Probing EFT operators in top-Z associated production with machine learning.

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14th Physics at Terascale
Helmholtz Alliance Meeting
23–24 Nov. 2021, Hamburg

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GROSSE HERAUSFORDERUNGEN

DESY.

CMS
Compact Muon Solenoid

Nicolas Tonon (1993-2021)

Will be sorely missing by his colleagues and friends

For his scientific excellence & innovation, and

his enthusiasm and motivation

For his vivacious personality, and

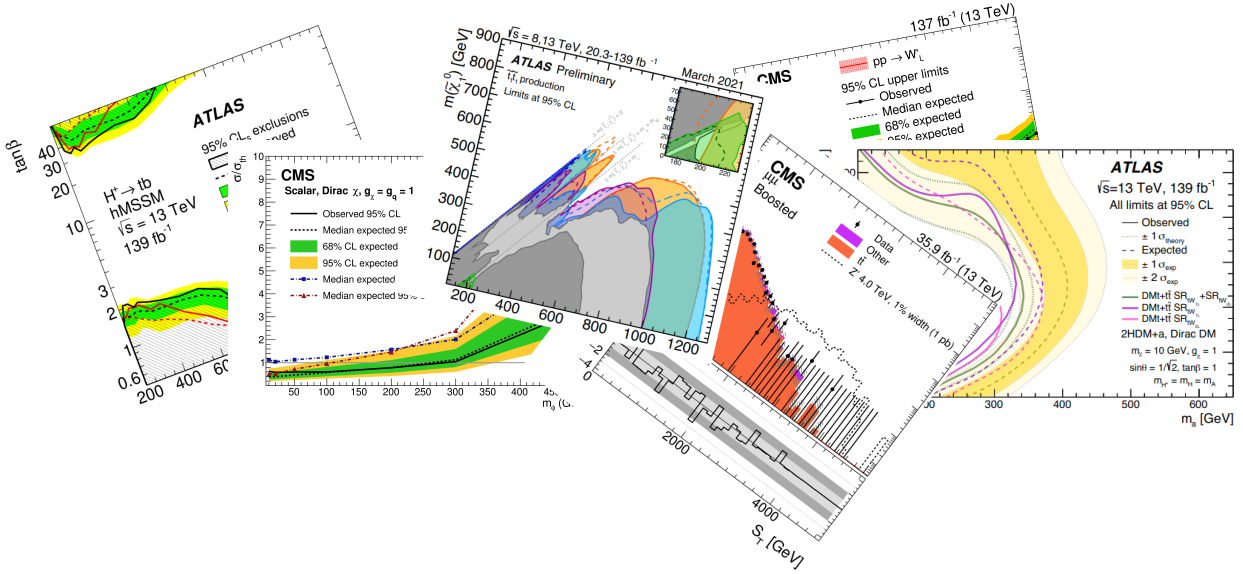
his never-disappearing smile

** There is an attempt to preserve Nicolas style in this presentation.*
Shadowed images are directly taken from his slides …

Top, new physics and the precision era

The heaviest known particle

- A portal to new phenomena in many BSM theories
- So far no sign!



Preisely measured at the LHC

- In multiple production mechanisms, also in association with other particles

Top, new physics and the precision era

The current situation

Motivates ambitious top physics programme to **reveal new physics** indirectly **through precision** measurements

An excellent testbed

Effective Field Theory (EFT) framework allows for systematic & model-independent interpretation of potential deviations in interactions between SM fields

Effective Field Theory in a nutshell

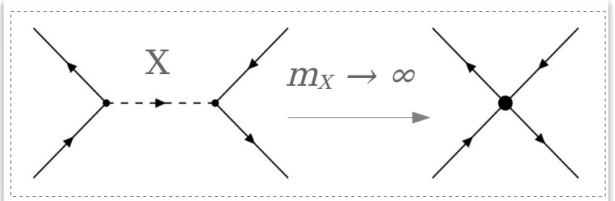
Expansion of the SM Lagrangian *not a new concept*

Wilson coefficients ↔ interaction strengths

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

Higher-order operators

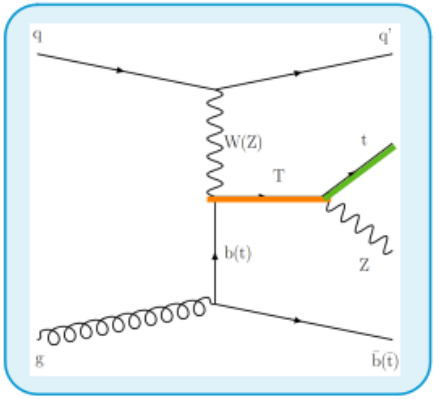
BSM energy scale ($\gg E_{LHC}$)



EFT example : Fermi theory of β-decay
(W boson → 4-fermions interaction)

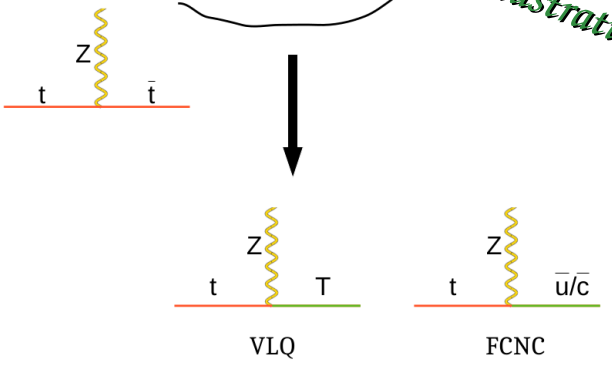
Powerful in describing BSM theories

- Depending on model and assumptions, each EFT operator can be a composition of BSM states and vice versa



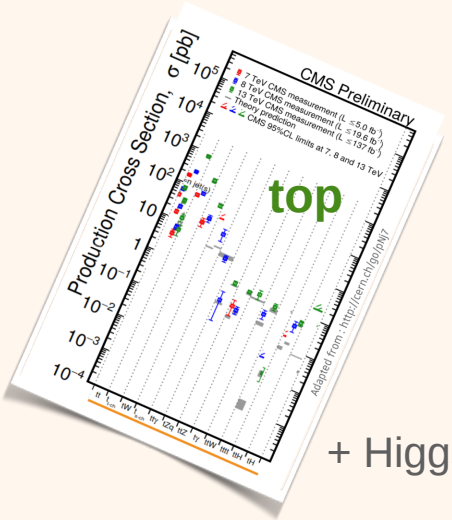
$$L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \ldots$$

