Lake Louise Winter Institute 2024: February 20, 2024

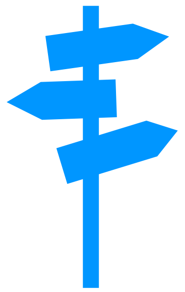
Probing EFT couplings in the top quark sector

Kelci Mohrman (University of Florida) on behalf of CMS

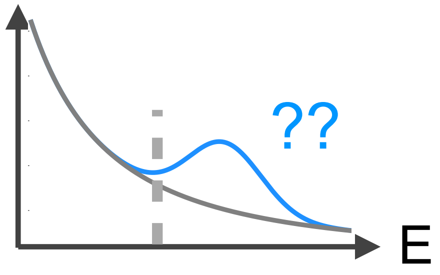
Image credit: From https://indico.cern.ch/event/1205625/overview

Motivation for indirect searches for new physics:
New physics has to be out there, but ...

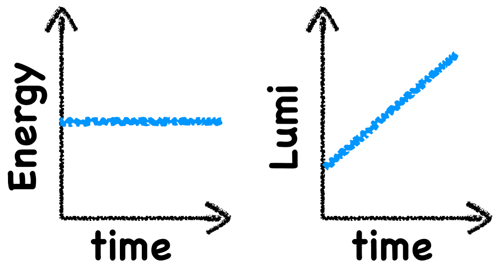
No conclusive indication of which direction to look



No guarantee BSM particles light enough to be produced at LHC



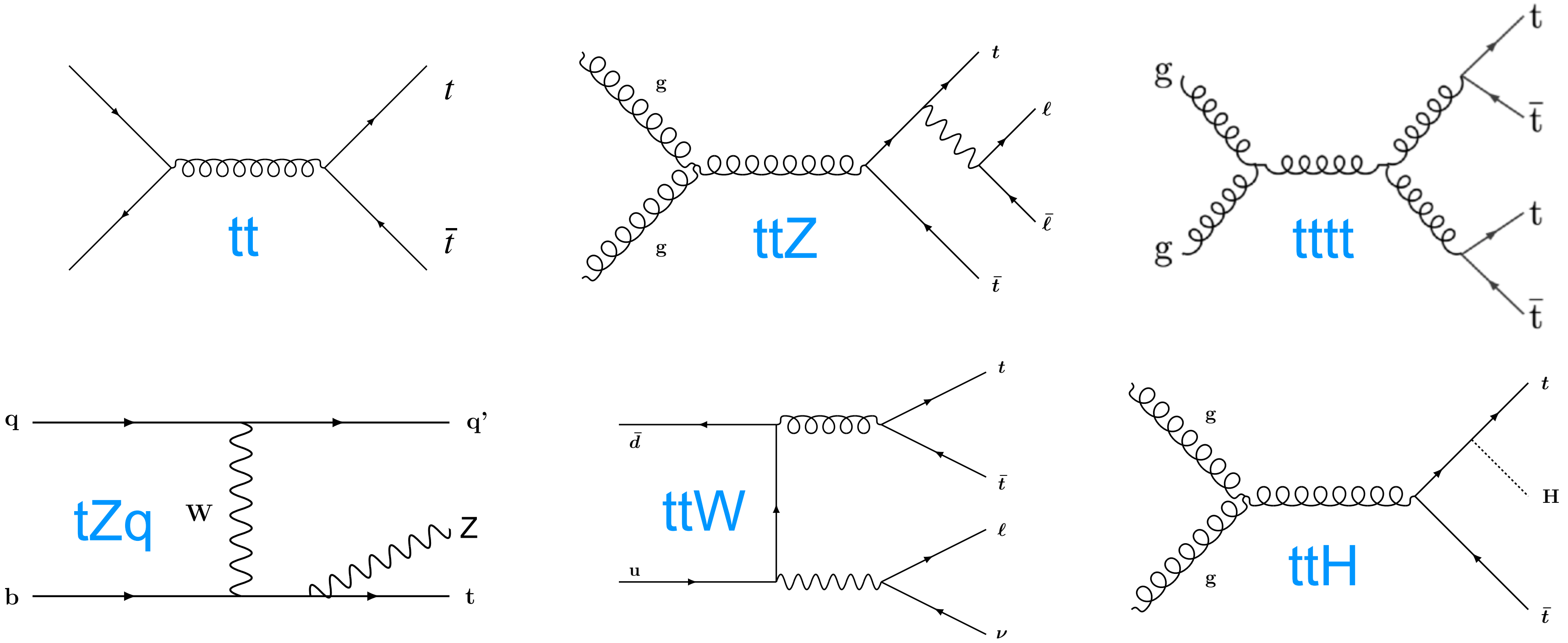
Energy not going up much (but stats are!)



Effective field theory (EFT) provides a relatively model independent way to describe possible effects of heavy new physics

Motivations for SM EFT in the top quark sector

- EFT is relatively general, useful for searches in many sectors, this talk focuses on the top sector
- Processes involving tops are relatively rare, and may be an interesting region for new physics to be hiding
- Garnering enough statistics to start probing in more detail



A few examples of top quark processes

UF UNIVERSITY of FLORIDA Kelci Mohrman, k.mohrman@ufl.edu

Brief introduction to SM EFT*

SM is lowest order piece in the expansion

Wilson Coefficients (WCs), strength of interaction

Operators are built of products of SM fields and their derivatives

$$\mathscr{L}_{\text{SM EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

Energy scale of NP

Note: EFT is not new, e.g. historical example of an EFT is Fermi theory for beta decay

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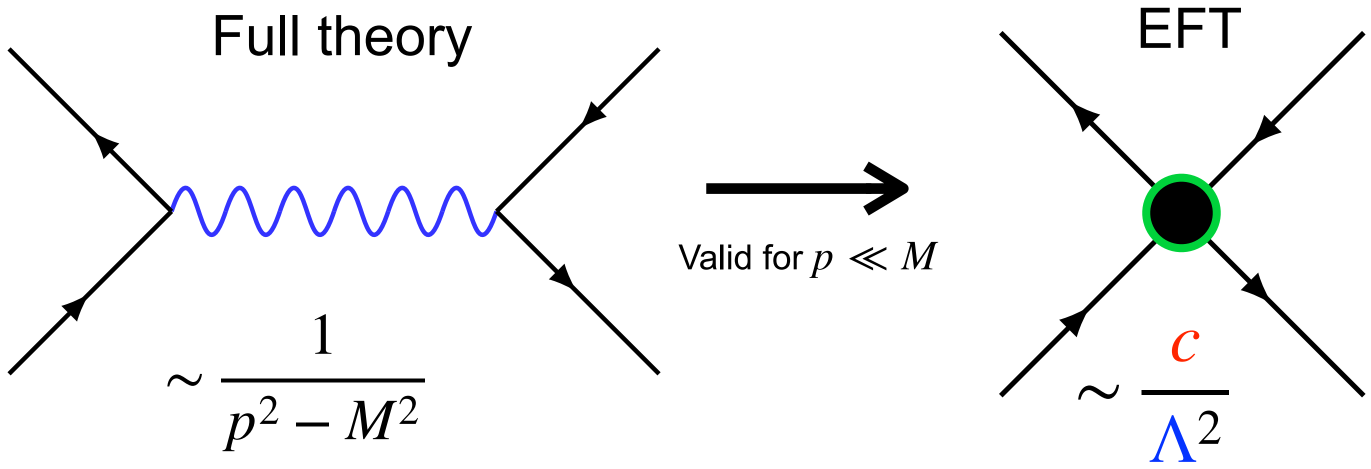
Energy scale of NP

Example of SMEFT in action:



$$\sim \frac{1}{p^2 - M^2}$$

$$\sim \frac{c}{\Lambda^2}$$

Note: EFT is not new, e.g. historical example of an EFT is Fermi theory for beta decay

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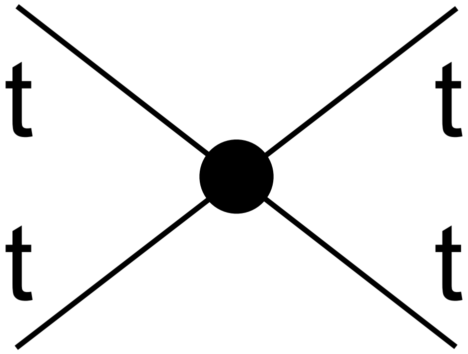
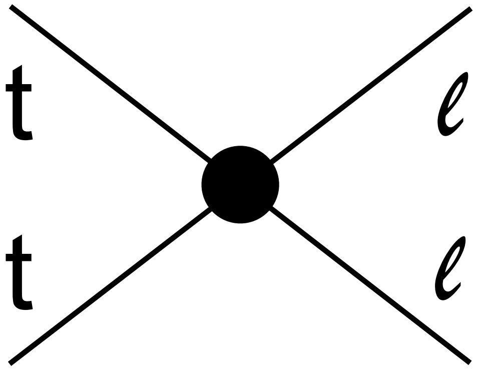
SM EFT operators involving top quarks

Focus on operators involving tops → ~40 operators[1]

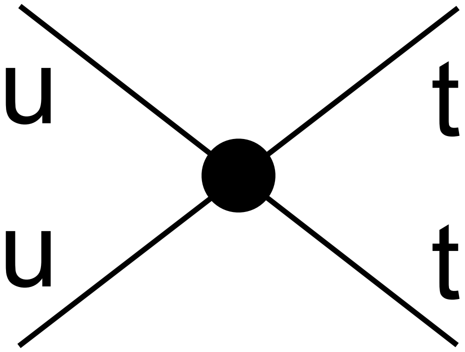
Can be generally grouped into 4 categories[2]



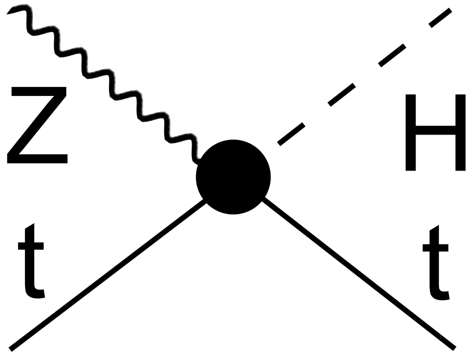
4 heavy[3] quarks



2 heavy quarks and 2 leptons

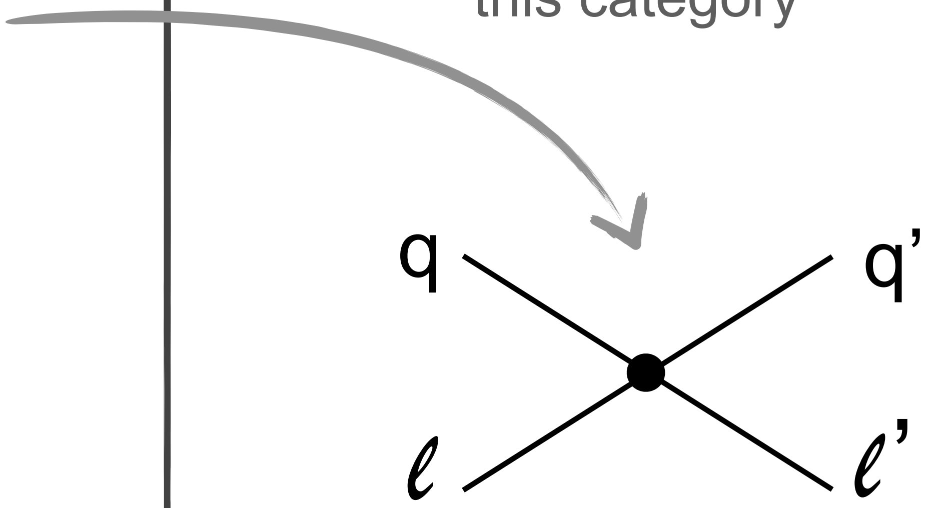


2 heavy quarks and 2 light quarks



2 heavy quarks and bosons

Relaxing charged lepton flavor conservation in this category



2 quark 2 lep interactions involving CLFV

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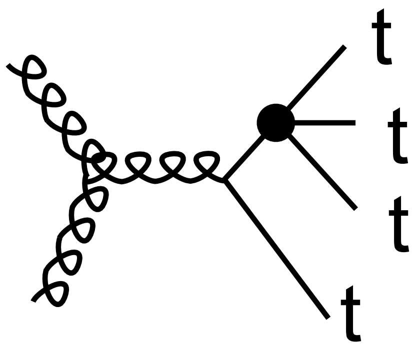
[1] The number quoted here is from the dim6top note (1802.07237) assumption described in the “baseline” section i.e. 4.1

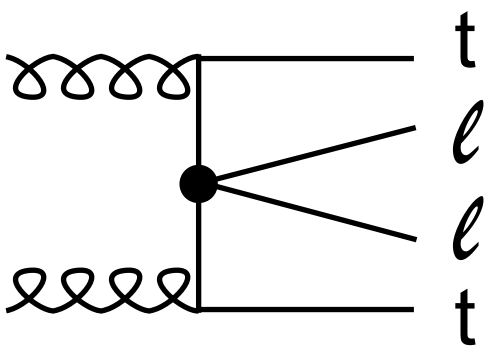
[2] In general an operator will give rise to multiple EFT vertices, here we just show an example vertex for an operator from each category

[3] Note: "heavy" means top or bottom, "light" is everything else, see dim6top model paper (1802.07237) for more details on the operators, also note the operators in the ~40 number quoted here does not include the FCNC operators

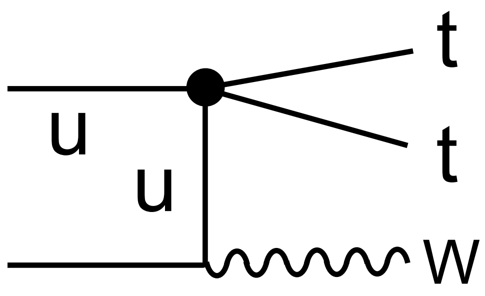
The EFT vertices can impact observables, where the strengths of the impacts are determined by the WCs that scale the vertices



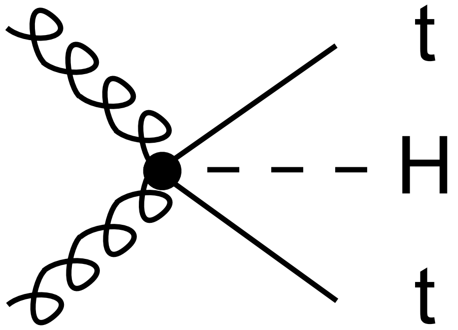
4 heavy quarks



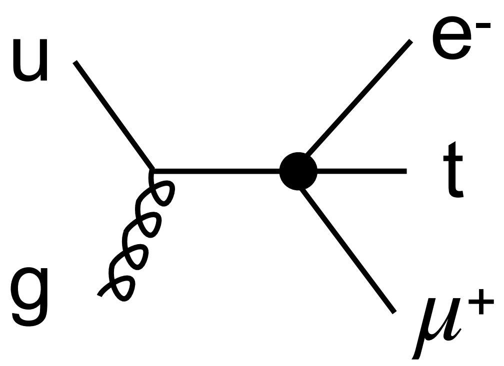
2 heavy quarks and 2 leptons



2 heavy quarks and 2 light quarks



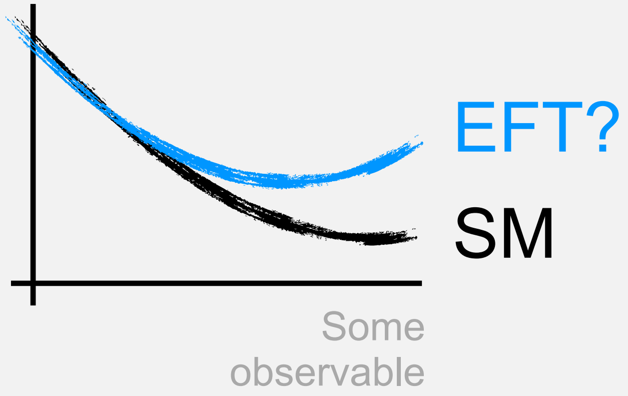
2 heavy quarks and bosons



CLFV interactions

Note: In general an operator will give rise to multiple EFT vertices, and there are also multiple types of vertices in each category, which can impact multiple signal processes. Here we just show an example vertex for an operator from each category impacting an example process.

