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UNRAVELLING NEW PHYSICS SIGNALS AT THE HL-LHC

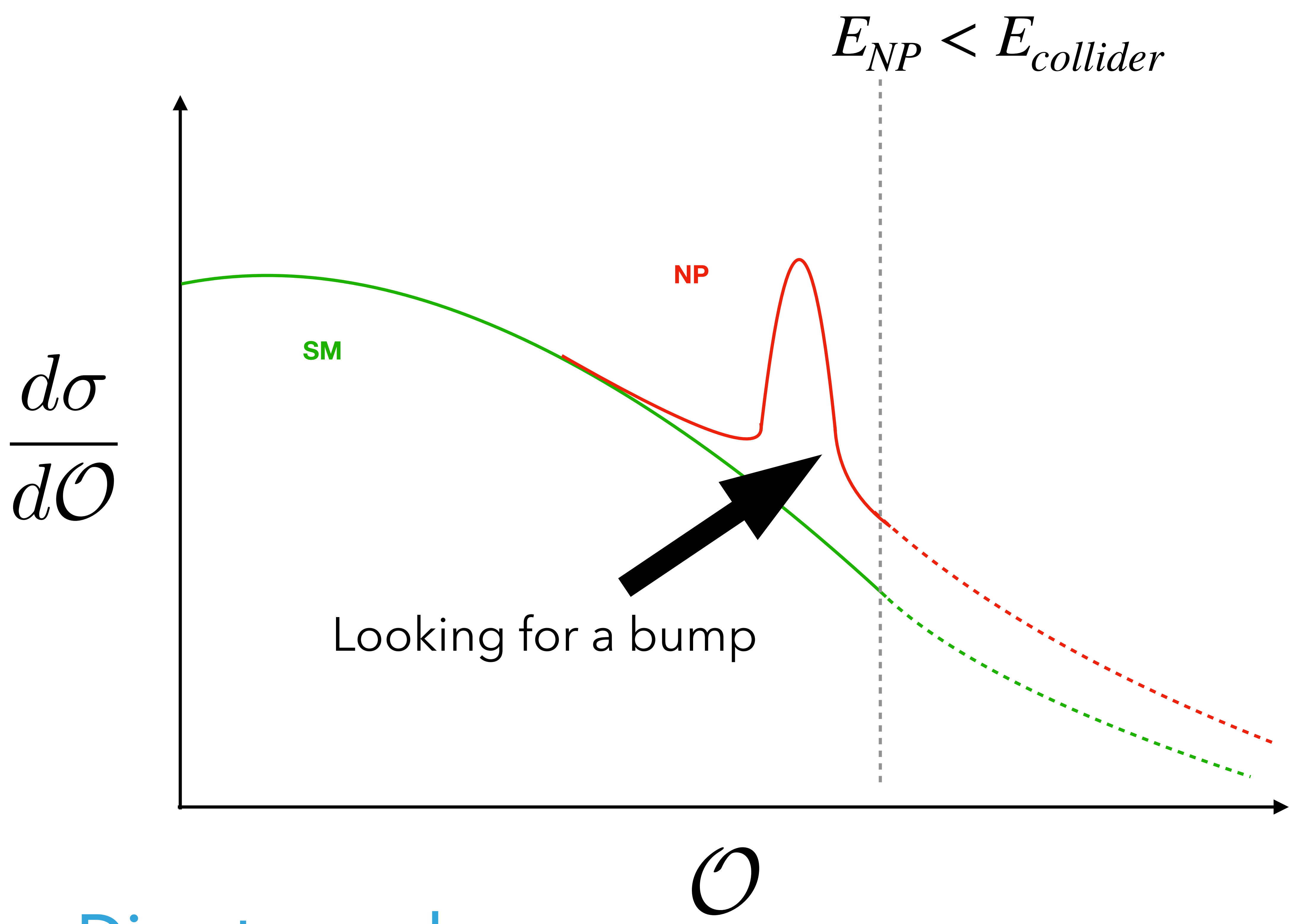
WITH FPF AND EIC CONSTRAINTS

OUTLINE

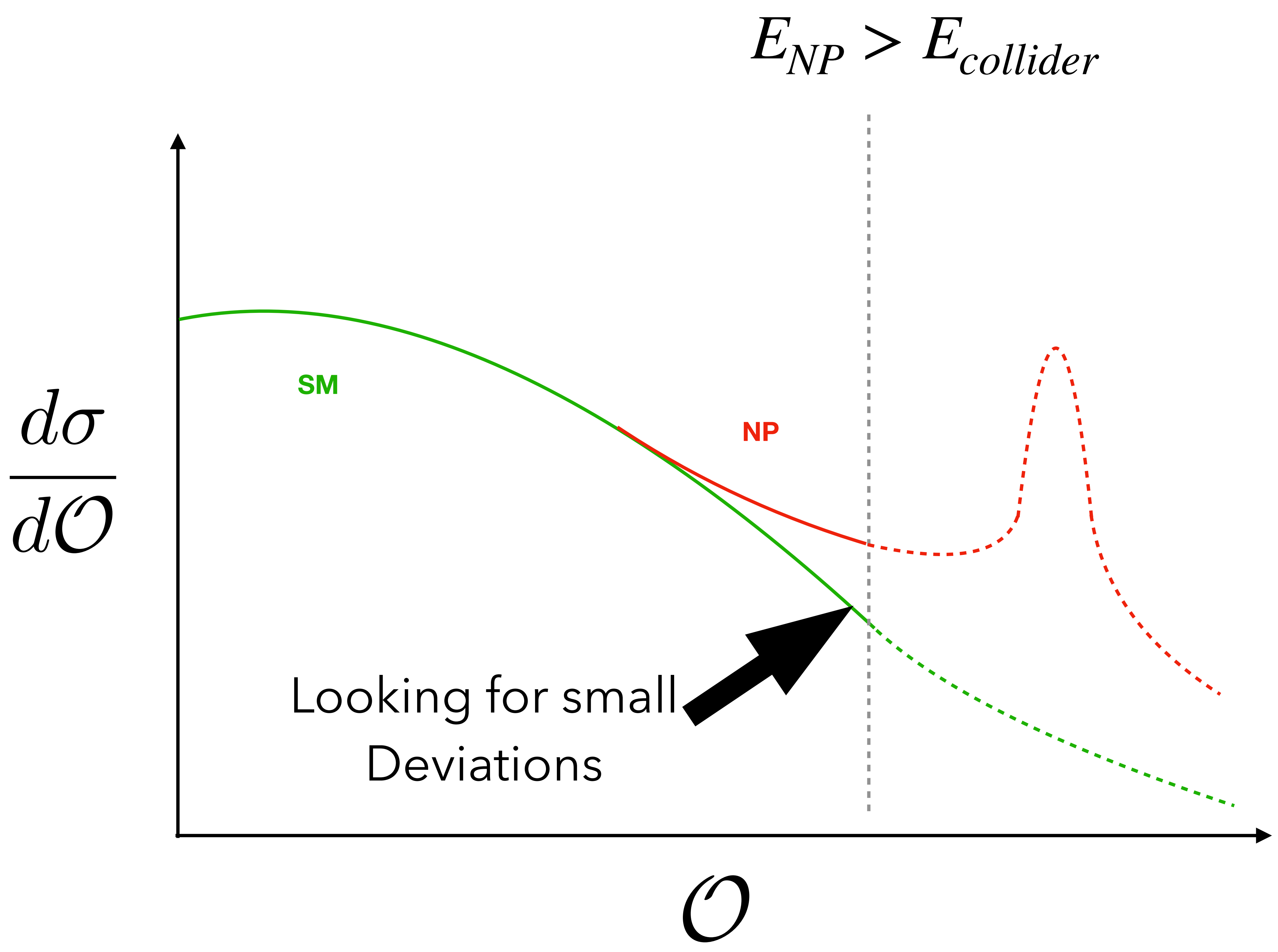
- ➡ BSM searches at the LHC
- ➡ PDFs and BSM interplay
- ➡ Possible BSM bias in PDF fits
- ➡ Complementary PDF constraints from EIC@BNL and FPF@CERN
- ➡ Preventing BSM bias at HL-LHC with EIC and FPF
  (in collaboration with Elie Hammou)

NEW PHYSICS SEARCHES

- PDFs crucial input, not only for precision physics buy also in new physics searches
- **Direct searches:** large background/signal uncertainties due to large-x PDF uncertainties
- **Indirect searches:** PDF uncertainties in the tails of distributions and possible BSM bias in large-x PDFs



Direct searches



Indirect searches

SMEFT: A FRAMEWORK FOR INDIRECT DISCOVERIES

- EFT is a well-defined theoretical approach for indirect searches
- Assuming new physics states heavy, can 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)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

- Full dim-6 basis of operators under SMEFT assumptions includes O(2500) operators [Grzadkowski et al, arXiv: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

EXTRACTING PARAMETERS FROM DATA

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

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

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

SMEFT WCs

Parameters determining PDFs at initial scale

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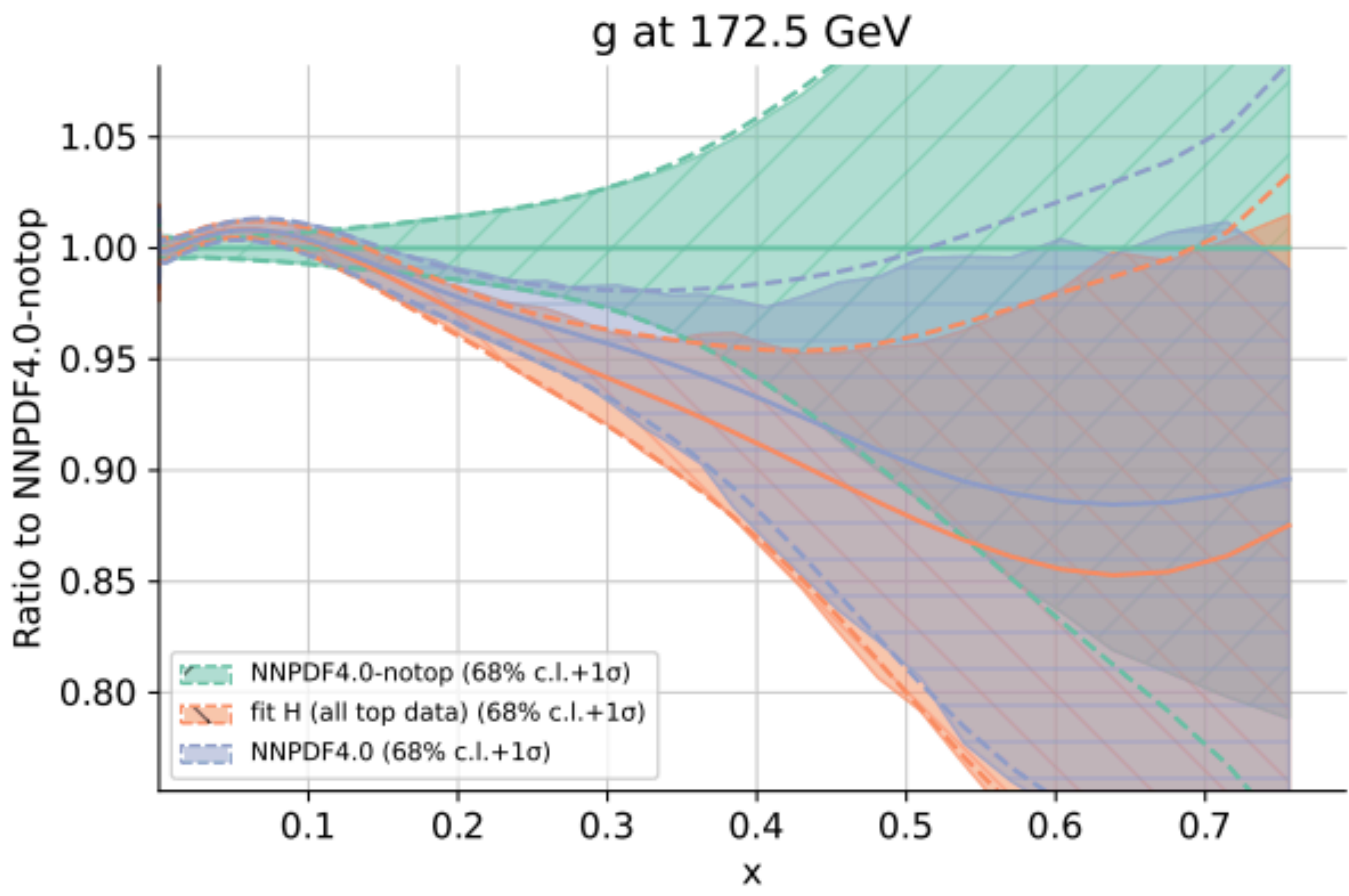
SMEFT WCs

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{c=0\}) \otimes \hat\sigma_i(\{c=0\})$$



