Dispelling the $\sqrt{L}$ myth for the High-Luminosity LHC

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Introduction

During phase-I LHC will collect roughly 300 fb^{-1} while at the end HL-LHC 3000 fb^{-1} should be available, **a factor 10 increase in statistics**.

It is generally believed that the sensitivity $\mathcal{S}$ on a parameter of interest scales as $\sqrt{L}$ because:

$$\mathcal{S} \simeq \frac{\mathrm{S}}{\sqrt{\mathrm{B}}} \simeq \sqrt{L}\frac{\sigma_S}{\sigma_B}$$

The $\sqrt{L}$ **scaling** is overly **conservative at best**, and **unrealistic in practice.**

This can be proven in at least four different examples:

- Measurement of **4 top quarks production cross-section**.
- Measurement of the **top mass** in in hadronic decays of boosted top quarks.
- Constrain **BSM** parameters **in electroweak processes** involving the **top quark**.
- Constrain **BSM** parameters **in Higgs boson** physics.

Introduction

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$$\delta \approx \sqrt{S} \approx \sqrt{L}$$

Focus of this talk.
(Other examples explained in arXiv:2402.07985)

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The Standard Model Effective Field Theory (SMEFT)

It is possible to Taylor expand the SM Lagrangian in terms of $\frac{E}{\Lambda}$:

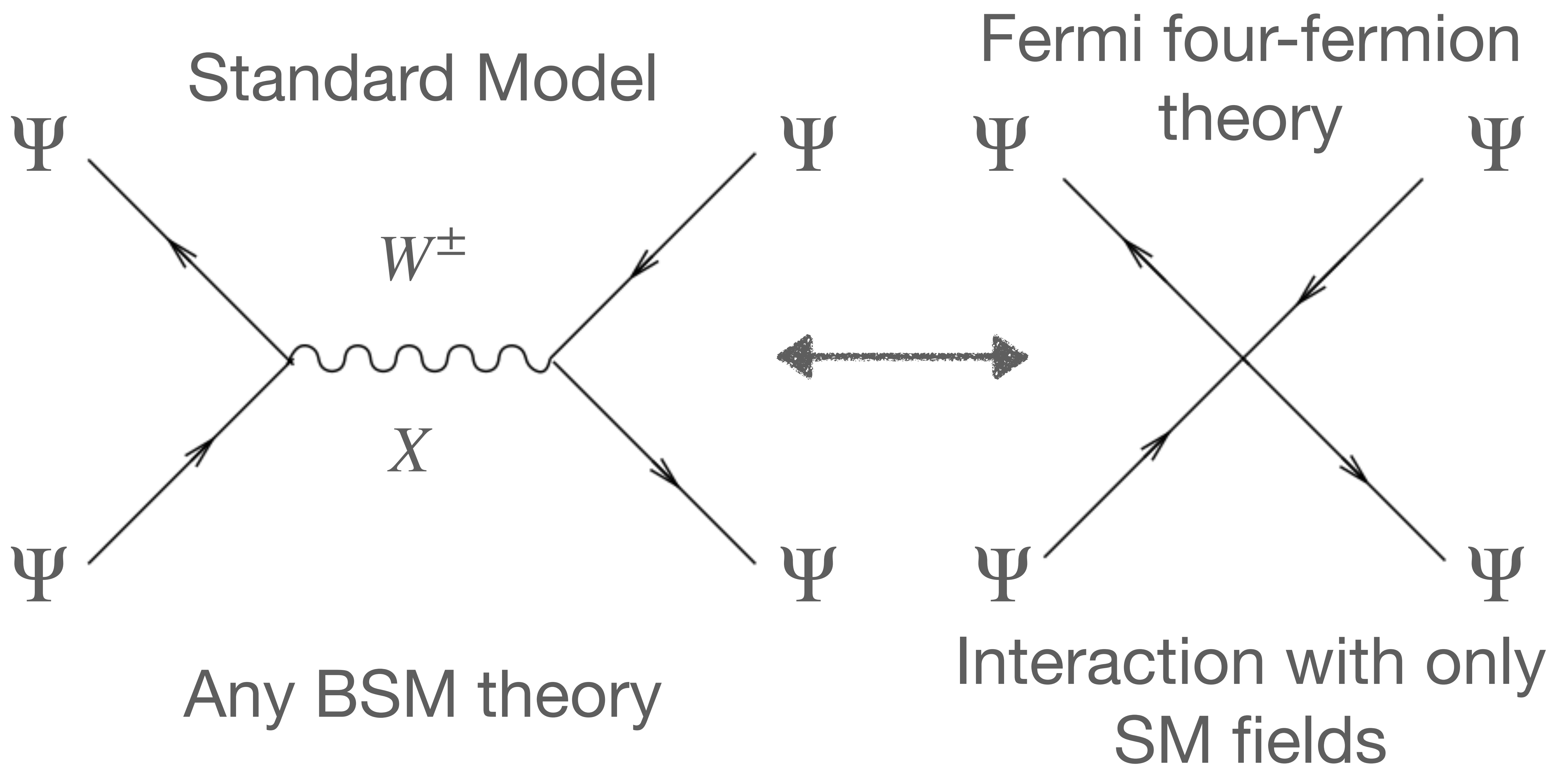
$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \dots$$

