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– A PERSONAL OVERVIEW

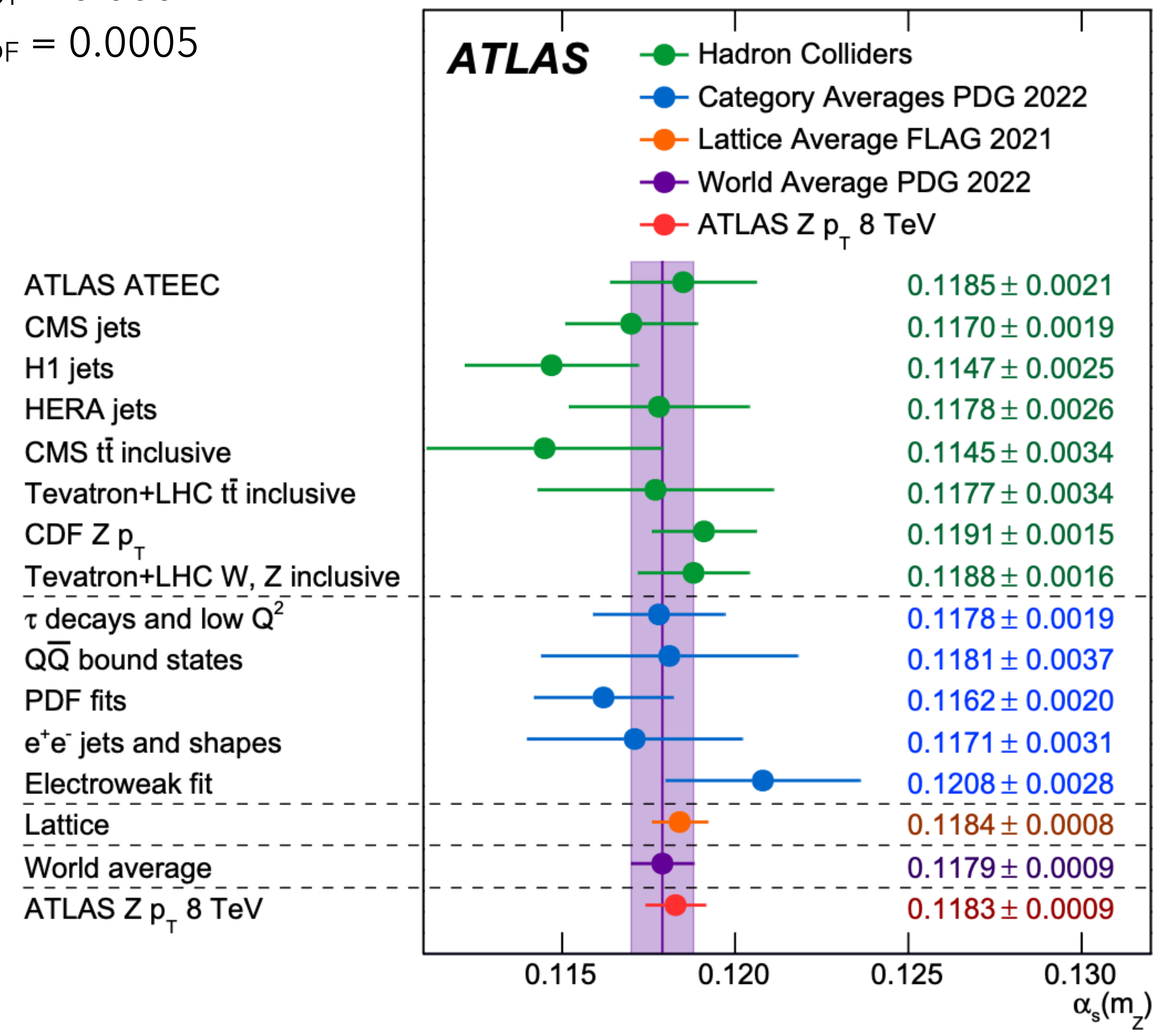
PDFS CRUCIAL INPUT FOR PRECISION PHYSICS

$$d\sigma^{pp\to ab} = \sum_{i,j} \boxed{f_i \otimes f_j} \otimes \boxed{d\hat{\sigma}^{ij\to ab}} + \ldots$$

ATLAS α_S determination

Δ_{TOT} = 0.0009

Δ_{PDF} = 0.0005

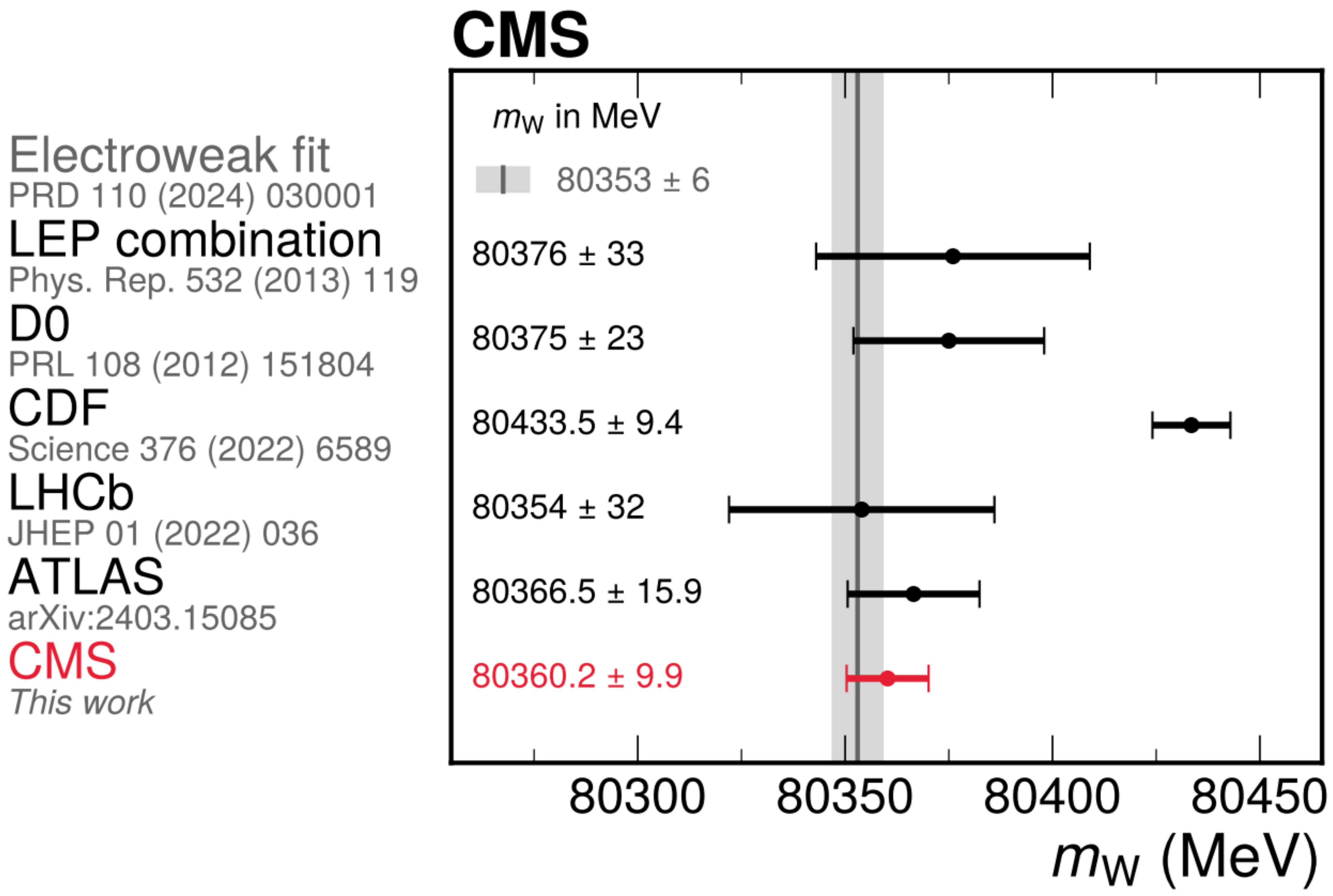


ATLAS collaboration, arXiv: 2309.12986

CMS M_W determination

Δ_{TOT} = 9.9 MeV

Δ_{PDF} = 4.4 MeV



CMS collaboration, arXiv: 2412.13872

OUTLINE

➡ Part I: progress and highlights on recent developments in PDF determination

➡ Part II: precision vs accuracy: new challenges and frontiers

PDF DETERMINATION

- Huge progress from first PDF determinations to where we stand now
  - ➡ Experimental data: many more precise measurements constraining PDFs
  - ➡ Theory: heavy quark schemes, aN3LO PDFs, inclusion of MHOUs in PDF error bands, EW and QED corrections, initial photon…
  - ➡ Methodology: uncertainty propagation, parametrisation bias, closure tests,…

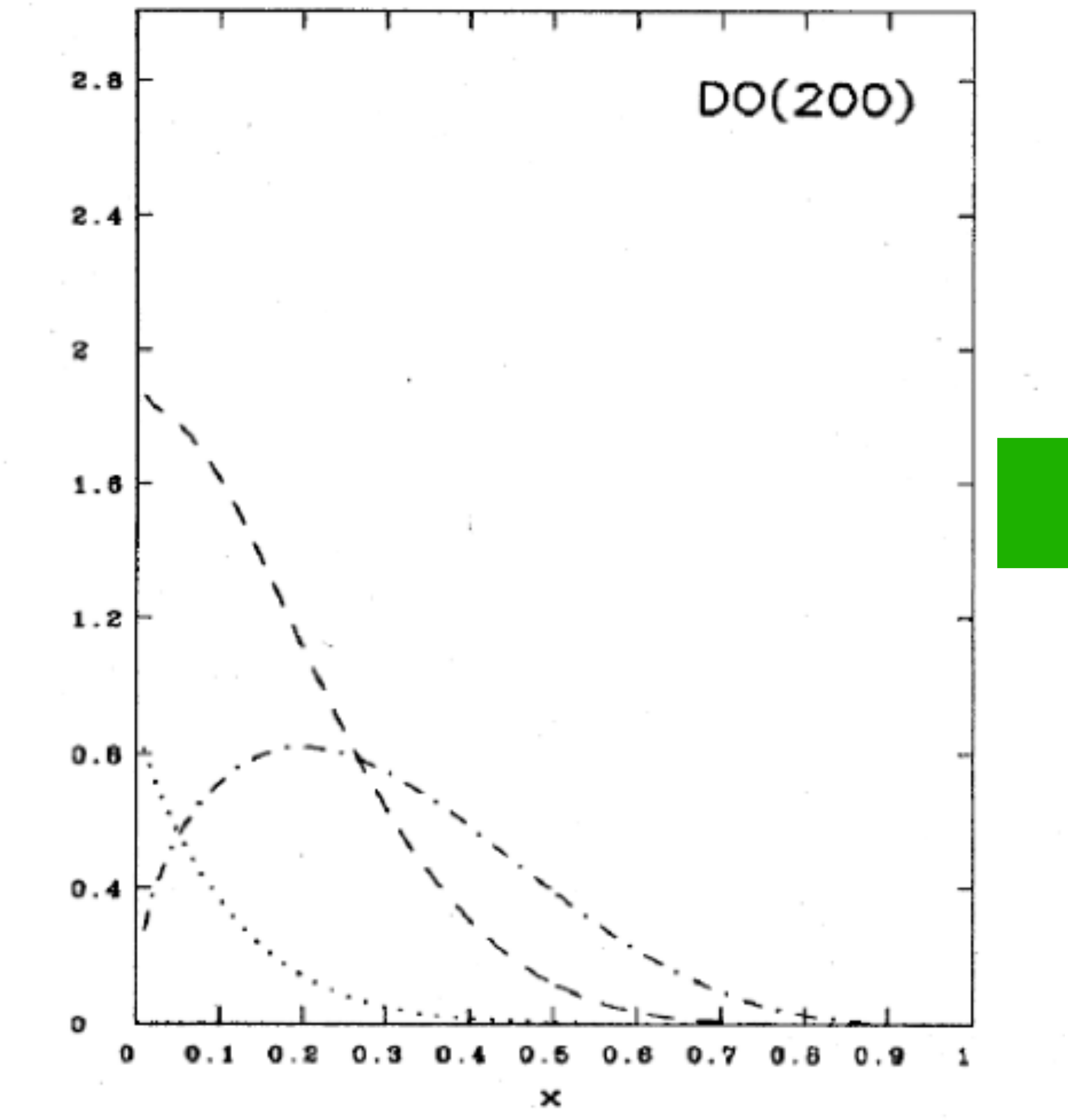
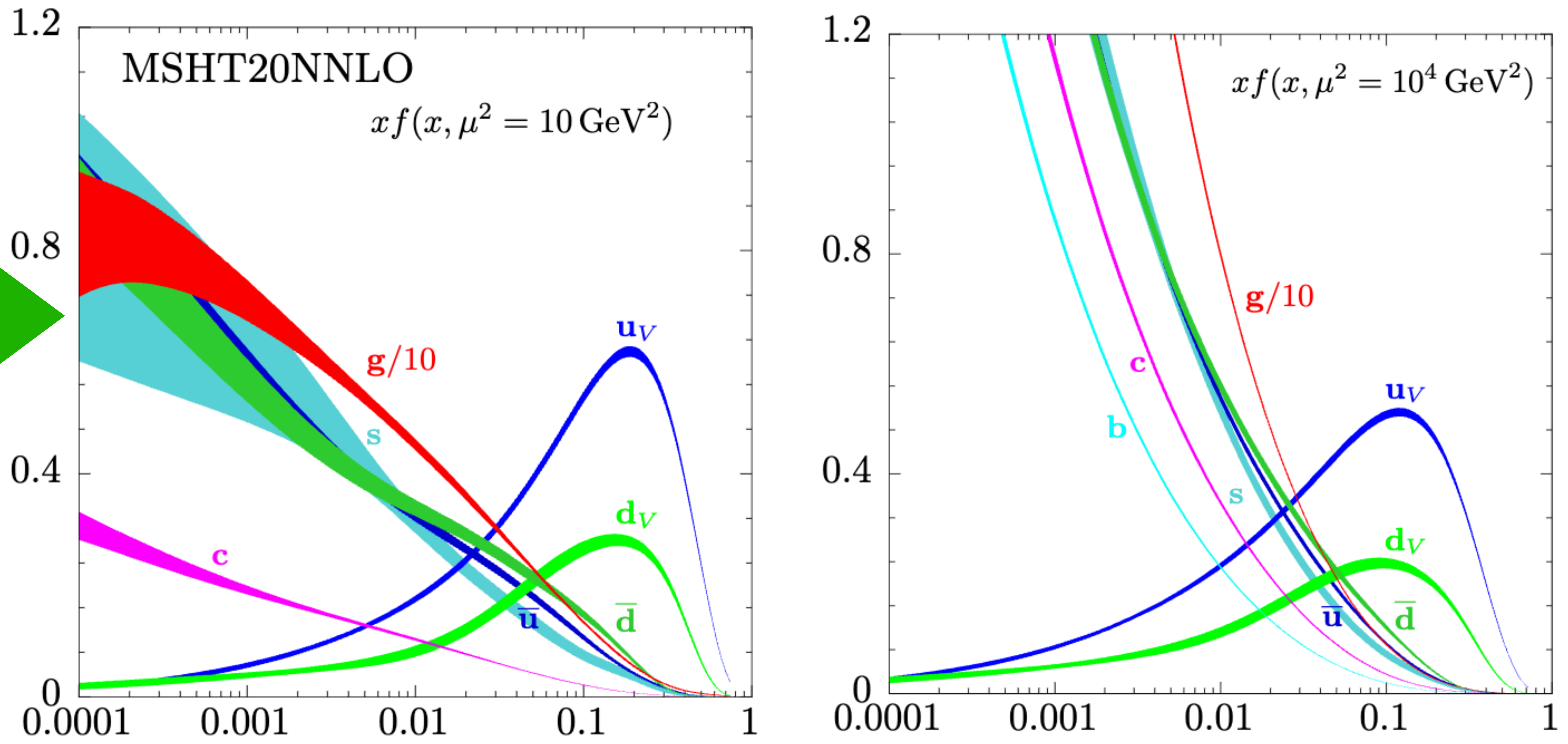


FIG. 27. "Soft-gluon" (Λ=200 MeV) parton distributions of Duke and Owens (1984) at Q^2=5 GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

40 years



Rev. Mod. Phys 1984

PDG 2024

PDF DETERMINATION

- Huge progress from first PDF determinations to where we stand now
  - ➡ Experimental data: many more precise measurements constraining PDFs
  - ➡ Theory: heavy quark schemes, aN3LO PDFs, inclusion of MHOUs in PDF error bands, EW and QED corrections, initial photon…
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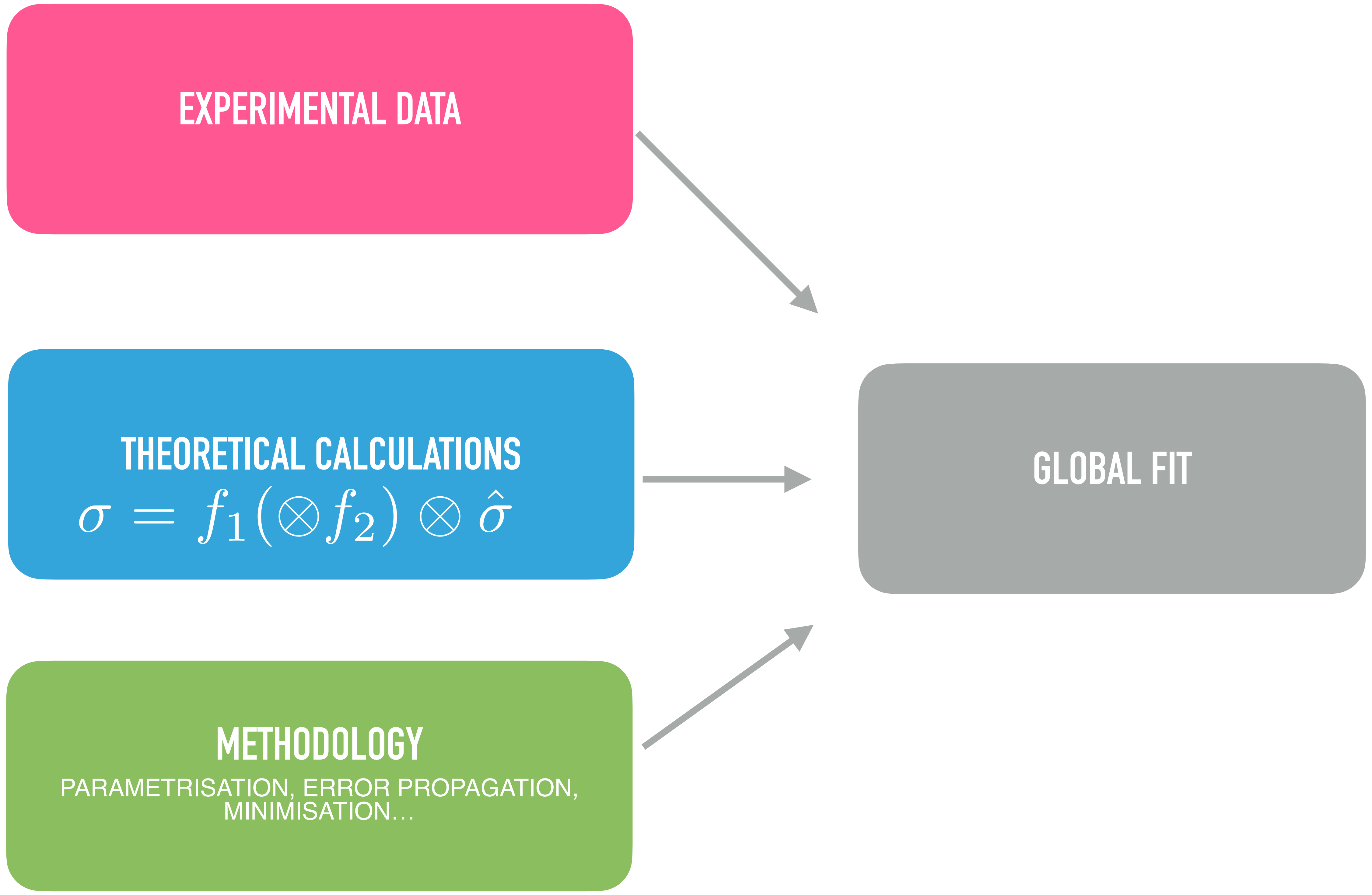


