PDFs and SMEFT interplay

[Hammou et al. (PBSP + Mangano), 2307.10370, JHEP]

[Costantini et al. (PBSP), 2402.03308, Eur.Phys.J.C]

[Cole et al. (PBSP), forthcoming]

European Research Council

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PBSP

Elie Hammou

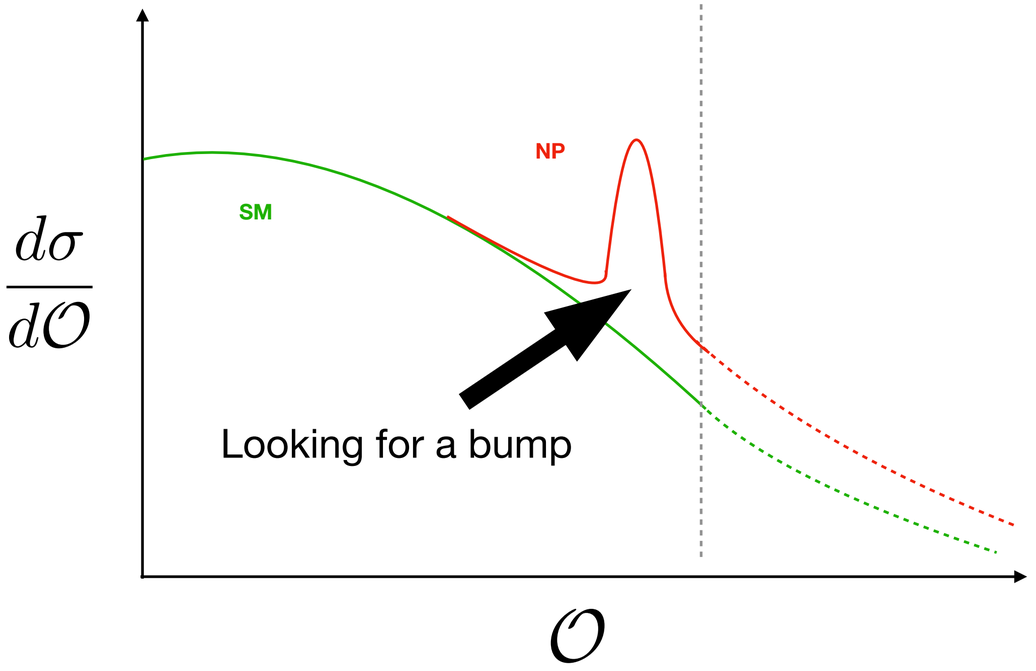
ATLAS UK PDF meeting, Queen Mary University of London, September 2025

New physics searches

Looking toward higher energy scales and indirect searches

Direct searches

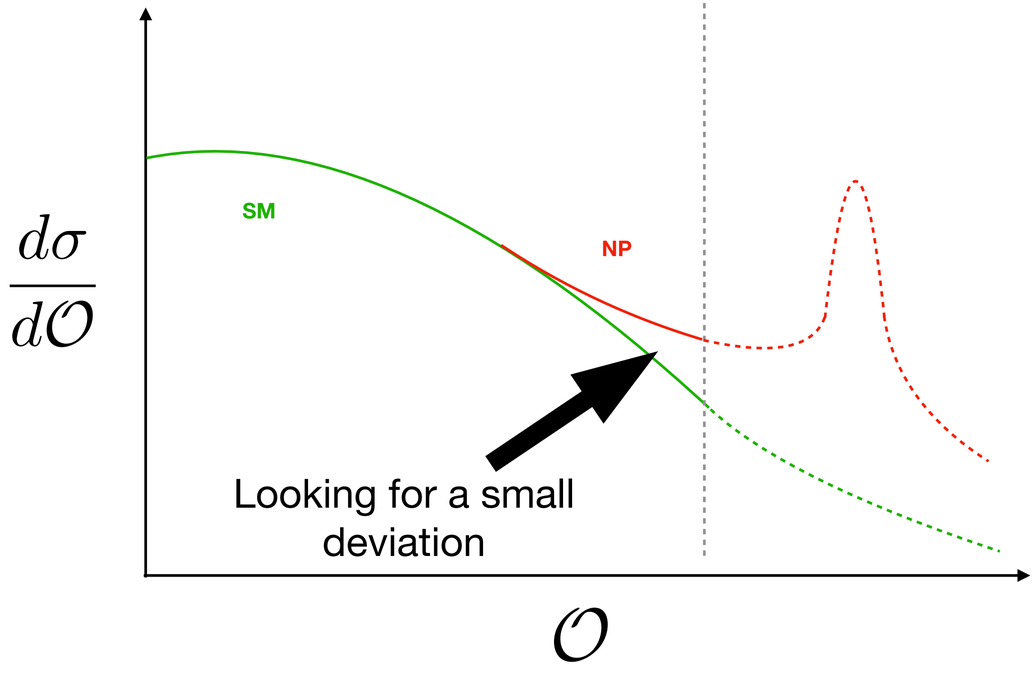
$E_{NP} < E_{collider}$



No luck so far…

Indirect searches

$E_{NP} > E_{collider}$



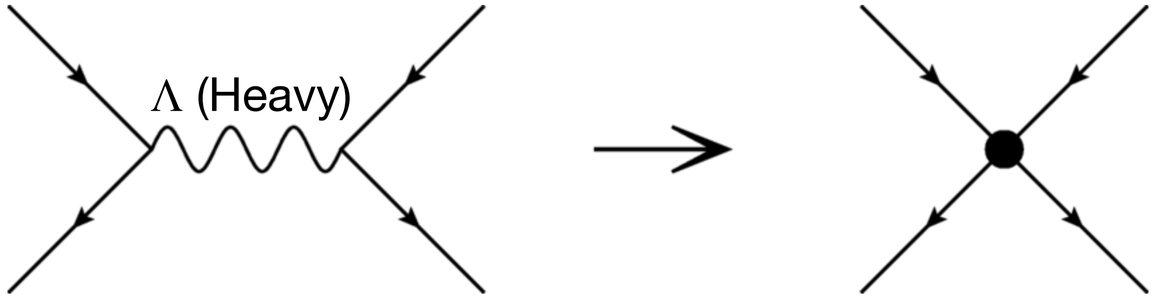
Requires precision

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]

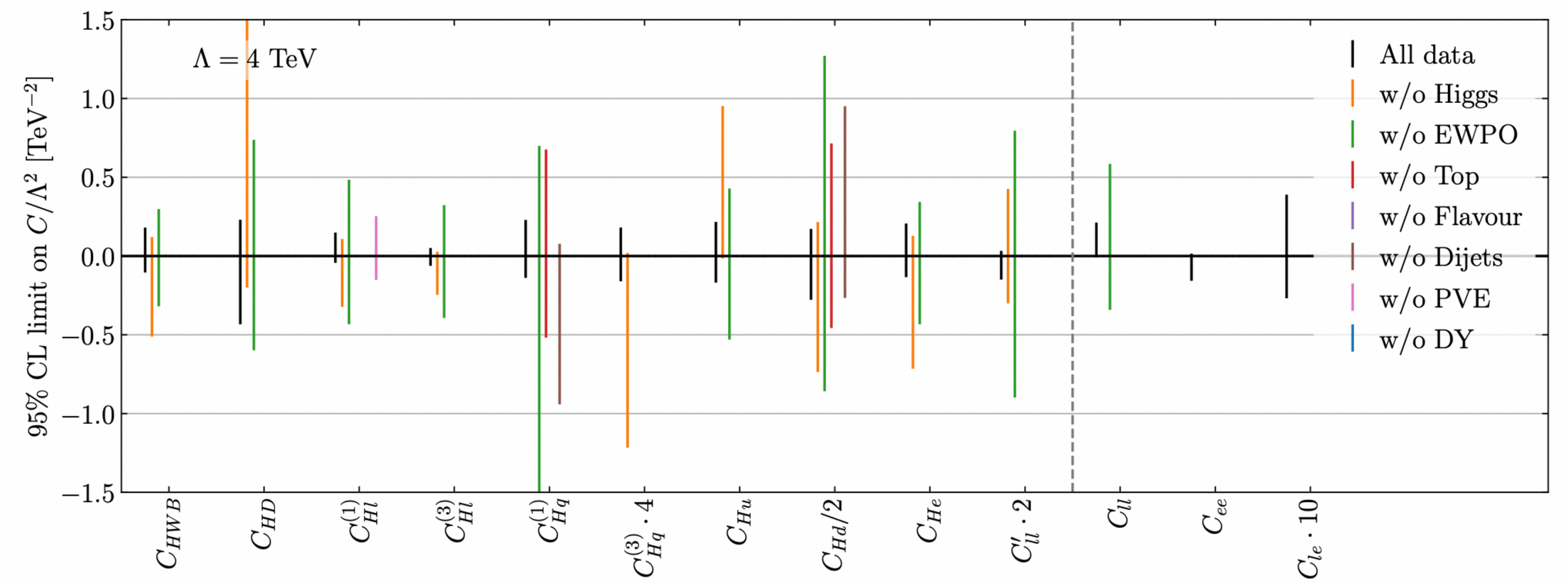
Obtain model independent Lagrangian:

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

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

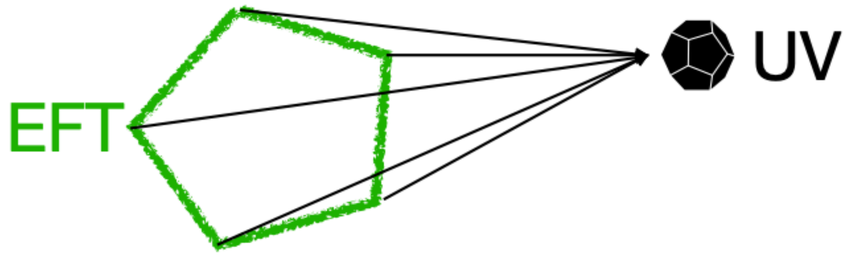
SMEFT fit from data

[SMEFiT, 2302.06660]



Can fit $\{\frac{c_i}{\Lambda^2}\}$:

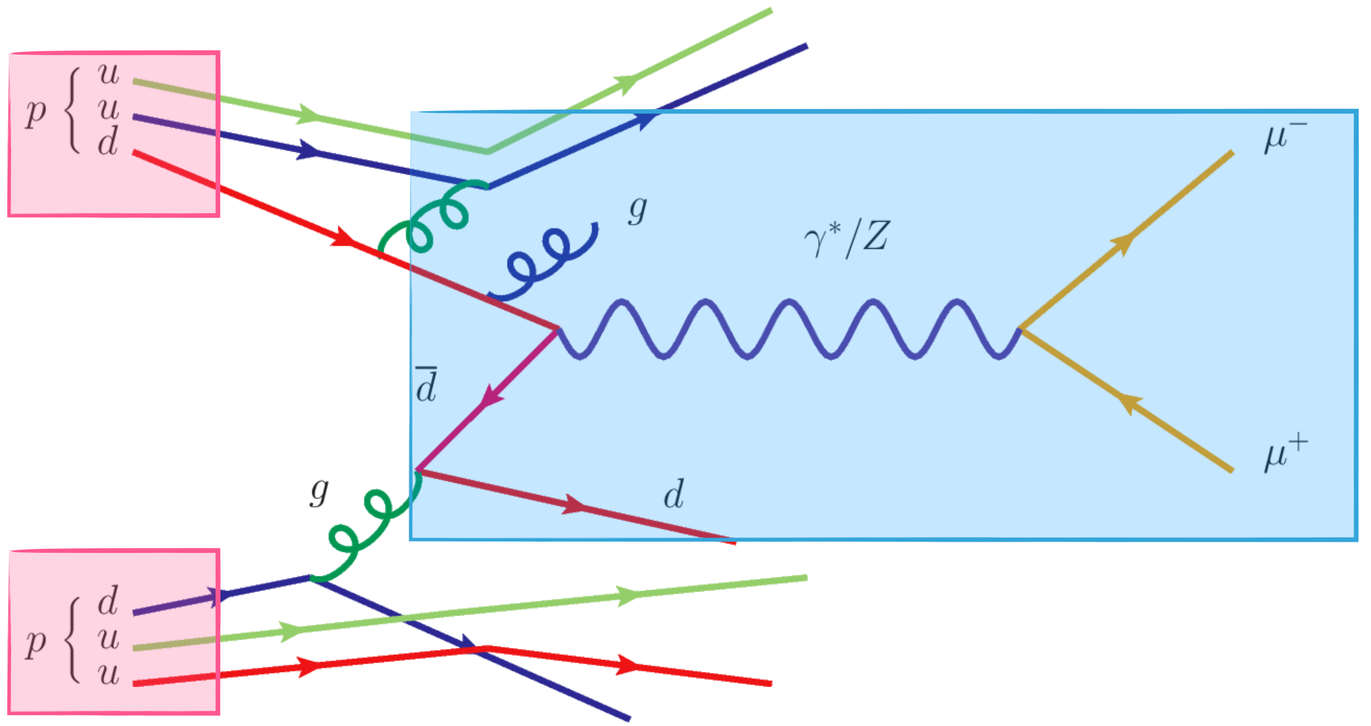
➡ can then be matched to a UV model



Hadron colliders, SMEFT and PDFs

Collinear factorization theorem

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



Parton Distribution Functions

Hard Scattering: Perturbative QCD + EW

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

Injecting new physics in HL-LHC projections

Description of the models

High-mass Drell-Yan

Heavy triplet under $SU(2)_L : W'$

- ➡ W'^{+} / W'^{-} and W_3'
- ➡ matching to SMEFT: oblique parameter $\hat{W}$

Heavy neutral boson under $U(1)_Y : Z'$

- ➡ Impacts only neutral current DY
- ➡ matching to SMEFT: oblique parameter $\hat{Y}$

Top pair production:

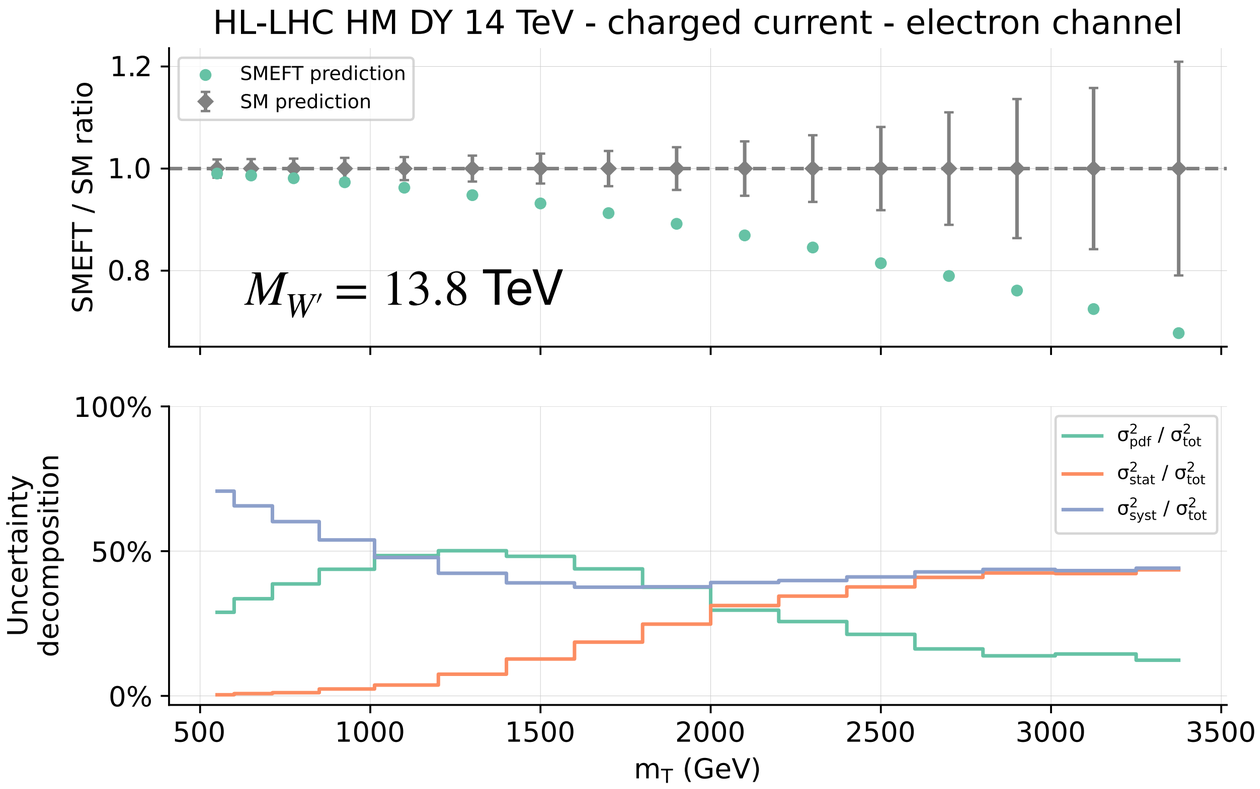
Heavy octet under $SU(3)_C : G'$

- ➡ Couples to third quark family
- ➡ matching to SMEFT: oblique parameter $\hat{Z}$

