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FITTING PDFS WITH LHC DATA: INTERPRETATION AND CHALLENGES

SYNERGY WORKSHOP BETWEEN EP/EA EXPERIMENTS AND PP/PA/AA EXPERIMENTS, CERN

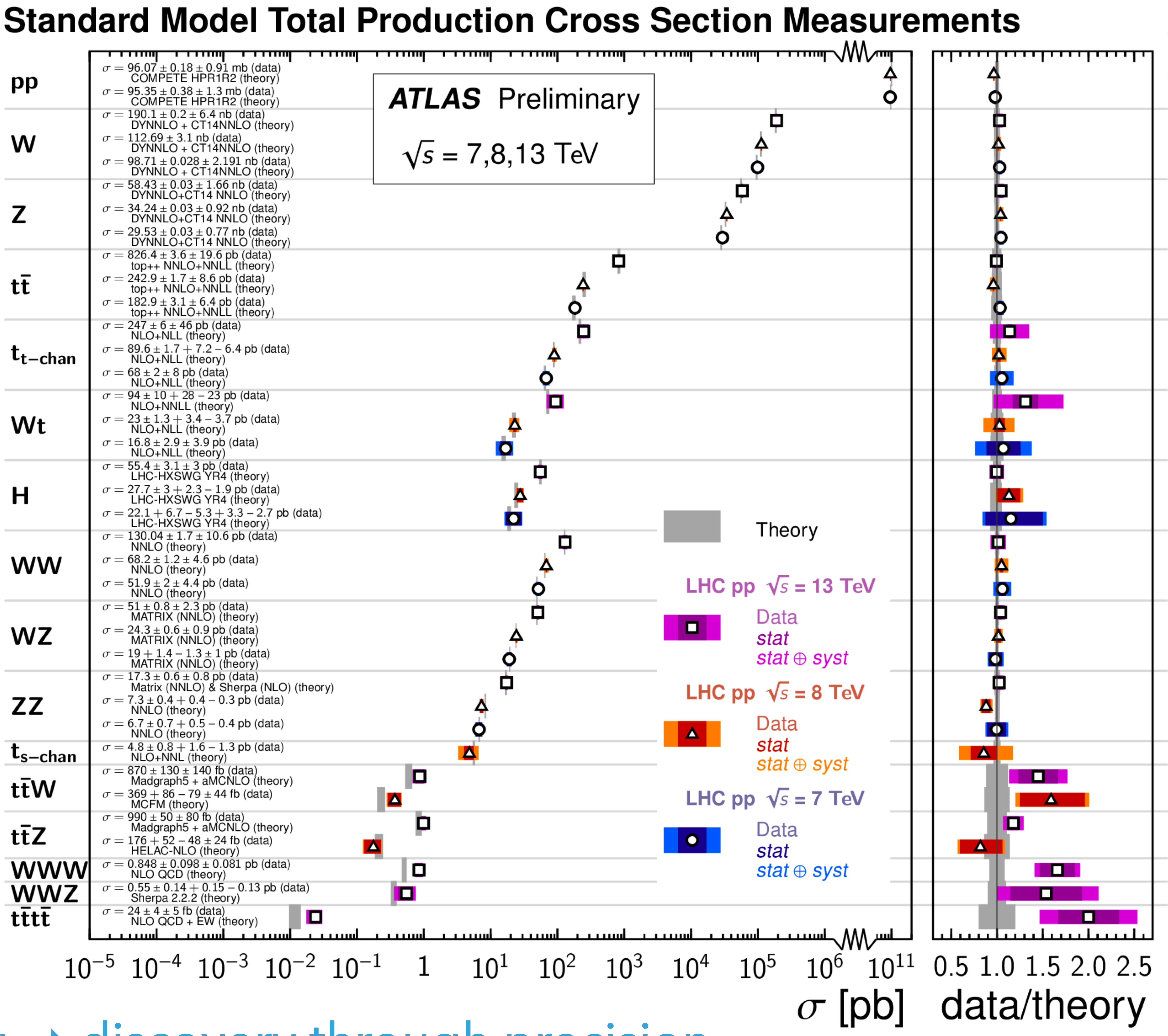
29TH FEBRUARY 2024

European Research Council
Established by the European Commission

PBSP

A NEW PRECISION ERA AT THE LHC

- Impressive range of precise cross section measurements and huge progress in theoretical calculations
- Overall stunning agreement between data and SM predictions although we know that SM is necessarily incomplete
- Precision essential both for BSM characterisation (direct discovery) and for indirect discovery



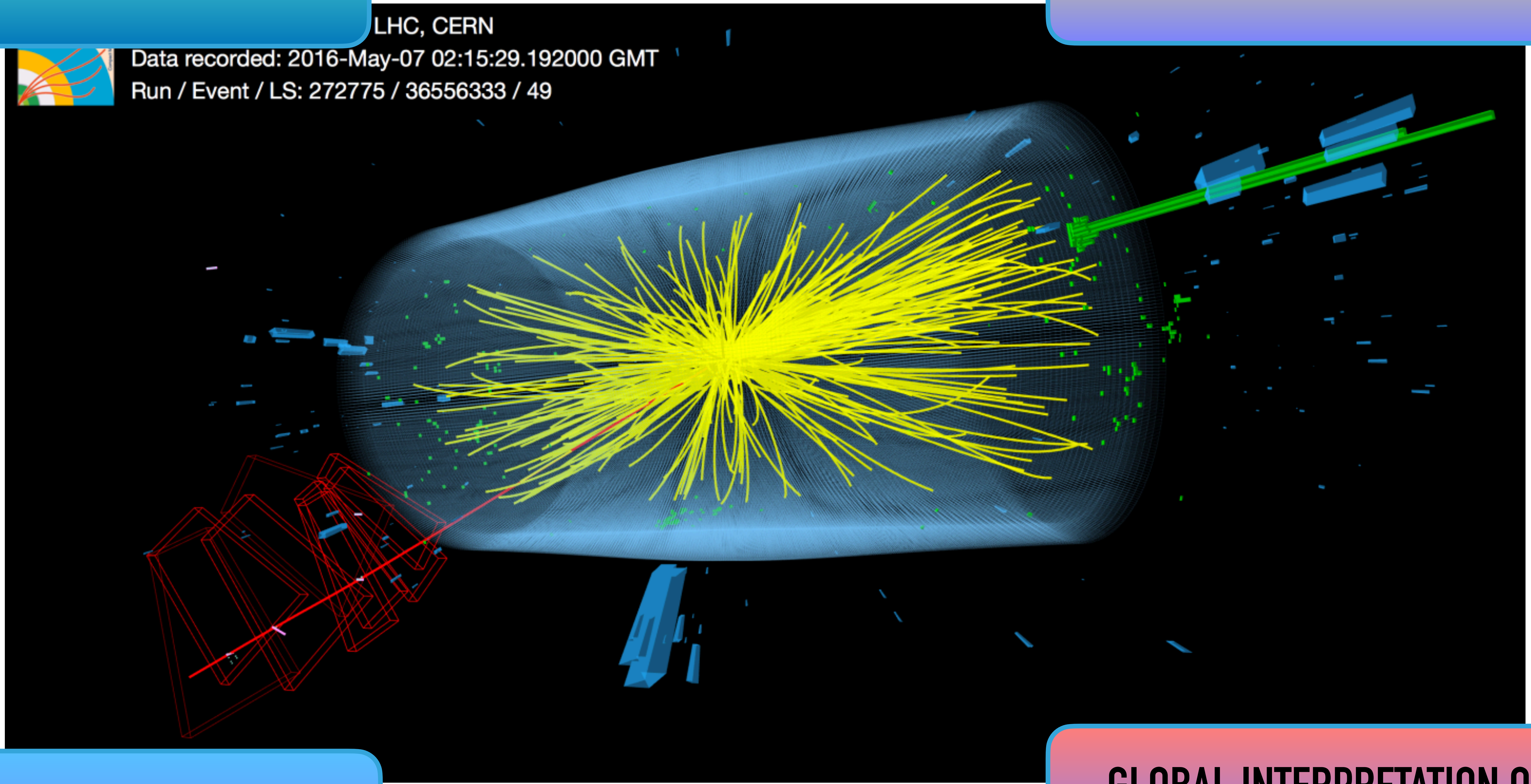
LHC paradigm: discovery → discovery through precision

OUTLINE

Part I

PROTON STRUCTURE

PRECISION PHYSICS



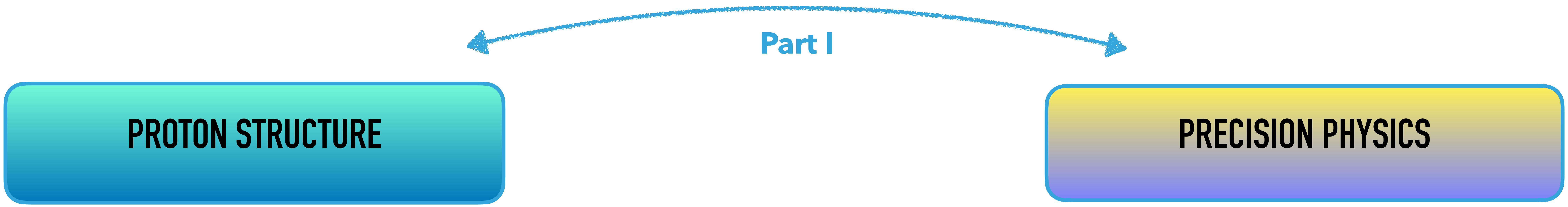
Part II

Part III

ACCURACY VS PRECISION

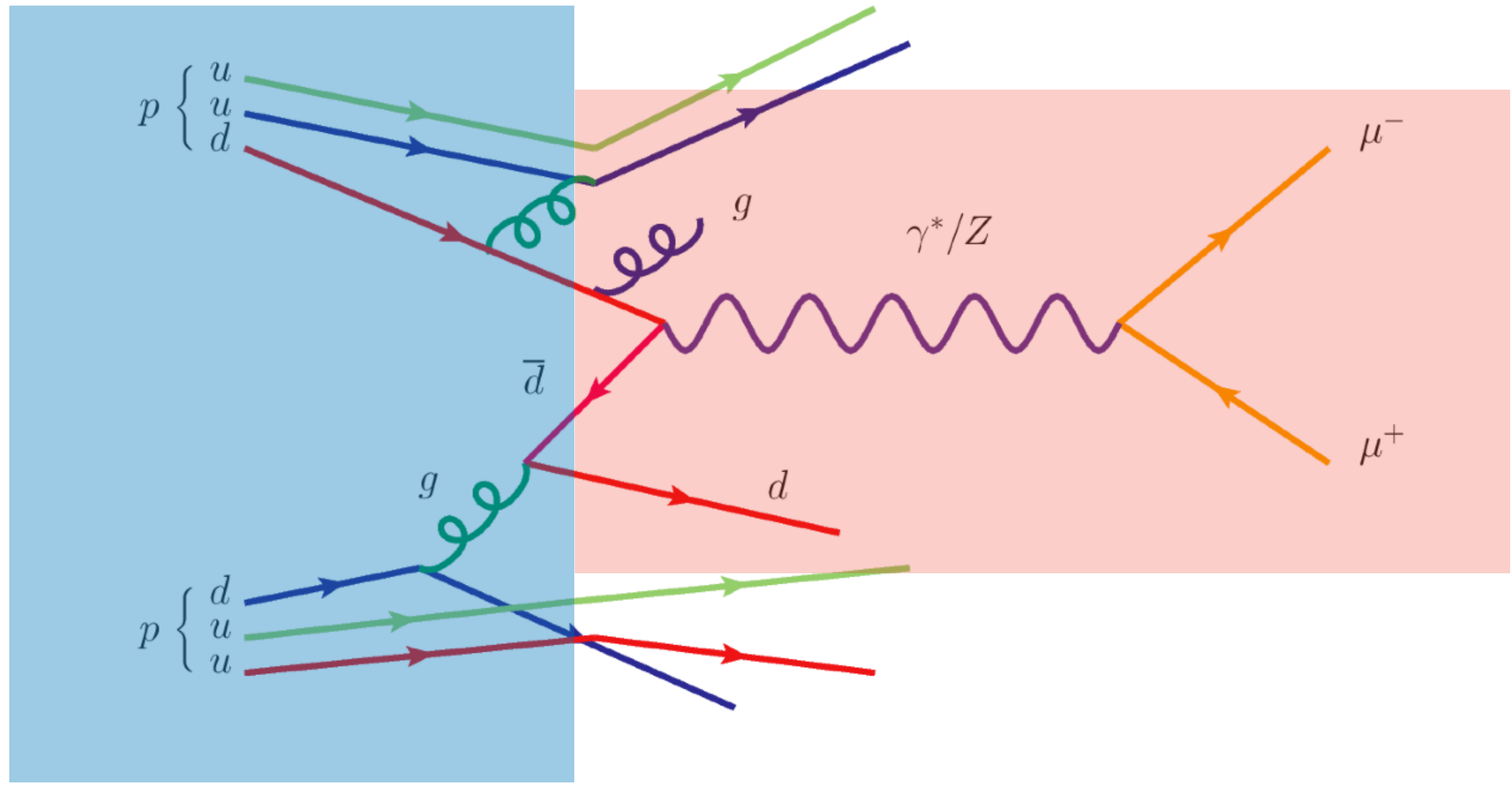
GLOBAL INTERPRETATION OF DATA

Part III



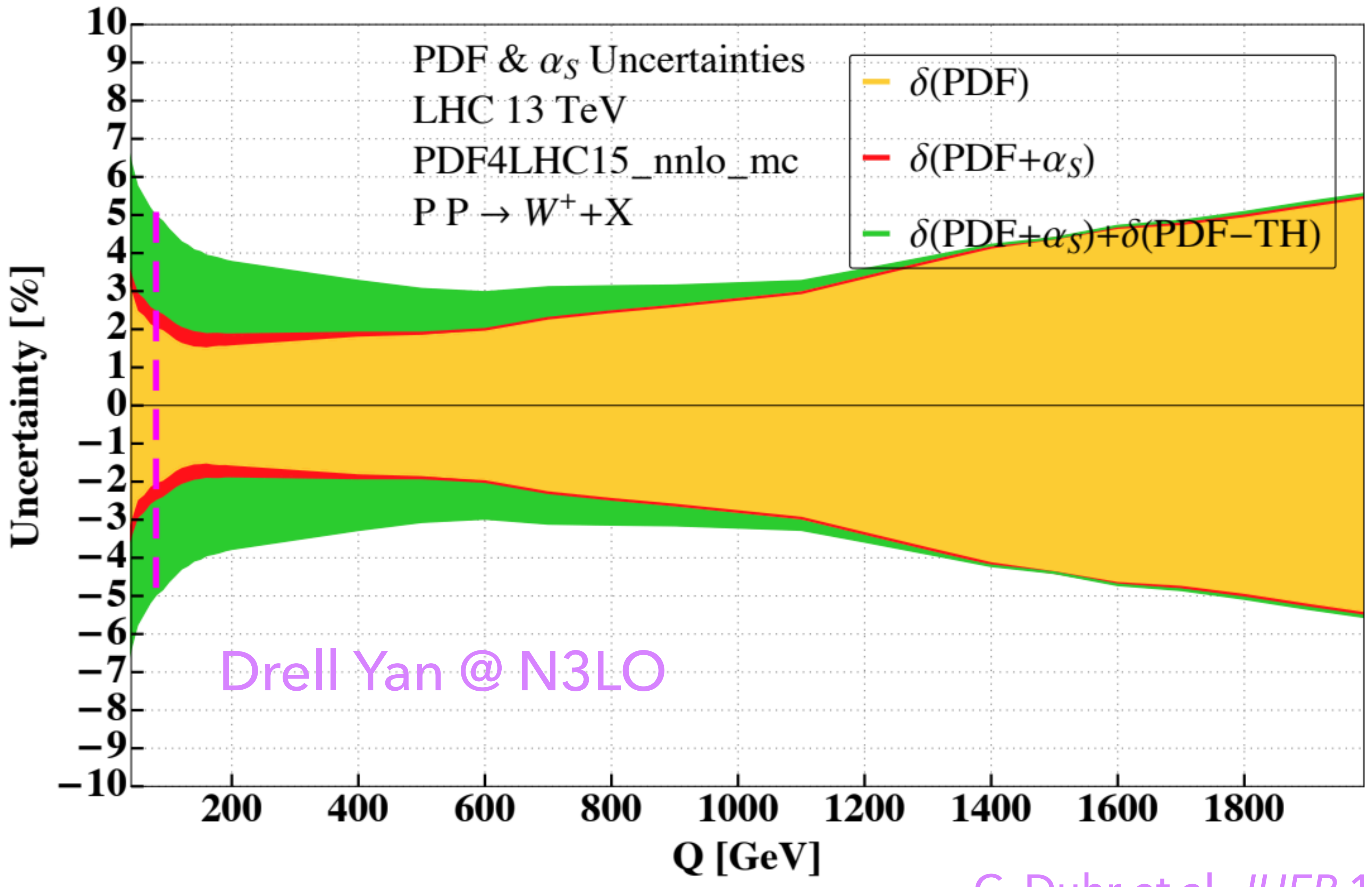
PROTON STRUCTURE AND PRECISION PHYSICS

PDFS ARE A CRUCIAL INPUT FOR PRECISION PHYSICS ...



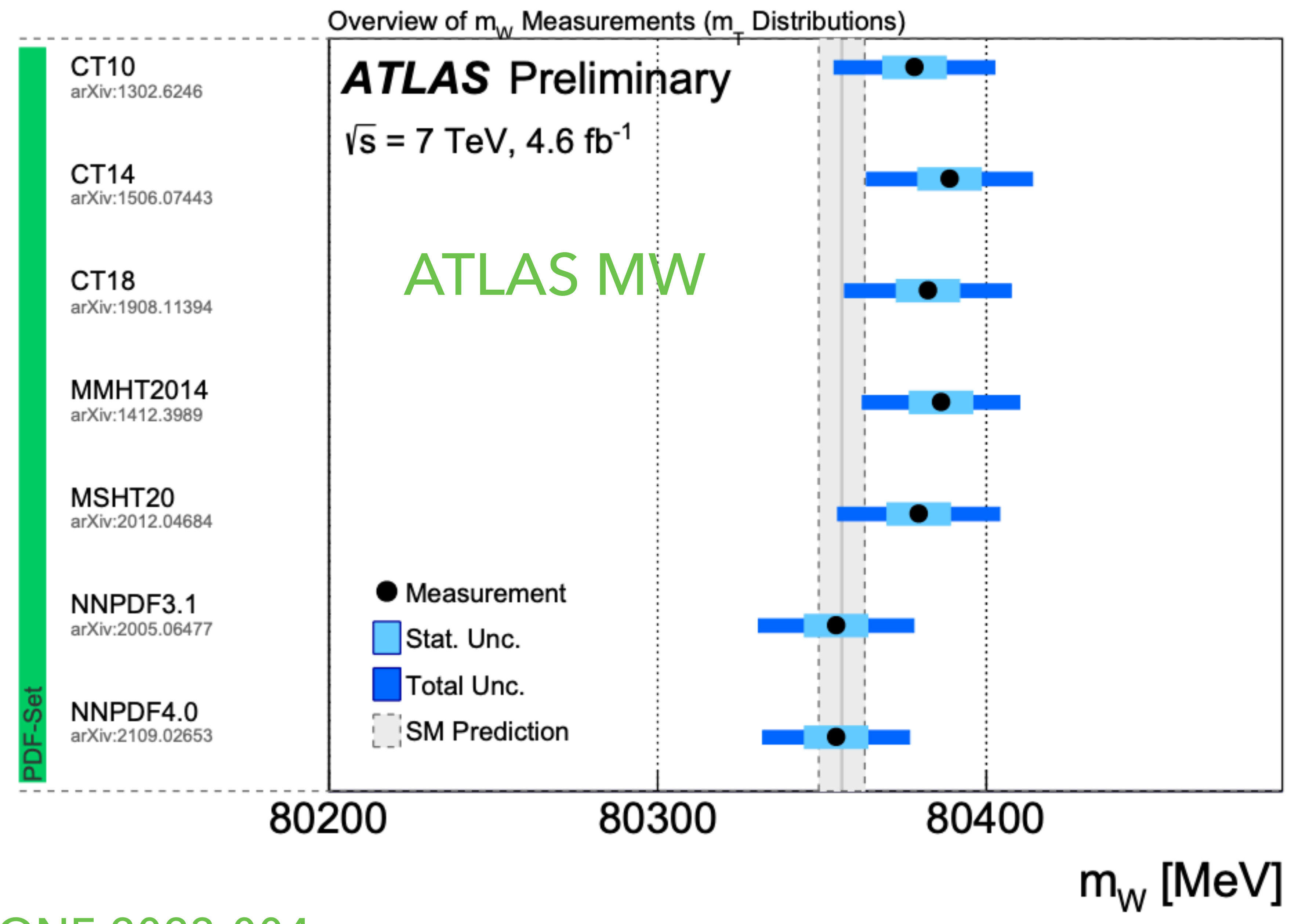
$$d\sigma^{pp\to ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij\to ab} + \dots$$

#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

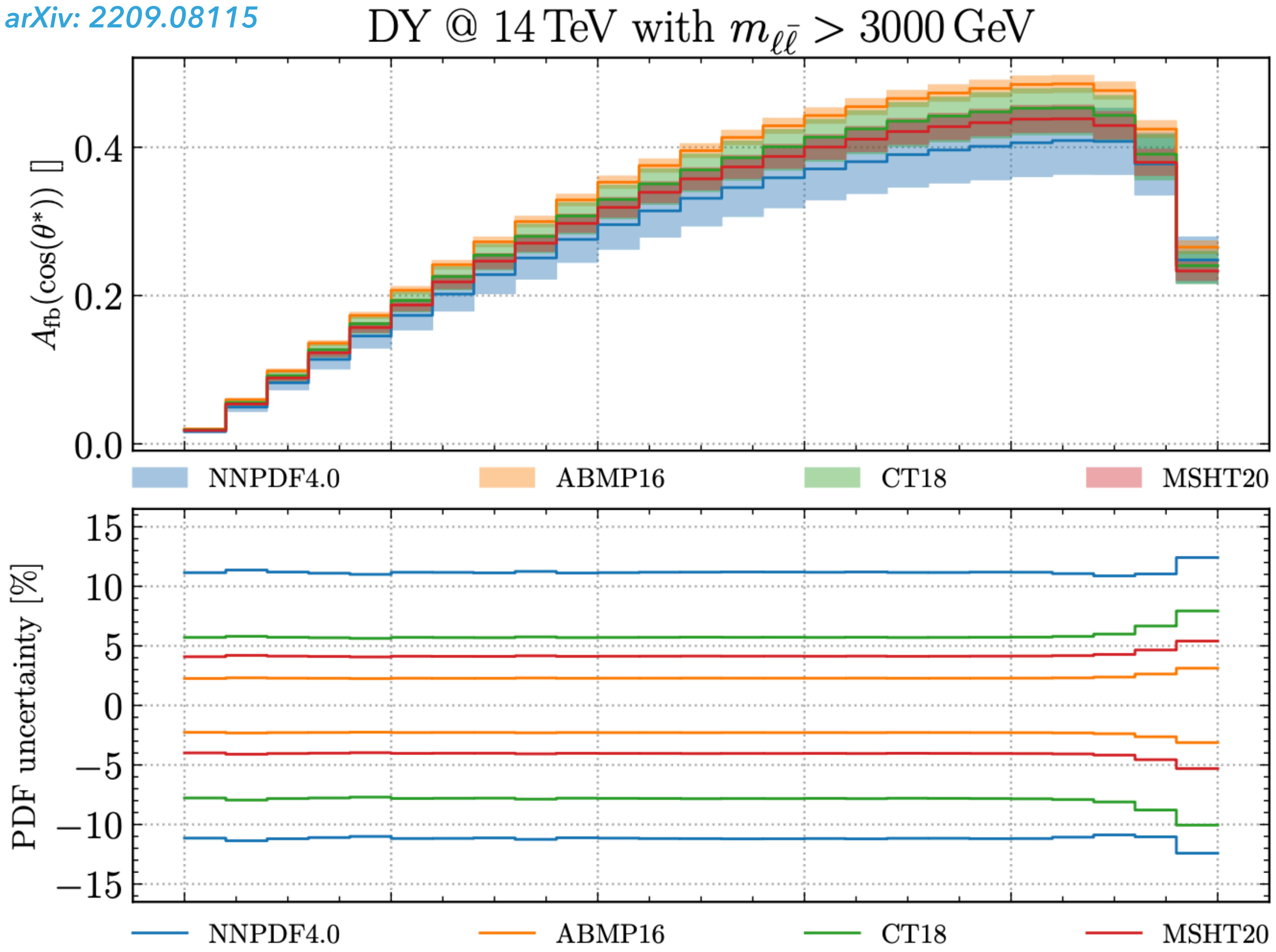
$$x \approx \frac{M}{\sqrt{S}}$$

High-mass final states

⇔

Large-x PDFs

Ball et al arXiv: 2209.08115



#3: Direct NP searches: e. g. heavy Z′ search in DY Forward-Backward asymmetry

… AND FOR NEW PHYSICS SEARCHES

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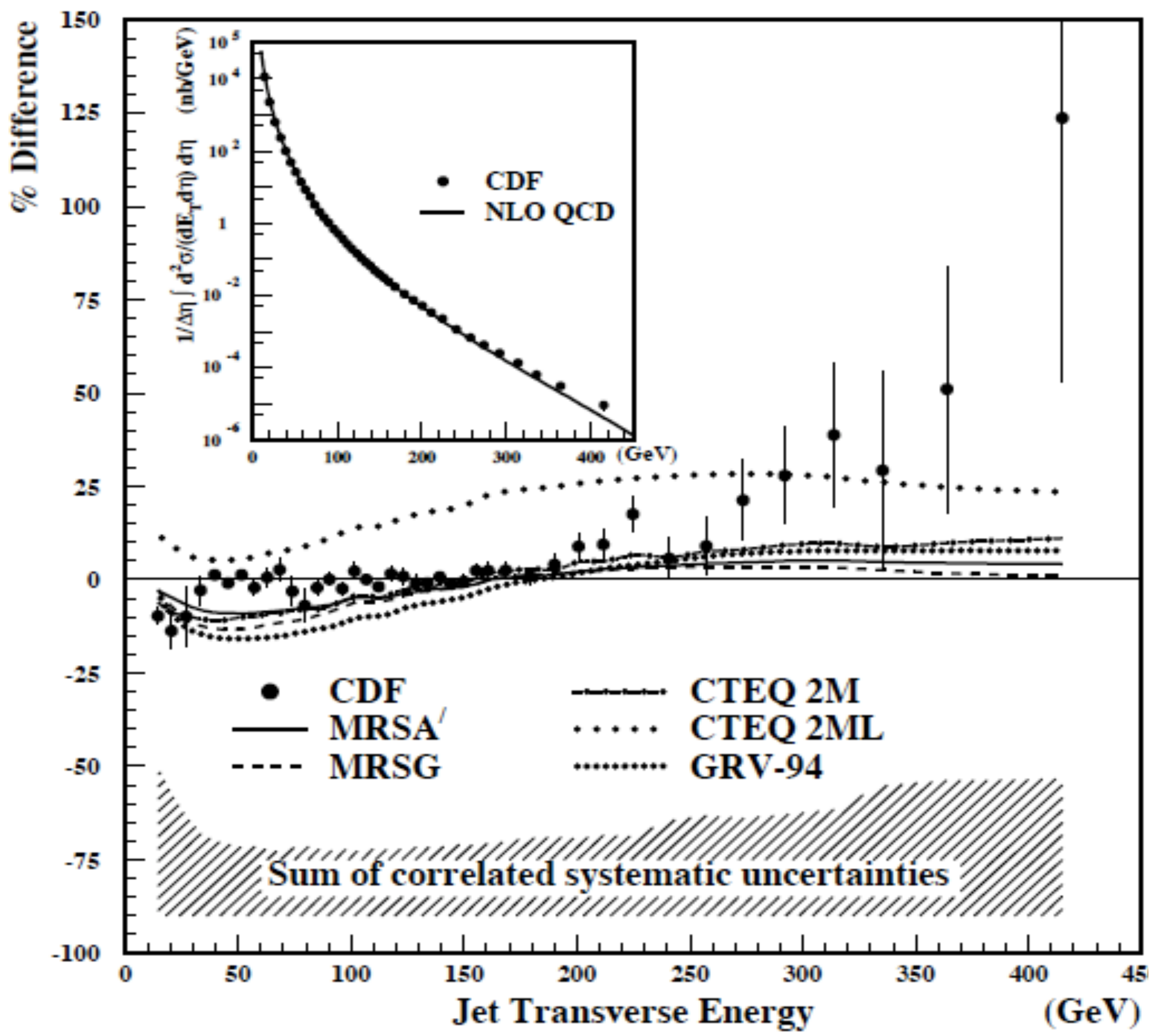
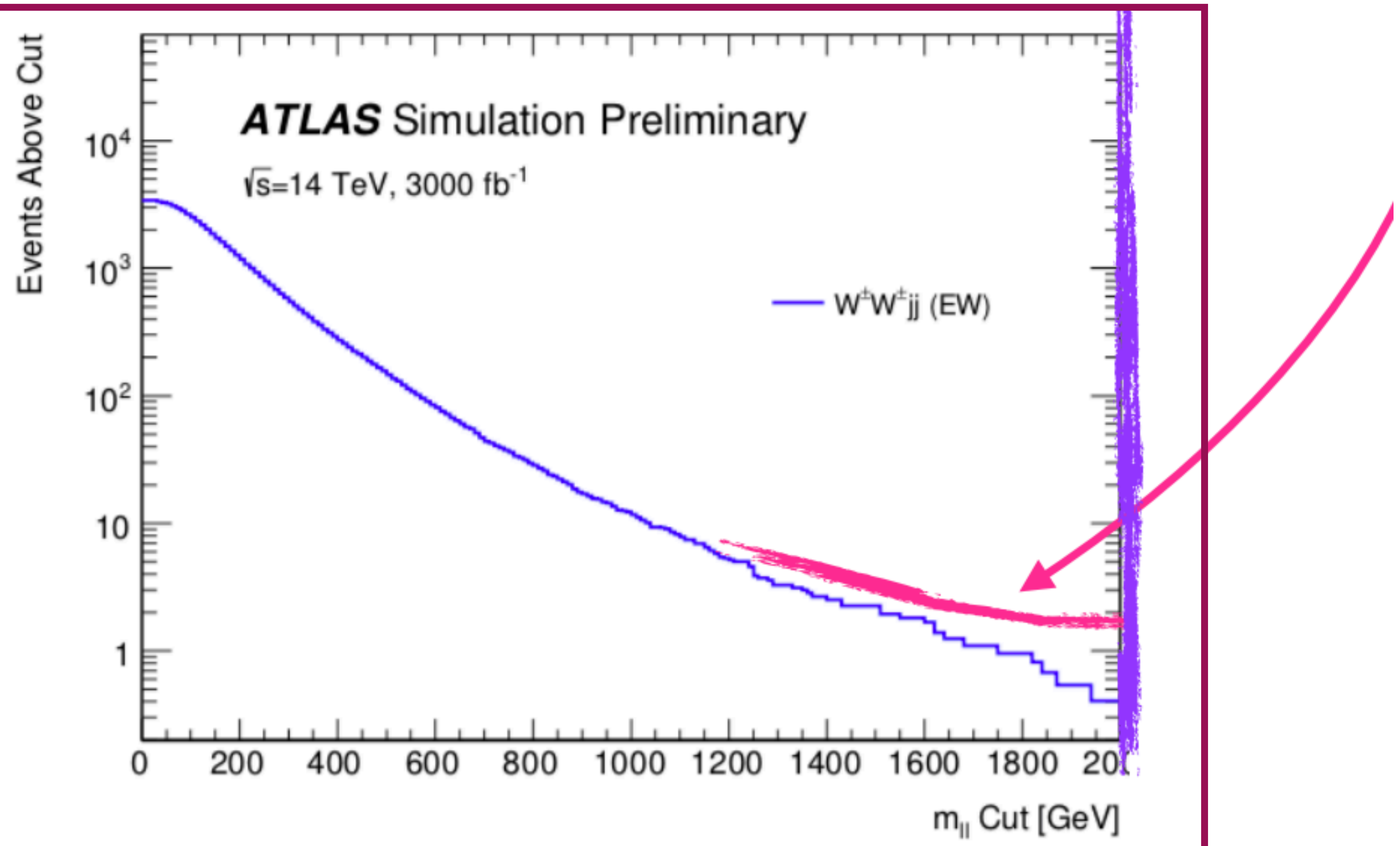
High-mass final states

⇔

Large-x PDFs





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?

