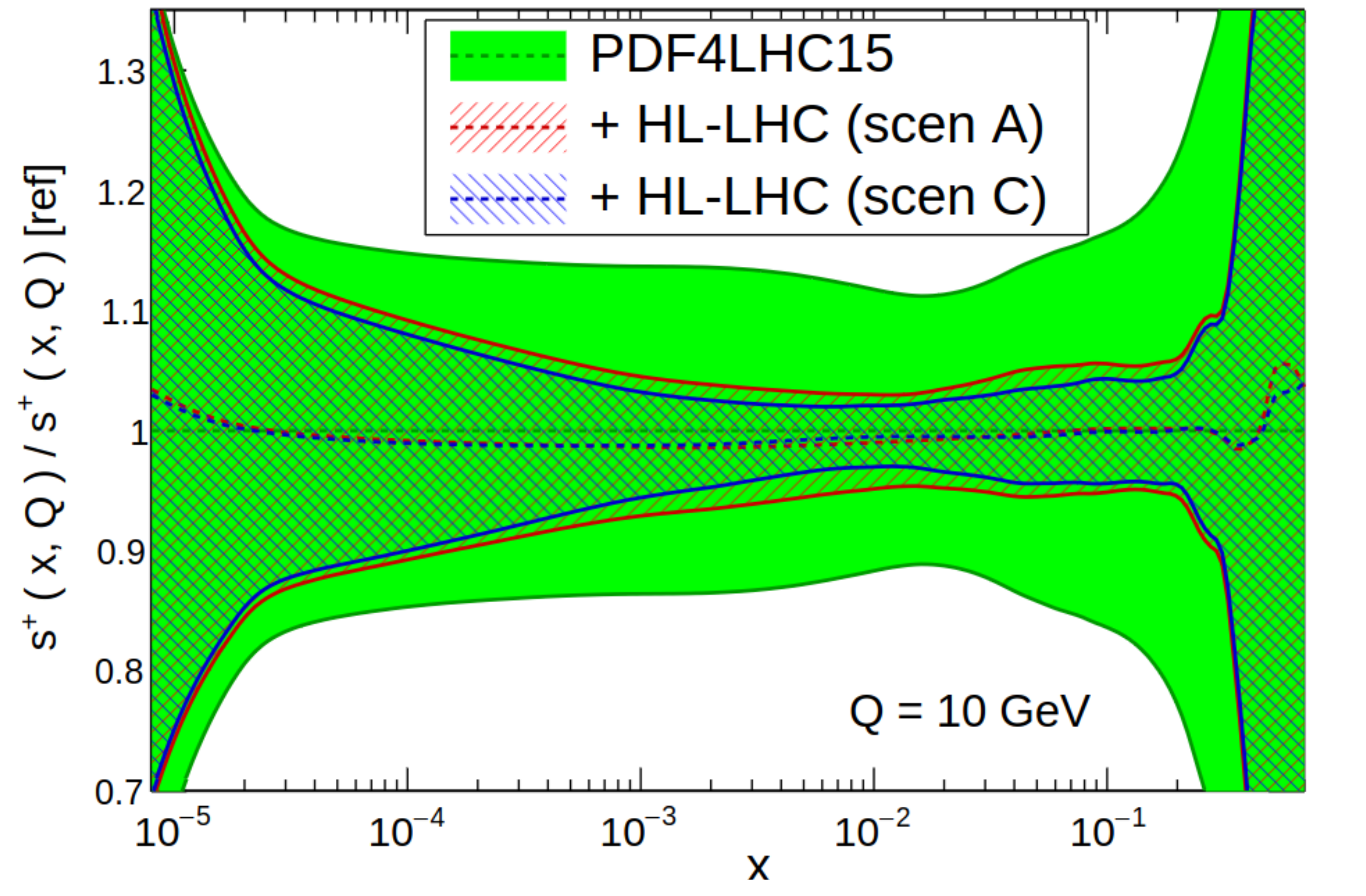


CMS PAS SM-20-004

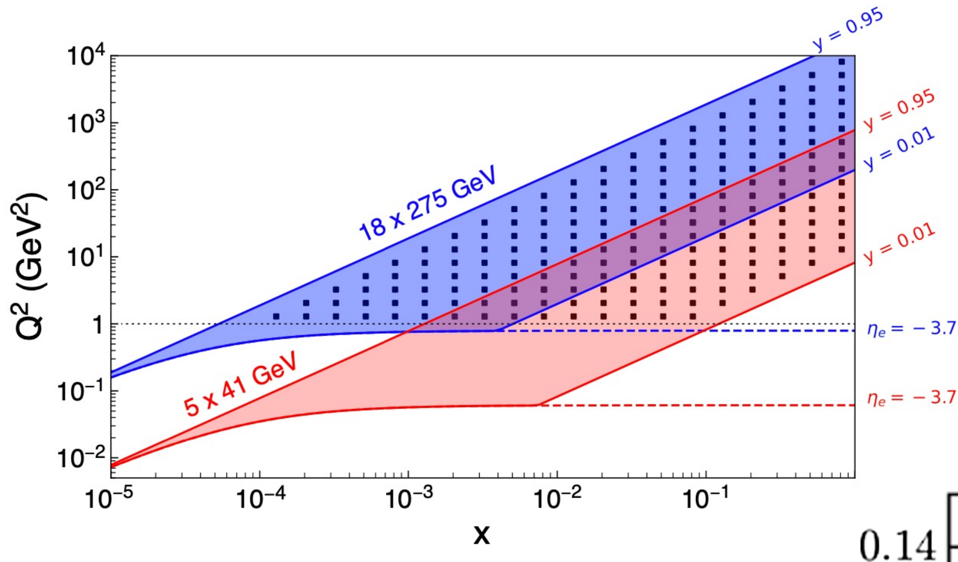
Future Data

- LHC continuing to have an impact, and **HL-LHC** projected to beyond that…
- …but these are only projections. Reality usually more complicated. Other experiments/colliders providing complementary information will be key.



