



European Research Council

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SIMUNET:

A NEW TOOL FOR SIMULTANEOUS EFT-PDF FITS AND FOR ASSESSING NEW PHYSICS AND PDF INTERPLAY

OUTLINE

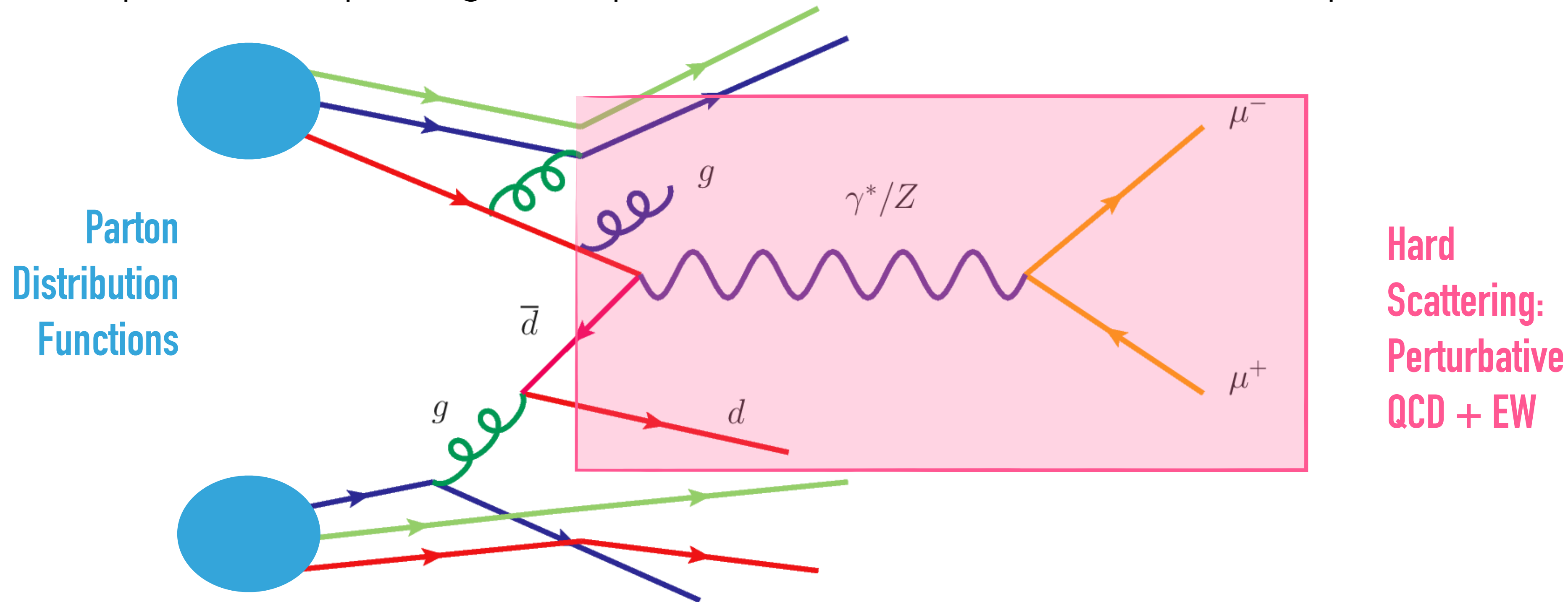
- Introduction
 - ➔ PDFs and the LHC physics programme
 - ➔ The impact of LHC data
- PDFs and New Physics
 - ➔ An unexpected interplay
 - ➔ PDFs can absorb New Physics
 - ➔ Simultaneous SMEFT and PDF fits
- SimuNET
 - ➔ A new tool for global interpretation of data
 - ➔ Applications
- Conclusions and outlook

INTRODUCTION

THEORETICAL PREDICTIONS AT THE LHC

$$\sigma^{pp \rightarrow ab} = \sum_{i,j=-n_f}^{n_f} \int dz_1 dz_2 f_i(z_1, \mu_F) f_j(z_2, \mu_F) \hat{\sigma}^{ij \rightarrow ab}(z_1 z_2 S, \alpha_s(\mu_R), \mu_F) + \mathcal{O}\left(\frac{\Lambda^n}{S^n}\right)$$

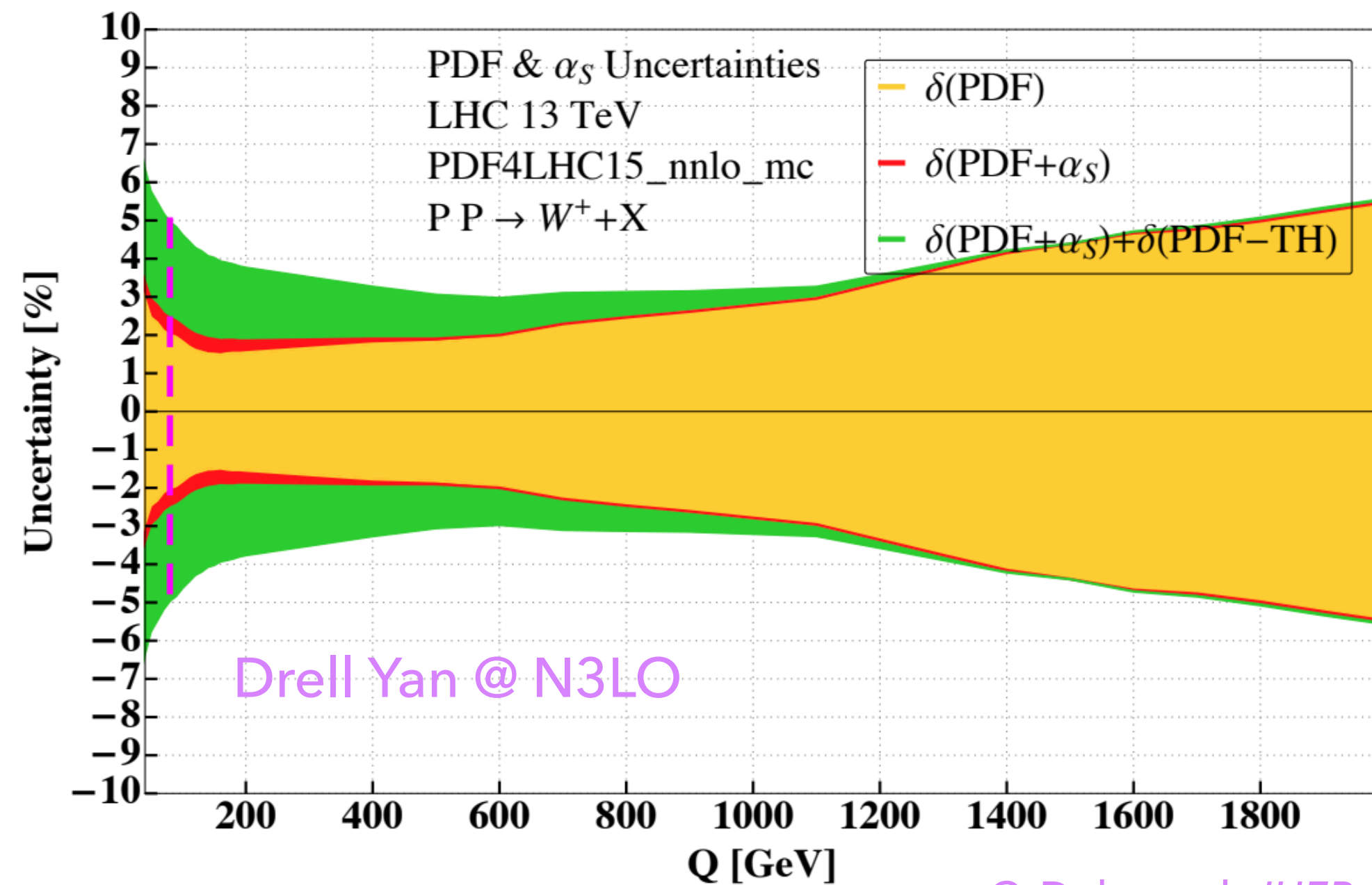
Collinear factorisation: separate long-distance **universal** information on proton structure in terms of partons (quarks, antiquark, gluons, photons...) from from short-distance parton interaction (hard scattering)



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

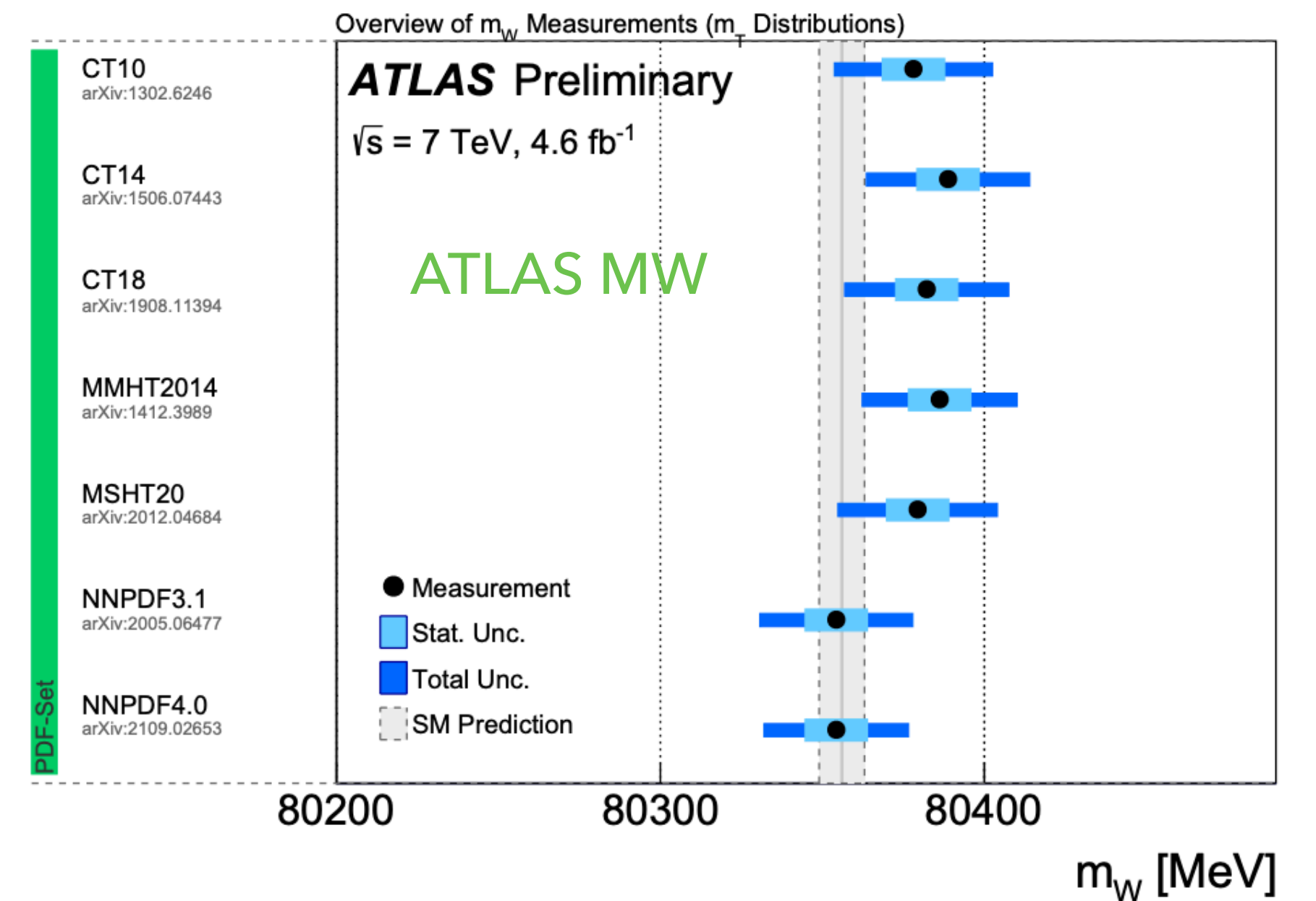
$$d\sigma^{pp \rightarrow ab} = \sum_{i,j} f_i \otimes f_j \otimes d\hat{\sigma}^{ij \rightarrow ab} + \dots$$

#1: Theory uncertainty of SM predictions



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

#2: Determination of SM parameters



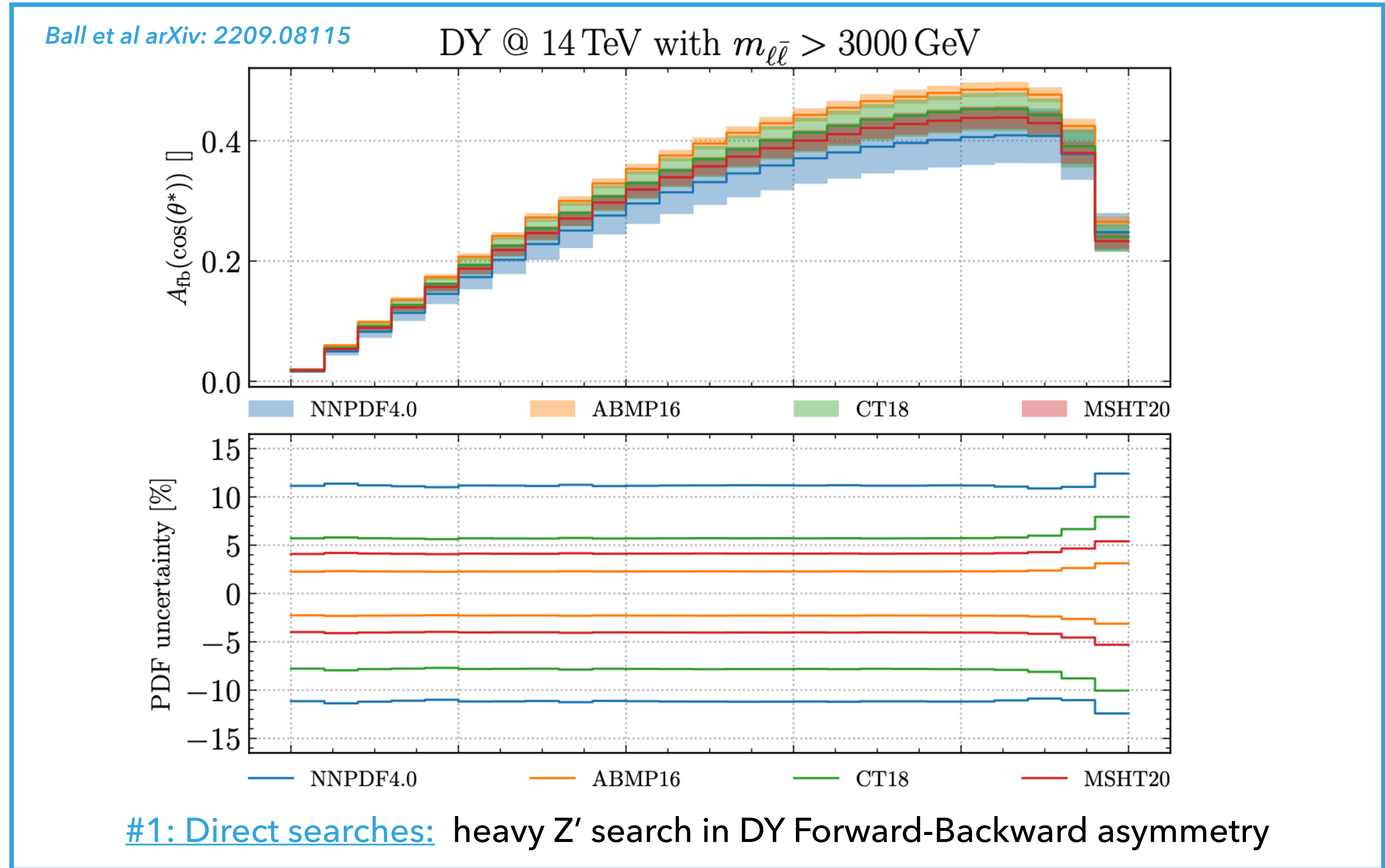
ATLAS-CONF-2023-004

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

High-mass final states



Large-x PDFs

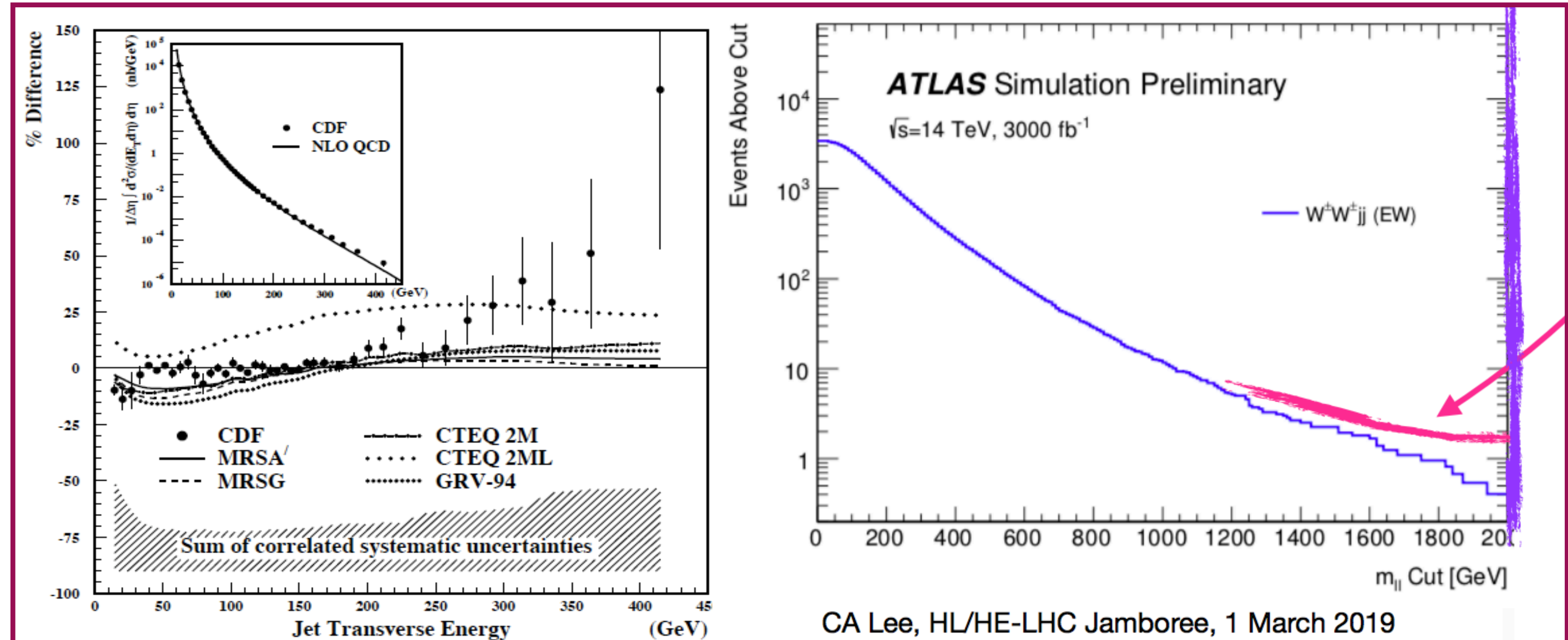


$$x \approx \frac{M}{\sqrt{S}}$$

High-mass final states



Large-x PDFs



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

PARTON DISTRIBUTION FUNCTIONS

$$f_i(x, \mu)$$

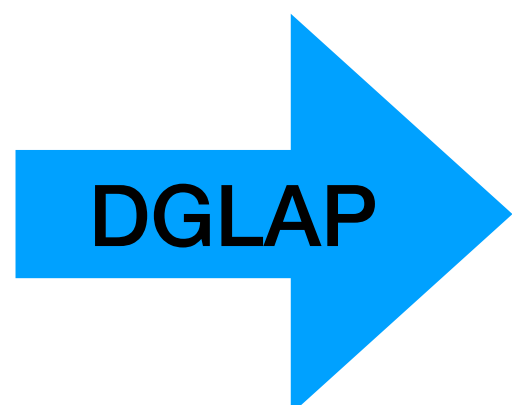
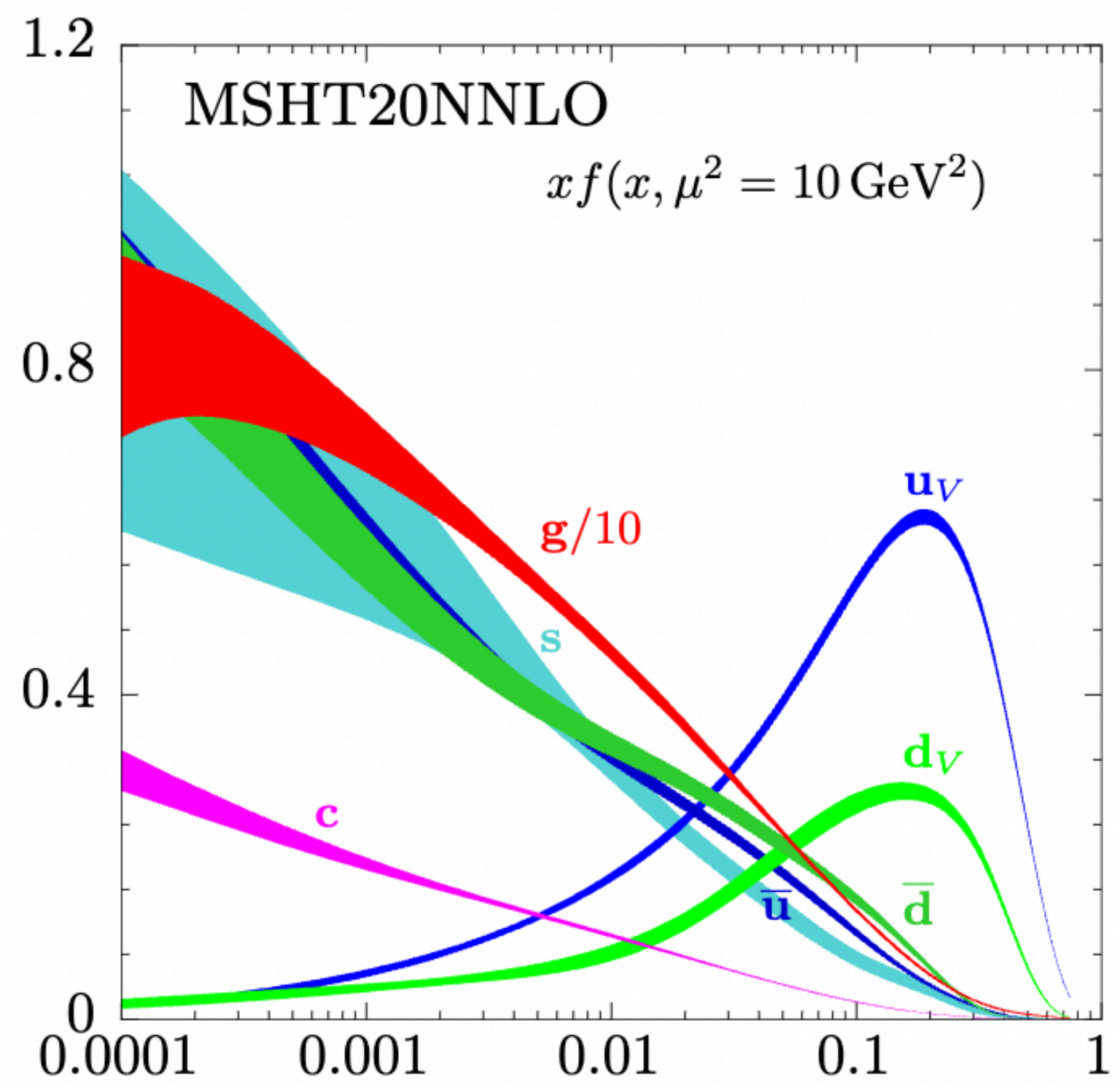
Perturbative QCD

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

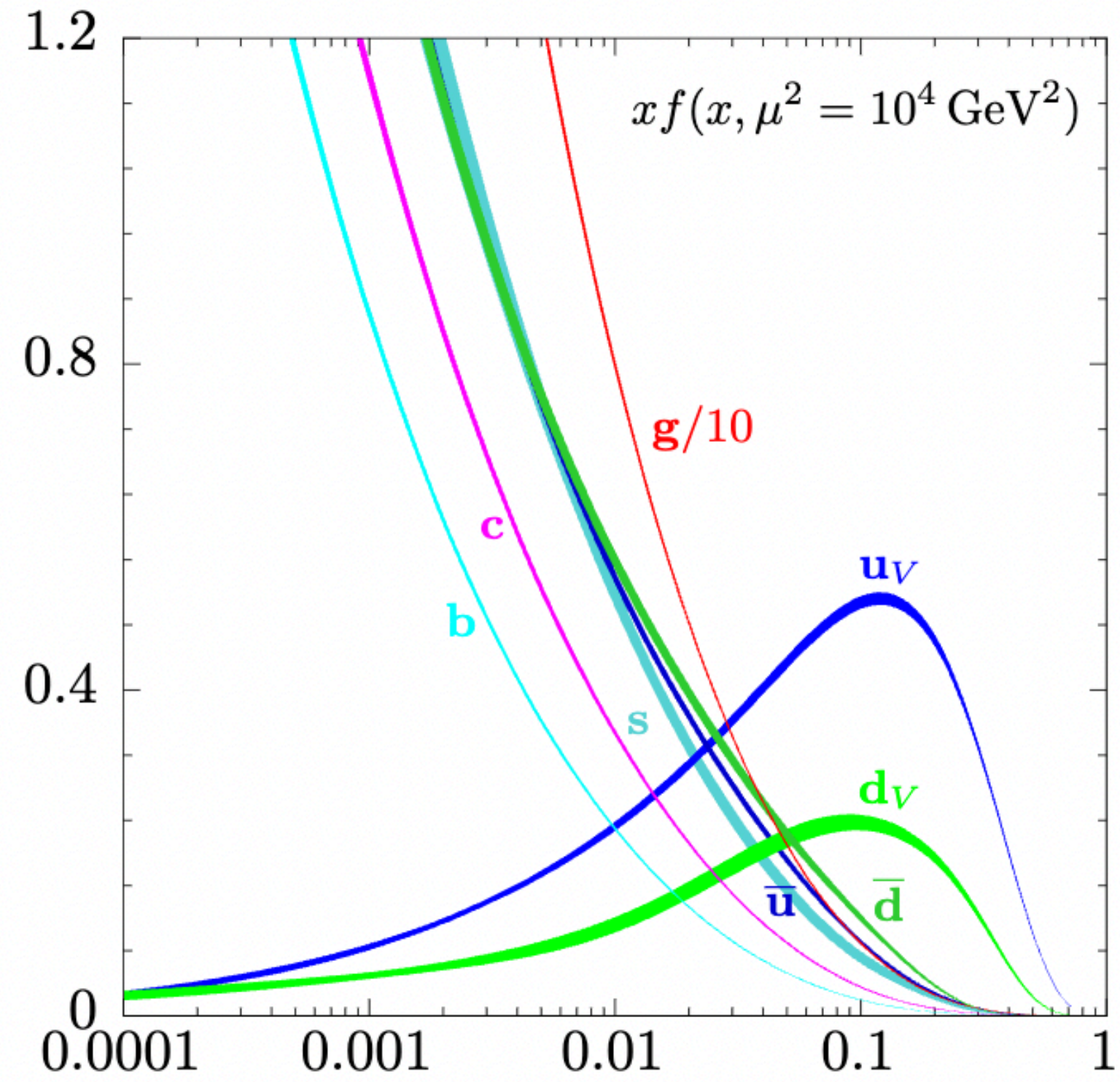
Splitting functions P_{ab} known up to approximate N3LO [Blumlein, Moch, Gehrman, von Manteufel, Sotnikov, Yang, Davies, Vogt, Bonvini, Marzani, ...]