Accuracy of PDF determinations has a limit that is determined by the accuracy of all ingredients entering a global fit

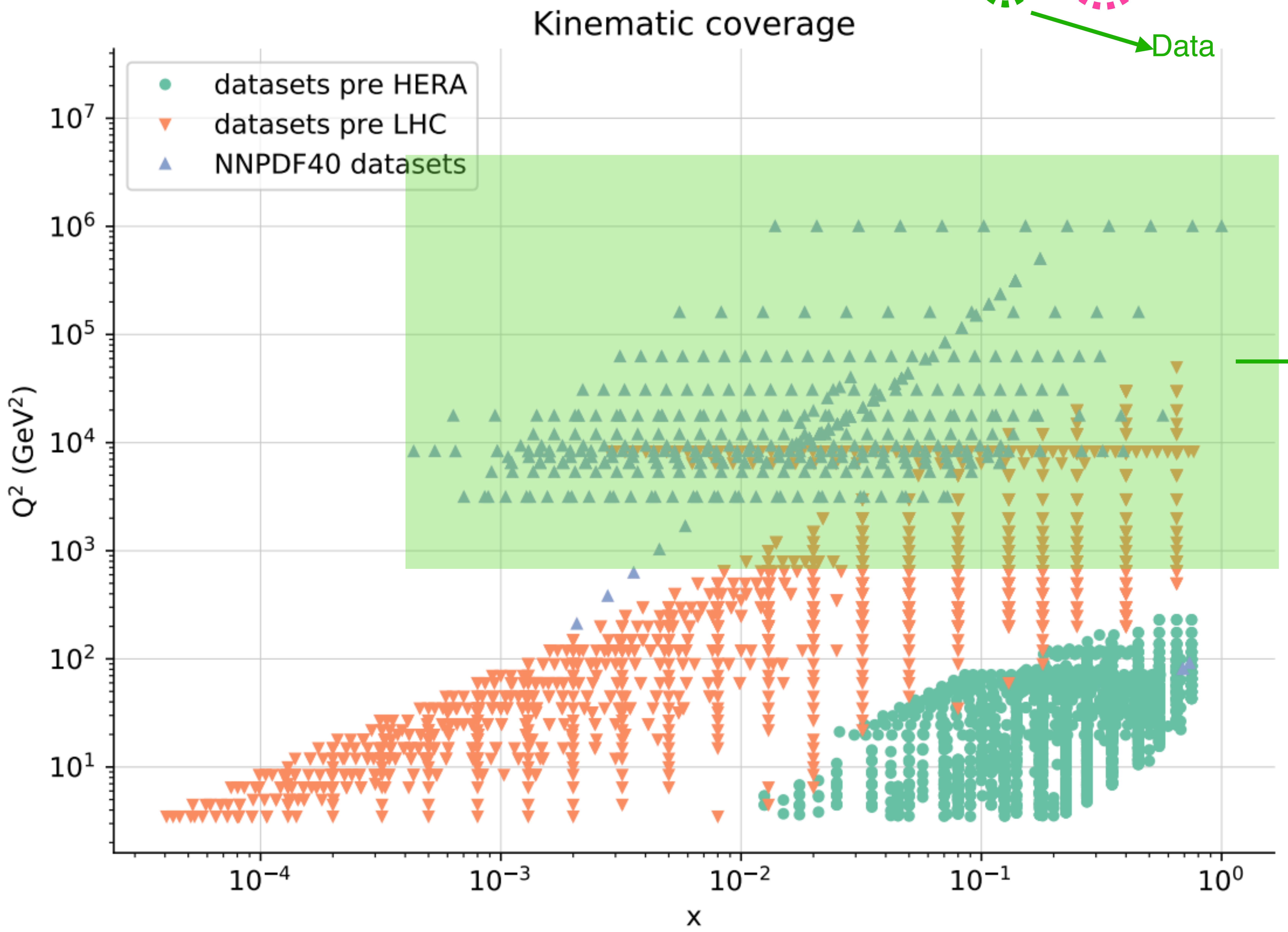
PROGRESS: DATA

$$f_i(x,\mu)$$

Perturbative QCD

Data

Splitting functions P_{ab} known up to approximate N3LO
[Blumlein, Moch, Gehrman, von Manteufel, Sotnikov, Yang, Davies, Vogt, Bonvini, Marzani,…]



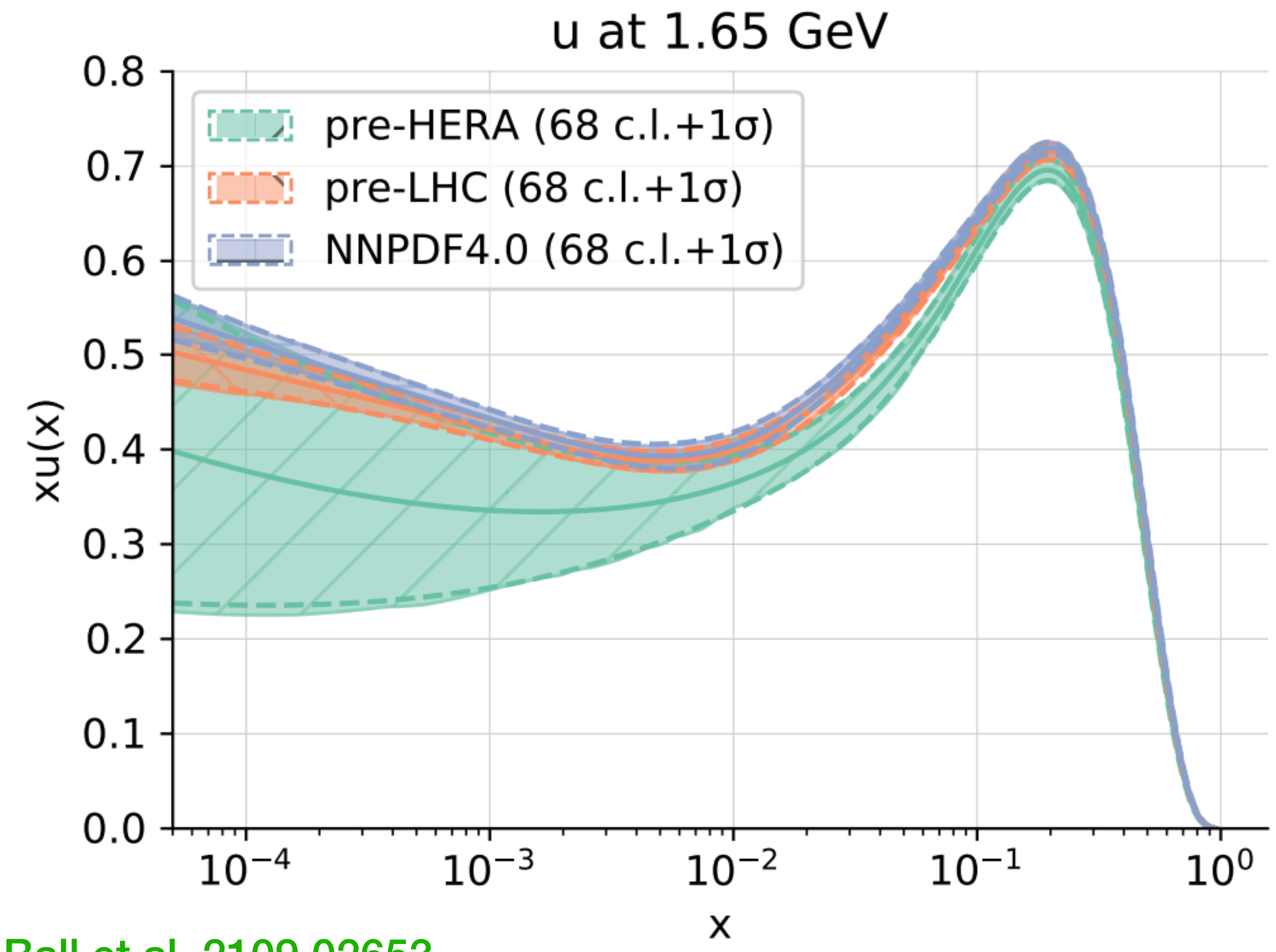
NNPDF4.0:
O(5000) datapoints,
about 30% from LHC

- Modern data show increasingly small statistical uncertainty and dominating correlated systematic uncertainties make global PDF fits challenging

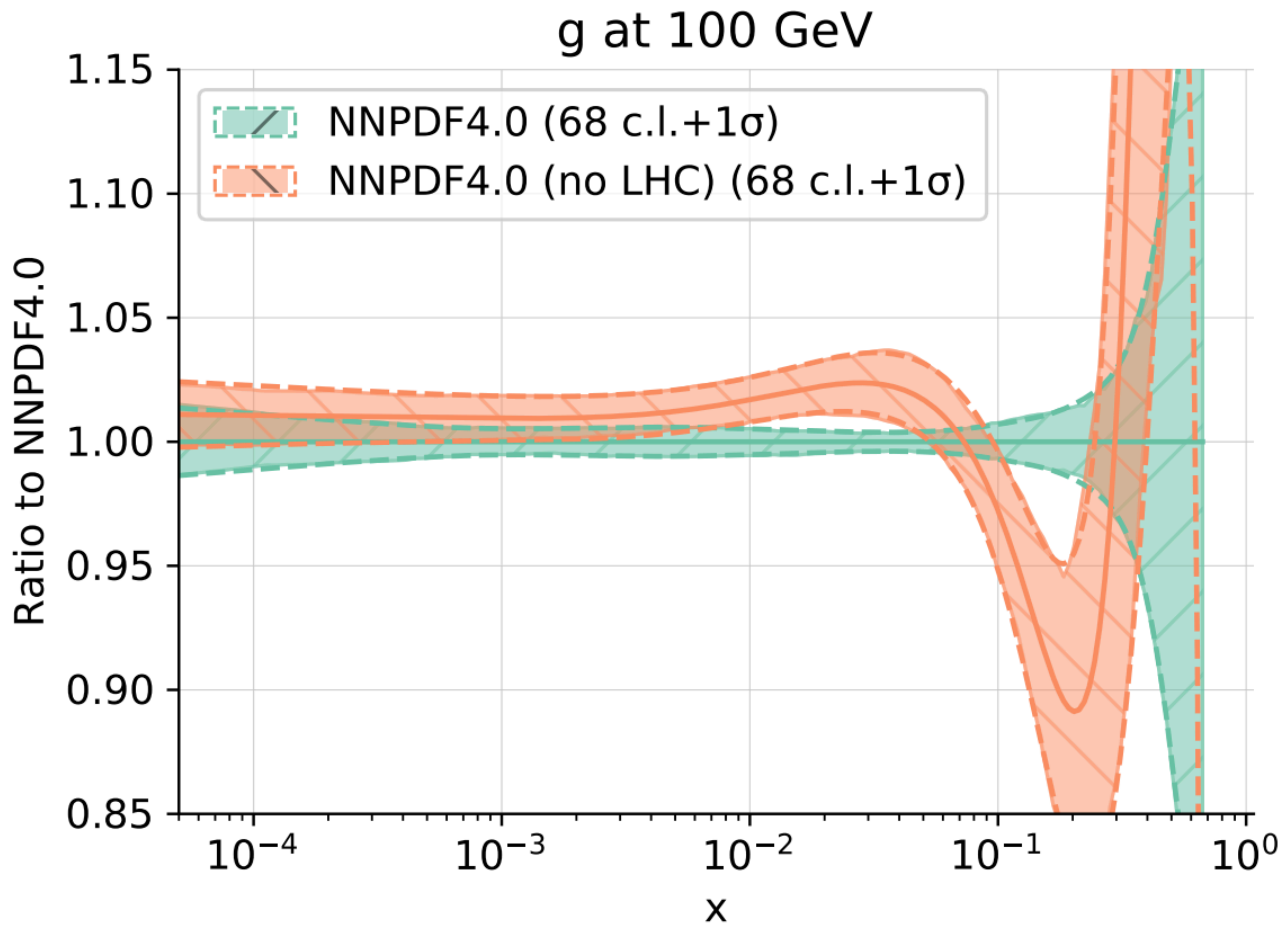
Kassabov, Nocera, Wilson 2207.00690
Bailey, Harland-Lang 1909.10541

