Constraining heavy new physics with the FPF

A study of the interplay of Parton Distribution Functions (PDFs) and BSM signals in global fits

Work with Maria Ubiali and her group:

[Hammou et al., 2307.10370, JHEP]

[Hammou et Ubiali, 2410.00963]

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Elie Hammou, University of Cambridge

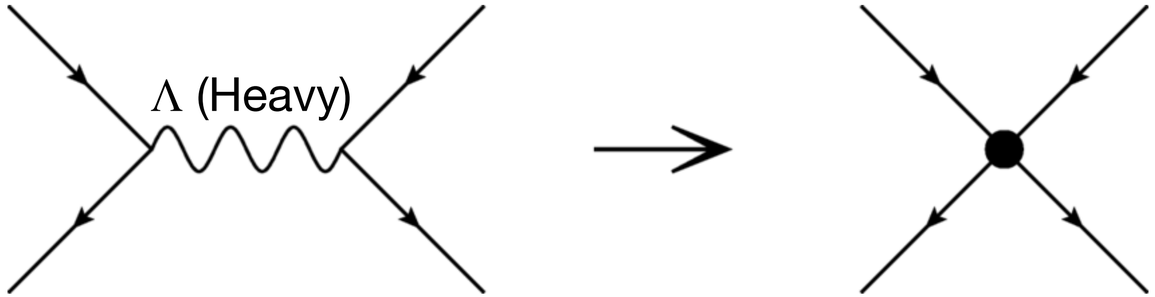
8th Forward Physics Facility meeting, Jan 2025, CERN

Indirect searches and Effective Field Theories

The Standard Model EFT (SMEFT)

Integrate heavy fields out:

UV Model



EFT Model

[10.1007/s10773-021-04723-1]

Obtain model independent Lagrangian:

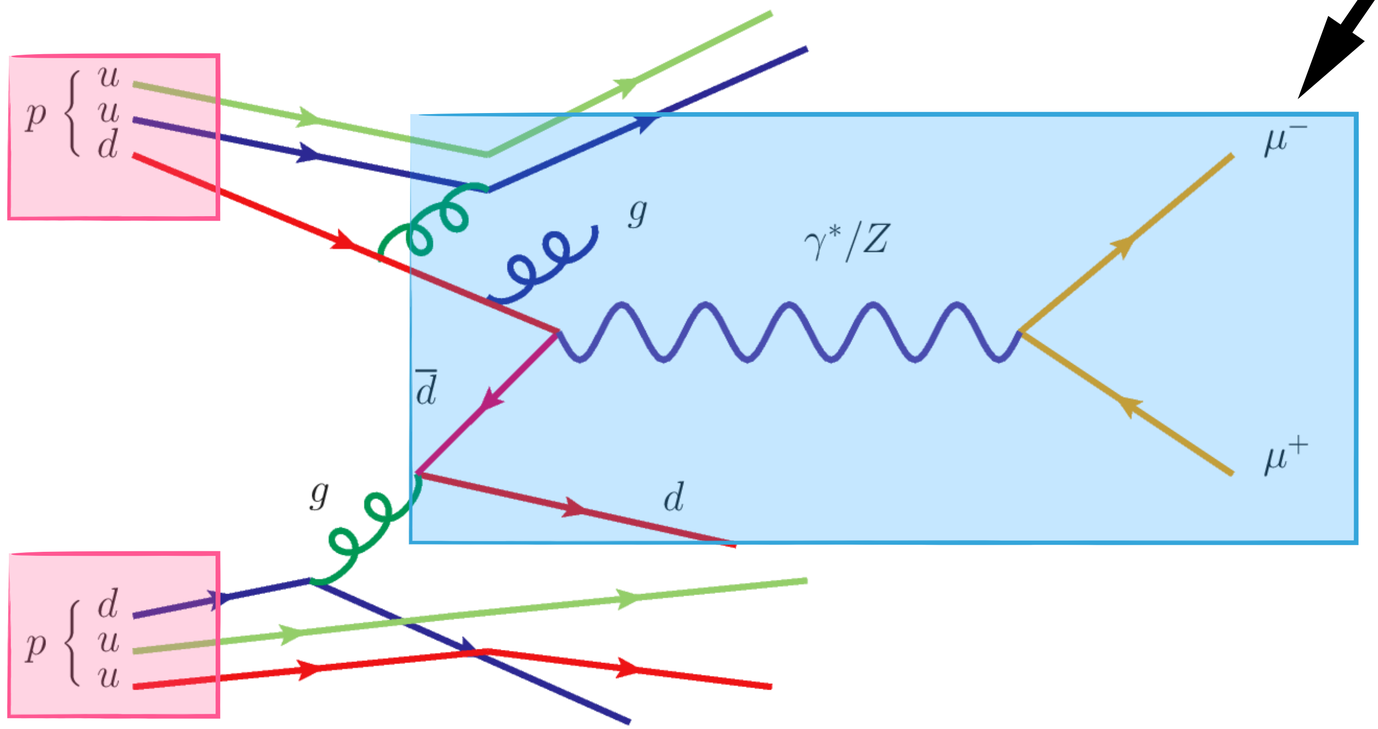
$$\mathscr{L}^{\text{UV}} = \mathscr{L}^{\text{SM}} + \mathscr{L}^{\text{Heavy}} \longrightarrow \mathscr{L}^{\text{SMEFT}} = \mathscr{L}^{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

- Dim 6 EFT operators with SM fields: $\mathcal{O}_i^{(6)}$
- Wilson coefficients fittable from data: $\frac{c_i}{\Lambda^2}$

Hadron colliders and PDFs

Collinear factorization theorem

SMEFT corrections



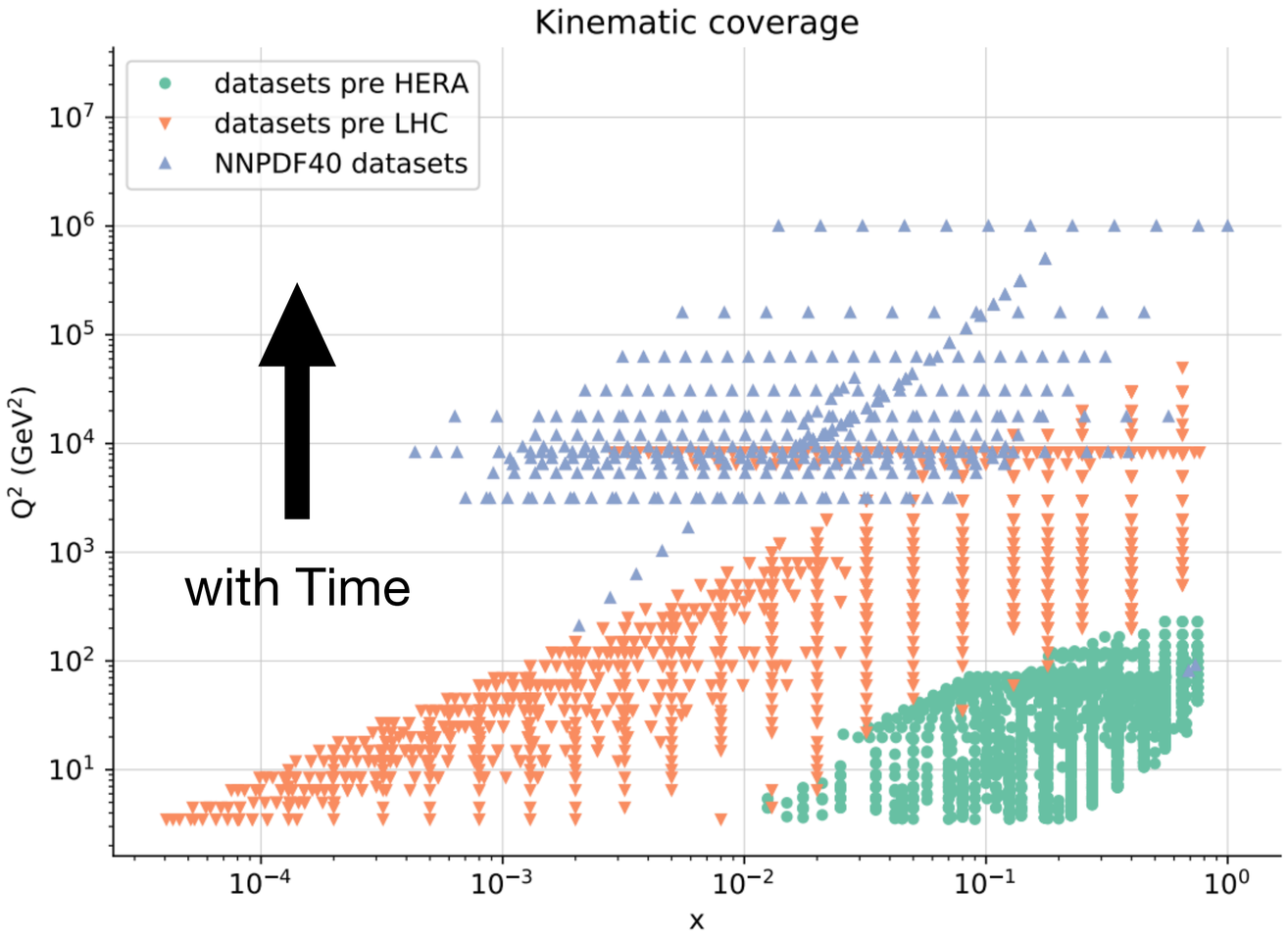
Parton Distribution Functions

Hard Scattering: Perturbative QCD + EW

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

Fitting PDF from data

The dataset used by NNPDF



Evolution of the dataset through time:

- Moved toward higher energies
- 30% is LHC data
- More to come with HL-LHC run

Risk of absorbing signs of heavy new physics in the PDFs?

[Ball et al., NNPDF4.0, 2109.02653]

Risk of absorbing new physics in PDFs?

Methodology for risk assessment

Perform a “NP absorption test”:

1. Choose a BSM model and a “true PDF” set
2. Produce BSM pseudodata
3. Fit PDFs on pseudodata assuming SM
4. Compare results with baseline PDFs (no BSM physics)

[2307.10370]

NP absorption criteria:

- Incompatible with baseline
- Fit quality does not deteriorate

➡ $\chi^2 = (Dat - Th)^\top \cdot \Sigma_{cov}^{-1} \cdot (Dat - Th)$

Risk:

➡ **PDFs have absorbed new physics signals**

BSM scenario: W' model

$pp \to l^- \bar{\nu} \quad M_{W'} = 13.8$ TeV

Generation of BSM pseudodata

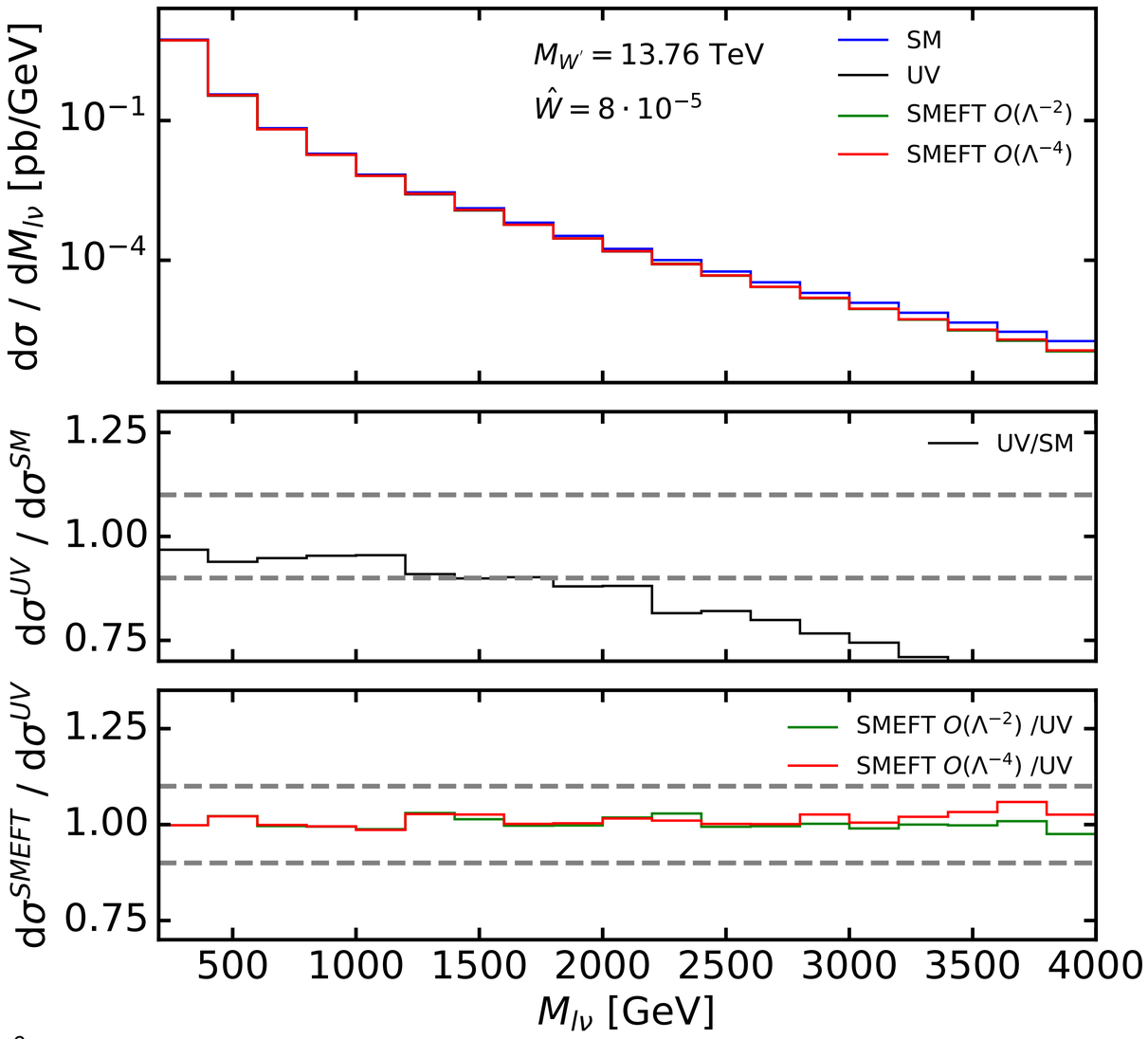
$$\mathscr{L}_{UV}^{W'} = \mathscr{L}_{SM} - \frac{1}{4} W'^{a}_{\mu\nu} W'^{a,\mu\nu} + \frac{1}{2} M_{W'}^2 W'^{a}_{\mu} W'^{a,\mu} - g_{W'} W'^{a,\mu} \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

