MARIA UBIALI
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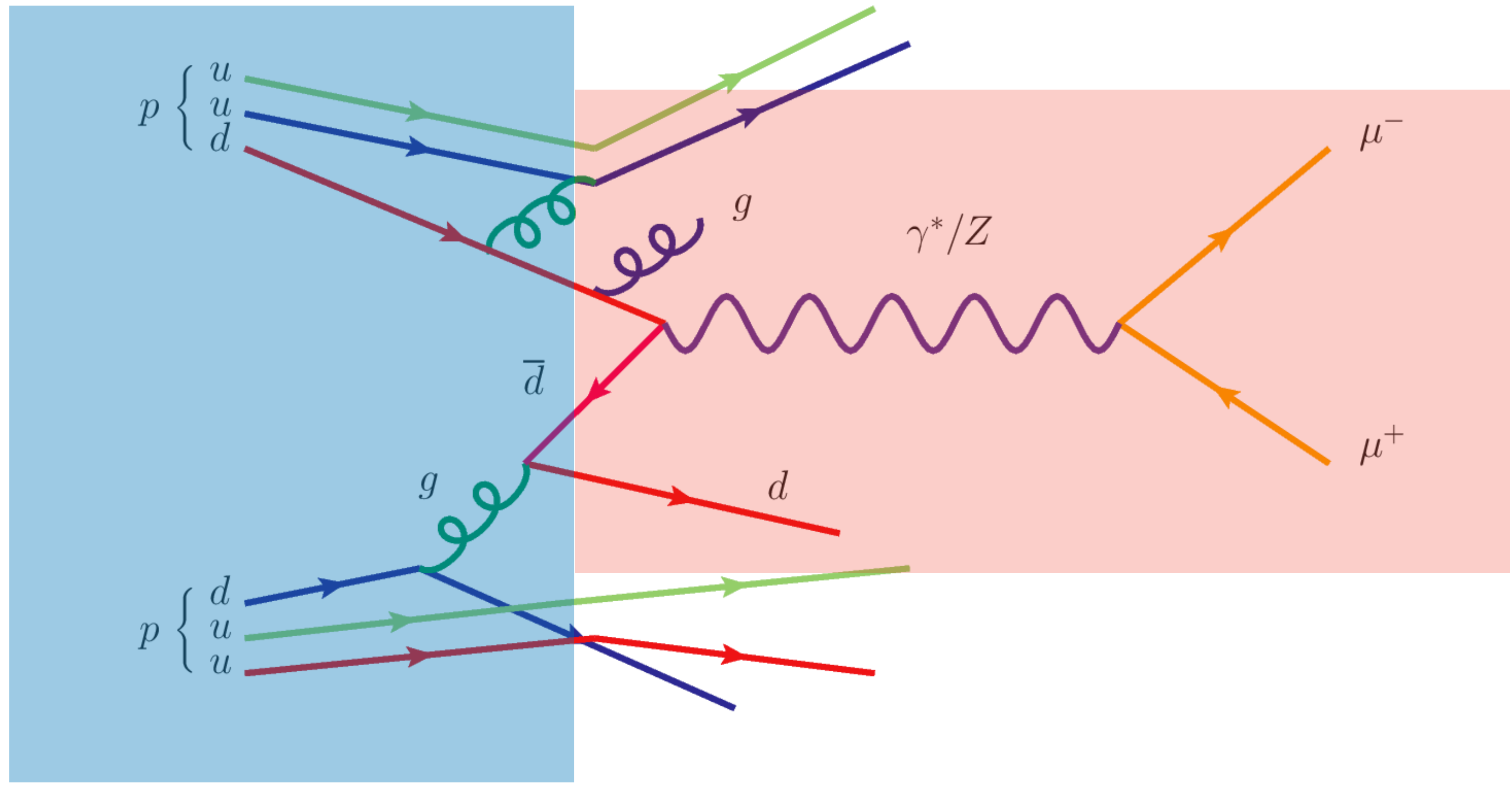
PARTON DISTRIBUTION FUNCTIONS

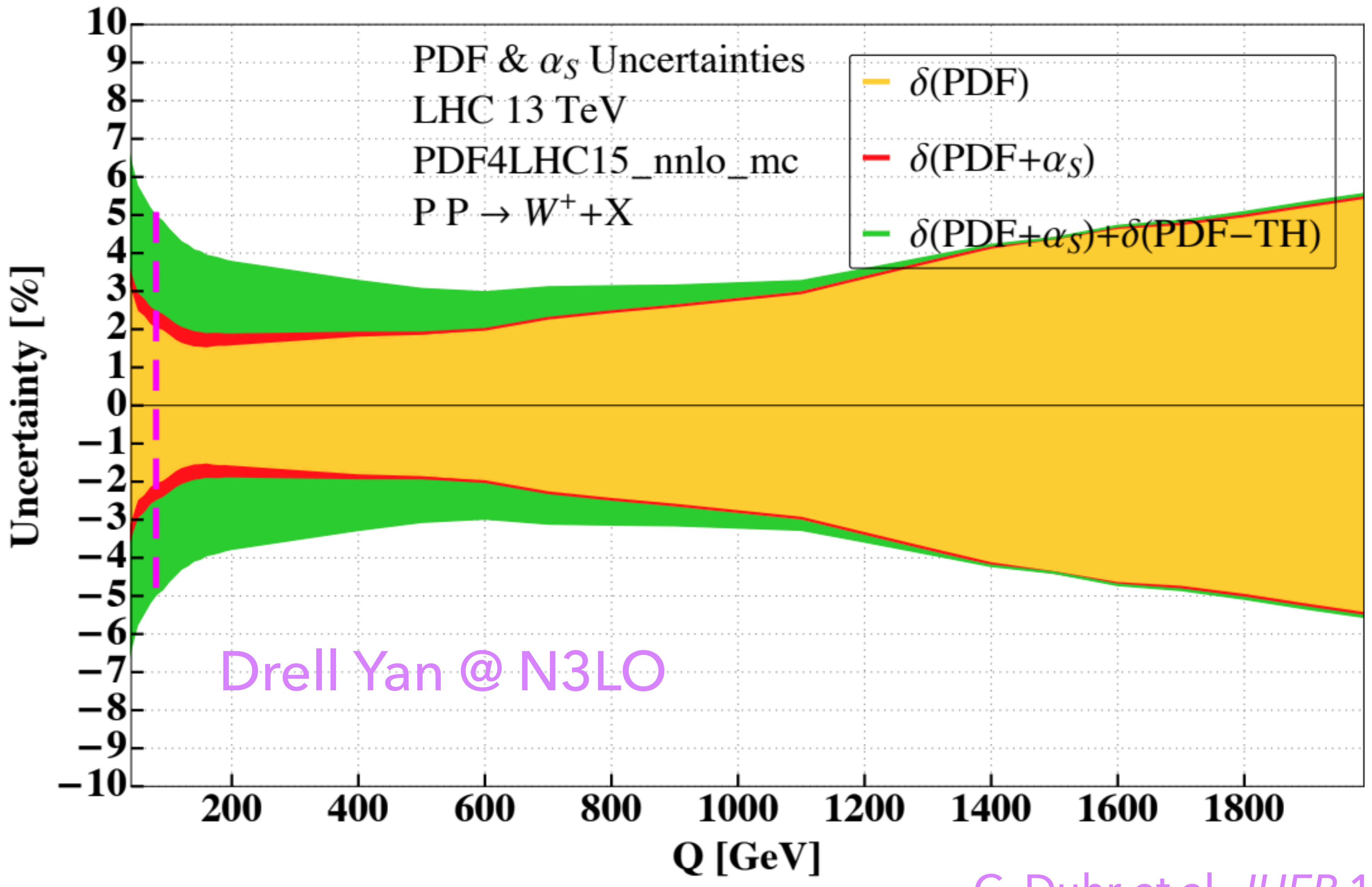
AND THEIR IMPACT ON THE PRECISION OF CURRENT THEORY CALCULATIONS

PDFS ARE CRUCIAL FOR PRECISION PHYSICS …



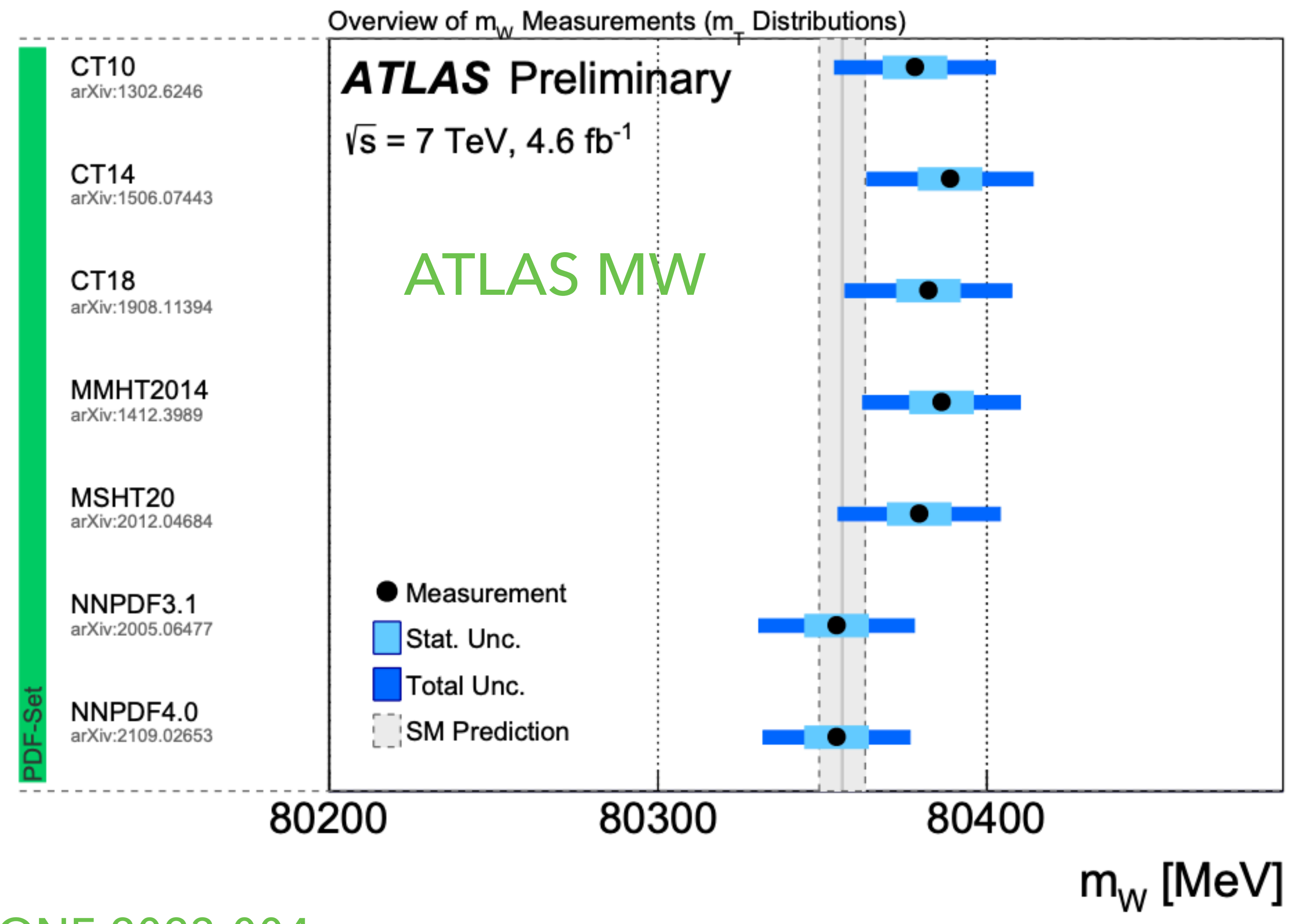
$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \ldots$$

#1: Theory uncertainty of SM predictions



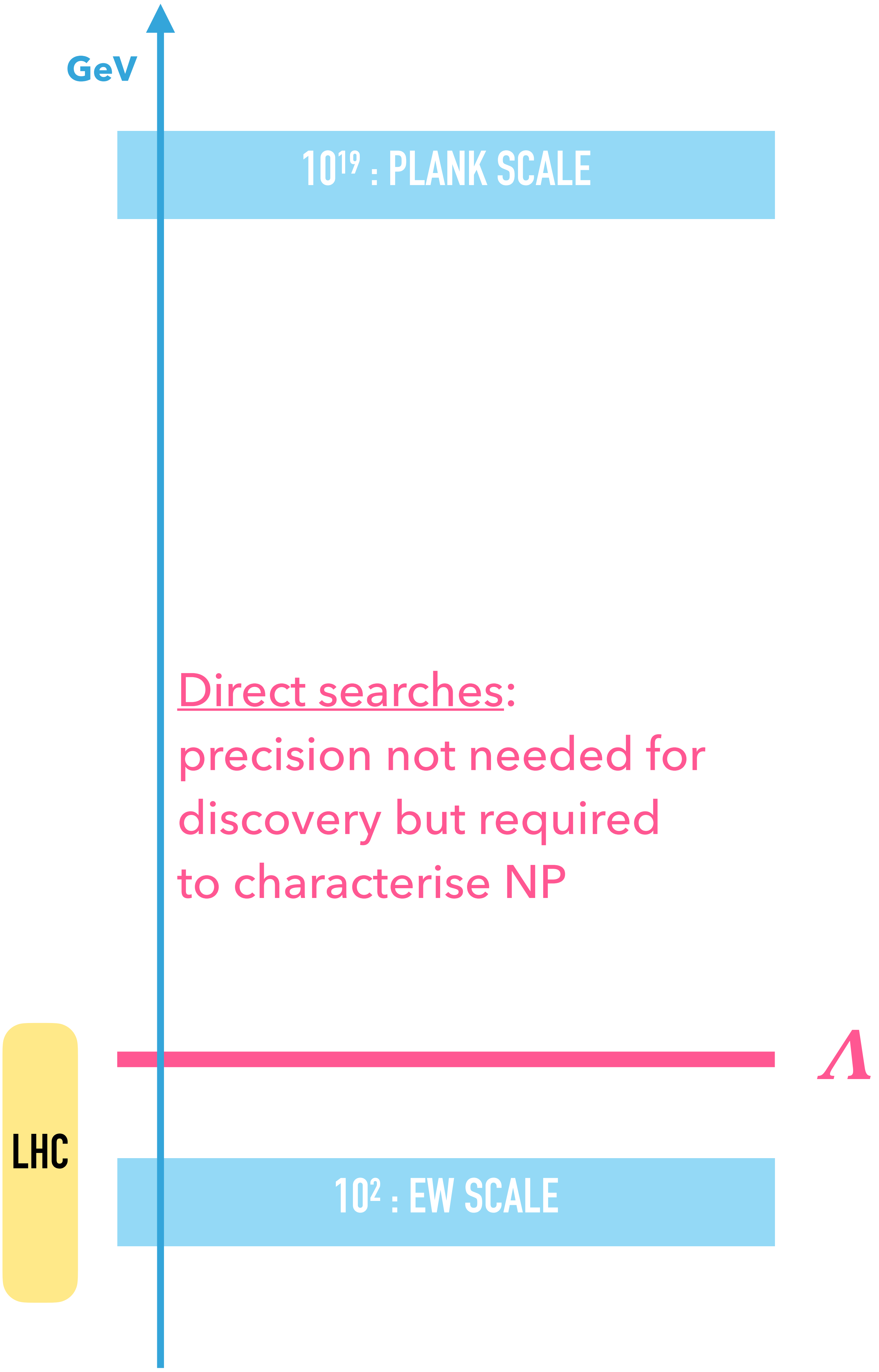
C. Duhr et al, *JHEP* 11 (2020) 143

#2: Determination of SM parameters

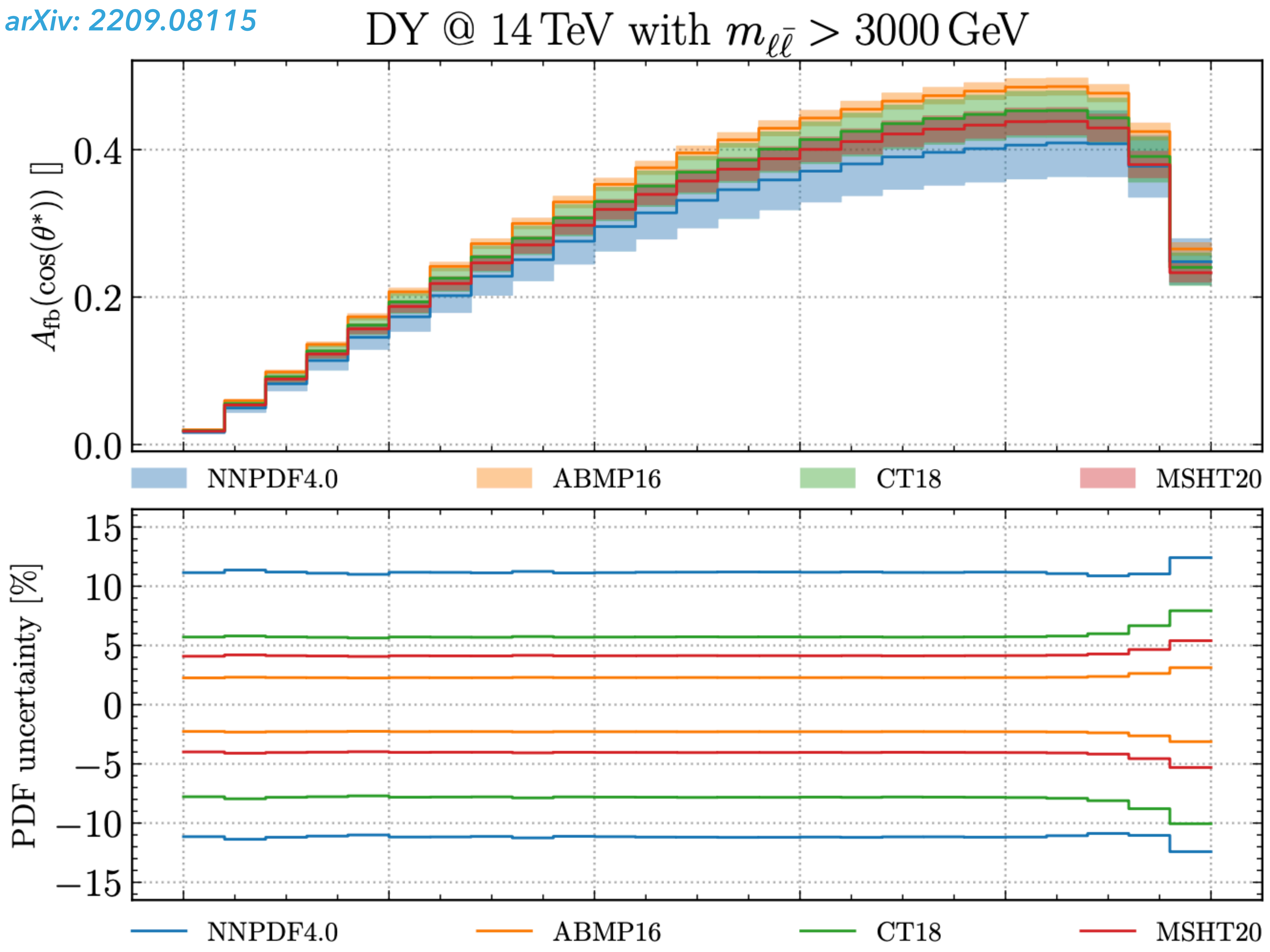


ATLAS-CONF-2023-004

. . . AND FOR NEW PHYSICS SEARCHES

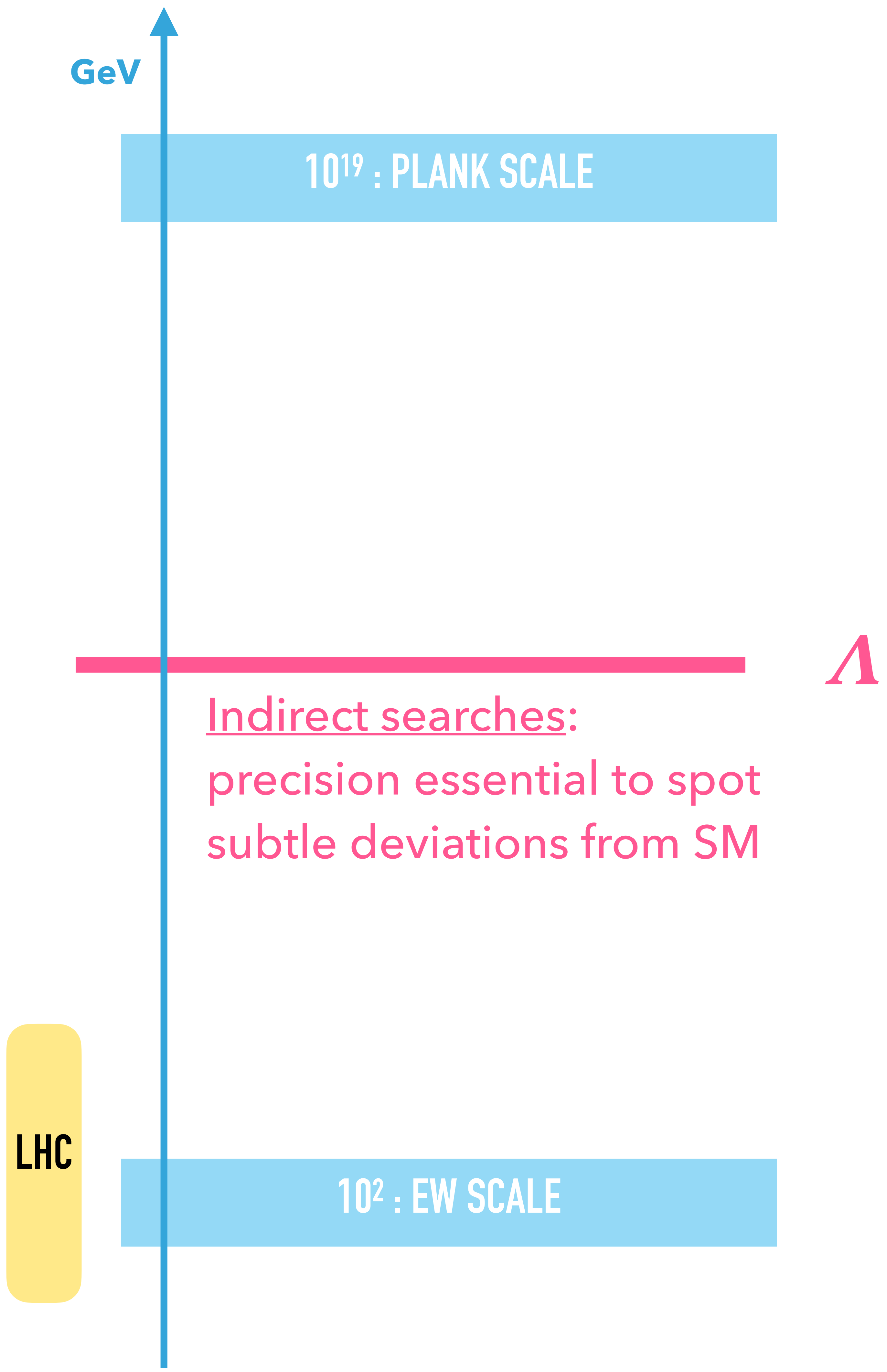


Ball et al arXiv: 2209.08115

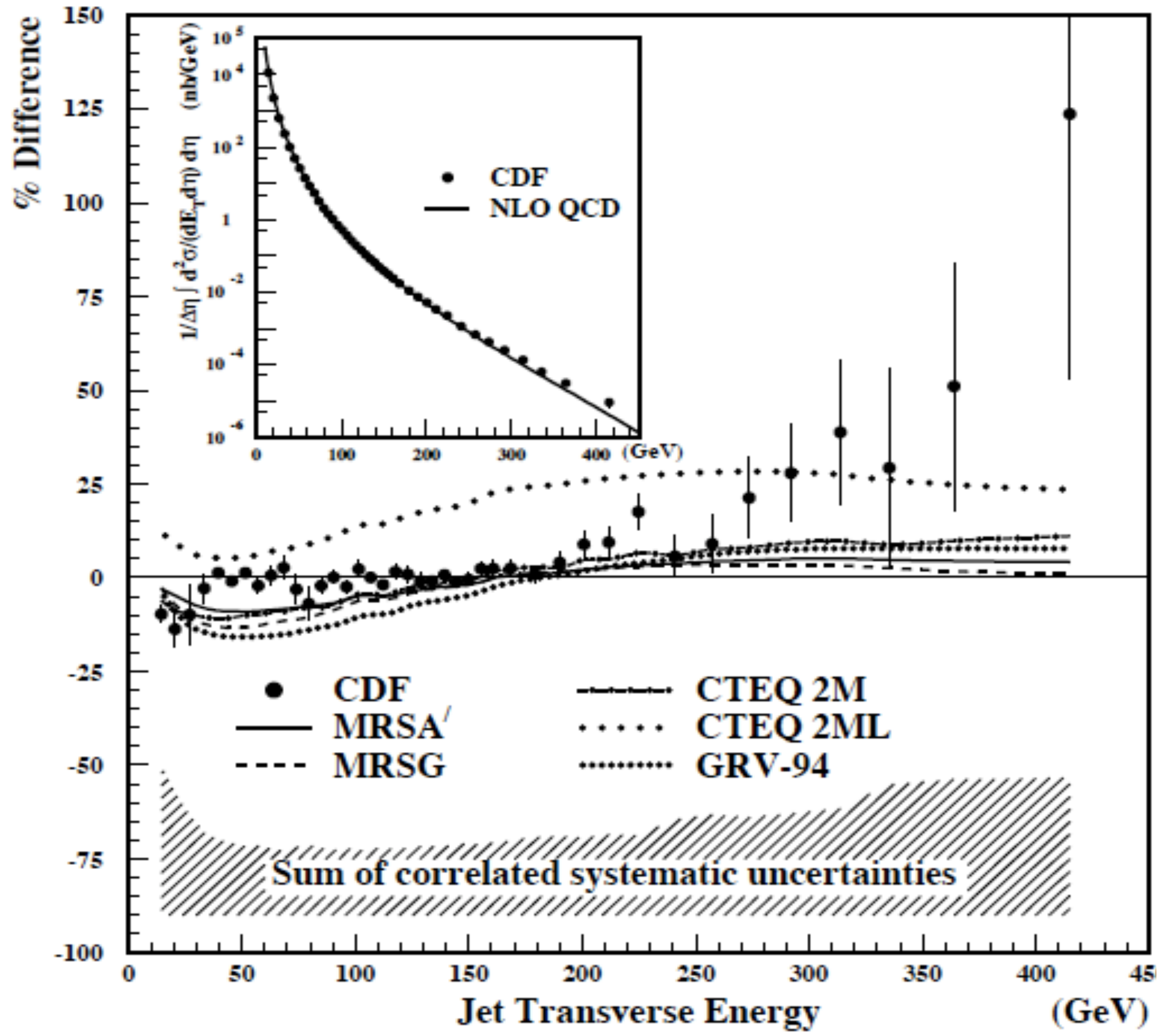


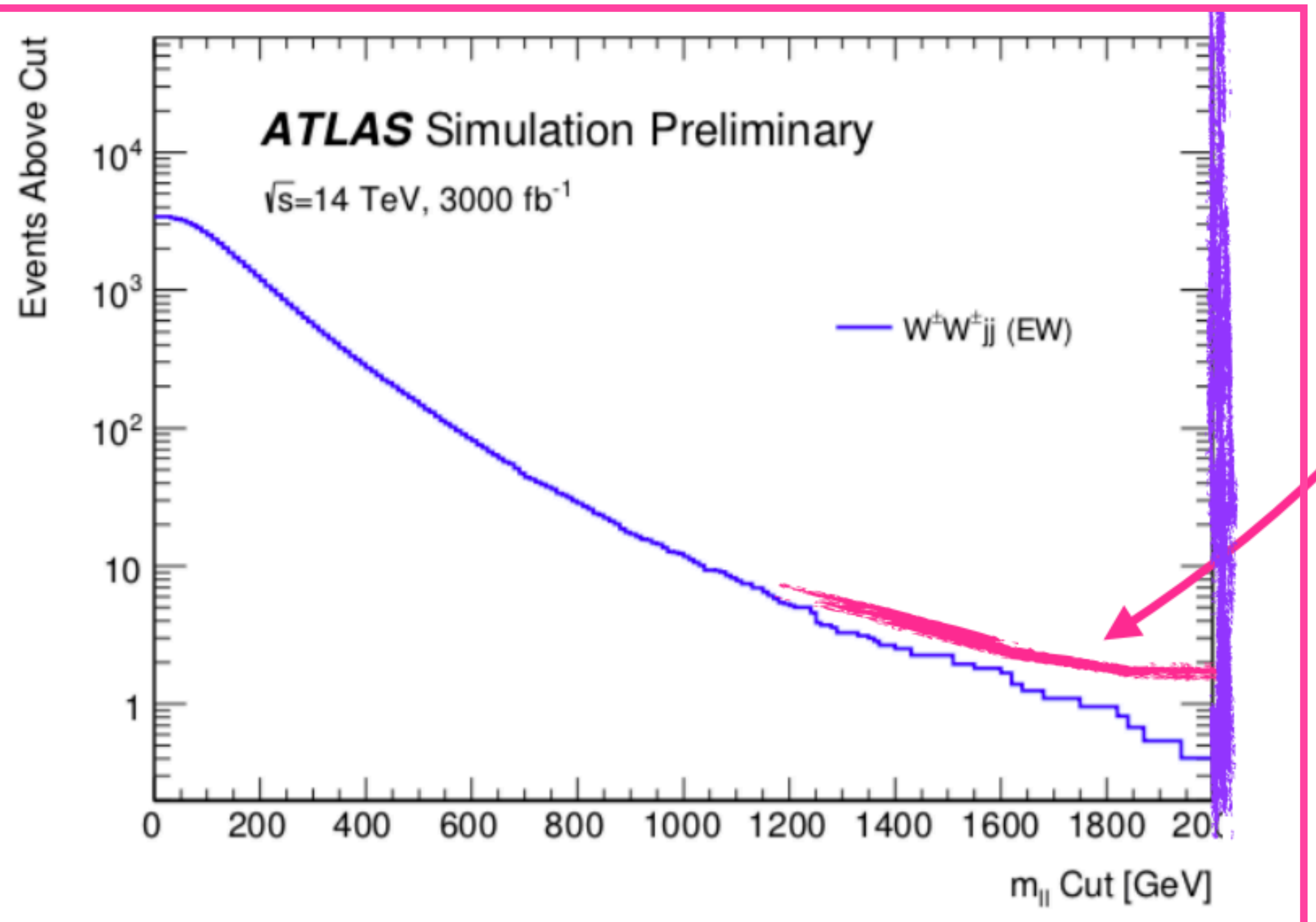
#1: Direct searches: heavy Z′ search in DY Forward-Backward asymmetry

. . . AND FOR NEW PHYSICS SEARCHES



Indirect searches: precision essential to spot subtle deviations from SM





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 (>2023)

New physics or limited understanding of proton structure?