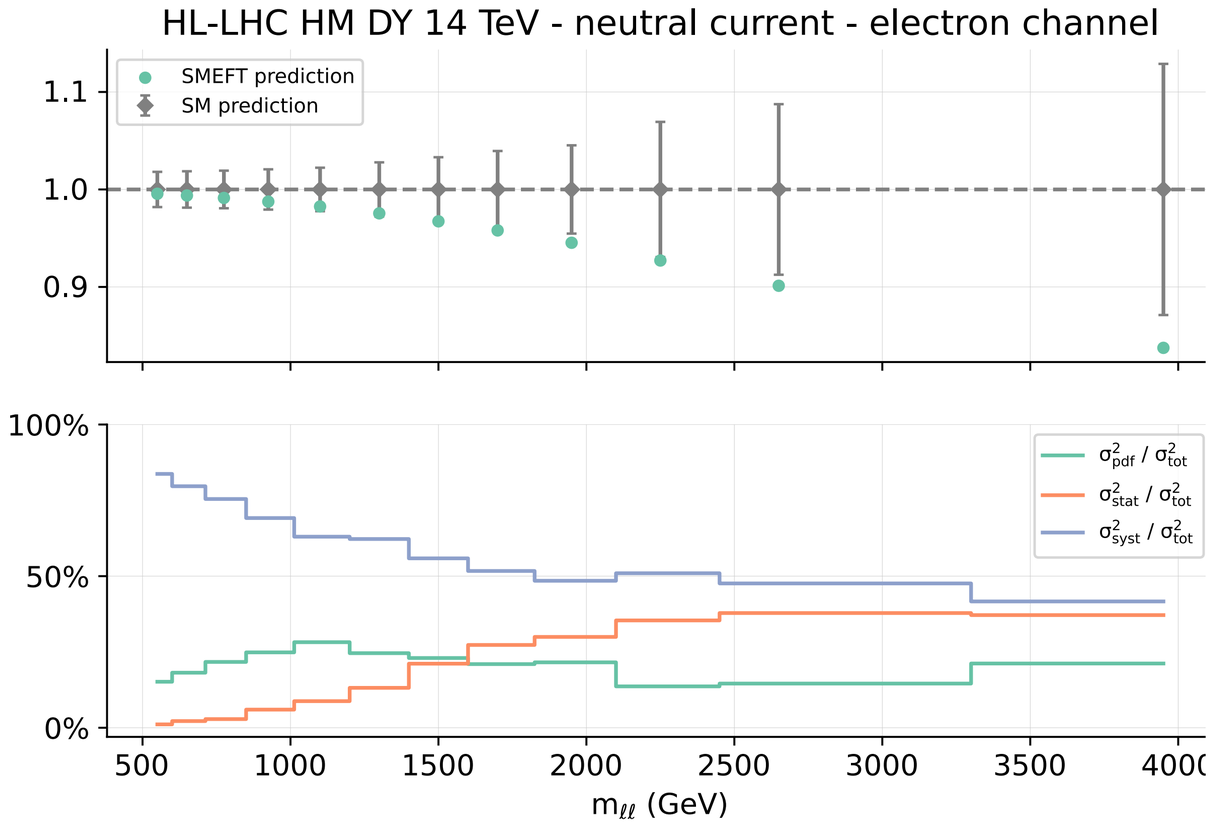
Injecting new physics in HL-LHC projections (DY)

Goal: recover it with a SMEFT fit

Charged current HMDY



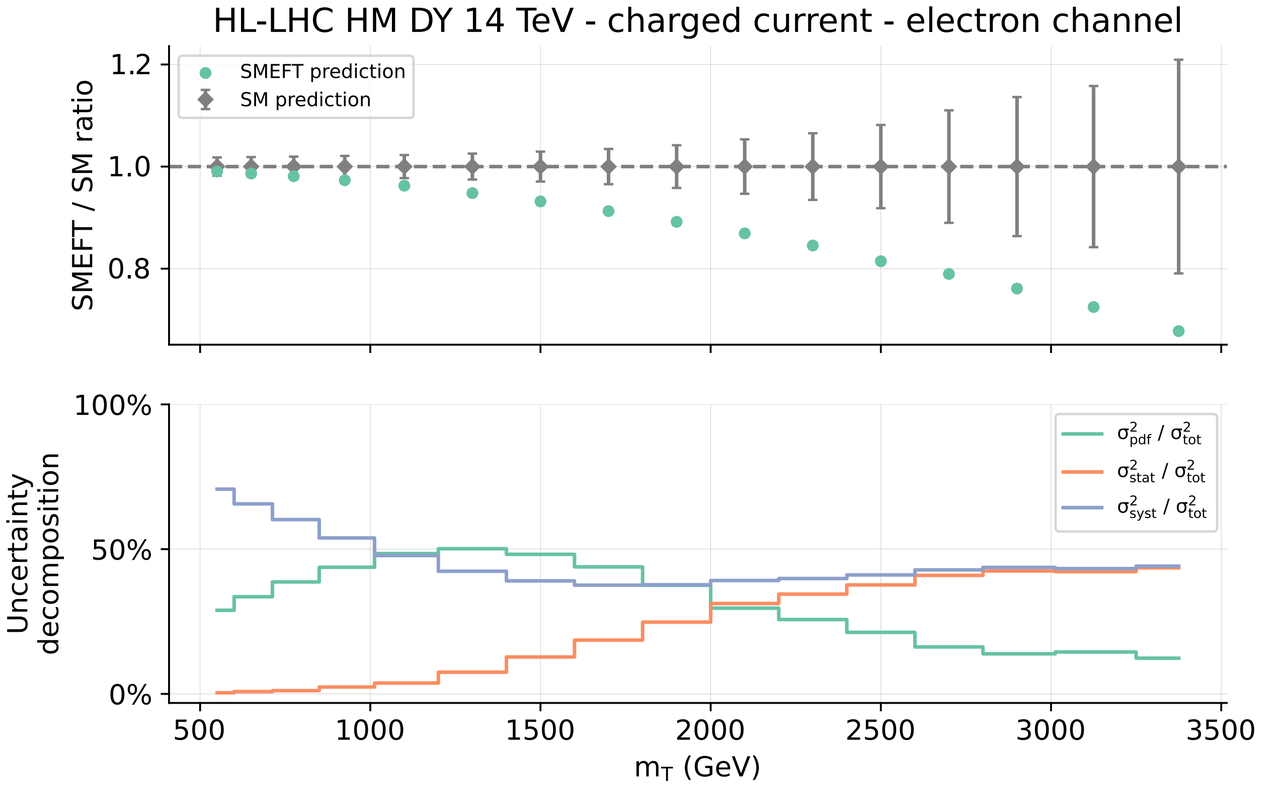
Neutral current HMDY

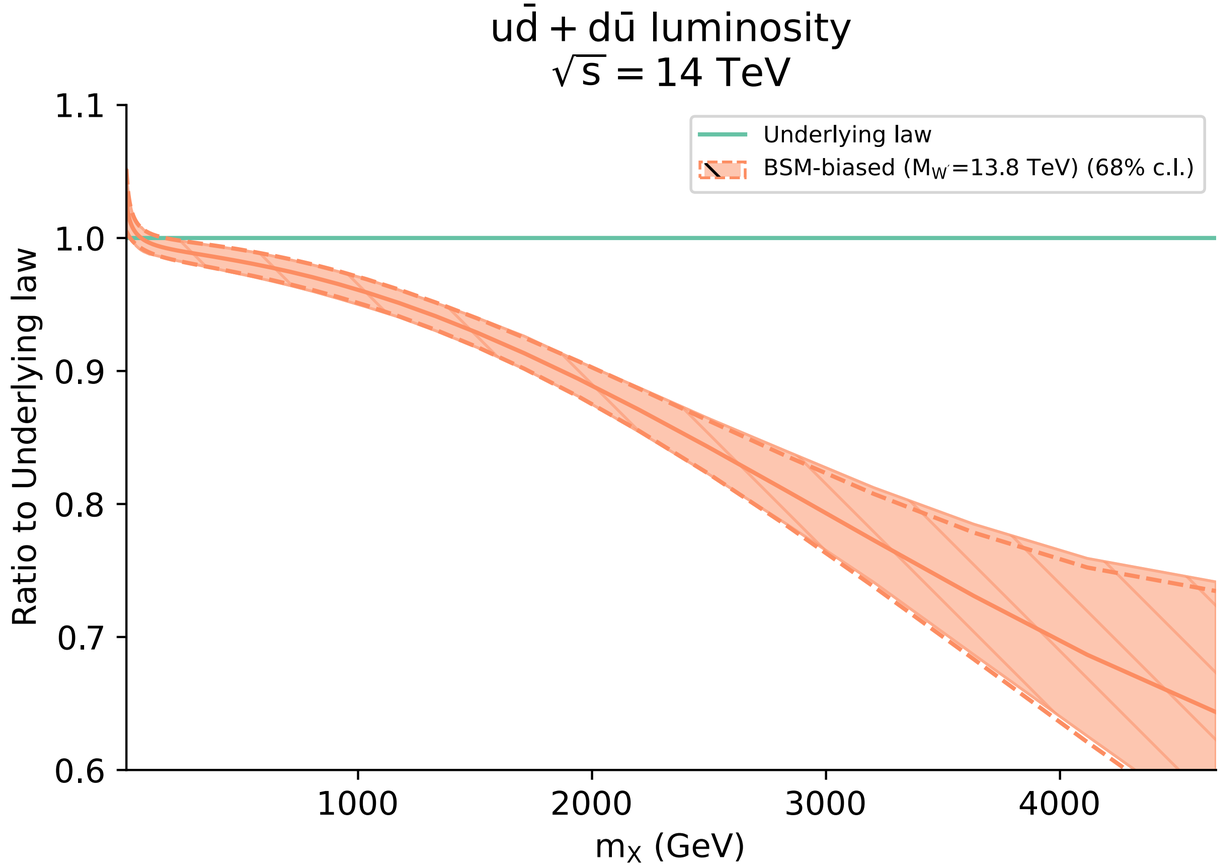


“BSM-biased” PDF in HMDY

PDFs are mimicking the SMEFT corrections

Charged current HMDY



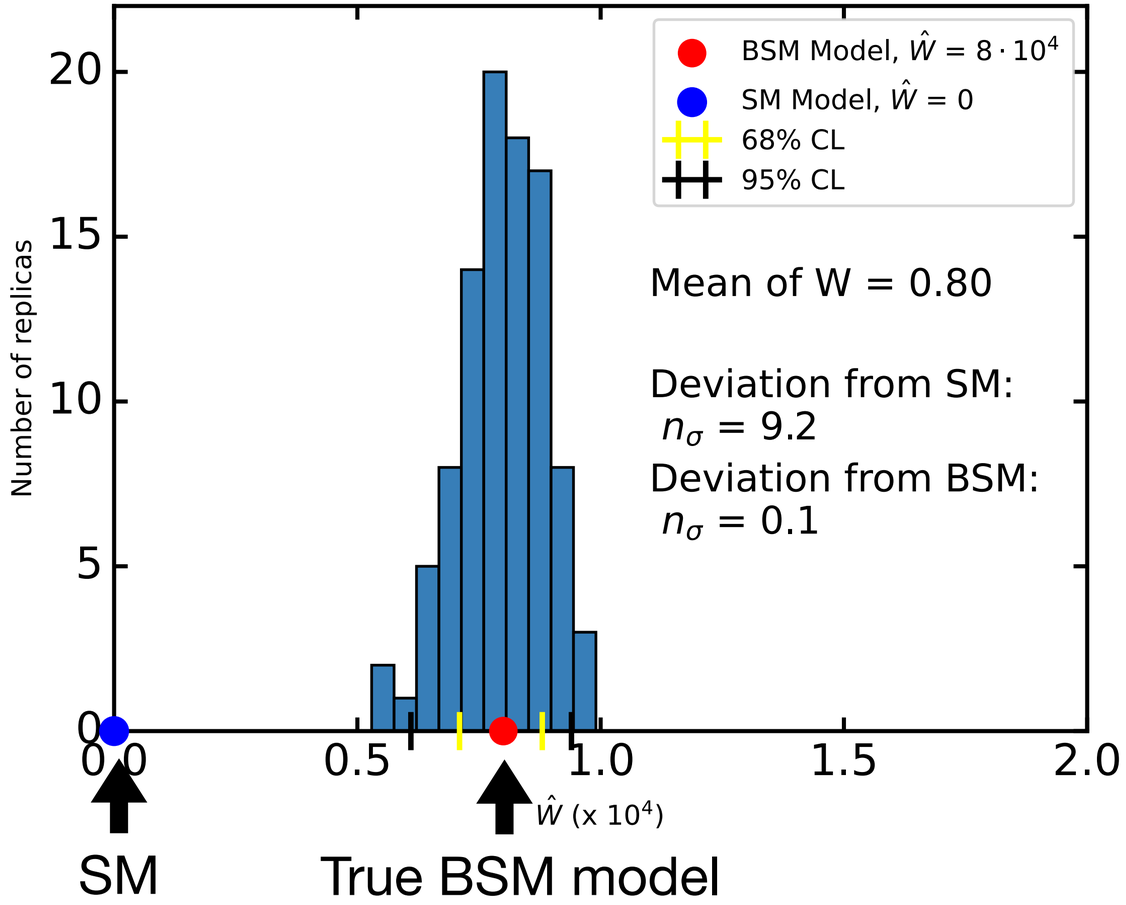


$$\mathscr{L}_{true} \otimes \hat{\sigma}_{BSM} \approx \mathscr{L}_{BSM-biased} \otimes \hat{\sigma}_{SM}$$