$$\mathscr{L}_{SMEFT}^{W'} = \mathscr{L}_{SM} - \frac{g_{W'}^2}{2M_{W'}^2} J_L^{a,\mu} J_{L,\mu}^{a}$$

$$J_L^{a,\mu} = \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L$$

→ Impacts Drell-Yan

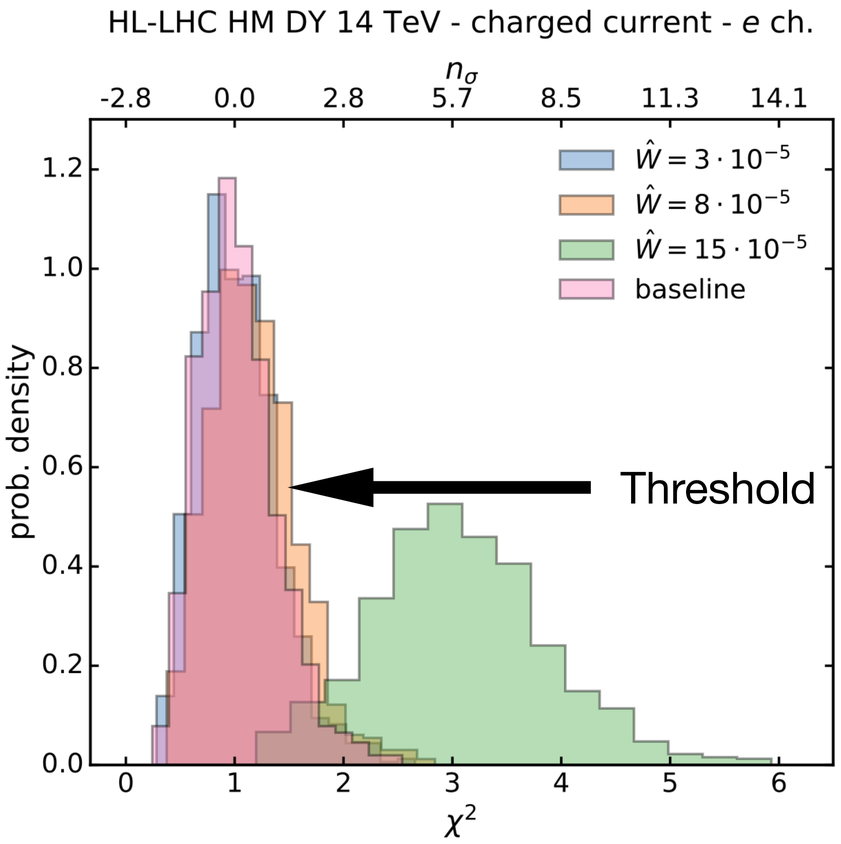
HL-LHC Projections



New physics absorption in the PDFs

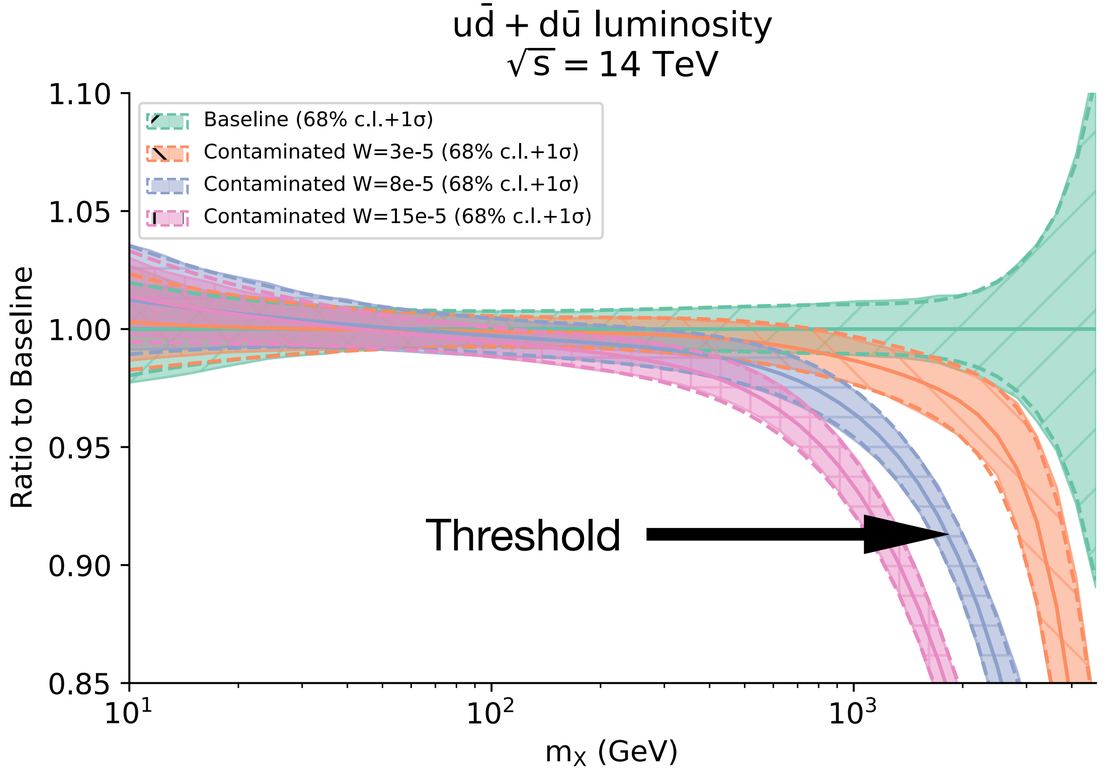
Comparison between BSM and baseline (SM) PDFs

Fit quality



$M_{W'} = 13.8$ TeV

Impact on PDFs

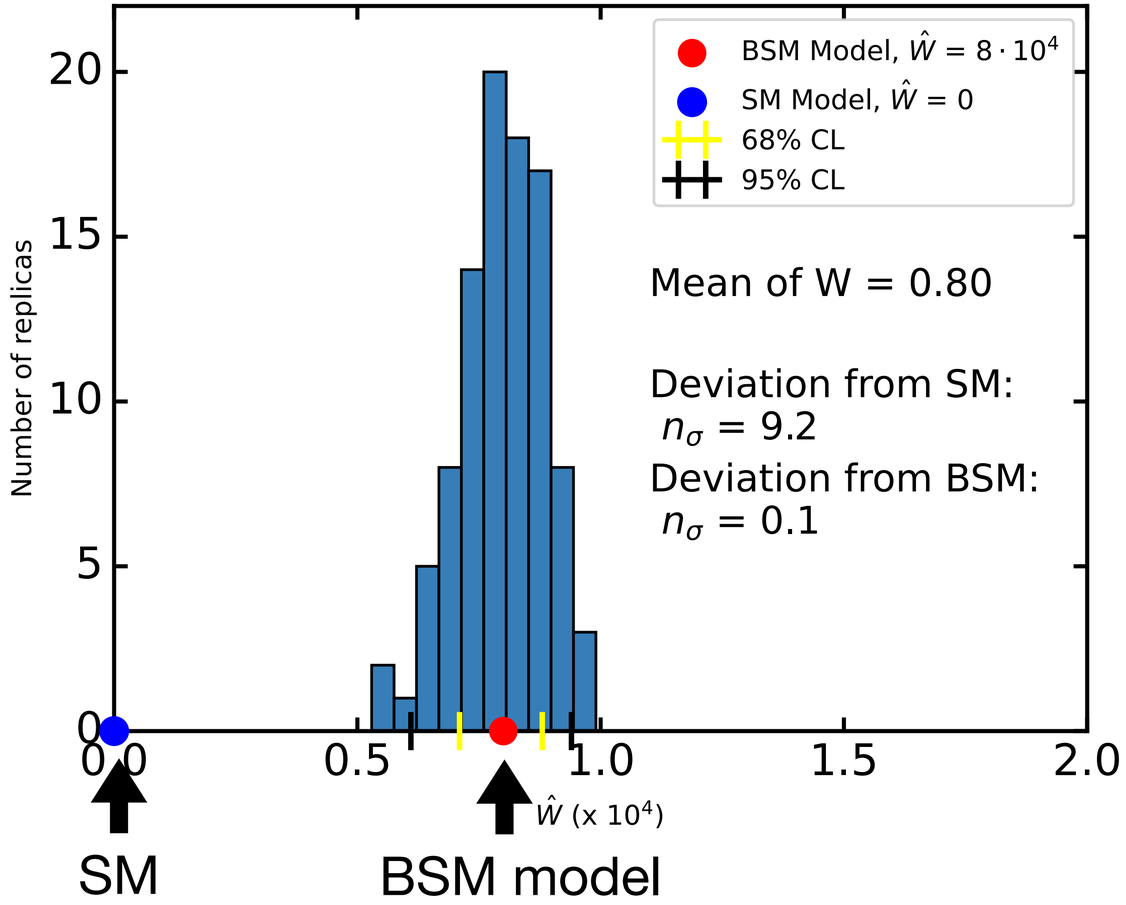


$$\sigma_{BSM}^{Data} \approx \hat{\sigma}_{SM} \otimes \mathscr{L}_{BSM}$$

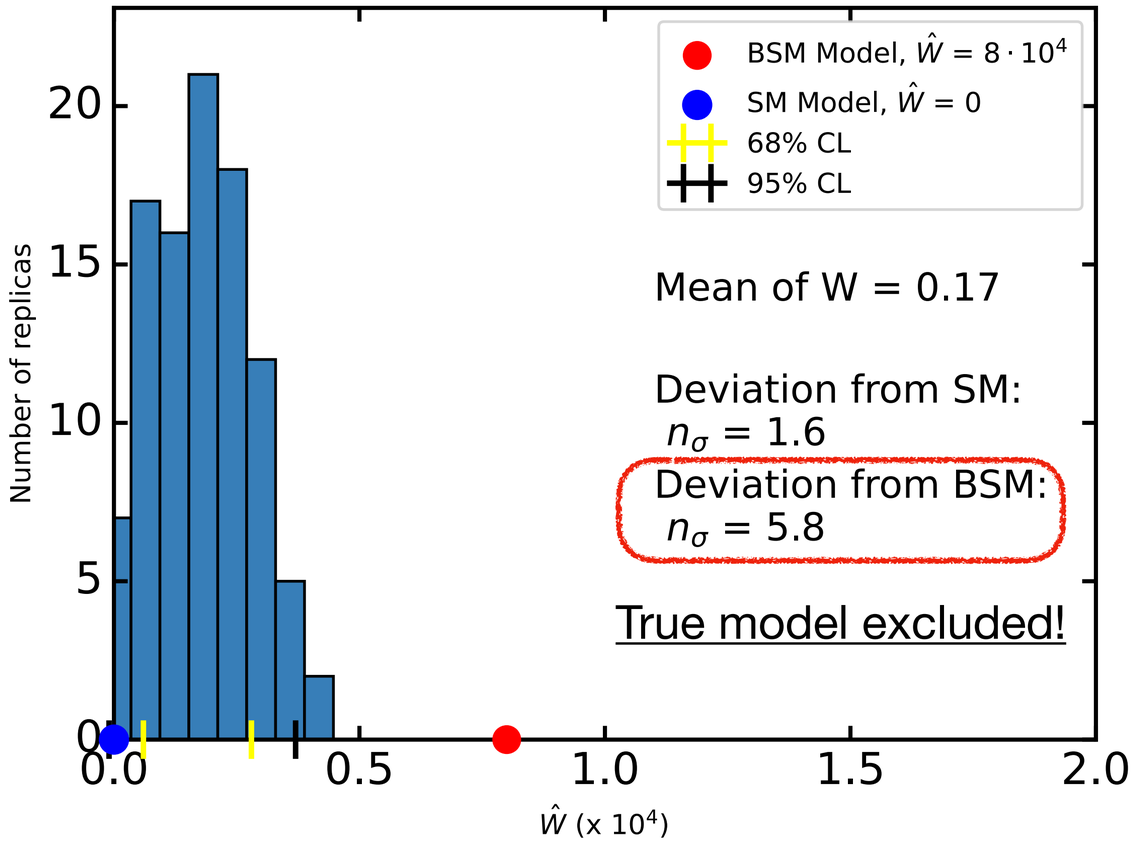
Missing new physics

Impact of the NP absorption in PDFs on SMEFT fits

SMEFT Fit with true PDF



SMEFT Fit with BSM PDF



Solution: synergy of high and low-energy data

Adding low-energy dataset constraining the large-x PDF region

Excessive antiquark PDF flexibility in large-x region:

➡ Accommodates real data and BSM pseudodata

➡ Allows NP absorption

Including low-energy large-x data:

