EFT based searches in the top-quark sector from CMS

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

Barbara Alvarez Gonzalez on behalf of the CMS Collaboration

Universidad de Oviedo

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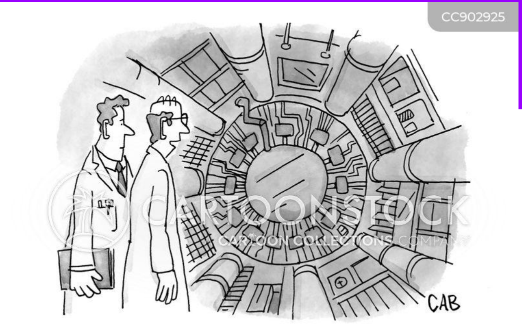
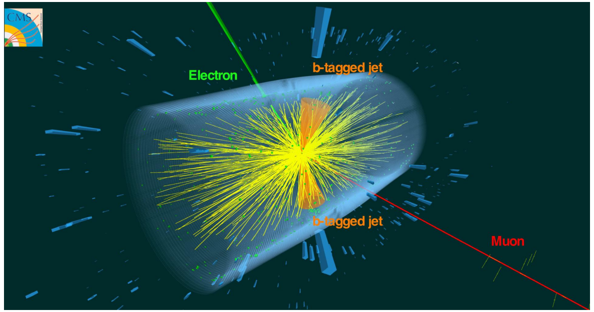
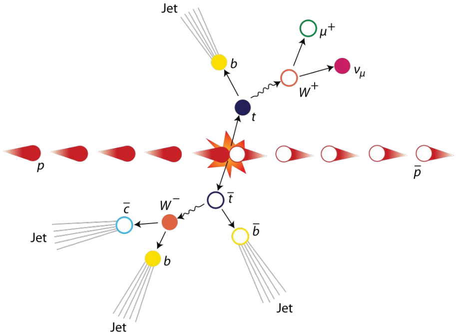
Overview

- Introduction
  - What is EFT?
  - Why is it important?
- The top quark as a key player
- CMS results with the full Run2 data, 138 fb^{-1}:
  - Phys. Rev. Lett. 132 (2024) 241802: *"Search for Baryon Number Violation in Top Quark Production and Decay Using Proton-Proton Collisions at 13 TeV"*
  - JHEP 12 (2023) 068: *"Search for physics beyond the standard model in top quark production with additional leptons in the context of effective field theory"*



"Once you have a collider, every problem starts to look like a particle."





What is EFT?

- Effective Field Theory (EFT) is a **framework in theoretical physics** that simplifies the study of **complex systems** by focusing on the relevant degrees of freedom at a given energy scale while **integrating out the higher-energy details**
- EFT operates on the principle that physical phenomena can be described differently at various energy scales
- EFT uses a series of **operators**, which are mathematical constructs representing interactions, each multiplied by **coefficients** that encapsulate the strength of these interactions
- **Applications:**
    - **Low-Energy Phenomena:** Examples include Fermi's theory of beta decay, which describes weak interactions at low energies
    - **High-Energy Physics:** EFT helps to describe processes **involving heavy particles like the top quark** without needing a full theory of everything

Why EFT is Important for Exploring Physics BSM?

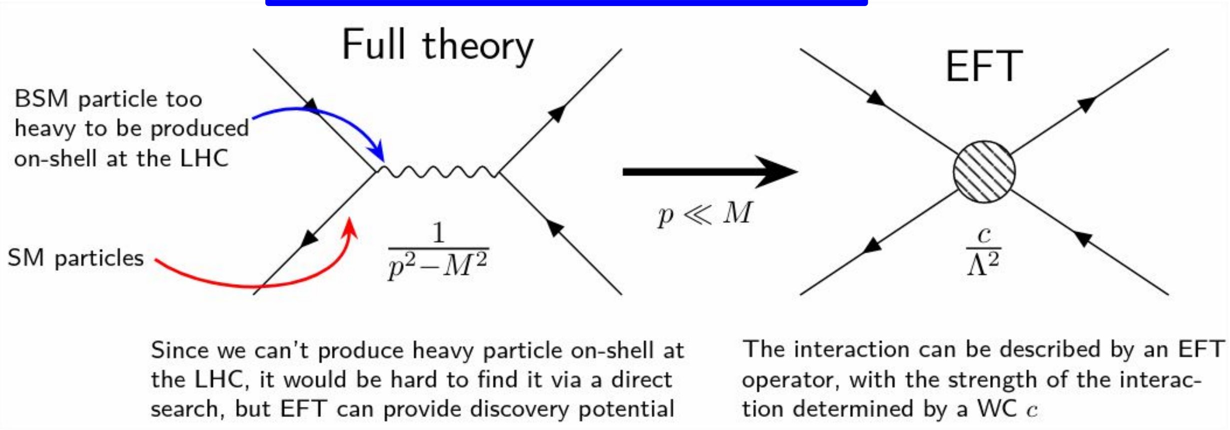
- The Standard Model (SM) of particle physics, while highly successful, **is known to be incomplete**
- EFT provides a structured approach to explore **potential new physics** beyond the SM by parameterizing unknown interactions in a systematic way
- **Flexibility and Broad Applicability:**
  - EFT is applicable across various energy scales
  - EFT remains **largely agnostic** about the specifics of the underlying high-energy theory

EFT helps bridge the gap between **theoretical predictions** and **experimental observations**

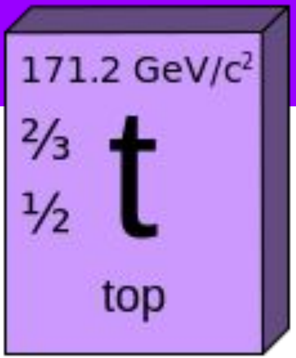
EFT Lagrangian

- Search new fundamental particles is motivated by the **strong evidence** for **phenomena not described by the SM**
- New particles may not be light enough to be produced at the LHC
- Indirect searches are needed if we want to probe these regimes
- Effective field theory (EFT) provides a framework for probing these higher energy scales

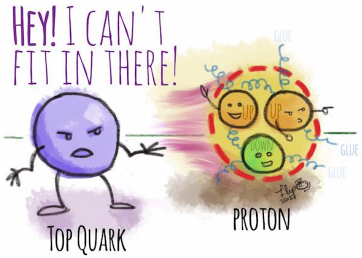
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$



The Top Quark: A Key Player in Particle Physics



- **The top quark is pretty unique:**
  - The **heaviest** of all known elementary particles
  - Due to its large mass, the top quark plays a crucial role in **EWSB**
  - Participates in strong interactions and comes in 3 colors making it subject to the rules of **Quantum Chromodynamics** (QCD)
  - Decay via the **weak force** ($t \to Wb$ ~100%)
  - Decays immediately after its production before hadronization
  - Top quarks are produced in high-energy collisions via processes like gluon-gluon fusion or quark-antiquark annihilation

