SM at LHC Workshop: July 10, 2023

Recent progress on EFT interpretations of top quarks measurements

Kelci Mohrman

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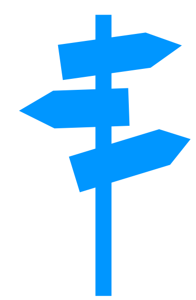
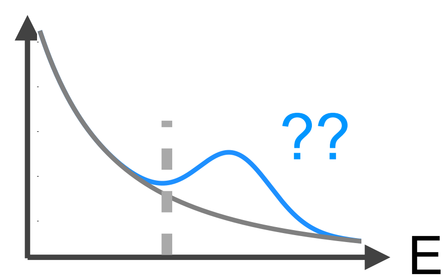
On behalf of the CMS and ATLAS Collaborations

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

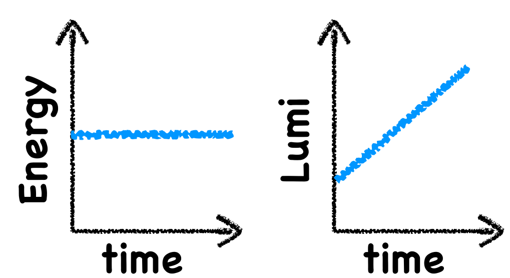
No conclusive indication of which direction to look



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

Brief introduction to EFT

- EFT treats the SM as the lowest order term in an expansion of higher-dimensional operators, that describe physics at a scale Λ, interacting with a strength determined by a dimensionless parameter called a Wilson coefficient, *c*
- If all Wilson coefficients (WCs) are 0, the SM Lagrangian is recovered
−> a non-zero WC would indicate new physics

Wilson Coefficient (strength of interaction)

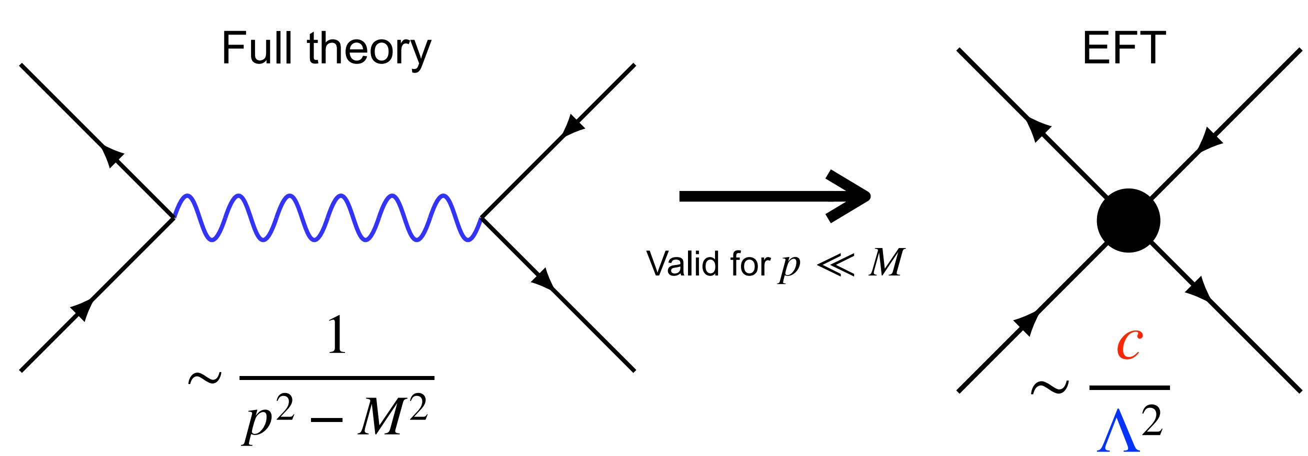
Energy scale of the new physics

Operators are built of products of SM fields and their derivatives

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

⟵ Focus on the **dim 6** terms, as they are the lowest order terms that contribute

- Example: If a heavy particle can't be produced on-shell at the LHC, would be hard to find via a direct search, but EFT can describe the interaction with a dim6 EFT operator, where the strength of the interaction is determined by the WC *c*



UF UNIVERSITY of FLORIDA Kelci Mohrman, University of Florida

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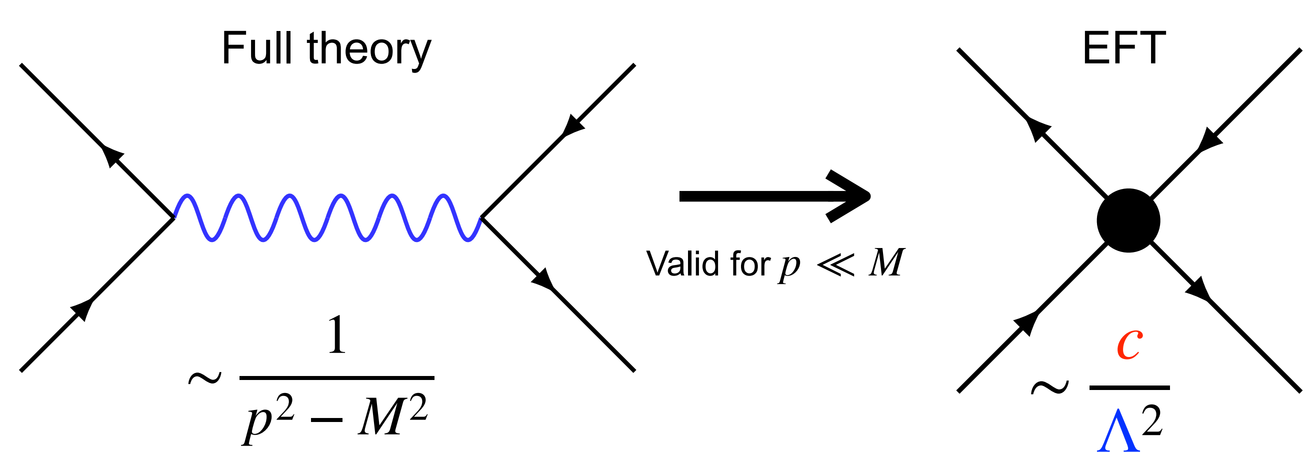
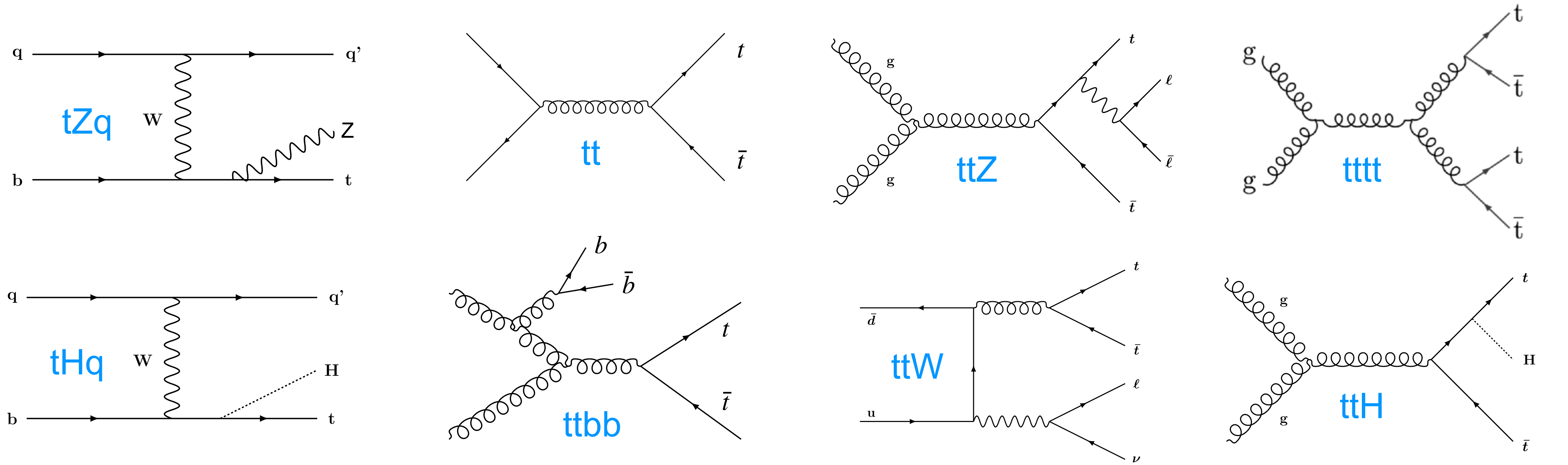


