Hidden new physics in PDF fits

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European Research Council
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Talk Overview

1 An Introduction to PDFs

2 Introduction to ‘BSM bias’

3 Methods to avoid ‘BSM bias’

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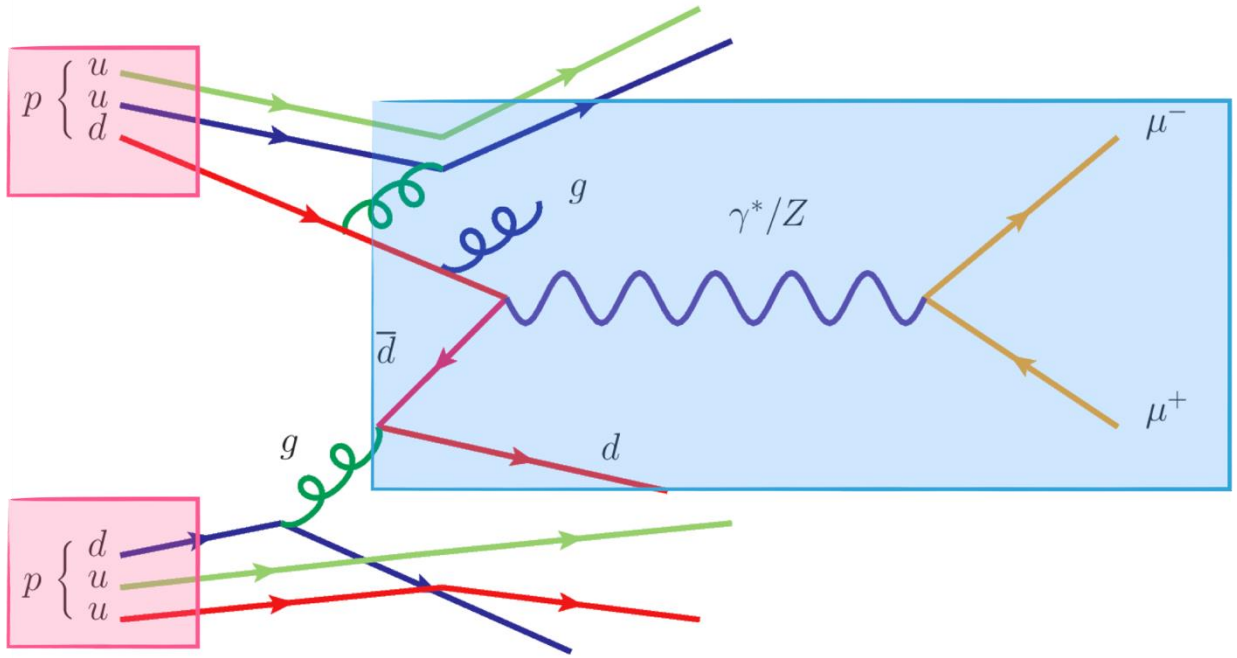
Introduction to PDFs

Parton Distribution Functions



Hard Scattering: Perturbative QCD + EW

- Collinear factorization → **universal PDFs**
- They describe the distribution of **proton longitudinal momentum** across partons

Set of PDFs for all quark **flavours** (+gluons) in the proton

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

$$f_{flav} = f_{flav}(x, Q^2)$$

How to fit PDFs?

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

Theory Predictions

Match with experimental datasets

Fermilab

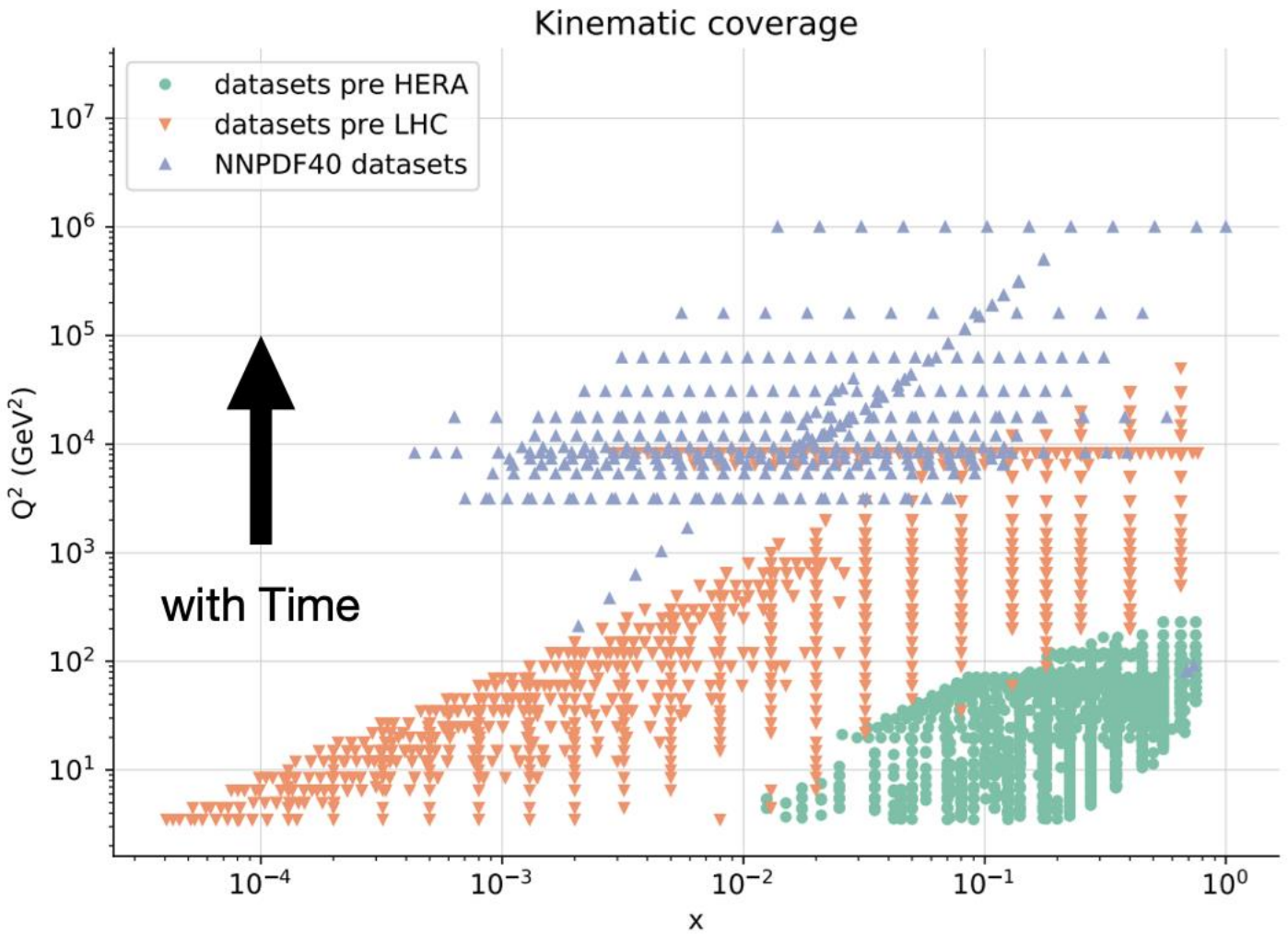
Constrained by sum and momentum rules and high/low-x limit behavior

Goal: Produce set of PDFs which best describe the data

Theory calculations

Partonic cross section at NNLO (aN3LO for DIS)

How to fit PDFs?