#4: Indirect NP searches

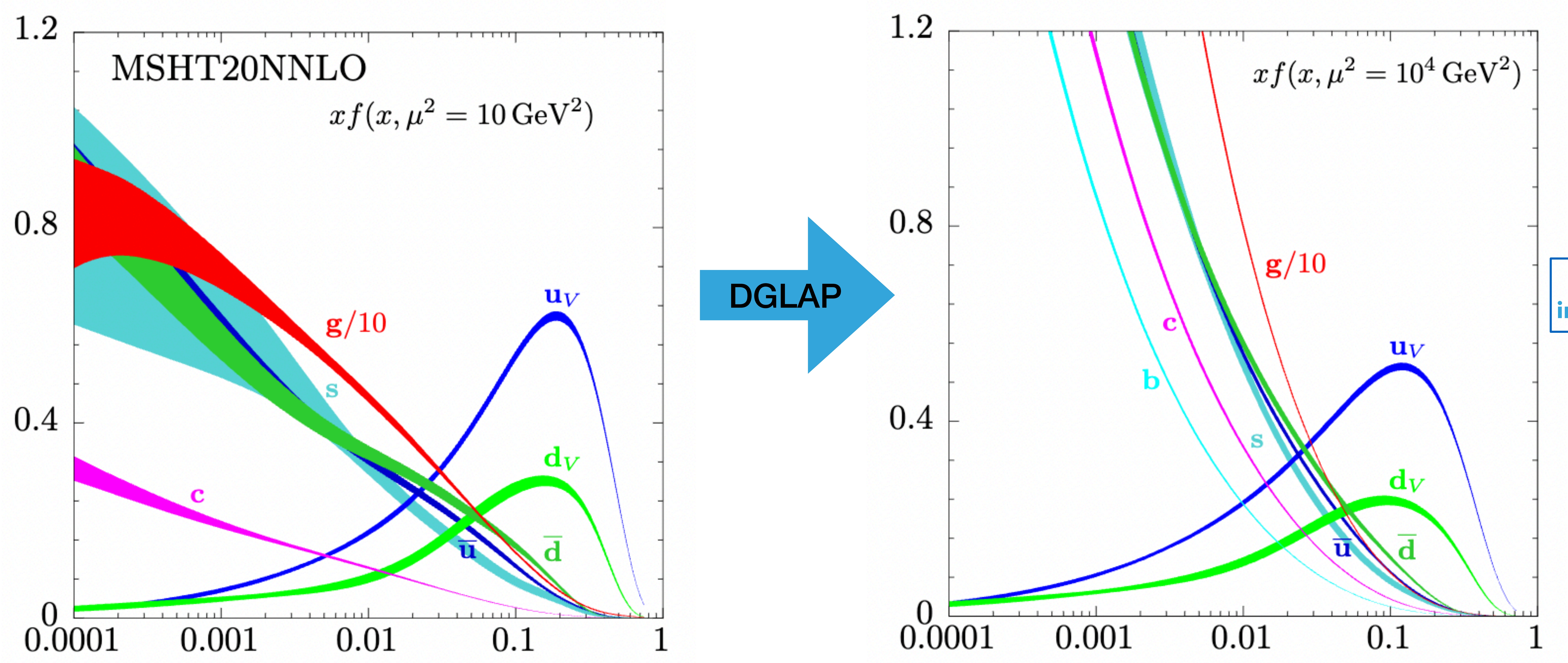
PARTON DISTRIBUTION FUNCTIONS $f_i(x,\mu)$

Perturbative QCD

$$\frac{d}{dt}\begin{pmatrix} q_i(x,t) \\ g(x,t) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \sum_{j=q,\bar{q}} \frac{d\xi}{\xi} \begin{pmatrix} P_{ij}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{ig}\left(\frac{x}{\xi},\alpha_s(t)\right) \\ P_{gj}\left(\frac{x}{\xi},\alpha_s(t)\right) & P_{gg}\left(\frac{x}{\xi},\alpha_s(t)\right) \end{pmatrix} \otimes \begin{pmatrix} q_j(\xi,t) \\ g(\xi,t) \end{pmatrix}$$

Splitting functions P_{ab} known up to approximate N^3LO [Blumlein, Moch, Gehrman, von Manteufel, Sotnikov, Yang, Davies, Vogt, Bonvini, Marzani,…]

Hadronic scale: global fit of PDFs



High scale: input to the LHC

PDG 2023

EXTRACTING FUNCTIONS FROM DATA

$$f_i(x, \mu)$$

Data

- Given a finite number of experimental data points **D** want a set of functions **f** with errors
- Mapping **D** into **f** is mathematically ill defined, nobody knows the true **f** ($\bar{f}$)
- Best we can do it to find best **f** given the data **D**.
- In Bayesian terms

$$P(f|D) \propto P(D|f)\, P(f)$$

✓ Likelihood ? Prior

Likelihood

$$P(D|f) \sim \exp(-\chi^2[f]/2)$$

$$\chi^2[f] = (D - T[f])\,(\mathrm{cov})^{-1}\,(D - T[f])$$

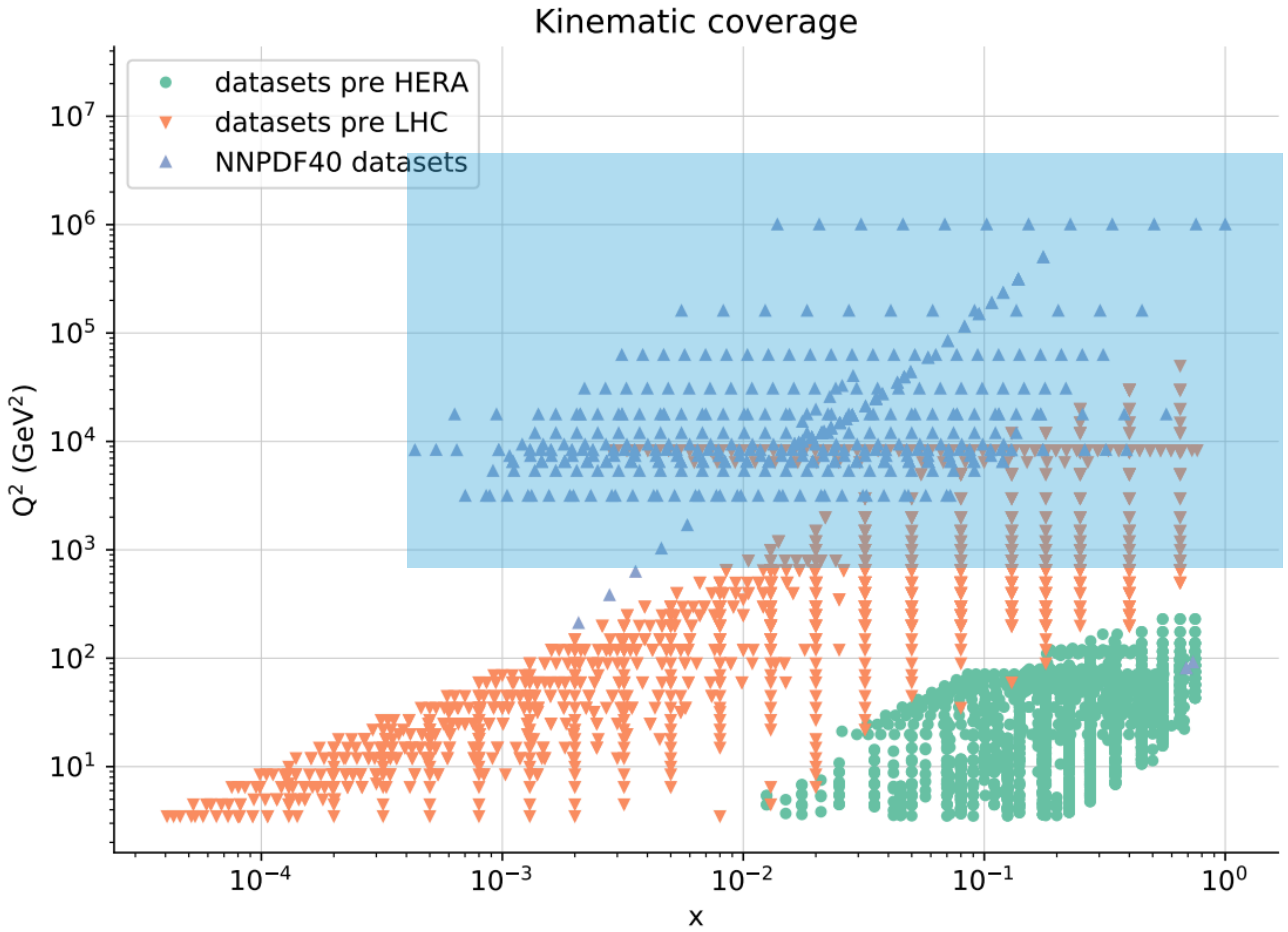
(D-T) ~ **accuracy**

Covariance matrix: experimental errors and correlations, **cov ~ precision**

Two ways of finding the prior:

- Explicit parametrization: parametrical modelling. Possible issue: often precision << accuracy then either data inconsistent or parametrization over-restrictive and tolerance needed so that precision ~ accuracy
- Non-parametrical inference: NNs or functional space sampling, use data to also infer probable 'smoothness' of f(x) and thus infer P(f) throughout the space of functions. Possible issue: numerically intensive, must have robust optimisation and stopping procedures

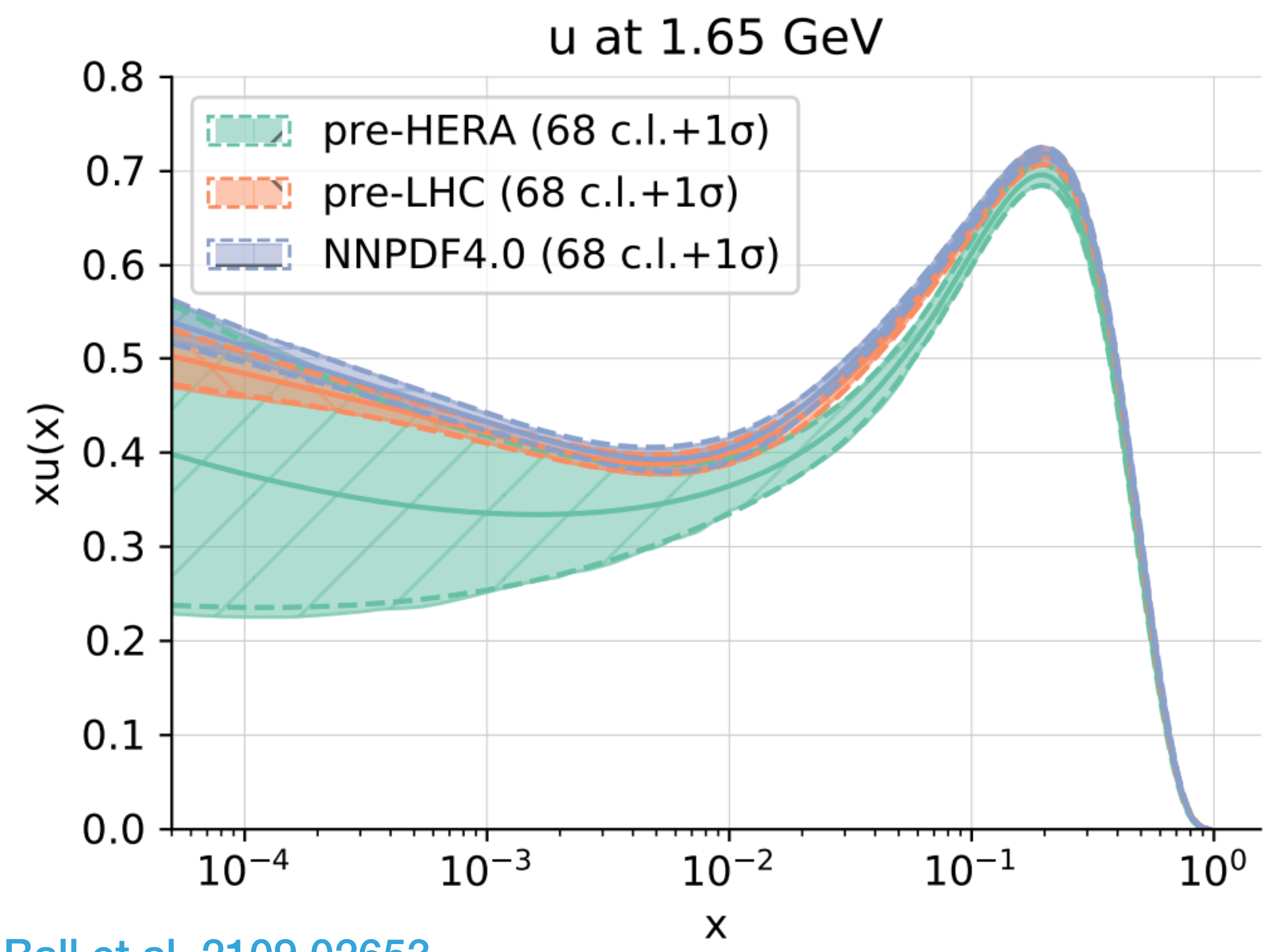
A WEALTH OF DATA FROM THE LHC



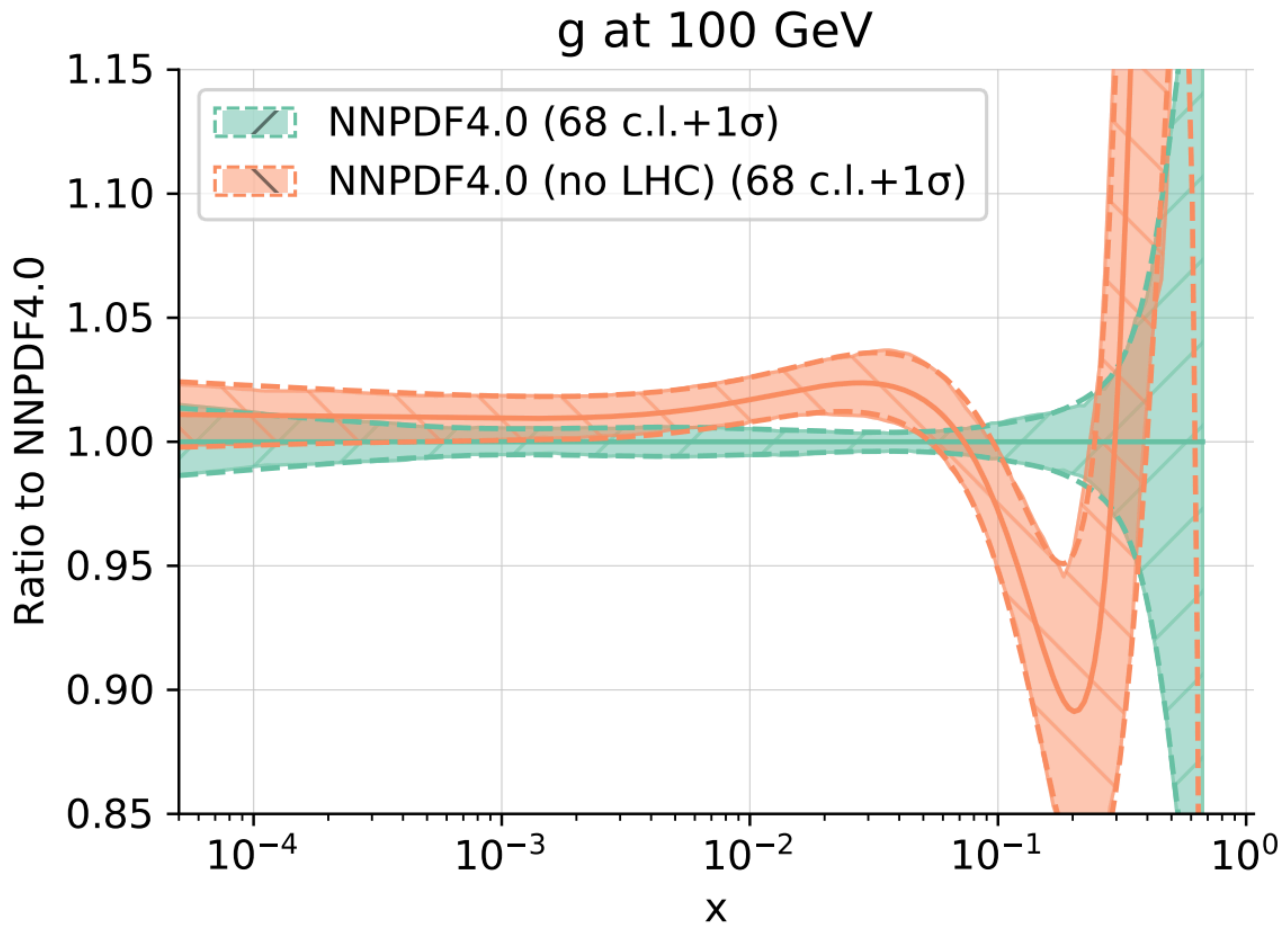
NNPDF4.0: About 30% of input data are LHC data!

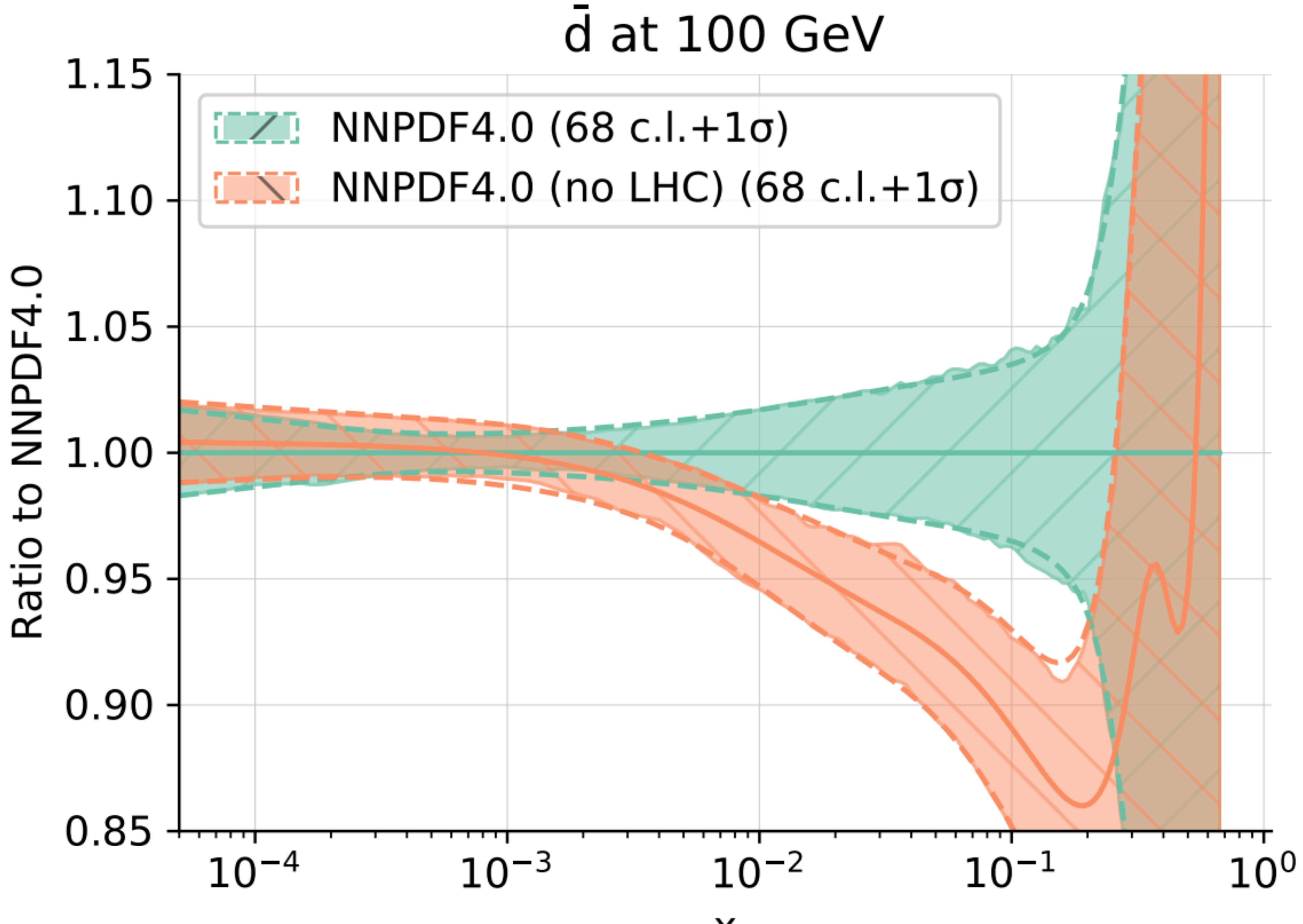
Ball et al, 2109.02653

IMPACT OF LHC DATA



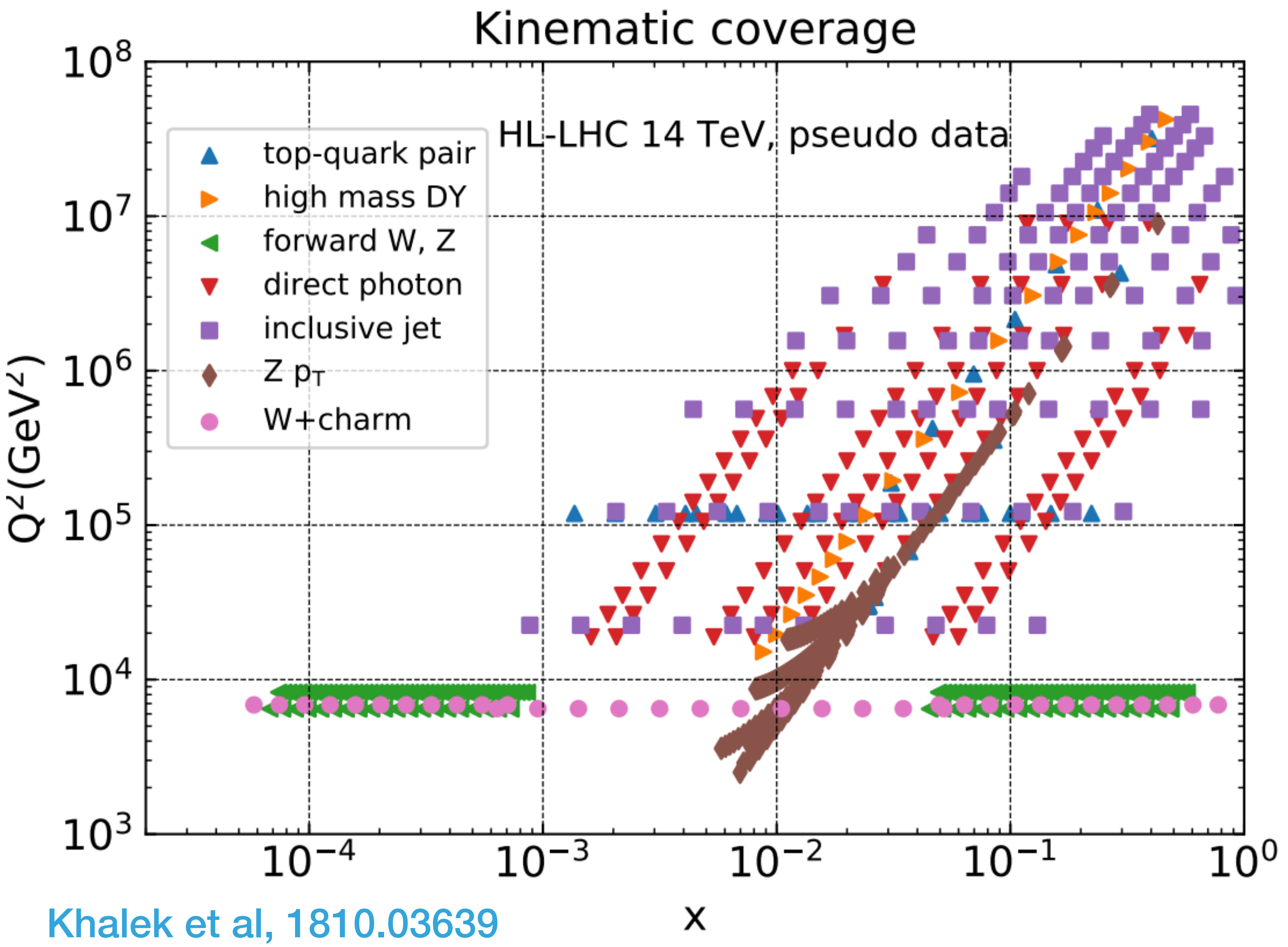
Ball et al, 2109.02653



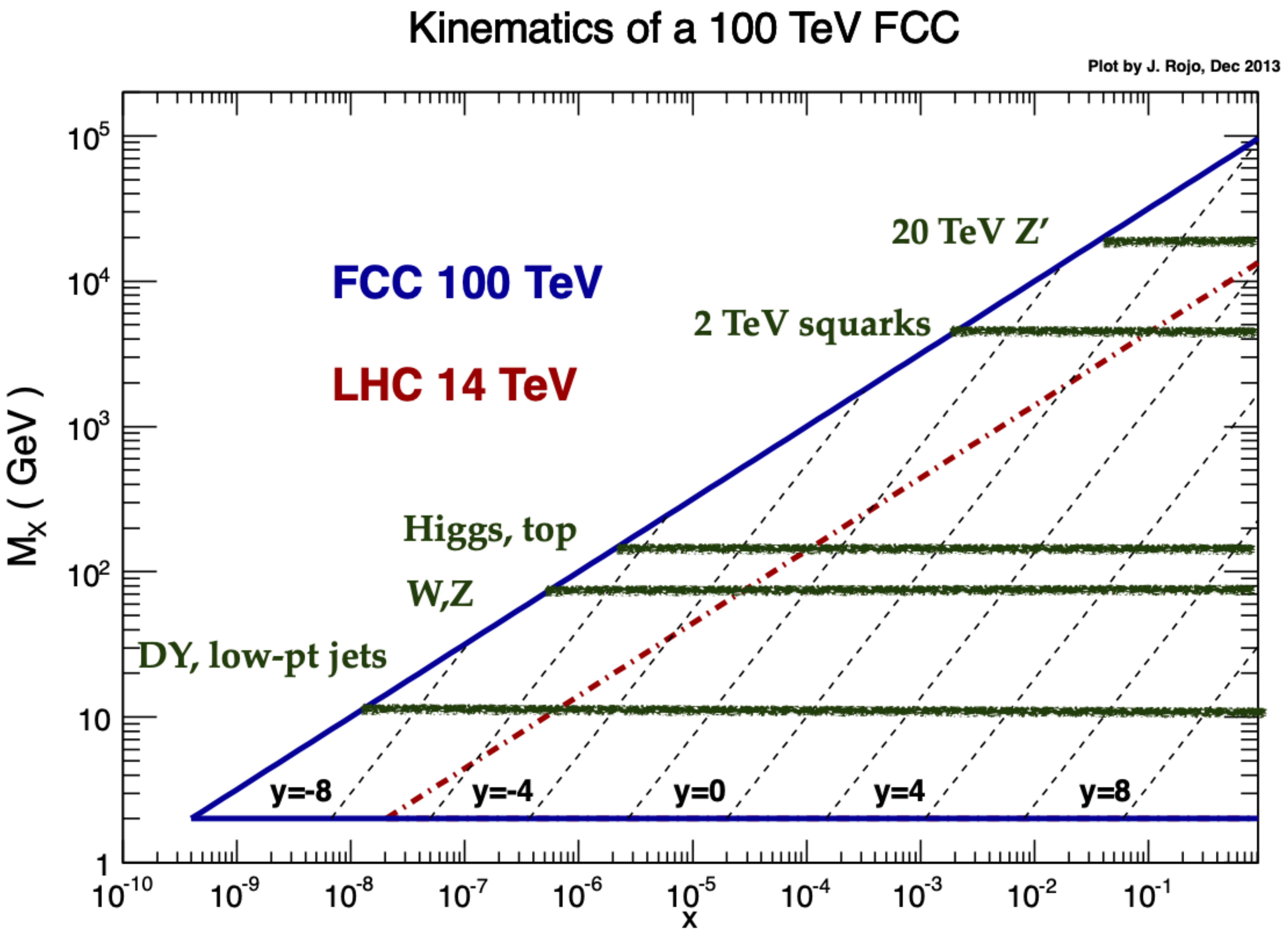


- HERA data crucial to constrain quark valence (up and to less extent down valence) across intermediate to small x and gluon at small x
- LHC high energy data crucial to provide additional constraints to PDFs, in particular in medium- to large-x gluon and quarks.
- Mild tension with older fixed-target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