Kassabov et al, arXiv:2303.06159

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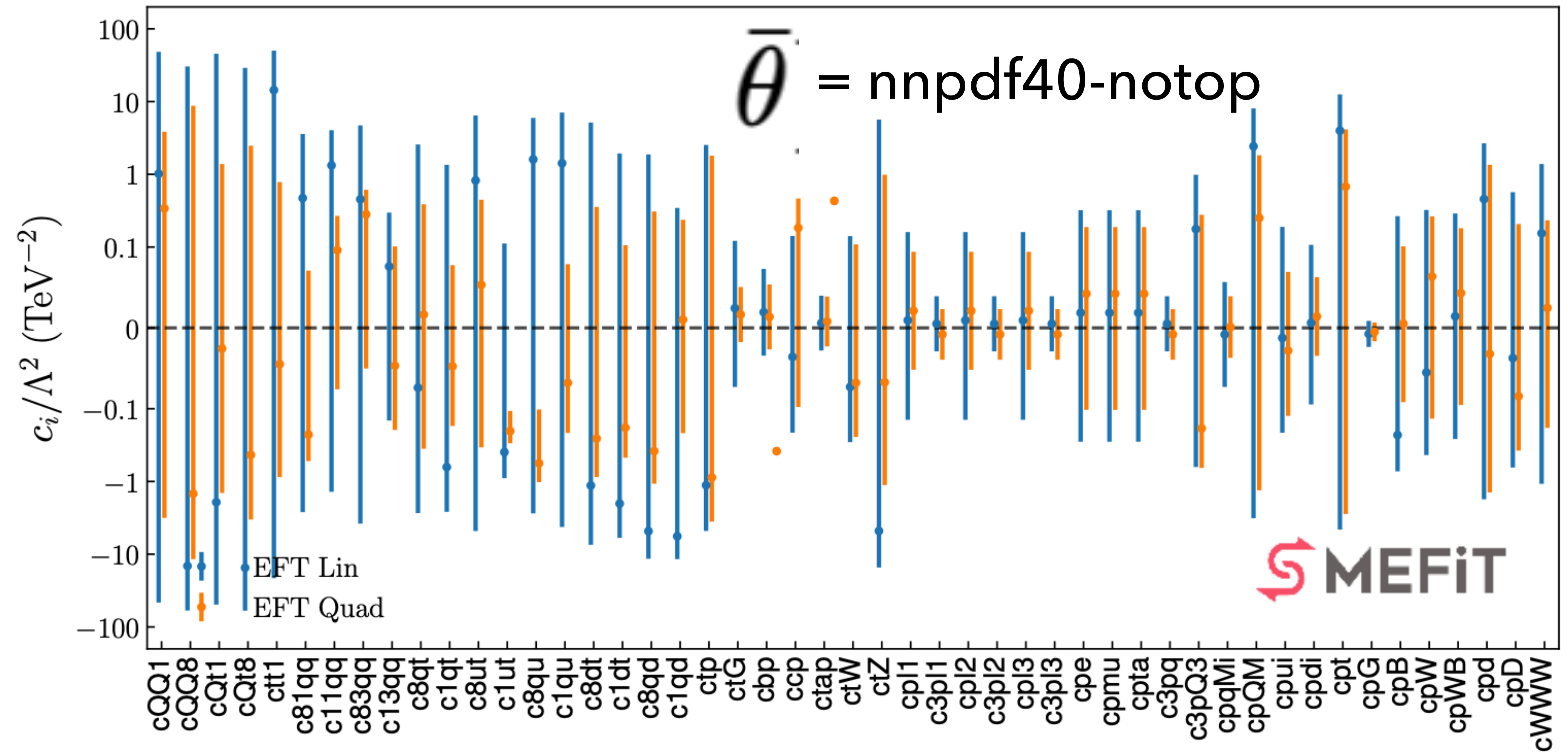
$$T_i(\{\theta\}) = {\rm PDFs}(\{\theta\},\{c=0\}) \otimes \hat{\sigma}_i(\{c=0\})$$

- ✓ In a fit of SMEFT Wilson Coefficients

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



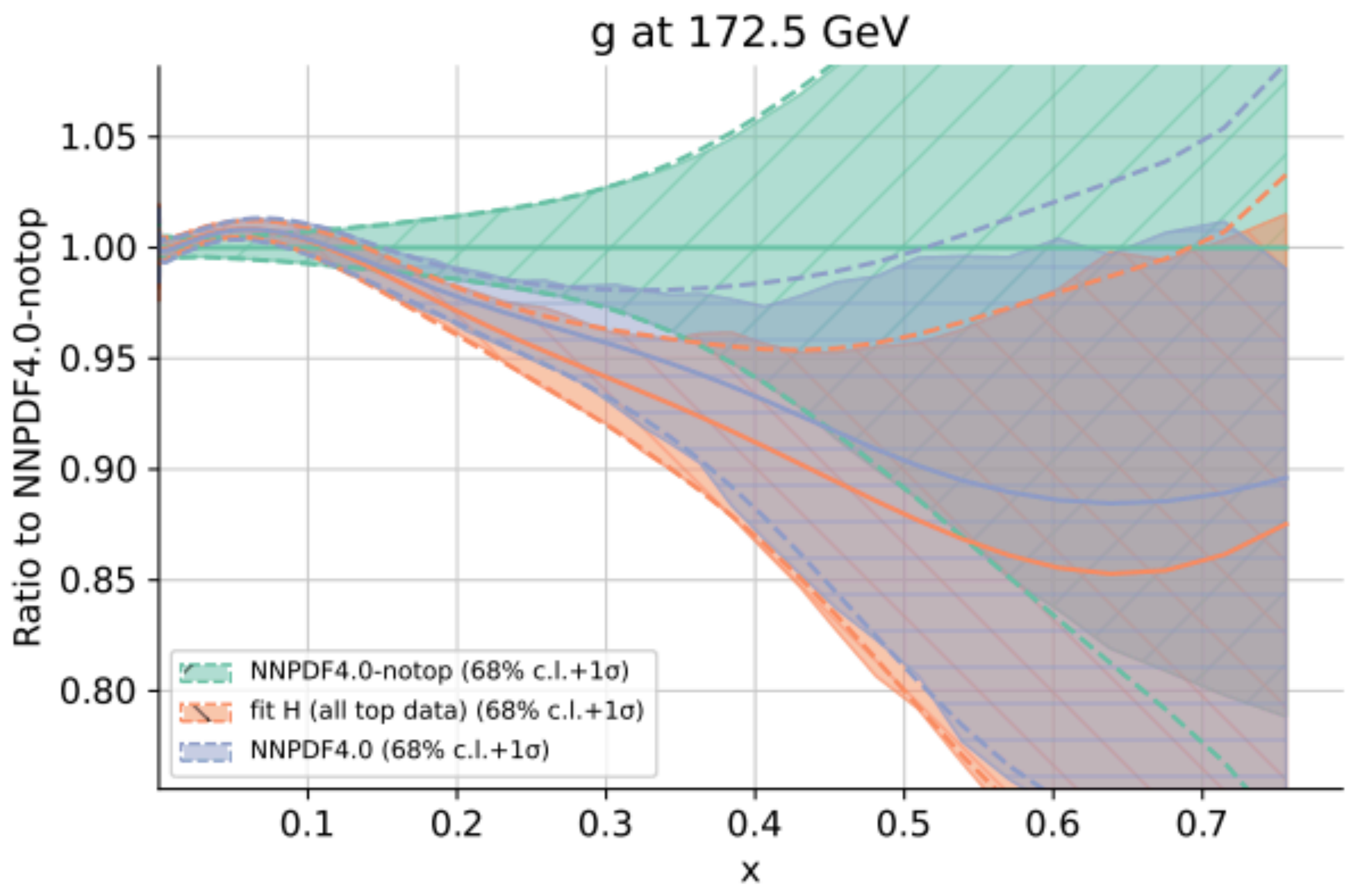
Ethier et al, arXiv: 2105.00006

PDF AND BSM INTERPLAY

- PDFs are low-scale quantities extracted from experimental data **at all scales**, without considering any potential high-energy bias in theory predictions 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** complexity of LHC environment might intertwine them



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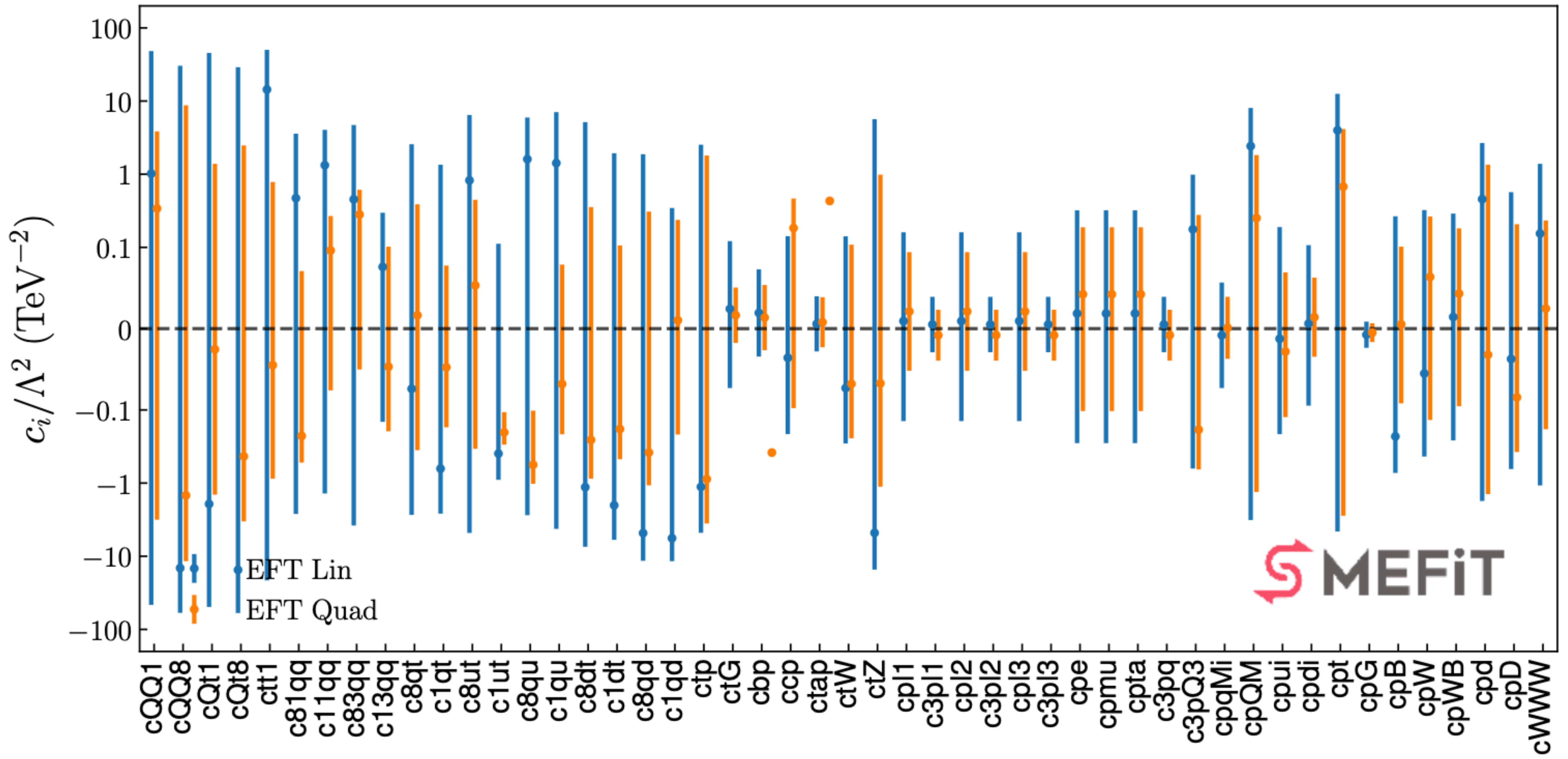

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PDF AND BSM INTERPLAY

➡ From the point of view of PDF fits:

- How to make sure that new physics effects are not inadvertently fitted away in a PDF fit?
- Antiquarks ✓ [PBSP + Mangano: 2307.10370] Gluon ≈ [PBSP + Gomez-Ambrosio, Nocera, in progress]

➡ From the point of view of BSM indirect searches (or specifically in SMEFT fits):

- What PDFs should be used? Are conservative PDFs good enough? What about flavour? ≈ [PBSP, in progress]
- How would the bounds change if PDF fits included the same operators that are fitted in SMEFT fit?