First approximate N3LO sets MSHT20aN3LO
 McGowan et al 2207.04739
 NNPDF40aN3LO
 Ball et al 2402.18635

Hadronic scale:
global fit of PDFs



High scale:
input to the LHC

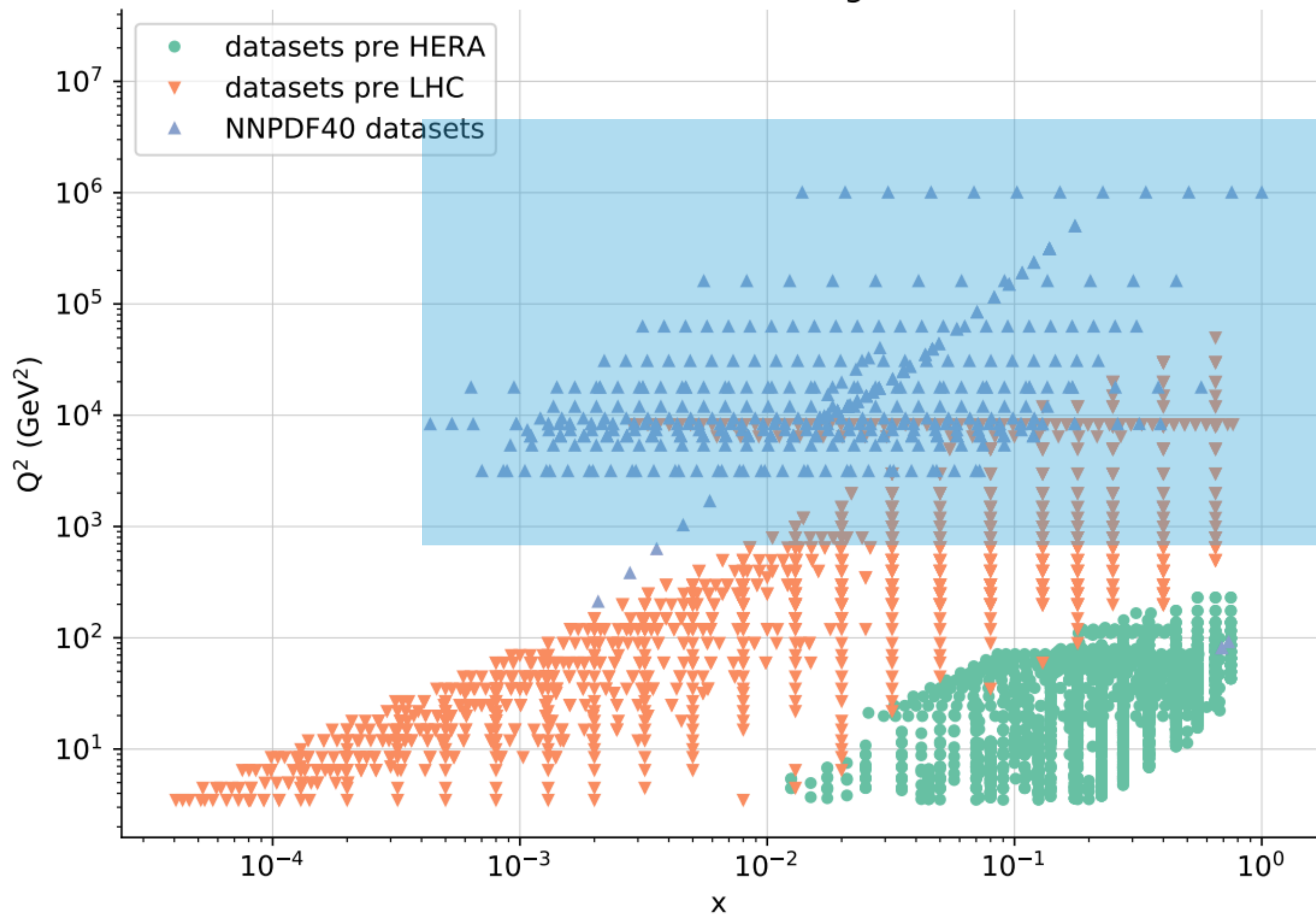


A WEALTH OF DATA FROM THE LHC

$$f_i(x, \mu)$$

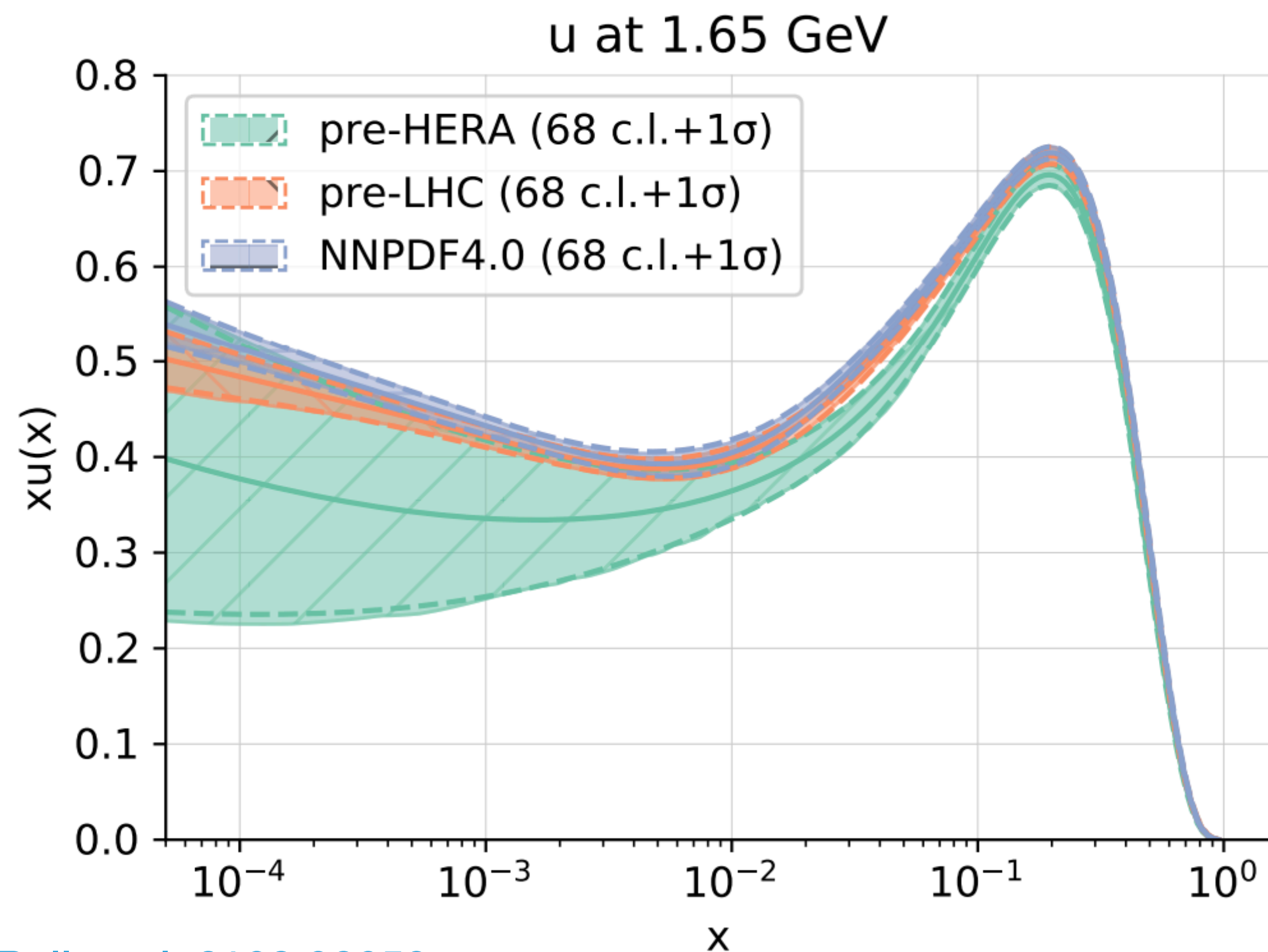
Data

Kinematic coverage



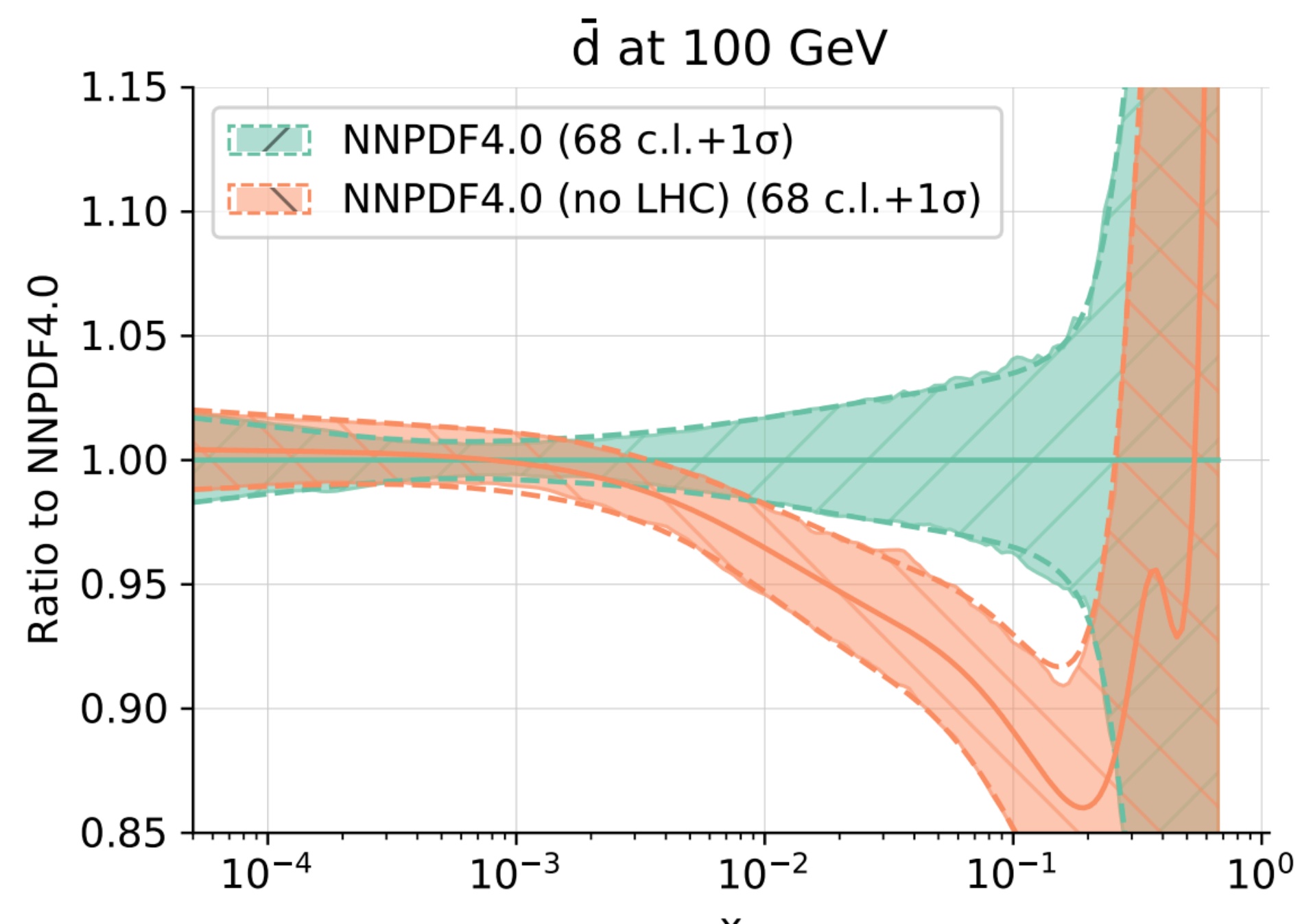
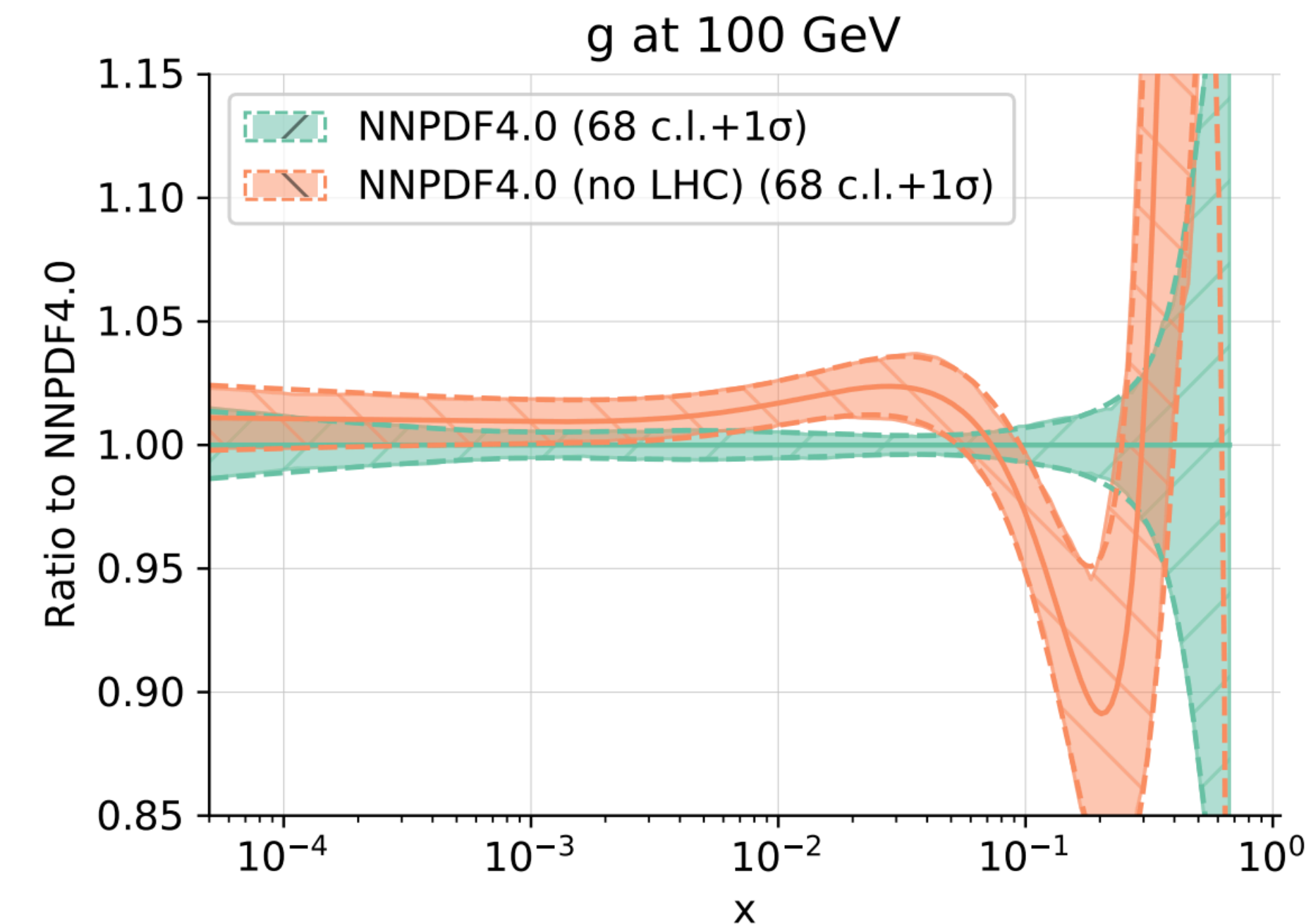
NNPDF4.0:
About 30% of
input data are
LHC data!

IMPACT OF LHC DATA

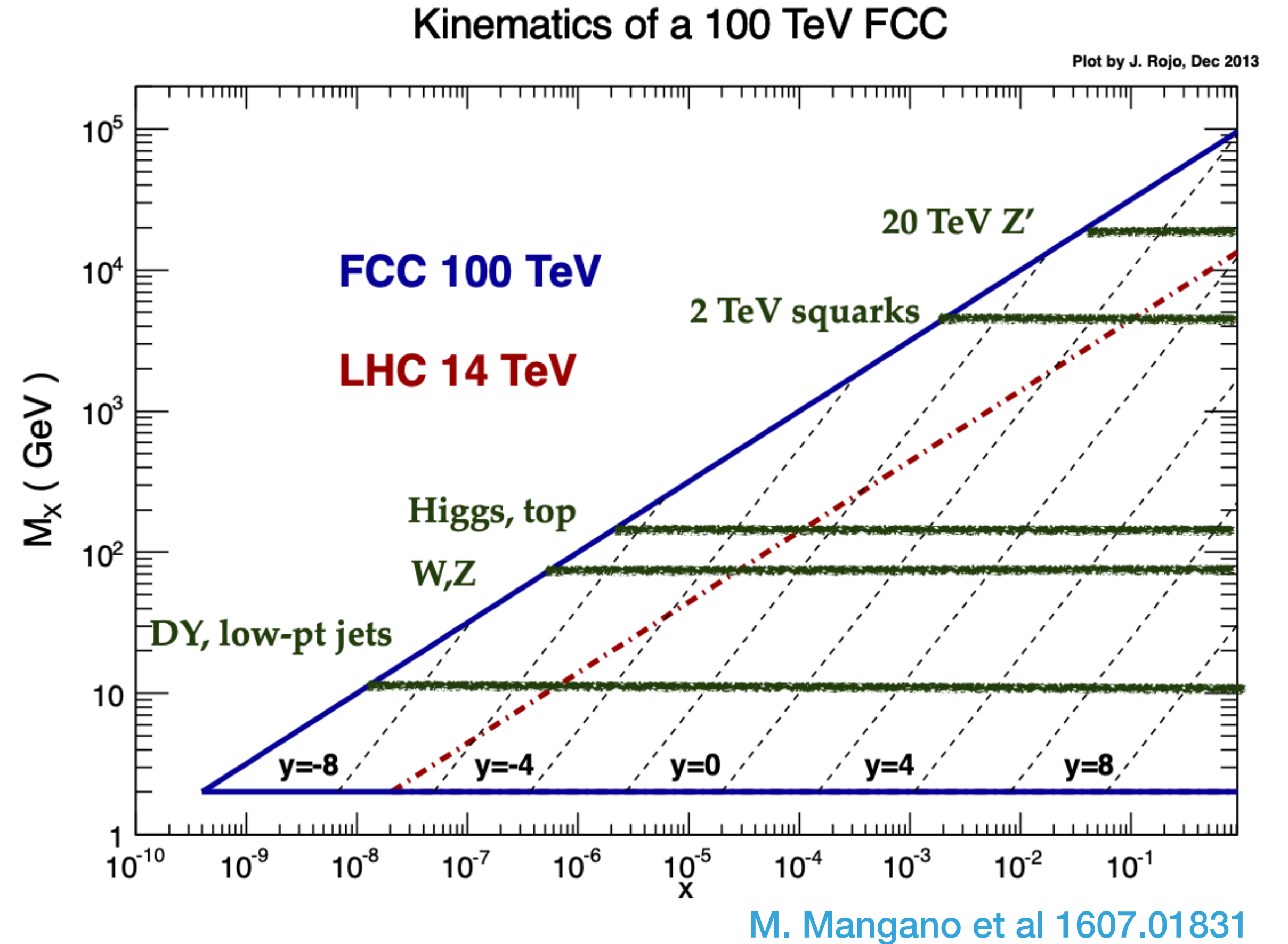
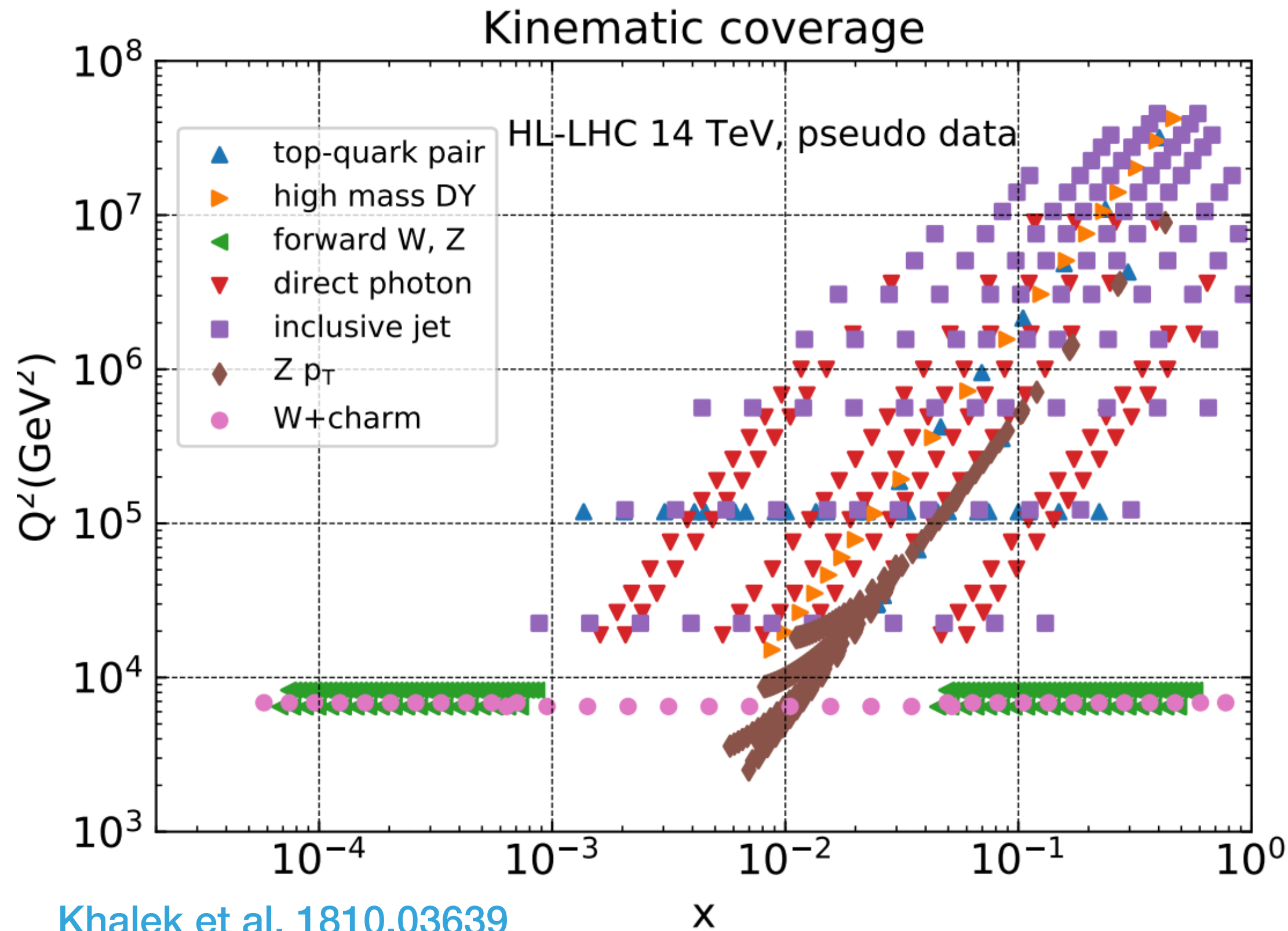