$$\mathcal{L}^{(d)} = \sum_i c_i \mathcal{O}_i^{(d)}$$

← All the possible local interactions allowed by symmetries.

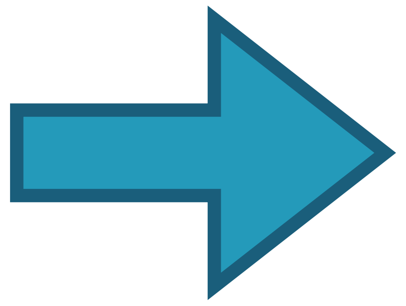
- c_i are called Wilson coefficients - **free parameters** of the model.
- $\mathcal{O}_i^{(d)}$ represent all the possible **operators**.

SMEFT: a different approach to new physics



- The SM can be considered as an effective low-energy theory.

- BSM physics can be thought of as modifications of the interactions containing only SM fields.

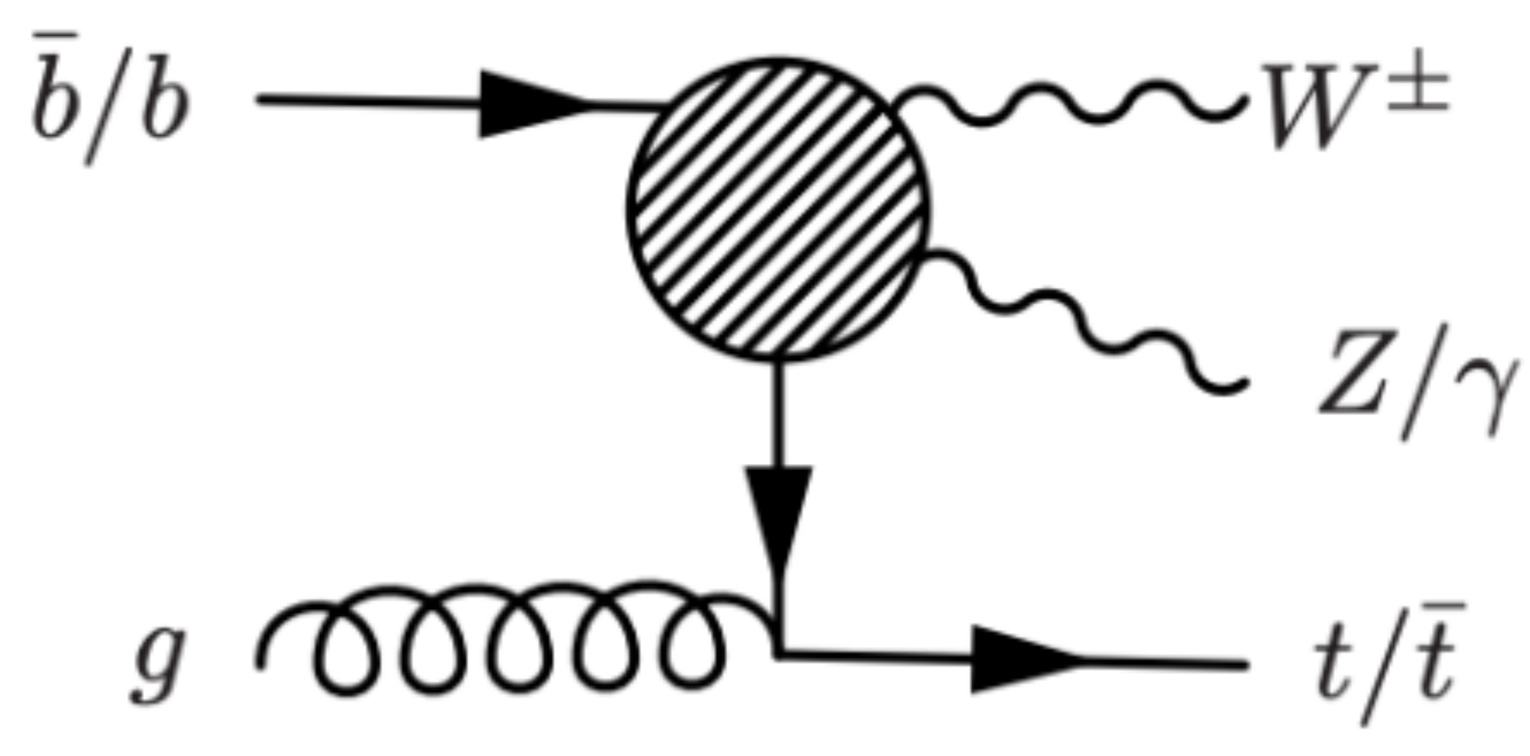


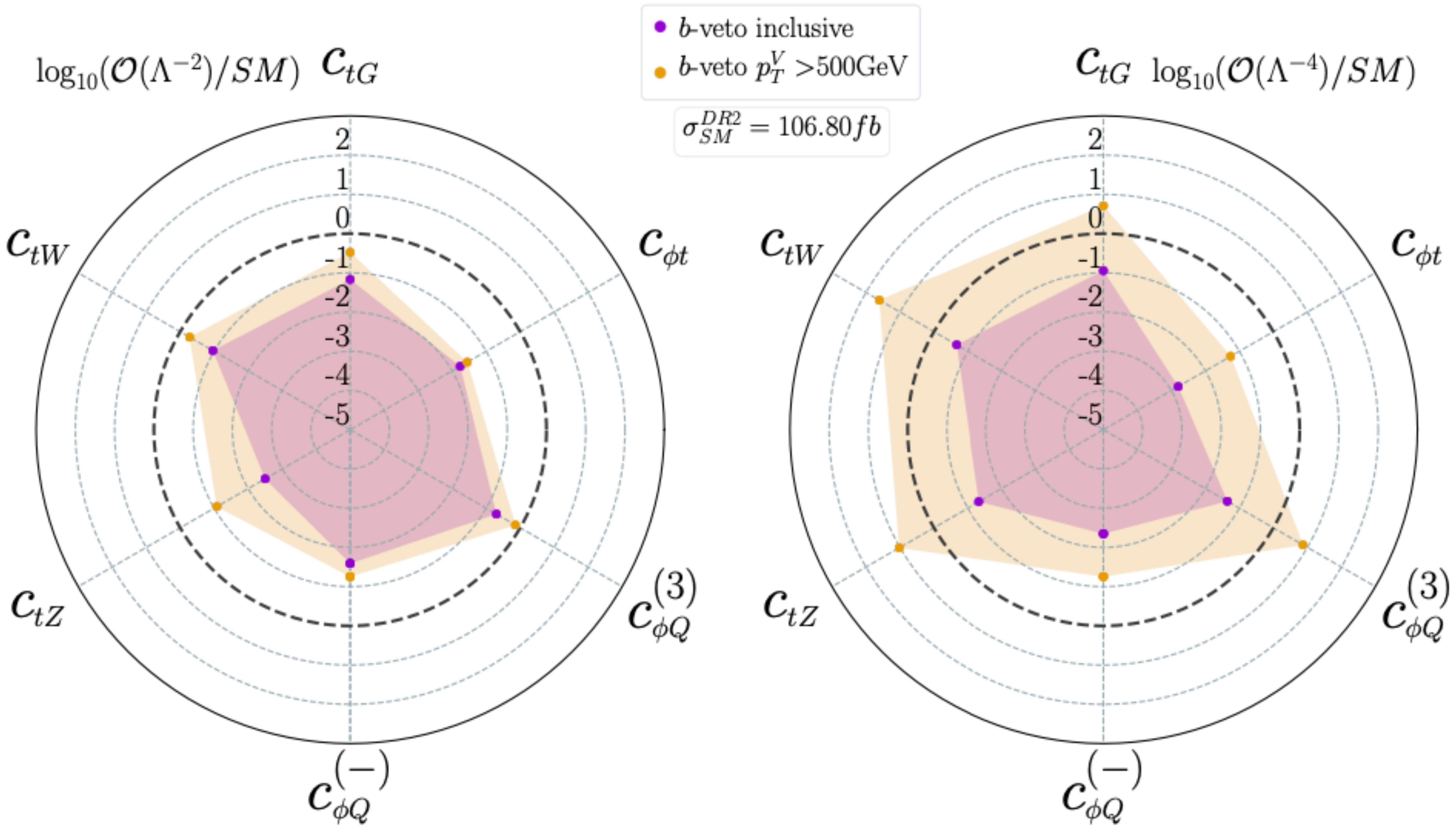
Completely **model independent**

The tWZ process

arXiv:1904.05637 arXiv:2111.03080

- tWZ has **never been observed**, however CMS has recently published the first evidence.
- Very challenging process:
  - **Small** predicted **cross-section** ($\sigma_{tWZ} = 136\ fb$).
  - **Large** irreducible **background** ($t\bar{t}Z$ process):
- Its discovery would allow the analysis of SMEFT operators only loosely constrained with possible new physics arising from **bW→tZ** vertices.
- This would lead in **energy growth** for some specific operators.





Simulation of EFT predictions

$$\mathcal{L} = \frac{1}{\Lambda^0}\mathcal{L}_{SM}^{(d=4)} + \frac{1}{\Lambda}\mathcal{L}^{(d=5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(d=6)} + \dots$$