#2: Indirect searches

OUTLINE

- Where we stand
  - ➡ Updates on PDF determination
  - ➡ The precision vs accuracy challenge
- New frontiers and challenges
  - ➡ Approximate N3LO PDFs
  - ➡ Missing Higher Order Uncertainties
  - ➡ PDF and new physics interplay
- Conclusions and outlook

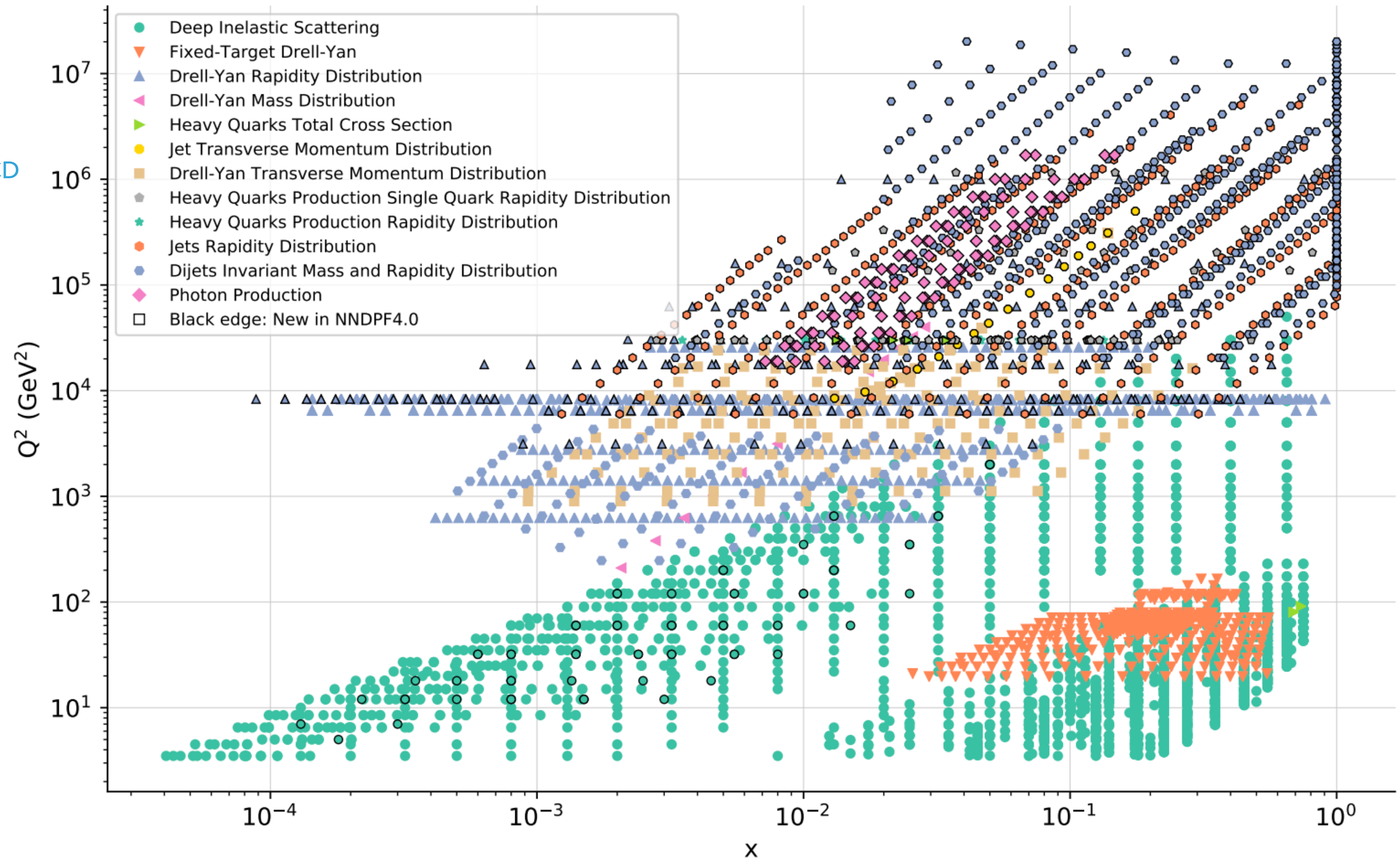
PART I: WHERE WE STAND

DETERMINATION OF PDFS

$$f_i(x, \mu)$$

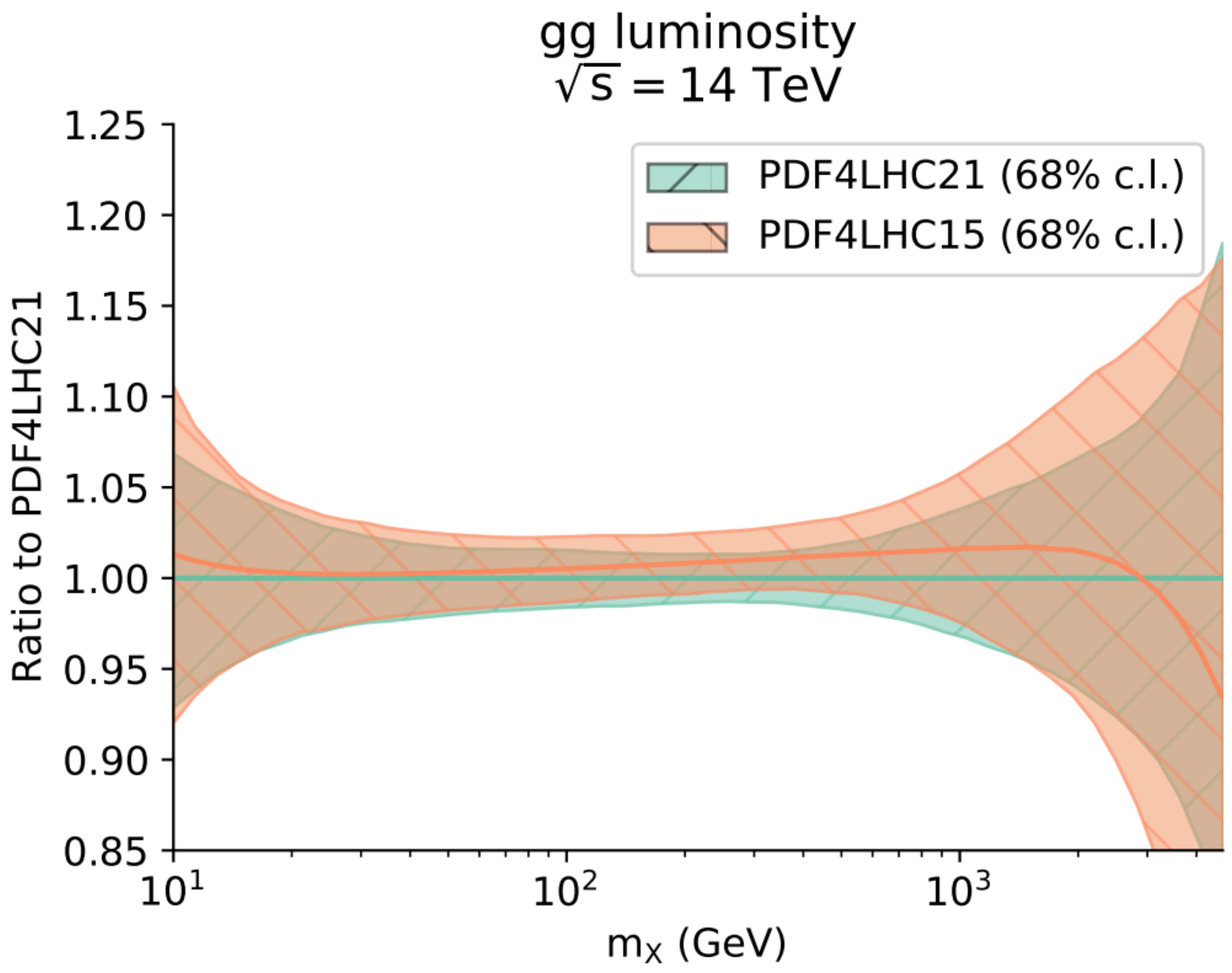
Data — Perturbative QCD

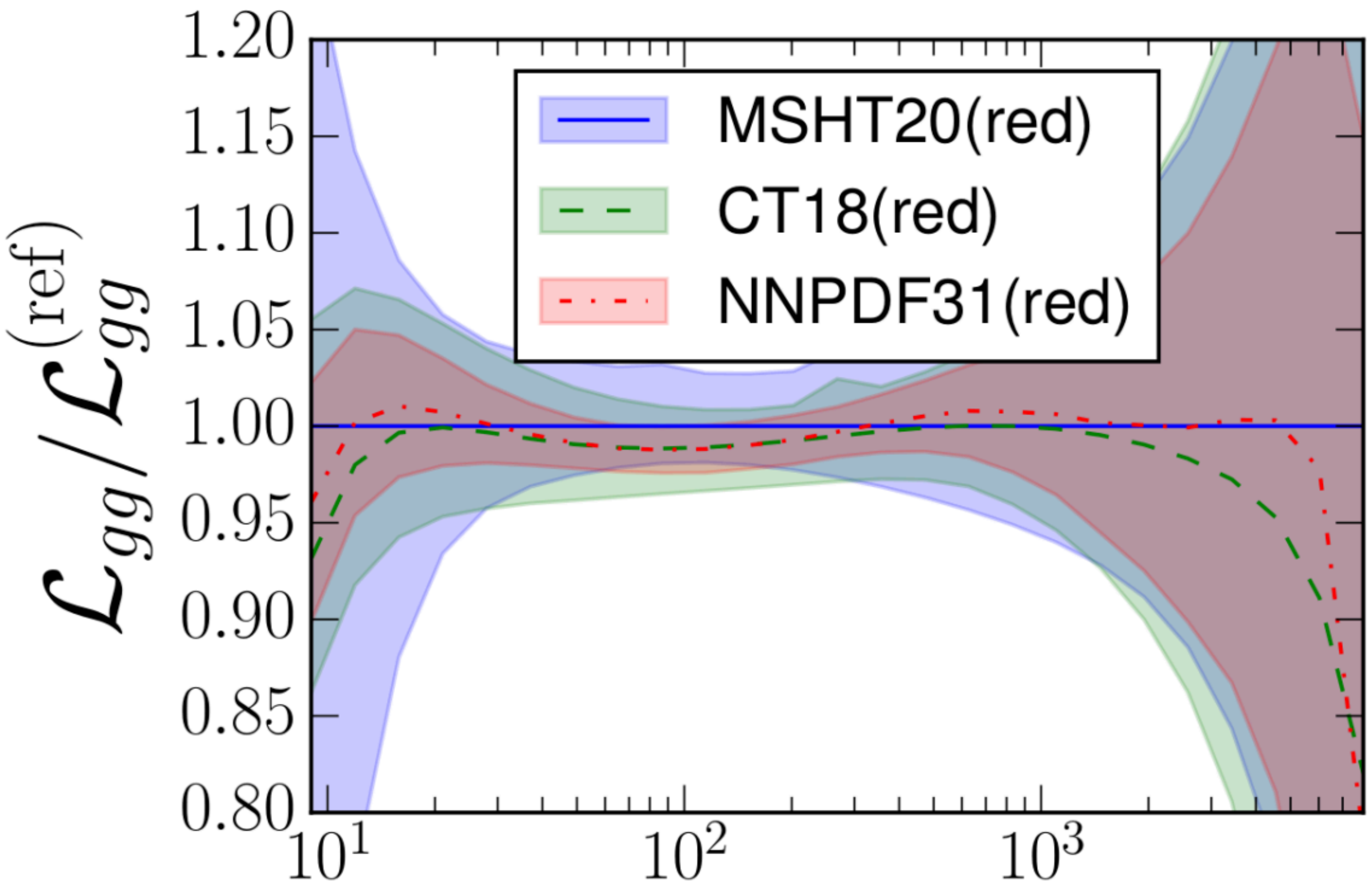
- DGLAP evolution equations fully known up to NNLO and partially at N^{3}LO
- Most theory predictions for processes in PDF fits known at NNLO (some at N^{3}LO)
- Precision of most data of order few %
- Mostly from correlated systematic uncertainties



THE PDF4LHC21 COMBINATION

PDF4LHC WG, arXiv: 2203.05506

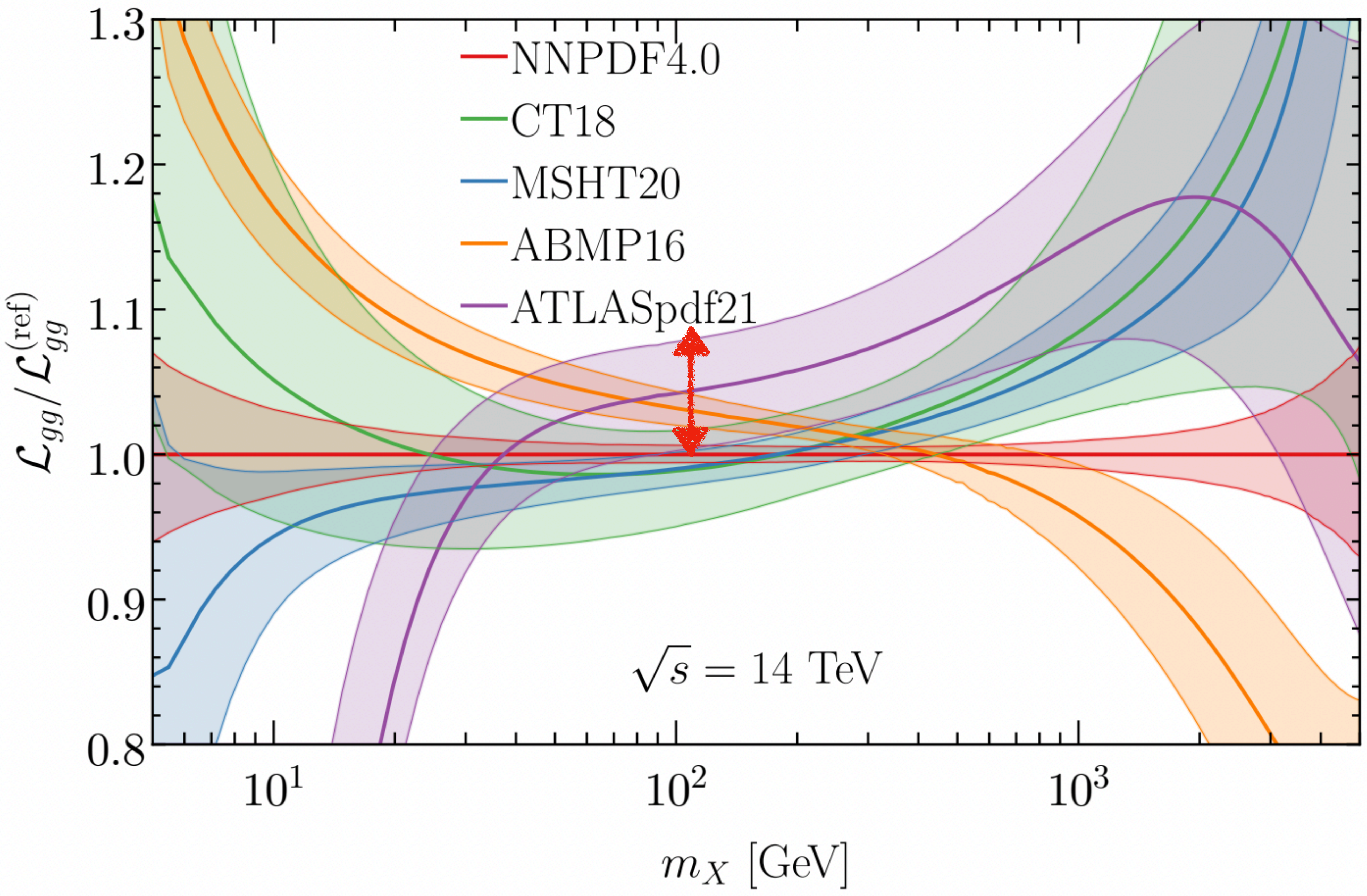


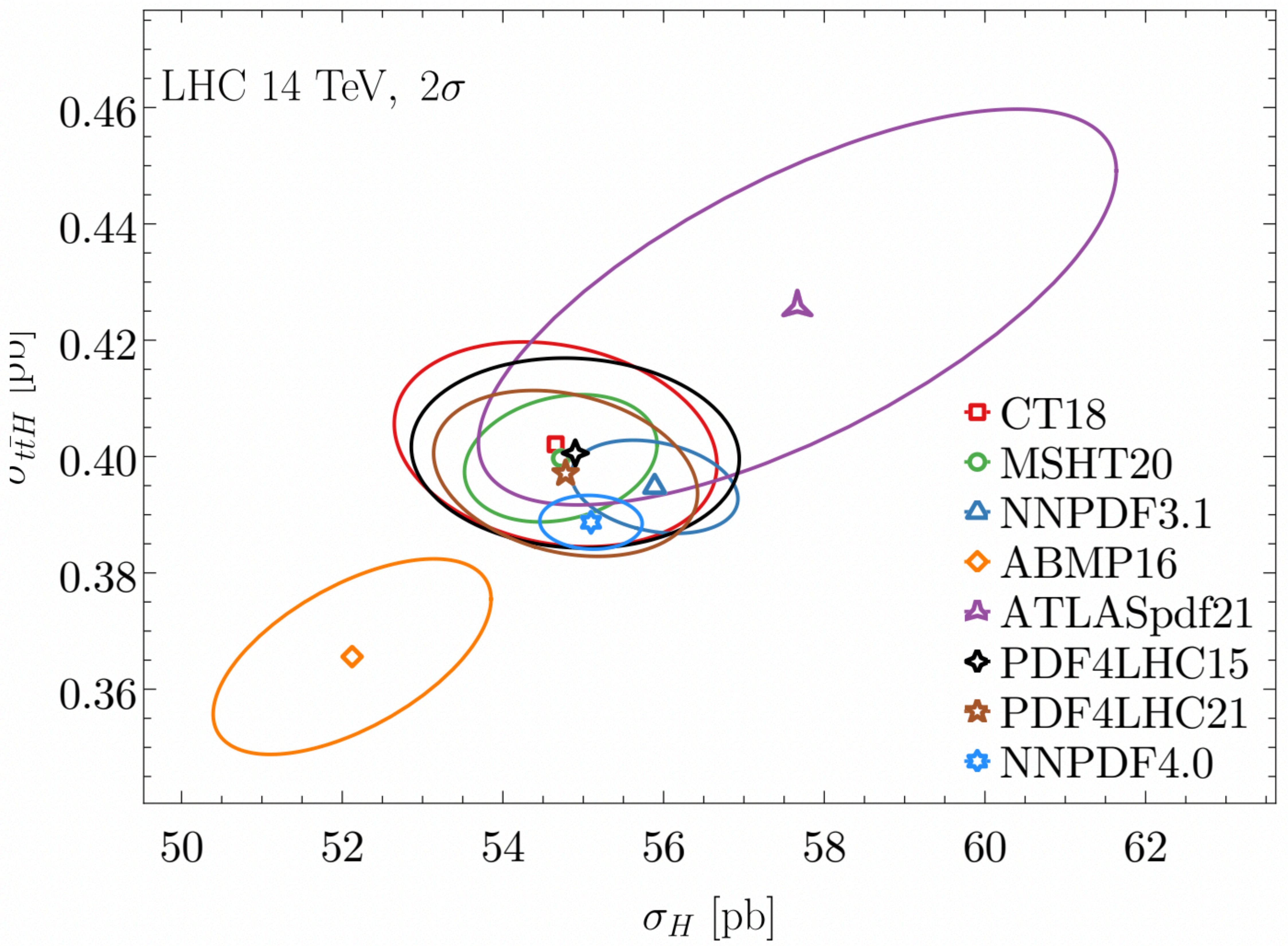


- In recent updates from global PDF fitting collaborations (NNPDF3.1, CT18, MSHT20, ABMP16) effect of LHC data driving PDF uncertainties down ➜ PDF4LHC21 combination of NNPDF31′, CT18′ and MSHT20′ smaller uncertainties than PDF4LHC15
- The increased precision of the data and their strong correlation demands methodological improvements (e. g. more flexible parametrisation that shifts PDFs outside nominal error band - MSHT) and shows some tension among (CT18 vs CT18Z)
- Benchmark among NNPDF3.1, MSHT20 and CT18: overall agreement, which improves once common dataset is used, differences in uncertainties with ΔCT18 ≳ ΔMSHT20 ≳ ΔNNPDF31
- NNPDF4.0 [arXiv:2109.02653], MSHT20aN3LO [arXiv:2207.04739] state-of-the-art post PDF4LHC21 sets

WHERE WE STAND NOW

Snowmass 2021 white paper [arXiv:2203.13923]





- NNLO sets: overall agreement around Higgs mass between global PDF sets with some shifts and differences in PDF uncertainties due to differences in methodologies and datasets included.
- NNPDF4.0 has the smallest uncertainty in the data region, towards 1% precision.
- aN3LO sets: see second part of this talk

NNPDF4.0: THE ROLE OF LHC DATA

Data set	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
CMS W asym. 7 TeV ($\mathcal{L} = 36$ pb^{-1})	✗	✗	✗	✗	✓
CMS Z 7 TeV ($\mathcal{L} = 36$ pb^{-1})	✗	✗	✗	✗	✓
CMS W electron asymmetry 7 TeV	✓	✓	✗	✓	✓
CMS W muon asymmetry 7 TeV	✓	✓	✓	✓	✗
CMS Drell-Yan 2D 7 TeV	✓	✓	✗	(✓)	✓
CMS Drell-Yan 2D 8 TeV	(✓)	✗	✗	✗	✗
CMS W rapidity 8 TeV	✓	✓	✓	✓	✓
CMS W, Z p_T 8 TeV ($\mathcal{L} = 18.4$ fb^{-1})	✗	✗	✗	(✓)	✗
CMS Z p_T 8 TeV	✓	✓	✗	(✓)	✗
CMS $W + c$ 7 TeV	✓	✓	✗	(✓)	✓
CMS $W + c$ 13 TeV	✗	✓	✗	✗	(✓)
CMS single-inclusive jets 2.76 TeV	✓	✗	✗	✗	✓
CMS single-inclusive jets 7 TeV	✓	(✓)	✗	✓	✓
CMS dijets 7 TeV	✗	✓	✗	✗	✗
CMS single-inclusive jets 8 TeV	✗	✓	✗	✓	✓
CMS 3D dijets 8 TeV	✗	(✓)	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 5 TeV	✗	✓	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	✓	✓	✗	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 8 TeV	✗	✗	✗	✗	✓
CMS $\sigma_{tt}^{\rm tot}$ 5, 7, 8, 13 TeV	✗	✗	✓	✗	✗
CMS $\sigma_{tt}^{\rm tot}$ 13 TeV	✓	✓	✓	✗	✗
CMS $t\bar{t}$ lepton+jets 8 TeV	✓	✓	✗	✗	✓
CMS $t\bar{t}$ 2D dilepton 8 TeV	✗	✓	✗	✓	✓
CMS $t\bar{t}$ lepton+jet 13 TeV	✗	✓	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	✗	✓	✗	✗	✗
CMS single top $\sigma_t + \sigma_{\bar{t}}$ 7 TeV	✗	✓	✓	✗	✗
CMS single top R_t 8, 13 TeV	✗	✓	✓	✗	✗
CMS single top 13 TeV	✗	✗	✗	✗	(✓)