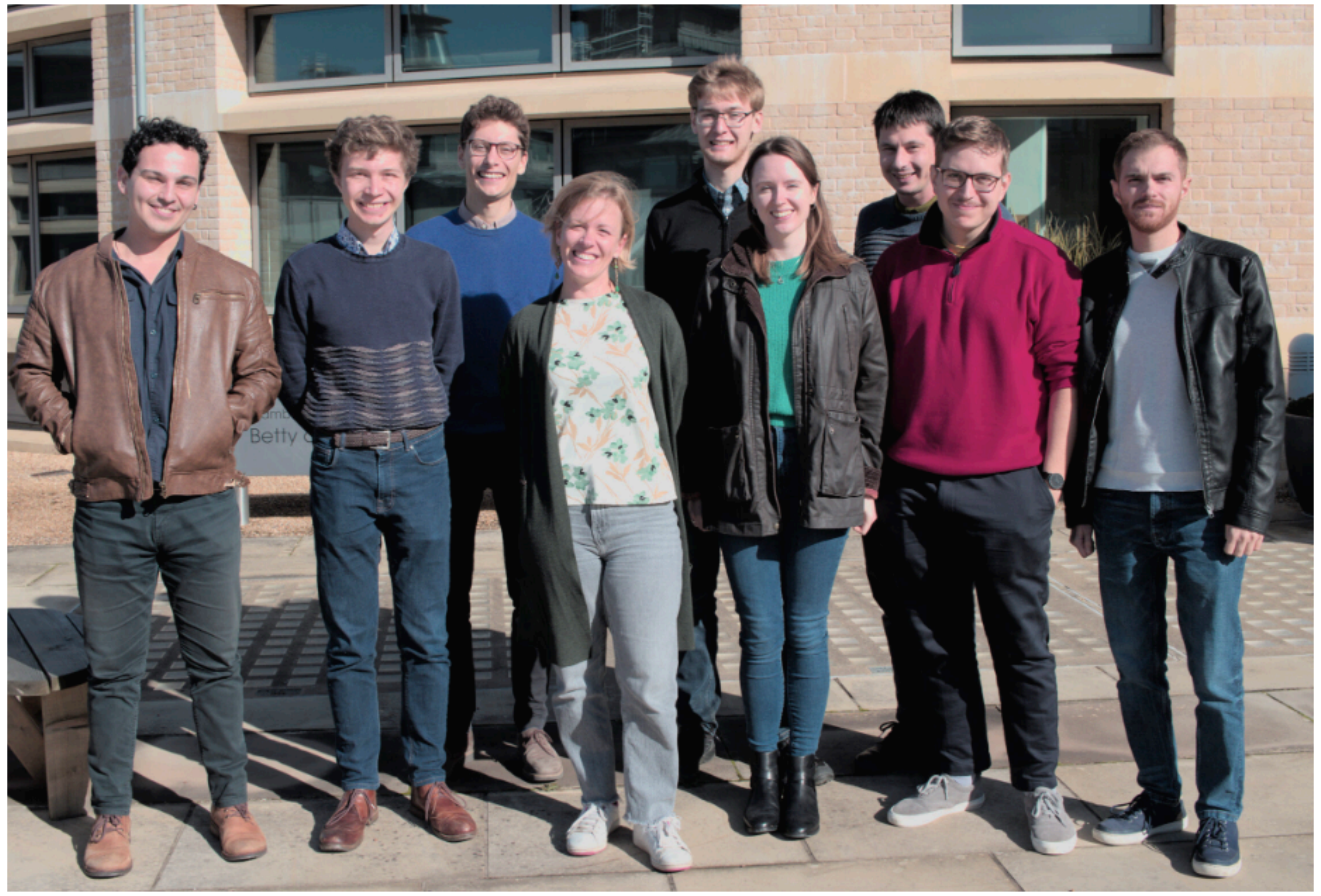
✓ [Top sector: PBSP + Rojo, 2303.06159]

✓ [Drell-Yan sector: PBSP + Greljo : 2104.02723, Iranipour + MU: 2201.07240]

≈ [Jet and Dijets: Greljo, Hammou, Merlotti, Smolkovic, MU, in progress]

PBSP

MU + Zahari Kassabov, Maeve Madigan, Luca Mantani, James Moore, Manuel Morales Alvarado, Ella Cole, Elie Hammou, Mark Costantini, Francesco Merlotti



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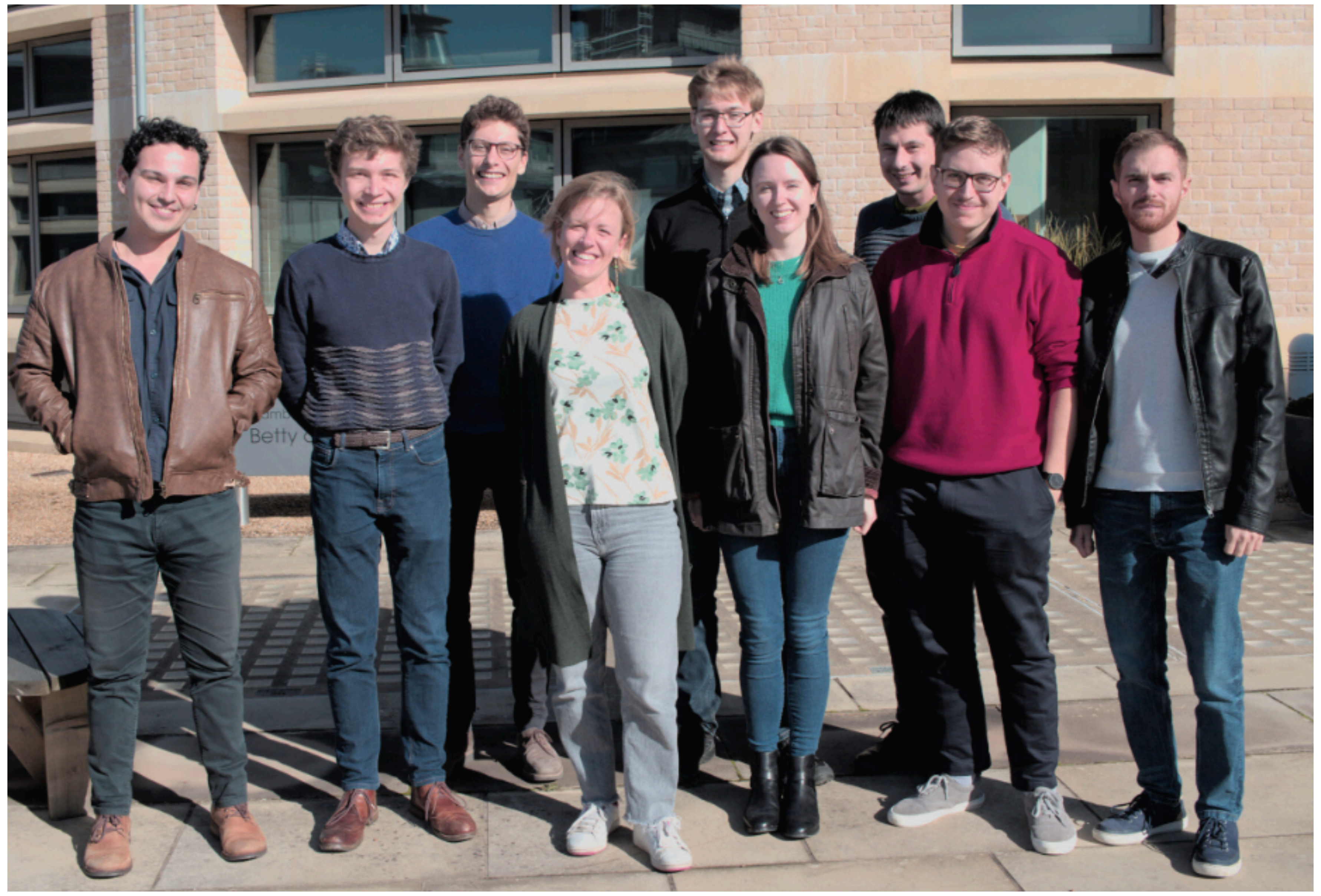

