Updates on PDFs

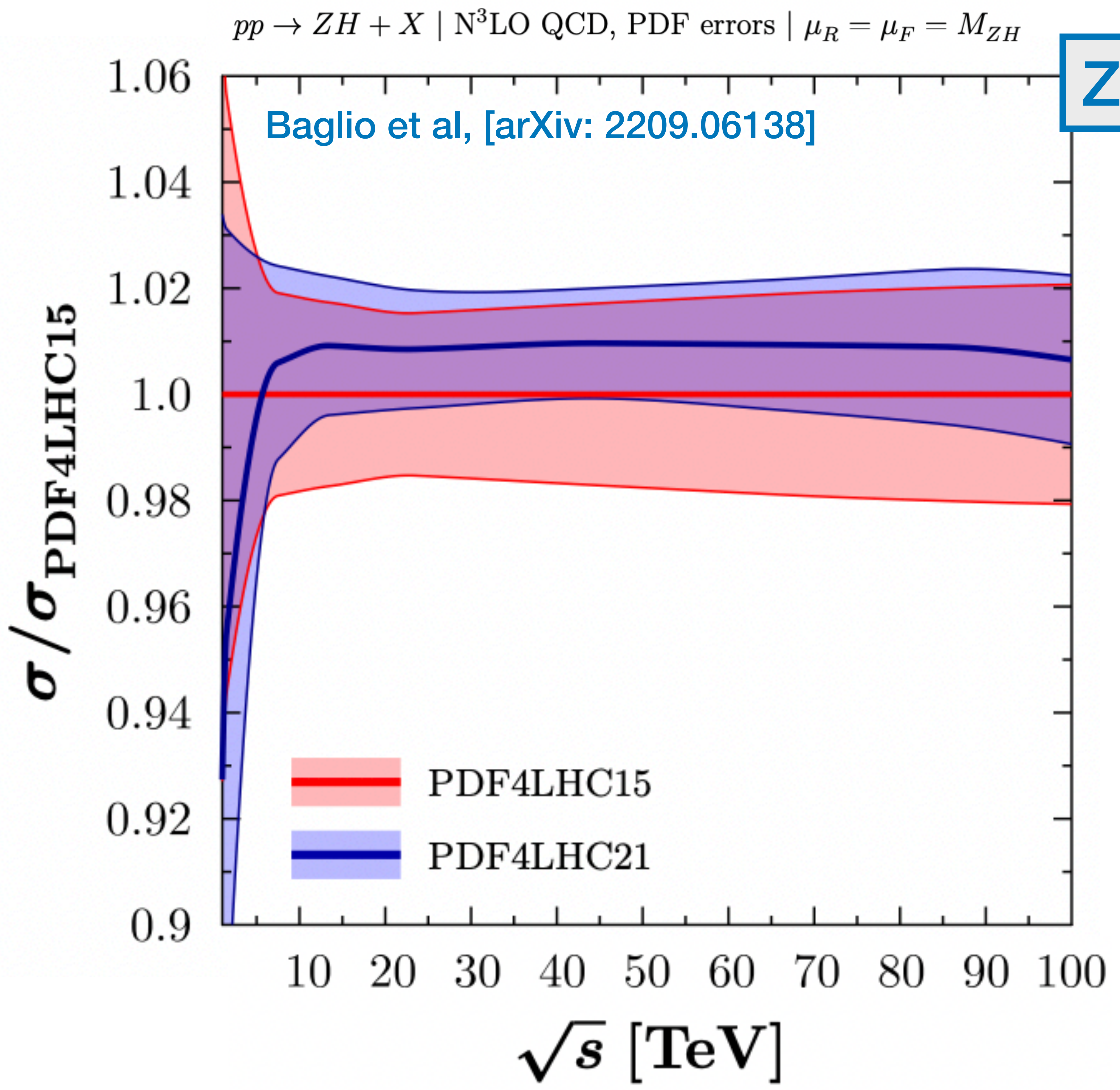
WG1 PDF subgroup:
J. Bendavid (CMS), J. Houston (ATLAS)
J. Houston, R. Thorne, M. Ubiali (Theory)

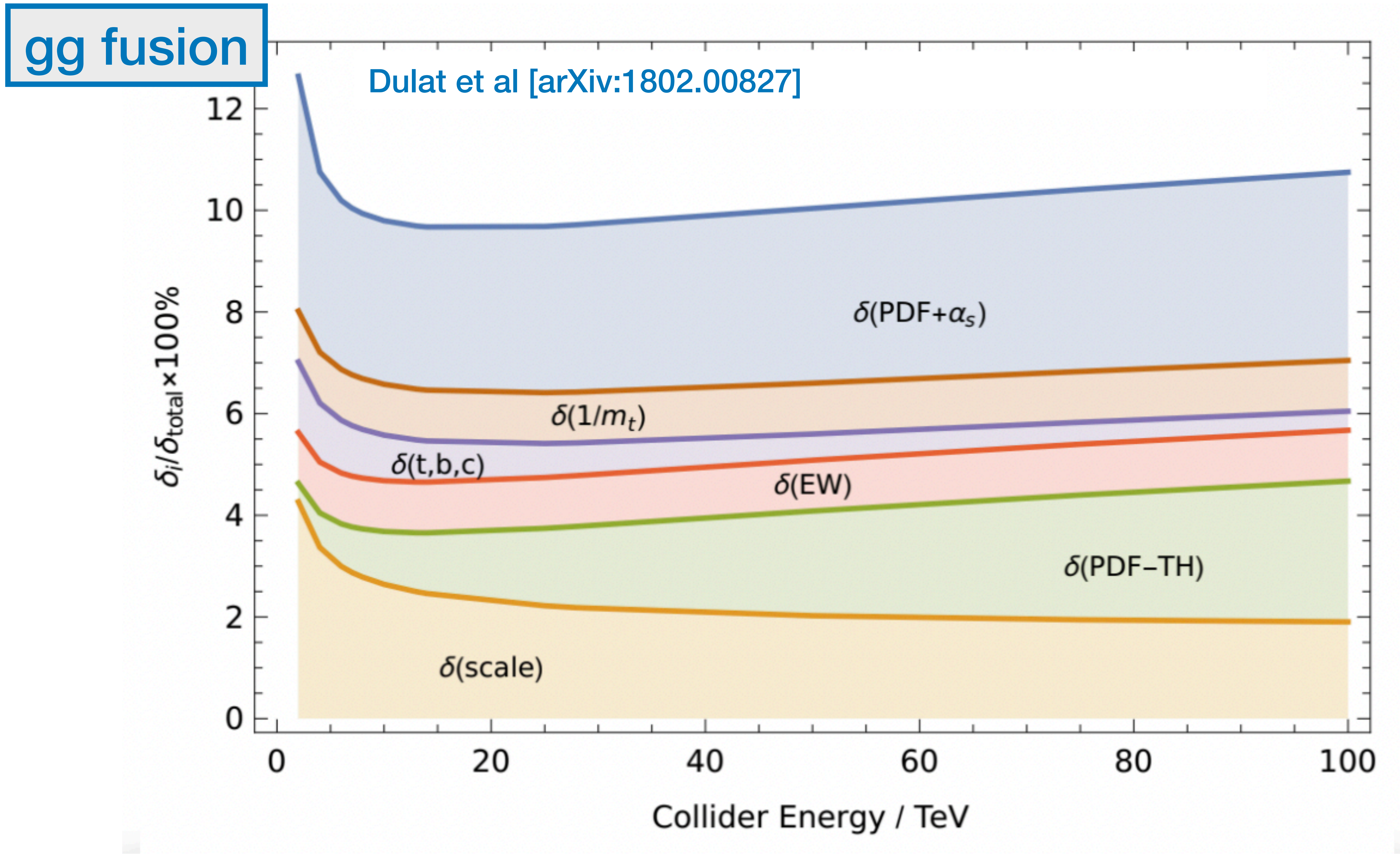
Outline

- Introduction
- Part I: Updates from PDF collaborations
- Part II: Towards N^3LO PDFs and ongoing benchmarks
- Conclusions

Introduction

PDFs and Higgs Physics

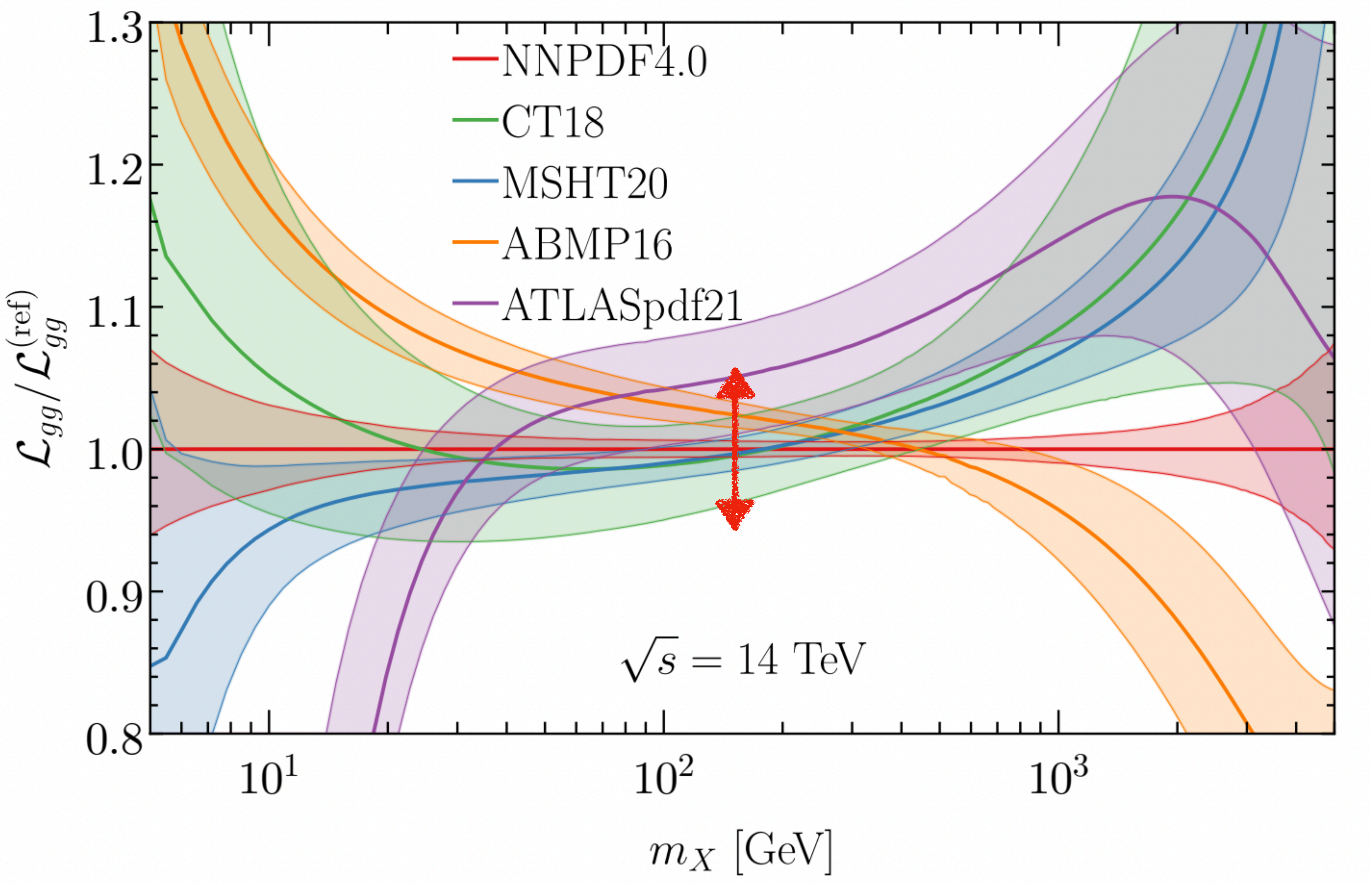




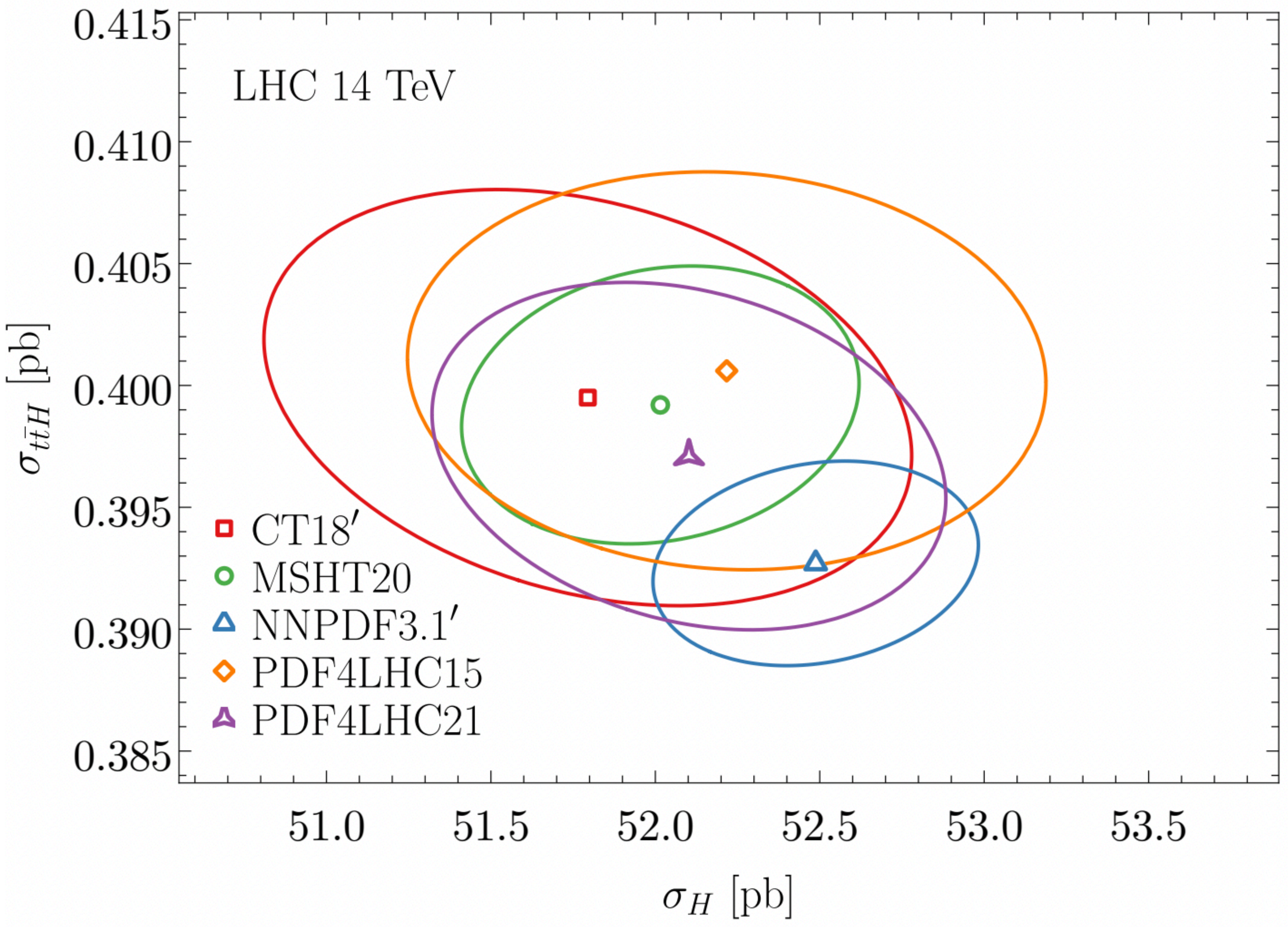
- Current theoretical uncertainty for Higgs xsec predictions dominated by PDF uncertainties.
- As of late 2022 mismatch between accuracy of predictions for Higgs partonic xsec and PDFs significant uncertainty, N^{3}LO for ggF arXiv:1503.06056, VBF arxiv:1606.00840, 1904.09990, 2004.04752 and VH arXiv: 2209.06138,2107.09085, 2207.07056
- New aN3LO from MSHT arXiv:2207.04739 and NNPDF (coming soon) - see part II of this talk

Where we stand

Snowmass 2021 white paper [arXiv:2203.13923]



PDF4LHC21 combination [arXiv:2203.05506]



- 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.
- PDF4LHC21 study [arXiv:2203.05506]: once a common dataset is used, global fits agree in broad M_x range, different uncertainties associated to different methodologies.

Part I:
Updates from PDF collaborations

CT updates

L2 sensitivity studies

ANL-182798, DESY-23-068, FERMILAB-PUB-23-276-T, MSUHEP-23-016, SMU-HEP-23-02, PITT-PACC-2315

Quantifying the interplay of experimental constraints in analyses of parton distributions

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(Dated: June 6, 2023)

Abstract

Parton distribution functions (PDFs) play a central role in calculations for the Large Hadron Collider (LHC). To gain a deeper understanding of the emergence and interplay of constraints on the PDFs in the global QCD analyses, it is important to examine the relative significance and mutual compatibility of the experimental data sets included in the PDF fits. Toward this goal, we discuss the L_2 sensitivity, a convenient statistical indicator for exploring the statistical pulls of individual data sets on the best-fit PDFs and identifying tensions between competing data sets. Unlike the Lagrange Multiplier method, the L_2 sensitivity can be quickly computed for a range of PDFs and momentum fractions using the published Hessian error sets. We employ the L_2 sensitivity as a common metric to study the relative importance of data sets in the recent ATLAS, CTEQ-TEA, MSHT, and reduced PDF4LHC21 PDF analyses at NNLO and approximate N3LO. We illustrate how this method can aid the users of PDFs to identify data sets that are important for a PDF at a given kinematic point, to study quark flavor composition and other detailed features of the PDFs, and to compare the data pulls on the PDFs for various perturbative orders and functional forms. We also address the feasibility of computing the sensitivities using Monte Carlo error PDFs. Together with the article, we present a companion interactive website with a large collection of plotted L_2 sensitivities for eight recent PDF releases and a C++ program to plot the L_2 sensitivities.