With more statistics, datasets moved towards **higher energies**

Risk of absorbing BSM deviations into PDFs

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

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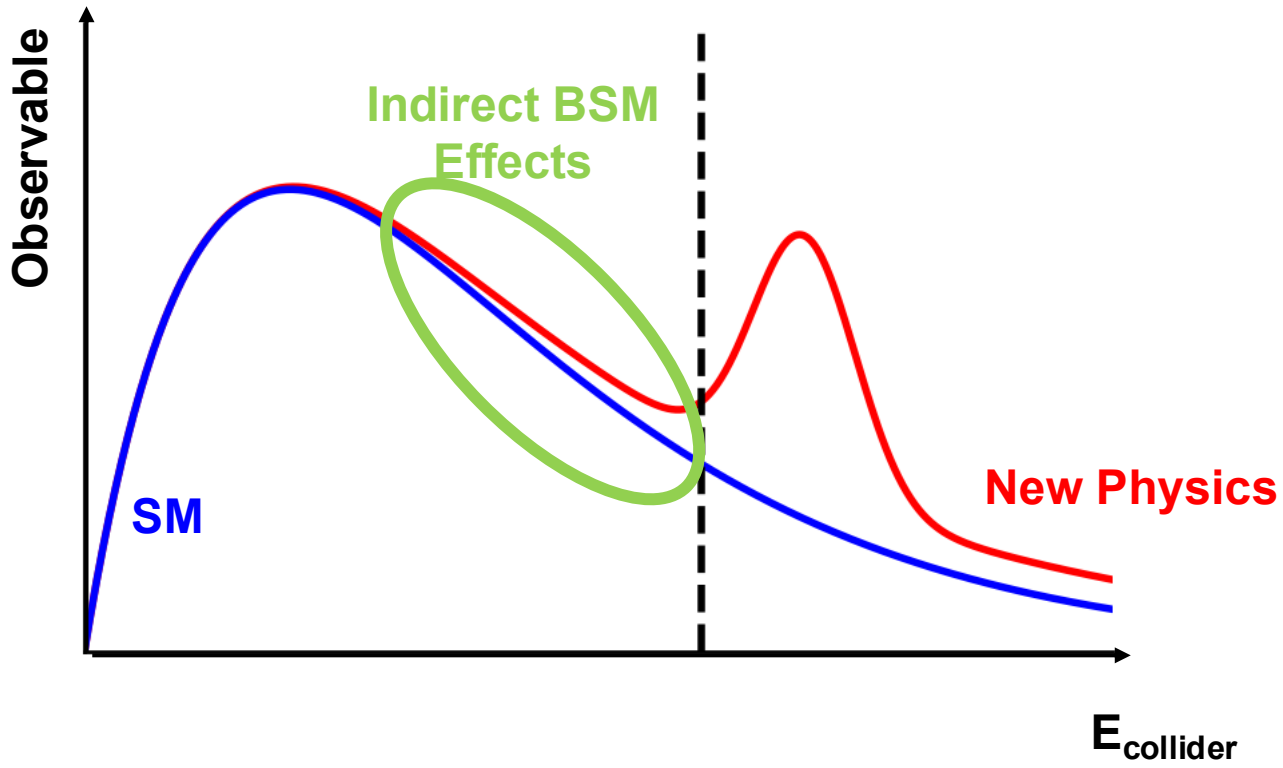
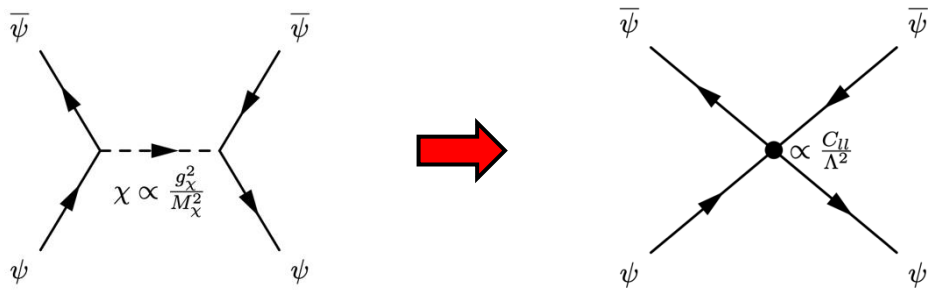
SMEFT– An Effective Plan

Standard model effective field theory (SMEFT) can be used to parameterise new physics for **indirect searches**

Crucial to disentangle PDF effects from BSM effects



Integrate out heavy fields

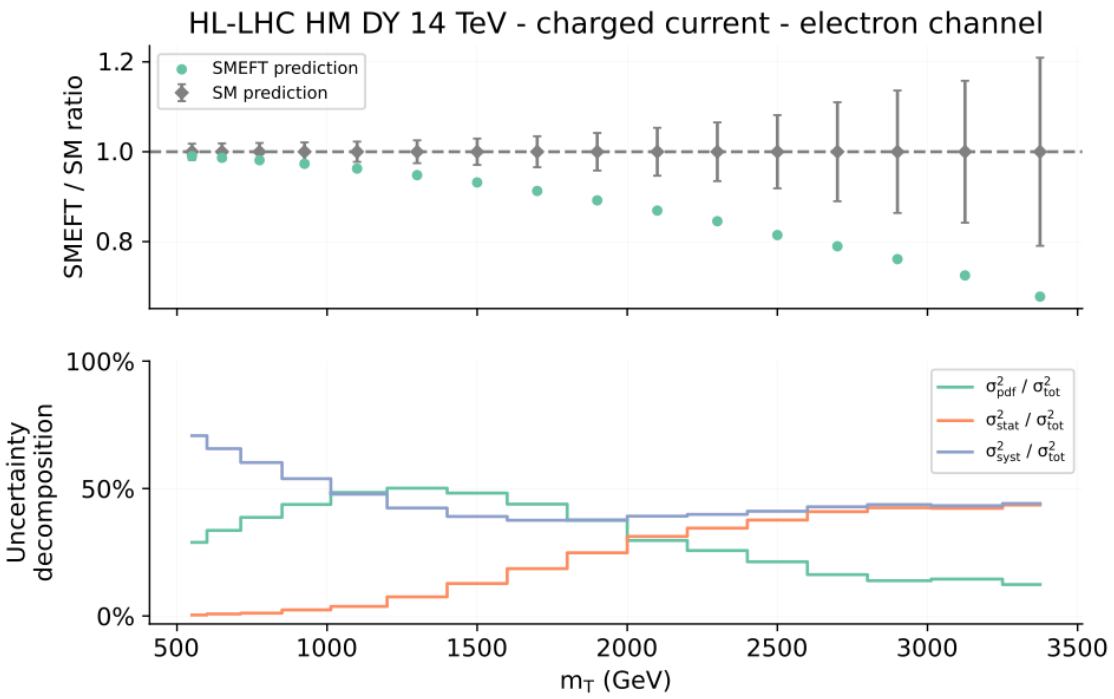


$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

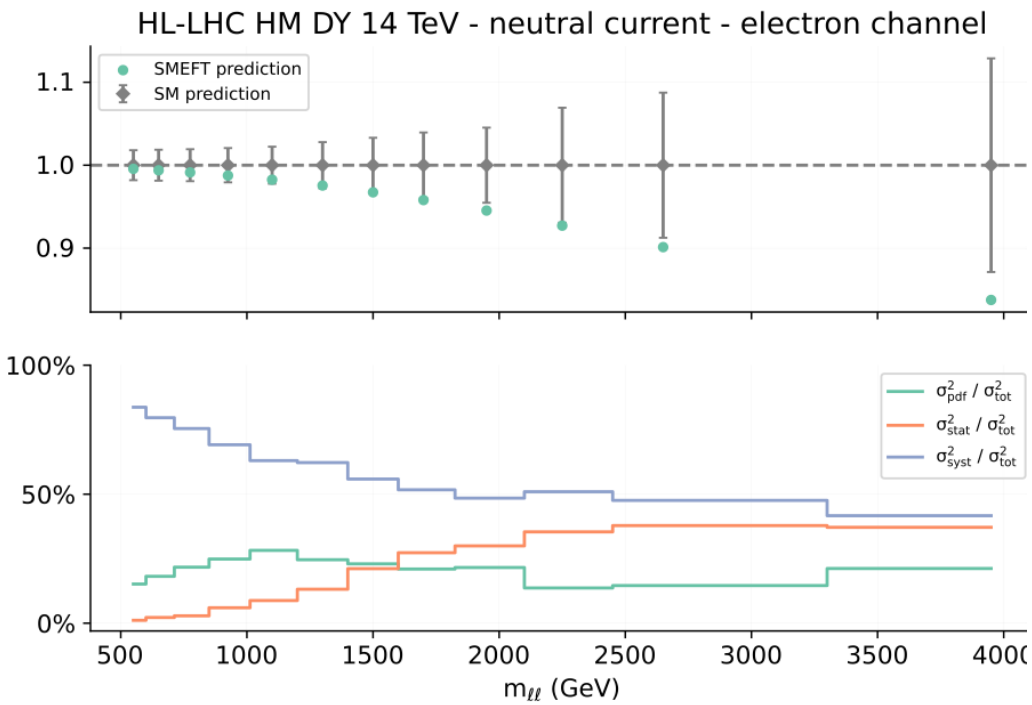
Injecting New Physics into HL-LHC Projections

A flavour universal *W'* with $M_{W'}$=*13.8TeV* injected into the data

Charged Current



Neutral Current



[PBSP, 2602.20235]