Illustration



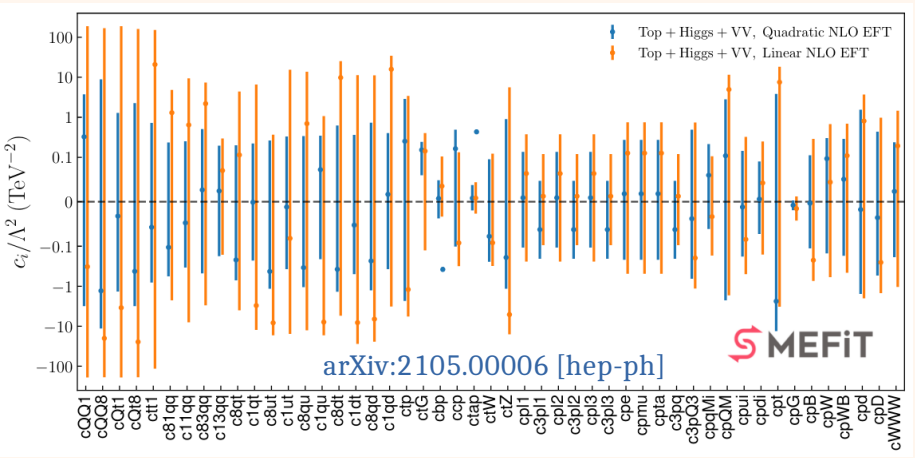
A global approach maximizing the discovery potential

Take measurements, as many as possible



+ Higgs + B-physics + …

Simultaneously constrain as many WC as possible



Important to consider

- Assess correlations between measurements
- Consider **all** processes when measuring in a given final state

Possible with the access to the data

Towards a global EFT measurement

- An experimental example in the multi-lepton final state

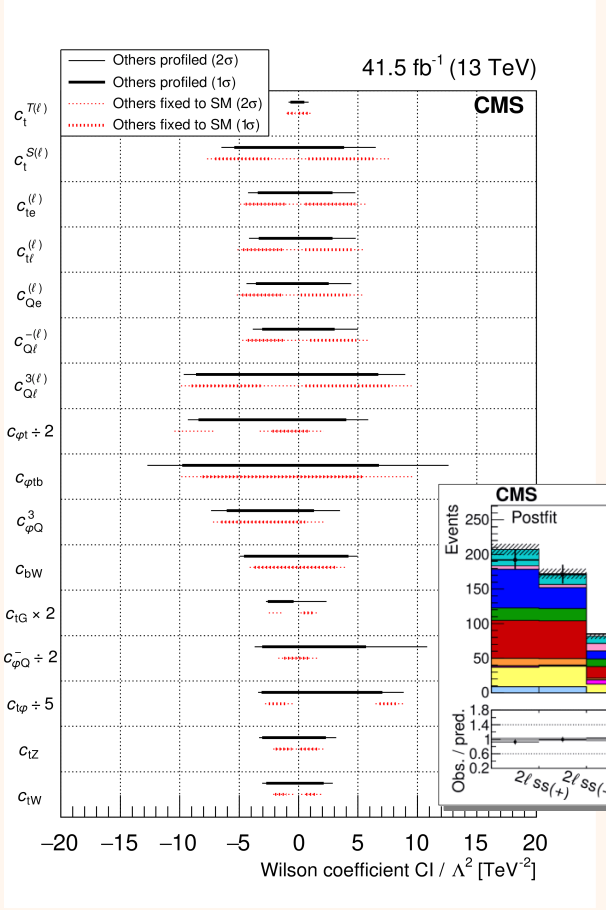
Operators involving two quarks and one or more bosons

Operator	Definition	WC	Lead processes affected
$^{\ddagger}O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi} (\varphi^\dagger \varphi)$	$c_{t\varphi} + ic_{t\varphi}^I$	$t\bar{t}H$, tHq
$O_{\varphi q}^{1(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$	$c_{\varphi Q}^- + c_{\varphi Q}^3$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j)$	$c_{\varphi Q}^3$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j)$	$c_{\varphi t}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j)$	$c_{\varphi tb} + ic_{\varphi tb}^I$	$t\bar{t}H$, $tl\bar{l}q$, tHq
$^{\ddagger}O_{uW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W_{\mu\nu}^I$	$c_{tW} + ic_{tW}^I$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{dW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\, \varphi W_{\mu\nu}^I$	$c_{bW} + ic_{bW}^I$	$t\bar{t}H$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uB}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} u_j)\, \tilde{\varphi} B_{\mu\nu}$	$(c_W c_{tW} - c_{tZ})/s_W + i(c_W c_{tW}^I - c_{tZ}^I)/s_W$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uG}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} T^A u_j)\, \tilde{\varphi} G_{\mu\nu}^A$	$g_s(c_{tG} + ic_{tG}^I)$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$

Operators involving two quarks and two leptons

Operator	Definition	WC	Lead processes affected
$O_{\ell q}^{1(ijkl)}$	$(\bar{\ell}_i \gamma^\mu \ell_j)(\bar{q}_k \gamma^\mu q_\ell)$	$c_{Q\ell}^{-(\ell)} + c_{Q\ell}^{3(\ell)}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell q}^{3(ijkl)}$	$(\bar{\ell}_i \gamma^\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_\ell)$	$c_{Q\ell}^{3(\ell)}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell u}^{(ijkl)}$	$(\bar{\ell}_i \gamma^\mu \ell_j)(\bar{u}_k \gamma^\mu u_\ell)$	$c_{t\ell}^{(\ell)}$	$t\bar{t}l\bar{l}$
$O_{eq}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_\ell)$	$c_{Qe}^{(\ell)}$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{eu}^{(ijkl)}$	$(\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_\ell)$	$c_{te}^{(\ell)}$	$t\bar{t}l\bar{l}$
$^{\ddagger}O_{\ell equ}^{1(ijkl)}$	$(\bar{\ell}_i e_j)\, \varepsilon\, (\bar{q}_k u_\ell)$	$c_t^{S(\ell)} + ic_t^{SI(\ell)}$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O_{\ell equ}^{3(ijkl)}$	$(\bar{\ell}_i \sigma^{\mu\nu} e_j)\, \varepsilon\, (\bar{q}_k \sigma_{\mu\nu} u_\ell)$	$c_t^{T(\ell)} + ic_t^{TI(\ell)}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$