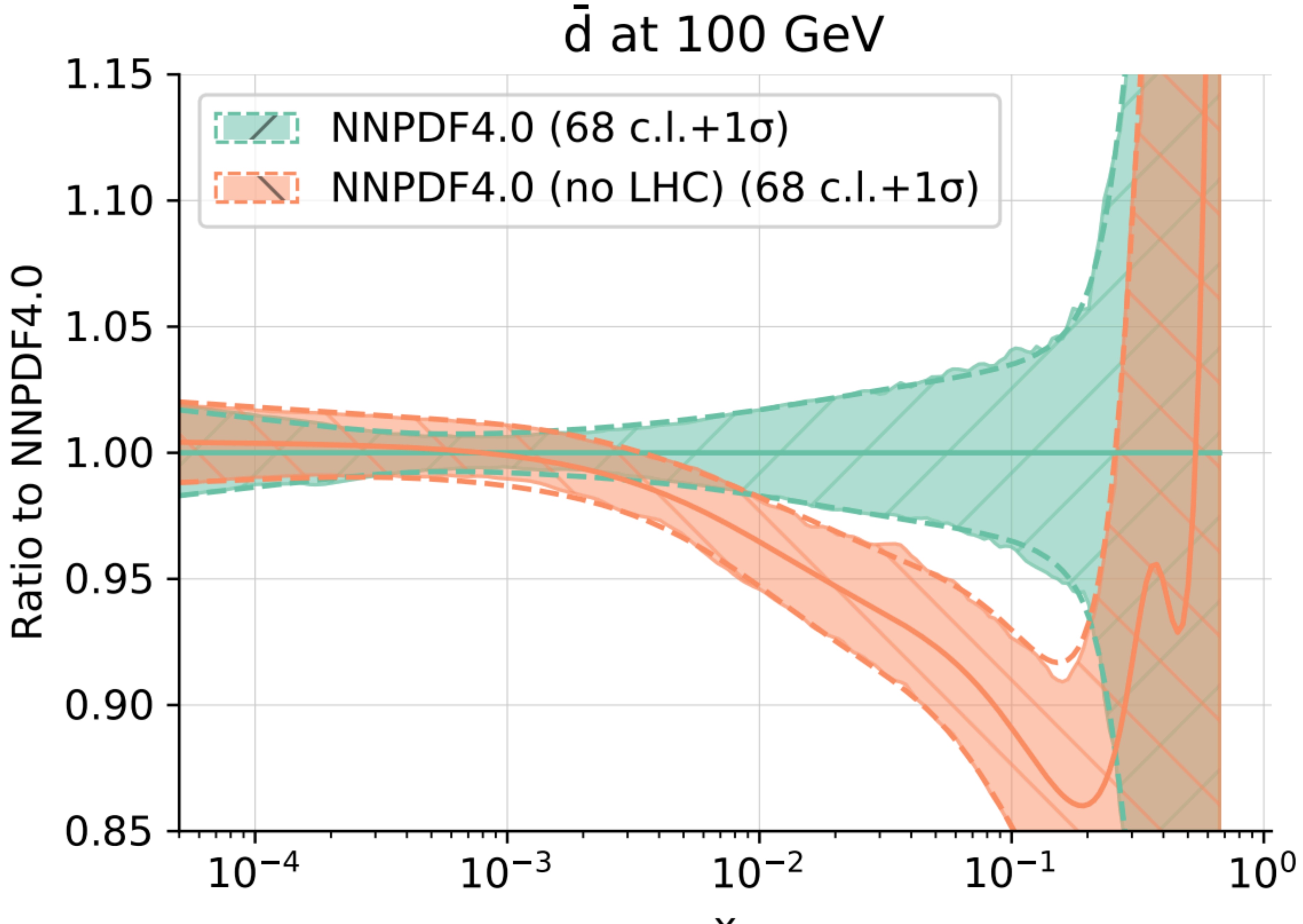
Ball et al, 2109.02653

PROGRESS: DATA



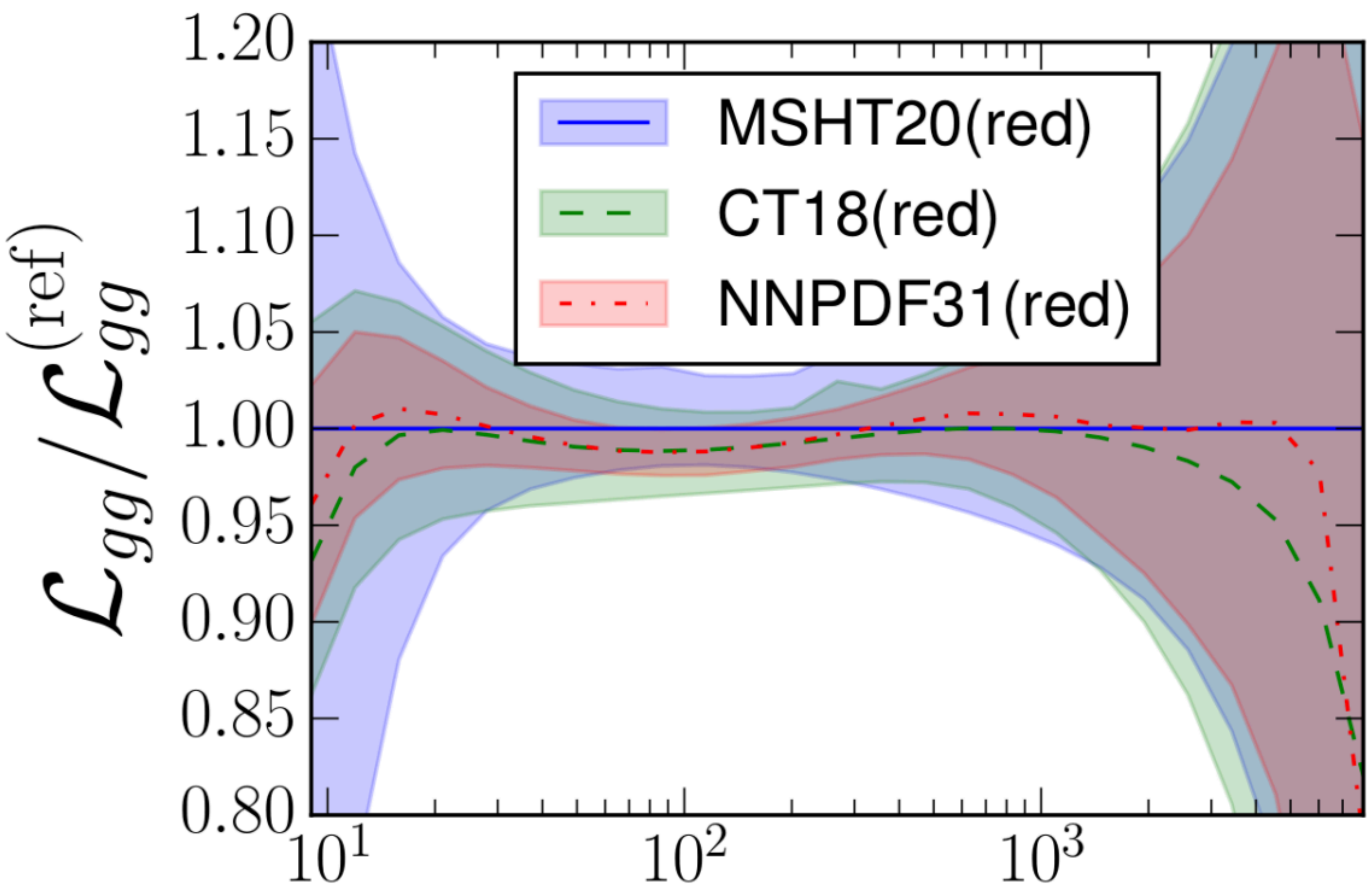
Ball et al, 2109.02653

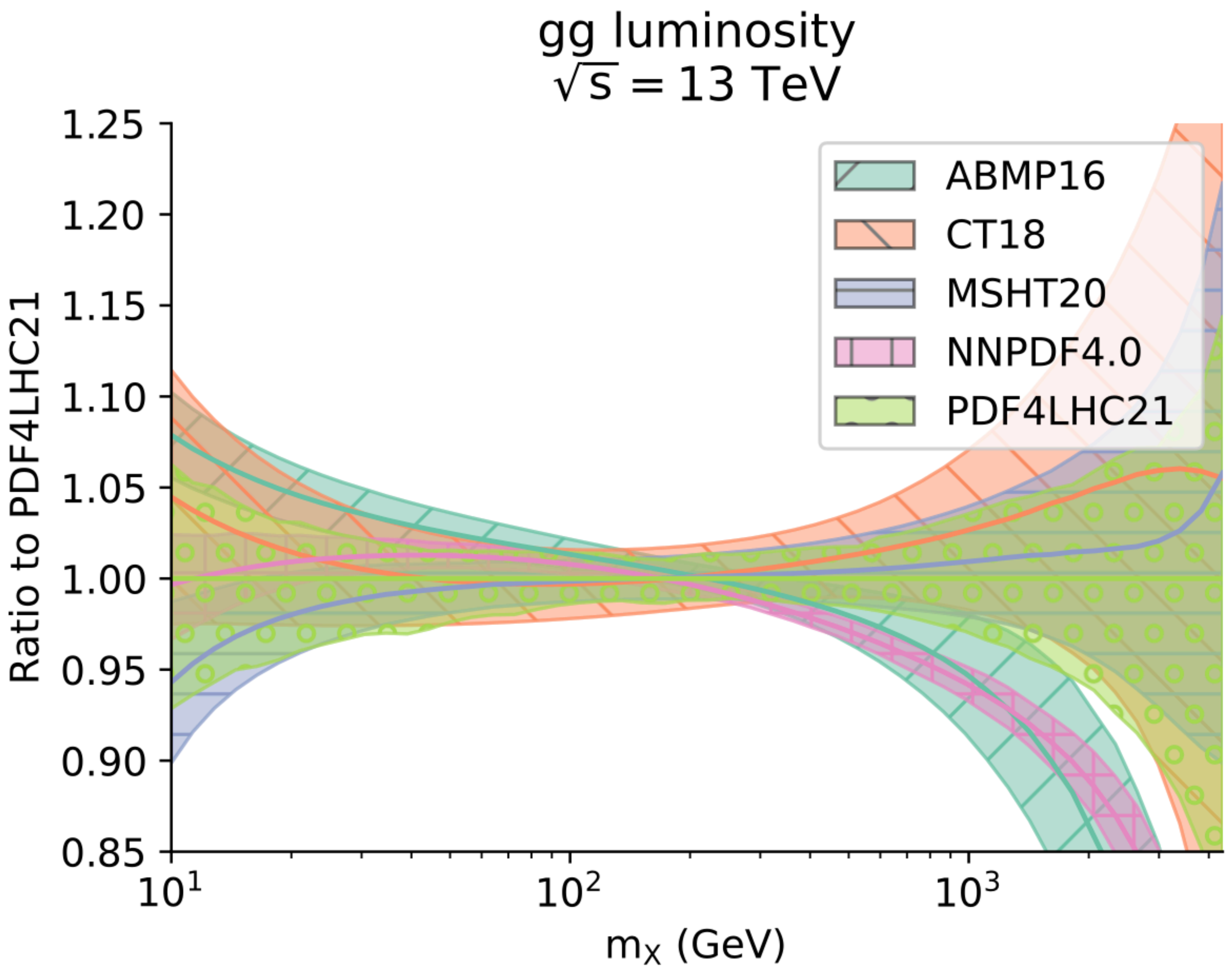




- **HERA** data crucial to constrain quark valence (up and to less extent down valence) across intermediate to small x and gluon at small x
- **LHC** high energy data crucial to provide additional constraints to PDFs, in particular in medium- to large-x gluon and quarks.
- Some **tension** with older fixed-target Drell-Yan and DIS data visible in the large-x region (especially gluon and anti-quarks)

DATA-DRIVEN PROGRESS





- In recent updates from global PDF fitting collaborations **effect of LHC data driving PDF uncertainties down**
  ➜ PDF4LHC21 combination of NNPDF31′, CT18′ and MSHT20′ smaller uncertainties than PDF4LHC15
- Benchmark among NNPDF3.1, MSHT20 and CT18: overall agreement, which improves once common dataset is used, **differences in uncertainties** associated with methodologies with ΔCT18 ≳ ΔMSHT20 ≳ ΔNNPDF31
- Increased precision of the data and their strong correlation demands methodological improvements (e. g. **more flexible parametrisation** that shifts PDFs outside nominal error band) and **>1 PDF fits** to accomodate some tension (CT18 vs CT18Z)

PROGRESS: TESTING THE METHODOLOGY

- Closure tests: key study to **statistically validate** various PDF fitting methodologies and **assess faithfulness of PDF uncertainties**
- Imagine we knew the law of Nature **G(w⁰)** and the true PDFs **w⁰** is fitting methodology able to reproduce it? Is the uncertainty faithful?
- Can also be used to check the effect of inconsistencies in the data

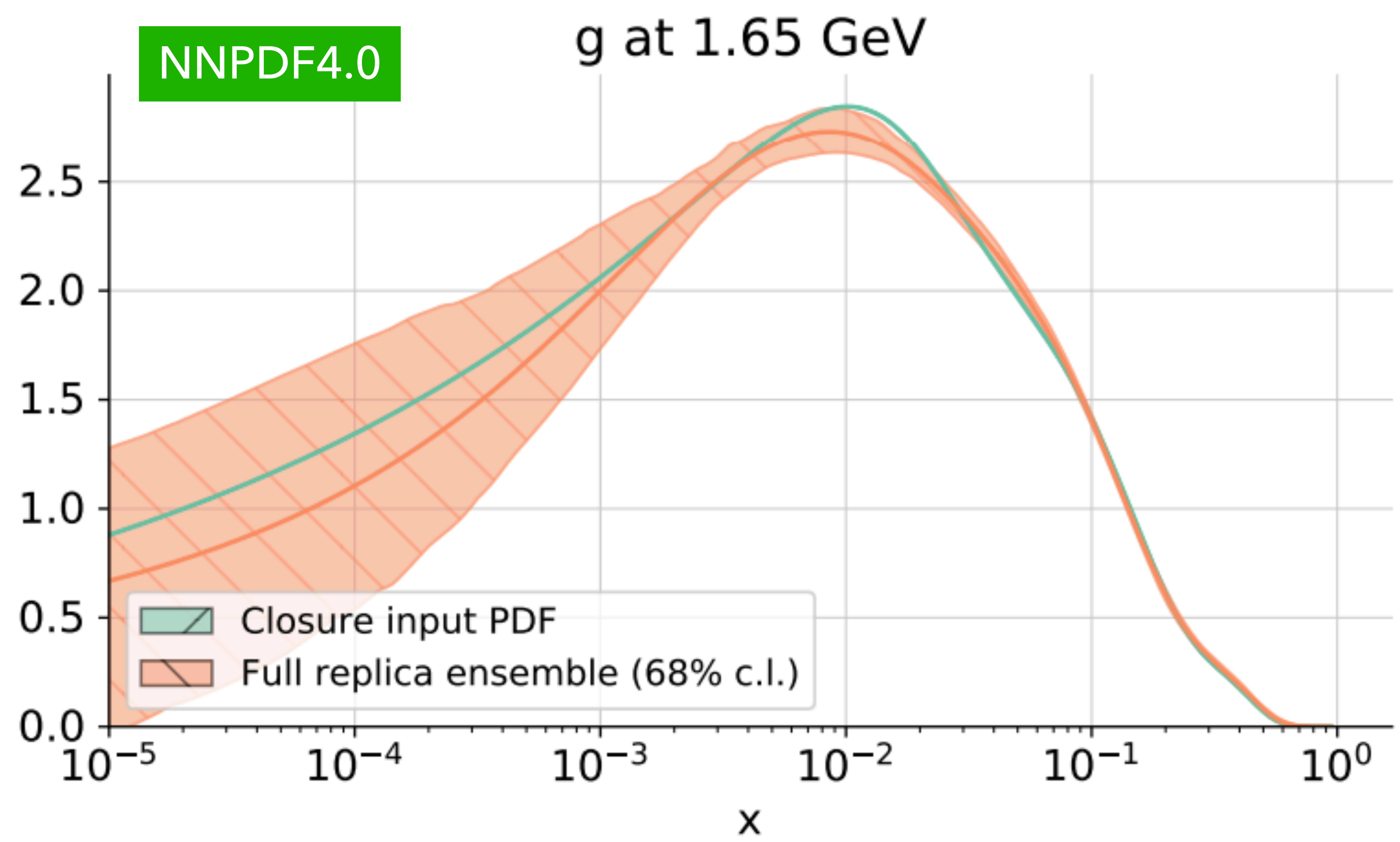
[Harland-Lang et al, arXiv:2407.07944, Costantini at al: arXiv:2503.17447]

$$y_0 = \mathcal{G}(w^0) + \eta$$

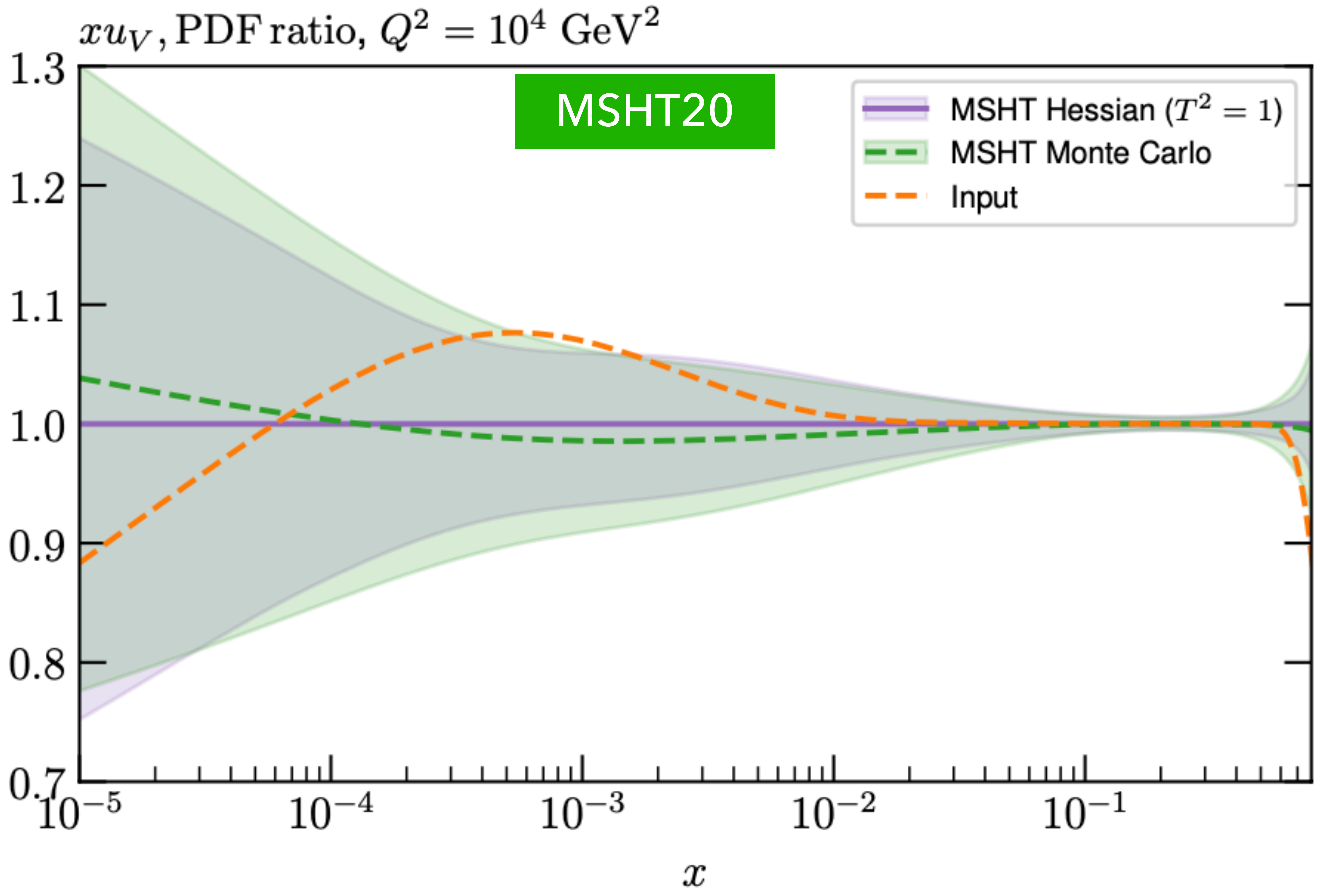
Experimental noise

Law of Nature

$\hat{\sigma}_{\rm NNLO} \otimes (f \otimes f)_{\text{“true” PDF}}$



Del Debbio et al, [arXiv: 2111.05787]



Harland-Lang et al, arXiv:2407.07944

PROGRESS: TESTING PDF PERFORMANCE ON NEW DATA

- To discriminate among PDF sets, test all global PDF sets agains **new precise** data from LHC data & DIS HERA jets data. How well do various PDF sets describe data that are **not yet** included in the fit?

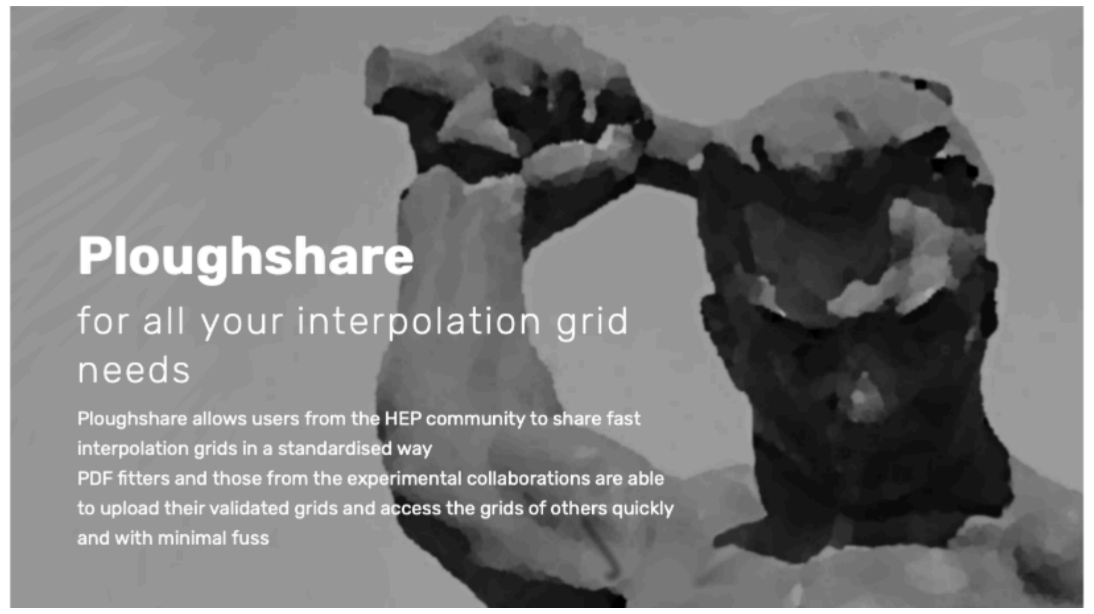
- **Generalisation test** is crucial and possible using exact NNLO predictions (no k-factor approximation) thanks to PineAPPL, NNLOJET, MATRIX and Ploughshare

PineAPPL

Carrazza et al: 2008.12789
Barontini et al: 2302.12124

NNLOJET

Gehrmann-De Ridder et al: 1507.02850, 1605.04295,2301.11827, Britzger et al: 2207.13735,Cruz-Martinez et al: 2501.13167



Ploughshare project, APPLgrid, FastNLO
Kluge et al: hep-ph/0609285
Carli et al: 0911.2985
Czakon et al: 1704.08551

MATRIX

Munich -- the MUlti-chaNnel Integrator at swiss (CH) precision --
Automates qT-subtraction and Resummation to Integrate X-sections