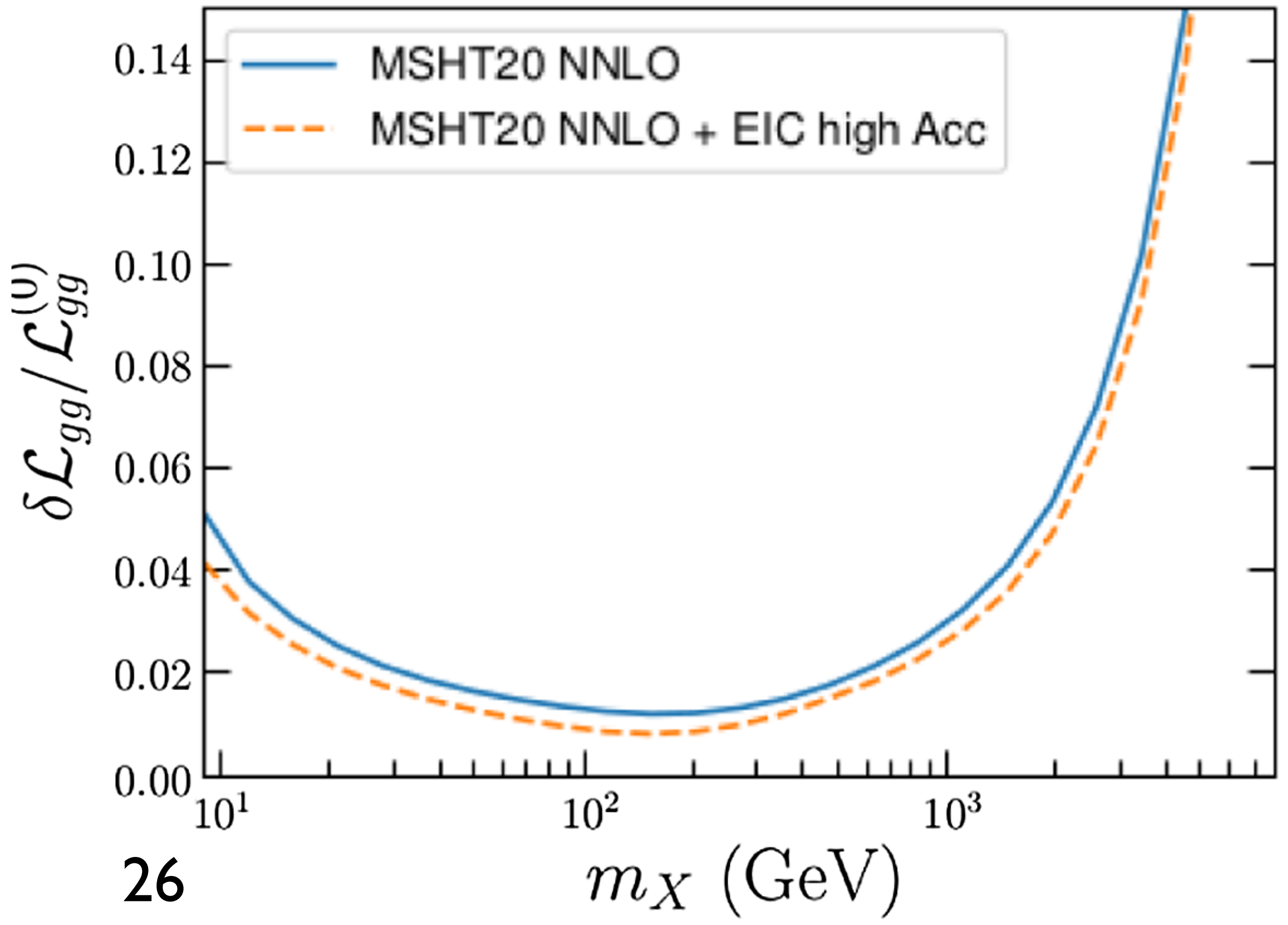


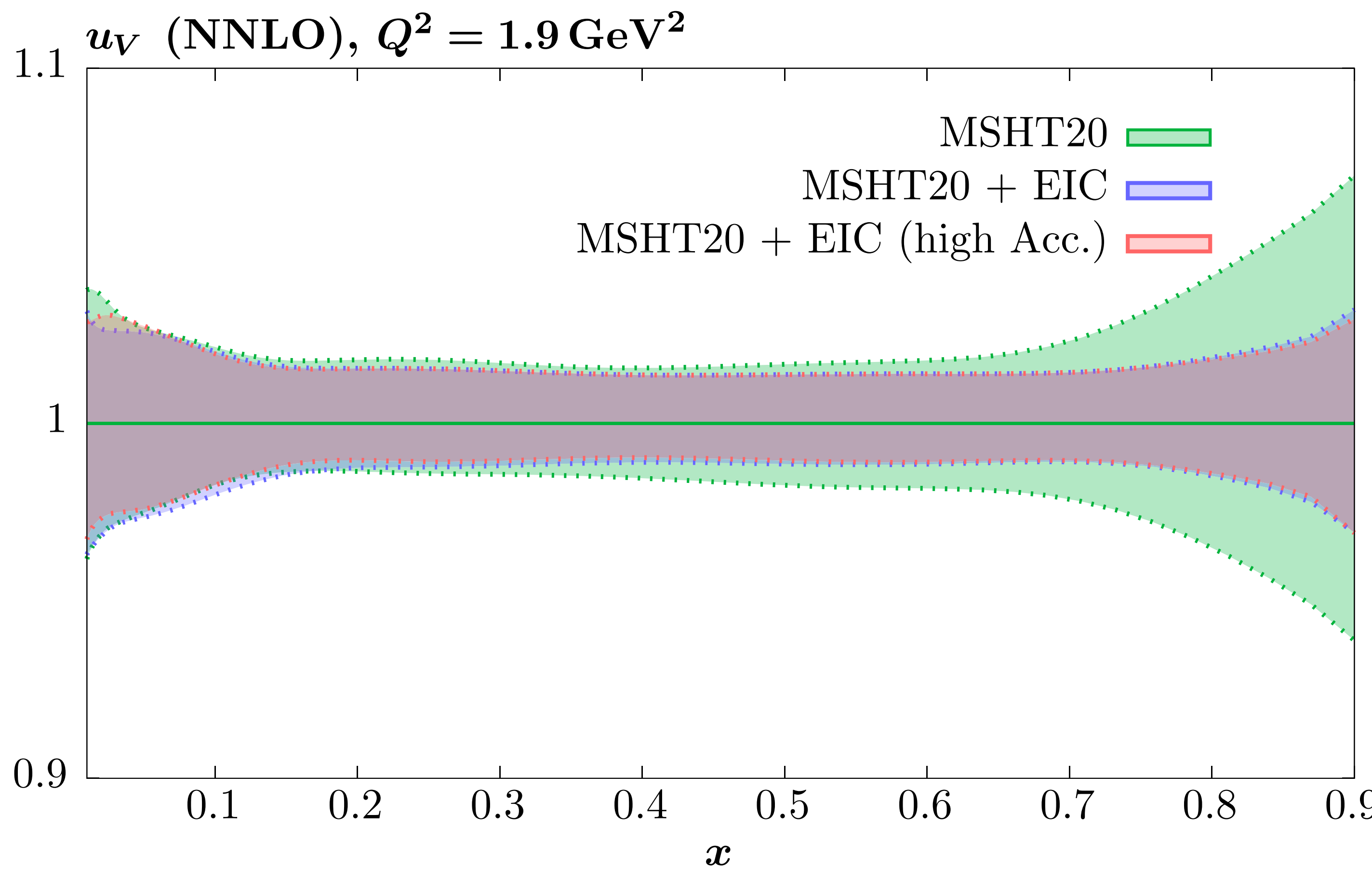
- Amongst many things the **EIC** will give us are better constraints on high x PDFs.