- Constraint large-x region
- Safe from NP absorption

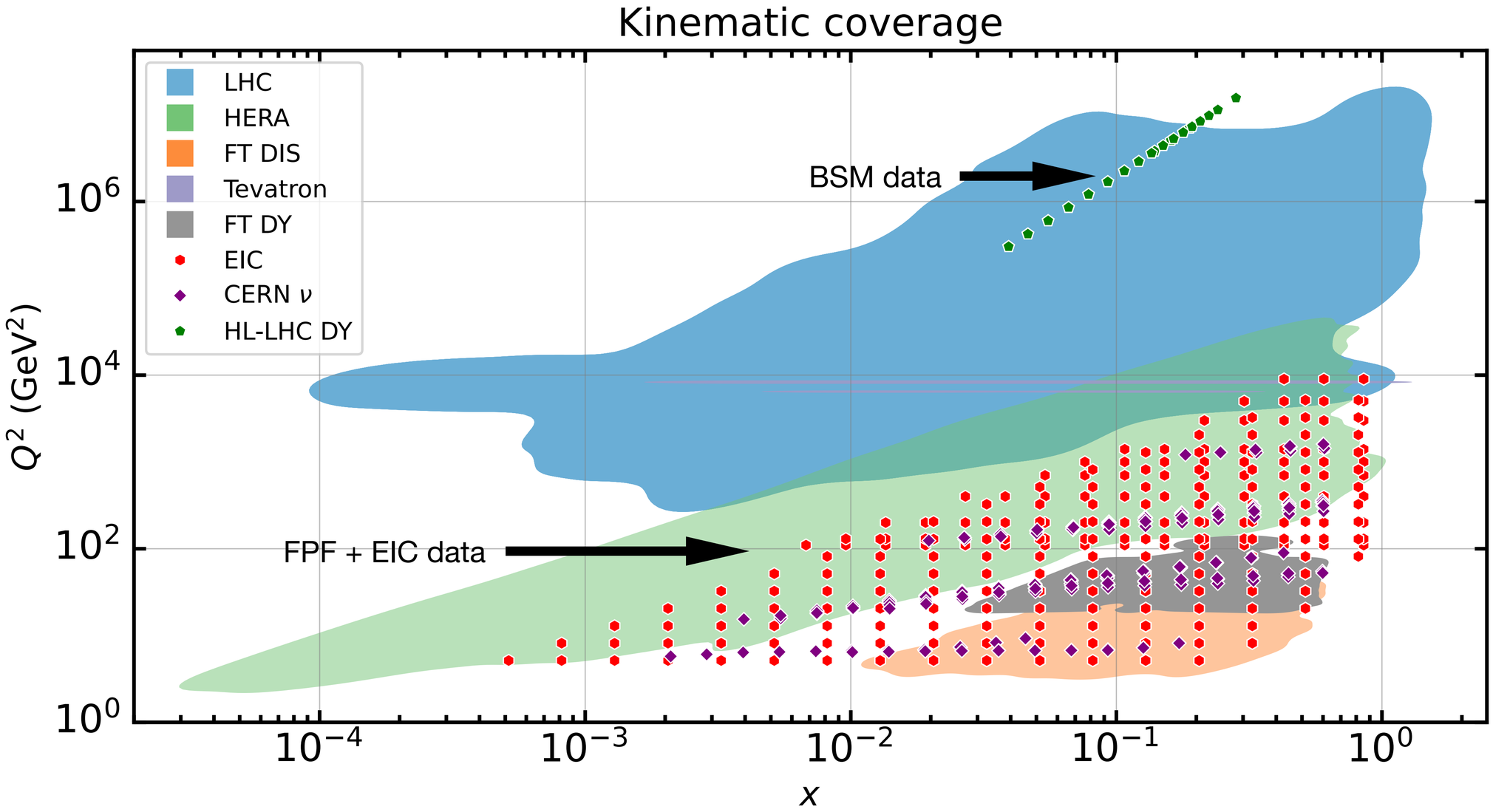
[Hammou et Ubiali, 2410.00963]

Projection data used:

- Electron Ion Collider (EIC)
- Forward Physics Facility (FPF)

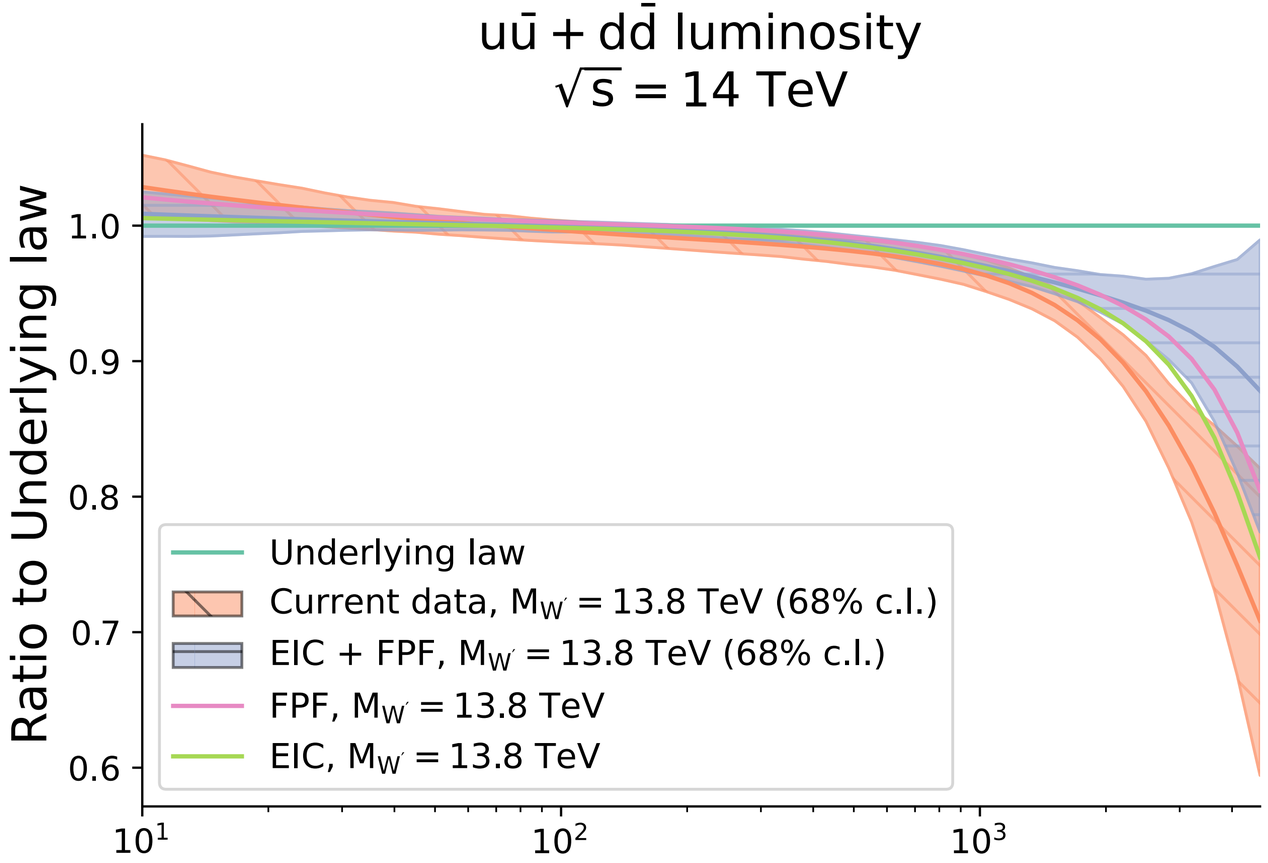
  (neutrino DIS)

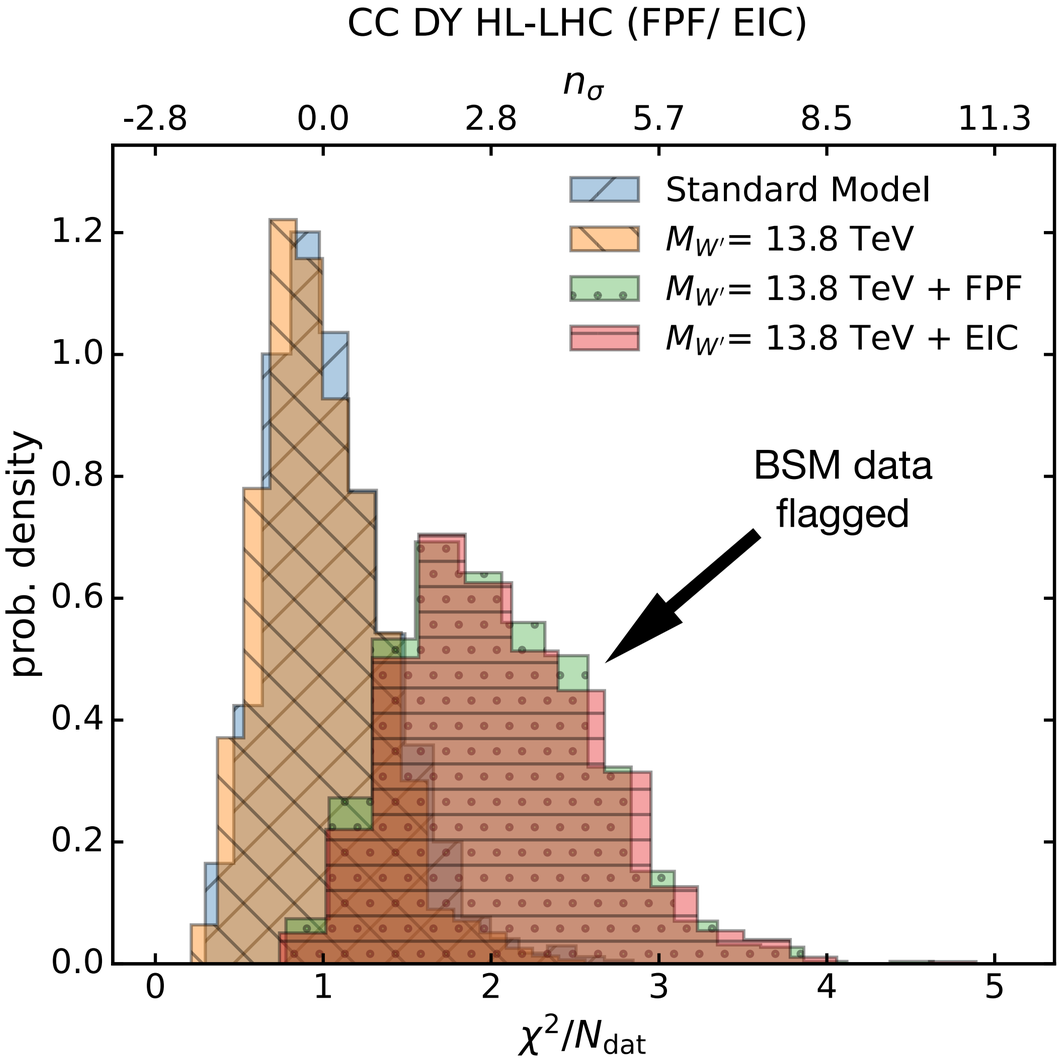
Future low energy data: kinematic coverage