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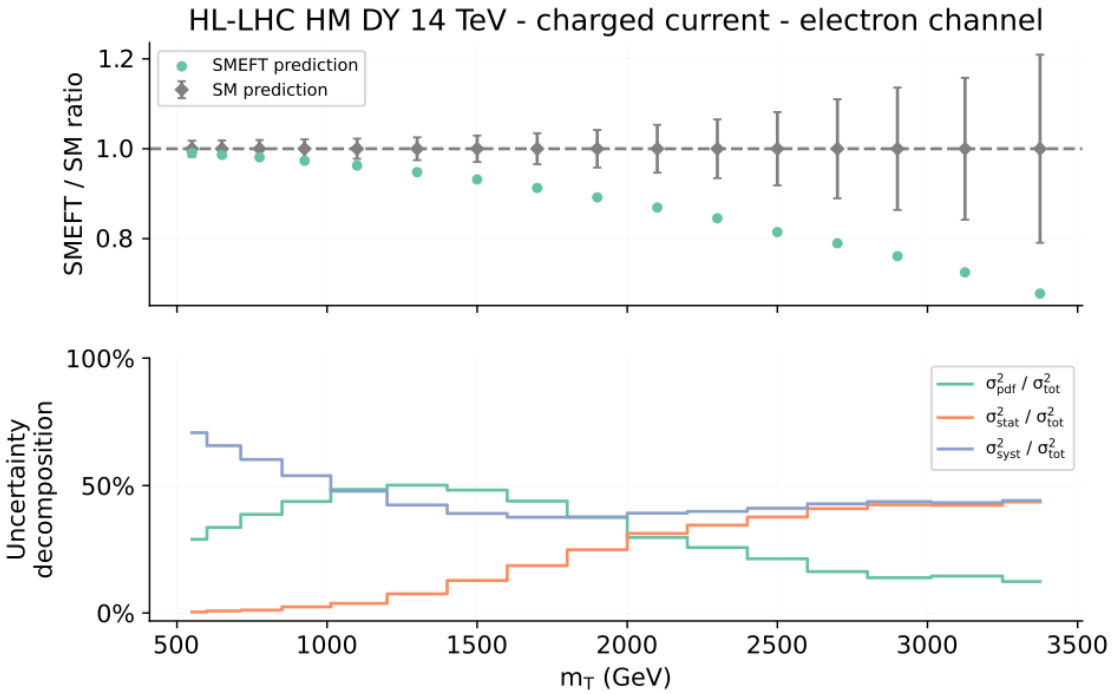
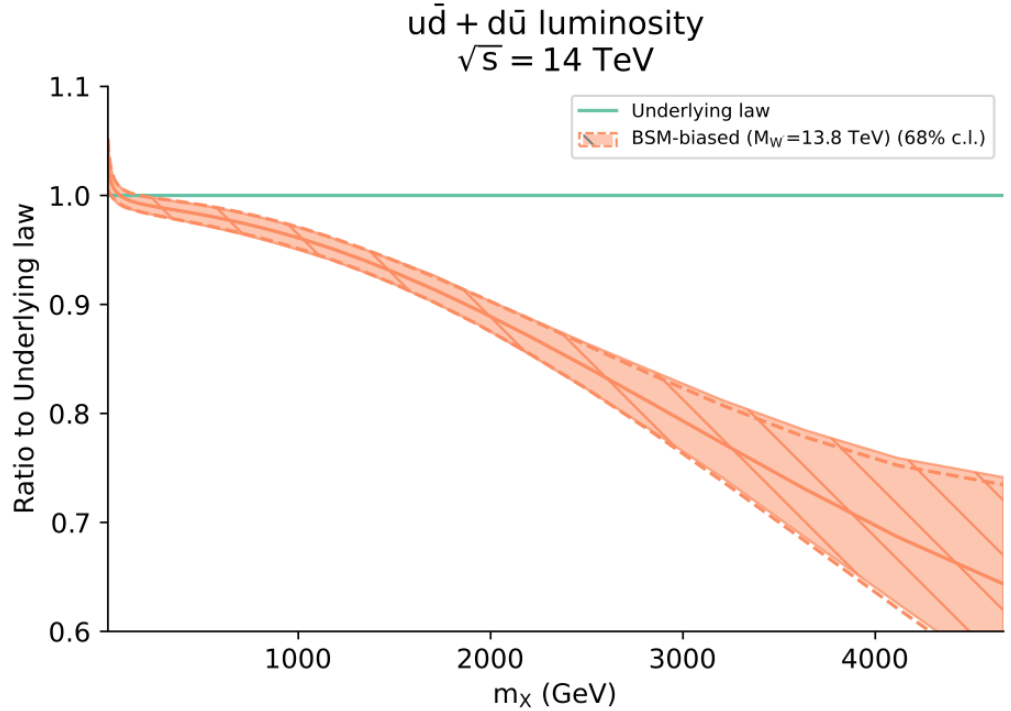


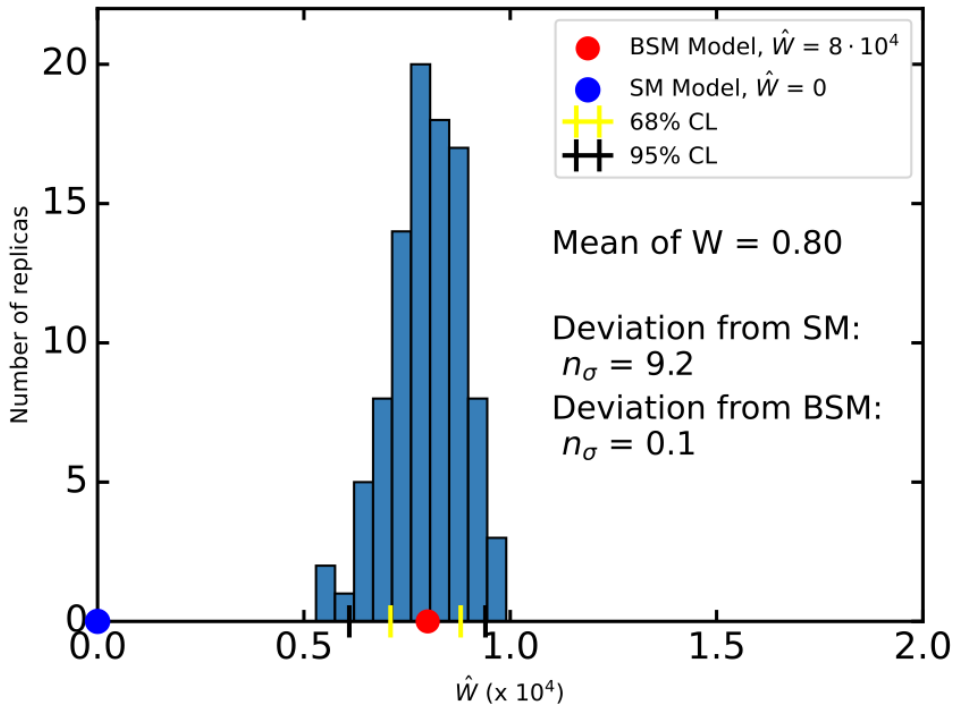
[PBSP, 2602.20235]



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

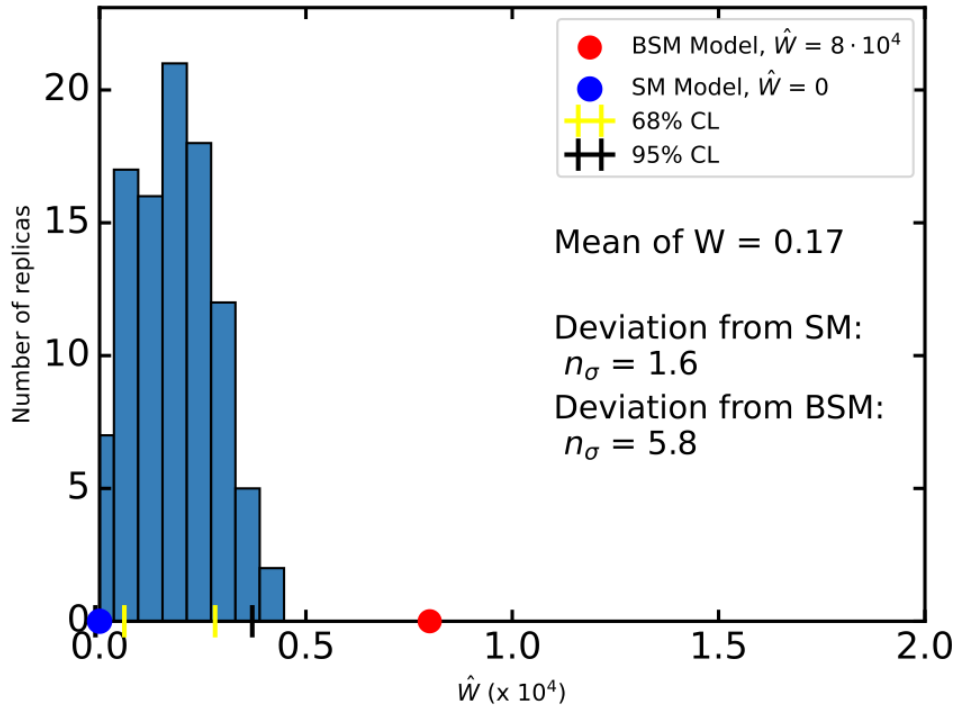
Missing New Physics

SMEFT Fit with True PDF



SMEFT Fit with BSM Biased PDF

- Misses new physics



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Tools for combating BSM bias in PDFs