- Expected impact in global PDF context moderate **but** complementarity is key. See BSM studies - what if see a disagreement in high energy data?

N. Armesto et al., arXiv:2309.11269

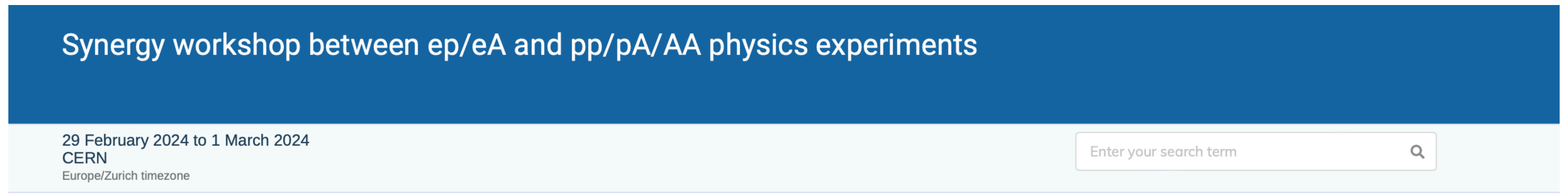




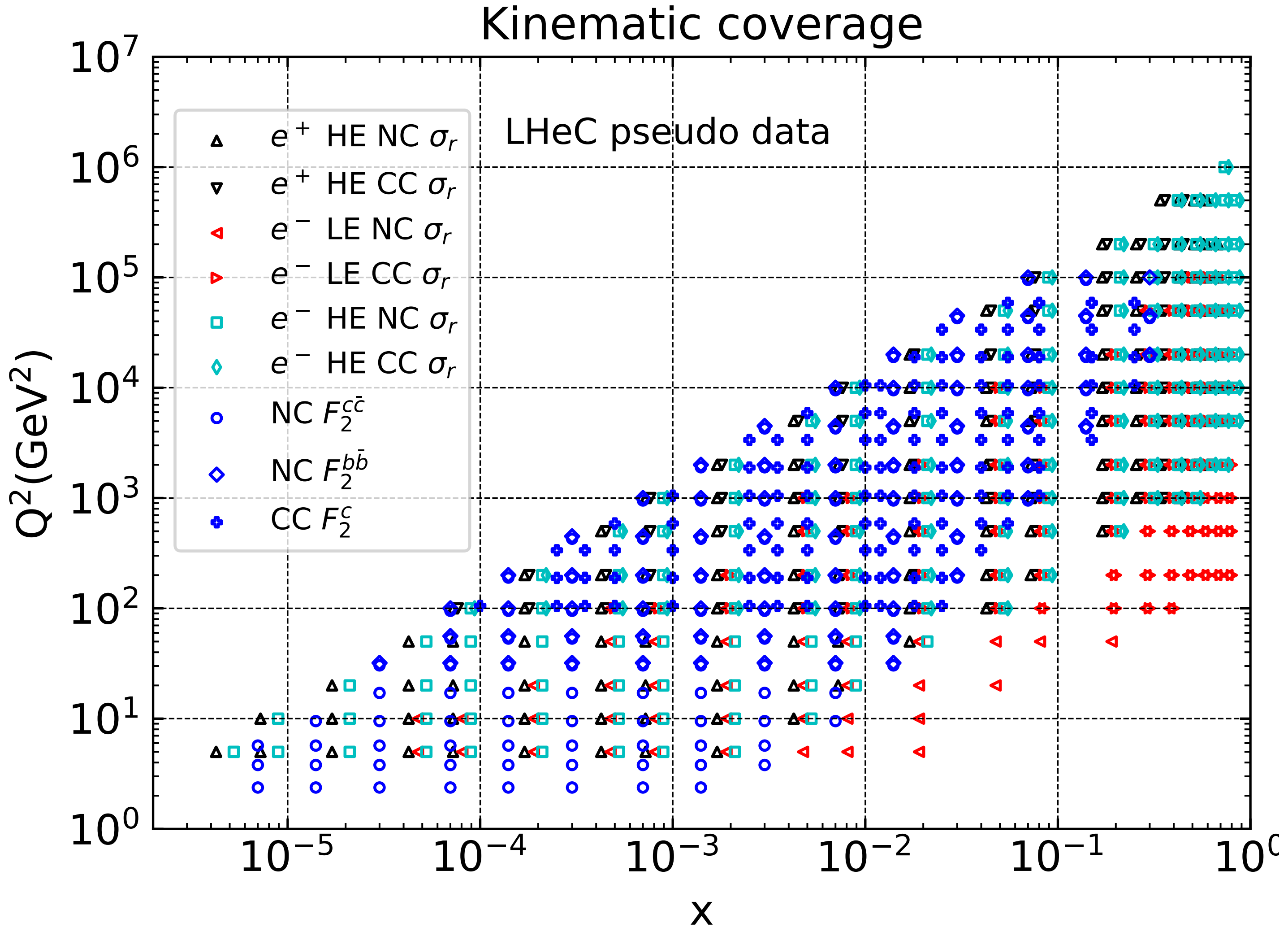
See talk by K. Wichmann

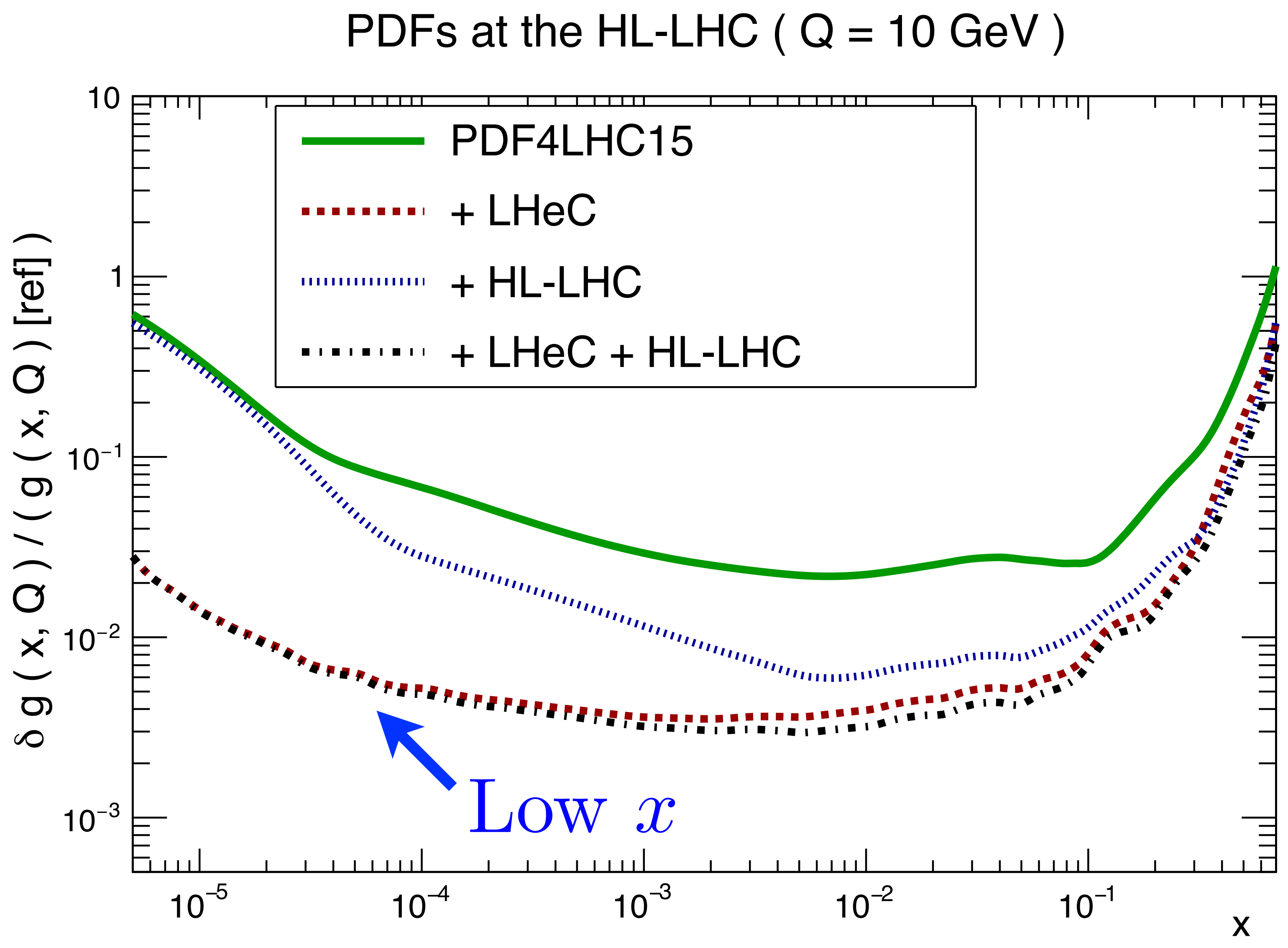
Future Data?