[Ball et al, 2109.02653](#)

- 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



- Thanks to luminosity upgrade, HL-LHC will go nearly two orders of magnitude higher in Q^2 , 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 Q^2 [Mangano et al 1607.01831]

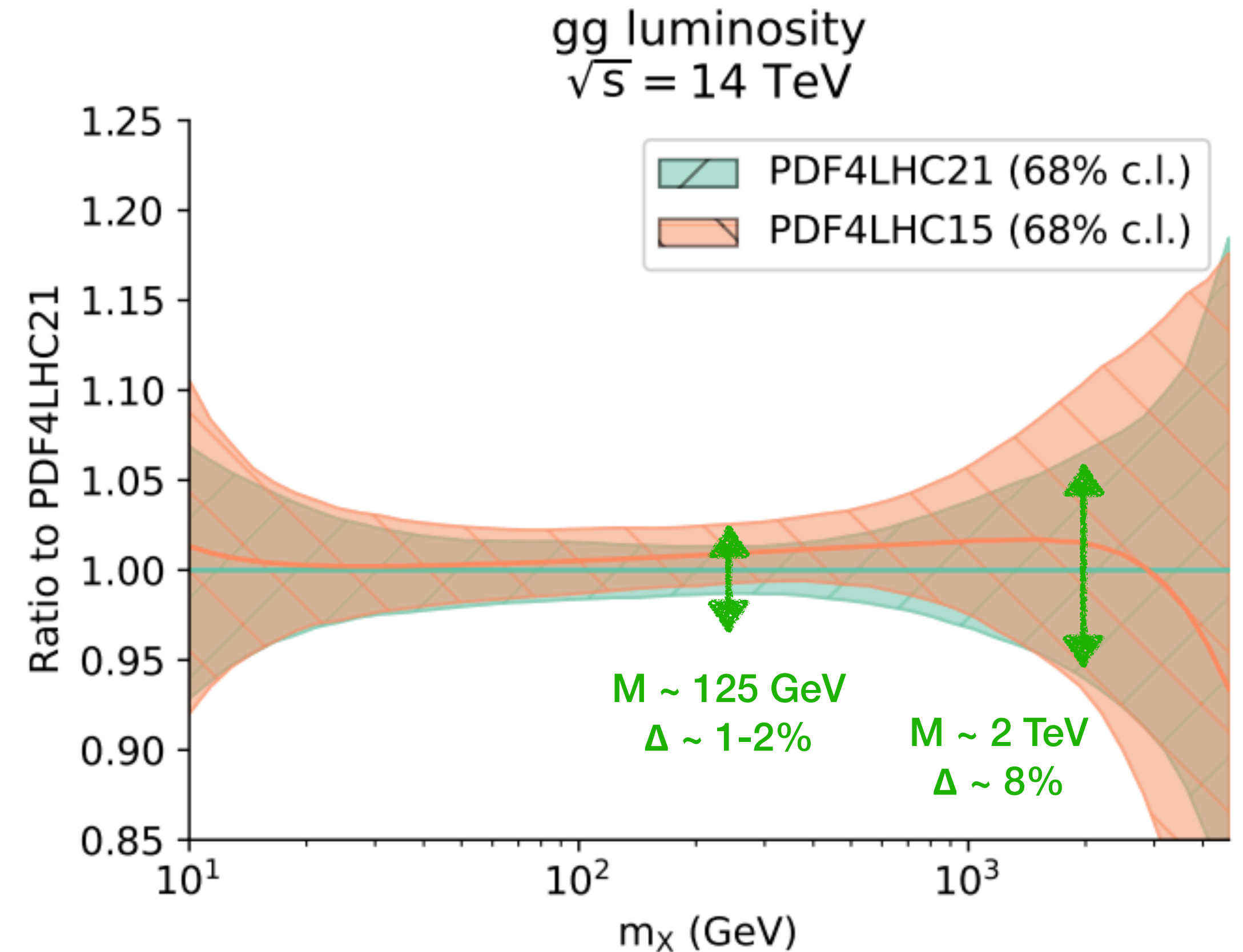
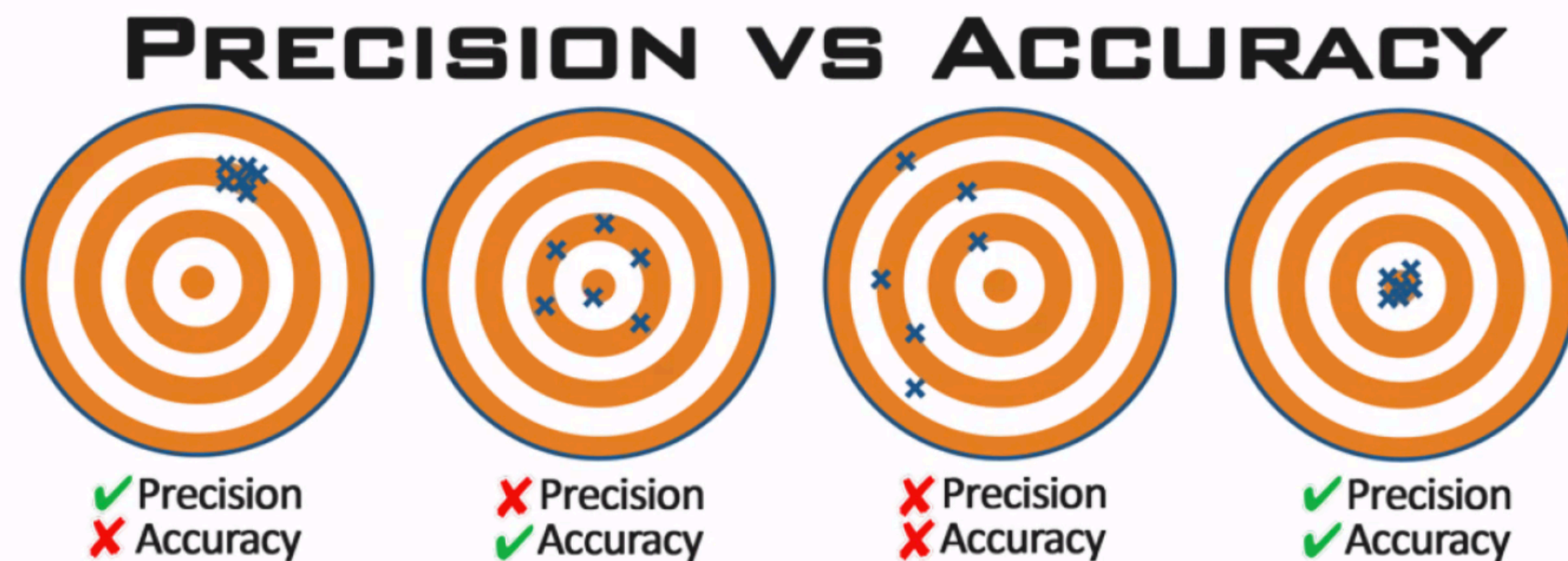
Large $x \leftrightarrow$ Large E and/or Large Y

THE PRECISION VERSUS ACCURACY CHALLENGE

Now that PDFs are getting more and more precise, it is crucial for them to be accurate.

Challenges:

- ▶ Genuine inconsistencies in experimental inputs
- ▶ Imperfect fitting methodology
- ▶ Inaccurate theoretical framework
 - ➔ Missing higher order uncertainties & N3LO
 - ➔ Other corrections (nuclear, non-perturbative effects...)
 - ➔ BSM effects - [second part of the talk](#)



PDF4LHC21 study 2203.05506

PDFS AND NEW PHYSICS: AN UNEXPECTED INTERPLAY

SMEFT: A FRAMEWORK FOR INDIRECT DISCOVERIES

- EFT is a well-defined theoretical approach for indirect searches
- Assumption: new physics states are heavy
- Write the Lagrangian with only light SM particles, BSM effects incorporated as a momentum expansion
- SMEFT: assume SM field content and gauge symmetries (apart from accidental)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

- Full dim-6 basis of operators under SMEFT assumptions includes **2499** operators [Grzadkowski et al, [arXiv:1008.4884](https://arxiv.org/abs/1008.4884)]
- Current SMEFT fits make flavour assumptions and restricted to a few observables/sectors & reduce the number of operators.
- Huge progress in global dim-6 SMEFT fits and matching with UV models [Veronica's talk tomorrow]

EXTRACTING PARAMETERS FROM DATA

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

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

SMEFT WCs

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Parameters determining PDFs at initial scale

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SMEFT WCs

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

$$T_i(\{\theta\}) = \text{PDFs}(\{\theta\}, \{c = 0\}) \otimes \hat{\sigma}_i(\{c = 0\})$$

EXTRACTING PARAMETERS FROM DATA

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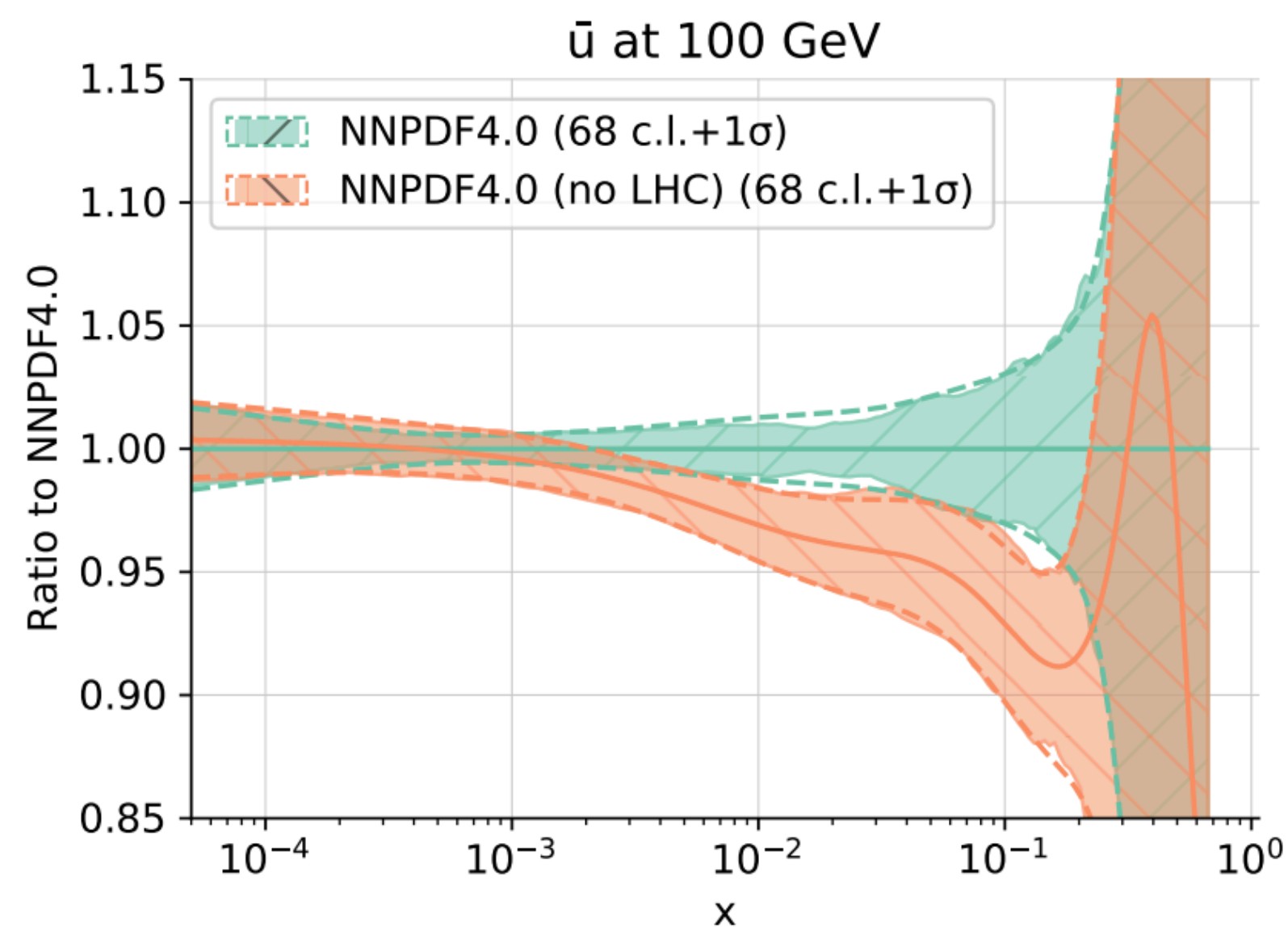
$$T_i(\{\theta\}) = \text{PDFs}(\{\theta\}, \{c = 0\}) \otimes \hat{\sigma}_i(\{c = 0\})$$

✓ In a fit of SMEFT Wilson Coefficients

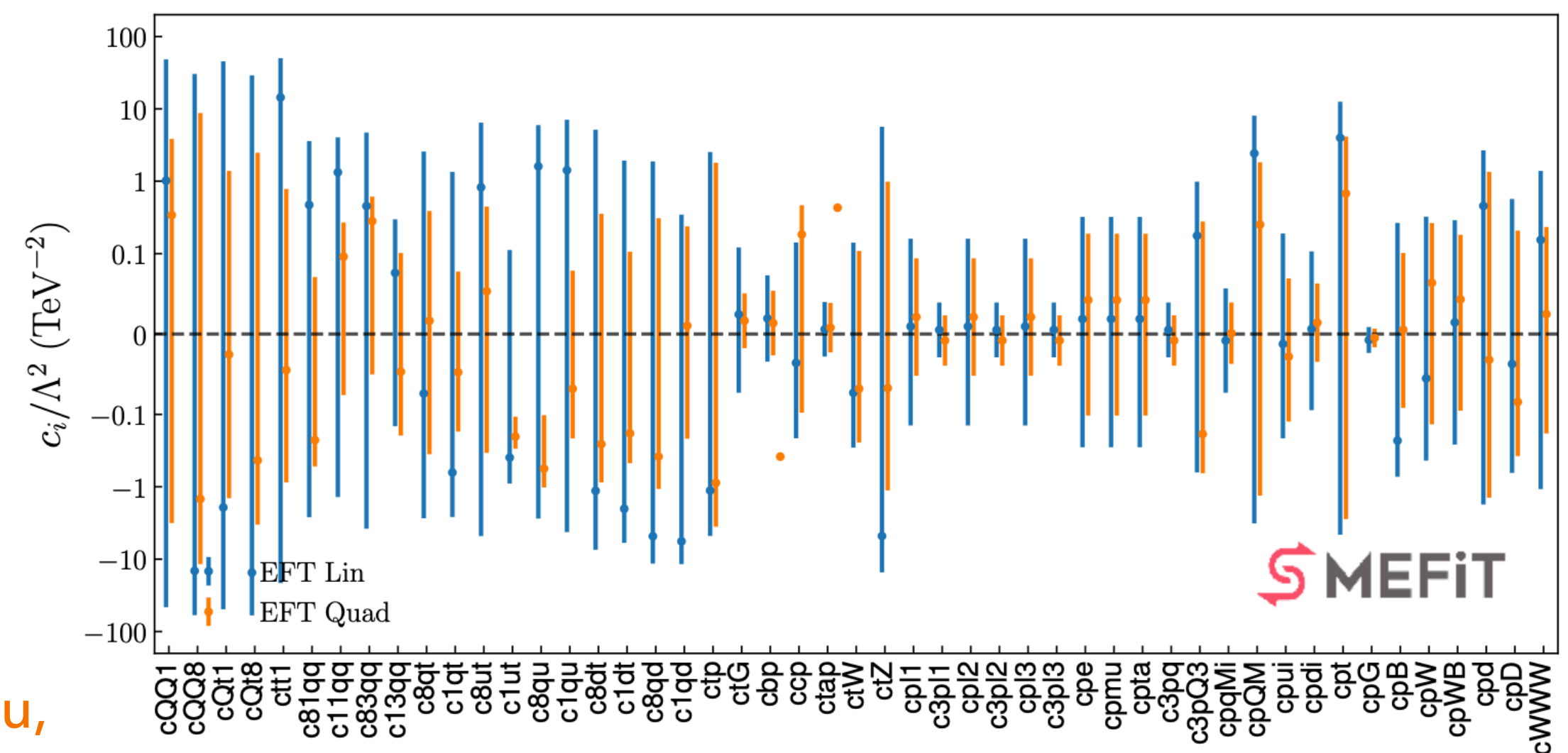
$$T_i(\{c\}) = \text{PDFs}(\{\theta = \bar{\theta}\}, \{c = 0\}) \otimes \hat{\sigma}_i(\{c\})$$

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

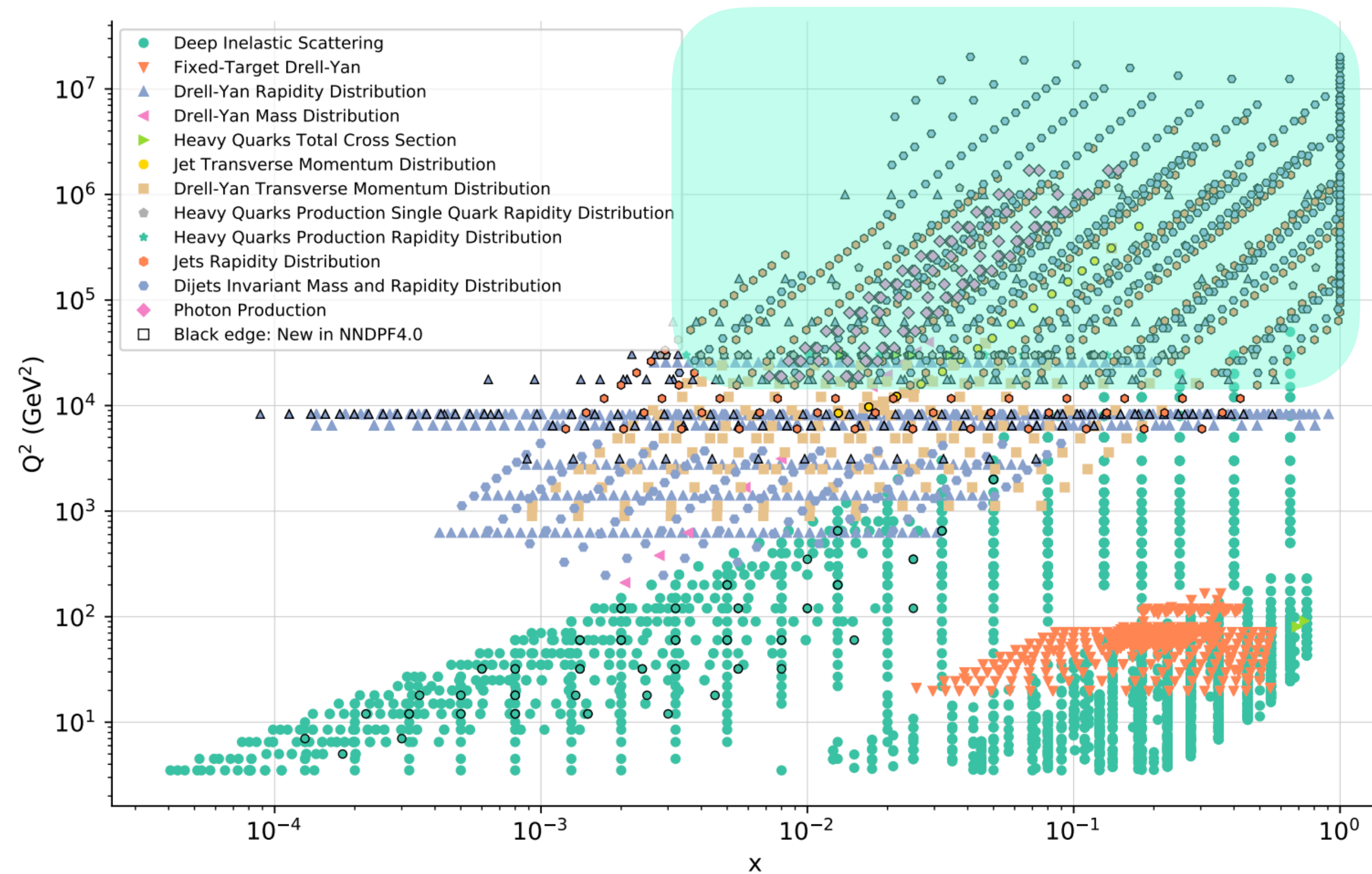


MU, M. Costantini, E. Hammou,
M. Madigan, L. Mantani, J.
Moore, M. Morales Alvarado



Ethier et al, arXiv: 2105.00006

DATA OVERLAP



➔ Top pair production and single top data included in SMEFT analysis

[Hartland et al 1901.05965] [Ellis et al 2012.02779]

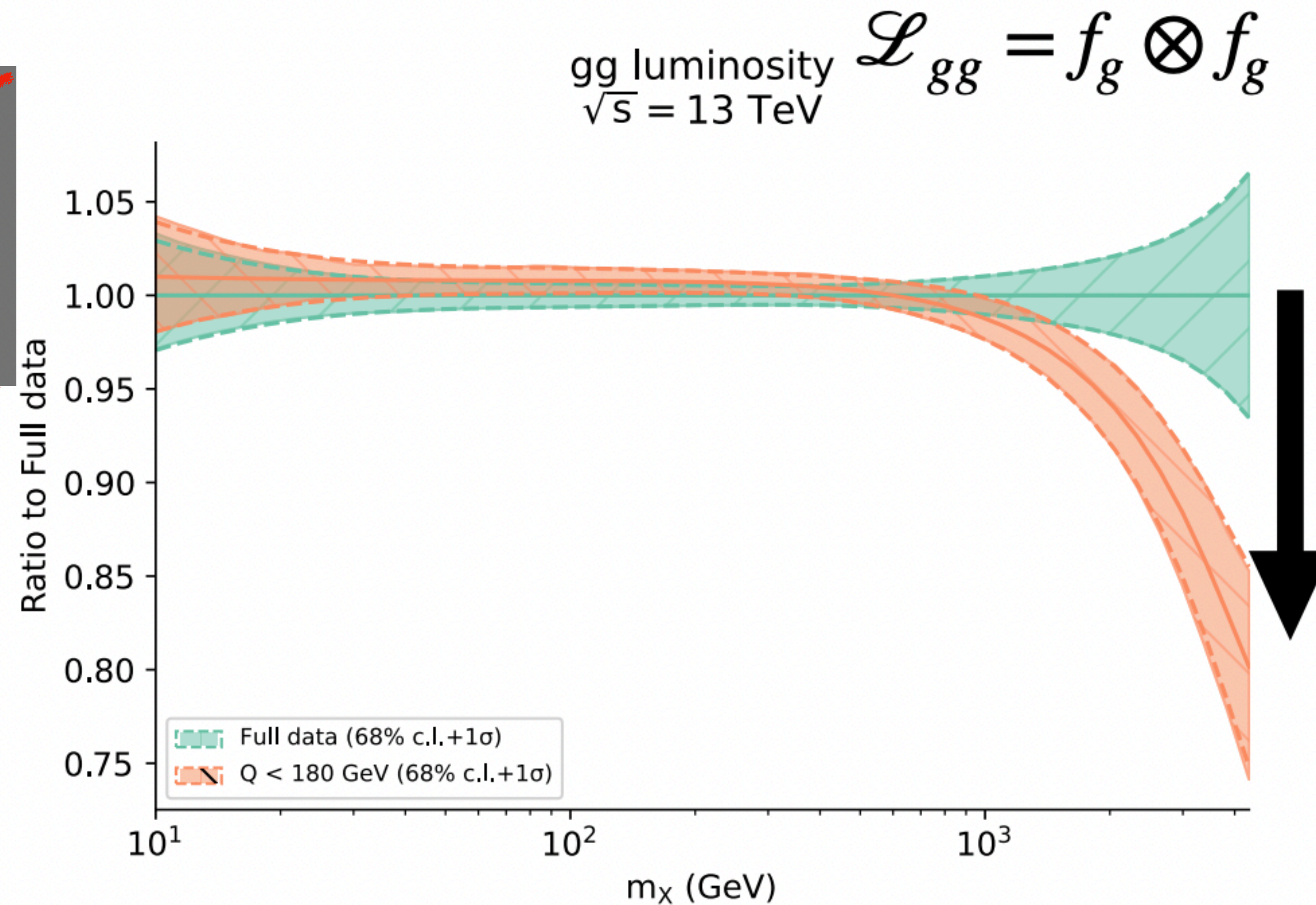
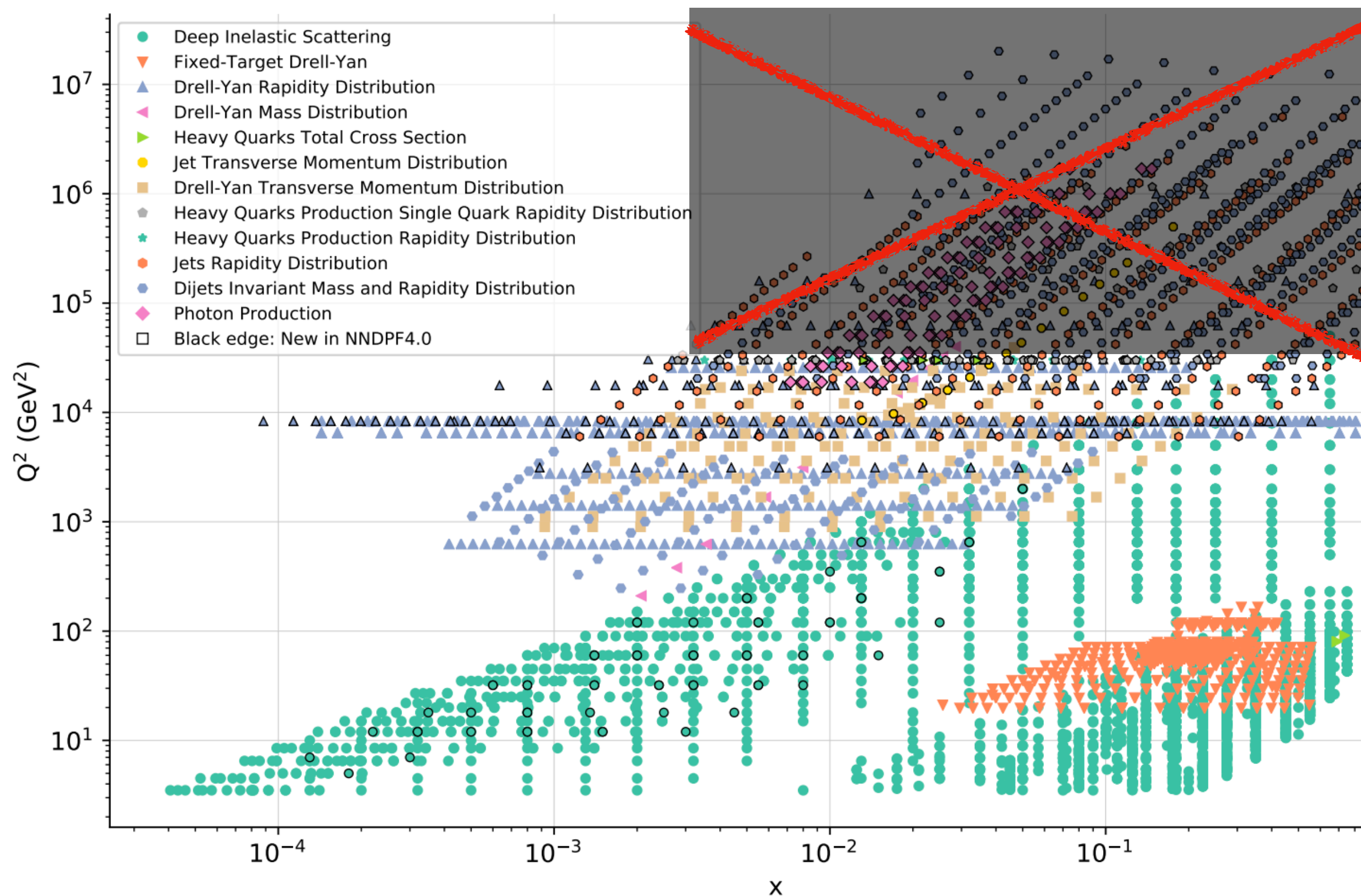
➔ Drell-Yan high mass data [Farina et al 1609.08157, Torre et al 2008.12978]