CONSTRAINTS FROM THE HL-LHC



Khalek et al, 1810.03639



M. Mangano et al 1607.01831

- Thanks to luminosity upgrade, HL-LHC will go nearly two orders of magnitude higher in Q2, populating the high-energy region, and this will allow to further constrain gluon and (anti)-quarks at large x [Khalek et al, 1810.03639]
- FCC-hh will go further up by two orders of magnitude in Q2 [Mangano et al 1607.01831]

Large x ⟷ Large E and/or Large Y

- FCC-eh and LHeC cover different kinematics [Mandy's talk]

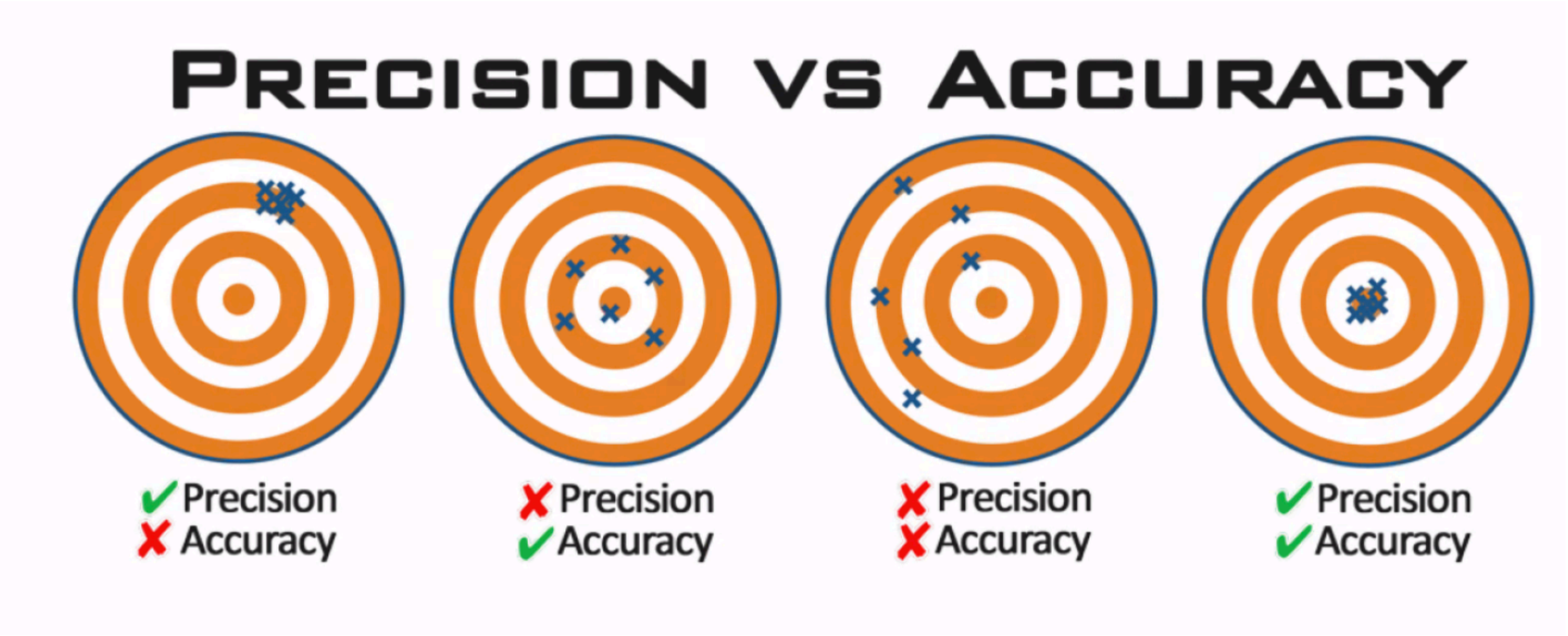
PROTON STRUCTURE

Part II

THE CORE OF THE INTERPRETATION CHALLENGE

ACCURACY VS PRECISION

THE PRECISION VERSUS ACCURACY CHALLENGE



PDF4LHC21, 2203.05506

Dataset	$N_{\rm pt}$	$\chi^2/N_{\rm pt}$		
		CT18	MSHT20	NNPDF3.1
BCDMS F_2^p	$329/163^{\dagger\dagger}/325^{\dagger}$	1.06	1.00	1.21
BCDMS F_2^d	$246/151^{\dagger\dagger}/244^{\dagger}$	1.06	0.88	1.10
NMC F_2^d/F_2^p	$118/117^{\dagger}$	0.93	0.93	0.90
NuTeV dimuon $\nu+\bar{\nu}$	38+33	0.79	0.83	1.22
HERAI+II	1120	1.23	1.20	1.22
E866 $\sigma_{pd}/(2\sigma_{pp})$	15	1.24	0.80	0.43
LHCb 7 TeV & 8TeV W,Z	29+30	1.15	1.17	1.44
LHCb 8 TeV $Z\to ee$	17	1.35	1.43	1.57
ATLAS 7 TeV W,Z (2016)	34	1.96	1.79	2.33
D0 Z rapidity	28	0.56	0.58	0.62
CMS 7 TeV electron $A_{\rm ch}$	11	1.47	1.52	0.76
ATLAS 7 TeV W,Z(2011)	30	1.03	0.93	1.01
CMS 8TeV incl. jet	$185/174^{\dagger\dagger}$	1.03	1.39	1.30
Total $N_{\rm pt}$	—	2263	1991	2256
Total $\chi^2/N_{\rm pt}$	—	1.14	1.15	1.20

Challenges

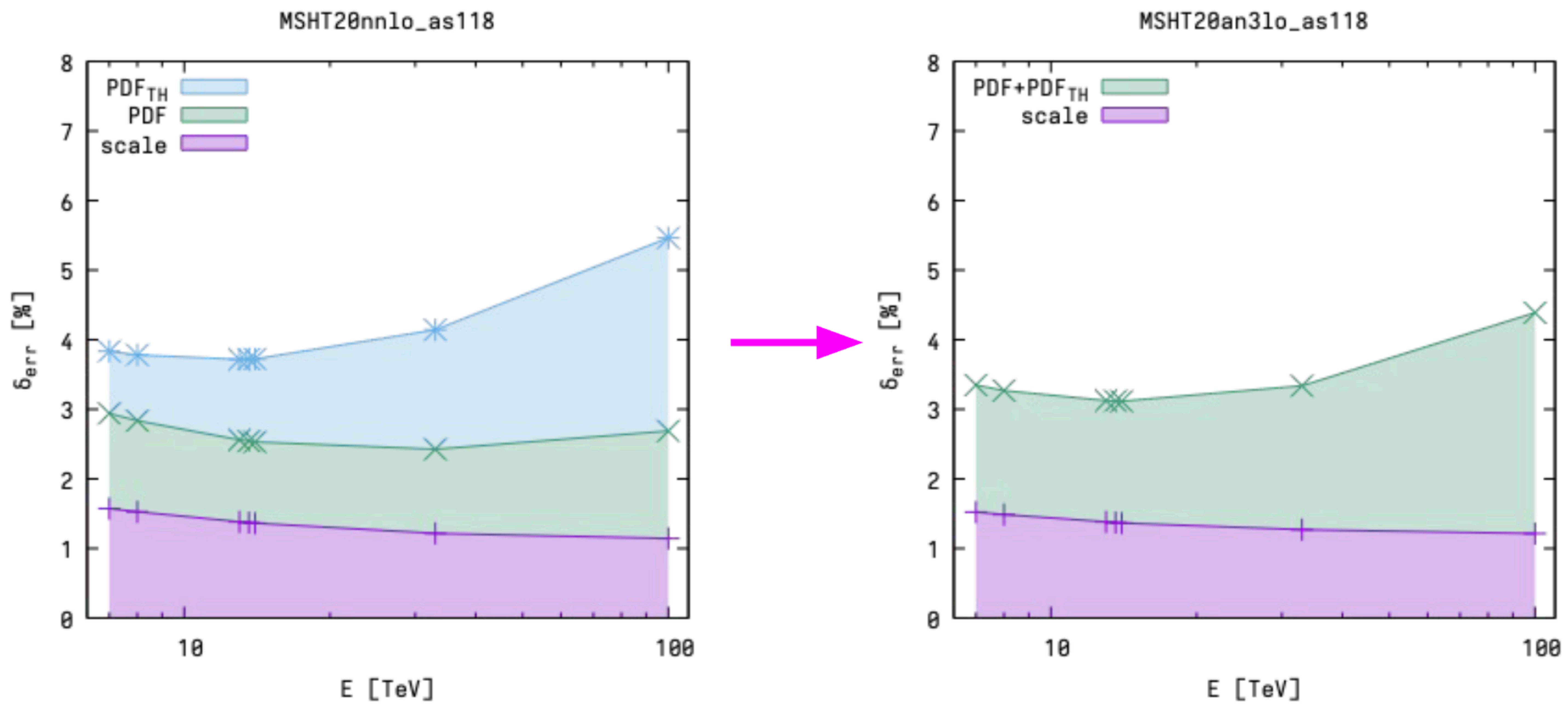
- Inconsistency or tension in data of experimental origin (underestimate of systematics…)
- Deficiencies in fitting methodology (data-driven parametrisation change, optimisation issues, overfitting…)
- Inaccuracy in theoretical framework
  - ➡ Missing higher order uncertainties (QCD, EW)
  - ➡ Other corrections (nuclear, higher-twist, non-perturbative effects…)
- Fitting away possible BSM signals

THE PRECISION VERSUS ACCURACY CHALLENGE: THE THEORY SIDE

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

- Standard global PDF fits based on fixed-order NNLO QCD calculations. PDF uncertainty reflects experimental uncertainty.
- N3LO is now the precision frontier for partonic cross sections (N3LO splitting functions partially known)
- Mismatch between perturbative order of partonic cross section and PDFs becoming significant source of uncertainty
- First aN3LO PDFs available: MSHT20aN3LO [arXiv:2207.04739] and NNPDF40aN3LO [on the arXiv tomorrow]

Gluon-gluon fusion into Higgs

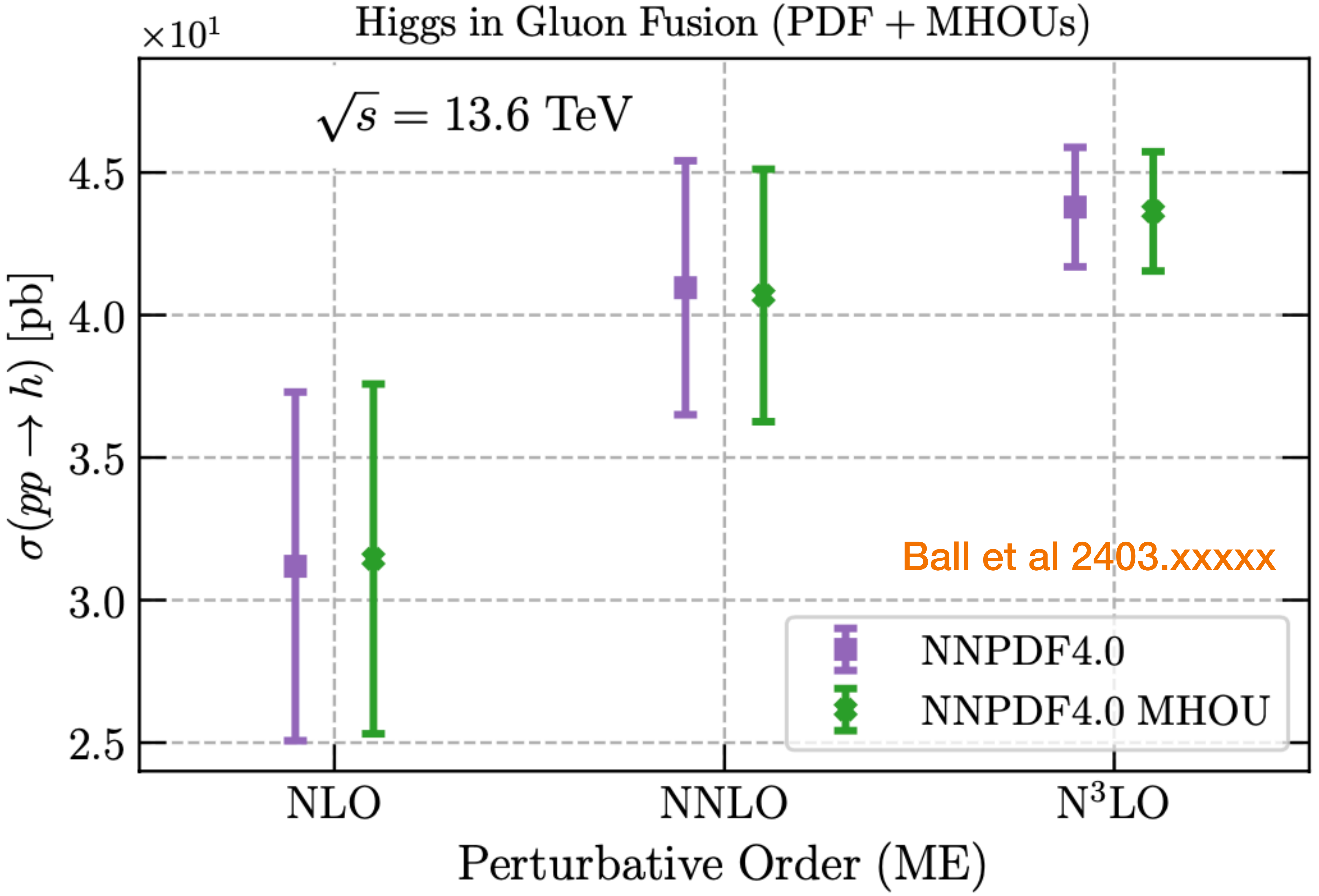


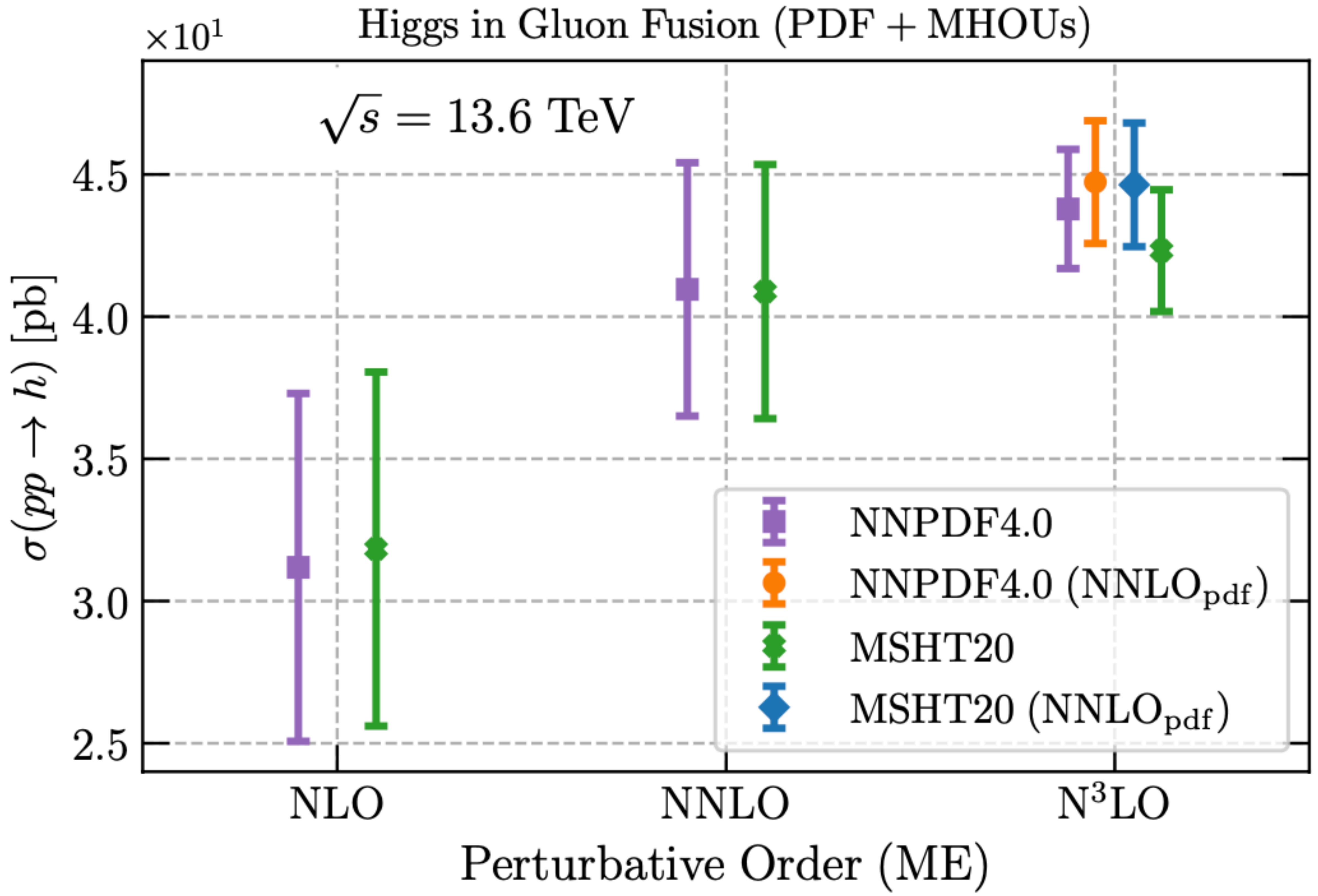
$$\delta(PDF-TH) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\rm NNLO-PDFs} - \sigma^{(2)}_{\rm NLO-PDFs}}{\sigma^{(2)}_{\rm NNLO-PDFs}}\right|$$

With aN3LO availability can see that this is over-conservative measure of mismatch between NNLO PDFs and N3LO partonic cross sections

Courtesy of A. Huss and G, Magni

THE PRECISION VERSUS ACCURACY CHALLENGE: THE THEORY SIDE





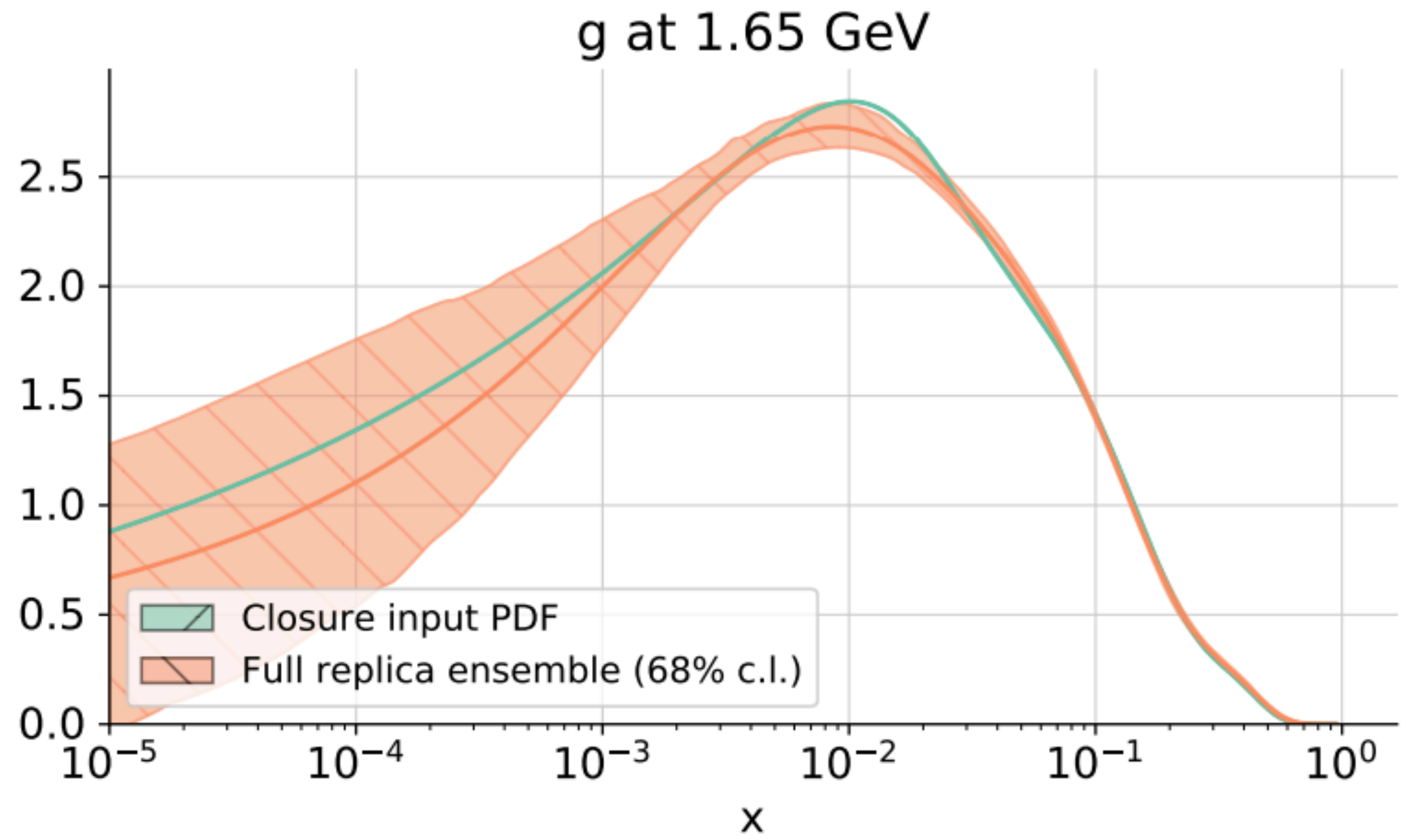
- Different ways of including Incomplete Higher Order Uncertainties (for N3LO PDFs) and Missing Higher Order Uncertainties (at all orders) [Ball et al 2401.10319, McGowan wt al 2207.04739, Kassabov et al 2207.07616]
- Benchmark of approximate aN3LO splitting functions in progress [Moch et al]
- aN3LO PDF sets and MHOU in NNLO PDF sets help with accuracy of theoretical prediction

THE PRECISION VERSUS ACCURACY CHALLENGE: THE METHODOLOGY SIDE

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 can be performed via closure tests **[Del Debbio et al, arXiv2111.05787]**

Test fitting methodology with consistent data (by construction)



✓ Closure tests assess methodology robustness and efficiency & faithfulness of uncertainty estimate.

✓ Input the "true" PDFs, generate MC data according to the "truth" with exp. uncertainty and check if what you get out of the fit corresponds to the truth

THE PRECISION VERSUS ACCURACY CHALLENGE: THE METHODOLOGY SIDE

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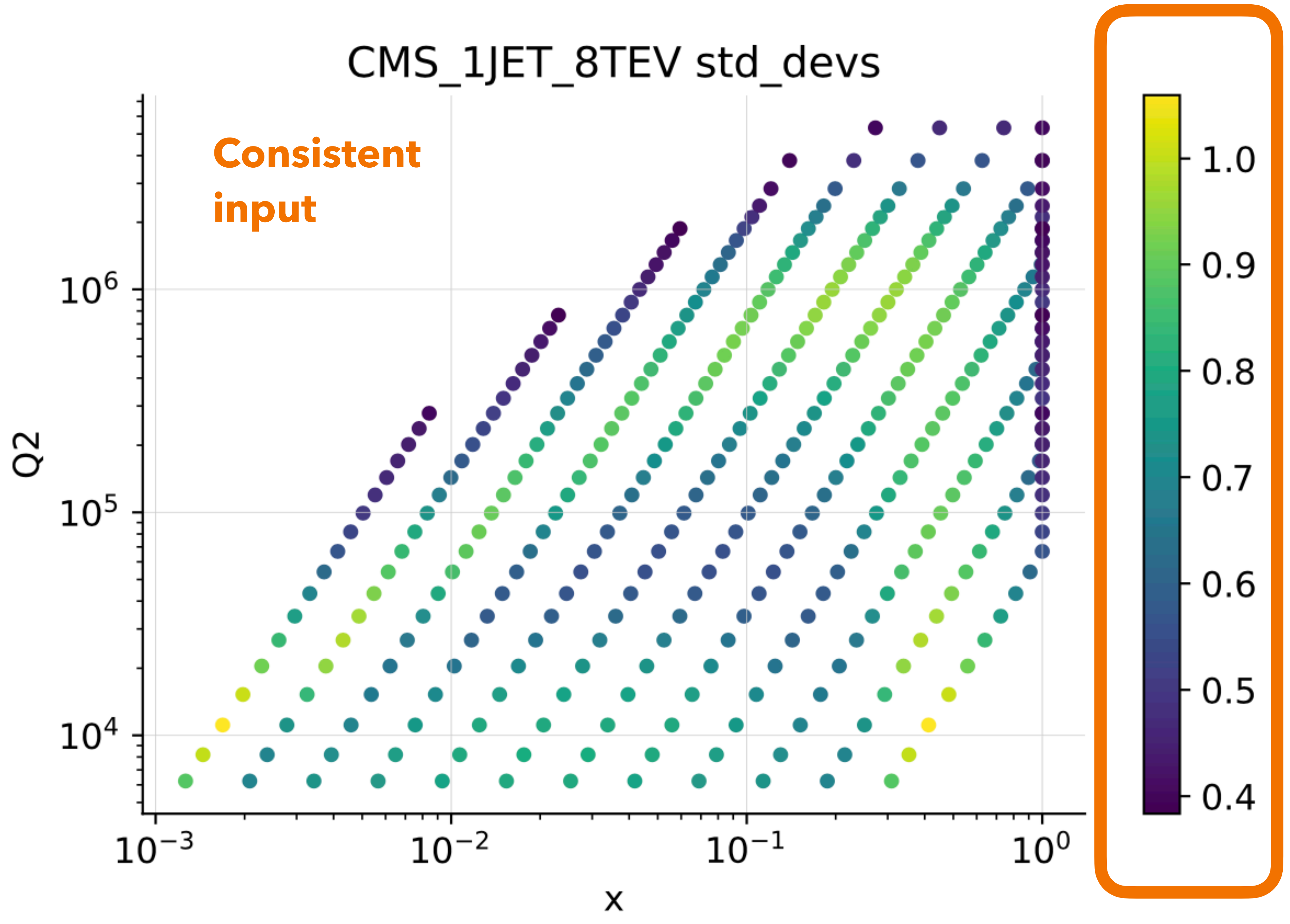
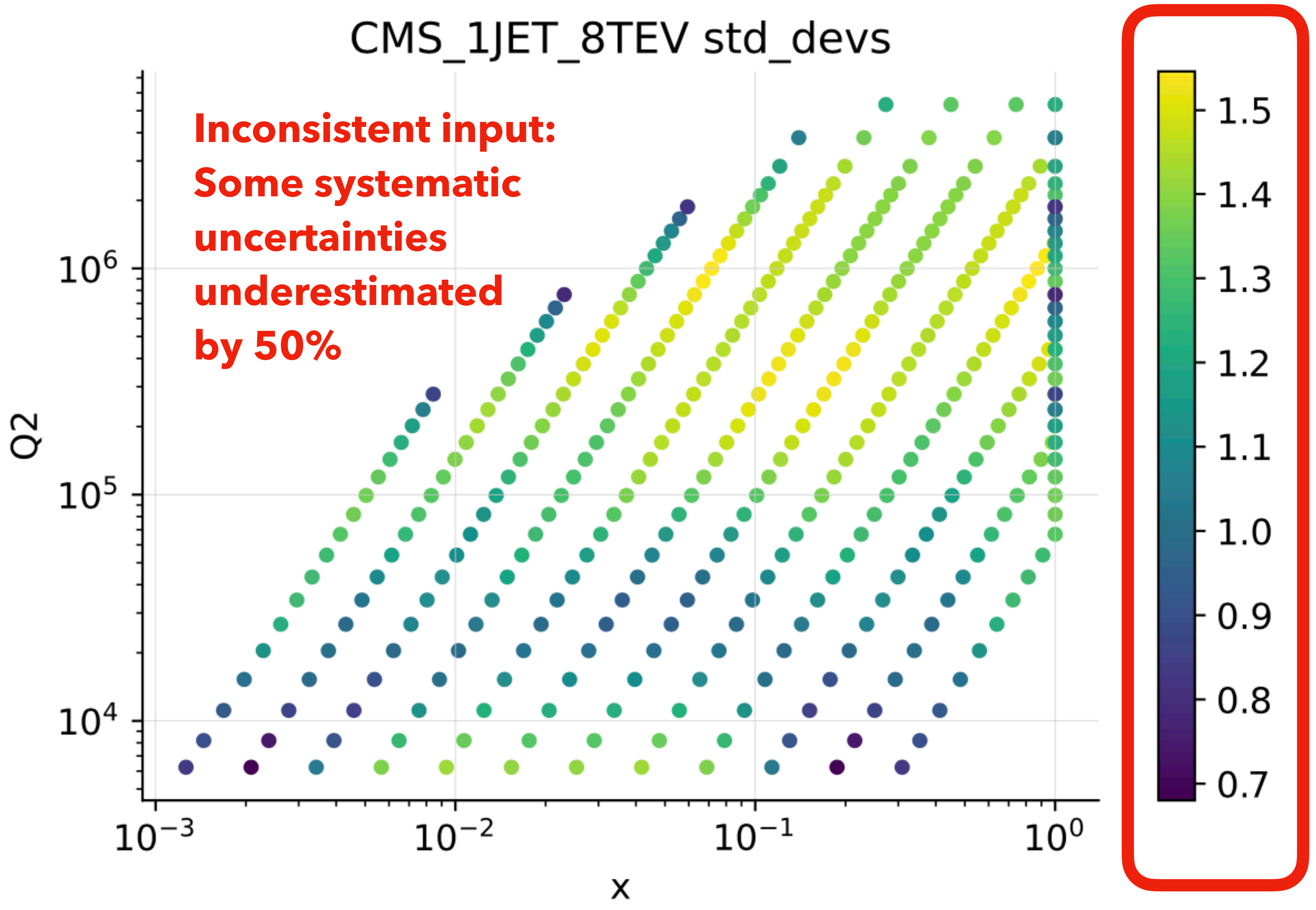
- Closure tests for <u>data region</u>: imagine we knew the law of Nature: is our fitting methodology able to reproduce it? Is the uncertainty faithful? Statistical validation of PDF uncertainties can be performed via closure tests **[Del Debbio et al, arXiv2111.05787]**
- What is experimentalists underestimated some systematics? **[Barontini, Costantini et al - work in progress]**