https://indico.cern.ch/event/1367865/overview

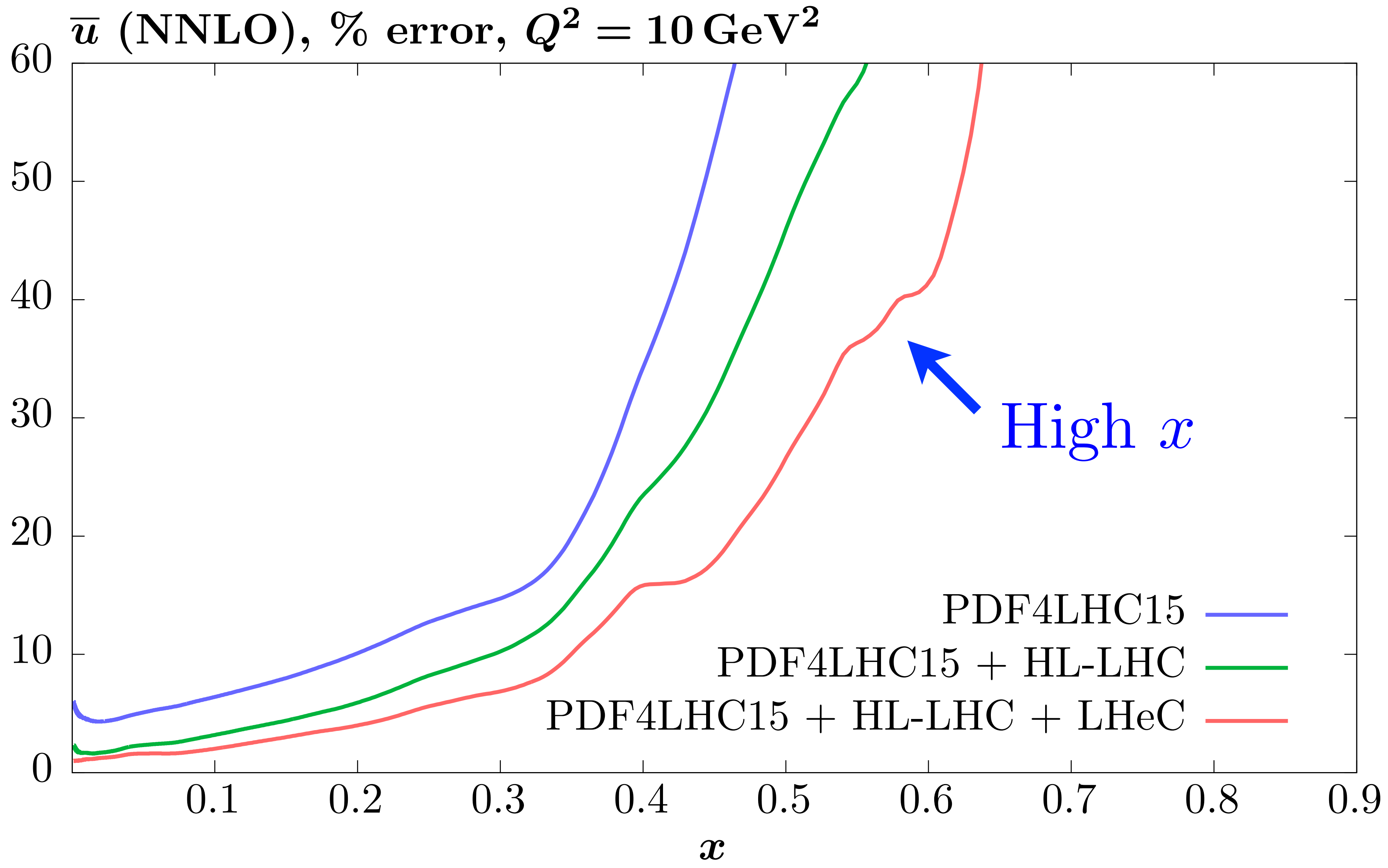


- In this context **LHeC** proposal also very advantageous.
- Clean and complementary ep data over wide region of phase space, with impressive PDF projections.