Impact on the PDF contamination

Flagging the BSM data





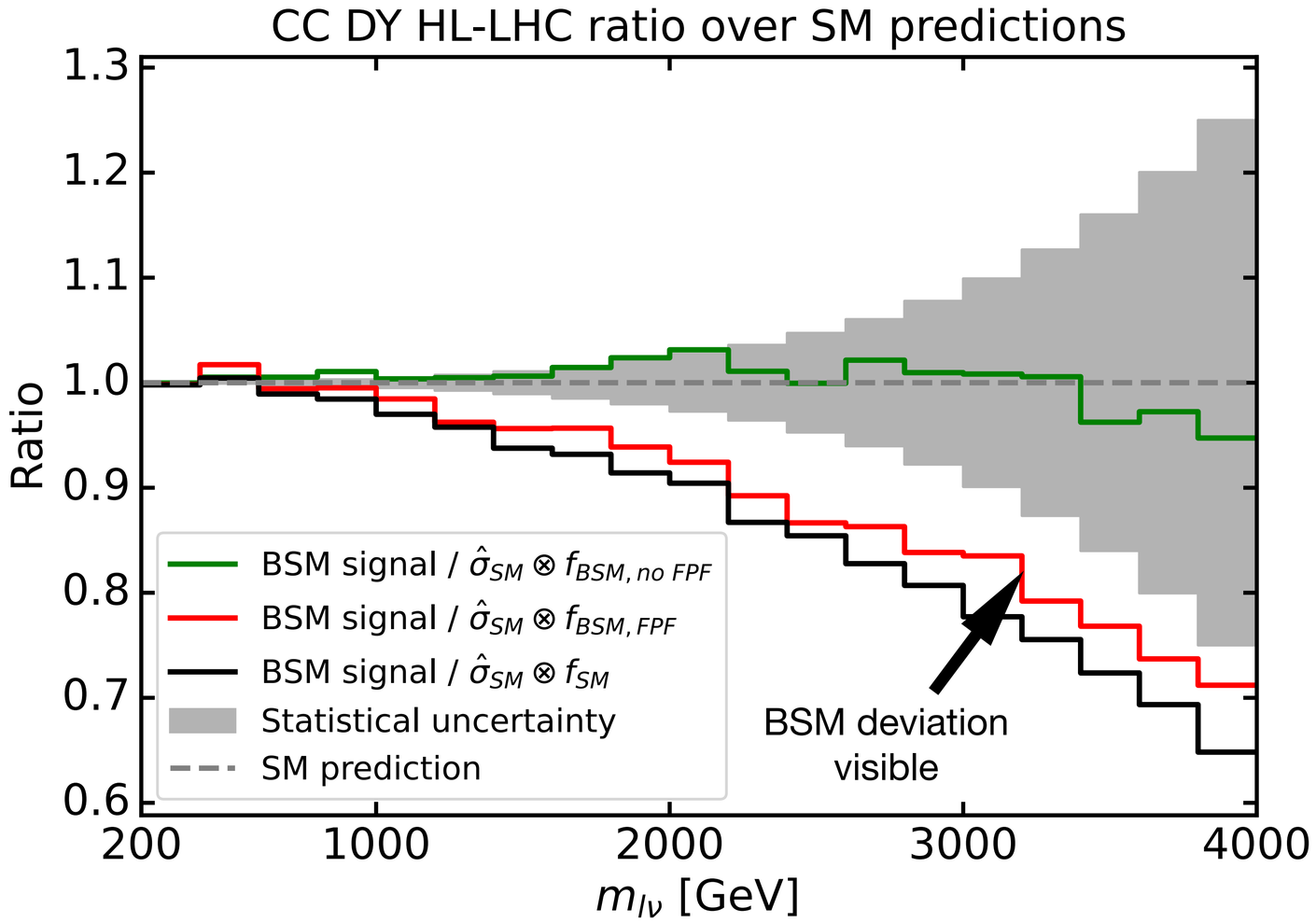
Recovering the signs of new physics

BSM data versus SM theory predictions

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

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

$M_{W'}$: 13.8 TeV



Shift of the contamination threshold: FPF

From the fit quality

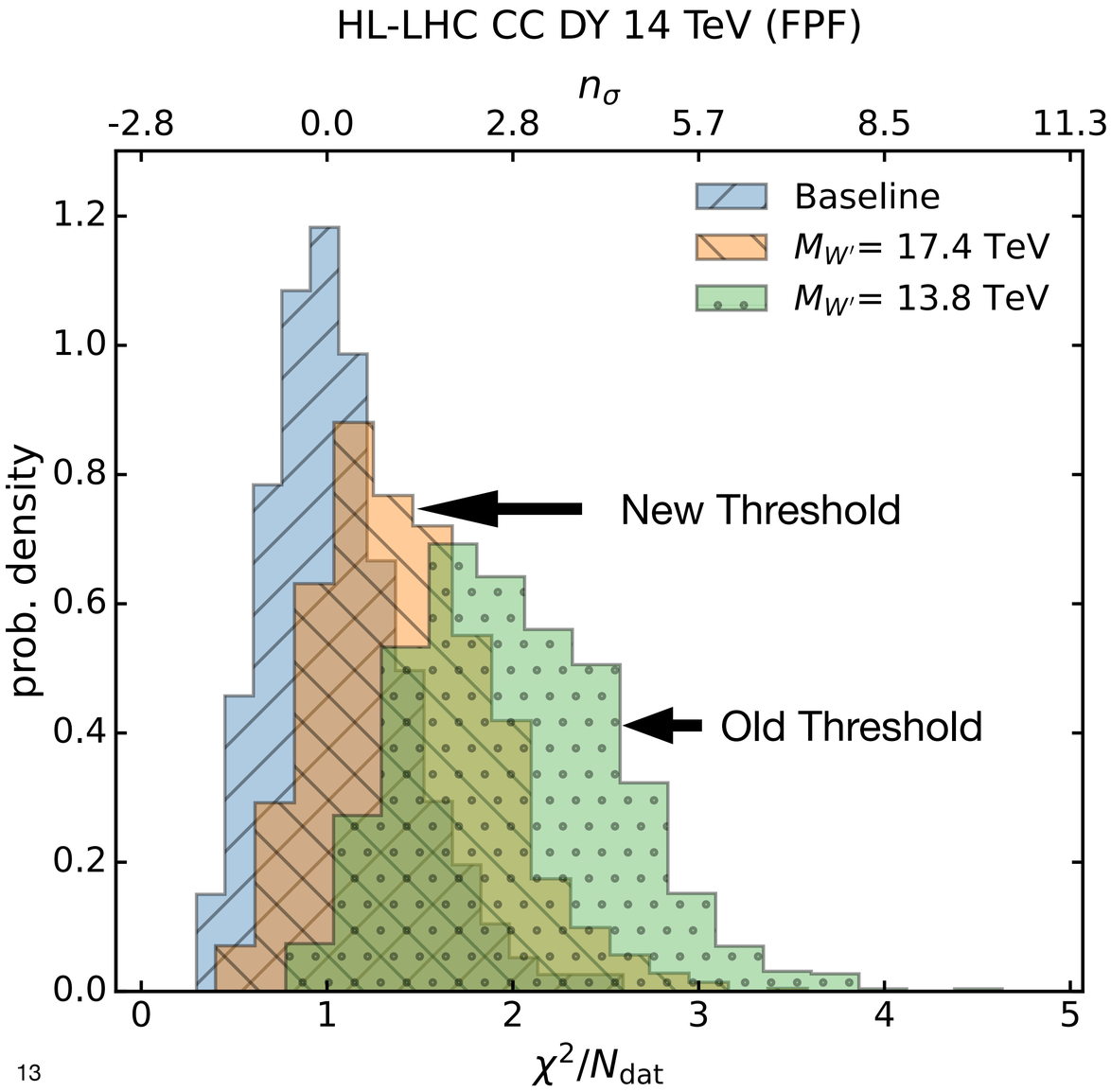
Not a complete solution:

Smaller deviations can still be absorbed

➡ risk at higher BSM mass

Reduction of the “blindspot”:

$$M_{W'} : 13.8 \rightarrow 17.4 \text{ TeV}$$



Shift of the contamination threshold: EIC

From the fit quality

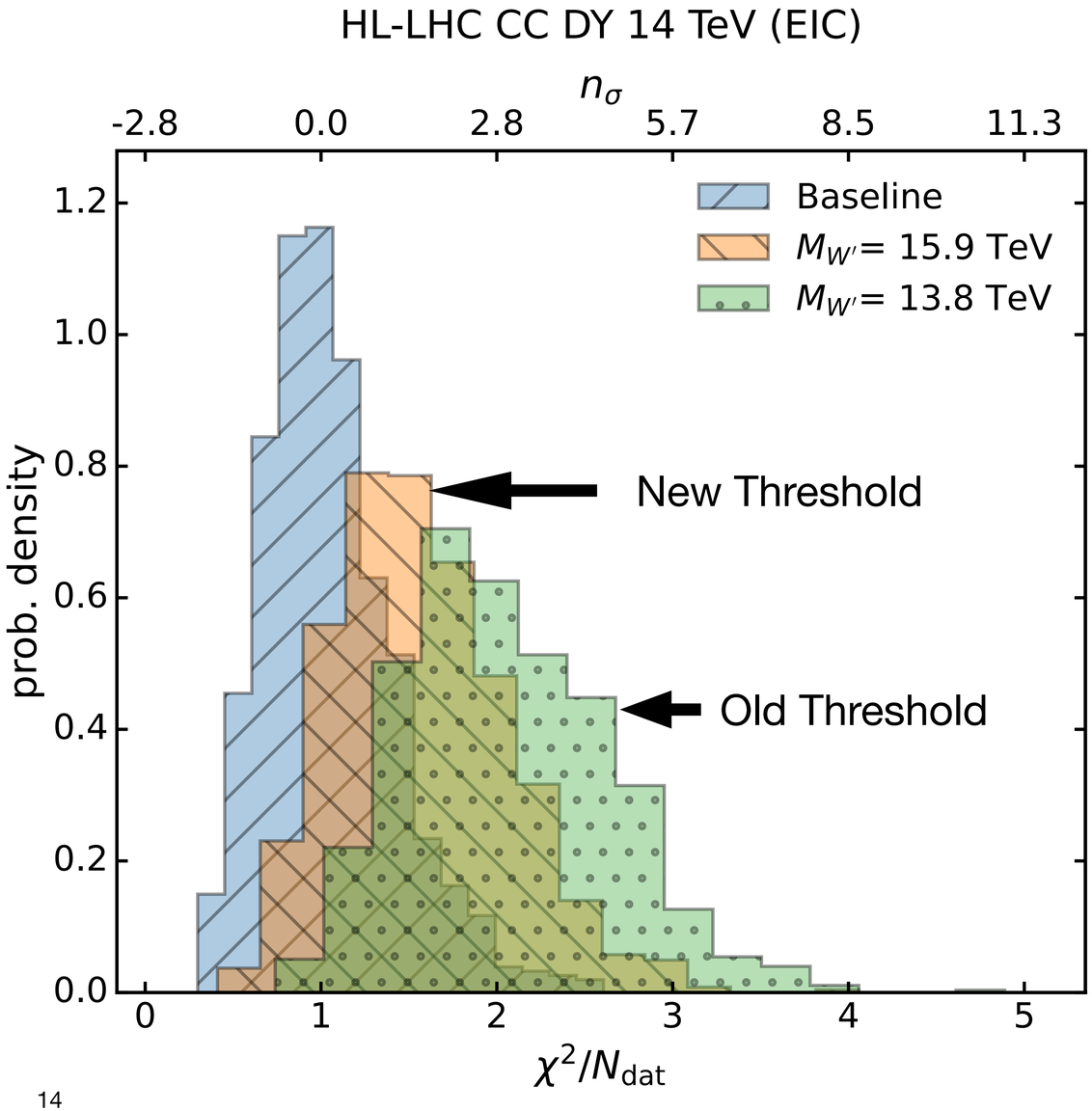
Not a complete solution:

Smaller deviations can still be absorbed

➡ risk at higher BSM mass

Reduction of the “blindspot”:

$M_{W'}: 13.8 \rightarrow 15.9$ TeV



Shift of the contamination threshold: FPF + EIC

From the fit quality

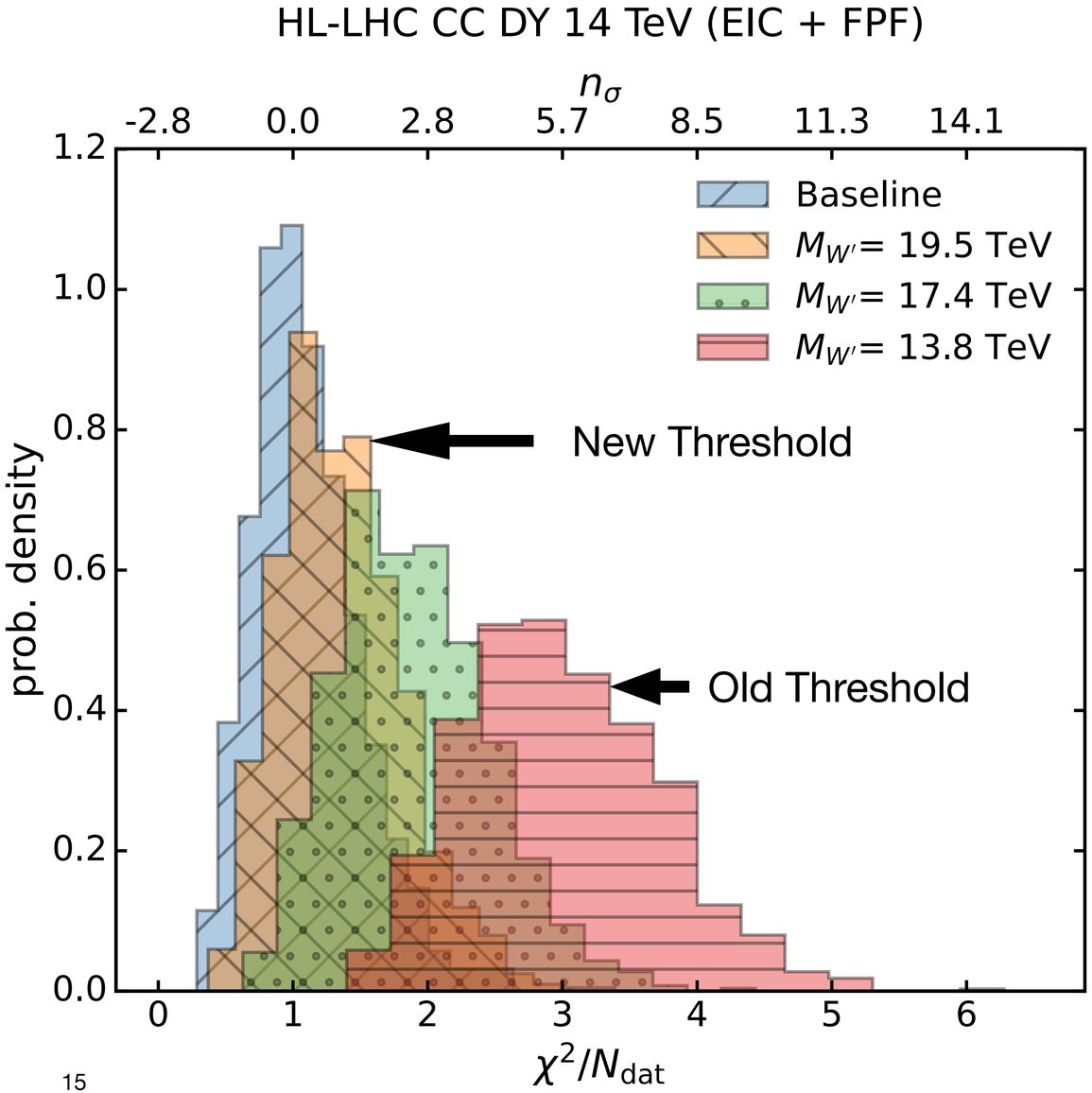
Not a complete solution:

Smaller deviations can still be absorbed

➡ risk at higher BSM mass

Reduction of the “blindspot”:

$$M_{W'} : 13.8 \rightarrow 19.5 \text{ TeV}$$



Summary and outlook

- Signs of W' got fitted away in PDF parametrisation
  - PDF mimic BSM behaviour
  - New physics is missed
- Constrain the PDFs more precisely:
  - Add precise large-x low-energy datasets into fits: FPF and EIC
  - Pushes the PDF/BSM mixing threshold toward higher energies
- More to come soon!
  - Working on other future DIS programmes: LHeC and FCC-eh [Hammou, Rojo et Ubiali, forthcoming]

You can contact me at:
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Thank you for your attention!

Extra slides

FPF and EIC projection data

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

TABLE IV: Summary of the EIC projected data included in this work, taken from Ref. [20].

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

TABLE V: Summary of the FPF projected data included in this work, taken from Ref. [21].