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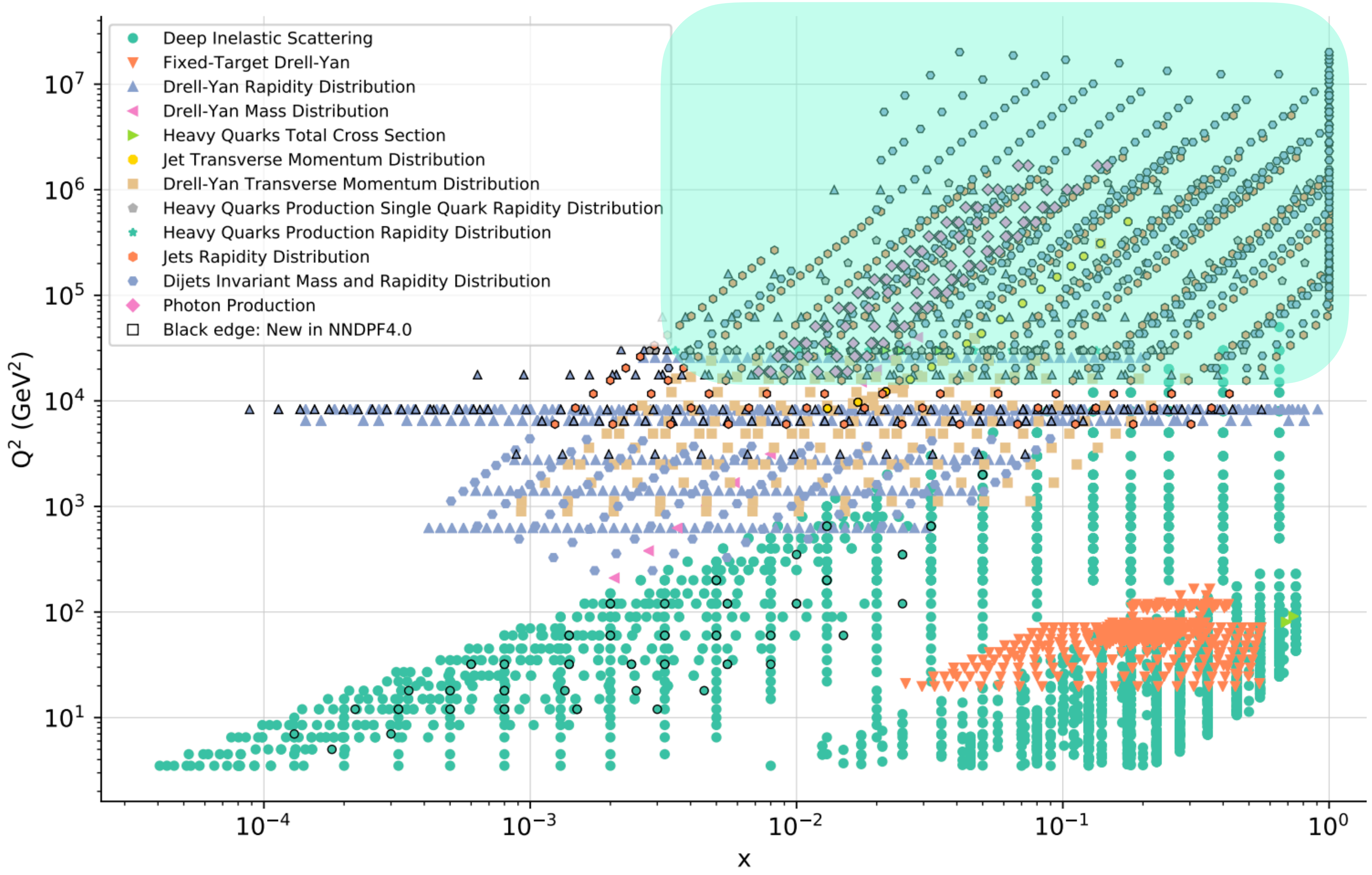
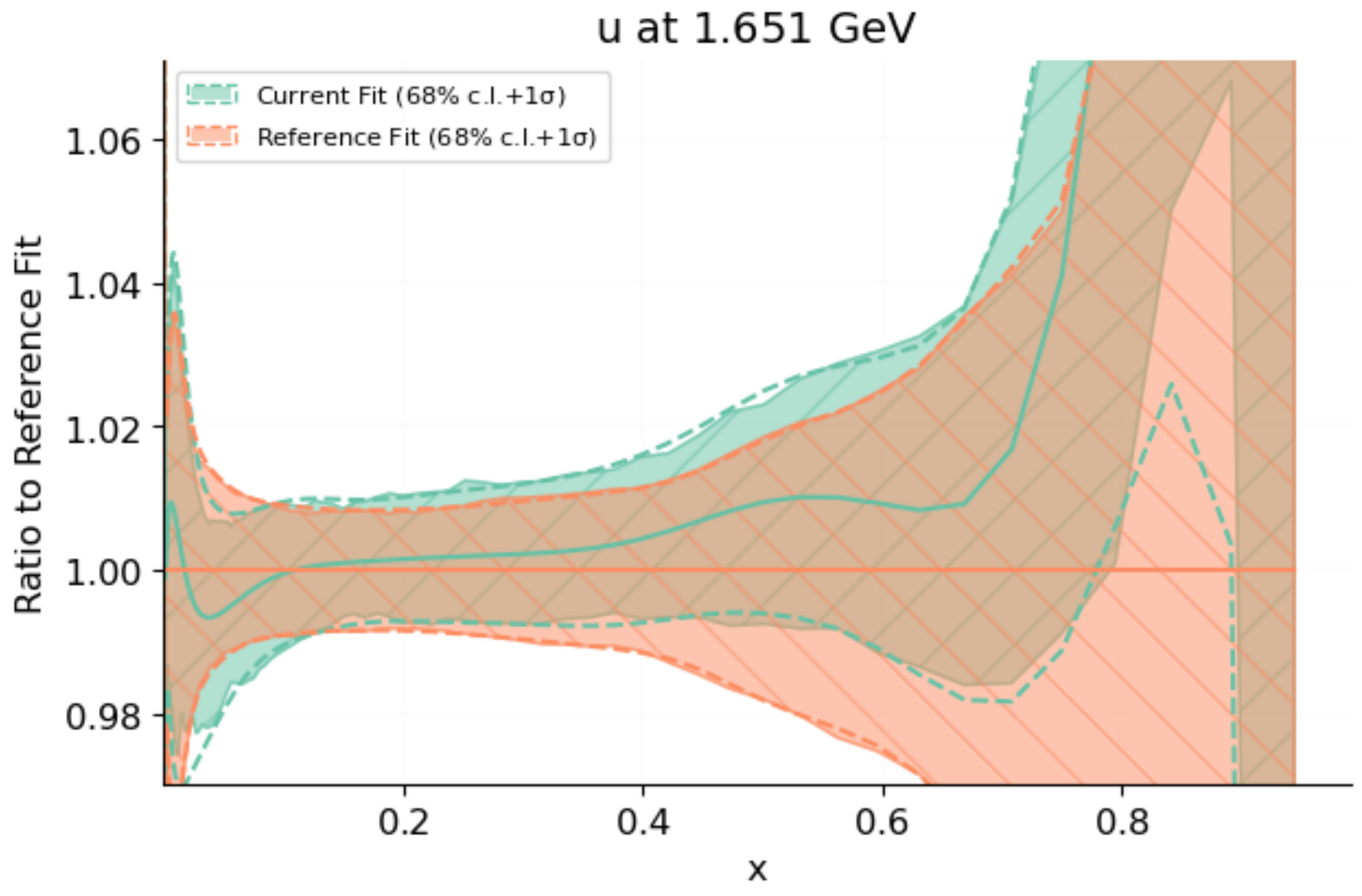
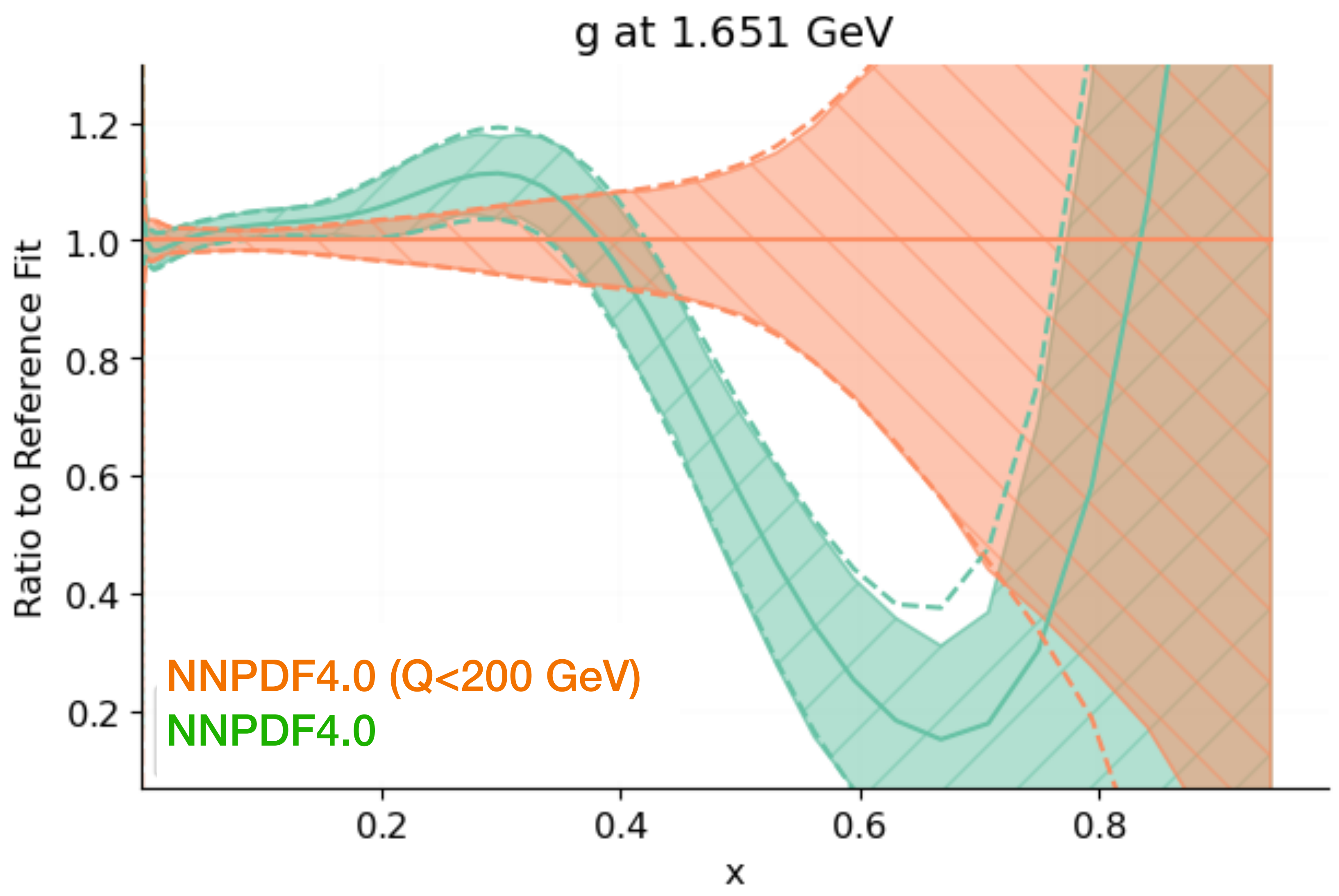
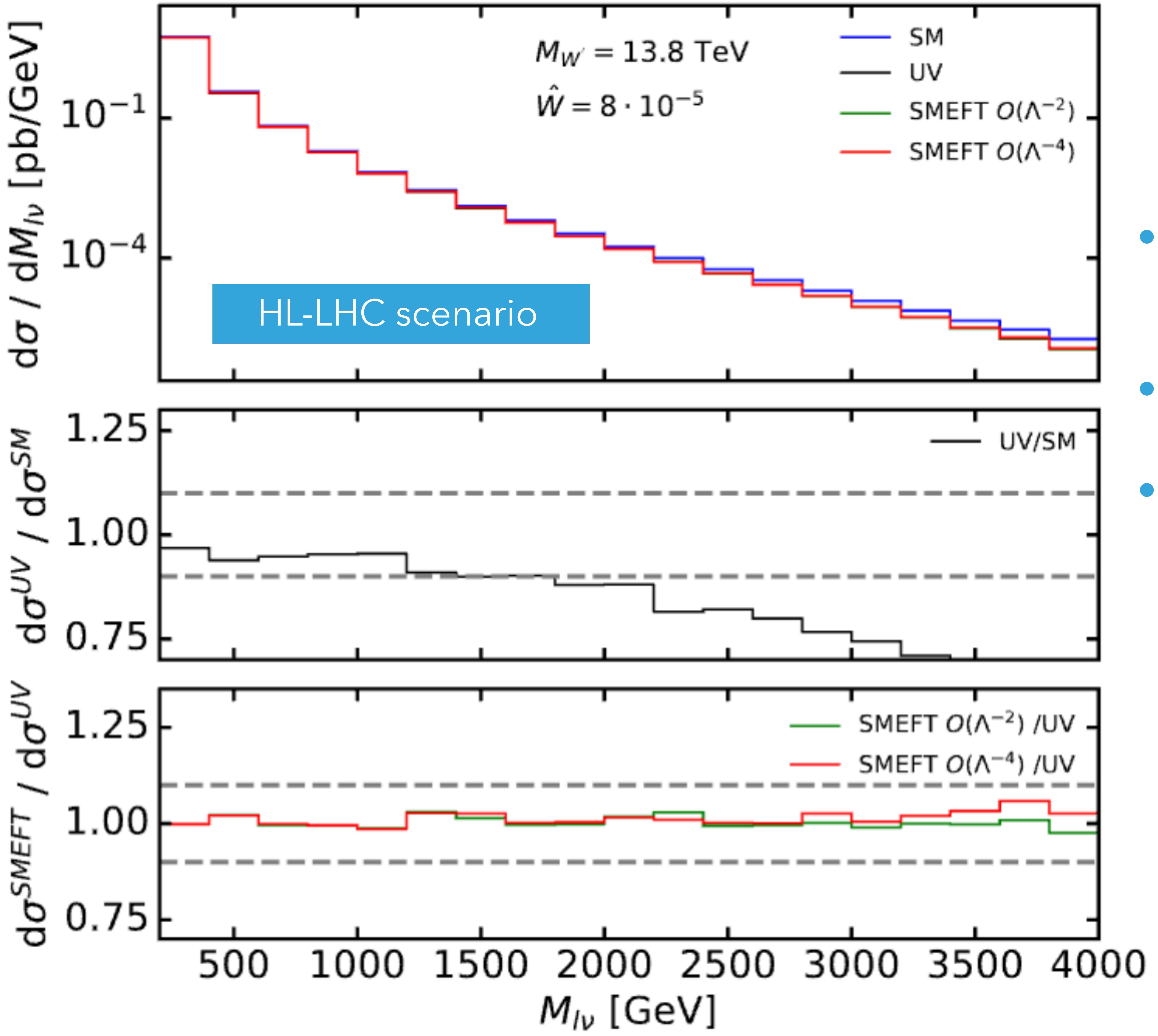






- Naive solution: remove all data above $Q > Q_{threshold}$
- Cutting away all high energy data would result in dramatic uncertainty increase and loss of accuracy, as we would rely on old data and on PDF fitters' ability to control extrapolation region.

CAN PDFS ABSORB NEW PHYSICS?



- Imagine to generate artificial data injecting a given underlying law:
  "True" law of nature =
  "True" PDFs + "True" BSM model

- Can inject directly UV model or SMEFT parametrisation in the region in which SMEFT approximation is good

- Fit PDFs **assuming SM**

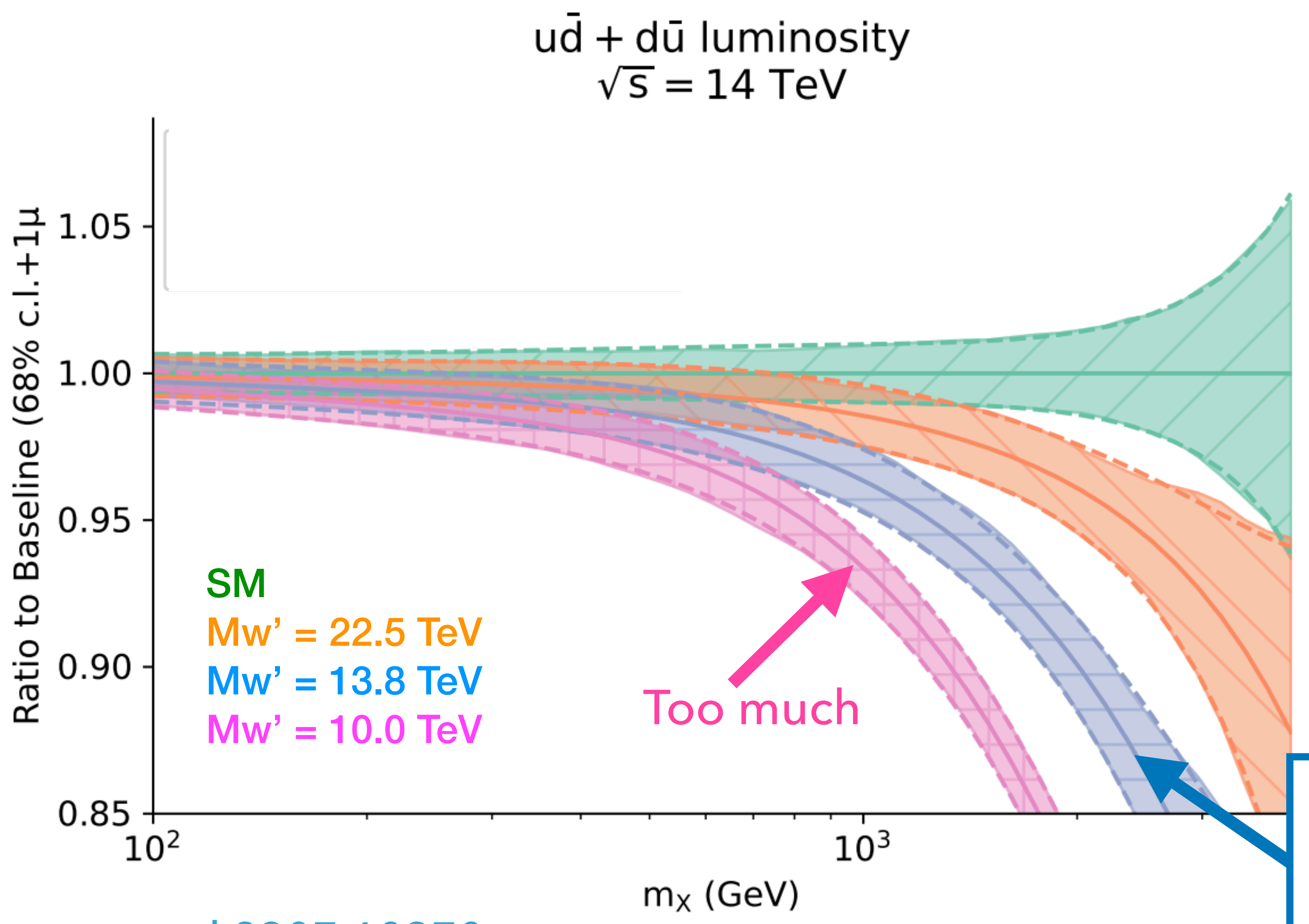
- If fit quality of BSM (data) with SM (theory) does not deteriorate with respect to SM (data) with SM (theory) and PDFs deviate from SM PDFs then the BSM signal is absorbed by the PDFs!