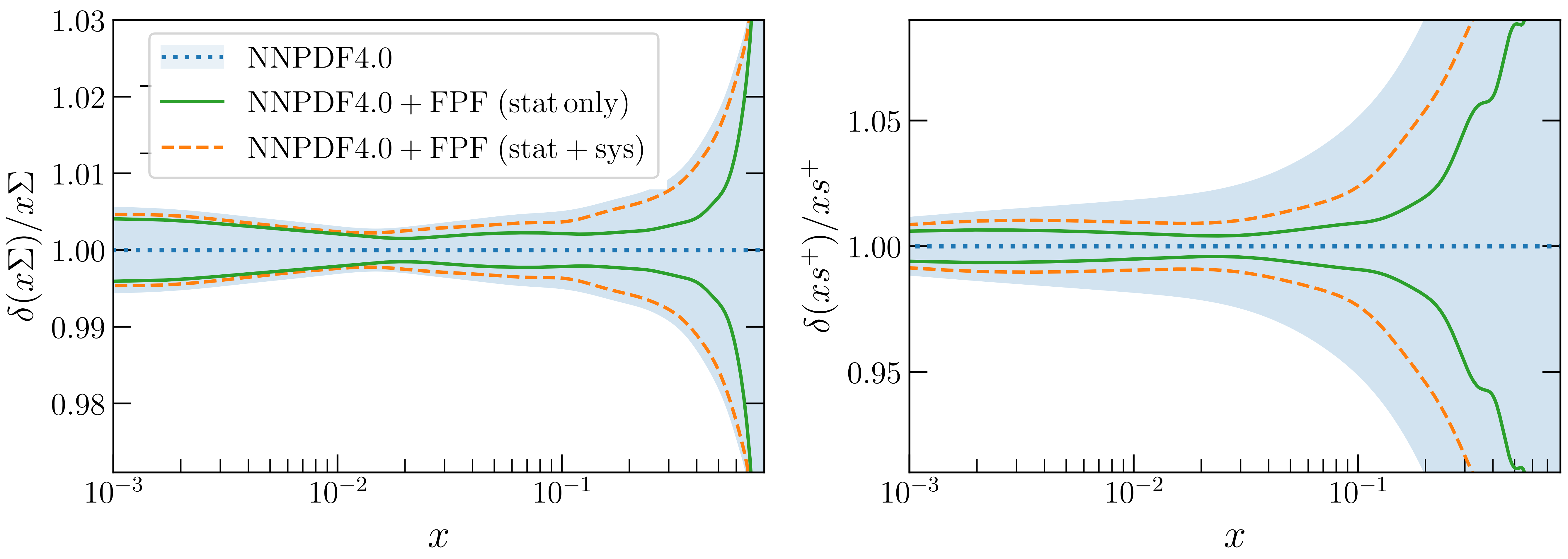


R. Abdul Khalek et al., arXiv:1906.10127

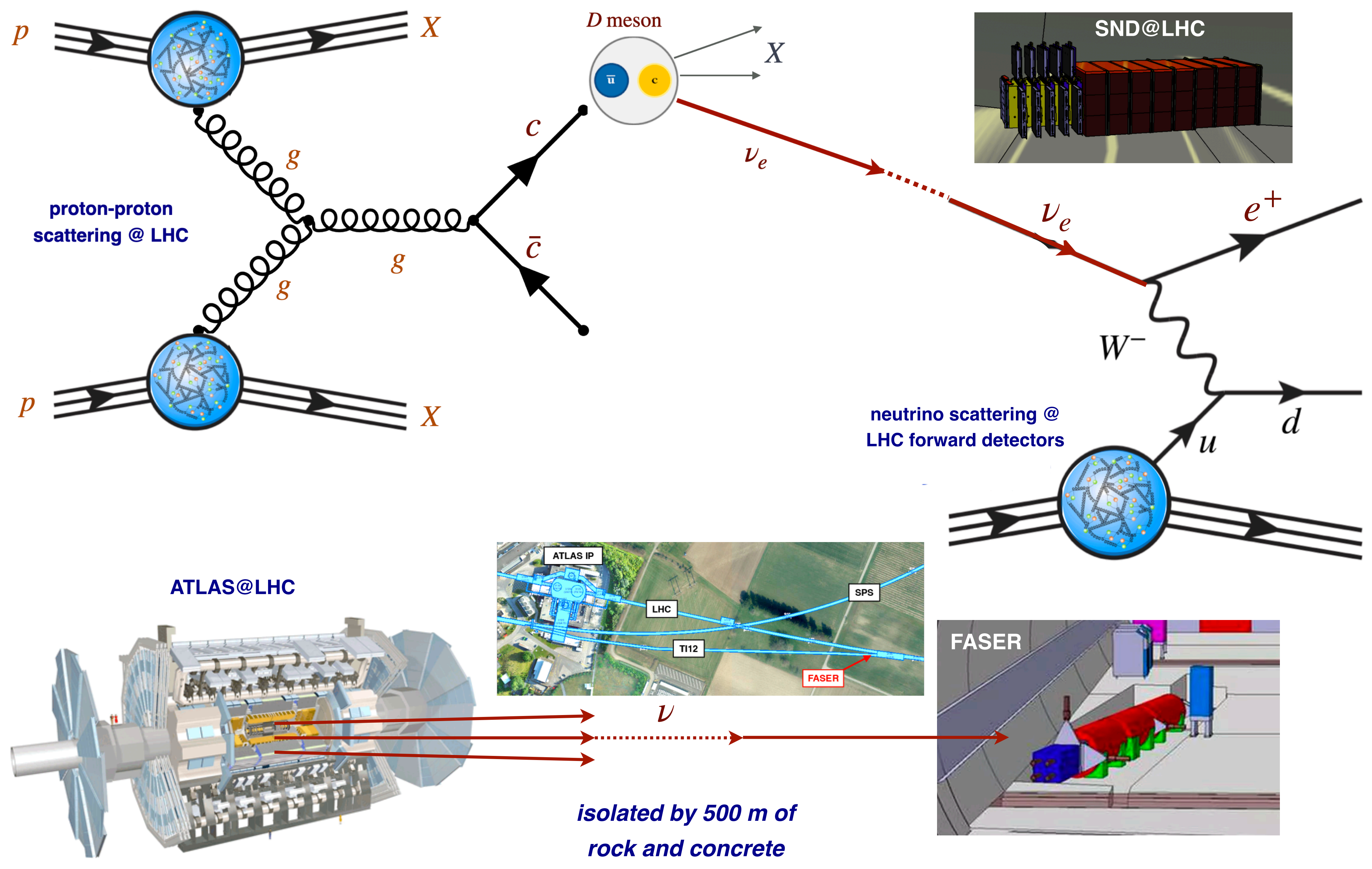


Future Data?

- **FPF** proposal to extend far forward detectors also shows promising potential for high energy (TeV) neutrino-induced DIS data at the LHC.
- Promising projected constraints on quark flavour structure.



J. Cruz-Martinez et al., arXiv:2309.09581



J. Rojo, PDF4LHC23

See talk by J. Rojo

Summary and Outlook

- ★ Parton Distribution Functions a key input in the LHC precision physics programme.
- ★ Precise and accurate PDF determination crucial. Global PDF fits currently the best way to achieve this.
- ★ A significant deal of experimental and theoretical progress: high precision LHC data driving PDF fits, and up to (approximate) N3LO will be the standard (+ NLO EW) for theory.
- ★ But the path to achieving accuracy and precision is not an easy one: clear understanding of PDF uncertainties and comparison of methodologies essential.
- ★ As always future data + experiments will play a key role in driving our understanding. Complementarity is key.
- ★ Steps to understanding the issues above will be discussed at this year's DIS, as well as updates on the significant progress that has been made. An exciting DIS programme awaits!

Thank you for listening!