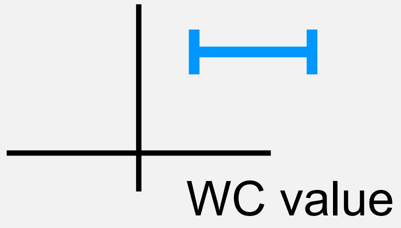
What: Compare prediction to data to find WC values



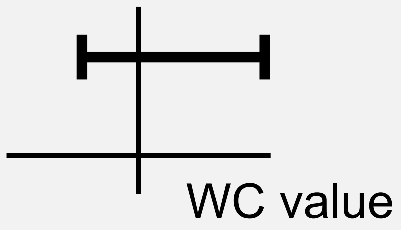
WC=0 NOT consistent with data

WC=0 consistent with data

Why: Any non-zero WC would be new physics!



New physics!!



Constraints and info on Λ probed

How?

Parameterize some prediction in terms of the WCs

Compare observation to prediction and extract best fit values and corresponding uncertainties for the WCs

Some recent TOP EFT analyses from CMS

We'll cover these two in this talk

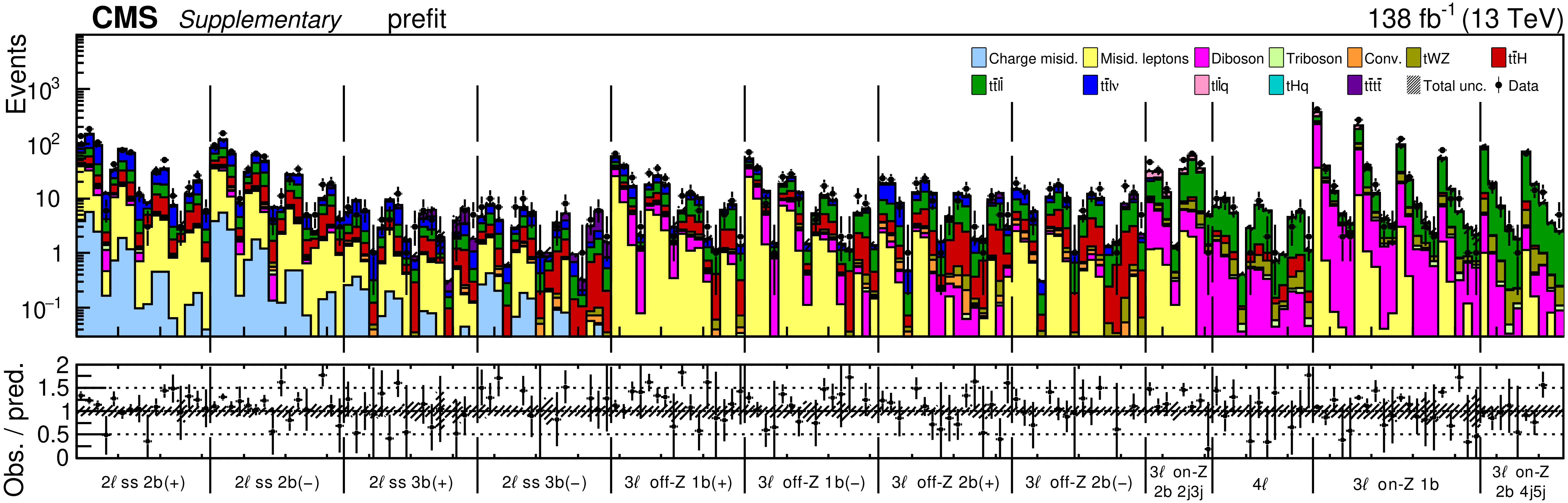
- Search for CLFV with trileptons, 6 WCs (fit individually)
  CSM-TOP-22-005 (Submitted to PRD)
- t(t)X multilepton, 26 WCs (fit individually and simultaneously)
  JHEP12(2023)068
- $t\bar{t}$ with boosted Z or H, singe lepton + jets, 8 WCs (fit individually and simultaneously)
  PRD 108 (2023) 032008
- Search for CLFV in $e\mu$ final states, 6 WCs (fit individually)
  JHEP 06 (2022) 082
- $t\bar{t}\gamma$ dilepton, Re and Im part of 1 WC (fit individually and together)
  JHEP 05 (2022) 091
- $t\bar{t}Z$ multilepton, 5 WCs (fit individually and simultaneously)
  JHEP 12 (2021) 083

t(t)X
multilepton
JHEP12(2023)068

CMS t(t)X multilepton (JHEP12(2023)068)

Uses SM EFT to probe potential new physics impacting associated top

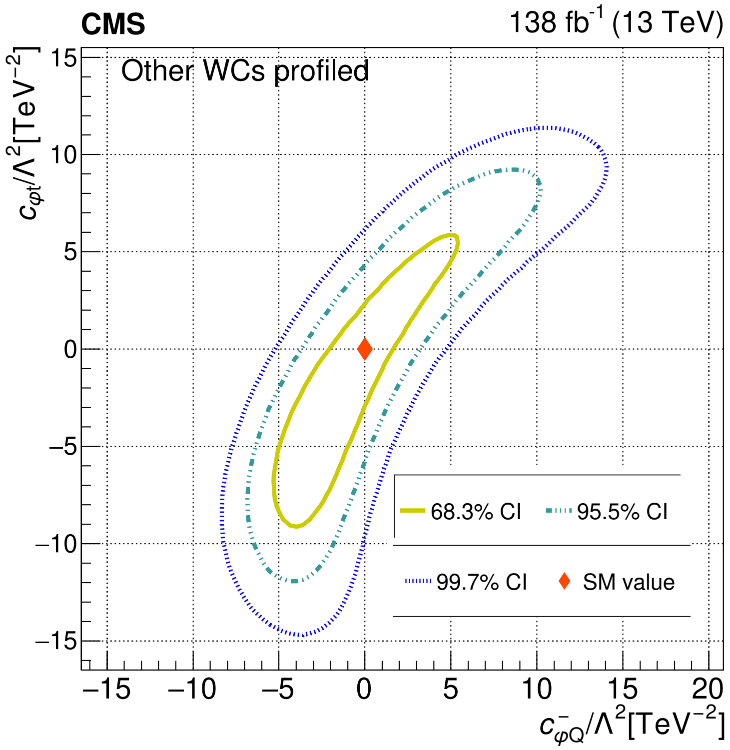
- Signal processes t(t)X: ttH, ttlν, ttll, tllq, tHq, tttt
- Targets multilepton final states (2lss or 3+ leptons) with jets and b jet(s)
- Simultaneously probe 26 dim6 Top EFT operators strongly impacting t(t)X



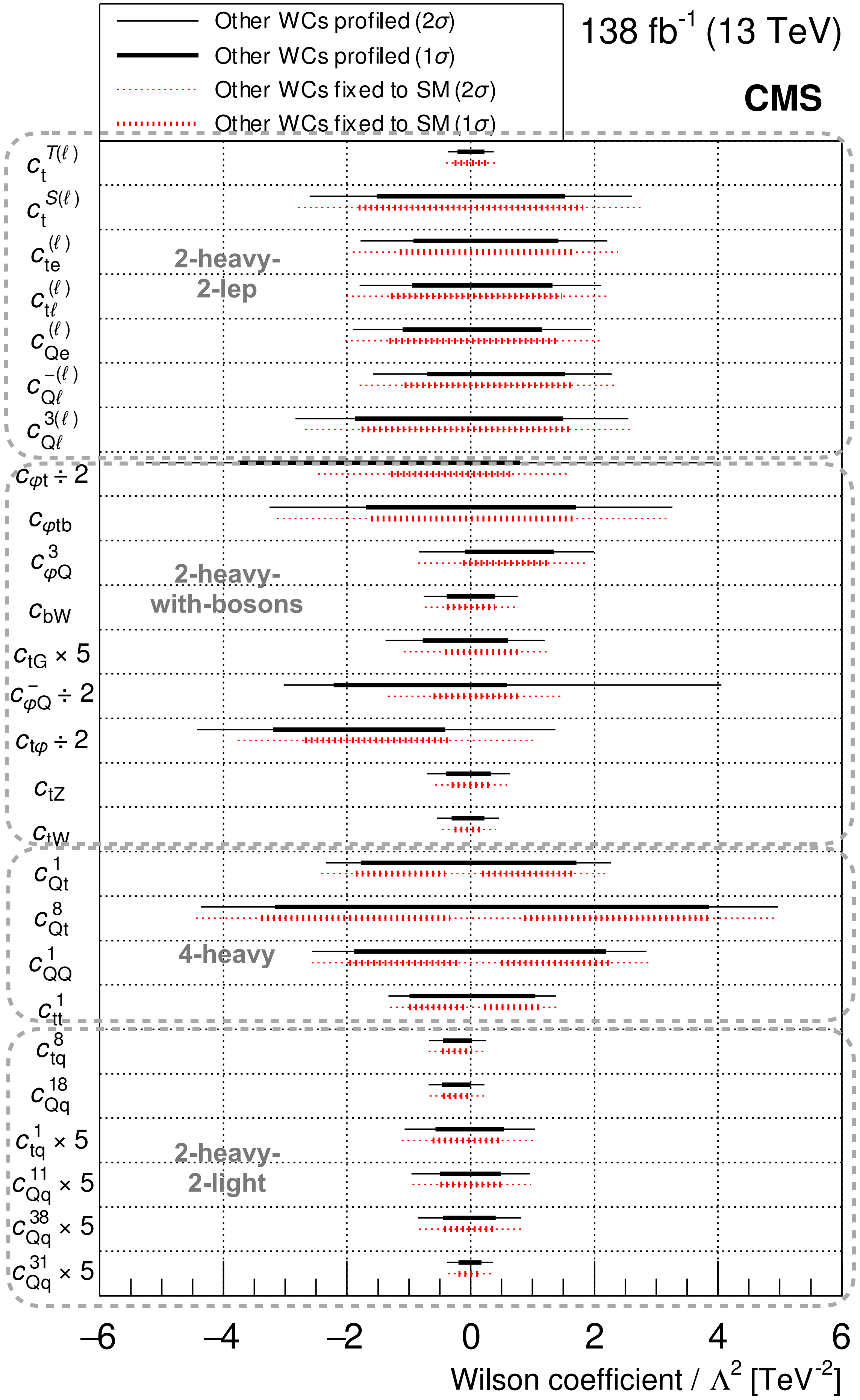
Parameterize each event weight in terms of the 26 WCs in order to to obtain the 26d quadratic parameterization for each 178 observable bins t(t)X multilepton JHEP12(2023)068

t(t)X Results

- Perform a likelihood fit where the 26 WCs are the POIs
- Extract the 1σ and 2σ confidence intervals for the WCs where other WCs are fixed to the SM (red) or **profiled simultaneously (black)**
- Results consistent with SM

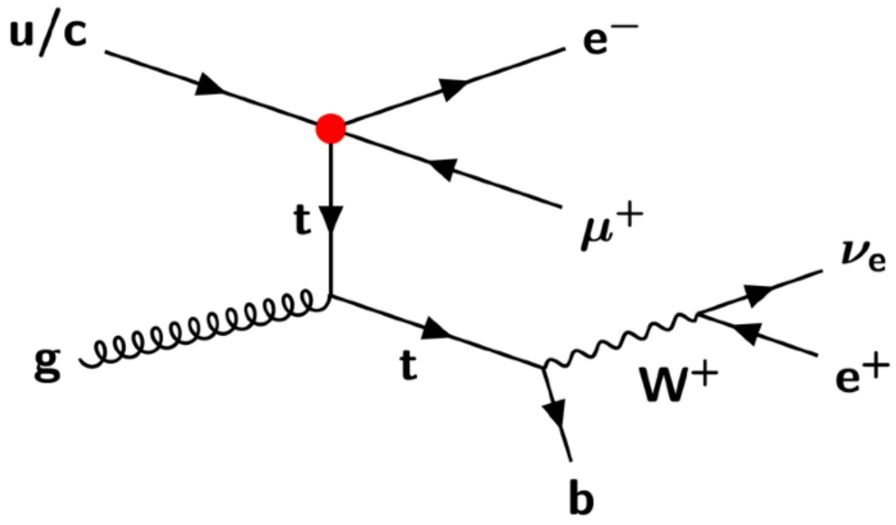


Example scan over 2 WCs to visualize correlations

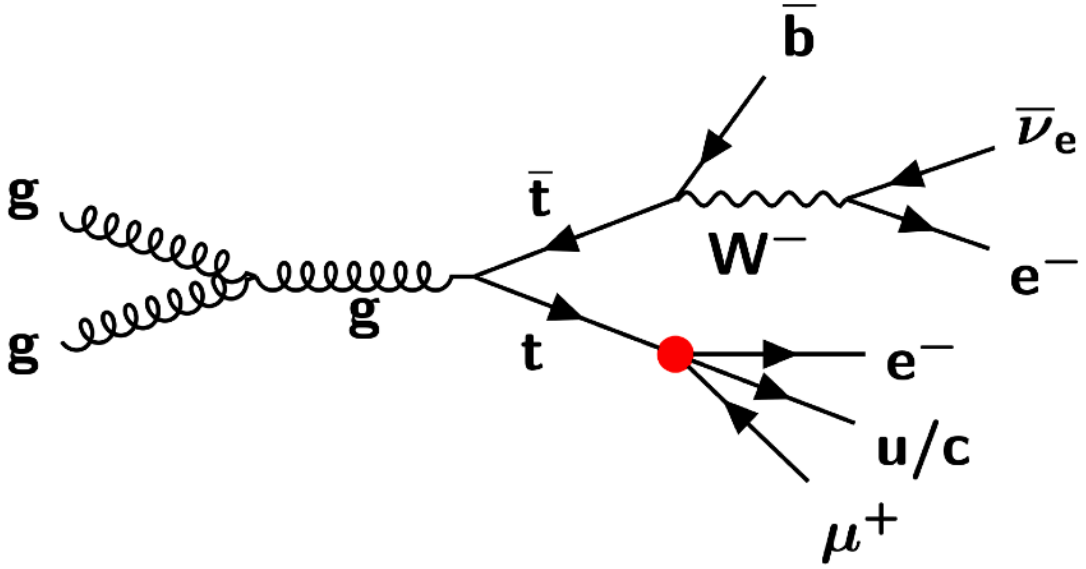


TOP-22-005: Search for CLFV in trilepton final states

- Signal regions target both production and decay of top quarks
  - Opposite-sign $e\mu$ pair + extra ℓ + jet(s) + at most 1 b jet
  - Split the SR based on mass of $e\mu$ pair (above or below 150GeV)