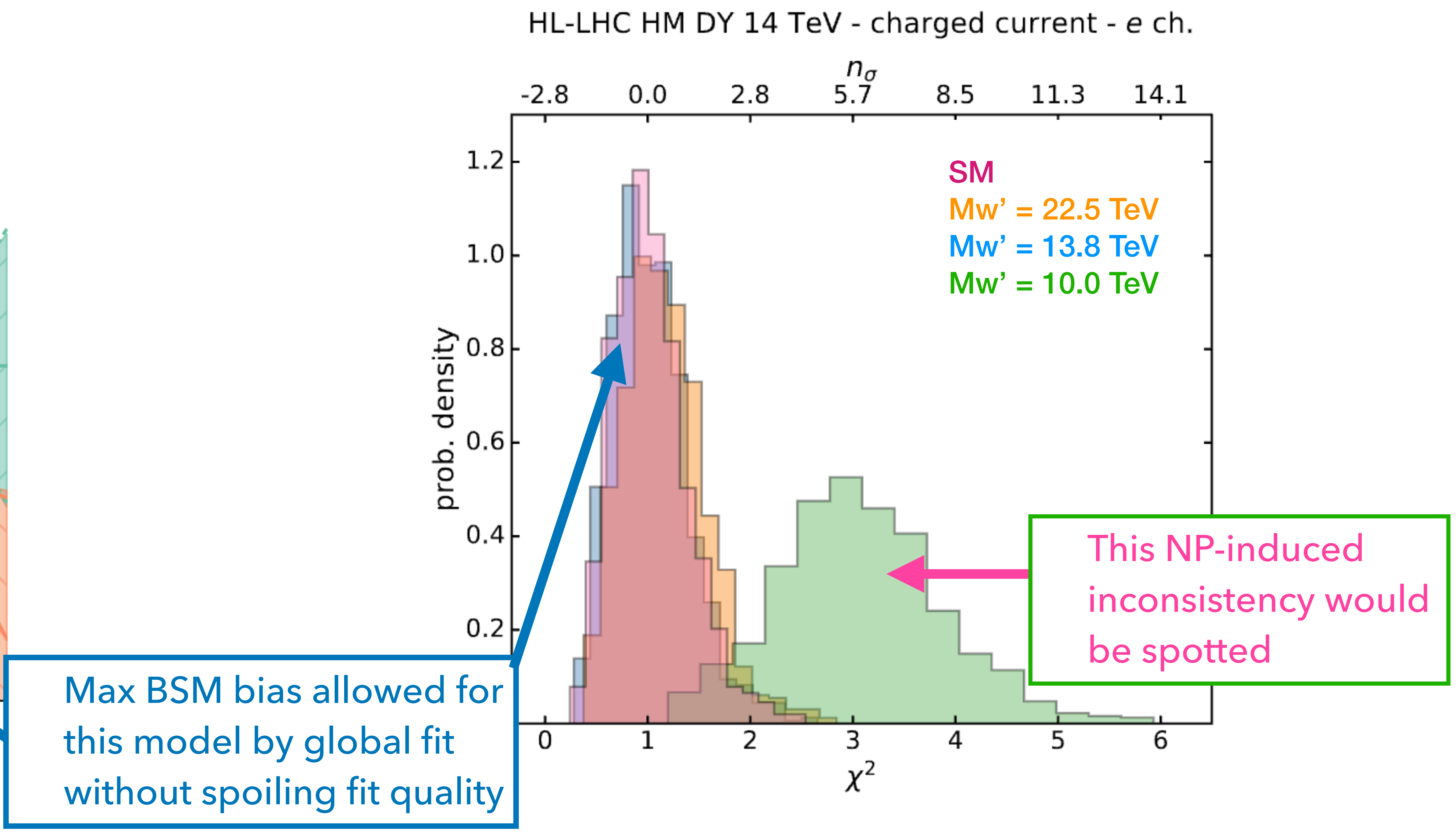
✓ $$\mathscr{L}^{W'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2_{W'}}{2M^2_{W'}} J^{a,\mu}_L J^a_{L,\mu} \qquad J^{a,\mu}_L = \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

✗ $$\mathscr{L}^{Z'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2_{Z'}}{2M^2_{Z'}} J^\mu_Y J_{Y,\mu} \qquad J^\mu_Y = \sum_f Y_f \bar{f} \gamma^\mu f$$

CAN PDFS ABSORB NEW PHYSICS? YES!

- 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 artificial 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

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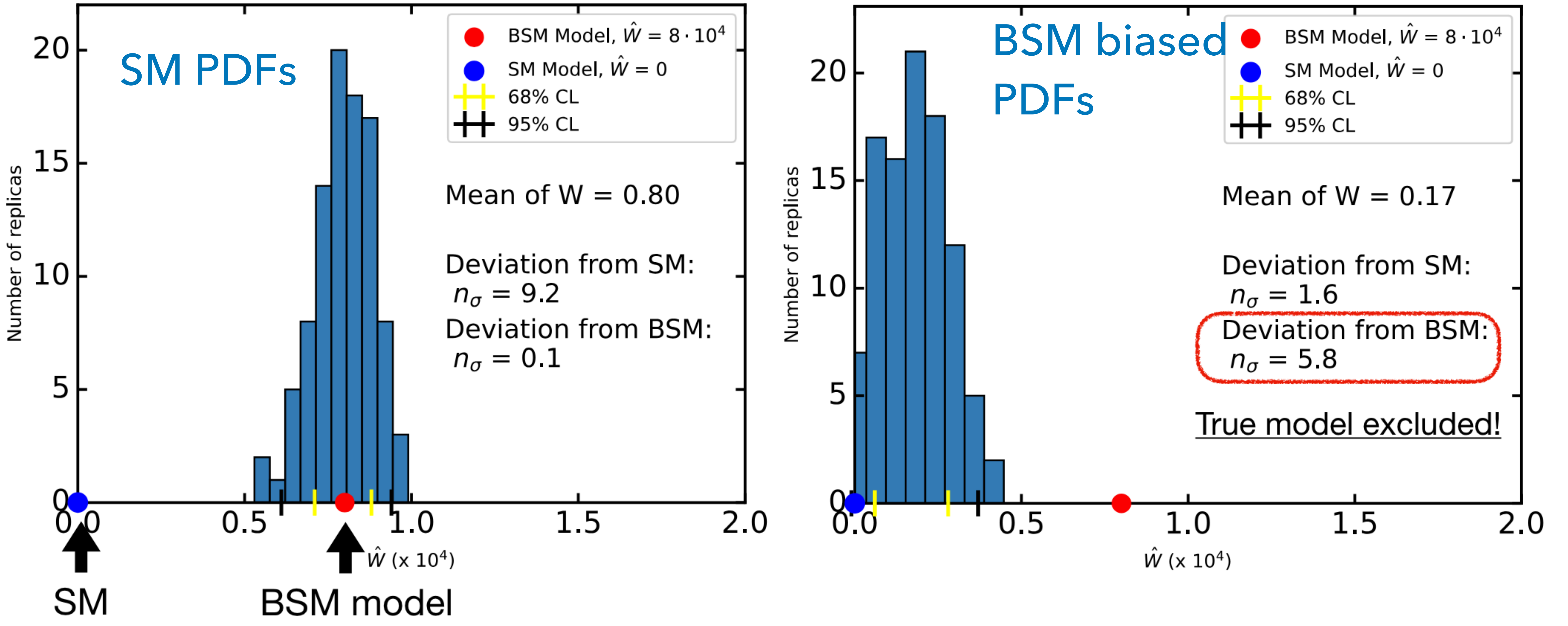
Consequence #1:
Would not see indirect effect of new physics as we would find SMEFT bounds compatible with the SM!



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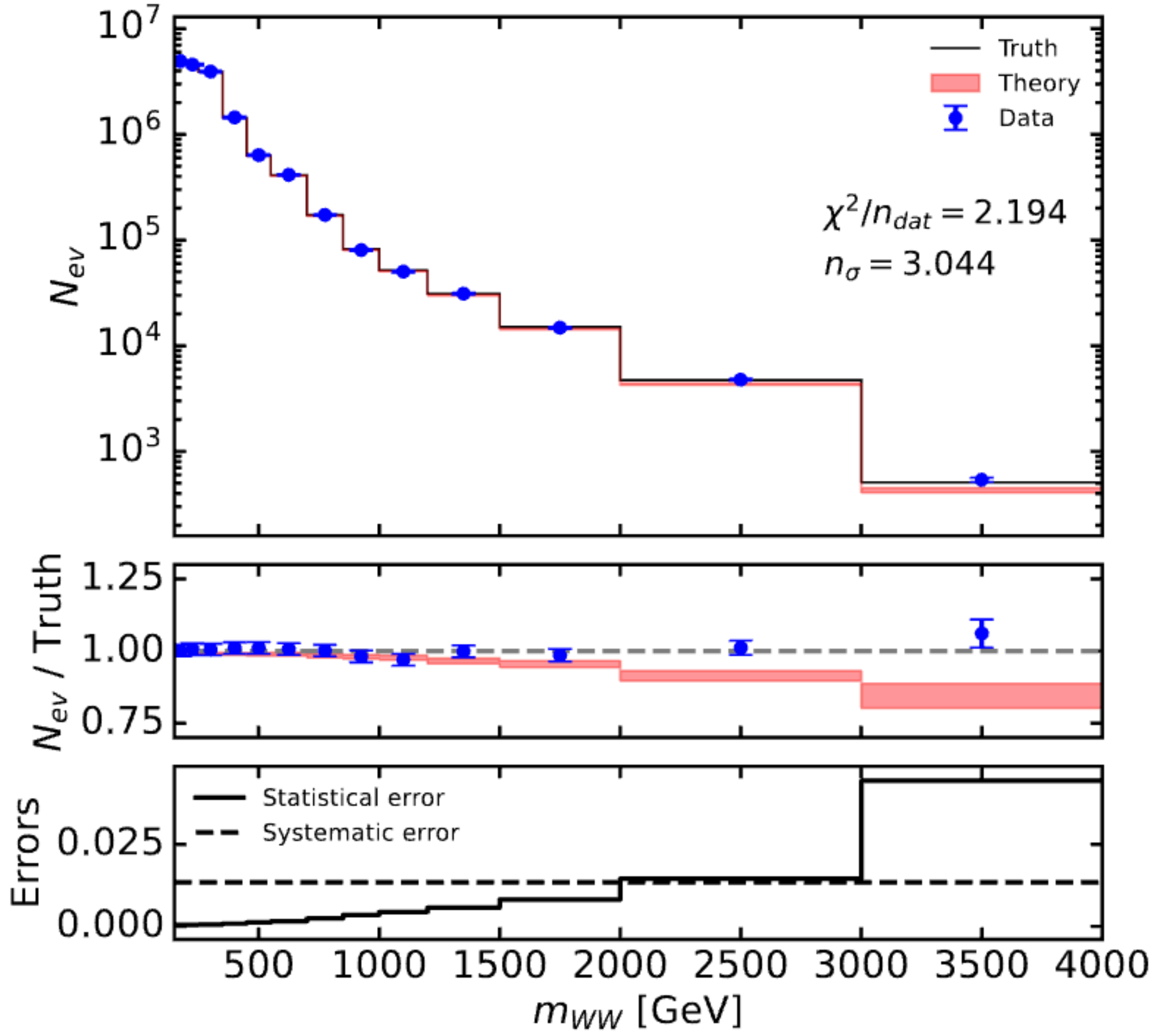
Consequence #2:
Would see New Physics effects where there are none (for example in WW)



E. Hammou, et al 2307.10370

HOW TO AVOID NEW PHYSICS CONTAMINATION?

- LHCb on-shell at high rapidity data do not help as quark probed at large x, antiquark at small x
- If we fit giving more weight (artificially increasing statistics) of fixed-target DY data on proton/deuteron the BSM-induced inconsistency would be flagged
- Need more accurate low-energy/large-x constraining measurements to really disentangle such effects

Flat direction in the anti-quark at large-x:

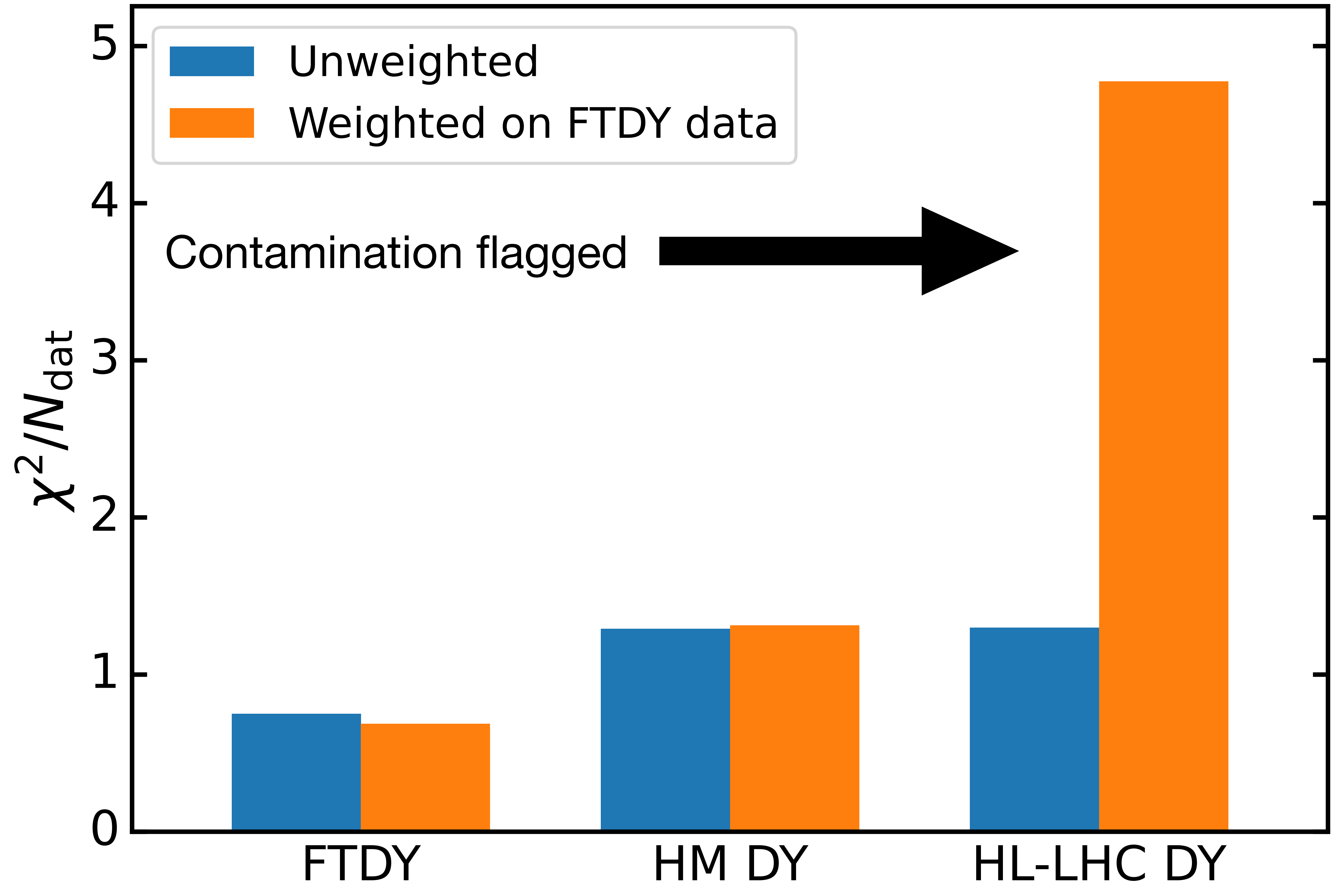
➡ Accommodates PDFs to artificial data with BSM injected