Test fitting methodology with inconsistent data





Statistical indicators of under (>1) or over (<1) estimated uncertainties allows to check effect of possible experimental inconsistencies on PDFs

THE PRECISION VERSUS ACCURACY CHALLENGE: THE METHODOLOGY SIDE

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- What is experimentalists underestimated some systematics? **[Barontini, Costantini et al - work in progress]**

- Suggest to identify a subset of precise and self-consistent measurements which we believe to be well described by theory to be used for **"reduced data PDF fits"**
- Involving both PDF fitting groups and experimental collaborations
- Similar to PDF4LHC benchmarking, but aimed at a deeper understanding of differences in PDFs and alleviate the need for tolerances
- Could consider a "PDF challenge" in which we provide you with pseudo data generated under a known probability distribution (including tensions) and we compare the PDF+uncertainties returned by the various PDF fitting approaches

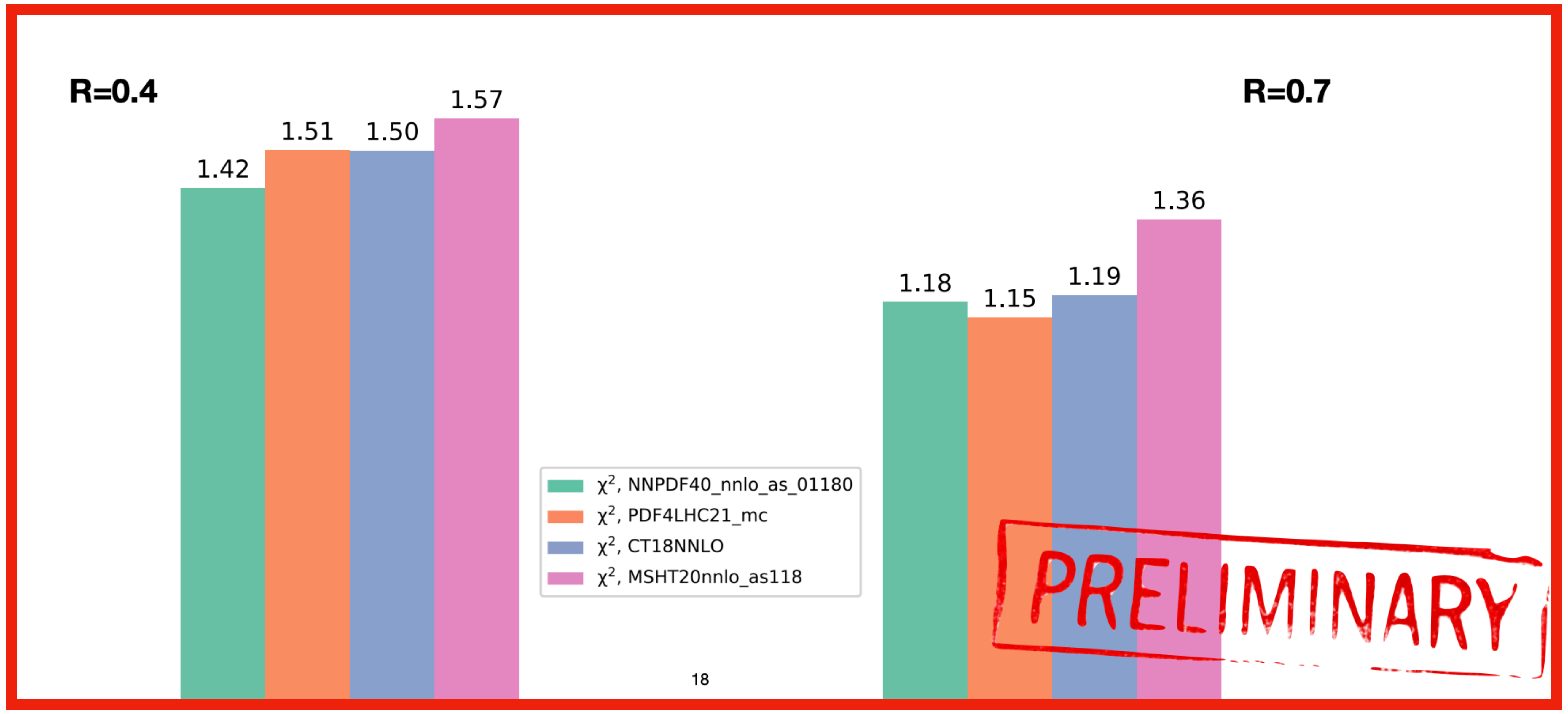
S. Amoroso's talk

THE PRECISION VERSUS ACCURACY CHALLENGE: THE METHODOLOGY SIDE

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

CMS inclusive jet data for R=0.4 and R=0.7, 13 TeV - 36.6fb-1 (not included in PDF fits)

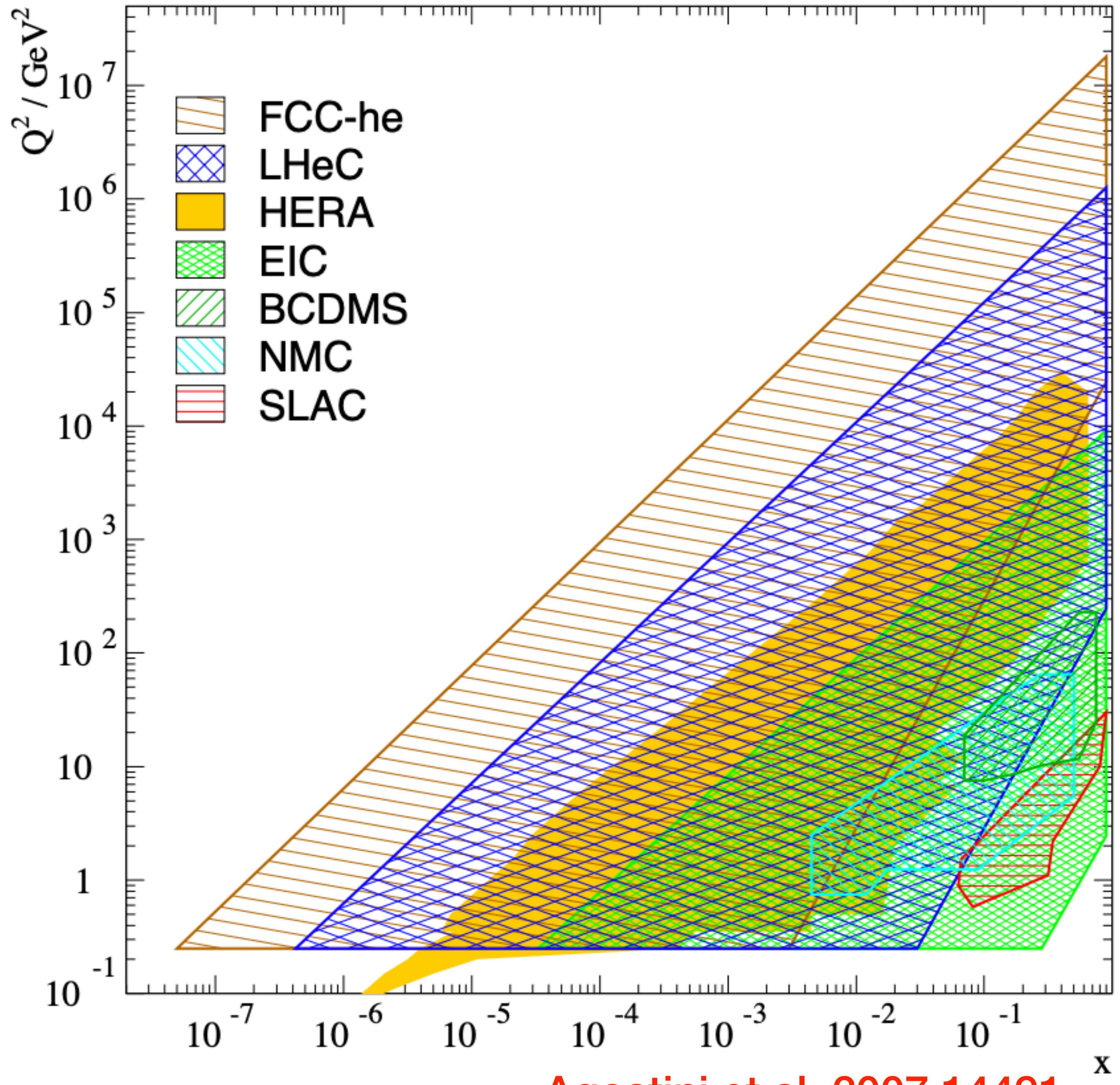


J. Cruz-Martinez's talk - PDF4LHC 23 - CERN

Ideally in collaboration with experimentalists

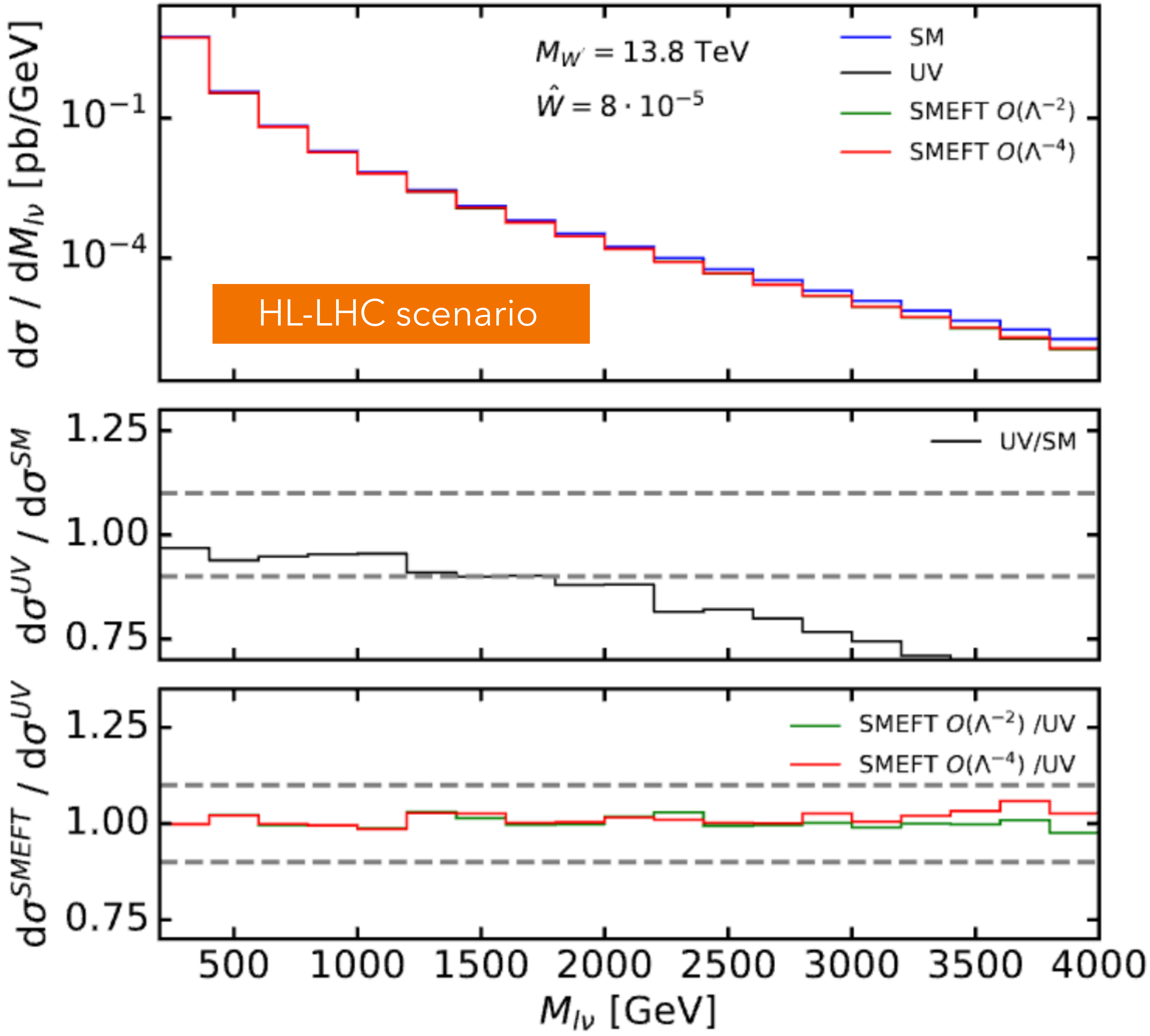
Even more powerful test from LHeC and FCC-he

LHeC, FCC-he, EIC test on new settings!



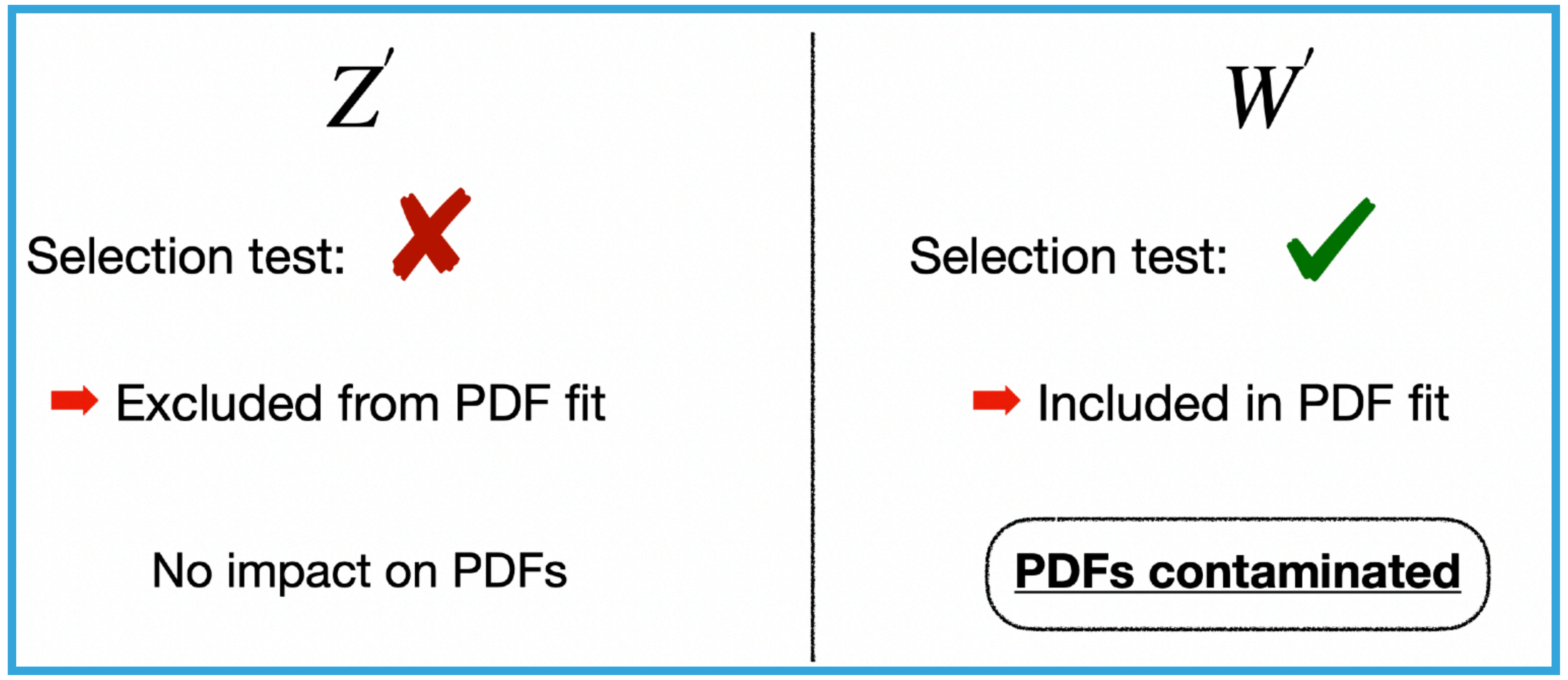
Agostini et al, 2007.14491

THE PRECISION VERSUS ACCURACY CHALLENGE: BSM "CONTAMINATION"



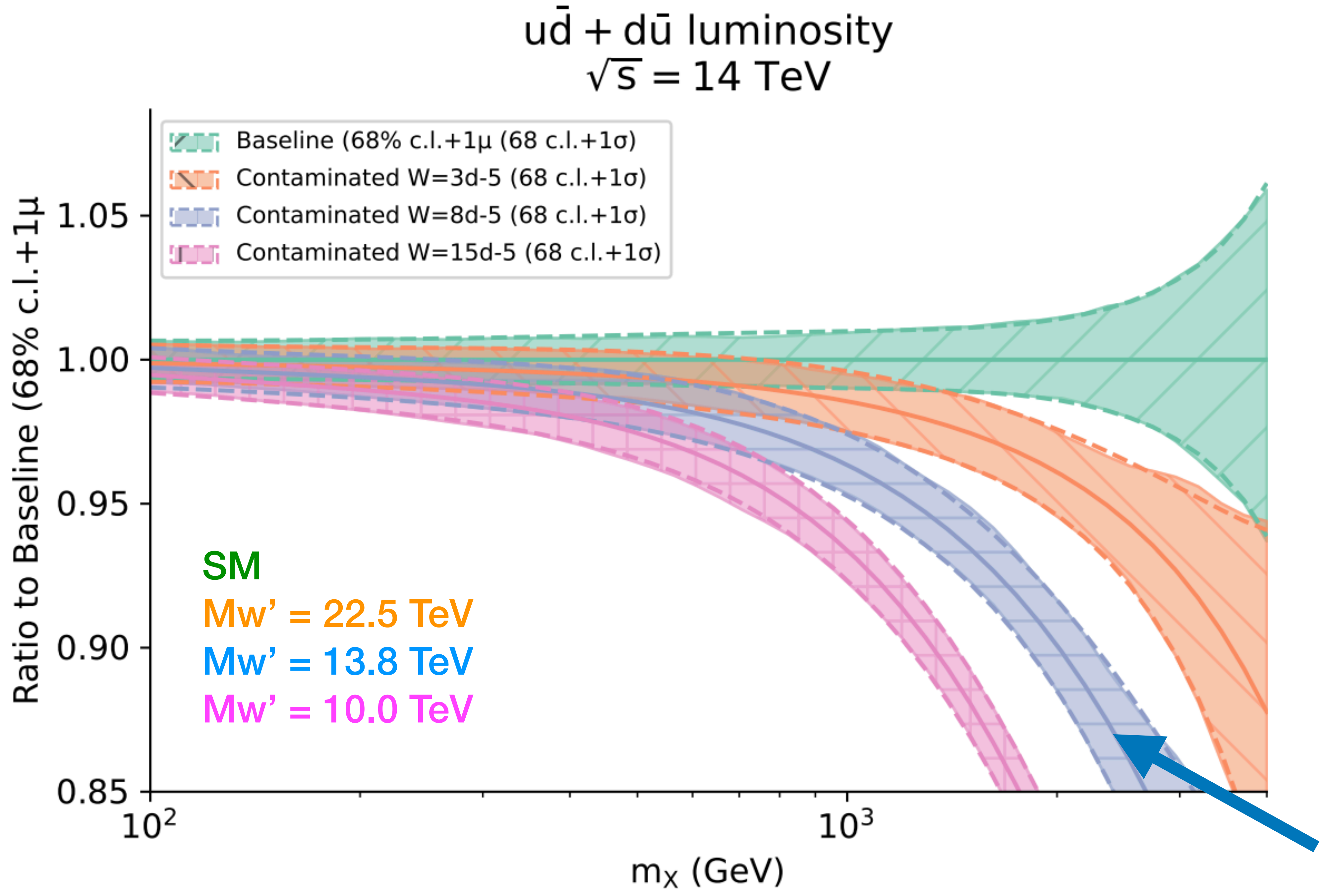
- Imagine that on top of the "true" PDFs one inject the "true" UV model in the MC data
- Generate artificial MC data assuming "true" law of nature = "true" PDFs + "true" UV model
- Fit PDFs assuming SM
- Can PDFs absorb signs of new physics?

E. Hammou, Z. Kassabov, M. Madigan, M. Mangano, L. Mantani, J. Moore, M. Morales, MU
2307.10370



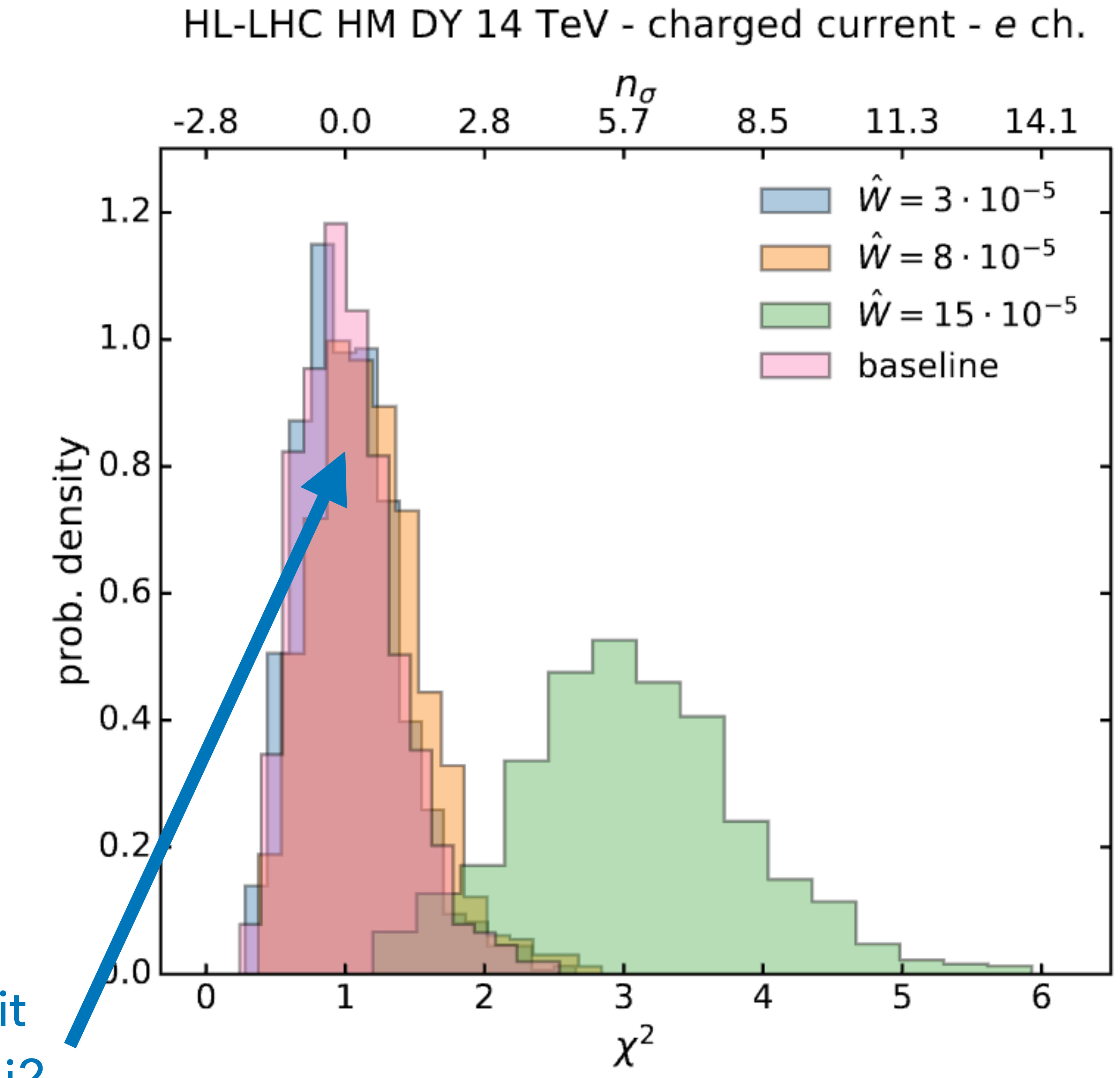
CAN PDFS ABSORB NEW PHYSICS? THE W' CASE AT HL-LHC

- The fit-quality of the global fit is unchanged even with signal from Mw' = 13.8 TeV injected in all data (mostly visible in HL-LHC NC and CC Drell-Yan data)
- Once we go beyond this point ,the fit-quality deteriorates due to the HL-LHC neutral current and charged current Drell-Yan MC data.
- Already for Mw' = 13.8 TeV the qq~ luminosity shifts far beyond the PDF uncertainties because anti-quark PDFs at large-x compensate or "fit away" the effect of New Physics and we would not know in a real fit.