The m($e\mu$)>150 region is enriched in top production events



The m($e\mu$)<150 region is enriched in top decay events

Kelci Mohrman, k.mohrman@ufl.edu

See also JHEP 06 (2022) 082 for previous CMS EFT LFV results

CLFV
trilep
TOP-22-005

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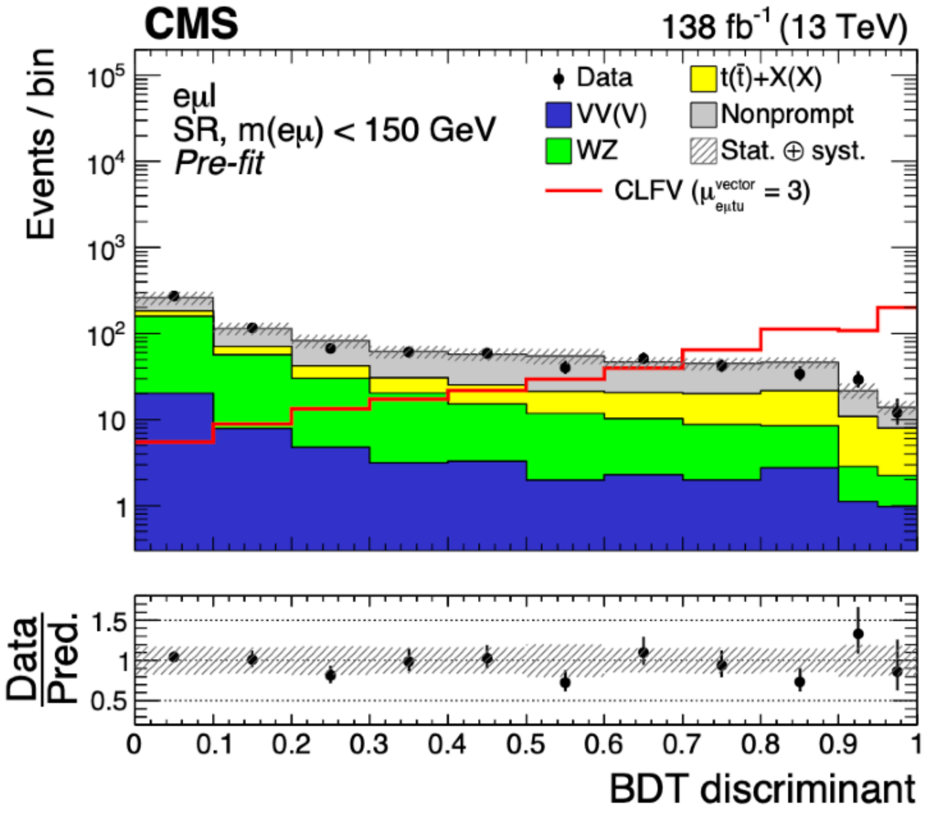
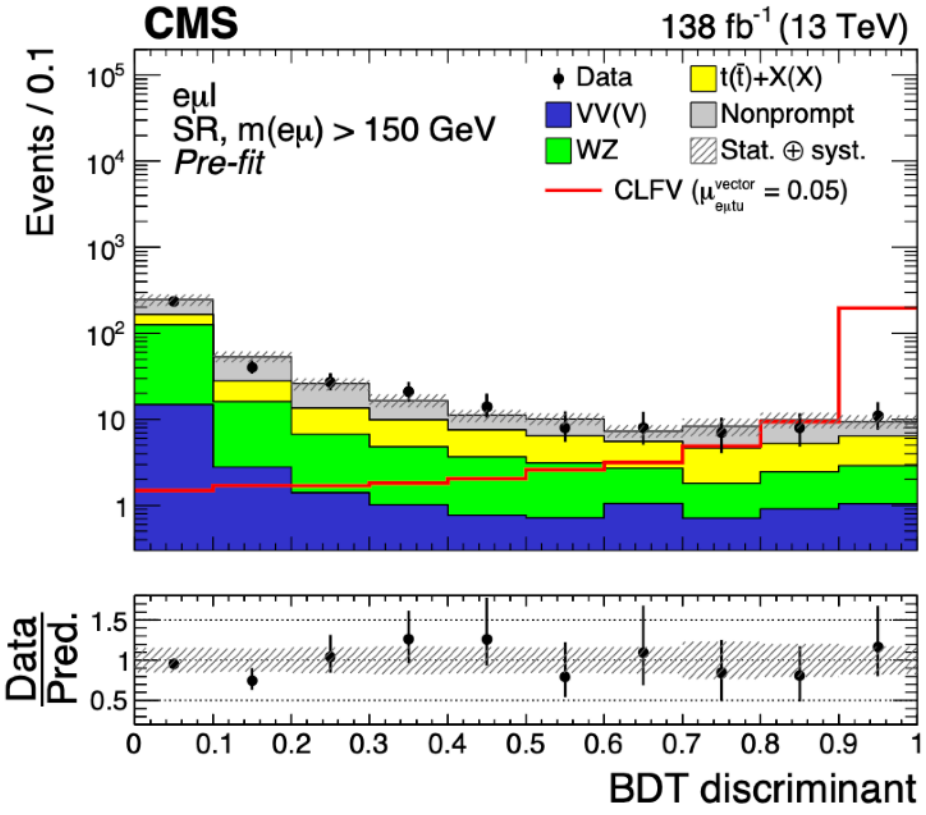
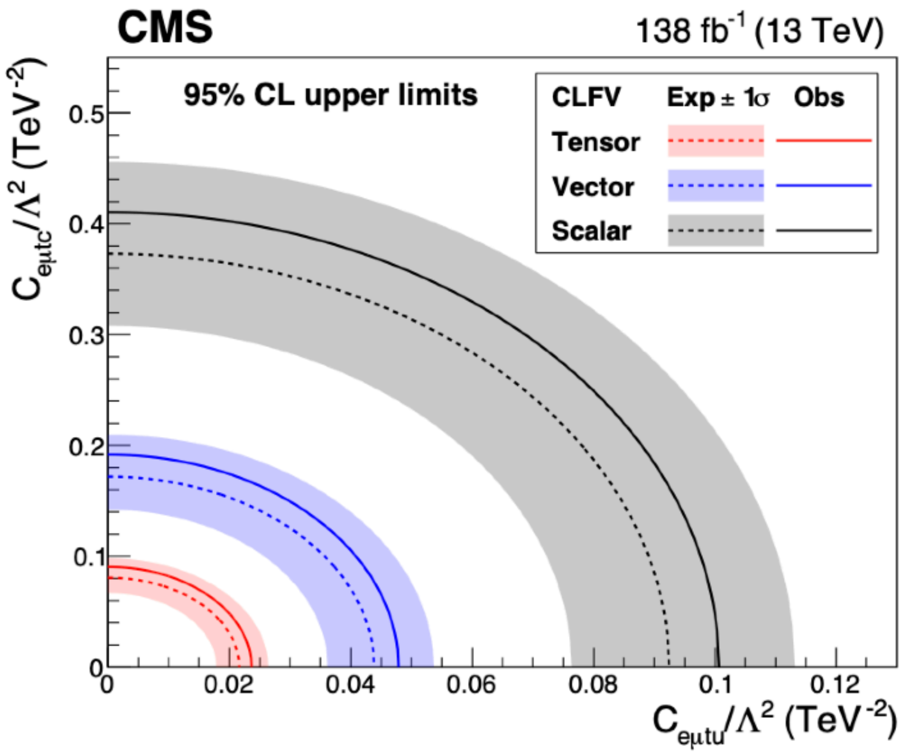




- BDTs are trained to target SR events
- A separate BDT is trained for each SR
- Results consistent with SM expectation



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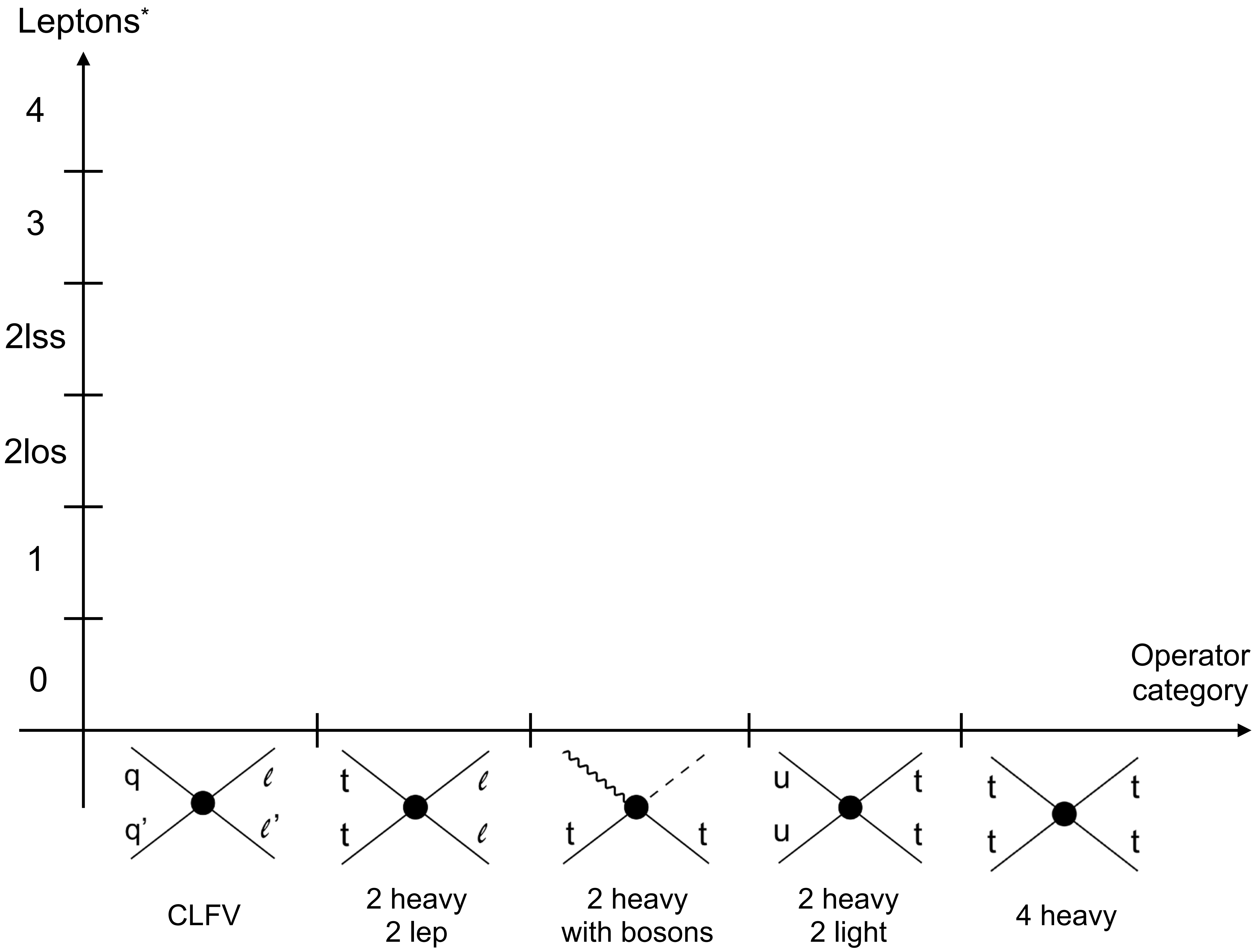
A map of some recent top EFT analyses[1]



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1 “Recent” means the past couple to few years; 2 These analyses sometimes also include ctG from the 2-heavywith-bosons category; 3 Also includes 2l OS final states
*The upper edge of the analyses’ y axis placement is based on the selection category with highest lep multiplicity, which can be inclusive
**Note: The number of WCs quoted for each category does not include the CP violating Im parts of WCs

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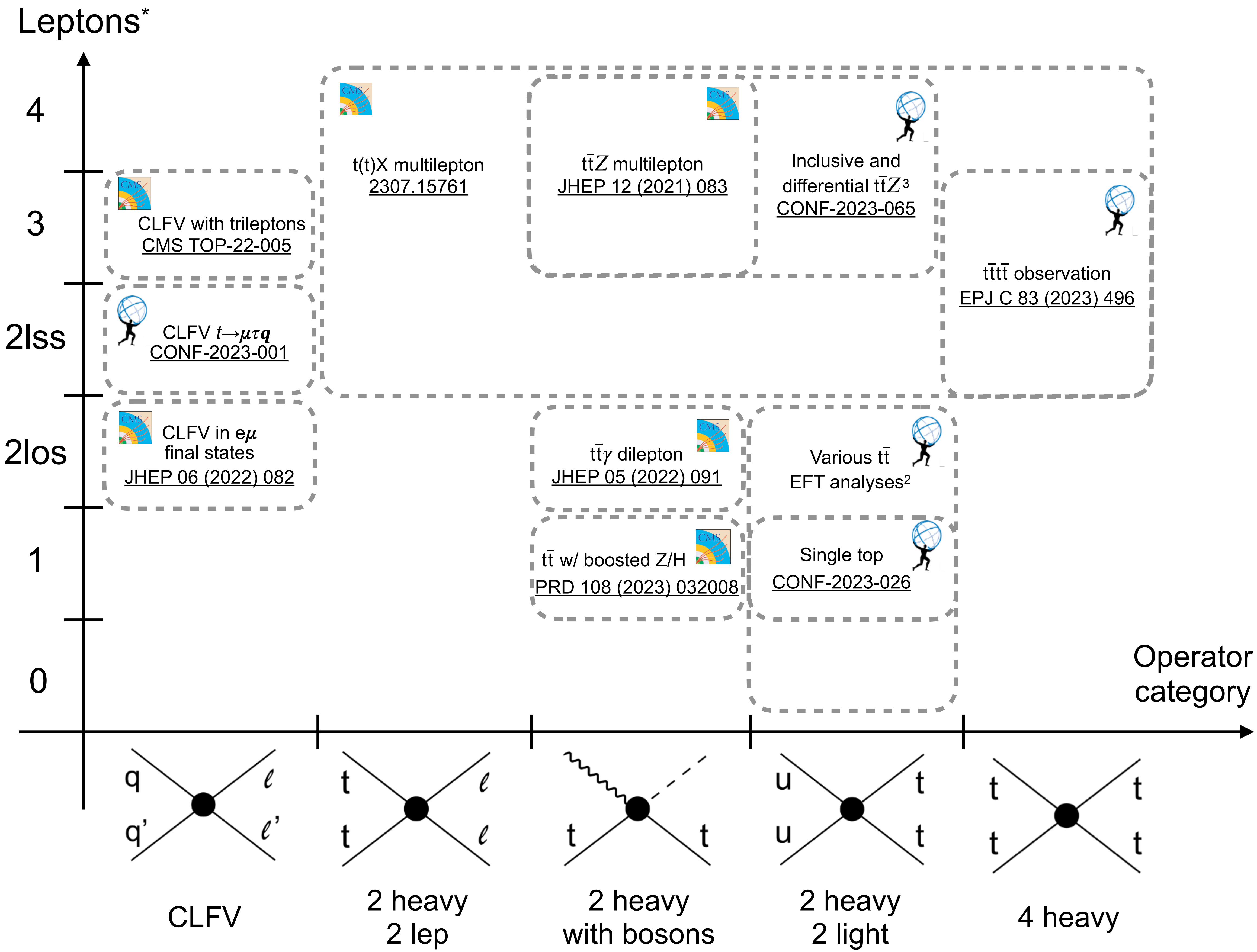

Leptons*

4

3

2lss

2los

1

0

CLFV with trileptons
CMS TOP-22-005

CLFV $t \rightarrow \mu\tau q$
CONF-2023-001

CLFV in $e\mu$ final states
JHEP 06 (2022) 082

t(t)X multilepton
2307.15761

$t\bar{t}Z$ multilepton
JHEP 12 (2021) 083

Inclusive and differential $t\bar{t}Z$[3]
CONF-2023-065

$t\bar{t}t\bar{t}$ observation
EPJ C 83 (2023) 496

$t\bar{t}\gamma$ dilepton
JHEP 05 (2022) 091

$t\bar{t}$ w/ boosted Z/H
PRD 108 (2023) 032008

Various $t\bar{t}$ EFT analyses[2]

Single top
CONF-2023-026

Operator category

CLFV

2 heavy 2 lep

2 heavy with bosons

2 heavy 2 light

4 heavy

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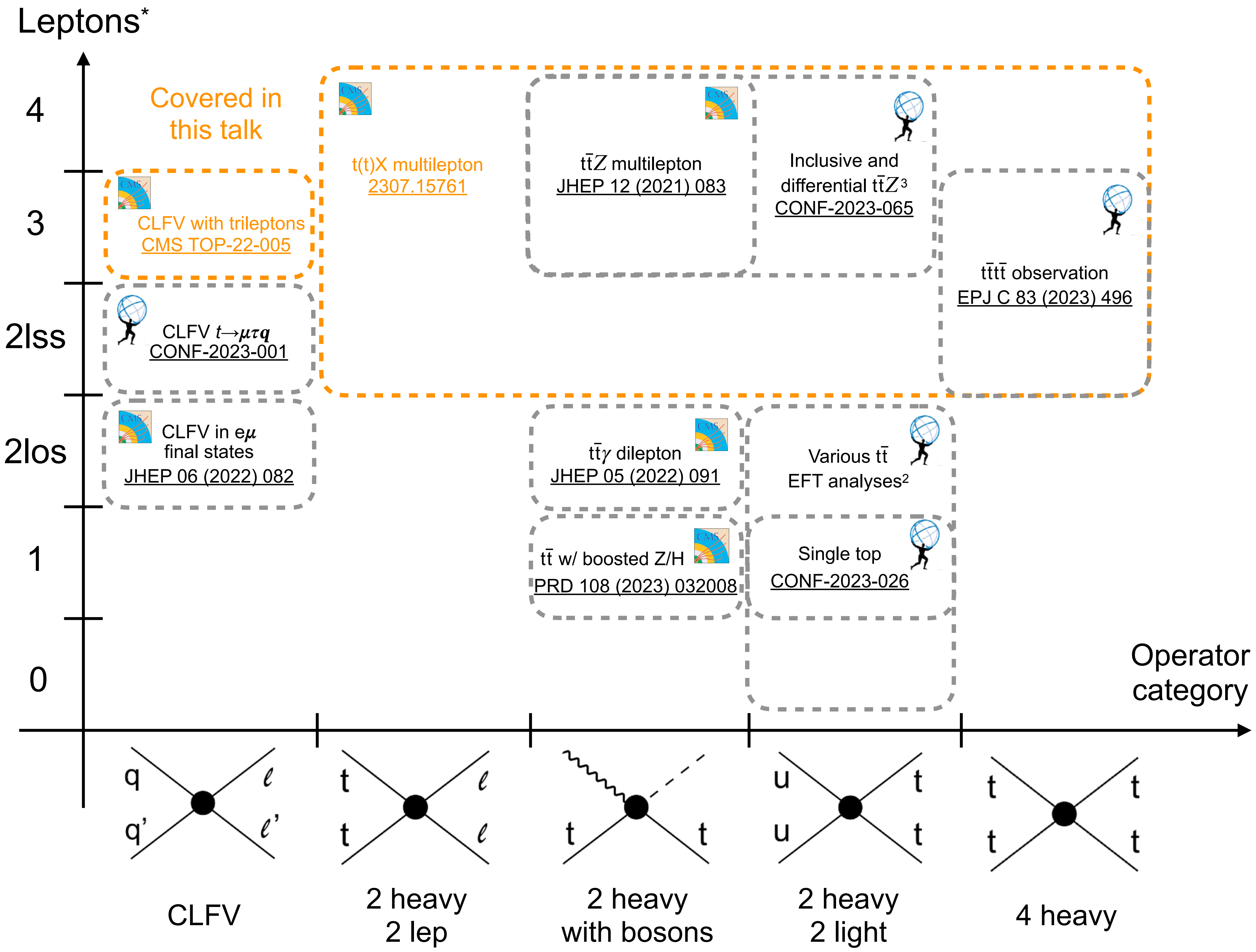