Using EFT to look for new physics in top processes

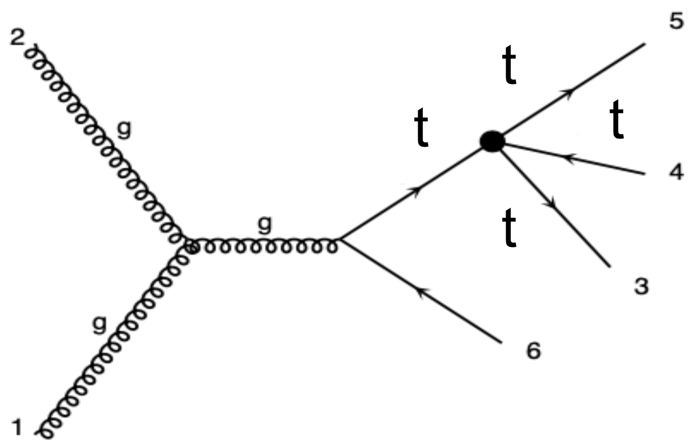
- EFT is a relatively general method of describing heavy new physics, can be used for many different types of searches
- This talk focuses on the top sector
  - Processes involving tops are relatively rare, and may be an interesting region for new physics to be hiding
  - Garnering enough statistics to start probing in more detail



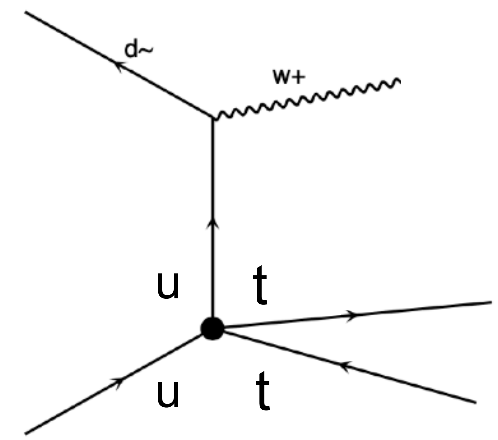
A few example top production diagrams

EFT vertices involving tops

- TOP EFT analyses aim to probe all possible EFT interactions involving top quarks, here is an example from each category:



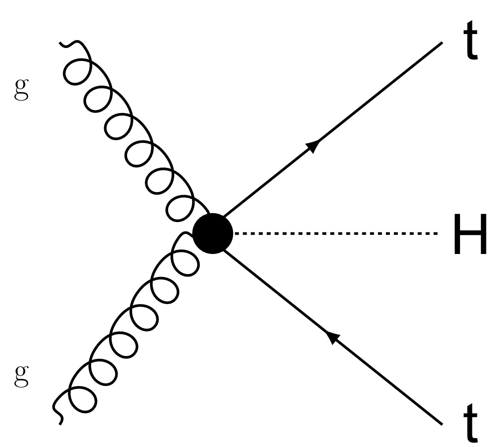
Operators involving 4 heavy quarks



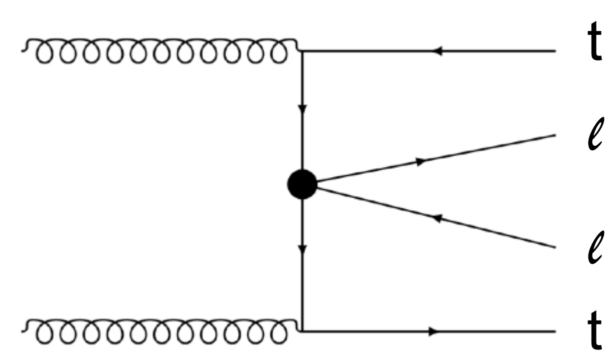
Operators involving two heavy quarks and 2 light quarks

Note: "heavy" means top or bottom, "light" is everything else

See dim6top model paper (1802.07237) for more details on the operators, note the operators shown here do not include the FCNC operators



Operators involving heavy quarks and bosons



Operators involving 2 heavy quarks and 2 leptons

EFT approaches

Indirect ⟷ Direct

Reinterpretation of measurements

Perform a fit to cross-section or unfolded differential distributions

Pros: Easier to preserve, to reinterpret, and combine, and no need to produce reco-level EFT simulations

Direct measurement

Perform fit directly with number of observed events with EFT fully simulated at detector level

Pros: fully account for acceptance effects, fully account for EFT contributions from many processes (and include all correlations)

ATLAS 2208.12095 is an example of an indirect approach, while CMS PAS TOP-22-006 is an example of direct approach

Some recent TOP EFT analyses

CMS

- t(t)X multilepton, 26 WCs (fit individually and simultaneously)
  CMS PAS TOP-22-006
- $t\bar{t}$ with boosted Z or H, singe lepton + jets, 8 WCs (fit individually and simultaneously)
  2208.12837 (accepted by PRD)
- $t\bar{t}\gamma$ dilepton, Re and Im part of 1 WC (fit individually and together)
  JHEP 05 (2022) 091
- $t\bar{t}Z$ multilepton, 5 WCs (individual and simultaneous fits)
  JHEP 12 (2021) 083

ATLAS

- Search for charged lepton flavor violation, 8 FCNC WCs
  ATLAS-CONF-2023-001
- $t\bar{t}t\bar{t}$ multilepton, 4 WCs (individual fits)
  Eur. Phys. J. C 83 (2023) 496
- $t\bar{t}$ charge asymmetry, single and di-lepton, 15 WCs (individual fits)
  2208.12095 (accepted by JHEP)
- $t\bar{t}$ all-hadronic, 8 WCs (fit individually and in pairs)
  JHEP 04 (2023) 80
- $t\bar{t}$ semi-leptonic, 2 WCs (fit individually and together),
  JHEP 06 (2022) 063
- Single top polarization, leptonic, Re and Im part of 1 WC (fit individually and together),
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ATLAS