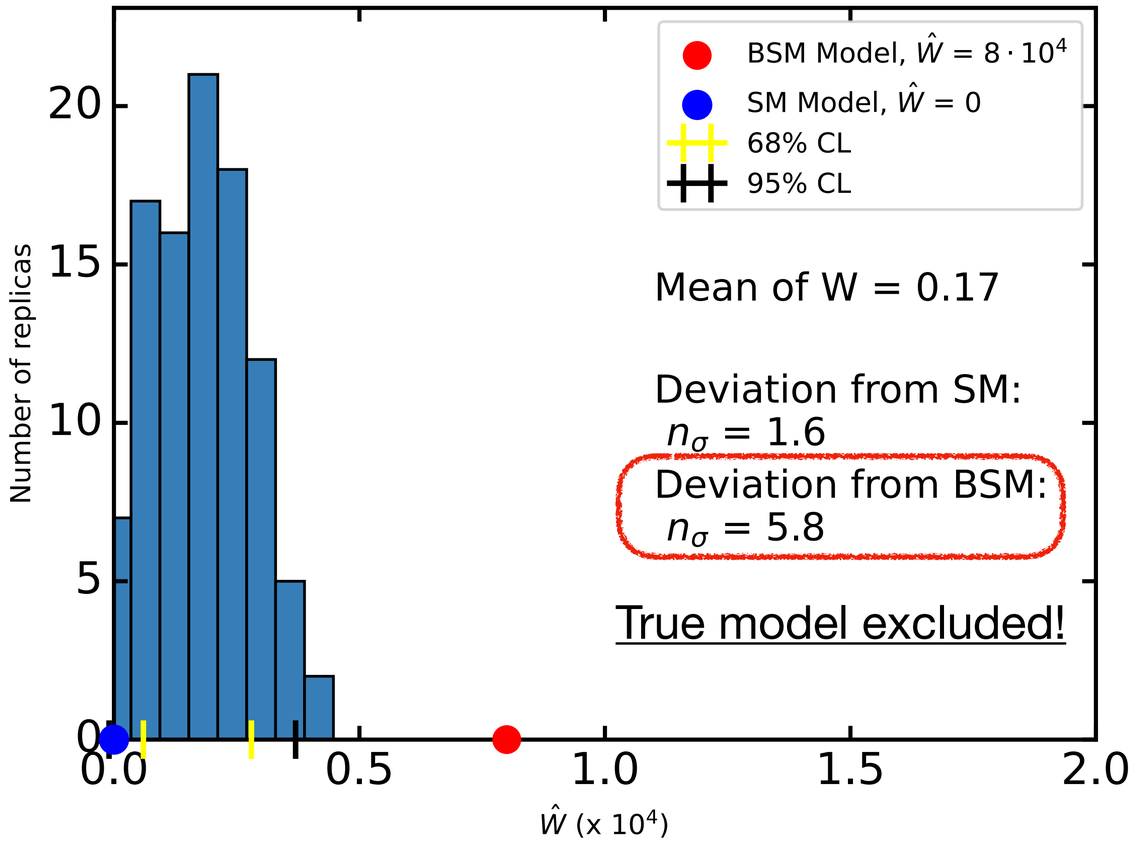
Missing new physics in Drell-Yan

Impact of the BSM-biased PDFs on SMEFT fits

SMEFT fit with true PDF

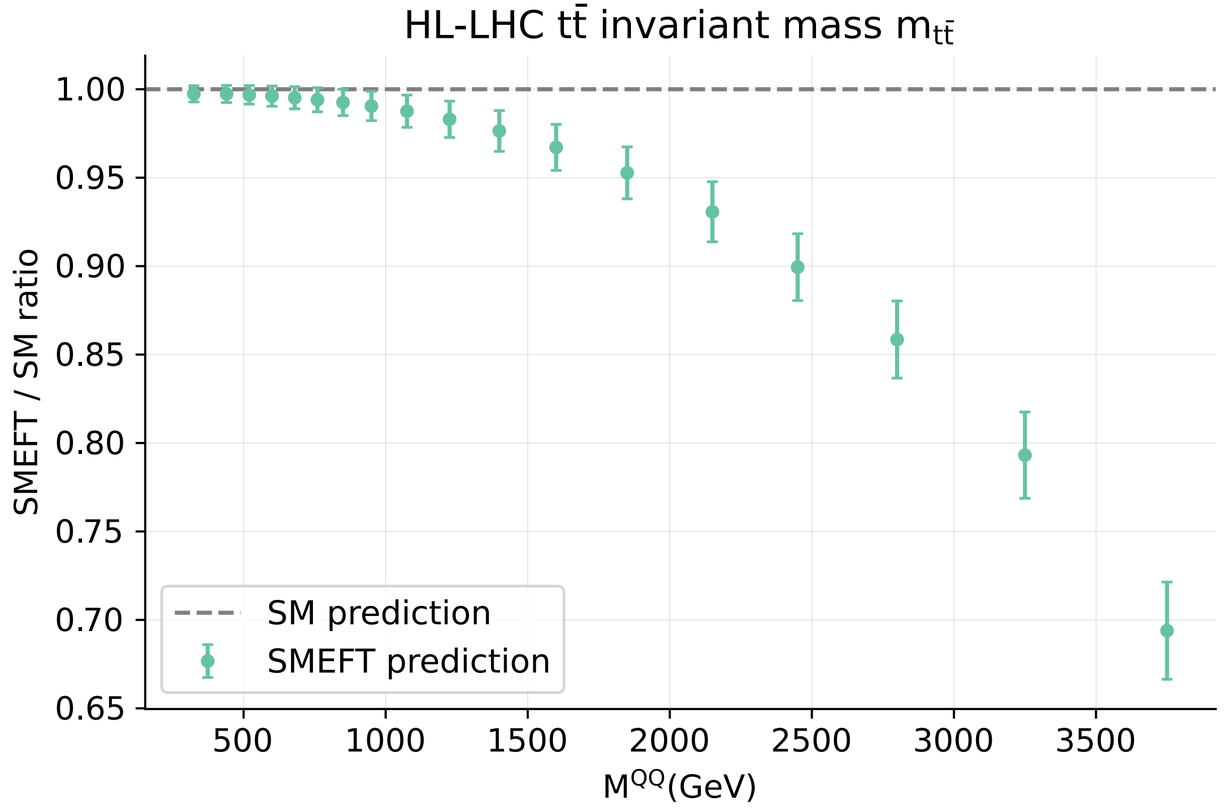


SMEFT fit with BSM-biased PDF

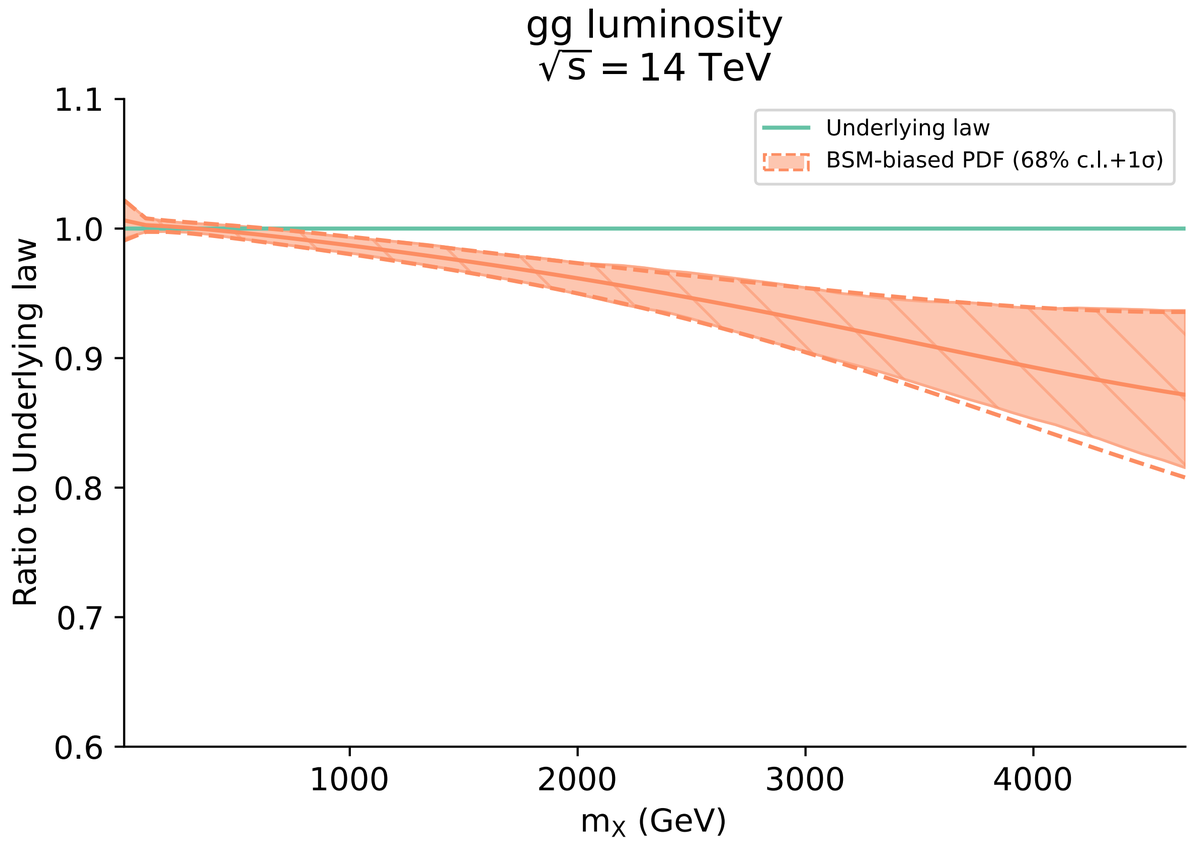


“BSM-biased” PDF in $t\bar{t}$

PDFs are partially mimicking the SMEFT corrections



$M_{G'} = 8$ TeV

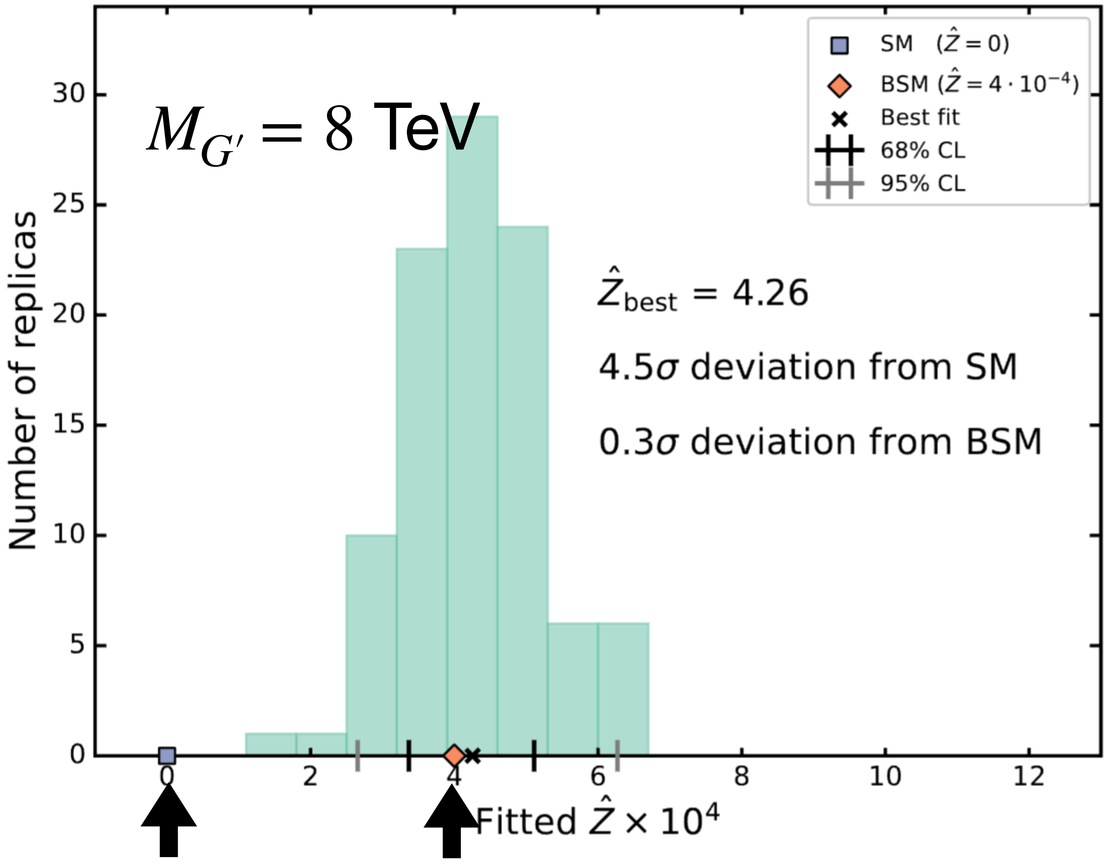


$$\mathscr{L}_{true} \otimes \hat{\sigma}_{BSM} \approx \mathscr{L}_{BSM-biased} \otimes \hat{\sigma}_{SM}$$

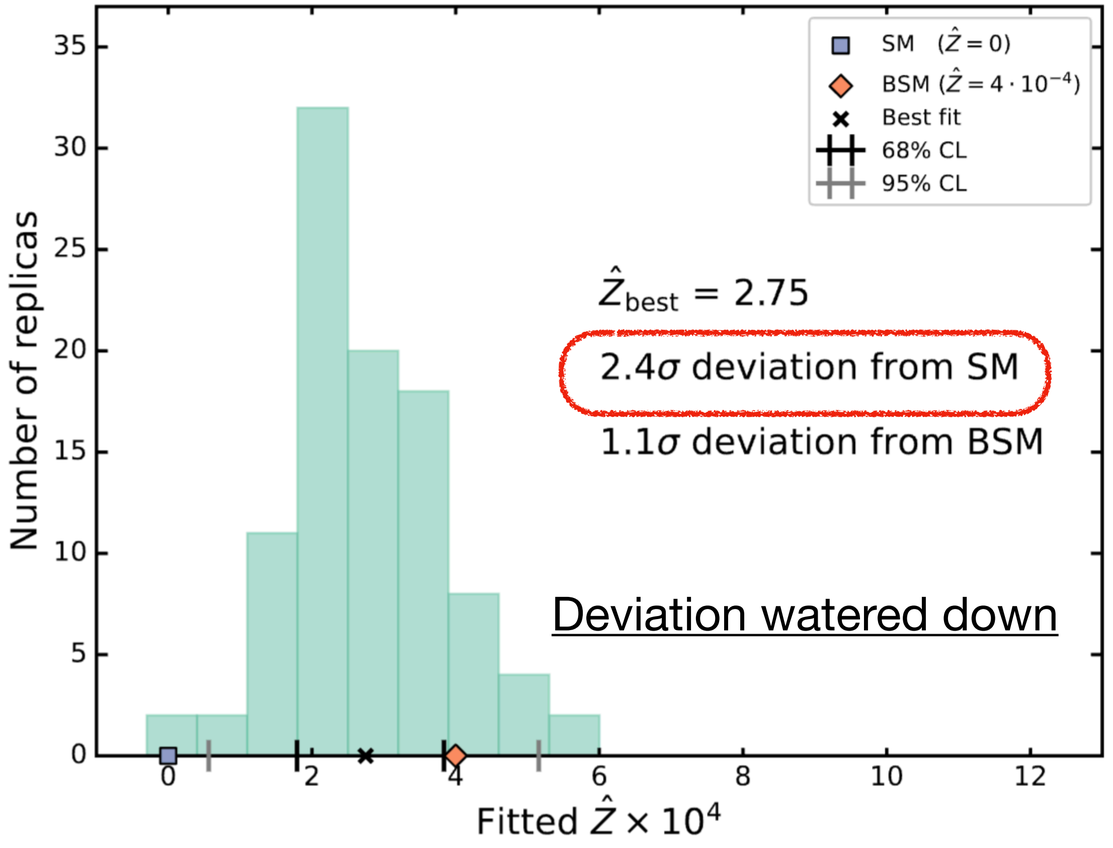
Diluting new physics deviation in the top sector

Same exercise with heavy gluon G' in ttbar at HL-LHC

SMEFT fit with true PDF



SMEFT fit with BSM-biased PDF



Separate and simultaneous fits of PDF and SMEFT

Comparison of the methodologies

Separate fits

PDF fit:

$$T(\{\theta\}, \{c = 0\}) = \text{PDF}(\{\theta\}) \otimes \hat{\sigma}(\{c = 0\})$$

➡ $\bar{\theta}$

Assumes SM: source of bias

SMEFT fit:

$$T(\{\theta = \bar{\theta}\}, \{c\}) = \text{PDF}(\{\theta = \bar{\theta}\}) \otimes \hat{\sigma}(\{c\})$$