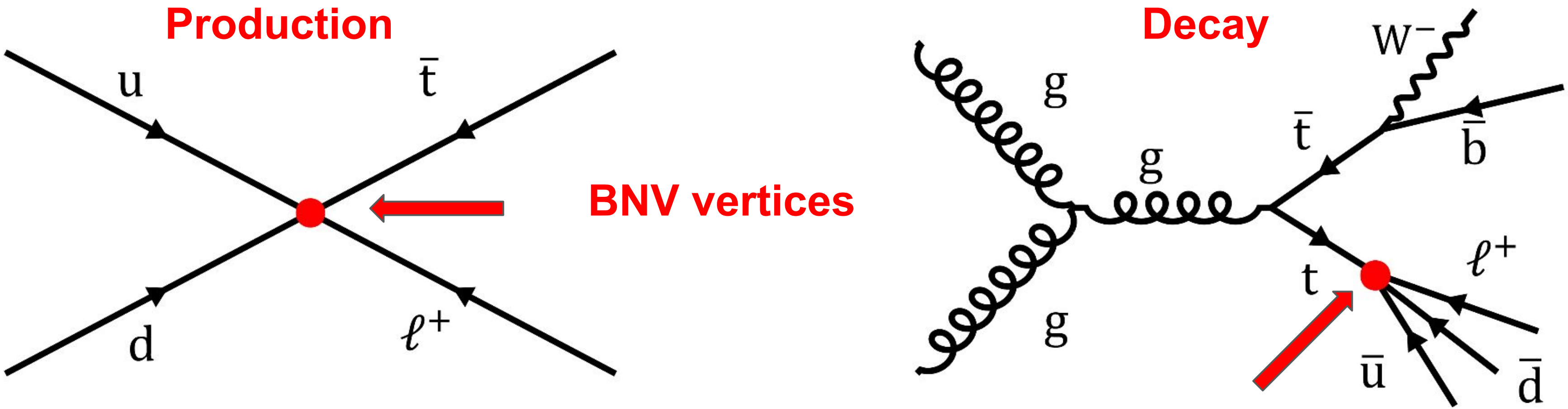


- **Top quark** provides a **clear signature** and is **abundantly produced** at the LHC
  - Ideal probe in indirect searches
- The most relevant EFT in top quark physics is the Standard Model EFT (SMEFT)

Baryon Number Violation: Intro

[Phys. Rev. Lett. 132 (2024) 241802](#)

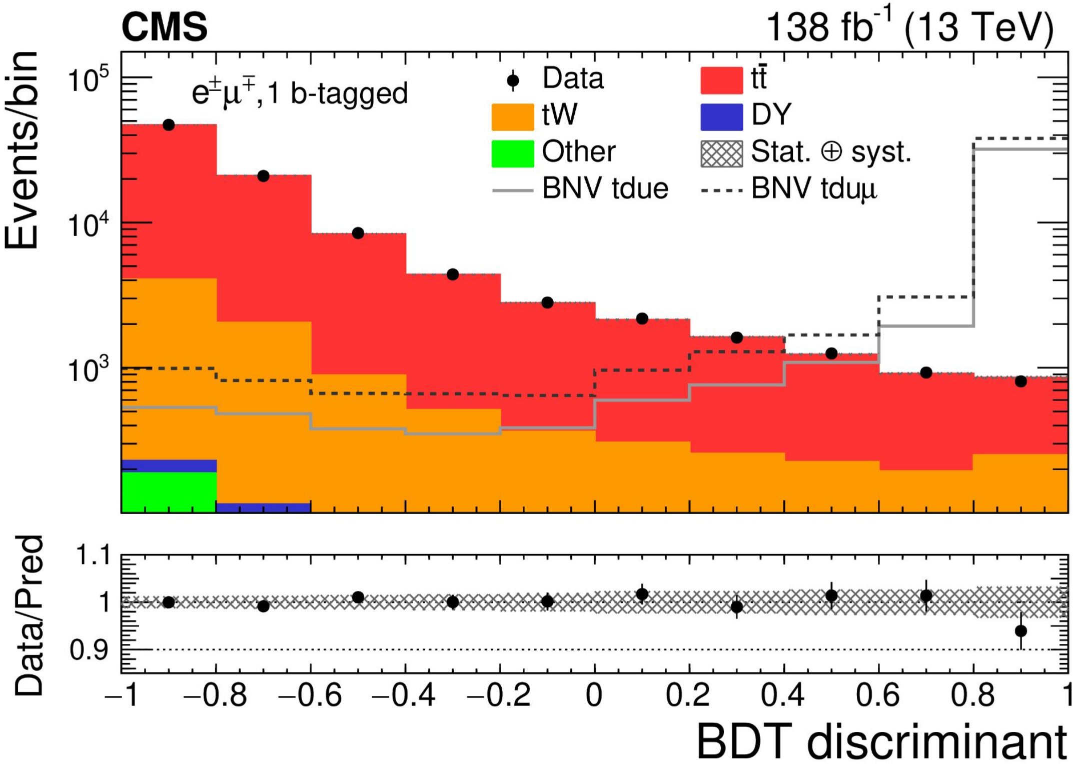
- A search for baryon number violating (**BNV**) interactions in top quark *production* and *decay*
- For the first time the production of **single top quarks** via **BNV** interactions is studied



- Events selected by requiring two oppositely-charged leptons (*electrons or muons*), exactly one b-tagged jet and high missing transverse momentum (>60 GeV):
  - One lepton is produced via the **BNV** interaction
  - The other lepton comes from the decay of the W boson from the top quark decay
- Analysis performed in **three categories**: e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$

Baryon Number Violation: Analysis Strategy

- Multivariate discriminants (**BDT**) to separate the signal from the **background** (tt, tW and DY)
- Examples of the predicted signal for the **BNV** interactions via **teud** (solid gray line) and **tμud** (dashed black line) vertices
- A binned maximum likelihood **fit** to the **BDT** output distributions is performed to search for the **BNV** processes

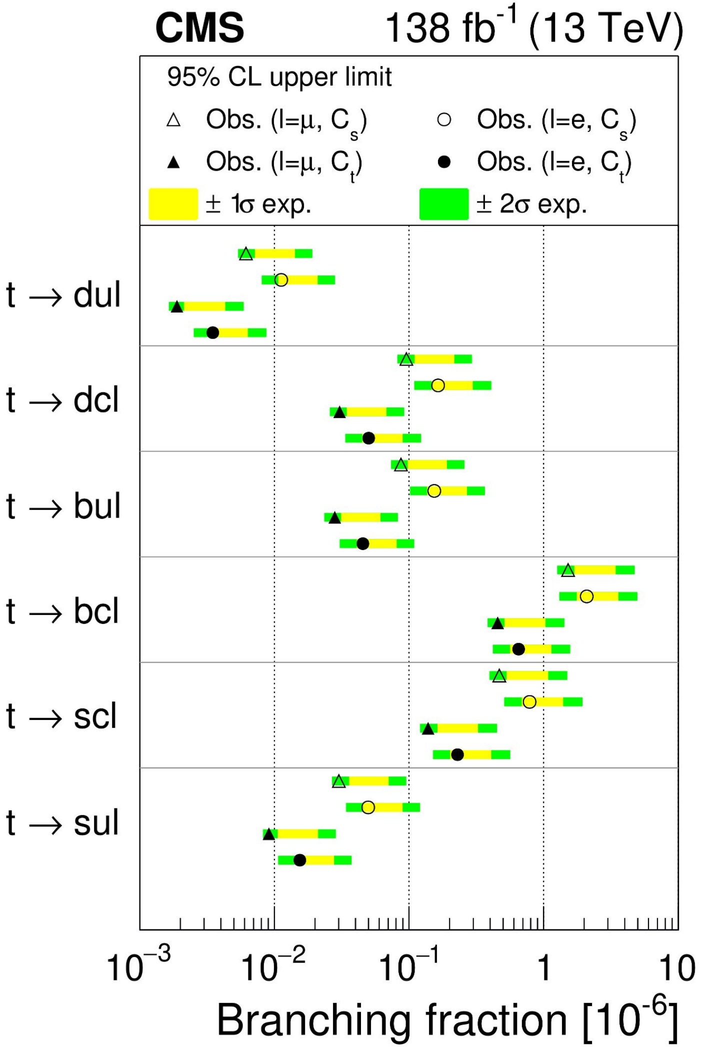


The 3 main uncertainties are: the normalization of the tW process, muon energy scale, and modeling of the top quark p_T spectrum