➡ Allows for BSM bias in qq~ luminosity

Including lower-energy large-x data:

- Constrain large-x region
- Safe from BSM contamination

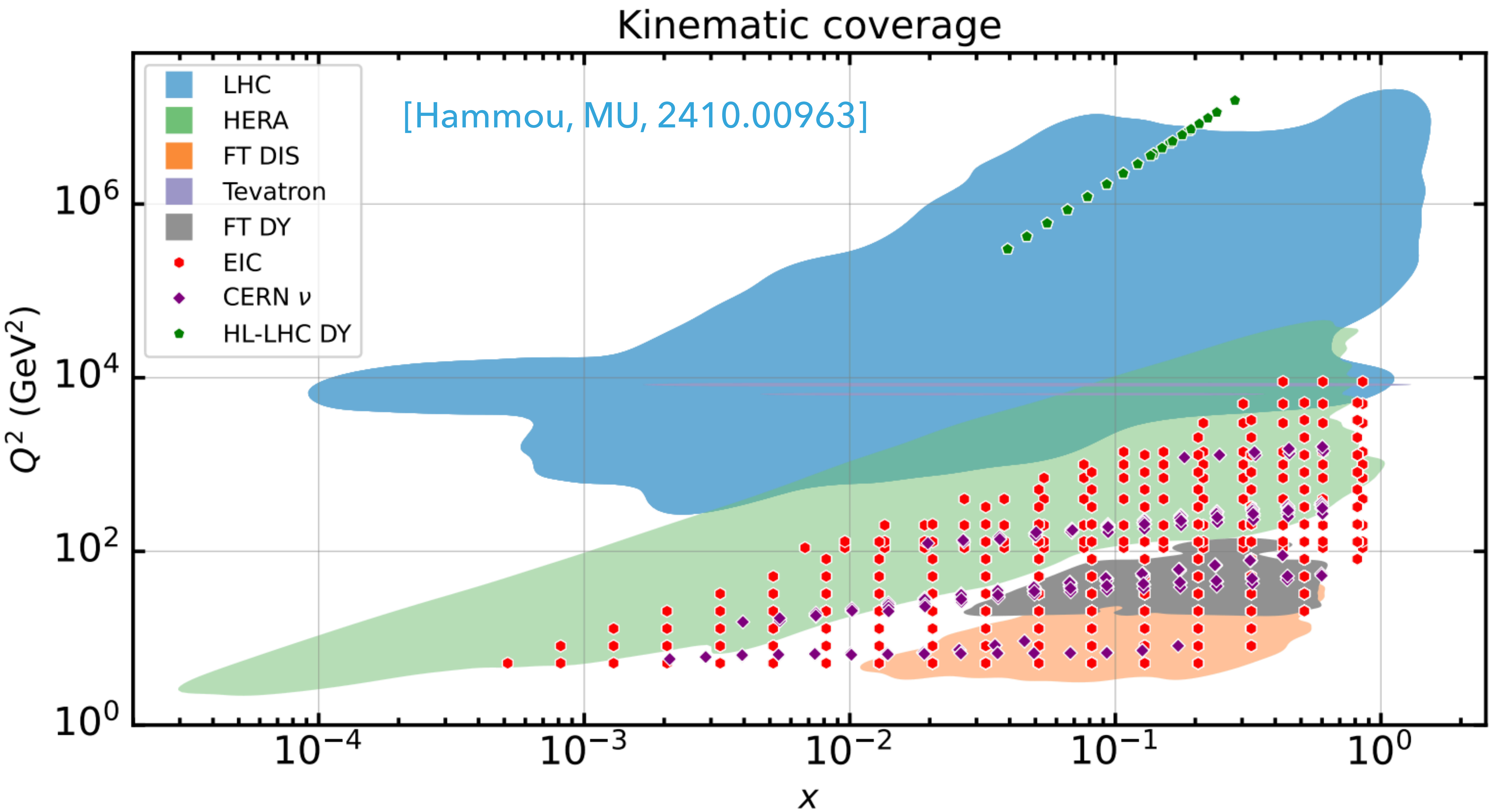
FTDY data weighted

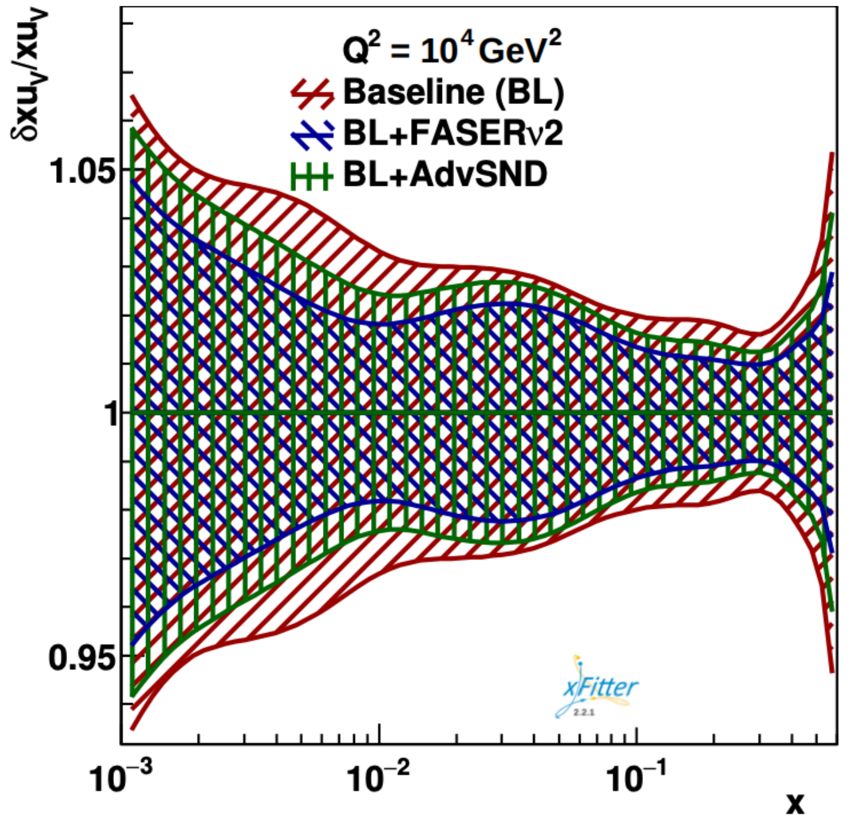


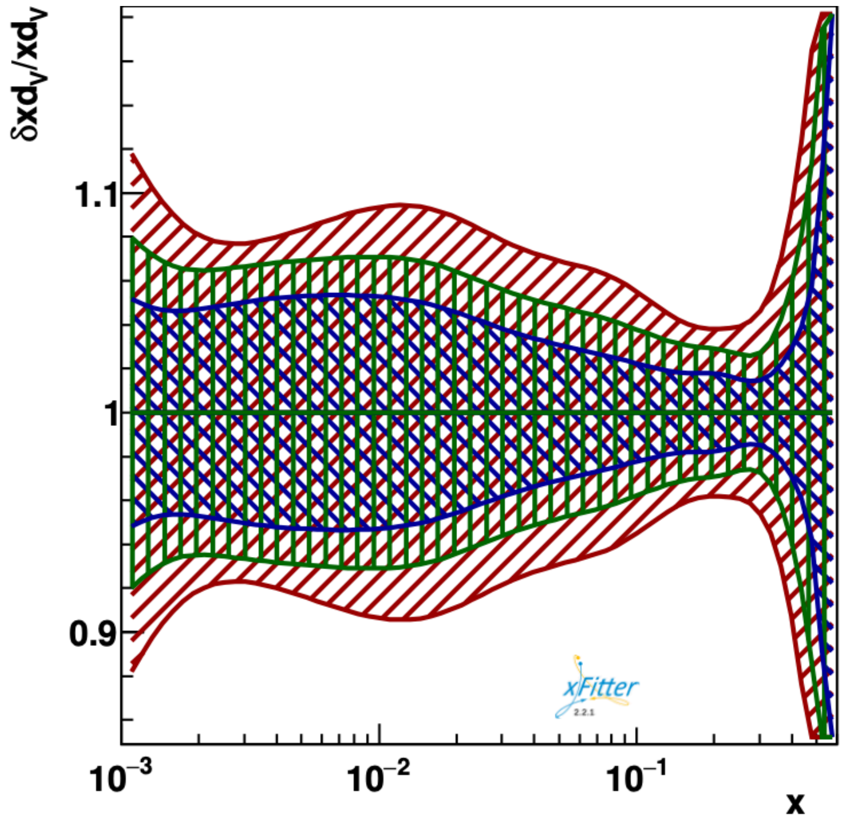
[Hammou, MU, 2410.00963]

PROJECTIONS FROM FORWARD PHYSICS FACILITY AT CERN

Observable	N_{dat}
FASERν	
$\tilde{\sigma}(\nu + N \to l^- + X)$	22
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + X)$	16
FLArE	
$\tilde{\sigma}(\nu + N \to l^- + X)$	43
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + X)$	39
$\tilde{\sigma}(\nu + N \to l^- + c/\bar{c} + X)$	31
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + c/\bar{c} + X)$	19
FASERν2	
$\tilde{\sigma}(\nu + N \to l^- + X)$	44
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + X)$	39
$\tilde{\sigma}(\nu + N \to l^- + c/\bar{c} + X)$	38
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + c/\bar{c} + X)$	30
AdvSND	
$\tilde{\sigma}(\nu + N \to l^- + X)$	33
$\tilde{\sigma}(\bar{\nu} + N \to l^+ + X)$	29
$\tilde{\sigma}(\nu + N \to l^- + c/\bar{c} + X)$	17







- Neutrino DIS measurements at the LHC FPF operating concurrently with the HL-LHC would provide handles on PDFs of proton and nuclei in the medium-large-x region