Covered in this talk

CLFV with trileptons
CMS TOP-22-005

t(t)X multilepton
2307.15761

$t\bar{t}Z$ multilepton
JHEP 12 (2021) 083

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CONF-2023-065

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CONF-2023-001

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PRD 108 (2023) 032008

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CONF-2023-026

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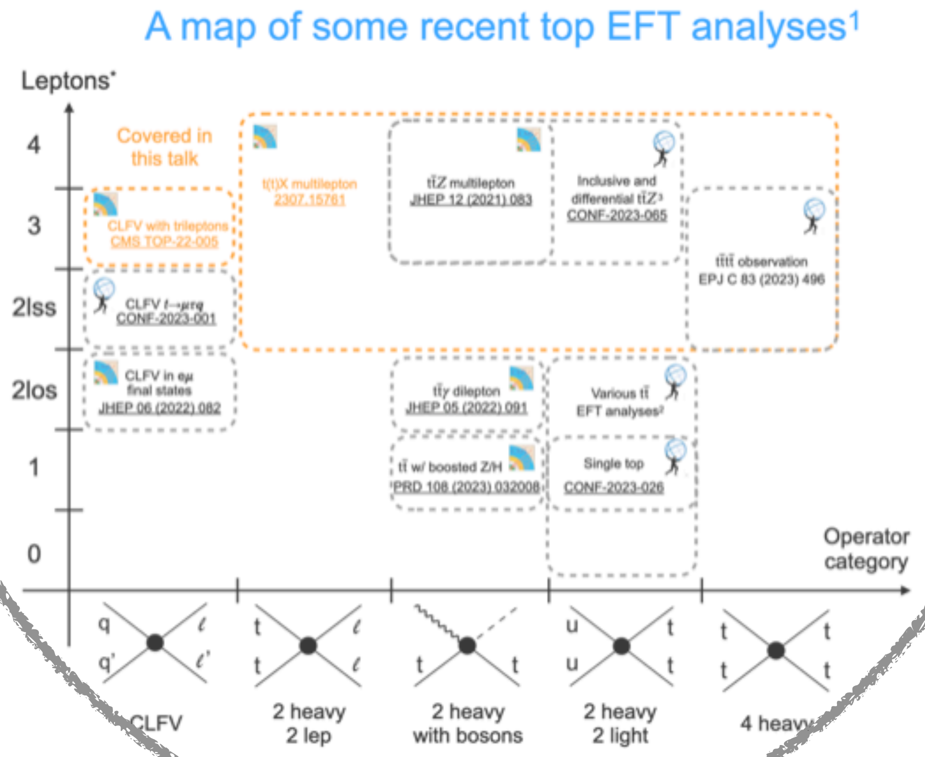
Top sector



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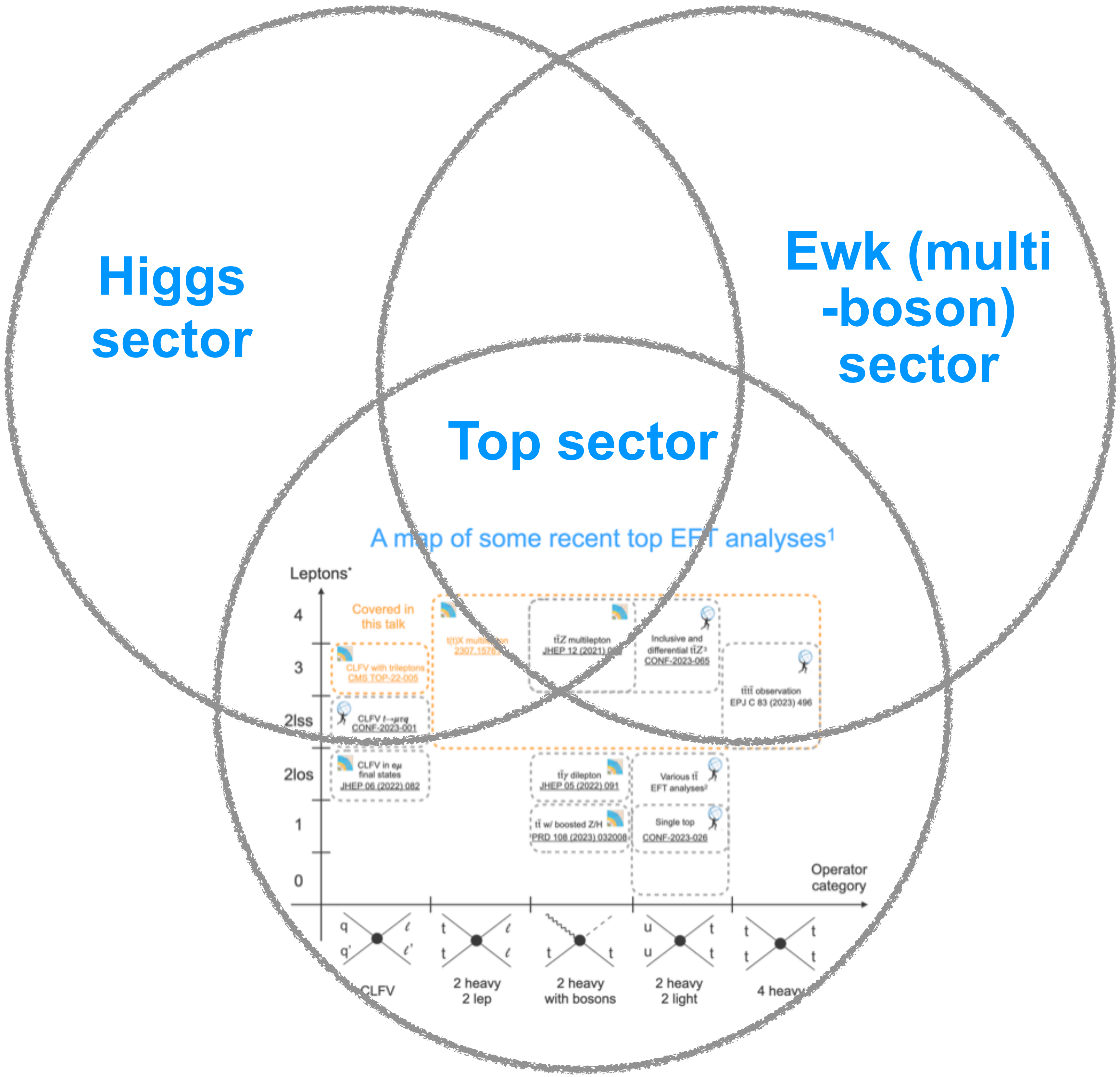

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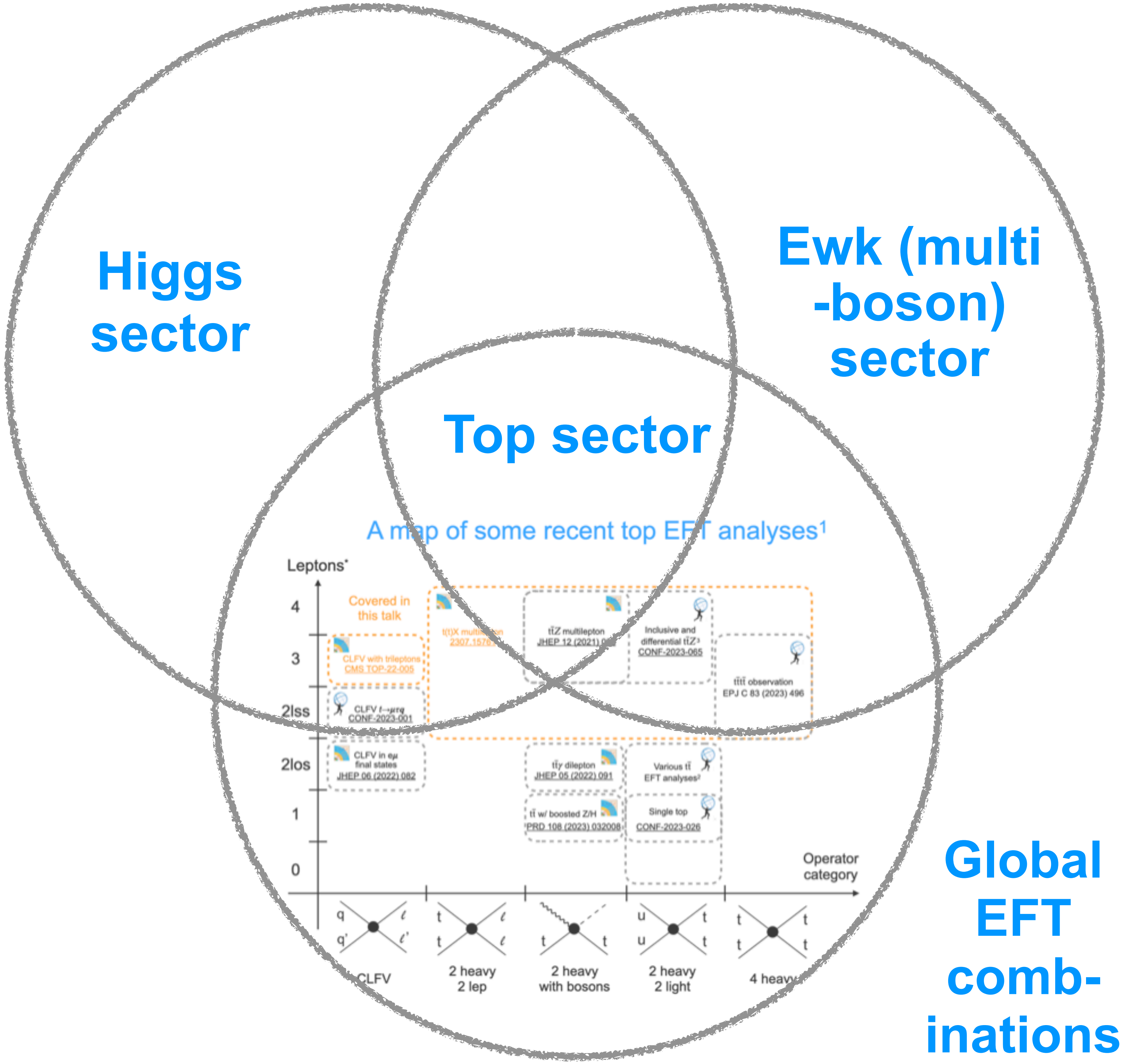


Higgs sector

Ewk (multi-boson) sector

Top sector

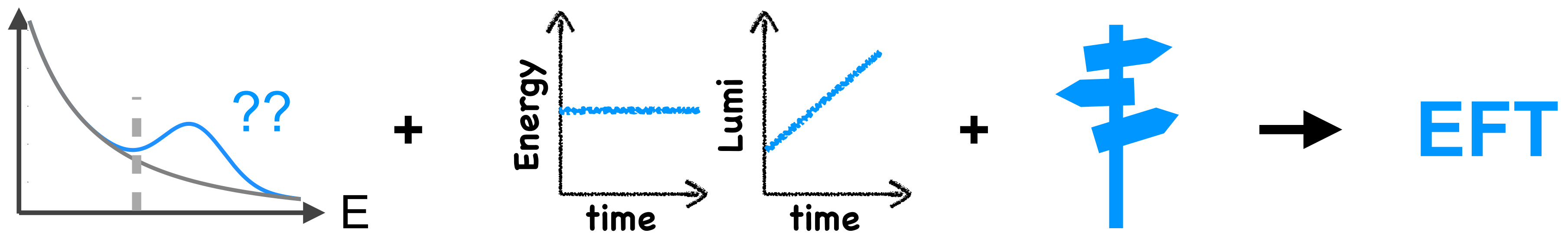
Global EFT combinations

→

Hopefully to new physics discoveries!

Summary and outlook for EFT in the top sector

- BSM is out there, but might not be light enough to make at the LHC
  => EFT aims to discover new physics via its off shell effects



- Many CMS EFT analyses in the top sector, two covered here:
  - t(t)X in multilepton final states
  - Search for CLFV in trilepton final states

- While no signal yet observed, still many new directions to improve and expanded, and combinations will be especially exciting
  - More data
  - Improvements in EFT modeling
  - Combinations within TOP
  - Combinations across sectors

} Hopefully leading to new physics discoveries!

UF UNIVERSITY of FLORIDA Kelci Mohrman, k.mohrman@ufl.edu

Backup

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^2} \boxed{c_i \, \mathcal{O}_i^{(6)}}$$

How many of these are there?

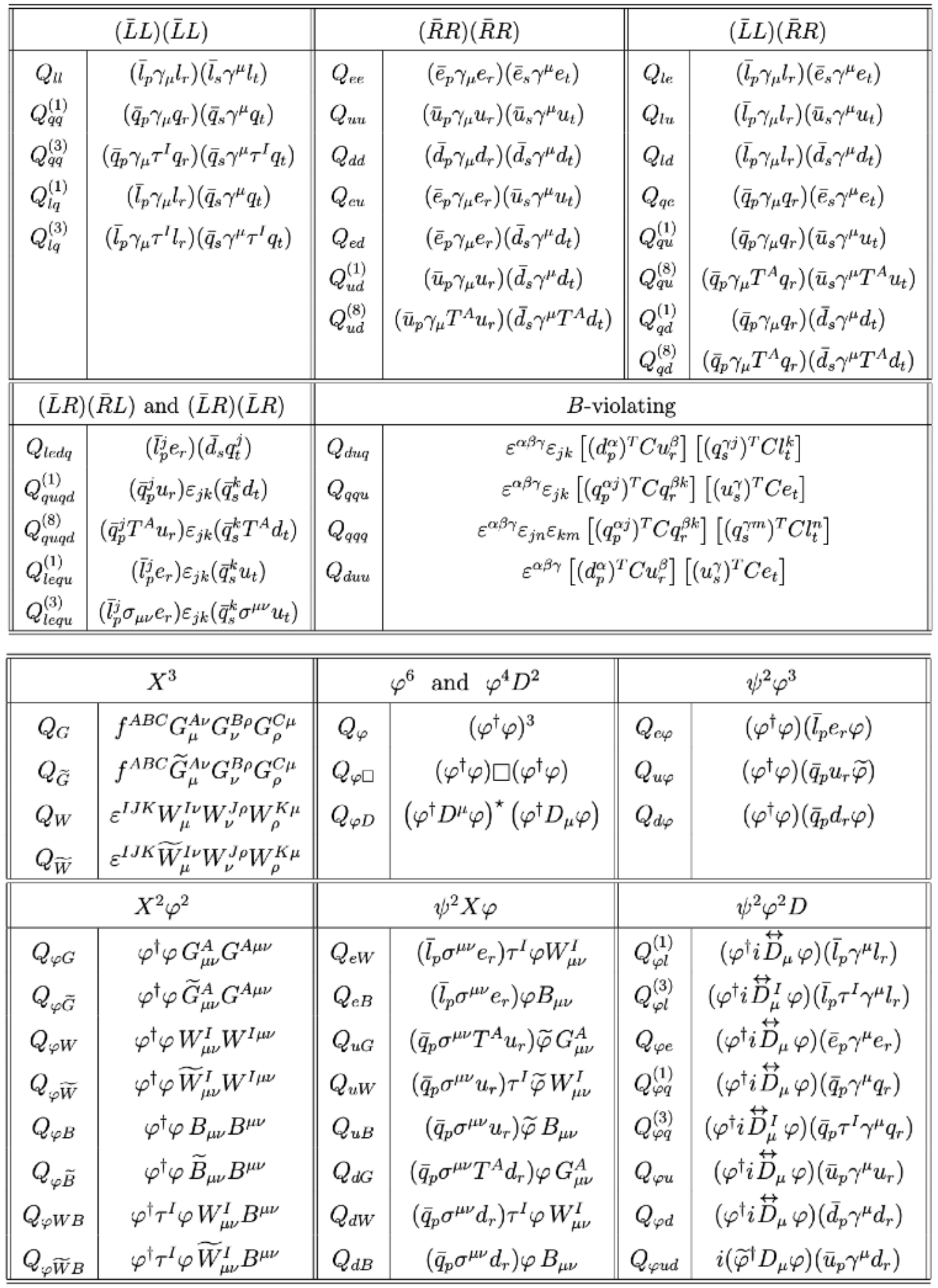
Depends on how you count...