Grazzini et al: 1711.06631

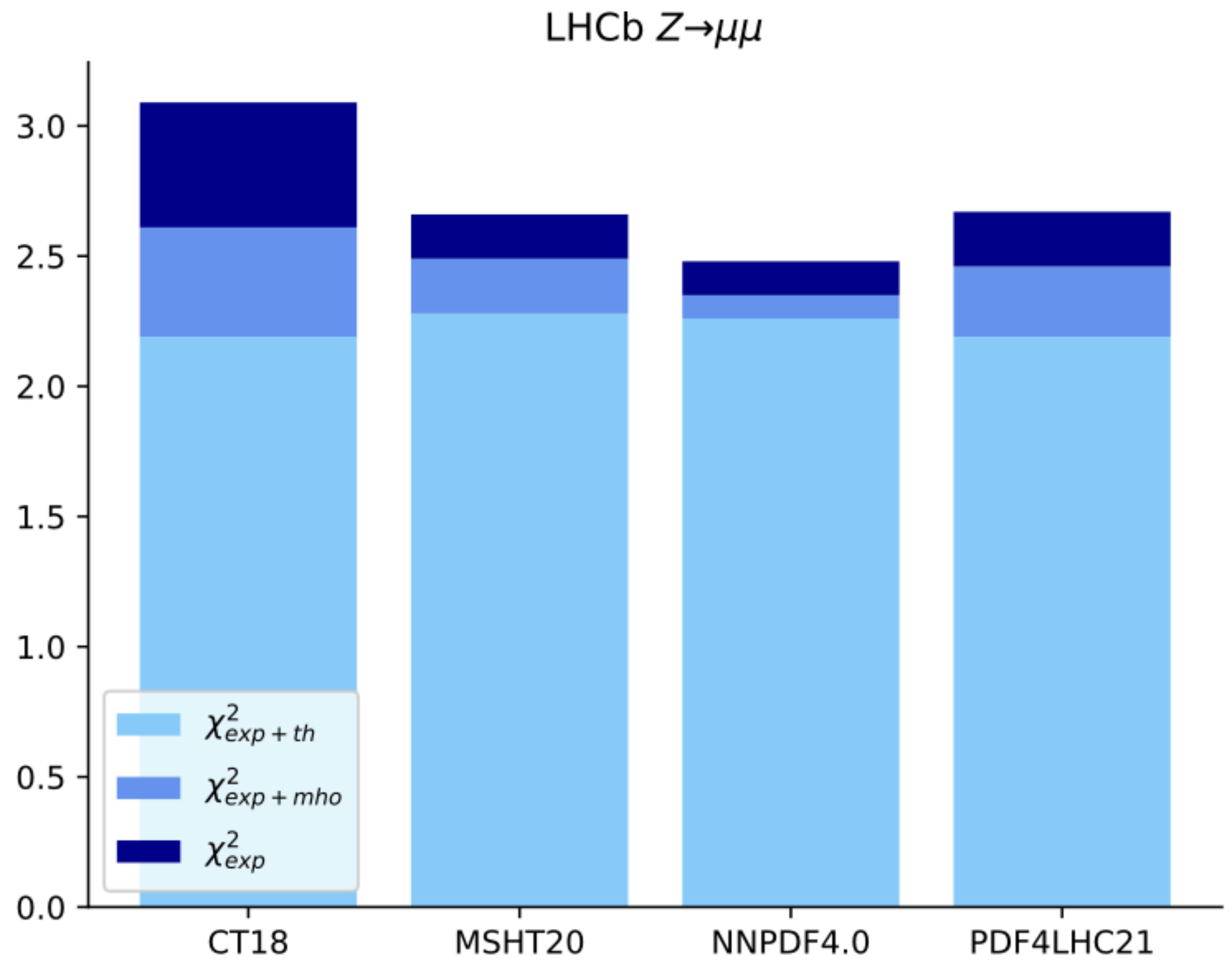
- Data-theory agreement with unseen data must be measured by considering **all sources of uncertainties**: experimental, missing higher order (MHOU), PDF uncertainties, α_s uncertainties by including all bin-by-bin correlations

$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} \left(T_i^{(0)} - D_i\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(T_j^{(0)} - D_j\right)$$

$$\boxed{\chi^2_{\rm exp+mho+pdf+as} \leftrightarrow \mathrm{cov} = \mathrm{cov}_{\rm exp} + \mathrm{cov}_{\rm mho} + \mathrm{cov}_{\rm pdf} + \mathrm{cov}_{\rm as}}$$

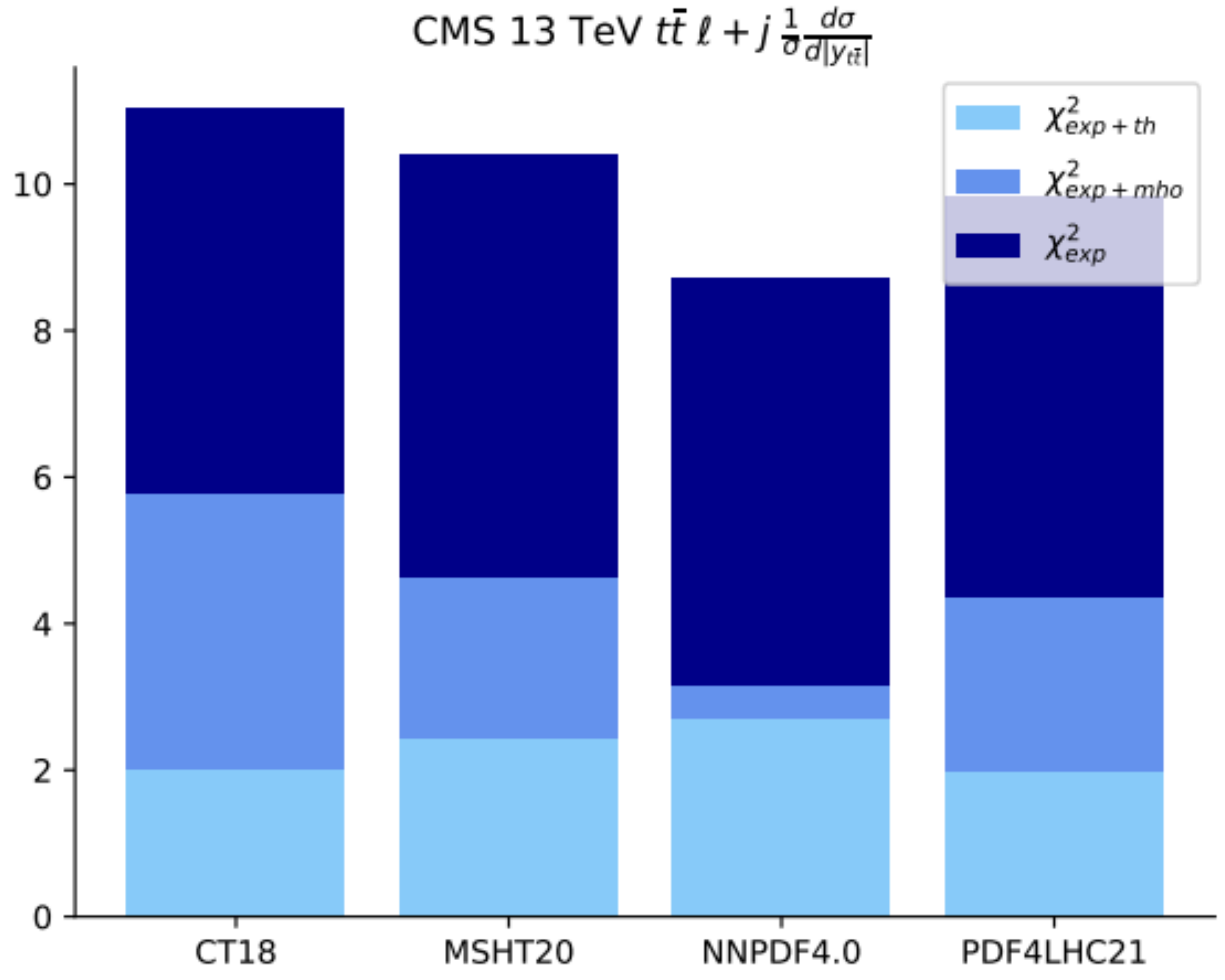
HOW WELL DO MODERN PDF SETS PERFORM?

Chiefa et al: 2501.10359



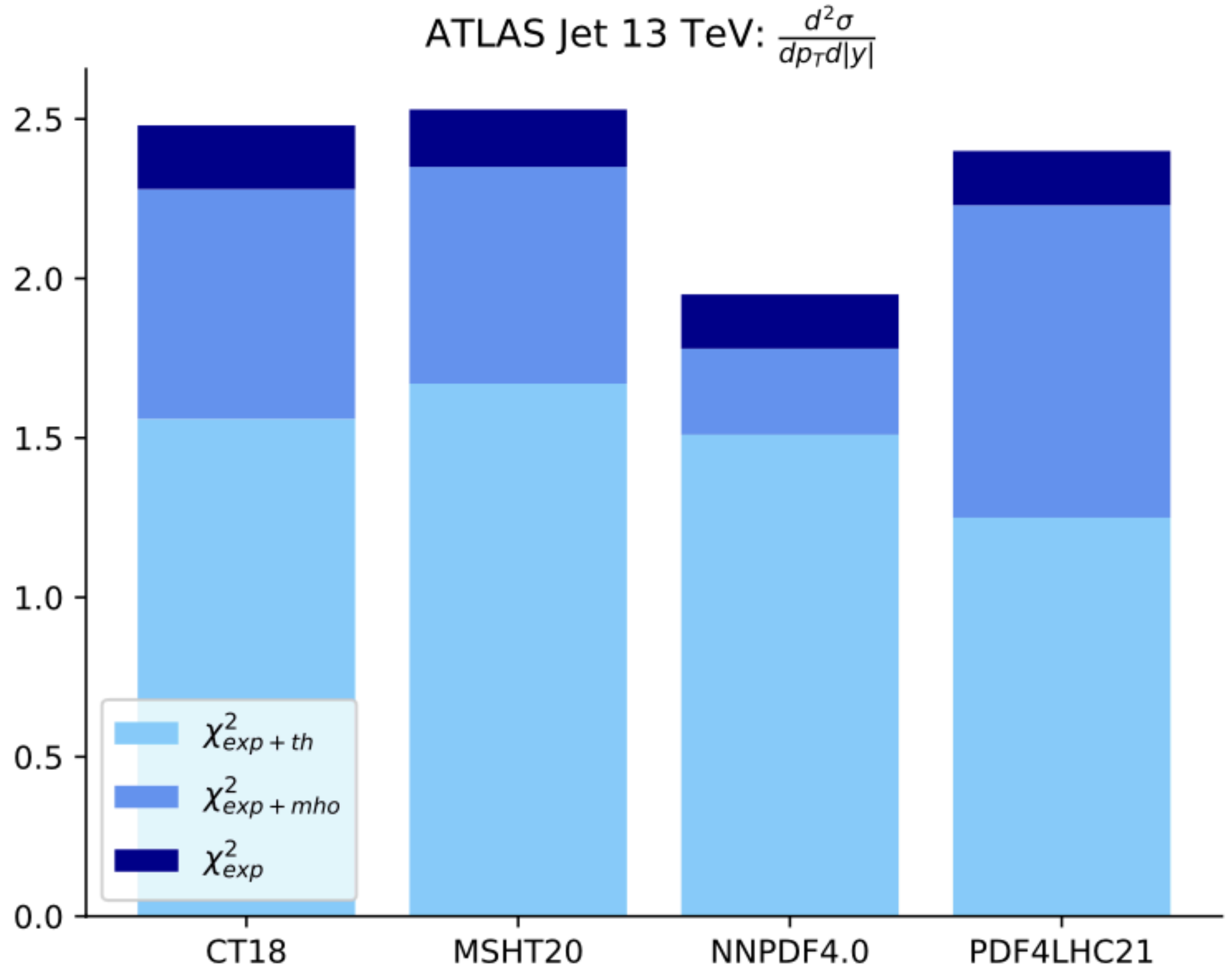
LHCb Z forward production at 13 TeV

LHCb collaboration [arXiv:2112.07458]



CMS tt~ production at 13 TeV, l+jet

CMS collaboration [arXiv:2108.02803]



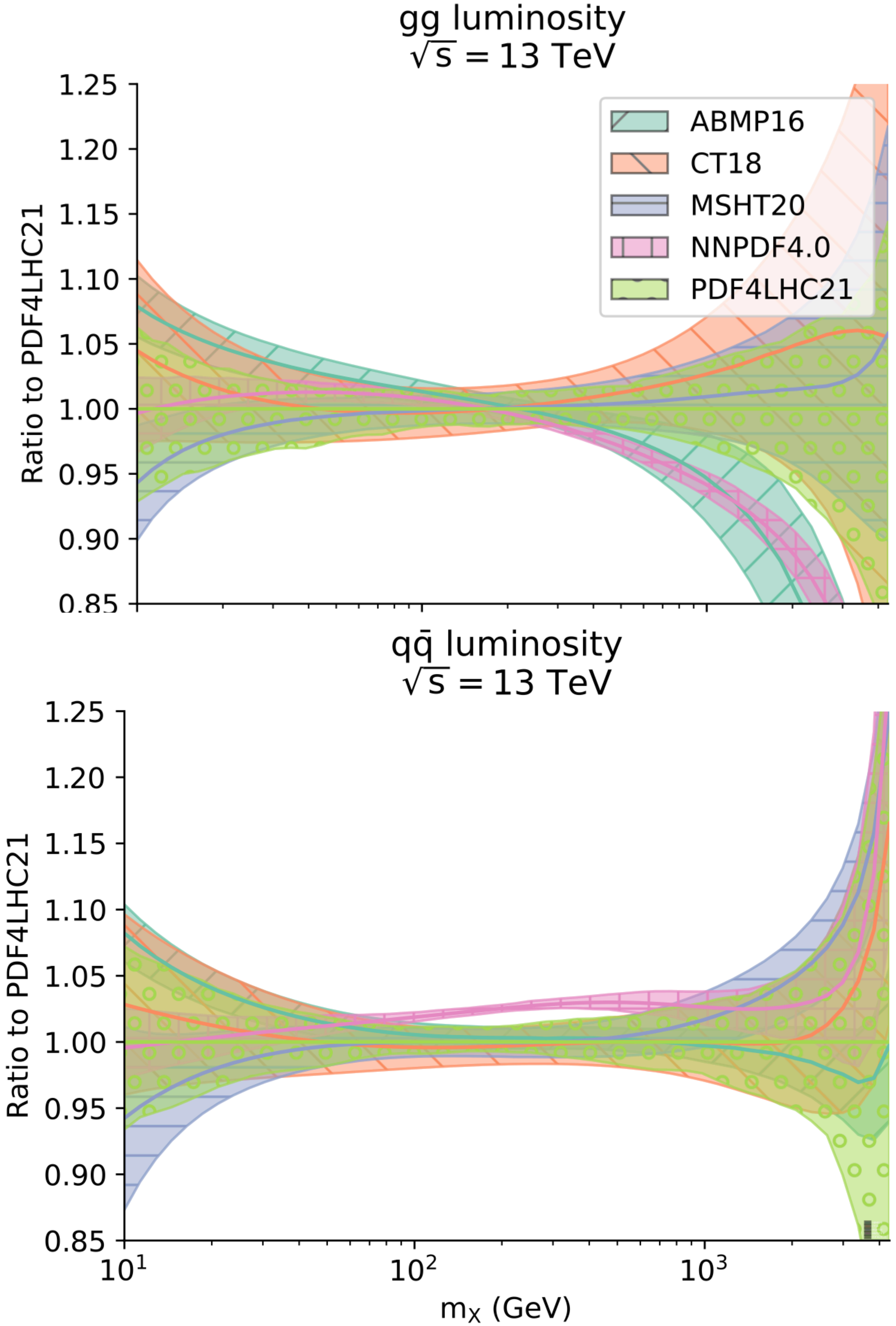
ATLAS incl. jet sec at 13 TeV, R=0.6, anti-kT

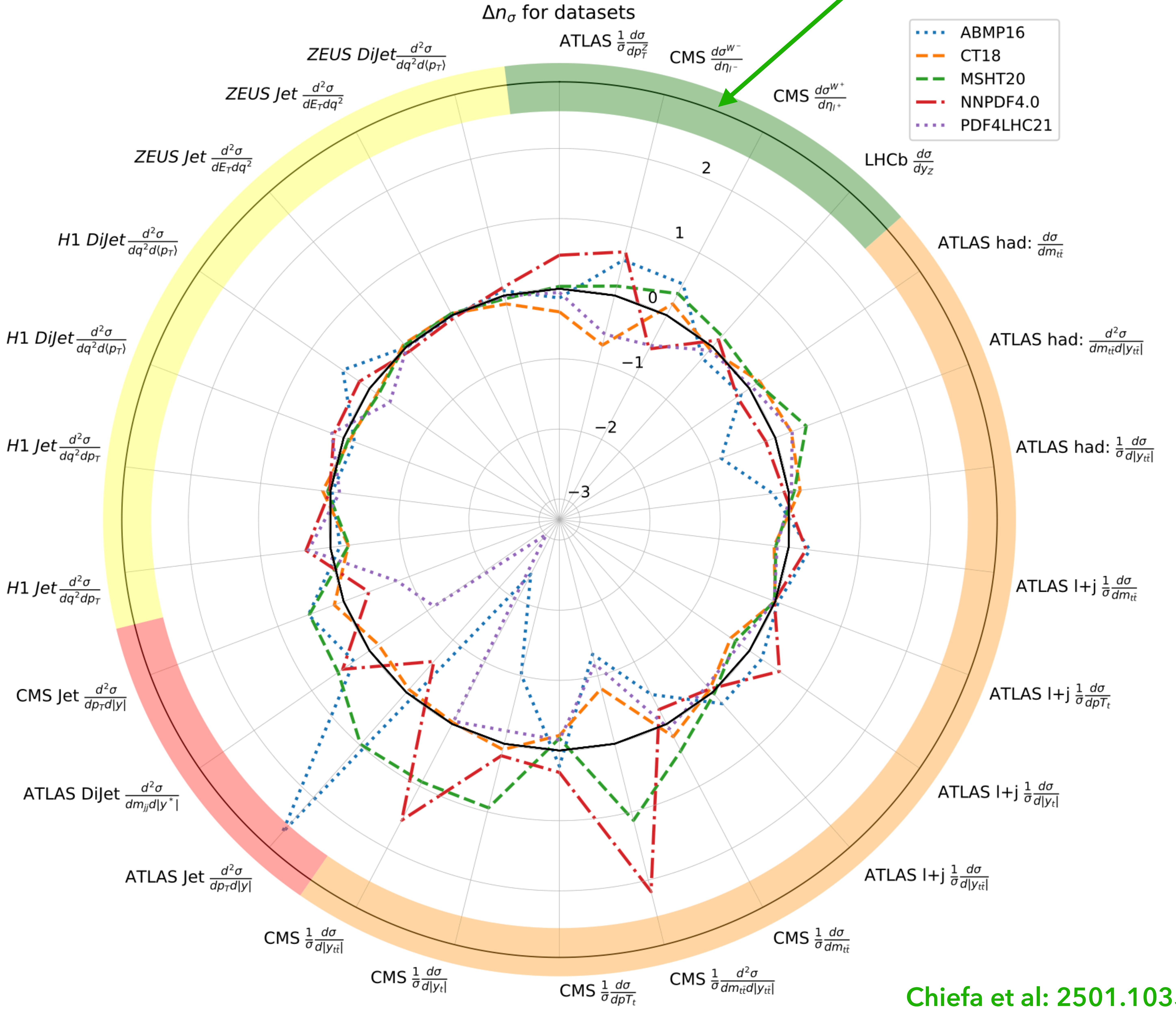
ATLAS collaboration [arXiv:1711.02692]

- Recently analysed 25 experimental distributions LHC@13 TeV and HERA jets measurements not yet included in any PDF analysis: inclusive jets, dijets, top differential distributions, W and Z production, Z pT, DIS jets [Chiefa et al, arXiv:2501.10359]
- Crucial to keep into account all sources of uncertainties and all bin-by-bin corrections.
- For some observables the inclusion of MHO uncertainties or PDF uncertainties changes the picture as compared to pure experimental chi2
- LHC@13 TeV measurements do not strongly discriminate among PDF sets so far.
- NNPDF4.0, despite being the most precise (smallest PDF uncertainties in data region) yields good agreement with data!