E. Hammou, et al 2307.10370

Max contamination allowed by global fit Without spoiling chi2



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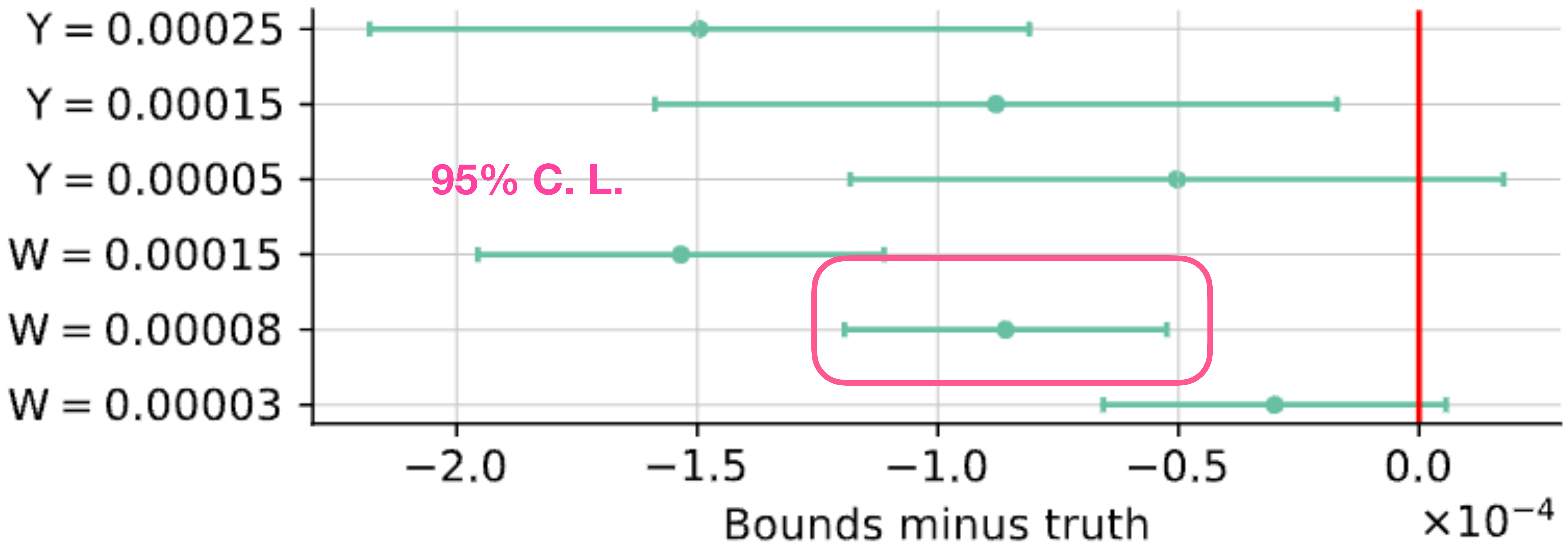
Consequence #1:
Would not see indirect effect of new physics as we would find SMEFT bounds compatible with the SM!



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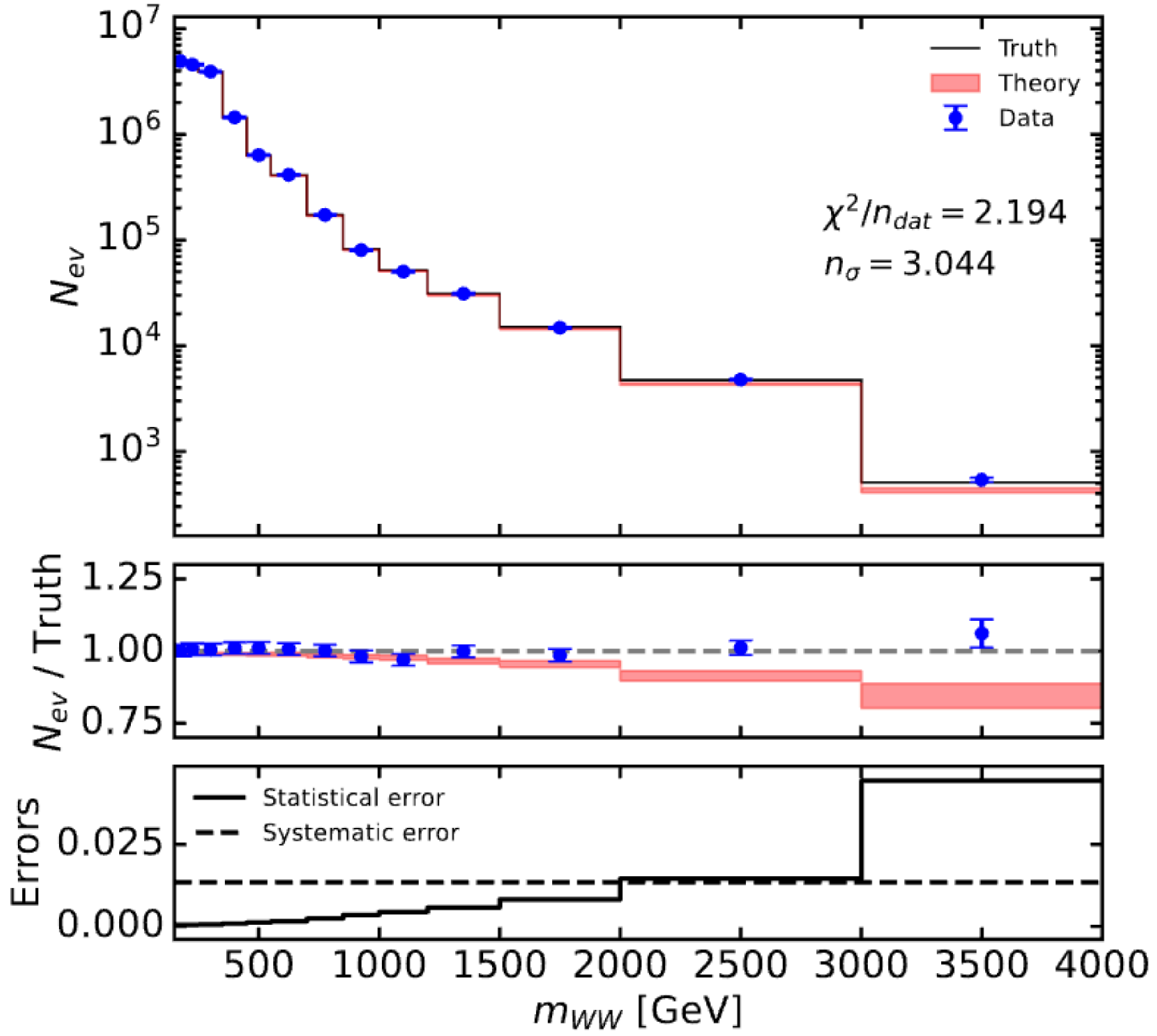


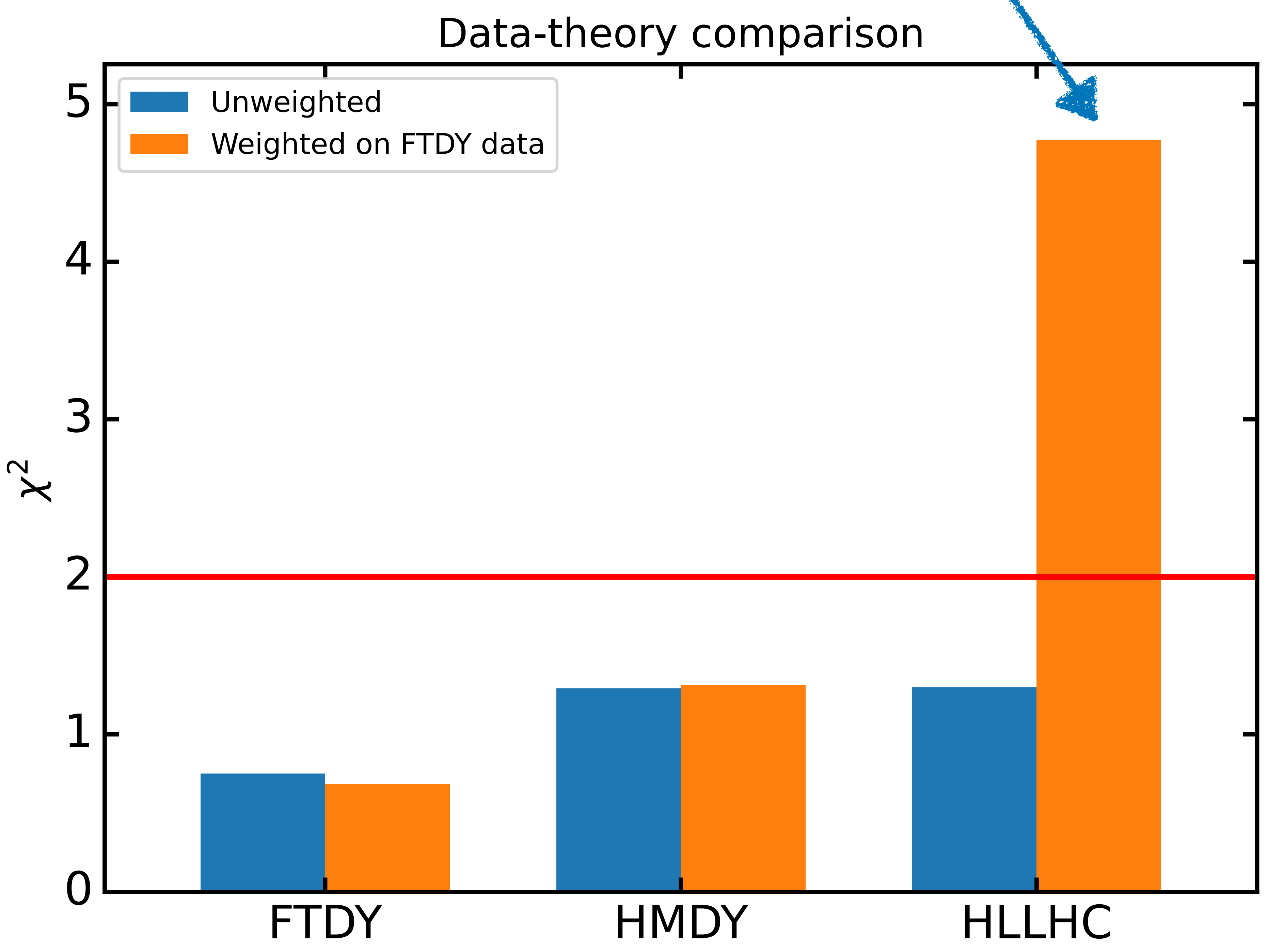
Consequence #2:
Would see New Physics effects where there are none (for example in WW)

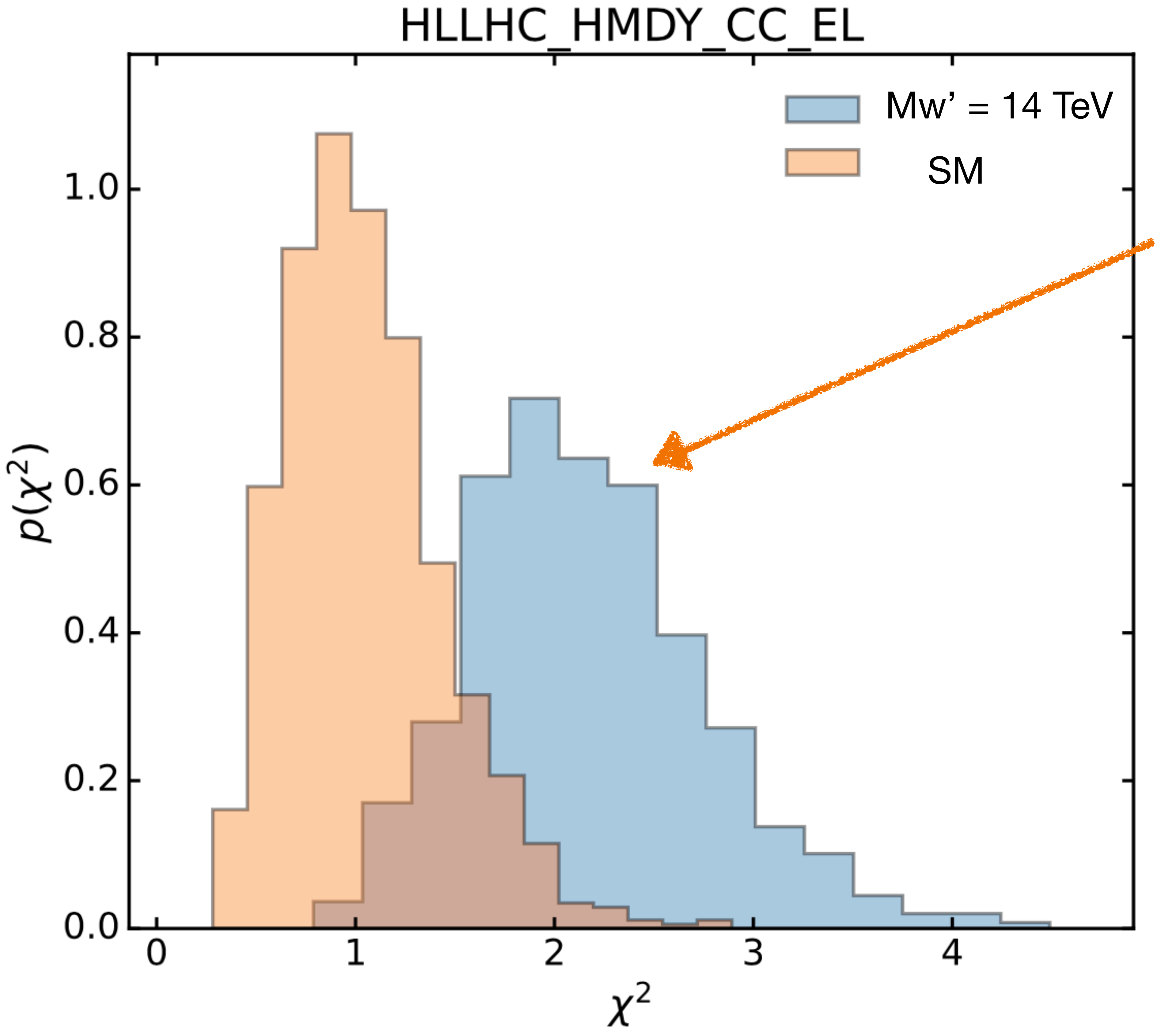
E. Hammou, et al 2307.10370

HOW TO AVOID NEW PHYSICS CONTAMINATION?

- LHCb on-shell and high rapidity data do not help as quark probed at large x, antiquark at small x
- Need more accurate low-energy/large-x constraining measurements to really disentangle such effects
- Strong motivation for synergy with ep experiments (FCC-eh, EIC and Forward Physics Facility) probing lower energies (hence no "contamination" from heavy new physics) and large-x

Low energy fixed target Drell-Yan data constrain antiquarks at large x, if they were more precise, tension with new-physics contaminated HL-LHC data would be evident!





Inclusion of FPF pseudo-data (FASERv, FASERv2, advSNDv) along with HL-LHC (DY NC and DY CC) pseudo-data would prevent new physics contaminations!

Hammou, Madigan, MU, in preparation

PRECISION PHYSICS

Part III

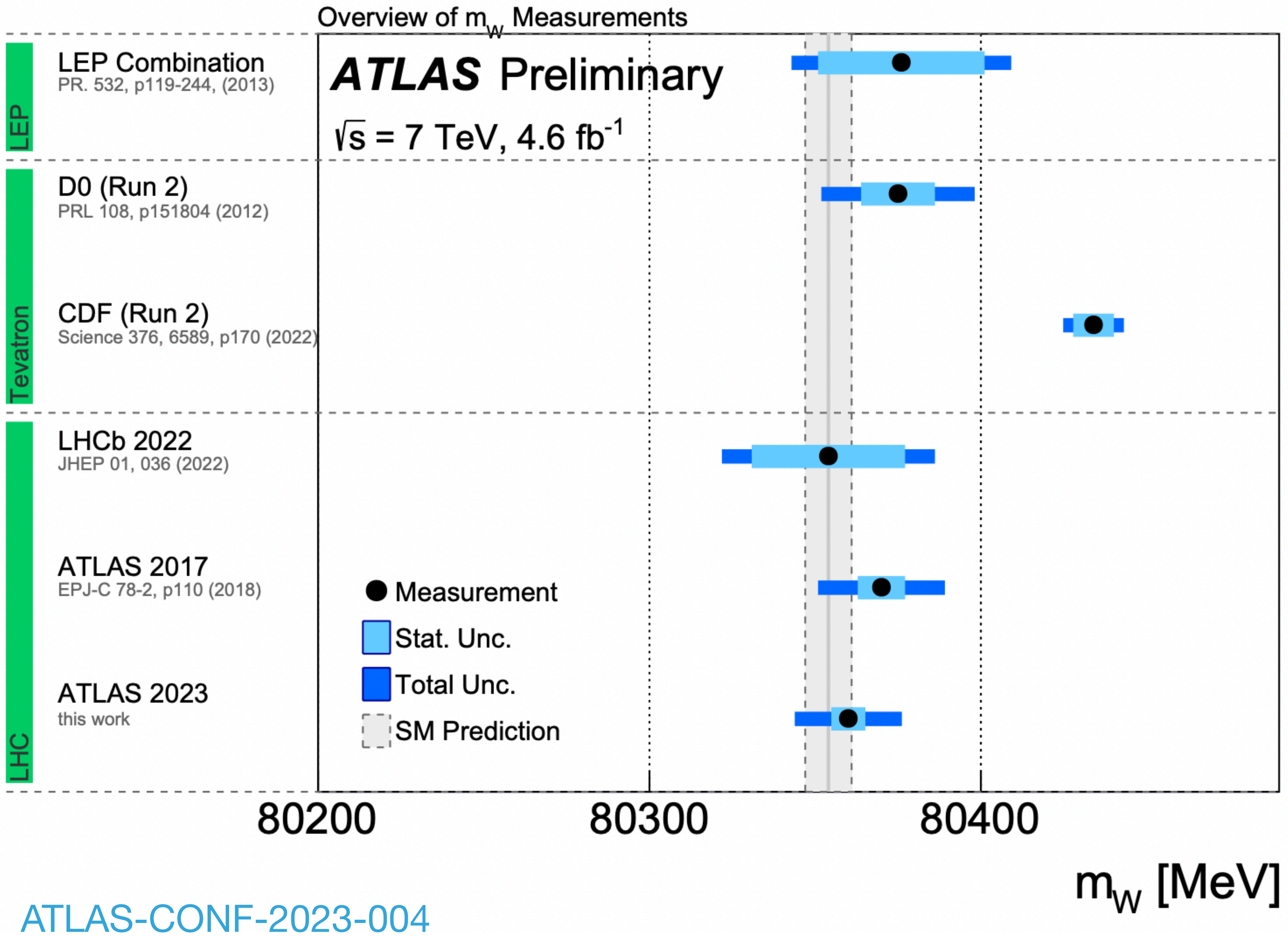
A GLOBAL INTERPRETATION OF THE LHC DATA

NEW PHYSICS SIGNATURES

GLOBAL INTERPRETATION OF DATA

Part III

GLOBAL INTERPRETATION OF LHC DATA



ATLAS-CONF-2023-004

Extremely precise LHC data & advances in theoretical predictions and statistical techniques allow to extract SM (and BSM) parameters to a great level of precision

- $\alpha_s(M_Z)$
- M_W
- Parton Distribution Functions
- SMEFT Wilson coefficients
- …

While huge progress made in determining each of these key ingredients of theoretical predictions from the data, not yet evident how to combine all these partial fits into a global interpretation of the LHC data. Simultaneous fits are pivotal step in this direction.

EXTRACTING PARAMETERS FROM DATA

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

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

α_s, EW parameters, SMEFT WCs…

Parameters determining PDFs at initial scale

EXTRACTING PARAMETERS FROM DATA

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

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

αs, EW parameters, 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 SM/BSM parameters

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

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

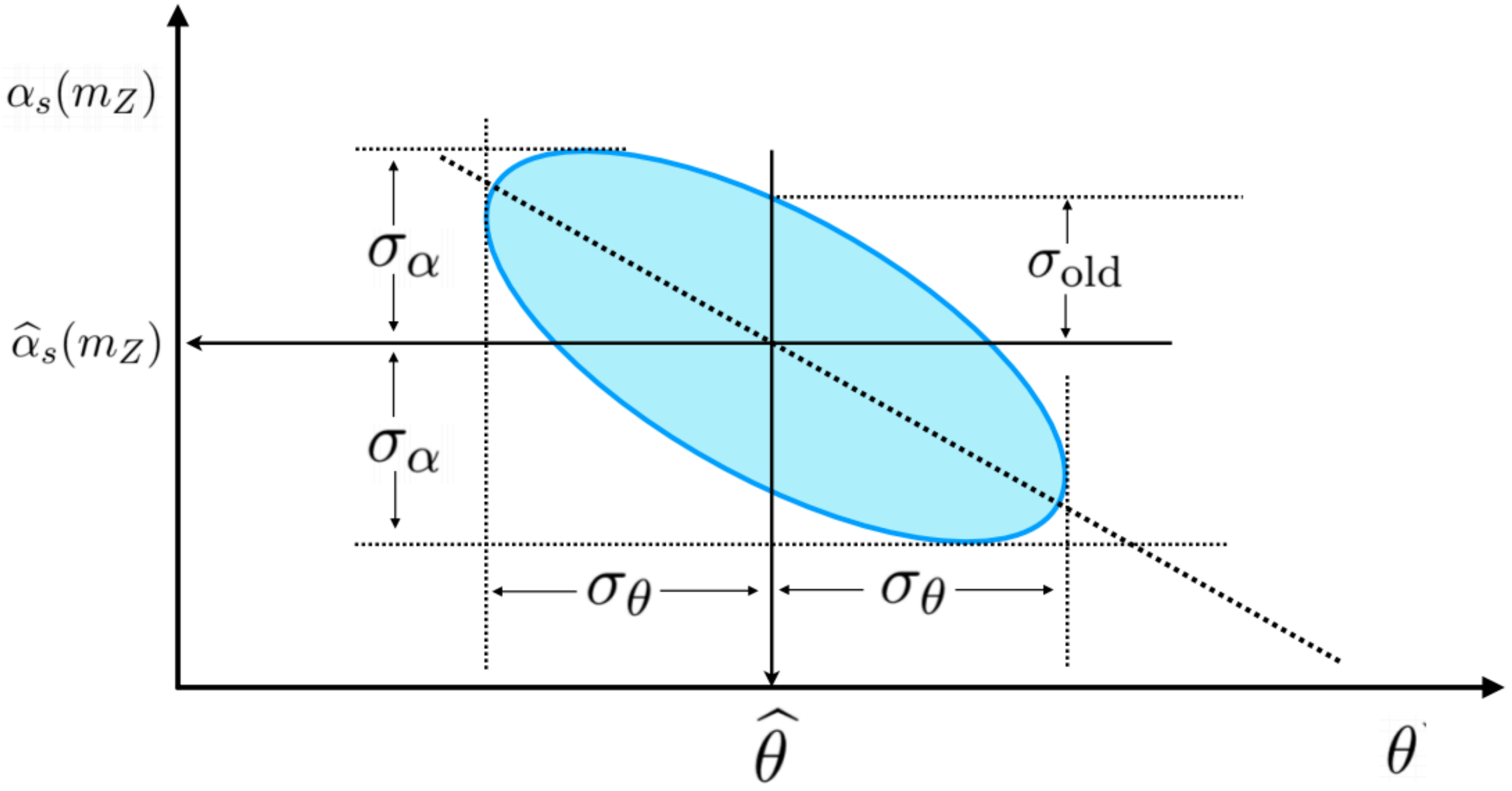
Only simultaneous fits keep correlations into account

PDFs AND α_s

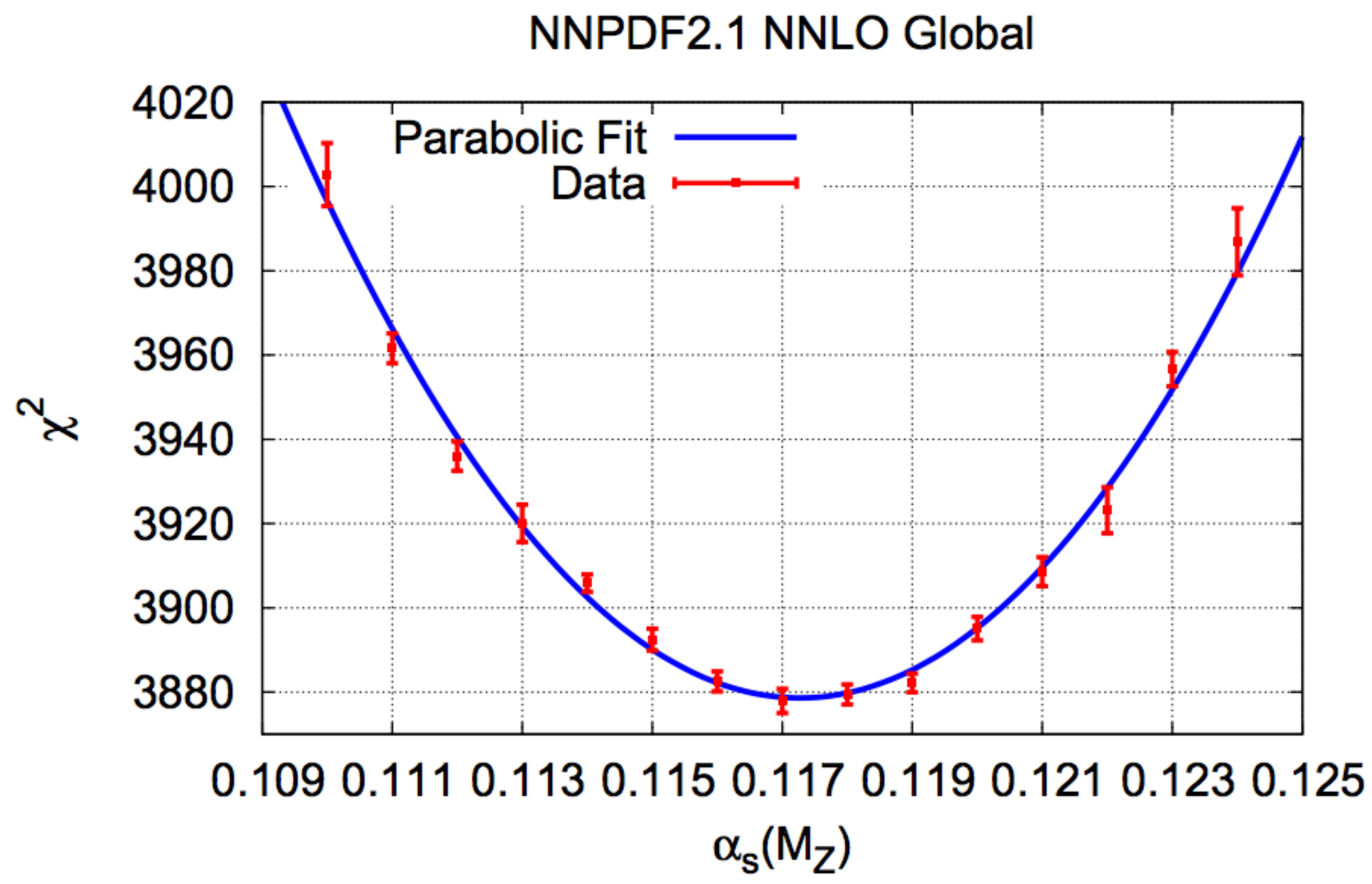
➡ PDFs and α_s strongly correlated (PDF evolution with the scale and hard cross sections)

➡ Cleanest determinations of α_s from processes that do not require knowledge of the PDFs

➡ A determination of α_s jointly with the PDFs has advantage that it is driven by the combination of many experimental measurements from several different processes.