- Flavor assumptions?
- Include or exclude B/L number violating operators?
- Count hermitian conjugates separately?
- …

Some ballpark numbers:

- With fewest assumptions, 1000s of operators
- With a flavor universality assumption, ~O(60)

The dim-6 EFT operators in the Warsaw basis (1008.4884)



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

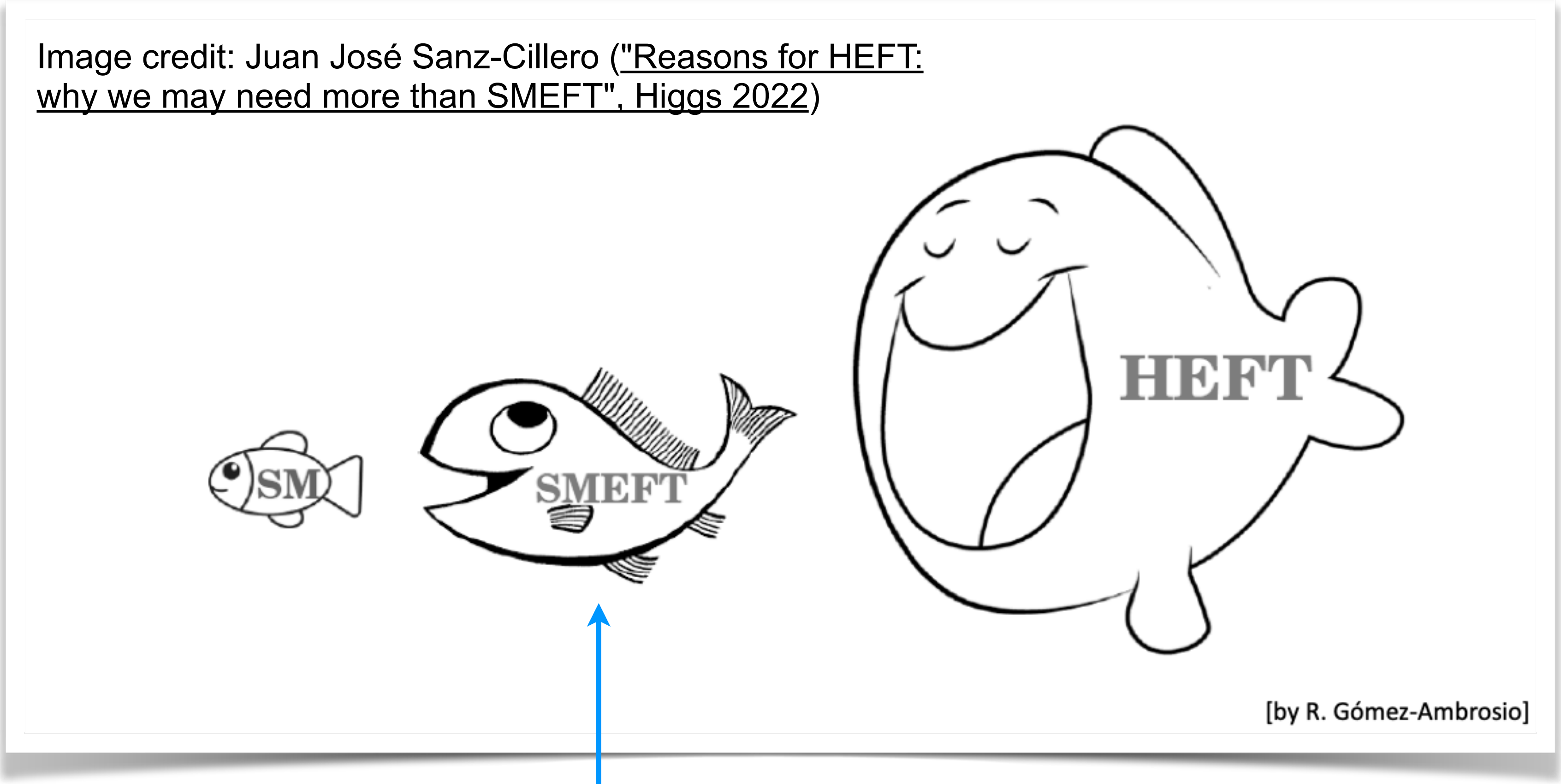
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Assumptions that go into SM EFT $\left(\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}\right)$

- TOP mainly uses SM EFT, i.e. assumes SM is correct and complete description of everything we can produce on shell
- Other EFTs (e.g. HEFT) can be more general

Image credit: Juan José Sanz-Cillero ("Reasons for HEFT: why we may need more than SMEFT", Higgs 2022)



[by R. Gómez-Ambrosio]

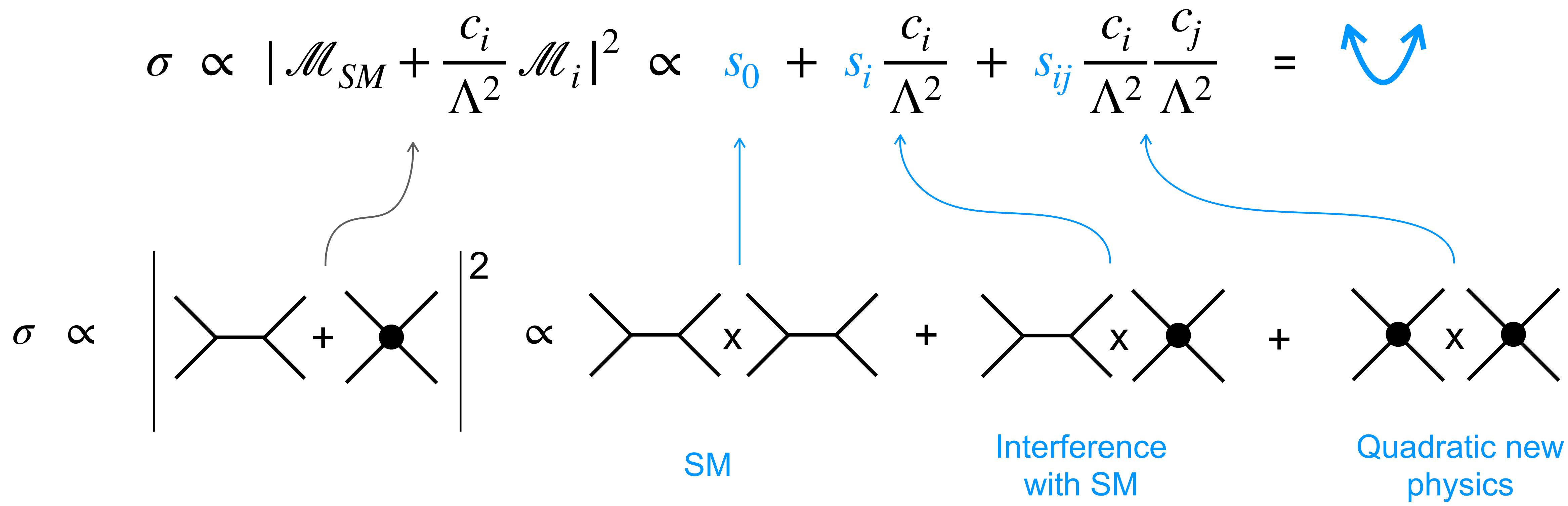
So for this talk, when we say "EFT" we generally mean "SM EFT"

SMEFT is a special case of HEFT in which the resonance at 125GeV is the SM Higgs*

*I.e., SMEFT assumes the SM Higgs complex doublet

How do observables depend on EFT? Let’s start with σ

If the EFT is modeled linearly in amplitude, the cross section is an *n*-quadratic in terms of the WCs (where *n* is number of WCs)



$$\sigma \propto |\mathscr{M}_{SM} + \frac{c_i}{\Lambda^2}\mathscr{M}_i|^2 \propto s_0 + s_i\frac{c_i}{\Lambda^2} + s_{ij}\frac{c_i}{\Lambda^2}\frac{c_j}{\Lambda^2} =$$

SM

Interference with SM

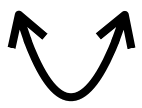
Quadratic new physics

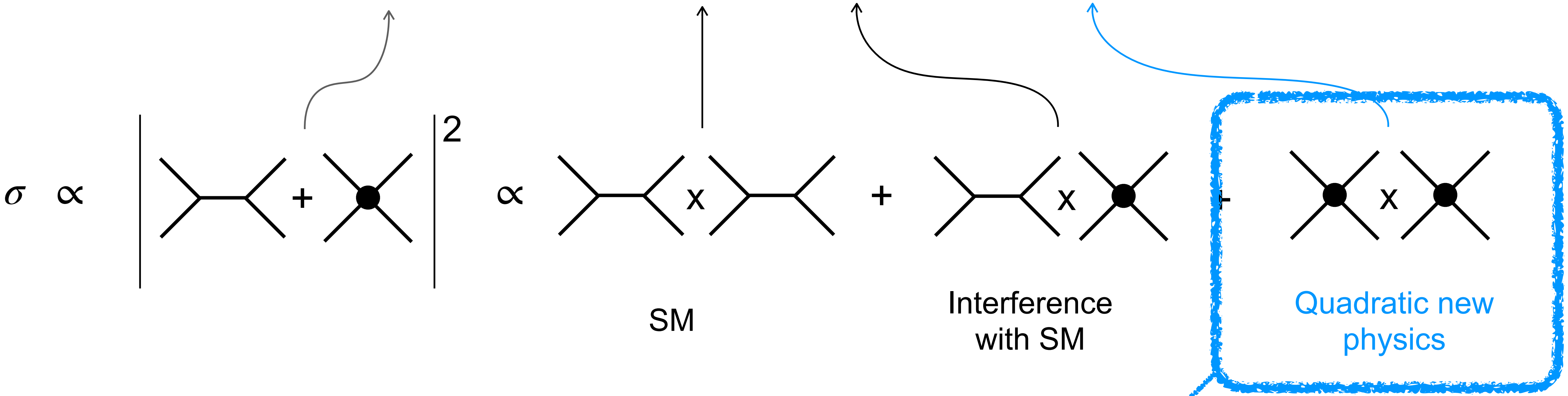
This holds for any cross section, inclusive or differential

How do observables depend on EFT? Let's start with σ

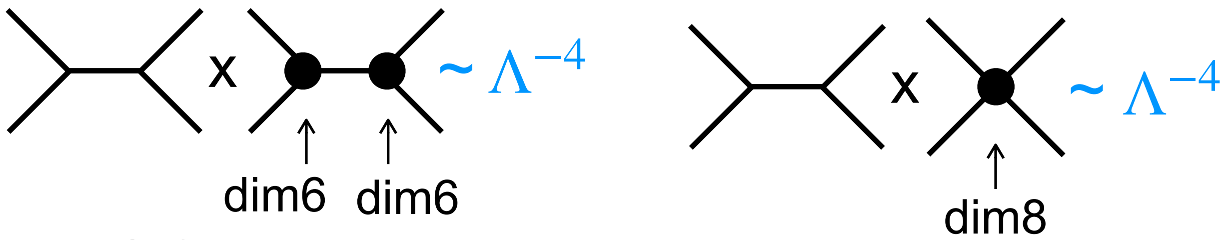
If the EFT is modeled linearly in amplitude, the cross section is an *n*-quadratic in terms of the WCs (where *n* is number of WCs)

$$\sigma \propto \left|\mathscr{M}_{SM} + \frac{c_i}{\Lambda^2}\mathscr{M}_i\right|^2 \propto s_0 + s_i\frac{c_i}{\Lambda^2} + s_{ij}\frac{c_i}{\Lambda^2}\frac{c_j}{\Lambda^2} =$$





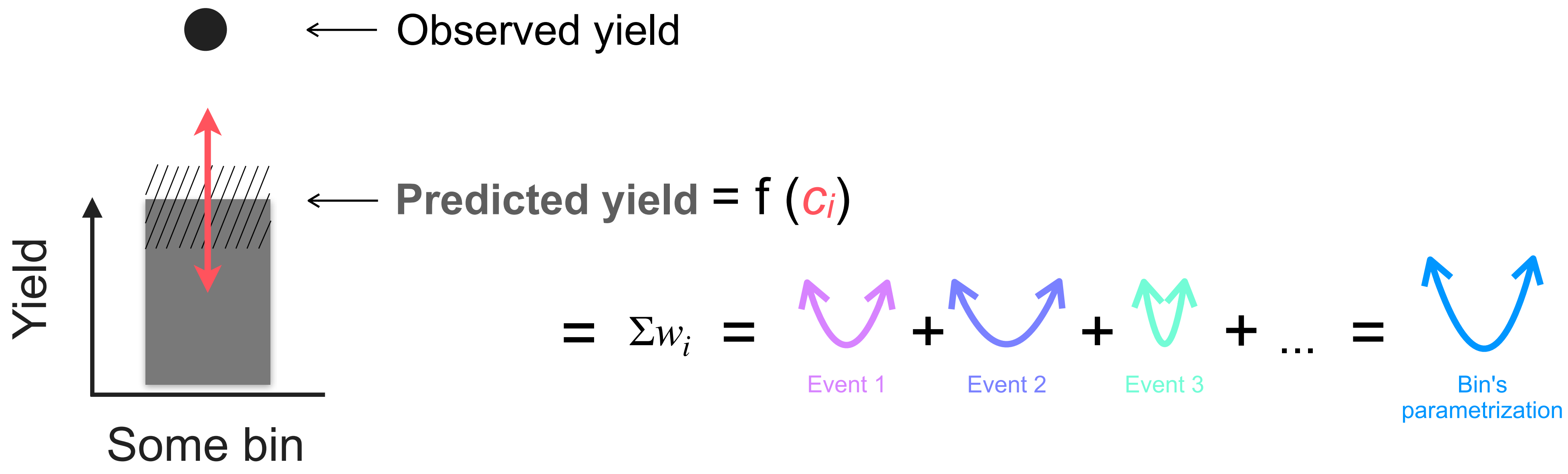
A complication: Other contributions at same Λ^{-4} order as quad piece, challenging to include



Kelci Mohrman, k.mohrman@ufl.edu

How to compare prediction to observation

1. Write the **prediction** in the observable bins as a function of WCs
   → Cross sections scale quadratically with WCs
   → Yield in any observable bin scales as n-dimensional quadratic in terms of the n WCs
2. Compare that to the observation to extract limits for the WCs



⟵ Observed yield

⟵ **Predicted yield** = f (c_i)

$= \Sigma w_i =$ Event 1 + Event 2 + Event 3 + … = Bin's parametrization

Advantageous vs more challenging aspects of the direct detector-level approach

Challenging

Analysis preservation/longevity

Reinterpretations

Need to produce detector-level EFT simulations

These challenging aspects for direct approaches are generally advantages of the indirect approach