HOW WELL DO MODERN PDF SETS PERFORM?

$$\Delta n_\sigma^{(i)} = \frac{\chi^{2(i)}_{\mathrm{exp+th}} - \left\langle \chi^2_{\mathrm{exp+th}} \right\rangle_{\mathrm{pdfs}}}{\sqrt{2/n_{\mathrm{data}}}}$$



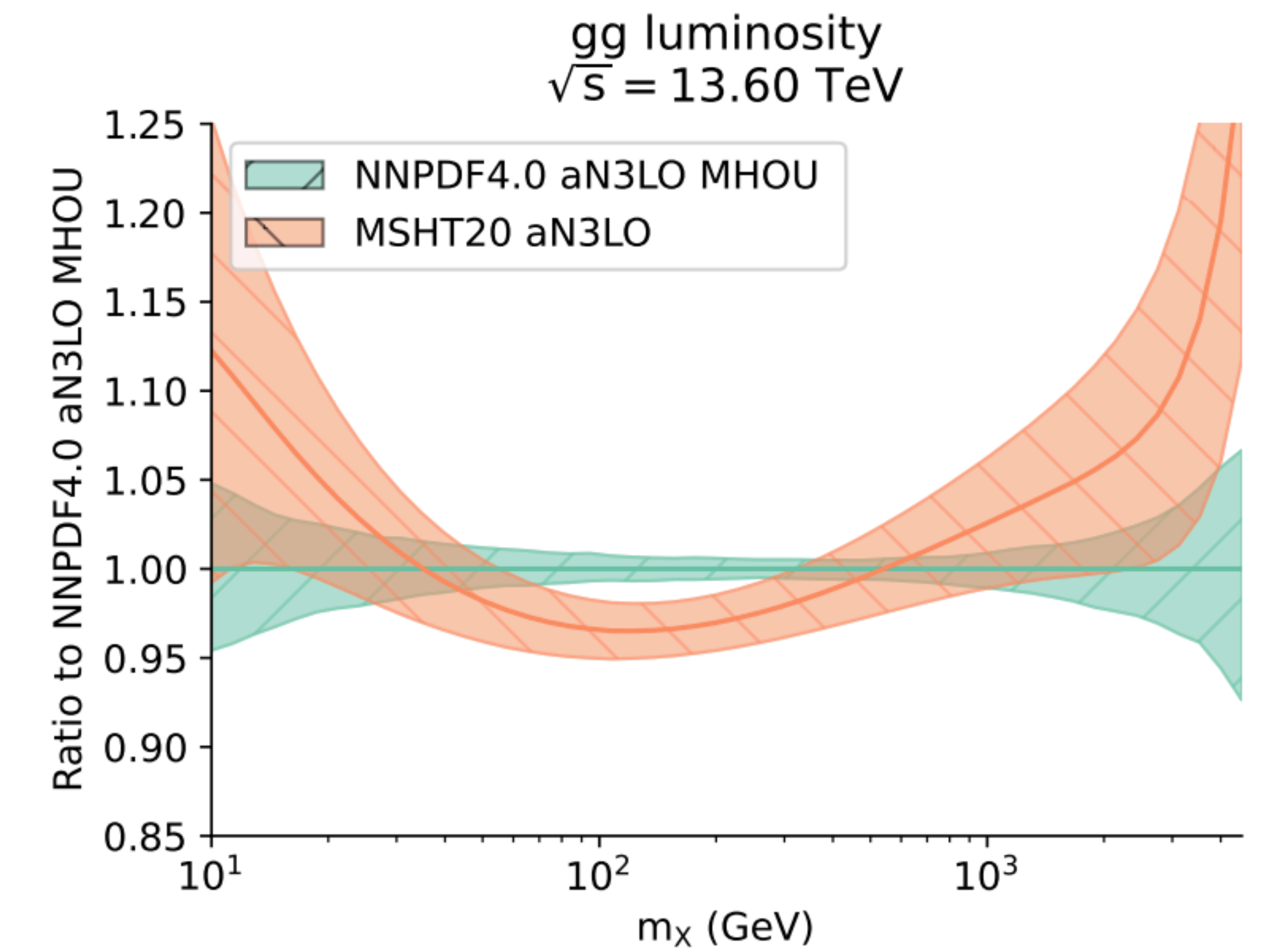


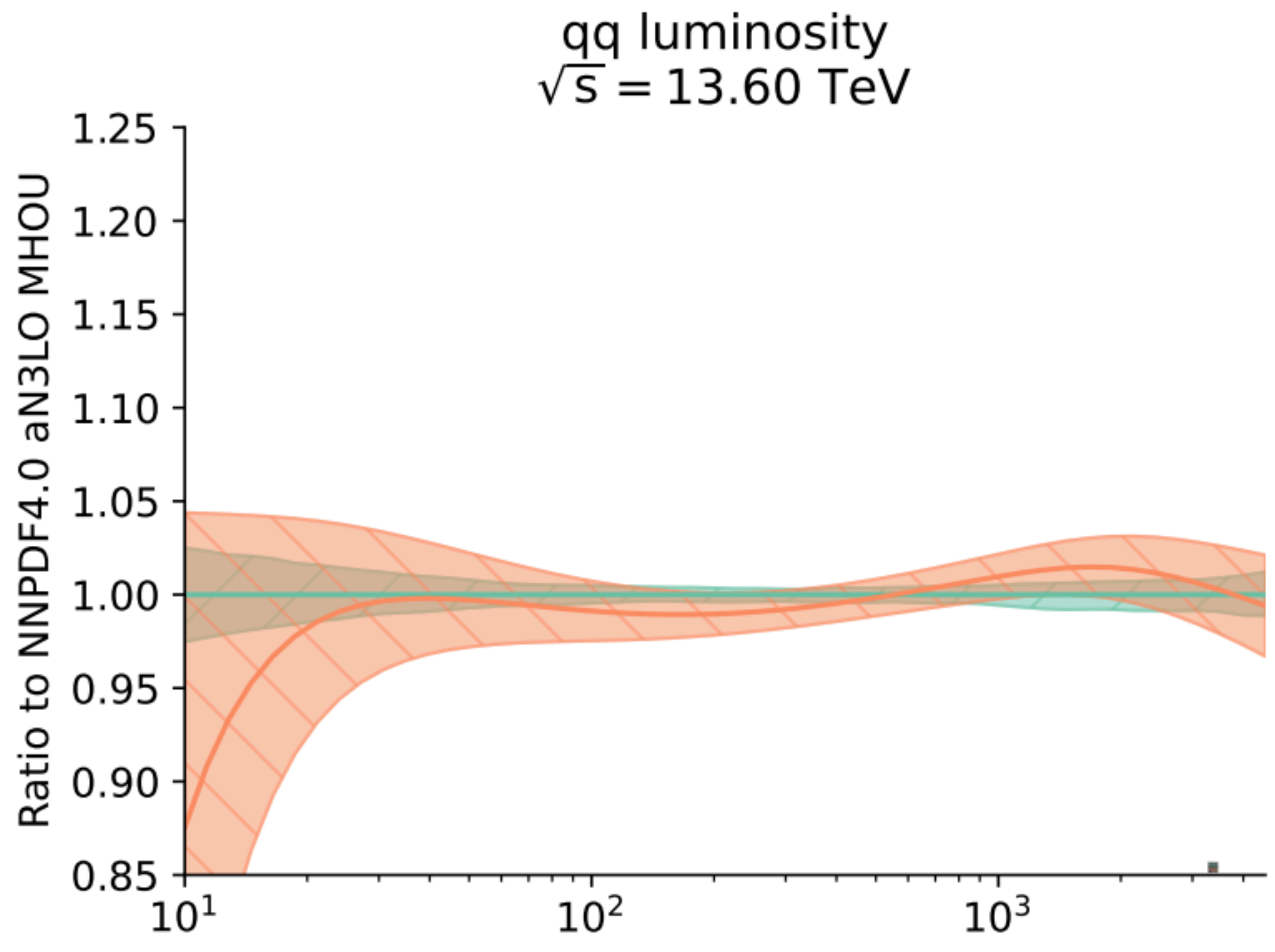
Chiefa et al: 2501.10359

TOWARDS N3LO PDFS

First N3LO PDF sets by MSHT [McGowan et al 2207.04739] and NNPDF [Ball et al 2402.18635] collaborations

- Order-by-order convergence improved in both PDF sets and in phenomenological predictions
- Rather good agreement between collaborations' results considering different input included and strategies for the approximation
- aN3LO necessary to match the order of computation of partonic cross sections





Cridge et al, arXiv:2411.05373

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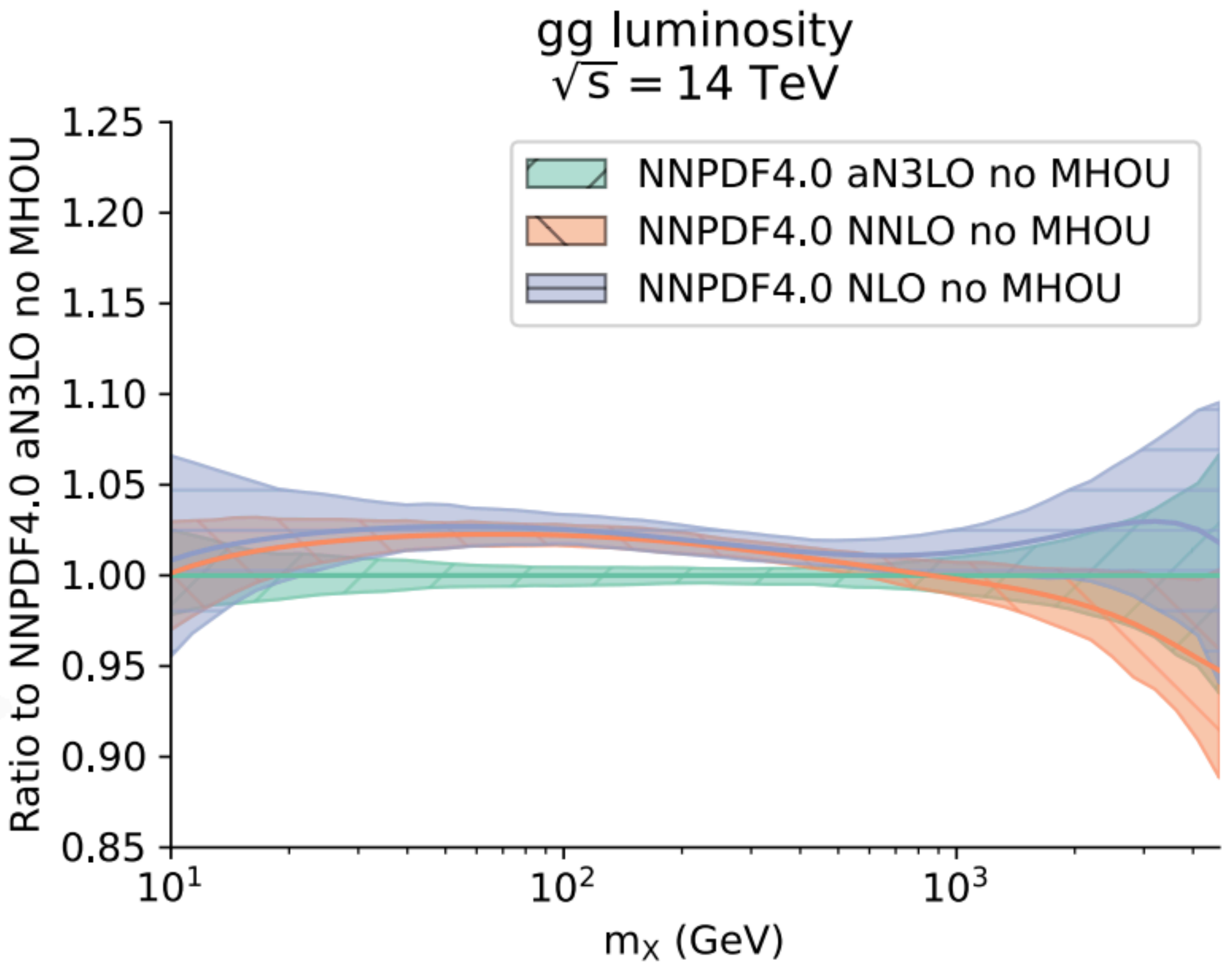
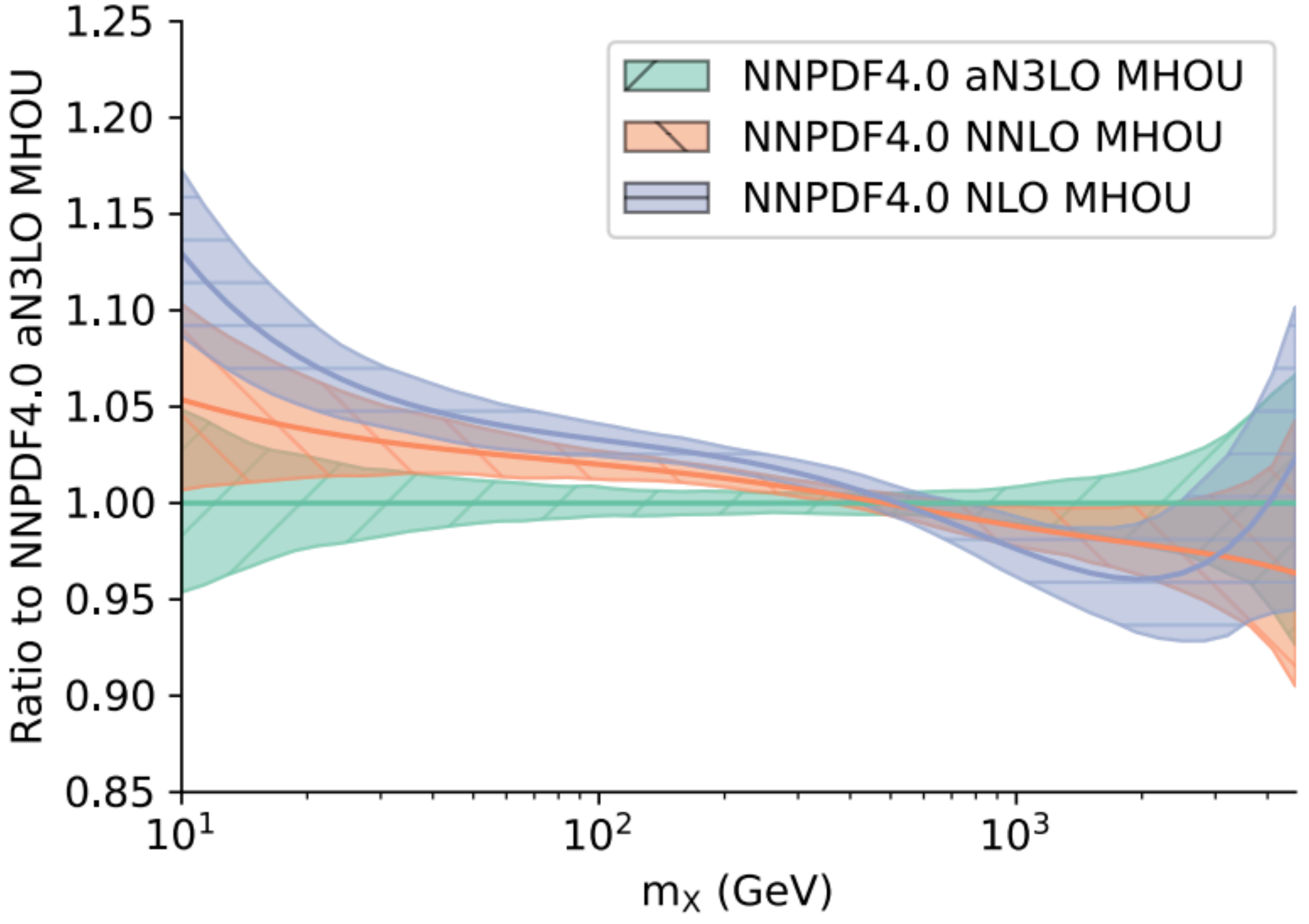


Results are not exact N3LO but rather aN3LO (approximated)

- Splitting functions not fully known, but known in enough limits and enough momenta to build a reasonable approximation [benchmark and references in arXiv:2406.16188]
- Fiducial pp predictions only accessible at NNLO (some only through K-factors)
- Effect of MHOUs estimated though scale variation greatly improves convergence



TOWARDS N3LO PDFS

Error estimate before aN3LO PDFs

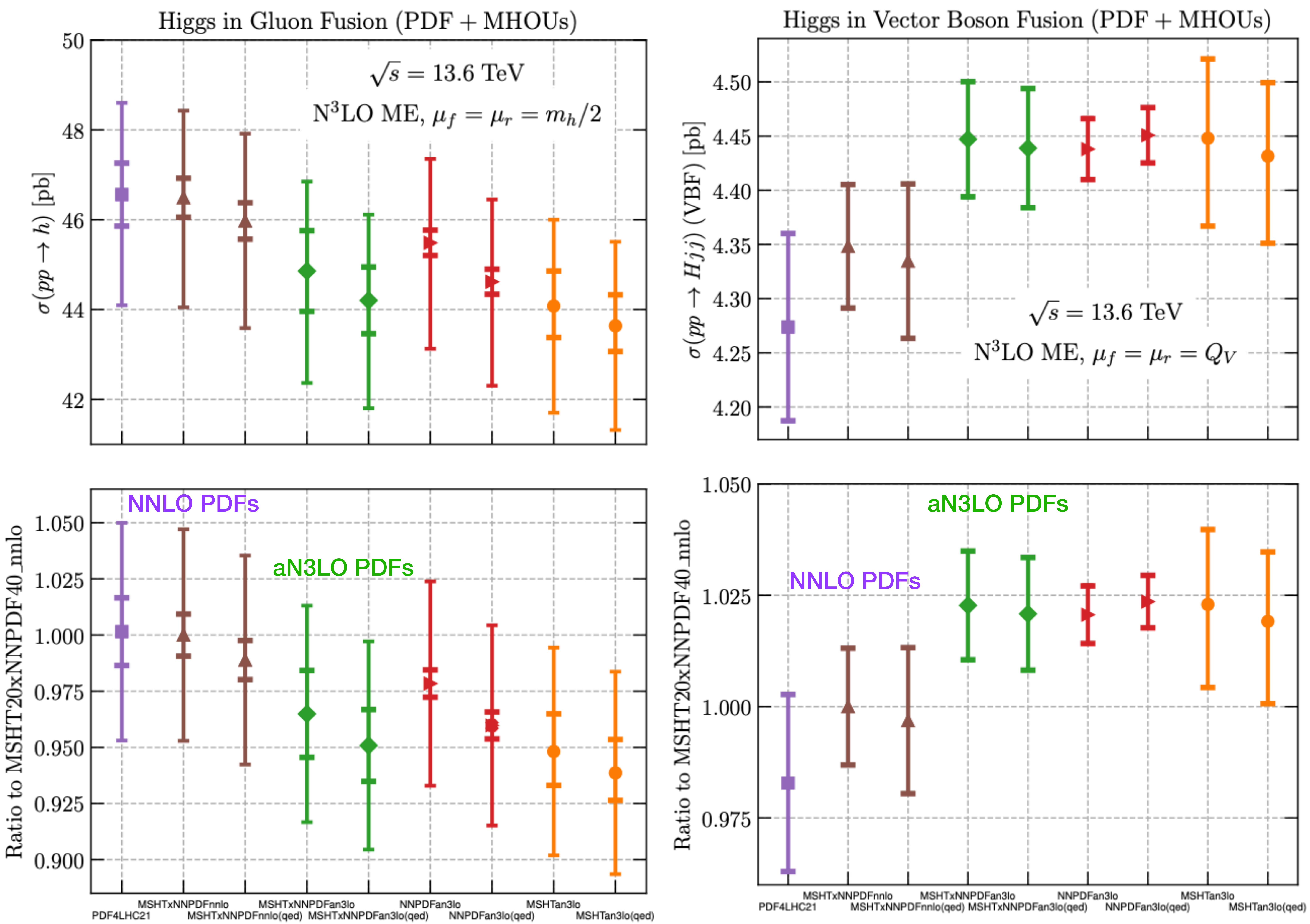
$$\Delta^{\rm app}_{\rm NNLO} \equiv \frac{1}{2}\left|\frac{\sigma^{\rm NNLO}_{\rm NNLO-PDF} - \sigma^{\rm NNLO}_{\rm NLO-PDF}}{\sigma^{\rm NNLO}_{\rm NNLO-PDF}}\right|$$