Ball, Carrazza, Del Debbio, Forte, Kassabov, Rojo, Slade, MU 1802.03398



Ball et al, 1110.2483

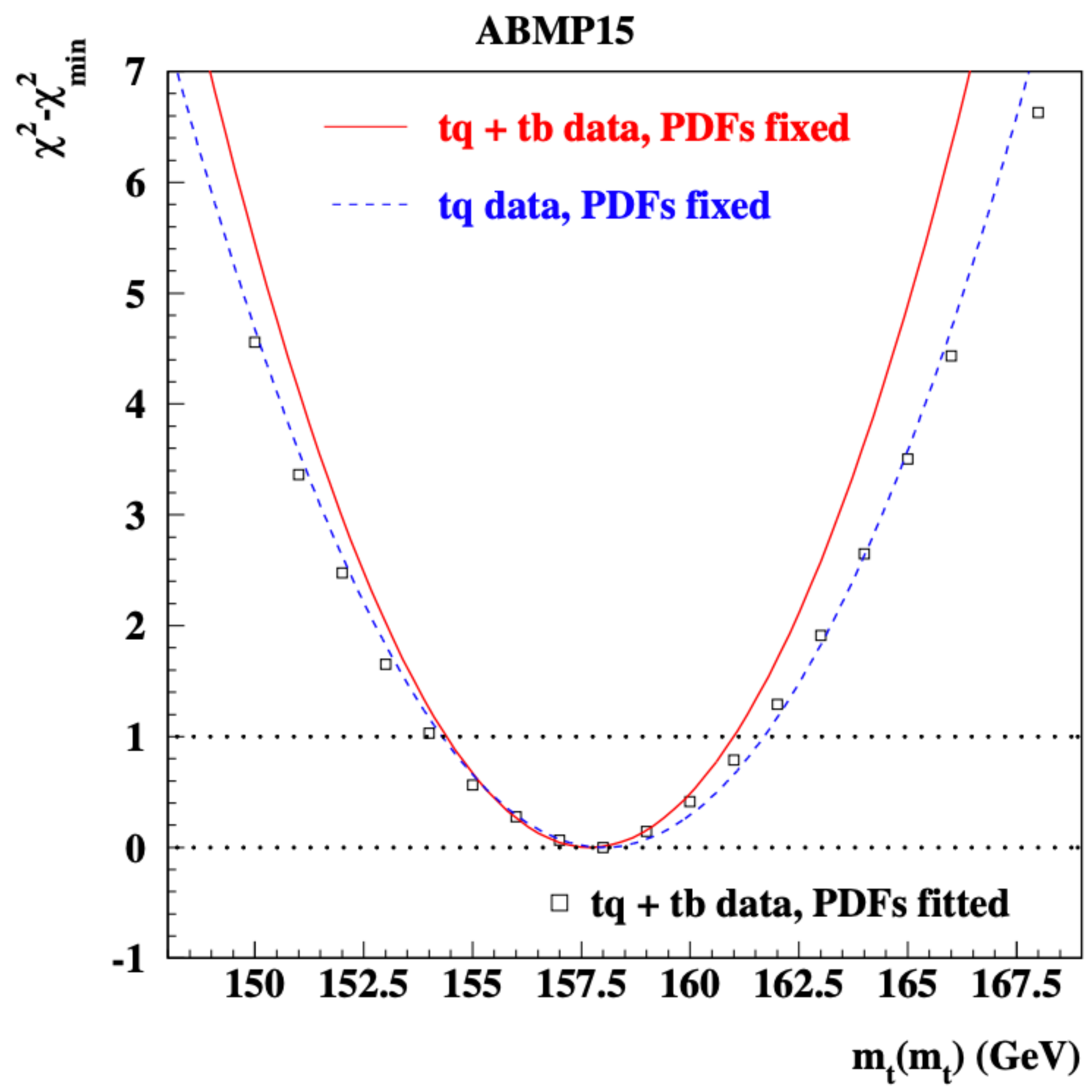
➡ Early determinations involve a scan over α_s and ignored PDF and α_s correlation in the fit

➡ Recent simultaneous determination of PDF and α_s using correlated replica method [NNPDF] or add parameter [MSHT]

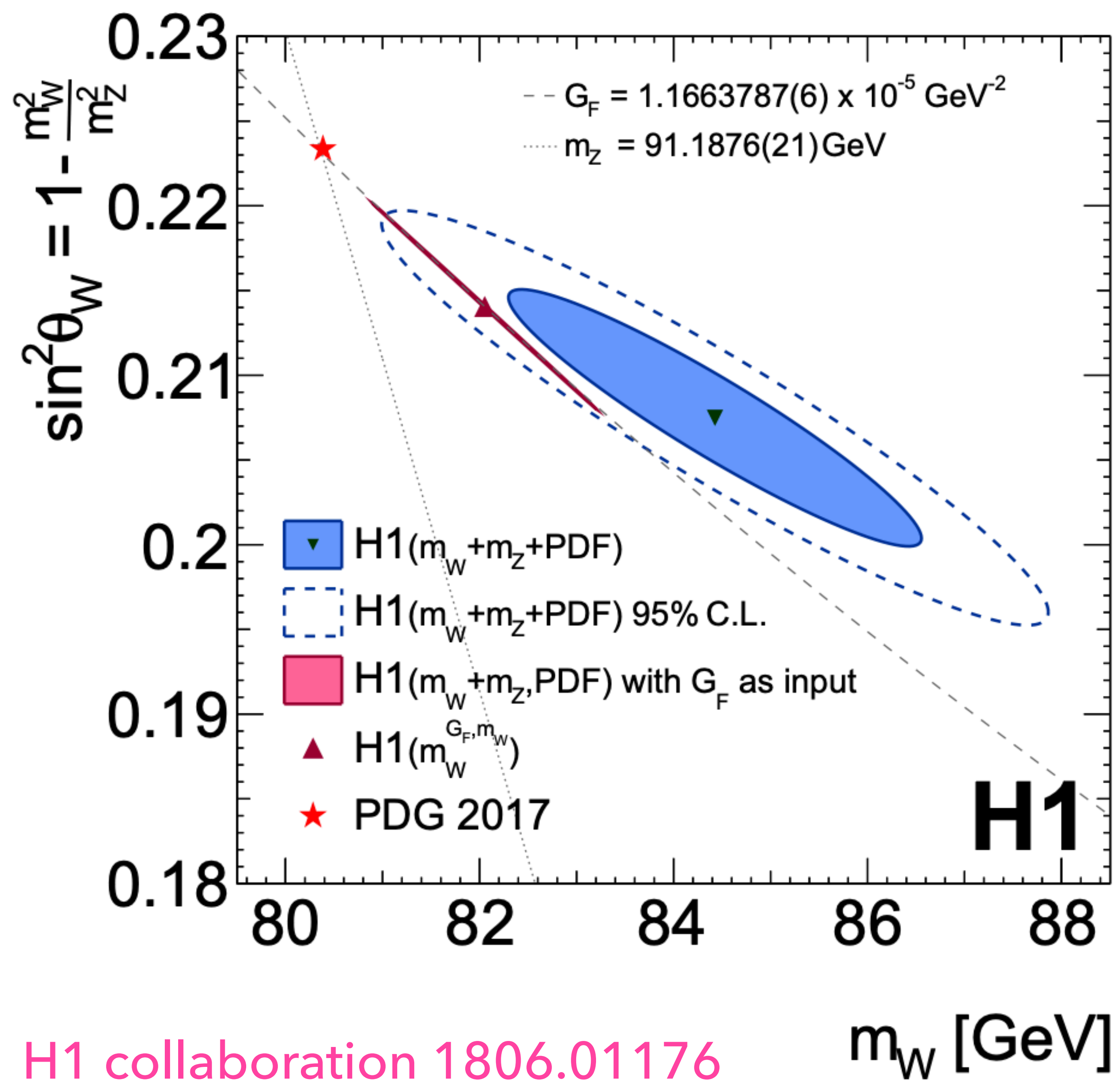
➡ Many determination of α_s from analyses of specific LHC processes have been published recently (from tt~, Z and W production, jets) ATLAS collaboration, arXiv:2309.09318

➡ How reliable are such partial determination of α_s ? [Forte, Kassabov 2001.04986]

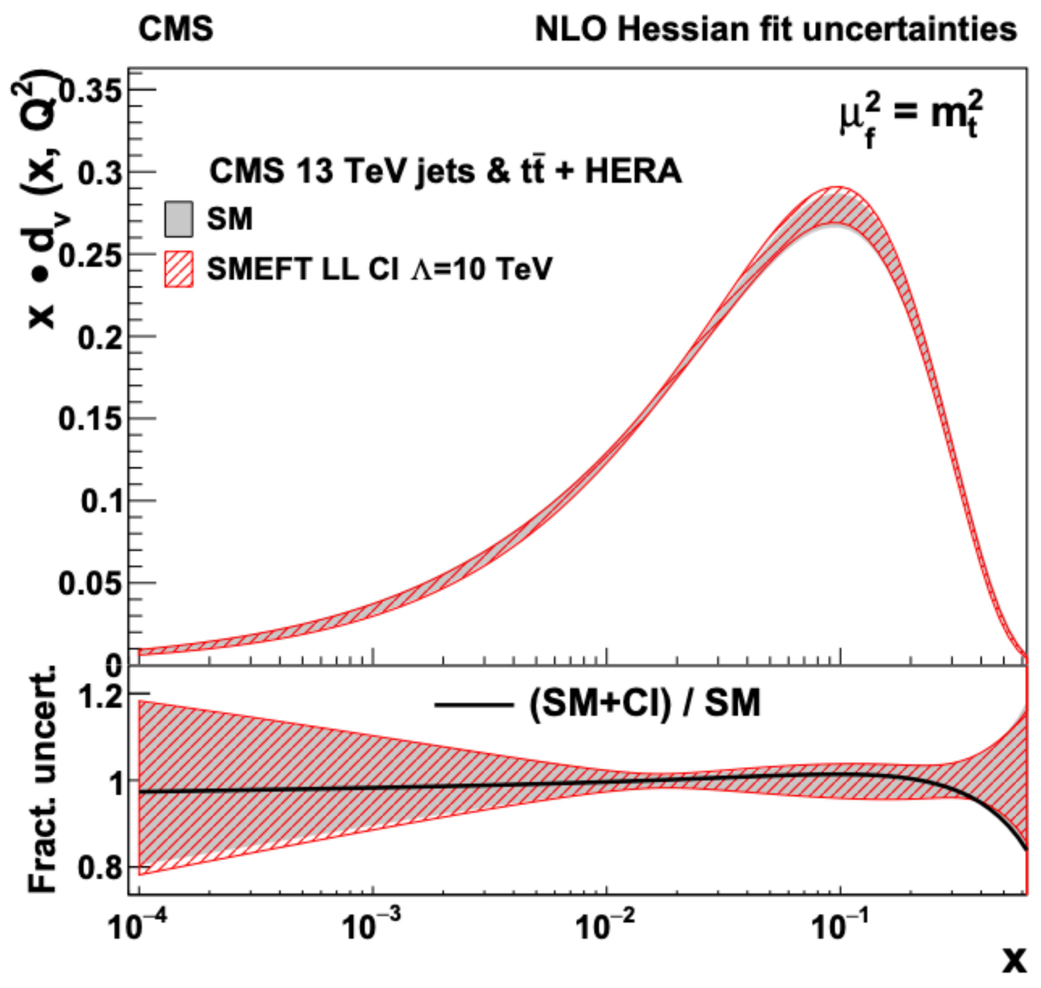
TOWARDS SIMULTANEOUS FITS OF PDF AND SM/BSM PARAMETERS



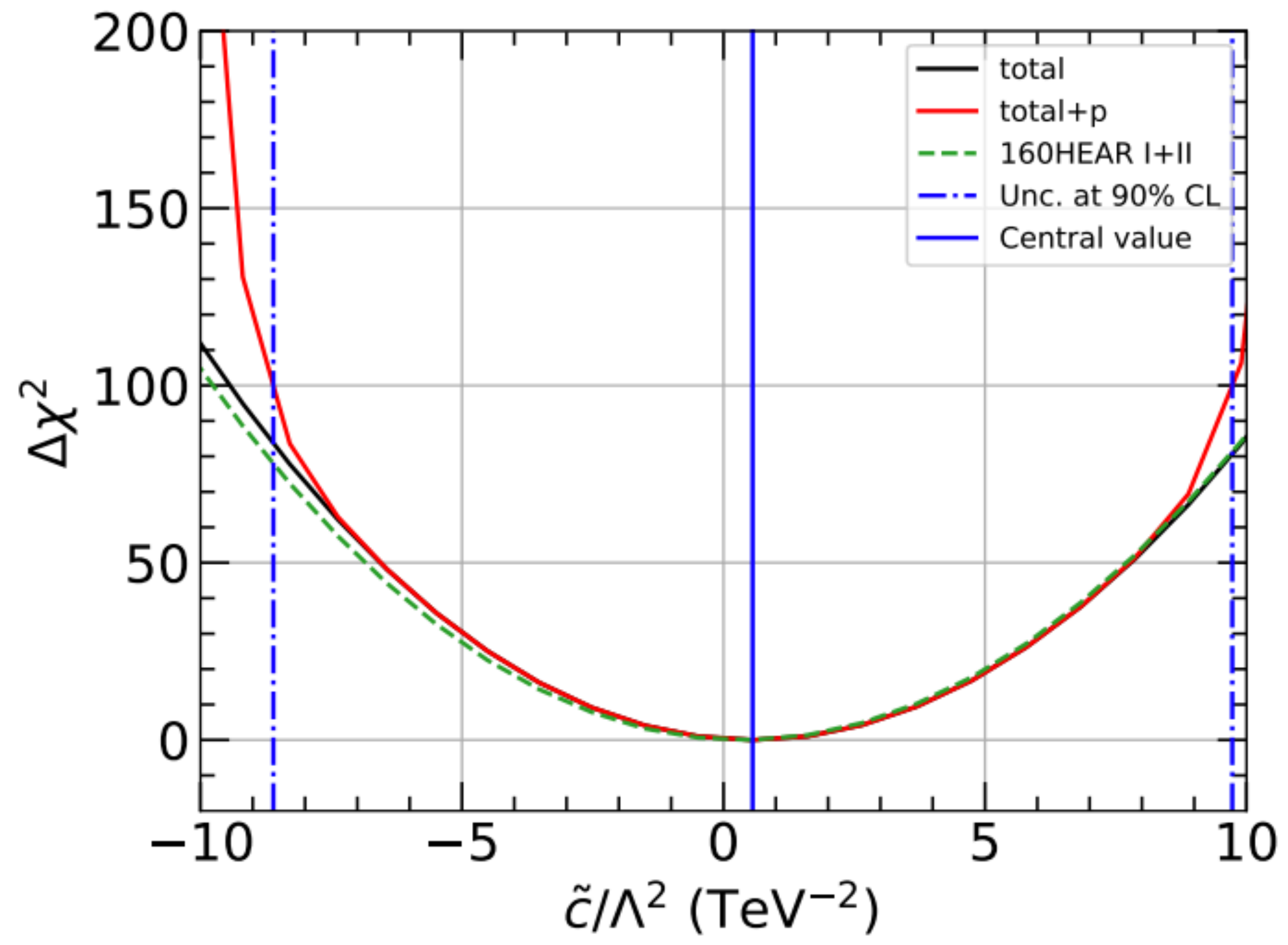
Alekhin, Moch, Thier 1608.05212



H1 collaboration 1806.01176



CMS collaboration, 2111.10431



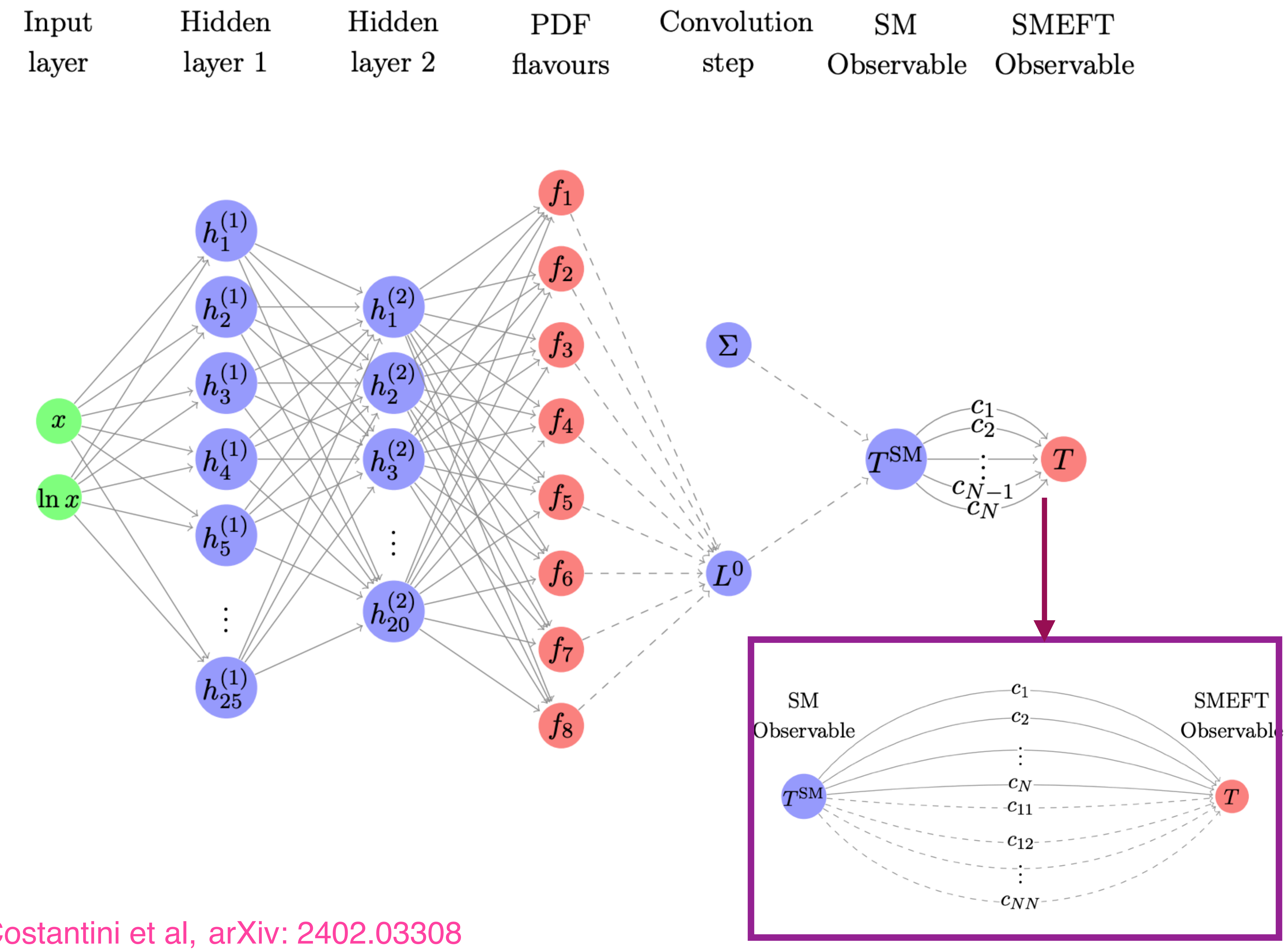
Liu, Sun, Gao, 2201.06586

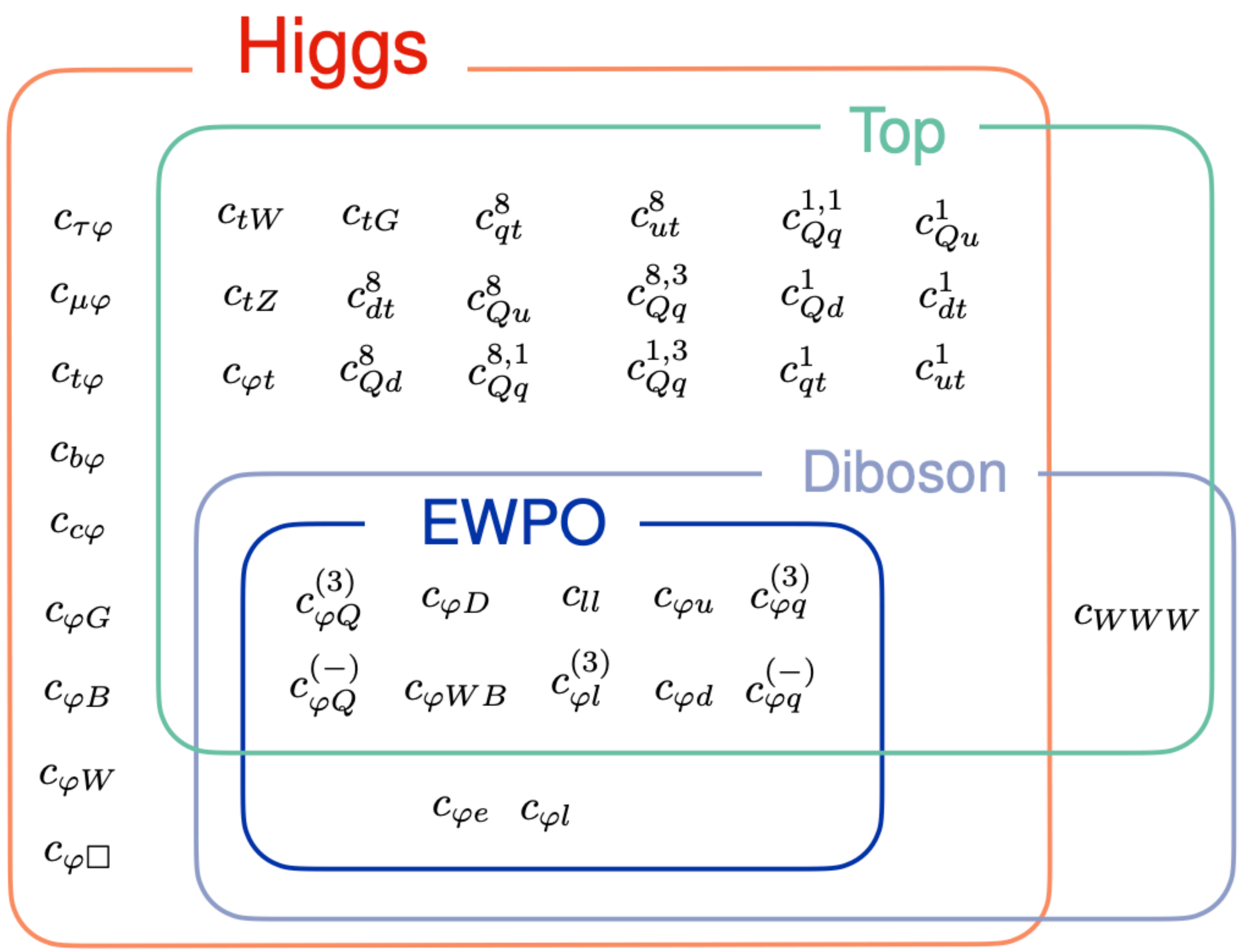
- Correlation of PDFs and the EW parameters or m_t weaker than in the case of α_s, but the very high accuracy which is sought suggests that the effect of simultaneous determination is not negligible [Alekhin et al 1608.05212] [H1 collab 1806.01176]
- Similar considerations for fits of polarised/ unpolarised PDFs, proton/nuclear PDFs or PDFs and FFs (universal fits)
- Lots of activity in simultaneous fits/ profiling of PDFs and SMEFT coefficients [Carrazza et al, 1905.05215][Greljo et al, 2104.02723] [Liu, Sun, Gao, 2201.06586] [CMS collaboration 2111.10431] [S. Iranipour, MU - arXiv: 2201.07240] [Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales, J. Rojo, MU - arXiv: 2303.06159] [M. Costantini, E. Hammou, Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales, MU - arXiv: 2303.06159]
- Scan-based methodologies inefficients when large number of SMEFT operators involved

SIMUNET: A PUBLIC TOOL FOR SIMULTANEOUS SMEFT/PDF FITS

- SimuNET recently release public tool can yield 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. Can include also PDF independent observables and is extendable to SM parameters!
- Can also be used to inject NP in the data and test for BSM contamination

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





Applied to top sector: Kassabov et al., arXiv: 2303.06159
Applied to DY sector: Iranipour, MU., arXiv: 2201.07240

M. Costantini et al, arXiv: 2402.03308

CONCLUSIONS AND OUTLOOK

- In an era of precision, need precise and accurate determination of proton subnuclear structure
- Lots of progress in theoretical framework: aN3LO PDFs, inclusion of MHOUs in PDF error bands
- New exciting avenues being explored, such as interplay between new Physics and PDFs, simultaneous fits
- Synergy between eP/eA experiments and PP/PA,AA experiments not only in kinematics complementarity that allows testing parametrisation of proton structure, but also pushing the boundaries of collinear factorisation and breaking this PDF/BSM degeneracy! This synergy is crucial to realise the full BSM search potential of the HL-LHC.

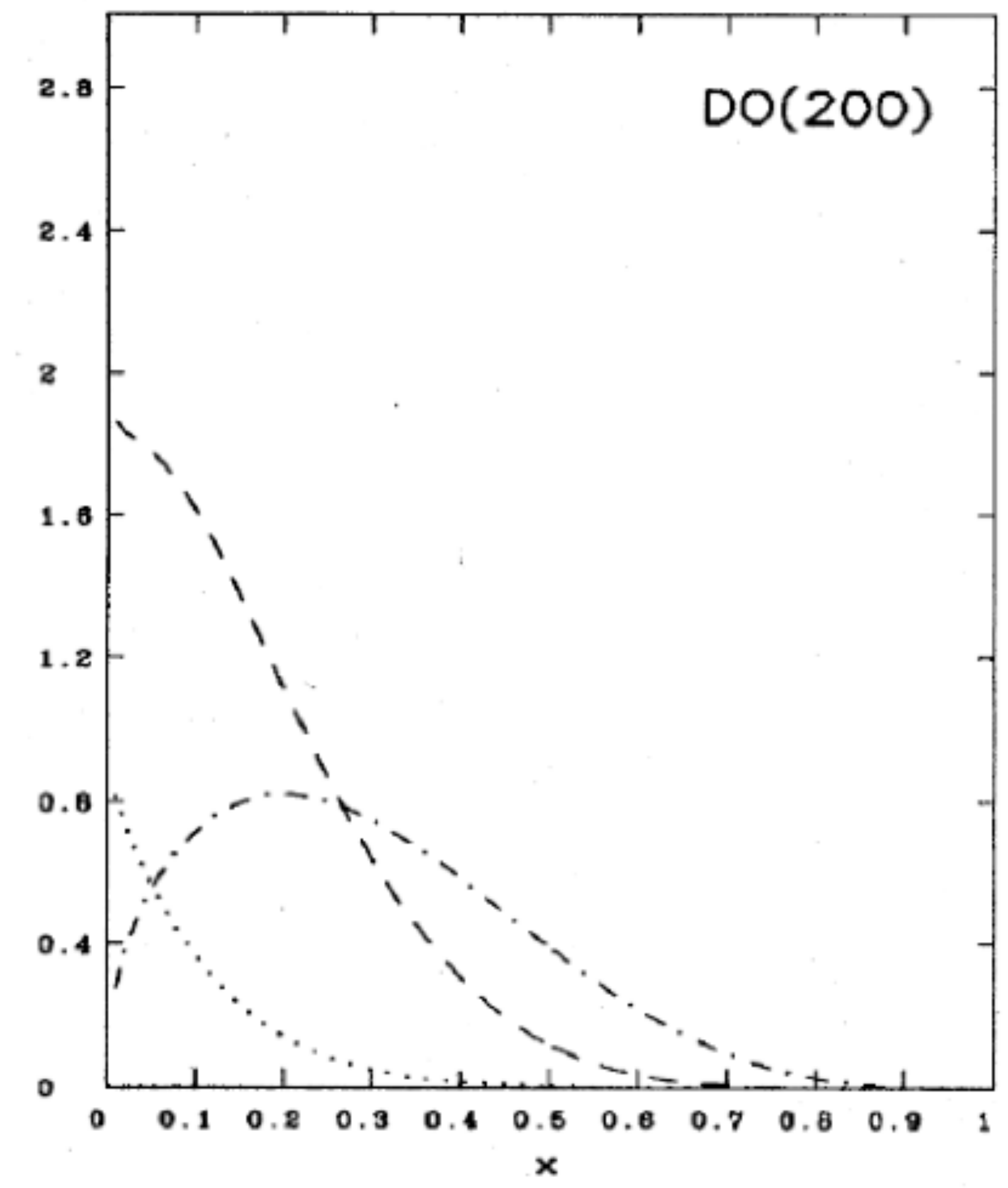
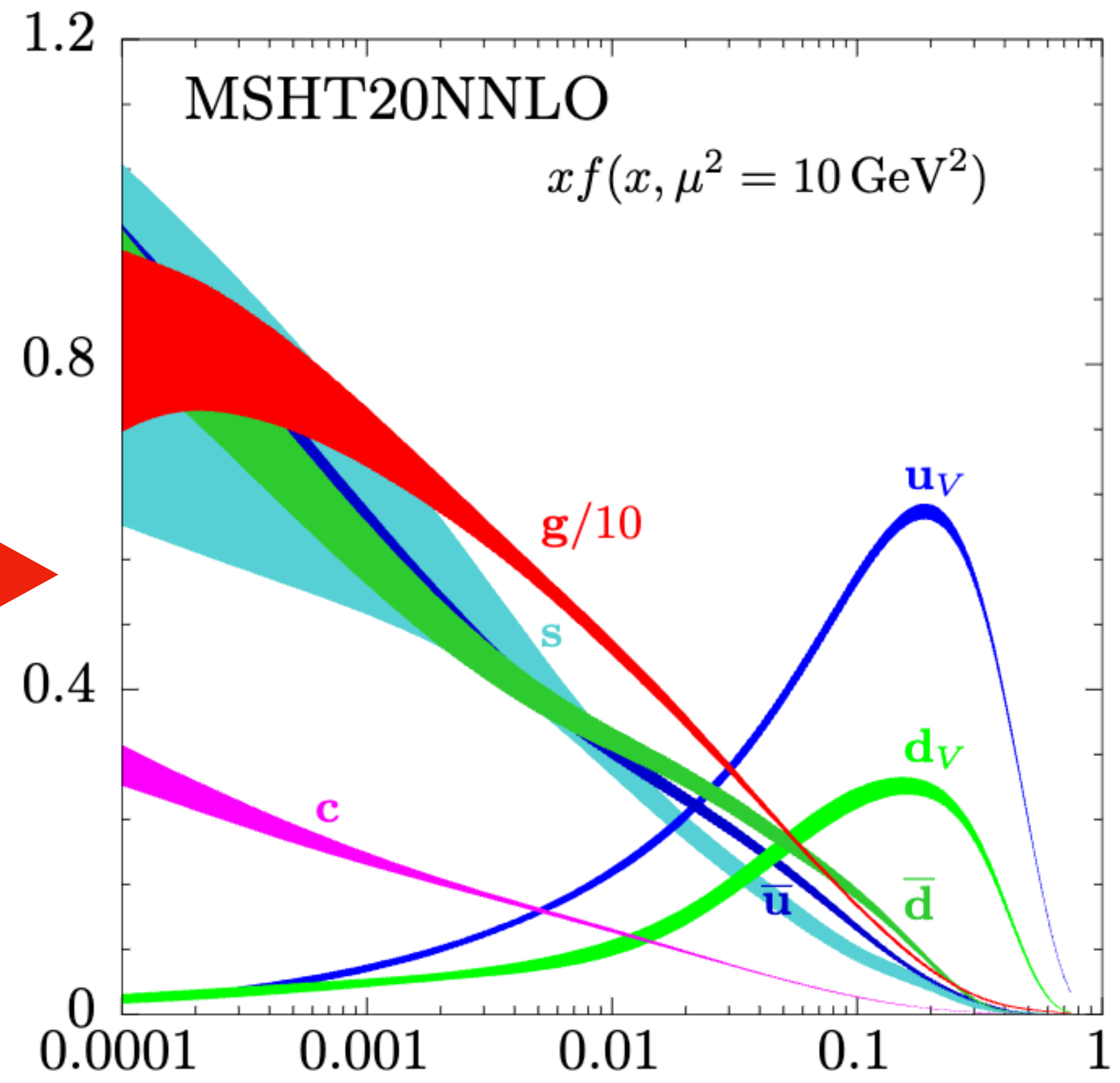


FIG. 27. "Soft-gluon" ($\Lambda = 200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2 = 5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).