Two websites can be used to explore L_2 sensitivity for CT18, MSHT20 (NNLO and aN3LO) and ATLASpdf21

https://www.physics.smu.edu/nadolsky/work/pdf4lhc21/L2sens/index2.html

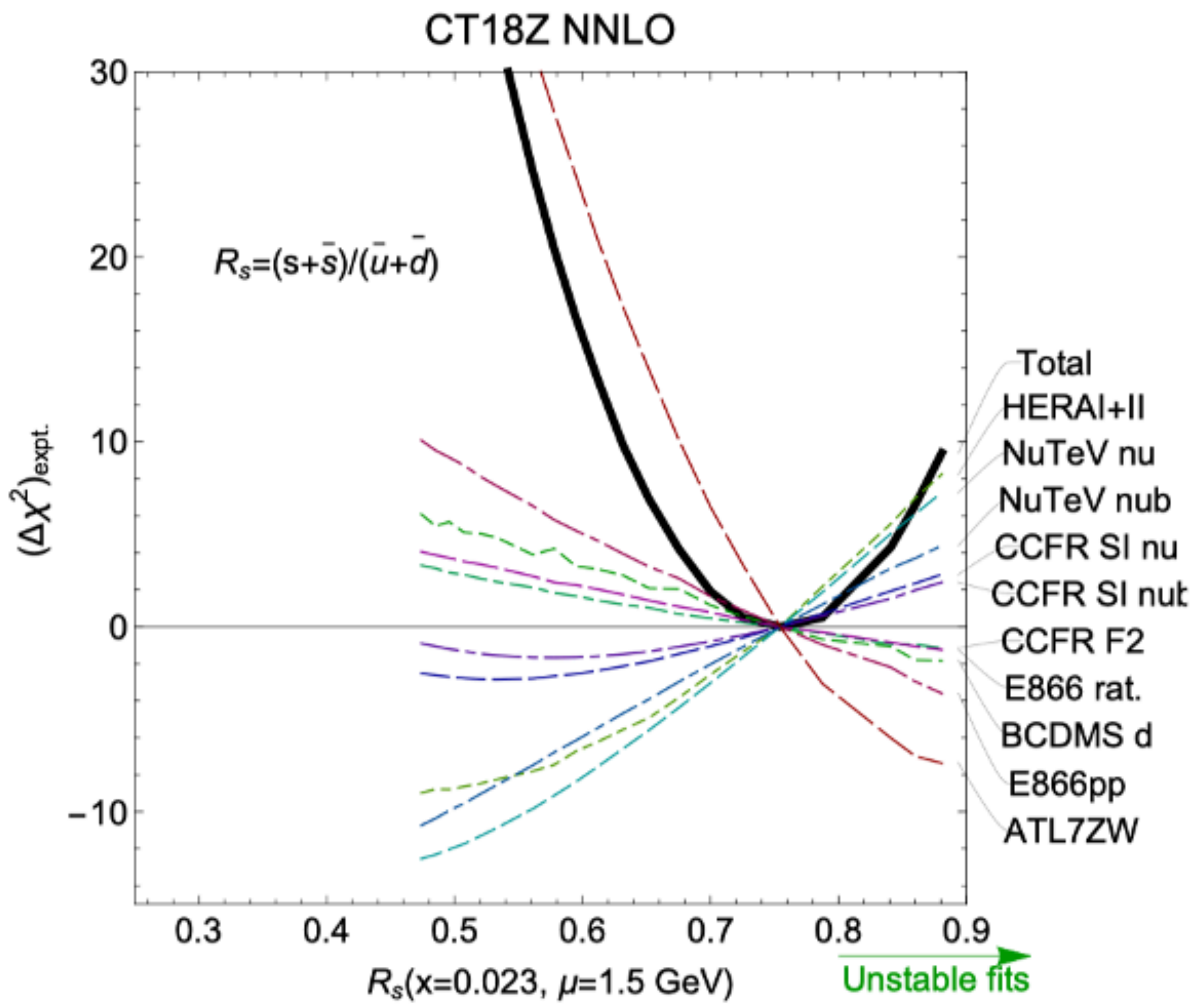
https://www.physics.smu.edu/nadolsky/work/pdf4lhc21/L2sens/index3.html

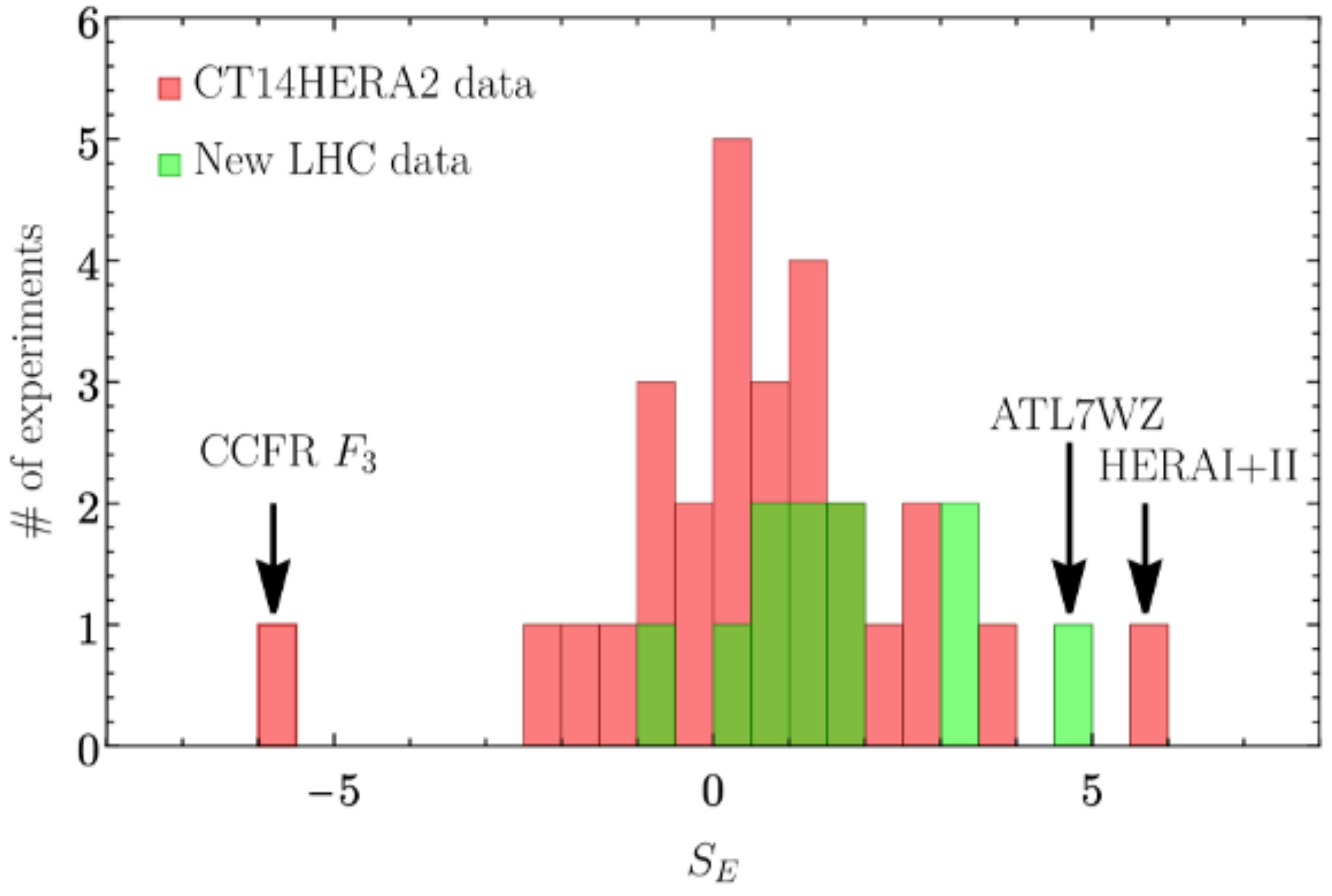
CT updates

@Joey Huston

More flexible strange parametrisation

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





$$S_E = \sqrt{\chi^2} - \sqrt{2N_E - 1}$$

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

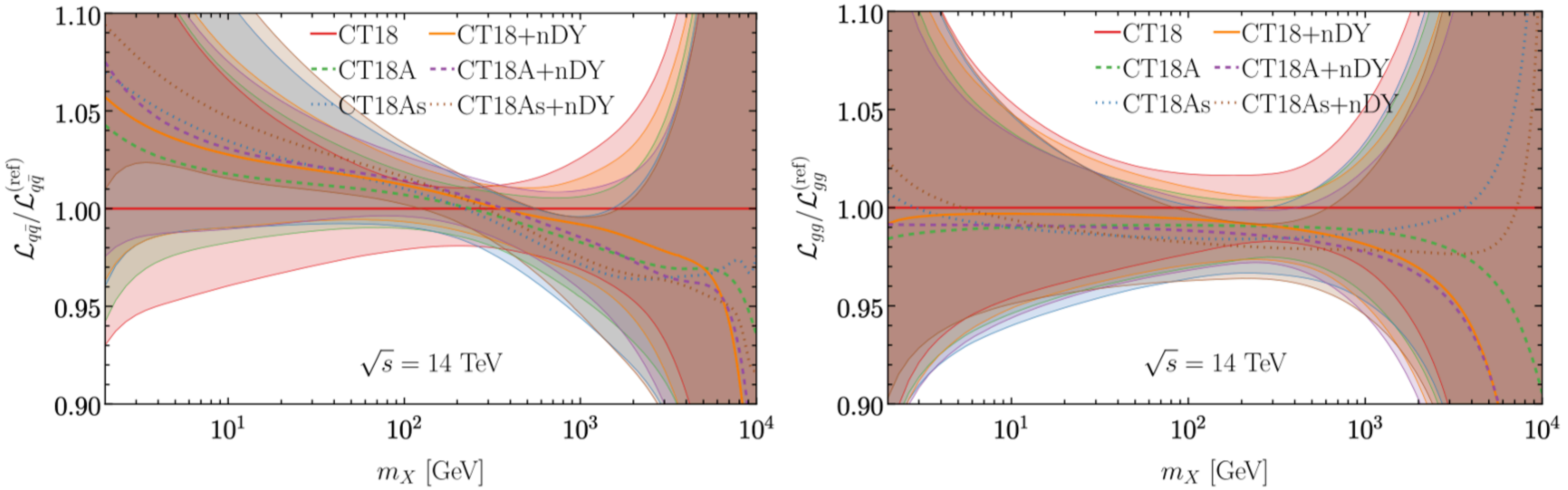
Hou et al, arXiv:2211.11064

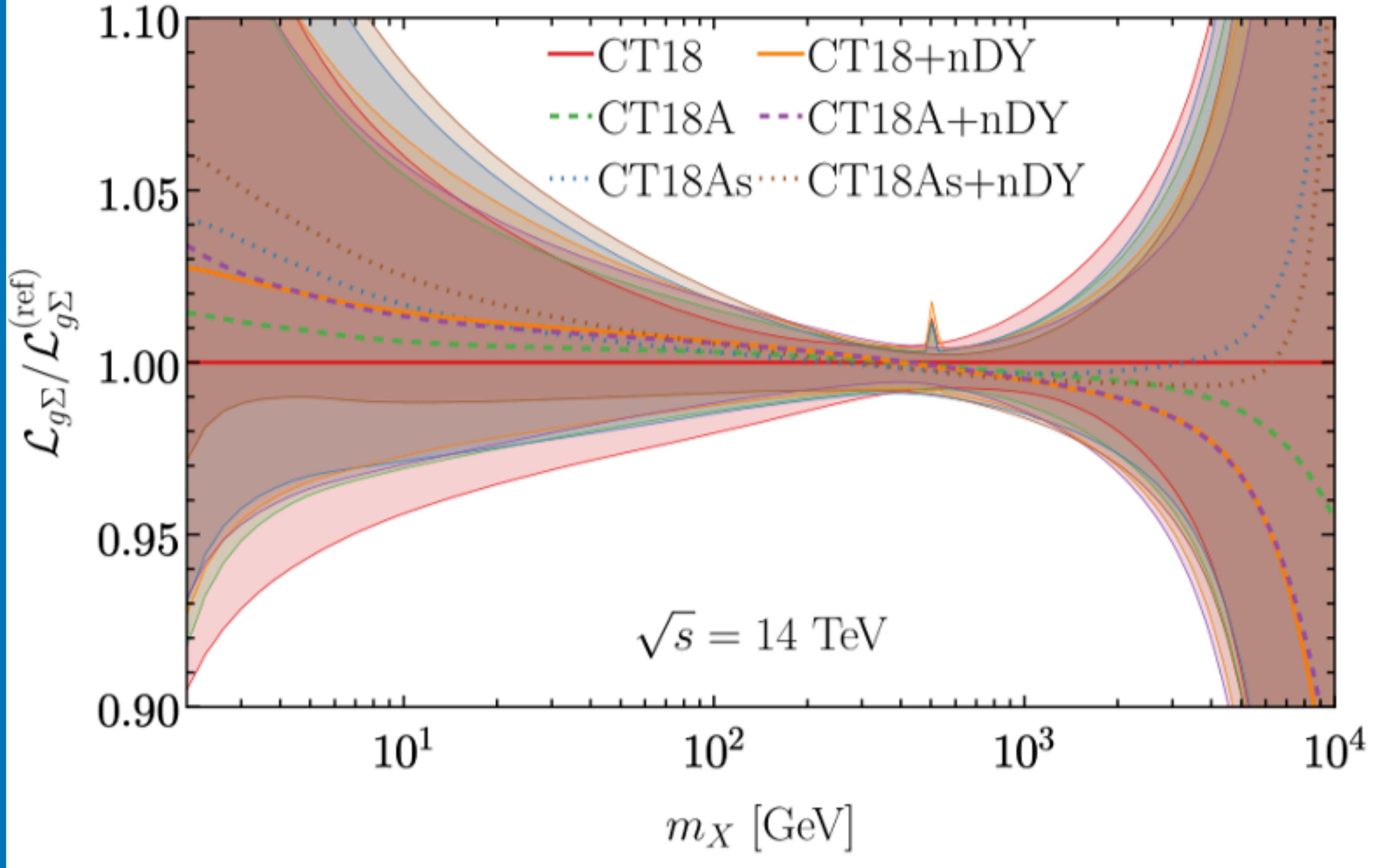
CT updates

@Joey Huston

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

New Drell-Yan data **[Phys.Rev.D 108 (2023) 3, 034030]**

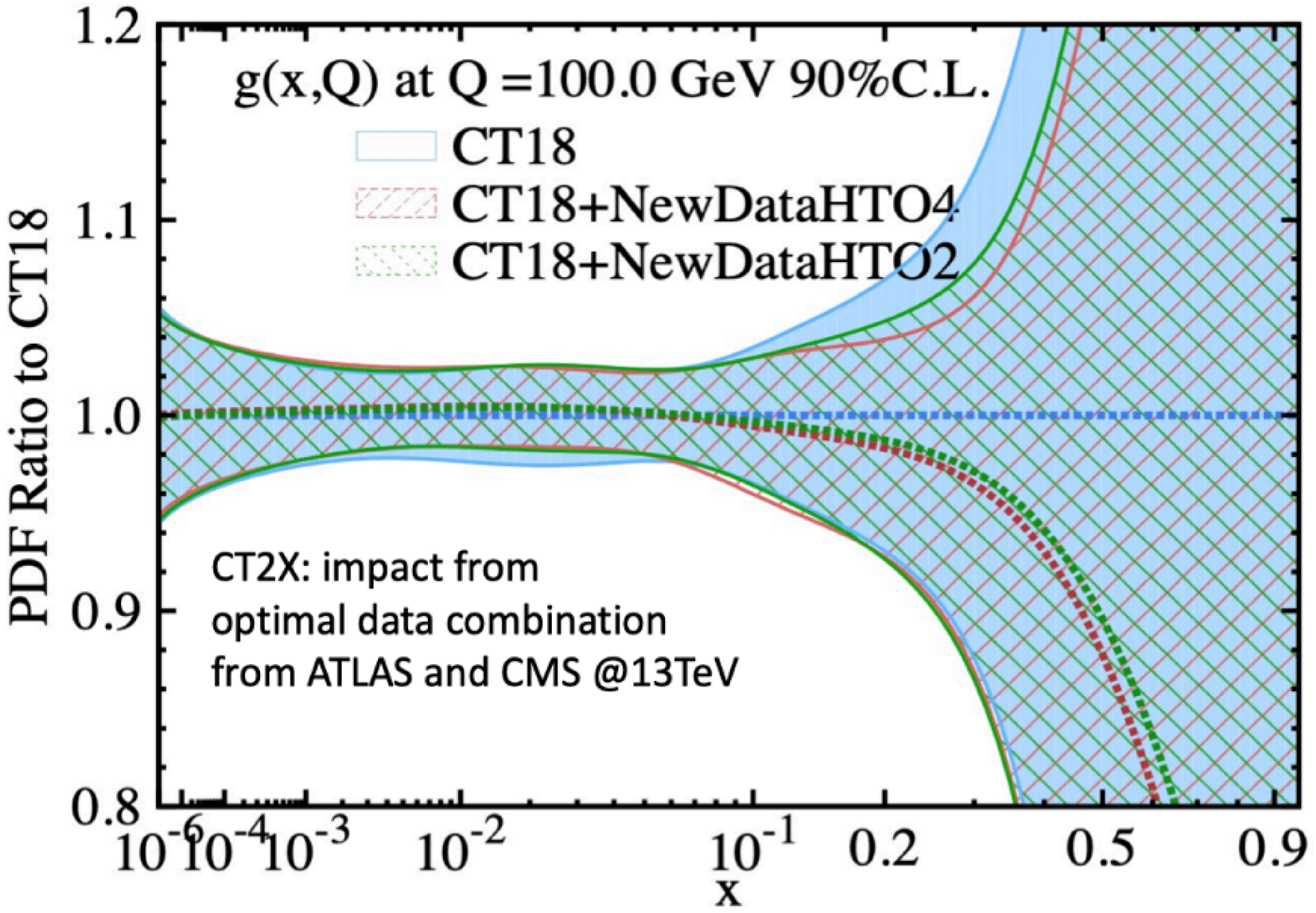




- The new Drell-Yan data increases (decreases) the quark-related luminosity at low (high) invariant mass
- …with a reduction in the size of the error bands
- The more flexible strangeness parameterization in CT18As can enlarge the uncertainty bands for quark-related parton luminosities