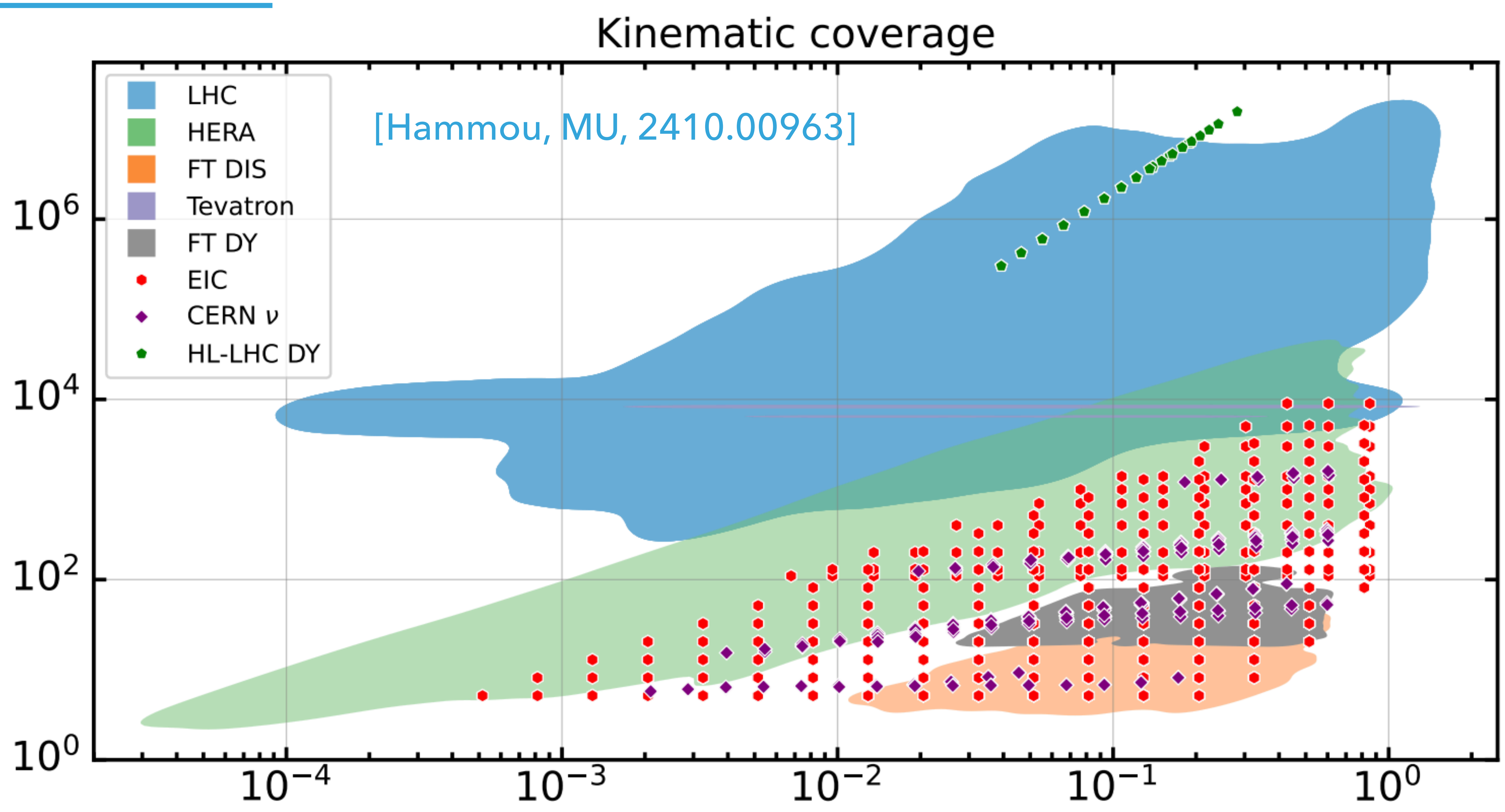
J Cruz-Martinez et al 2309.09581

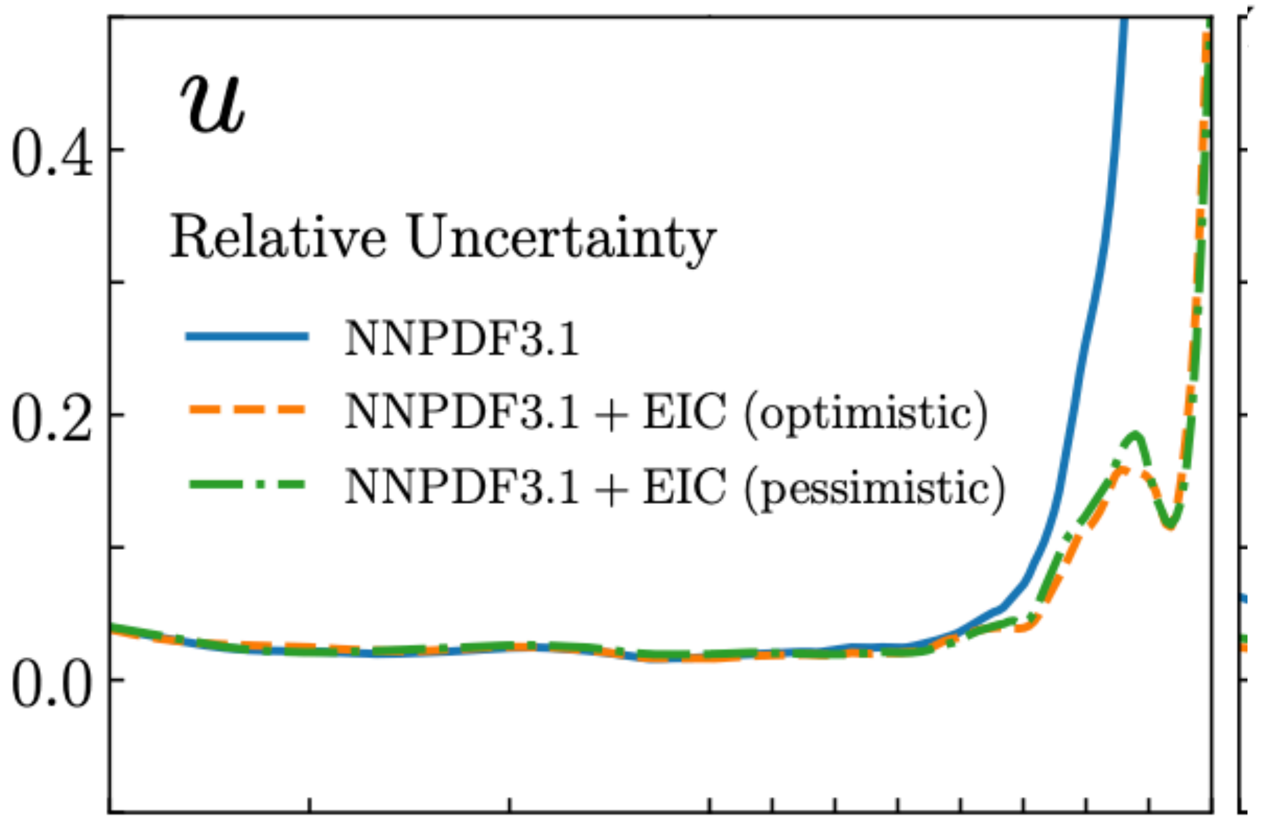
PROJECTIONS FROM THE EIC AT BNL

Observable	N_{dat}	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]
Charged Current			
$\tilde{\sigma}(e^- + p \to \nu + X)$	89 (89)	140.7	100
$\tilde{\sigma}(e^+ + p \to \bar{\nu} + X)$	89 (89)	140.7	10
Neutral Current (proton)			
$\tilde{\sigma}(e^- + p \to e^- + X)$	181 (131)	140.7	100
	181 (131)	63.2	100
	126 (91)	44.7	100
	87 (76)	28.6	100
$\tilde{\sigma}(e^+ + p \to e^+ + X)$	181 (131)	140.7	10
	181 (131)	63.2	10
	126 (91)	44.7	10
	87 (76)	28.6	10
Neutral Current (deuteron)			
$\tilde{\sigma}(e^- + d \to e^- + X)$	116 (116)	89.0	10
	107 (107)	66.3	10
	76 (76)	28.6	10
$\tilde{\sigma}(e^+ + d \to e^+ + X)$	116 (116)	89.0	10
	107 (107)	66.3	10
	76 (76)	28.6	10

Optimistic scenario

Pessimistic scenario

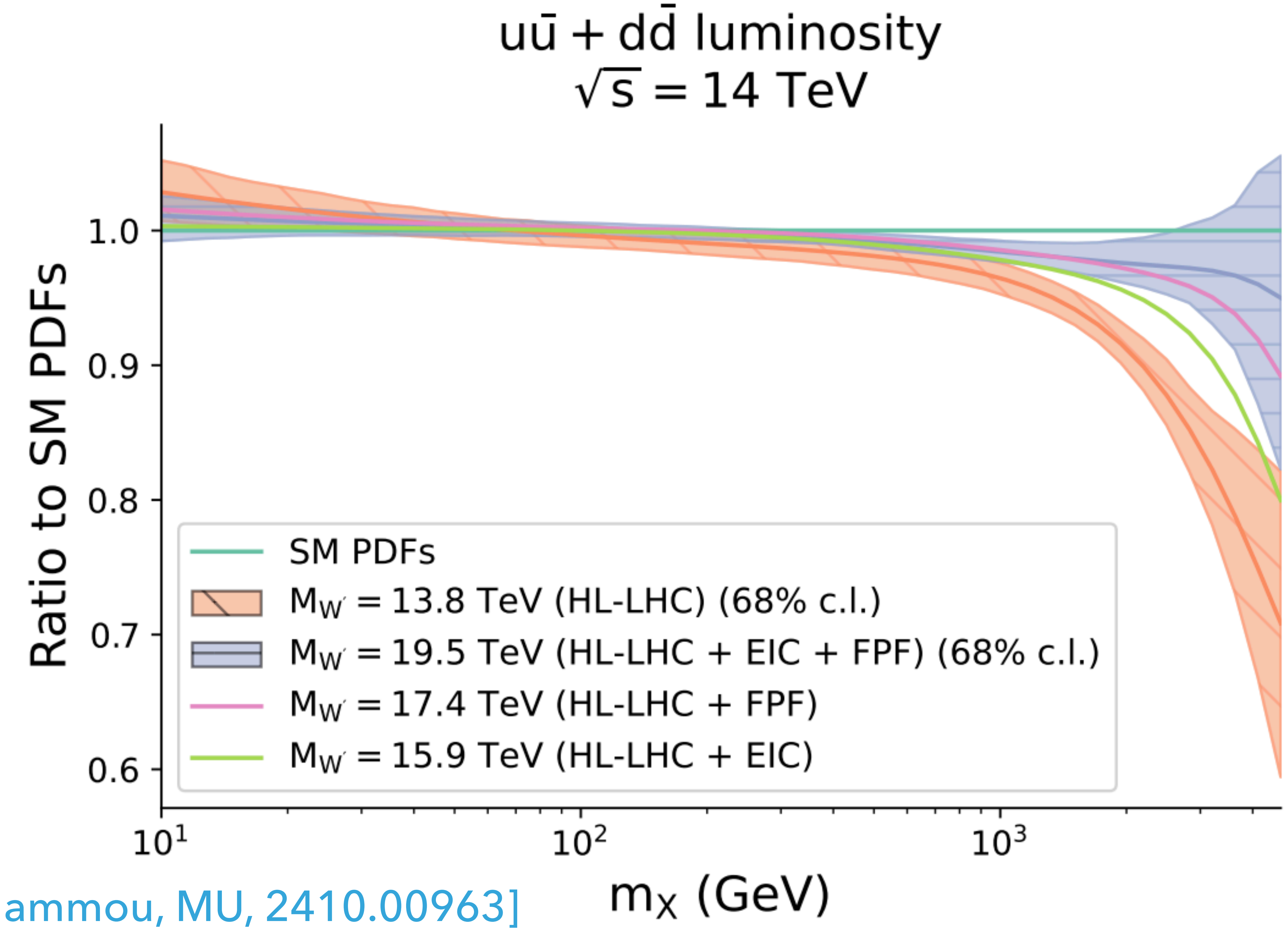




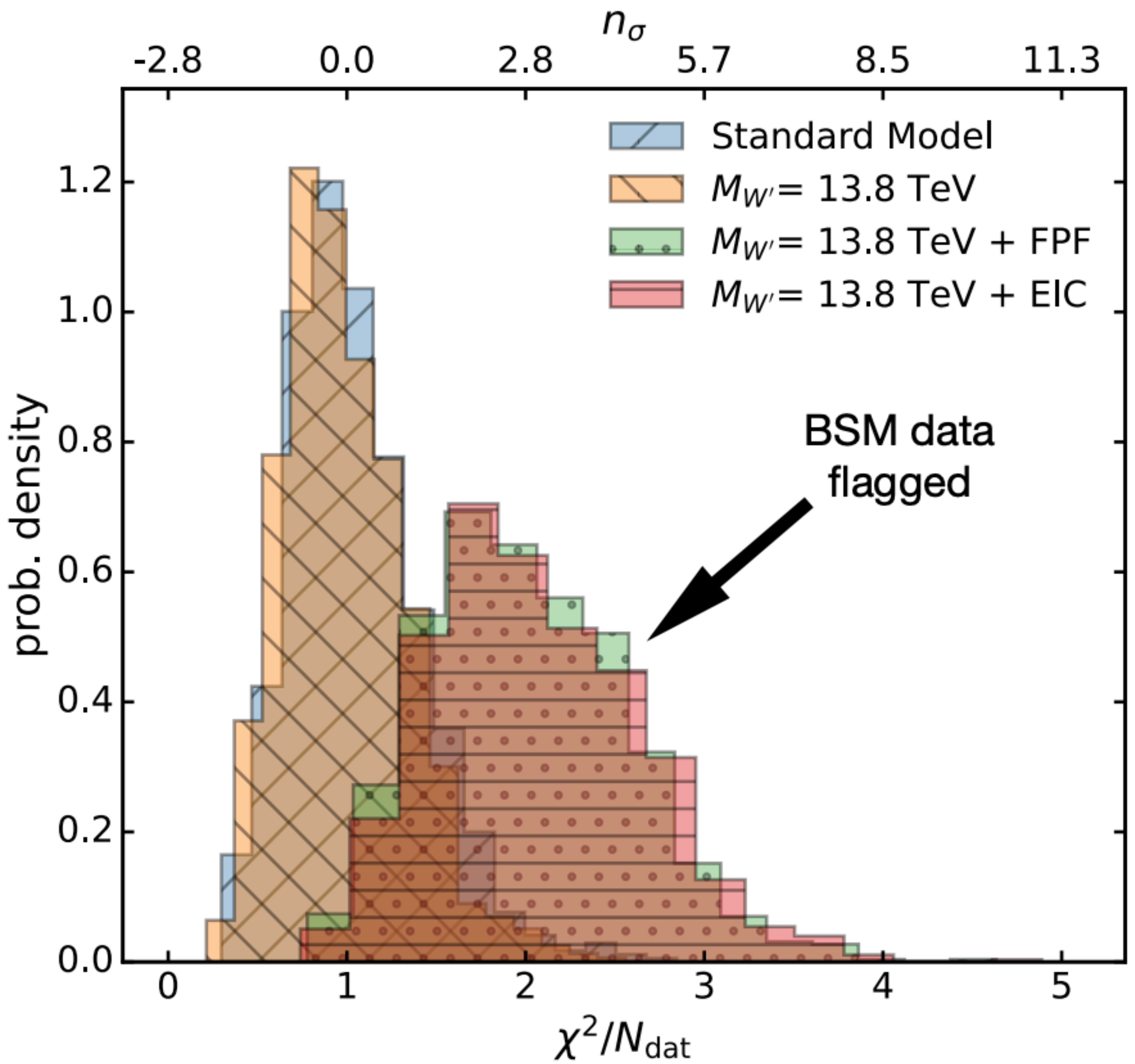
- NC and CC DIS measurements at the EIC would provide handles on up and down quarks at medium-large-x
- They would also constrain SMEFT 4-fermion operators

R. A. Khalek et al, 2102.00018
C. Bissolotti et al, 2307.09459

EIC AND FPF WOULD PREVENT BSM INDUCED BIAS



[Hammou, MU, 2410.00963]