Actual error using aN3LO PDFs

$$\Delta^{\rm exact}_{\rm NNLO} \equiv \left|\frac{\sigma^{\rm N^3LO}_{\rm N^3LO-PDF} - \sigma^{\rm N^3LO}_{\rm NNLO-PDF}}{\sigma^{\rm N^3LO}_{\rm N^3LO-PDF}}\right|.$$

	ggF	VBF
$\Delta_{\rm NNLO}$ (app)	1.6%	0.5%
$\Delta_{\rm NNLO}$ (actual)	3.3%	2.3%

Previous estimates of the effect of NNLO/N3LO mismatch were **optimistic**



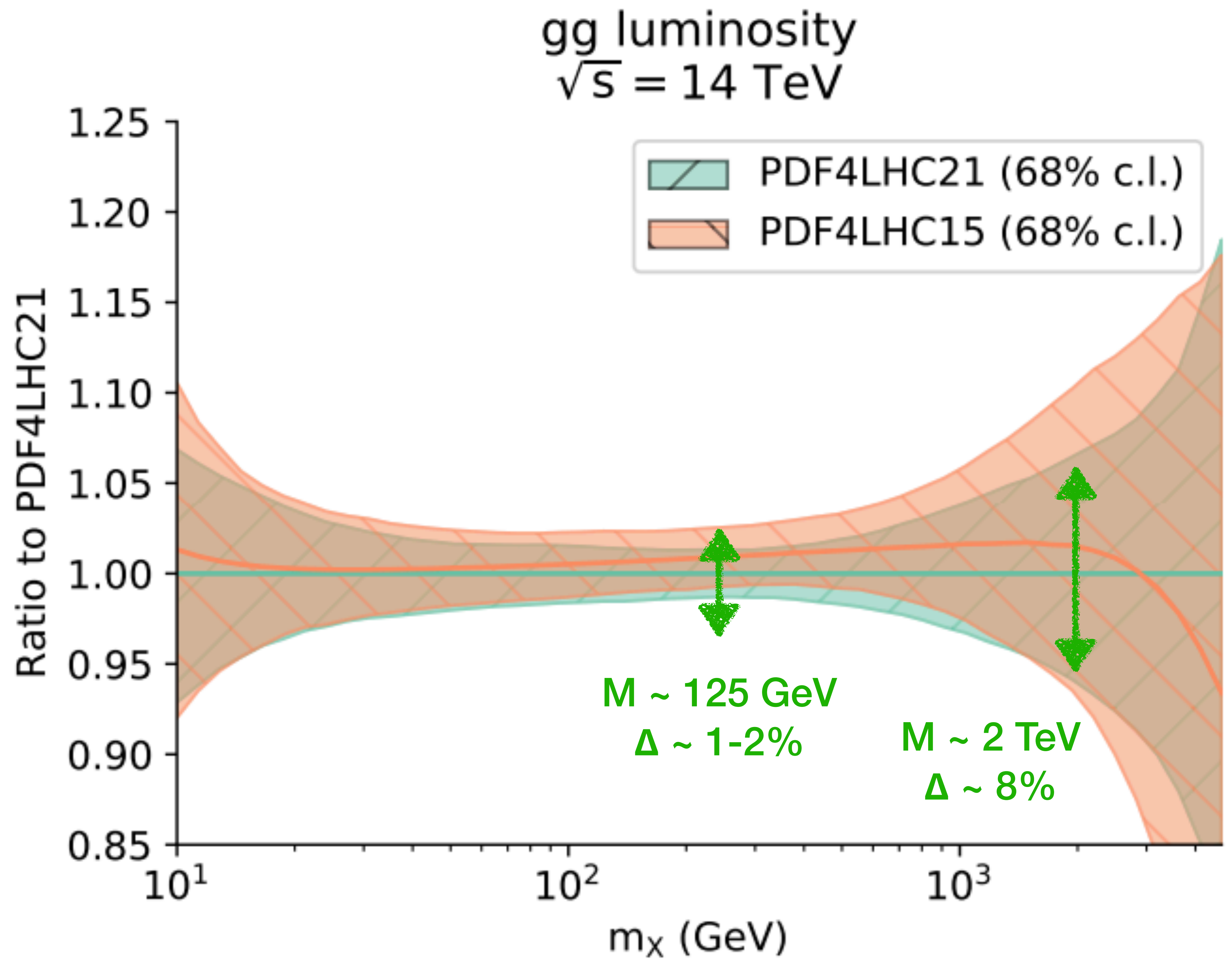
Cridge et al, arXiv:2411.05373

PART II: PRECISION VS ACCURACY – NEW CHALLENGES, NEW FRONTIERS

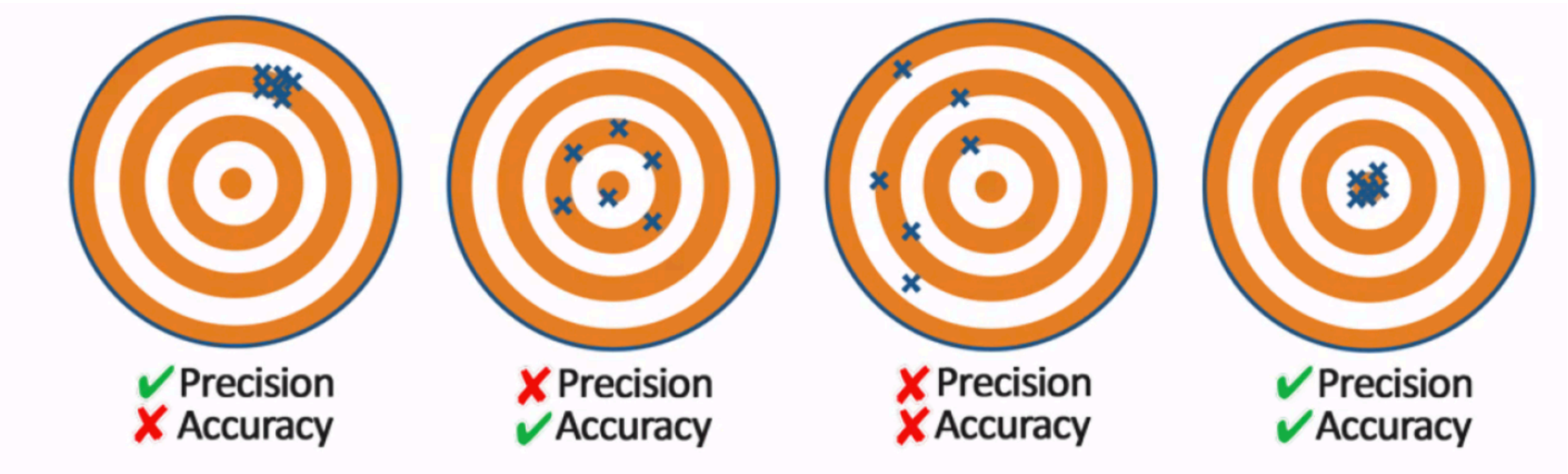
THE PRECISION VERSUS ACCURACY CHALLENGE

At a time of precision physics, it is time for precision PDF determination, does precision match accuracy?
Highly non trivial challenges

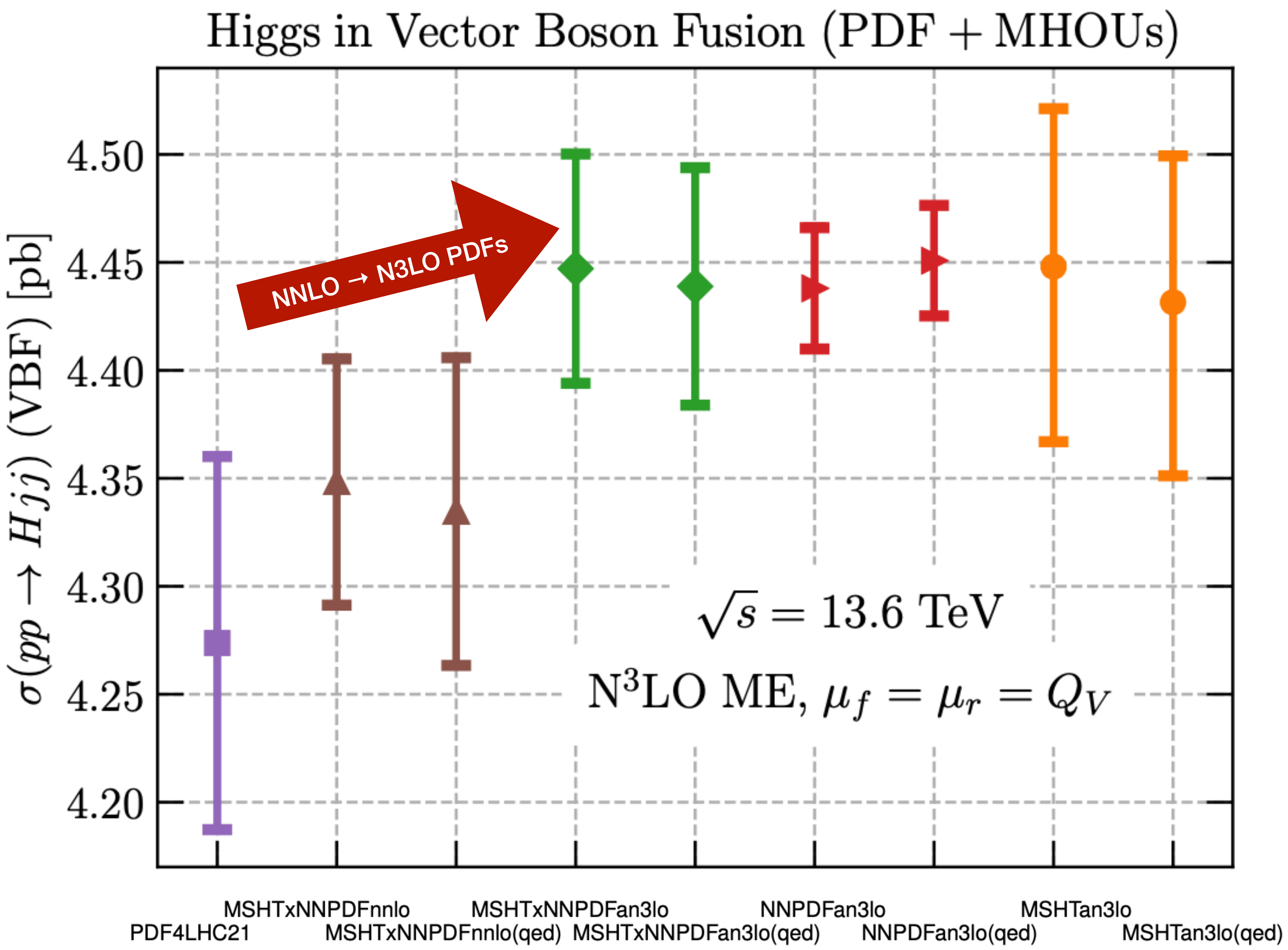
- Genuine inconsistencies in experimental inputs (possible underestimated, over-correlated systematics…)
- Imperfect fitting methodology (parametrisation, error propagation…)
- Inaccurate theoretical framework
  - ➡ Missing higher orders (exact N3LO, resummation…)
  - ➡ Other corrections (electroweak, nuclear, higher-twists, other non-perturbative effects…)
  - ➡ BSM effects in the high energy tails of distributions



PDF4LHC21 study 2203.05506



CHALLENGE #1: N3LO PDFS AND MISSING HIGHER ORDER UNCERTAINTIES



e.g. Higgs in VBF @ N3LO

MSHT+NNPDF arXiv:2411.05373

- Shift between results obtained with NNLO PDFs and with aN3LO PDFs more significant than expected
- Next steps:
    - As more N3LO theory ingredients become available, **aN3LO PDFs updated** by improving convergence of results obtained with different methodologies
    - **Exact N3LO evolution**, exact NNLO grids for hadronic coefficients and N3LO k-factors
- Every step of the way becomes computationally more costly and complex for a smaller and smaller improvements. But ***extremely needed!***
- What about other effects? Resummation, higher twists, power correction…
- Estimate of incomplete N3LO terms and MHO uncertainties still computed via scale variations: is there a better way?

CHALLENGE #2: DETERMINATION OF SM PARAMETERS

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
MSHT20 [37]	0.11839	0.00040	0.44	−0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
CT18A [29]	0.11982	0.00050	0.36	−0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

ATLAS collaboration, arXiv:2309.12986

Significantly different results obtained when using different input PDFs.

- ATLAS determination of α_S from neutral-current Drell-Yan Z pT measurement most precise α_S determination ever performed from a single experiment
  $\Delta_{\alpha,\mathrm{TOT}} = 9 \times 10^{-4}$ with $\Delta_{\alpha,\mathrm{PDF}} = 5 \times 10^{-4}$ (MSHT20aN3LO)
  But
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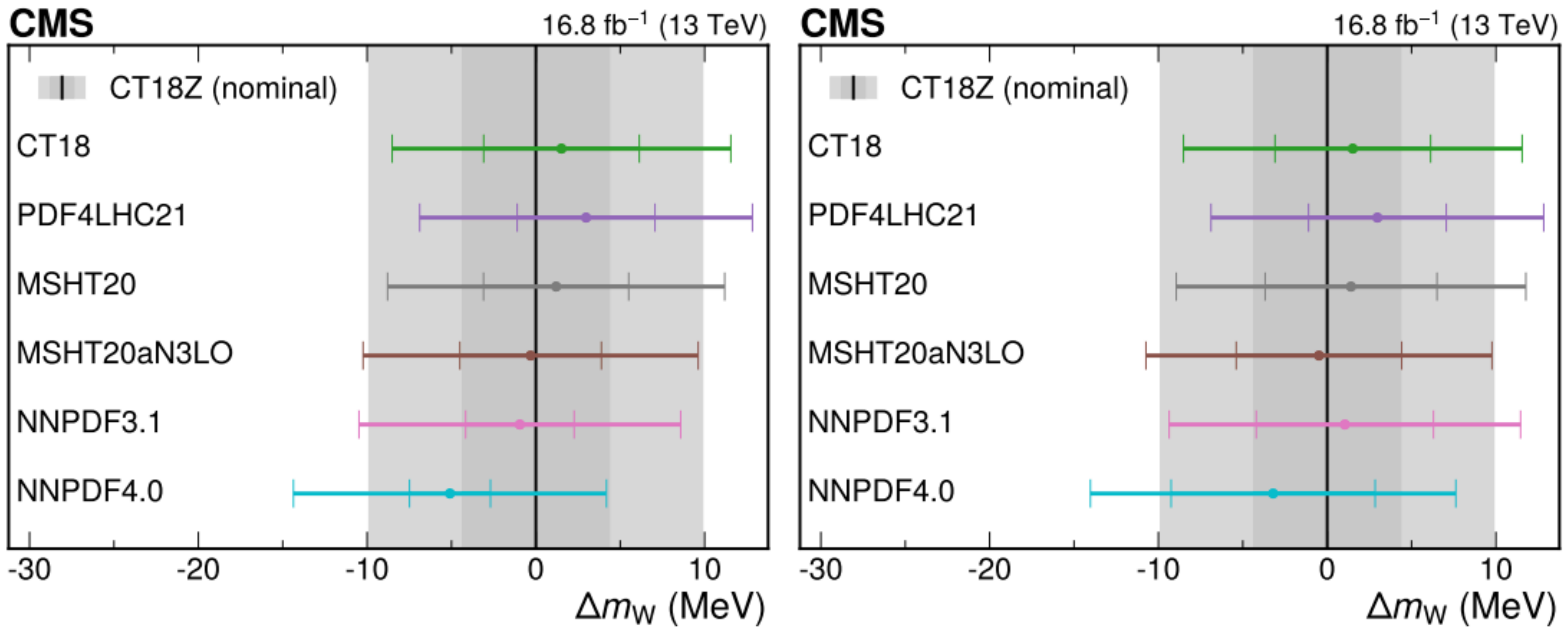

CMS collaboration, arXiv: 2412.13872

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- Similar situation in Mw determination **[ATLAS-CONF-2023-004]**
  $\Delta_{MW,PDF} = 7.7$ (14.6) MeV in $p_{T,l}$ (m_T) channel **(CT18)**
  But
  $\delta_{MW,PDFS} = 17$ (21) MeV **(shift MSHT20 versus NNPDF4.0)**

- CMS Mw: inflate PDF uncertainties by a factor and profile with CMS data decreases shift between PDF set (but effectively giving much larger weight to a given measurement as compared to all experiments that determine PDFs in global fit)

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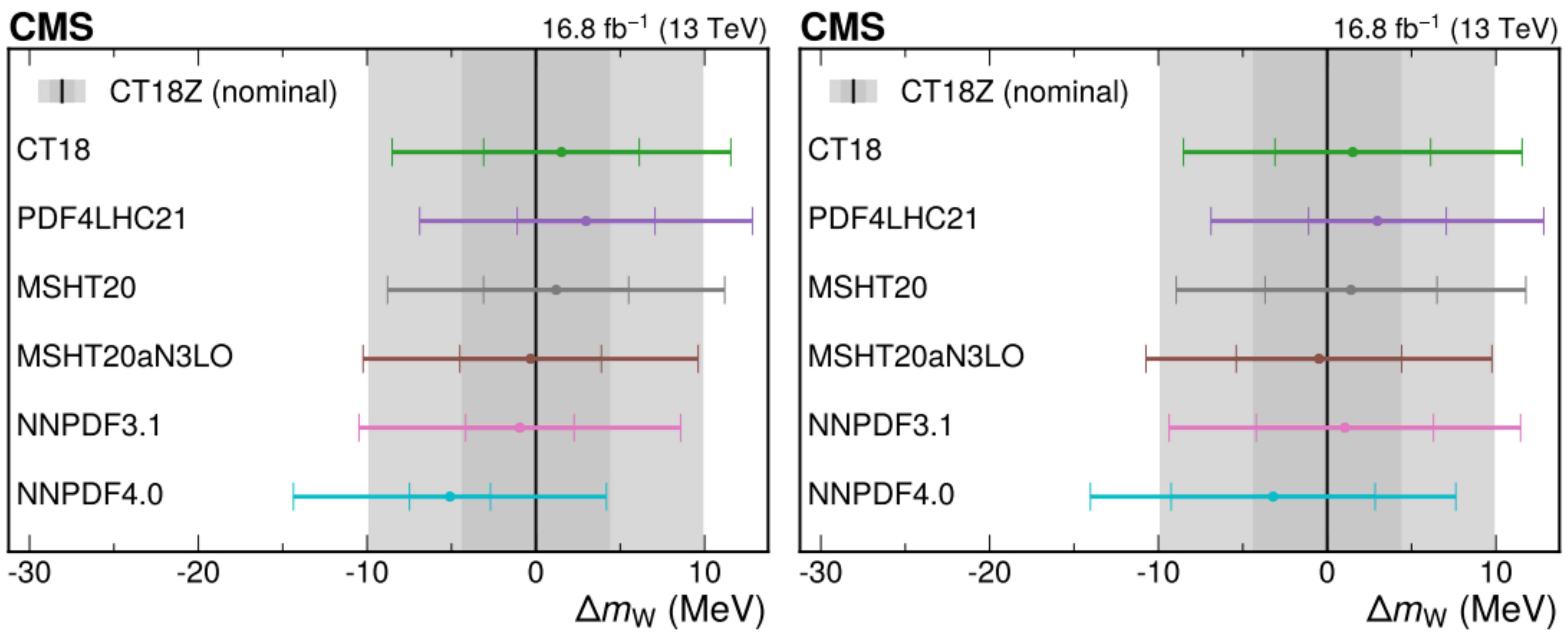

CMS collaboration, arXiv: 2412.13872

Can a better solution be achieved?
Simultaneous PDF-SM fits? Profiling over all data?