Advantageous

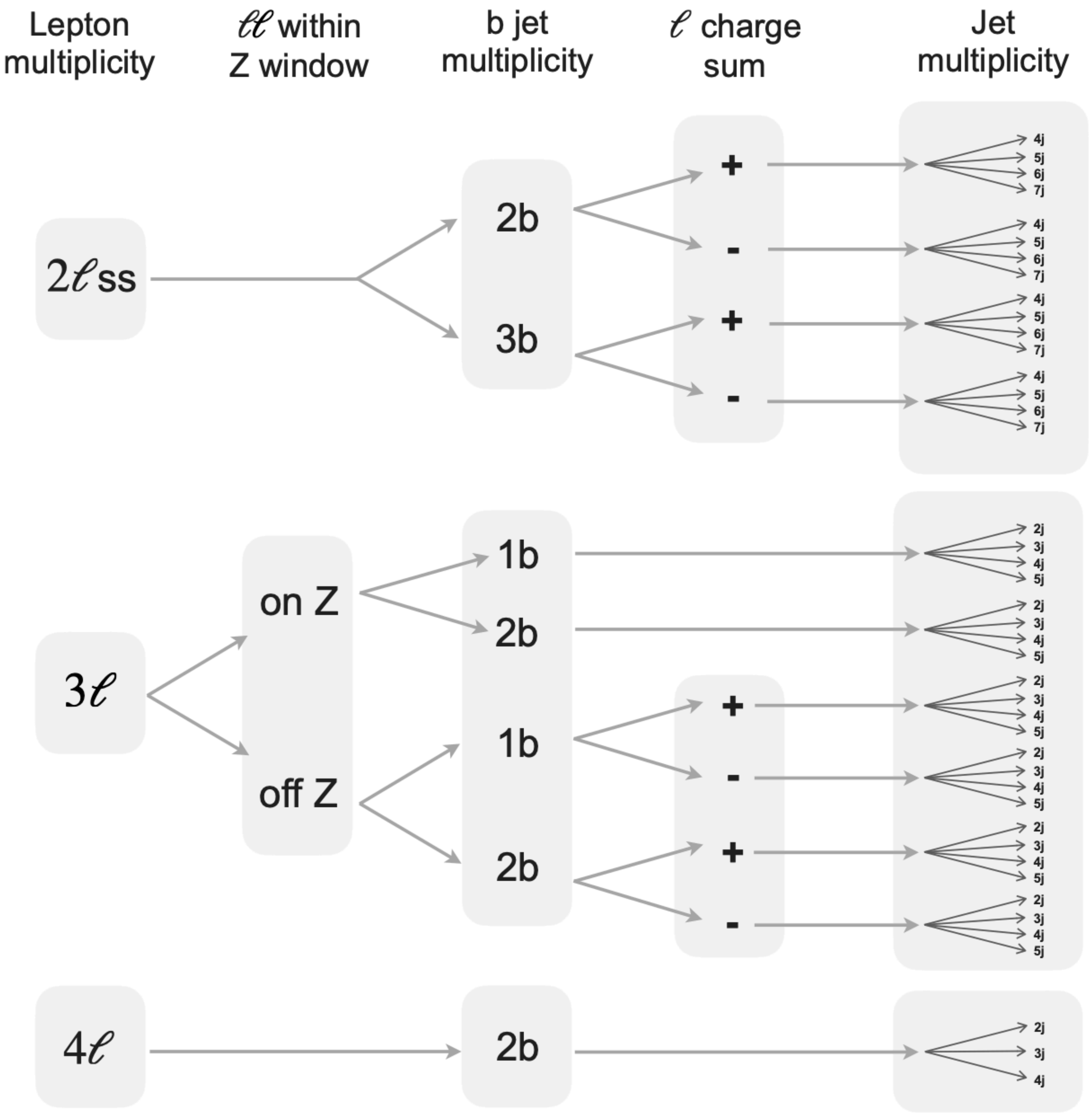
More information available → potential for more sensitivity

Can handle final states with complicated admixtures of processes all affected differently by EFT

Account for all relevant correlations

UF UNIVERSITY of FLORIDA Kelci Mohrman, k.mohrman@ufl.edu

TOP-22-006 event selection summary



4 to 7+ jets

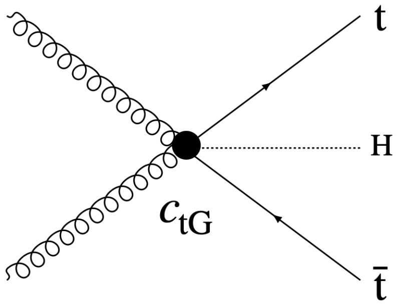
2 to 5+ jets

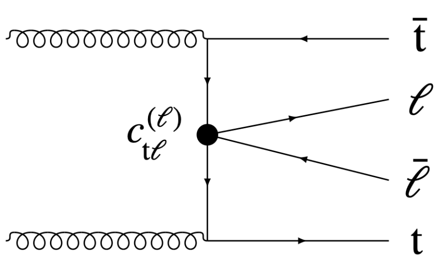
2 to 4+ jets

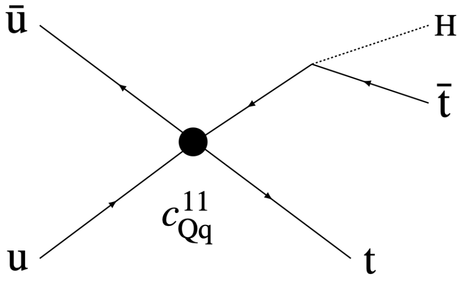
(Note: All highest multiplicity categories (for lep and jets) are inclusive)

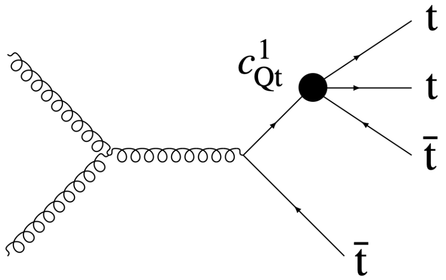
TOP-22-006 details

Operator category	Wilson coefficients
Two-heavy (2hqV)	$c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$
Two-heavy-two-lepton (2hq2ℓ)	$c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$
Two-heavy-two-light (2hq2lq)	$c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$
Four-heavy (4hq)	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$



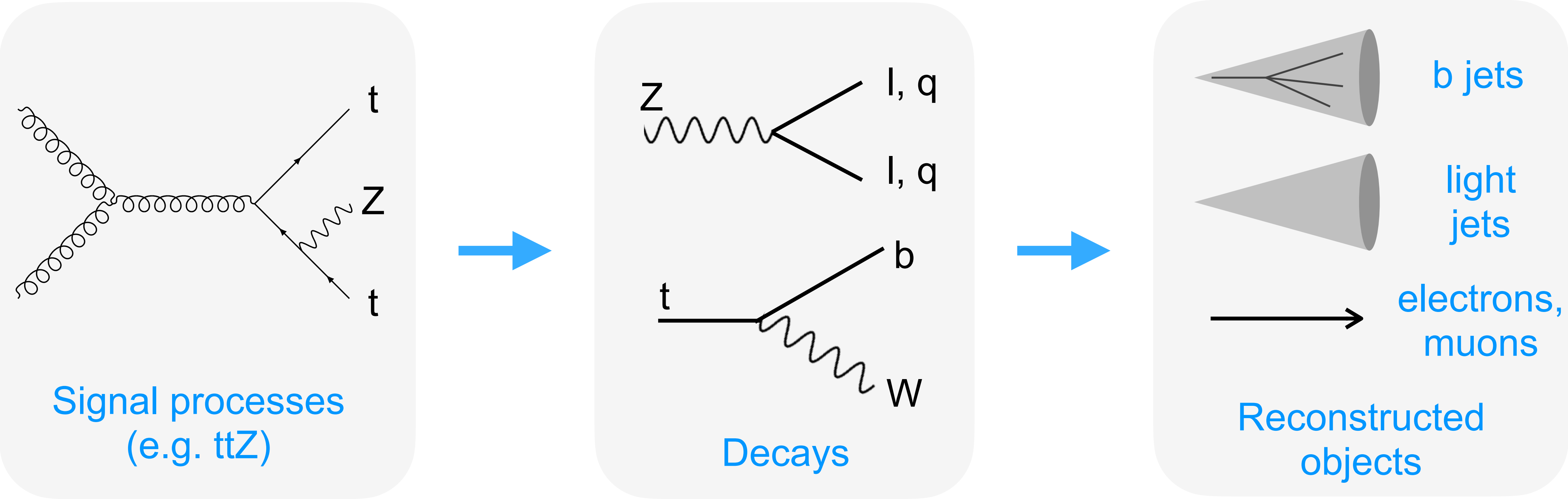






Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Kinematical variable
2ℓss 2b	2	No requirement	2	>0, <0	4, 5, 6, ≥7	$p_{T}(\ell j)_{max}$
2ℓss 3b	2	No requirement	≥3	>0, <0	4, 5, 6, ≥7	$p_{T}(\ell j)_{max}$
3ℓ off-Z 1b	3	$\lvert m_{Z} - m_{\ell\ell}\rvert > 10\,\text{GeV}$	1	>0, <0	2, 3, 4, ≥5	$p_{T}(\ell j)_{max}$
3ℓ off-Z 2b	3	$\lvert m_{Z} - m_{\ell\ell}\rvert > 10\,\text{GeV}$	≥2	>0, <0	2, 3, 4, ≥5	$p_{T}(\ell j)_{max}$
3ℓ on-Z 1b	3	$\lvert m_{Z} - m_{\ell\ell}\rvert < 10\,\text{GeV}$	1	No requirement	2, 3, 4, ≥5	$p_{T}(Z)$
3ℓ on-Z 2b	3	$\lvert m_{Z} - m_{\ell\ell}\rvert < 10\,\text{GeV}$	≥2	No requirement	2, 3, 4, ≥5	$p_{T}(Z)$ or $p_{T}(\ell j)_{max}$
4ℓ	≥4	No requirement	≥2	No requirement	2, 3, ≥4	$p_{T}(\ell j)_{max}$

TOP-22-006 experimental signatures

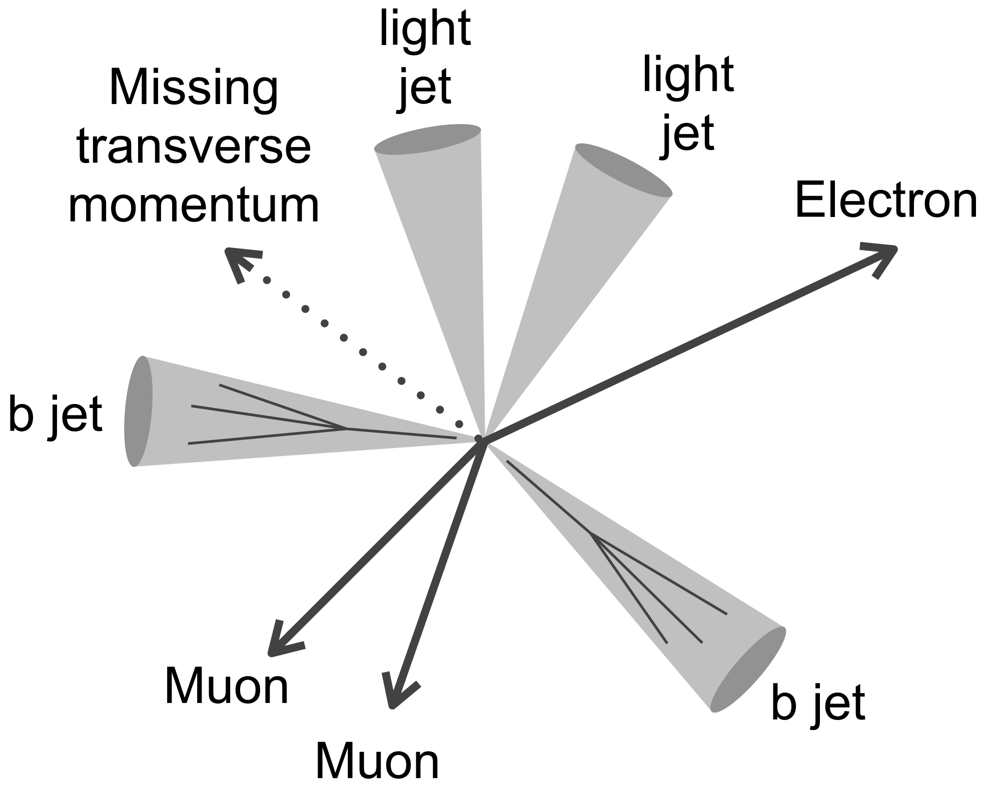


Signal processes (e.g. ttZ)

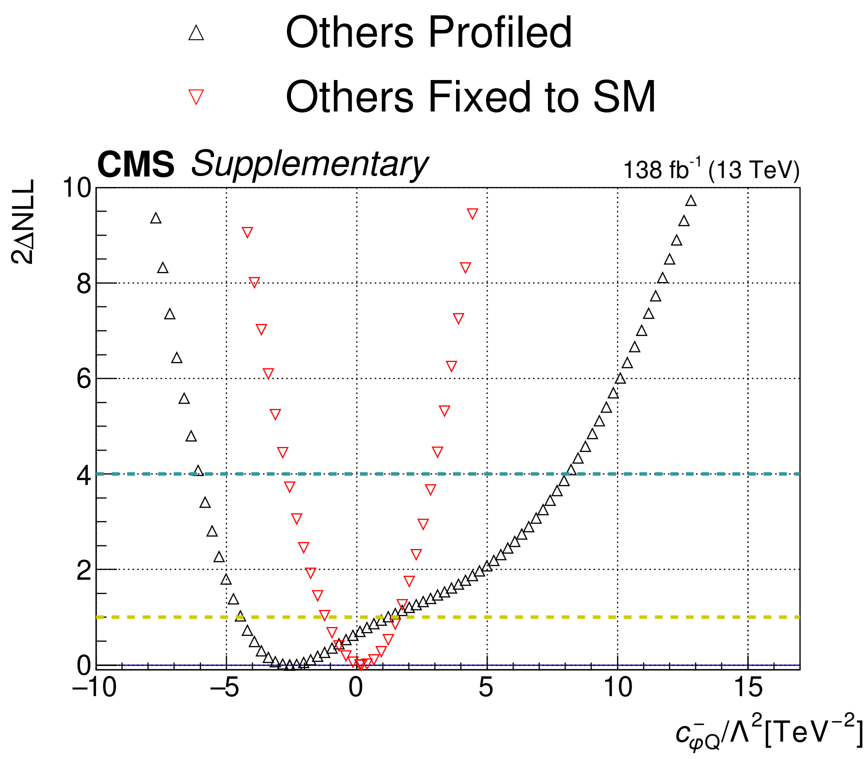
Decays

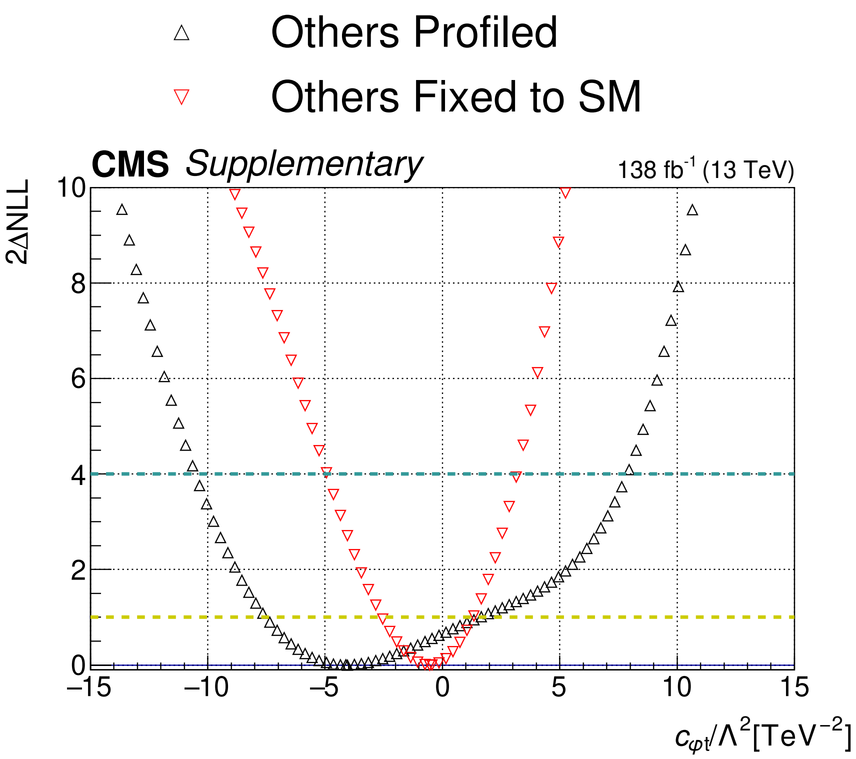
Reconstructed objects

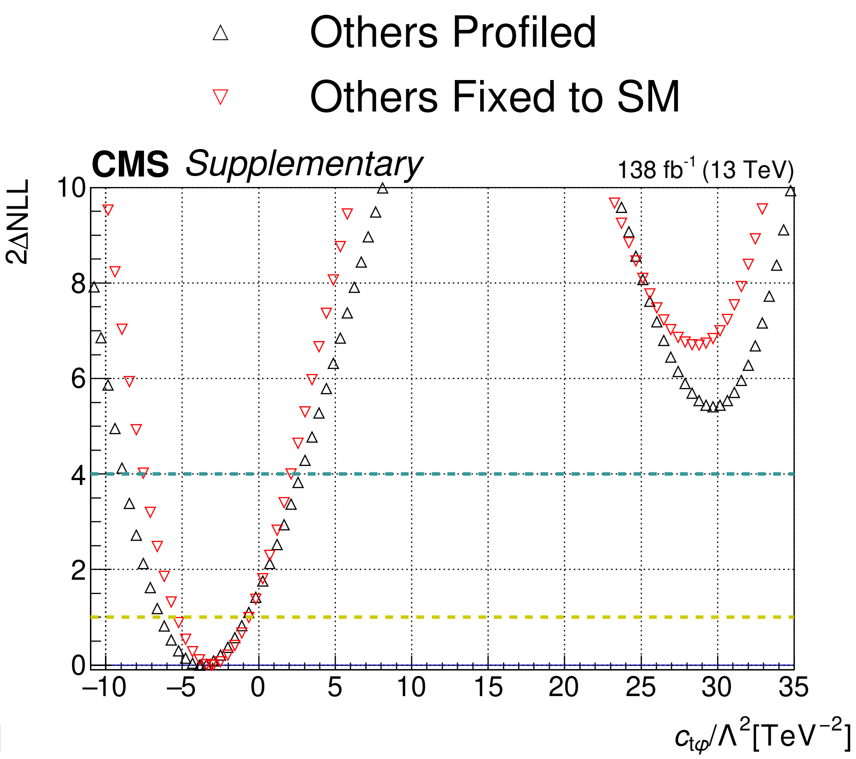
- We're interested in leptonic decays of associated top processes
- These lead to signatures of leptons, jets, and b jets