Simultaneous fit of PDF and new physics

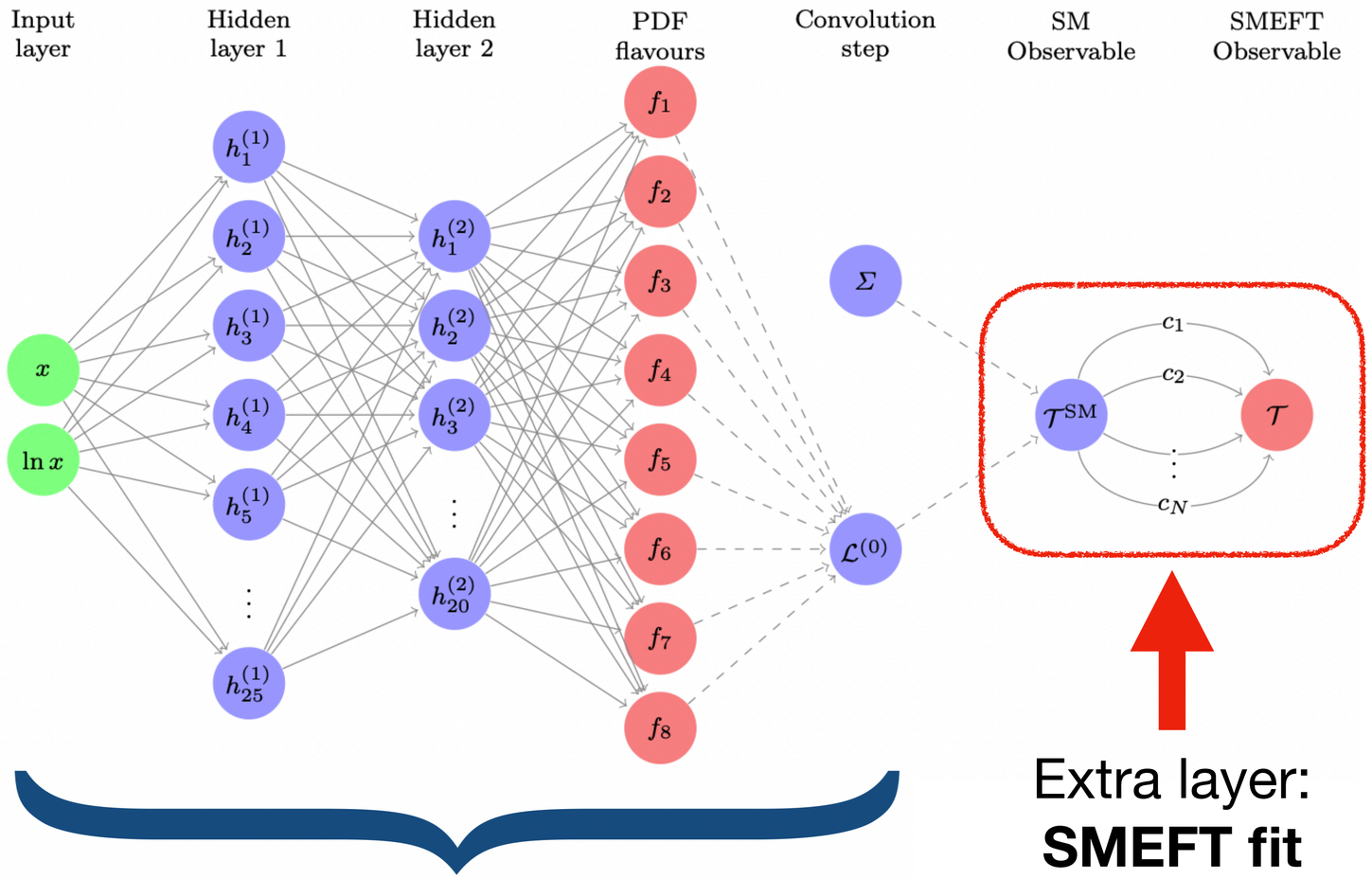
Presentation of the tool: SIMUnet

SIMUnet:

- Open-source tool: github.com/HEP-PBSP/SIMUnet

  [2402.03308]

- Fits PDFs and WC simultaneously

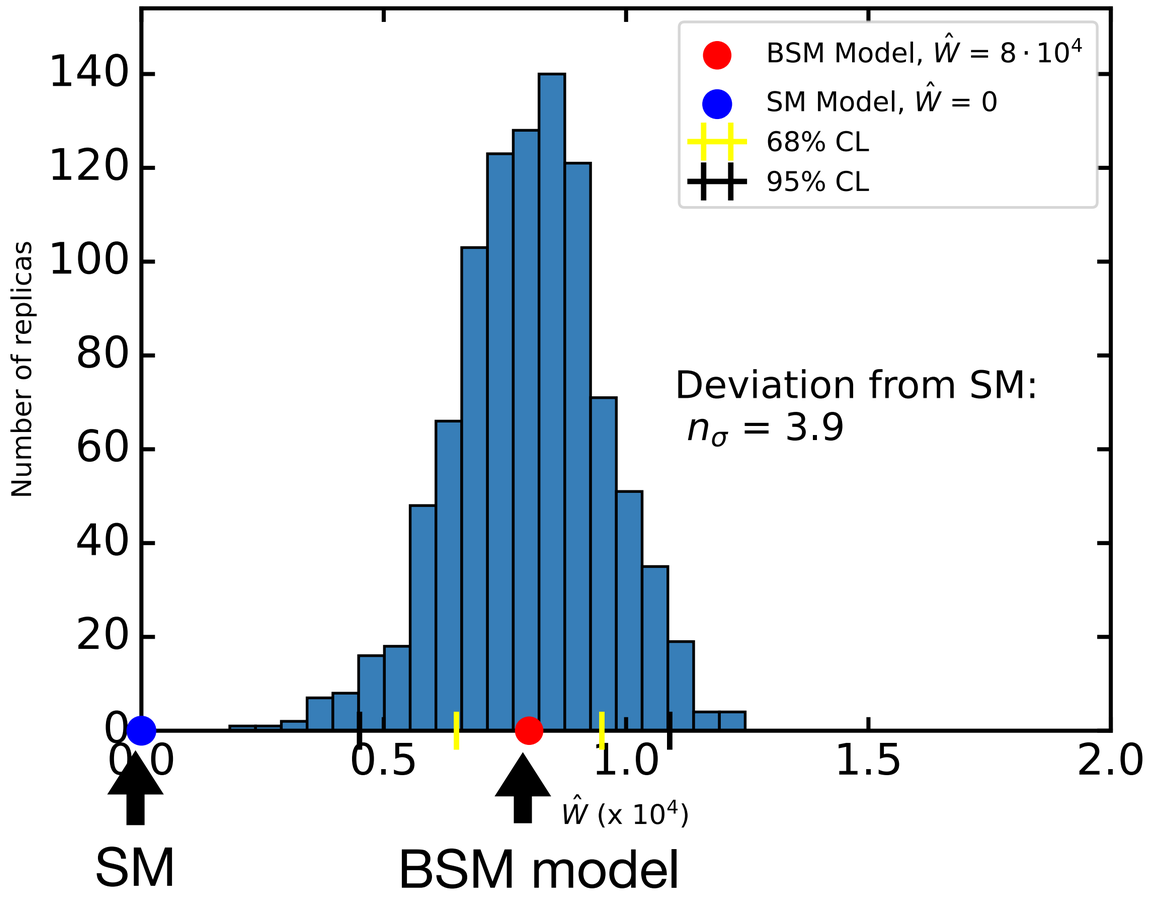


[Iranipour et Ubiali, 2201.07240]

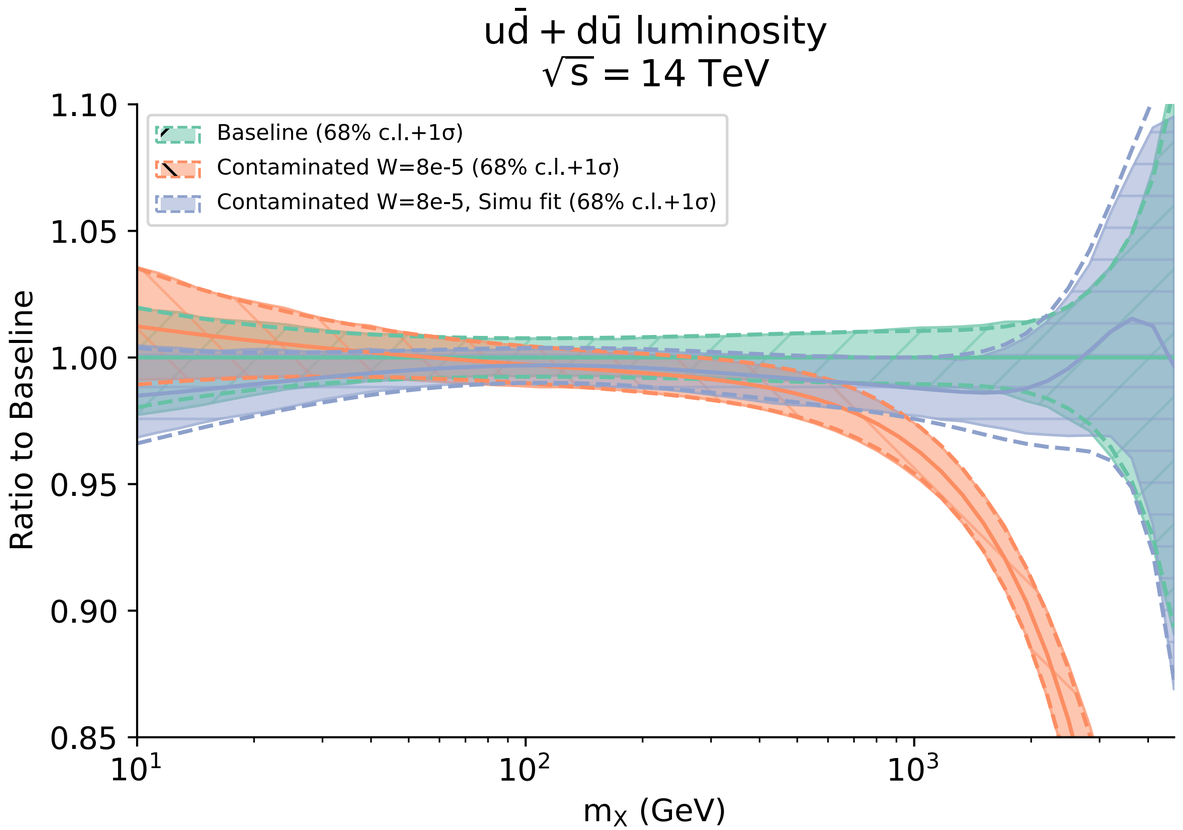
Simultaneous fit of PDF and new physics

Disentangling PDF contamination

SMEFT Fit



PDF Fit



New physics scenarios: Z'

Generation of the pseudodata

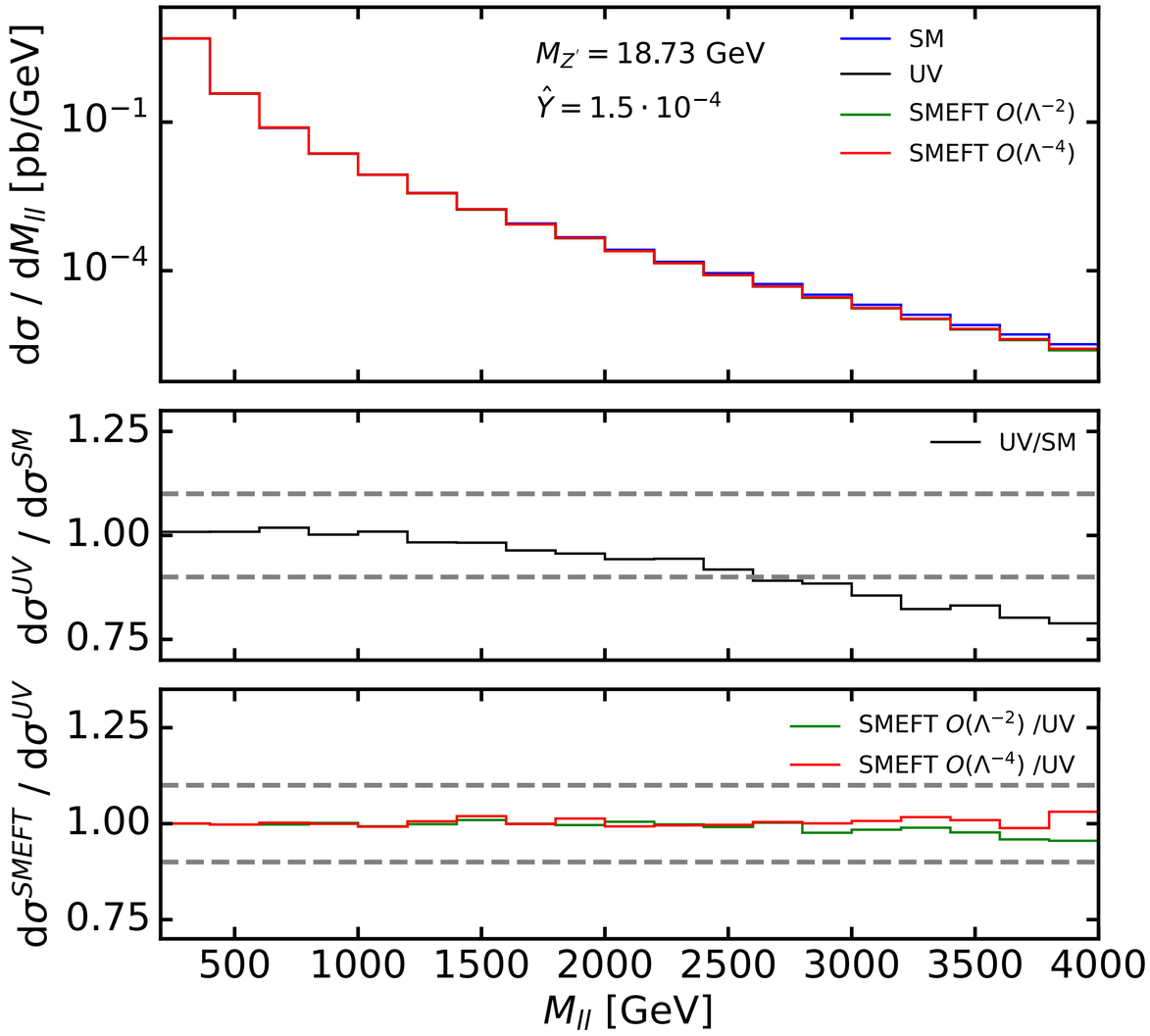
$$\mathscr{L}^{Z'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2_{Z'}}{2M^2_{Z'}} J^{\mu}_{Y} J_{Y,\mu}$$