Significantly different results obtained when using different input PDFs.

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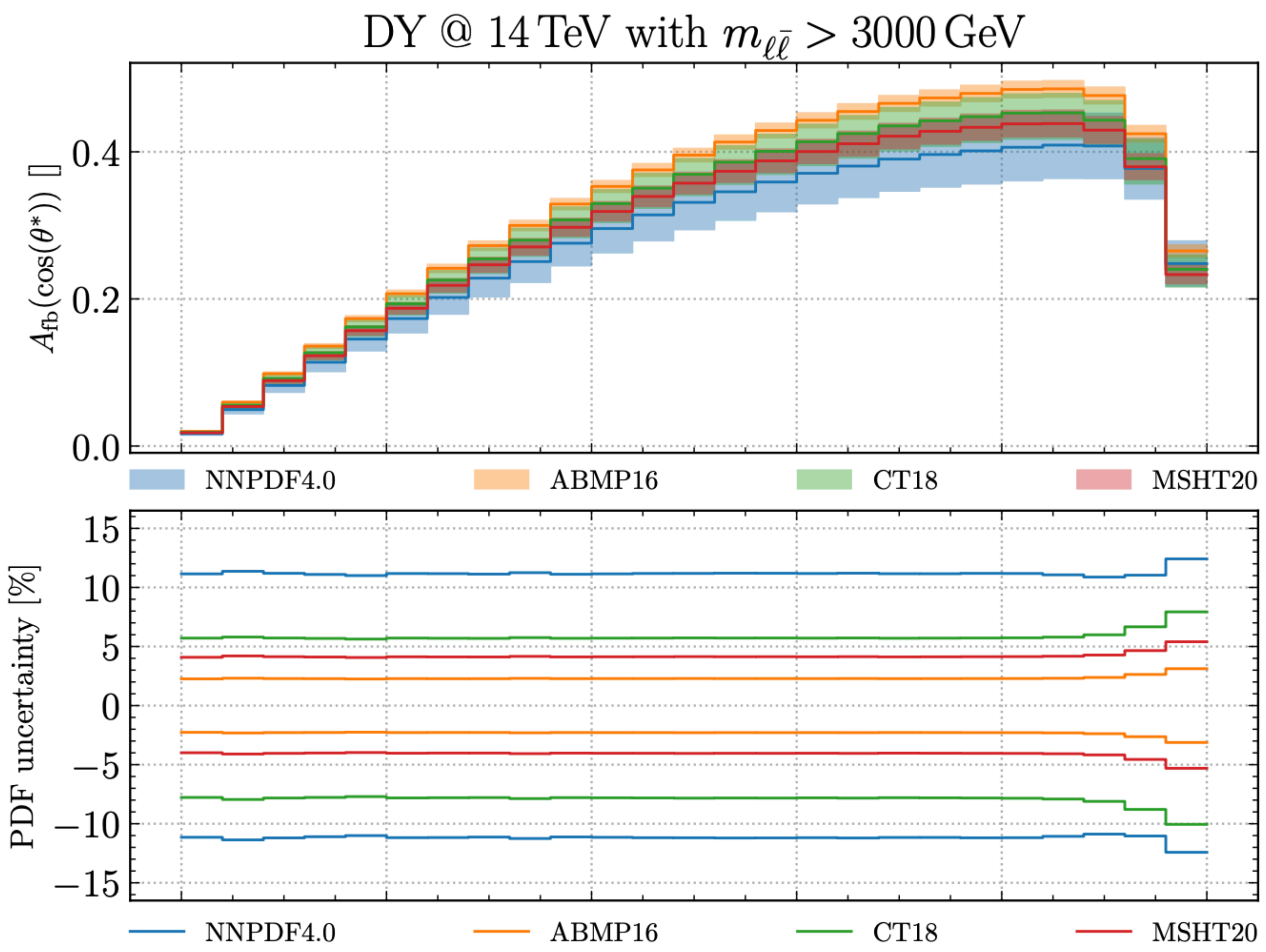
CHALLENGE #3: PRECISE PDFS FOR NEW PHYSICS SEARCHES

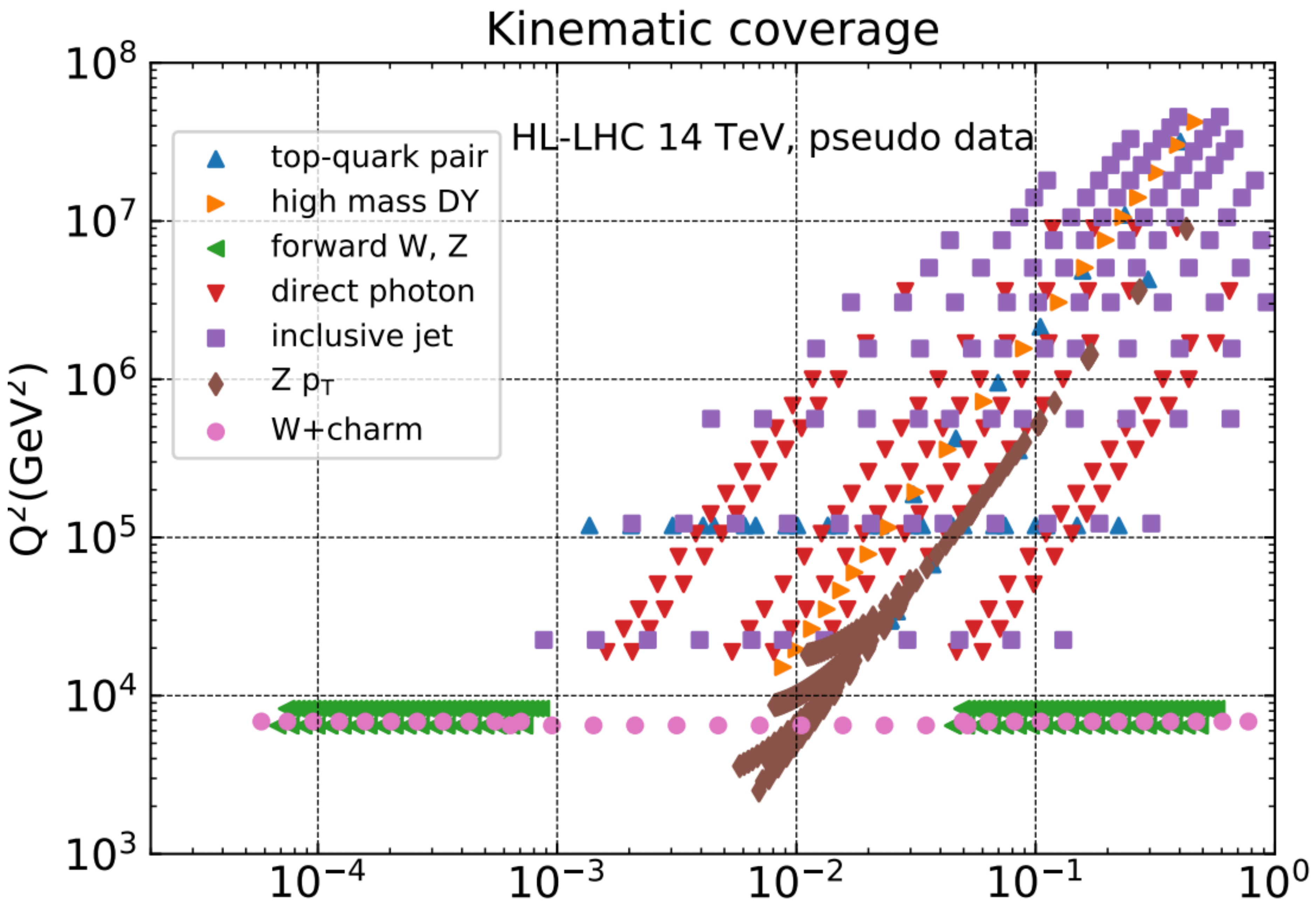


e. g. Heavy Z′ search in DY Forward-Backward asymmetry

Ball et al arXiv: 2209.08115

- Large-x PDF affected by large uncertainties
- Reducing PDF uncertainties in large-x region is essential to characterise any possible new physics and to interpret deviations in the tails of experimental distributions
- Looking forward: **HL-LHC (and FCC-hh)**

Large x ⟷ Large E and/or Large Y



Khalek et al, 1810.03639

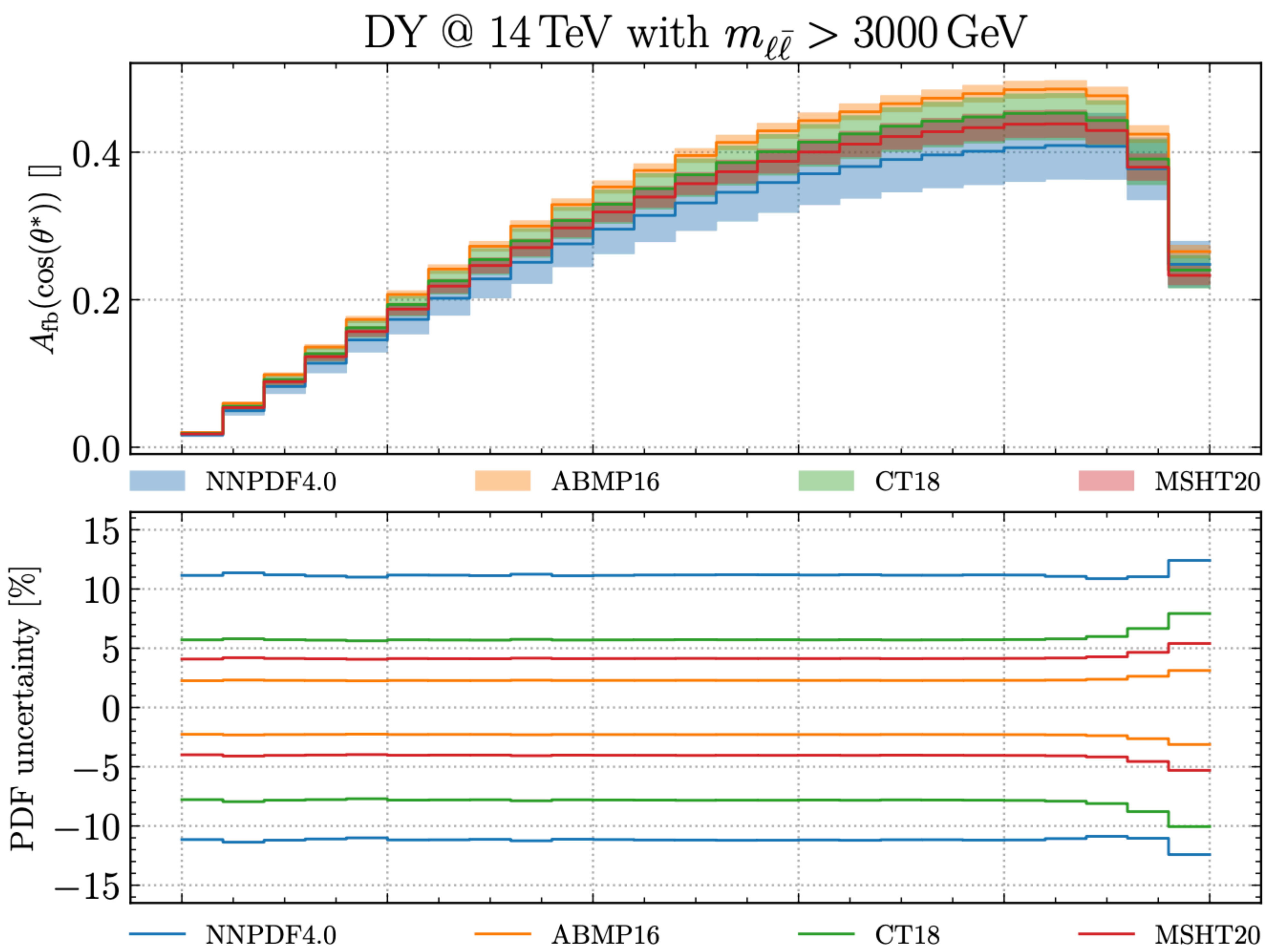
$$x \approx \frac{M}{\sqrt{S}}$$

High-mass final states

⇔

Large-x PDFs

CHALLENGE #3: PRECISE PDFS FOR NEW PHYSICS SEARCHES



e. g. Heavy Z′ search in DY Forward-Backward asymmetry

Ball et al arXiv: 2209.08115

$$\boxed{x \approx \frac{M}{\sqrt{S}}}$$

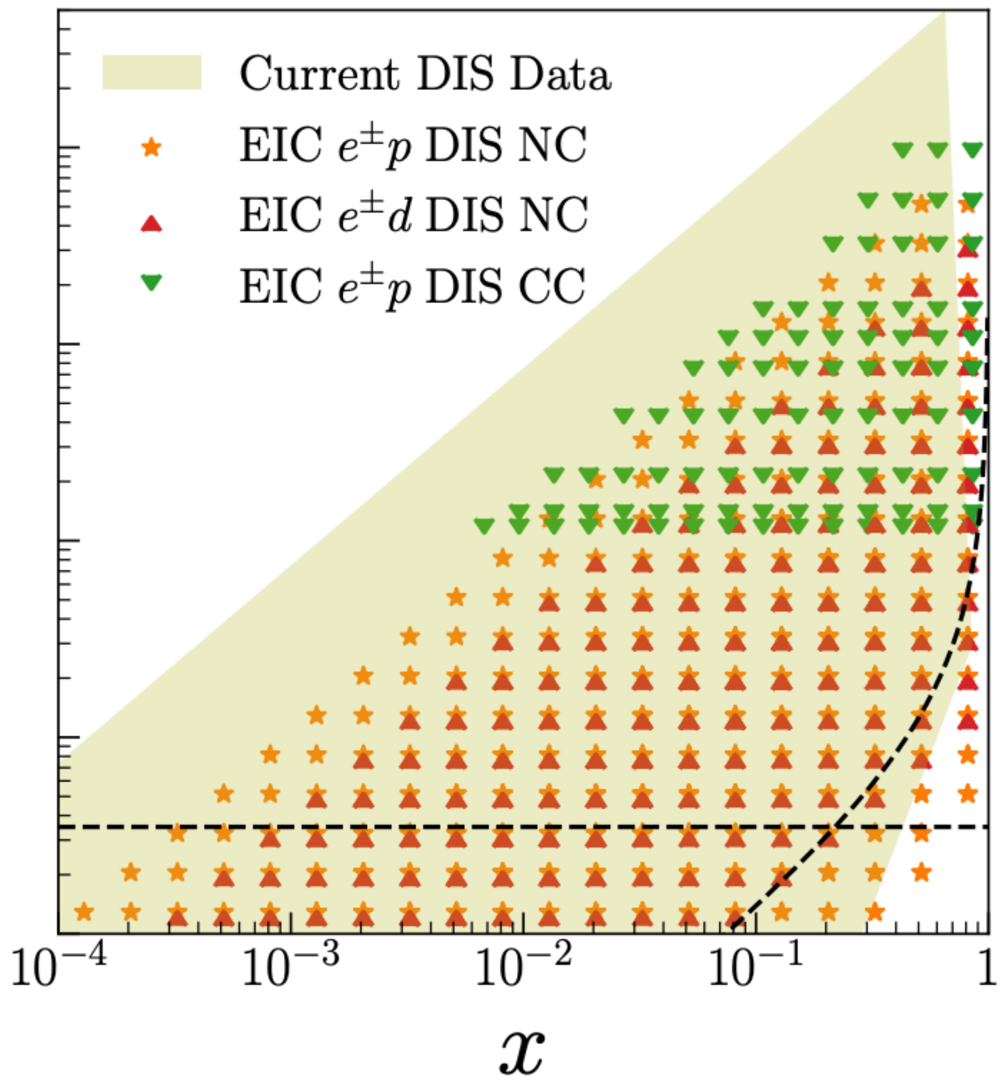
High-mass final states

⇔

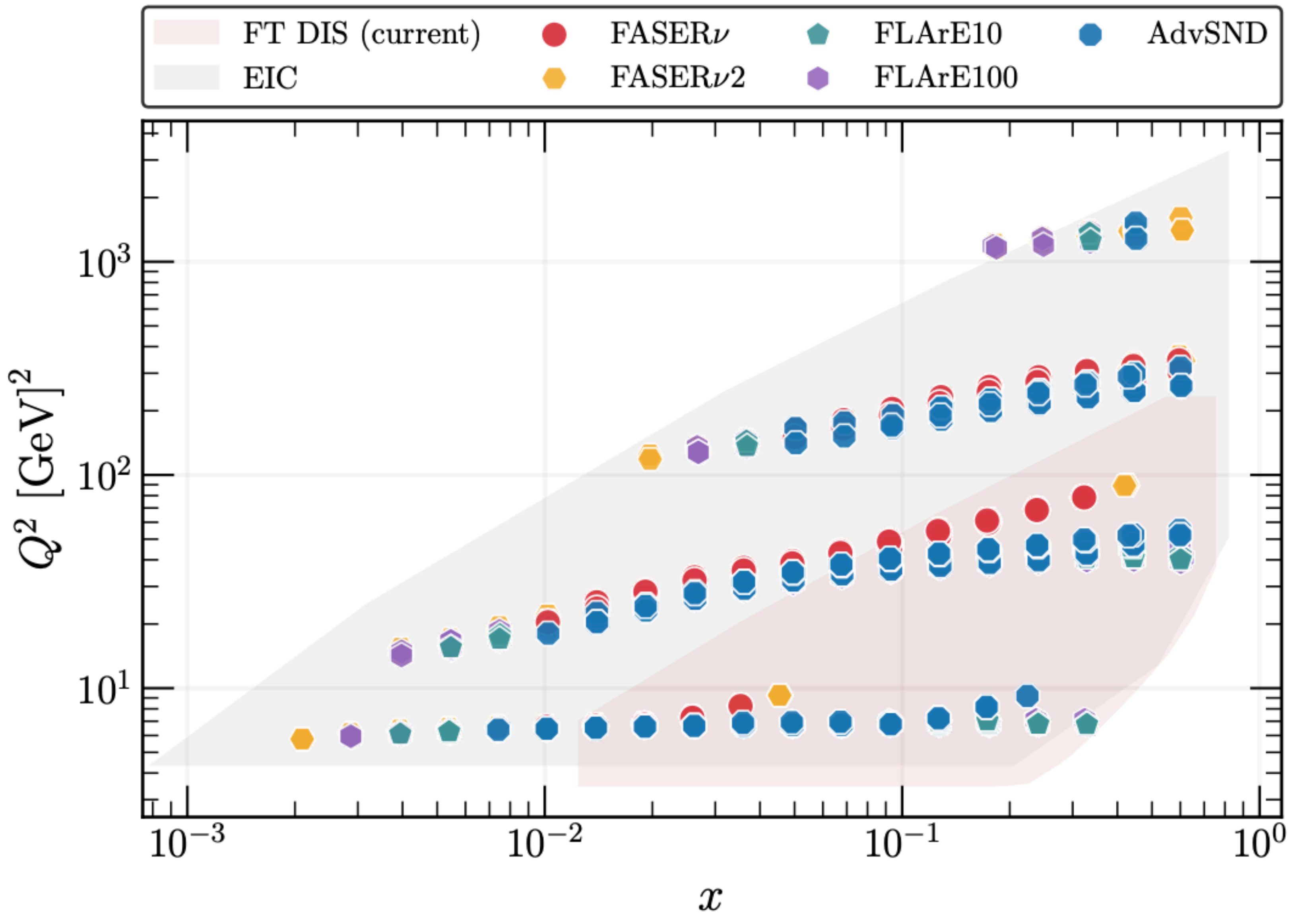
Large-x PDFs

- Large-x PDF affected by large uncertainties
- Reducing PDF uncertainties in large-x region is essential to characterise any possible new physics and to interpret deviations in the tails of experimental distributions
- Looking forward: **JLab, EIC, Forward Physics Facilities…**