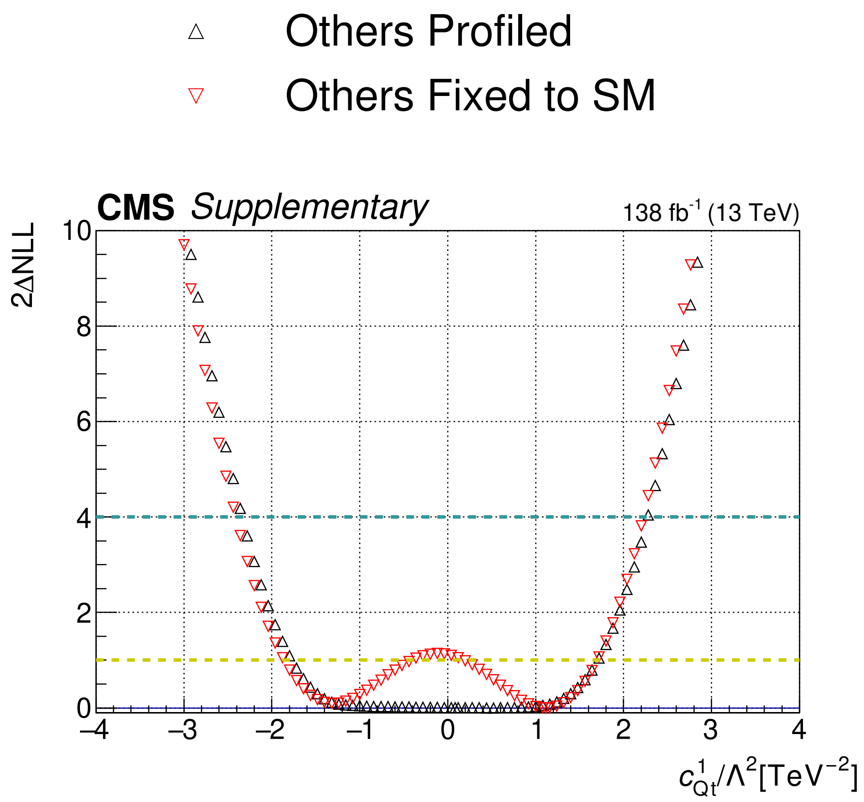


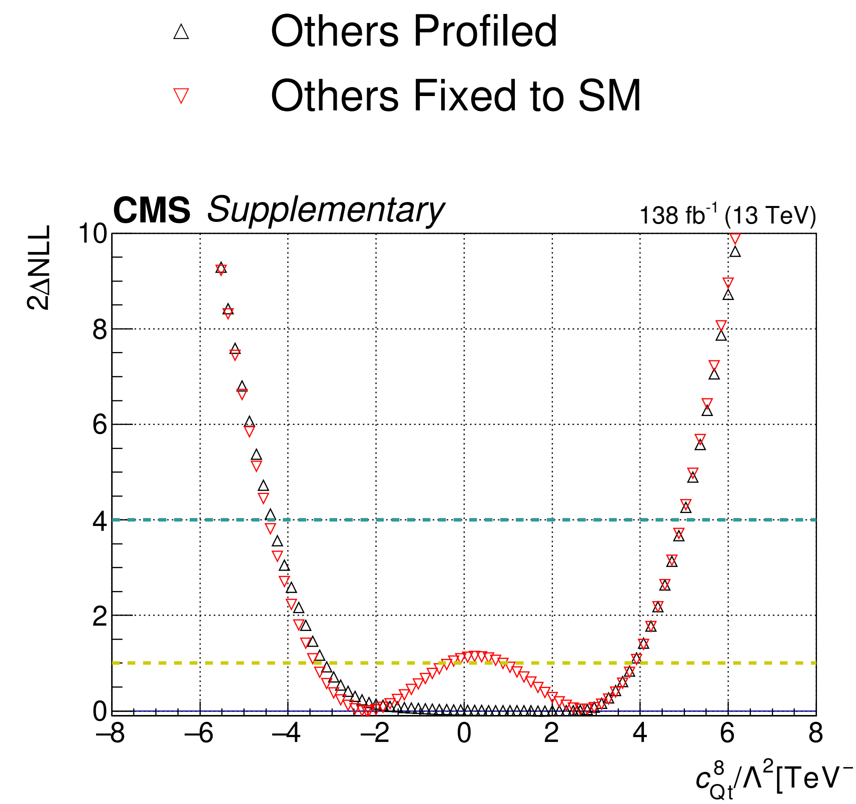
Example one-dimensional scans TOP-22-006

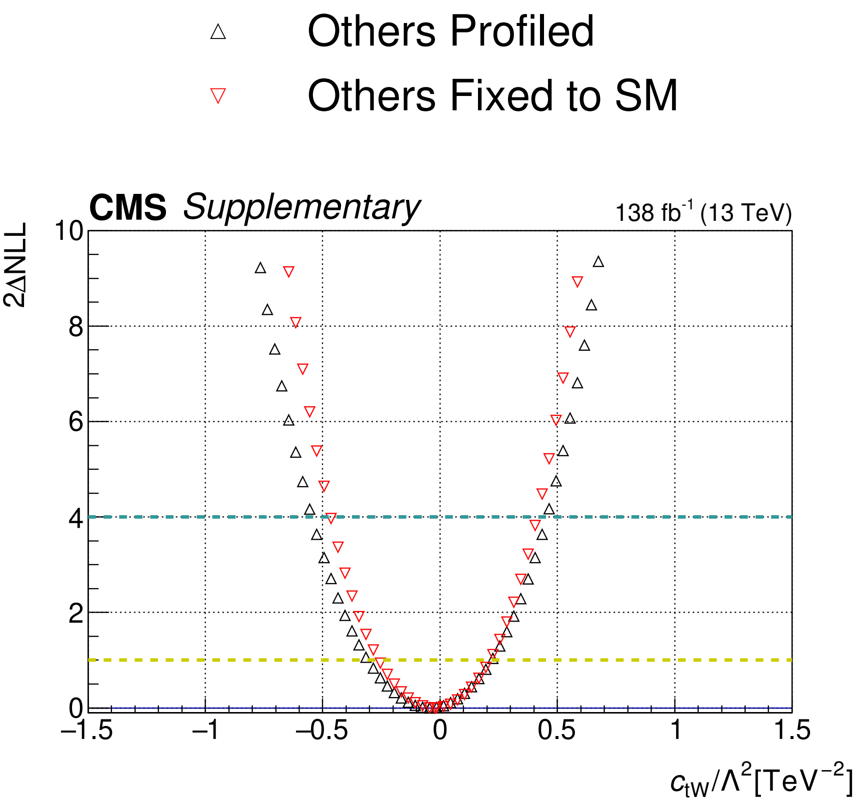






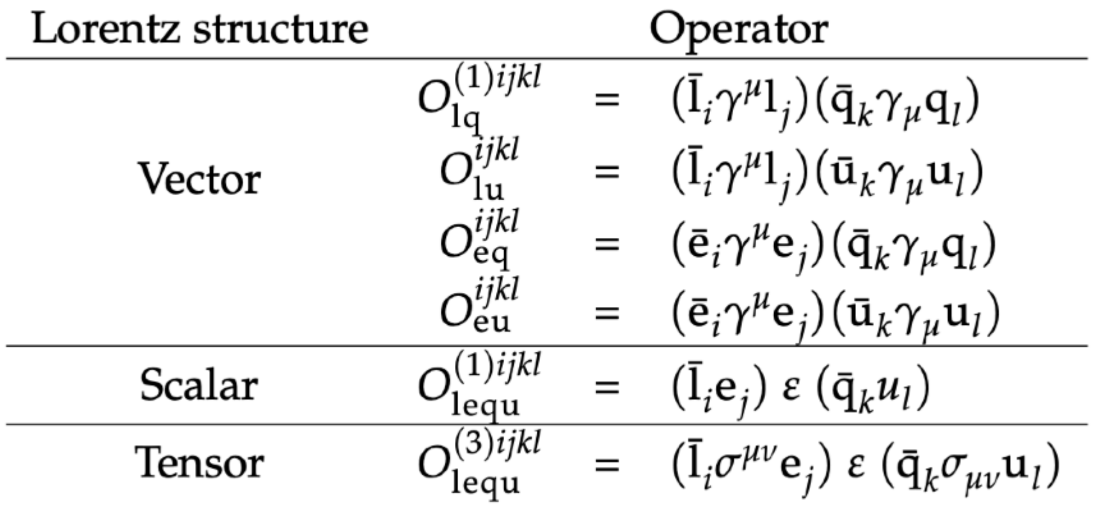






Details of TOP 22-005

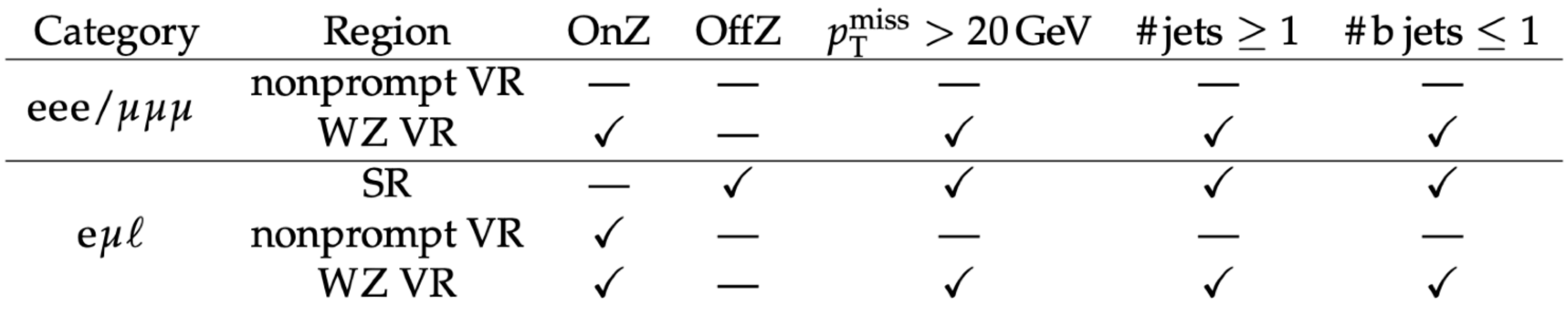
- Analysis signature:
    - Opposite charge e-mu pair
    - Third lepton coming from leptonic top decay
    - Require jet(s), at most one of which is b jet



Lorentz structure	Operator
Vector	$O_{\mathrm{lq}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k \gamma_\mu \mathrm{q}_l)$
	$O_{\mathrm{lu}}^{ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k \gamma_\mu \mathrm{u}_l)$
	$O_{\mathrm{eq}}^{ijkl} = (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k \gamma_\mu \mathrm{q}_l)$
	$O_{\mathrm{eu}}^{ijkl} = (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k \gamma_\mu \mathrm{u}_l)$
Scalar	$O_{\mathrm{lequ}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k u_l)$
Tensor	$O_{\mathrm{lequ}}^{(3)ijkl} = (\bar{\mathrm{l}}_i \sigma^{\mu\nu} \mathrm{e}_j)\ \varepsilon\ (\bar{\mathrm{q}}_k \sigma_{\mu\nu} \mathrm{u}_l)$

- Signal samples parameterized via dim6 EFT WCs, no interference with SM, (WCs are probed individually, i.e. any interference among WCs is ignored)
- Backgrounds: Prompt (e.g. WZ), nonprompt (fakes from ttbar or DY)

Table 3: Summary of the selection criteria used to define different event regions.



Category	Region	OnZ	OffZ	$p_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$	#jets ≥ 1	#b jets ≤ 1
eee/$\mu\mu\mu$	nonprompt VR	—	—	—	—	—
	WZ VR	✓	—	✓	✓	✓
$e\mu\ell$	SR	—	✓	✓	✓	✓
	nonprompt VR	✓	—	—	—	—
	WZ VR	✓	—	✓	✓	✓

Kelci Mohrman, k.mohrman@ufl.edu

Details of TOP 22-005

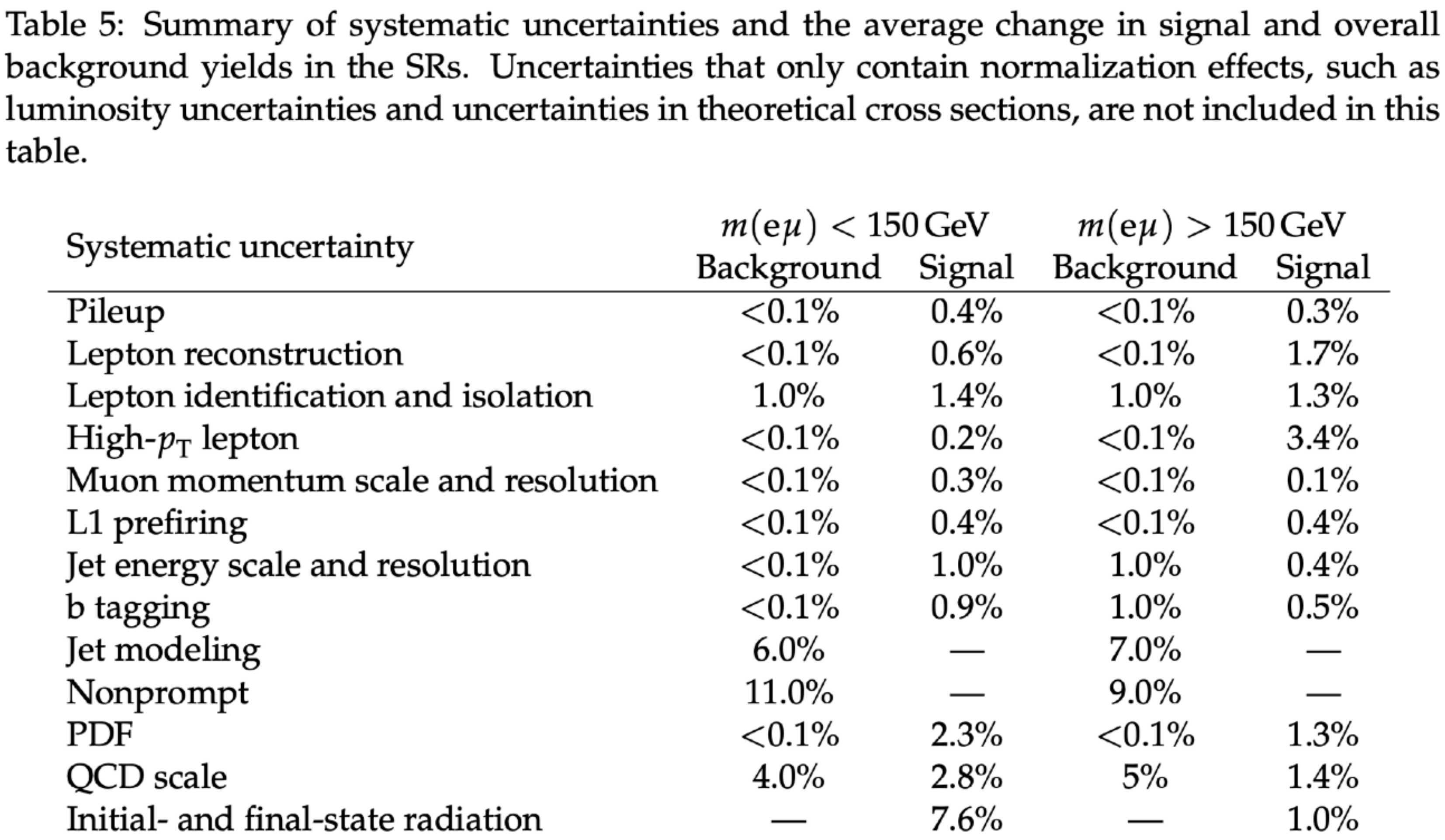


Table 5: Summary of systematic uncertainties and the average change in signal and overall background yields in the SRs. Uncertainties that only contain normalization effects, such as luminosity uncertainties and uncertainties in theoretical cross sections, are not included in this table.