➔ Inclusive Jets data [Alte et al 1711.07484]

➔ Dijets data [Krauss et al 1611.00767] [Alioli et al 1706.03068] [Bordone et al 2103.10332]

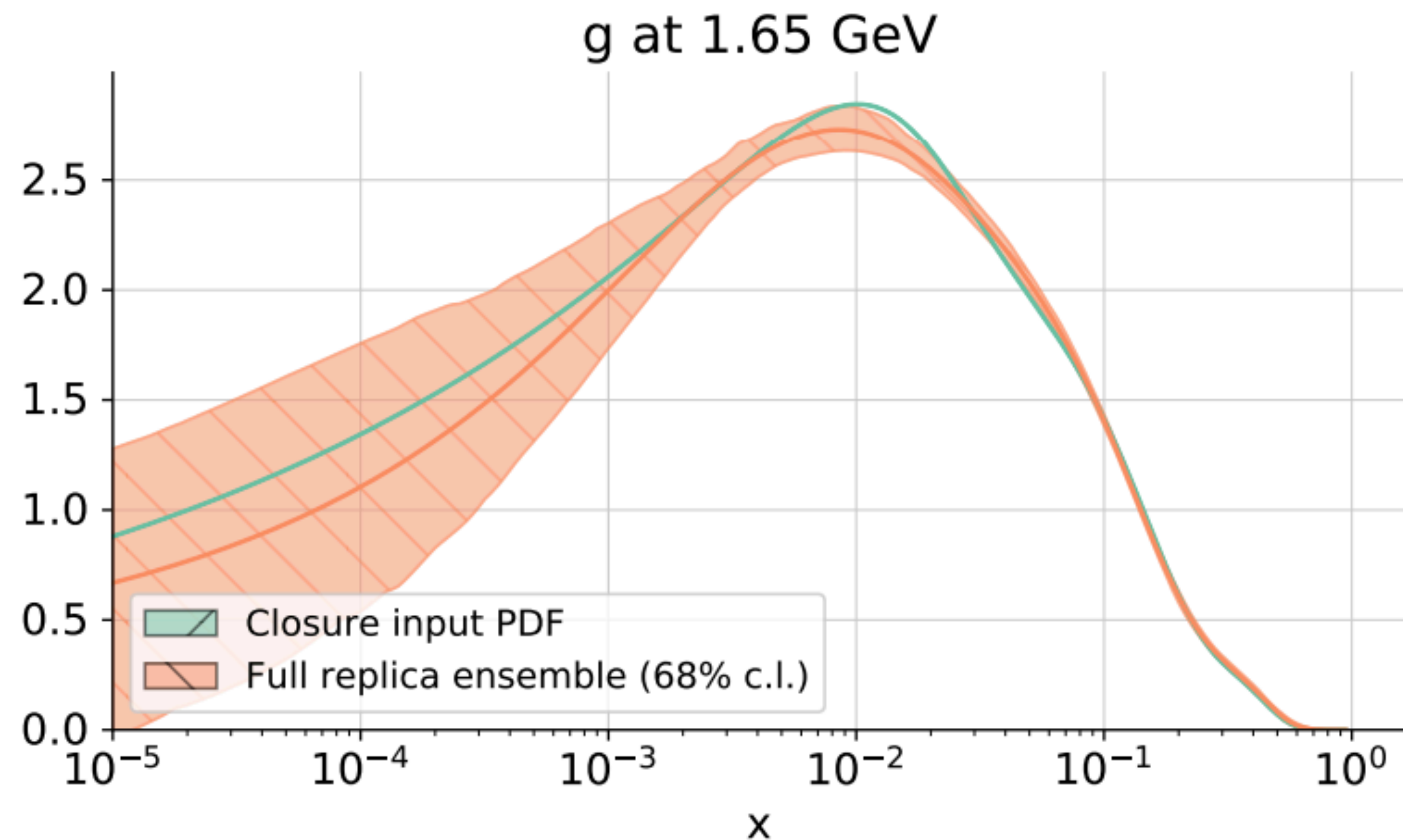
➔ Overlap enhanced in HL-LHC projections [Abdul Khalek et al 1810.03639]

DATA OVERLAP



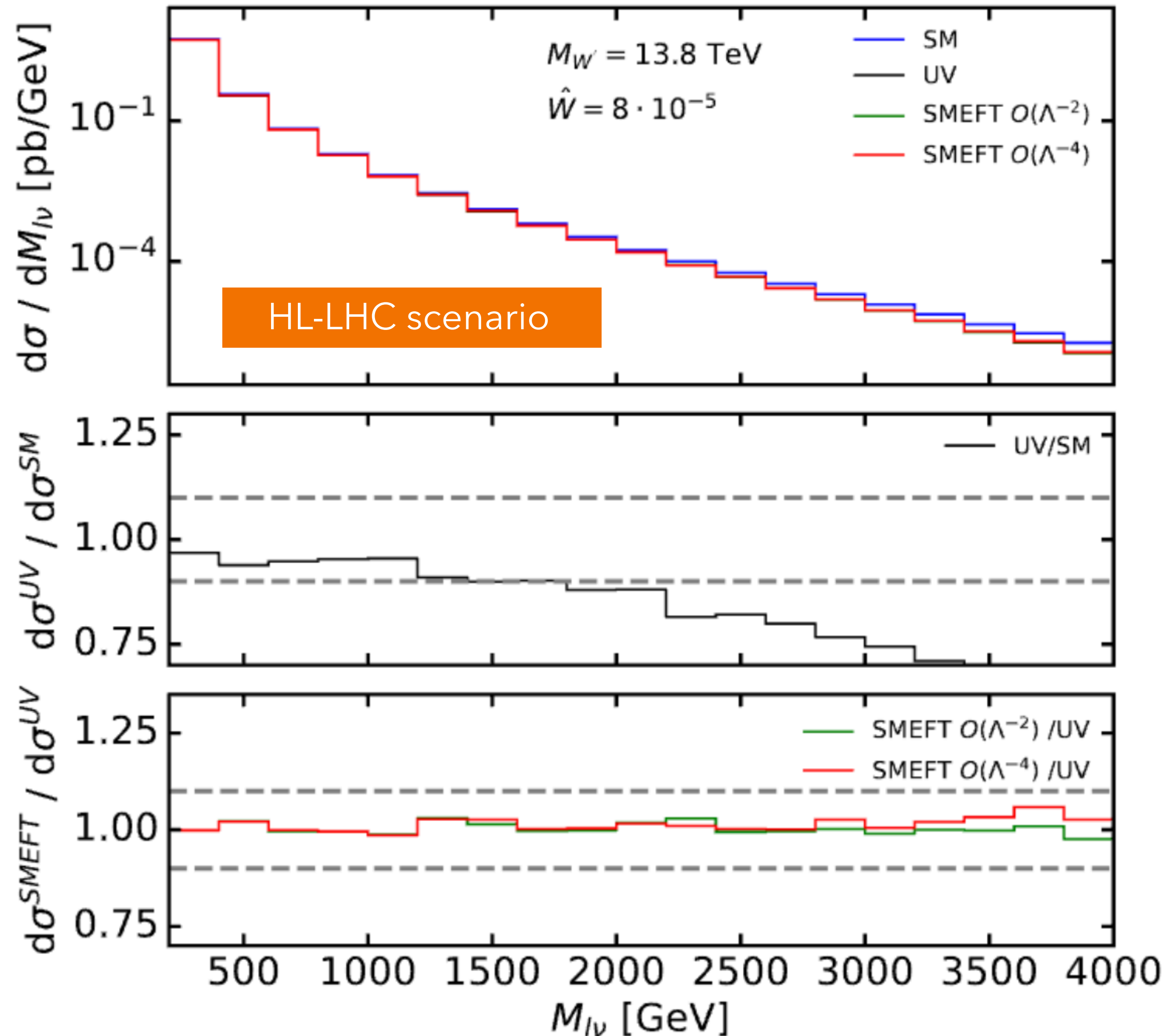
- Naive solution: remove all data above $Q > Q_{\text{high}}$ for example $Q_{\text{high}} \approx m_{\text{top}}$
- However away all high energy data would result in dramatic uncertainty increase and loss of precision. Knowledge of PDFs at large x would rely on rather old DIS data and on ability to define uncertainties in the extrapolation region

CAN PDFS ABSORB NEW PHYSICS?



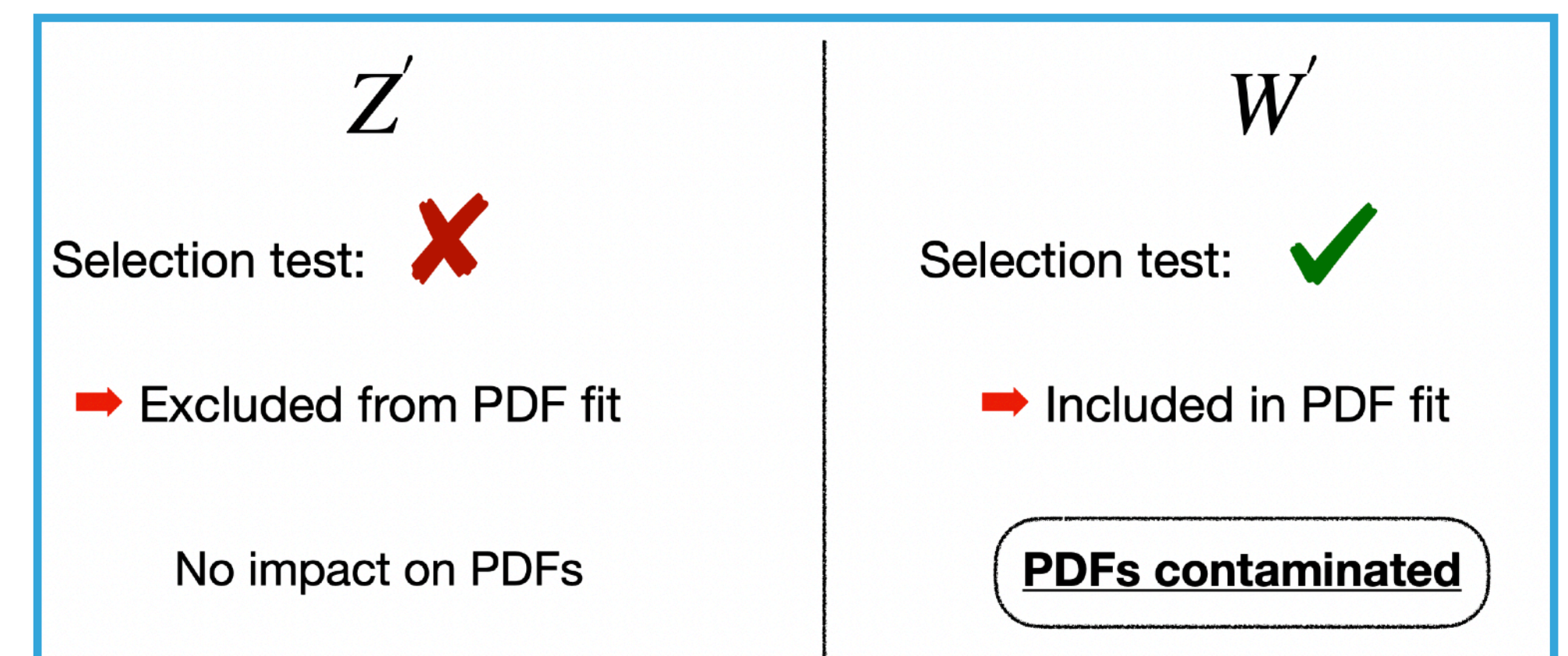
- ✓ NNPDF methodology routinely tested via closure test (in the data region) [Del Debbio, Giani, Wilson, 2111.05787] and future test (in the extrapolation region) [Cruz-Martinez, Forte, Nocera, 2103.08606].
- ✓ Closure tests assess methodology robustness and efficiency & faithfulness of uncertainty estimate.
- ✓ 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
- ✓ Can we test if we can “safely” add high M data using this statistical test?

CAN PDFS ABSORB NEW PHYSICS?



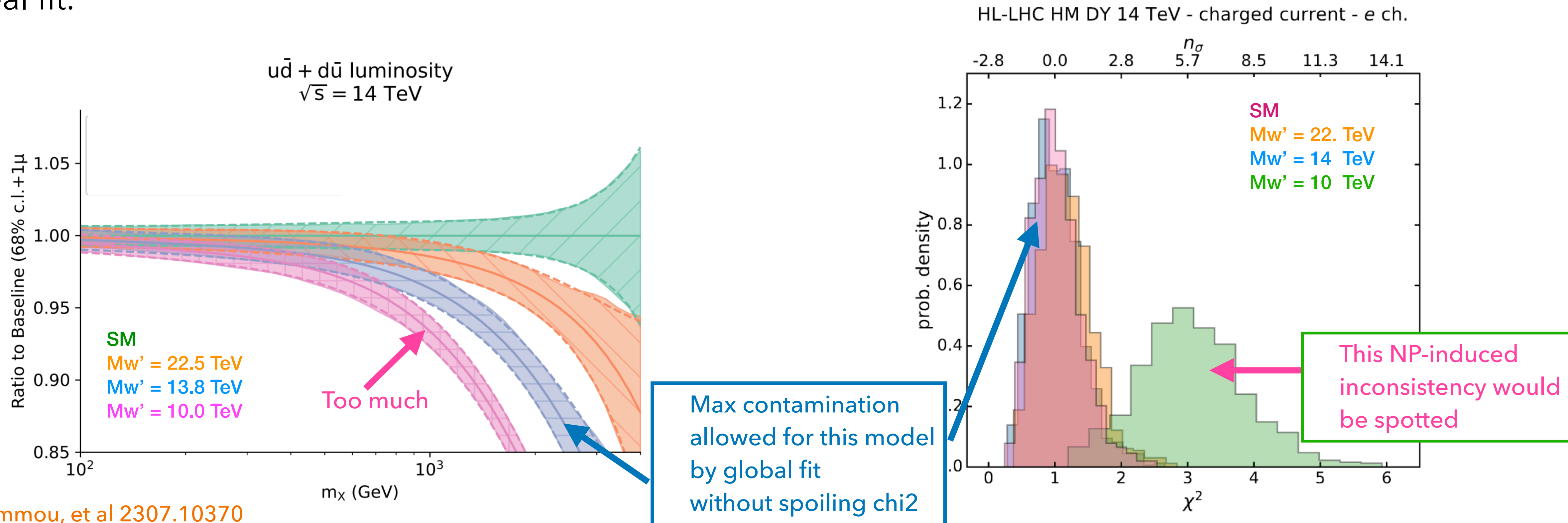
- Imagine that on top of the “true” PDFs one inject the “true” BSM model in the MC data
- Generate artificial MC data assuming “true” law of nature = “true” PDFs + “true” BSM model
- Fit PDFs assuming SM
- Can PDFs absorb signs of new physics?

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

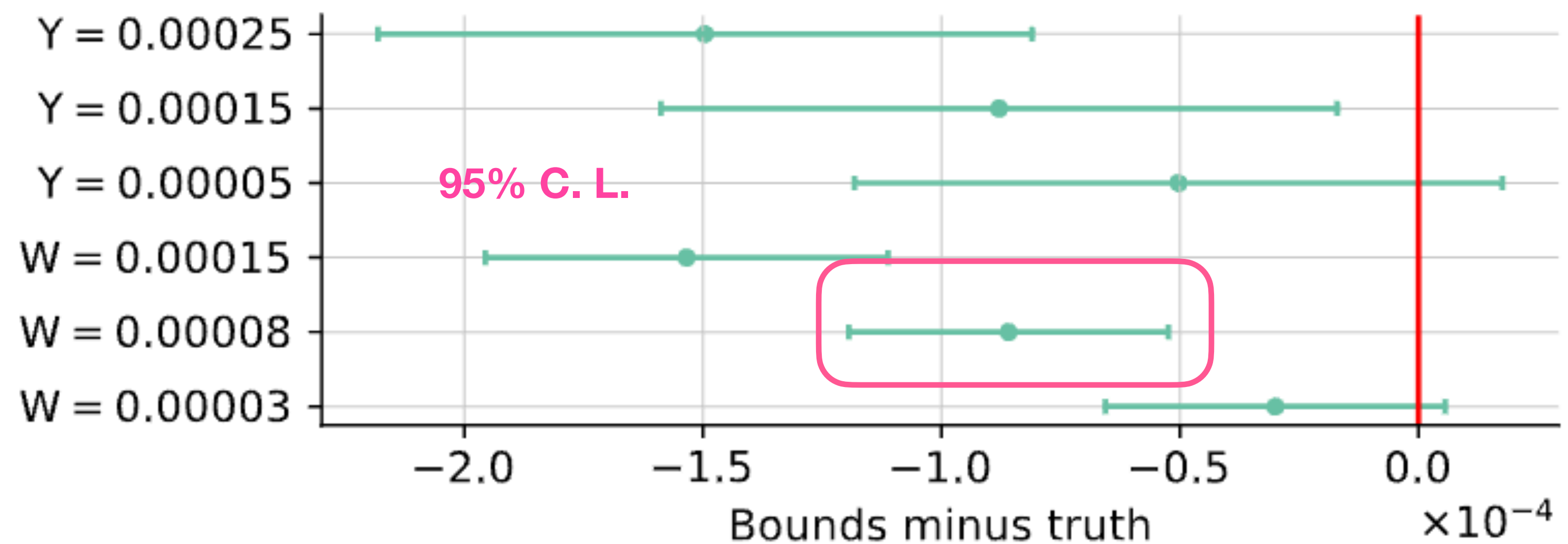
- The fit-quality of the global fit is unchanged even with signal from $M_{W'} = 13.8$ TeV injected in all data (mostly visible in HL-LHC NC and CC Drell-Yan data)
- Once we go beyond this point, the fit-quality deteriorates due to the HL-LHC neutral current and charged current Drell-Yan MC data.
- Already for $M_{W'} = 13.8$ TeV the $qq \sim$ 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.



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

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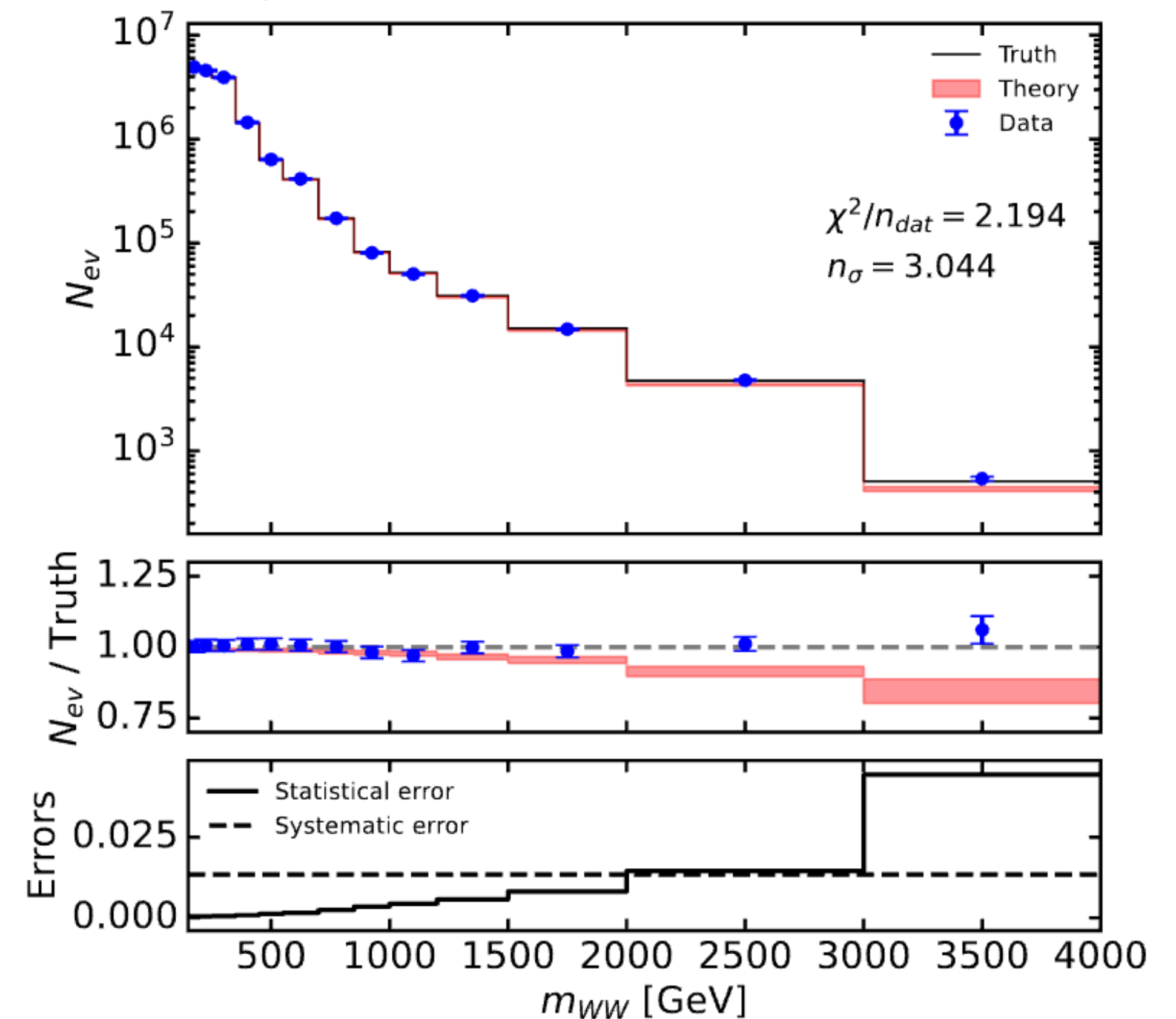
Consequence #1:
Would not see indirect effect of new physics as we would find SMEFT bounds compatible with the SM!