Two methods of ‘safe’ PDF fitting

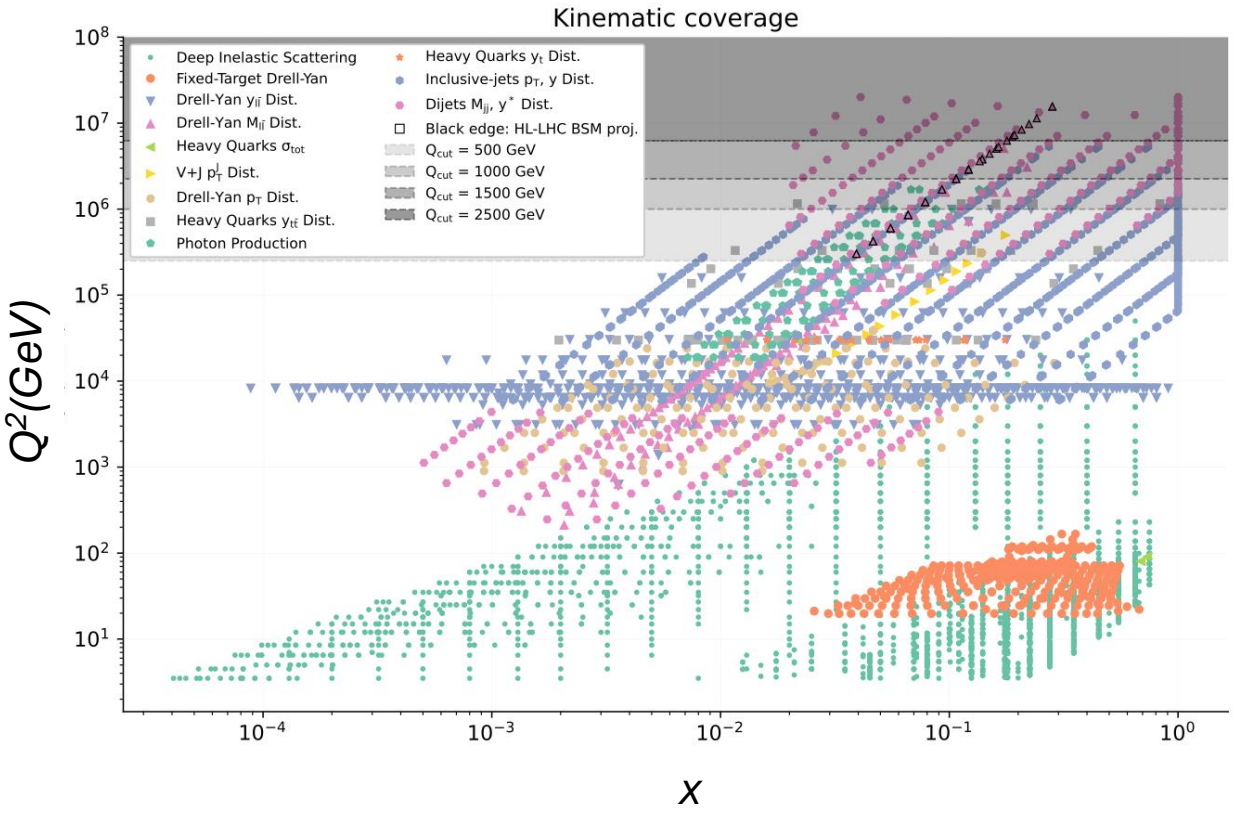
1 - Separate fit with conservative PDF

Fit PDF on set of data below the energy scale where BSM effects are present

Then, fit SMEFT using this ‘conservative’ PDF

Cons

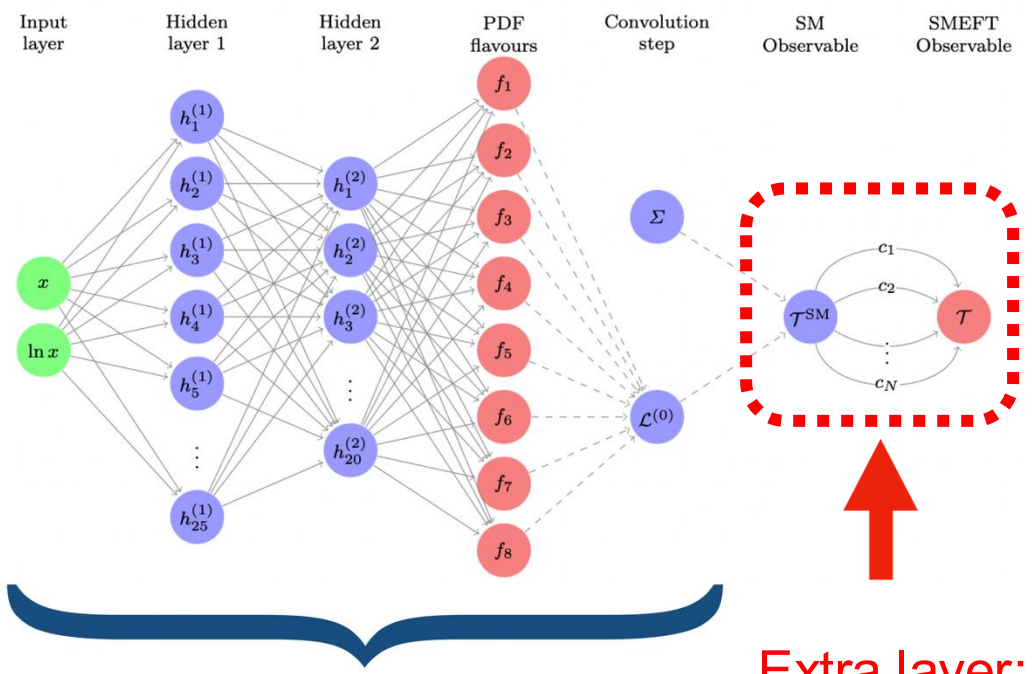
- Assumes SM
- Removes useful constraints in large-x regions



Tools for combating BSM bias in PDFs

Two methods of ‘safe’ PDF fitting

2 – Simultaneous PDF + SMEFT fit

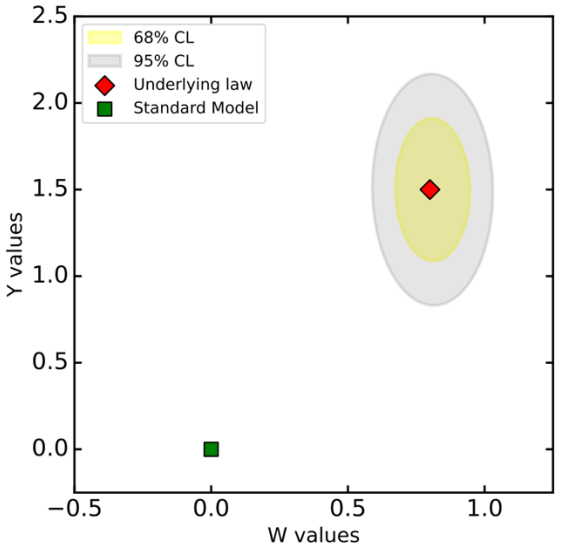


[Iranipour et Ubiali, 2201.07240]

SIMUnet:

- Open-source tool: github.com/HEP-PBSP/SIMUnet [PBSP, 2402.03308]
- Fits PDFs and Wilson coefficients simultaneously
- Performs contaminated PDF fits through injection of BSM effect

PDFs for New Physics searched in HMDY

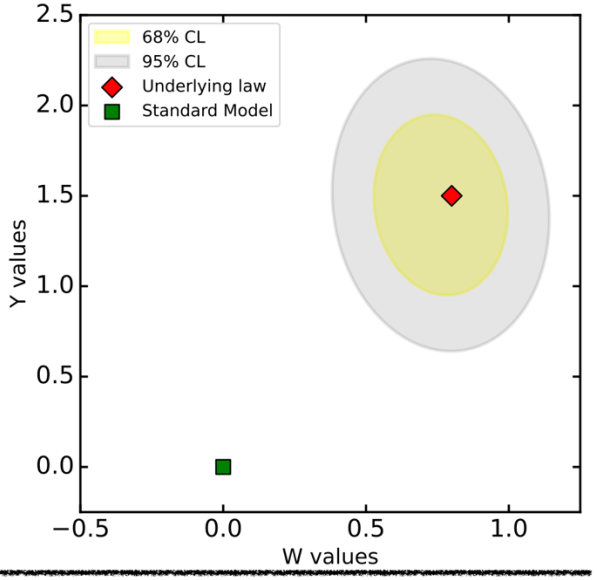


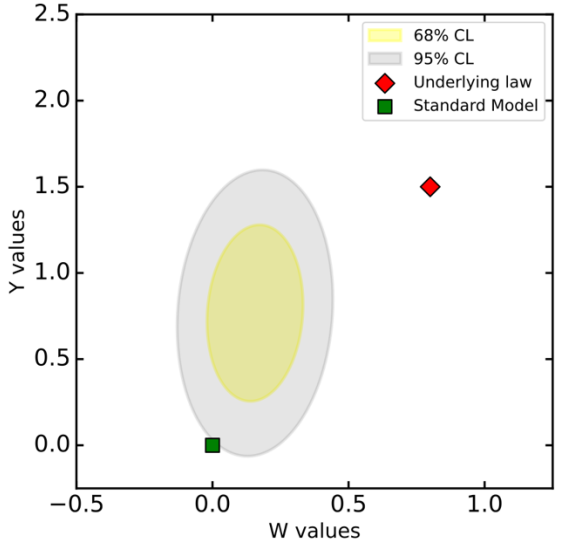
SMEFT only fit
(True PDF)

✗ Impossible

Simultaneous fit
(no PDF assumption)