Baryon Number Violation: Results

- **A total of 24 WCs probed individually**
- No significant deviation from the SM prediction is observed
- Upper limits are placed on the strength of the BNV couplings and are **translated** to limits on the branching fractions for the BNV top quark decays:
  - Circles for electrons
  - Triangles for muons
  - C_t shown with filled markers
  - C_s shown with open markers
- Considering **BNV** vertices in the production of top quarks increases the sensitivity of this search
- The improved previous collider results (8 TeV Phys. Lett. B 731 (2014) 173) by multiple orders of magnitude

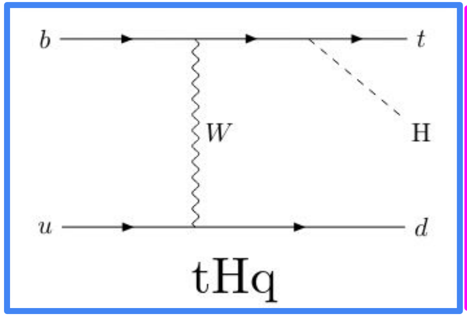
See Ece Asilar´s talk for Lepton Flavor Violation

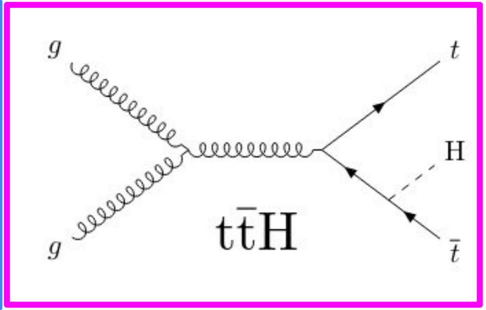


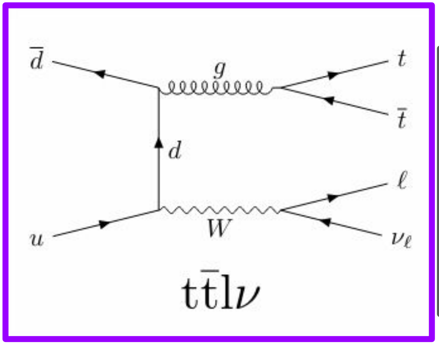
BSM in Top+X: Signal Processes

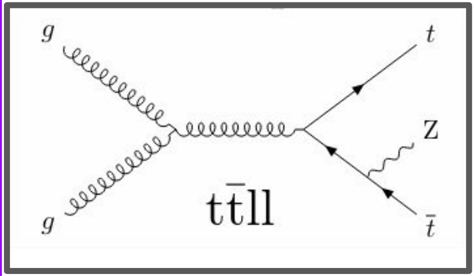
JHEP 12 (2023) 068

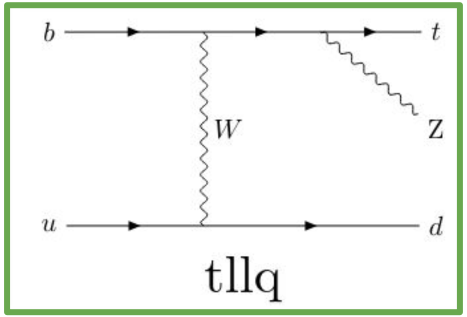
- Analysis focuses on operators that couple the **top quark** to leptons, bosons, and other heavy quarks
- Concentrates on **associated top processes** and model how EFT operators affect expected yields
  - 6 signal processes: **ttlv**, **ttll**, **tllq**, **ttH**, **tHq**, **tttt**
  - Low cross section processes
  - Clean well isolated signal region

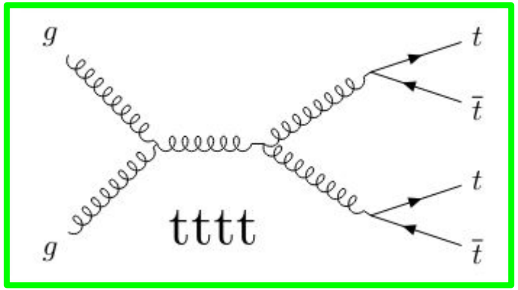






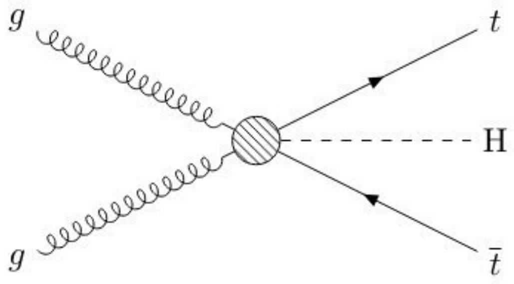




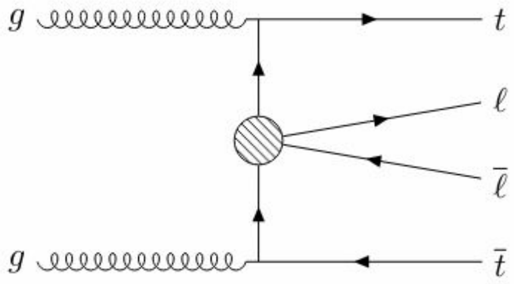


BSM in Top+X: Operators

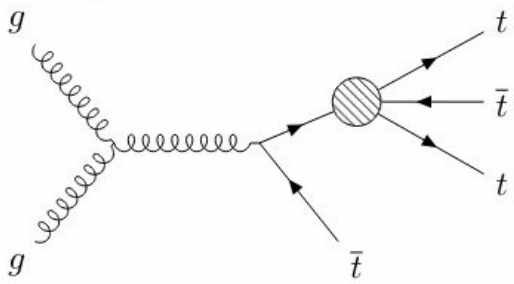
Focus on 26 operators, which can be grouped together into **4 different categories**



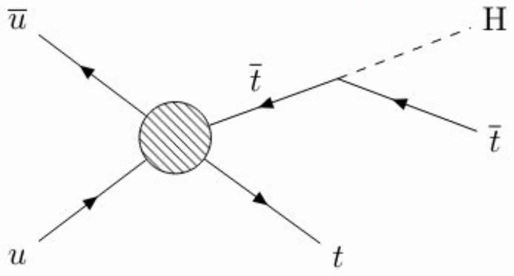
Operators involving heavy quarks and bosons