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

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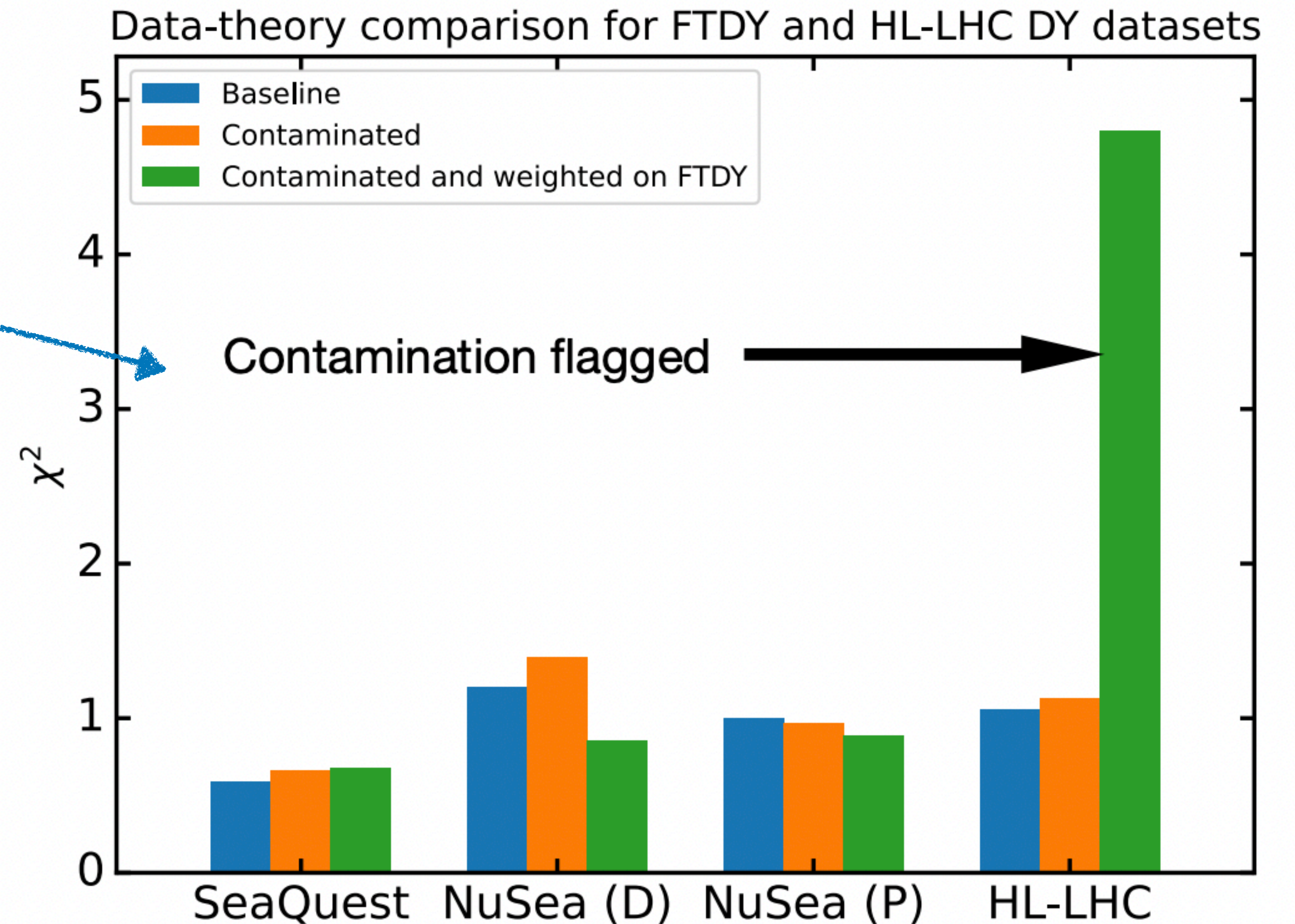
Consequence #2:
Would see New Physics effects where there are none (for example in WW)



HOW TO AVOID NEW PHYSICS CONTAMINATION?

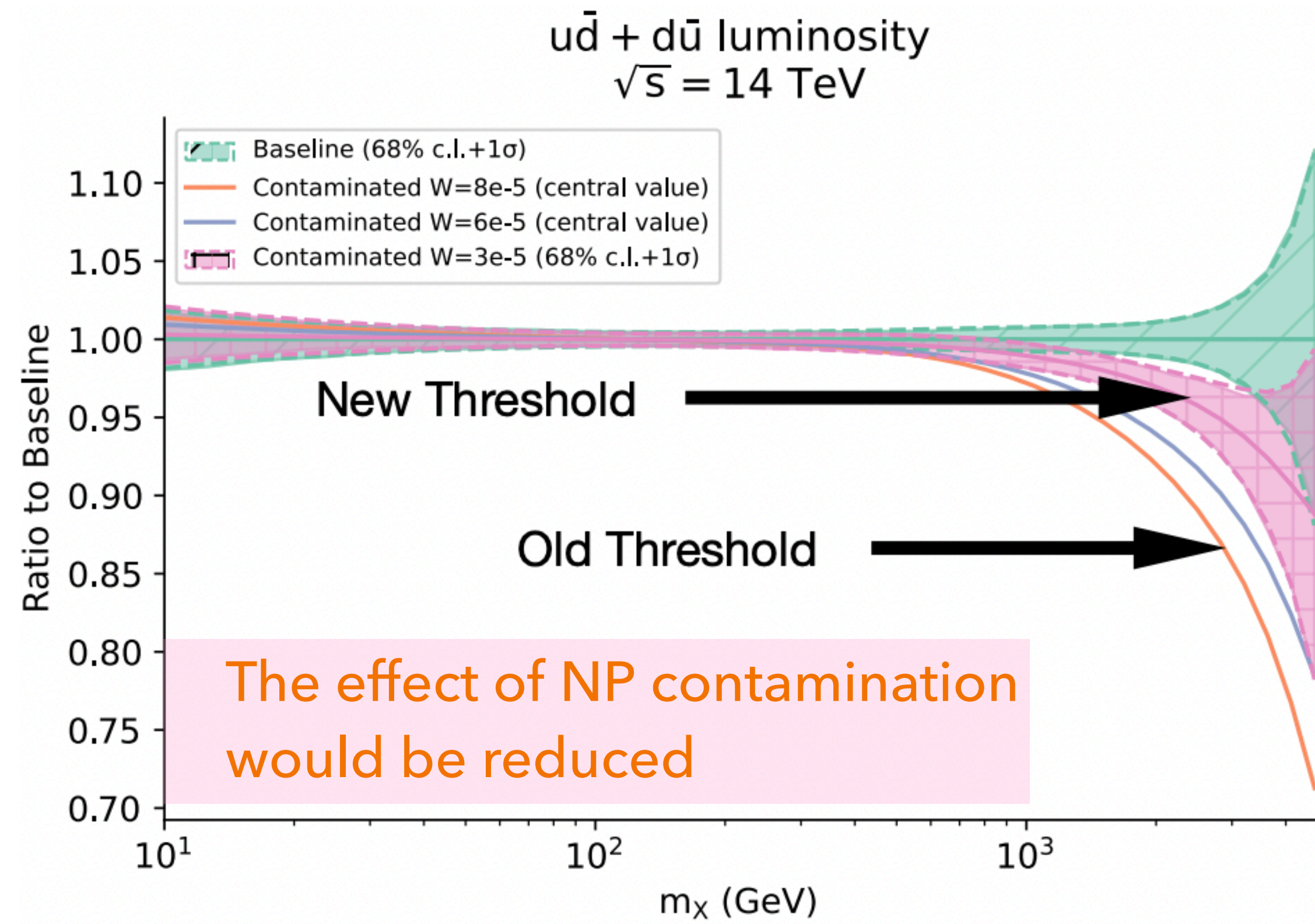
- LHCb on-shell at high rapidity data do not help as quark probed at large x , antiquark at small x
- Need more accurate low-energy/large- x constraining measurements to really disentangle such effects

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!

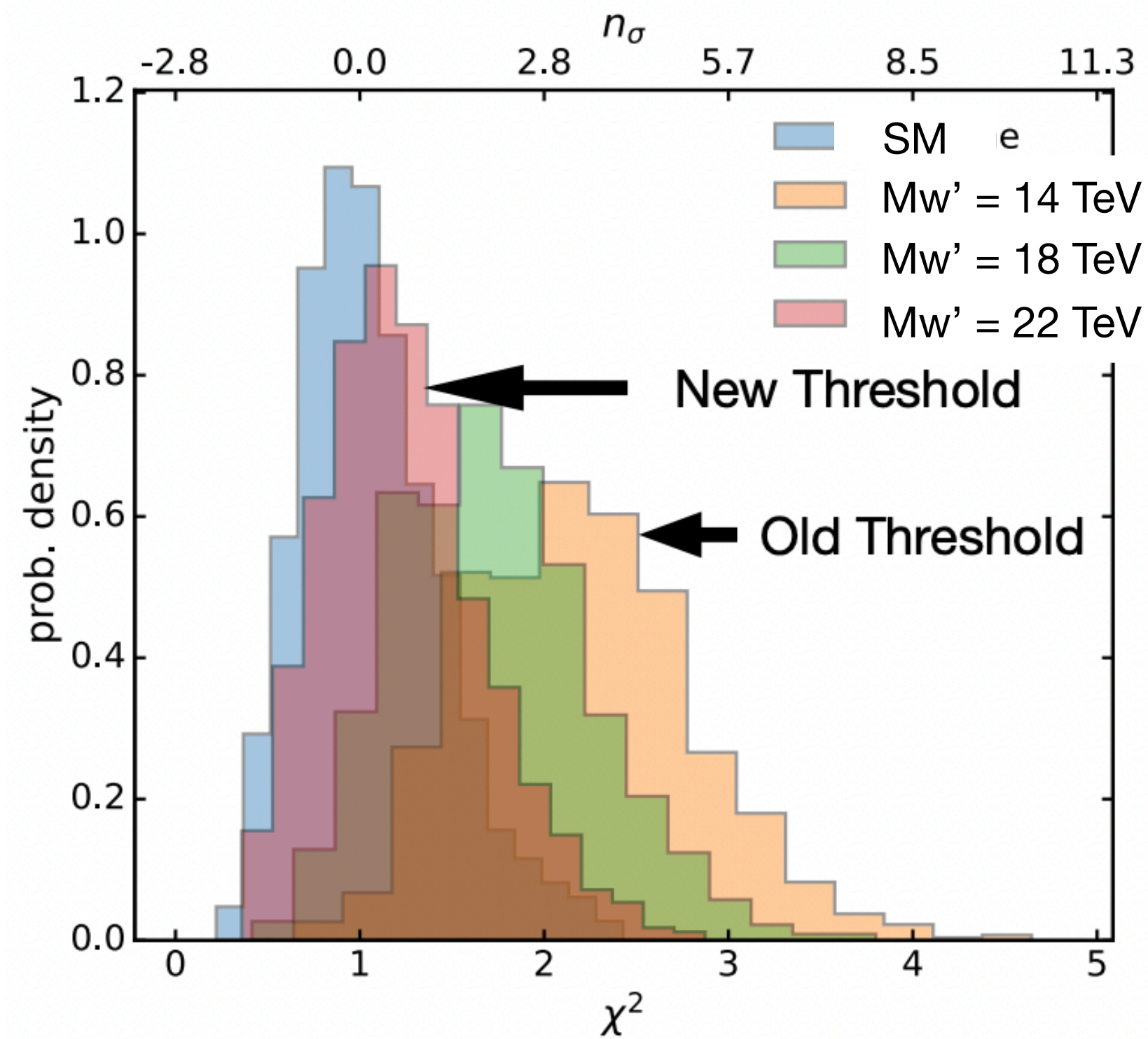


HOW TO AVOID NEW PHYSICS CONTAMINATION?

- LHCb on-shell at 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
- New study: add FPF pseudo-data [Cruz-Martinez et al arXiv:2309.09581] and redo HL-LHC contamination exercise



HL-LHC HM DY 14 TeV - charged current - electron channel

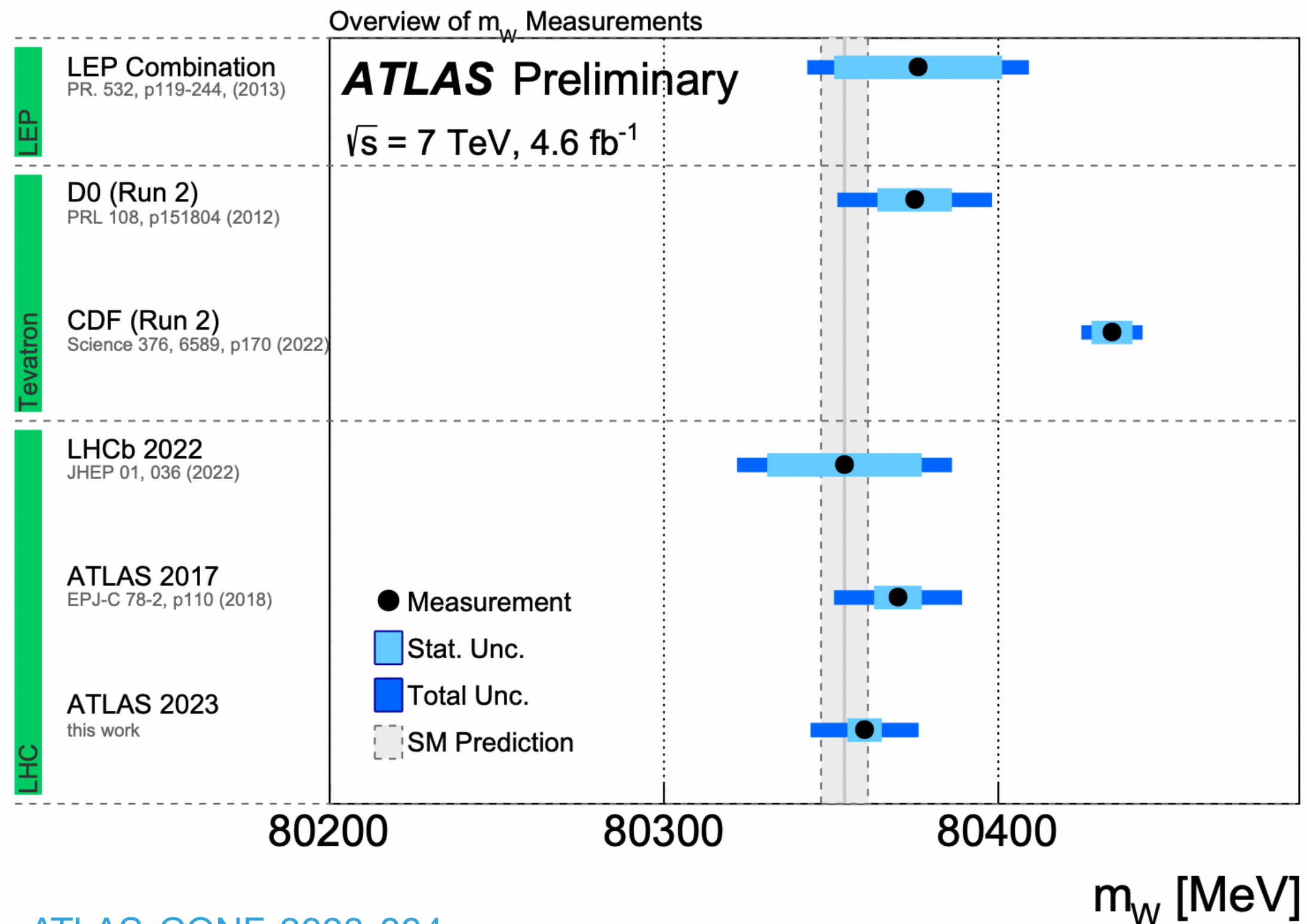


14 TeV \rightarrow 22 TeV

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, MU, in preparation

A NEW TOOL FOR GLOBAL INTERPRETATION OF THE 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

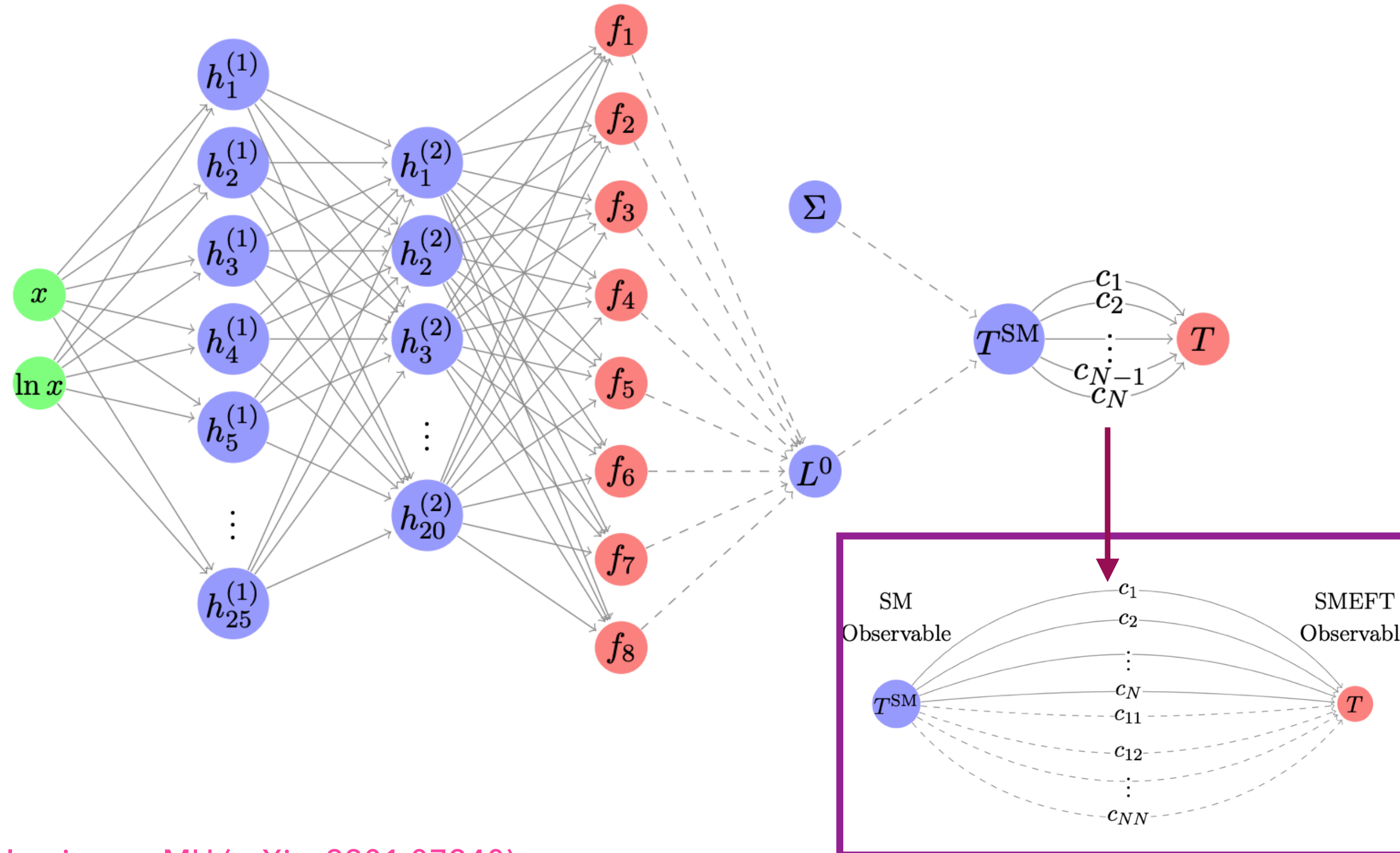
- $\alpha_s(M_Z)$
- M_W
- Parton Distribution Functions
- SMEFT Wilson coefficients
- ...

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.

SIMUNET: A TOOL FOR SIMULTANEOUS FITS

- How to perform simultaneous fits of PDFs and SM/BSM parameters?
- SimuNET 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! Extendable to SM parameters!

Input layer Hidden layer 1 Hidden layer 2 PDF flavours Convolution step SM Observable SMEFT Observable



Linear dim-6 operator

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

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

Quadratic dim-6 operator

$$T(\hat{\theta}) = T^{\text{SM}}(\theta) \cdot \left(1 + \sum_{n=1}^N c_n R_{\text{SMEFT}}^{(n)} + \sum_{1 \leq n \leq m \leq N} c_{nm} R_{\text{SMEFT}}^{(n,m)} \right)$$

$c_n c_m$

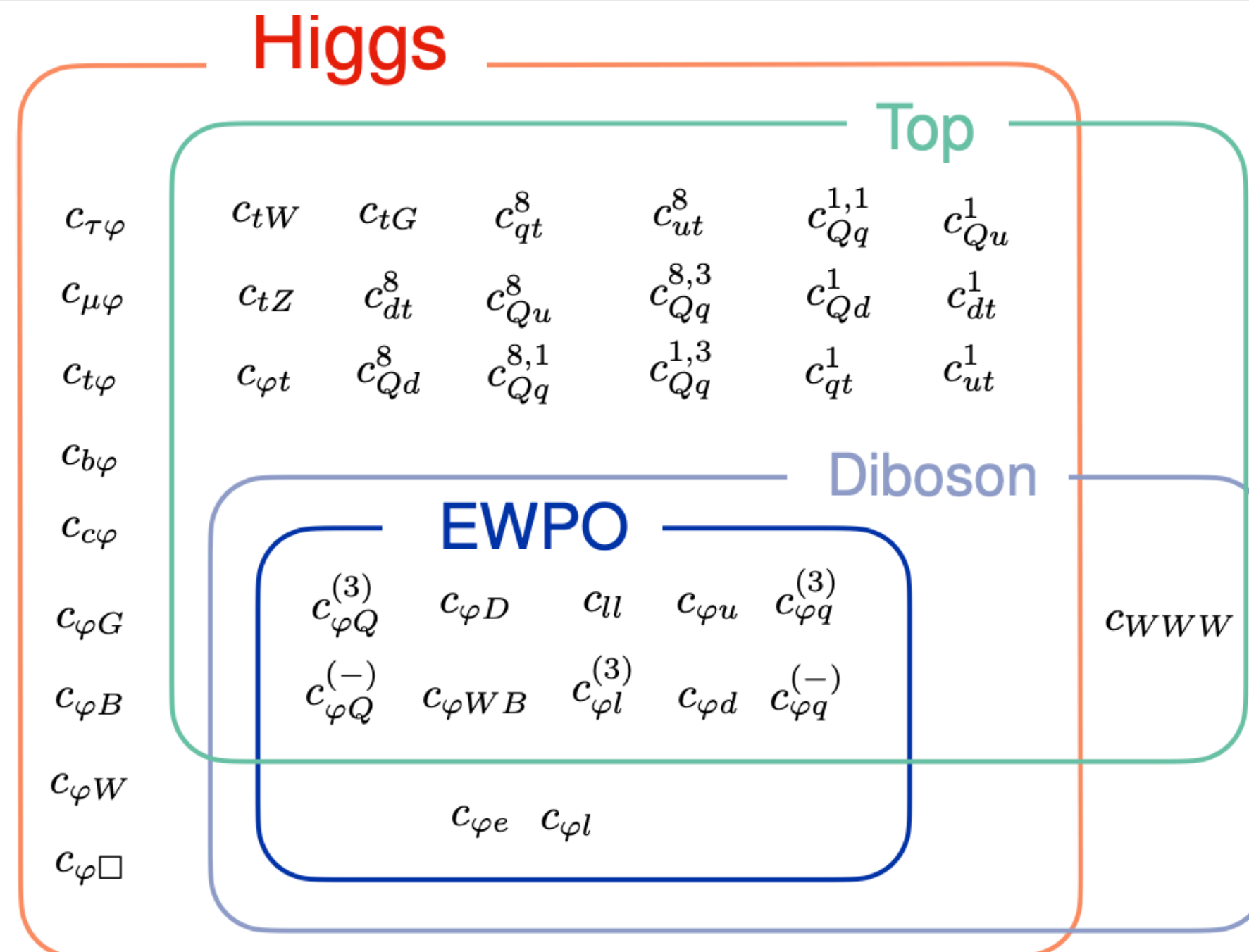
SIMUNET: A TOOL FOR SIMULTANEOUS FITS

SimuNET released open-source with detailed documentation & allow users

<https://github.com/HEP-PBSP/SIMUnet>

- ✓ PDF only fits
- ✓ 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}
```



40 SMEFT operators can be fitted alongside PDFs

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<https://github.com/HEP-PBSP/SIMUnet>

- ✓ PDF only fits
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- {dataset: CMS_SINGLETOPW_8TEV_TOTAL, simu_fac: "EFT_NLO", use_fixed_predictions: True}
```

- ✓ Inject any new physics model in the data and check robustness against PDF absorbing it

```
dataset_inputs :  
- {dataset: LHCb_Z_13TEV_DIELECTRON, frac: 0.75, cfac: ['QCD']}  
- {dataset: CMSDY1D12, frac: 0.75, cfac: ['QCD', 'EWK'], contamination: 'EFT_LO'}
```


SIMUNET: INPUT DATA

Exp.	\sqrt{s} (TeV)	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	8	$\sigma(t\bar{t}Z)$	20.3	1
		$\sigma(t\bar{t}W)$	20.3	1
	13	$\sigma(t\bar{t}Z)$	36.1	1
		$1/\sigma d\sigma(t\bar{t}Z)/dp_T^Z$	139	6
CMS	8	$\sigma(t\bar{t}Z)$	19.5	1
		$\sigma(t\bar{t}W)$	19.5	1
	13	$\sigma(t\bar{t}Z)$	35.9	1
		$1/\sigma d\sigma(t\bar{t}Z)/dp_T(Z)$	77.5	3
ATLAS	8	$\sigma(t\bar{t}\gamma)$	20.2	1
		CMS	8	$\sigma(t\bar{t}\gamma)$