Systematic uncertainty	$m(e\mu) < 150\,\text{GeV}$ Background	$m(e\mu) < 150\,\text{GeV}$ Signal	$m(e\mu) > 150\,\text{GeV}$ Background	$m(e\mu) > 150\,\text{GeV}$ Signal
Pileup	<0.1%	0.4%	<0.1%	0.3%
Lepton reconstruction	<0.1%	0.6%	<0.1%	1.7%
Lepton identification and isolation	1.0%	1.4%	1.0%	1.3%
High-p_T lepton	<0.1%	0.2%	<0.1%	3.4%
Muon momentum scale and resolution	<0.1%	0.3%	<0.1%	0.1%
L1 prefiring	<0.1%	0.4%	<0.1%	0.4%
Jet energy scale and resolution	<0.1%	1.0%	1.0%	0.4%
b tagging	<0.1%	0.9%	1.0%	0.5%
Jet modeling	6.0%	—	7.0%	—
Nonprompt	11.0%	—	9.0%	—
PDF	<0.1%	2.3%	<0.1%	1.3%
QCD scale	4.0%	2.8%	5%	1.4%
Initial- and final-state radiation	—	7.6%	—	1.0%

Important input variables for BDT targeting the top decay:

- The invariant mass of the OSSF lepton pair
- The number of b-tagged jets
- The invariant mass of the flavor-violating top quark candidate

Important input variables for BDT targeting the top production:

- The invariant mass of the LFV eμ pair
- The pT of the LFV electron
- The pT of the LFV muon

- The largest post-fit uncertainties are the statistical uncertainties from the limited number of simulated events
- By convention, positive Wilson coefficients are assumed, and the one-dimensional upper limits on a given Wilson coefficient, C_a/Λ^2, are obtained by taking the square root of the upper limits on the corresponding signal strength μ_a
- Results can also be converted into branching ratio for $B(t \rightarrow e\mu q)$, with q=u or c

Details of TOP 22-005

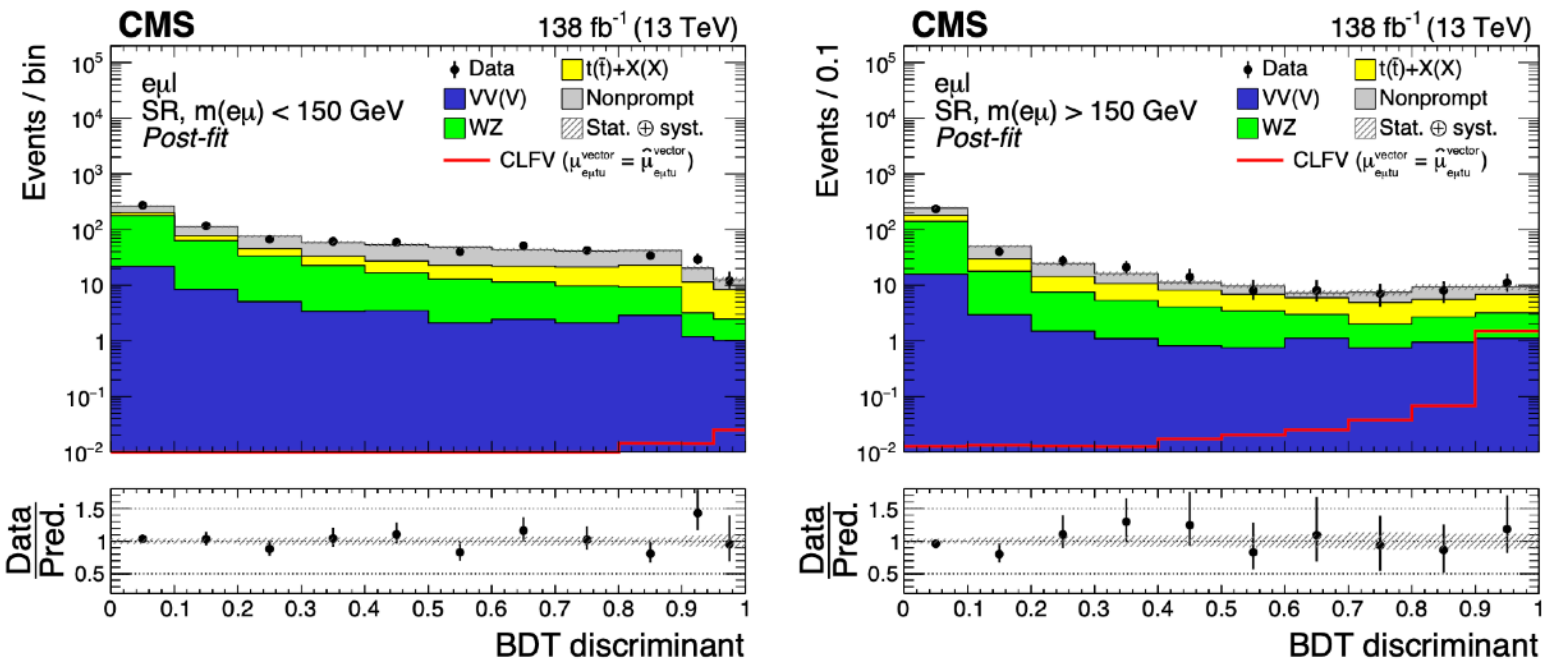
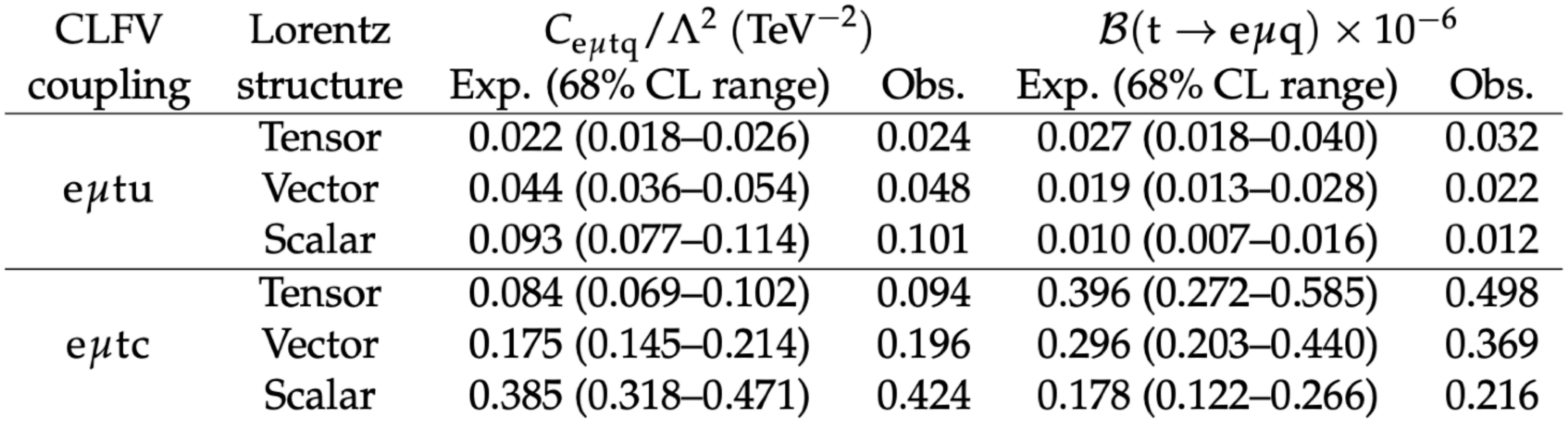
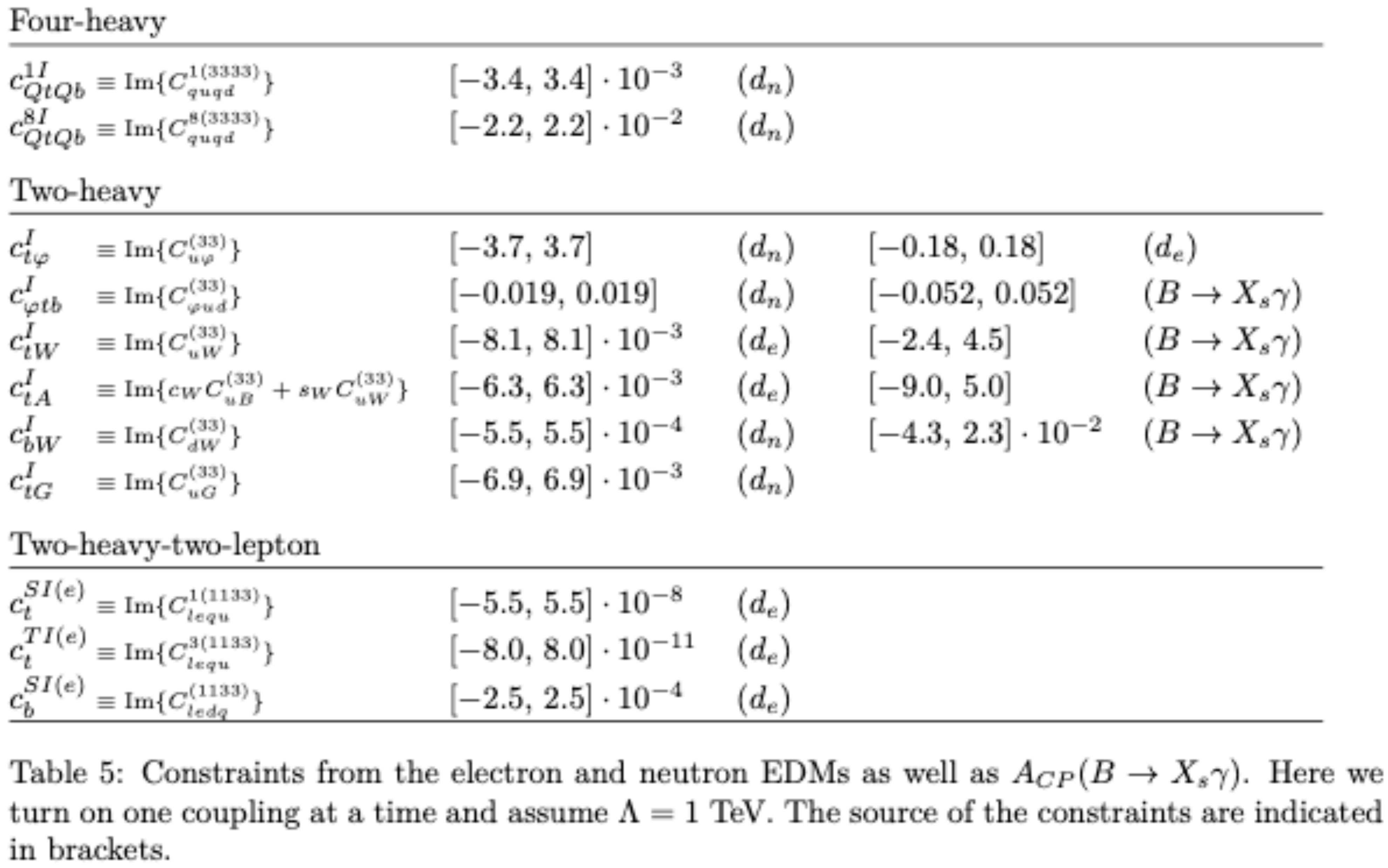


Figure 5: Distributions of the post-fit BDT discriminant targeting the CLFV top quark decay (left) and production (right) signal. Contributions from the two signal modes (production and decay) are combined within each SR and are shown as the solid red line. The post-fit signal strength ($\mu^{\text{vector}}_{e\mu tu} = \hat{\mu}^{\text{vector}}_{e\mu tu}$) is used to normalize the signal cross sections. The hatched bands indicate post-fit uncertainties (statistical and systematic) for the SM background predictions.



CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	Obs.	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	Obs.
$e\mu tu$	Tensor	0.022 (0.018–0.026)	0.024	0.027 (0.018–0.040)	0.032
	Vector	0.044 (0.036–0.054)	0.048	0.019 (0.013–0.028)	0.022
	Scalar	0.093 (0.077–0.114)	0.101	0.010 (0.007–0.016)	0.012
$e\mu tc$	Tensor	0.084 (0.069–0.102)	0.094	0.396 (0.272–0.585)	0.498
	Vector	0.175 (0.145–0.214)	0.196	0.296 (0.203–0.440)	0.369
	Scalar	0.385 (0.318–0.471)	0.424	0.178 (0.122–0.266)	0.216

Constraints on CP violating operators in dim6top (1802.07237 i.e. dim6top note)



Four-heavy					
$c_{QtQb}^{1I} \equiv \mathrm{Im}\{C_{quqd}^{1(3333)}\}$	$[-3.4, 3.4] \cdot 10^{-3}$	(d_n)		
$c_{QtQb}^{8I} \equiv \mathrm{Im}\{C_{quqd}^{8(3333)}\}$	$[-2.2, 2.2] \cdot 10^{-2}$	(d_n)		
Two-heavy					
$c_{t\varphi}^{I} \equiv \mathrm{Im}\{C_{u\varphi}^{(33)}\}$	$[-3.7, 3.7]$	(d_n)	$[-0.18, 0.18]$	(d_e)
$c_{\varphi tb}^{I} \equiv \mathrm{Im}\{C_{\varphi ud}^{(33)}\}$	$[-0.019, 0.019]$	(d_n)	$[-0.052, 0.052]$	$(B \to X_s\gamma)$
$c_{tW}^{I} \equiv \mathrm{Im}\{C_{uW}^{(33)}\}$	$[-8.1, 8.1] \cdot 10^{-3}$	(d_e)	$[-2.4, 4.5]$	$(B \to X_s\gamma)$
$c_{tA}^{I} \equiv \mathrm{Im}\{c_W C_{uB}^{(33)} + s_W C_{uW}^{(33)}\}$	$[-6.3, 6.3] \cdot 10^{-3}$	(d_e)	$[-9.0, 5.0]$	$(B \to X_s\gamma)$
$c_{bW}^{I} \equiv \mathrm{Im}\{C_{dW}^{(33)}\}$	$[-5.5, 5.5] \cdot 10^{-4}$	(d_n)	$[-4.3, 2.3] \cdot 10^{-2}$	$(B \to X_s\gamma)$
$c_{tG}^{I} \equiv \mathrm{Im}\{C_{uG}^{(33)}\}$	$[-6.9, 6.9] \cdot 10^{-3}$	(d_n)		
Two-heavy-two-lepton					
$c_{t}^{SI(e)} \equiv \mathrm{Im}\{C_{lequ}^{1(1133)}\}$	$[-5.5, 5.5] \cdot 10^{-8}$	(d_e)		
$c_{t}^{TI(e)} \equiv \mathrm{Im}\{C_{lequ}^{3(1133)}\}$	$[-8.0, 8.0] \cdot 10^{-11}$	(d_e)		
$c_{b}^{SI(e)} \equiv \mathrm{Im}\{C_{ledq}^{(1133)}\}$	$[-2.5, 2.5] \cdot 10^{-4}$	(d_e)		

Table 5: Constraints from the electron and neutron EDMs as well as $A_{CP}(B \to X_s\gamma)$. Here we turn on one coupling at a time and assume $\Lambda = 1$ TeV. The source of the constraints are indicated in brackets.