- Including the EIC and FPF artificial data alongside the HL-LHC ones reduces the BSM-bias in PDF luminosity
- The HL-LHC data with Mw′ = 13.8 TeV injected would be excluded from the fit as their theoretical description with the SM would be too poor and the data would be considered inconsistent
- EIC and FPF inclusion would push the threshold of BSM bias up to Mw′~20 TeV and would make the effect on PDFs much smaller

EIC AND FPF WOULD PREVENT BSM INDUCED BIAS

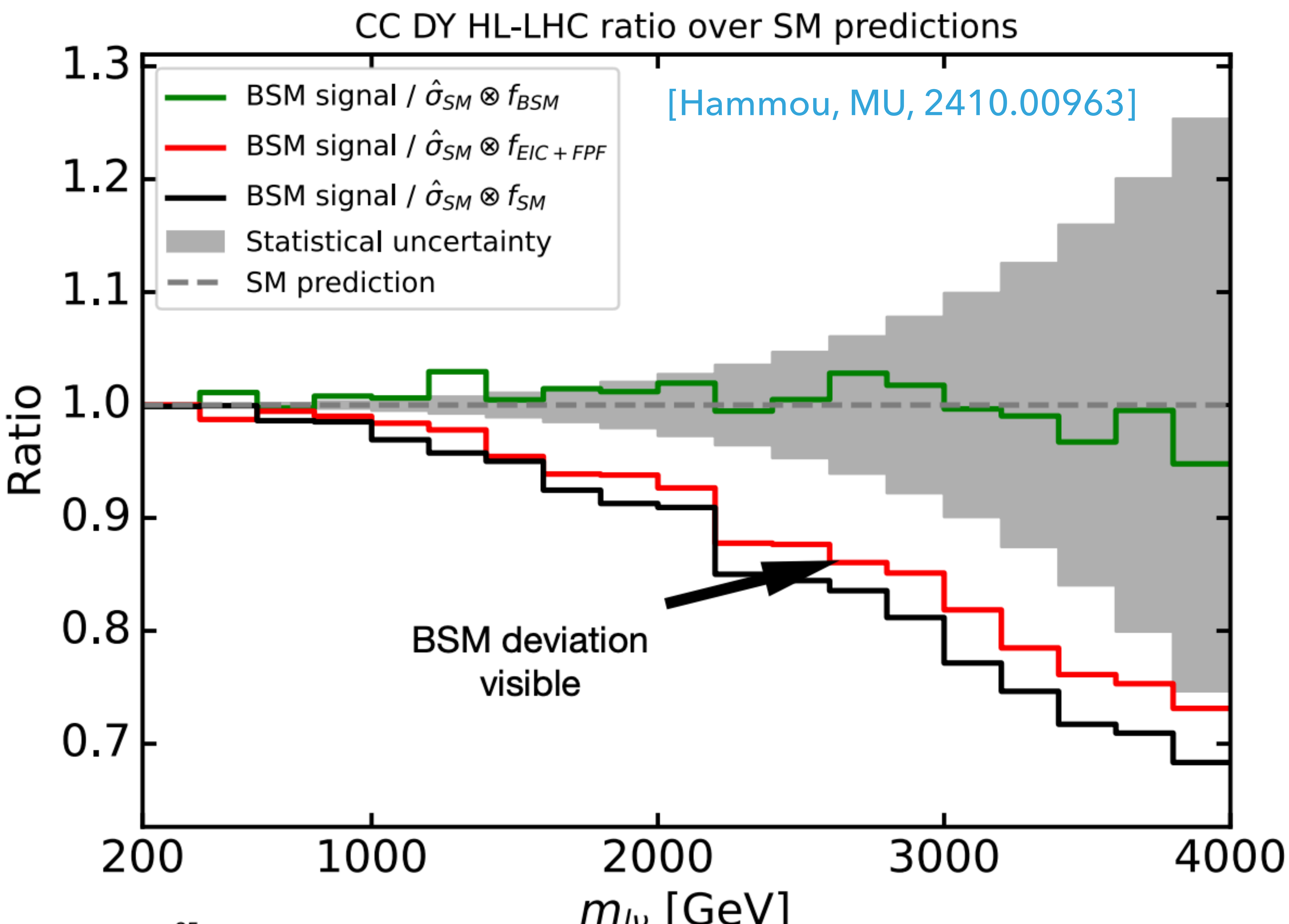
- ✓ Potential BSM effects, which might otherwise be absorbed into the PDFs, can be disentangled in high-energy measurements by incorporating EIC and FPF measurements in a global PDF analysis
- ✓ This minimises the risk of BSM-induced bias in PDF fits and allow for more consistent identification of BSM effects in high energy data, which can then be analysed separately.

$$\hat{\sigma}_{BSM} \otimes \mathscr{L}_{SM} \approx \boxed{\hat{\sigma}_{SM} \otimes \mathscr{L}_{BSM}}$$

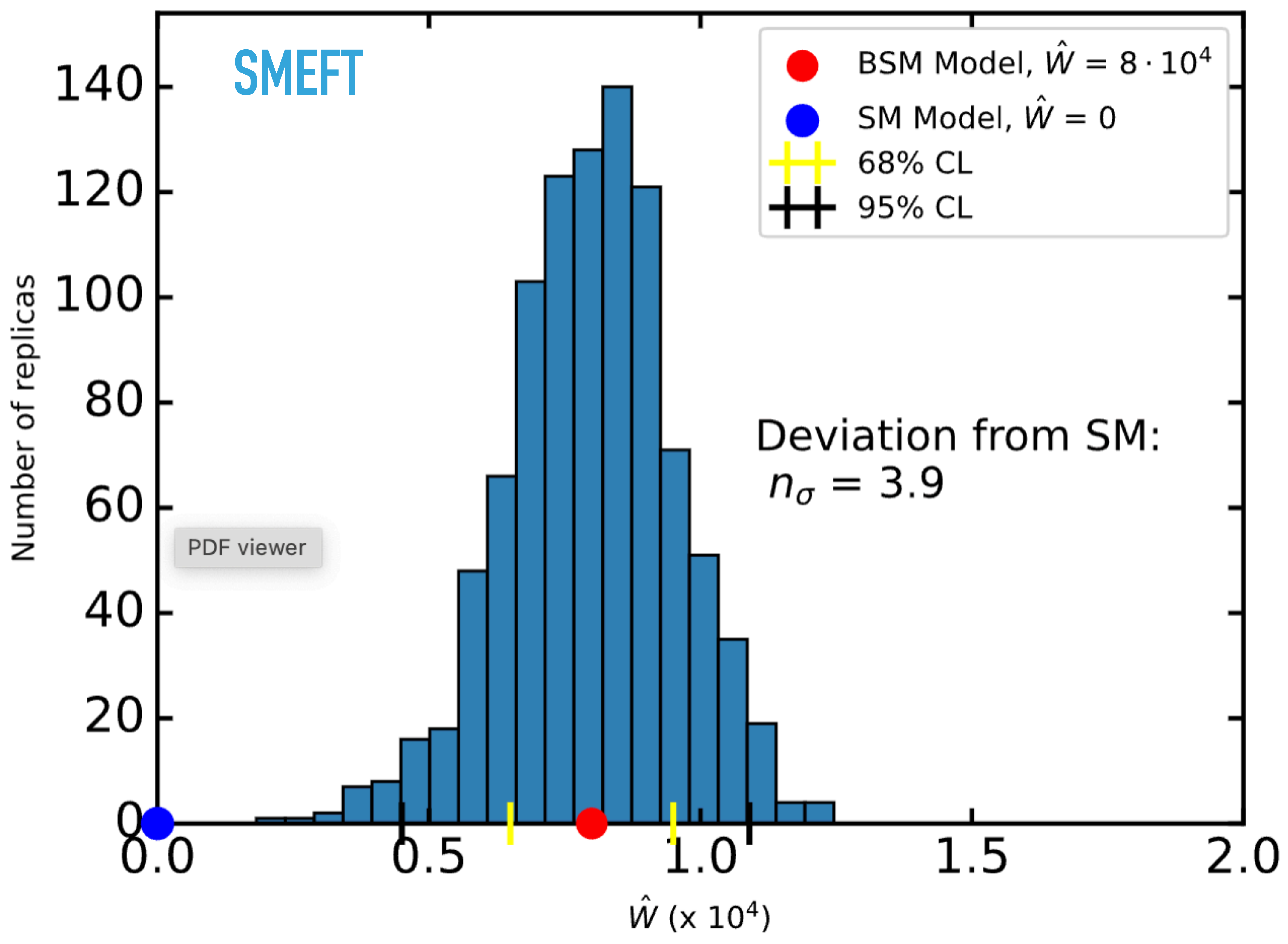
$$\Downarrow$$

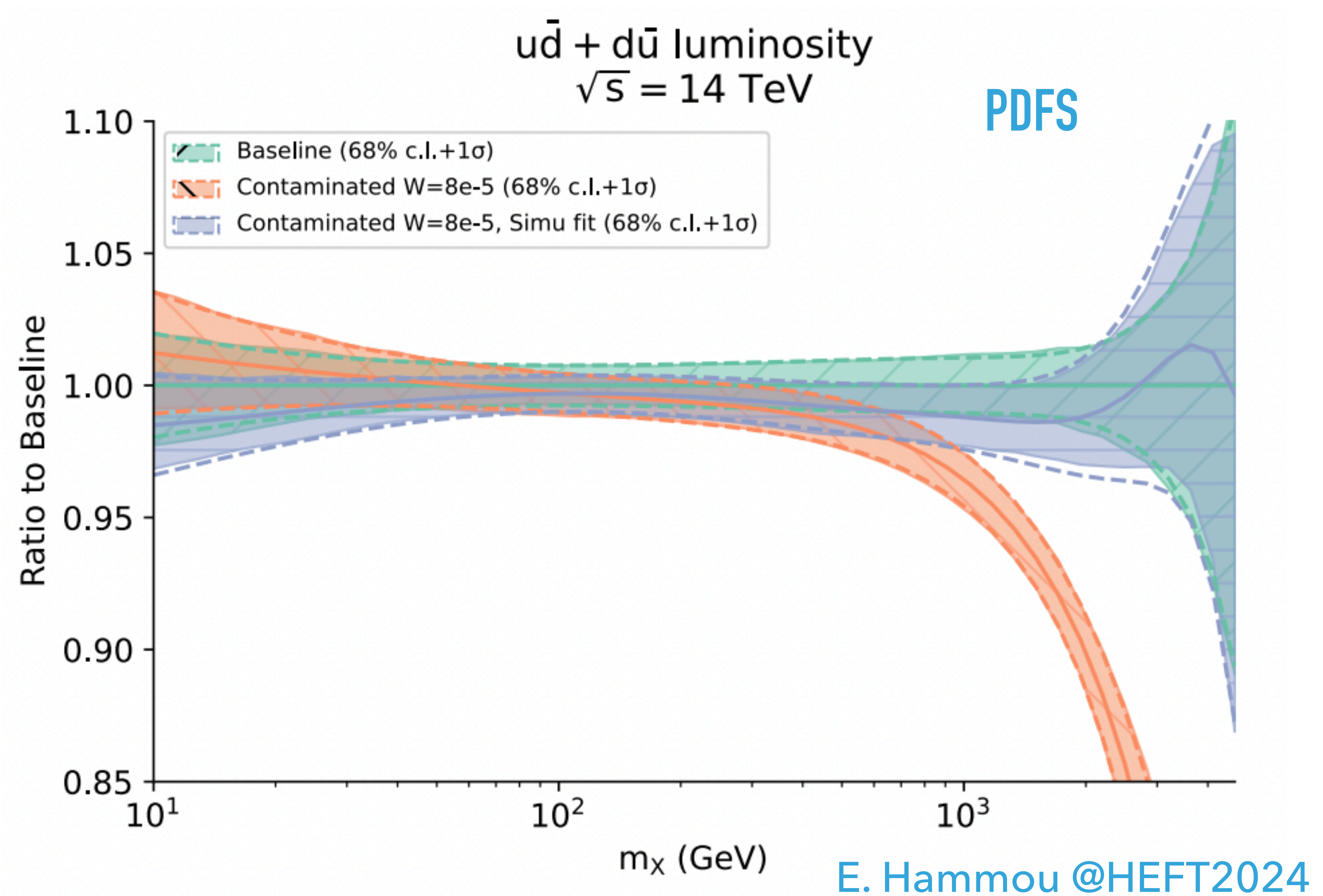
$$\hat{\sigma}_{BSM} \otimes \mathscr{L}_{SM} \neq \boxed{\hat{\sigma}_{SM} \otimes \mathscr{L}_{EIC+FPF}}$$

$M_{W'}$: 13.8 TeV



SIMULTANEOUS FIT OF NEW PHYSICS AND SMEFT





E. Hammou @HEFT2024

✓ 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, Hammou et al - in preparation]

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? Yes
  - ➡ Identified a UV scenario such that the high-mass HL-LHC invariant mass can absorb NP and quantified effect
  - ➡ Important to disentangle large-x from high-energy / lower-energy
  - ➡ More scenarios to be explored, especially large-x gluons (jets, top)

- Complementary large-x constraints on the quarks and anti-quarks from Electron-Ion Collider (EIC) and Forward Physics Facility (FPF) projections display a key disentangling power.
- Similar study in progress considering LHeC projections [Ahmadova et al 2503.17727, Hammou, Rojo, MU in preparation]
- Lattice data can also help in the same direction
- Robust methodology to identify inconsistencies in PDF fit is paramount [Barontini et al,2503.17447]

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.