Associate TtV production SMEFT&PDFs

Experiment	\sqrt{s} (TeV)	Channel	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	8	dilepton	A_C	20.3	1
	13	ℓ +jets	A_C	139	5
CMS	8	dilepton	A_C	19.5	3
	13	ℓ +jets	A_C	138	3
ATLAS & CMS combination	8	ℓ +jets	A_C	20	6

Top charge asymmetry SMEFT only

Exp.	\sqrt{s} (TeV)	Channel	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	7	dilepton	$\sigma(t\bar{t})$	4.6	1
			$\sigma(t\bar{t})$	20.3	1
		$1/\sigma d\sigma/dm_{t\bar{t}}$	20.2	5	
		ℓ +jets	$\sigma(t\bar{t})$	20.2	1
			$1/\sigma d\sigma/d y_t $	20.3	4
	$1/\sigma d\sigma/d y_{t\bar{t}} $	20.3	4		
	13	dilepton	$\sigma(t\bar{t})$	36.1	1
		hadronic	$\sigma(t\bar{t})$	36.1	1
		$1/\sigma d^2\sigma/d y_{t\bar{t}} dm_{t\bar{t}}$	36.1	10	
		ℓ +jets	$\sigma(t\bar{t})$	139	1
$1/\sigma d\sigma/dm_{t\bar{t}}$			36	8	
CMS	5	combination	$\sigma(t\bar{t})$	0.027	1
	7	combination	$\sigma(t\bar{t})$	5.0	1
	8	combination	$\sigma(t\bar{t})$	19.7	1
		dilepton	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	19.7	16
		ℓ +jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	19.7	9
	13	dilepton	$\sigma(t\bar{t})$	43	1
		$1/\sigma d\sigma/dm_{t\bar{t}}$	35.9	5	
		ℓ +jets	$\sigma(t\bar{t})$	137	1
			$1/\sigma d\sigma/dm_{t\bar{t}}$	137	14

Tt production SMEFT&PDFs

Experiment	\sqrt{s} (TeV)	Channel	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	8	dilepton	$\sigma_{\text{tot}}(tW)$	20.3	1
		single-lepton	$\sigma_{\text{tot}}(tW)$	20.2	1
	13	dilepton	$\sigma_{\text{tot}}(tW)$	3.2	1
		dilepton	$\sigma_{\text{fid}}(tZj)$	139	1
CMS	8	dilepton	$\sigma_{\text{tot}}(tW)$	12.2	1
	13	dilepton	$\sigma_{\text{tot}}(tW)$	35.9	1
		dilepton	$\sigma_{\text{fid}}(tZj)$	77.4	1
		dilepton	$d\sigma_{\text{fid}}(tZj)/dp_T^t$	138	3
	single-lepton	$\sigma_{\text{tot}}(tW)$	36	1	

Single top + V production SMEFT only

Exp.	\sqrt{s} (TeV)	Channel	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	7	t -channel	$\sigma_{\text{tot}}(t)$	4.59	1
			$\sigma_{\text{tot}}(\bar{t})$	4.59	1
			$1/\sigma d\sigma(tq)/dy_t$	4.59	3
		ℓ +jets	$1/\sigma d\sigma(\bar{t}q)/dy_{\bar{t}}$	4.59	3
			8	t -channel	$\sigma_{\text{tot}}(t)$
	$\sigma_{\text{tot}}(\bar{t})$	20.2	1		
	13	t -channel	$1/\sigma d\sigma(tq)/dy_t$	20.2	3
			$1/\sigma d\sigma(\bar{t}q)/dy_{\bar{t}}$	20.2	3
			s -channel	$\sigma_{\text{tot}}(t + \bar{t})$	20.3
	13	t -channel	$\sigma_{\text{tot}}(t)$	3.2	1
$\sigma_{\text{tot}}(\bar{t})$			3.2	1	
s -channel		$\sigma_{\text{tot}}(t + \bar{t})$	139	1	
CMS	7	t -channel	$\sigma_{\text{tot}}(t) + \sigma_{\text{tot}}(\bar{t})$	1.17, 1.56	1
	8	t -channel	$\sigma_{\text{tot}}(t)$	19.7	1
			$\sigma_{\text{tot}}(\bar{t})$	19.7	1
	s -channel	$\sigma_{\text{tot}}(t + \bar{t})$	19.7	1	
13	t -channel	$\sigma_{\text{tot}}(t)$	2.2	1	
		$\sigma_{\text{tot}}(\bar{t})$	2.2	1	
	ℓ +jets	$1/\sigma d\sigma/d y^{(t)} $	35.9	4	

Single top production SMEFT&PDFs

Experiment	\sqrt{s} (TeV)	Channel	Observable	\mathcal{L} (fb $^{-1}$)	n_{dat}
ATLAS	13	multi-lepton	$\sigma_{\text{tot}}(t\bar{t}\bar{t})$	139	1
		single-lepton	$\sigma_{\text{tot}}(t\bar{t}\bar{t})$	139	1
		ℓ +jets	$\sigma_{\text{tot}}(t\bar{t}\bar{b}\bar{b})$	36.1	1
CMS	13	multi-lepton	$\sigma_{\text{tot}}(t\bar{t}\bar{t})$	137	1
		single-lepton	$\sigma_{\text{tot}}(t\bar{t}\bar{t})$	35.8	1
	all-jet	$\sigma_{\text{tot}}(t\bar{t}\bar{b}\bar{b})$	35.9	1	
	dilepton	$\sigma_{\text{tot}}(t\bar{t}\bar{b}\bar{b})$	35.9	1	
	ℓ +jets	$\sigma_{\text{tot}}(t\bar{t}\bar{b}\bar{b})$	35.9	1	

$TtTt$ and $TtBb$ production SMEFT only

SIMUNET: INPUT DATA

Exp.	\sqrt{s} (TeV)	Observable	\mathcal{L} (fb ⁻¹)	n _{dat}
ATLAS and CMS	7 and 8	$\mu_{H \rightarrow \mu^+ \mu^-}$	5 and 20	22
CMS	13	μ_H	35.9	24
ATLAS	13	μ_H	80	25
ATLAS	13	$\mu_{H \rightarrow Z \gamma}$	139	1
ATLAS	13	$\mu_{H \rightarrow \mu^+ \mu^-}$	139	1

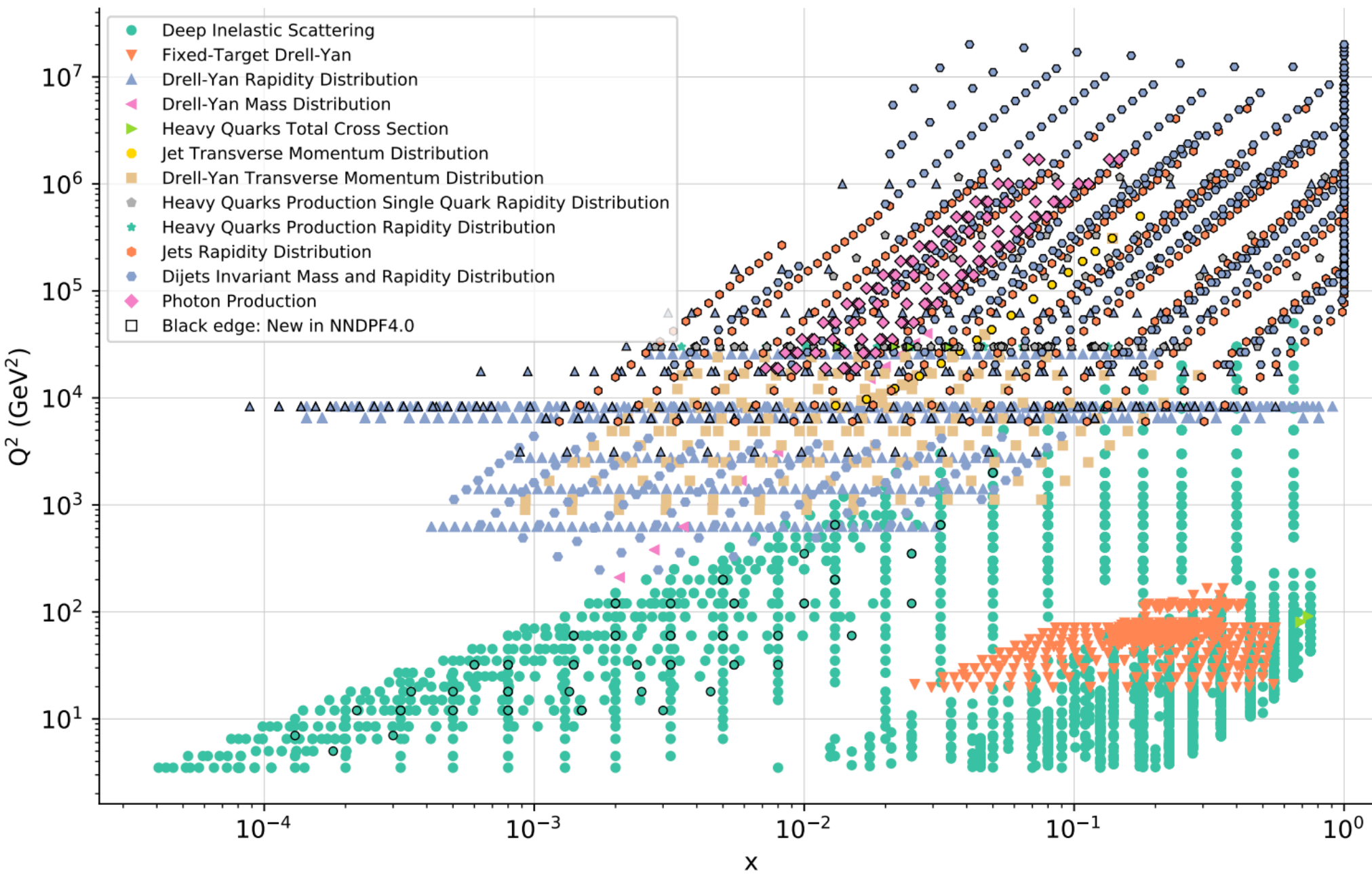
Higgs signal strength SMEFT only

Exp.	\sqrt{s} (TeV)	Observable	\mathcal{L} (fb ⁻¹)	n _{dat}
LEP	0.182	$d\sigma_{WW}/d\cos(\theta_W)$	0.164	10
LEP	0.189	$d\sigma_{WW}/d\cos(\theta_W)$	0.588	10
LEP	0.198	$d\sigma_{WW}/d\cos(\theta_W)$	0.605	10
LEP	0.206	$d\sigma_{WW}/d\cos(\theta_W)$	0.631	10
ATLAS	13	$d\sigma_{W+W-}/dm_{e\mu}$	36.1	13
ATLAS	13	$d\sigma_{WZ}/dm_T$	36.1	6
ATLAS	13	$d\sigma(Zjj)/d\Delta\phi_{jj}$	139	12
CMS	13	$d\sigma_{WZ}/dp_T$	35.9	11

Di-boson SMEFT only

Exp.	\sqrt{s} (TeV)	Observable	\mathcal{L} (fb ⁻¹)	n _{dat}
LEP	0.250	Z observables		19
LEP	0.196	$\mathcal{B}(W \rightarrow l^- \bar{\nu}_l)$	3	3
LEP	0.189	$\sigma(e^+e^- \rightarrow e^+e^-)$	3	21
LEP	0.209	$\hat{\alpha}^{(5)}(M_Z)$	3	1

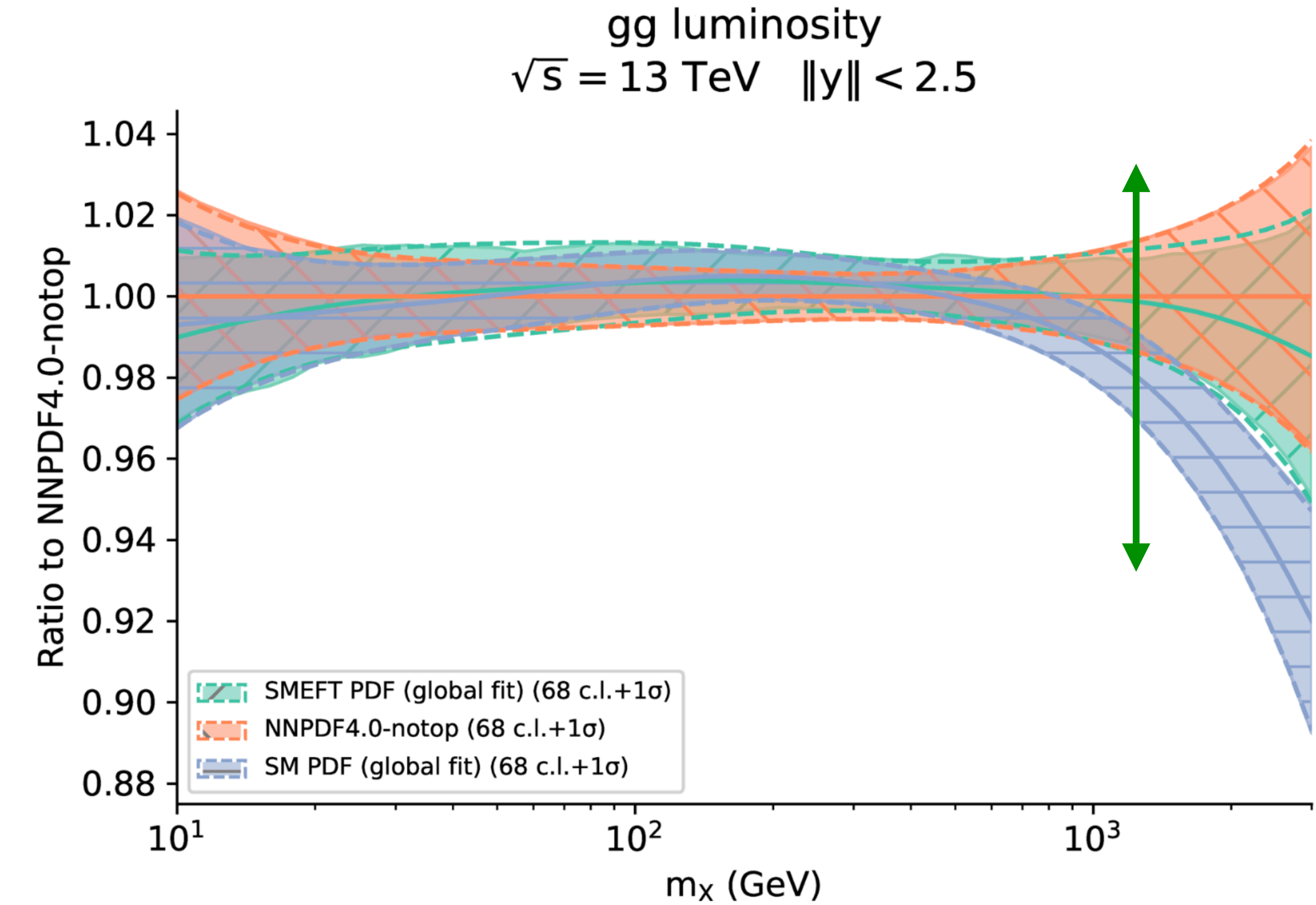
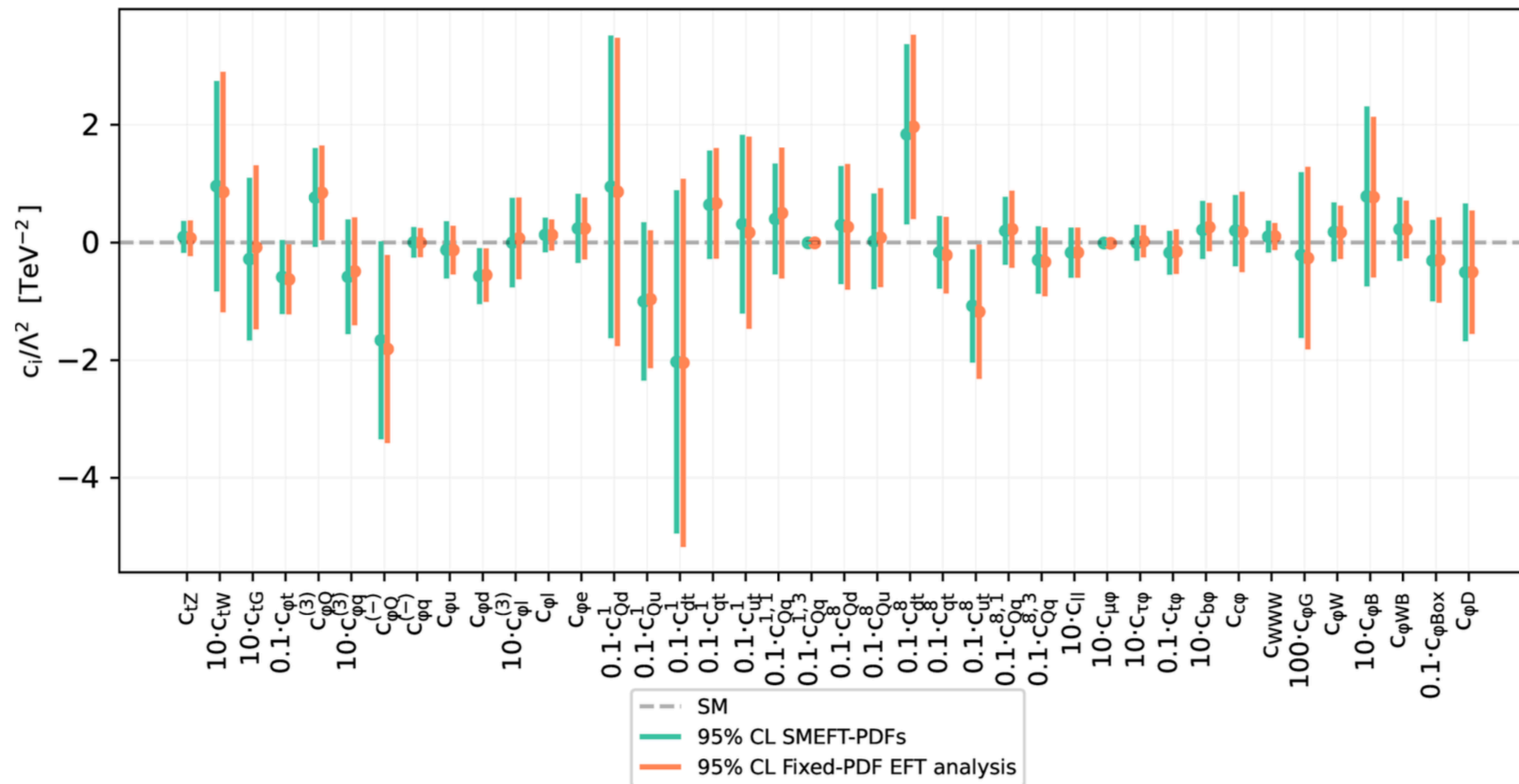
EWPO SMEFT only



Total of ~ 5000 input datapoints, some constraining only SMEFT, some only PDFs, some both SMEFT & PDFs

+O(4000) data from DIS, DY, jets, di-jets, W and Z production, Z pT - PDF only

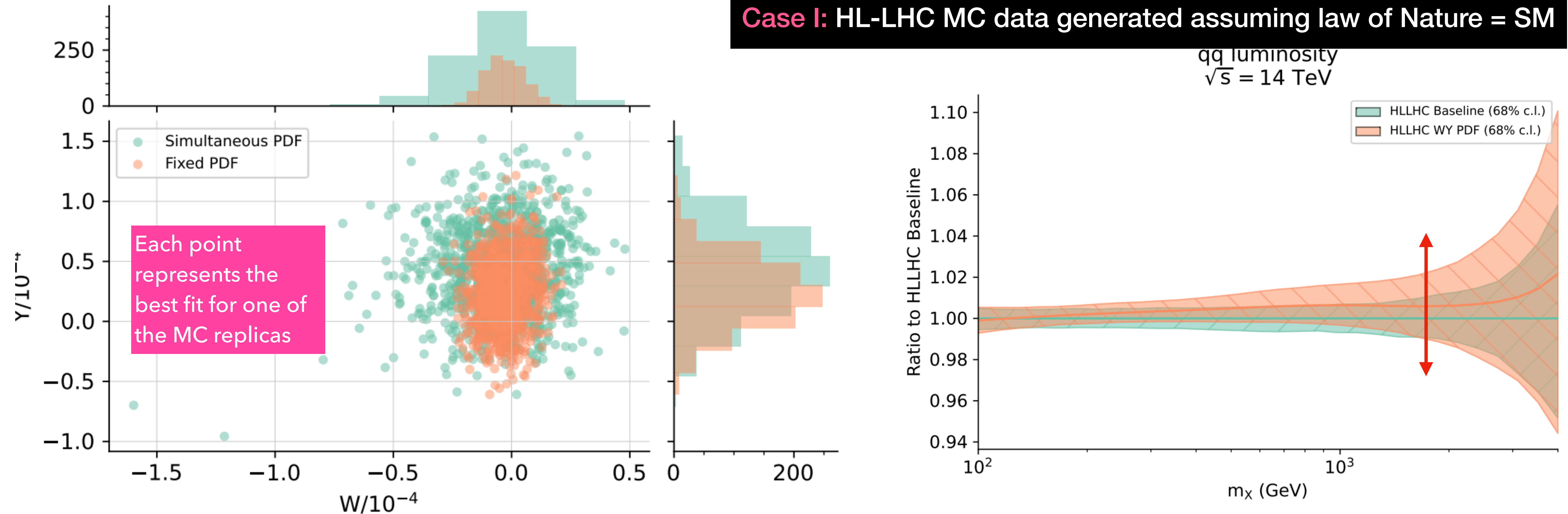
Costantini, Hammou, Madigan, Mantani, Moore, Morales, MU - arXiv: 2402.03308



- ✓ Simultaneous analysis of PDFs and 40 operators in the **top+Higgs+EWPO+di-boson sector** using simuNET method shows that WCs are stable, while PDF uncertainties broaden and PDF fitted simultaneously alongside WCs sits nicely between PDF-only fit without top data and PDF fit including all data - sign of partial NP absorption
- ✓ Explore New Physics model affecting the gluons [Hammou, Merlotti, MU - in progress] [Costantini, Lonigro, Mantani, Nocera, MU - in progress]