Large x ⟷ Low/Medium E

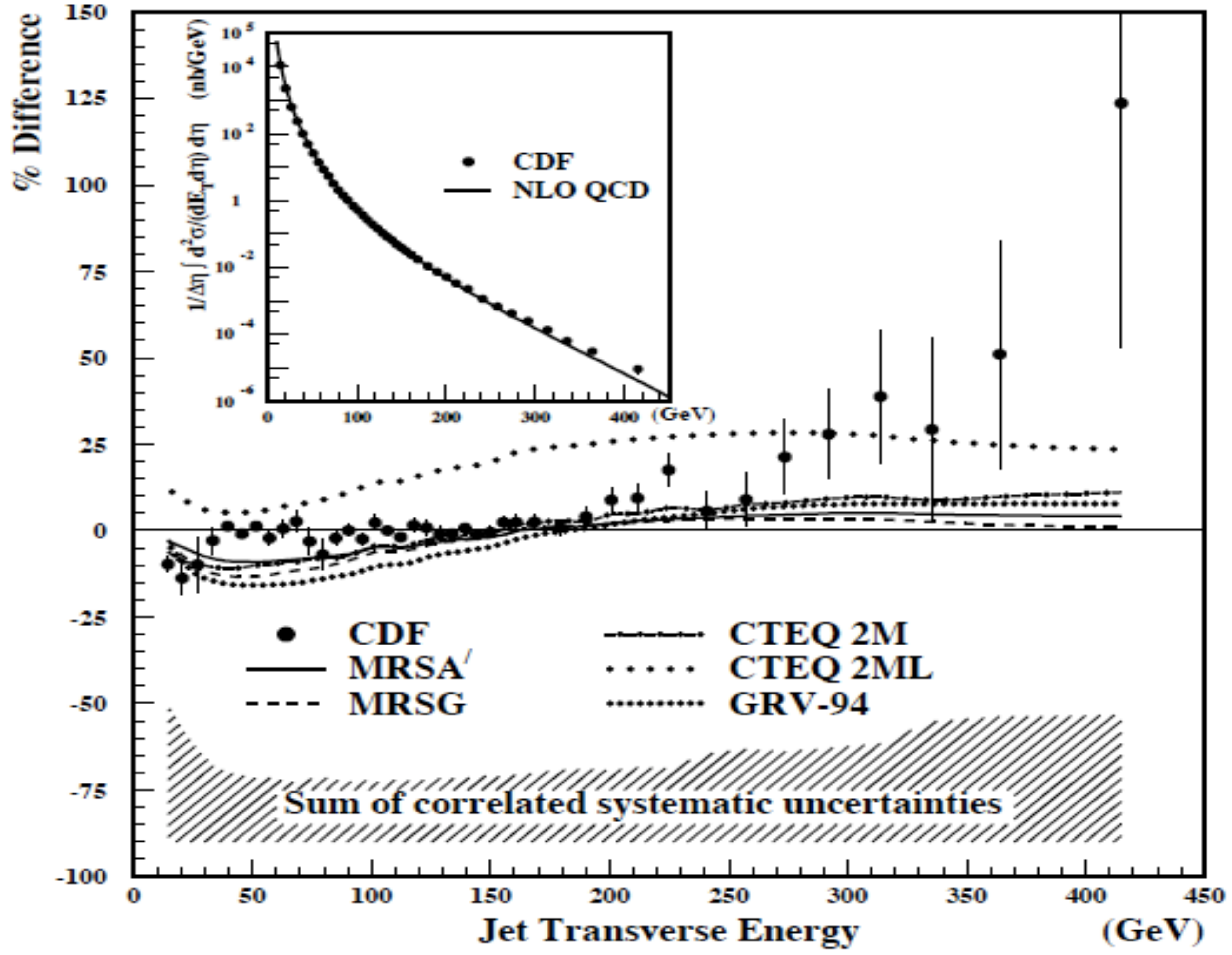


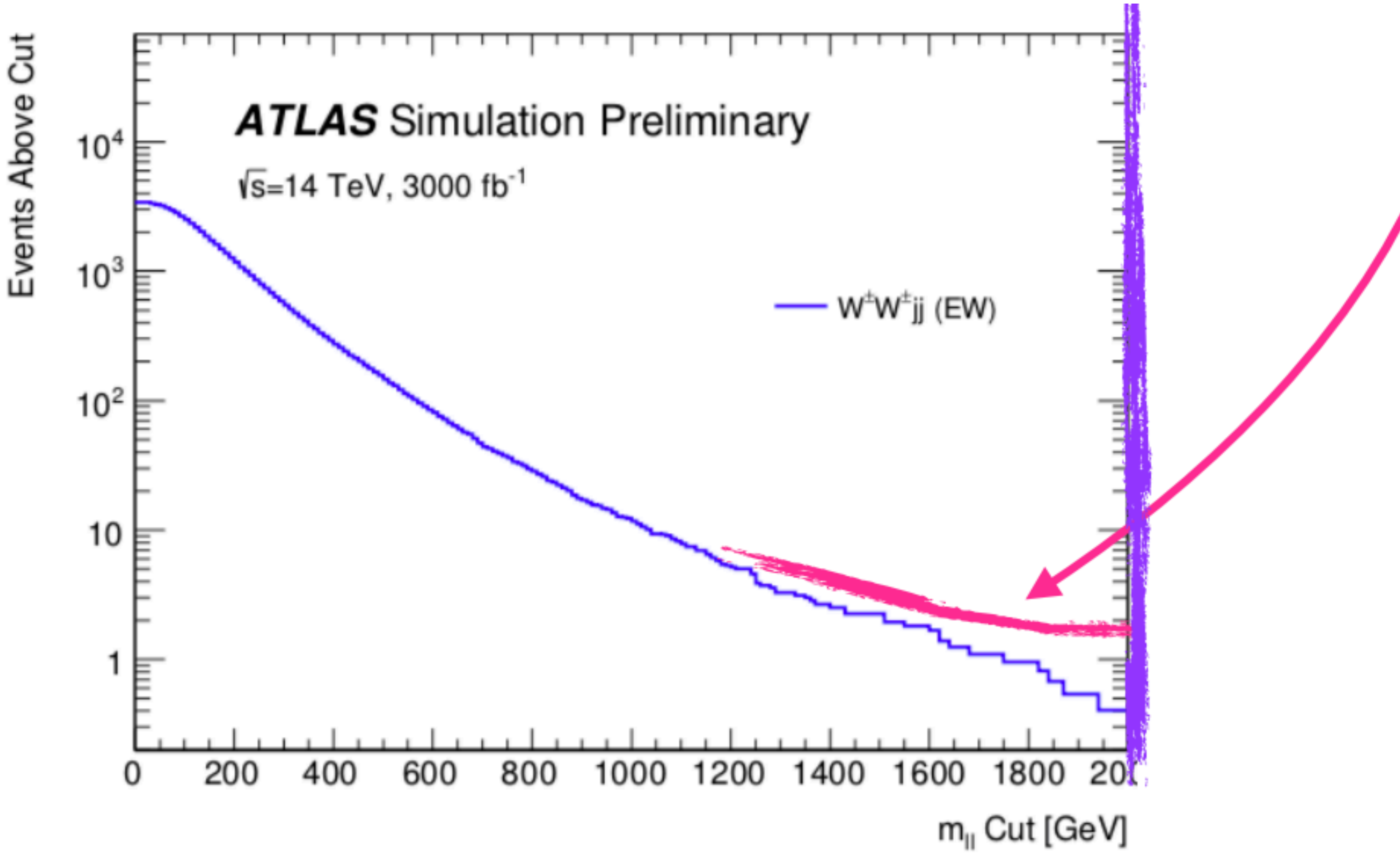
Khalek et al, 2102.00018



J Cruz-Martinez et al 2309.09581

CHALLENGE #3: PRECISE PDFS FOR NEW PHYSICS SEARCHES





CA Lee, HL/HE-LHC Jamboree, 1 March 2019

➡ Discrepancy between QCD calculation and CDF jets data (1995)

At that time no information on PDF uncertainties and theory predictions strongly depended on gluon shape at x>0.1. Once data included in the CTEQ fit, discrepancy disappeared.

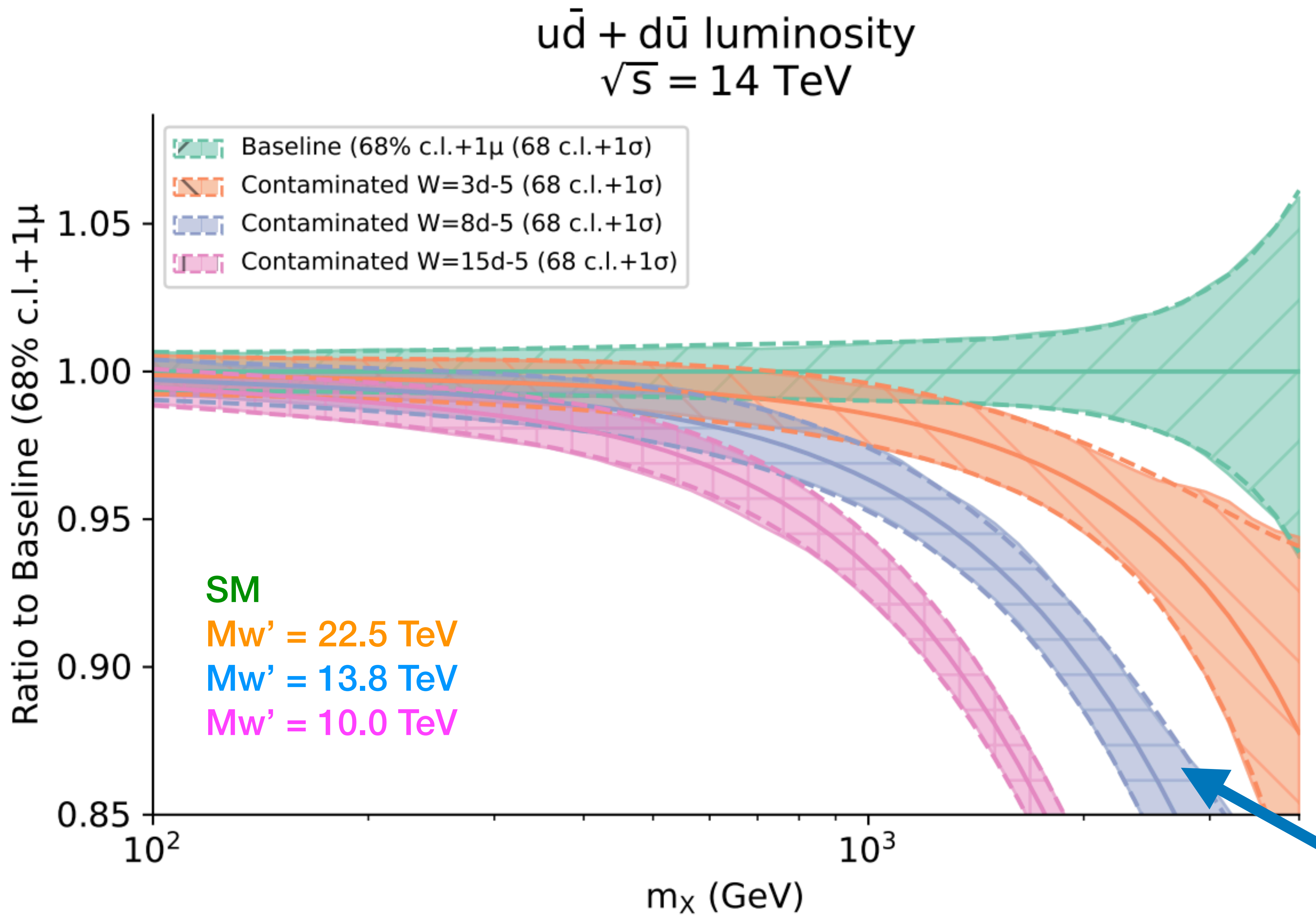
➡ Deviations from SM predictions in high energy tails (>2025)

New physics or limited understanding of proton structure?

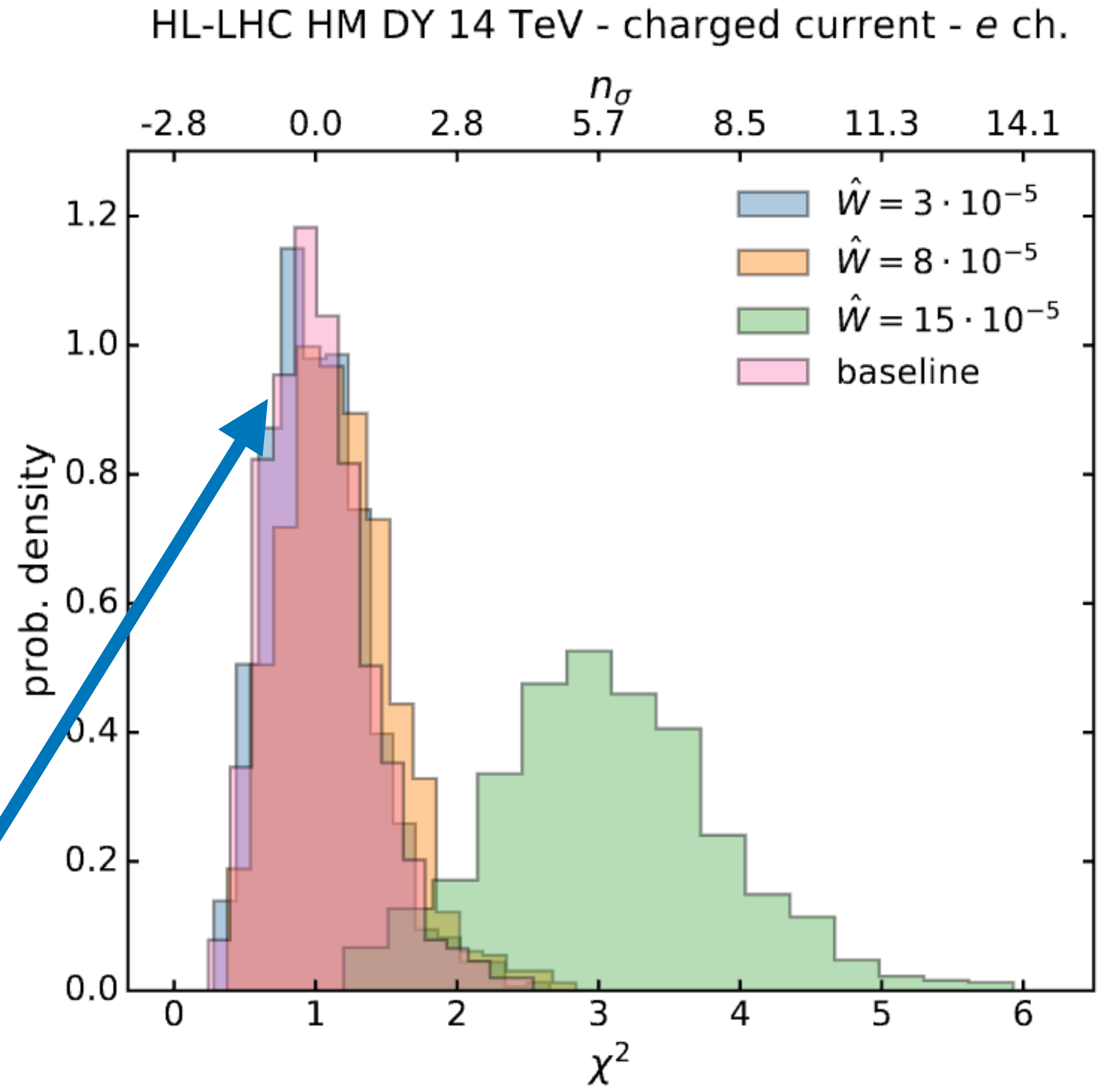
CHALLENGE #3: PRECISE PDFS FOR NEW PHYSICS SEARCHES

- Inject the "true" NP model and "true" PDFs in artificial data included in global fit
- Generate **HL-LHC** pseudo-data assuming
  "true" law of nature = "true" PDFs + "true" UV model
- Fit PDFs assuming SM
- **Can PDFs absorb signs of new physics? Yes**
- Important to tackle the issue (simultaneous fits, complementary constraints, test observables) and broaden understanding (gluon, strange)

Z'	W'
Selection test: ✗	Selection test: ✓
➡ Excluded from PDF fit	➡ Included in PDF fit
No impact on PDFs	**PDFs contaminated**



Max BSM bias allowed by global fit Without spoiling χ^2



Hammou, Madigan, Mangano, Mantani, Moore, Morales, MU 2307.10370

CONCLUSIONS AND OUTLOOK

- In an era of precision at LHC, need precise and accurate PDFs
- Impressive advances in theory inputs and experimental inputs, pressure to validate and understand methodological differences.
- Tools like closure tests and generalisation tests are crucial to test methodology robustness, effects of possible experimental inconsistencies and even possible effects of new physics in the high energy tails
- Crucial reproducibility & open-source tools (and fitting codes)

- Much to look forward to at DIS2025 as far as PDFs are concerned

Updates from collaborations - R. Thorne, O Zenaiev, T Hobbs, T R Rabemananjara WG1
HQ schemes - V. Bertone WG1
Determination of αS and PDFs - R Stegeman, T Cridge WG1
aN3LO combination - T. Cridge WG1
HL-LHC and other experiments synergies - K Wichmann, MU WG1/6
Higher twists - A Accardi WG1
Parametrisation studies - A Courtoy WG1
Closure tests with inconsistent data - MU WG1
Bayesian fits of PDFs - L Mantani WG1

… and much more!!