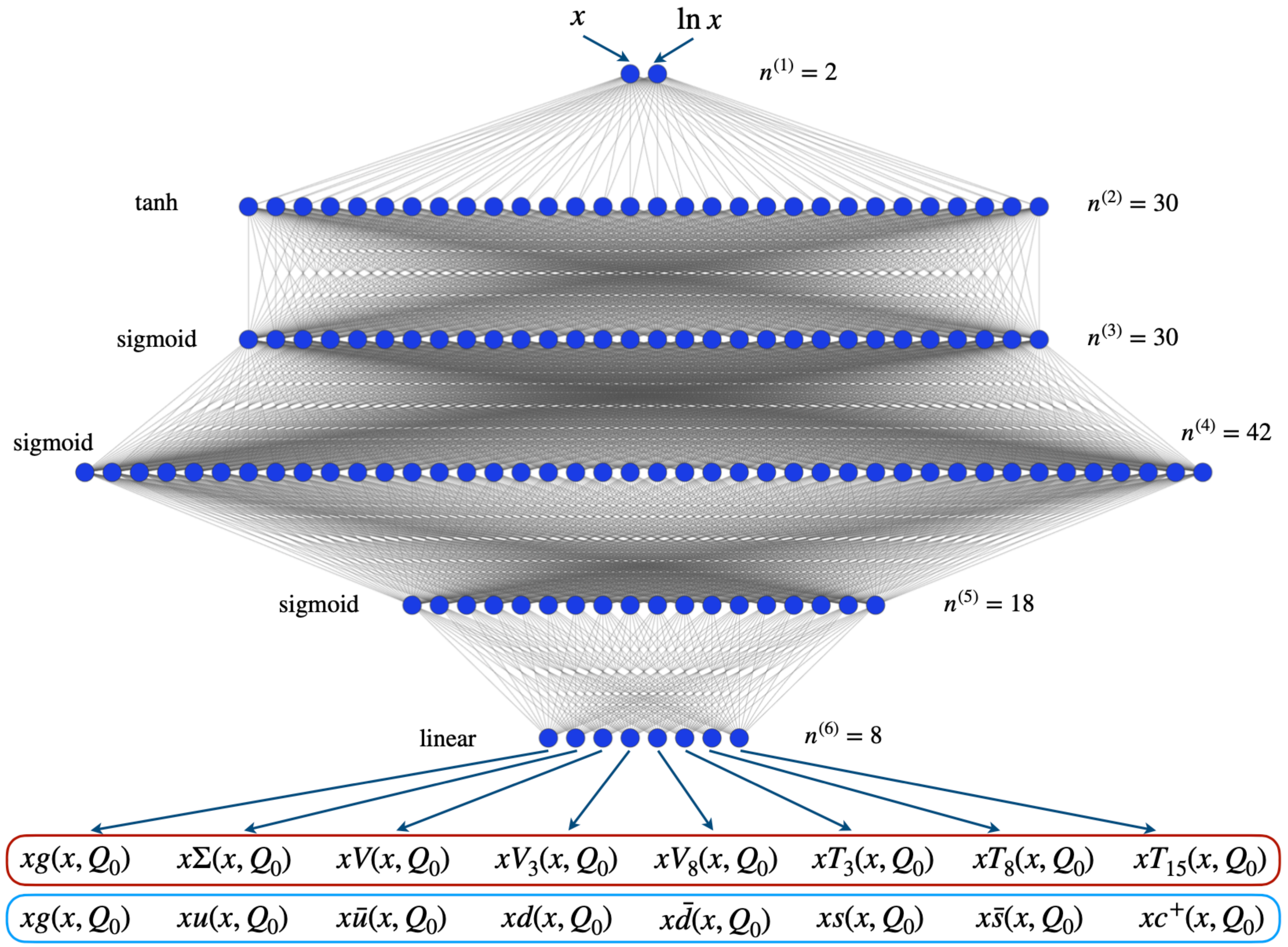
Data set	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV ($\mathcal{L} = 35$ pb^{-1})	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV ($\mathcal{L} = 4.6$ fb^{-1})	✓	✓	✗	(✓)	✓
ATLAS low-mass DY 7 TeV	✓	✓	✗	(✓)	✗
ATLAS high-mass DY 7 TeV	✓	✓	✗	(✓)	✓
ATLAS W 8 TeV	✗	(✓)	✗	✗	✓
ATLAS DY 2D 8 TeV	✗	✓	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	✗	✓	✗	(✓)	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	✗	✓	✓	✗	✗
ATLAS W+jet 8 TeV	✗	✓	✗	✗	✓
ATLAS Z p_T 7 TeV	(✓)	✗	✗	(✓)	✗
ATLAS Z p_T 8 TeV	✓	✓	✗	✓	✓
ATLAS $W + c$ 7 TeV	✗	✓	✗	(✓)	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	✓	✓	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 7, 8 TeV	✗	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 13 TeV ($\mathcal{L} = 3.2$ fb^{-1})	✓	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ 13 TeV ($\mathcal{L} = 139$ fb^{-1})	✗	✓	✗	✗	✗
ATLAS $\sigma_{tt}^{\rm tot}$ and Z ratios	✗	✗	✗	✗	(✓)
ATLAS $t\bar{t}$ lepton+jets 8 TeV	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	✗	✓	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	✓	(✓)	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	✗	✓	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	✗	✓	✗	✗	✗
ATLAS direct photon production 8 TeV	✗	(✓)	✗	✗	✗
ATLAS direct photon production 13 TeV	✗	✓	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	✗	✓	✓	✗	✗
ATLAS single top diff. 7 TeV	✗	✓	✗	✗	✗
ATLAS single top diff. 8 TeV	✗	✓	✗	✗	✗

- NNPDF4.0 based on larger set of data from LHC Run I and Run II
- Open-source public code **[arXiv:2109.02671]**
- O(4500) data points and first time inclusion of di-jets preferred over inclusive jets based on perturbative stability **[Khalek et al, 2005.11327]**

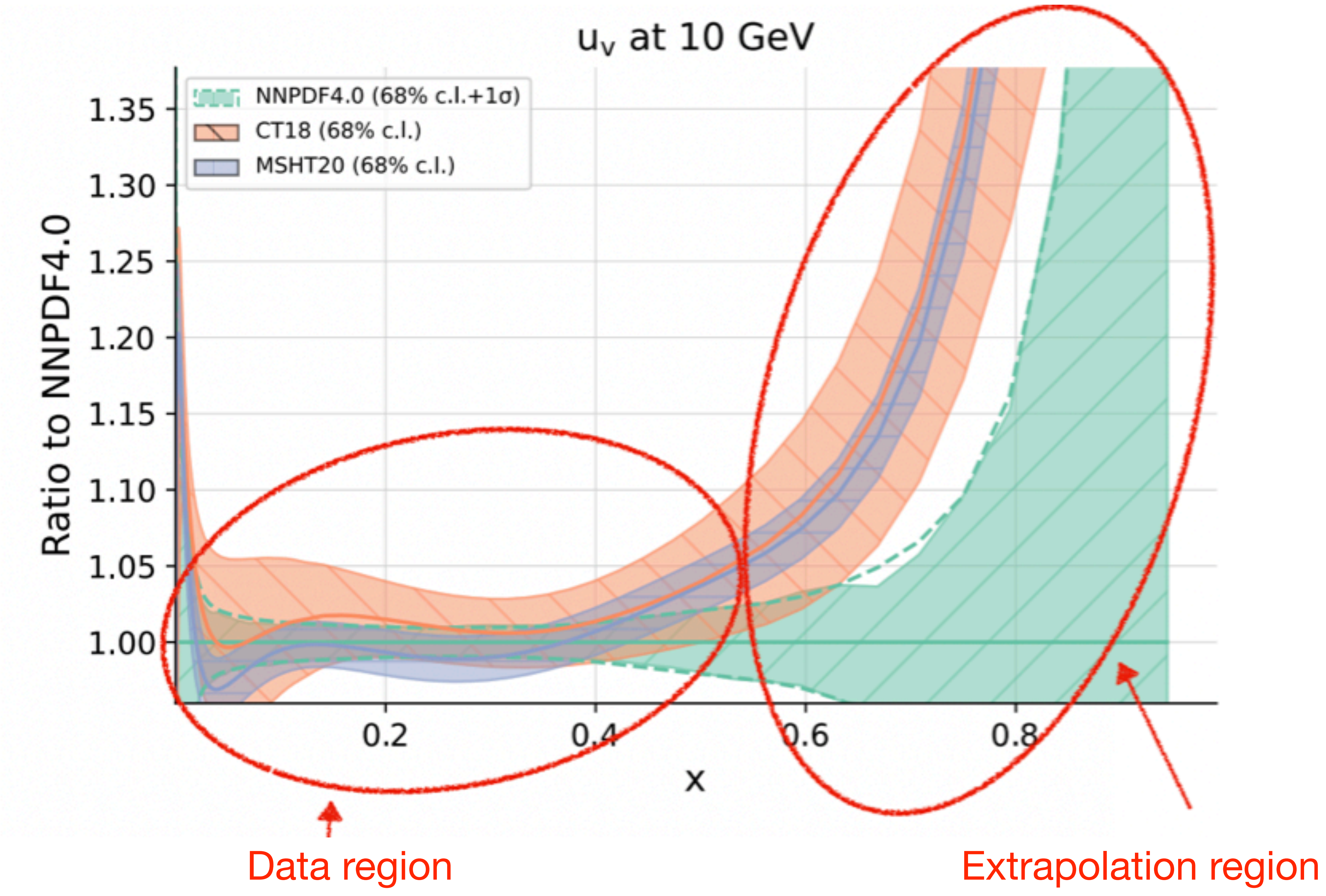
NNPDF4.0: THE ROLE OF METHODOLOGY

- Single neural network to parametrise 8 independent PDF combinations (g, u, d, s, u~, d~, s~, c=c~)
- Optimisation strategy based on gradient descent rather than genetic algorithm (NNPDF3.1)
- Hyper-optimised methodology: scan of the hyper parameter space to find optimal minimisation settings (optimiser, initialiser, stopping patience, number of layers, learning rate, epochs, activation function) by minimising χ^2_{val}

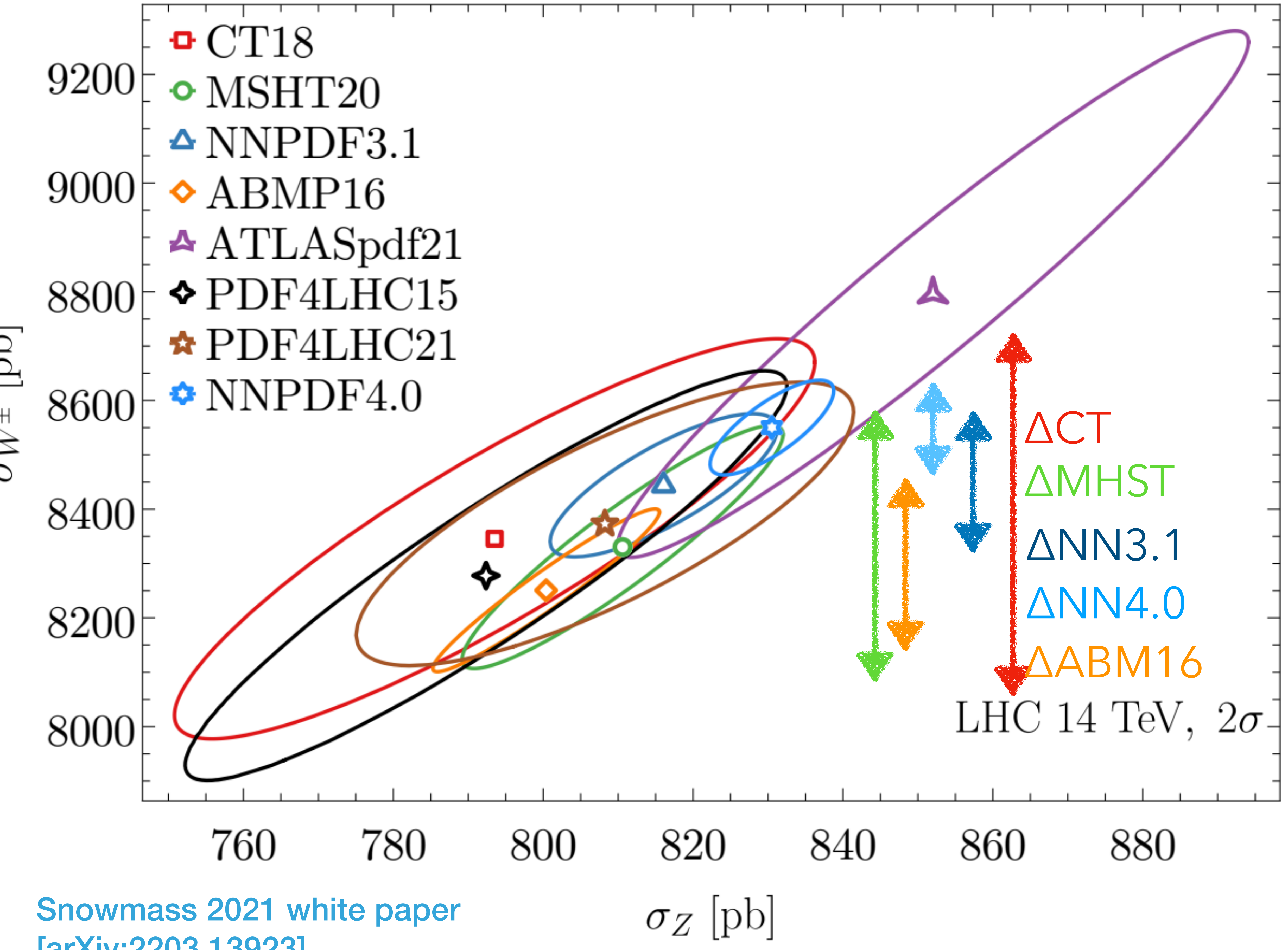
[**Carrazza et al, arXiv:1907.05075**]



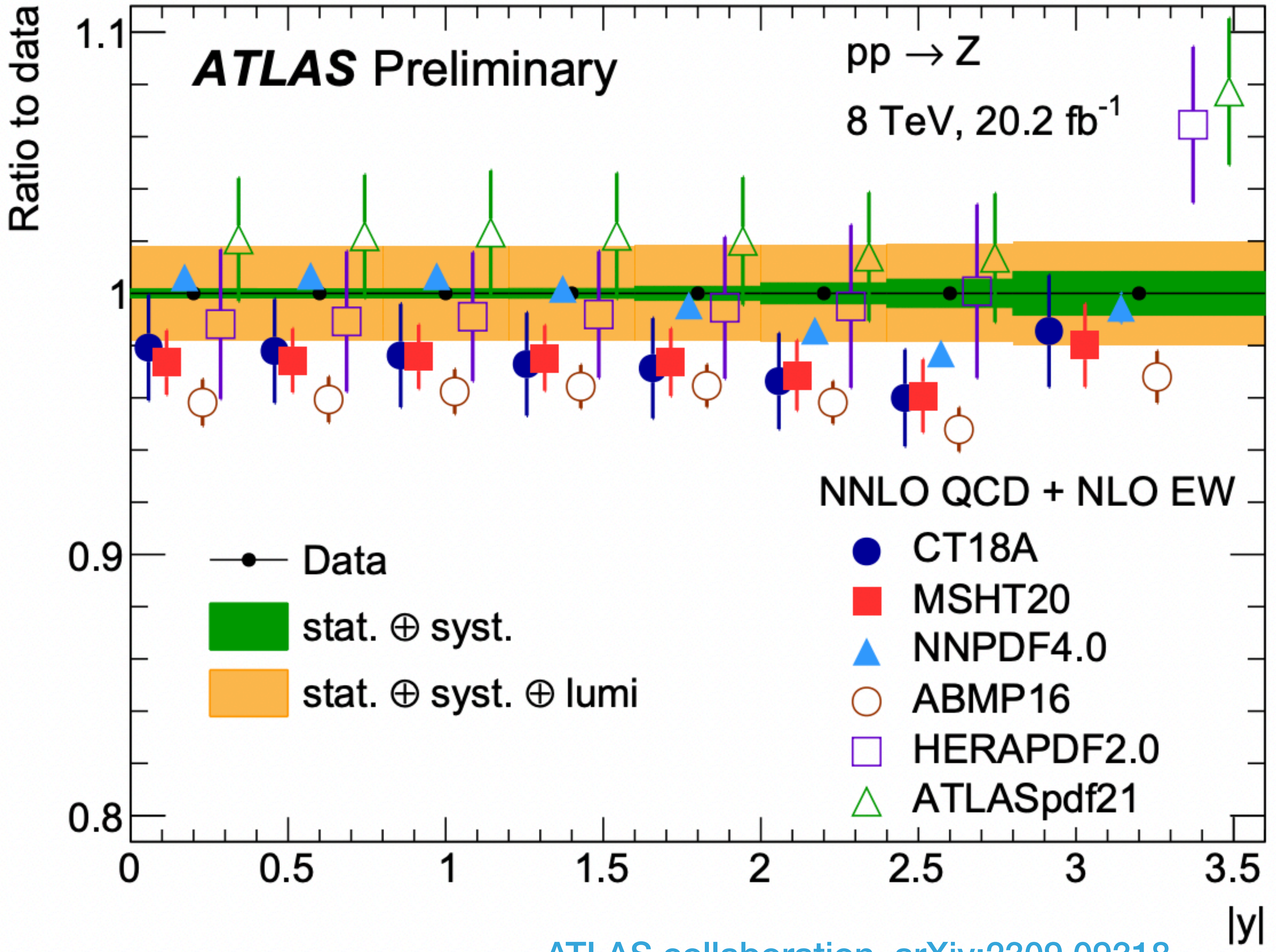
Thanks to superior methodology NN40 displays smaller uncertainty than NN3.1, O(500) extra LHC data further decrease uncertainties and shift PDFs.



PHENOMENOLOGICAL IMPLICATIONS



Snowmass 2021 white paper [arXiv:2203.13923]



ATLAS collaboration, arXiv:2309.09318

- Extremely precise predictions and small PDF uncertainties for electroweak observables: implications for extraction of SM precision parameters, like αs from Z pT distribution and Mw from W mT distributions

PHENOMENOLOGICAL IMPLICATIONS

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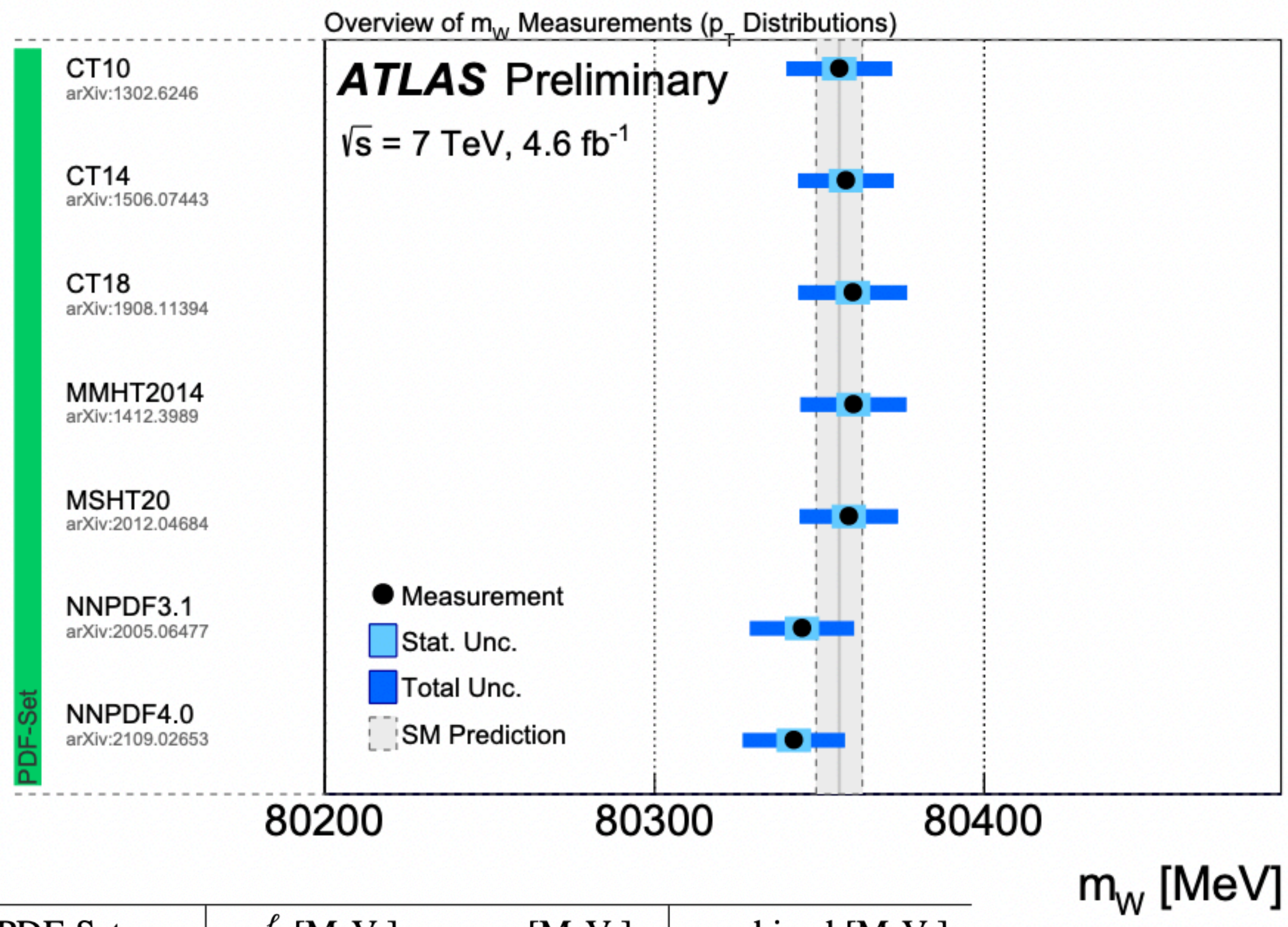
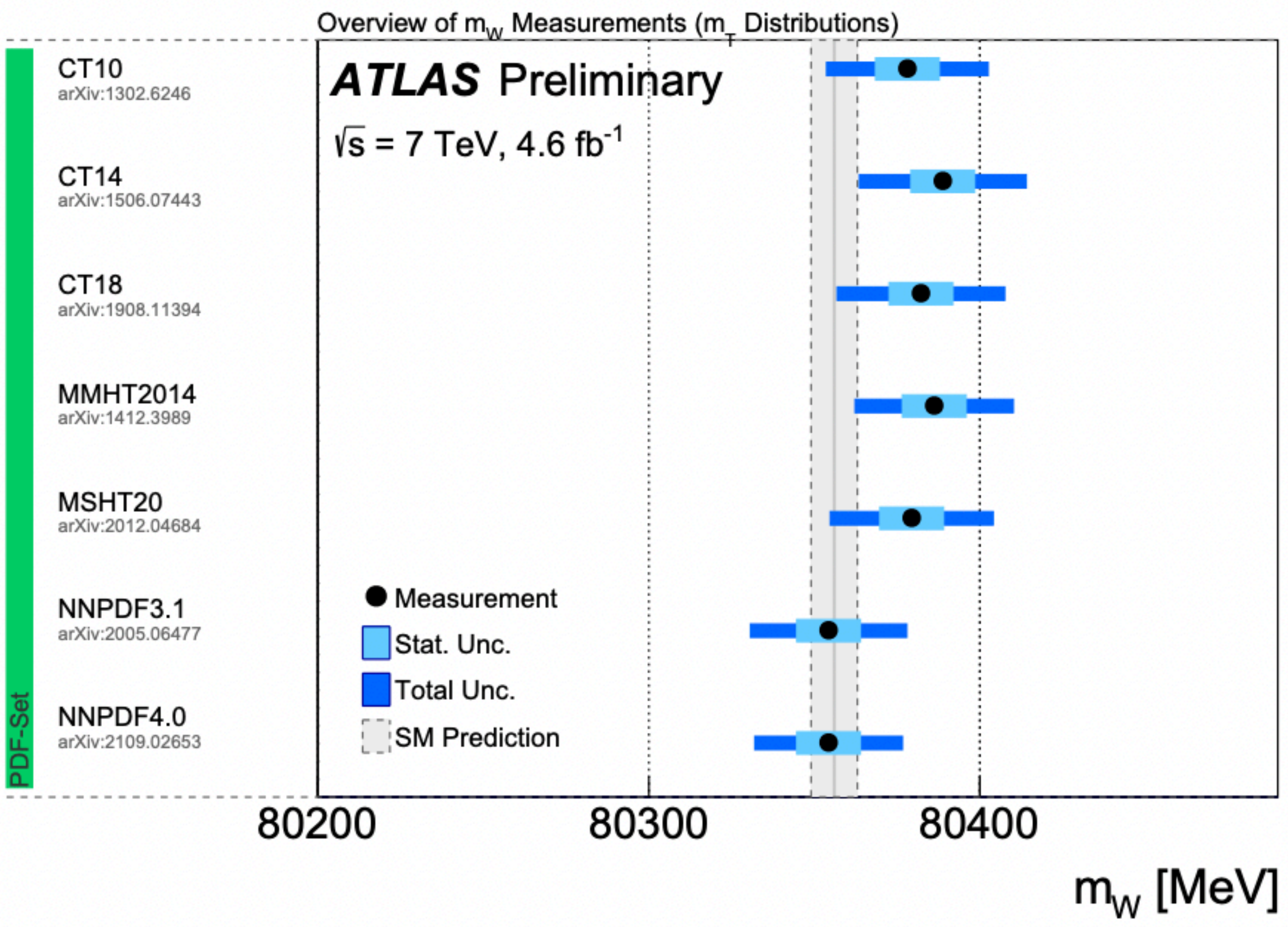


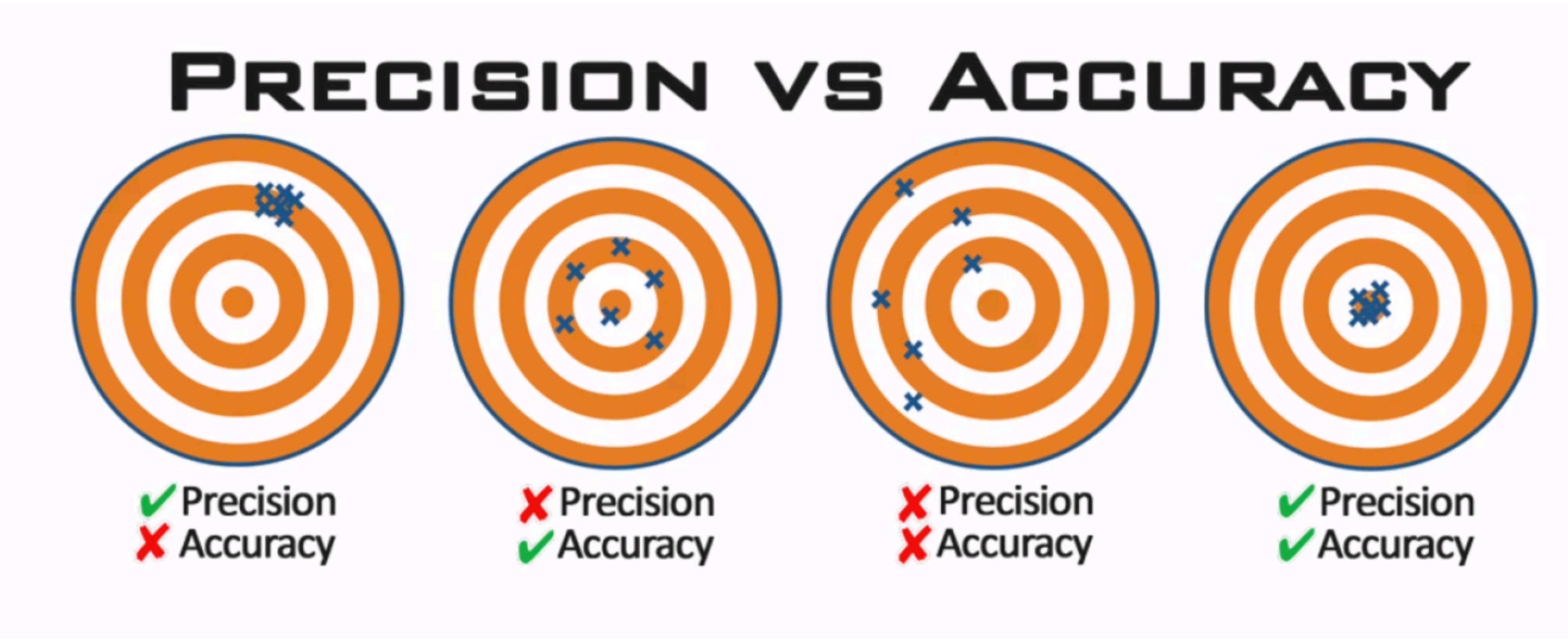


PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

- Different PDF uncertainties yield slightly different total uncertainties.
- Differences of ~18 MeV between central values obtained with NNPDF4.0 and CT18 comparable (larger) than measurement uncertainty
- Important to confirm results and understand the reason behind the differences

THE PRECISION VERSUS ACCURACY CHALLENGE

- Inconsistency or tension in data
- Data-driven parametrisation change
- Changes in fitting methodology
- Theoretical framework
  - ➡ Missing higher order uncertainties
  - ➡ Other corrections (nuclear, non-perturbative effects…)
  - ➡ BSM effects