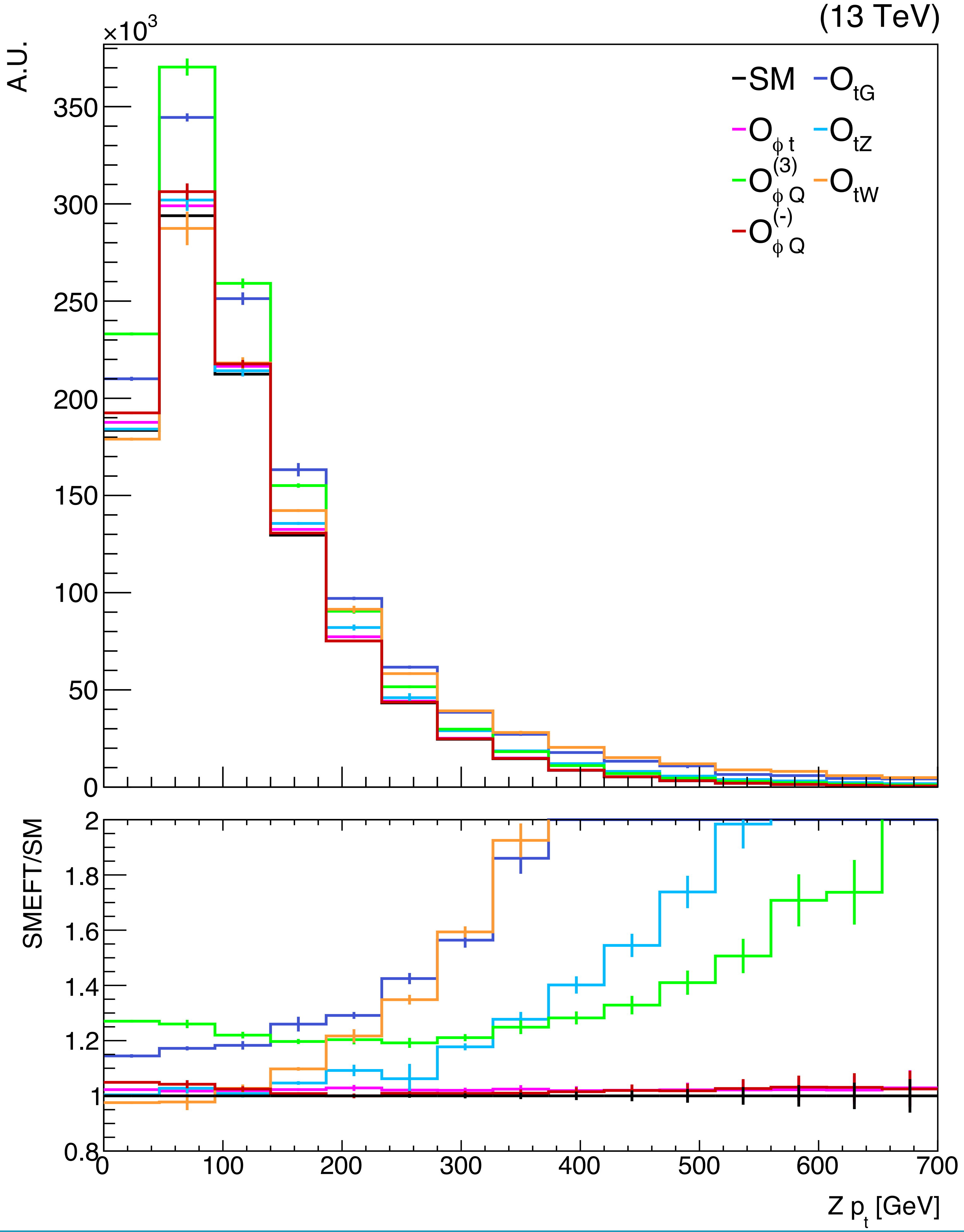
$$\sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2}$$

- MC samples generated with MadGraph5 using the **SMEFT@NLO** model.
- Production of samples to test the **effect of the operators** on relevant variables of the process.
- Event showered with **PYTHIA8**.
- Operators are tested setting as value for the corresponding Wilson coefficients one.
- Λ is kept fixed at the value of 1 TeV.