✓ Doable



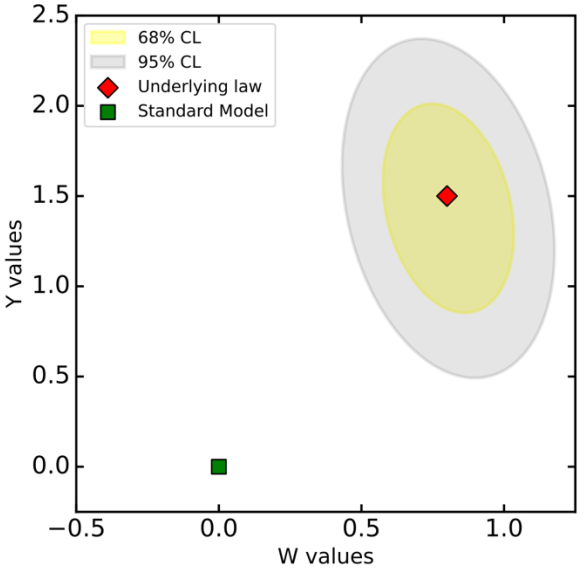


SMEFT only fit
(BSM-biased PDF)

✗ Wrong

SMEFT only fit
(Conservative PDF)

✓ Doable



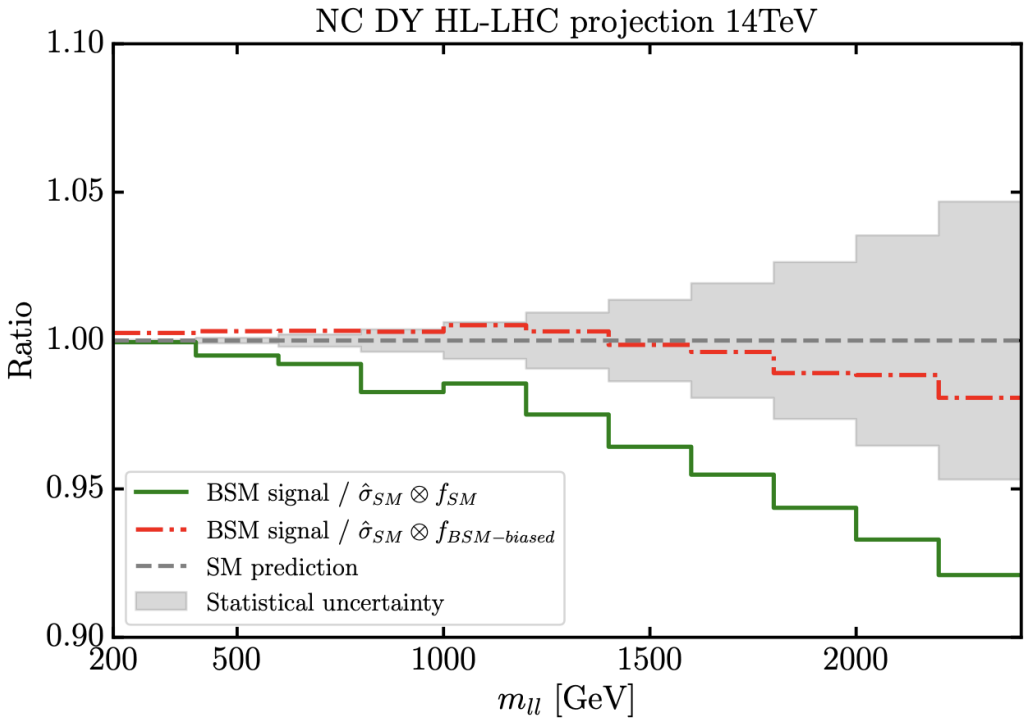
Other Recommendations

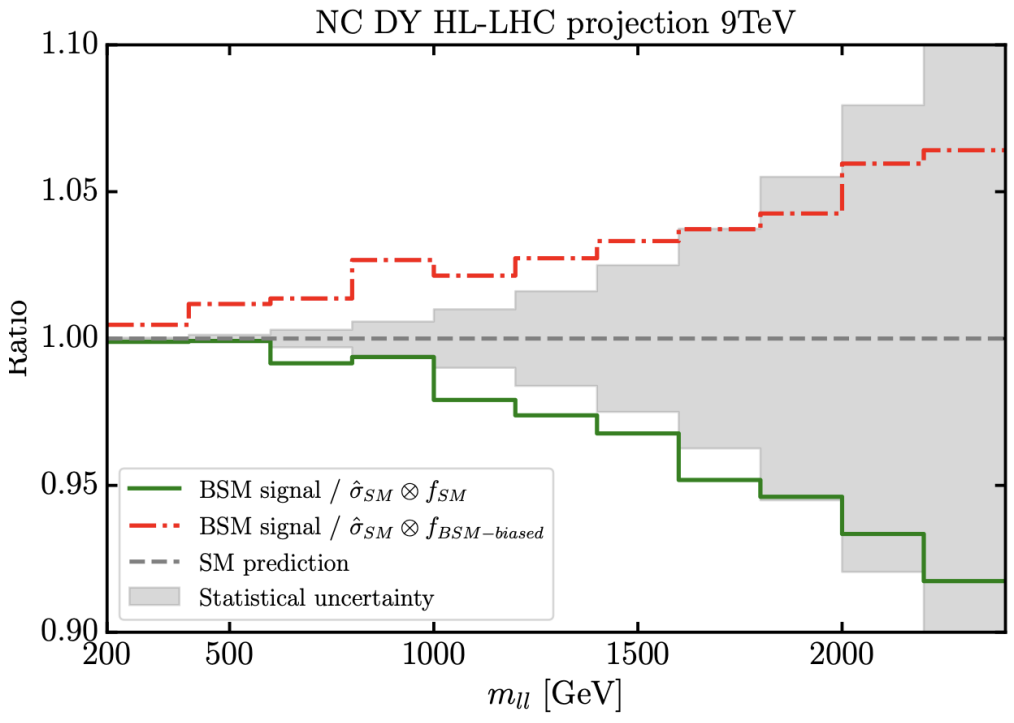
Break the degeneracy between ***x*** and ***M$_{ll}$***

$$M^2 = x_1 x_2 s$$

$$f_i = f_i(x)$$

$$SMEFT \sim \frac{M^2}{\Lambda^2}$$





Summary and Future Work

- Signs of new physics can be fitted away in PDF
  - Inaccurate PDFs
  - Missed New Physics

- Can combat this with conservative fit or simultaneous PDF + SMEFT fits [SIMUnet 2402.03308]

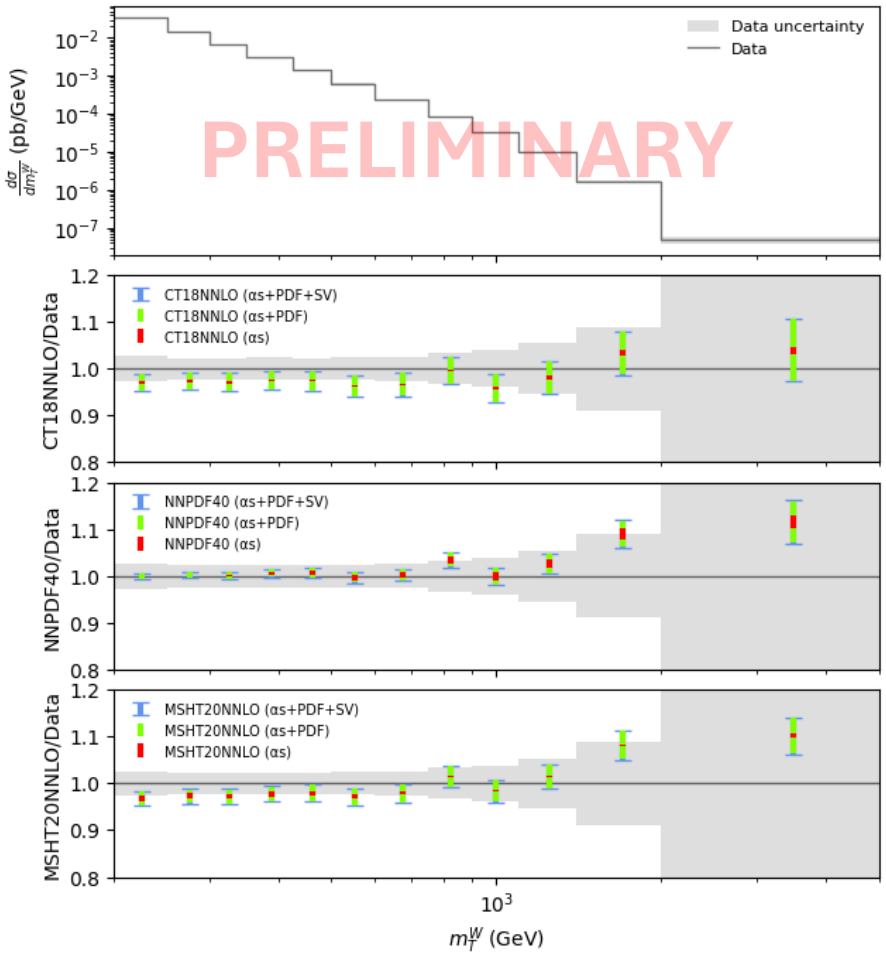
PBSP

- Explored BSM and PDF interplay in HMDY and top sector

- Developing a Bayesian framework for simultaneous PDF + SMEFT fits [2510.03391]