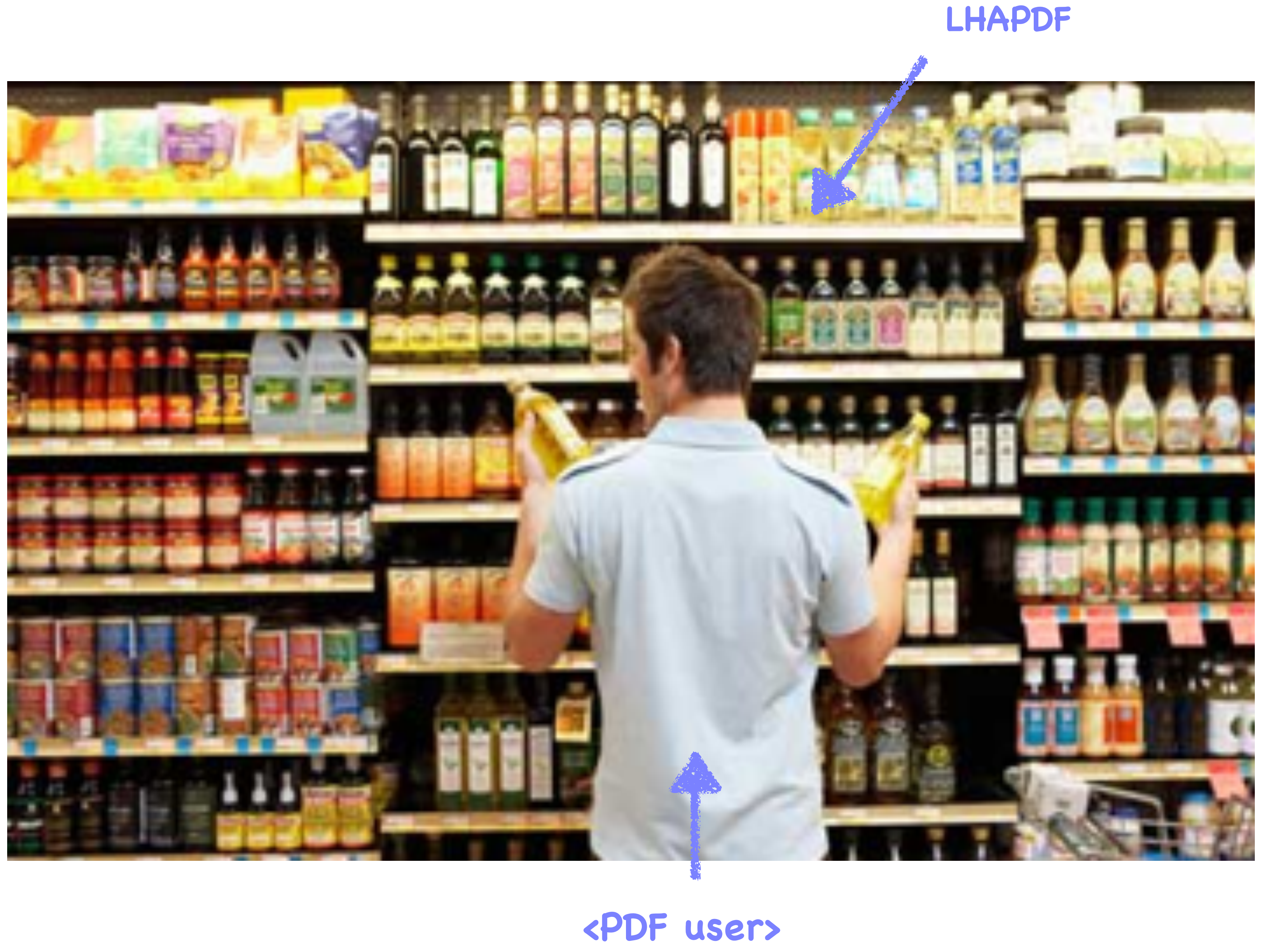


Methodology robustness

- Closure tests for data region: imagine we knew the law of Nature, is our fitting methodology able to reproduce it? Is the uncertainty faithful? Statistical validation of PDF uncertainties via closure tests
  [Del Debbio et al, Eur.Phys.J.C 82 (2022) 4, 330]
  [Barontini et al - in progress]

Generalisation/ extrapolation

- Future tests: how well do PDF describe data that are not included in the fit (either in data or extrapolation region)? Help to discriminate among PDF sets
  [J. Cruz-Martinez et al, Acta Phys.Polon.B 52 (2021) 243]
  [NNPDF collaboration - in progress]



PART II: NEW FRONTIERS

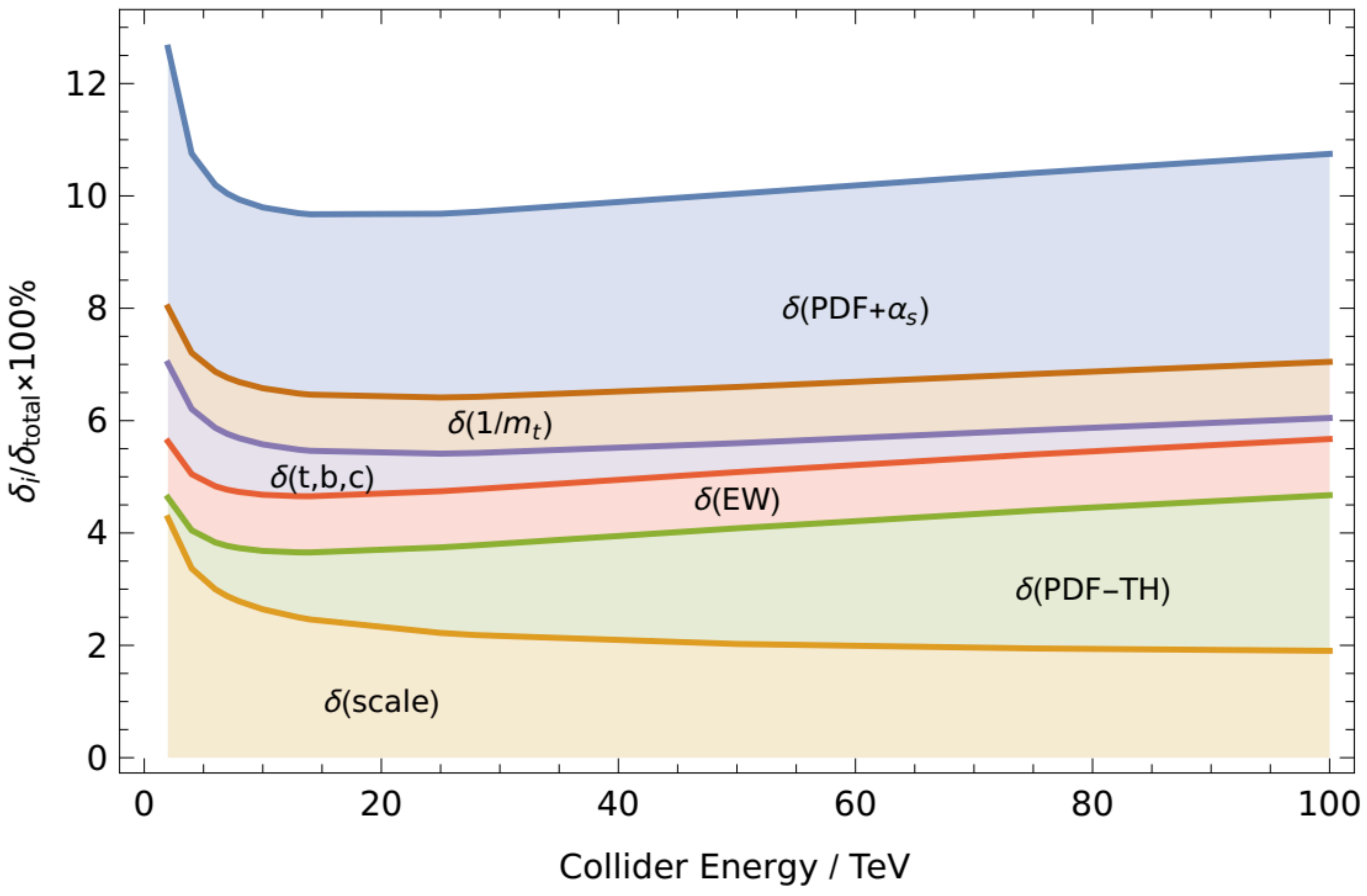
THEORETICAL PREDICTIONS IN PDF FITS

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- Standard global PDF fits based on fixed-order NNLO QCD calculations (using fast interpolation grid for NLO predictions accompanied by local K-factors for NNLO). PDF uncertainty reflects experimental uncertainty.
- N³LO is now the precision frontier for partonic cross sections (huge progress in N³LO splitting functions) [S. Moch's talk]
- Mismatch between perturbative order of partonic cross section and PDFs significant source of uncertainty

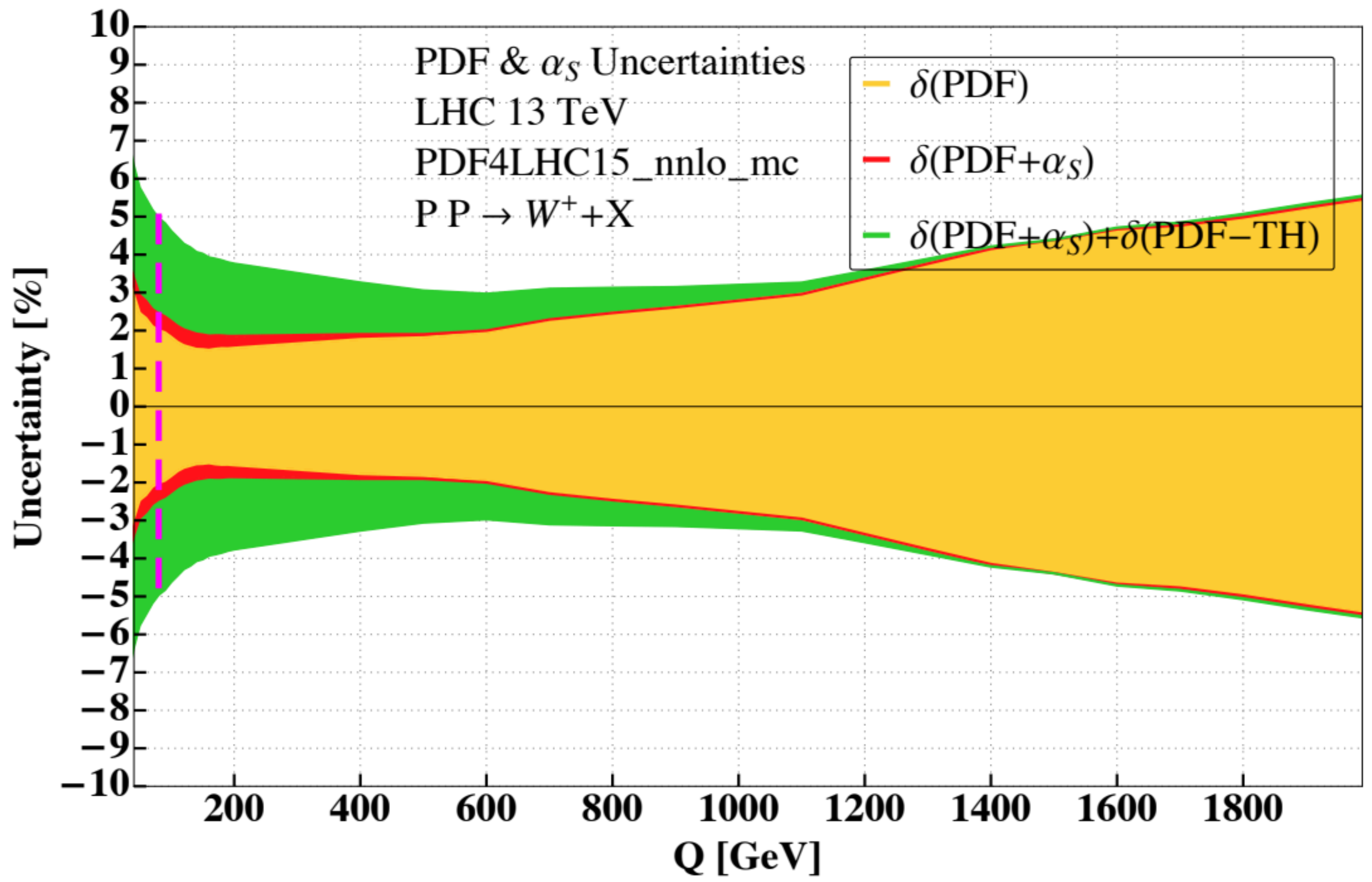
$$\delta(PDF - TH) = \frac{1}{2} \left| \frac{\sigma^{(2)}_{\mathrm{NNLO-PDFs}} - \sigma^{(2)}_{\mathrm{NLO-PDFs}}}{\sigma^{(2)}_{\mathrm{NNLO-PDFs}}} \right|$$

Gluon-gluon fusion into Higgs



M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

Drell-Yan



C. Duhr et al, JHEP 11 (2020) 143

#1 - APPROXIMATE N3LO PDFS

➡ Several ingredients required to perform N^{3}LO PDF fits, many available some missing [S. Moch's talk]
➡ Only publicly available aN^{3}LO PDF determination is from the MSHT collaboration [McGowan et al, arXiv:2207.04739]
➡ NNPDF has presented preliminary aN^{3}LO results and paper is to appear soon

MSHT

- All available theory input at the time of publication included (impact of new ingredients being explored)
- Incomplete N3LO terms added as variation in the prior and estimated by fitting nuisance parameters to the data (hence **posterior determined by fitting data**)
- No MHOU associated with NNLO contributions

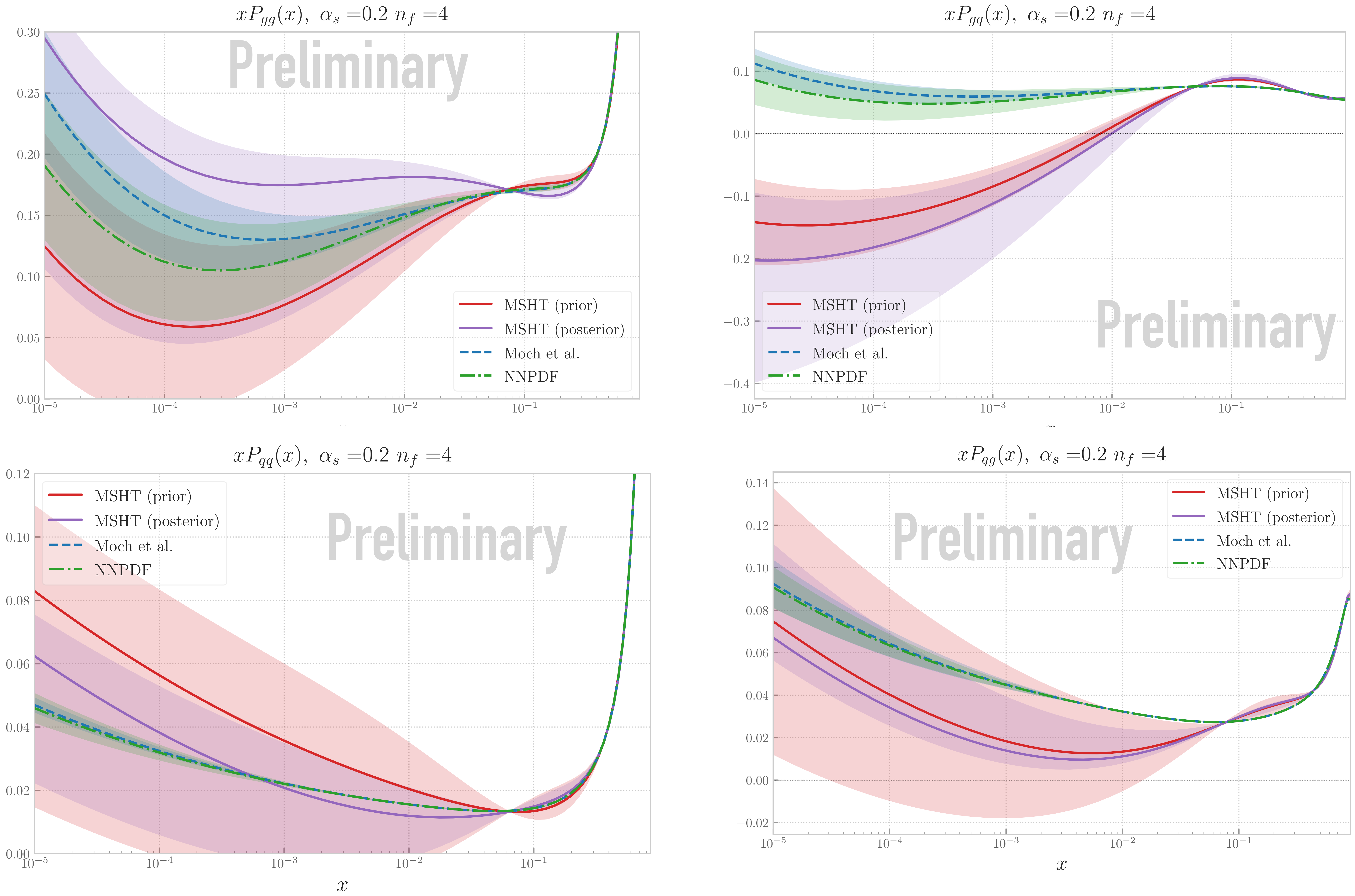
NNPDF

- More theory inputs published in between and included, in particular 6(1) extra momentum for P_{qg}, P_{qq} (P_{gq}, P_{gg}), some terms in the large n_f limit, sub-leading small-x and large-x terms.
- **Only theory inputs** and their variations added to an additional theory covariance matrix associated with incomplete missing higher orders (IHOU)
- MHOU associated with NNLO included via theory covariance matrix

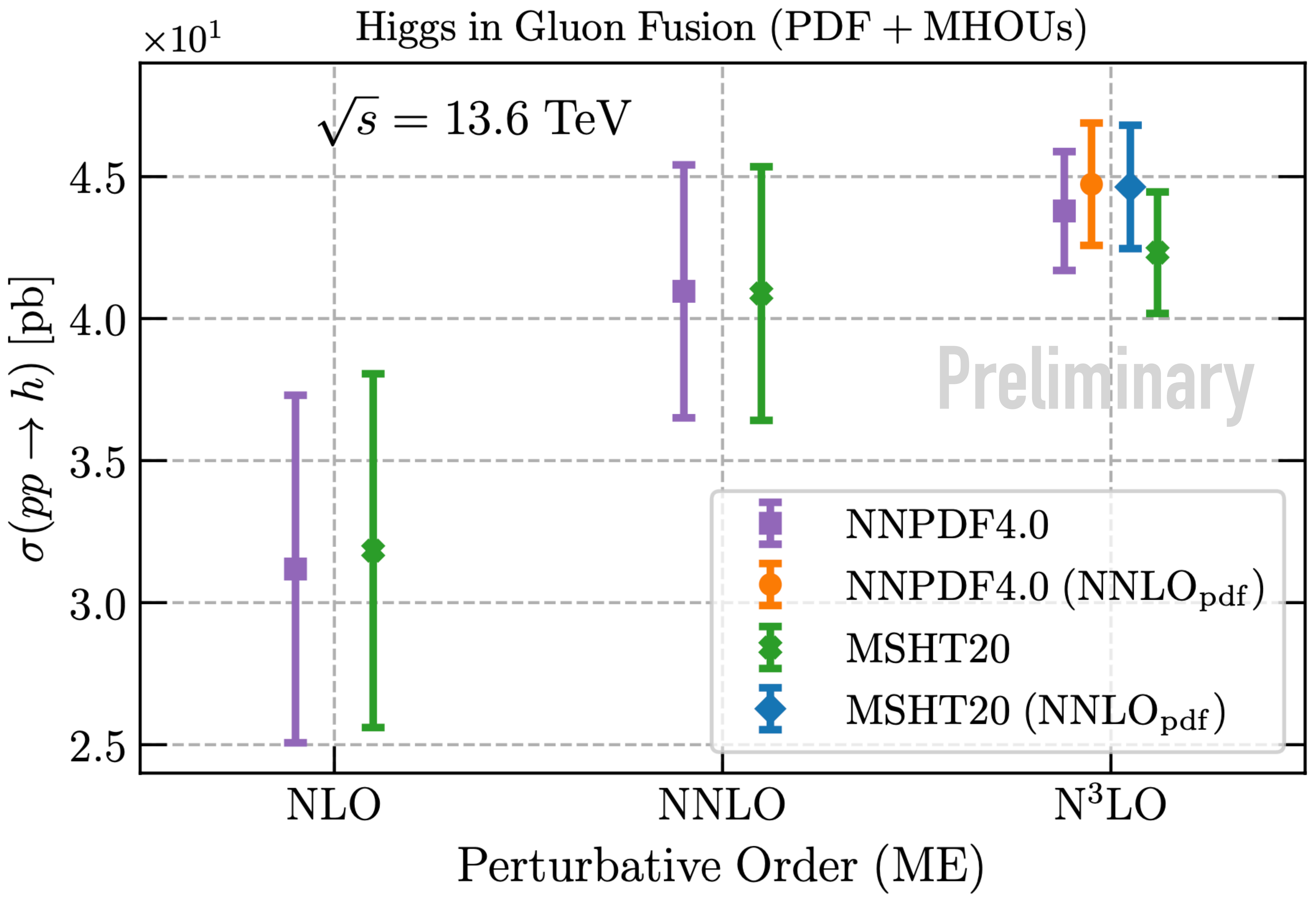
#1 – APPROXIMATE N3LO PDFS

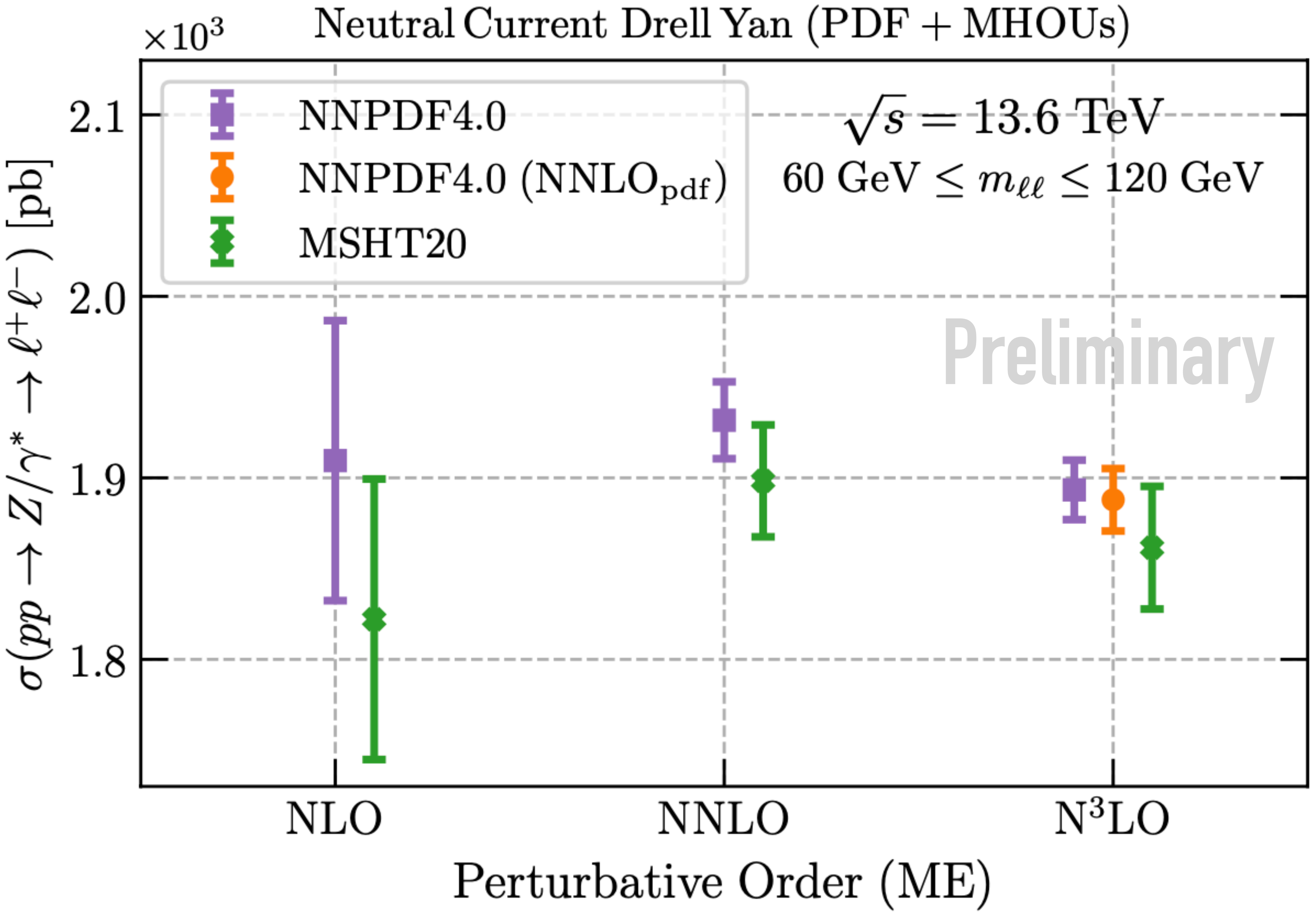
MSHT prior = pre-fit variation
MSHT posterior = MSHTaN3LO
NNPDF = NNPDF40aN3LO
Moch at al = theory papers

- Different known ingredients included and different ways of parametrising sub-leading contributions produces different candidates (IHOU)
- Benchmarking exercise started before Summer in Les Houches to check the impact of the aN3LO splitting functions
- Write-up in preparation for Les Houches proceedings



#1 – APPROXIMATE N3LO PDFS





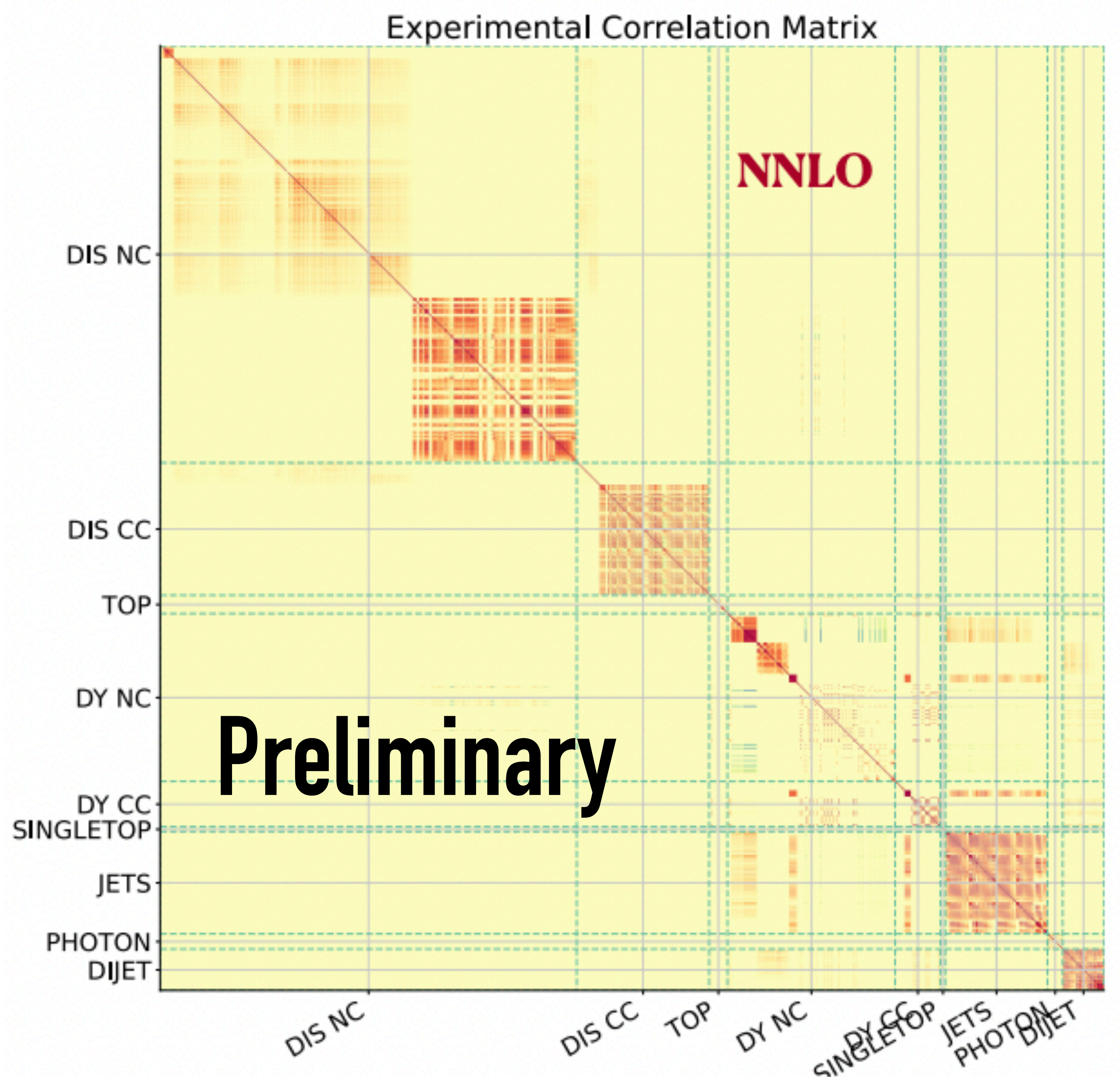
#2 – MISSING HIGHER ORDER UNCERTAINTIES IN PDF FITS

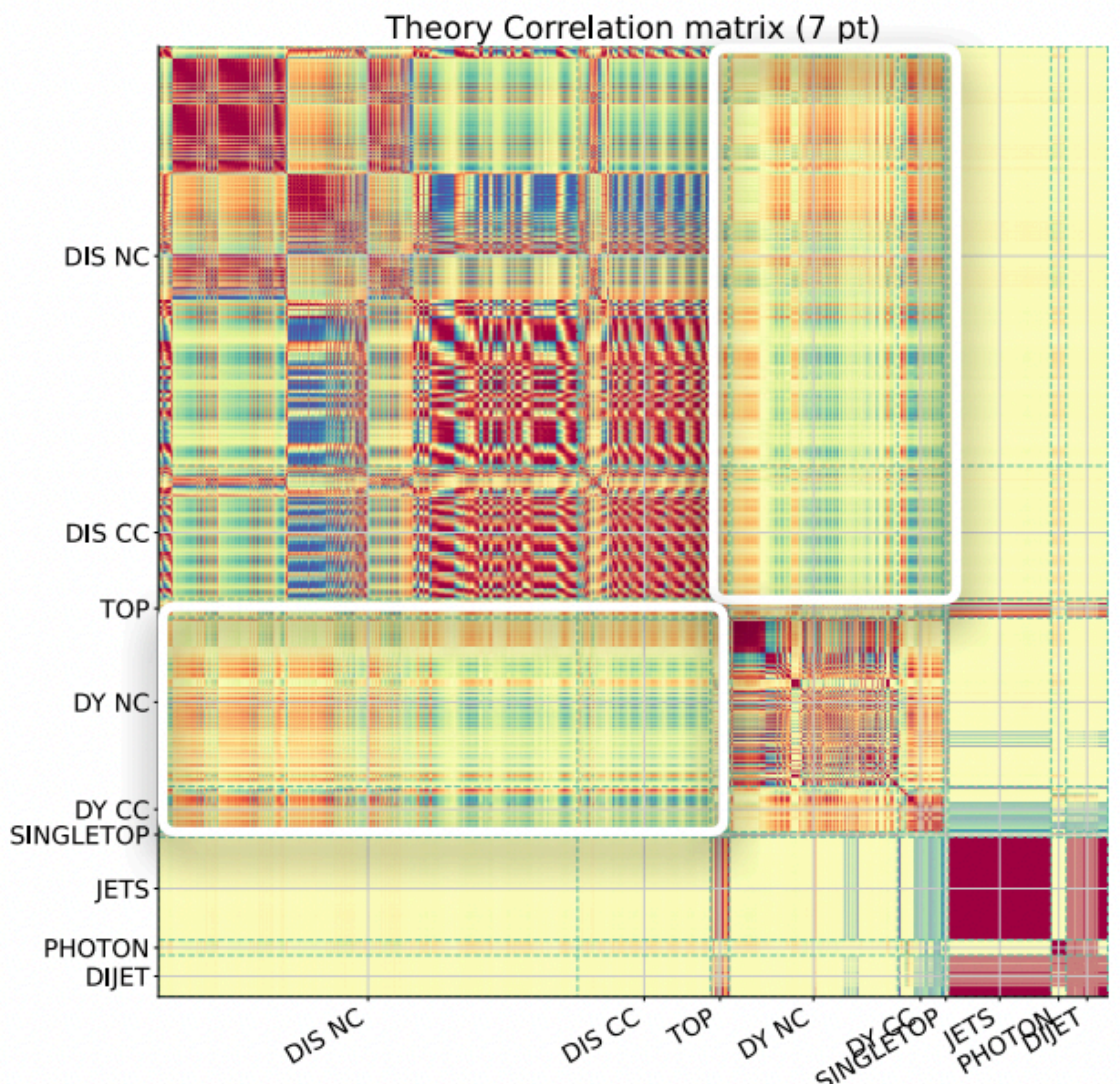
➡PDF uncertainties only include experimental component: how to include uncertainty associated to truncation of perturbative expansion in theoretical predictions used in PDF fits?