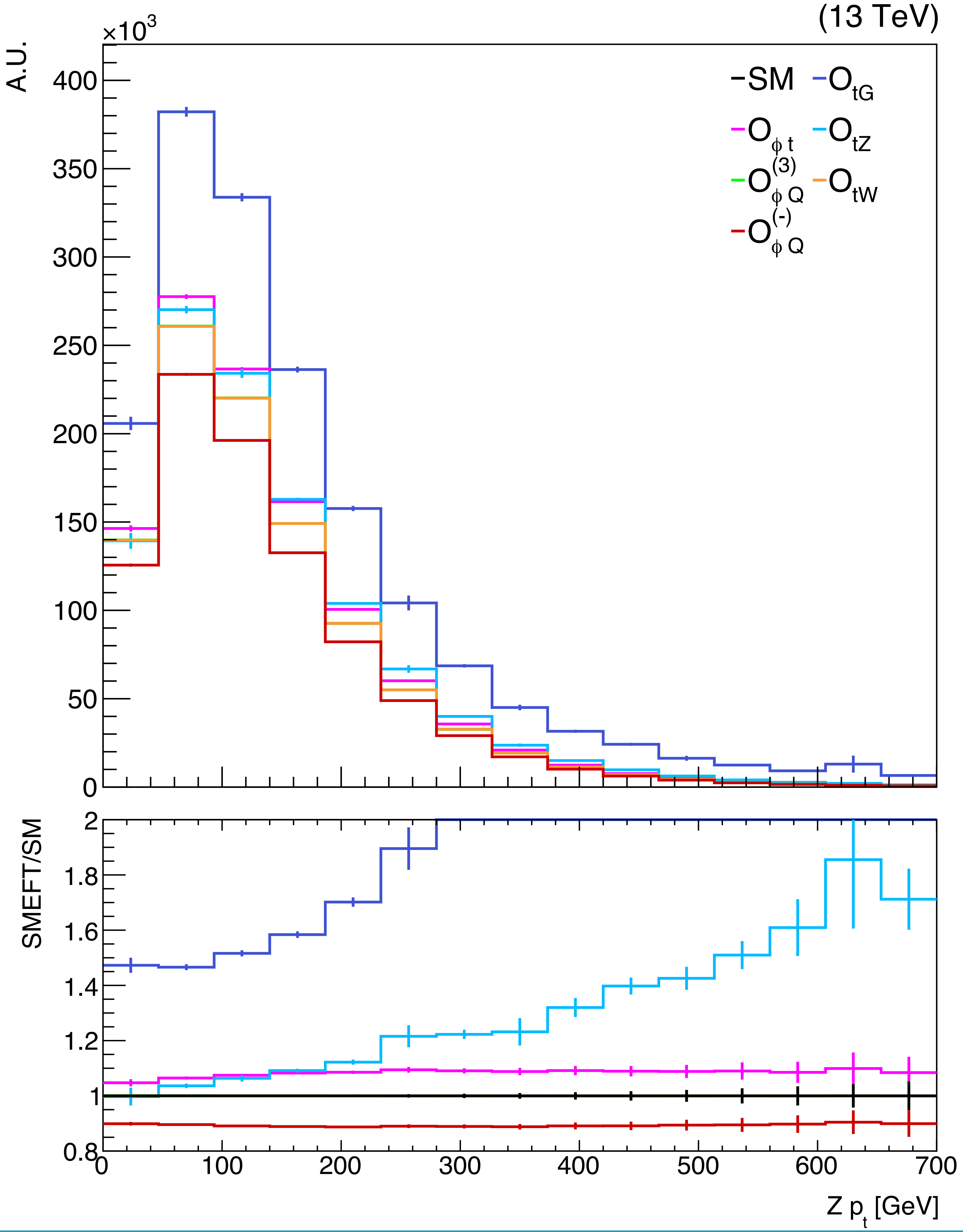
Z p_t distributions

Comparison between SM distributions and SMEFT distributions obtained through reweighting.

tWZ



$t\bar{t}Z$



- Excess for the $\mathcal{O}^{(3)}_{\phi Q}$ operator shows energy growth in **tWZ.**
- Also the $\mathcal{O}_{tZ}$ operator shows energy growth for both **tWZ** and **$t\bar{t}$Z**.
- **tWZ** is more sensitive than **$t\bar{t}$Z** to most of the operators.

The CMS measurement and EFT interpretation

The **first evidence** of the **tWZ process** was recently reported by the CMS experiment.