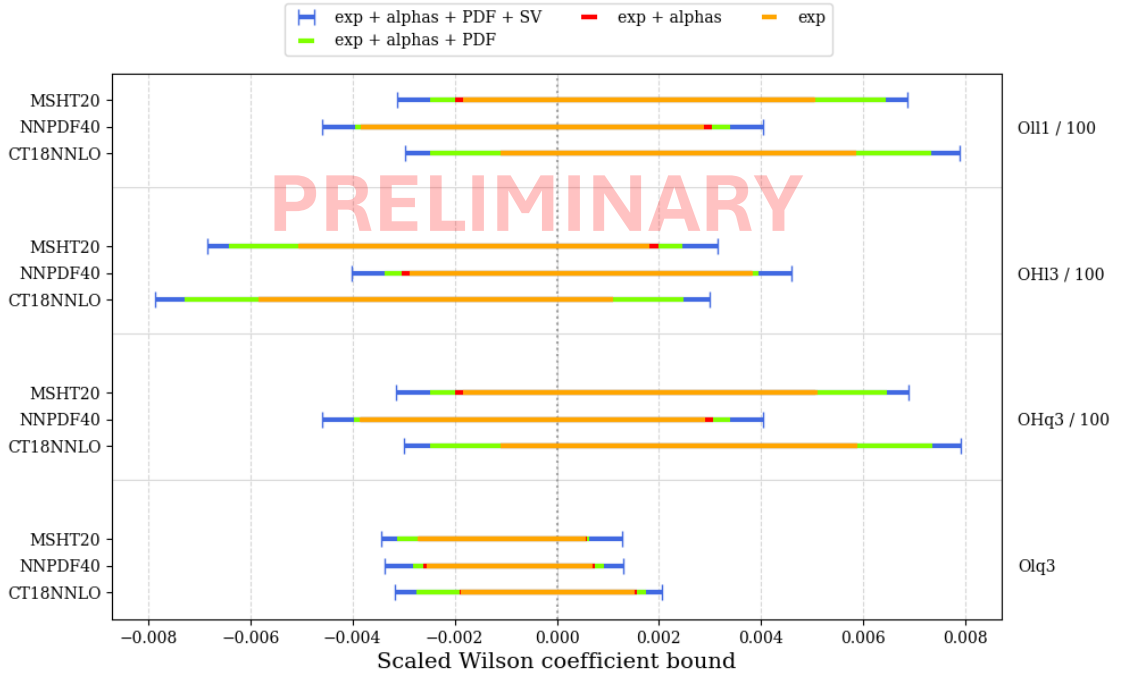
Backup Slides

A look into PDF-SMEFT interplay

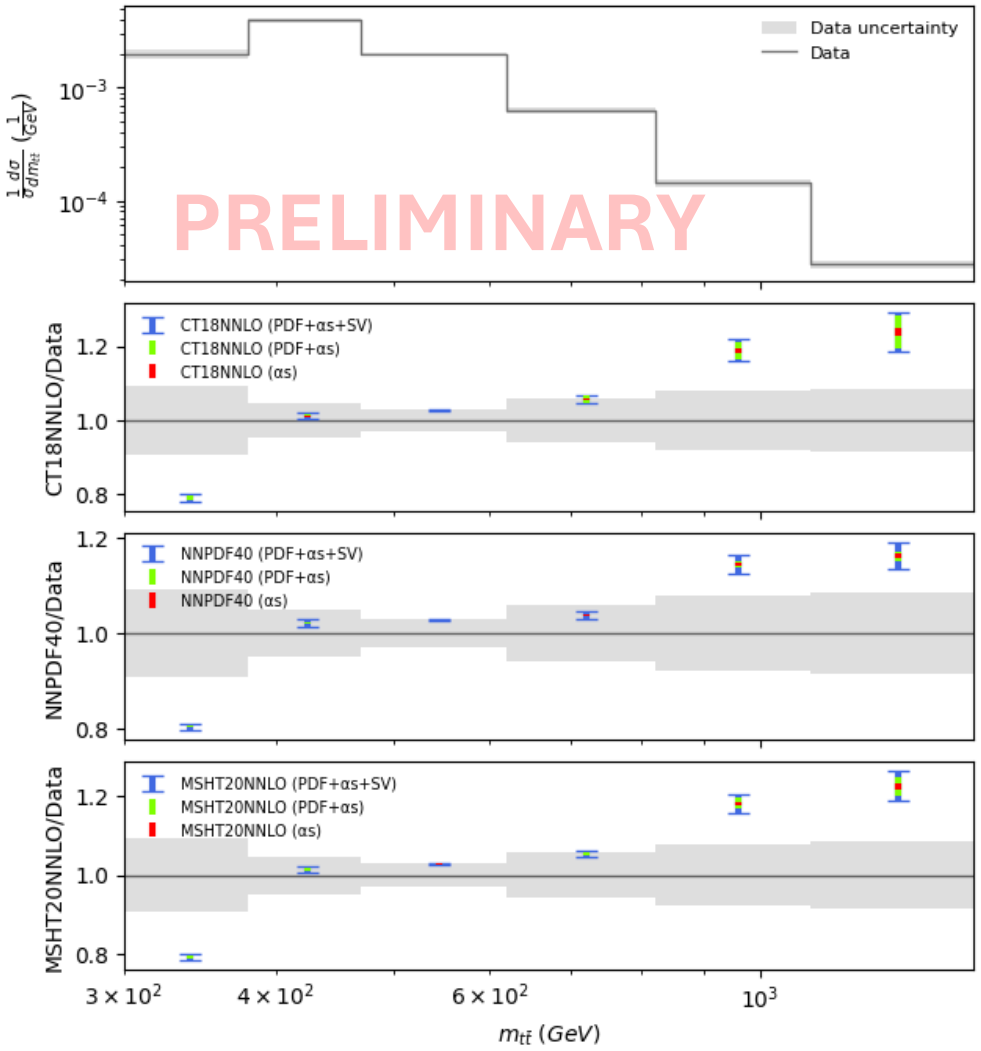


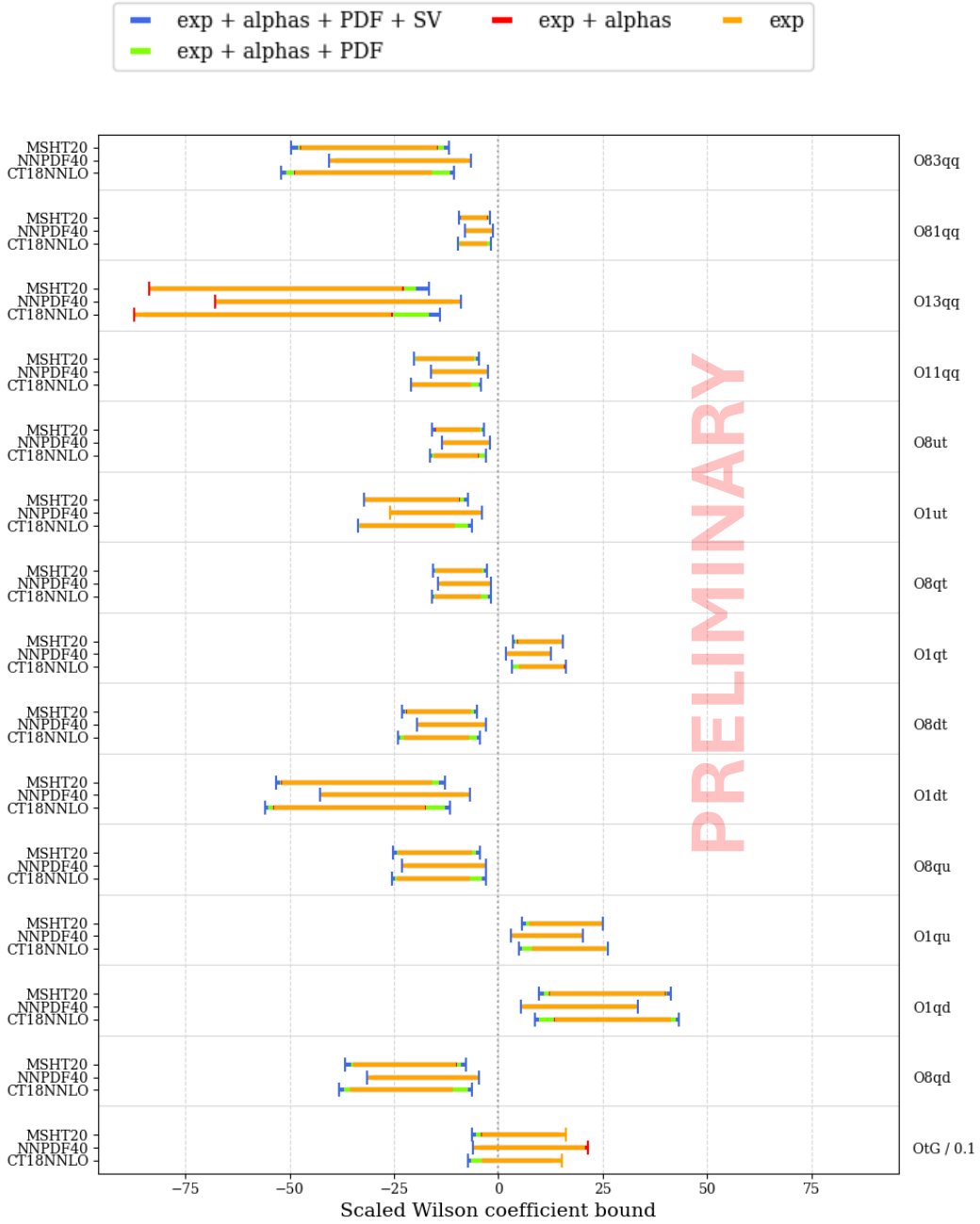
Performing SMEFT fits with different PDF sets yields different bounds on Wilson coefficients