CT updates

New top-quark data, impact of new baseline and scale choice [arXiv:2307.11153]



Theory predictions:

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

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

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

Optimal baseline consists of 1D absolute Xsec from

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

Reduction in scale uncertainty observed in ggF Higgs region

MSHT updates

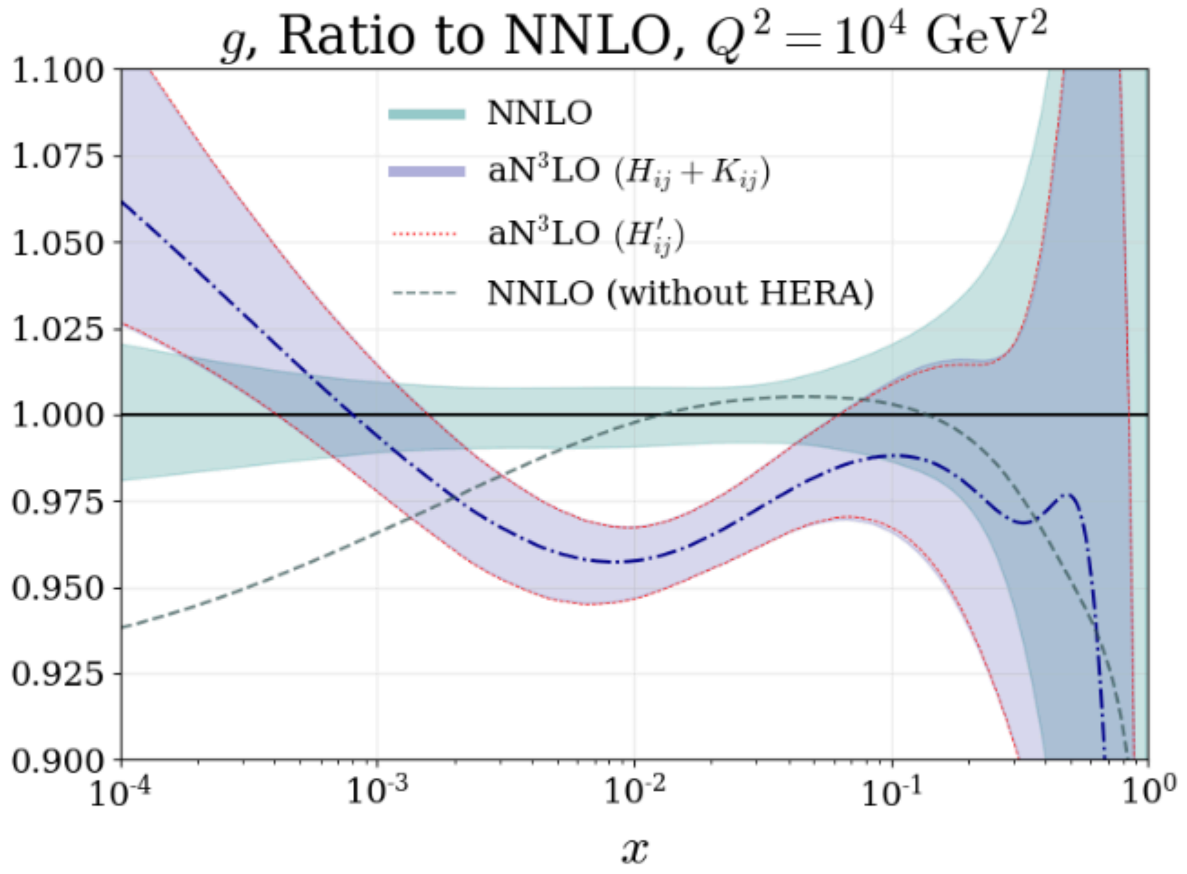
@Lucian Harland-Lang

- Range of projects being pursued post-MSHT20 release: **(More later)**

  ★ **MSHTaN3LO** - first global PDF fit at approximate N3LO order.

  ★ Combines known N3LO info with unknown pieces + theory uncertainty.

  J. McGowan et al., Eur.Phys.J.C 83 (2023) 3



- Follow up study. Impact of LHC inclusive jet vs. dijet data at up to aN3LO:

  ★ Fit quality better for dijet case irrespective of order (NNLO vs. aN3LO).

  In preparation - stay tuned.

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

Jet fit:

	$N_{\rm pts}$	NNLO	aN^{3}LO
ATLAS 7 TeV jets	140	1.54	1.46
CMS 7 TeV jets	158	1.29	1.32
ATLAS 8 TeV jets	171	1.96	1.90
CMS 8 TeV jets	174	1.83	1.80
Total Jets	643	1.67	1.63

Dijet fit:

	$N_{\rm pts}$	NNLO	aN^{3}LO
ATLAS 7 TeV dijets	90	1.06	1.12
CMS 7 TeV dijets	54	1.43	1.39
CMS 8 TeV dijets	122	1.05	0.82
Total Dijets	266	1.13	1.04

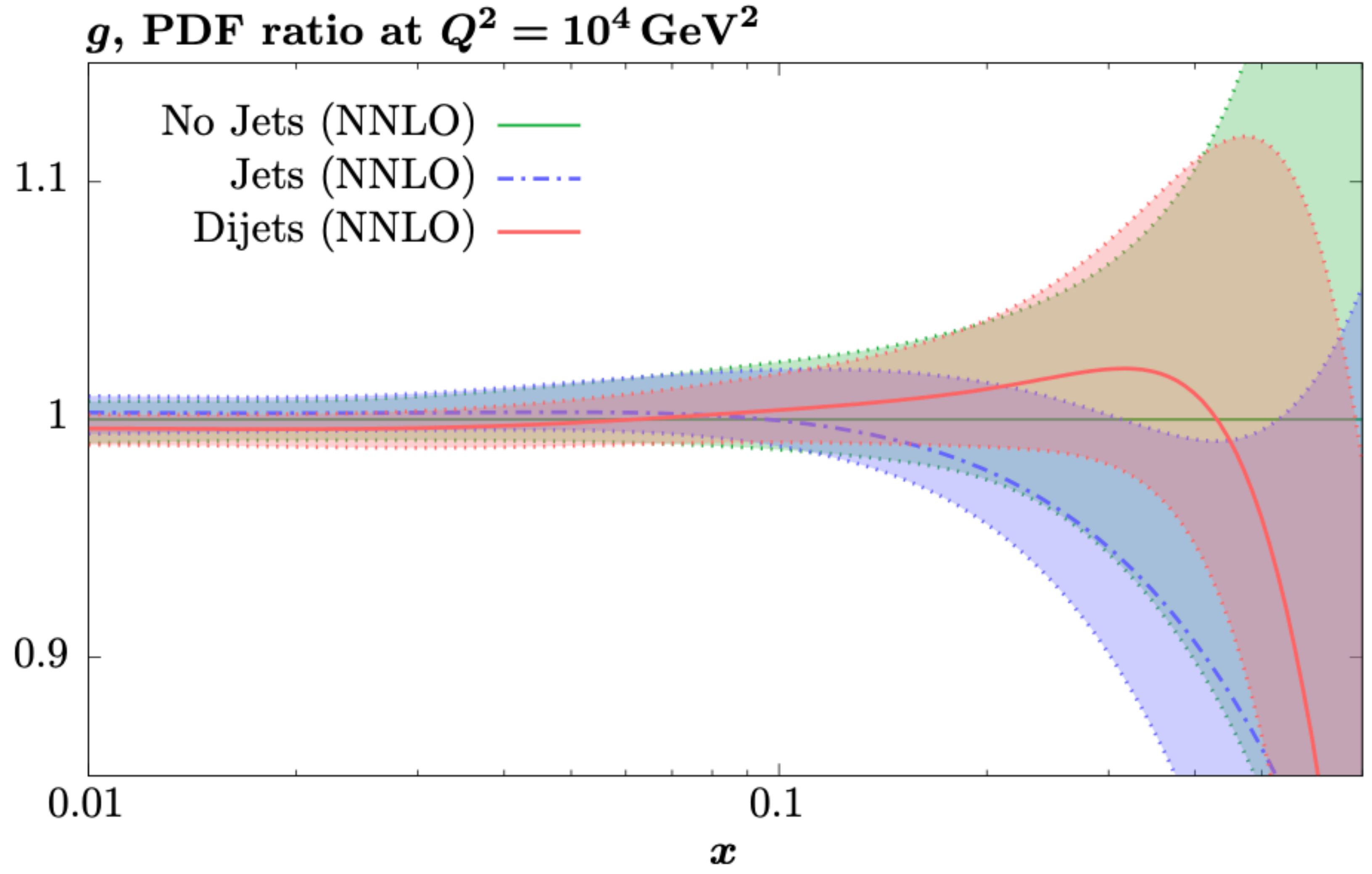
MSHT updates

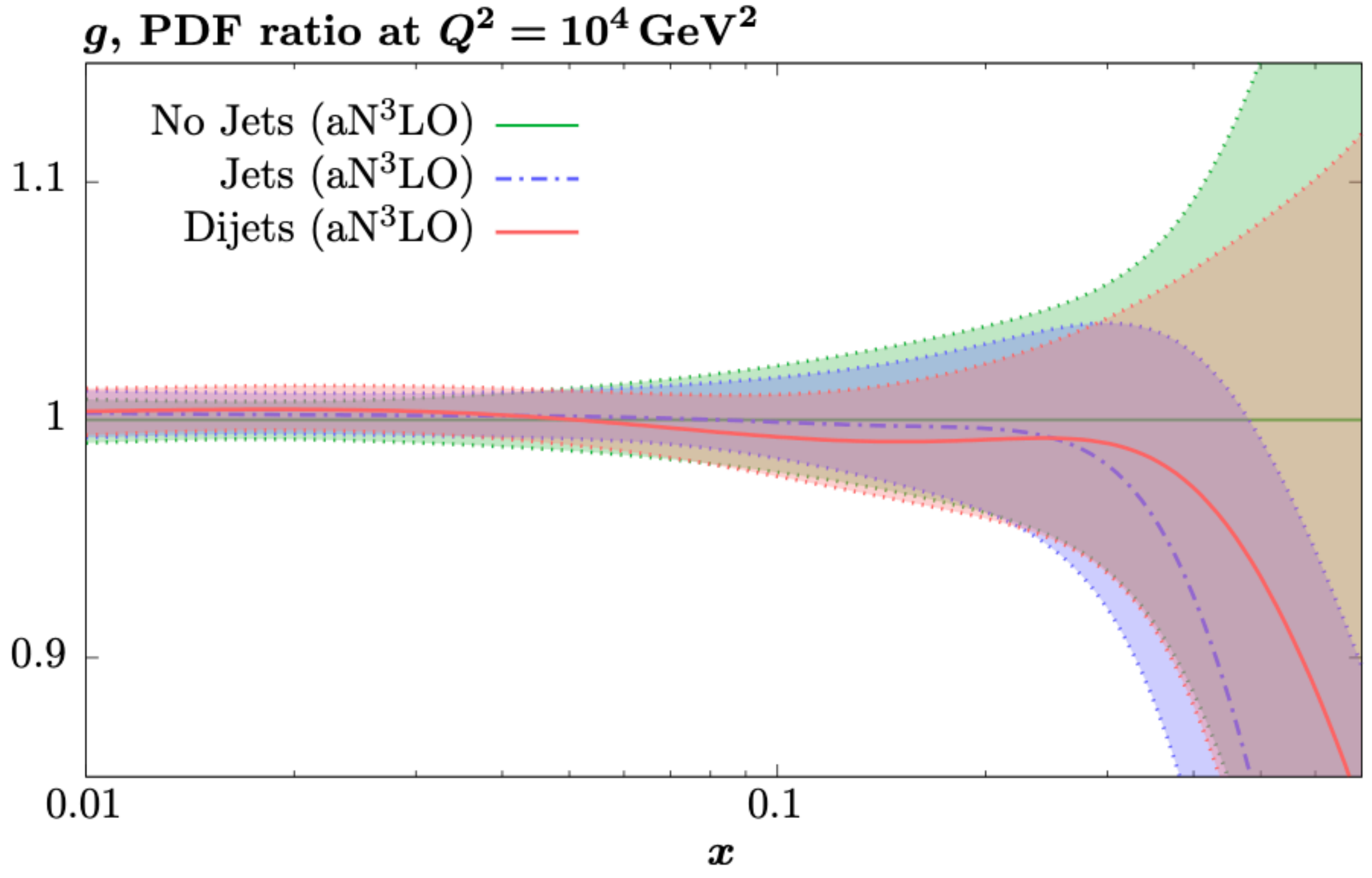
@Lucian Harland-Lang

★ Some difference in PDFs at NNLO…

★ …but more stable at aN3LO. → Some preference for dijet data.

★ Dijets somewhat more constraining.

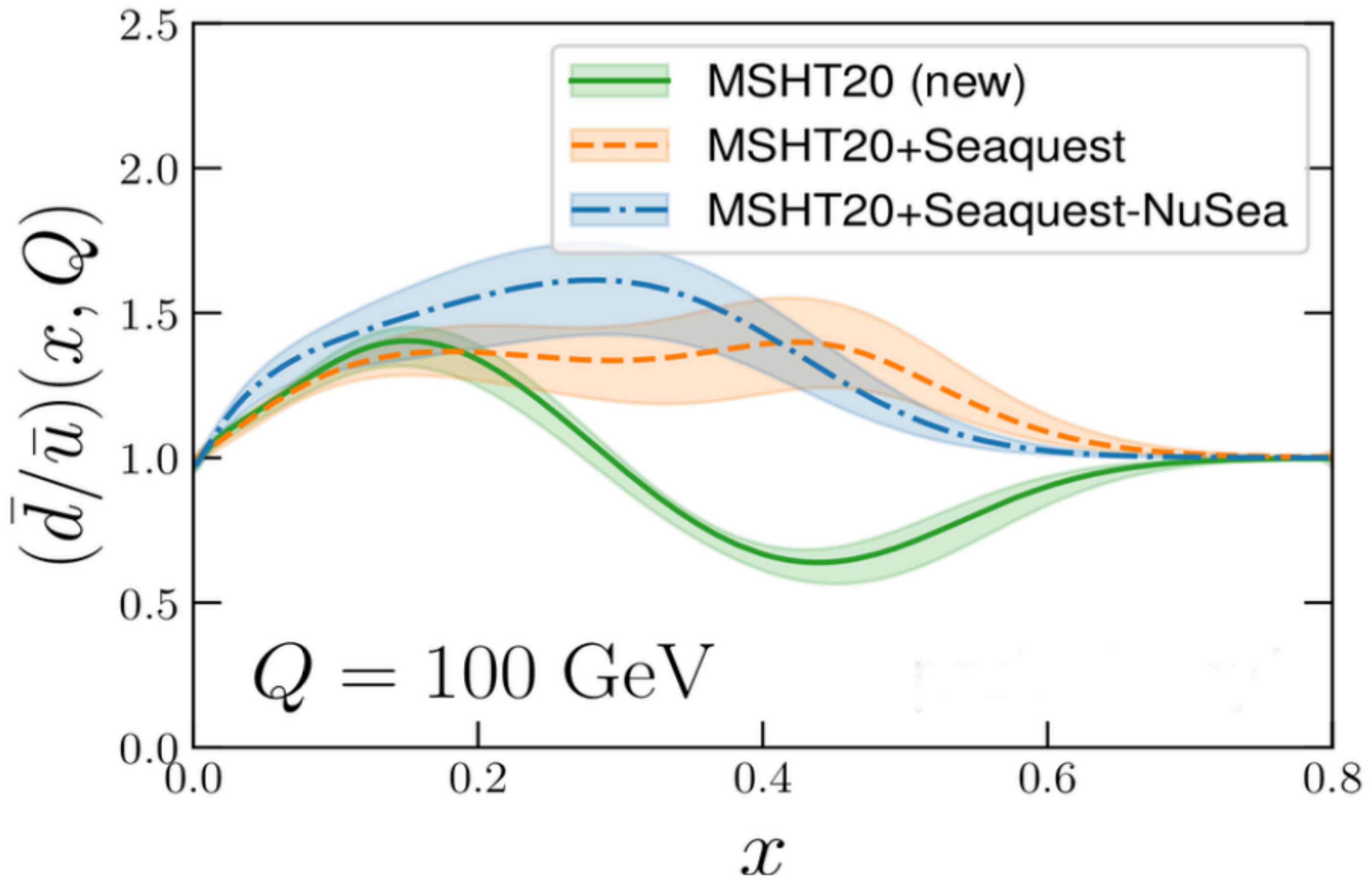




- Other datasets being looked at, e.g. Seaquest:

  ★ Sensitive to high x quark flavour decomposition.

  ★ Find it raises the $x\ \bar{d}/\bar{u}$. Some tension with other data.