Operators involving 2 heavy quarks and 2 leptons



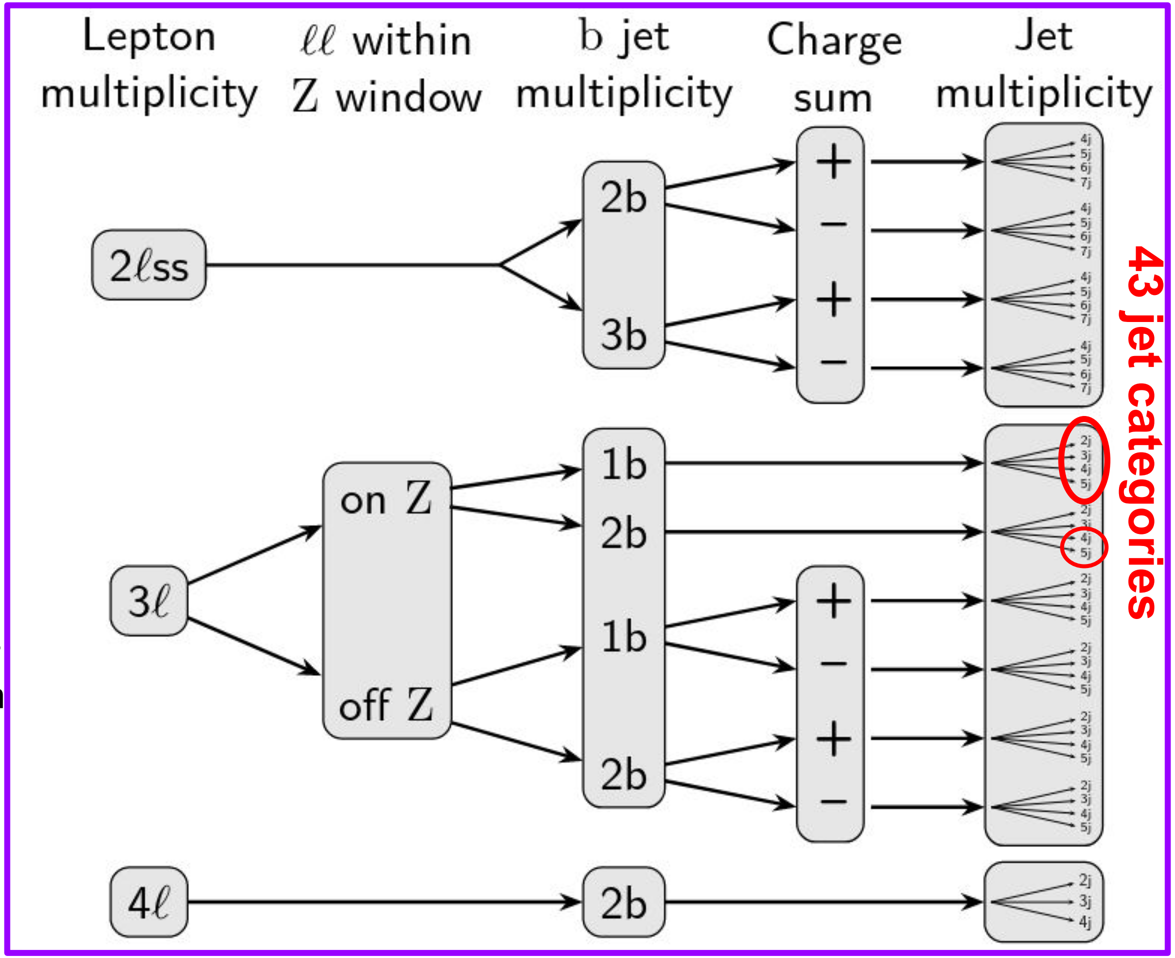
Operators involving 4 heavy quarks



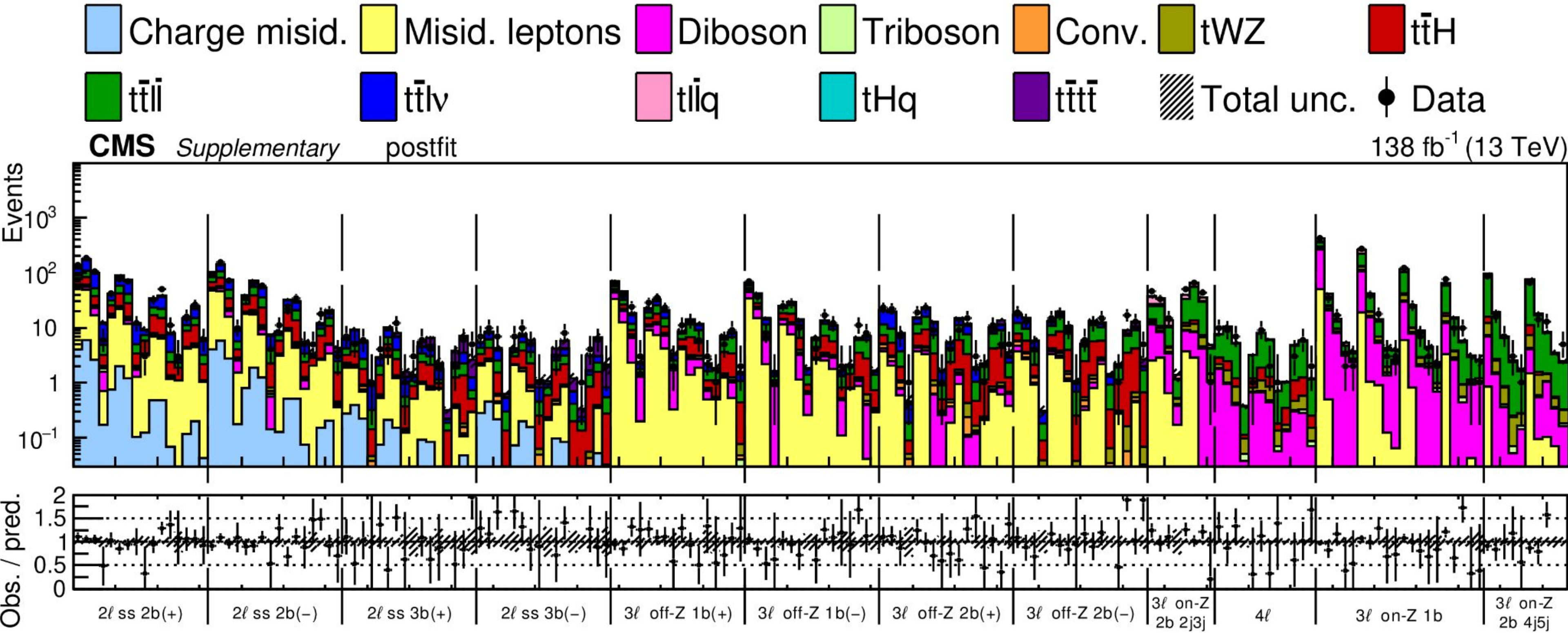
Operators involving 2 heavy quarks and 2 light quarks

BSM in Top+X: Event Selection

- Aims to discriminate between signal processes as much as possible:
  - **2lss:** ttH and ttW (split by charge)
  - **3l on Z:** ttll (2b), tllq (1b)
  - **3l off Z:** non-resonant ttll and tllq (2-quark 2-lepton EFT contributions)
  - **≥ 4l:** ttH and ttll
- Use different variables to optimize sensitivity to EFT effects
  - **$p_T(lj)_{max}$:** p_T of the leading lepton plus jet pairs **(39 categories)**
  - **$p_T(Z)$:** p_T of the opposite sign lepton pair **(6 categories)**