All possible operators & processes



top + x

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Global limits using event yields in categories

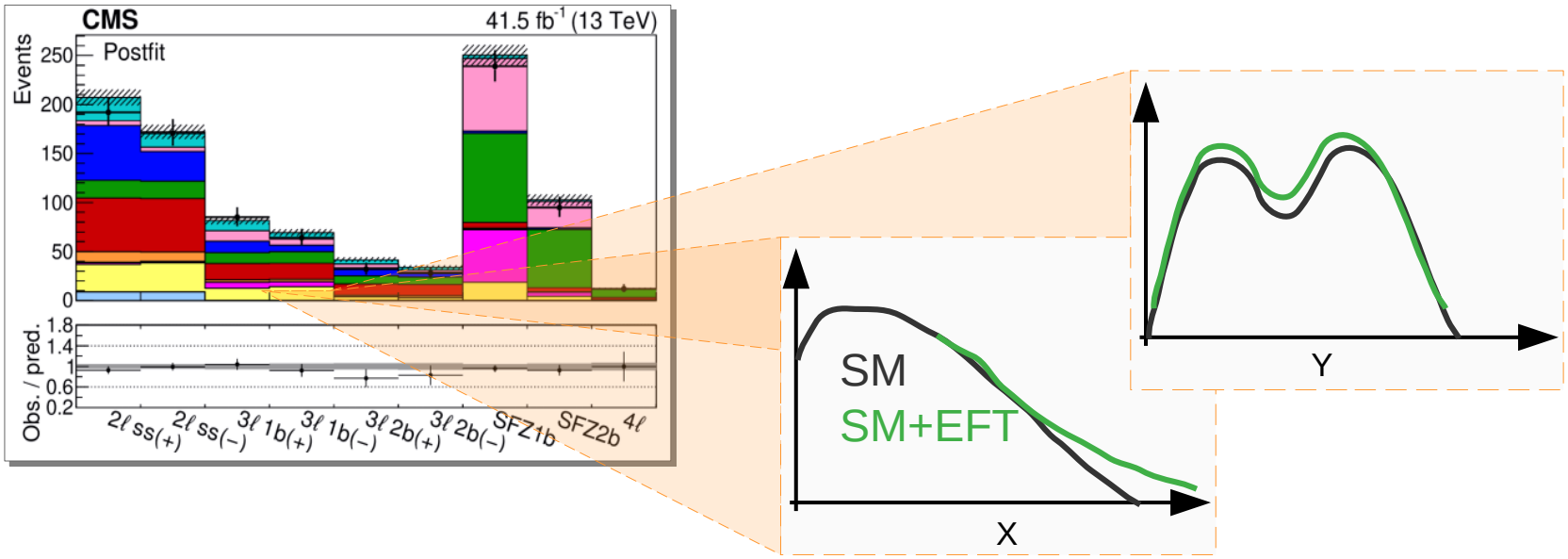
EFT and Multivariate Techniques

Machine Learning (ML)

- *EFT operators usually …*
  - impact both cross section & kinematics
  - introduce new coupling structures leading to **subtle kinematics modifications**
  - **correlate** deviations in many different processes/observables (expected patterns)

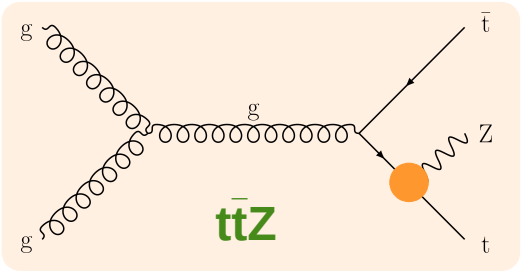
    → No single observable can constrain full parameter space

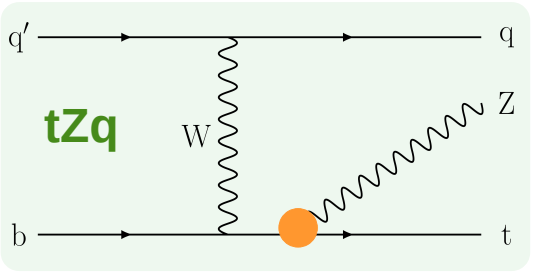
⇒ Perfect match for machine-learning (ML) techniques !

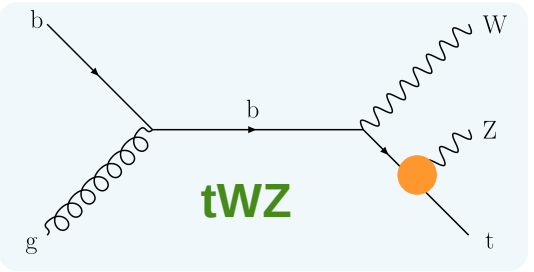


Probing top-Z interactions with ML

- Three processes including top quark and Z boson in 3ℓ and 4ℓ final state







138 fb^{-1}

- Target 3 top-Z associated production modes
  - Complementary, probe similar EFT operators
- Consider up to 5 operators simultaneously
- Analysis strategy entirely optimized to search for EFT effects
  - Simulated at detector-level (→ Direct measurement ≠ reinterpretation)

New **Use novel machine-learning techniques** to improve sensitivity to WCs

Reference :