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This talk will focus mainly on these two analyses, together they cover most of the (non FCNC) TOP EFT WCs

(Primarily missing are the four-heavy WCs that do not impact tttt, these would be probed with ttbb)

$t\bar{t}$ Charge Asymmetry

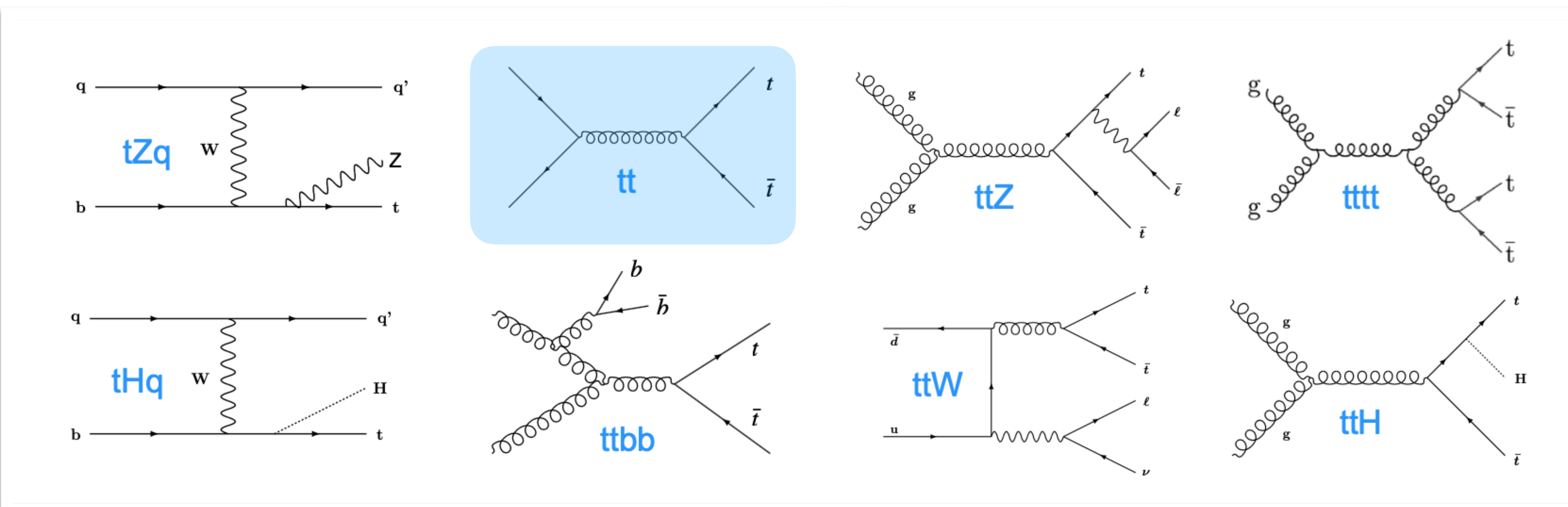
ATLAS 2208.12095
(accepted to JHEP)

Introduction to $t\bar{t}$ charge asymmetry

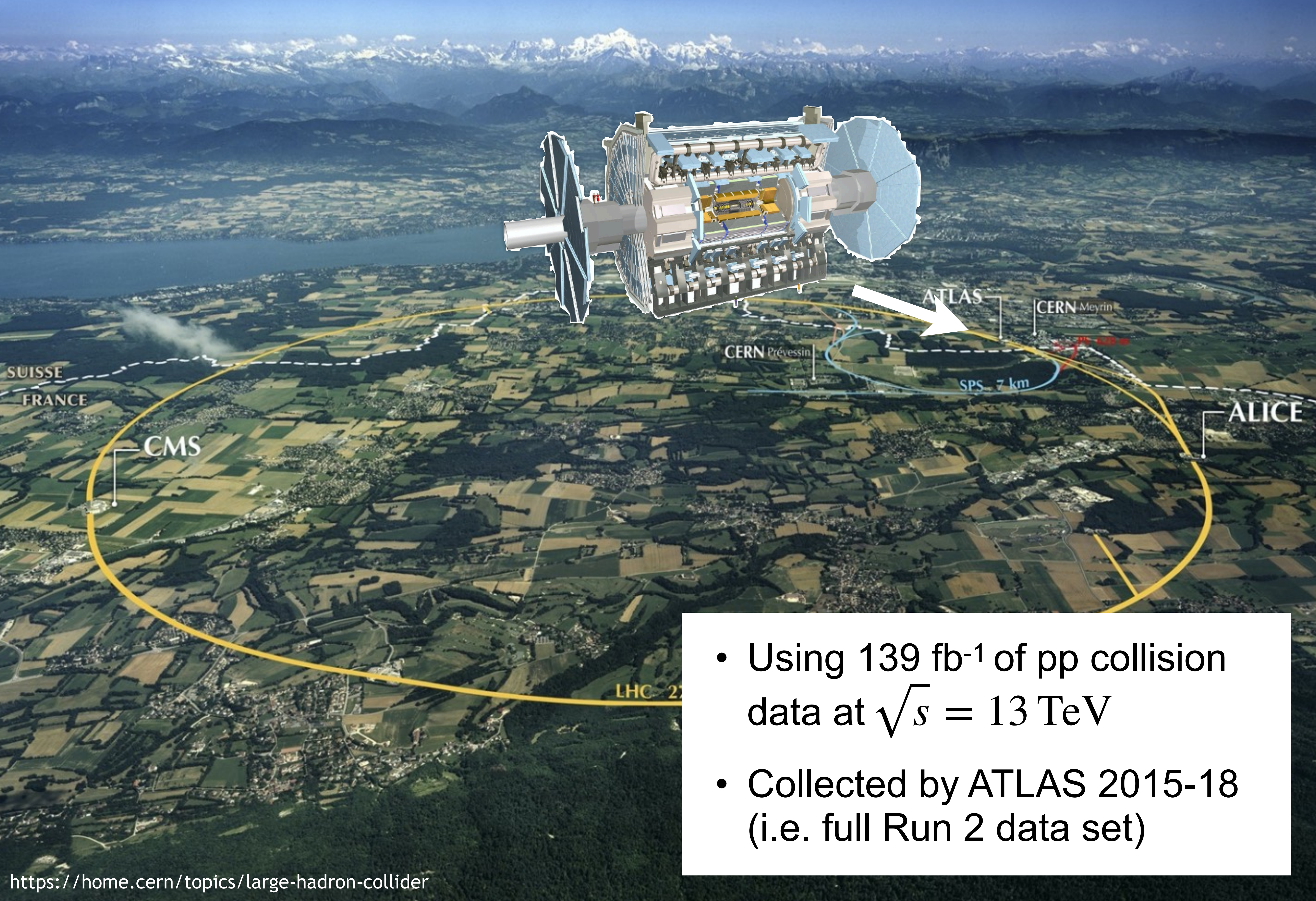
- This analysis studies the central-forward charge asymmetry in $t\bar{t}$
  - Tops (anti tops) produced mainly in the direction of the q ($\bar{q}$)
  - Because of proton PDF, more tops produced with more longitudinal momentum (and more antitops produced centrally)

$$A_C^{t\bar{t}} = \frac{N(\Delta|y_{t\bar{t}}| > 0) - N(\Delta|y_{t\bar{t}}| < 0)}{N(\Delta|y_{t\bar{t}}| > 0) + N(\Delta|y_{t\bar{t}}| < 0)},$$