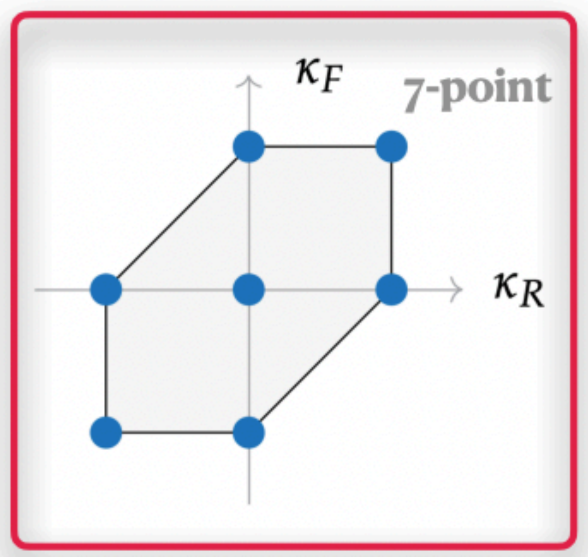
➡One option is to construct a theory covariance matrix from scale-varied cross sections and combine it with the experimental covariance matrix

$$\chi^2 = \sum_{m,n=1}^{N} (d_m - t_m)(\text{cov}_{\text{exp}} + \text{cov}_{\text{th}})^{-1}_{mn}(d_n - t_n)$$

- Assumptions: experimental and theoretical errors independent and Gaussian



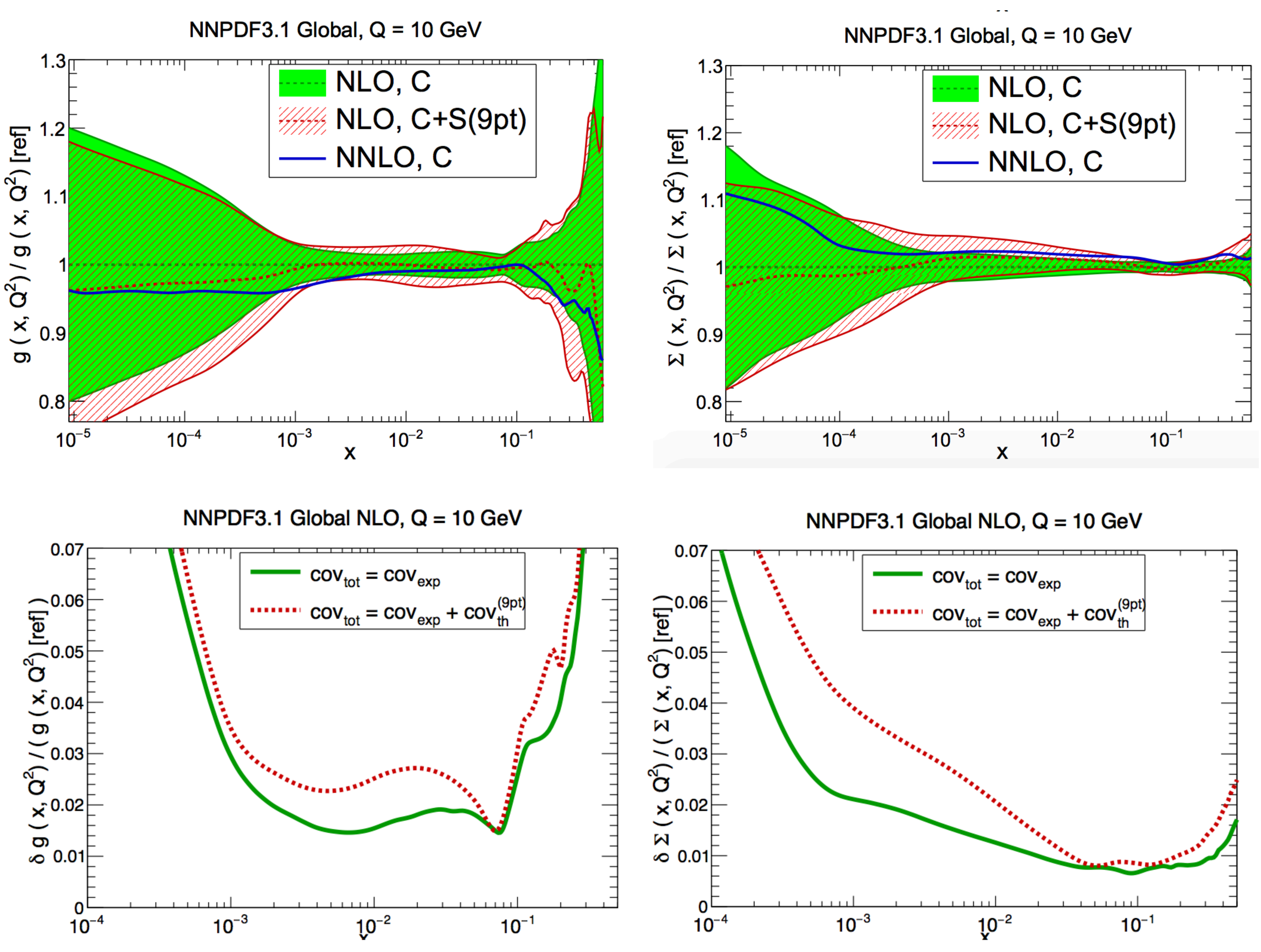




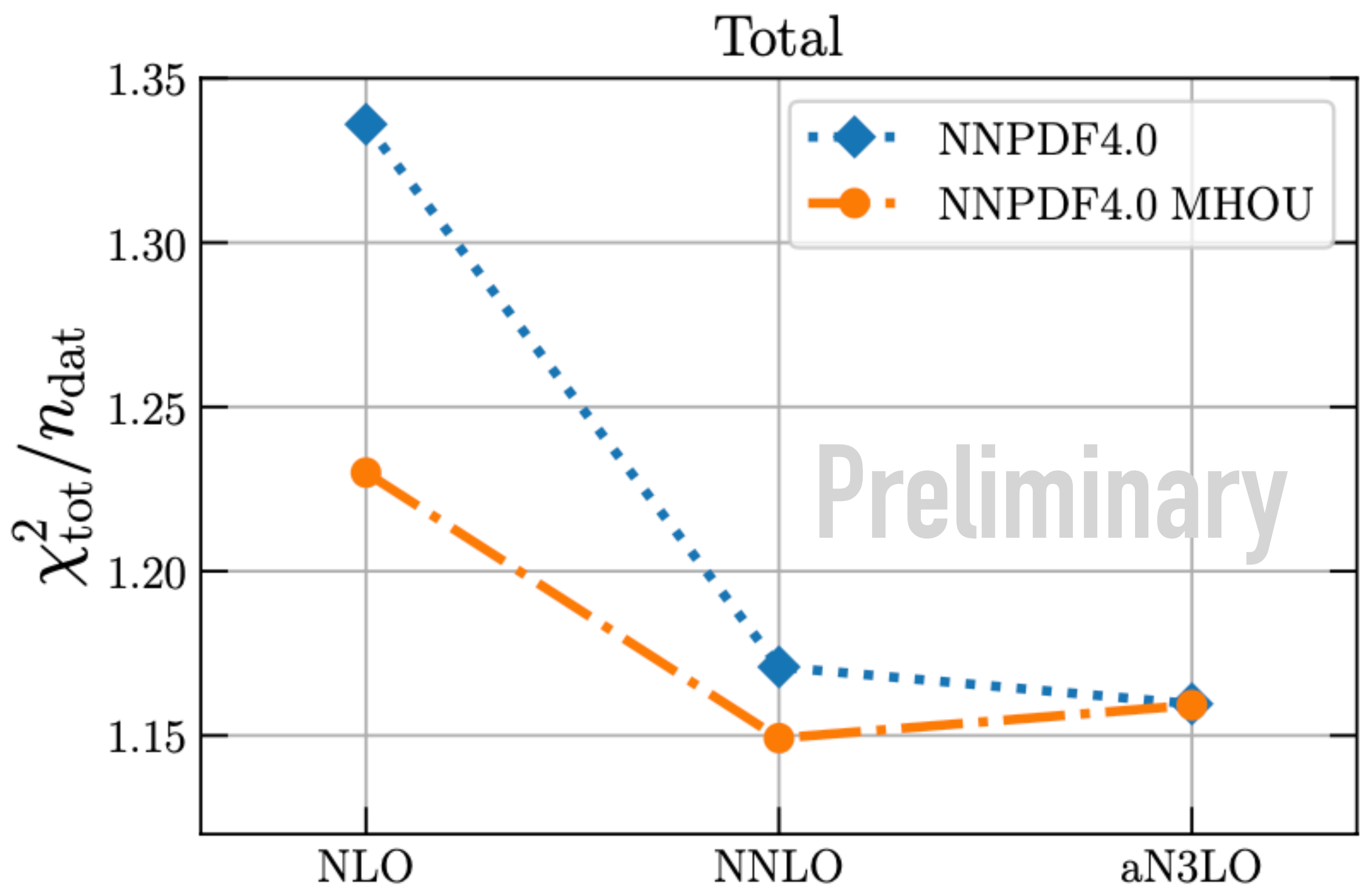
7-pts variation

[NNPDF: 1906.10698]
NNLO paper in preparation

#2 – MISSING HIGHER ORDER UNCERTAINTIES IN PDF FITS



Abdul Khalek et al *Eur.Phys.J.C* 79 (2019) 11



➡ NNPDF40NNLO with MHOU and NNPDF40aN3LO will be published soon

$$Cov_{ij} = Cov_{ij,EXP} + Cov_{ij,MHOU} + Cov_{ij,IHOU}$$

➡ Missing correlation between scale variation in PDF fits and hard cross sections [Harland-Lang, Thorne Eur.Phys.J.C 79 (2019) 3, 225] [Ball, Pearson arXiv:2105.05114]

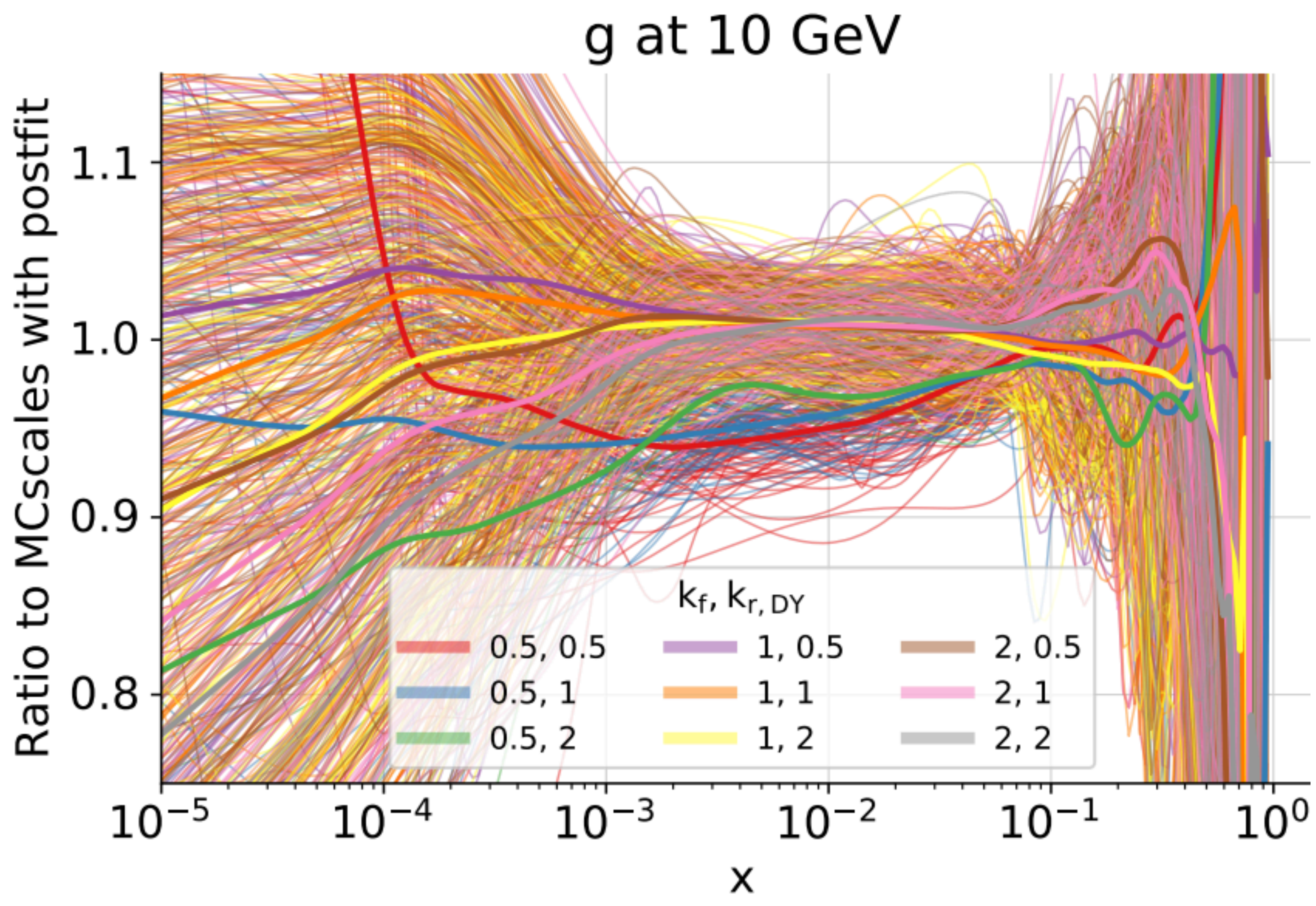
#2 – MISSING HIGHER ORDER UNCERTAINTIES IN PDF FITS

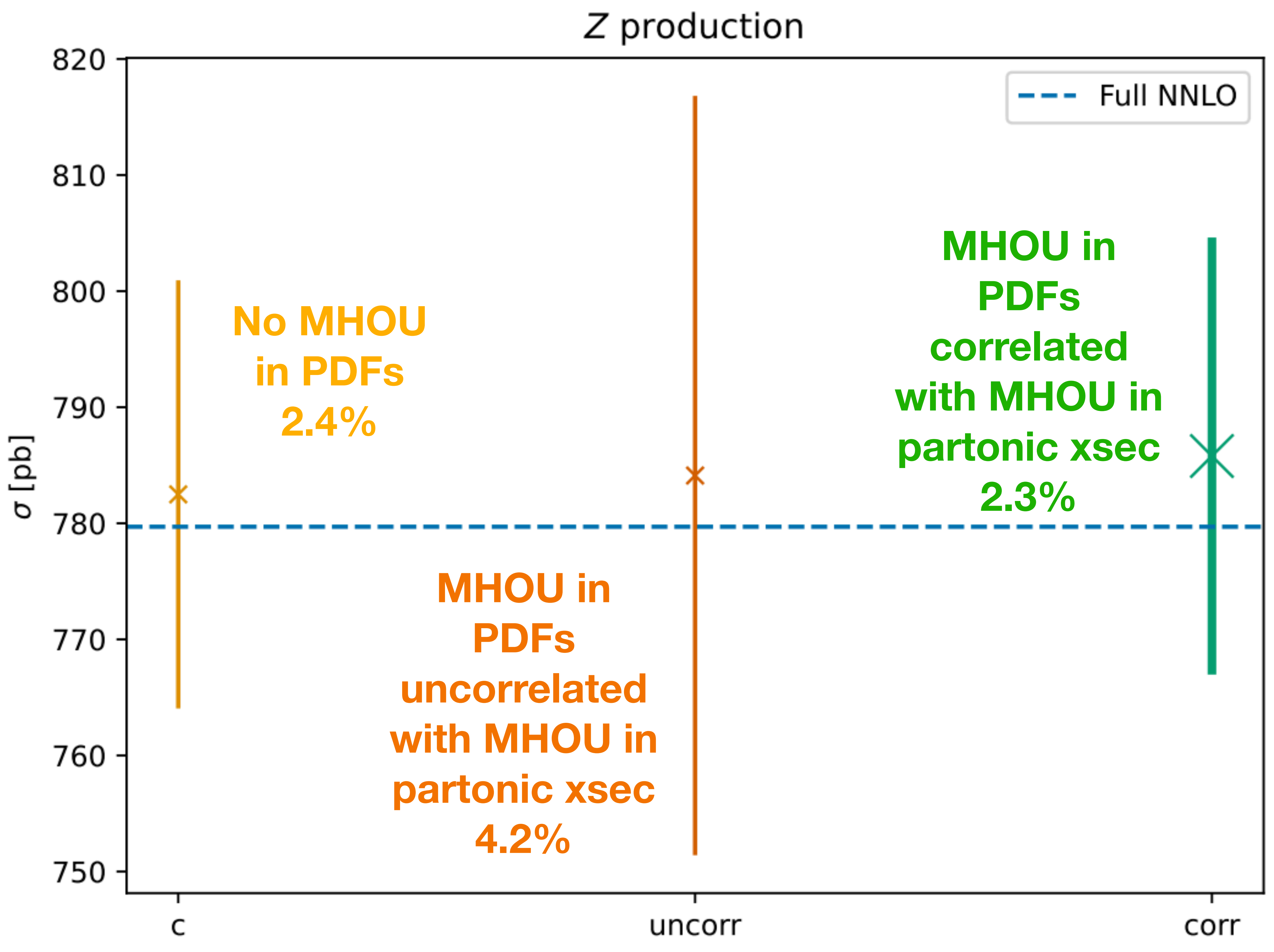
➡ Alternatively, MCscales [Kassabov et al, 2207.07616]: renormalisation and factorisation scales treated as free parameters of the fixed-order theory, that induce an uncertainty on the theory predictions included in a PDF fit & need to be propagated.

➡ Joint sampling of experimental uncertainty (propagated to PDF uncertainty by MC sampling) by specifying a suitable prior probability distribution of all possible scale choices & a-posteriori criterion based on agreement with the data.

➡ Can compute full PDF+SCALE uncertainty in cross sections by matching the scales in the hard cross section computation with the scales in the MCscale PDF set: correlation fully taken into account

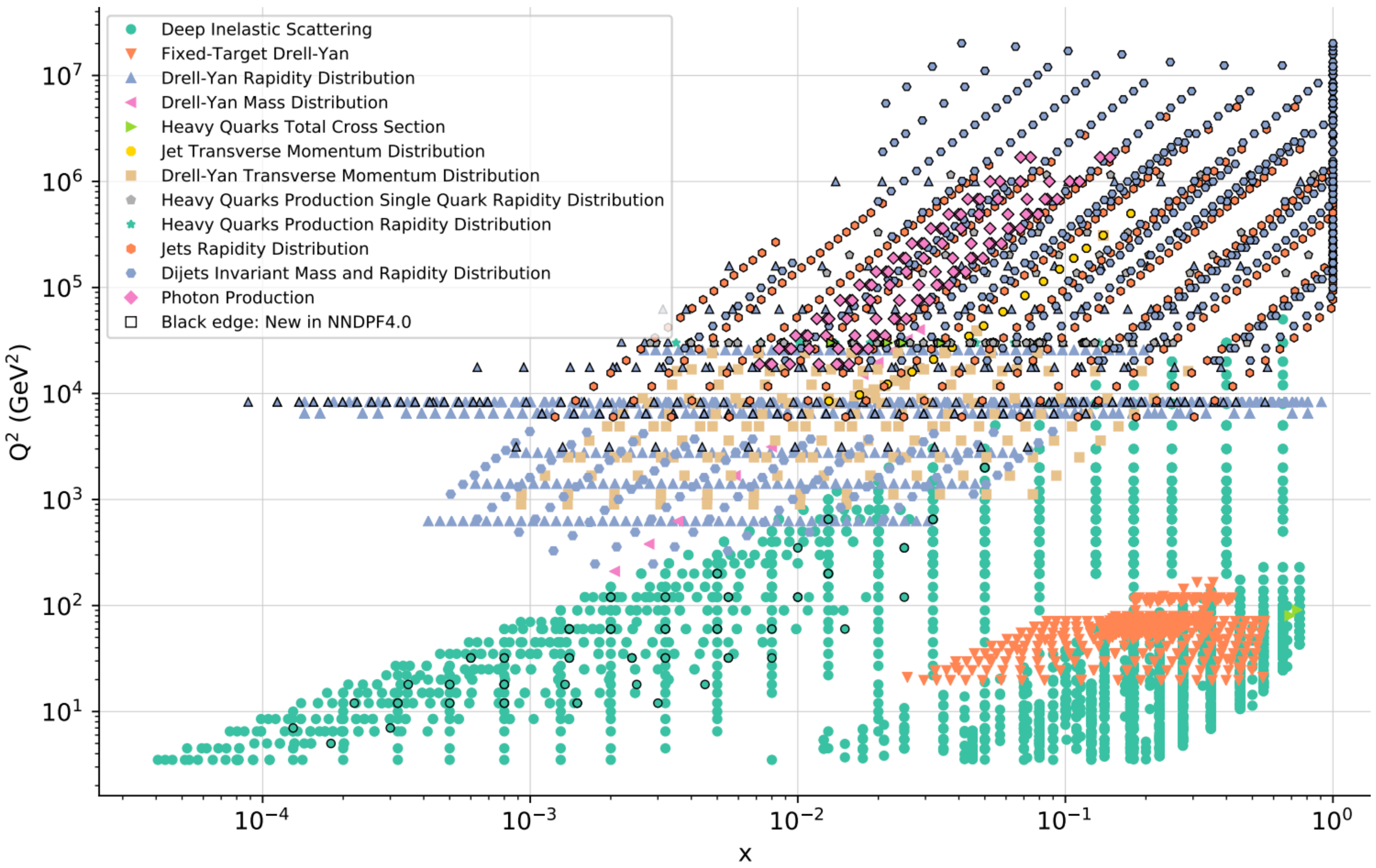
Kassabov et al: 2207.07616]





#3 – PDF AND NEW PHYSICS INTERPLAY

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\, {\rm cov}^{-1}_{ij}\, (T_j(\{\theta\},\{c\}) - D_j)$$



NNPDF4.0, Ball et al, arXiv: 2109.02653

$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_z)$, M_w, θ_w, SMEFT WCs.....

Parameters determining PDFs at initial scale

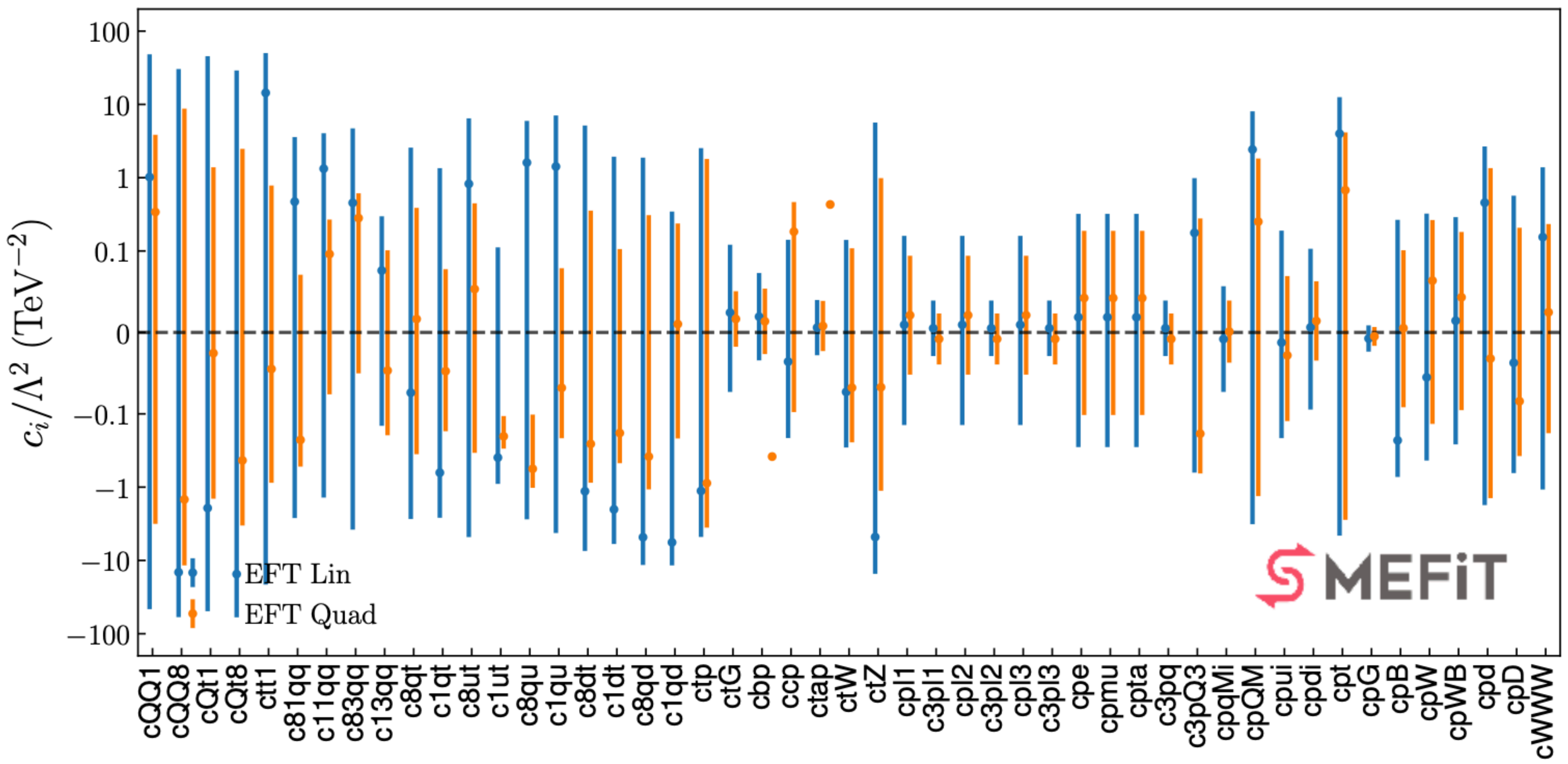
✓ In a PDF fit typically

$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{c=\bar{c}\}) \otimes \hat{\sigma}_i(\{c=\bar{c}\})$$

#3 – PDF AND NEW PHYSICS INTERPLAY

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\, {\rm cov}^{-1}_{ij}\, (T_j(\{\theta\},\{c\}) - D_j)$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$



$$T_i(\{\theta\},\{c\}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat\sigma_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_z)$, M_w, θ_w ,SMEFT WCs.....