$$J^{\mu}_{Y} = \sum_{f} Y_f \bar{f} \gamma^{\mu} f$$

Impacts neutral current Drell-Yan processes

$$p\bar{p} \to l^+ l^-$$

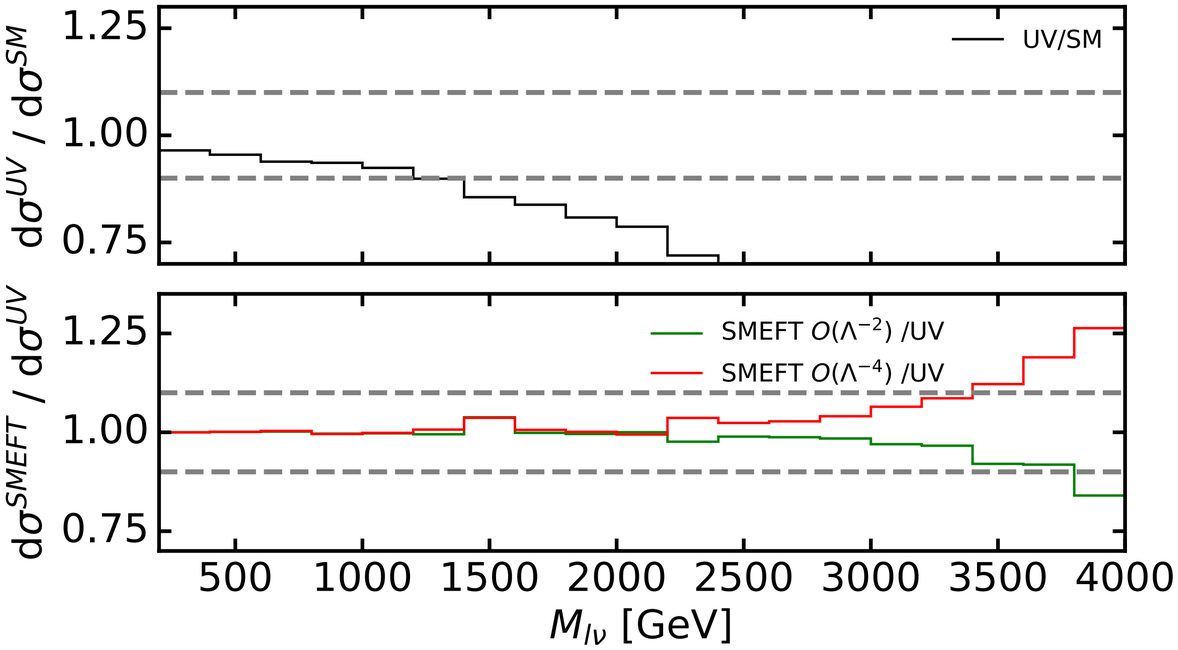
$M_{Z'} = 18.7$ TeV



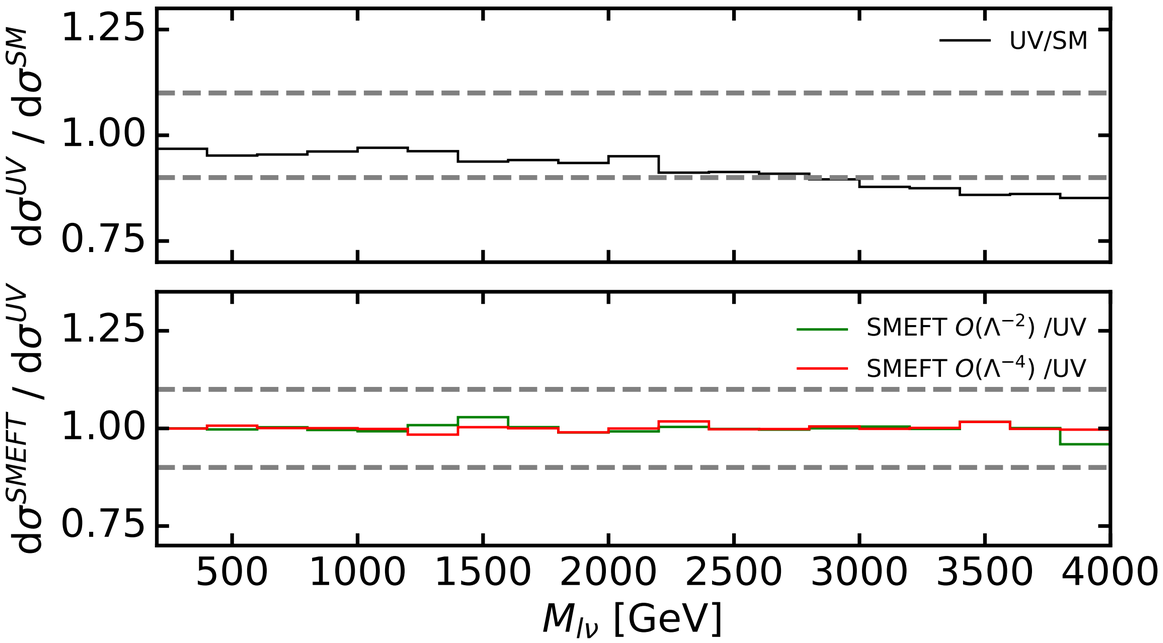
New physics scenarios: W'

Consideration of different masses

$M_{W'} = 10$ TeV



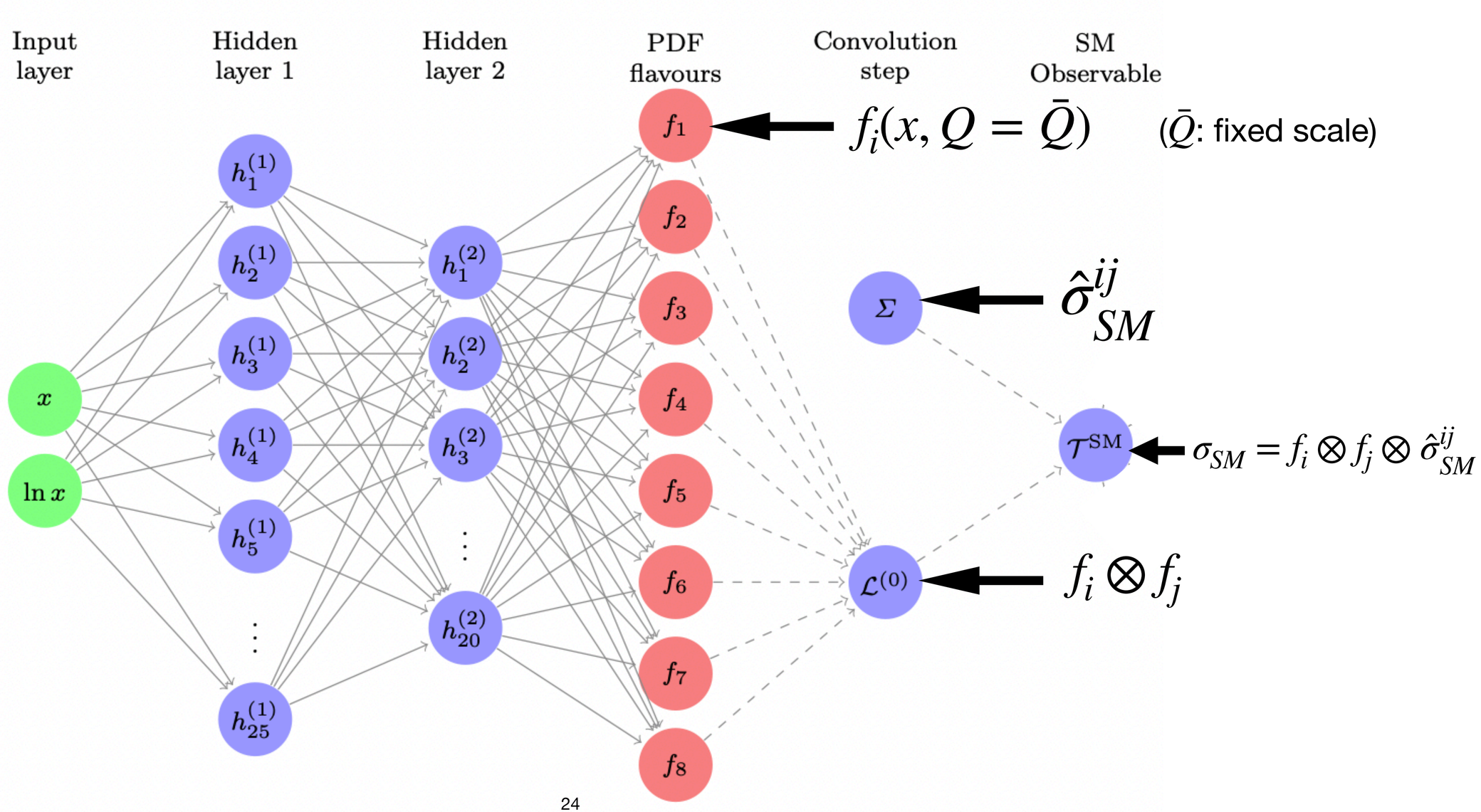
$M_{W'} = 22.5$ TeV



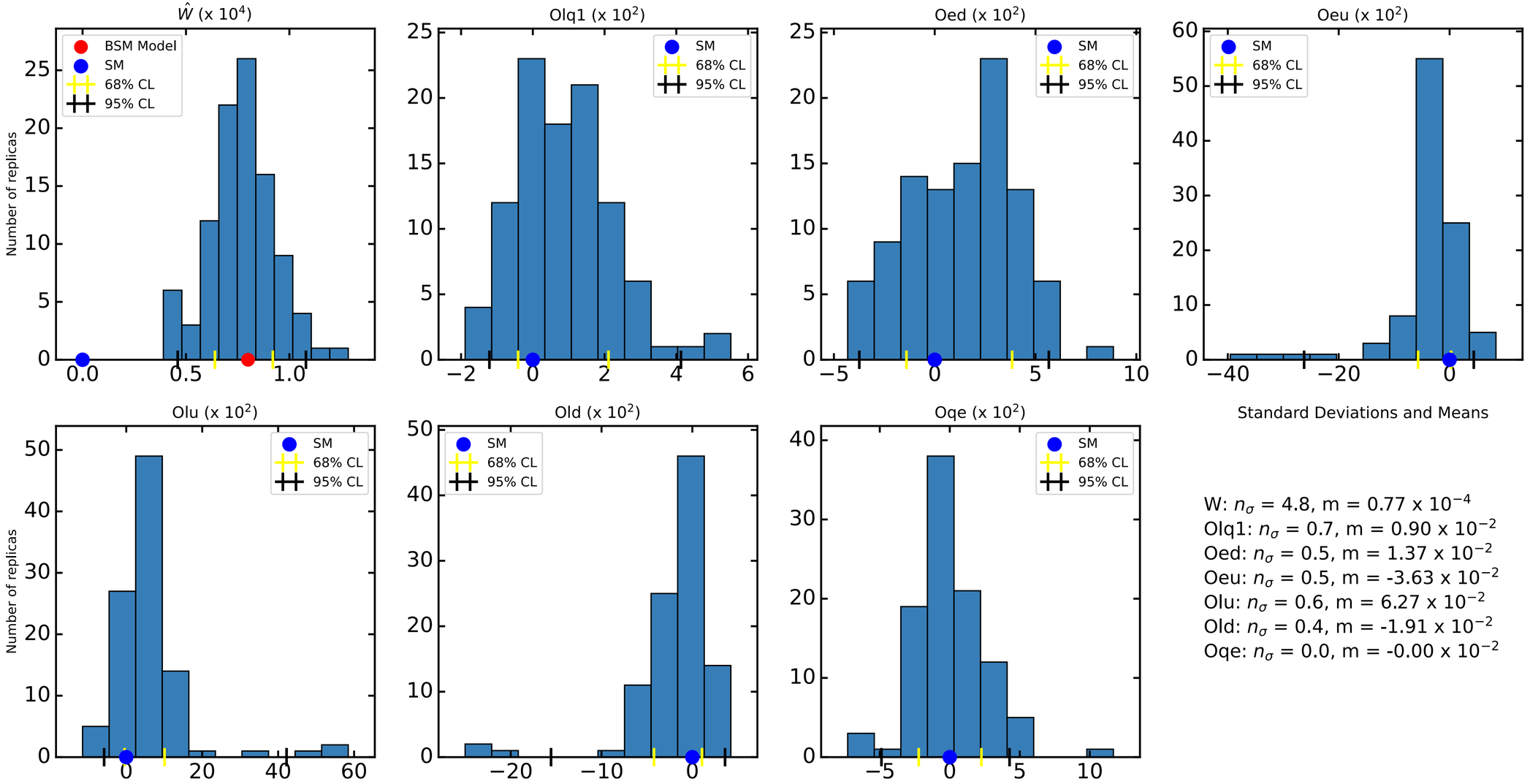
List of deviations

	HL-LHC		Stat. improved	
Dataset	$\chi^2/n_{\rm dat}$	n_σ	$\chi^2/n_{\rm dat}$	n_σ
W^+H	1.17	0.41	1.77	1.97
W^-H	1.08	0.19	1.08	0.19
W^+Z	1.08	0.19	1.49	1.20
W^-Z	0.99	-0.03	1.02	0.05
ZH	1.19	0.44	1.67	1.58
W^+W^-	2.19	3.04	2.69	4.31
VBF $\rightarrow$ H	0.70	-0.74	0.62	-0.90