Where $\Delta|y_{t\bar{t}}| = |y_t| - |y_{\bar{t}}|$ is the difference between the absolute value of the top-quark rapidity and the absolute value of the top-antiquark rapidity



The LHC and ATLAS

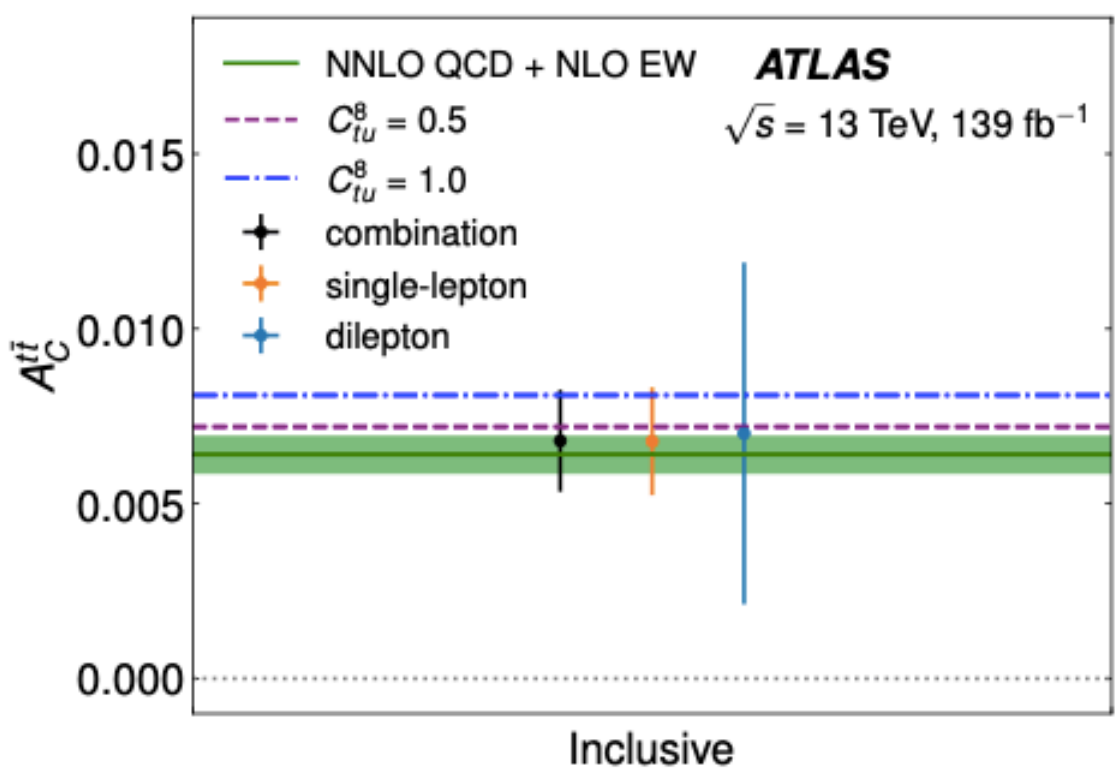


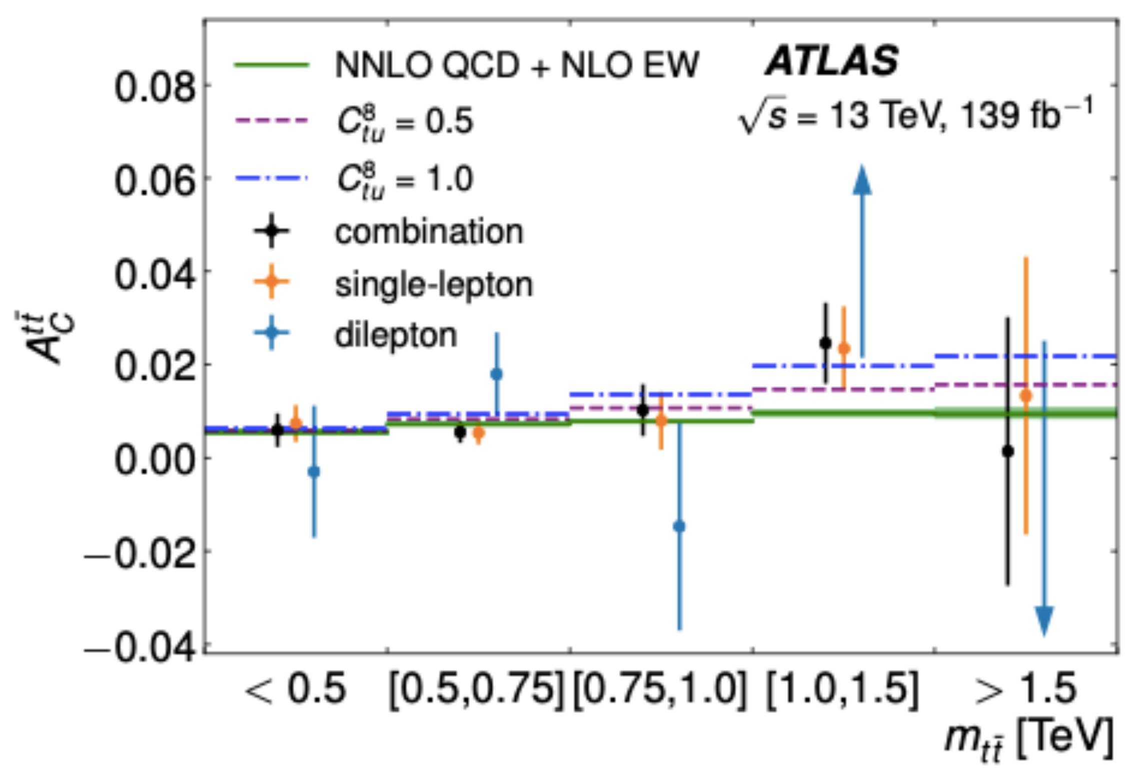
- Using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13\,\mathrm{TeV}$
- Collected by ATLAS 2015-18 (i.e. full Run 2 data set)

https://home.cern/topics/large-hadron-collider

The measurement and results

- Single-lepton (resolved and boosted topologies) and dilepton (resolved) channels
- Differential measurements performed as a function of the invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system
- Unfolding performed to correct for detector resolution and acceptance effects
- Results are consistent with SM calculation





The $A_c^{t\bar{t}}$ is measured to be 0.0068±0.0015,
which differs from 0 by by 4.7 standard deviations

EFT approaches

Indirect ⟵⟶ Direct

Reinterpretation of measurements

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Pros: Easier to preserve, to reinterpret, and combine, and no need to produce reco-level EFT simulations