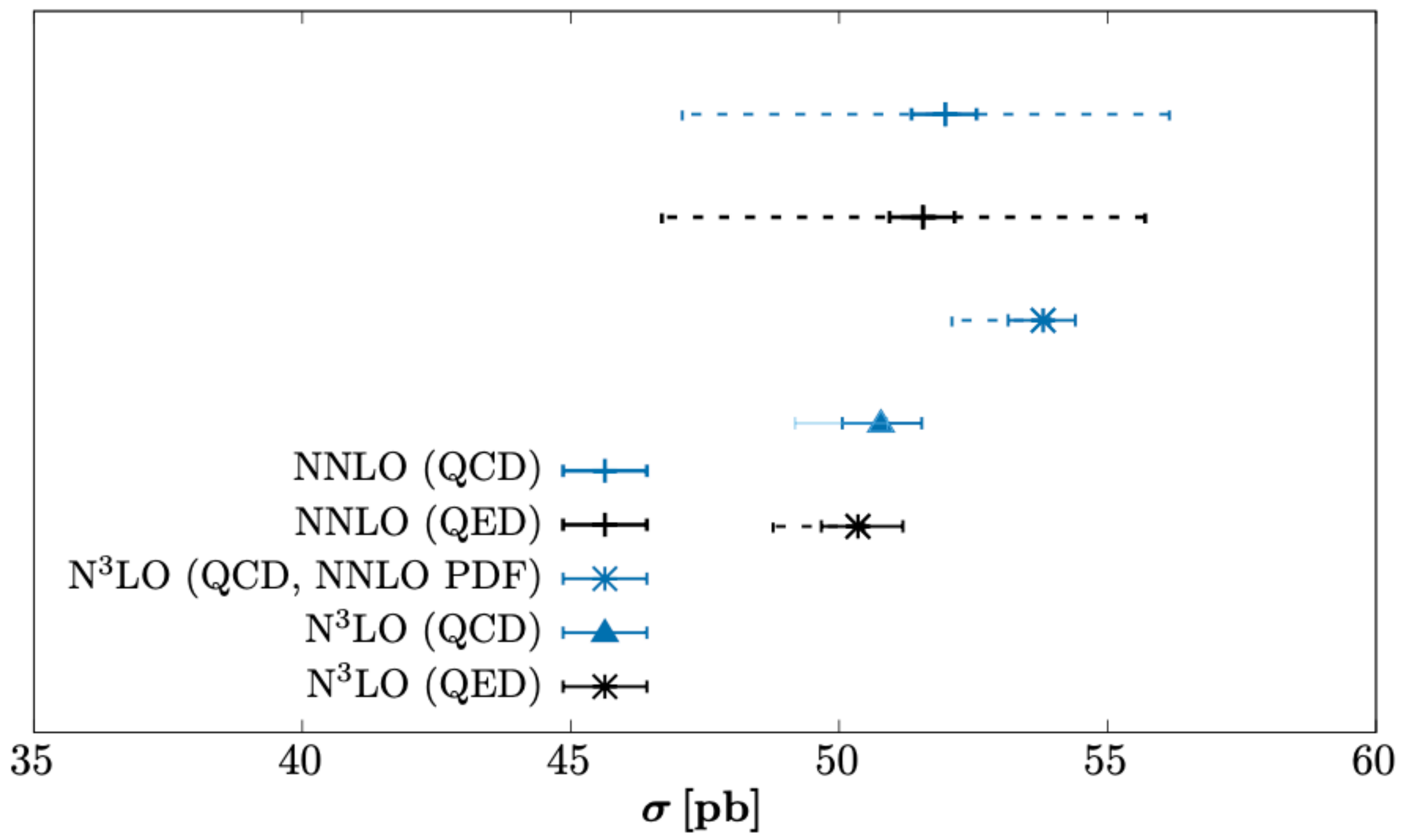
MSHT updates

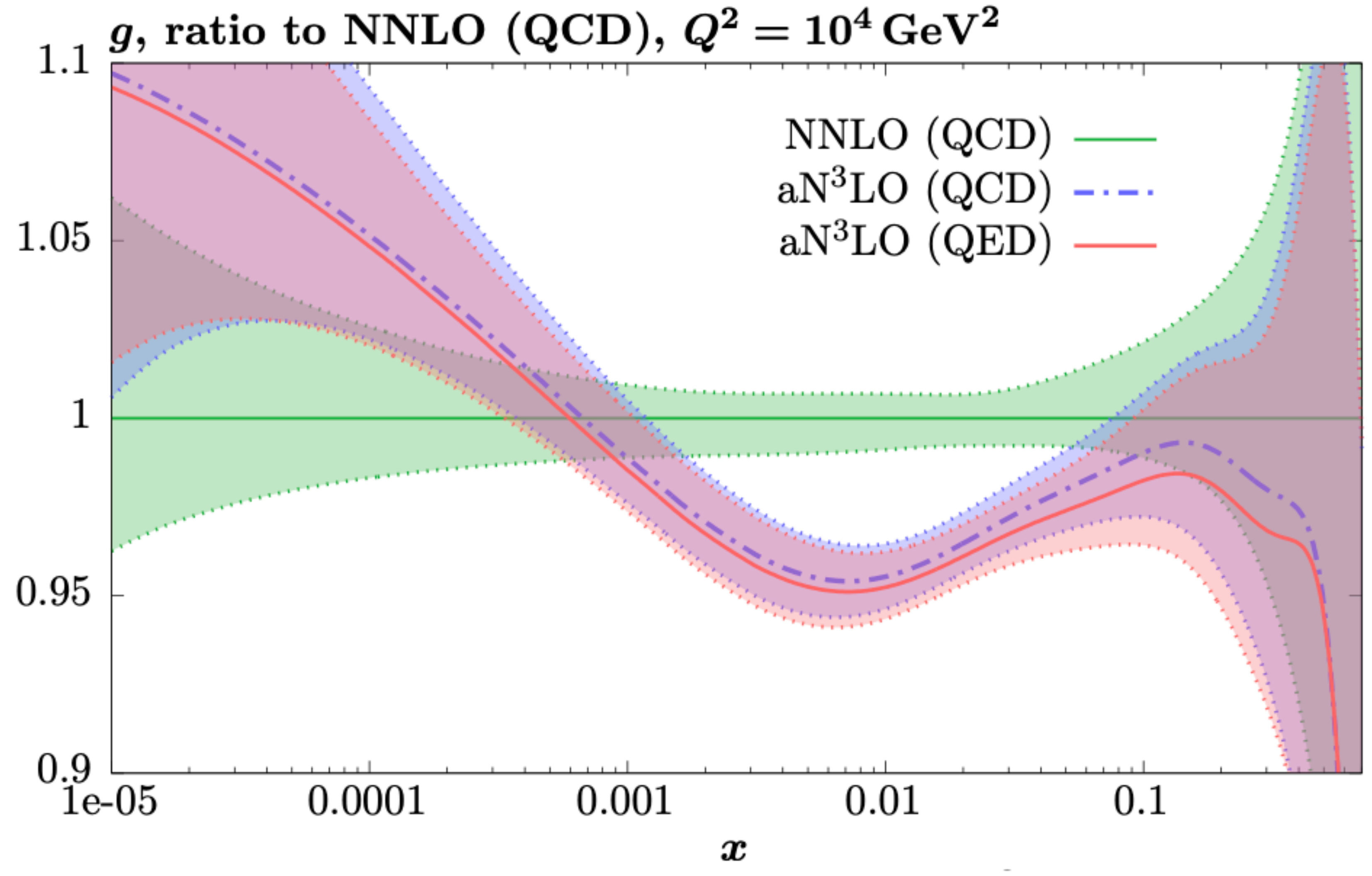
@Lucian Harland-Lang

- Combining aN3LO QCD with QED effects in MSHT fit.
  - ★ Question: what is effect of QED DGLAP/photon PDF on aN3LO fit? Same as NNLO?
  - ★ Include both in MSHT fit.

$$P_{ij} = \frac{\alpha}{2\pi} P_{ij}^{(0,1)} + \frac{\alpha\alpha_S}{(2\pi)^2} P_{ij}^{(1,1)} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2)} + \frac{\alpha_S}{2\pi} P_{ij}^{(1,0)} + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ij}^{(2,0)} + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ij}^{(3,0)} + \left(\frac{\alpha_S}{2\pi}\right)^4 P_{ij}^{(4,0)} .$$

- ★ Effect on PDFs very similar to NNLO case. E.g. some (further) reduction in gluon due to momentum sum rule.
- ★ Leads to further mild reduction in e.g. ggH.

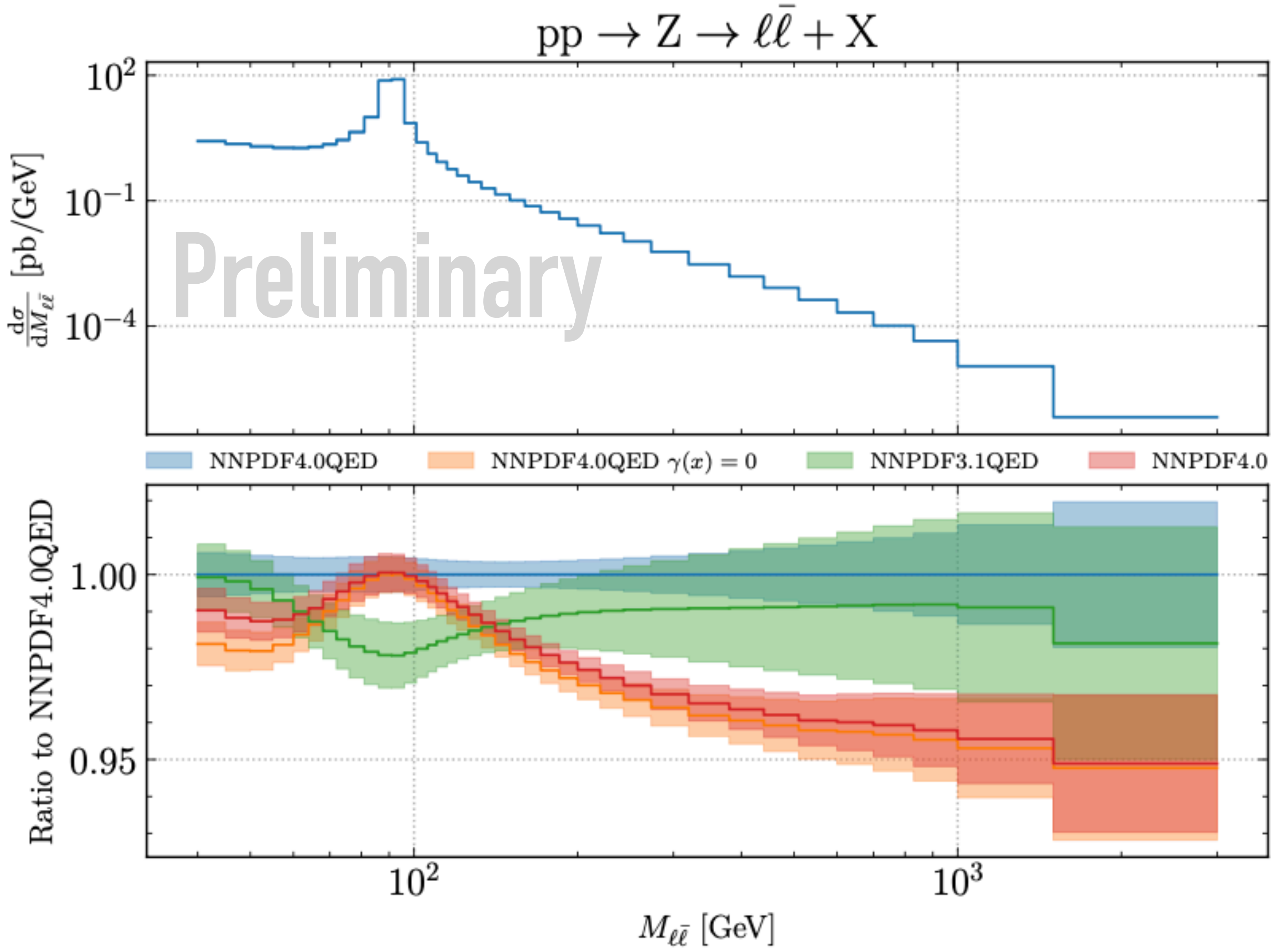


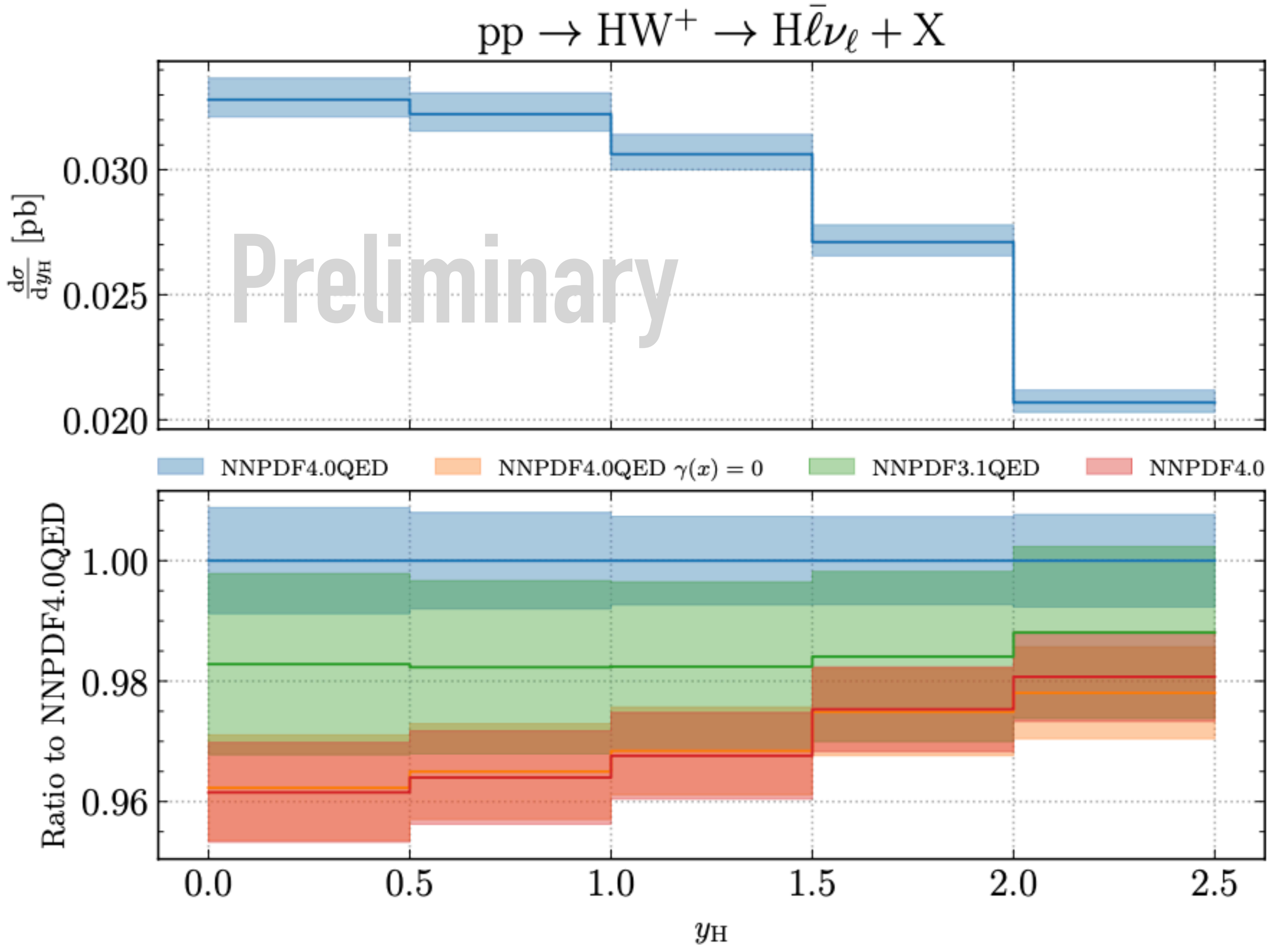


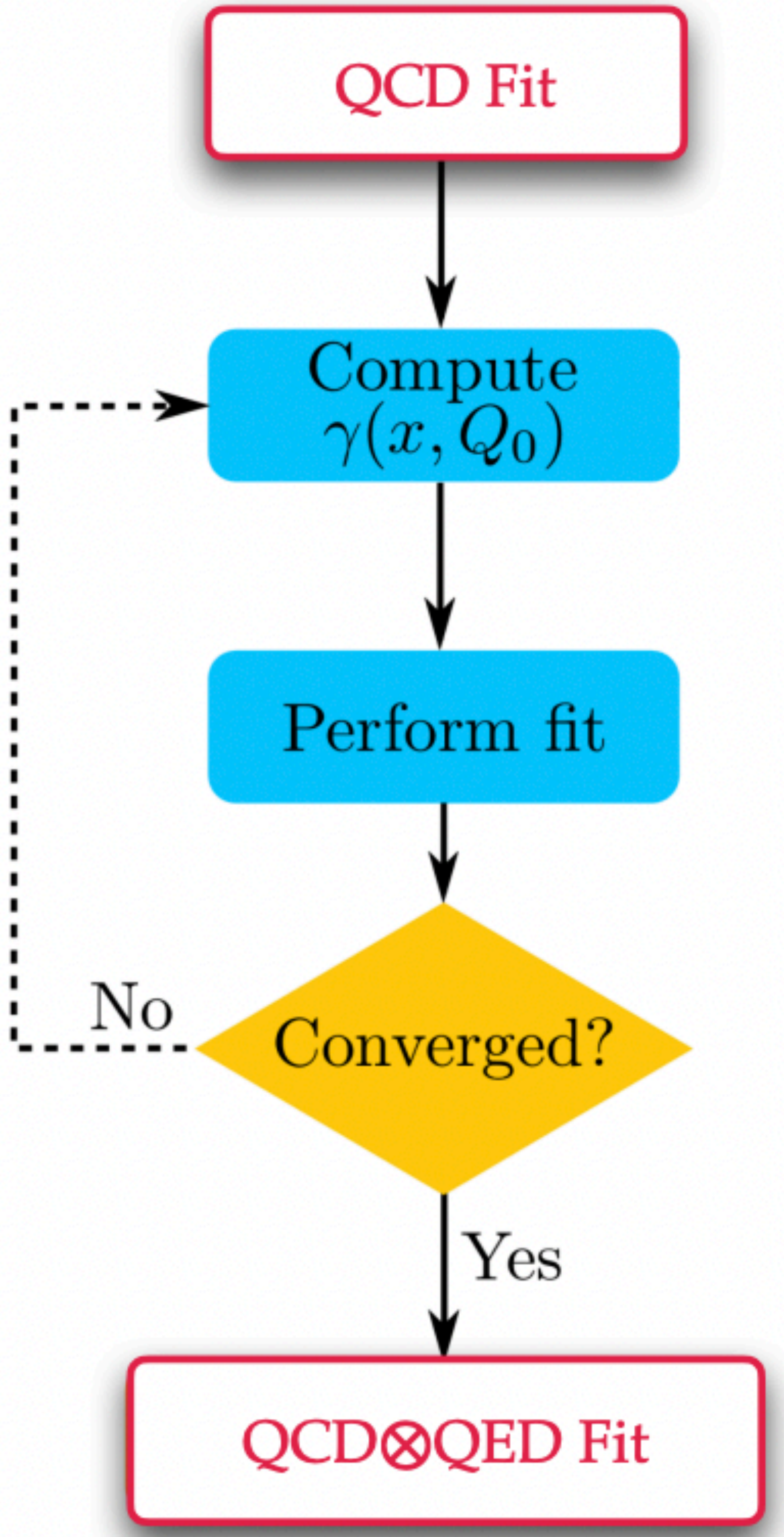
In preparation - stay tuned.