NNPDF methodology

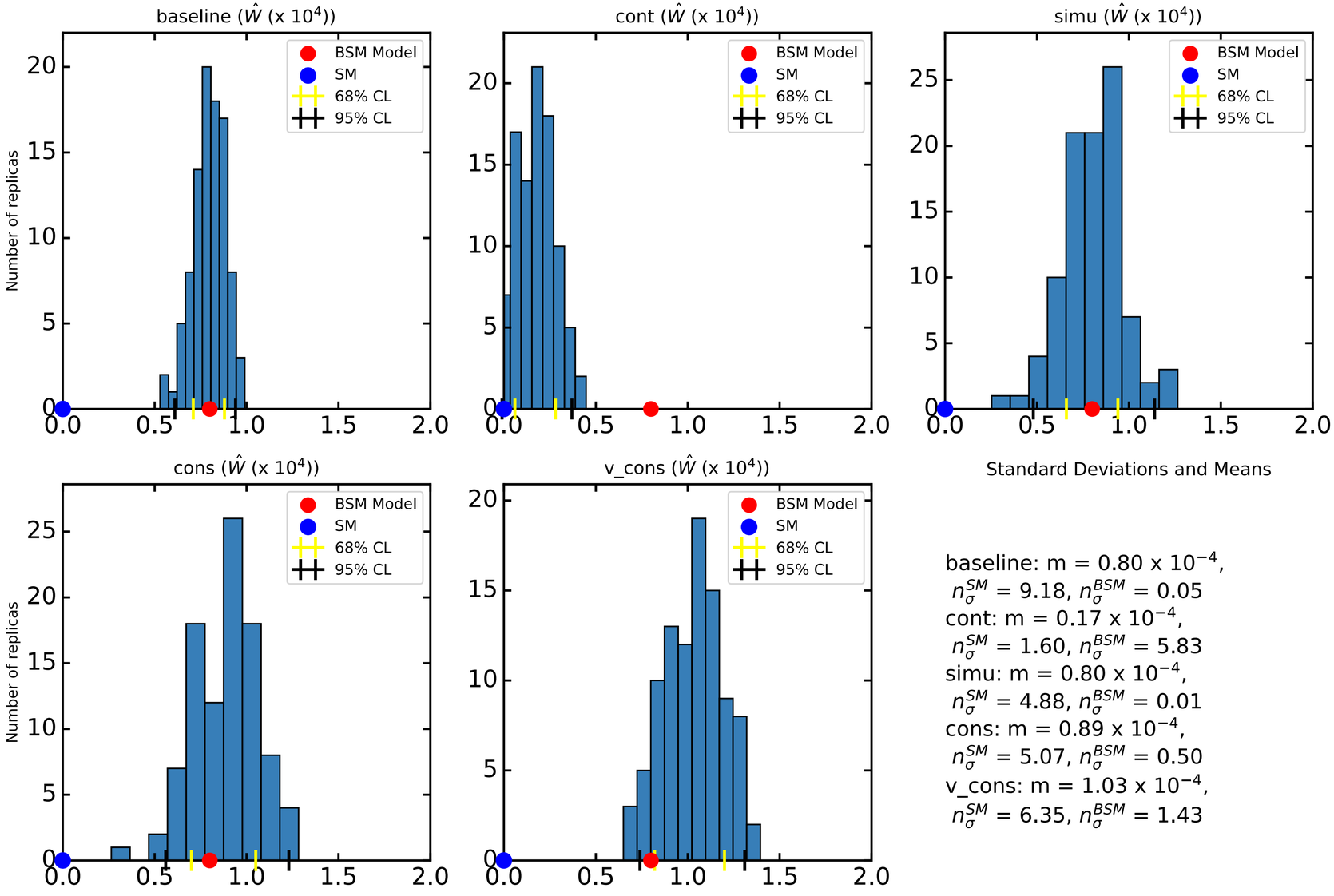


Global SMEFT fit, 4 fermions operators



W: n_σ = 4.8, m = 0.77 x 10^{-4}
Olq1: n_σ = 0.7, m = 0.90 x 10^{-2}
Oed: n_σ = 0.5, m = 1.37 x 10^{-2}
Oeu: n_σ = 0.5, m = -3.63 x 10^{-2}
Olu: n_σ = 0.6, m = 6.27 x 10^{-2}
Old: n_σ = 0.4, m = -1.91 x 10^{-2}
Oqe: n_σ = 0.0, m = -0.00 x 10^{-2}

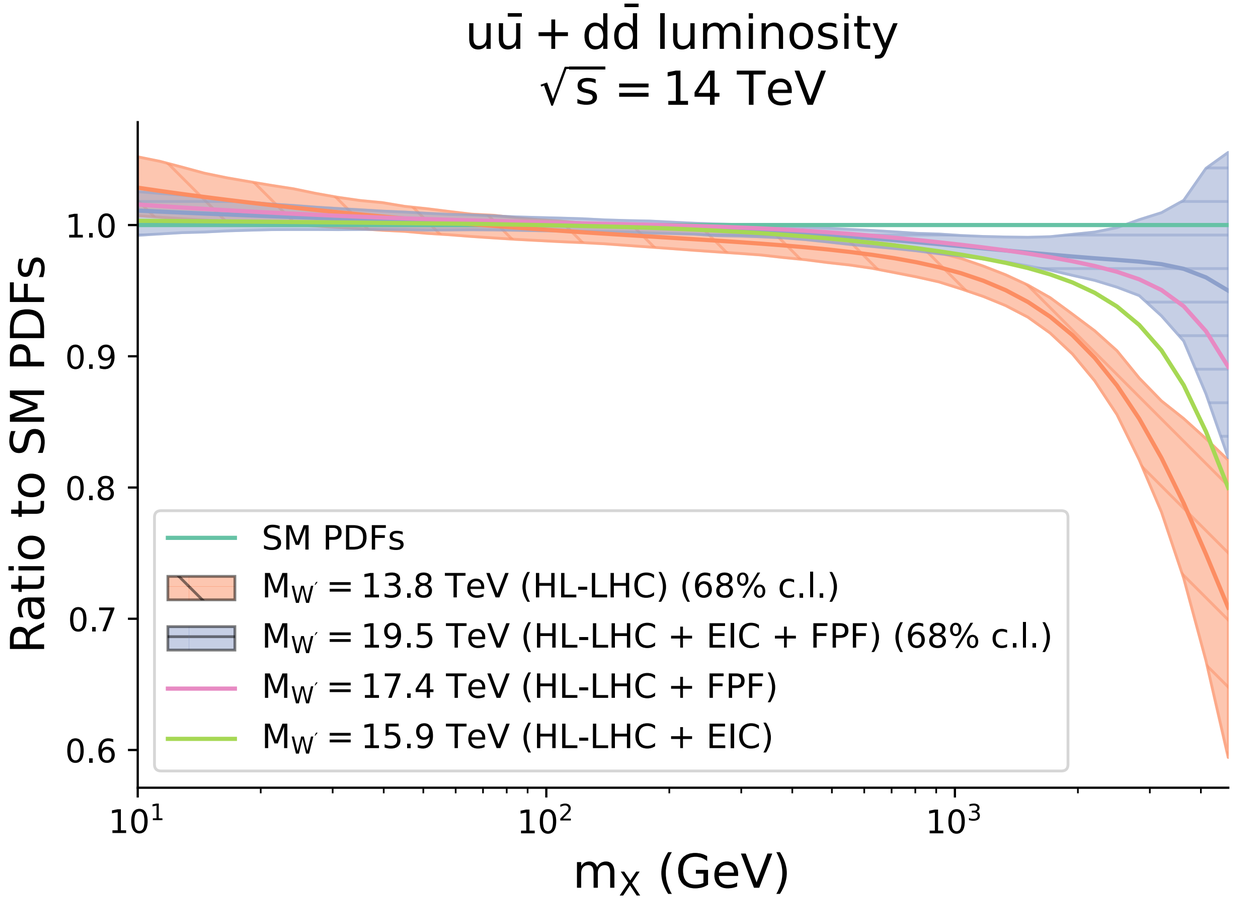
SMEFT fits with different PDFs

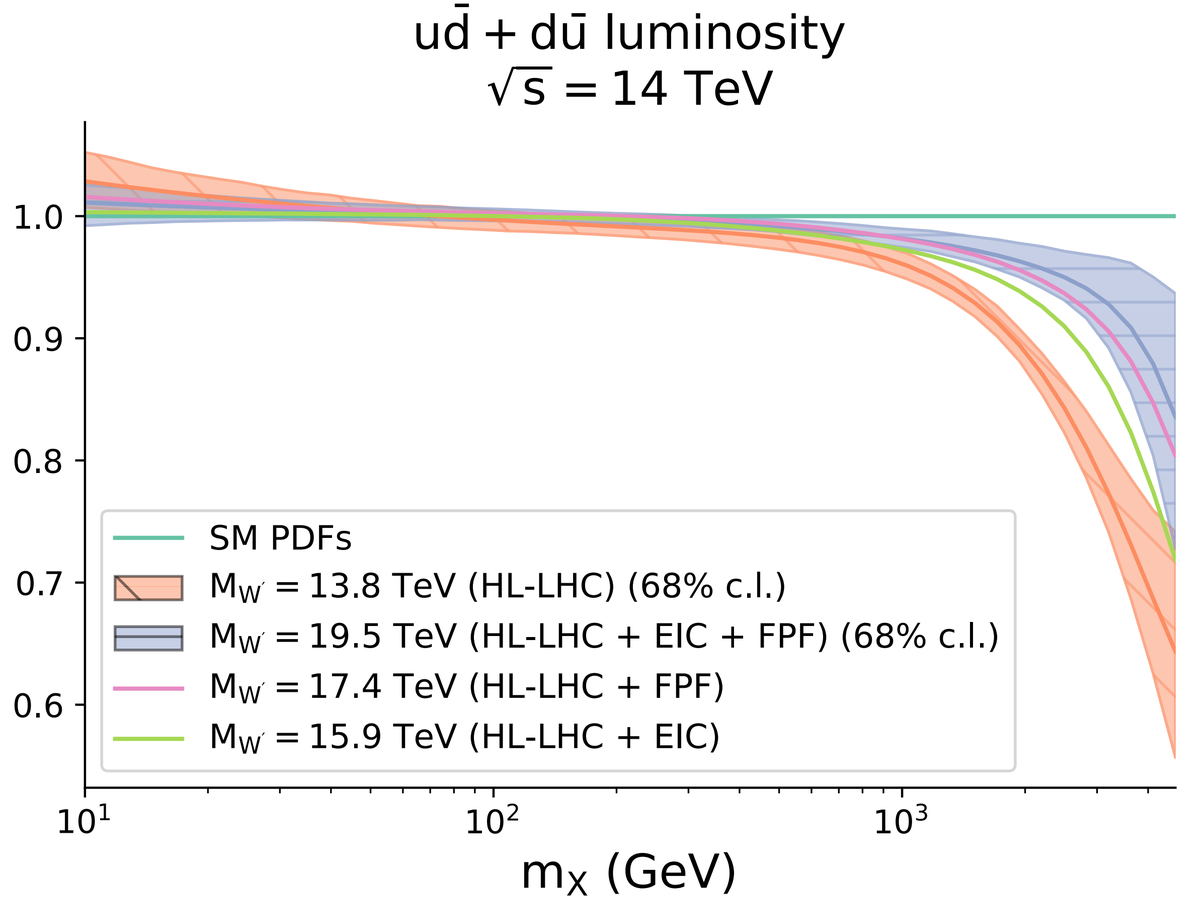


baseline: m = 0.80 x 10^{-4},
n_σ^{SM} = 9.18, n_σ^{BSM} = 0.05
cont: m = 0.17 x 10^{-4},
n_σ^{SM} = 1.60, n_σ^{BSM} = 5.83
simu: m = 0.80 x 10^{-4},
n_σ^{SM} = 4.88, n_σ^{BSM} = 0.01
cons: m = 0.89 x 10^{-4},
n_σ^{SM} = 5.07, n_σ^{BSM} = 0.50
v_cons: m = 1.03 x 10^{-4},
n_σ^{SM} = 6.35, n_σ^{BSM} = 1.43