➡ $\bar{c}$

Need to make sure SM assumption is true

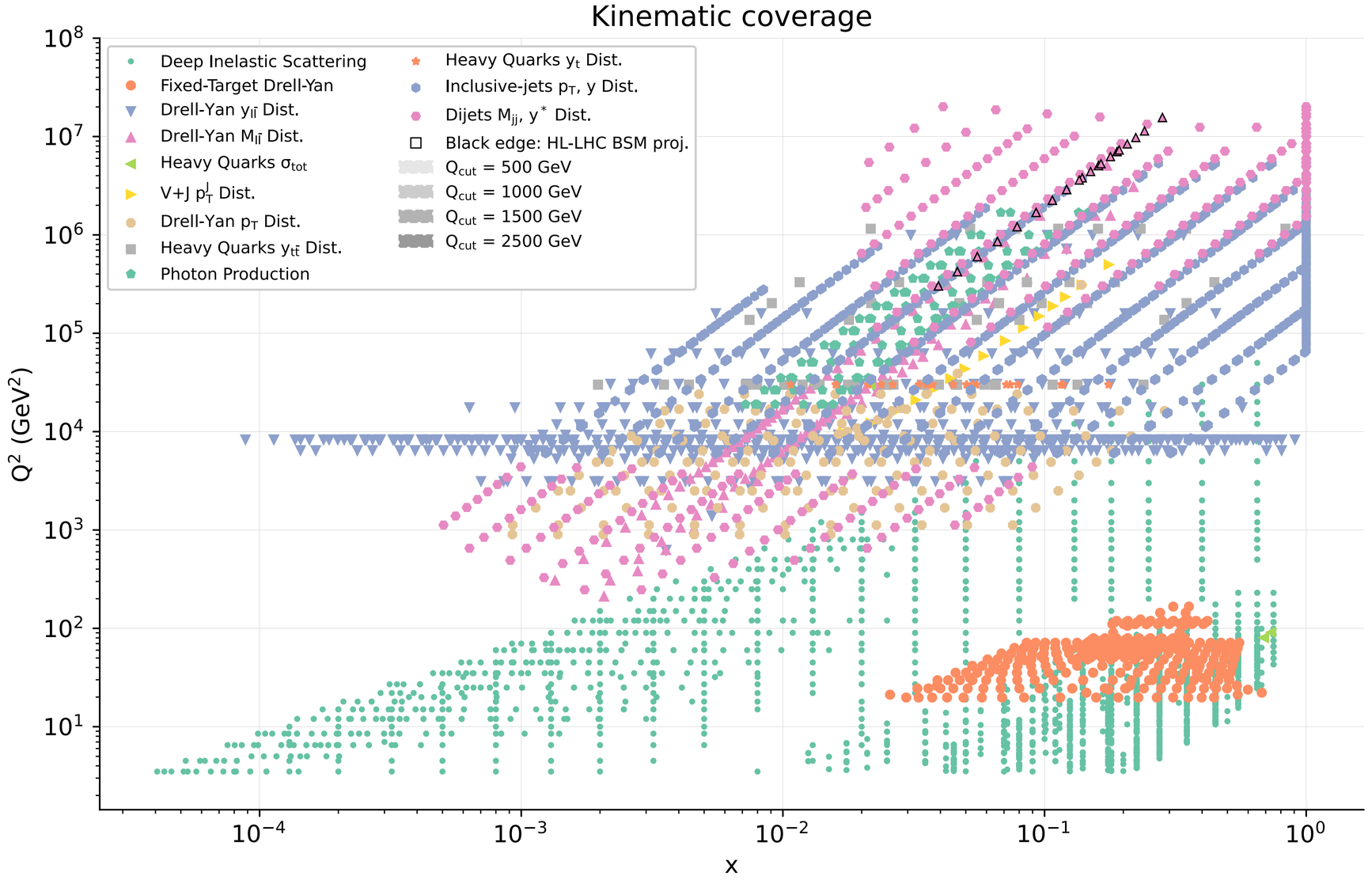
Simultaneous fits

$$T(\{\theta\}, \{c\}) = \text{PDF}(\{\theta\}) \otimes \hat{\sigma}(\{c\})$$

➡ $\{\bar{\theta}, \bar{c}\}$

Removes assumption-based bias

Safe separate fits: “conservative” PDFs

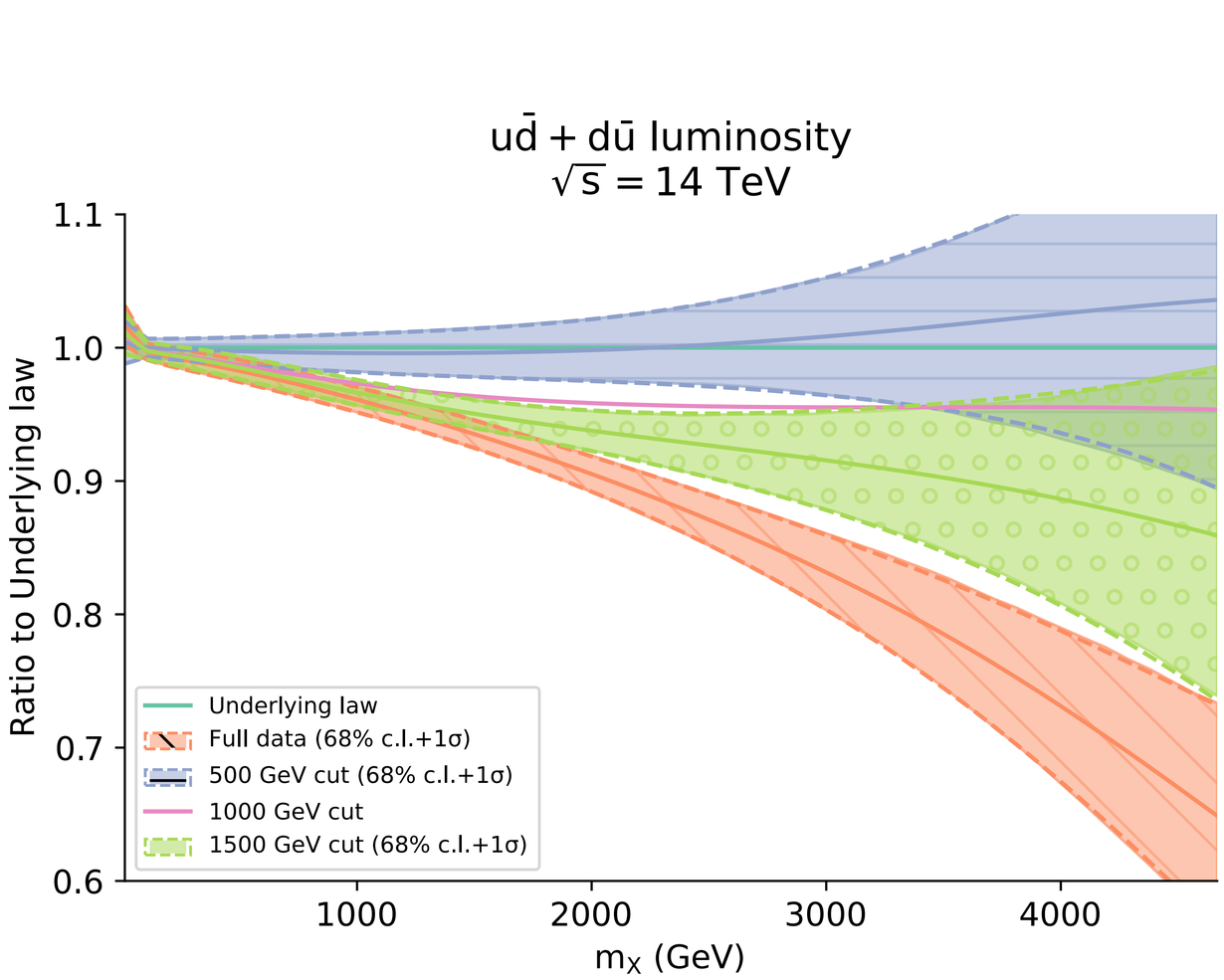


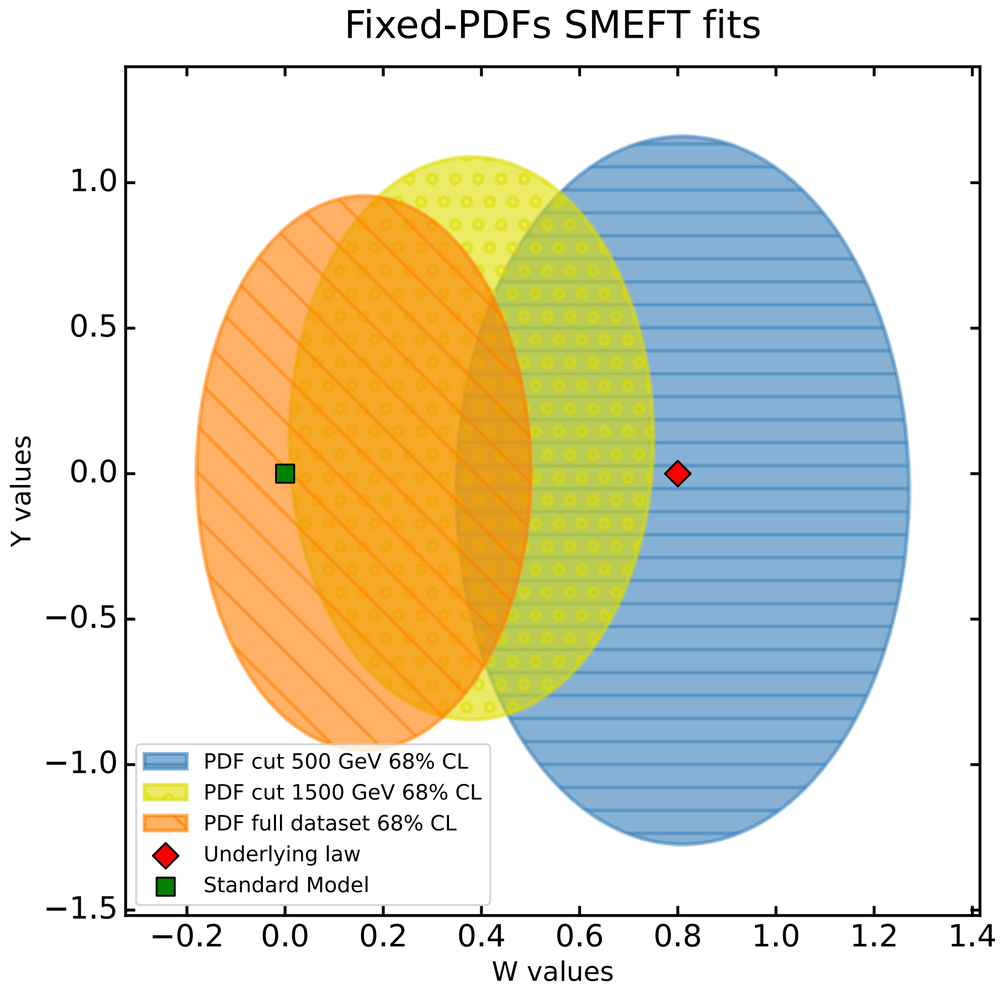
Agnostic energy cuts

“Conservative” separate fits

[PBSP, forthcoming]

Impact on PDF and SMEFT bounds for DY





Simultaneous fit of PDF and SMEFT

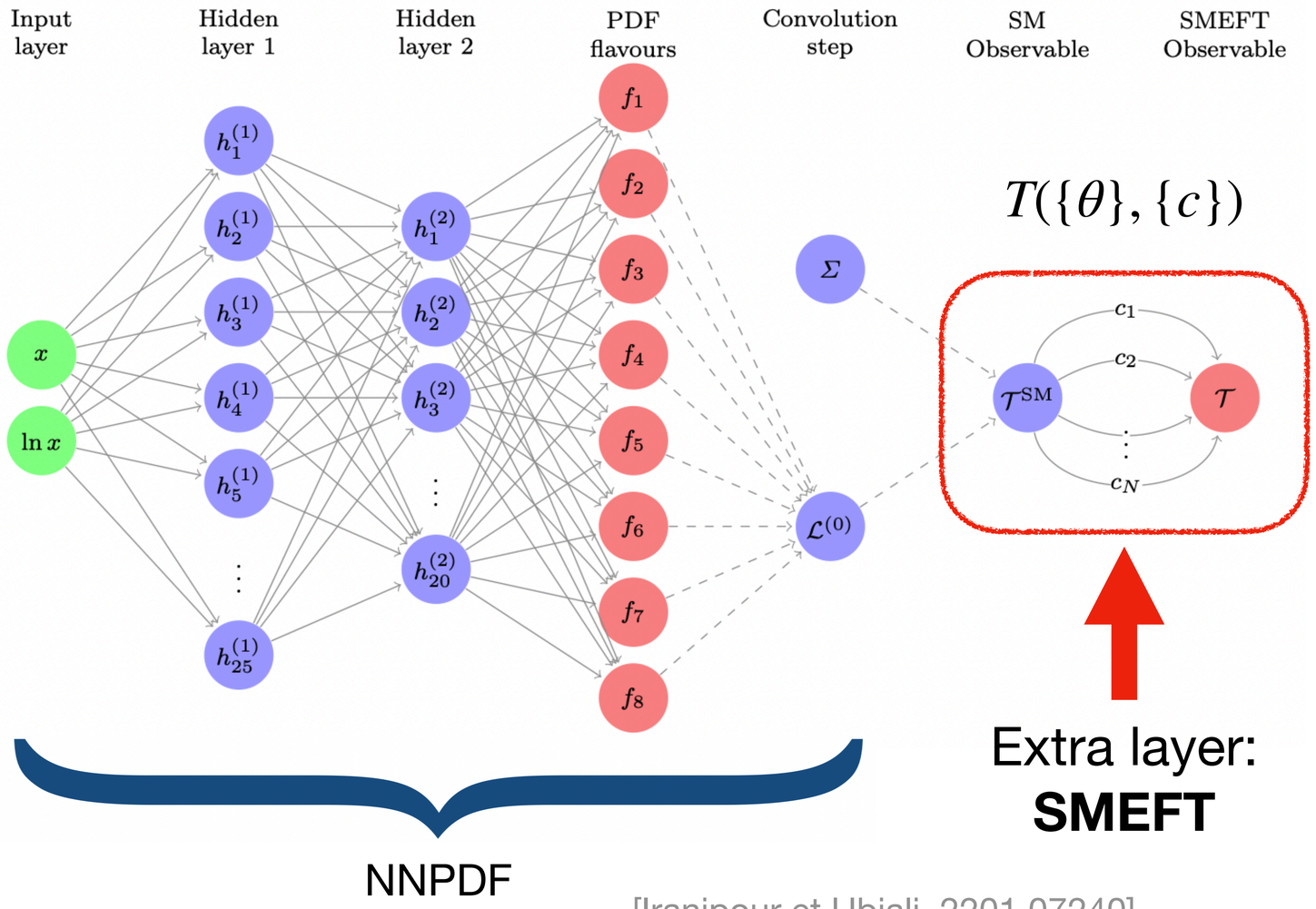
Presentation of the tool: SIMUnet

SIMUnet:

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

  [PBSP, 2402.03308]