PDFs can be dominant theory uncertainty here



CMS ttbar 13TeV 2-Leptons





Injecting New Physics into HL-LHC Projections

A flavour universal *W'* with $M_{W'}$=*13.8TeV* injected into the data

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

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

No datasets are flagged by current selection criteria

[PBSP, 2602.20235]

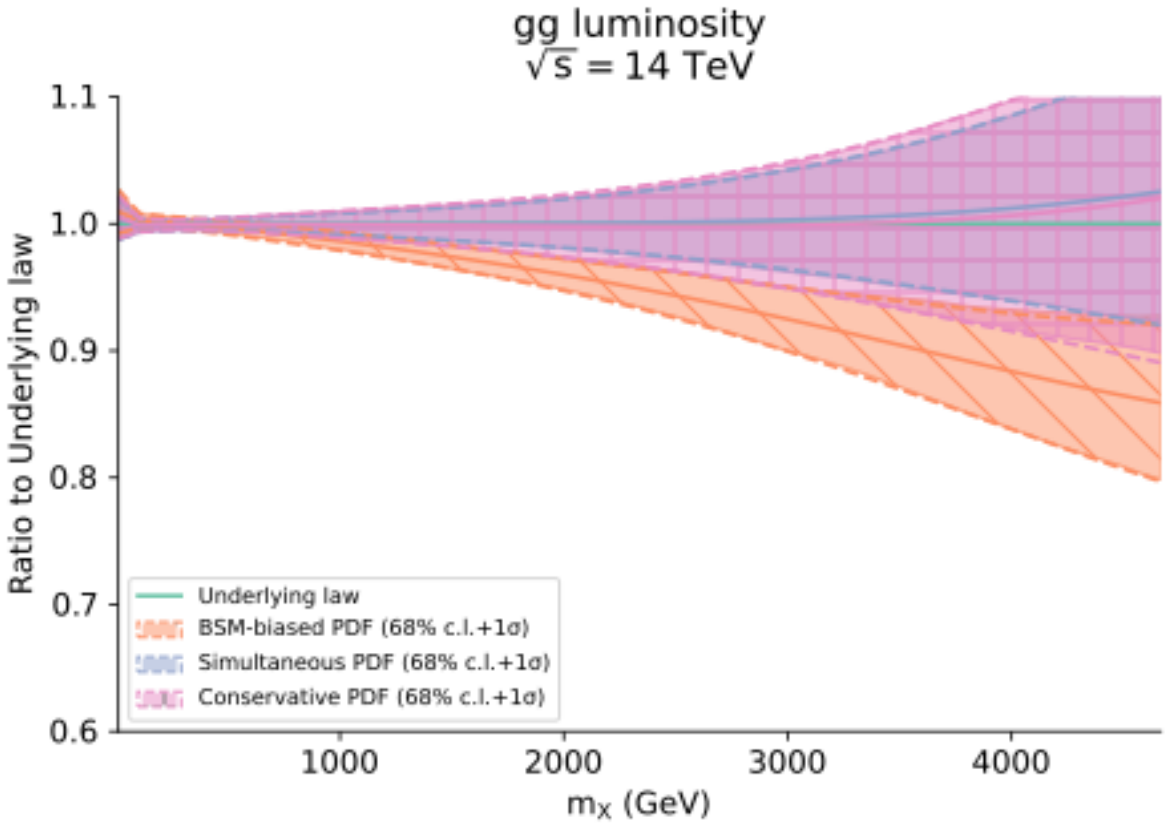
$$\mathcal{L}_{true} \otimes \hat{\sigma}_{BSM} \approx \mathcal{L}_{BSM-biased} \otimes \hat{\sigma}_{SM}$$

PDFs for New Physics searched in Top Sector

A massive Coloron (“heavy gluon”) injected into the data

Partial **BSM absorption** into gg PDF

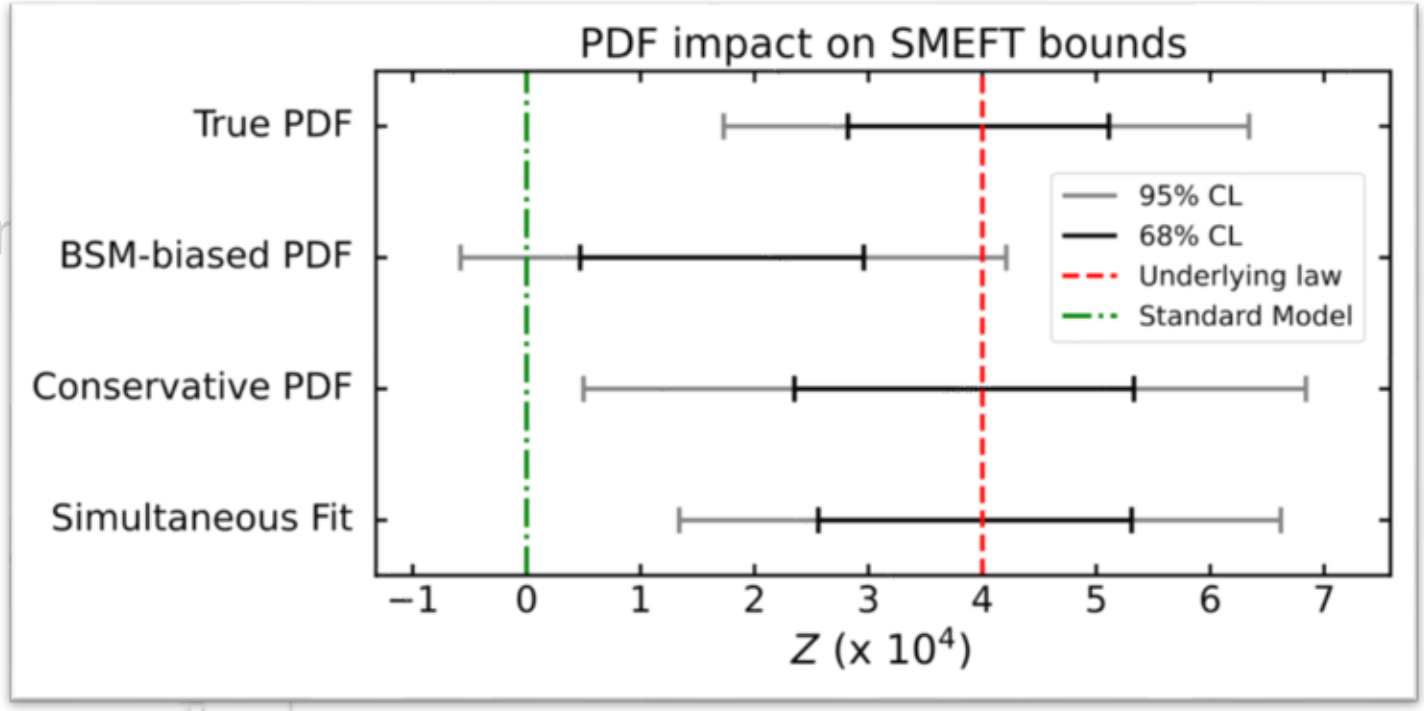
SMEFT bounds deviate from the true underlying injected effect