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{c=\bar c\}) \otimes \hat\sigma_i(\{c=\bar c\})$$

✓ In a fit of (B)SM parameters

$$T_i(\{c\}) = {\rm PDFs}(\{\bar\theta\},\{\bar c\}) \otimes \hat\sigma_i(\{c\})$$

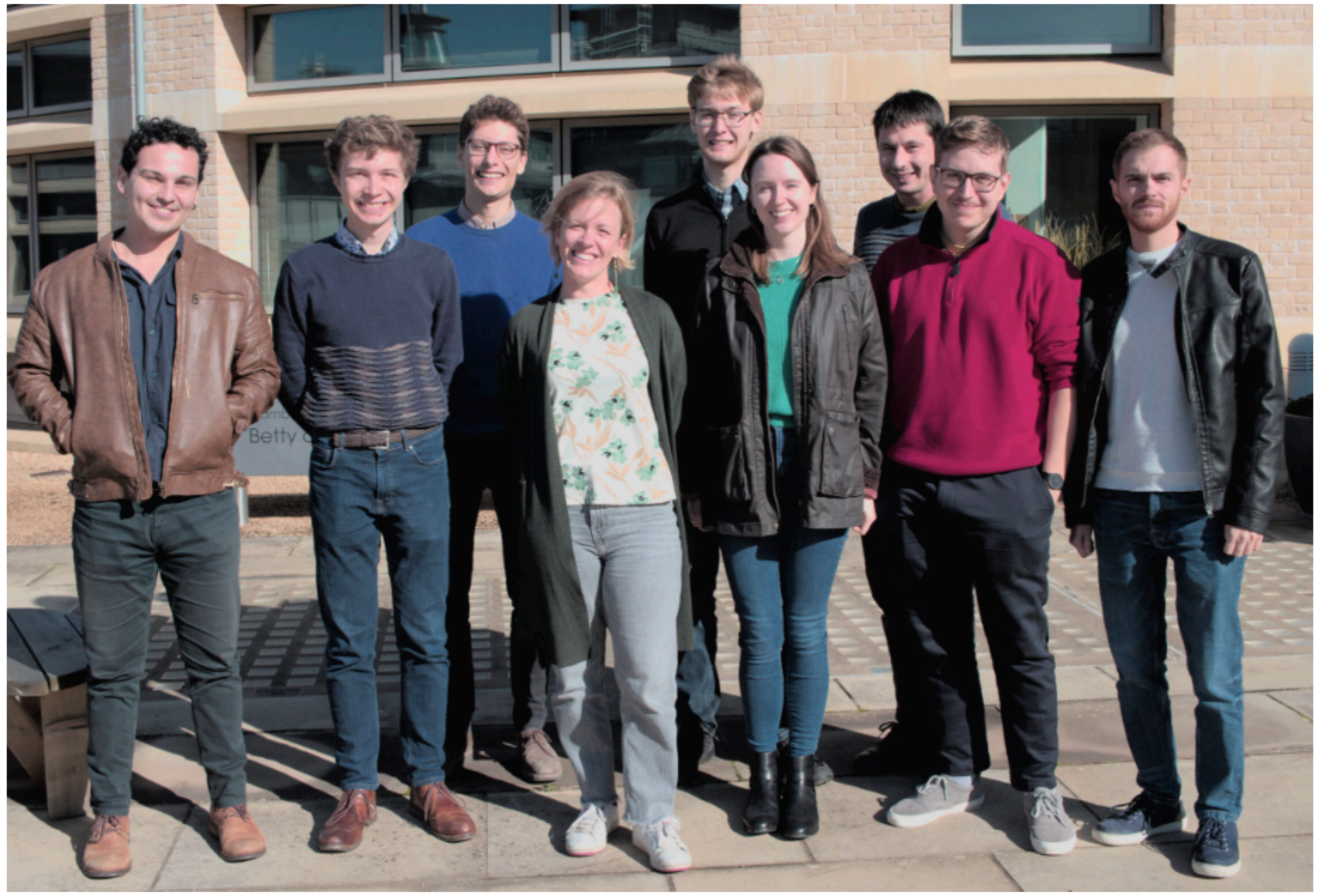
Ethier et al, arXiv: 2105.00006

#3 – PDF AND NEW PHYSICS INTERPLAY

- From the point of view of PDF fits:
  - ➡ How to make sure that new physics effects are not inadvertently fitted away in a PDF fit?
- From the point of view of SMEFT fits:
  - ➡ Should I make sure I am using a clean set of PDFs in a SMEFT analysis? How to define it? Is it enough?
  - ➡ How would the bounds change if I was consistently using PDFs that include in the fit the same operators that I am fitting?

PBSP

MU + Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales Alvarado, E. Hammou, M. Costantini

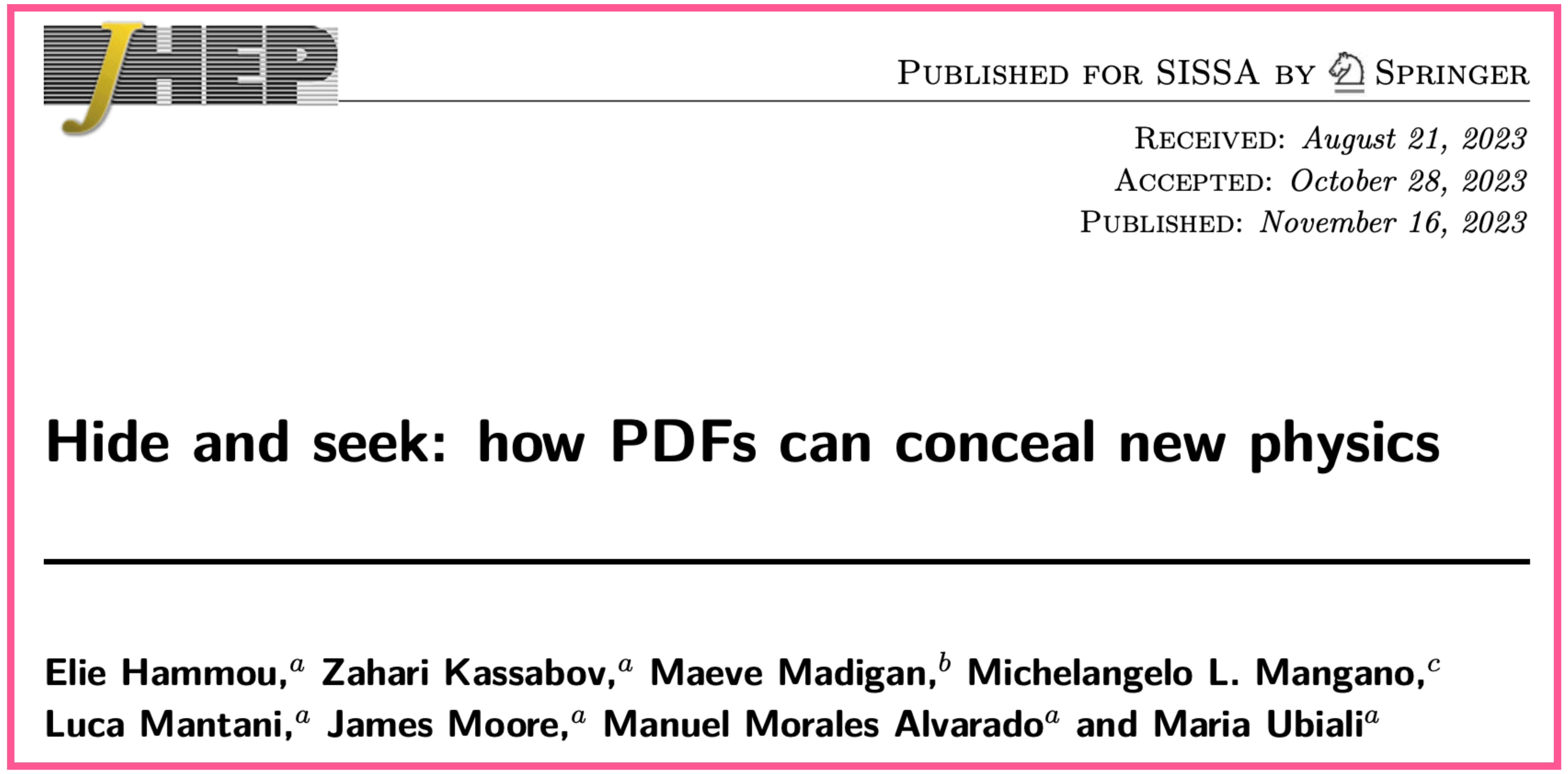


#3 – PDF AND NEW PHYSICS INTERPLAY

- From the point of view of PDF fits:
  - ➡ How to make sure that new physics effects are not inadvertently fitted away in a PDF fit?

✦ With current experiments, at the HL-LHC found a model involving a new heavy W′ that would affect high energy Drell-Yan tails. If there was a new heavy W′ PDF fits would have same quality but PDFs (hence theory predictions at LHC) would be significantly different. Large-x PDFs would absorb New Physics in this case!

✦ Need orthogonal input from low-energy experiments!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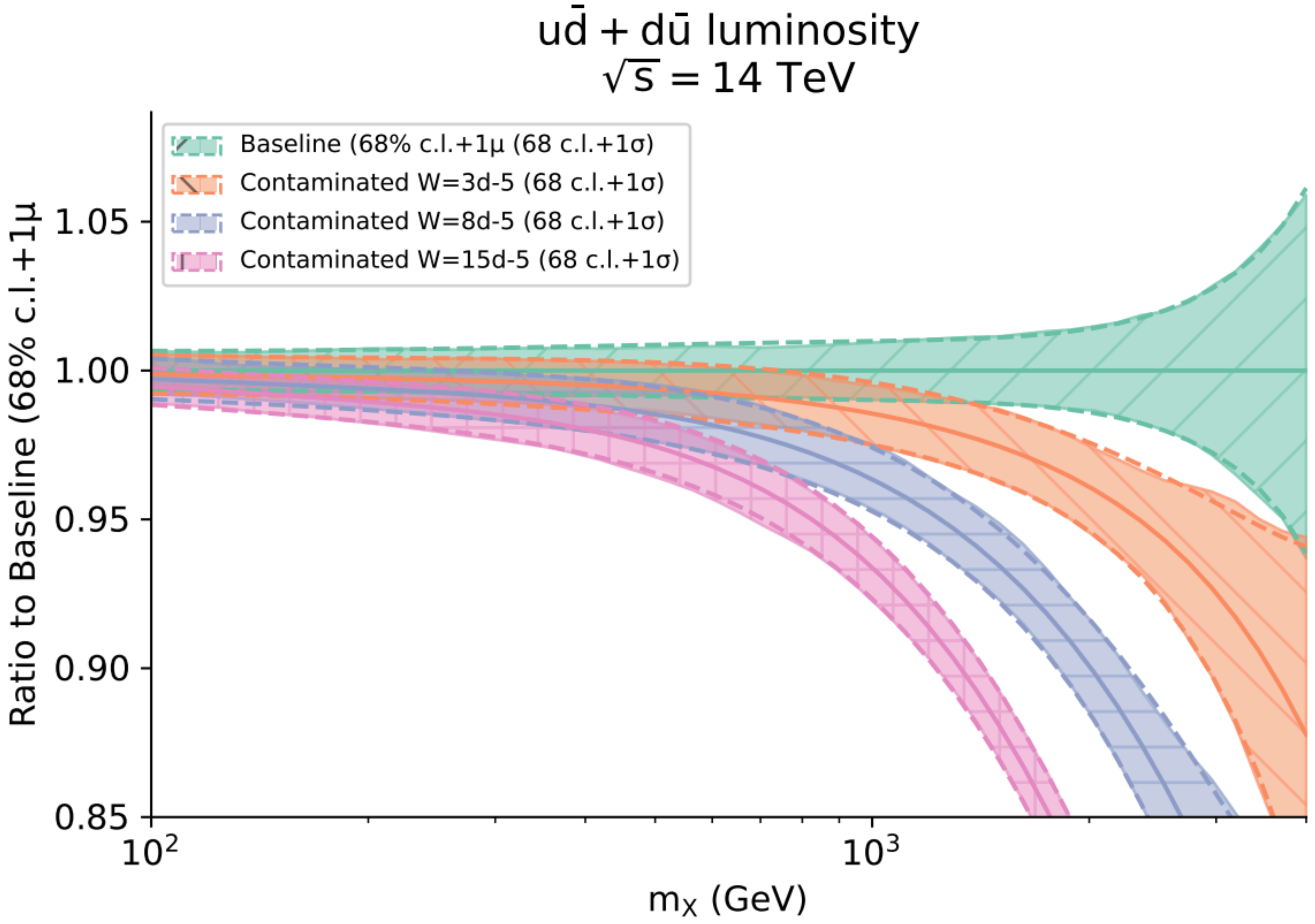
Hide and seek: how PDFs can conceal new physics

Elie Hammou,[a] Zahari Kassabov,[a] Maeve Madigan,[b] Michelangelo L. Mangano,[c] Luca Mantani,[a] James Moore,[a] Manuel Morales Alvarado[a] and Maria Ubiali[a]



#3 – PDF AND NEW PHYSICS INTERPLAY

- From the point of view of PDF fits:
  - ➡ How to make sure that new physics effects are not inadvertently fitted away in a PDF fit?
- From the point of view of SMEFT fits:
  - ➡ Should I make sure I am using a clean set of PDFs in a SMEFT analysis? How to define it? Is it enough?
  - ➡ How would the bounds change if I was consistently using PDFs that include in the fit the same operators that I am fitting?

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

➡ Simultaneous fits of SMEFT and PDFs

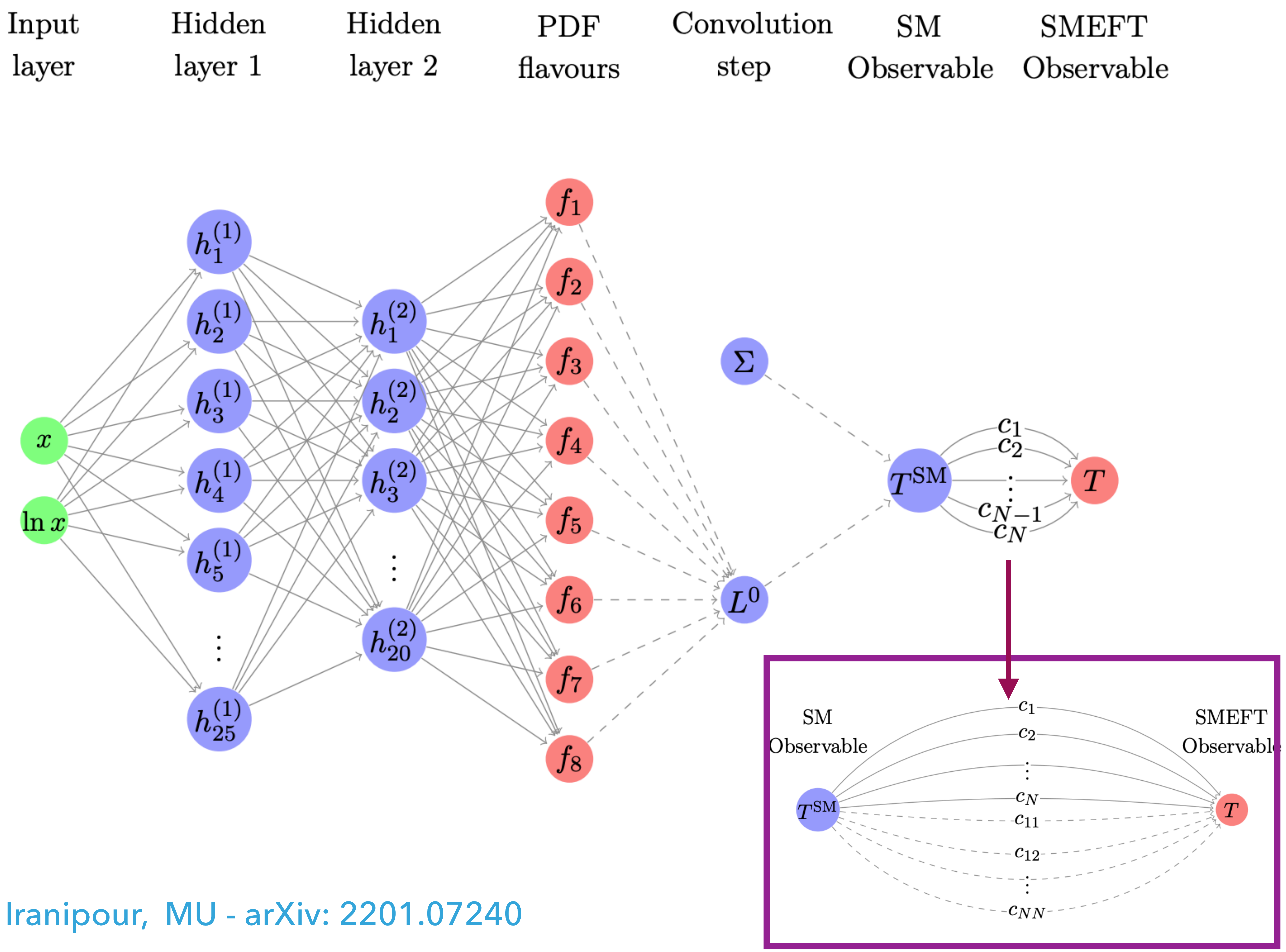
$$T(\{\theta_k\},\{c_i\})$$

$$f(\{\theta_k\})$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \cdots$$

#3 – PDF AND NEW PHYSICS INTERPLAY

- How to perform simultaneous fits?
- SimuNET [soon available open-source] yields simultaneous fit of PDFs and SMEFT coefficients, it does not have limit in number of parameters that can be fitted alongside PDFs at the initial scale!



Linear dim-6 operator

$$T(\hat{\theta}) = \Sigma(\{c_n\}) \cdot L^0(\theta) = T^{\rm SM}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R^{(n)}_{\rm SMEFT}\right)$$

$$T^{\rm SM}(\theta) = \Sigma^{\rm SM} \cdot L^0(\theta)$$

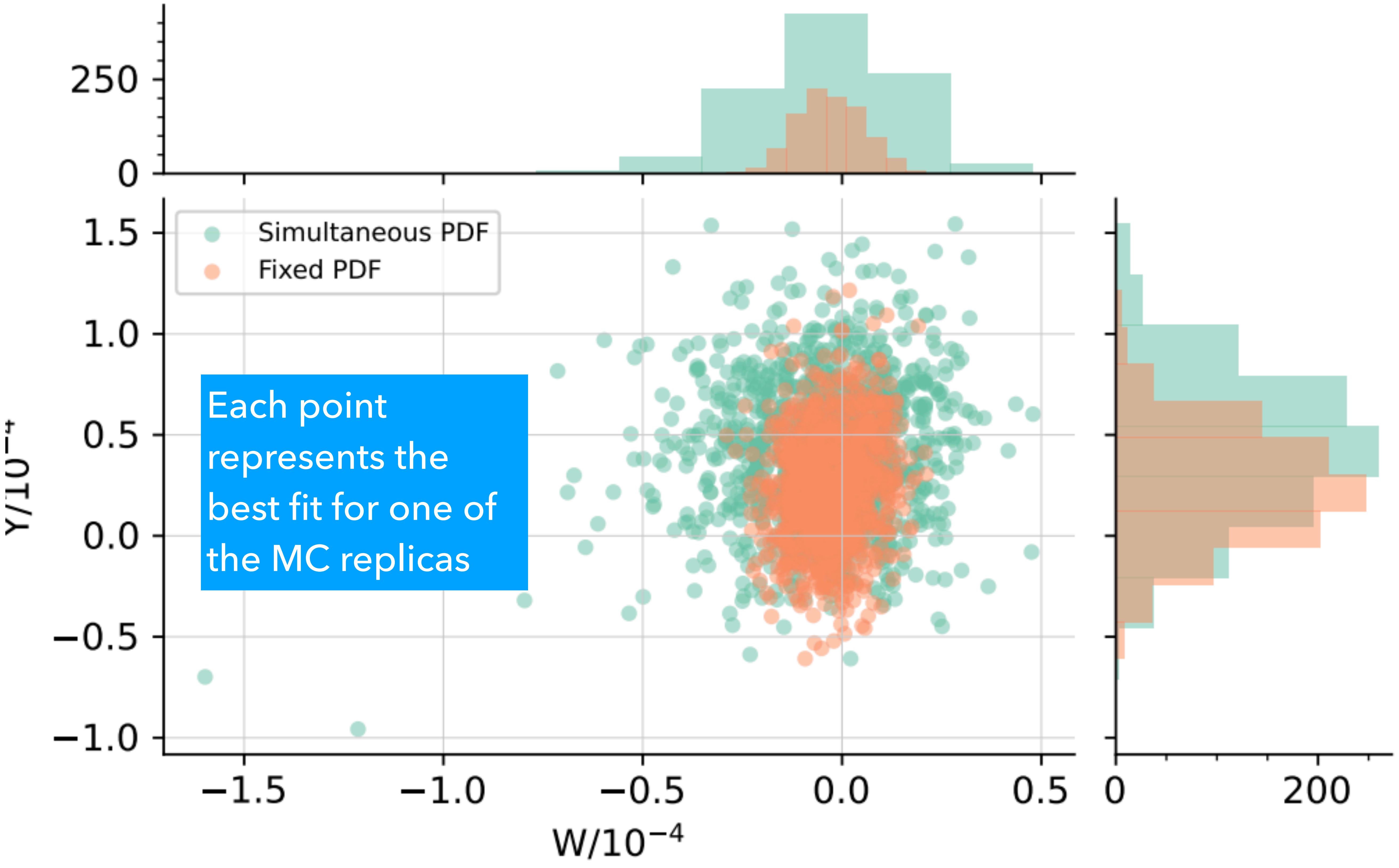
Quadratic dim-6 operator

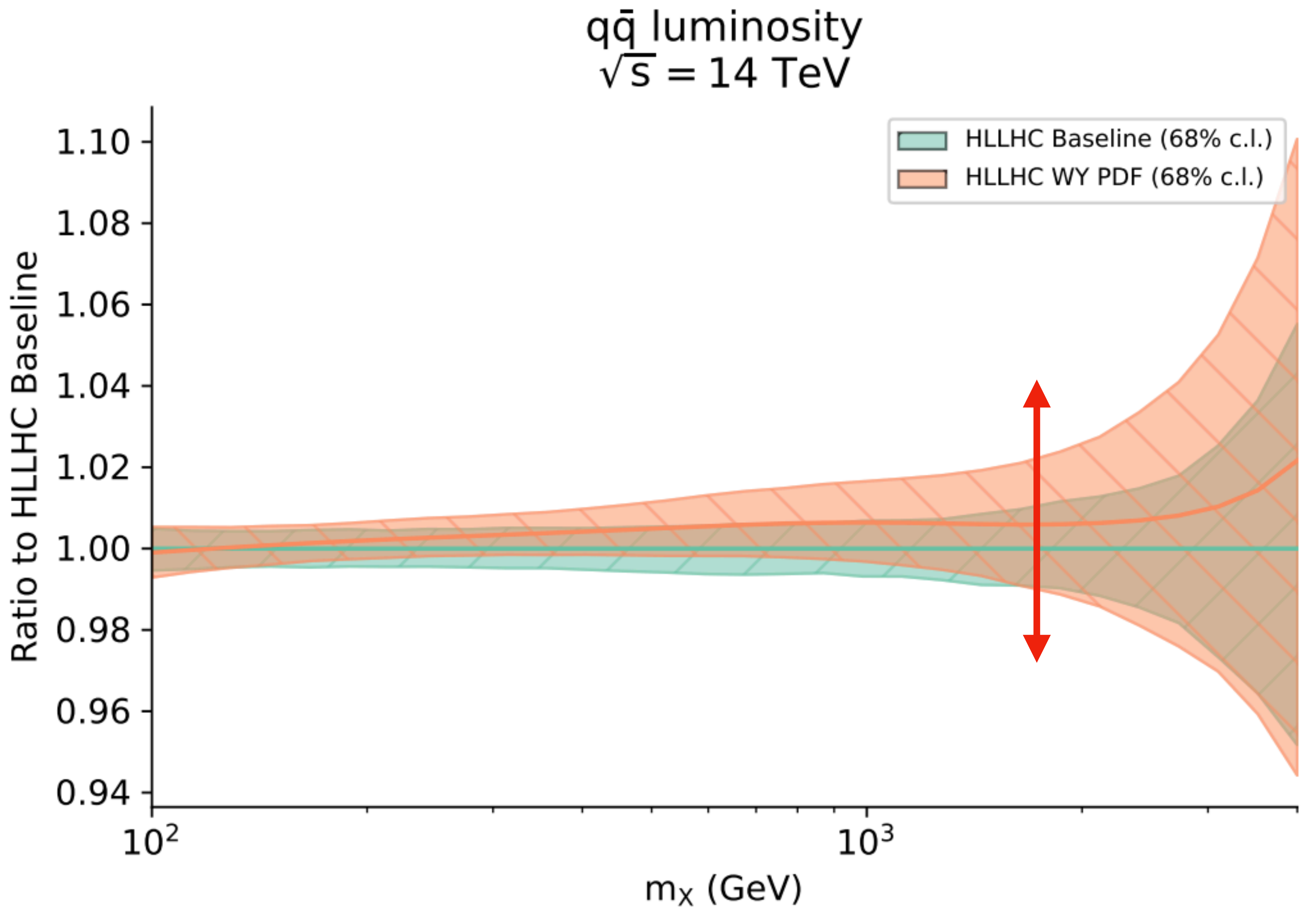
$$T(\hat{\theta}) = T^{\rm SM}(\theta) \cdot \left(1 + \sum_{n=1}^{N} c_n R^{(n)}_{\rm SMEFT} + \sum_{1\le n\le m\le N} c_{nm} R^{(n,m)}_{\rm SMEFT}\, ,\right)$$