S. Iranipour, MU - arXiv: 2201.07240

Case I: HL-LHC MC data generated assuming law of Nature = SM

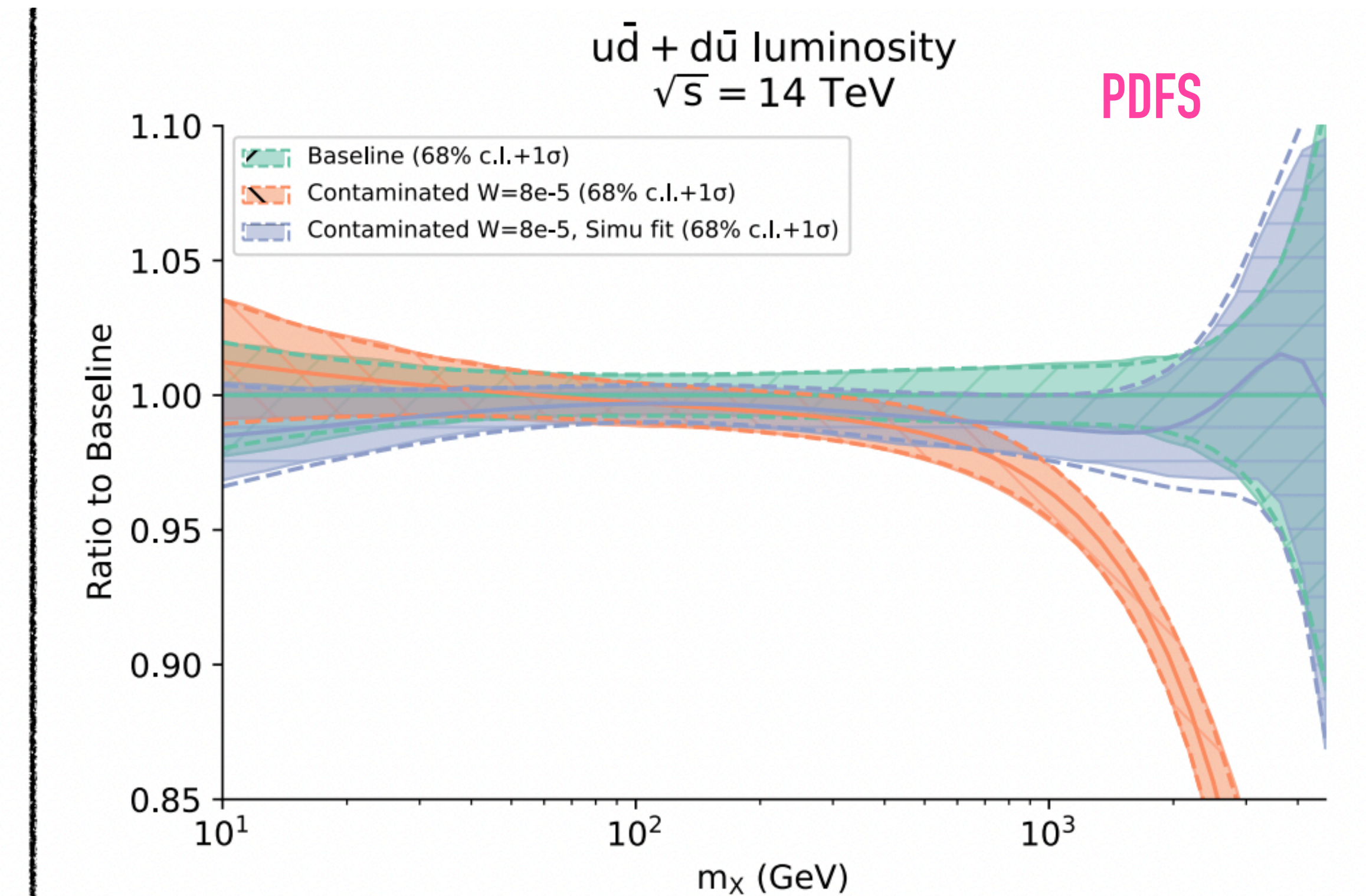
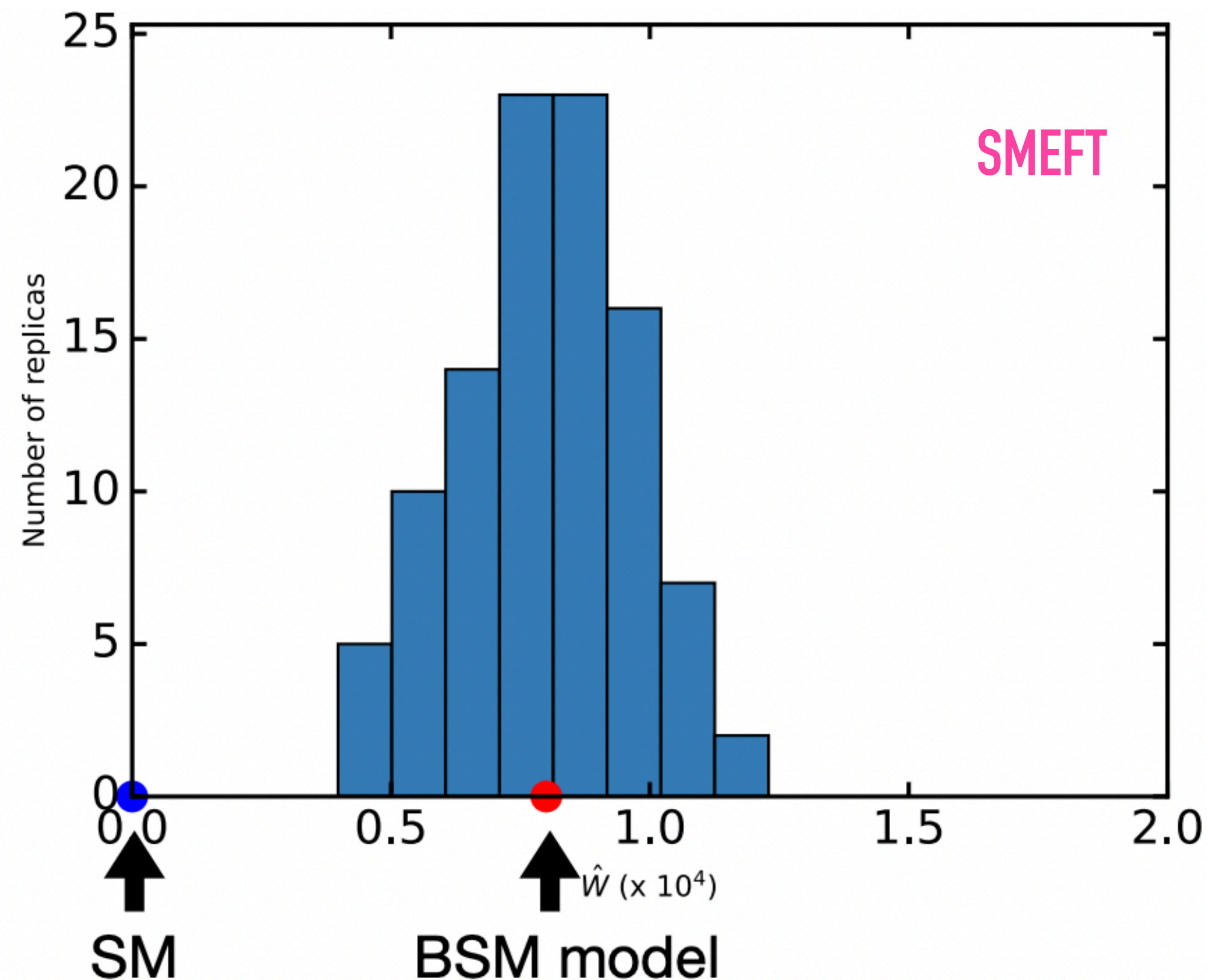


✓ Simultaneous analysis of PDFs and **Drell-Yan sector** Wilson coefficient in the context of universal parameters of DIS + DY (including HL-LHC projections) using simuNET method shows if HL-LHC projections were generated by using a SM model, then WCs bounds broaden and PDF uncertainties change significantly once SMEFT effects allowed in theory predictions entering PDF fit

[Greljo et al 2104.02723] [Iranipour, MU 2201.07240]

Case II: HL-LHC MC data generated assuming law of Nature = W' model

E. Hammou's slides @Moriond 2024



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✓ Simultaneous analysis of PDFs and **Drell-Yan sector** Wilson coefficient in the context of universal parameters of DIS + DY (including HL-LHC projections) using simuNET method shows that if HL-LHC projections were generated by using a W' BSM model, the simultaneous fit would be able to find the "true" SM PDFs and the "true" SMEFT value!

[Costantini et al - inpreparation]

CONCLUSIONS AND OUTLOOK

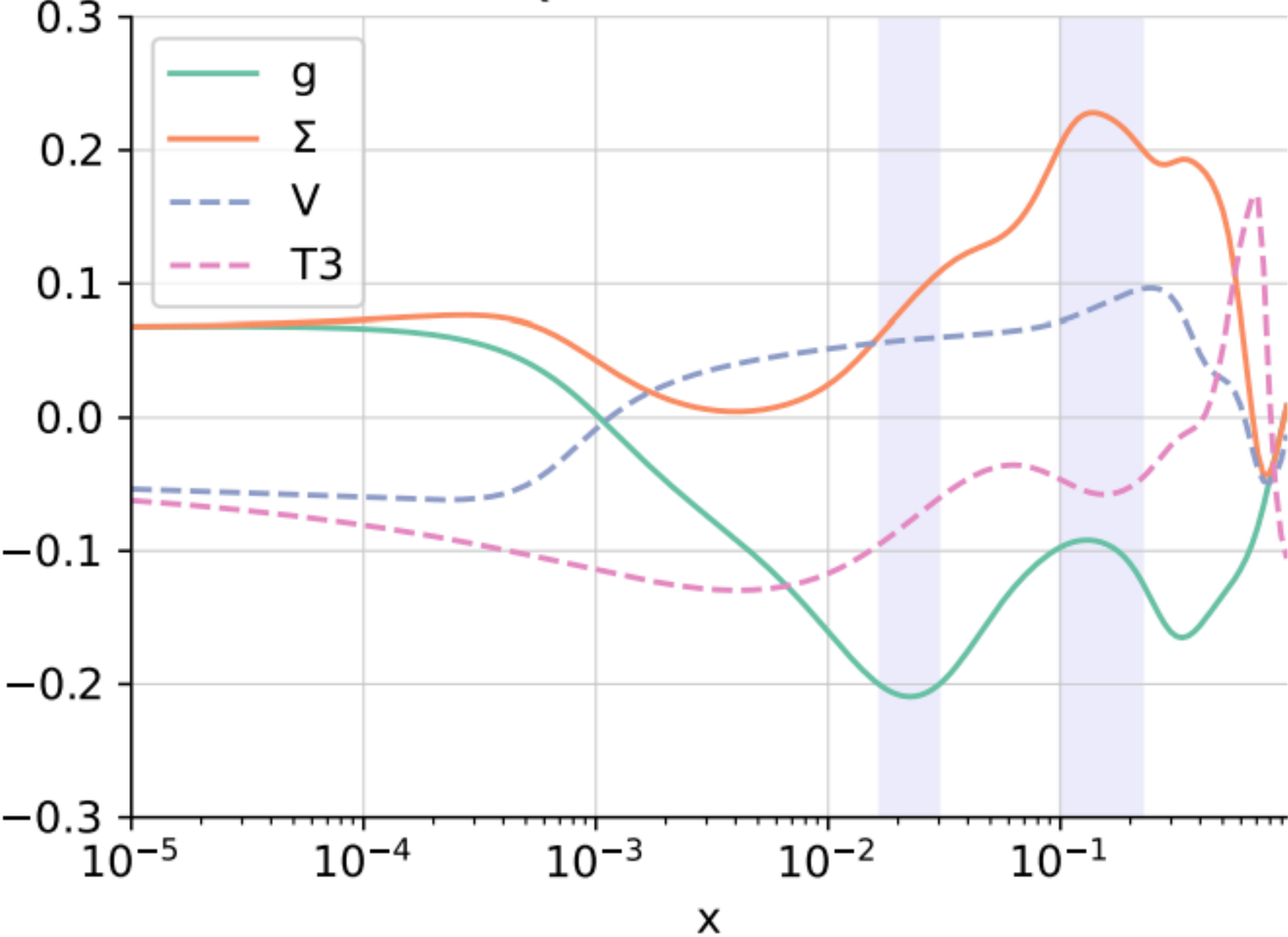
- Interplay between indirect new physics searches via (SM)EFT fits and PDFs is going to be more and more relevant as we move to the High-Luminosity LHC phase
- Can PDF absorb new physics?
 - ➔ Identified a “naive” UV scenario such that the high-mass HL-LHC invariant mass can absorb NP and quantified effects
 - ➔ Important to disentangle large-x from high-energy / low-energy (for example FPF)
 - ➔ More realistic scenarios to explore, especially large-x gluons (jets, top)
- Simultaneous fits
 - ➔ General simuNET methodology for simultaneous fits linear SMEFT + PDFs for an arbitrary number of SMEFT operators has been developed
 - ➔ Open source code <https://github.com/HEP-PBSP/SIMUnet>
 - ➔ Effect of simultaneous fits on PDFs and SMEFT depends on the sector
 - ➔ Quadratic SMEFT corrections: need a new methodology to determine joint probability distribution beyond Monte Carlo sampling (Bayesian PDFs) [Costantini, Madigan, Mantani, Moore arXiv:2404.10056]
 - ➔ Bayesian methodologies can clarify aspects of prior dependence also in SM fits!

THANK YOU FOR YOUR ATTENTION

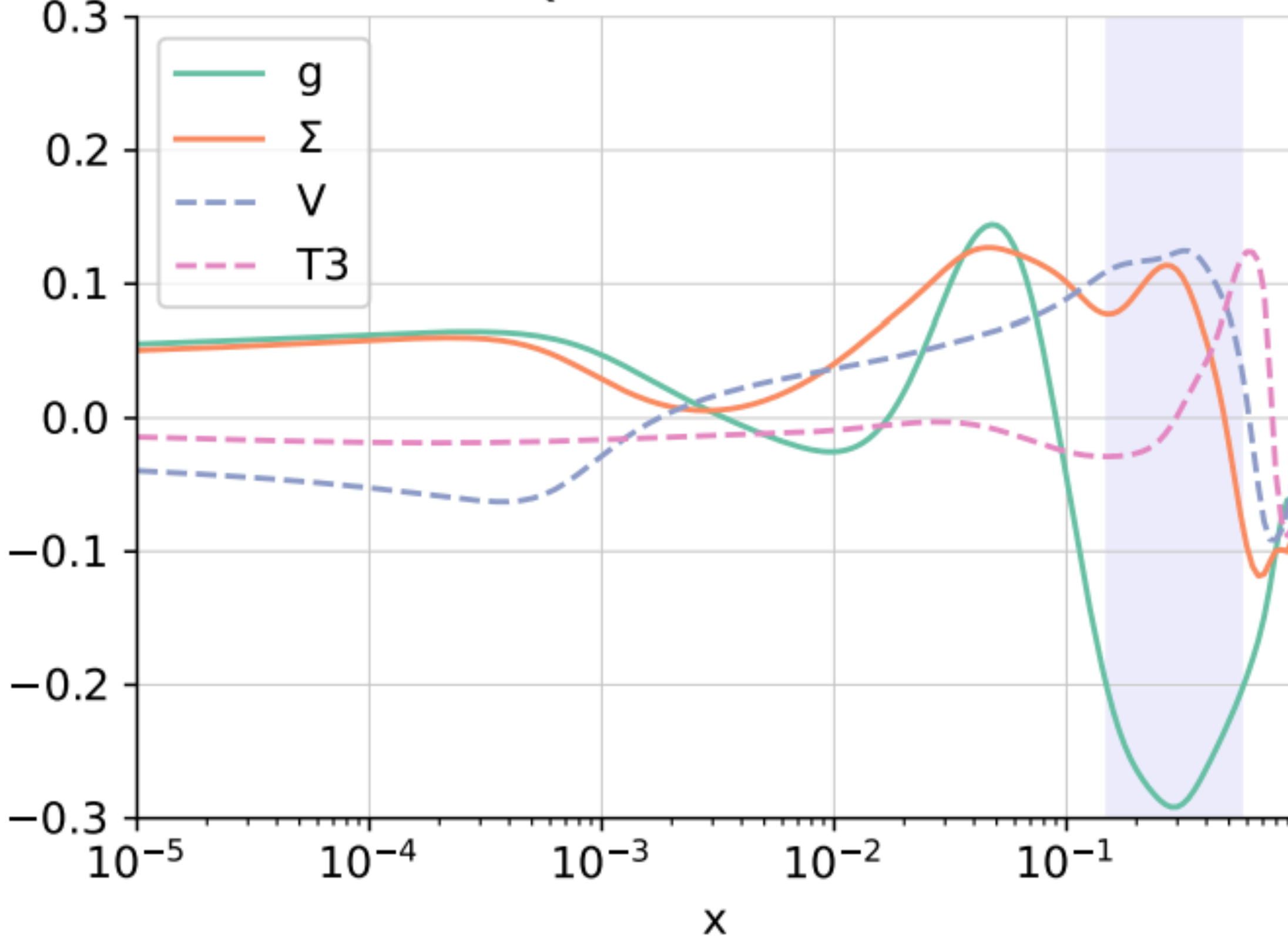
EXTRA MATERIAL

SMEFT AND PDF CORRELATIONS

Correlation c_{tG} - Fixed SM PDFs
 $Q = 172.5 \text{ GeV}$



Correlation c_{ut}^8 - Fixed SM PDFs
 $Q = 172.5 \text{ GeV}$

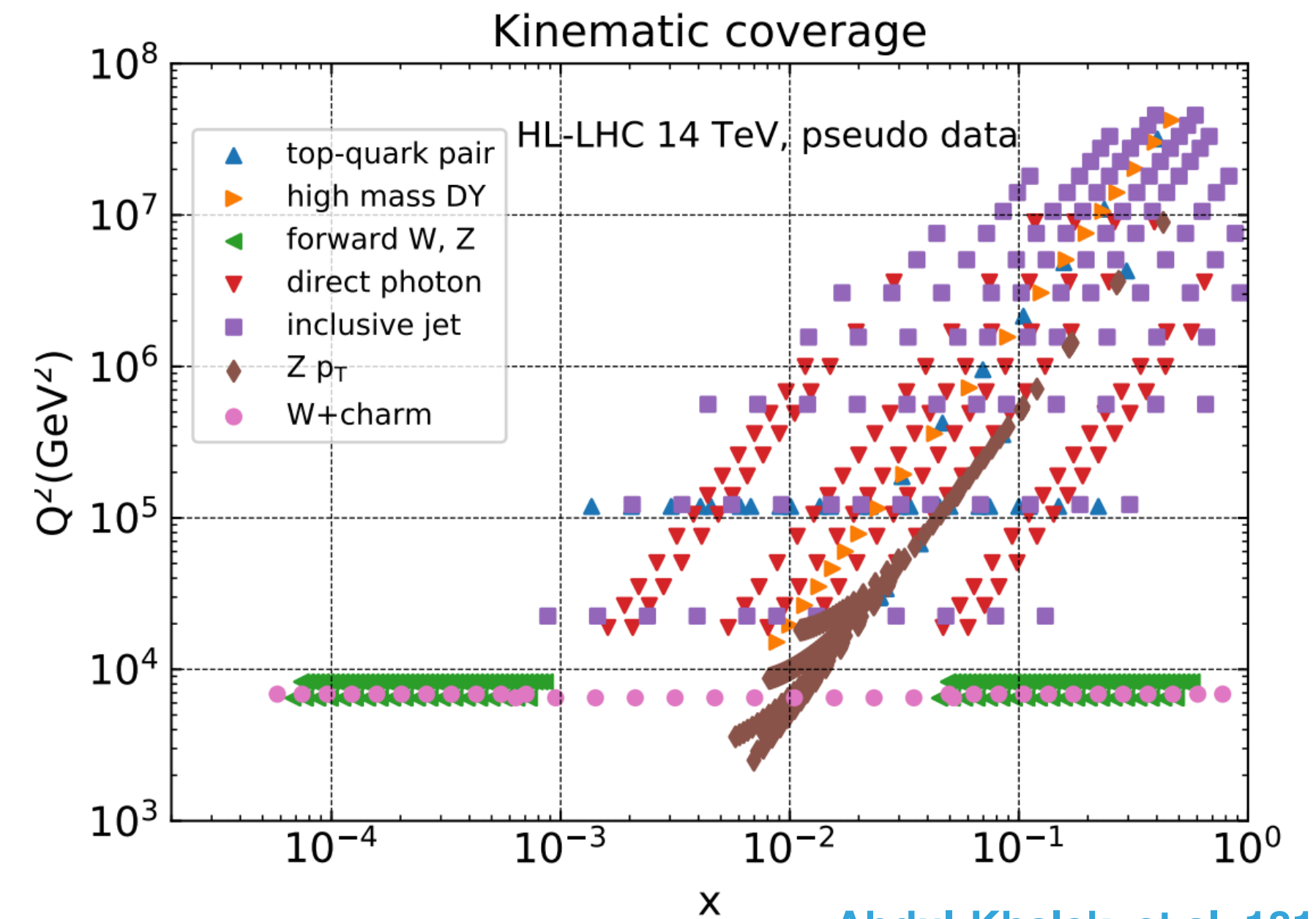


DRELL-YAN DATA PROJECTIONS @HL-LHC

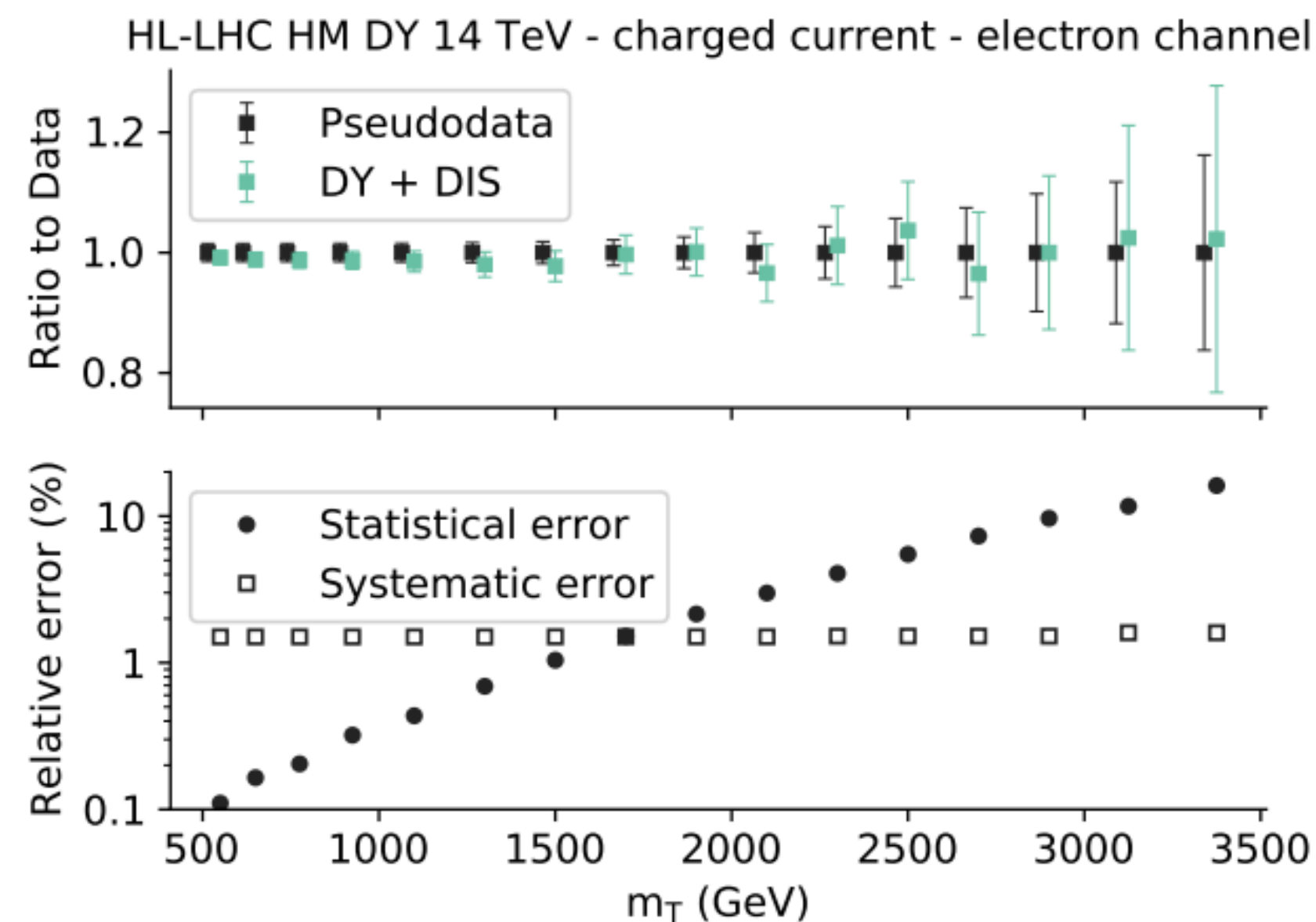
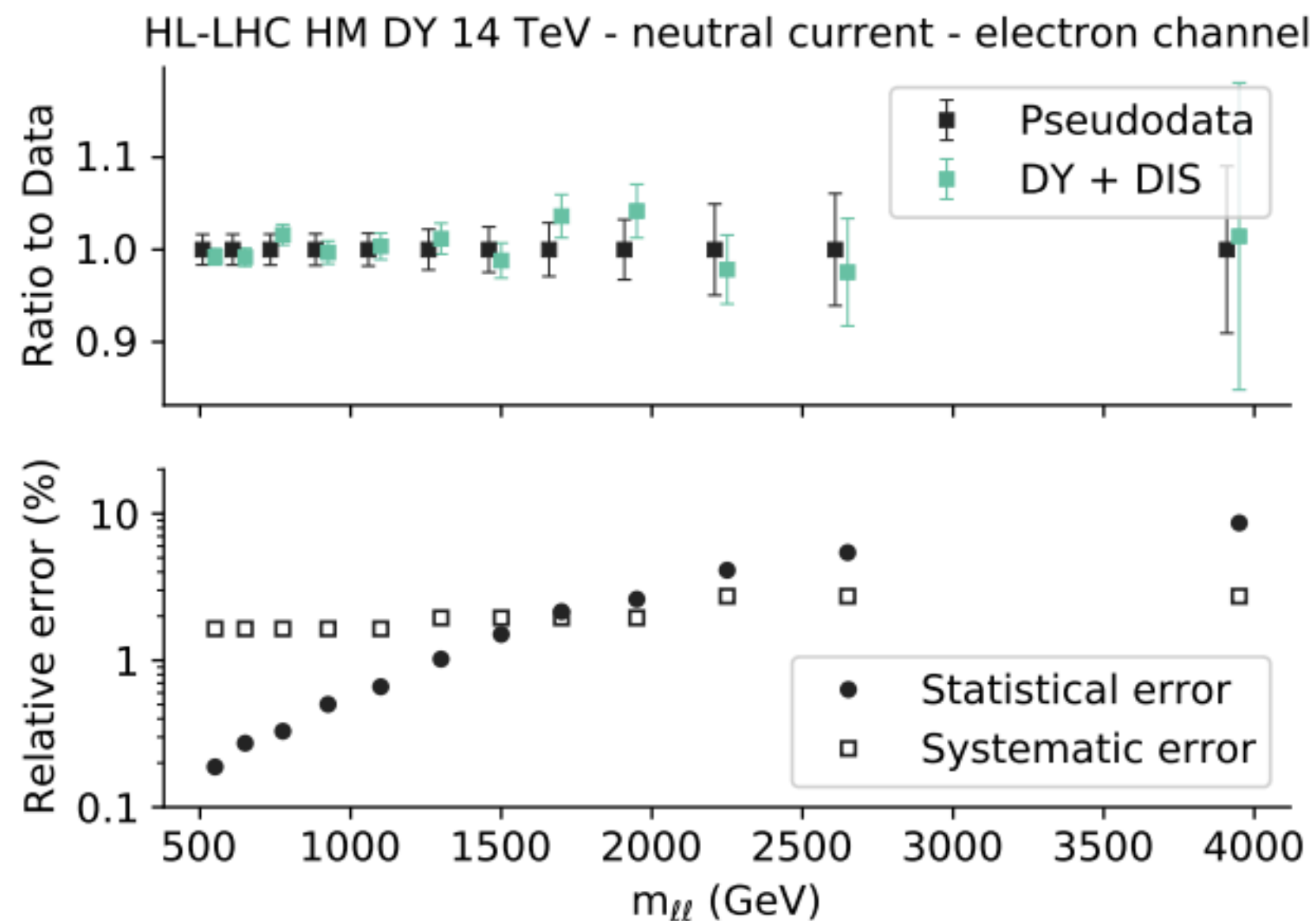
- Add HL-LHC projections for both NC and CC in PDF fit

$$\sigma_i^{\text{hllhc}} \equiv \sigma_i^{\text{th}} \left(1 + \lambda \delta_{\mathcal{L}}^{\text{exp}} + r_i \delta_{\text{tot},i}^{\text{exp}} \right), \quad i = 1, \dots, n_{\text{bin}}$$

$$\delta_{\text{tot},i}^{\text{exp}} = \left((\delta_i^{\text{stat}})^2 + \sum_{j=1}^{n_{\text{sys}}} \left(f_{\text{red},j} \delta_{i,j}^{\text{sys}} \right)^2 \right)^{1/2}$$