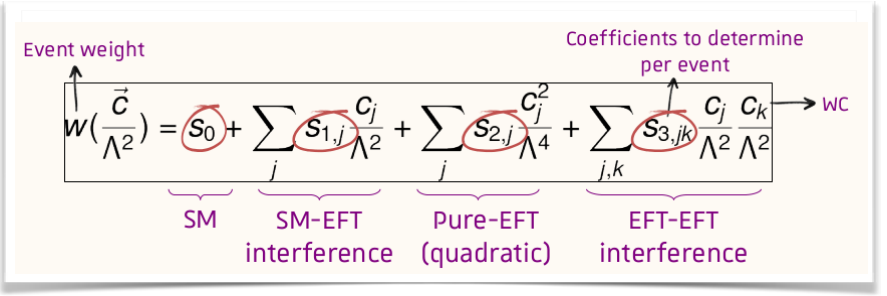
- *Probing effective field theory operators in the associated production of top quarks with a Z boson in multilepton final states at √s=13 TeV,* arXiv:2107.13896 (Submitted to JHEP)
  - *Learning to detect new top-quark interactions,* CERN Courier (Sep/Oct 2021)

Simulation of signal with EFT

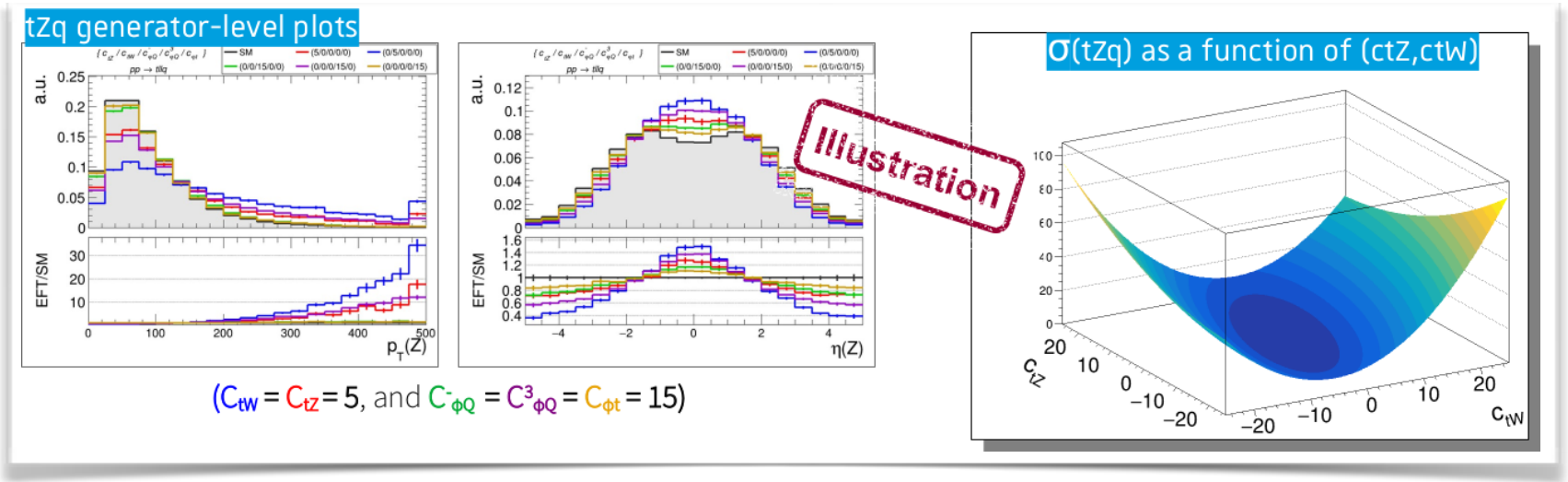
$\mathcal{O}_{tZ}$, $\mathcal{O}_{tW}$, $\mathcal{O}^{-}_{\phi Q}$, $\mathcal{O}^{3}_{\phi Q}$ and $\mathcal{O}_{\phi t}$

- Dim6top model used arXiv:1802.07237
  - Operators affecting top-Z couplings *(conserving CP, lepton & baryon numbers)*
  - Intereference with SM for ttZ and tZq

- Full simulation including EFT weights at generator level

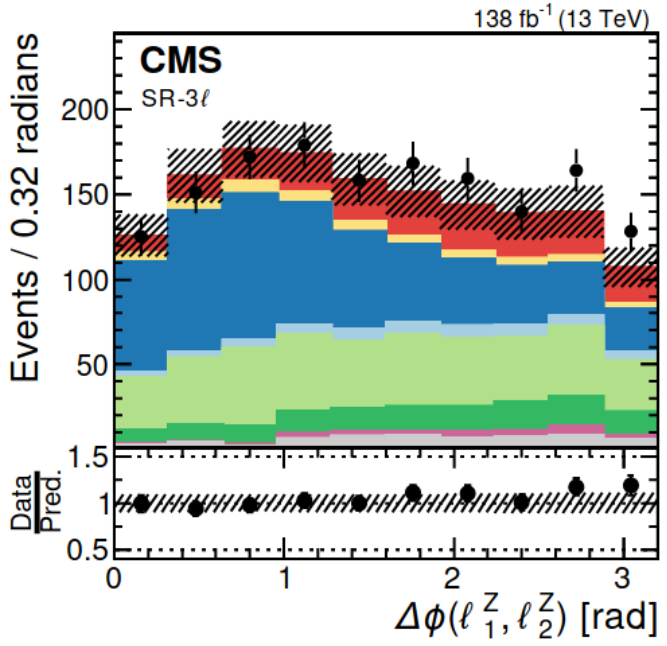


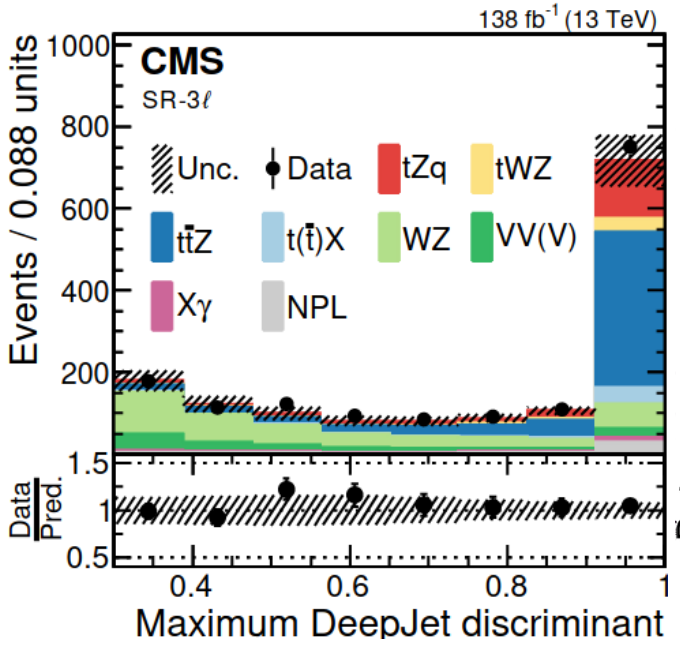
- Possible to model any observable in any EFT scenario
  - Correlations between observables preserved