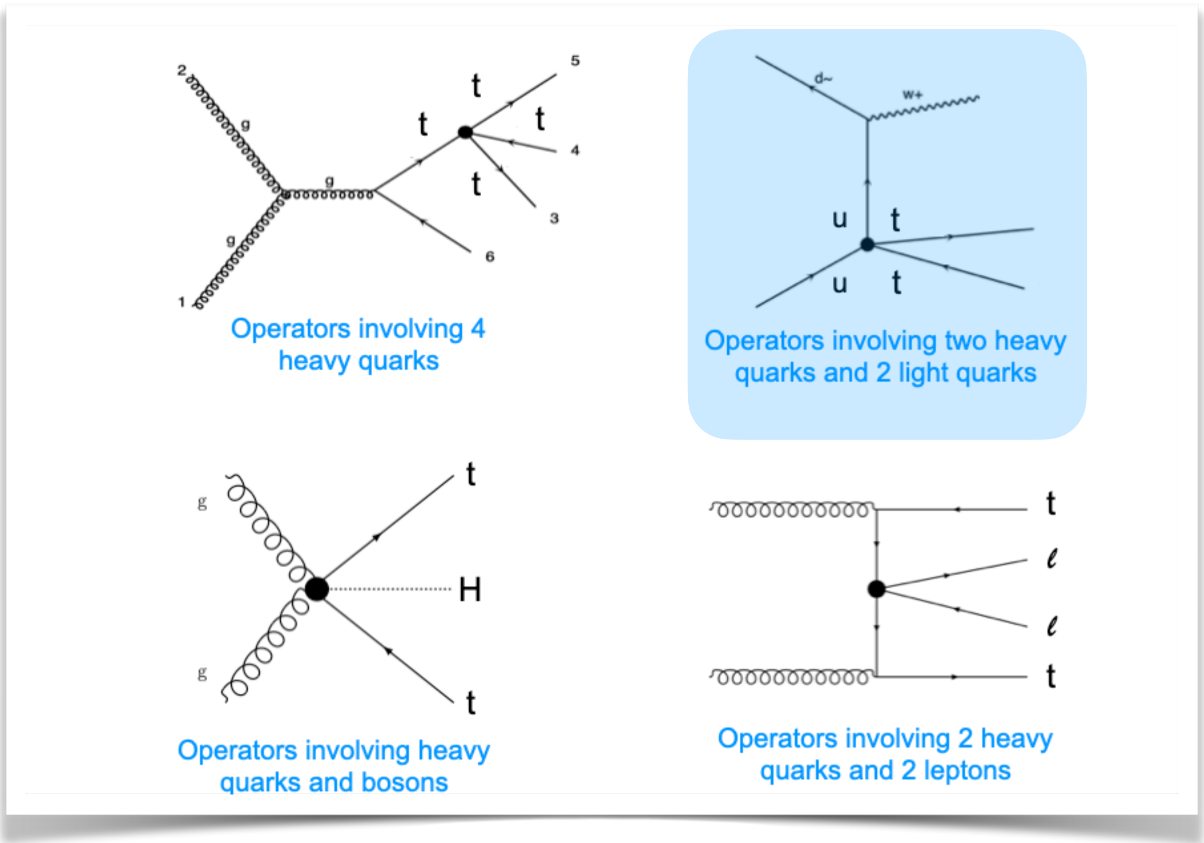
This analysis **ATLAS 2208.12095** uses an indirect approach

Direct measurement

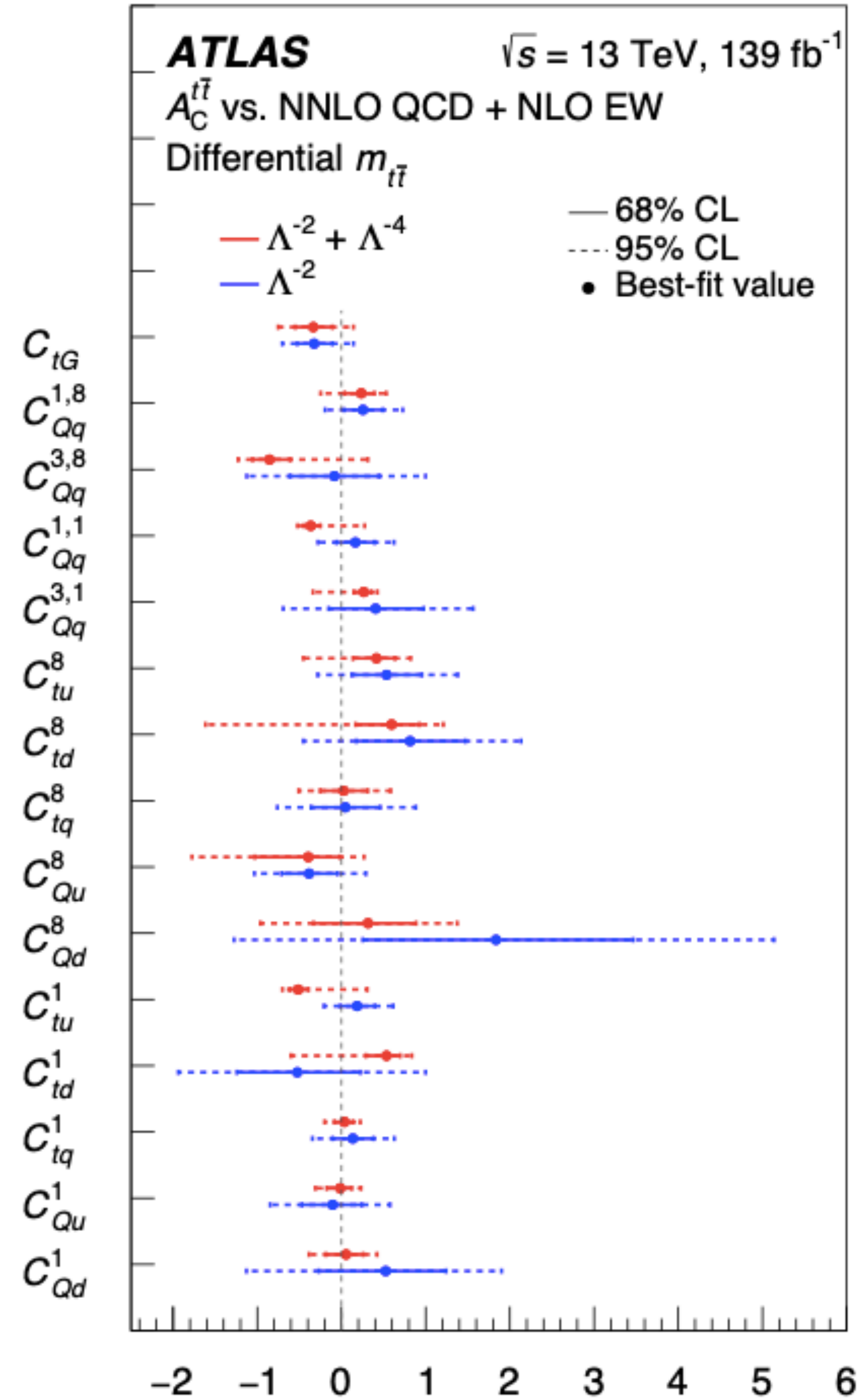
Perform fit directly with number of observed events with EFT fully simulated at detector level