- Fits PDFs and WC simultaneously
- Performs BSM closure tests

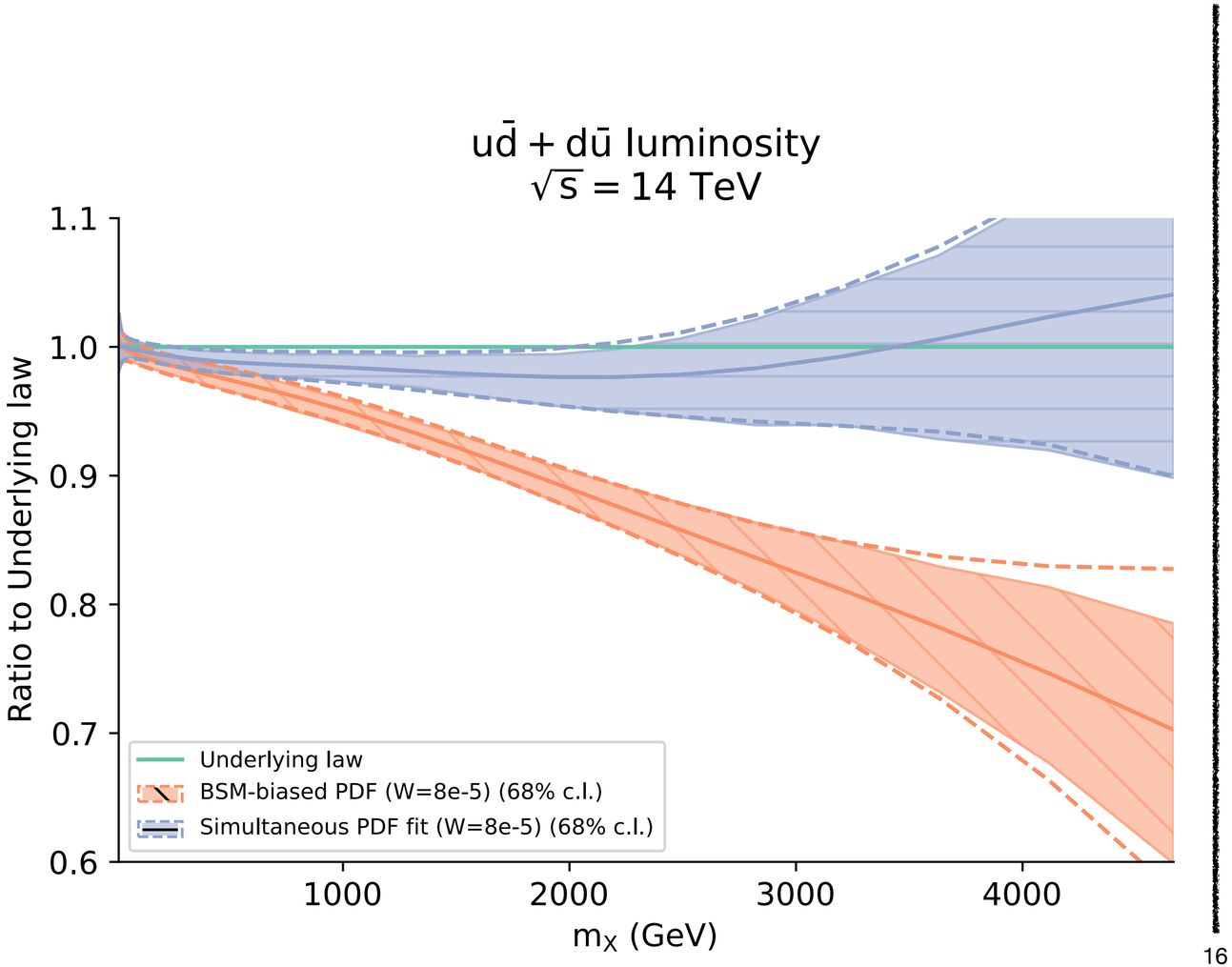


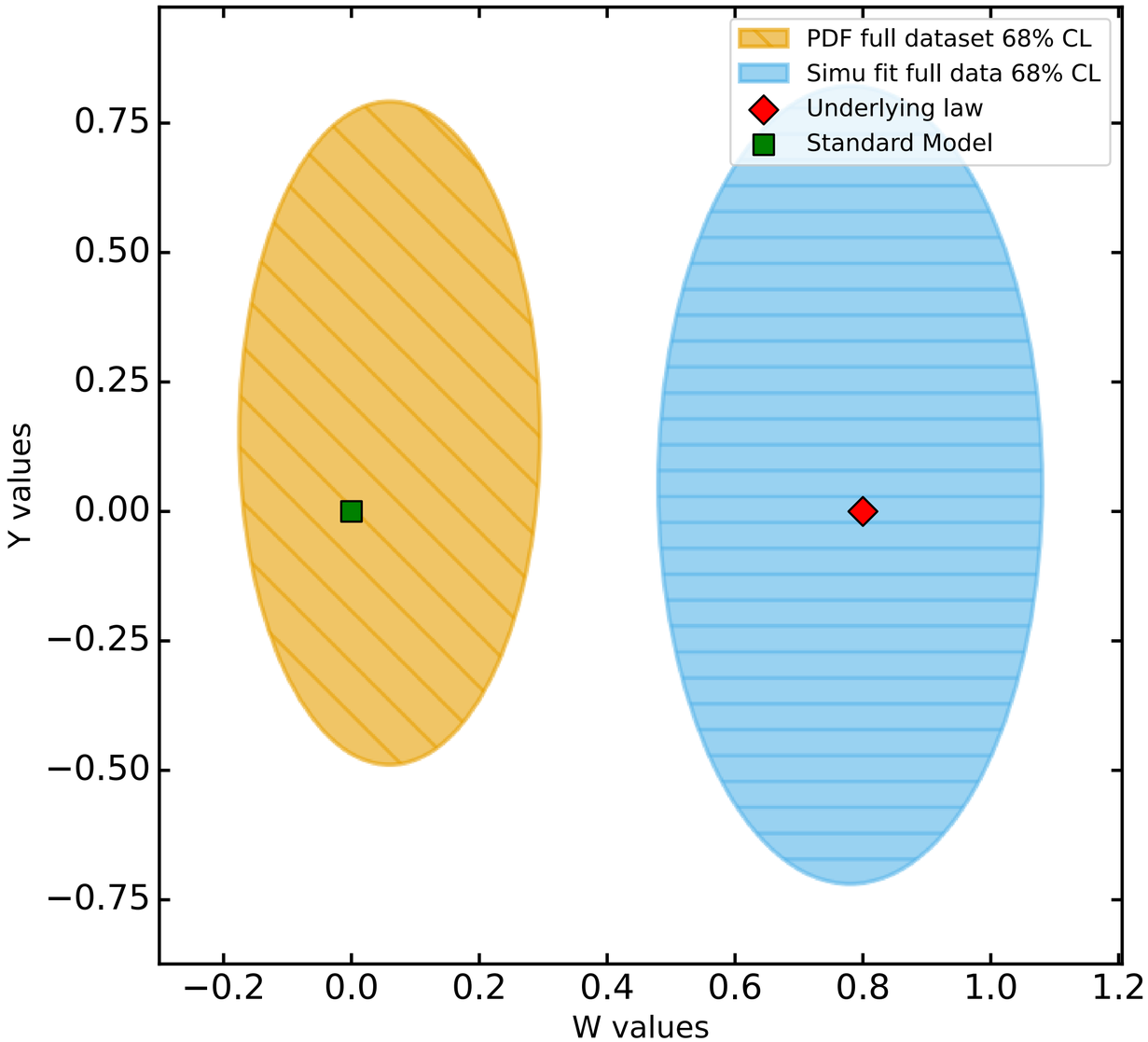
[Iranipour et Ubiali, 2201.07240]

Simultaneous fit of PDF and SMEFT

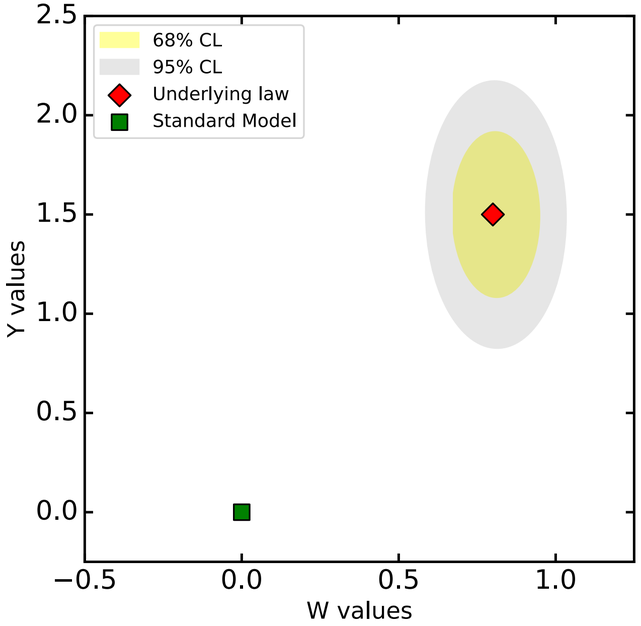
[PBSP, forthcoming]

Marginal distributions for DY





PDFs for new physics searches in HMDY

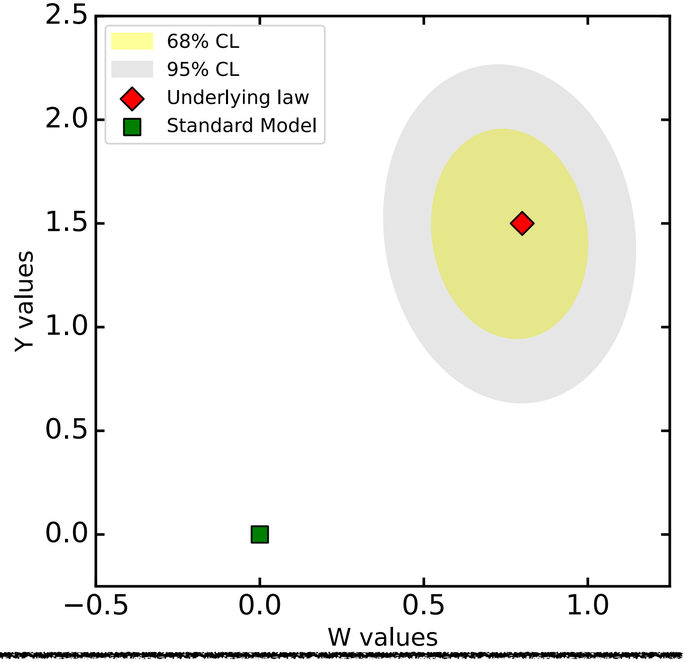


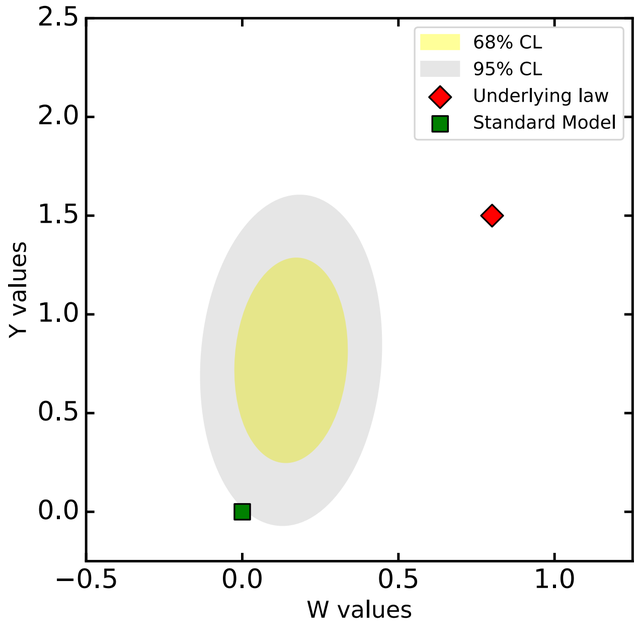
SMEFT only fit
(True PDF)

✗ Impossible

Simultaneous fit
(no PDF assumption)

✓ Doable



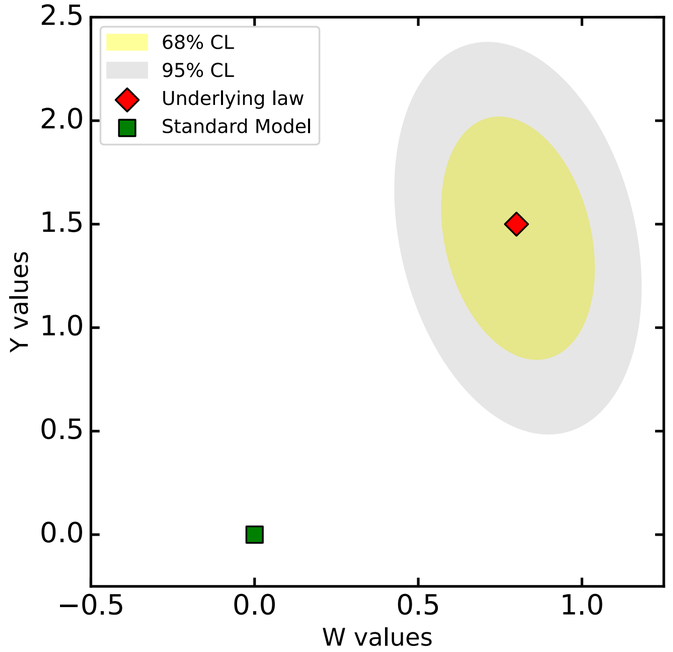


SMEFT only fit
(BSM-biased PDF)

✗ Wrong

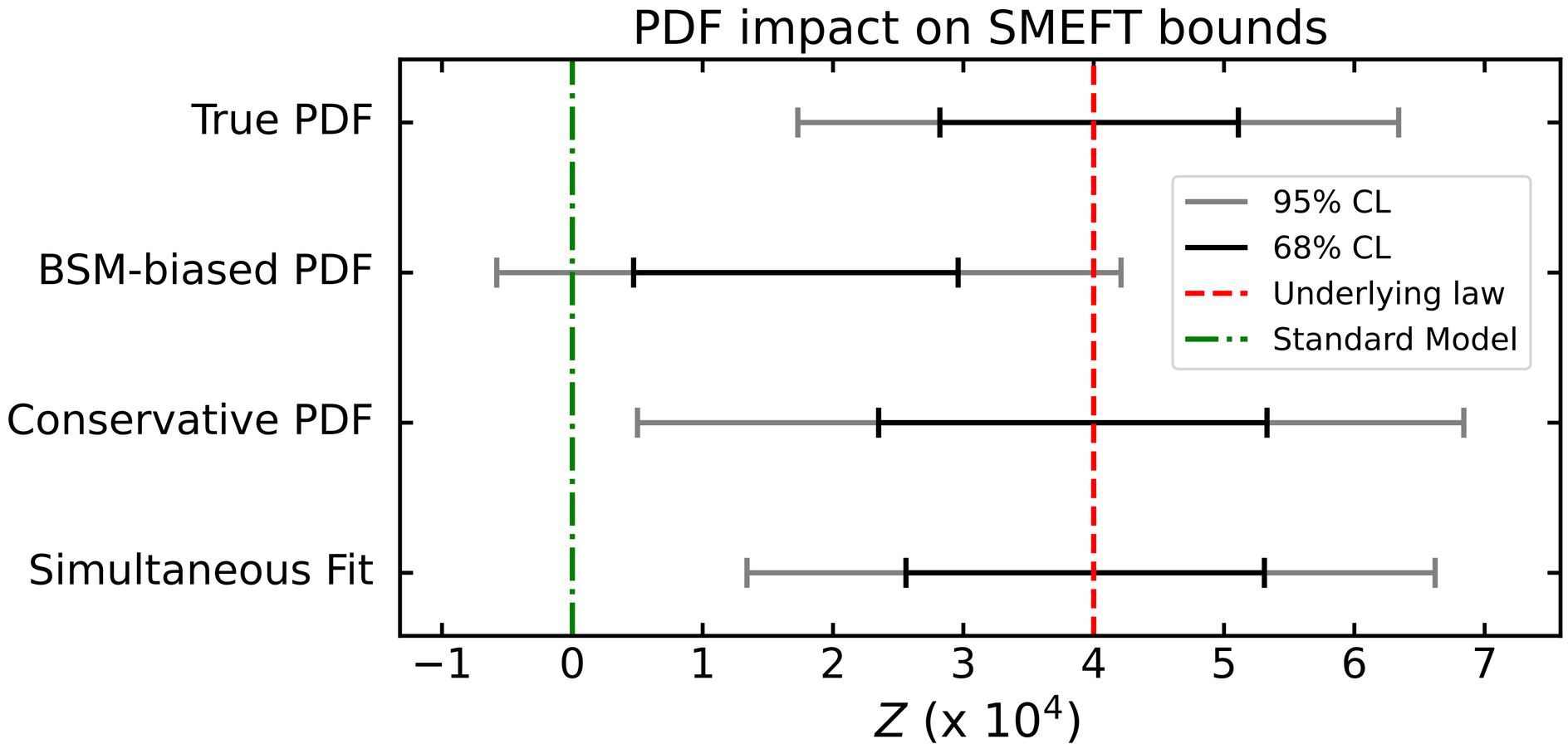
SMEFT only fit
(Conservative PDF)