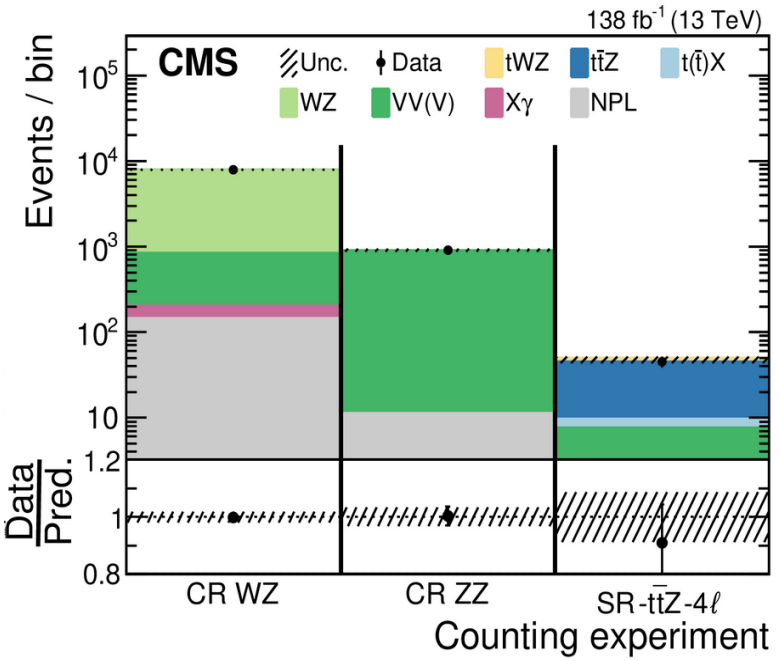


Event selection and reconstruction

- Events selected with at least three isolated leptons
- A Z boson candidate with $|m_{\ell\ell}-91| < 15$ GeV
- A top quark candidate with the remaing lepton, $p_{T,miss}$, and a b-jet
  - DNN-base b-tagging (ε~75 % / mistag ~1 %)
- Allowing for add. jets (also with broad |η| for tZq)
- Divided to SR and CR's based on lepton and (b-)jet multiplicities