PDFs for New Physics searched in Top Sector

A massive Coloron (“heavy gluon”) injected into the data

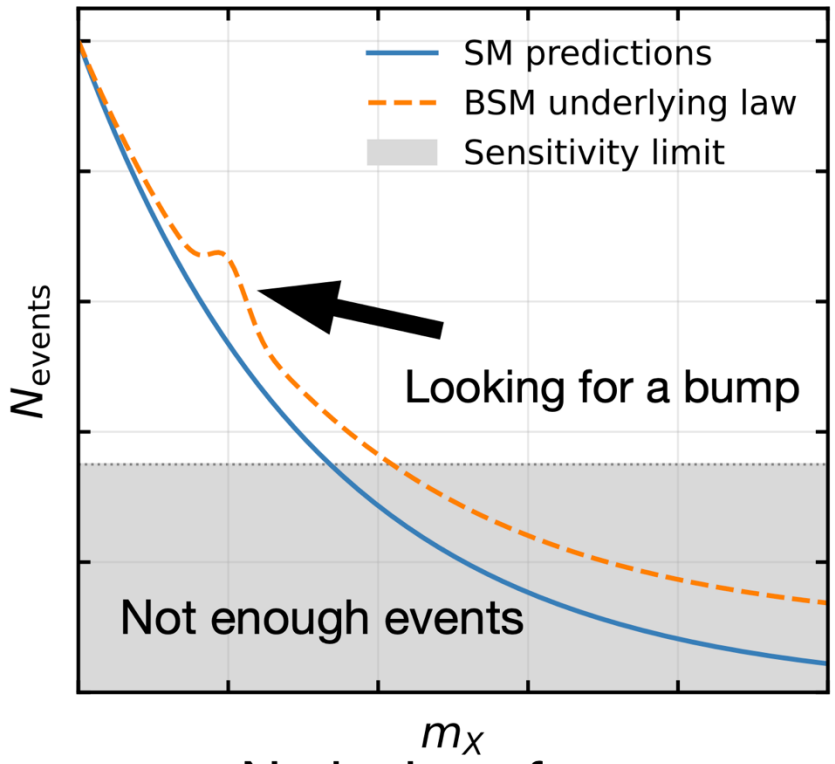
Partial **BSM absorption** into gg



SMEFT bounds deviate from the true underlying injected effect

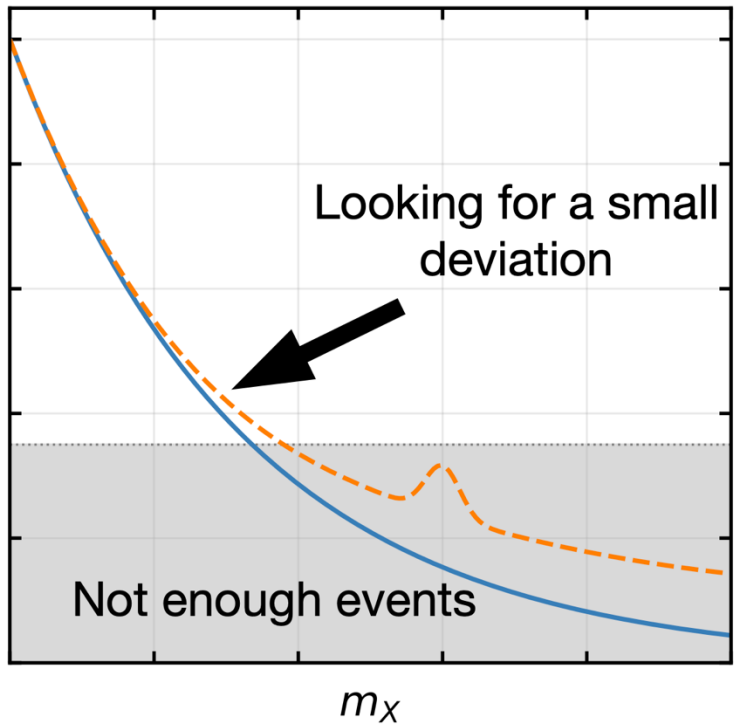
“Correct” diagram for indirect searches

Direct searches



No luck so far…

Indirect searches



Requires precision

New physics scenarios: W'

From UV to the SMEFT

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

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

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

Matching to the SMEFT:

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

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

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Z' Model

Neutral boson associated to $U(1)_Y$

$$\mathcal{L}_{\rm UV}^{Z'} = \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'^\mu$$
$$- g_{Z'} Z'_\mu \sum Y_f \bar{f} \gamma^\mu f - Y_\varphi g_{Z'} (Z'_\mu \varphi^\dagger i D^\mu \varphi + \text{h.c.}) \,.$$

$$\mathcal{L}_{\rm SMEFT}^{Z'} = \mathcal{L}_{\rm SM} - \frac{g'^2 \hat{Y}}{2 m_W^2} J_Y^\mu J_{Y,\mu}, \qquad \hat{Y} = \frac{g_{Z'}^2}{M_{Z'}^2} \frac{m_W^2}{g'^2} \,.$$

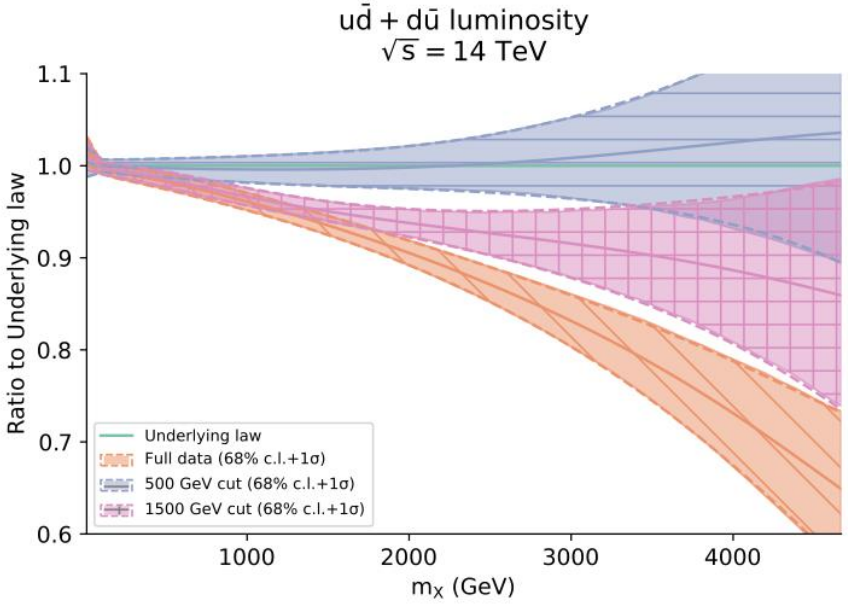
G' Model

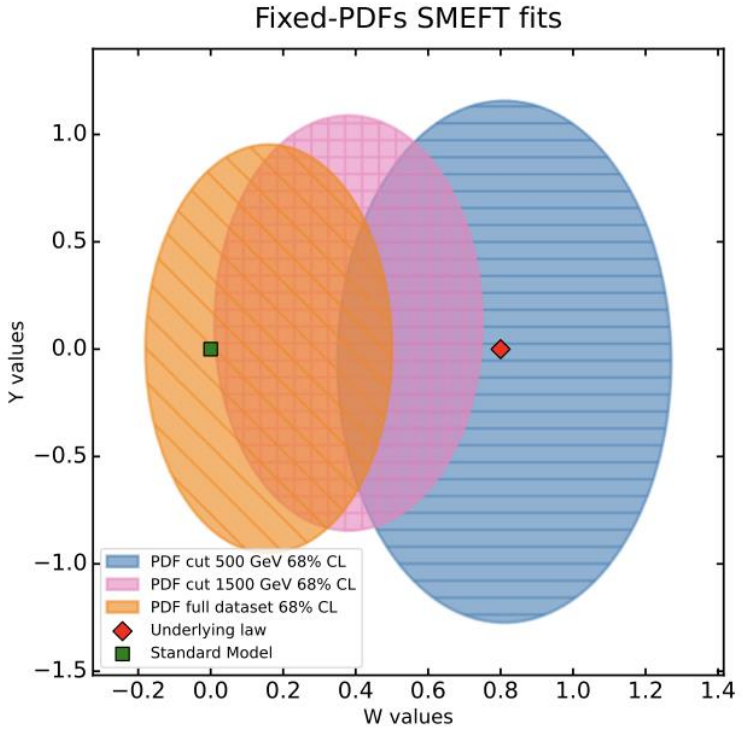
Heavy gluon under $SU(3)_C$

$$\mathcal{L}_{\rm UV}^{\mathcal{G}} = \mathcal{L}_{\rm SM} - \frac{1}{4} \mathcal{G}^a_{\mu\nu} \mathcal{G}^{a,\mu\nu} + \frac{1}{2} M_{\mathcal{G}}^2 \mathcal{G}^a_\mu \mathcal{G}^{a,\mu} - g_{\mathcal{G}} \mathcal{G}^a_\mu \sum_a \bar{q} \gamma^\mu T^a q,$$

$$\mathcal{L}_{\rm SMEFT}^{\mathcal{G}} = \mathcal{L}_{\rm SM} - \frac{g_s^2 \hat{Z}}{2 m_W^2} \left[\mathcal{O}_{Qq}^{(1,8)} + \mathcal{O}_{Qu}^{(8)} + \mathcal{O}_{Qd}^{(8)} + \mathcal{O}_{tu}^{(8)} + \mathcal{O}_{td}^{(8)} + \mathcal{O}_{qt}^{(8)} \right], \quad \hat{Z} = \frac{g_{\mathcal{G}}^2}{g_s^2} \frac{m_W^2}{M_{\mathcal{G}}^2},$$

Other tools – Energy Cut Offs





SM only pseudodata only shows change in uncertainties as cut off is increased