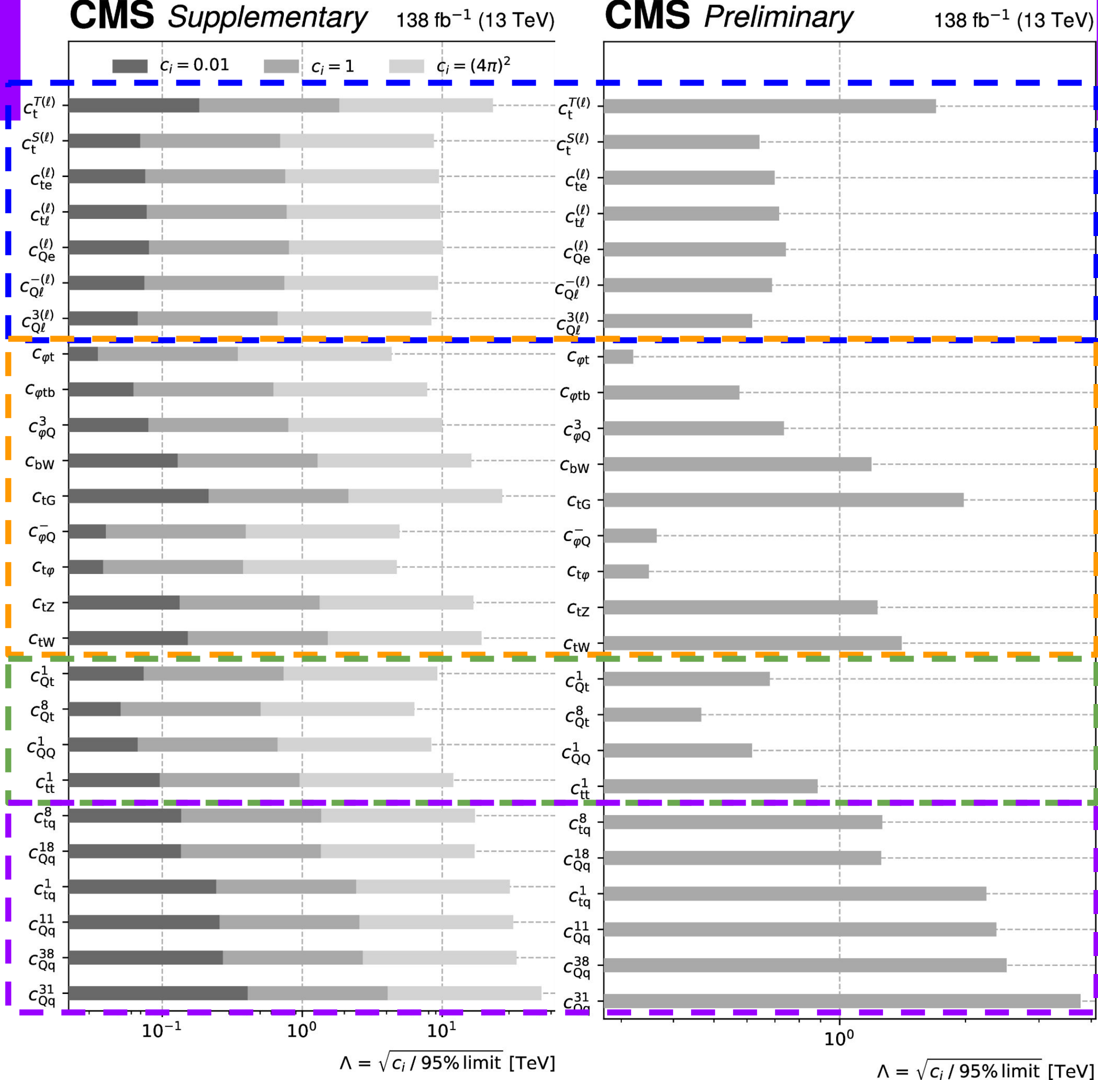
BSM in Top+X: Kinematic variables per category



$p_T(lj)_{max}$ | $p_T(Z)$

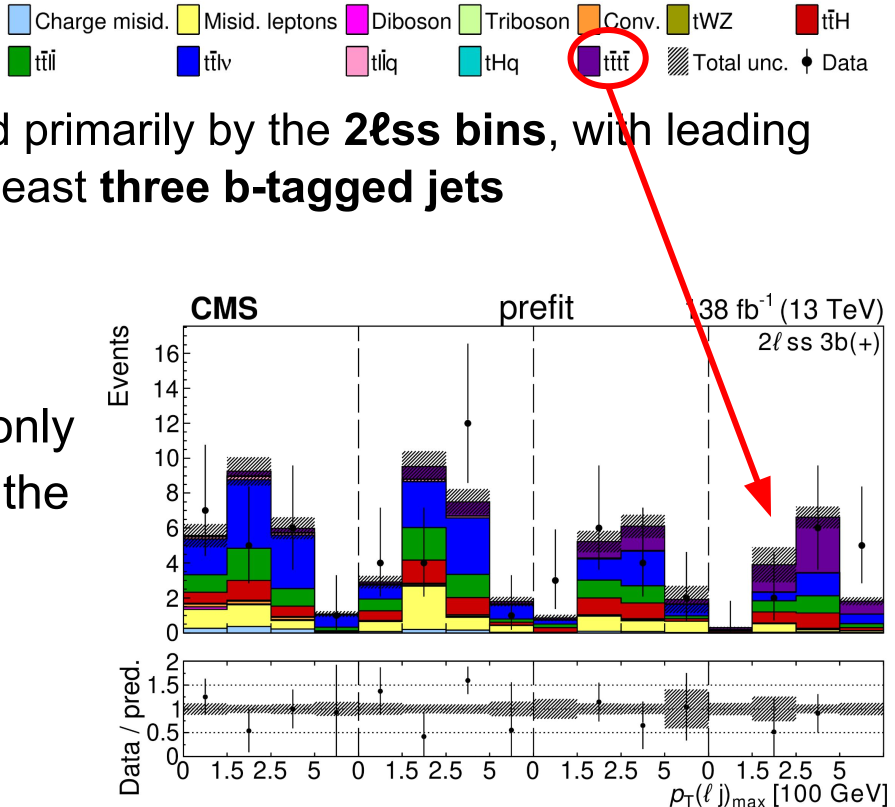
BSM in Top+X: Results

- The postfit values are obtained by **simultaneously fitting** all 26 WCs and the NPs
- Most results dominated by **statistical uncertainties**, the main syst. unc. is NLO norm
- Limits on WCs translated to limits in the **new physics scale:**
  - **2 heavy quarks+2 leptons:**
    - Λ > O(800 GeV) - O(1 TeV)
  - **heavy quarks+bosons:**
    - Λ > O(300 GeV) - O(1 TeV)
  - **4 heavy quarks:**
    - Λ > O(700 GeV) - O(1 TeV)
  - **2 heavy quarks+2 light quarks:**
    - Λ > O(1 TeV) - O(3 TeV)



BSM in Top+X: Sensitivity Results

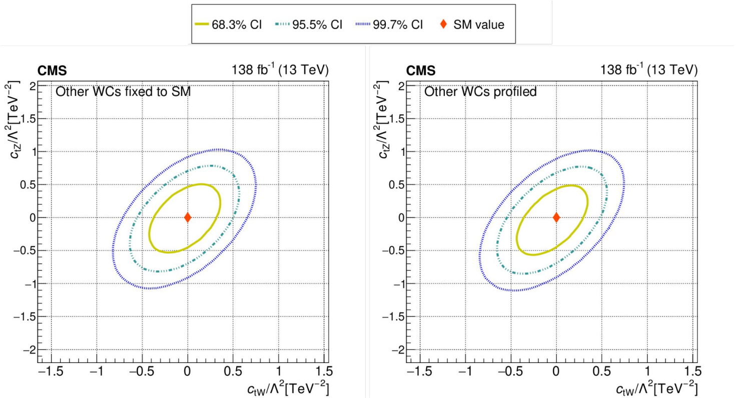
- Interpretation of sensitivity
  - Identification of bins that provide the leading contributions to each Wilson Coefficient category
- Example of **4 heavy quark operators**:
  - The sensitivity to these WCs is provided primarily by the **2ℓss bins**, with leading contributions from the bins requiring at least **three b-tagged jets**
  - 4-top enriched region