NNPDF updates

- 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]

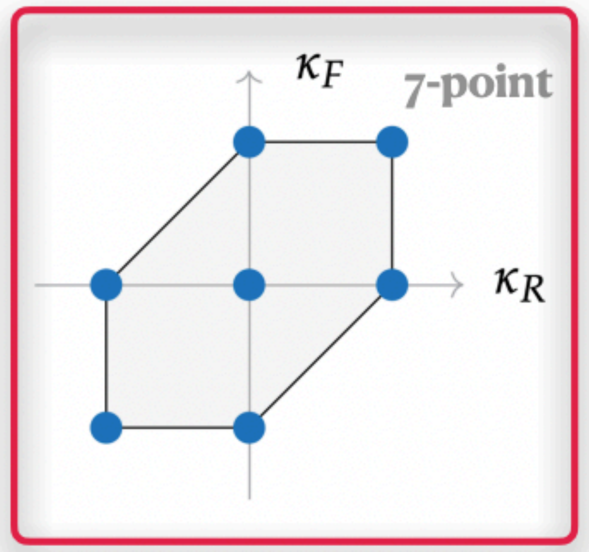
@Tanjona R. Rabemananjara

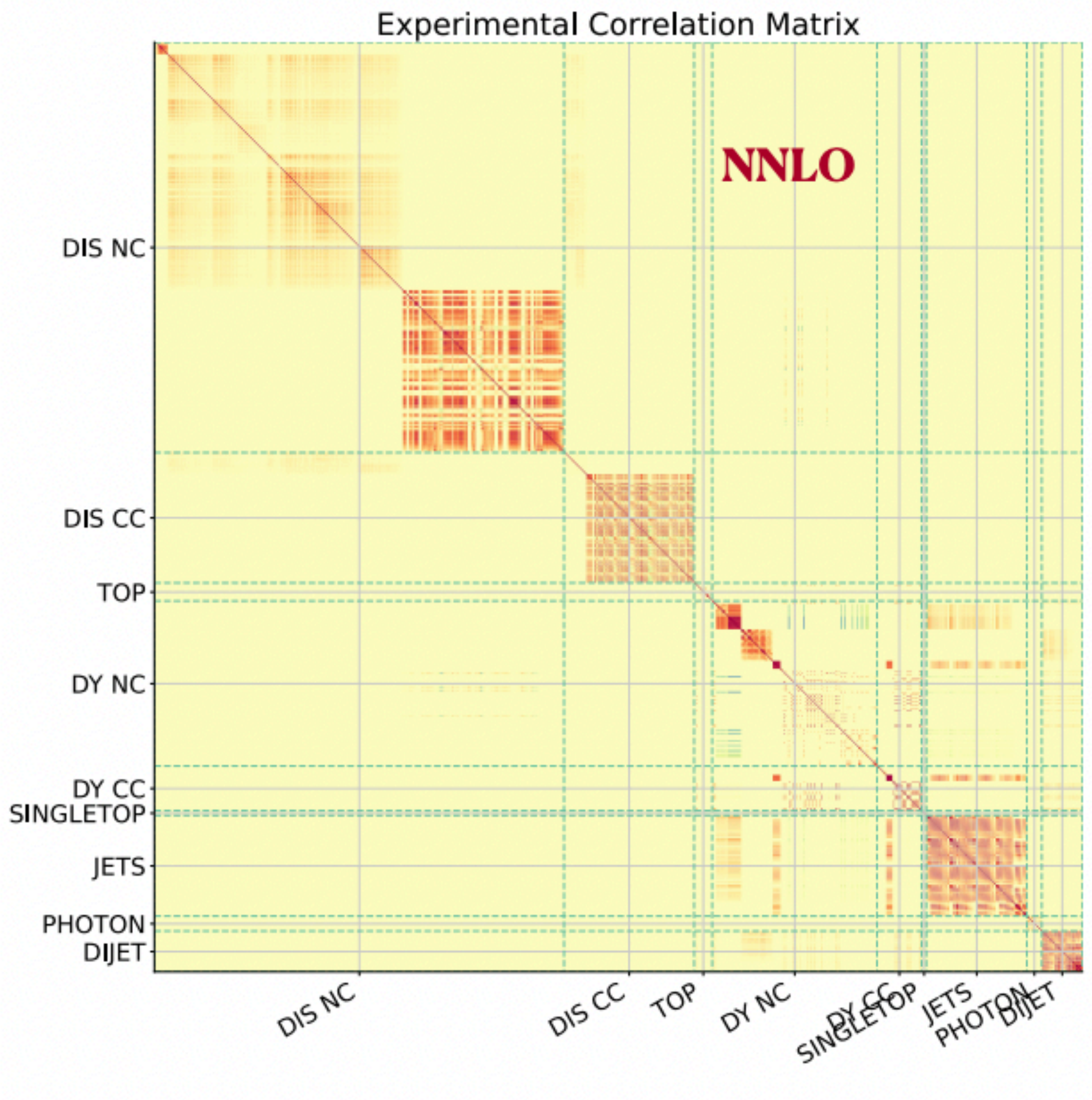
NNPDF40QED - arXiv:2311.xxxxx

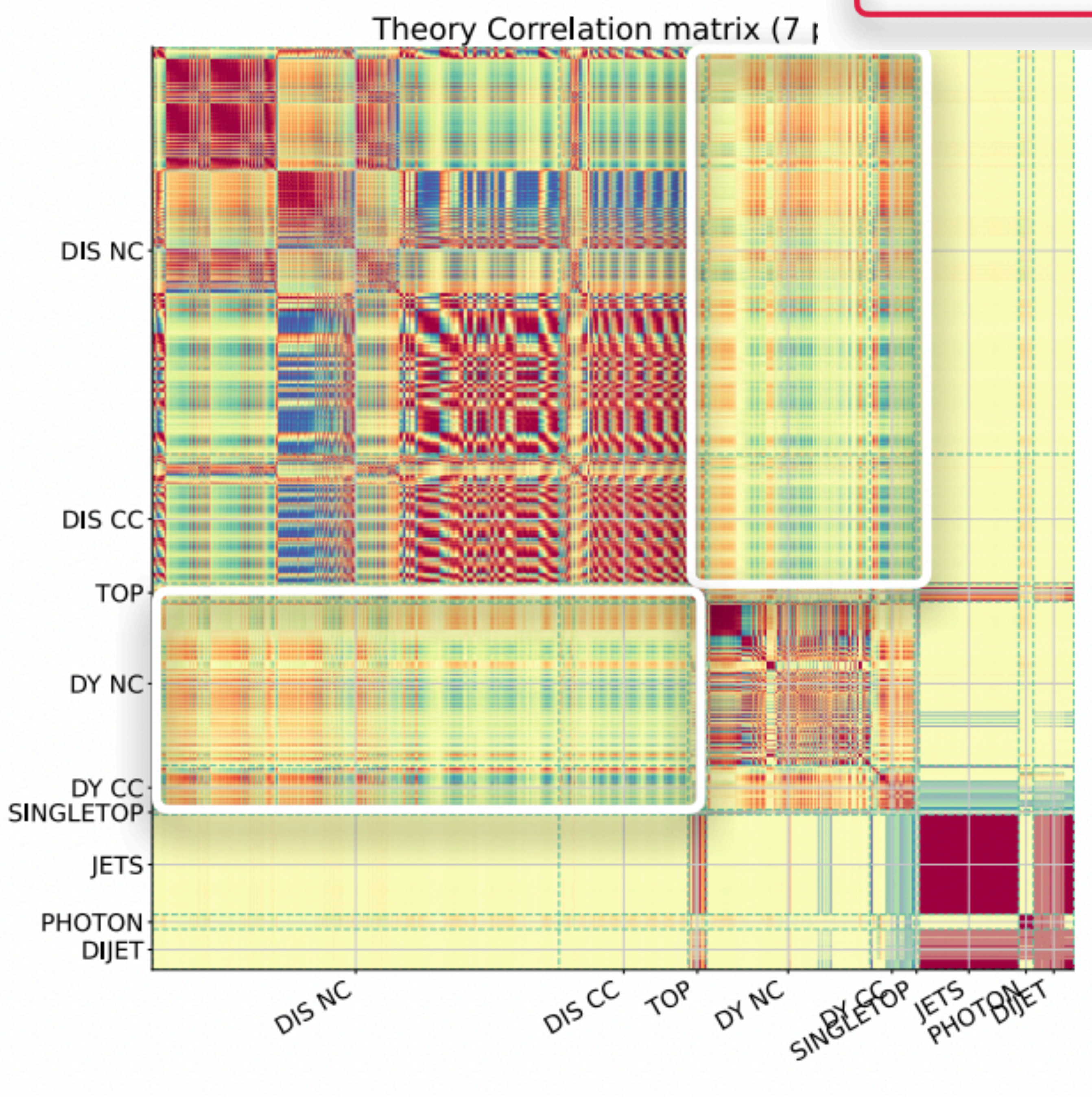
NNPDF updates

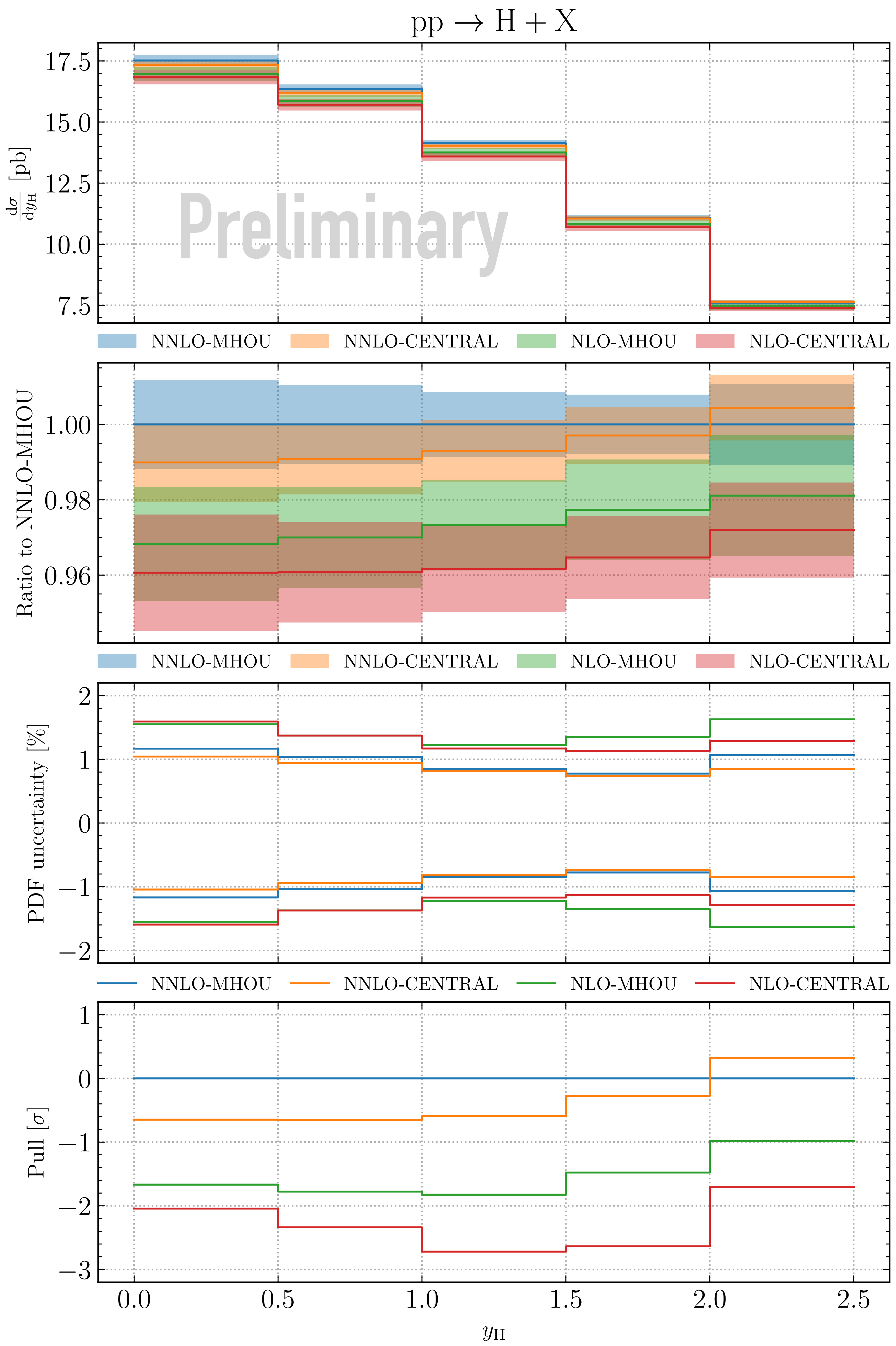
- **NNPDF4.0MHOU:** First NNLO PDF set including Missing Higher Order Uncertainties (MHOU) via theory covariance matrix approach **Ball et al [arXiv: 1905.04311,1906.10698, 2105.05114]**
- MHOUs estimate by varying μ_F and μ_R in parton evolution and in the partonic cross sections used to build theory cov matrix

$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} (T_i - D_i)\,({\rm cov}_{\rm exp} + {\rm cov}_{\rm th})^{-1}_{ij}\,(T_j - D_j)$$