PDG 2023

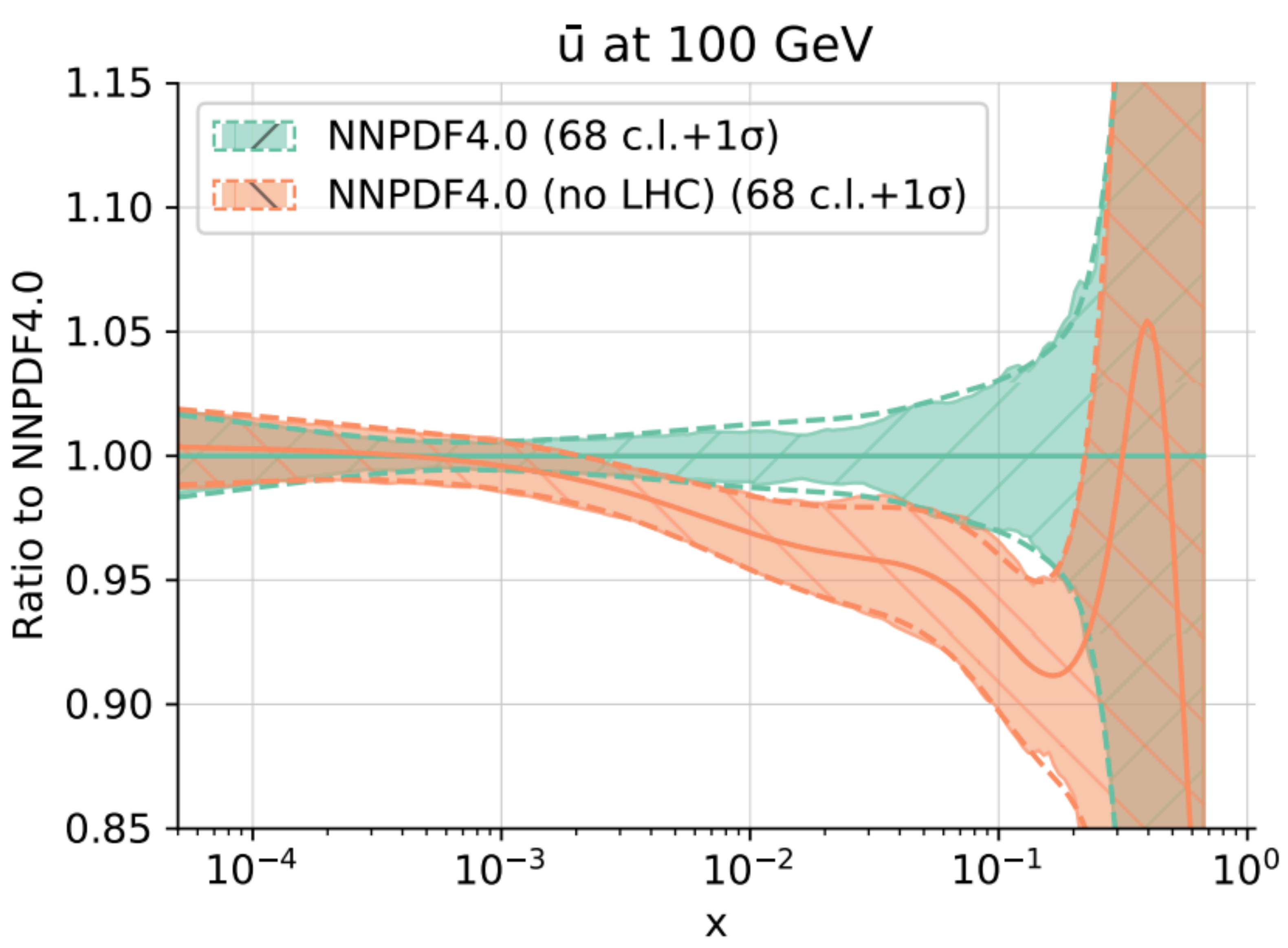
EXTRA MATERIAL

PDF AND SMEFT INTERPLAY

- PDFs are low-scale quantities extracted from experimental data at all scales, without considering any potential high-scale contamination due to new physics.

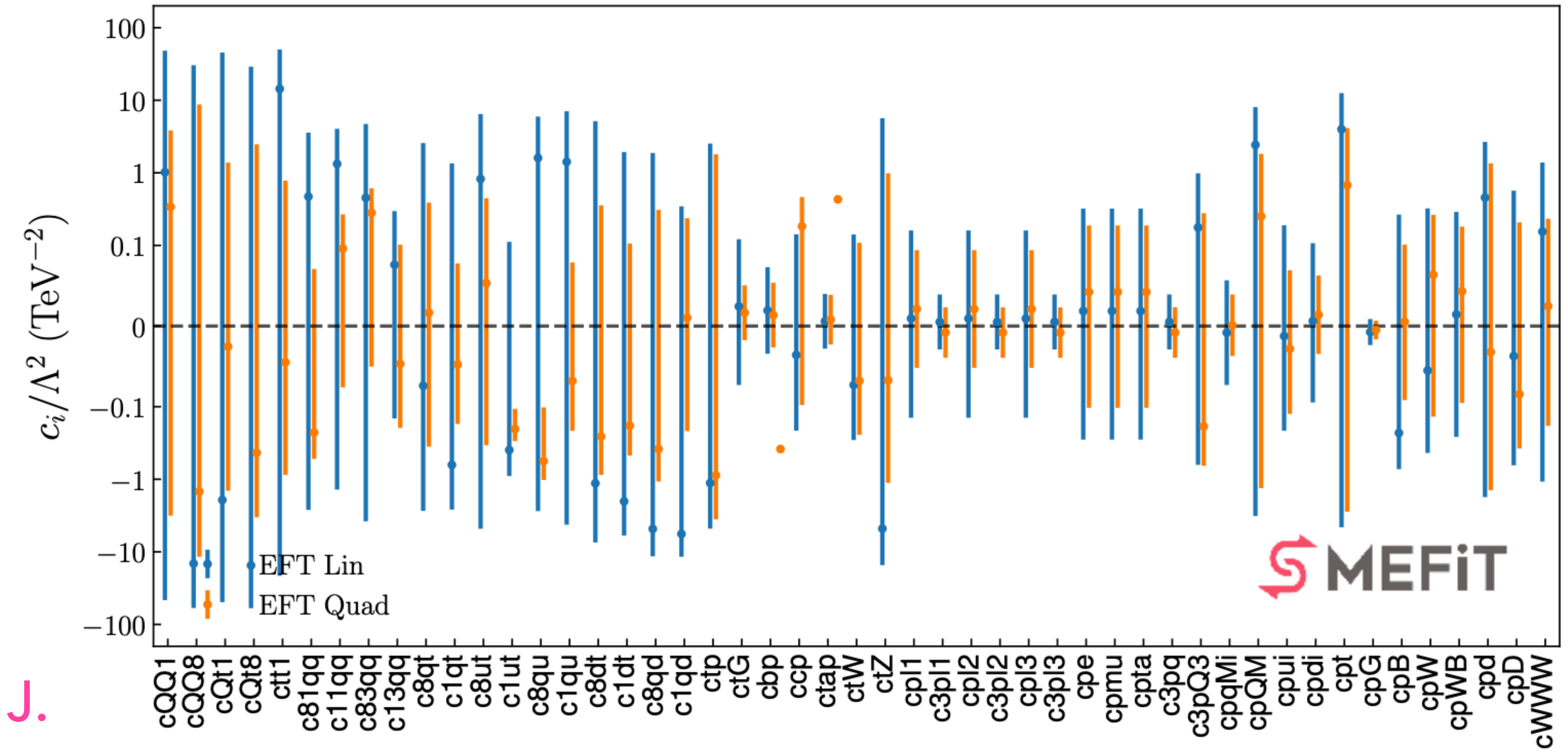
- (SM)EFT fits are performed by assuming a priori that PDFs are SM-like.

- In principle low-scale physics is separable from high-scale physics, BUT the complexity of LHC environment might well intertwine them. Data overlap.



Ball et al, arXiv:2109.02653

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

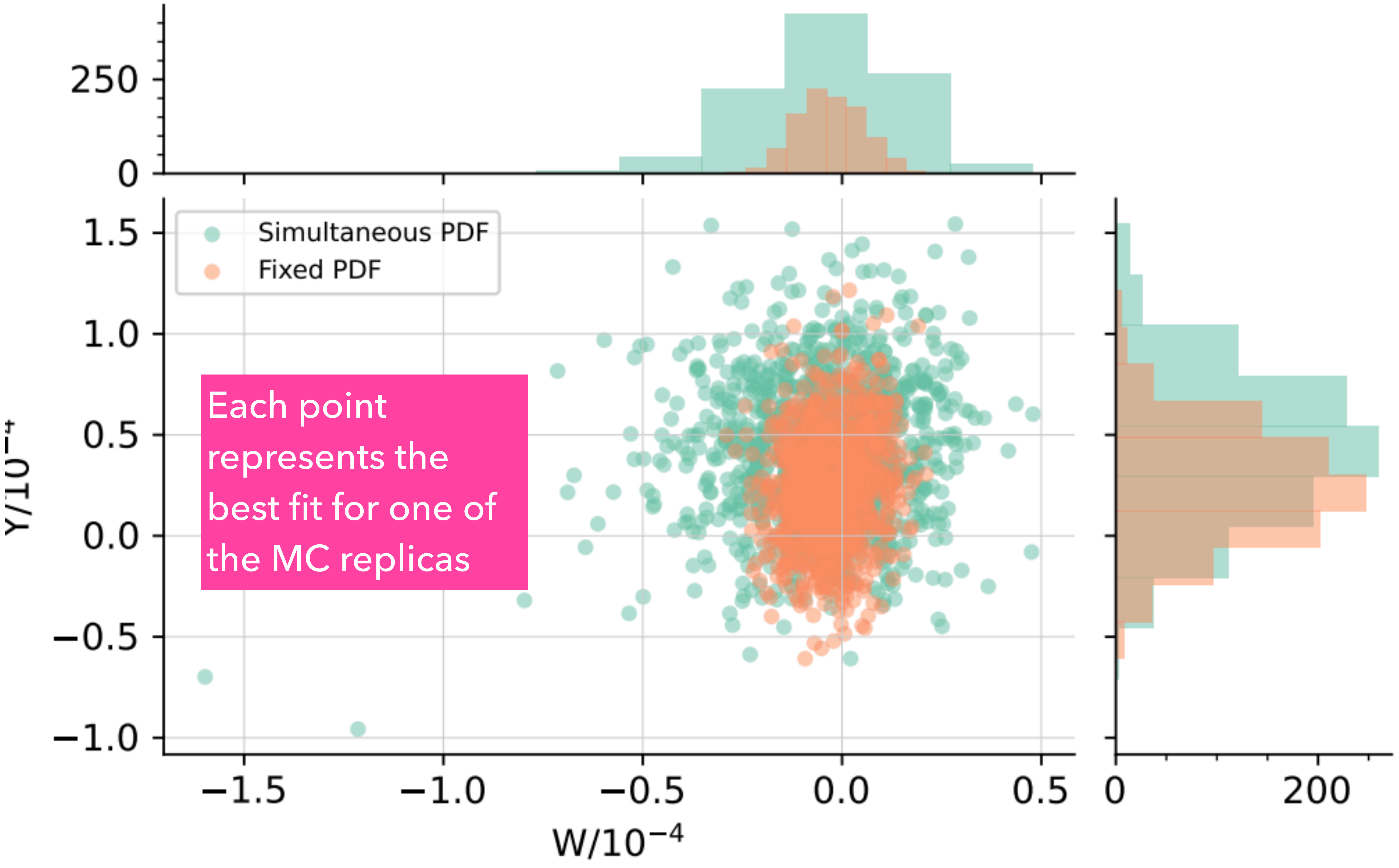


Ethier et al, arXiv: 2105.00006

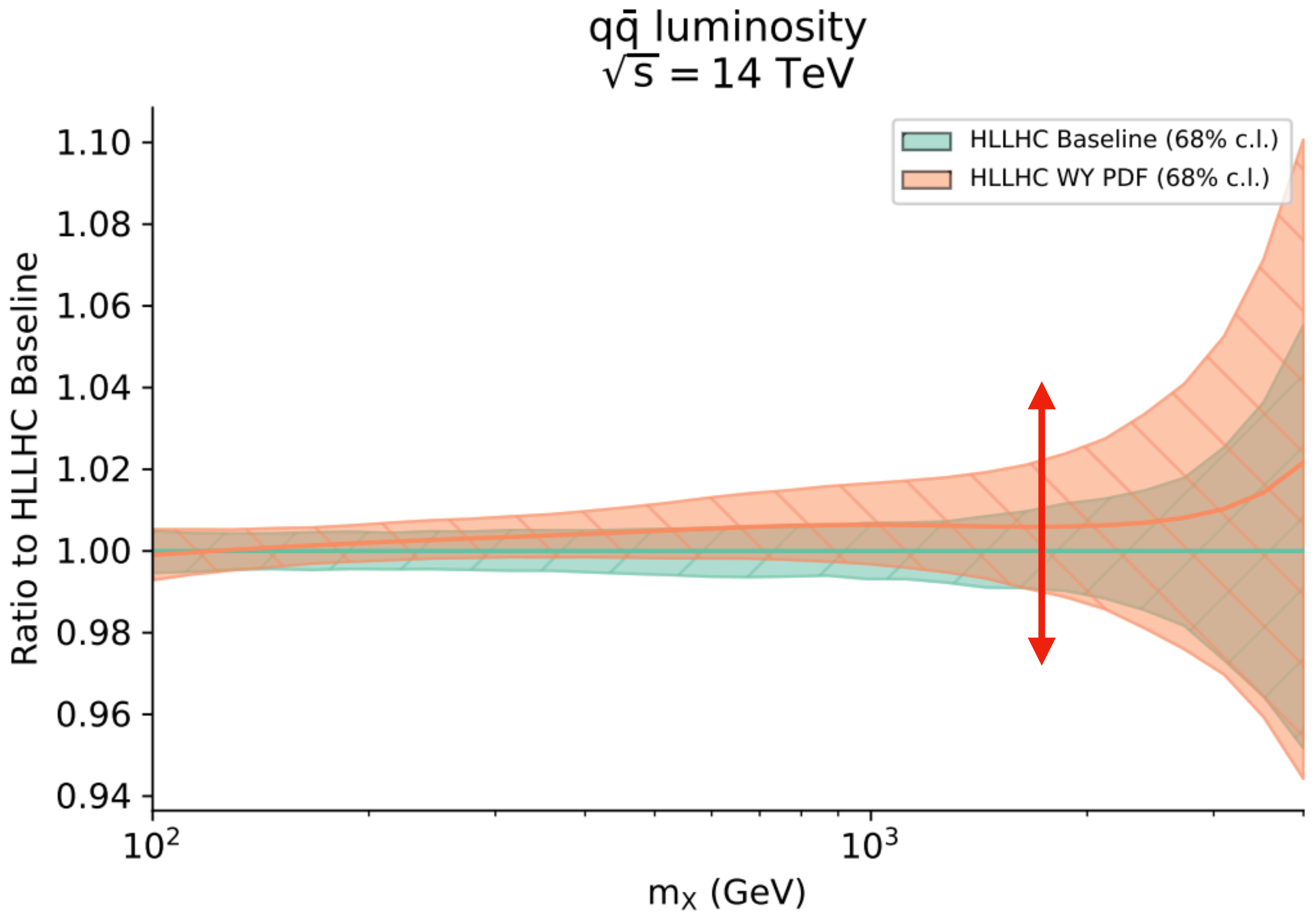
OPEN QUESTIONS

- 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? Can PDFs absorb new physics?
- 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?

SIMUNET: A TOOL FOR SIMULTANEOUS FITS



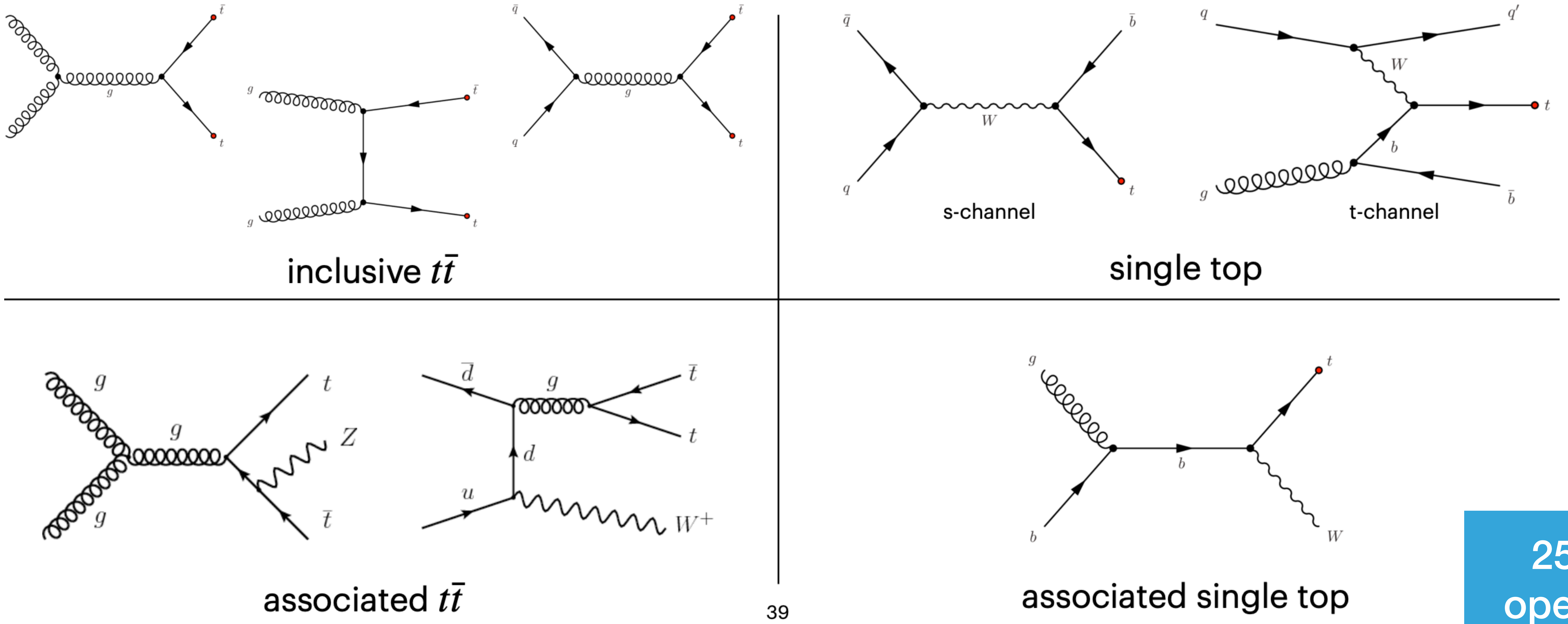
S. Iranipour, MU - arXiv: 2201.07240



✓ 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

THE TOP SECTOR

- After testing methodology on small number of WC, stress-test on large SMEFT parameters space.
- Huge amount of Run II top quark data from ATLAS and CMS
- Four basic processes: inclusive tt~ and asymmetry (inclusive and differential), single top (inclusive and differential), associated ttV production, associated single top production



25 (21) dim-6 operators at the quadratic (linear) SMEFT

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

THE TOP SECTOR

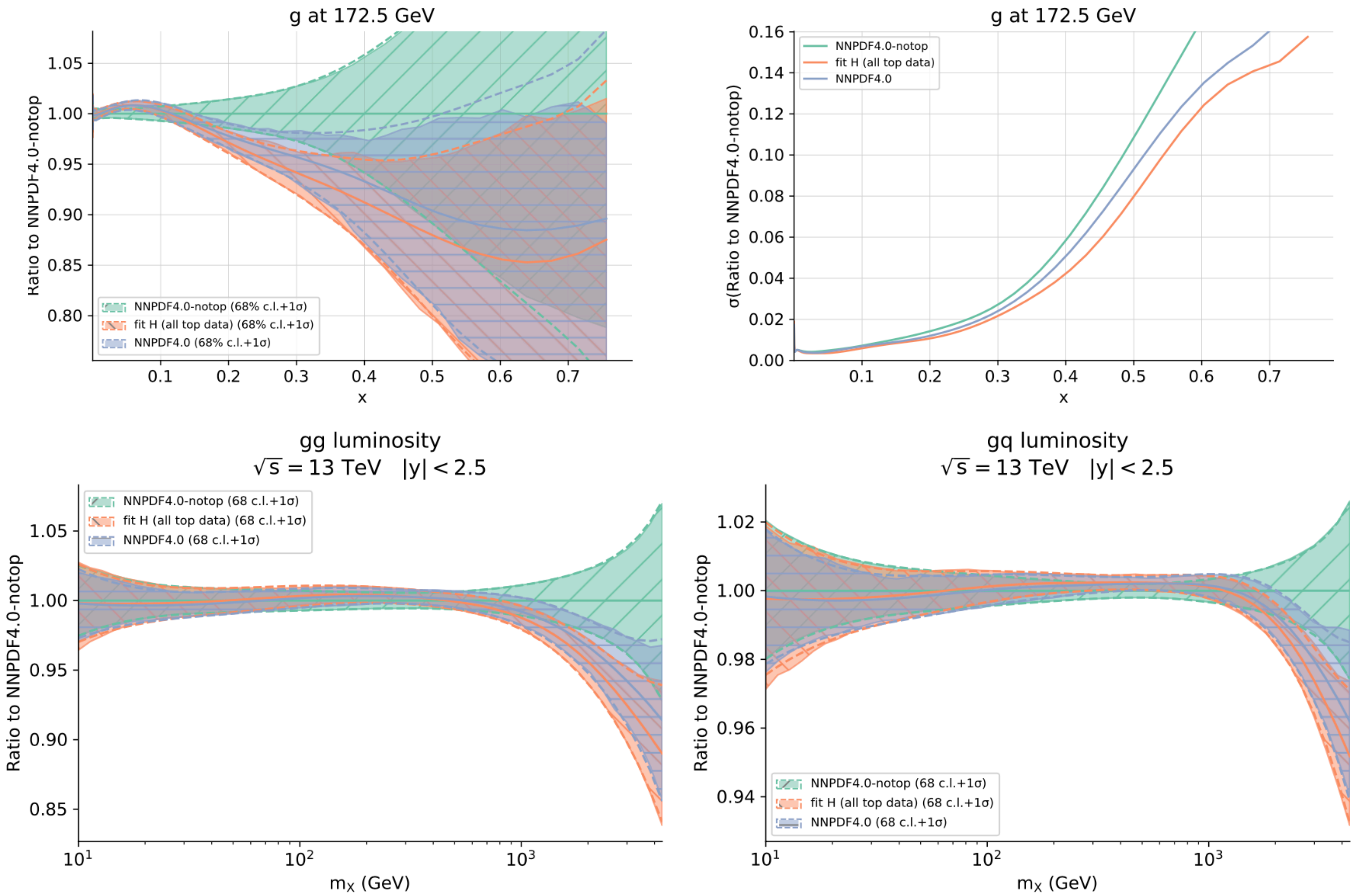
DoF	Definition (Warsaw basis)
c_{QQ}^{1}	$2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$
c_{QQ}^{8}	$8c_{qq}^{3(3333)}$
c_{Qt}^{1}	$c_{qu}^{1(3333)}$
c_{Qt}^{8}	$c_{qu}^{8(3333)}$
c_{tt}^{1}	$c_{uu}^{(3333)}$
$c_{Qq}^{1,8}$	$c_{qq}^{1(i33i)} + 3c_{qq}^{3(i33i)}$
$c_{Qq}^{1,1}$	$c_{qq}^{1(ii33)} + \frac{1}{6}c_{qq}^{1(i33i)} + \frac{1}{2}c_{qq}^{3(i33i)}$
$c_{Qq}^{3,8}$	$c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)}$
$c_{Qq}^{3,1}$	$c_{qq}^{3(ii33)} + \frac{1}{6}(c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)})$
c_{tq}^{8}	$c_{qu}^{8(ii33)}$
c_{tq}^{1}	$c_{qu}^{1(ii33)}$
c_{tu}^{8}	$2c_{uu}^{(i33i)}$
c_{tu}^{1}	$c_{uu}^{(ii33)} + \frac{1}{3}c_{uu}^{(i33i)}$
c_{Qu}^{8}	$c_{qu}^{8(33ii)}$
c_{Qu}^{1}	$c_{qu}^{1(33ii)}$
c_{td}^{8}	$c_{ud}^{8(33jj)}$
c_{td}^{1}	$c_{ud}^{1(33jj)}$
c_{Qd}^{8}	$c_{qd}^{8(33jj)}$
c_{Qd}^{1}	$c_{qd}^{1(33jj)}$

25 (21) dim-6 operators at the quadratic (linear) SMEFT

Operator	Coefficient	Definition
$\mathcal{O}_{\varphi Q}^{(1)}$	$-\ (c_{\varphi Q}^{(1)})$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{tW}$	c_{tW}	$i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi}W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{tB}$	$-\ (c_{tB})$	$i(\bar{Q}\tau^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	c_{tG}	$i(\bar{Q}\tau^{\mu\nu}T_A t)\tilde{\varphi}G_{\mu\nu}^A + \text{h.c.}$

DoF	Definition
$c_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(1)} - c_{\varphi Q}^{(3)}$
c_{tZ}	$-\sin\theta_W c_{tB} + \cos\theta_W c_{tW}$

PDF-ONLY FIT



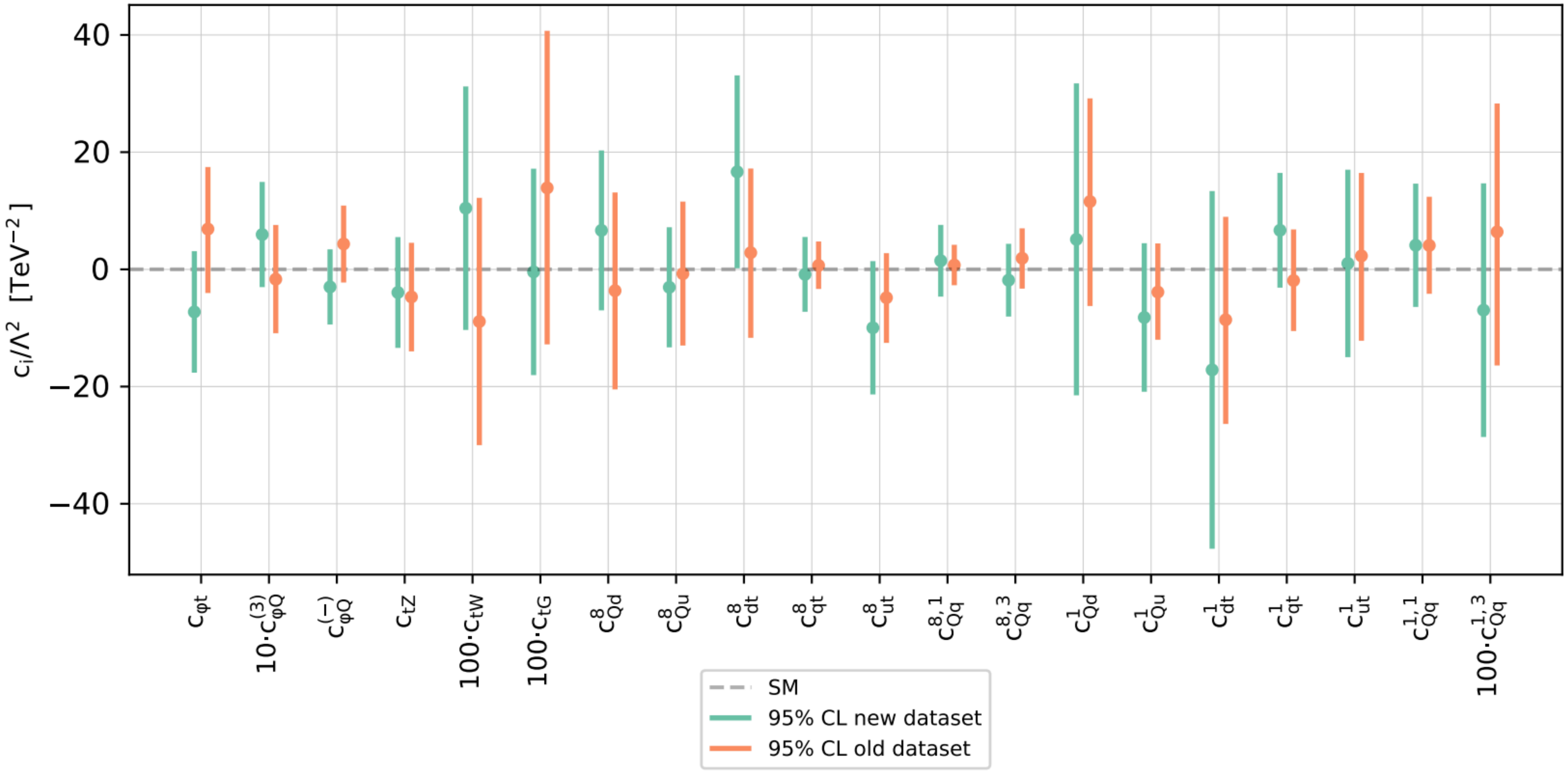
78 new datapoints in the top sector as compared to NNPDF4.0