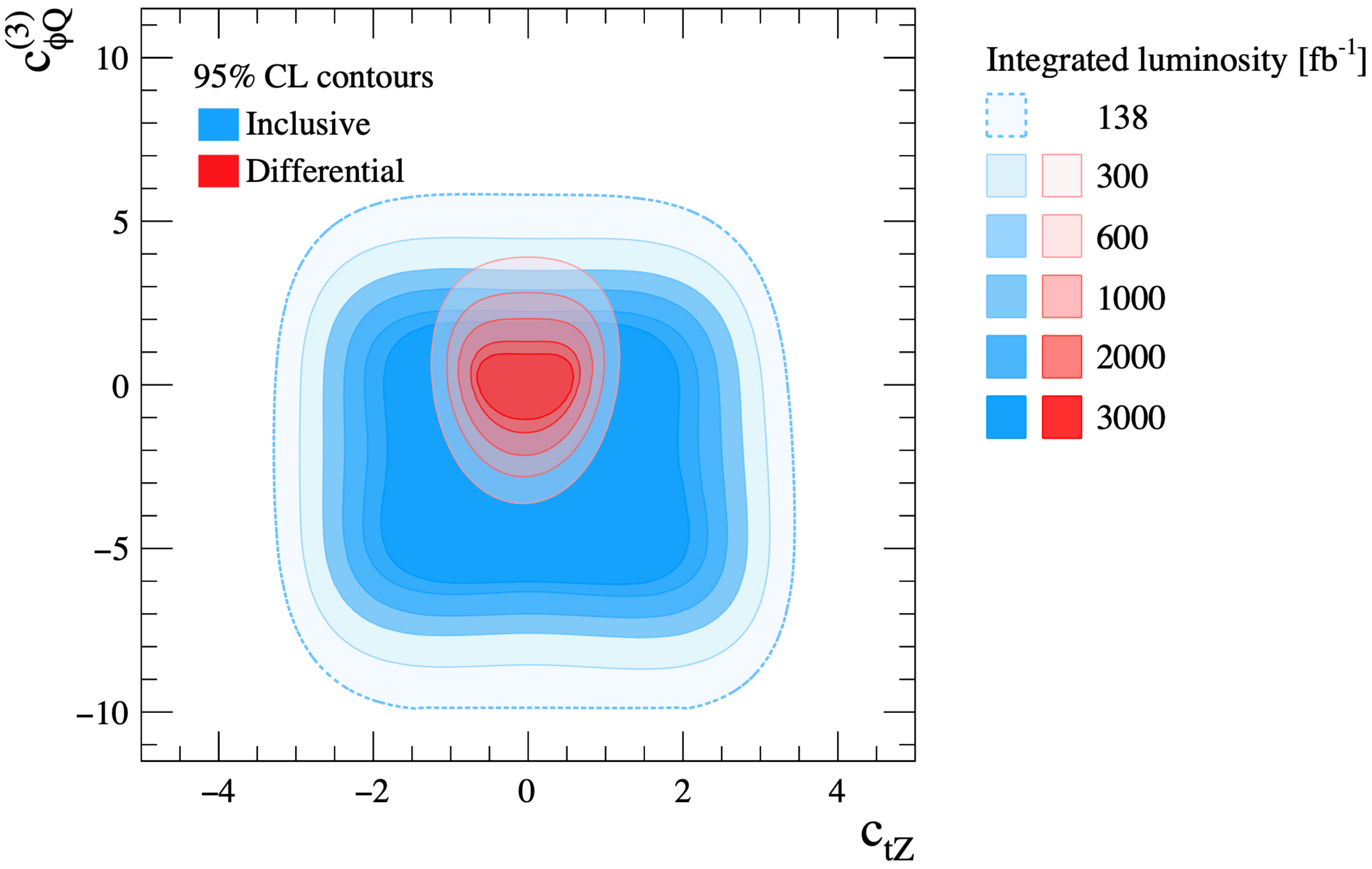
Analysis performed on 138 fb^{-1} in 3 and 4 leptons final states using ML algorithms to distinguish the tWZ process from the background, mostly $t\bar{t}Z$.

Observed (expected) **significance** = 3.5σ (1.4σ)

σ_{tWZ} = 0.37 ± 0.05(stat) ± 0.10(syst) pb

Building on this result, we were able to compute limits on the Wilson coefficients of the $\mathcal{O}_{\phi Q}^{(3)}$ and $\mathcal{O}_{tZ}$ operators.

EFT limits and prospectives for HL-LHC



Collecting enough data to perform a **differential measurement in Z** p_T would allow to set **much tighter constraints** on the Wilson coefficients.

Conclusion

When projecting the sensitivity to a parameter of interest in scenarios with larger integrated luminosity, **the sensitivity is often scaled by** $\sqrt{L}$.

However the **sensitivity improvement** from higher statistics is not only related to the increase in the number of events:

- Improved estimation and constraint of **systematics uncertainties**.
- **More advanced analysis strategies**.

With the HL-LHC, we will be able to **challenge the Standard Model with unprecedented precision**, offering the potential for possible surprises.