NNPDF40MHOU - arXiv:2312.xxxxx

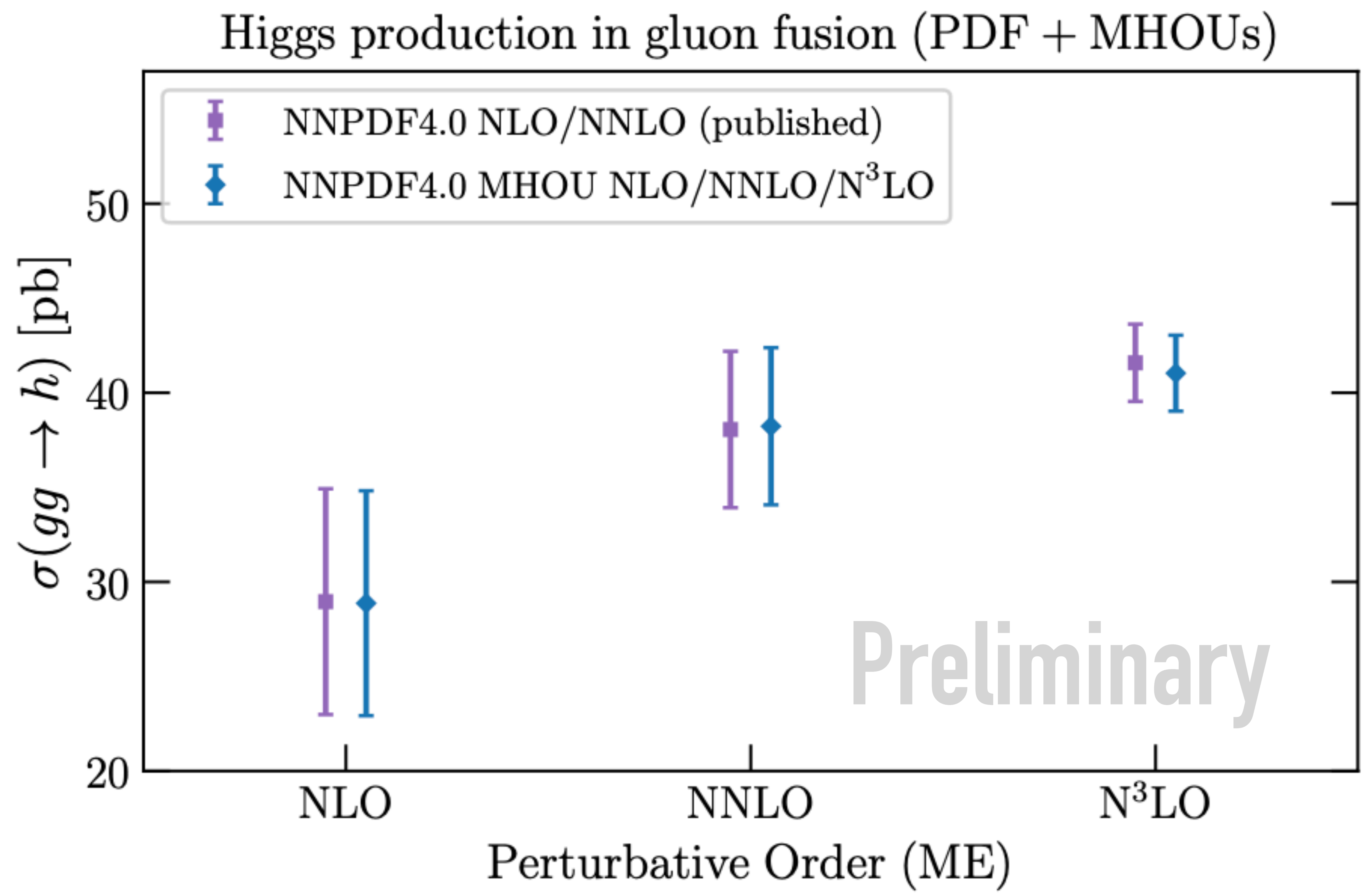
NNPDF updates

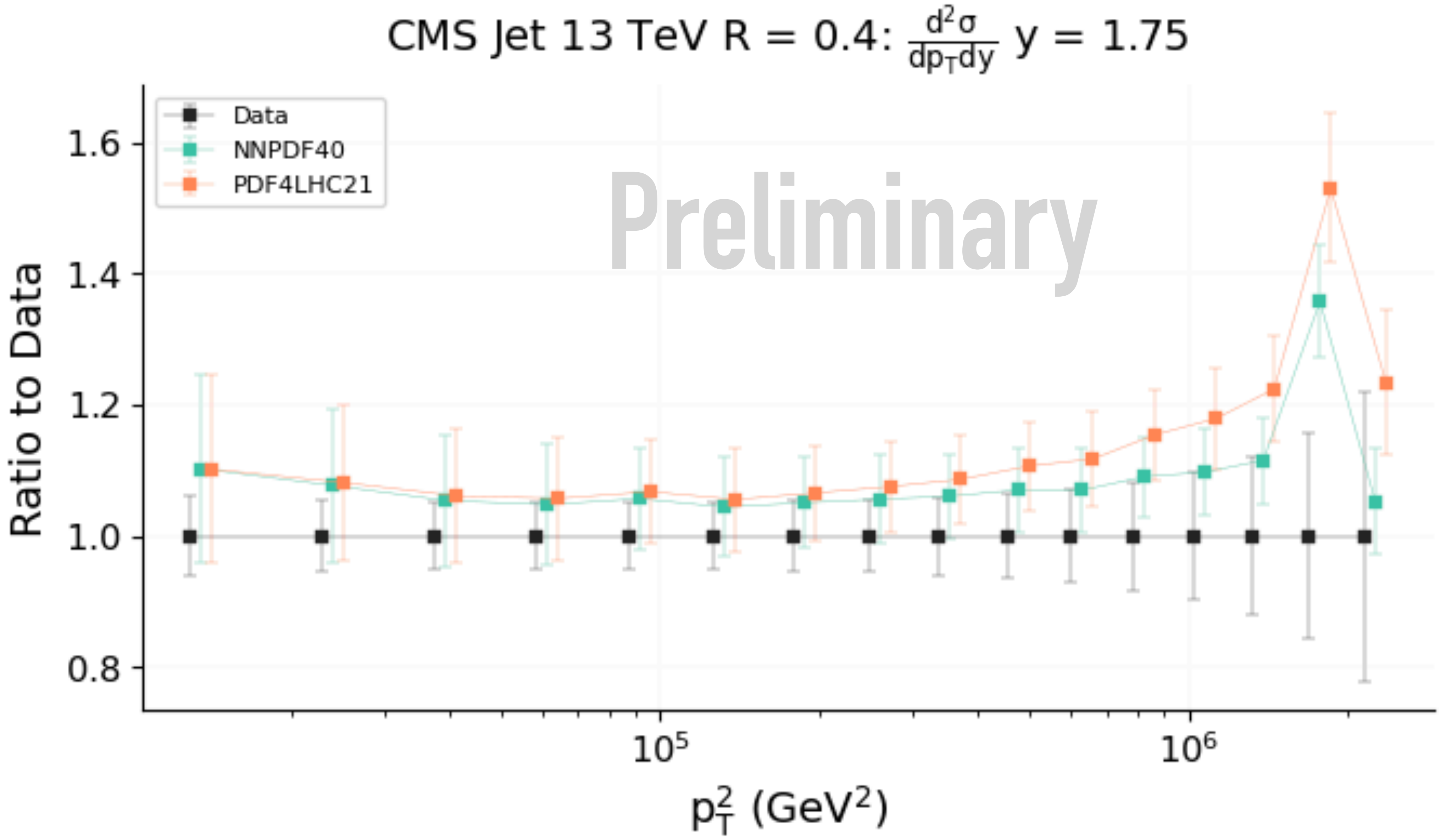
- **NNPDF4.0N3LO:** Approximate N3LO PDFs built by using available N3LO theory ingredients and estimating Incomplete Higher Order Uncertainties (IHOUs) associated to unknown N3LO ingredients
  Hekhorn, Magni [arXiv: 2306.15294] + NNPDF in preparation

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

- PDF sets with MHOUs vs MHOUs and IHOUs contributions test perturbative convergence

- **NNPDF4.0pheno**: A systematic exploration of the data-theory agreement between predictions obtained with NNPDF4.0 and other global data sets with plethora of new and precise datasets that the LHC experiments have provided since the release of the latest PDF - future test [J. Cruz-Martinez et al, Acta Phys.Polon.B 52 (2021) 243]





Part II:
aN^{3}LO PDFs theory benchmark

Approximate N^{3}LO PDFs

- Several ingredients required to perform N^{3}LO PDF fits, many available some missing

➡ 4-loop DGLAP Splitting Functions to evolve PDFs

$$Q^2 \frac{df_i}{dQ^2} = P_{ij}(x, \alpha_s) \otimes f_i(x, Q^2)$$

non-singlet - large n_F limit [NPB 915 (2017) 335; arXiv:2308.07958]
- small-x [JHEP 08 (2022) 135] and large-x [JHEP 10 (2017) 041] limits
- lowest 8 Mellin moments [JHEP 06 (2018) 073]

singlet - large n_F limit [NPB 915 (2017) 335; arXiv:2308.07958, arXiv:2310.01245]
- small-x [JHEP 06 (2018) 145] and large-x [NPB 832 (2010) 152; JHEP 04 (2020) 018; JHEP 09 (2022) 155] limits
- lowest 5 (10) Mellin moments [PLB 825 (2022) 136853; ibid. 842 (2023) 137944; ibid. 846 (2023) 138215]

➡ PDF matching conditions to change number of PDF flavours at heavy-quark matching scales
- all known [NPB 820 (2009) 417; NPB 886 (2014) 733; JHEP 12 (2022) 134] except for complete $A^{(3)}_{H,g}$ [arXiv::2311.00644]

$$f_i^{(n_f+1)}(x, Q^2) = A_{ij}(x, \alpha_s) f_j^{(n_f)}(x, Q^2)$$

➡ DIS Structure Functions
- DIS NC (massless) [NPB 492 (1997) 338; PLB 606 (2005) 123; NPB 724 (2005) 3]
- DIS CC (massless) [NPB 813 (2009) 220]
- Massive from param. combining known limits and damping functions [NPB 864 (2012) 399]

$$F_k = x \sum_{i=-n_f}^{n_f} C_{k,i}(x, \alpha_s) \otimes f_i(x, Q^2), \quad k = \{1,2,3\}$$

➡ Hadronic cross section
- Drell-Yan (inclusive) [JHEP 11 (2020) 143]
- Drell-Yan (differential in p_T) [PLB 845 (2023) 138125]
- Drell-Yan (differential in rapidity) [PRL 128 (2022) 052001]

Approximate N³LO PDFs

- The only public available aN³LO PDF determination is from the MSHT collaboration arXiv:2207.04739.
- NNPDF has presented preliminary aN³LO results and paper is in preparation - **to be released before Christmas**

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 IHOU
- MHOU associated with NNLO included via theory covariance matrix

Approximate Splitting Functions

- How to combine the different limits?
  In Mellin space, for each power of nf

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

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

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

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

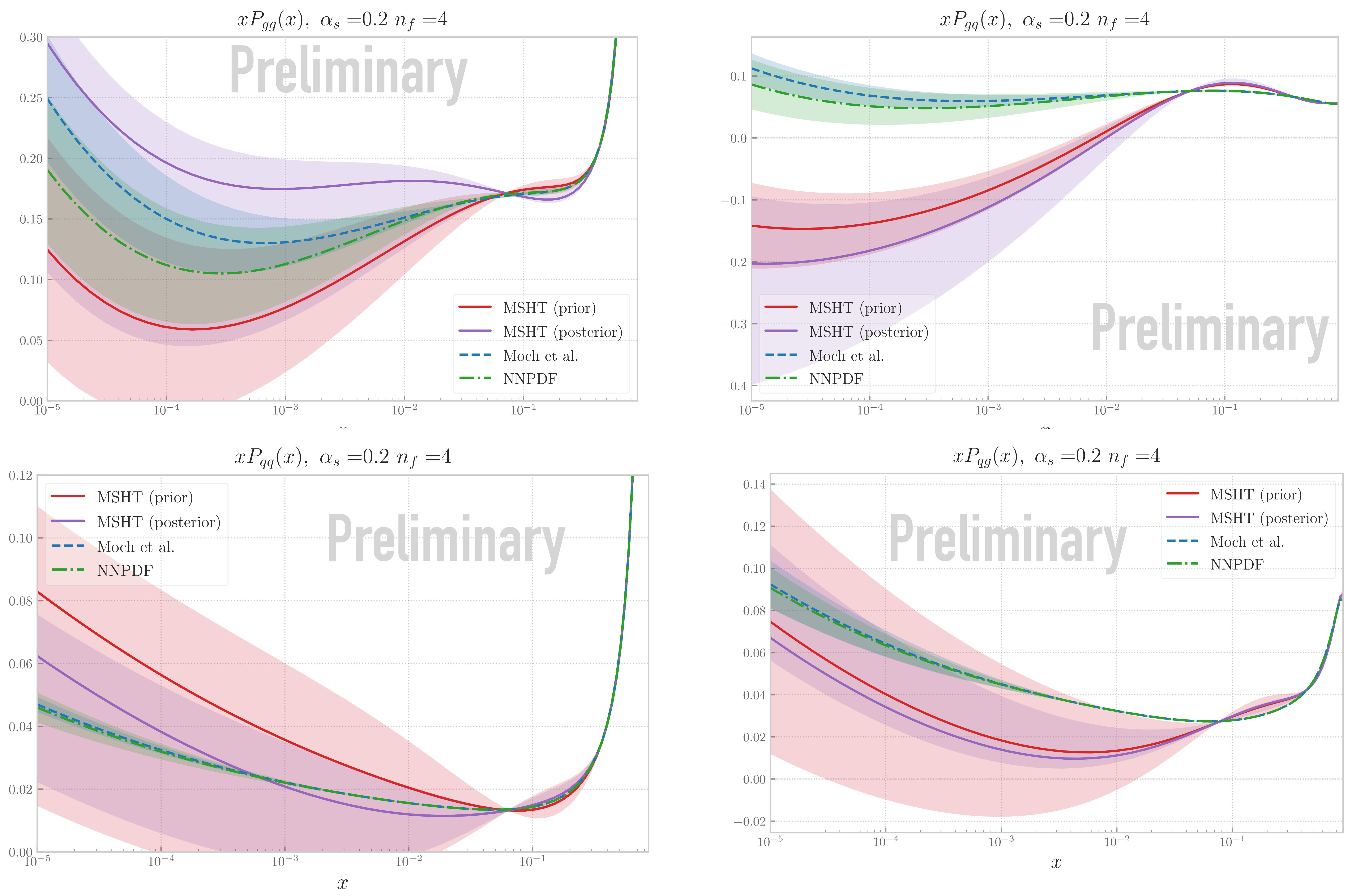
$\gamma^{(3)}_{qq,\mathrm{ps}}(N)$	$G_1(N)$	$\mathcal{M}[(1-x)\ln^2(1-x)]$	➡ Large-N contribution
	$G_2(N)$	$-\frac{1}{(N-1)^2} + \frac{1}{N^2}$	➡ Small-N contribution
	$\{G_{3,\dots,8}(N)\}$	$\frac{1}{N^4},\ \frac{1}{N^3},\ \mathcal{M}[(1-x)\ln(1-x)]$ $\mathcal{M}[(1-x)^2\ln(1-x)^2],\ \frac{1}{N-1} - \frac{1}{N},\ \mathcal{M}[(1-x)\ln(x)]$	➡ 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 constraining it between NNPDF and MSHT (extra prior parameter)

Benchmarking Splitting Functions

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

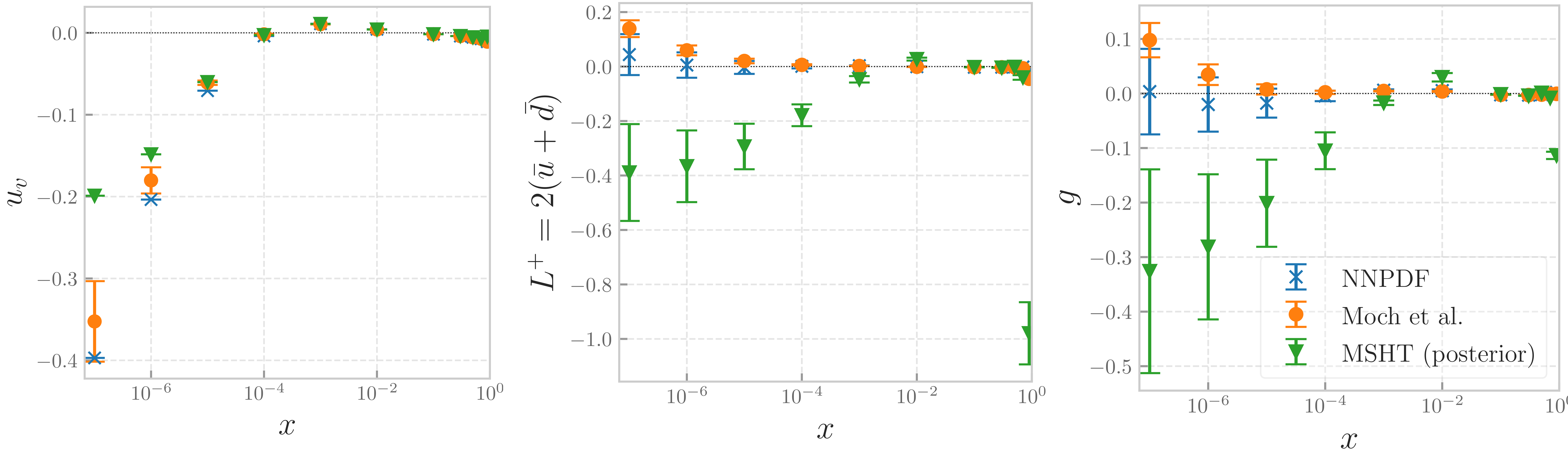
- Benchmarking exercise started before Summer in Les Houches to check the impact of the aN3LO splitting functions
- Write-up in preparation for Les Houches proceedings