Pros: fully account for acceptance effects, fully account for EFT contributions from many processes (and include all correlations)

ATLAS 2208.12095 EFT results

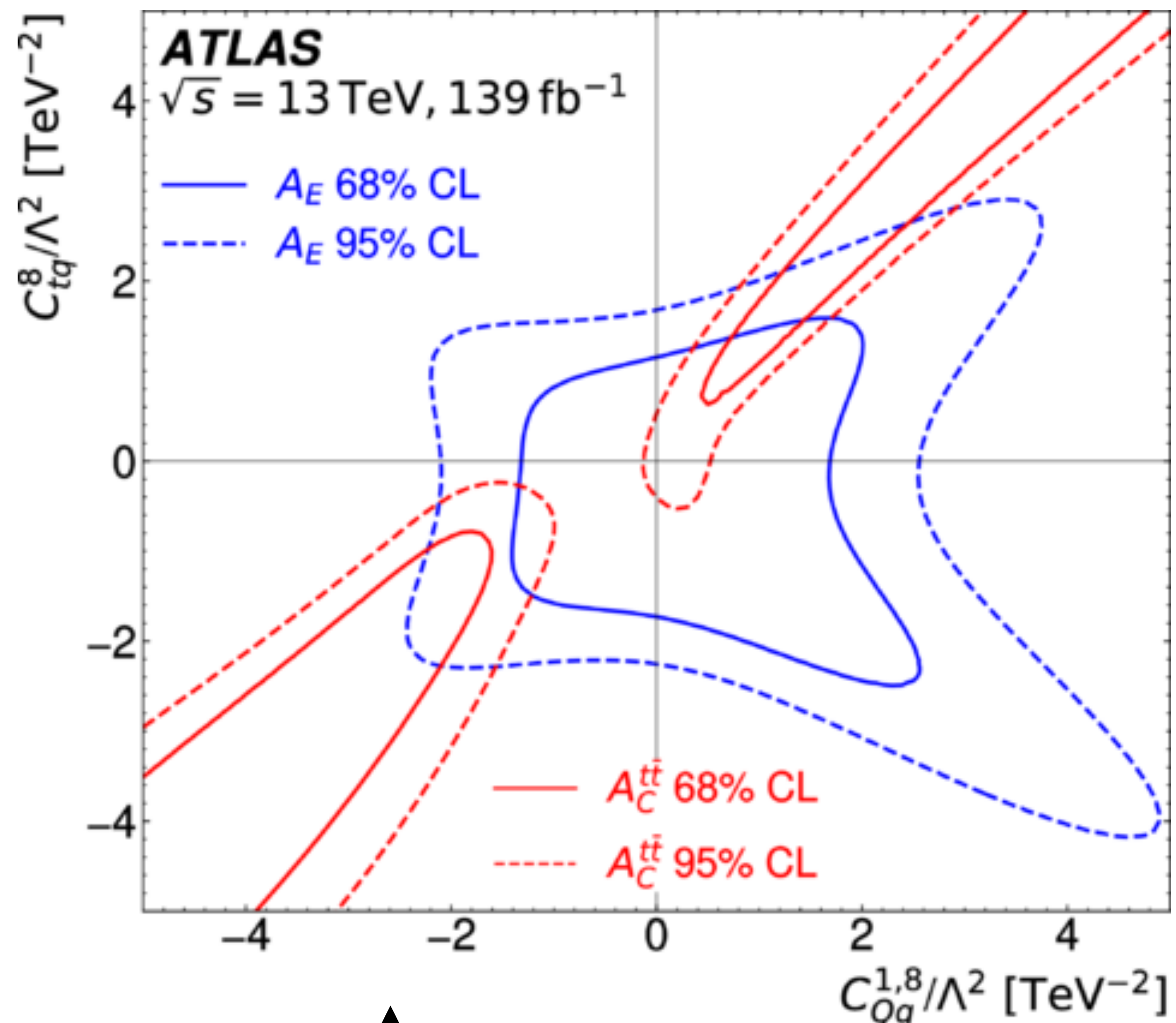


- Uses an indirect approach to study 15 WCs:
  - Includes all 14 operators from the 2-light-quark-2-heavy-quark group (plus ctG)
  - The WCs are fit individually and in pairs, using the $A_c^{t\bar{t}}$ in bins of $m_{t\bar{t}}$
  - Results consistent with the SM



ATLAS 2208.12095 EFT results

- WCs are also fit in pairs
  - The measurement is complimentary to EFT interpretations of energy asymmetry measurements (ATLAS Eur. Phys. J. C 82 (2022) 374)
  - Helps to break flat directions



For example, the flat direction in cQq18 and ctq8 is broken in the energy asymmetry measurement

t(t)X Multilepton

CMS PAS TOP-22-006

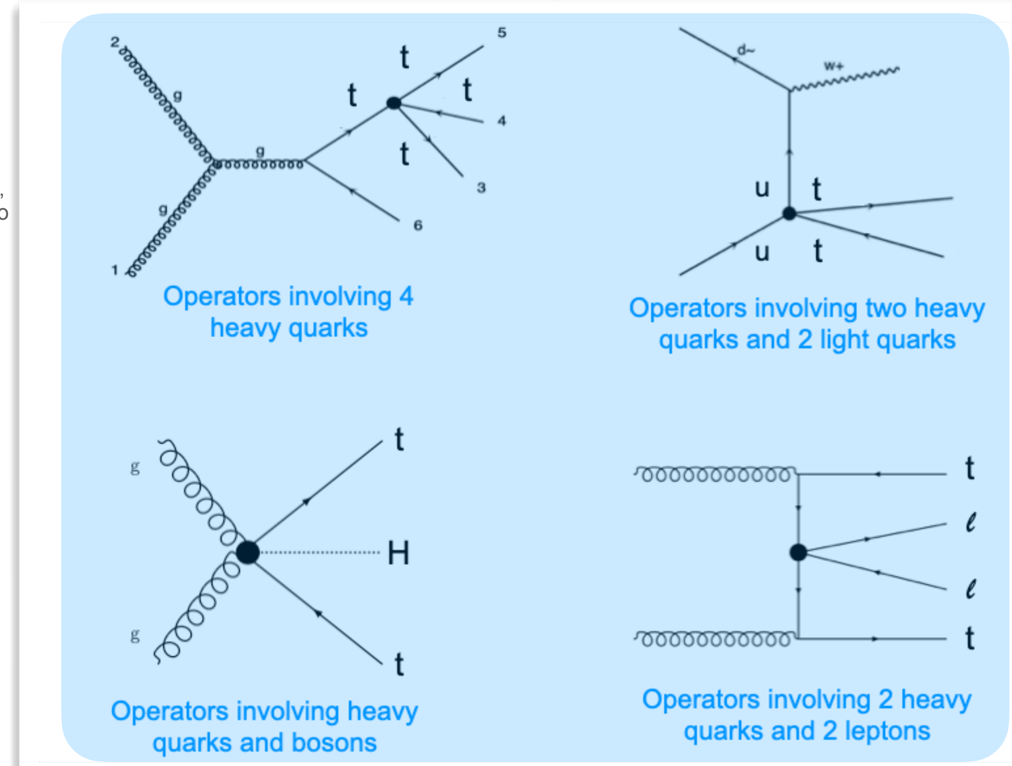
Introduction to TOP-22-006

- Uses EFT to probe potential new physics impacting associated top
  - Signal processes t(t)X: ttH, ttlnu, ttll, tllq, tHq, tttt
  - Global approach, probe all 26 dim6 TOP EFT operators impacting these processes