✓ Doable



PDFs for new physics searches in $t\bar{t}$

Same exercise with heavy gluon in ttbar at HL-LHC



Comparing conservative and simultaneous fits

Conservative separate fits

Pros:

- Easier
- Less parameters per fit

Cons:

- Difficult to figure out optimal cutoff (manageable)
- **Cannot use precise high-energy observables to constrain PDFs**

Simultaneous fits

Pros:

- Entire dataset constrains PDF and SMEFT
- High-energy observables constrain PDF

Cons:

- More parameters -> more uncertainty (manageable)
- **Risk to absorb SM error as SMEFT signal**

Summary and outlook

- Signs of new physics fitted away in PDF parametrisation
  - Exclude true underlying law (DY) / water down BSM deviation (ttbar)
  - **Must be aware of this source of bias**
- Practical recommendations:
  - Conservative PDFs for SMEFT fits
  - Simultaneous fits of PDFs and SMEFT (**SIMUnet** tool already available)
- Ongoing work:
  - Ongoing study on real jet data [Greljo, Hammou, Merlotti, Smolkovic, Ubiali, forthcoming]
  - Developing a bayesian framework [Costantini, Moore, Mantani, Schutze, Ubiali, forthcoming (PDF)]
  - Allowing choice in PDF modelisation [Hammou, ter Hoeve, Shutze, in progress (SMEFT)]

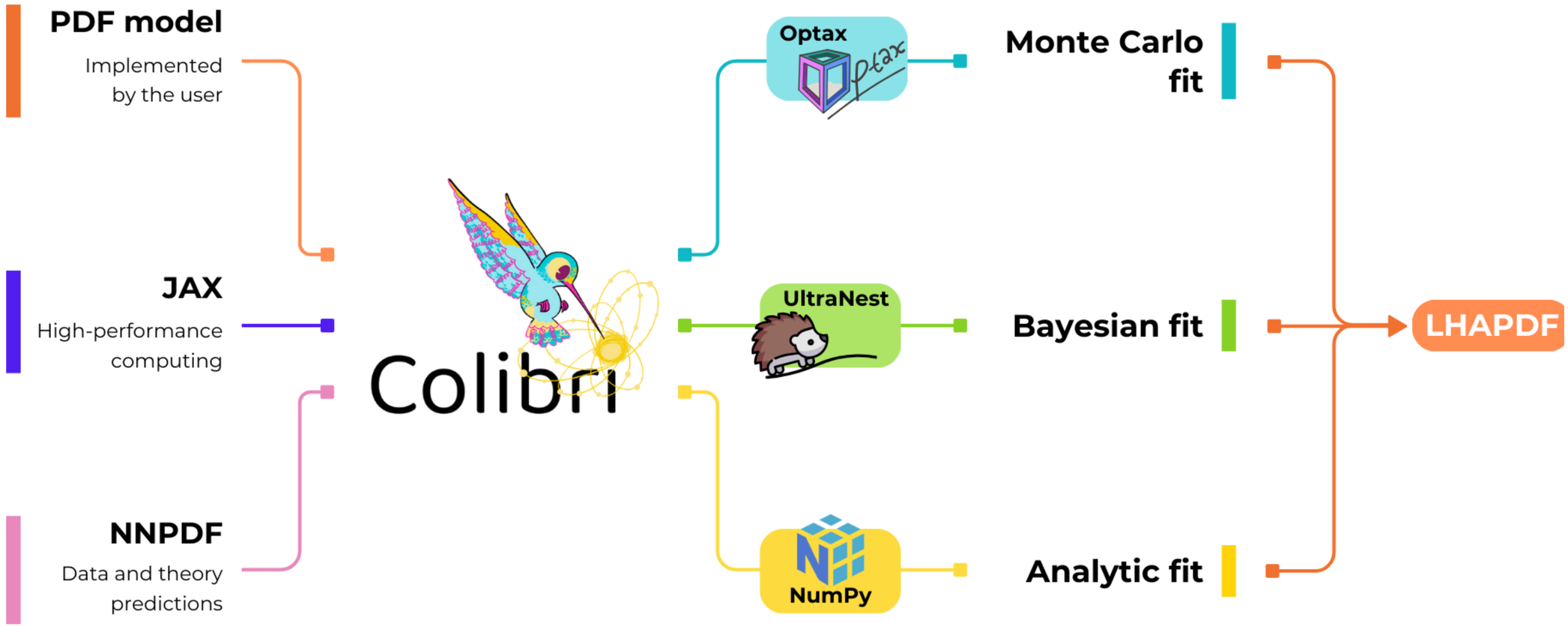
You can contact me at:
eh651@cam.ac.uk

Thank you for your attention!

Extra slides

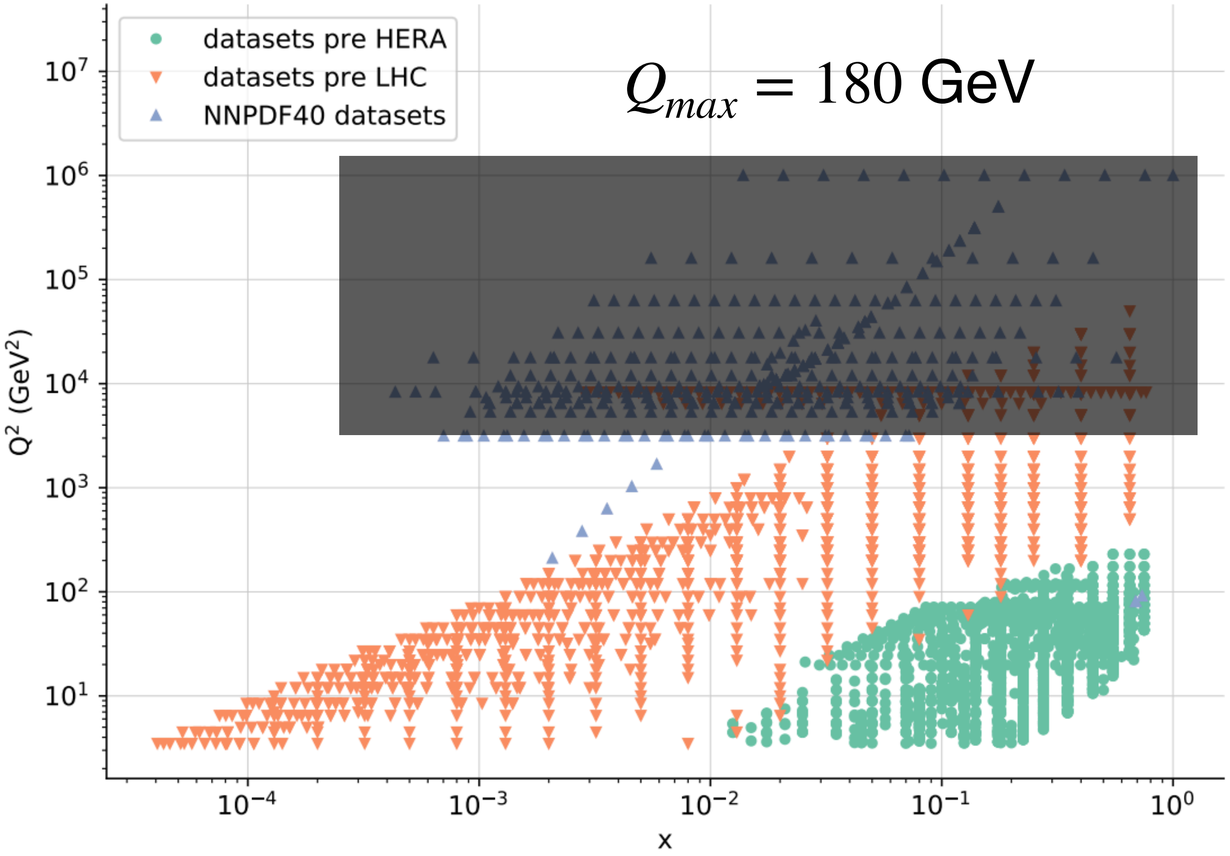
Upcoming: Colibri

Model-flexible framework for bayesian fits

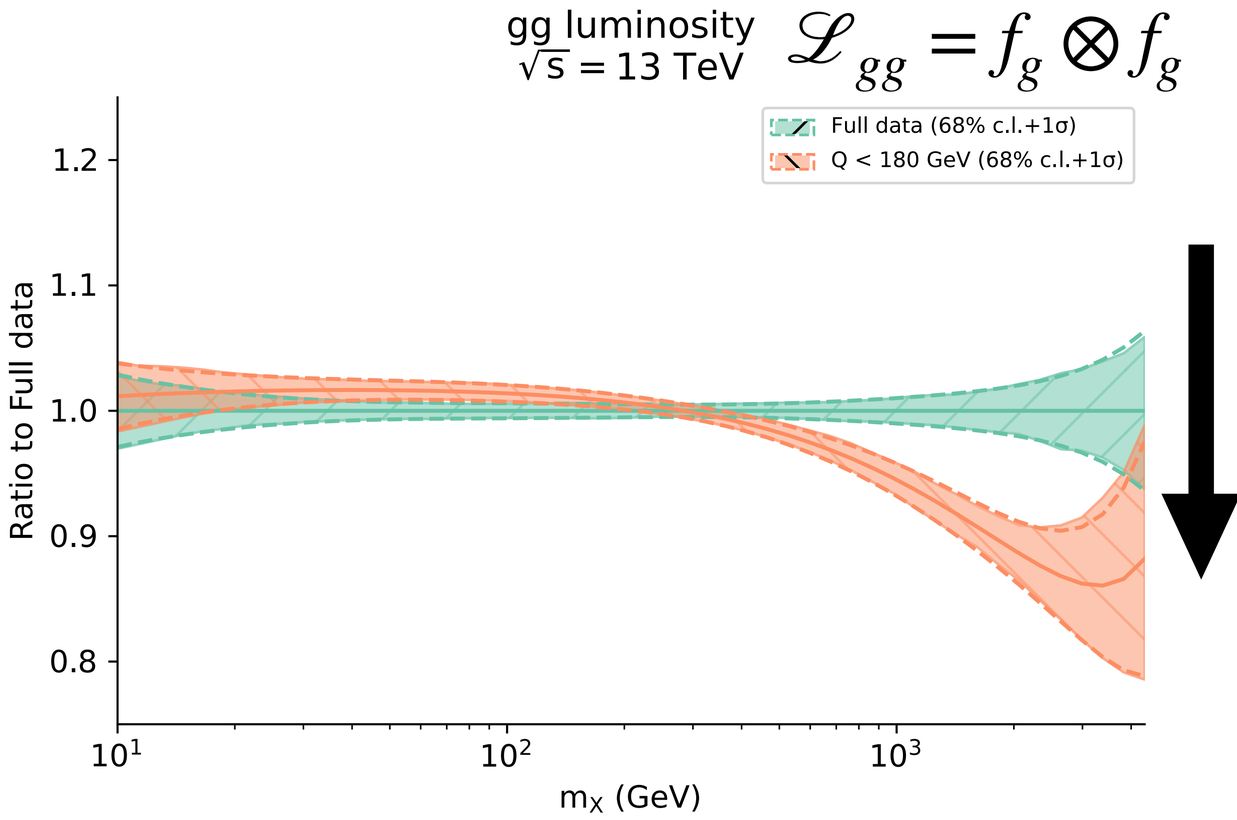


Discrepancy between low and high-energy data fits

Kinematic coverage



Impact of energy cut



Potential pitfalls of PDF fitting

- No theory constraint available (e.g. from lattice)

  ➡ Only determined from measurements

- Very flexible parametrisation by necessity

  ➡ Can mimic deviations in the observables

- Assumes SM in theory predictions

- Large-x PDF mostly constrained by high-energy measurements

  ➡ Risk to absorb BSM deviations!

PDF fitting: selection criteria

Exclusion of incompatible datasets (NNPDF criteria)

Two criteria:

$$\chi^2 = (D - T_{SM})^T \cdot V_{cov}^{-1} \cdot (D - T_{SM})$$

- χ^2-statistics:
  - $\frac{\chi^2}{n_{dat}} > 1.5$ → excluded

- n_σ standard deviation:
  - $n_\sigma > 2$ → excluded

$$n_\sigma = \frac{\chi^2 - 1}{\sigma_{\chi^2}}$$

New physics scenarios: W'

From UV to the SMEFT

Heavy triplet under $SU(2)_L$: W'

$$\mathscr{L}^{W'}_{UV} = \mathscr{L}_{SM} - \frac{1}{4} W'^{a}_{\mu\nu} W'^{a,\mu\nu} + \frac{1}{2} M^2_{W'} W'^{a}_{\mu} W'^{a,\mu} - g_{W'} W'^{a,\mu} \sum_{f_L} \bar{f}_L T^a \gamma^\mu f_L - g_{W'} (W'^{a,\mu} \varphi^\dagger T^a i D_\mu \varphi + \text{h.c.})$$

➡ Creates two charged particles: W'^{+} / W'^{-} and a neutral one: W'_3

Matching to the SMEFT:

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

→ $$\mathscr{L}^{W'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2 \hat{W}}{2m^2_W} J^{a,\mu}_L J^a_{L,\mu} \qquad \hat{W} = \frac{g^2_{W'}}{g^2} \frac{m^2_W}{M^2_{W'}} \propto \frac{c}{\Lambda^2}$$

New physics parameter

New physics scenarios: W' $pp \to l^- \bar{\nu}$ $M_{W'} = 13.8$ TeV

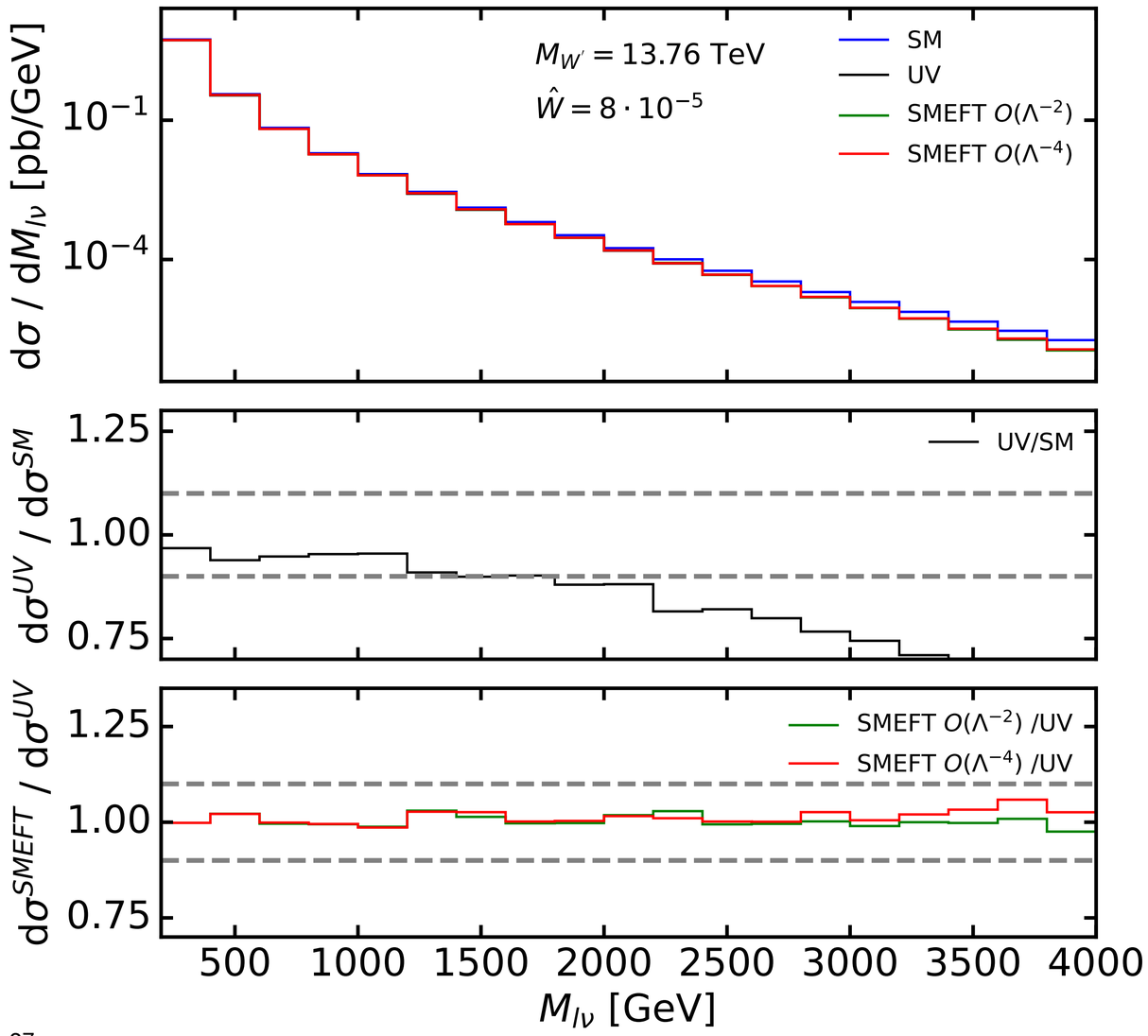
Generation of the pseudodata

$$\mathscr{L}^{W'}_{SMEFT} = \mathscr{L}_{SM} - \frac{g^2 \hat{W}}{2m_W^2} J_L^{a,\mu} J^a_{L,\mu}$$