Benchmarking Splitting Functions

@Giacomo Magni
@Tom Cridge

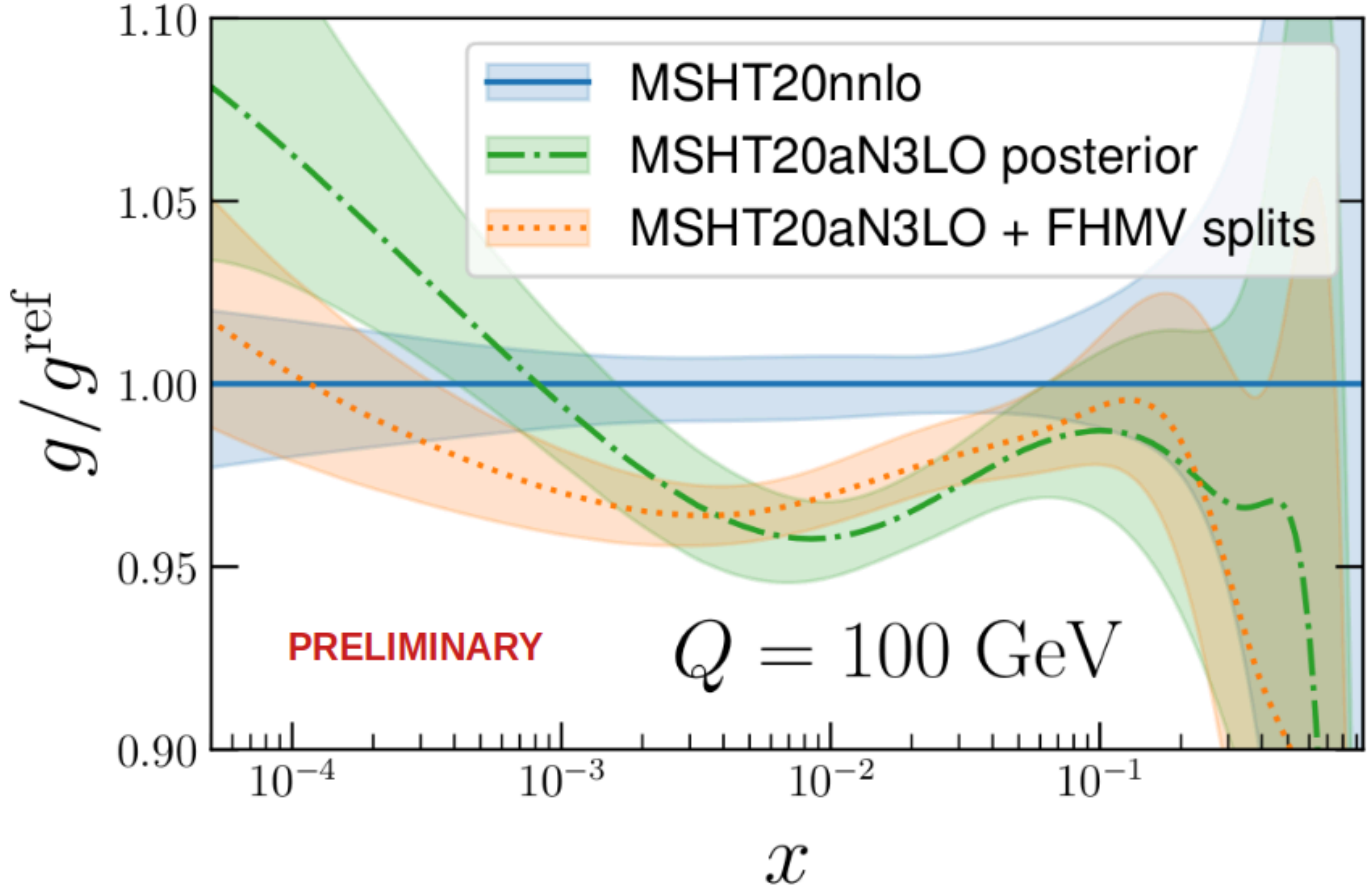
➡ Relative difference to NNLO

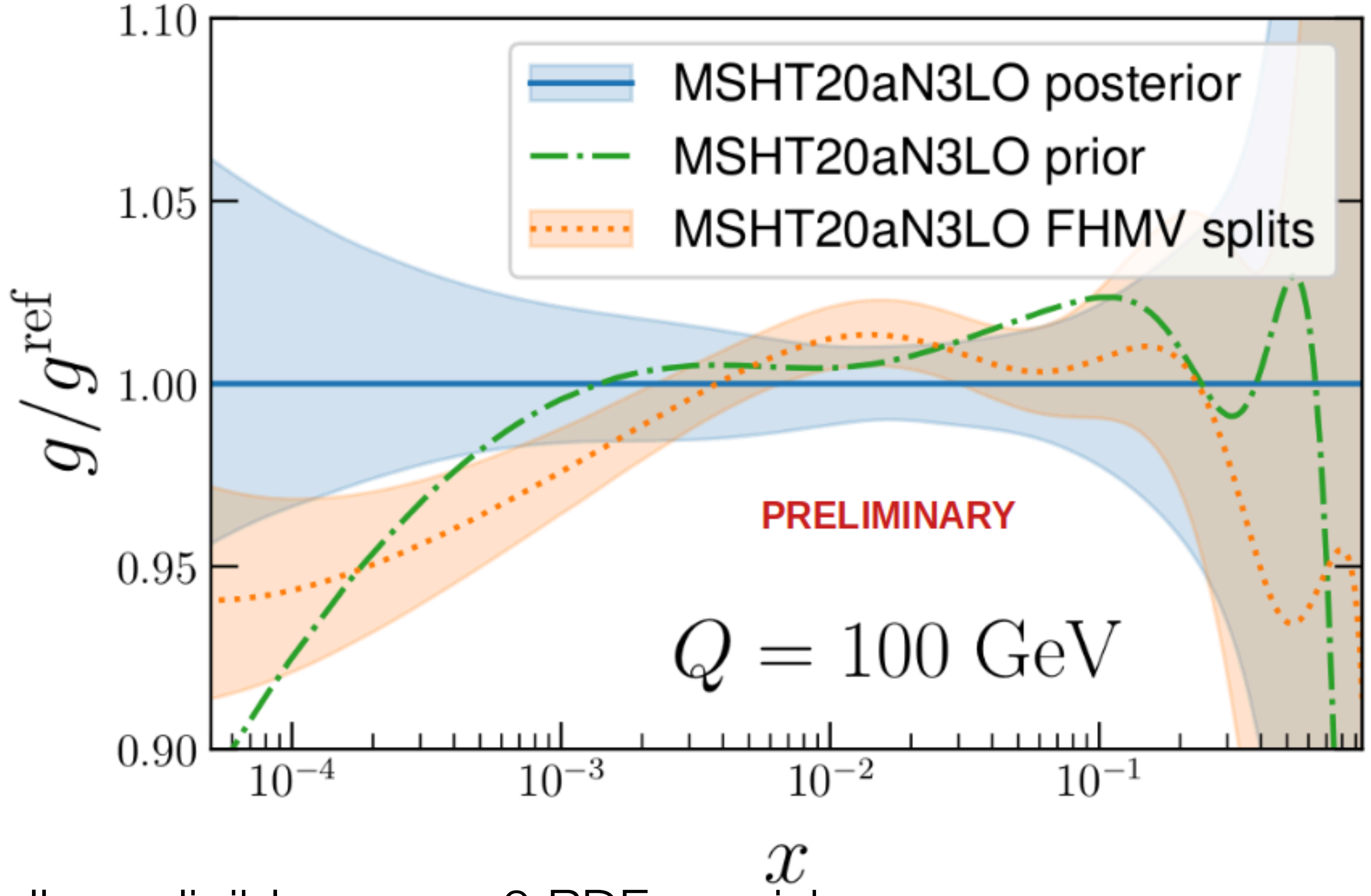


- Non-Singlet: variation in parametrisation is phenomenologically negligible as x → 0 PDFs vanish
- Singlet: difference due to poor knowledge of small-x logs (extra momentum improves constraint on small-x log in P_{gq}, P_{gg})

Benchmarking Splitting Functions

@Tom Cridge





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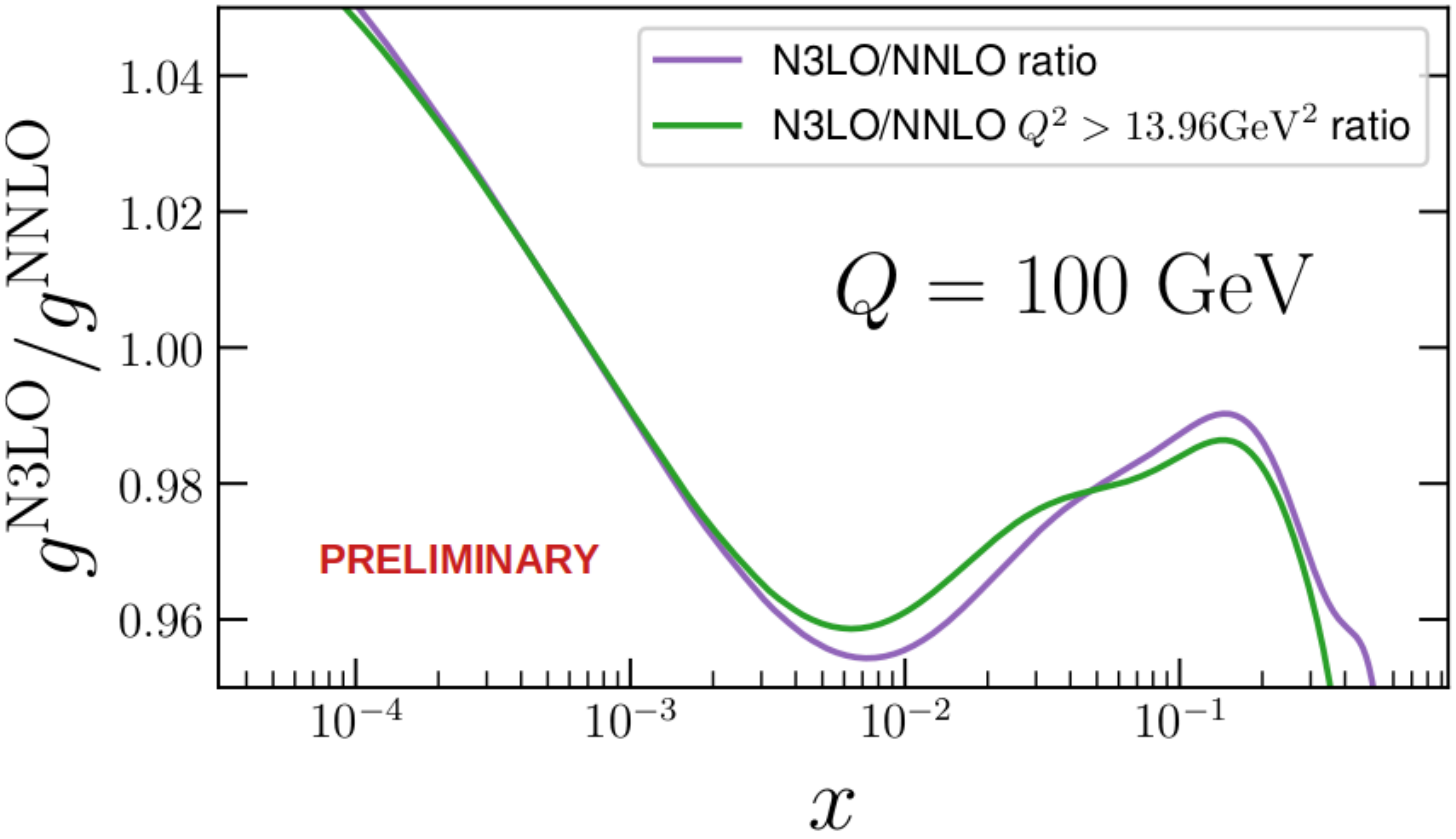
- Inclusion of new momenta by Moch et al in MSHTaN3Lo results in a ~1.5% rise in the gluon at x~10^{-2} **[preliminary]**
- Next: massless coefficient functions, matching conditions, and massive DIS to conclude benchmark of theory ingredients.
- Benchmark between PDFs is more involved (methodology, kinematic coverage, kinematic cuts)…

Effects of cuts on PDFs



@Tom Cridge

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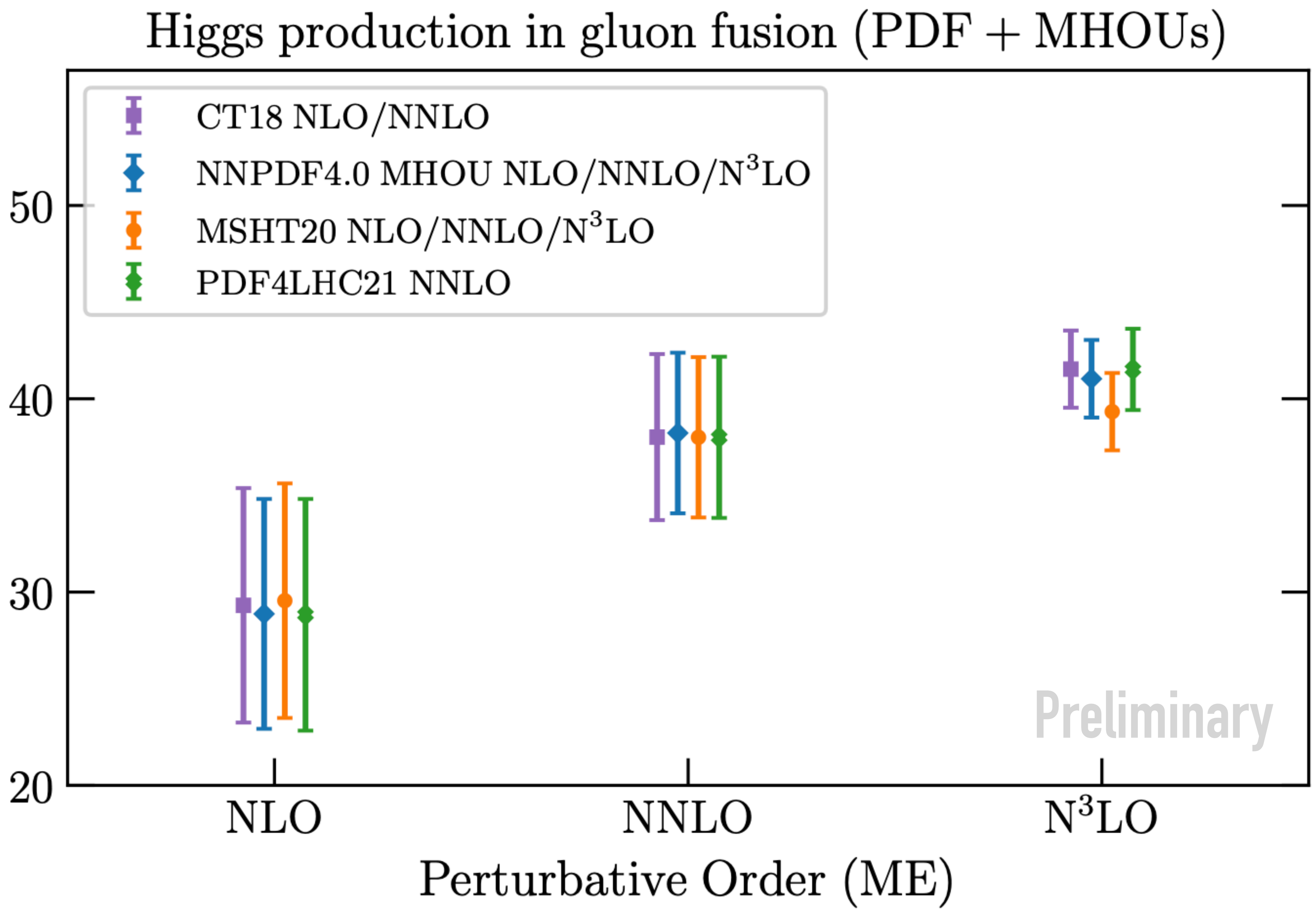
- Benchmark between PDFs is more involved (methodology, kinematic coverage, kinematic cuts)
- Raising the Q^2 cut (in line with NNPDFaN3LO) also increases the gluon around x~10^{-2} **[preliminary]**

Impact on phenomenology

@Giacomo Magni



Impact on phenomenology

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

Over-conservative measure of mismatch between NNLO PDFs and N3LO partonic cross sections

Courtesy of Giacomo Magni, Tom Cridge and Alexander Huss

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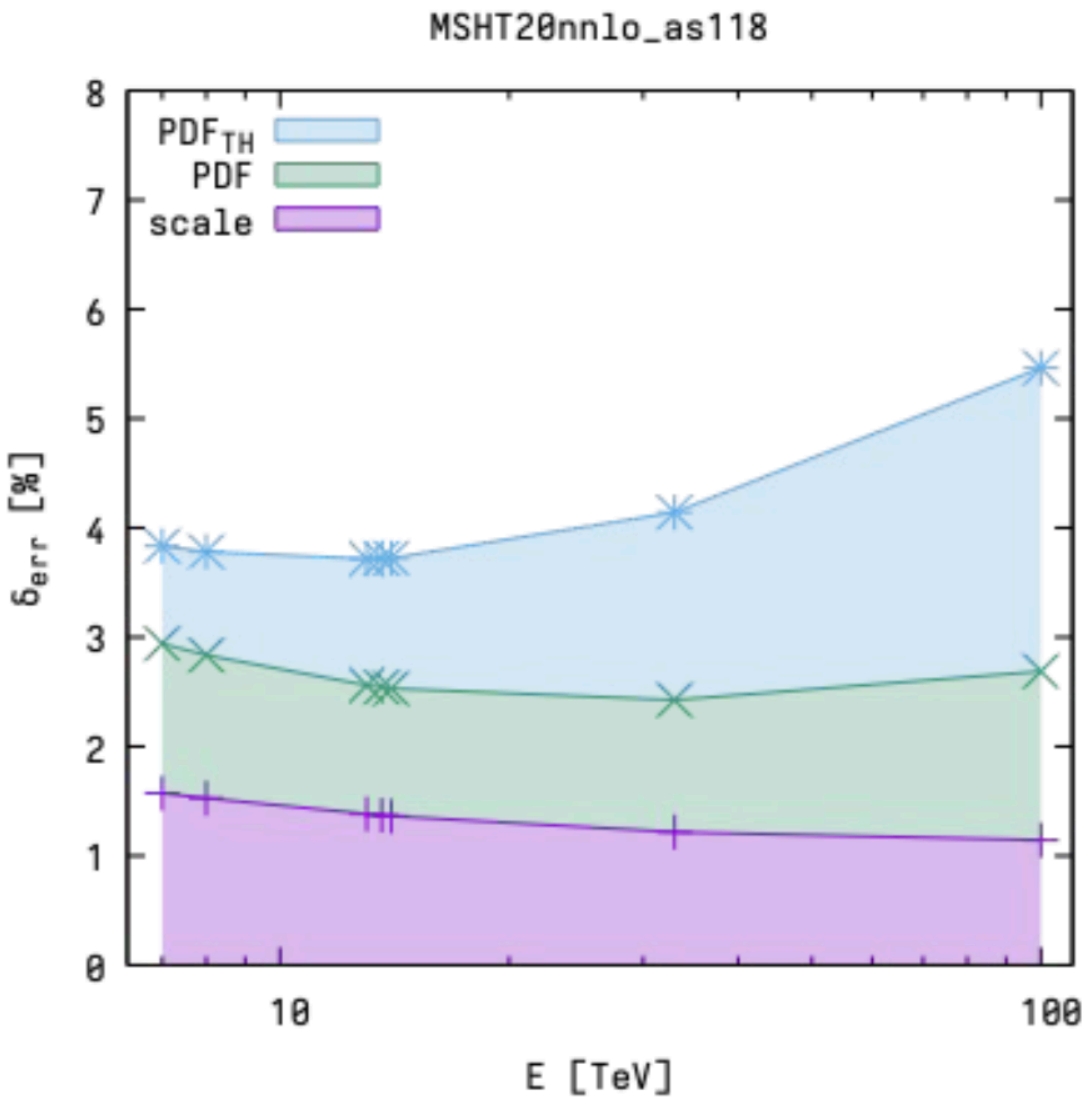

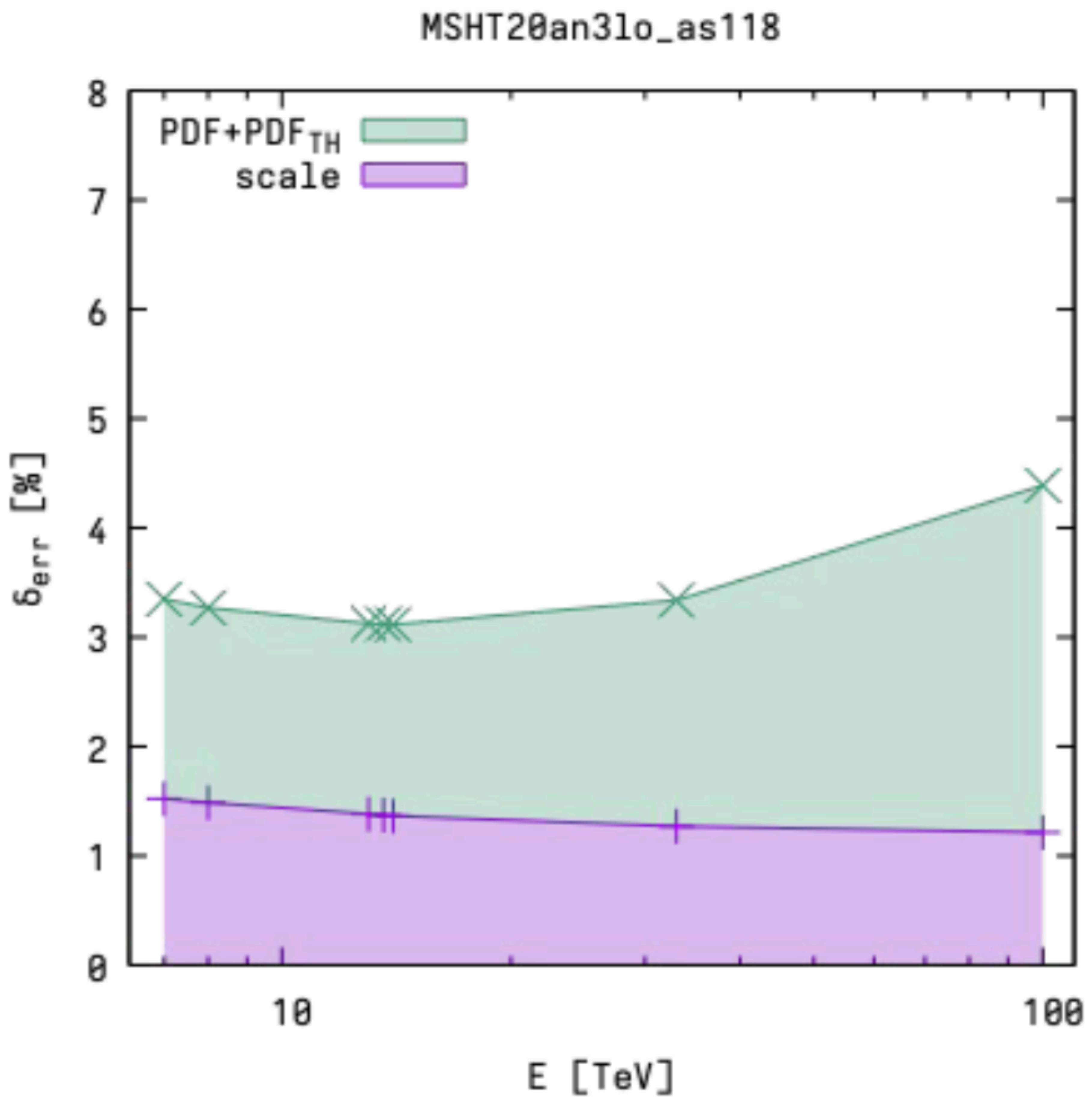

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Conclusions

- Lots of progress from PDF collaborations tackling needs dictated by new precision frontiers at the LHC