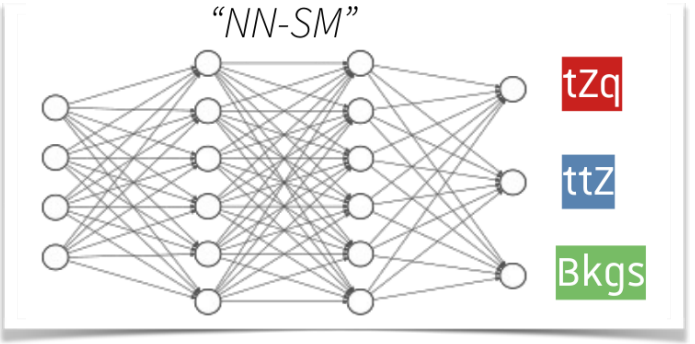




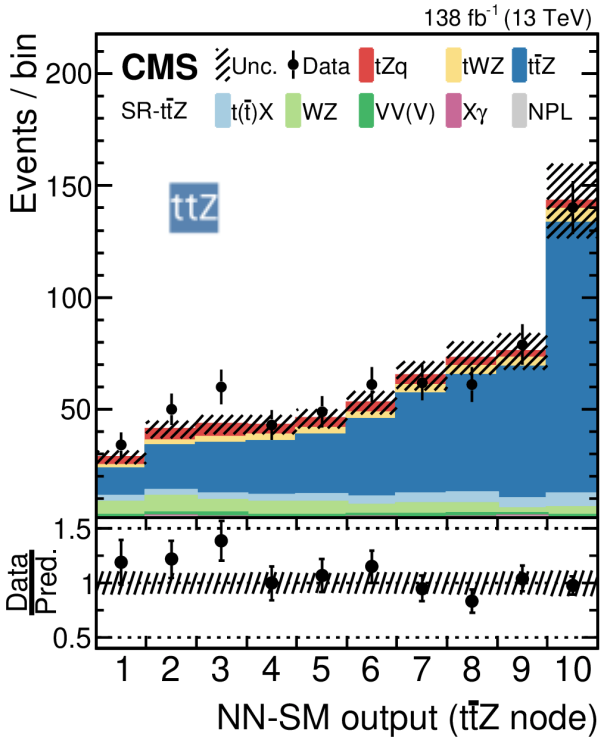


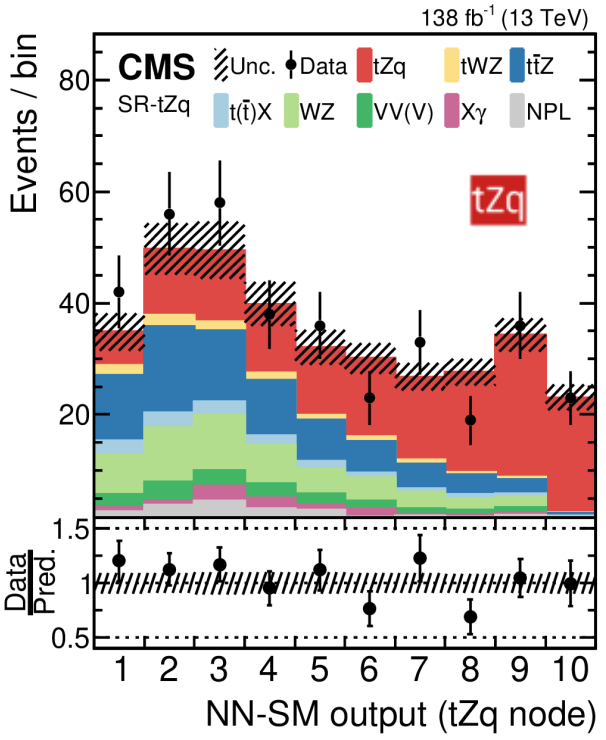
ML for top-Z events against backgrounds

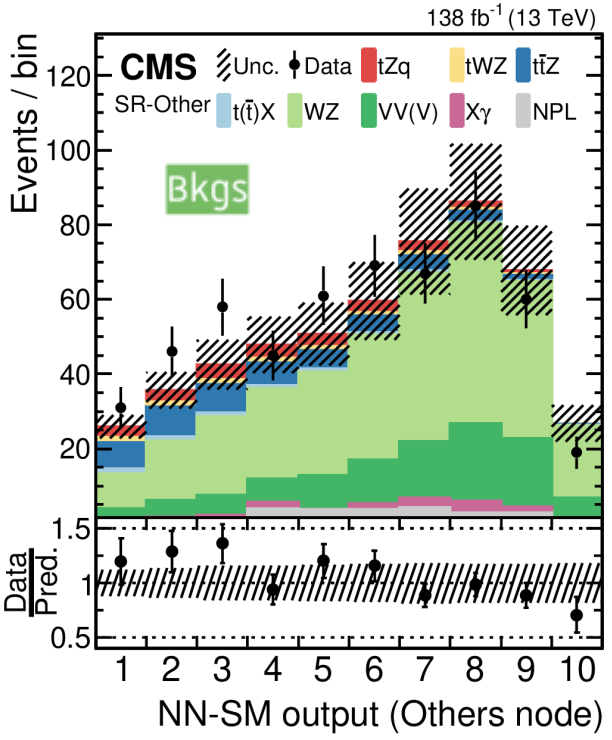
- SR-3ℓ drives the analysis' sensitivity
  - Sub-divided based on DNN discriminant
- Multiclass classifier trained
  - 3 orthogonal subregions based on events maximum node value



⇨ Obtain categories very pure in targeted processes!

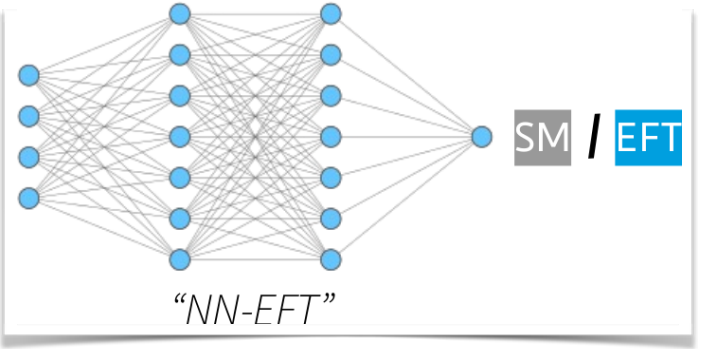






ML for EFT against SM

- Binary classifier to separate SM from SM+EFT for various non-zero WC's
  - Learn non-trivial patterns due to new physics out of high-dimensional data
  - Construct optimized observables



$\mathcal{O}_{tZ}$, $\mathcal{O}_{tW}$, $\mathcal{O}^{-}_{\phi Q}$, $\mathcal{O}^{3}_{\phi Q}$ and $\mathcal{O}_{\phi t}$

- Separate trainings for tZq & ttZ

- Separate trainings for individual operators & all 5 simultaneously

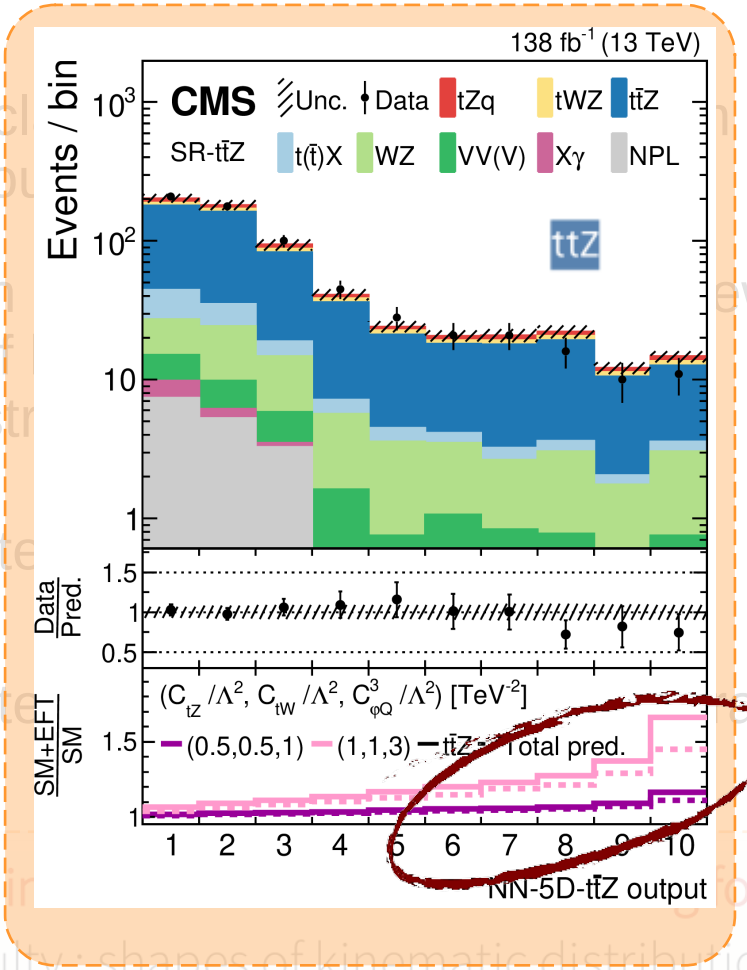
SM/EFT interference included in training for first time in LHC analysis