Shift of the contamination threshold

Impact on PDF luminosities

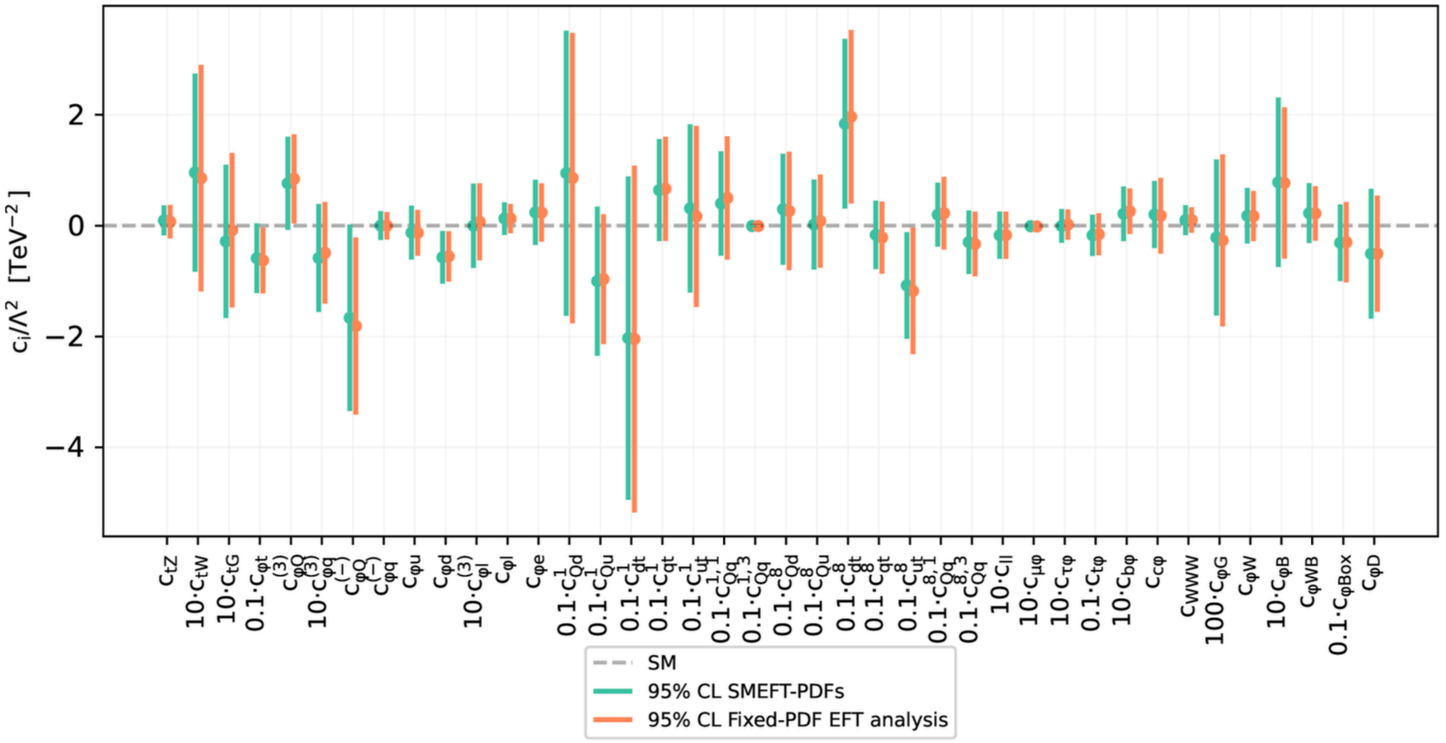




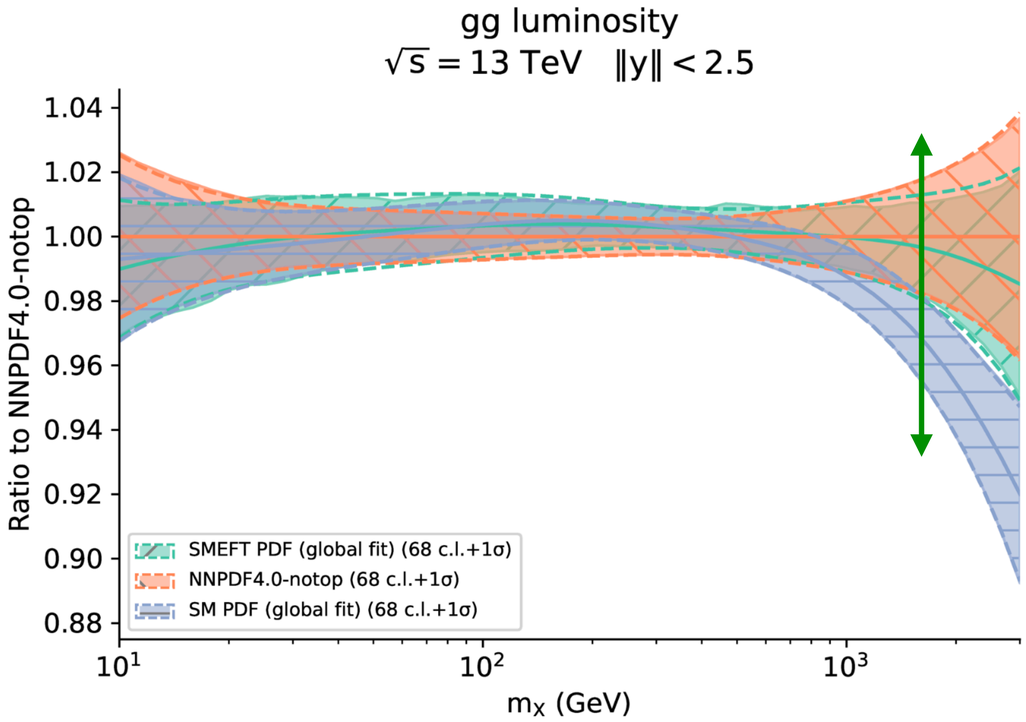
Application to the top sector (real data)

In progress

SMEFT Fit

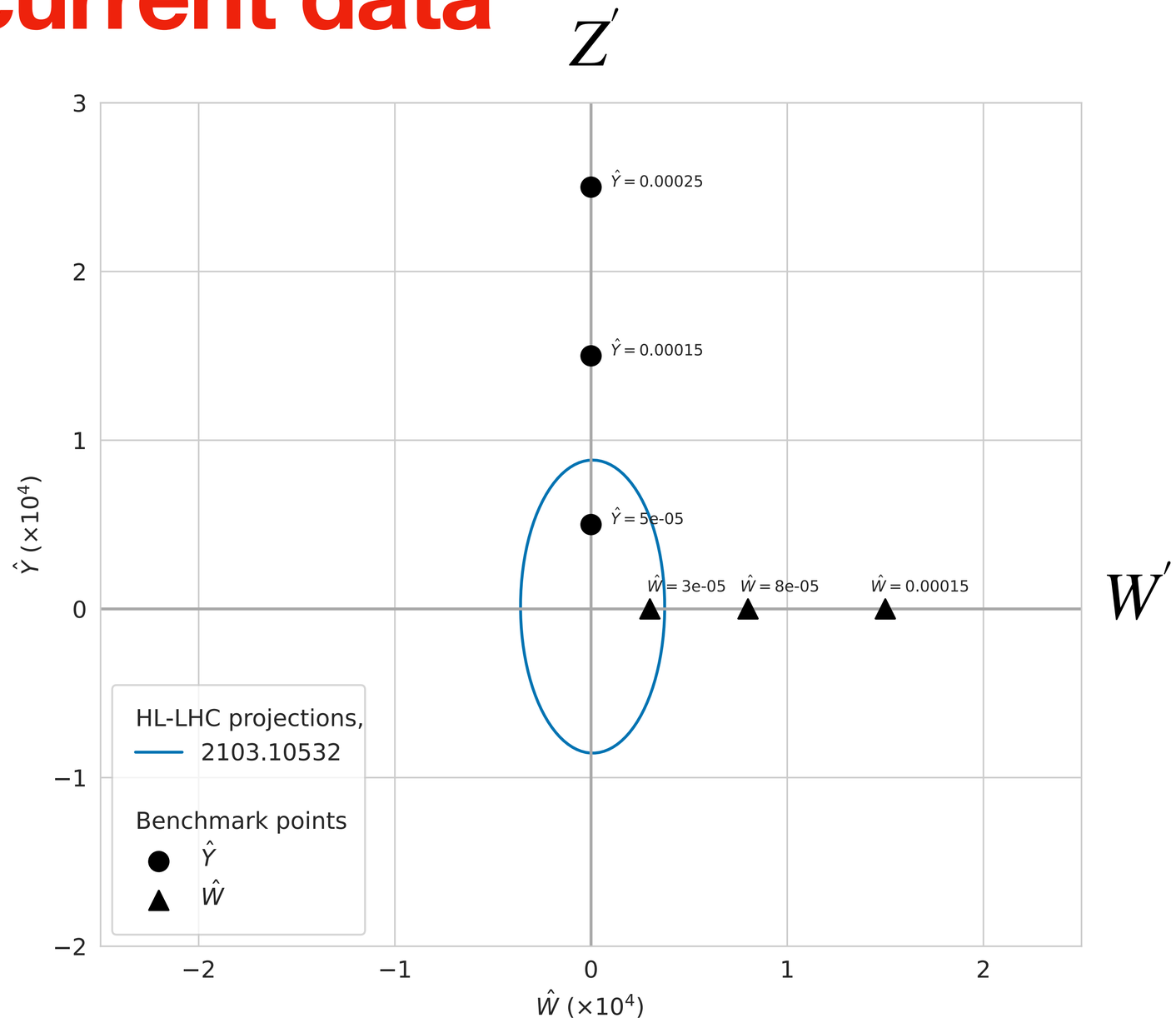


PDF Fit



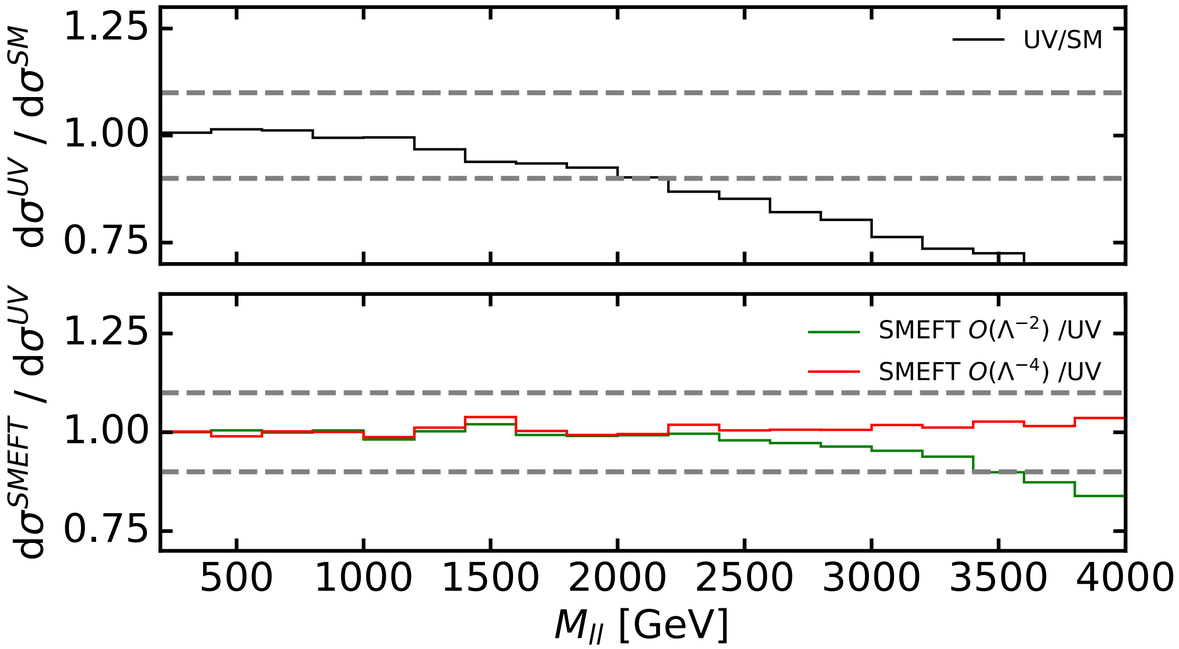
Constraints from current data

- New physics scenarios compared to constraints at 95% CL

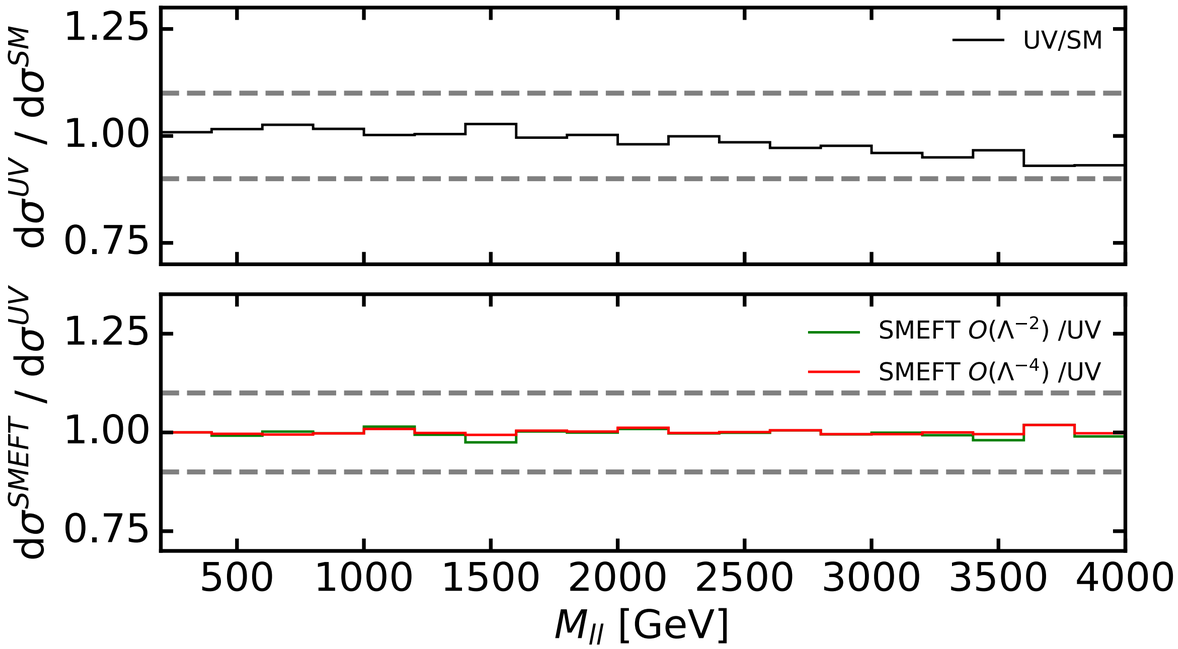


New physics scenarios: Z'

$M_{Z'} = 14.5$ TeV

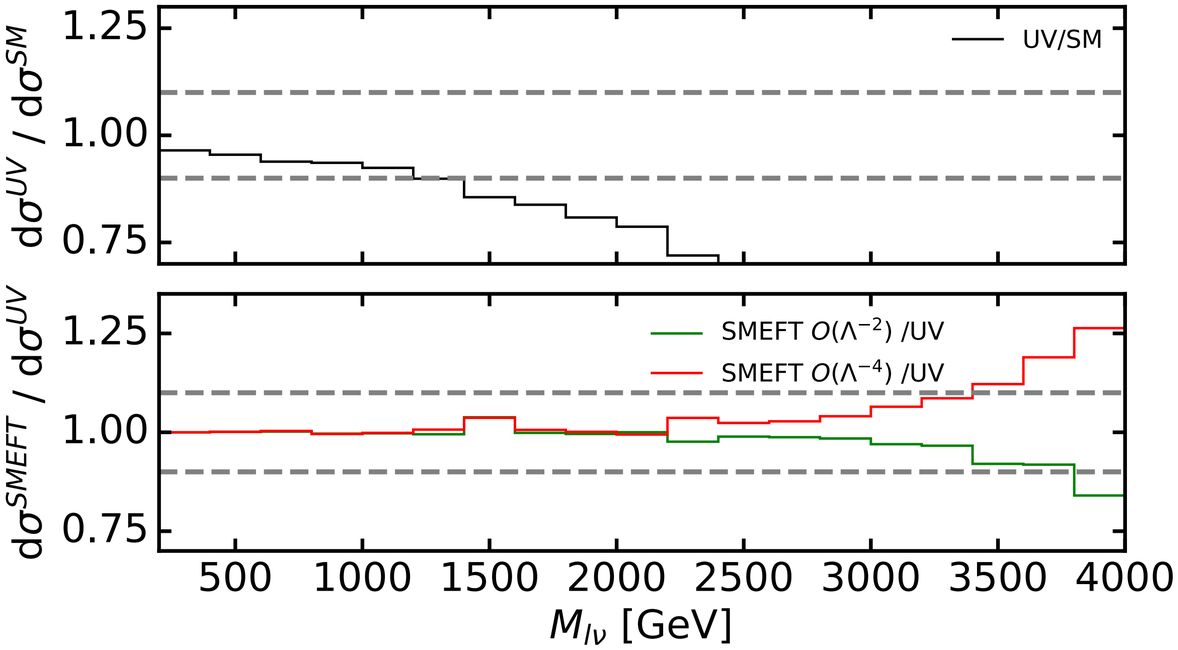


$M_{Z'} = 32.5$ TeV



New physics scenarios: W'

$M_{W'} = 10$ TeV



$M_{W'} = 22.5$ TeV