➡ Impacts CC and NC Drell-Yan

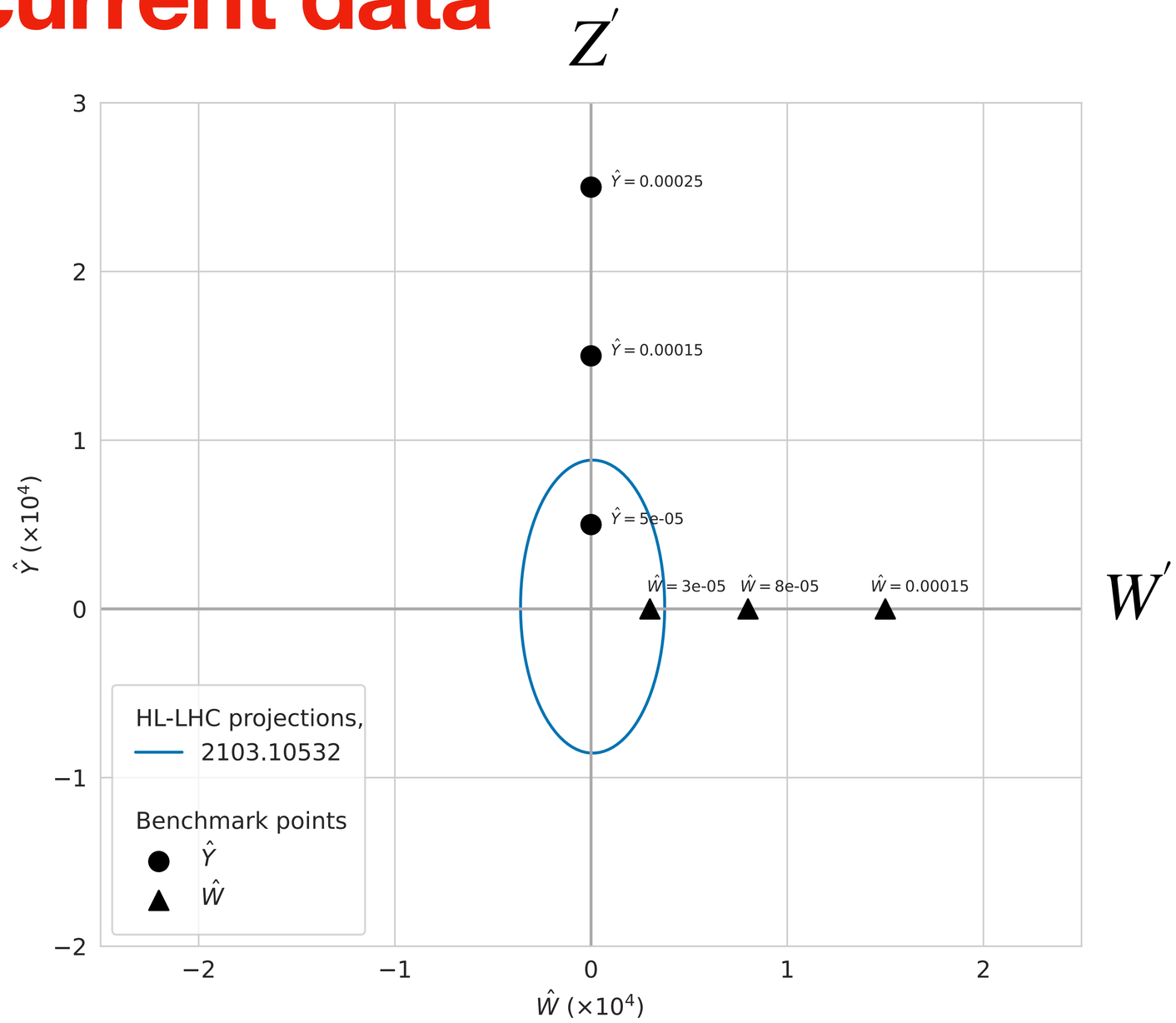
$$\hat{W} = \frac{g^2_{W'}}{g^2} \frac{m^2_W}{M^2_{W'}} \propto \frac{c}{\Lambda^2}$$

$$\hat{W} \leftrightarrow M_{W'} \quad (g_{W'} = 1)$$



Constraints from current data

- New physics scenarios compared to constraints at 95% CL



Impact of contamination: fake deviations

SM predictions with:

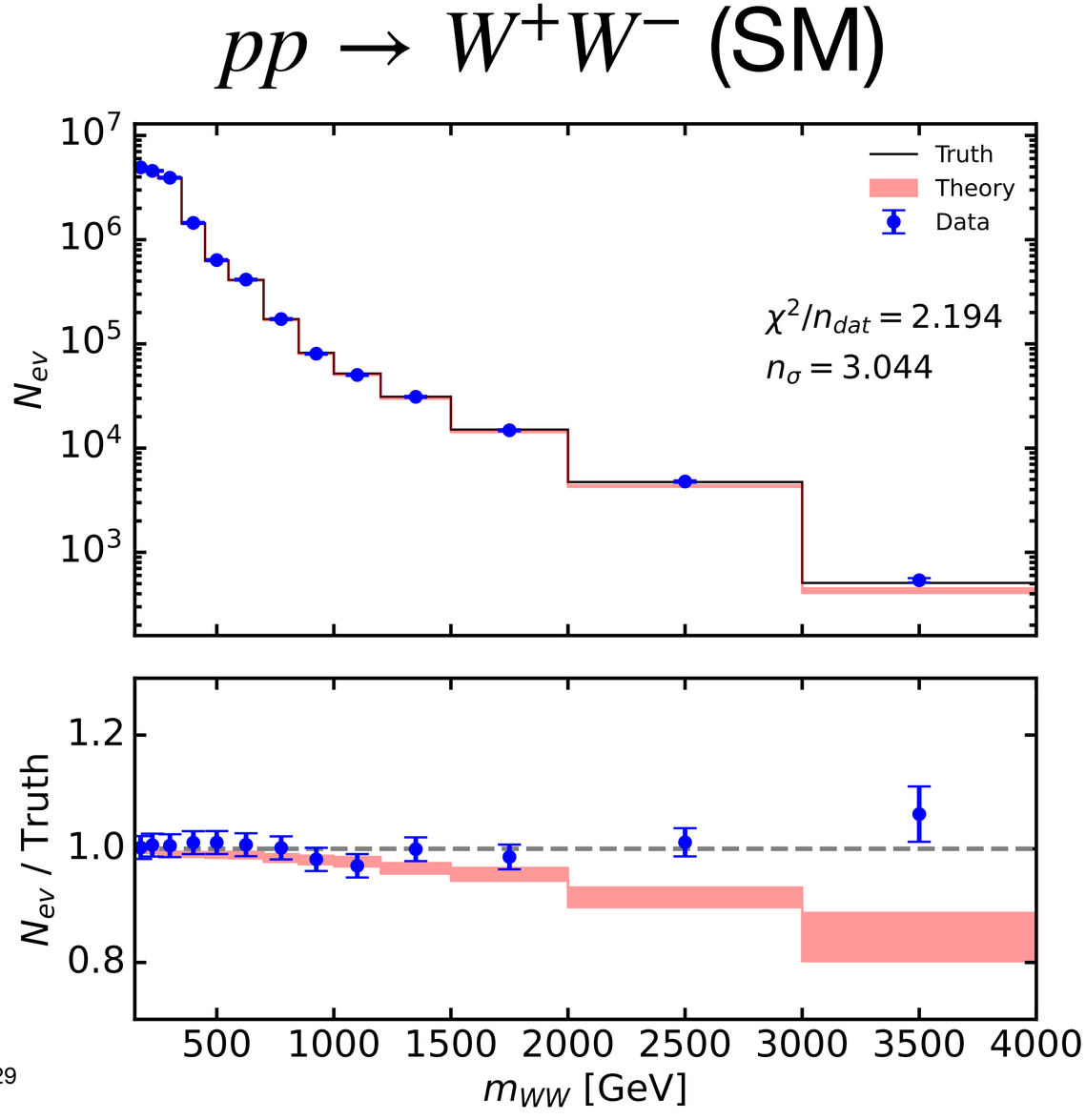
- Contaminated PDFs (red)
- True PDFs (black)

➡ Fake deviation in other sectors

Also seen in:

WH, WZ, ZH production

HL-LHC Projections



Comparing SMEFT bounds for different PDFs

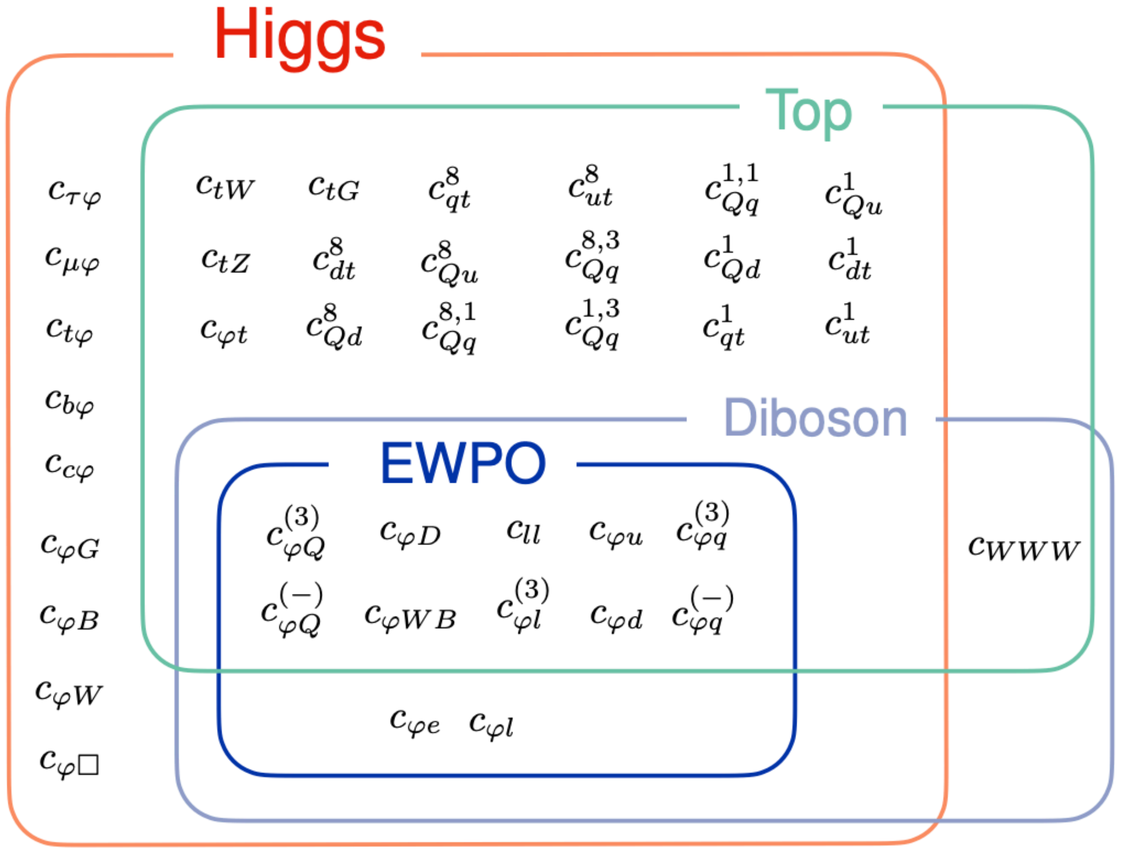
Injection of W' and Z' in Drell-Yan

Fit	$\hat{W} \times 10^5$ (UL = 0.8)		$\hat{Y} \times 10^5$ (UL = 1.5)	
	95% CI	n_σ **(SM/UL)**	**95% CI**	n_σ **(SM/UL)**
True PDF	(0.64, 0.98)	9.00 / 0.11	(0.99, 2.03)	5.50 / 0.00
BSM-biased PDF	(-0.08, 0.39)	1.34 / 5.51	(0.11, 1.44)	2.26 / 2.16
Cons. PDF	(0.50, 1.1)	5.29 / 0.03	(0.68, 2.22)	3.73 / 0.18
Simu. fit	(0.44, 1.05)	4.91 / 0.28	(0.79, 2.09)	4.39 / 0.15