Including WCs from all four categories

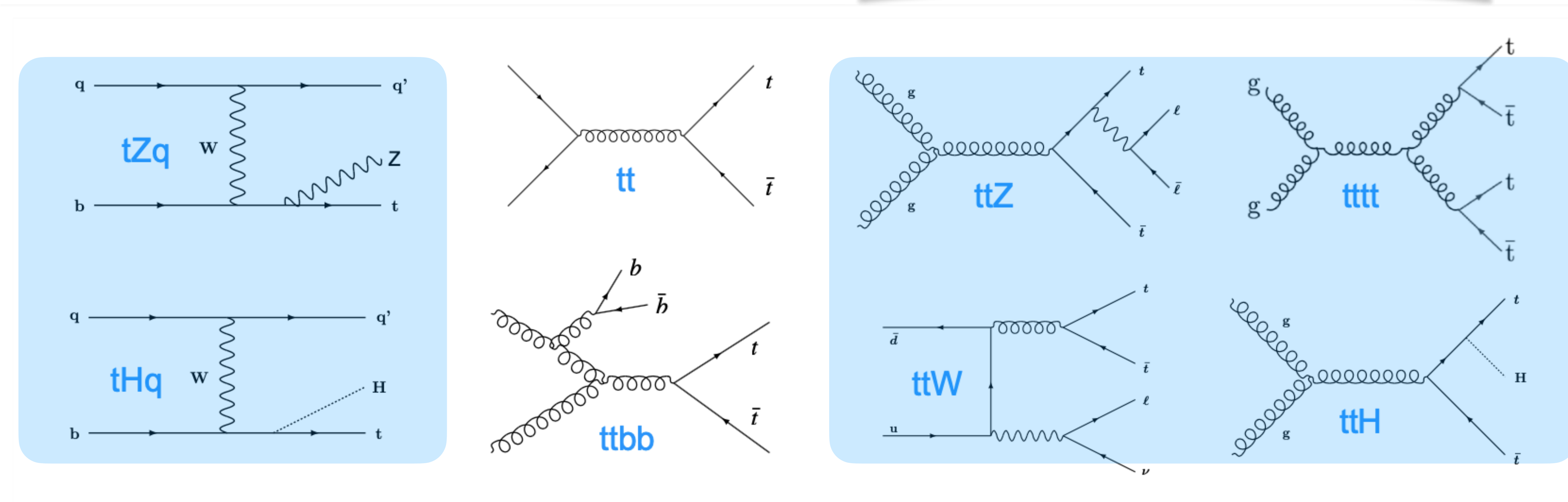
Include the 4 that impact 4t, not sensitive to the ttbb

Include all 9 from this category



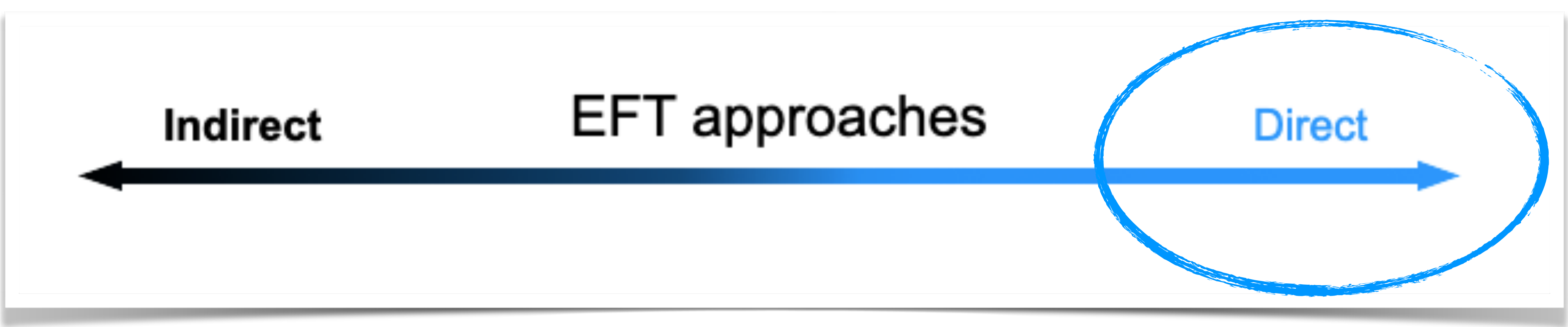
Include 6/14 of the 2light-2heavy operators (not sensitive to the ones with RH light quarks)

Include 7/8 of the 2quark-2lepton operators, not sensitive to one with no t-t-l-l vertex



Strategy for multilepton EFT analysis

- We focus on multilepton signatures, advantages but also challenges:
  - Multiple signal processes and many WCs can contribute to same final state signatures
  - Not possible to fully disentangle, so analysis cannot be easily constructed as a reinterpretation of cross section measurement
- To target EFT directly, model the EFT effects directly at detector level



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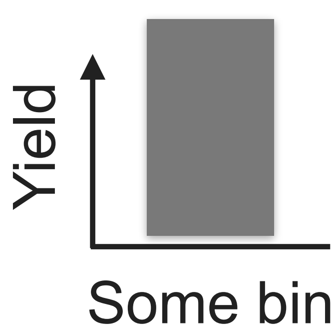

$= f(c_1, c_2, c_3, \ldots)$

We want to write the predicted yield in a given observable bin as a function of the WCs

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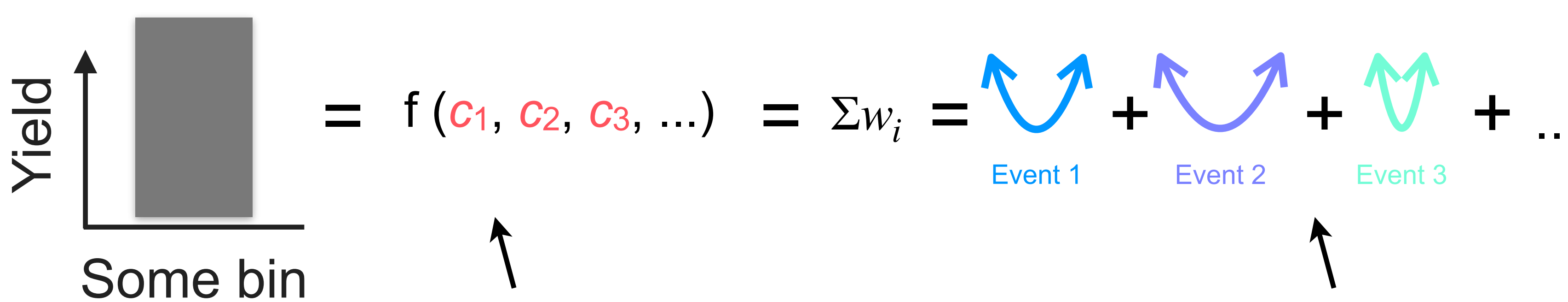