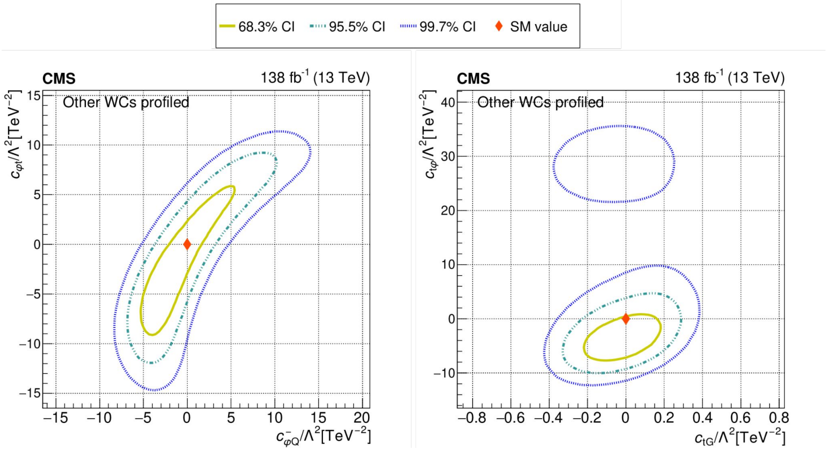


- A fit is performed only to these bins
- The **resulting confidence intervals** are only degraded by about **4 - 6%** with respect to the fit with all bins included

Summary

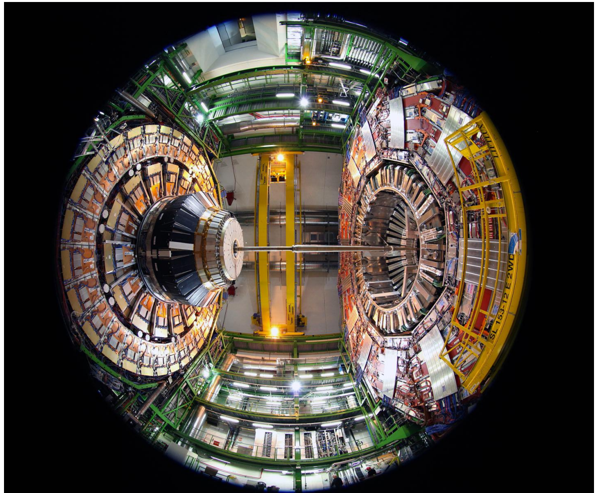
- EFT is a **powerful technique** for indirect searches of **BSM** physics at the LHC
- Rich and active program of CMS EFT analyses in the top quark sector
- The results are **consistent** with SM expectations
  - BNV much improved results given the new center-of-mass energy, increase statistics and the addition of **BNV** vertices in the production of top quarks
  - Setting limits on 26 independent Wilson coefficients, also exploring correlations among the WCs
- In the future, EFT approaches will benefit greatly from increased statistics of the current LHC and HL-LHC

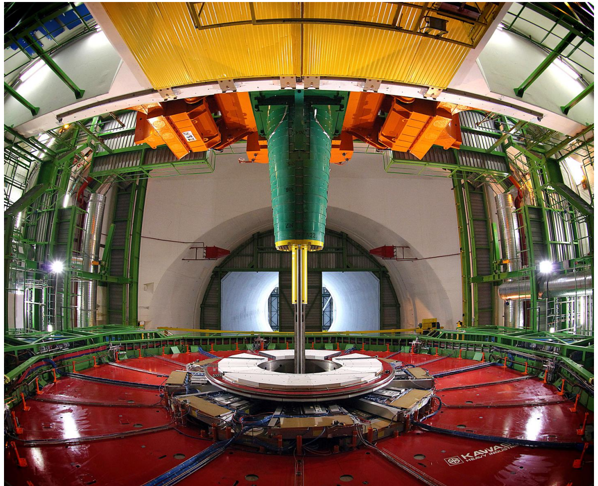


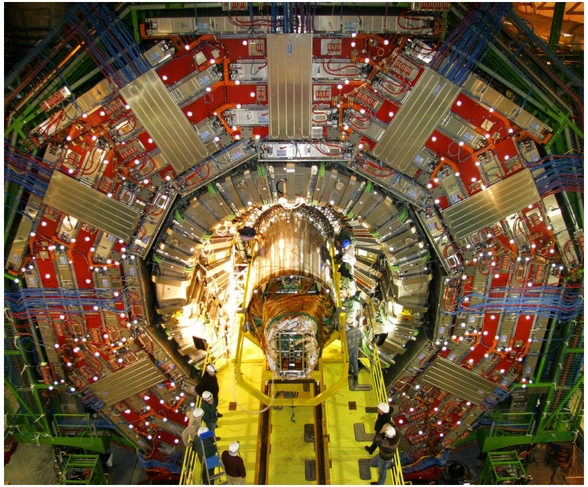



THANK YOU :)

BACK-UP SLIDES







Baryon Number Violation

Phys. Rev. Lett. 132 (2024) 241802

Theoretical inclusive cross sections for single top quark production (ST) and top quark-antiquark pair production with the decay (TT) via BNV interactions, assuming a top quark mass of 172.5 GeV, the top quark decay width 1.33 GeV, Λ= 1 TeV, and Ct= 1 or Cs= 1

Process	$\sigma(C_t = 1)$ [pb]	$\sigma(C_s = 1)$ [pb]
ST (tℓud)	$31.5 \pm 2.1 \pm 1.0$	$10.7 \pm 0.7 \pm 0.4$
ST (tℓus)	$8.1 \pm 0.3 \pm 0.5$	$2.8 \pm 0.1 \pm 0.2$
ST (tℓub)	$3.31 \pm 0.13 \pm 0.06$	$1.14 \pm 0.05 \pm 0.02$
ST (tℓcd)	$2.77 \pm 0.22 \pm 0.01$	$0.96 \pm 0.01 \pm 0.07$
ST (tℓcs)	$0.79 \pm 0.02 \pm 0.11$	$0.27 \pm 0.01 \pm 0.04$
ST (tℓcb)	$0.28 \pm 0.03 \pm 0.04$	$0.10 \pm 0.01 \pm 0.01$
TT	$0.007 \pm 0.002 \pm 0.001$	$0.007 \pm 0.002 \pm 0.001$

Baryon Number Violation

Phys. Rev. Lett. 132 (2024) 241802

Vertex	C_x	C_x/Λ^2 [TeV^{-2}] Exp.	C_x/Λ^2 [TeV^{-2}] Obs.	$\mathcal{B}_x$ [10^{-6}] Exp.	$\mathcal{B}_x$ [10^{-6}] Obs.
teud	s	0.055	0.048	0.015	0.011
	t	0.031	0.027	0.005	0.003
tμud	s	0.046	0.036	0.010	0.006
	t	0.025	0.020	0.003	0.002
tecd	s	0.207	0.184	0.208	0.164
	t	0.114	0.102	0.063	0.050
tμcd	s	0.178	0.141	0.153	0.095
	t	0.100	0.080	0.048	0.030
teus	s	0.115	0.101	0.063	0.050
	t	0.064	0.056	0.019	0.015
tμus	s	0.102	0.079	0.050	0.030
	t	0.056	0.043	0.015	0.009
tecs	s	0.448	0.403	0.973	0.786
	t	0.243	0.218	0.286	0.229
tμcs	s	0.394	0.311	0.752	0.468
	t	0.217	0.169	0.228	0.138
teub	s	0.199	0.178	0.191	0.154
	t	0.109	0.097	0.057	0.045
tμub	s	0.168	0.134	0.136	0.087
	t	0.095	0.076	0.044	0.028
tecb	s	0.718	0.657	2.503	2.090
	t	0.405	0.367	0.795	0.652
tμcb	s	0.703	0.564	2.393	1.521
	t	0.386	0.307	0.722	0.455