- Difficulty : shapes of kinematic distributions depend on WC values

  → Train under many different scenarios, NNs learn to interpolate between WC values

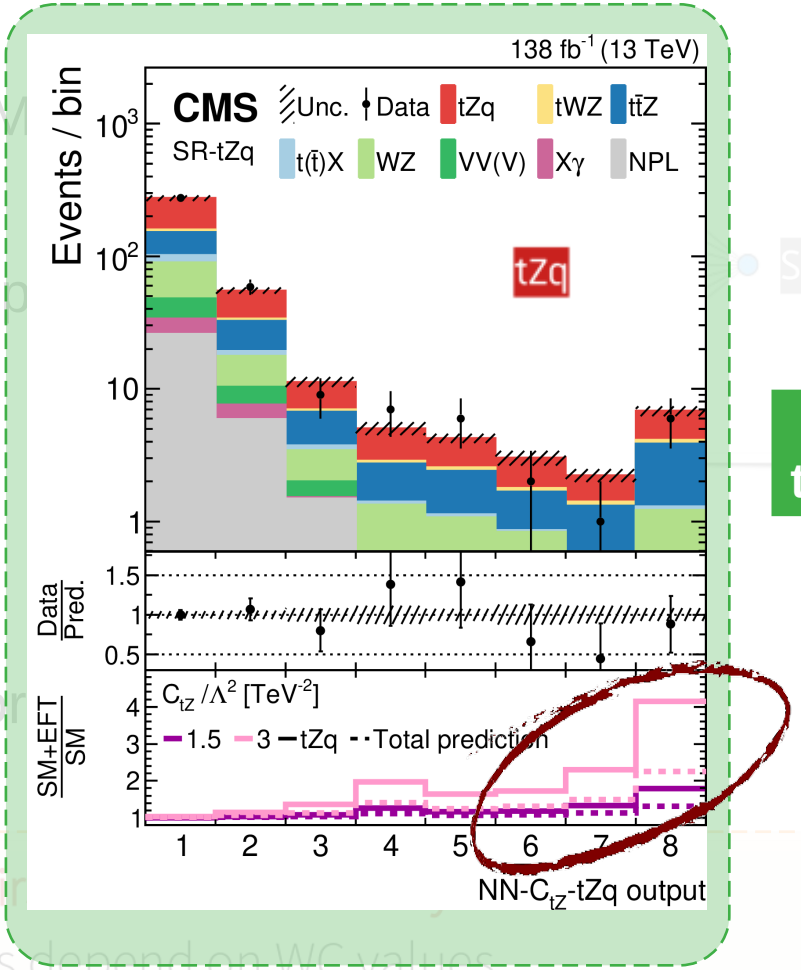
ML for EFT against SM

5D training



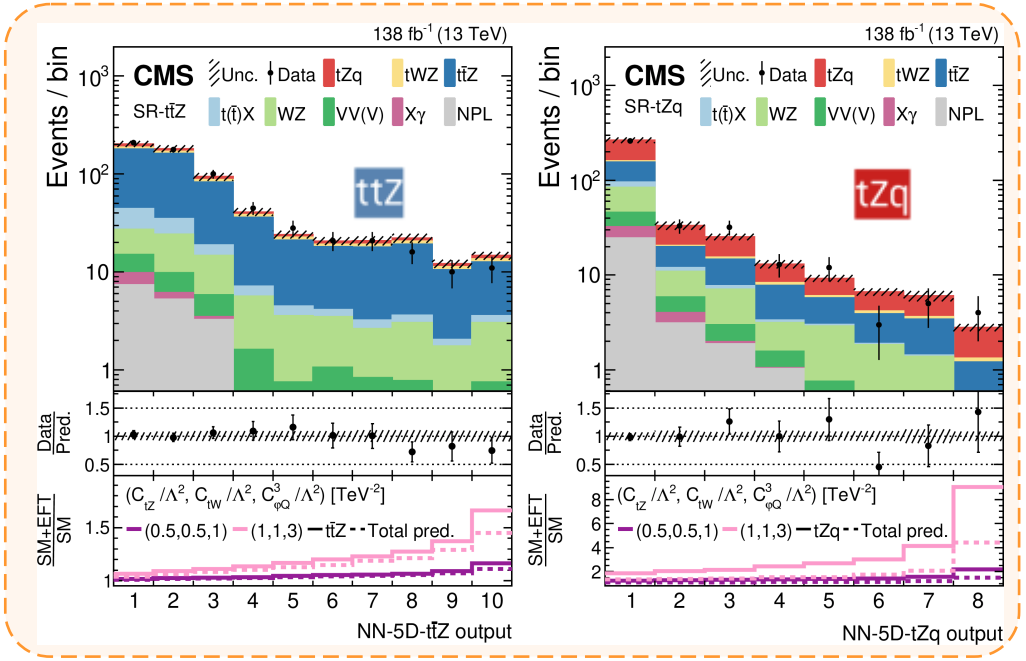
Also for tZq

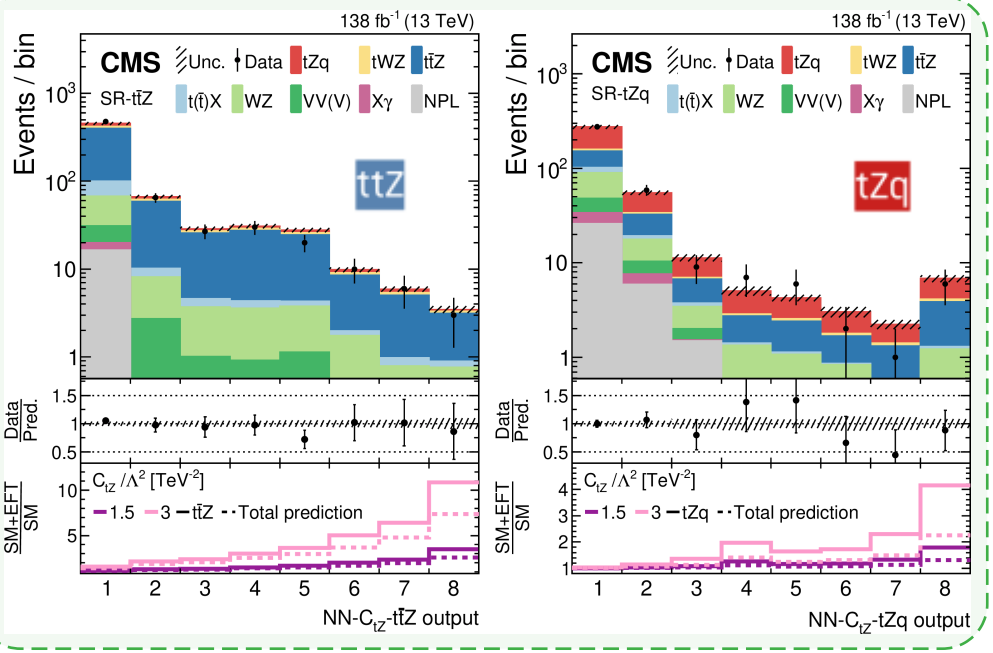
1D training



Also for ttZ and other individual WC's

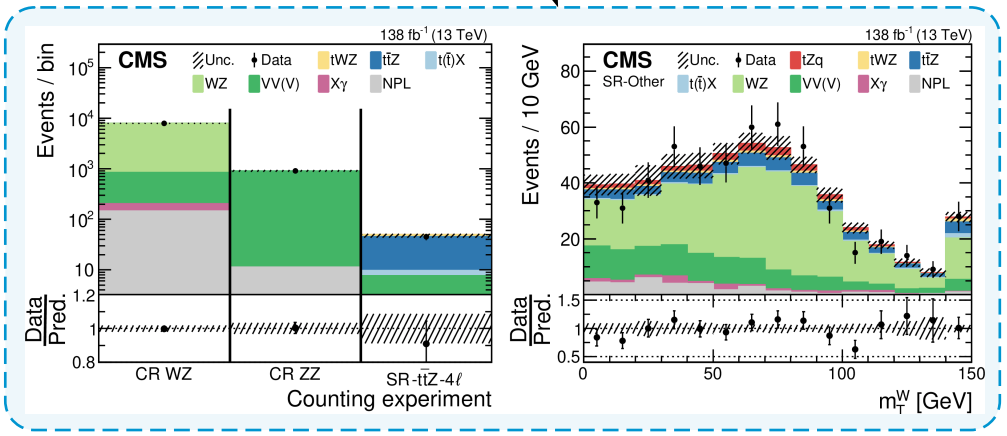
Signal extraction





5D fit

1D fit

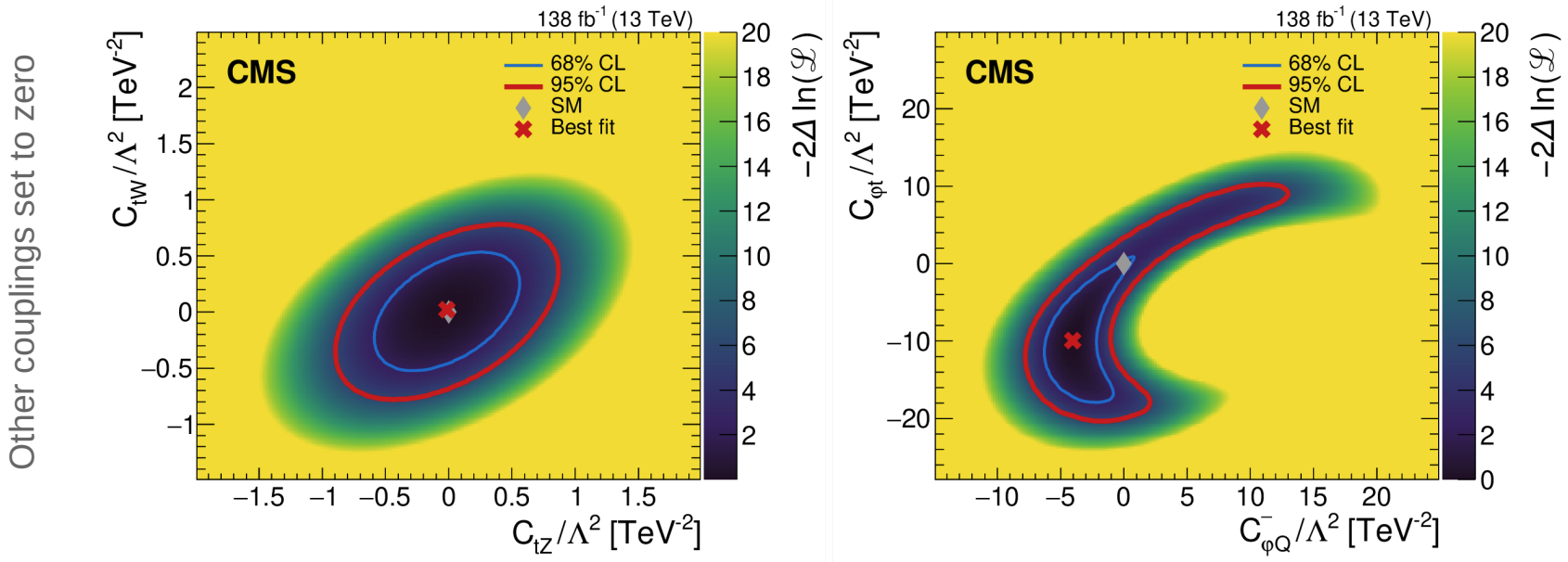


- Simultaneous fit of 6 regions per year, for *every* and *all* couplings

Results

- Significant sensitivity gains using optimal observables
  - 20–70% reduction in widths of confidence intervals wrt counting experiment

WC/Λ^2 $[TeV^{-2}]$	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$



SUMMARY

- Constrain top-electroweak EFT operators with t(t̄)Z production in multilepton channels
  - EFT effects parameterized at detector-level via event weights
- Rely on novel ML techniques to enhance sensitivity to EFT
  - Significant sensitivity gains from shape information
  - Not the 'new default', but complementary tool with great potential – active research area !
- Obtain **best direct limits to date** from multilepton final states on several Wilson coefficients
  - All 95 % CL confidence intervals contain the SM predictions