Abdul-Khalek et al, 1810.03639

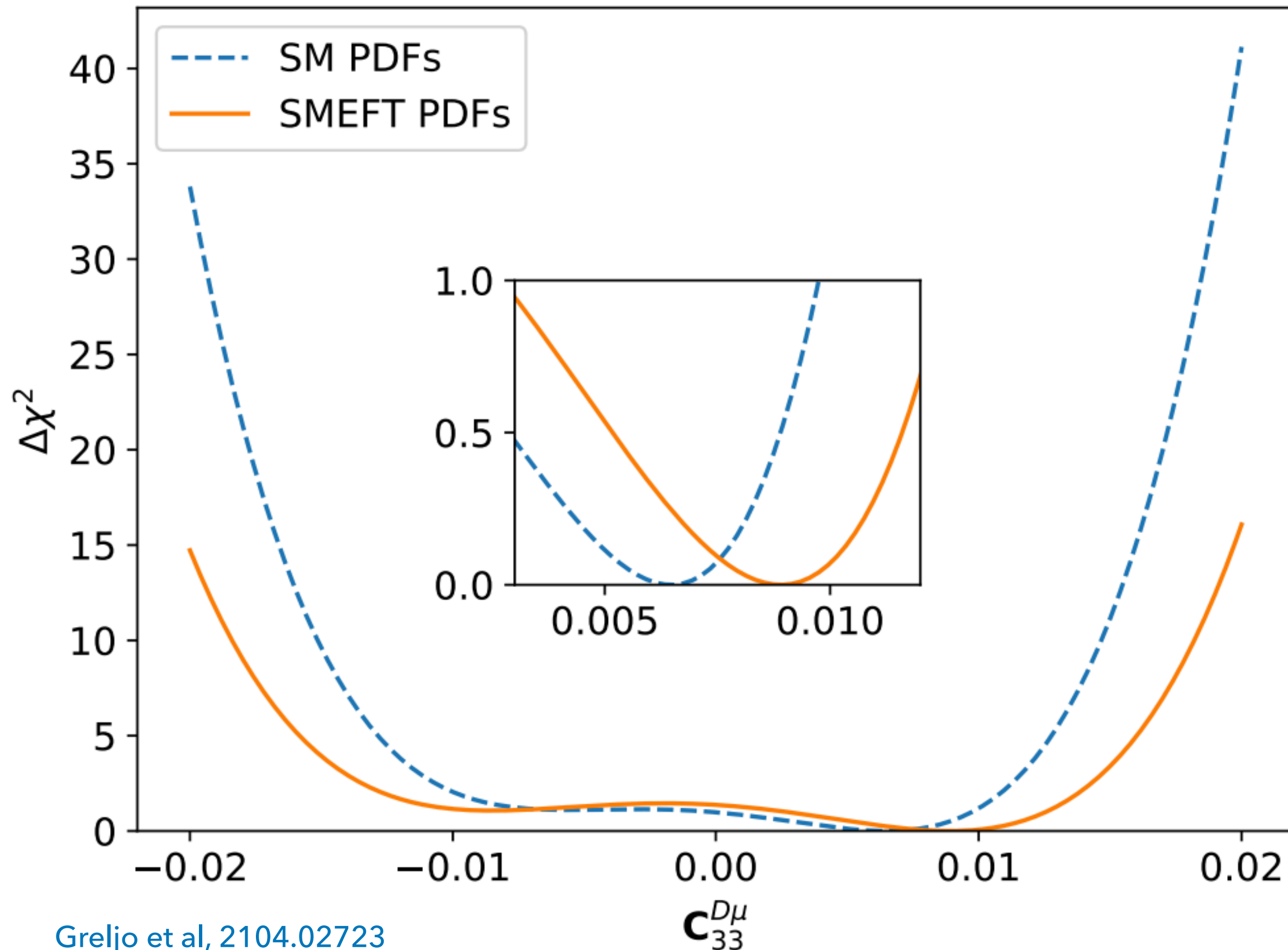


+ muon channel

FLAVOUR-SPECIFIC 4-FERMIONS OPERATORS COUPLING MUONS AND B-QUARKS

- Consider a scenario with a single non-zero WC among gauge invariant four-fermion operators built from the SM quark and lepton $SU(2)_L$ doublets
- If the observed deviations in $R(K^{(*)})$ due to new physics, generically expect $|C_{33}^{D\mu}| \gtrsim 0.001$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C_{33}^{D\mu}}{v^2} (\bar{d}_L^3 \gamma_\mu d_L^3) (\bar{\mu}_L \gamma^\mu \mu_L)$$

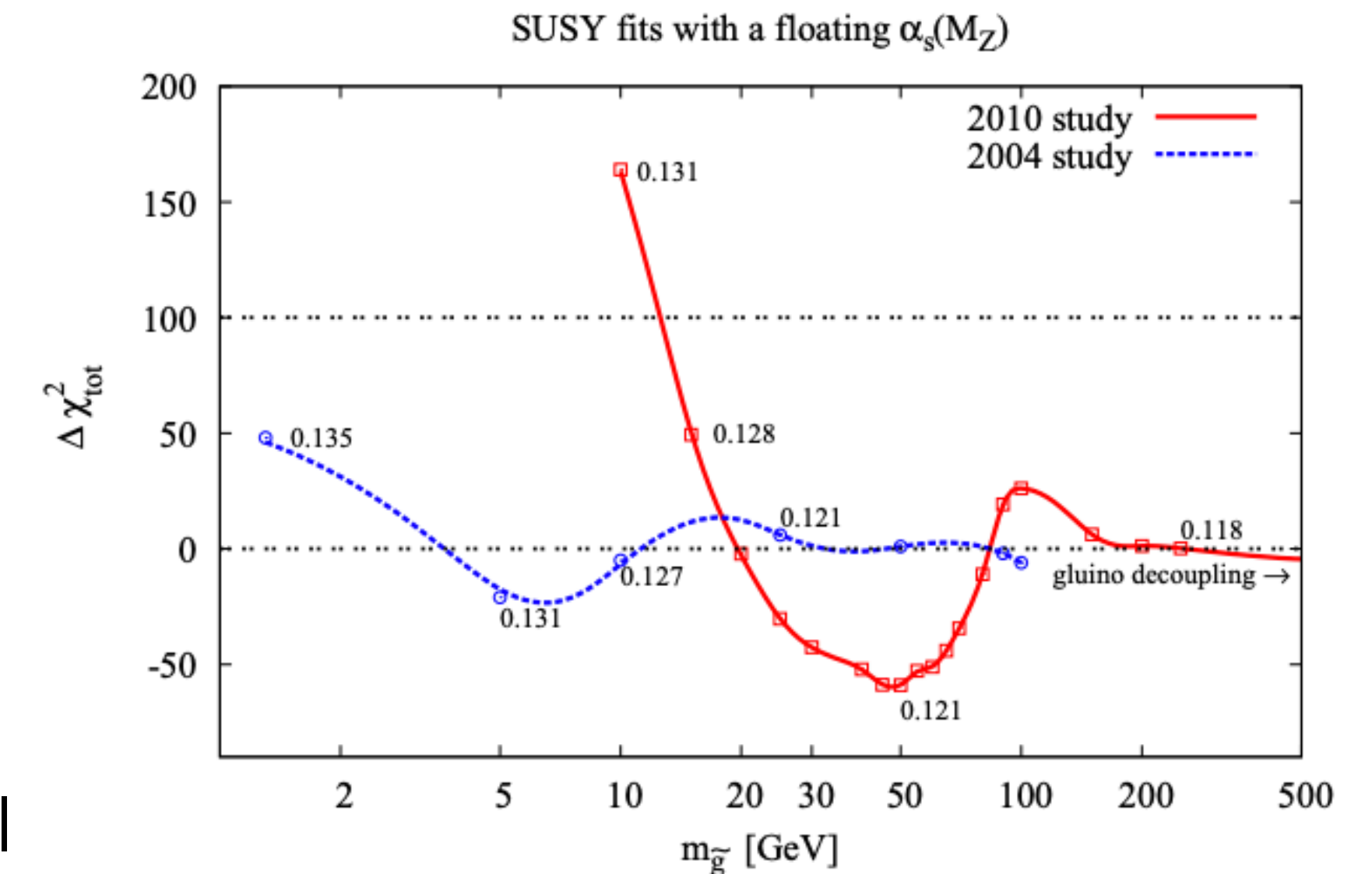
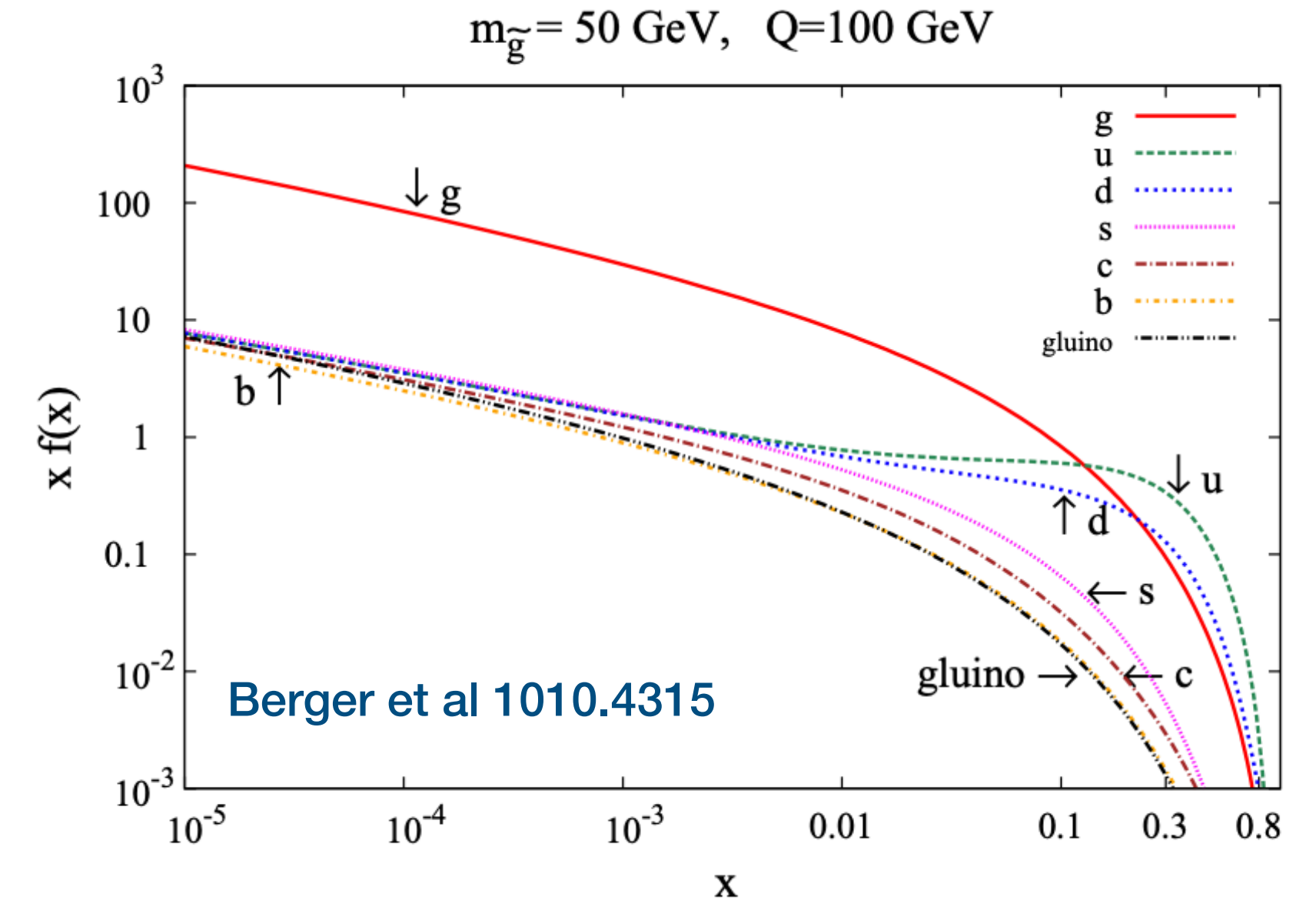
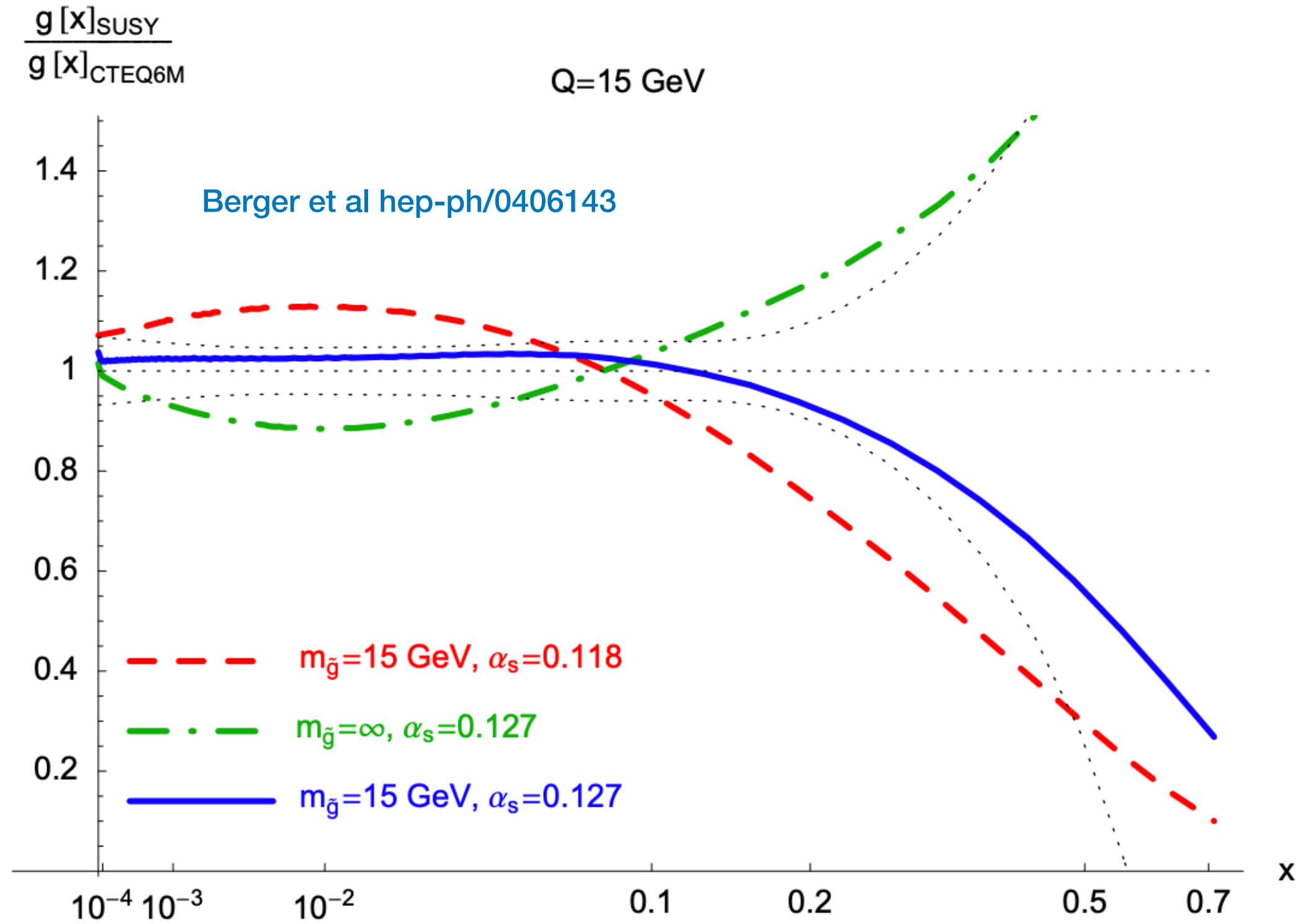


Greljo et al, 2104.02723

	SM PDFs	SMEFT PDFs	best-fit shift	broadening
$C_{33}^{D\mu} \times 10^2$ (68% CL)	[-0.1, 1.1]	[-0.3, 1.2]	0.06	25%
$C_{33}^{D\mu} \times 10^2$ (95% CL)	[-1.0, 1.2]	[-1.2, 1.4]	0.06	18%

- From PDF point of view, new physics only in Drell-Yan muon data and PDF constrained by Drell-Yan electron data
- Measurements in separate leptonic final states is of utmost importance to test BSM scenarios that account for violations of Lepton Flavour Universality.

DISCOVERY THROUGH PRECISION: A DARK PHOTON EXAMPLE



- Pre-LHC studies: what is there was a light SUSY coloured partner?
- A light SUSY Parton would modify DGLAP equation and running of α_s
- Comparison to data excludes any light coloured parton on increasing mass range as more (and more precise) data are included in the global PDF fit

DISCOVERY THROUGH PRECISION: A DARK PHOTON EXAMPLE

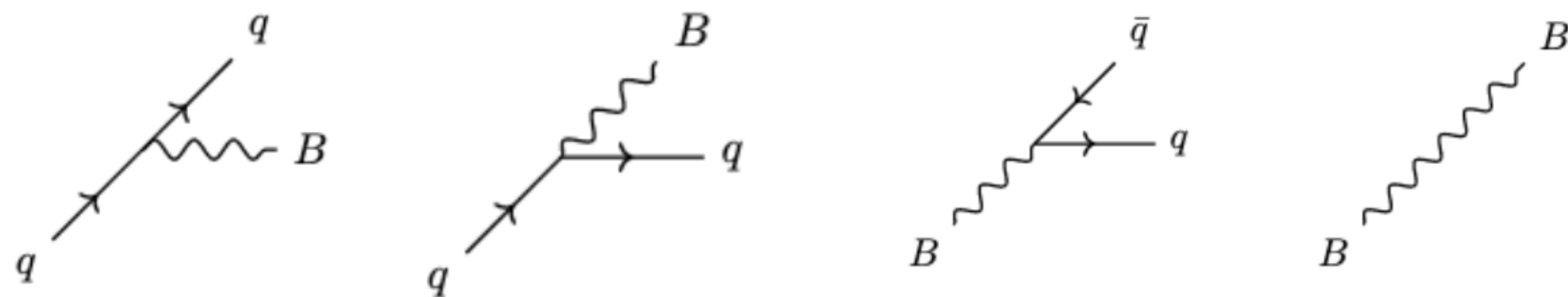
M. McCullough, J. Moore, MU, arXiv:2203.12628

- Idea: now PDFs are known very precisely, and their uncertainties will continue to reduce in the near future with the HL-LHC, could we do the same for a colourless particle too?
- If there was a lepto-phobic dark photon weakly coupled to quarks via effective Lagrangian

$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \not{B} q \quad m_B \in [2, 80] \text{ GeV}$$

it would appear among the partons of the proton.

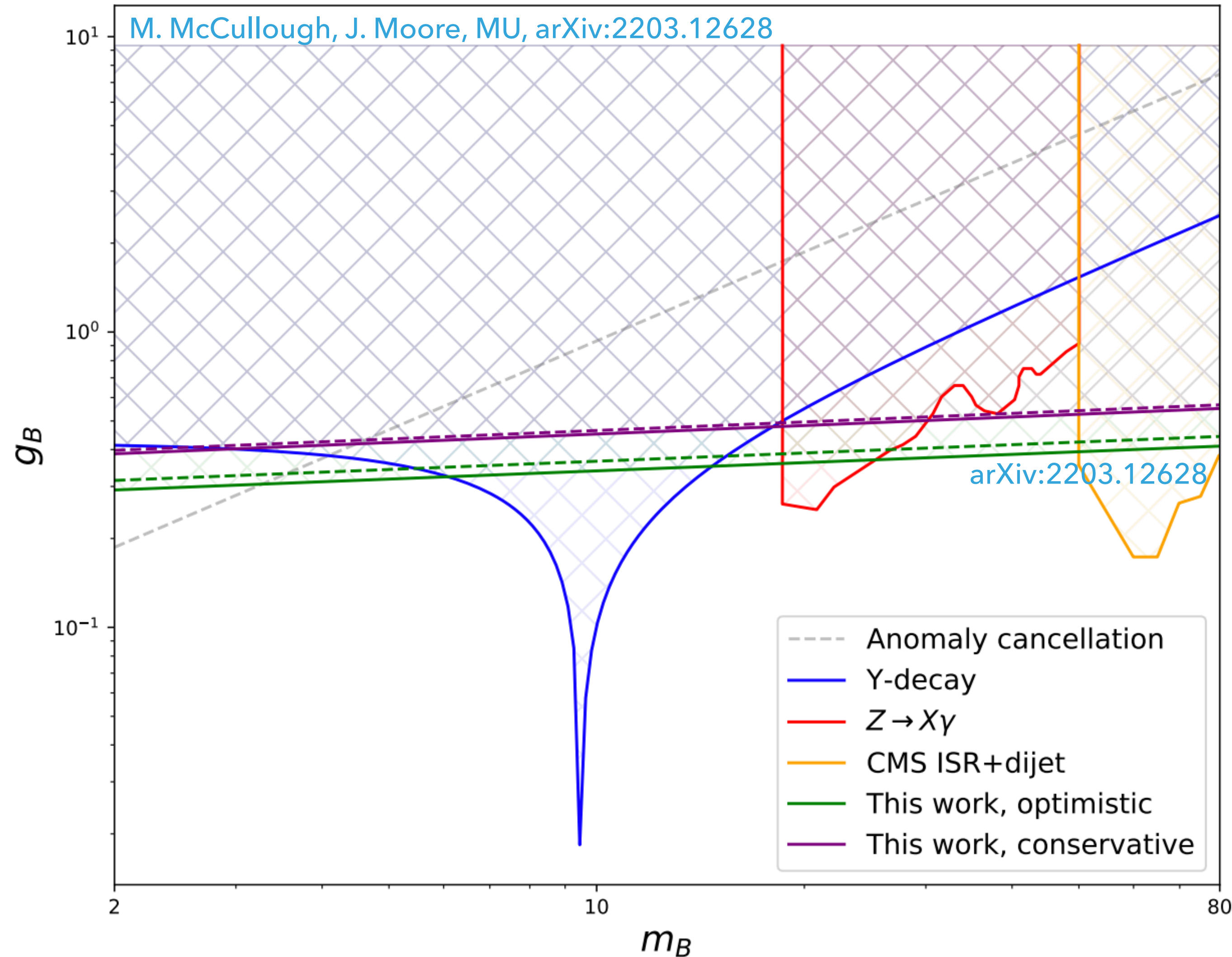
- To include the dark photon as a constituent of the proton: compute the dark photon splitting functions, and add them to DGLAP evolution. Starting from an appropriate initial-scale ansatz (dark photon generated dynamically off quarks and antiquarks at threshold) and a reference PDF set, evolve using the modified DGLAP equations



$$P_{ij} = \left(\frac{\alpha_s}{2\pi} \right) P_{ij}^{(1,0,0)} + \left(\frac{\alpha_s}{2\pi} \right)^2 P_{ij}^{(2,0,0)} + \left(\frac{\alpha_s}{2\pi} \right)^3 P_{ij}^{(3,0,0)} + \left(\frac{\alpha}{2\pi} \right) P_{ij}^{(0,1,0)} + \left(\frac{\alpha_s}{2\pi} \right) \left(\frac{\alpha}{2\pi} \right) P_{ij}^{(1,1,0)} + \left(\frac{\alpha}{2\pi} \right)^2 P_{ij}^{(0,2,0)} + \left(\frac{\alpha_B}{2\pi} \right) P_{ij}^{(0,0,1)} + \dots ,$$

$$\alpha_B \sim 0.001$$

DISCOVERY THROUGH PRECISION: A DARK PHOTON EXAMPLE



- The presence of the dark Parton would modify the evolution of standard quarks and gluon.
- Interesting that dark photon effect in PDFs is dominant but was not taken into account in recent publication about evidence for dark photons in DIS data [N. T. Hunt-Smith et al arXiv:2302.11126]

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