Expected and observed 95% CL upper limits on the BNV effective couplings and top quark BNV branching fractions

Ideal EFT Parametrization

- Model the EFT contributions
- Matrix element can be written as the sum of SM and new physics components

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i$$

c_i are the Wilson coefficients

- Since σ ∝ M^2 → the cross section will have a quadratic dependence on the WCs

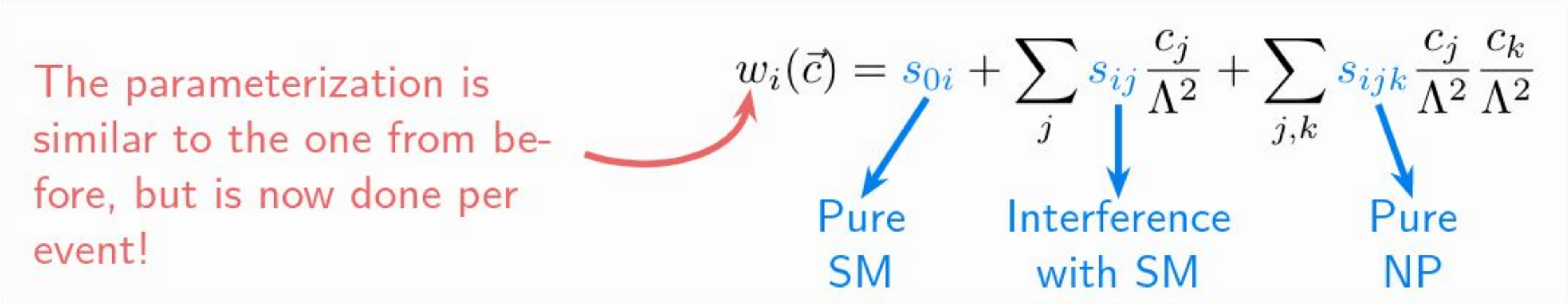
$$d\sigma(\vec{c}) \propto \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i\right|^2 \propto s_0 + \sum_j s_j \frac{c_j}{\Lambda^2} + \sum_{j,k} s_{jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

- s_0: Pure SM
- s_j: Interference with SM
- s_{jk}: Pure NP

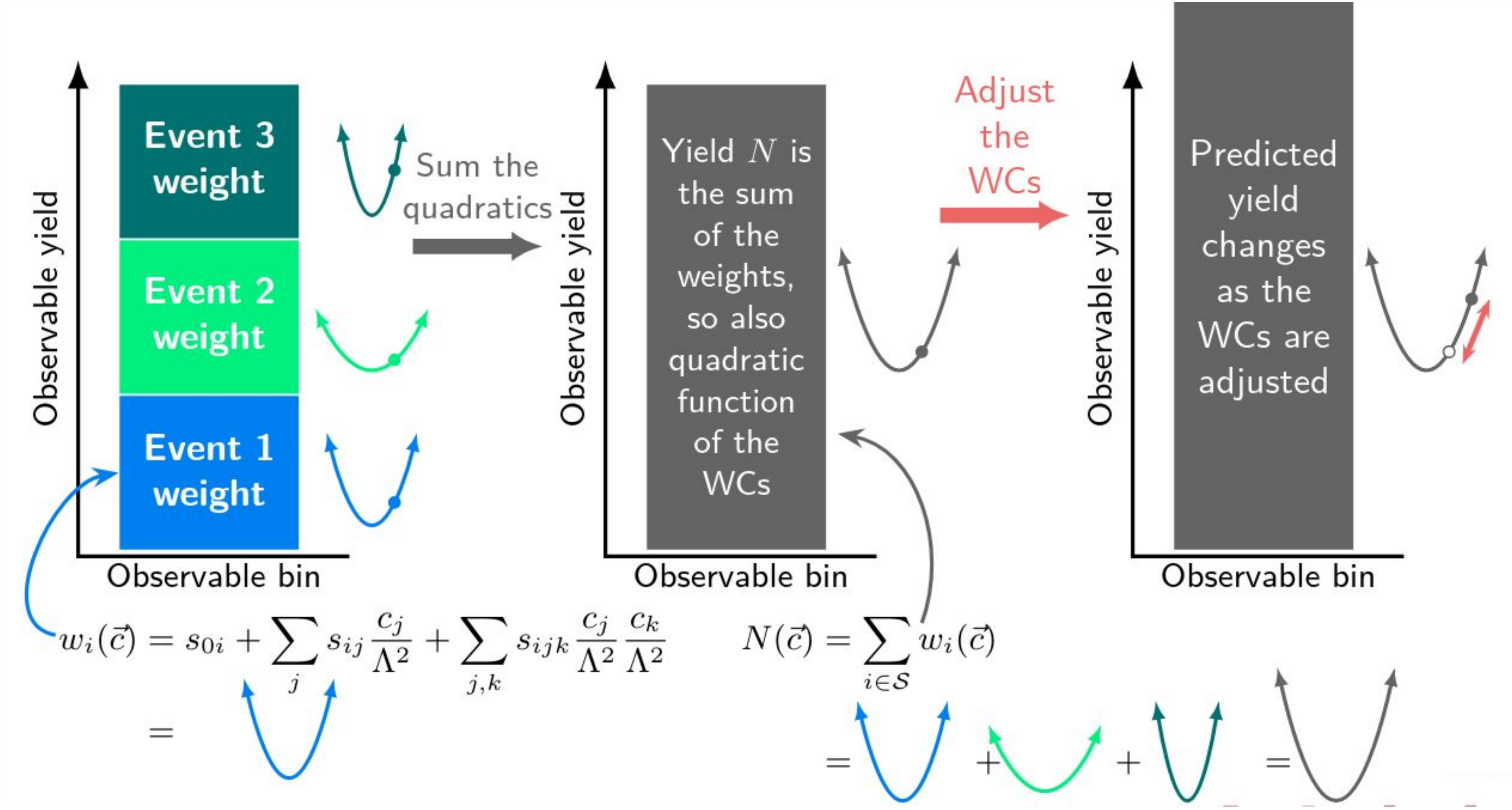
- Far too computationally intensive. Would need O(100) MC samples per signal process

Real EFT Parametrization

- Model the EFT contributions event by event
- Build a **weight function per event** based on a 26-dimensional quadratic parametrization using the Madgraph event reweighting technique:



Real EFT Parametrization



Real EFT Parametrization

- Signal contribution is modeled at leading order, **LO**, using *MadGraph5_aMC@NLO* with **dim6top** model
- Using **Warsaw basis** of gauge invariant dimension-6 operators providing **tree-level modeling** for the effects
- In the analysis, it is assumed that the EFT effects impact each lepton generation on the same way

Object Requirements

Object requirements for the 43 event selection categories. Requirements separated by commas indicate a division into subcategories. The kinematical variable that is used in the event category is also listed

Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Differential variable
2ℓss 2b	2	No requirement	2	>0, <0	4,5,6,$\geq$7	$p_T(\ell j0)$
2ℓss 3b	2	No requirement	≥ 3	>0, <0	4,5,6,$\geq$7	$p_T(\ell j0)$
3ℓ off-Z 1b	3	$\lvert m_Z - m_{\ell\ell}\rvert > 10\,GeV$	1	>0, <0	2,3,4,$\geq$5	$p_T(\ell j0)$
3ℓ off-Z 2b	3	$\lvert m_Z - m_{\ell\ell}\rvert > 10\,GeV$	≥ 2	>0, <0	2,3,4,$\geq$5	$p_T(\ell j0)$
3ℓ on-Z 1b	3	$\lvert m_Z - m_{\ell\ell}\rvert \leq 10\,GeV$	1	No requirement	2,3,4,$\geq$5	$p_T(Z)$
3ℓ on-Z 2b	3	$\lvert m_Z - m_{\ell\ell}\rvert \leq 10\,GeV$	≥ 2	No requirement	2,3,4,$\geq$5	$p_T(Z)$ or $p_T(\ell j0)$
4ℓ	$\geq$4	No requirement	≥ 2	No requirement	2,3,$\geq$4	$p_T(\ell j0)$