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

SMEFT-ONLY FIT

$$\sigma_{\rm eft}\left(\boldsymbol{c}/\Lambda^2\right) = \sigma_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \sigma_{{\rm eft},i}\frac{c_i}{\Lambda^2}\,.$$

Linear SMEFT

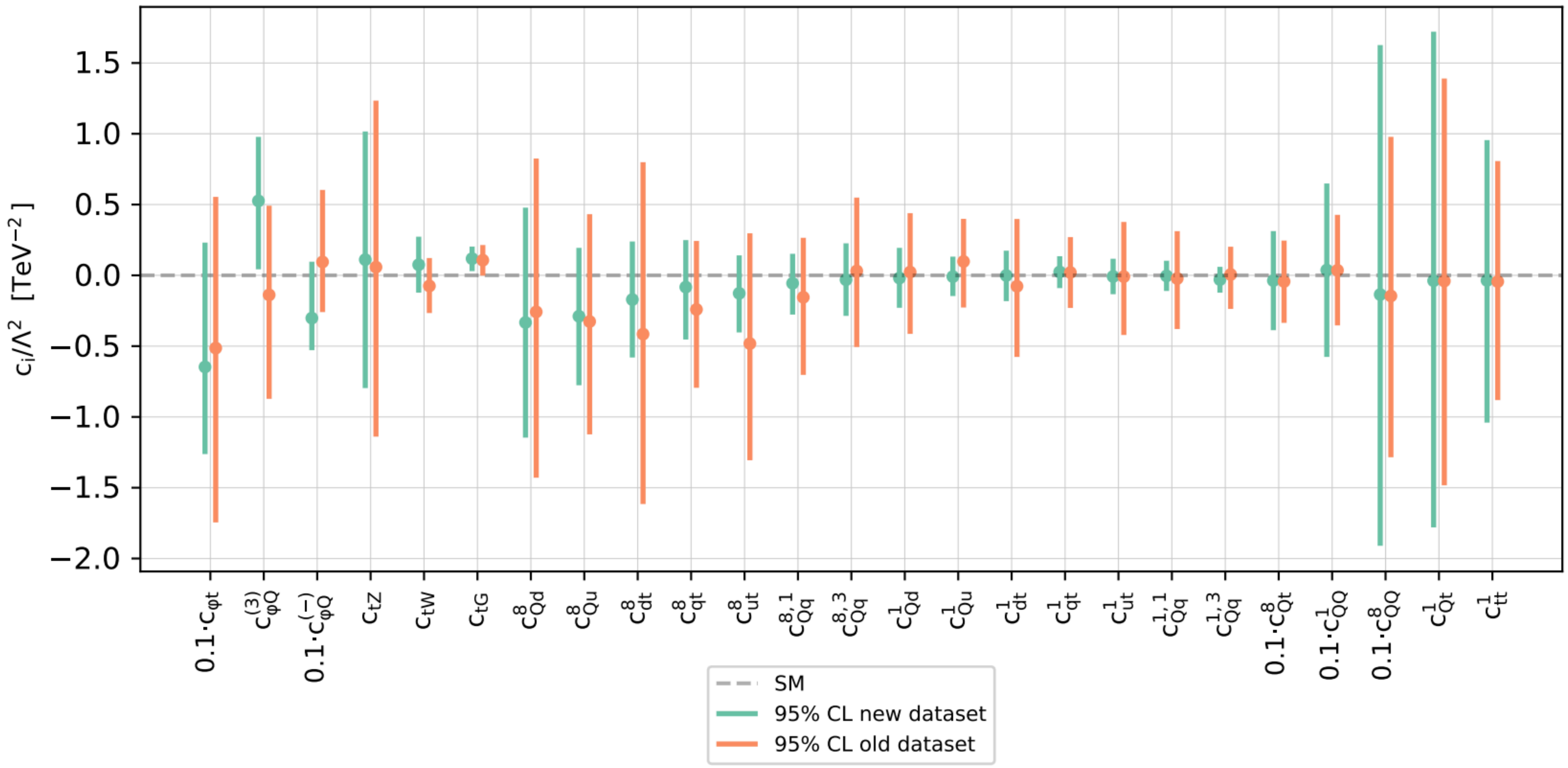


Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales, J. Rojo, MU - arXiv: 2303.06159

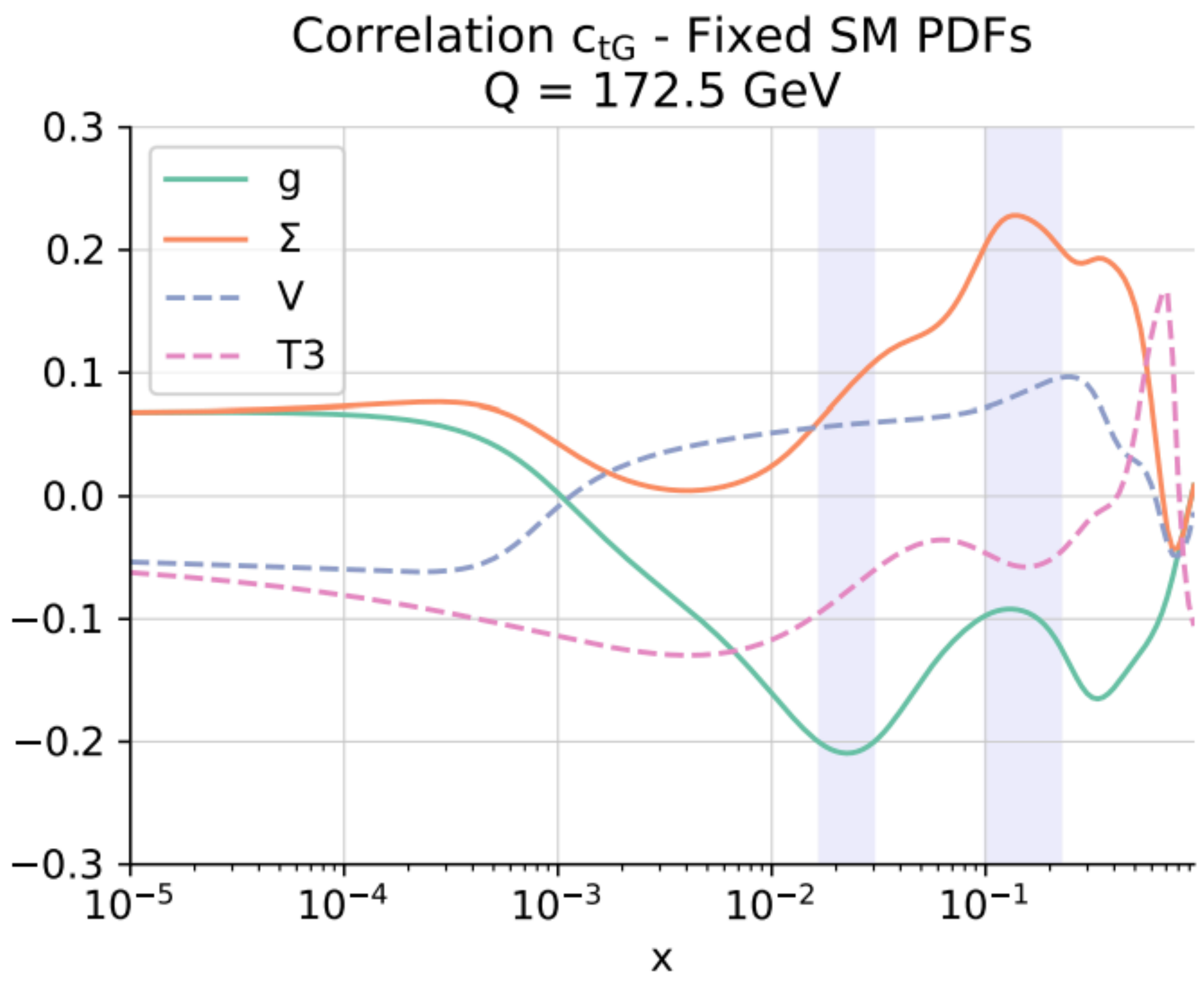
SMEFT-ONLY FIT

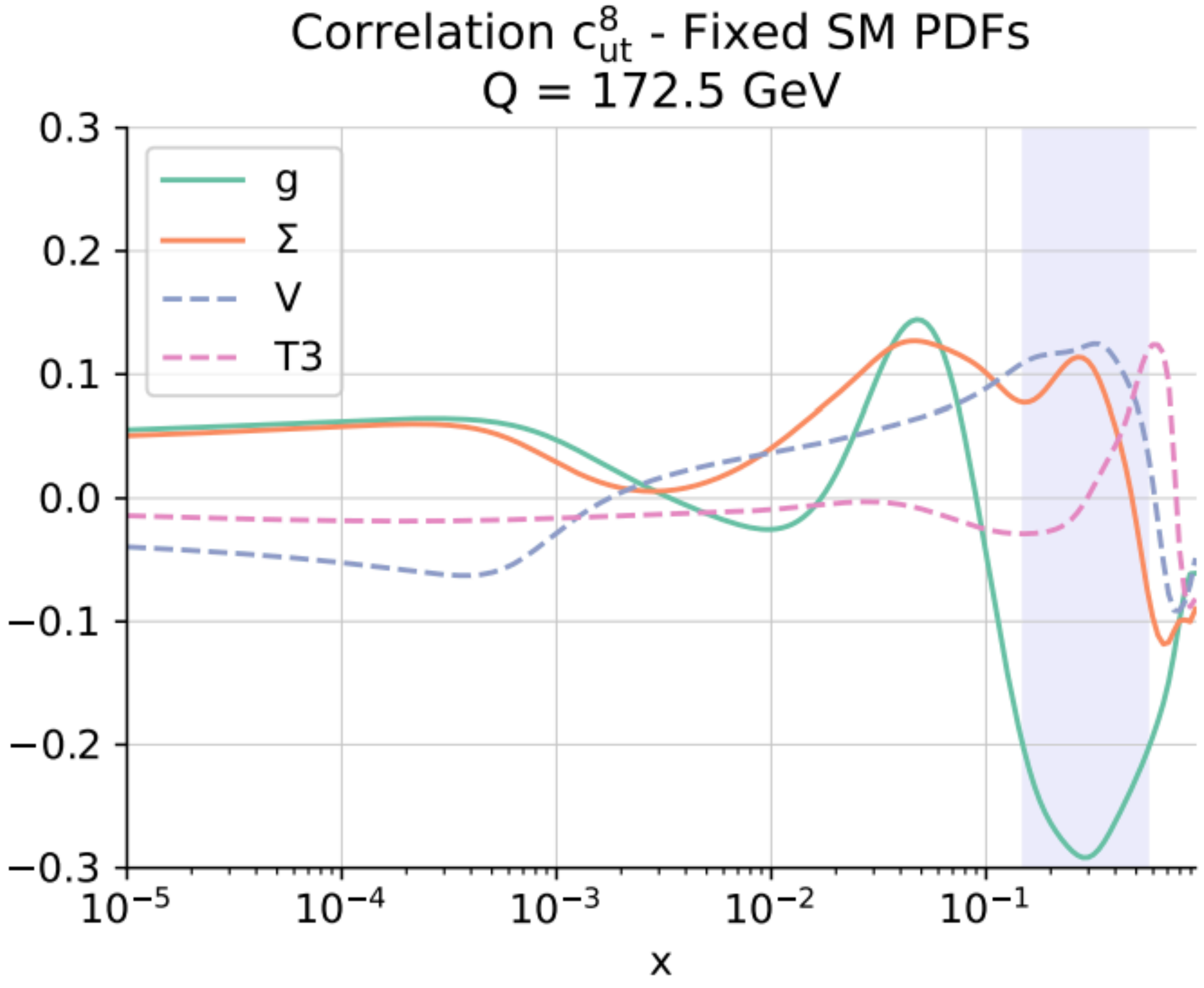
$$\sigma_{\text{eft}}\left(\boldsymbol{c}/\Lambda^2\right) = \sigma_{\text{SM}} + \sum_{i=1}^{n_{\text{op}}} \sigma_{\text{eft},i}\frac{c_i}{\Lambda^2} + \sum_{i,j=1}^{n_{\text{op}}} \sigma_{\text{eft},ij}\frac{c_i c_j}{\Lambda^4}$$

Quadratic SMEFT

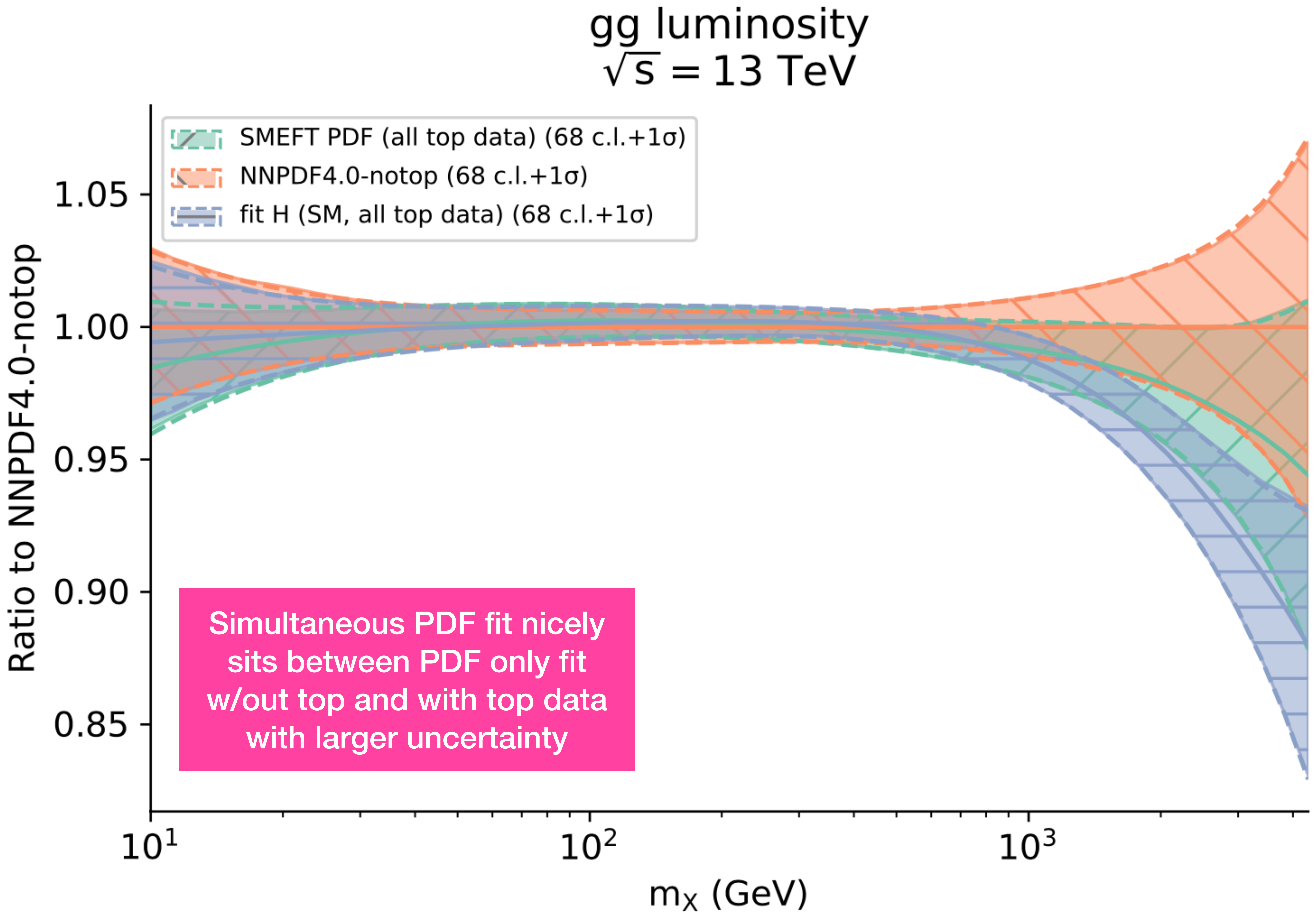


SMEFT AND PDF CORRELATIONS





SIMULTANEOUS PDF-SMEFT FIT

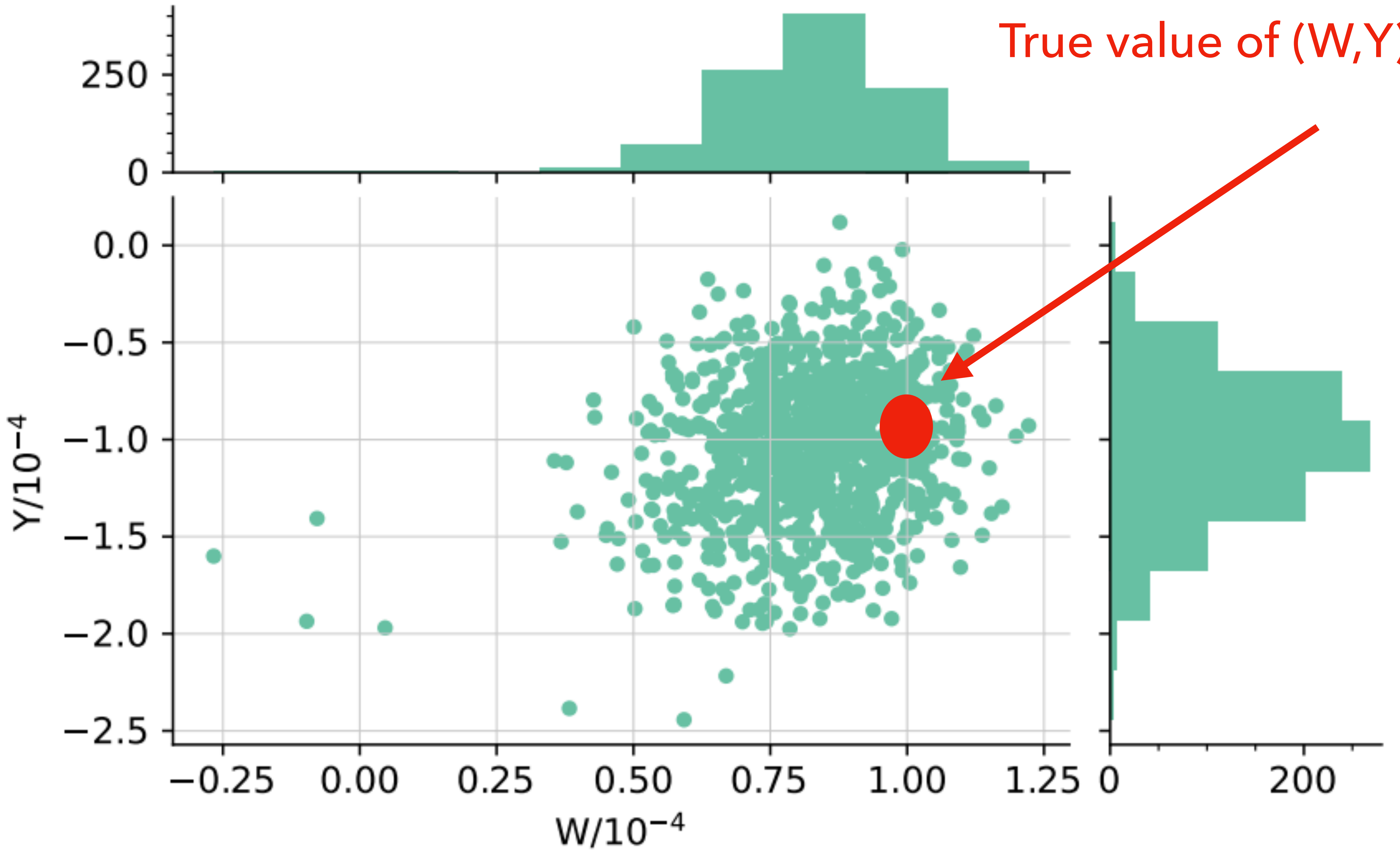


Linear SMEFT

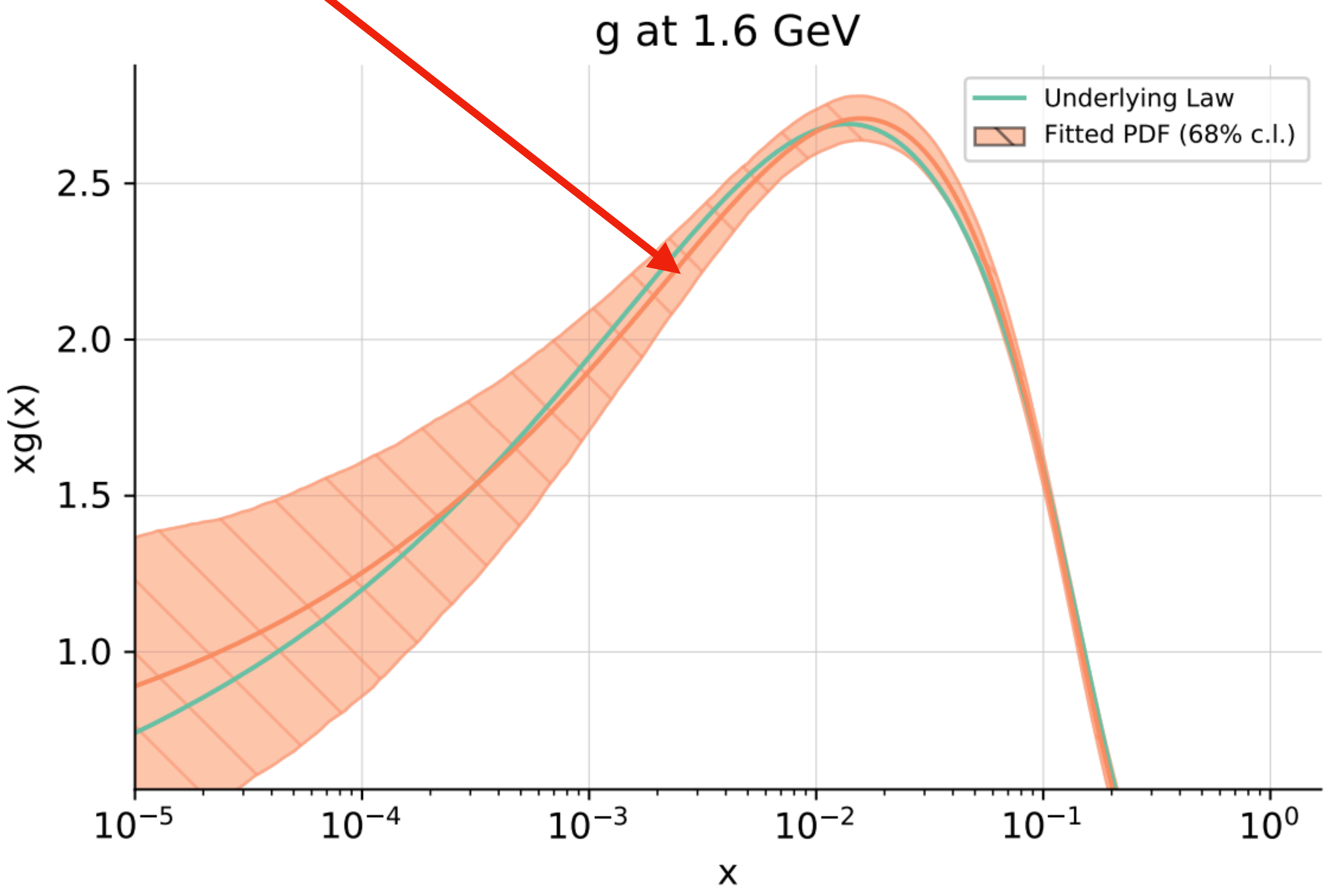
RESULTS: DRELL-YAN DATA @HL-LHC

S. Iranipour, MU - arXiv: 2201.07240

True value of (W,Y) . 10^5 = (-10,10)



True PDFs = MMHT2020



✓ Simultaneous analysis of PDFs and W&Y SMEFT 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 PDFs change significantly once SMEFT effects allowed in theory predictions entering PDF fit

✓ Stress-tested and shown robustness with closure tests

SIMUNET: A TOOL FOR SIMULTANEOUS FITS

SimuNET will be released open-source with detailed documentation & will allow users

- ✓ PDF only fits (NNPDF4.0 with more data)
- ✓ SMEFT only fits - linear SMEFT
- ✓ Simultaneous SMEFT & PDFs - linear SMEFT

```
dataset_inputs:
- {dataset: NMC, frac: 0.75}
- {dataset: ATLASTTBARTOT7TEV, cfac: [QCD], simu_fac: "EFT_NLO"}
- {dataset: CMS_SINGLETOPW_8TEV_TOTAL, simu_fac: "EFT_NLO", use_fixed_predictions: True}
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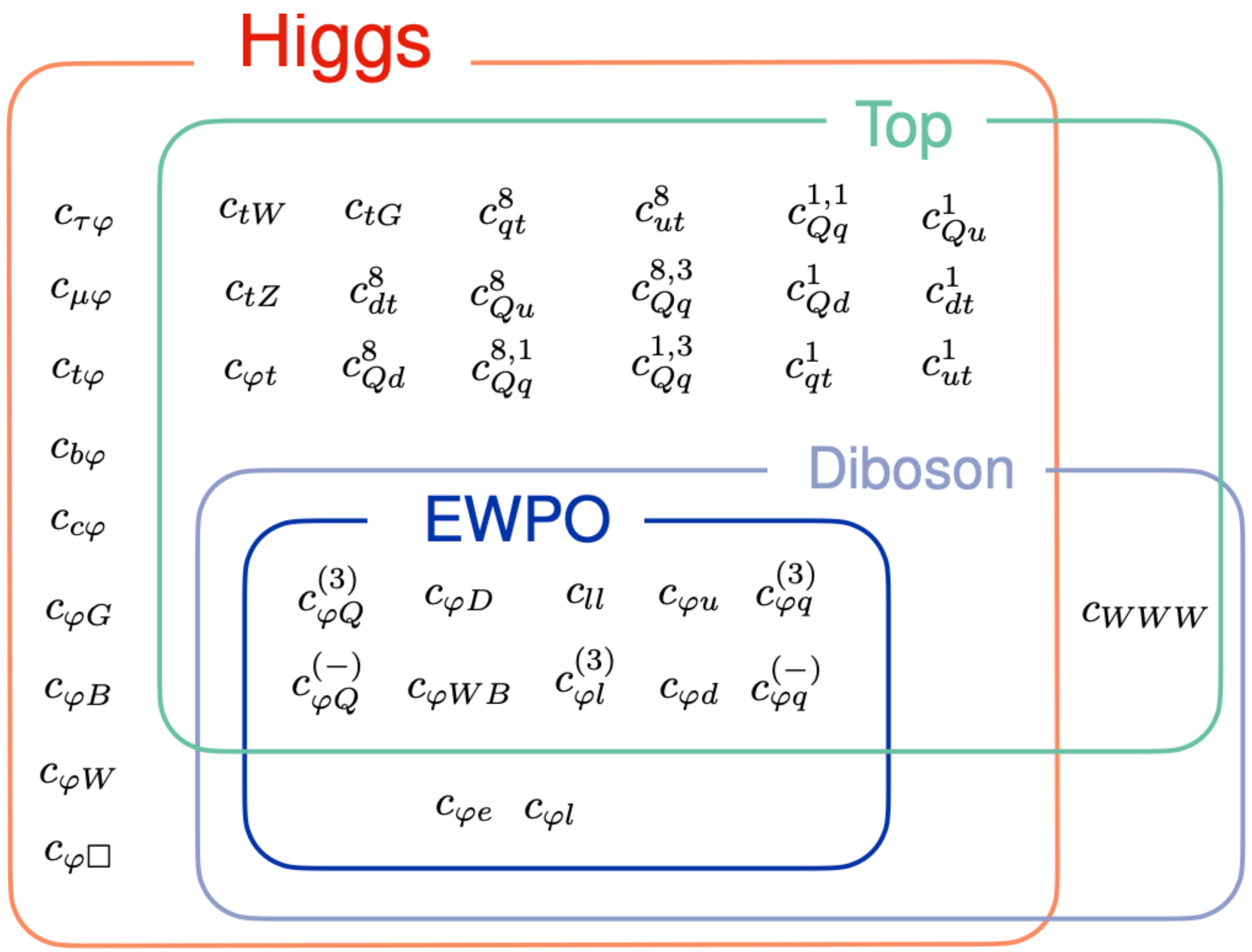

M. Costantini, E Hammou, M. Madigan, L. Mantani, J. Moore, M. Morales, MU

arXiv: 2401.xxxx

SIMUNET: A TOOL FOR SIMULTANEOUS FITS

SimuNET will be released open-source with detailed documentation & will allow users

- ✓ PDF only fits (NNPDF4.0 with more data)
- ✓ SMEFT only fits - linear SMEFT
- ✓ Simultaneous SMEFT & PDFs - linear SMEFT

```
dataset_inputs:
- {dataset: NMC, frac: 0.75}
- {dataset: ATLASTTBARTOT7TEV, cfac: [QCD], simu_fac: "EFT_NLO"}
- {dataset: CMS_SINGLETOPW_8TEV_TOTAL, simu_fac: "EFT_NLO", use_fixed_predictions: True}
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- ✓ Inject any new physics model in the data and check robustness against PDF absorbing it

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dataset_inputs:
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```

M. Costantini, E Hammou, M. Madigan, L. Mantani, J. Moore, M. Morales, MU

arXiv: 2402.03308