$$c_n c_m$$

S. Iranipour, MU - arXiv: 2201.07240

#3 – PDF AND NEW PHYSICS INTERPLAY

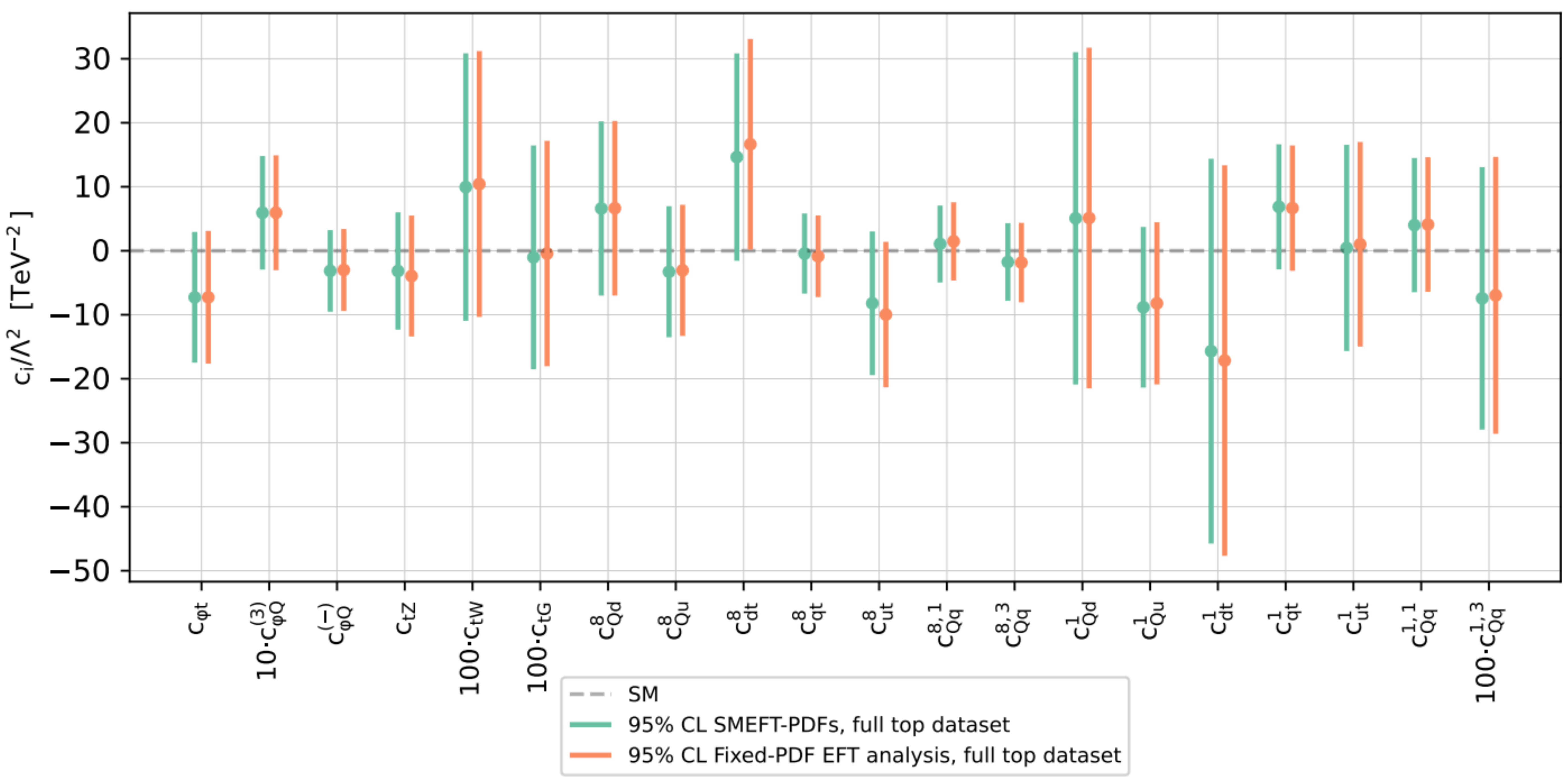


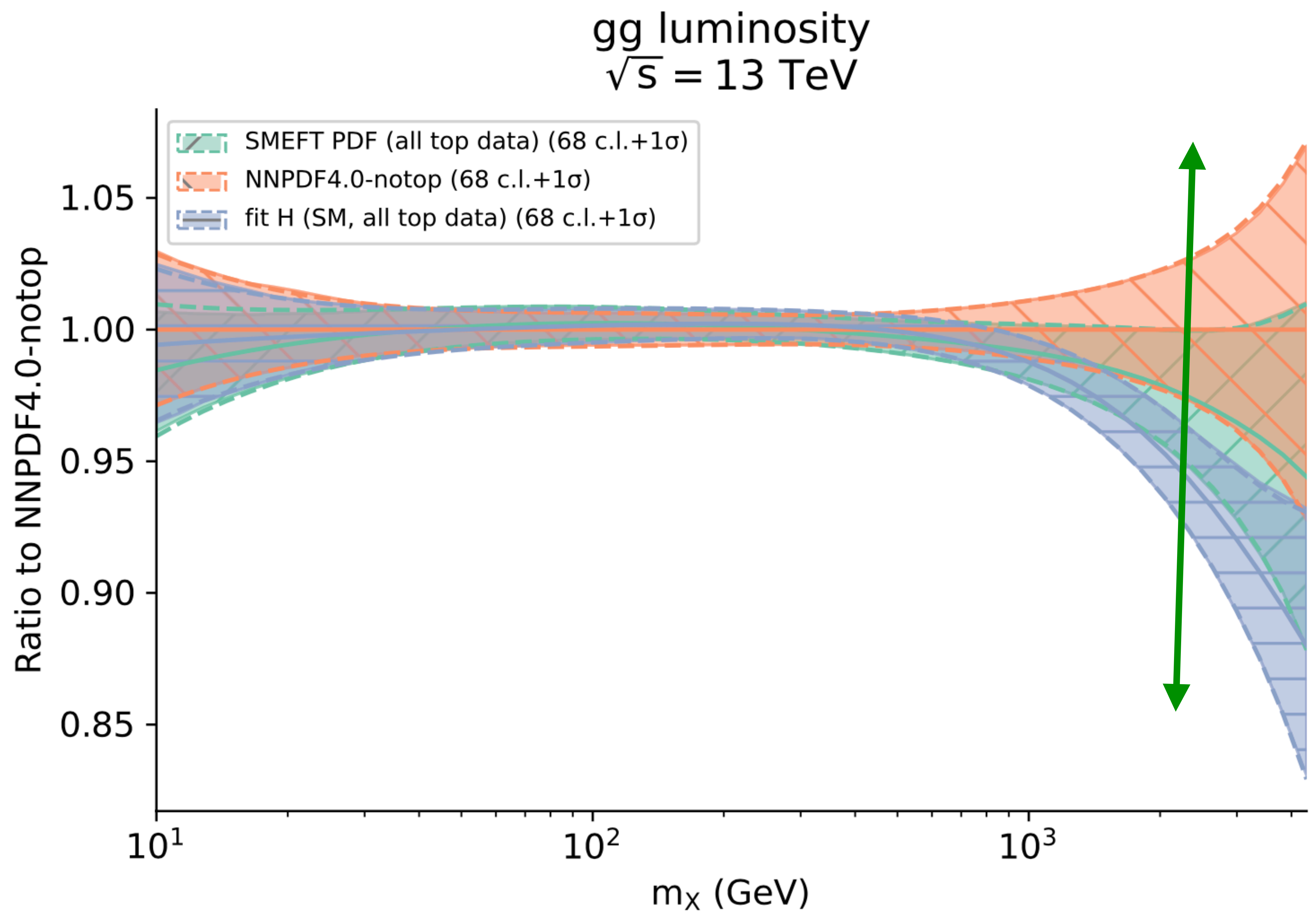


S. Iranipour, MU - arXiv: 2201.07240

✓ Simultaneous analysis of PDFs and **Drell-Yan sector** Wilson coefficient of DIS + DY (including HL-LHC projections) using simuNET method shows that at HL-LHC the effect of interplay becomes important as WCs bounds broaden and PDF uncertainties change significantly once SMEFT effects allowed in theory predictions entering PDF fit

#3 – PDF AND NEW PHYSICS INTERPLAY





Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales, J. Rojo, MU - arXiv: 2303.06159

✓ Simultaneous analysis of PDFs and more than 20 operators in the **top sector** using simuNET method shows that WCs are stable, while PDF uncertainties broaden and PDF fitted simultaneously alongside WCs site nicely between PDF-only fit without top data and PDF fit including all top data

CONCLUSIONS AND OUTLOOK

- In an era of precision, need precise and accurate PDFs
- Lots of progress in theoretical framework: aN3LO PDFs, inclusion of MHOUs in PDF error bands
- No time to mention QED sets and intrinsic charm studies
- New exciting avenues being explored, for example interplay between new Physics and PDFs, hinting to complementarity of low-energy experiments/lattice to determine large-x PDFs (EIC, FFP)

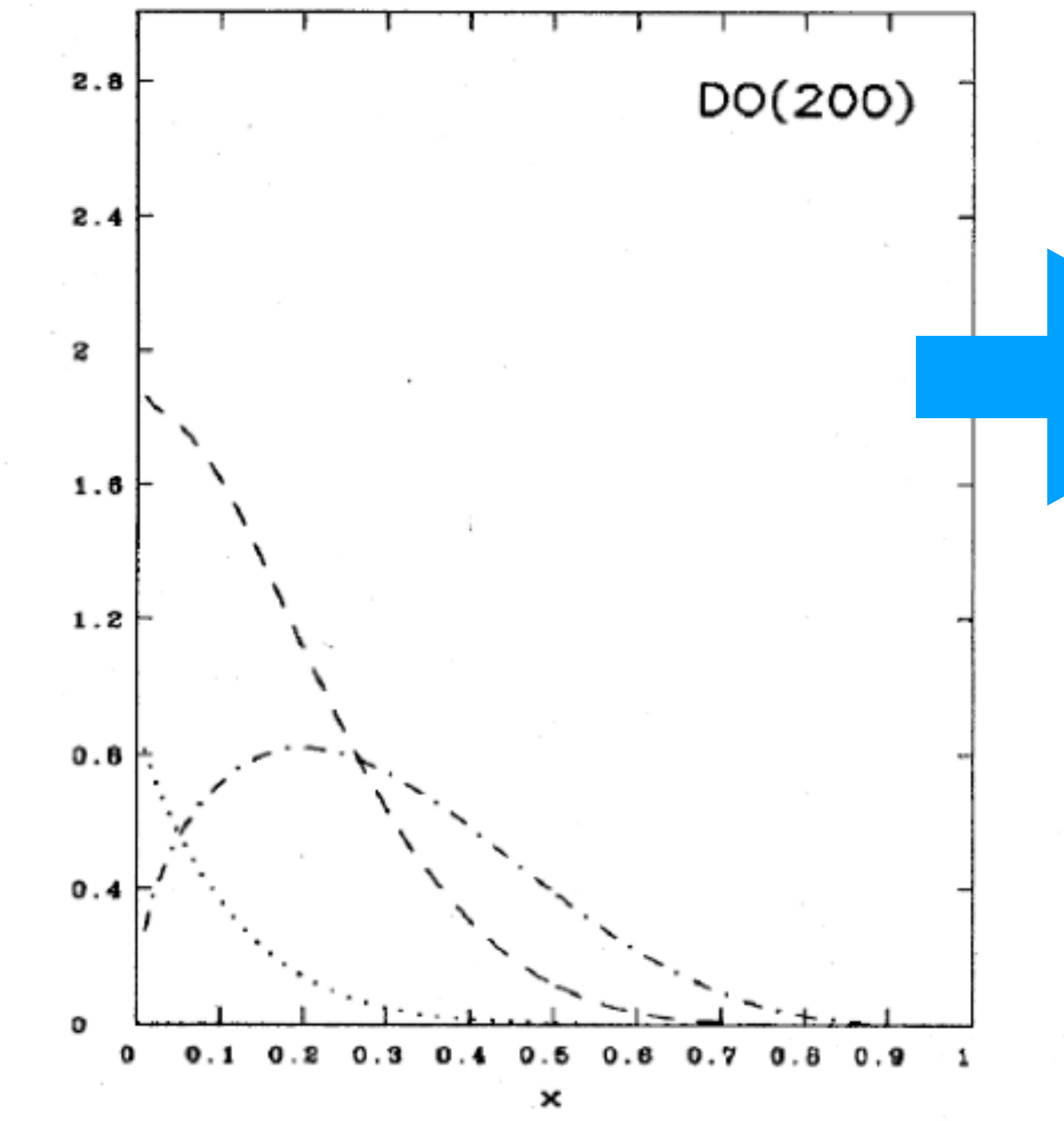
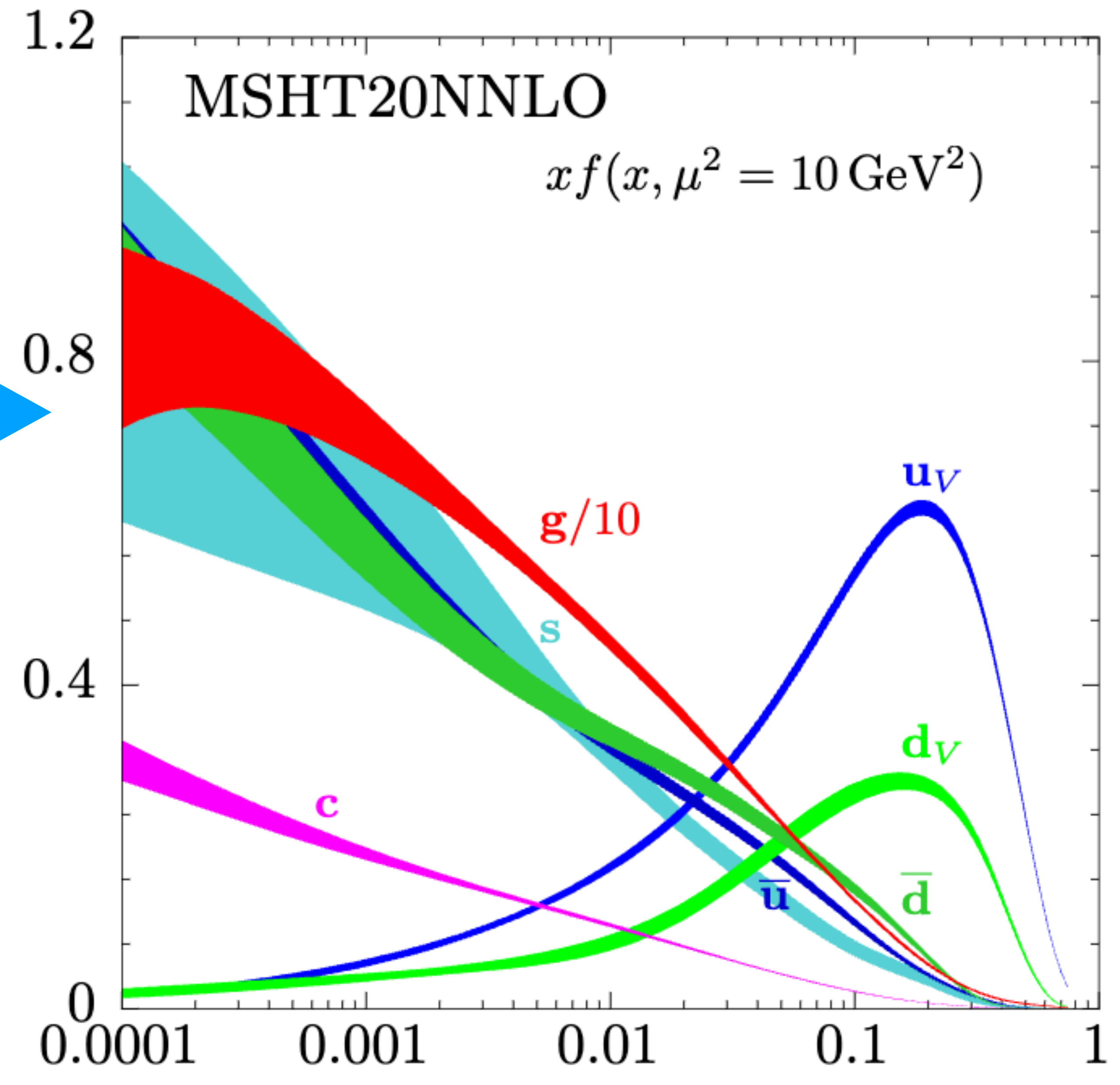


FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).



EXTRA MATERIAL

APPROXIMATE N3LO SPLITTING FUNCTIONS

- How to combine the known existing limits?
  In Mellin space, for each power of n_f

$$\gamma_{ij}(N) = -\int_0^1 dx\, x^{N-1} P_{ij}(x)$$

$$\gamma_{ij}^{(3)} = \gamma_{ij,n_f^3}^{(3)} + \gamma_{ij,N\to\infty}^{(3)} + \gamma_{ij,N\to 0}^{(3)} + \tilde{\gamma}_{ij}^{(3)}$$

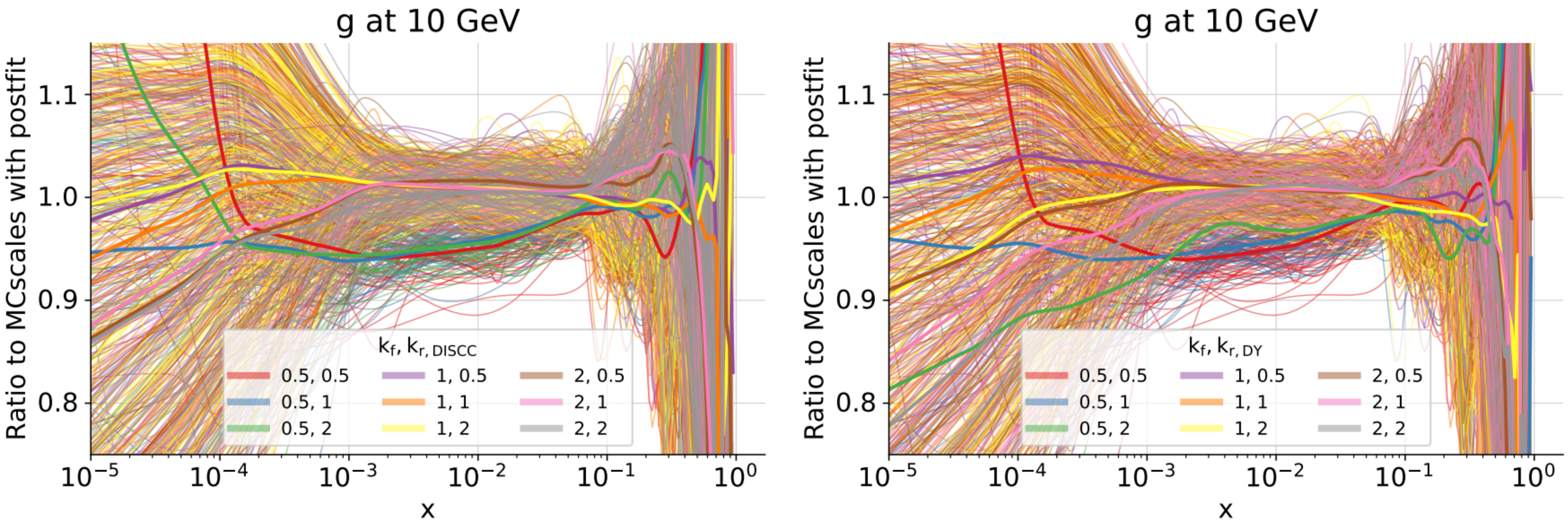
$$\tilde{\gamma}_{ij} = \sum_l a_{ij}^{(l)} G_l(N)$$

- For example, in NNPDF fit, for the P_{qq} splitting function

$\gamma_{qq,\mathrm{ps}}^{(3)}(N)$	$G_1(N)$	$\mathcal{M}[(1-x)\ln^2(1-x)]$	➡ Large-N contribution
	$G_2(N)$	$-\frac{1}{(N-1)^2}+\frac{1}{N^2}$	➡ Small-N contribution
	$\{G_{3,\dots,8}(N)\}$	$\frac{1}{N^4},\ \frac{1}{N^3},\ \mathcal{M}[(1-x)\ln(1-x)]$ $\mathcal{M}[(1-x)^2\ln(1-x)^2],\ \frac{1}{N-1}-\frac{1}{N},\ \mathcal{M}[(1-x)\ln(x)]$	➡ Sub-leading small-N and large-N contributions
	$\{G_9(N),\ G_{10}(N)\}$	$\mathcal{M}[(1-x)(1+2x)],\ \mathcal{M}[(1-x)x^2],$ $\mathcal{M}[(1-x)x(1+x)],\ \mathcal{M}[(1-x)]$	➡ Sub-leading

- Varying the sub-leading basis produces different candidates ➜ Incomplete Higher Order Uncertainty (IHOU)
- Different choice of basis and approaches in varying basis between NNPDF and MSHT and playing it the fit

THE MCSCALES APPROACH



✓ Main idea of MCscales: the renormalisation and factorisation scales are free parameters of the fixed-order theory, that induce an uncertainty on the theory predictions included in a PDF fit & need to be propagated

✓ Joint sampling of experimental uncertainty (propagated to PDF uncertainty by MC sampling) by specifying a suitable prior probability distribution of all possible scale choices & a-posteriori criterion based on agreement with the data.

$$P\left(k_f = \xi_f, k_{r_1} = \xi_1, \ldots, k_{r_{N_\mathrm{p}}} = \xi_{N_\mathrm{p}}\right) = P(\omega)$$

with $\omega \in \Omega = \{(\xi_f, \xi_1, \ldots, \xi_{N_\mathrm{p}}) \,\forall\, \xi_f, \xi_1, \ldots, \xi_{N_\mathrm{p}} \in \Xi\}$

3^{1+N_p} elements, with N_p = 5, p=DIS NC, DIS CC, DY, JET, TOP

Choose prior = choose P(ω)

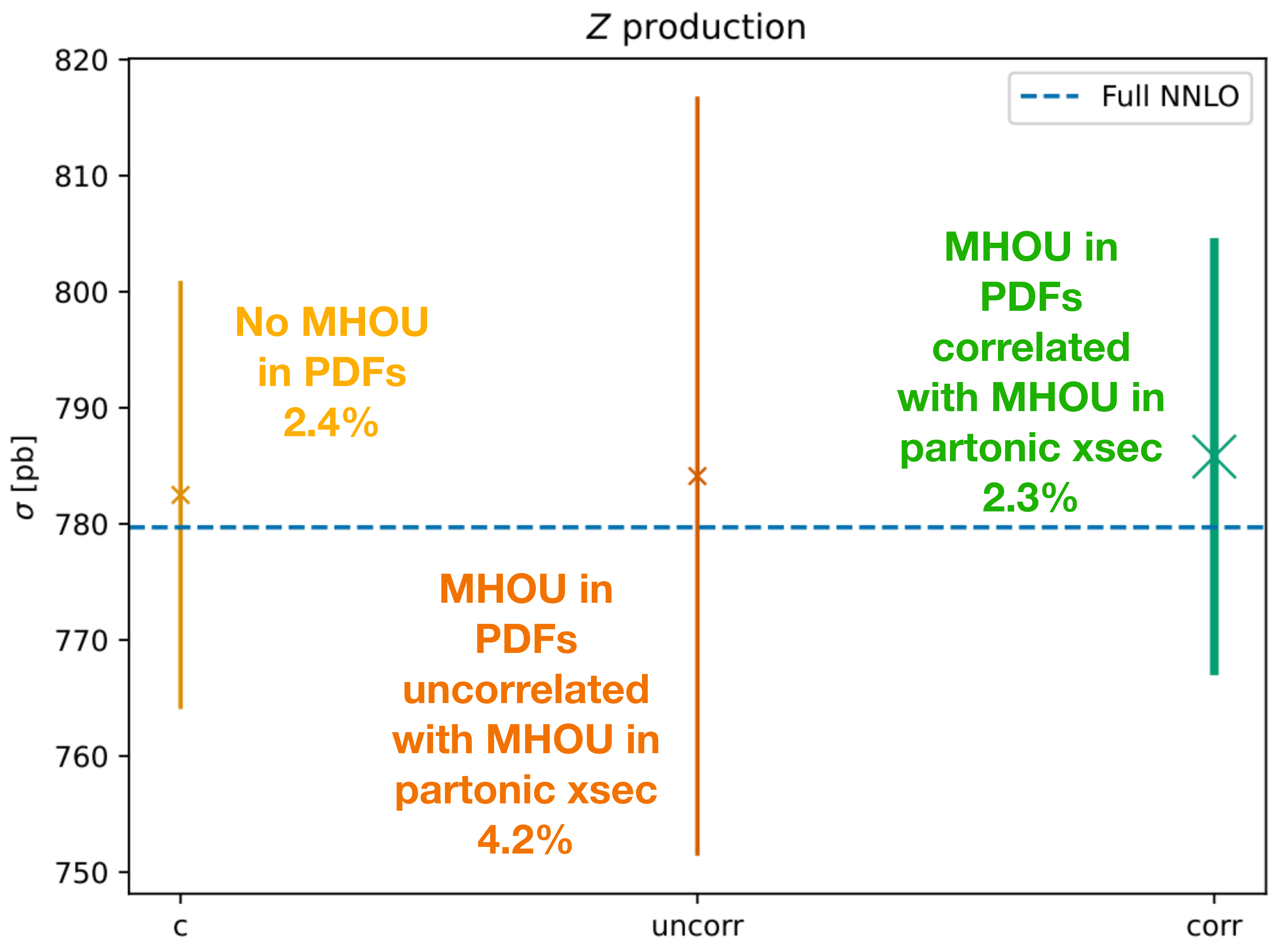
Posterior

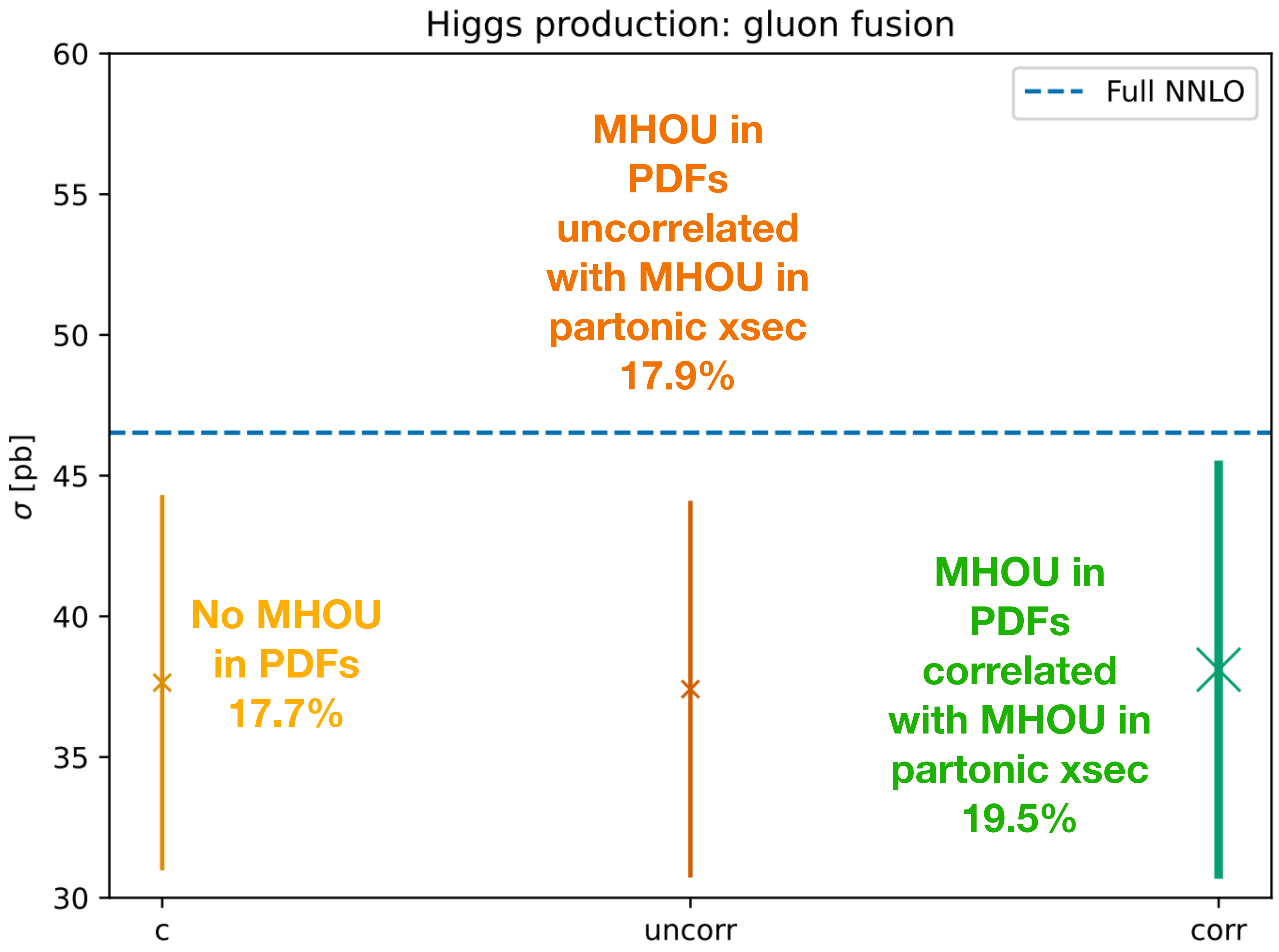
$$\chi^2_n > \langle \chi^2 \rangle_{n\,|\,\omega^{(n)}=\{1,\ldots,1\}} + 4\,\mathrm{std}(\chi^2)_{n\,|\,\omega^{(n)}=\{1,\ldots,1\}}$$