NLO theoretical cross sections used for normalizing the signal simulation samples

Process	Cross section (pb)
$t\bar{t}H$	0.215 [20]
$t\bar{t}l\bar{l}$	0.281 [20]
$t\bar{t}l\nu$	0.235 [21]
$tl\bar{l}q$	0.076 [15]
tHq	0.071 [20]
$t\bar{t}t\bar{t}$	0.012 [22]

The 1 and 2 σ uncertainty intervals extracted from the likelihood fits

WC/Λ^2 [TeV^{-2}]	2σ Interval (others profiled)	2σ Interval (others fixed to SM)
$c_{\mathrm{t}}^{T(\ell)}$	[-0.37, 0.37]	[-0.40, 0.40]
$c_{\mathrm{t}}^{S(\ell)}$	[-2.60, 2.59]	[-2.80, 2.80]
$c_{\mathrm{te}}^{(\ell)}$	[-1.76, 2.20]	[-1.90, 2.39]
$c_{\mathrm{t}\ell}^{(\ell)}$	[-1.78, 2.10]	[-2.01, 2.20]
$c_{\mathrm{Qe}}^{(\ell)}$	[-1.89, 1.94]	[-2.04, 2.12]
$c_{Q\ell}^{-(\ell)}$	[-1.56, 2.27]	[-1.80, 2.33]
$c_{Q\ell}^{3(\ell)}$	[-2.81, 2.54]	[-2.68, 2.58]
$c_{\varphi\mathrm{t}}$	[-10.76, 7.91]	[-4.95, 3.19]
$c_{\varphi\mathrm{tb}}$	[-3.23, 3.23]	[-3.15, 3.19]
$c_{\varphi Q}^{3}$	[-0.81, 2.01]	[-0.84, 1.91]
c_{bW}	[-0.75, 0.76]	[-0.75, 0.75]
$c_{\mathrm{t}G}$	[-0.27, 0.24]	[-0.22, 0.25]
$c_{\varphi Q}^{-}$	[-6.09, 8.20]	[-2.66, 2.95]
$c_{\mathrm{t}\varphi}$	[-8.98, 2.85]	[-7.68, 2.15]
$c_{\mathrm{t}Z}$	[-0.70, 0.63]	[-0.58, 0.59]
c_{tW}	[-0.54, 0.45]	[-0.47, 0.41]
c_{Qt}^{1}	[-2.71, 2.66]	[-2.75, 2.62]
c_{Qt}^{8}	[-5.15, 5.74]	[-5.24, 5.66]
c_{QQ}^{1}	[-3.03, 3.28]	[-3.04, 3.28]
c_{tt}^{1}	[-1.56, 1.60]	[-1.54, 1.63]
c_{tq}^{8}	[-0.67, 0.25]	[-0.68, 0.24]
c_{Qq}^{18}	[-0.68, 0.21]	[-0.67, 0.21]
c_{tq}^{1}	[-0.21, 0.21]	[-0.22, 0.20]
c_{Qq}^{11}	[-0.19, 0.19]	[-0.19, 0.19]
c_{Qq}^{38}	[-0.17, 0.16]	[-0.17, 0.16]
c_{Qq}^{31}	[-0.08, 0.07]	[-0.08, 0.07]

WC/Λ^2 [TeV^{-2}]	1σ Interval (others profiled)	1σ Interval (others fixed to SM)
$c_{\mathrm{t}}^{T(\ell)}$	[-0.21, 0.21]	[-0.26, 0.26]
$c_{\mathrm{t}}^{S(\ell)}$	[-1.52, 1.50]	[-1.82, 1.82]
$c_{\mathrm{te}}^{(\ell)}$	[-0.91, 1.40]	[-1.13, 1.68]
$c_{\mathrm{t}\ell}^{(\ell)}$	[-0.92, 1.31]	[-1.27, 1.47]
$c_{\mathrm{Qe}}^{(\ell)}$	[-1.08, 1.14]	[-1.32, 1.40]
$c_{Q\ell}^{-(\ell)}$	[-0.68, 1.52]	[-1.06, 1.64]
$c_{Q\ell}^{3(\ell)}$	[-1.84, 1.49]	[-1.76, 1.63]
$c_{\varphi\mathrm{t}}$	[-7.66, 1.59]	[-2.59, 1.34]
$c_{\varphi\mathrm{tb}}$	[-1.67, 1.68]	[-1.62, 1.67]
$c_{\varphi Q}^{3}$	[-0.06, 1.37]	[-0.11, 1.27]
c_{bW}	[-0.39, 0.39]	[-0.39, 0.39]
$c_{\mathrm{t}G}$	[-0.16, 0.12]	[-0.09, 0.15]
$c_{\varphi Q}^{-}$	[-4.50, 1.12]	[-1.19, 1.58]
$c_{\mathrm{t}\varphi}$	[-6.53, -0.84]	[-5.50, -0.63]
$c_{\mathrm{t}Z}$	[-0.39, 0.32]	[-0.31, 0.32]
c_{tW}	[-0.31, 0.22]	[-0.26, 0.21]
c_{Qt}^{1}	[-2.03, 1.98]	[-2.05, -0.75] and [0.49, 1.97]
c_{Qt}^{8}	[-3.75, 4.38]	[-3.93, -0.95] and [1.51, 4.30]
c_{QQ}^{1}	[-2.21, 2.49]	[-2.28, -0.53] and [0.90, 2.47]
c_{tt}^{1}	[-1.16, 1.20]	[-1.16, -0.28] and [0.43, 1.22]
c_{tq}^{8}	[-0.45, 0.03]	[-0.47, 0.02]
c_{Qq}^{18}	[-0.47, -0.01]	[-0.46, -0.00]
c_{tq}^{1}	[-0.11, 0.11]	[-0.12, 0.10]
c_{Qq}^{11}	[-0.10, 0.10]	[-0.10, 0.10]
c_{Qq}^{38}	[-0.09, 0.08]	[-0.09, 0.08]
c_{Qq}^{31}	[-0.04, 0.03]	[-0.04, 0.03]

Leading Categories

Grouping of WCs	WCs	Lead categories
Two heavy two leptons	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
Four heavy	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
Two heavy two light "$t\bar{t}l\nu$-like"	c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}	2ℓss
Two heavy two light "$tl\bar{l}q$-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
Two heavy with bosons "$t\bar{t}l\bar{l}$-like"	c_{tZ}, $c_{\varphi t}$, $c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
Two heavy with bosons "tXq-like"	$c_{\varphi Q}^{3}$, $c_{\varphi tb}$, c_{bW}	3ℓ on-Z
Two heavy with bosons with significant impacts on many processes	c_{tG}, $c_{t\varphi}$, c_{tW}	3ℓ and 2ℓss

Operators

Focus on 26 operators, which can be grouped together into **4 different categories**

[**Reference:** *Interpreting top-quark LHC measurements in the standard-model effective field theory*]

Operator category	WCs
Two heavy quarks	$c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$
Two light quarks two heavy quarks	$c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$
Four heavy quarks	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

Aim to include all operators that **significantly impact** processes in which one or more top quarks are produced in association with charged leptons