- Some extremely relevant for Higgs physics

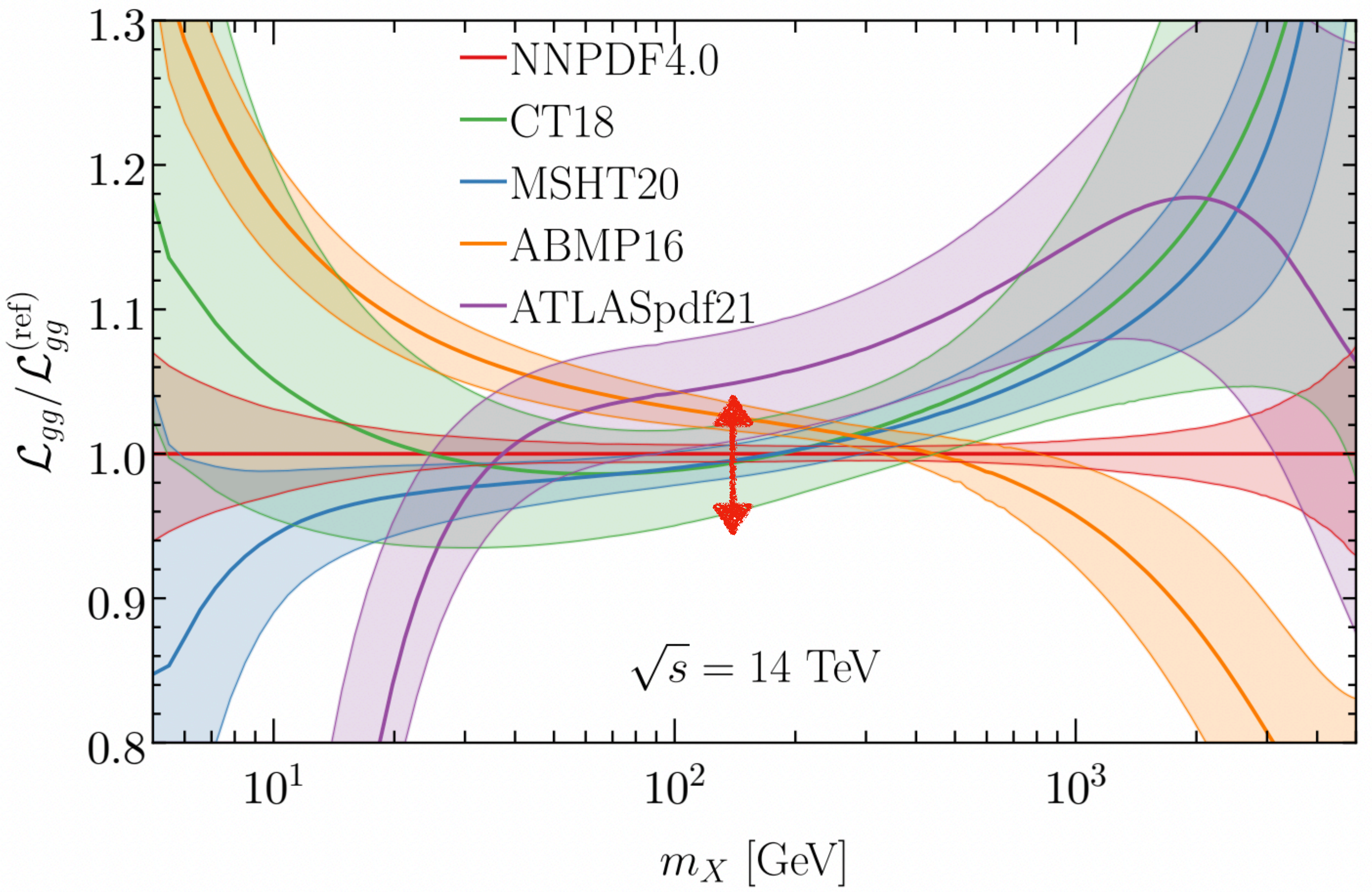
  ➡ QED PDF sets - **EW corrections especially relevant for large invariant mass final states**
  ➡ aN3LO PDF sets - **remove over-conservative theory mismatch uncertainty**
  ➡ Inclusion of MHOUs - **more accurate PDF determination**
  ➡ More data from the LHC - **increase precision of PDF determination**

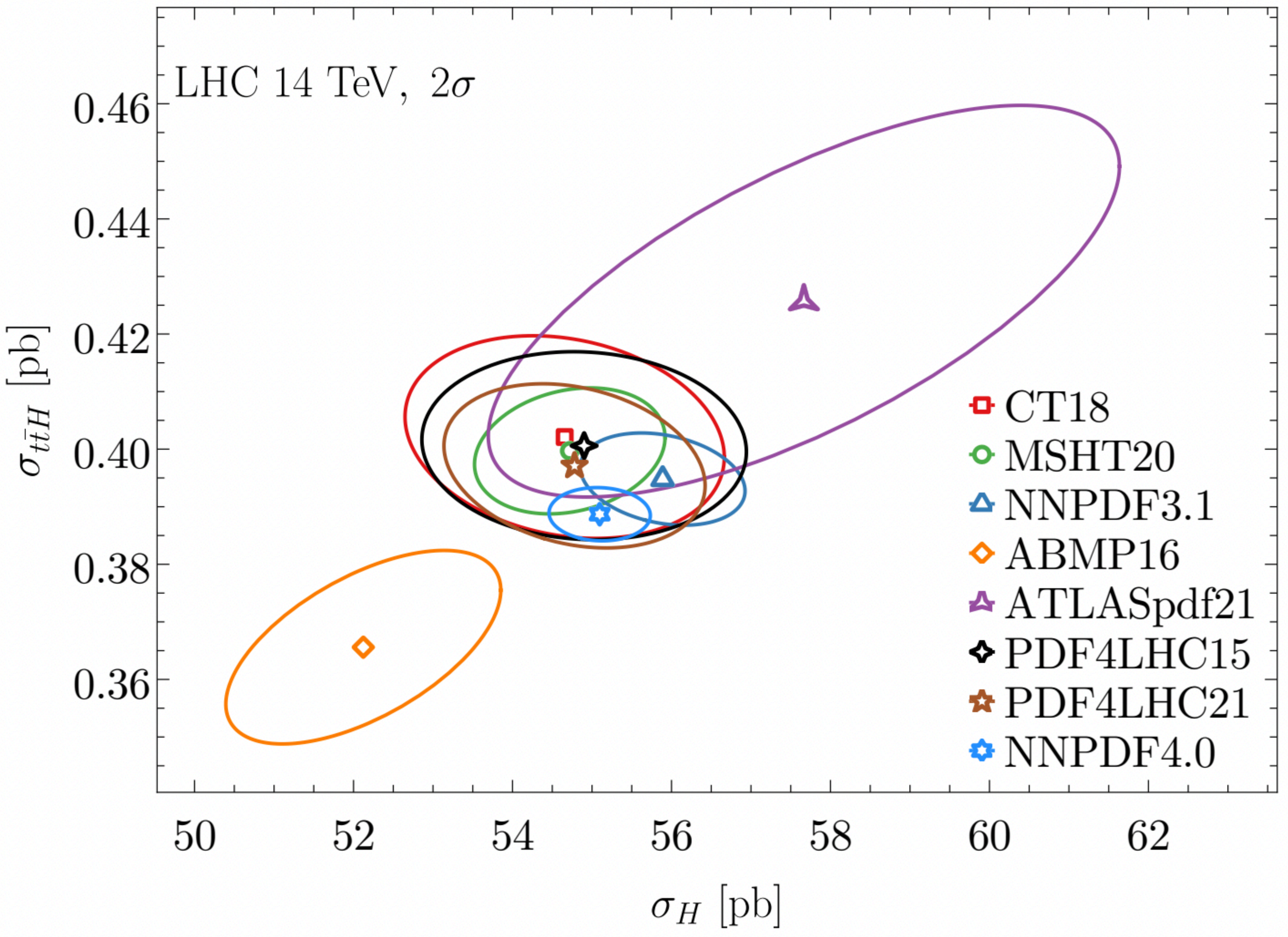
- On Friday **PDF4LHC** meeting
  https://indico.cern.ch/event/1311146/

  ➡ More on the aN3LO benchmark **(Robert Thorne)**
  ➡ News from CT & L2 sensitivity **(Joey Huston)**
  ➡ News from MSHT **(Lucian Harland Lang)**
  ➡ News from NNPDF **(Juan Rojo)**
  ➡ Talks on replicability of the PDF4LHC exercise **(Pavel Nadolsky)**, Implications of NNPDF40 for LHC physics **(Juan Cruz-Martinez)** and how PDFs might fit away New Physics **(James Moore)**

Extra material

Where we stand





- Overall agreement around Higgs mass between global PDF sets in gg channel with differences in PDF uncertainties due to differences in methodologies and datasets included.
- In qqbar channel similar trend with slightly larger tension around Higgs mass.
- PDF4LHC21: once a common dataset is used, global fits agree in broad Mx range, different uncertainties.

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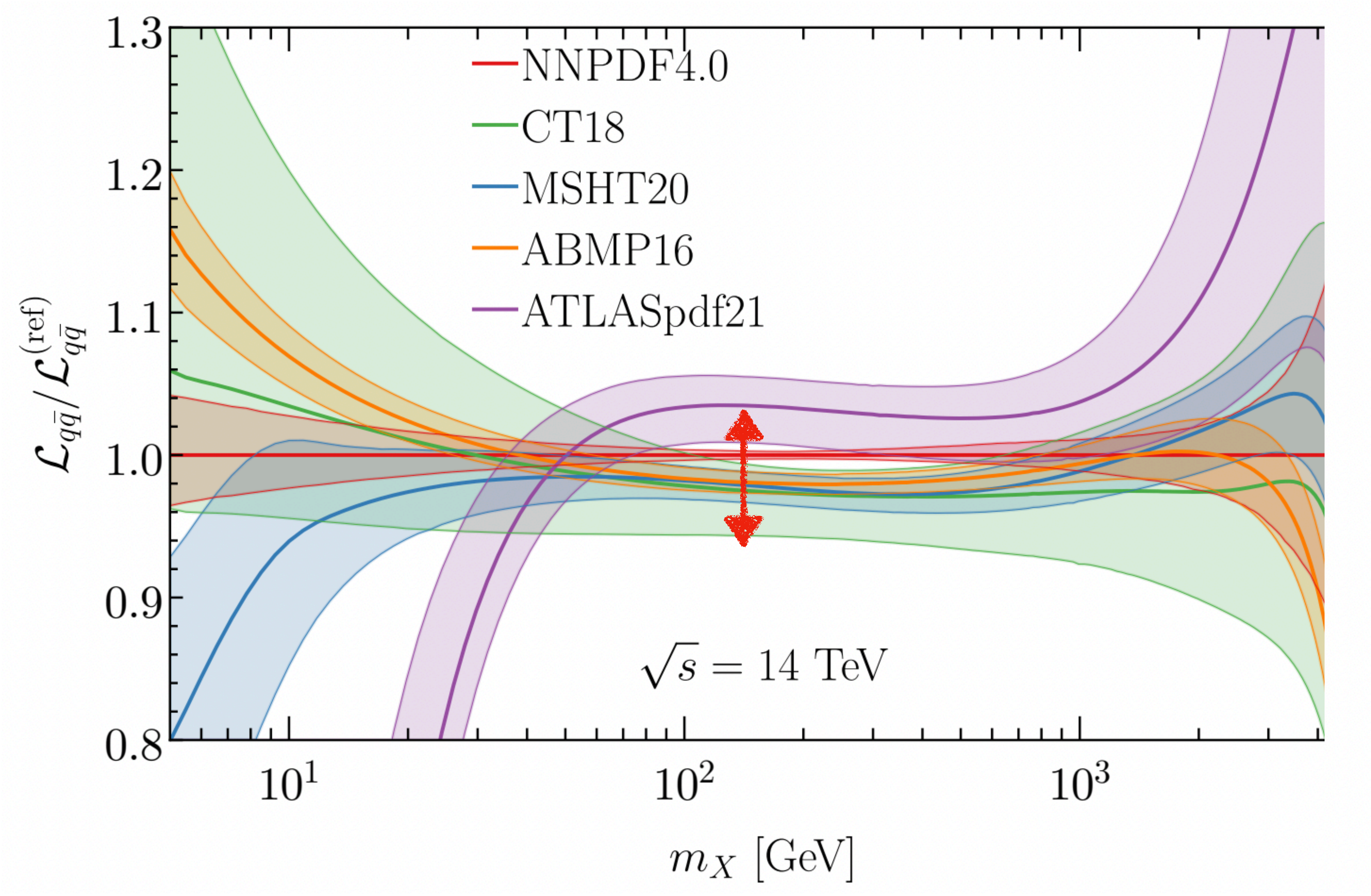

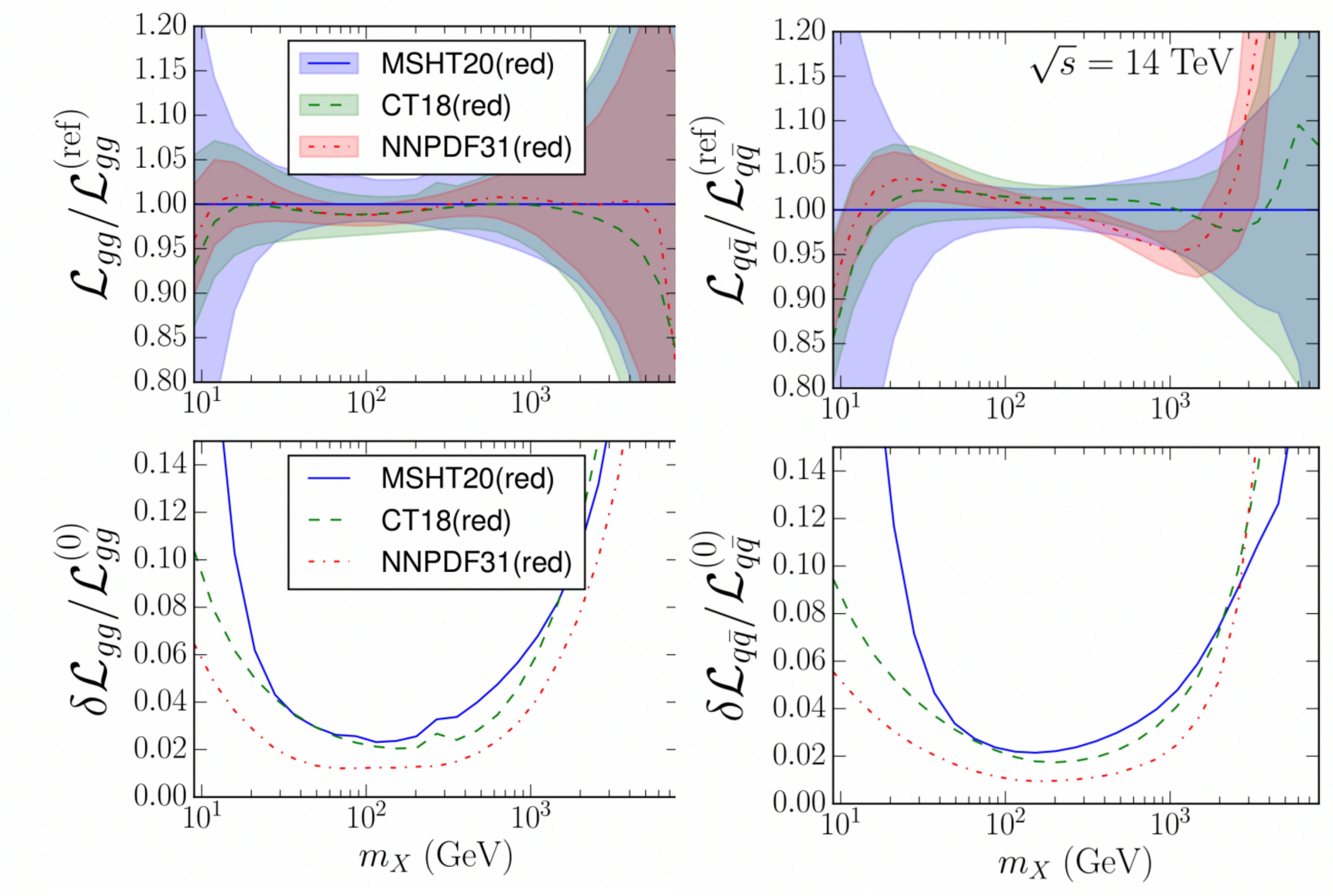

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