THE MCSCALES APPROACH

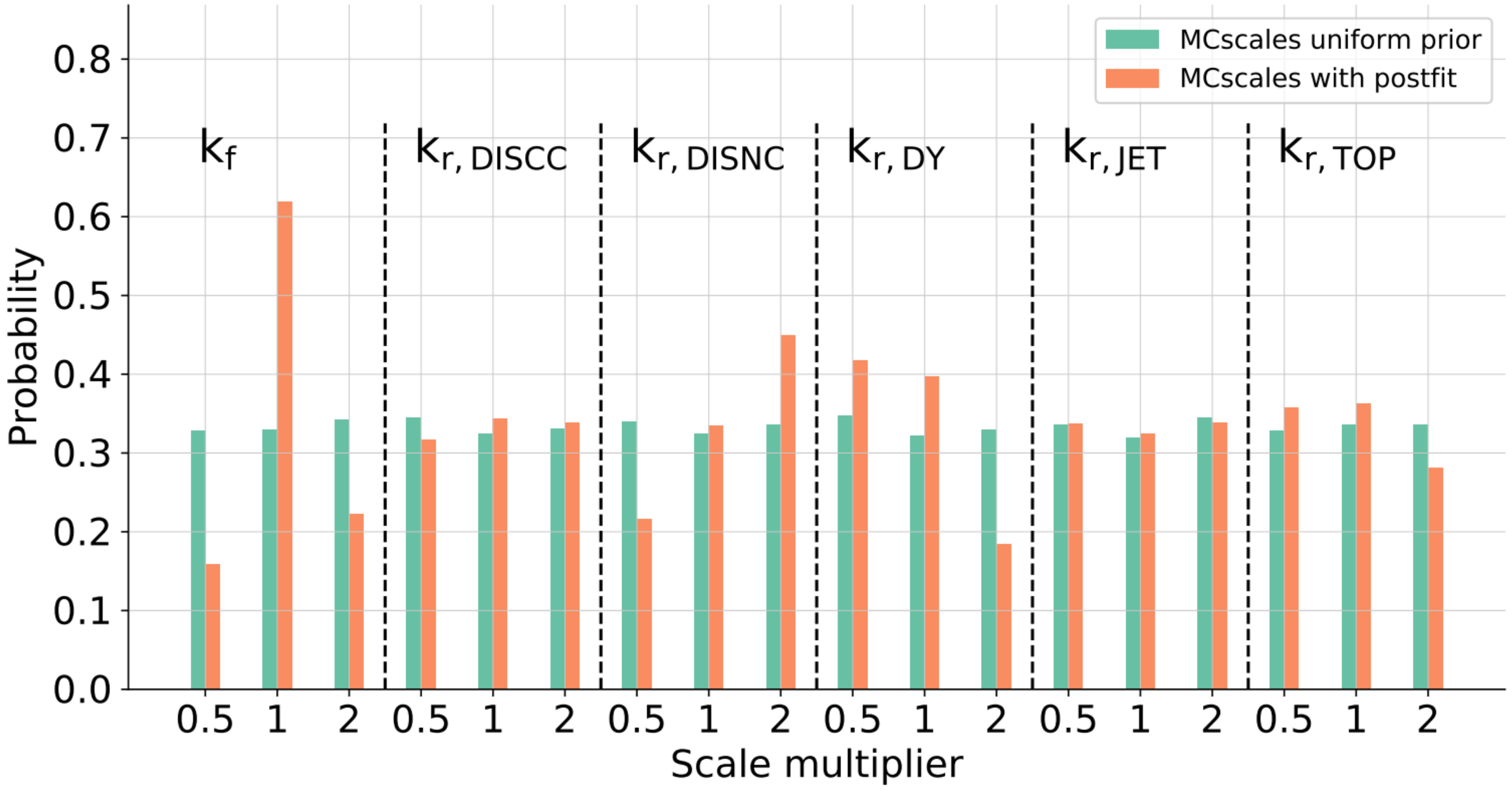
✓Can compute full PDF+SCALE uncertainty in cross sections at NLO by matching the scales in the hard cross section computation with the scales in the MCscale PDF set: correlation fully taken into account

$$\left\{\sigma_n = \hat{\sigma}_p(k_f^{(n)}, k_{r_p}^{(n)}) \otimes f_n(k_f^{(n)}, k_{r_p}^{(n)}) \;\; \forall n = 1, \ldots, N\right\}$$





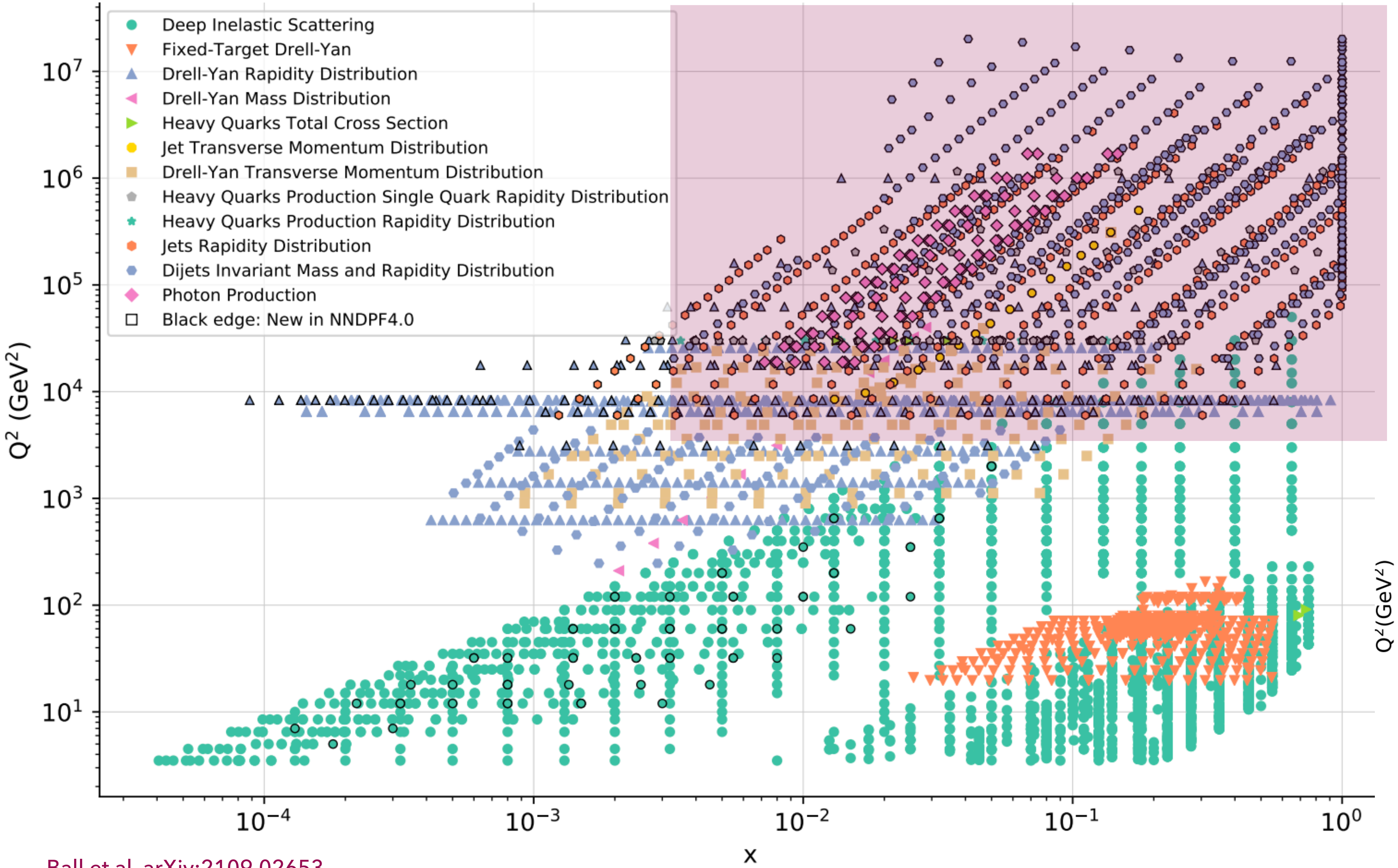
THE MCSCALES APPROACH



- ✓ Can look at the distribution of each of the scales over replicas.
- ✓ Flat distribution for the MCscales uniform prior.
- ✓ After applying postfit observe preference for central factorisation scale.
- ✓ Each process affected in a different way.

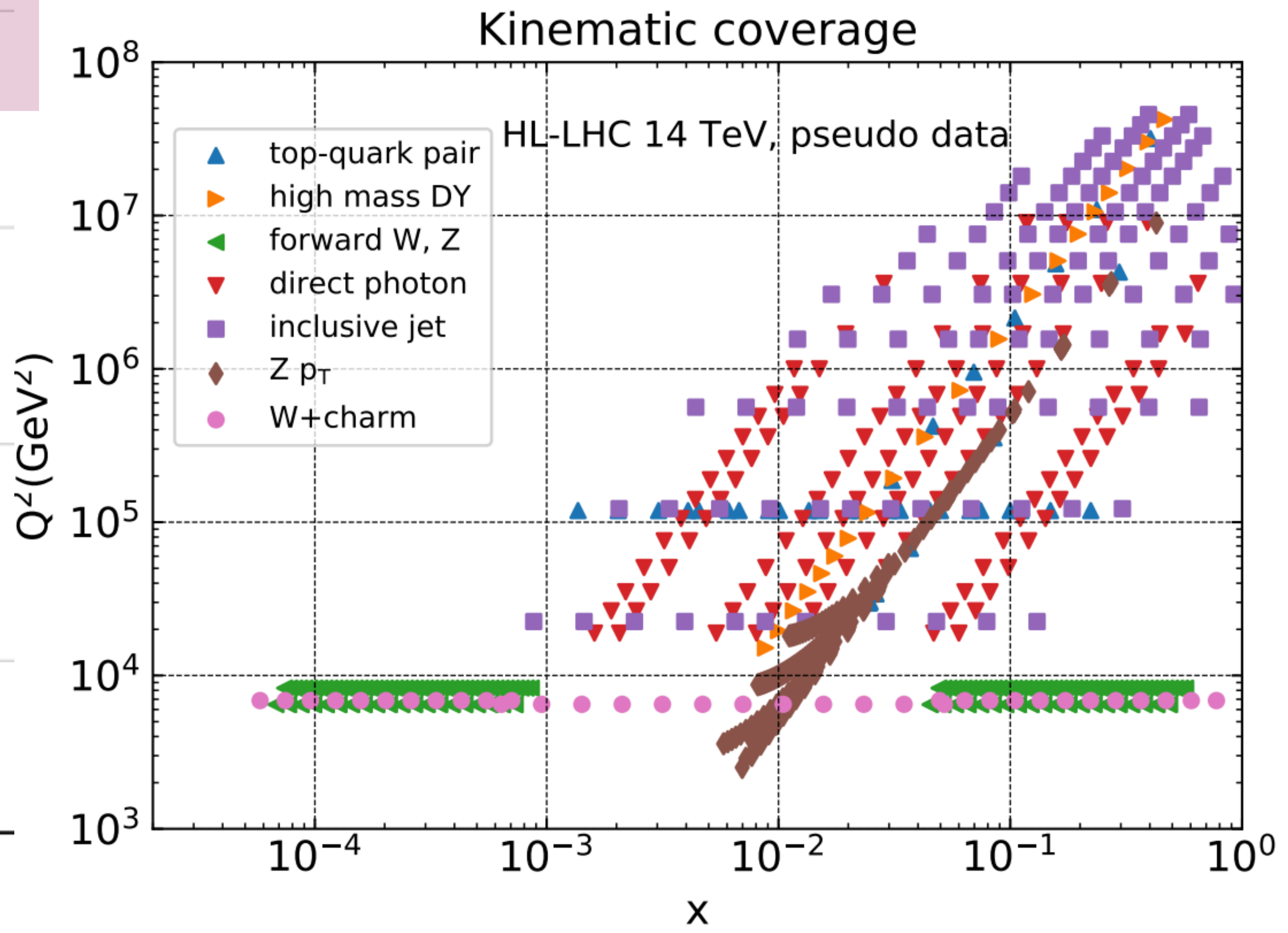
Scale multipliers	Process	Preferred values
(k_f, k_r)	DIS CC	$(1, 1)$
	DIS NC	$(1, 2)$
	DY	$(1, 1)$
	Jets	$(1, \frac{1}{2})$
	Top	$(1, 1)$

OVERLAP BETWEEN DATA IN PDF AND SMEFT FITS



Ball et al, arXiv:2109.02653

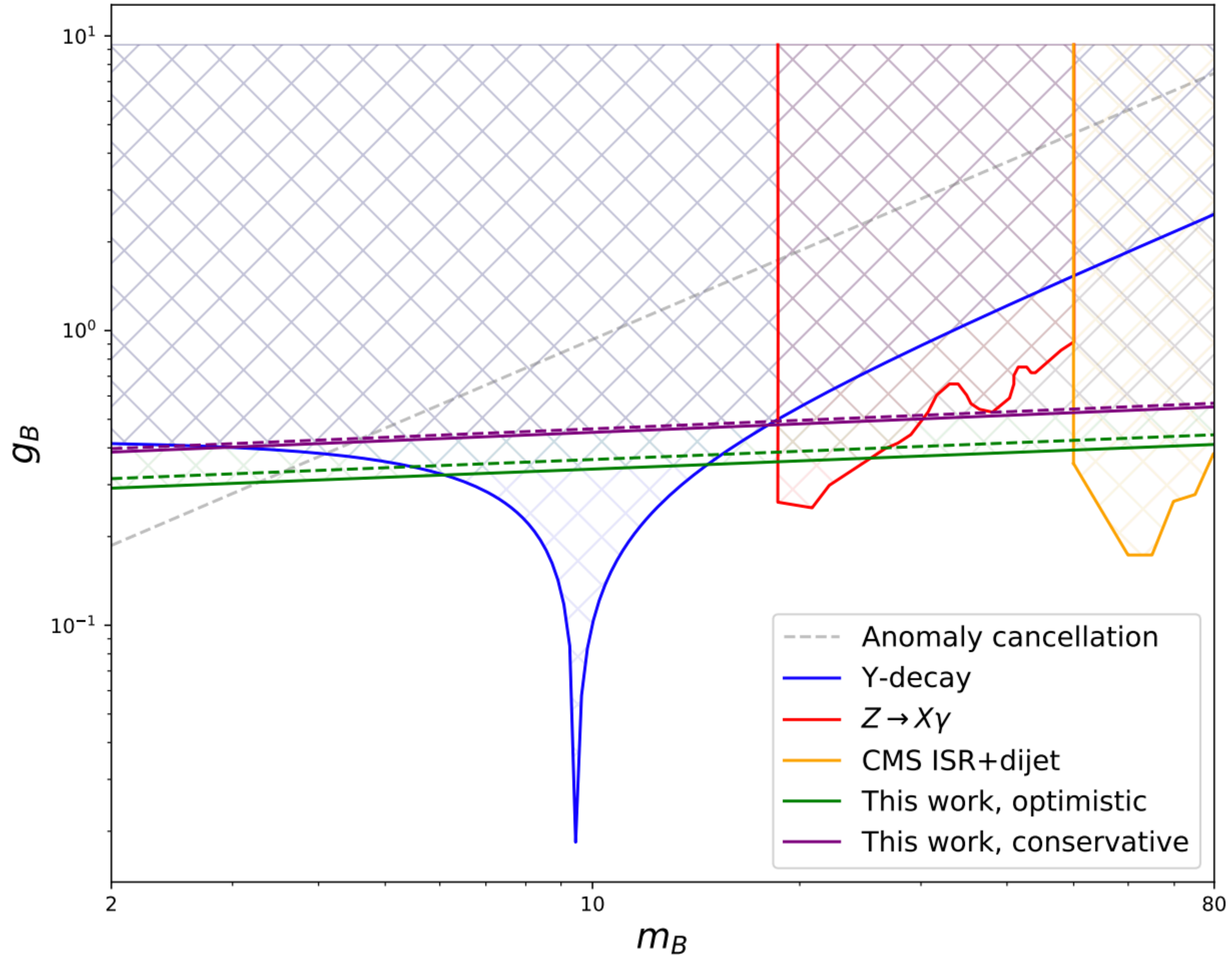
- ➡ Top pair production and single top data included in SMEFT analysis [Hartland et al 1901.05965] [Ellis et al 2012.02779]
- ➡ Dijets data in [Bordone et al 2103.10332] [Alioli et al 1706.03068]
- ➡ Drell-Yan data in [Farina et al 1609.08157] [Torre et al 2008.12978]
- ➡ Inclusive jets in [Alte et al 1711.07484]
- ➡ Overlap enhanced in HL-LHC projections [Abdul Khalek et al,1810.03639]



Abdul Khalek et al, arXiv:1810.03639

DARK PHOTON

M. McCullough, J. Moore, MU, arXiv:2203.12628



- If there was a lepto-phobic dark photon weakly coupled to quarks, it would appear among the partons of the proton.

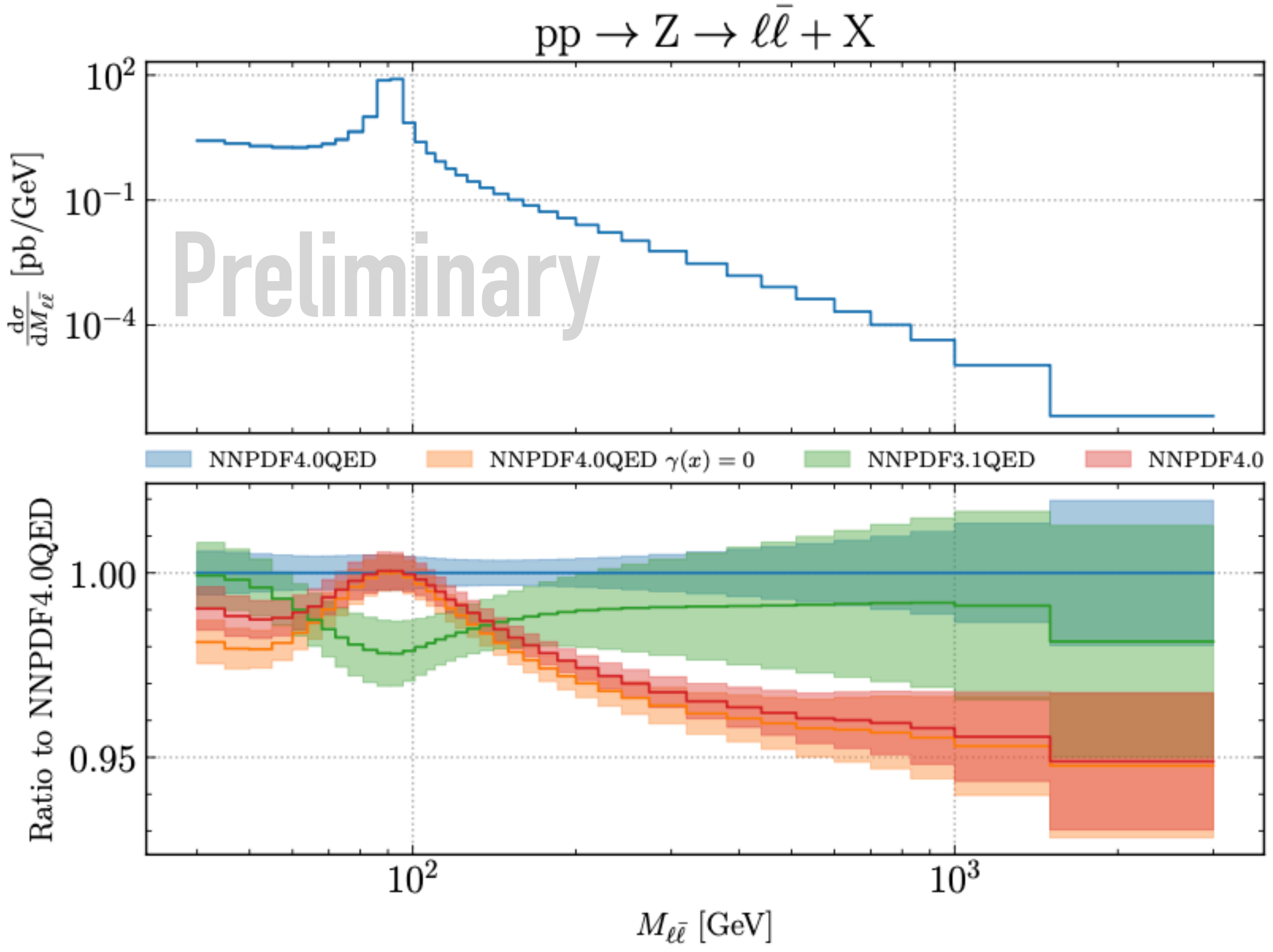
$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \not{B} q$$

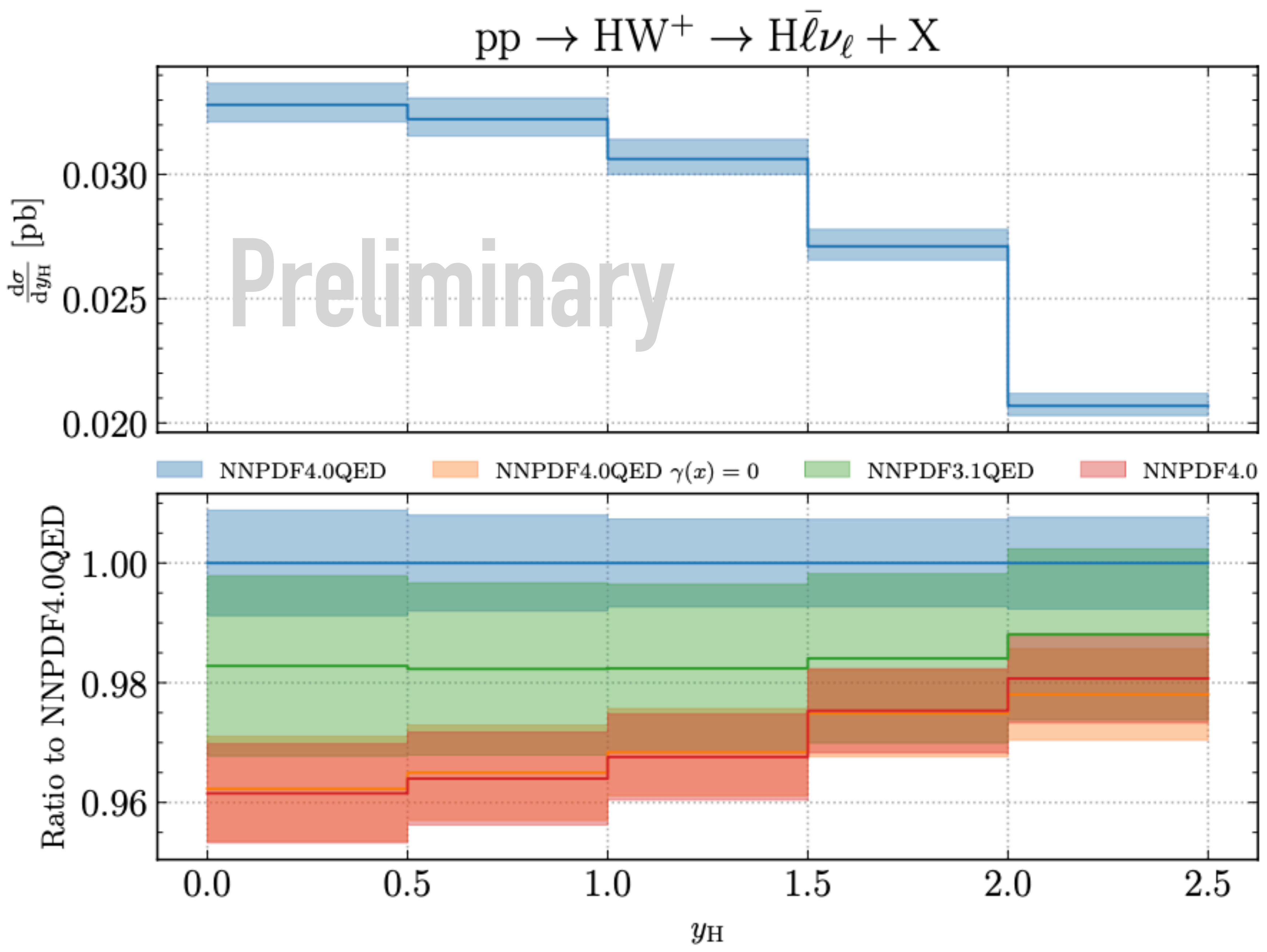
- The presence of the dark Parton would modify the evolution of standard quarks and gluon.

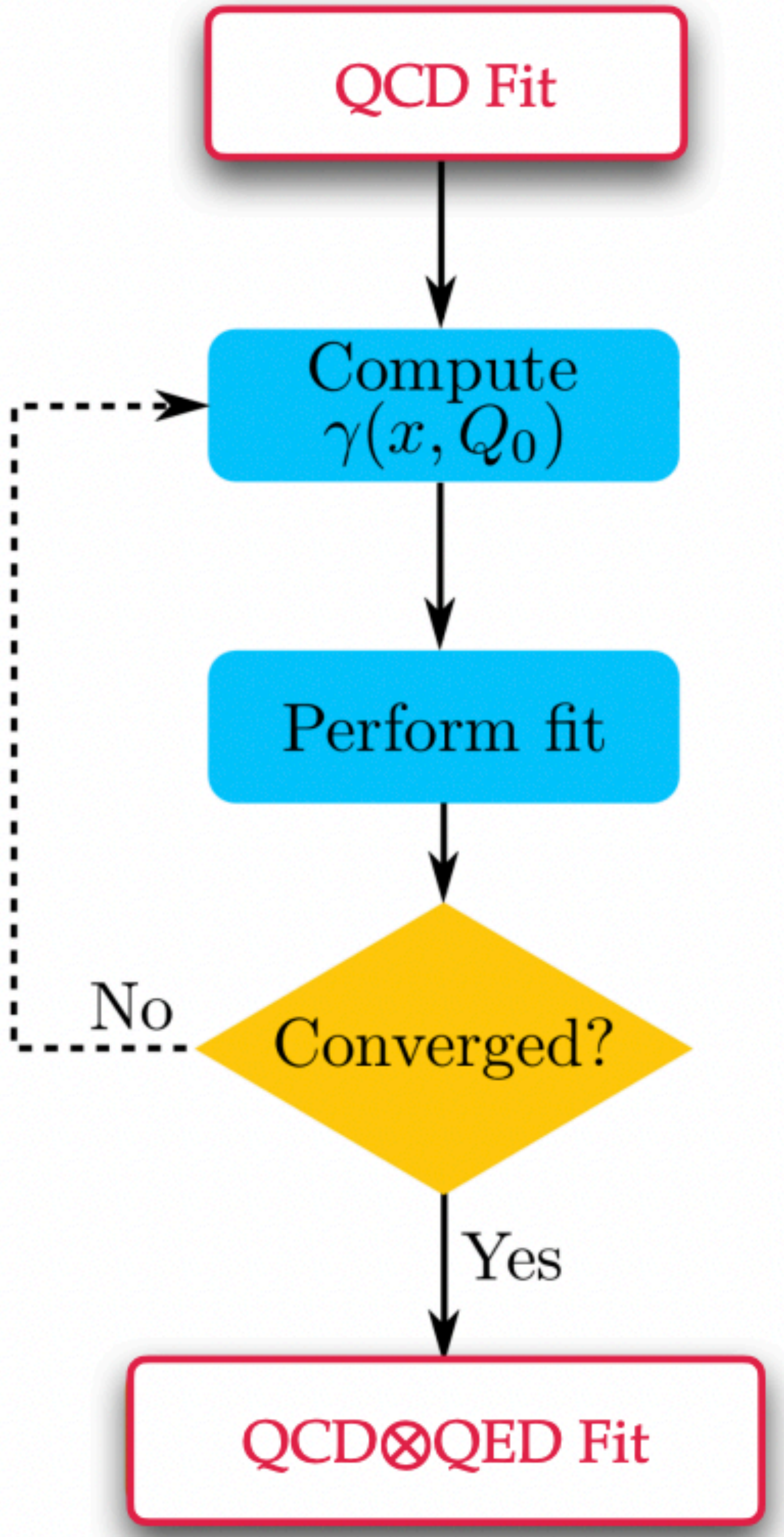
- Precise LHC data can indirectly constrain parameter space of the dark photon in a competitive way compared to direct searches

NNPDF40QED

- Two main changes required to account for QED effects in PDF fits: modified DGLAP equations including $O(\alpha_s\alpha)$ and $O(\alpha^2)$ terms and mixed QCDxQED sum rules implemented in new theory pipeline given by EKO [Candido, Hekhorn, Magni arXiv:2202.02338] and Yadism [Candido, Hekhorn in preparation]
- **NNPDF4.0QED:** PDFs and photon determined such that they satisfy sum rules
- Photon iteratively computed during the fit using structure function input a la LUXQED Manohar, Nason, Salam, Zanderighi [arXiv:1607.04266,1708.01256]







NNPDF [arXiv:1712.07053]

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