Simultaneous fit of PDF and new physics

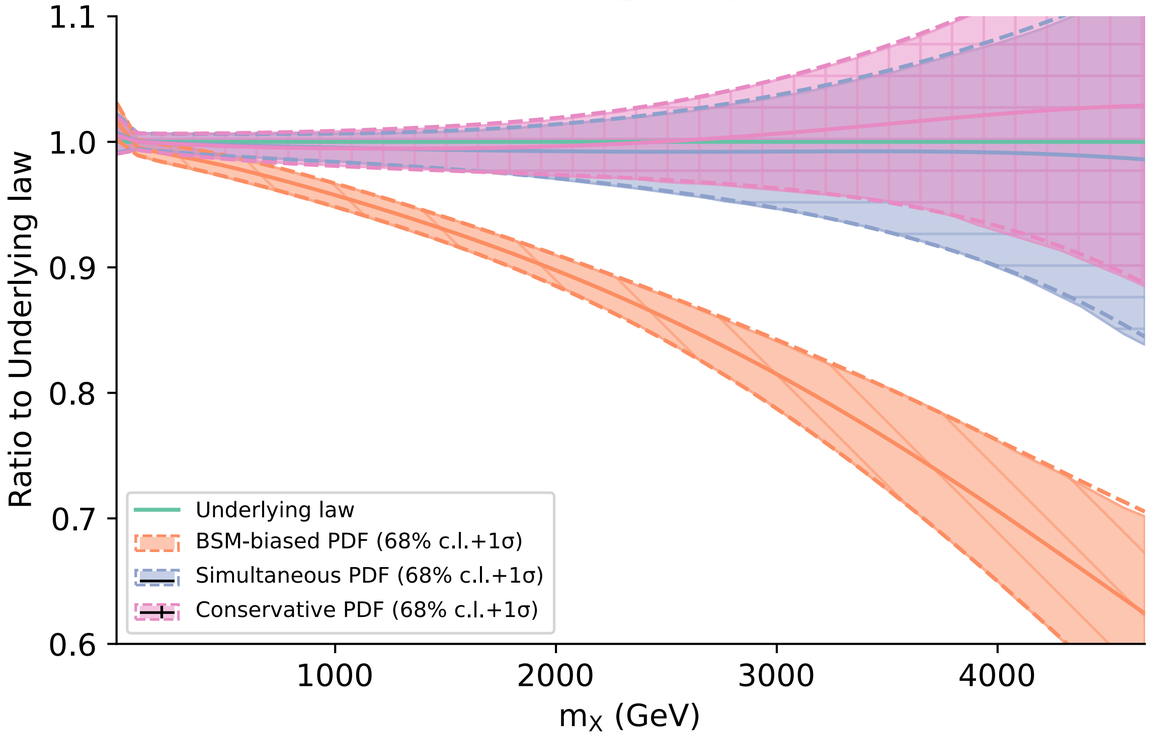
SMEFT operators implemented

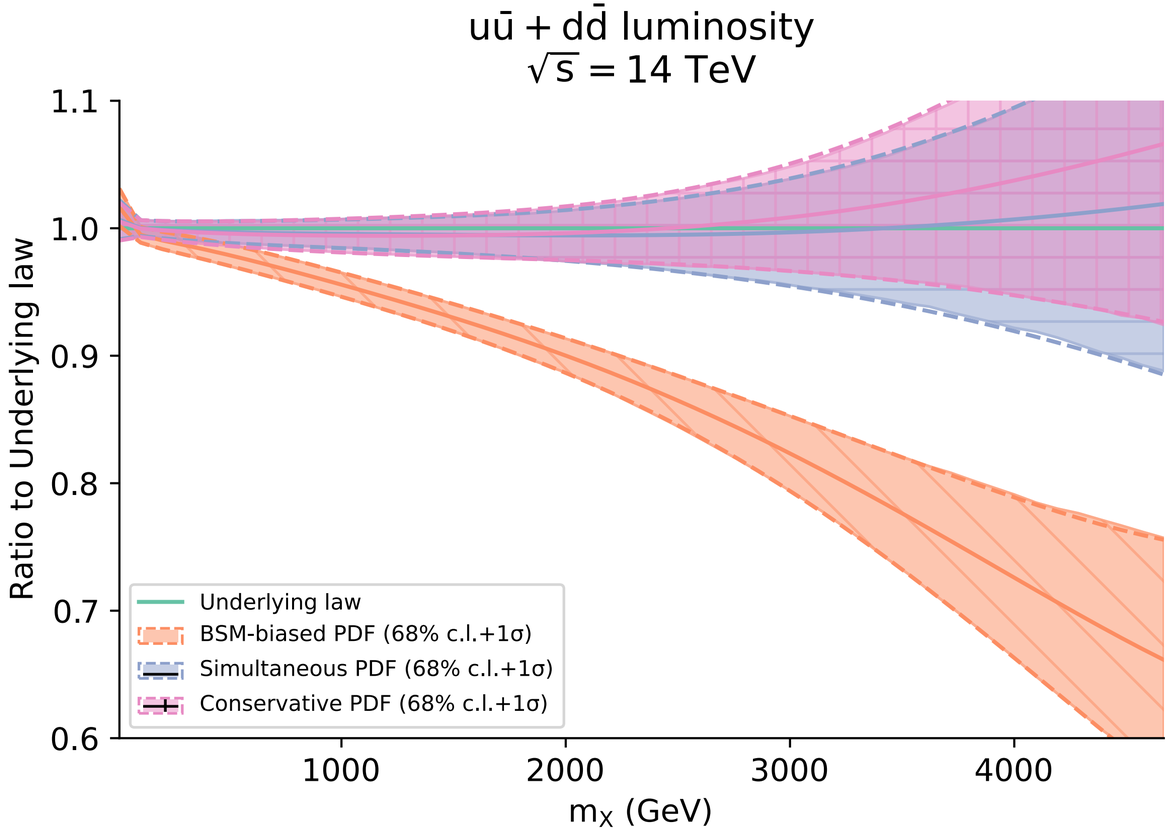
- 40 operators implemented
- Observables:
  - top sector
  - diboson
  - Higgs
  - Drell-Yan
  - EW Precision Observables



PDFs for new physics searches in HMDY

PDF luminosities





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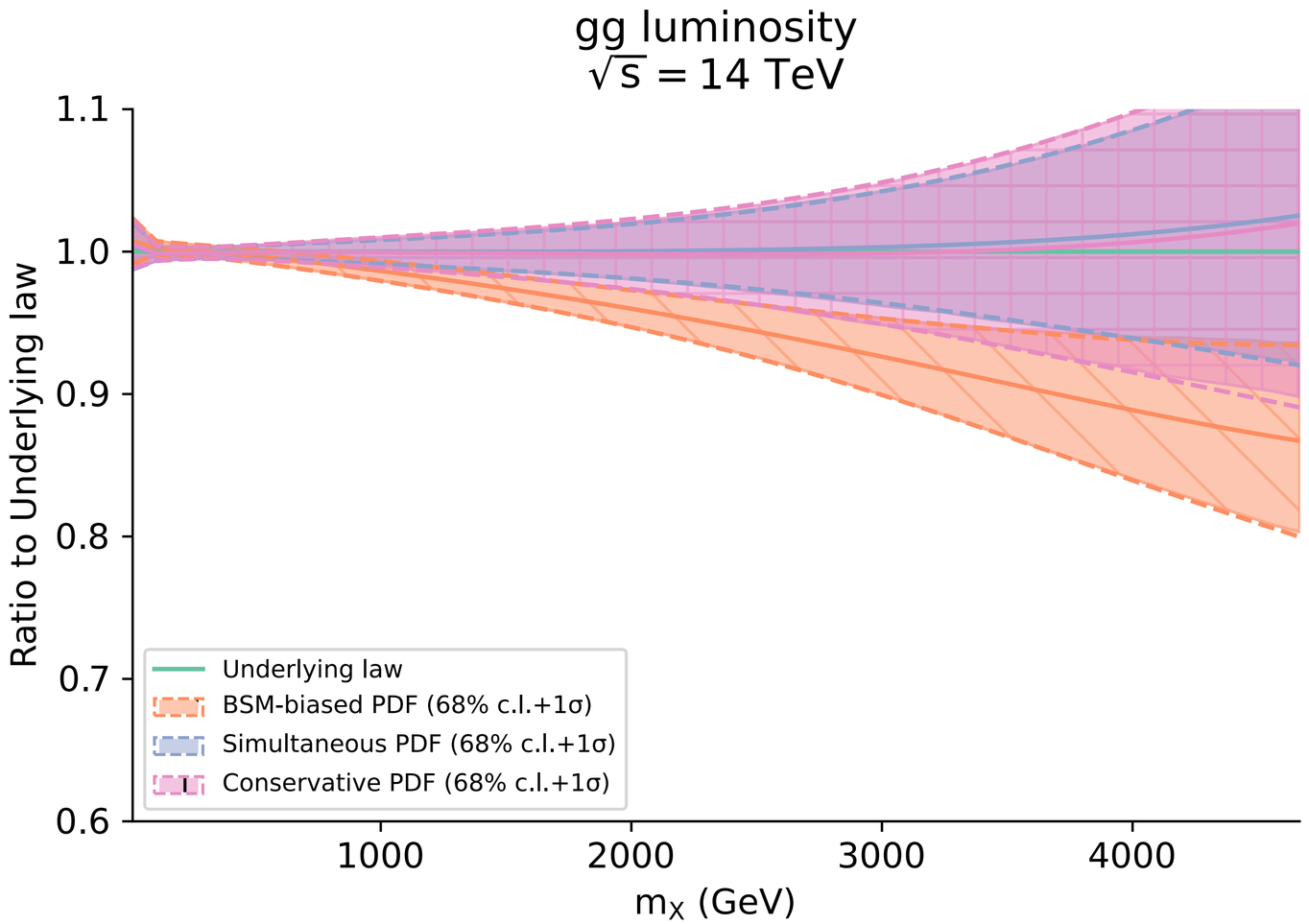
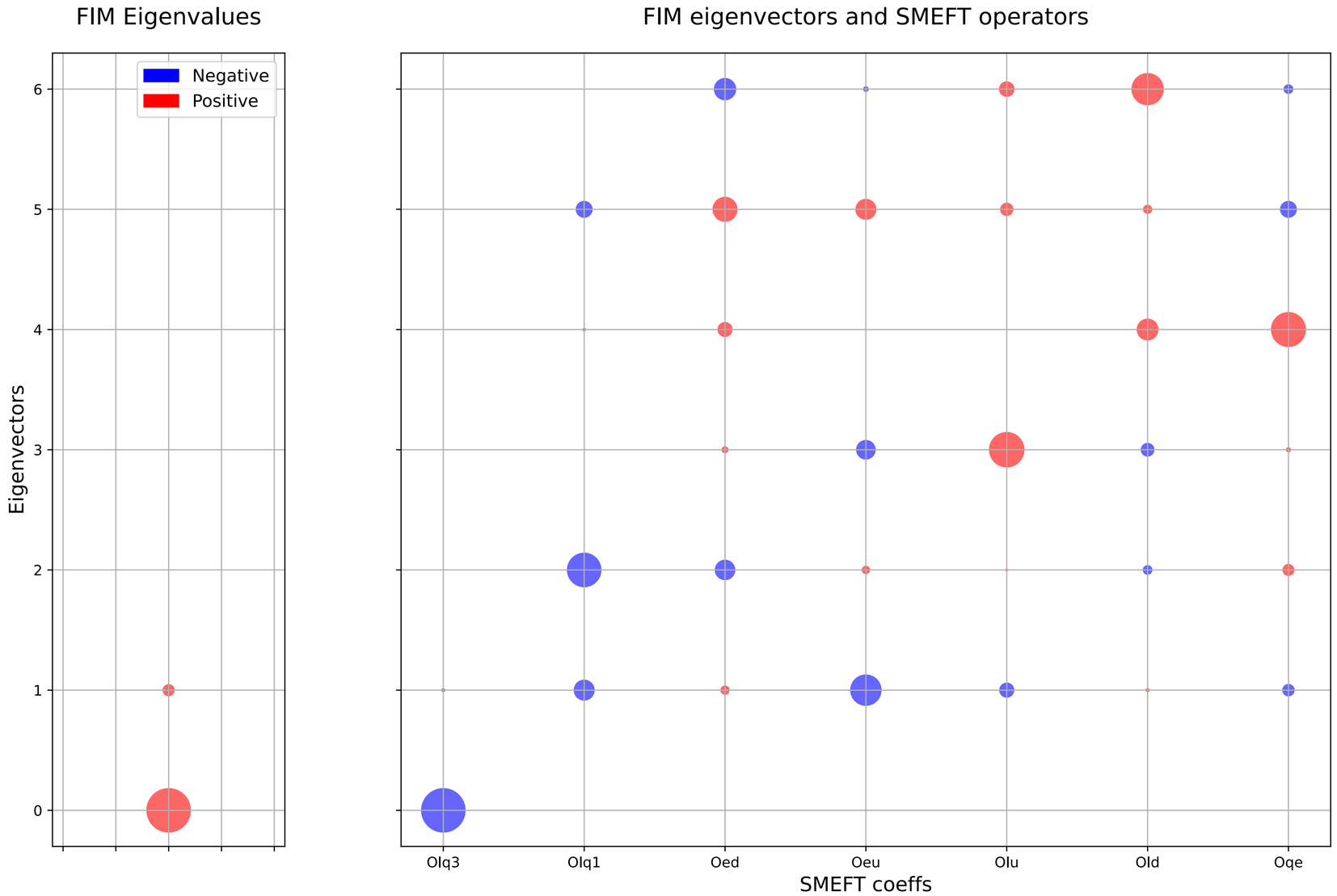
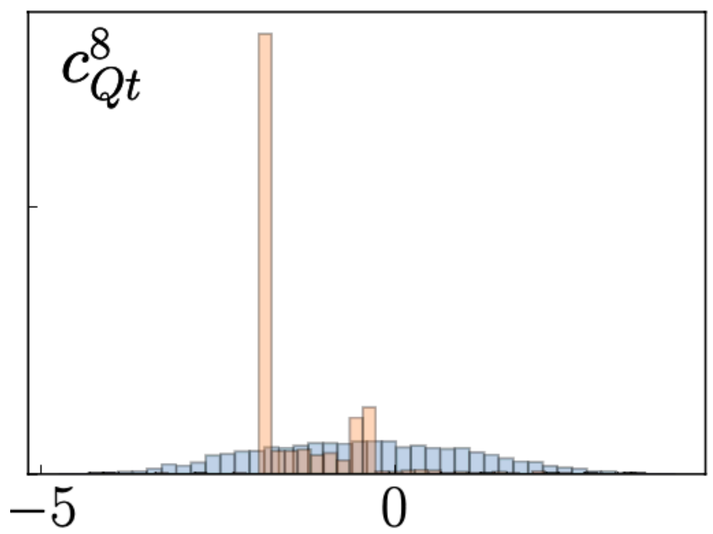
Same exercise with heavy gluon in ttbar at HL-LHC

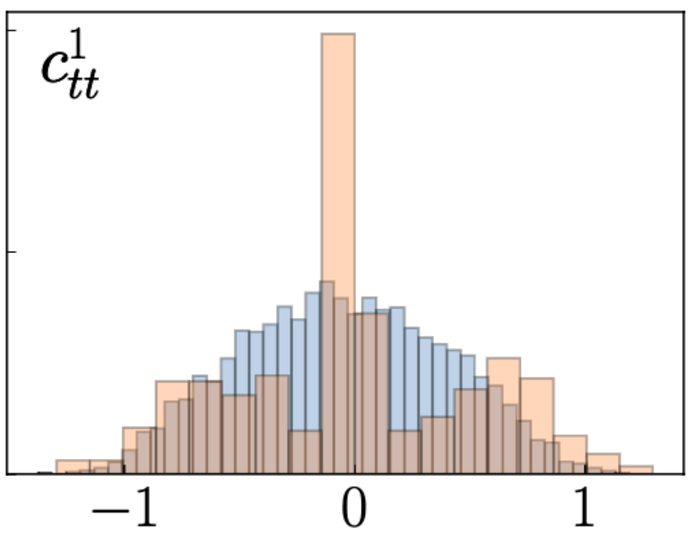


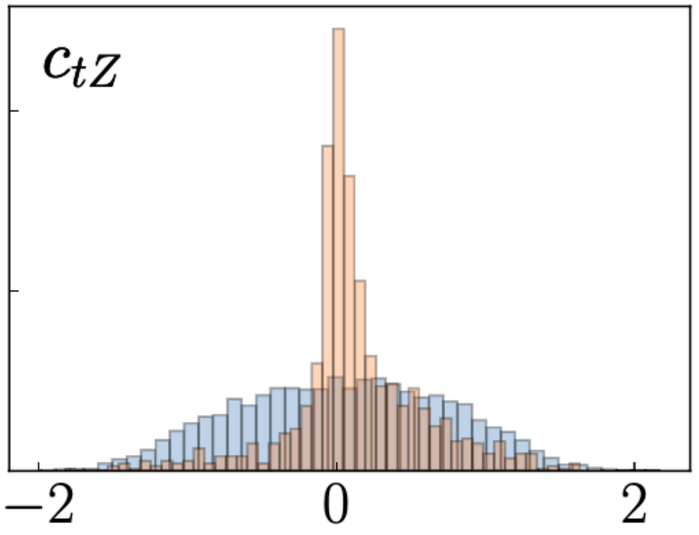
SMEFT PCA results



BEYOND MONTE CARLO AND NEURAL NETWORKS







- In the quadratic SMEFT fit observed disagreement between MC method and Bayesian method. Very different posterior (hence different CLs)

- Study of MC versus Bayesian method based on nested sampling for PDF fits and SMEFT fits [Costantini, Madigan, Mantani, Moore arXiv:2404.10056]

- Towards a general Bayesian methodology for simultaneous fits [Costantini, Mantani, Ubiali, in progress]

Let's consider a simple scenario: 1 operator, 1 datapoint

$$\chi^2 = \frac{(\sigma(c) - \sigma_{exp})^2}{\delta\sigma^2} \qquad \Delta\chi^2 = \chi^2 - \chi_{min} = 1 \quad \rightarrow \quad [c_-, c_+]$$