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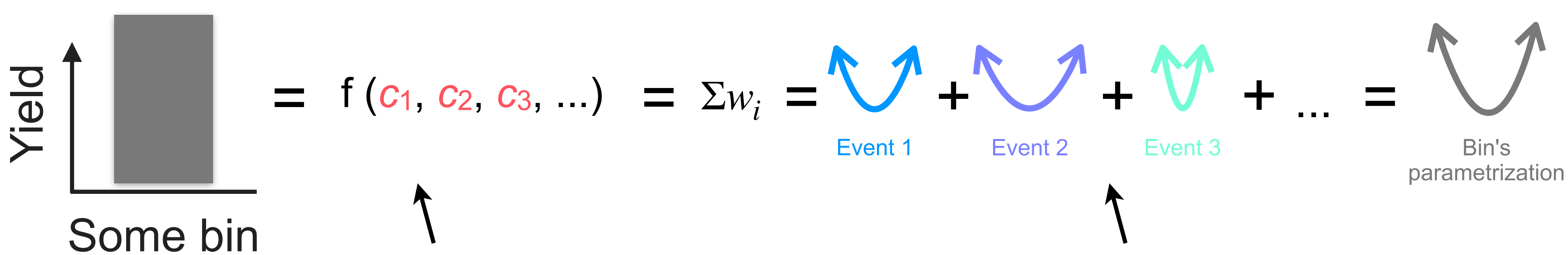

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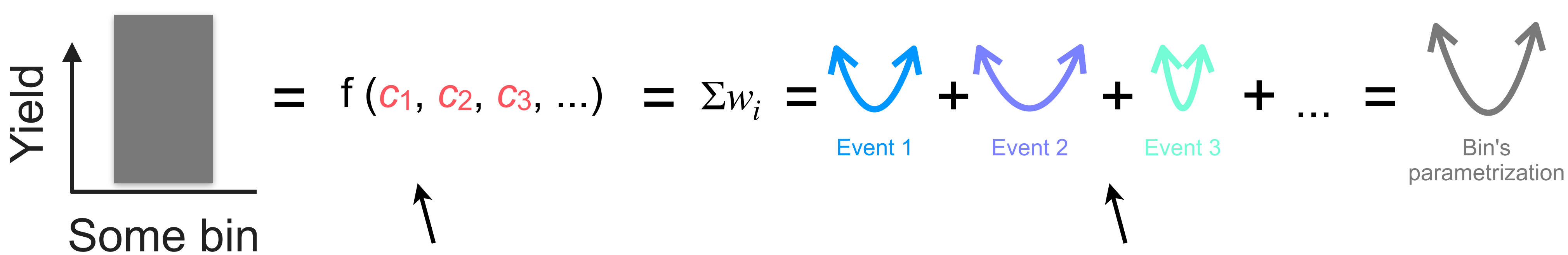

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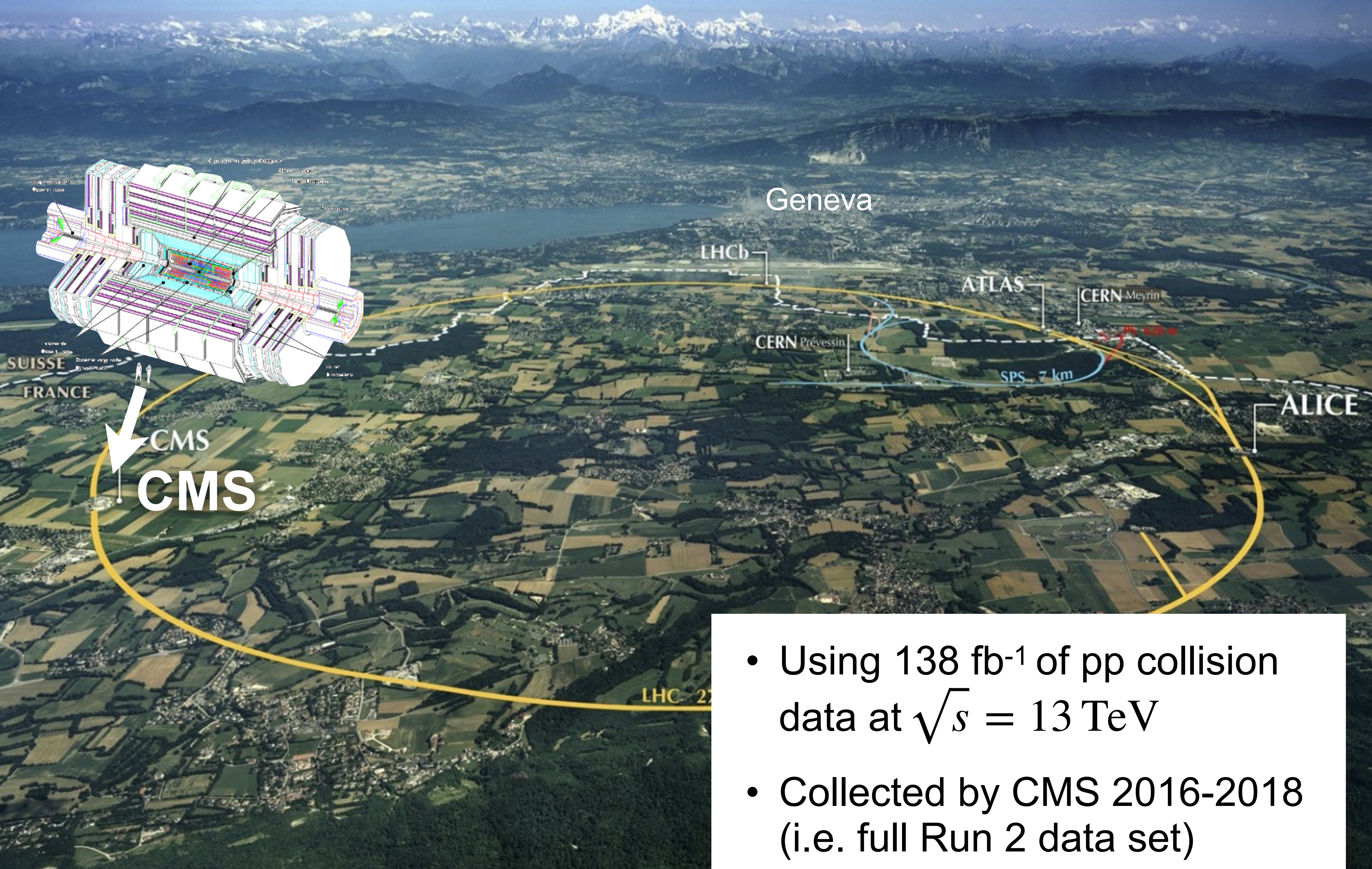
Quadratically parametrize weight of each simulated event in terms of the WCs

Note: These are actually *n*-dimensional quadratics for each event, where *n* = number of WCs (so 26d for TOP-22-006), following approach developed in TOP-19-001, Some more technical details analysis approach in LHC EFT WG presentation

The LHC and CMS



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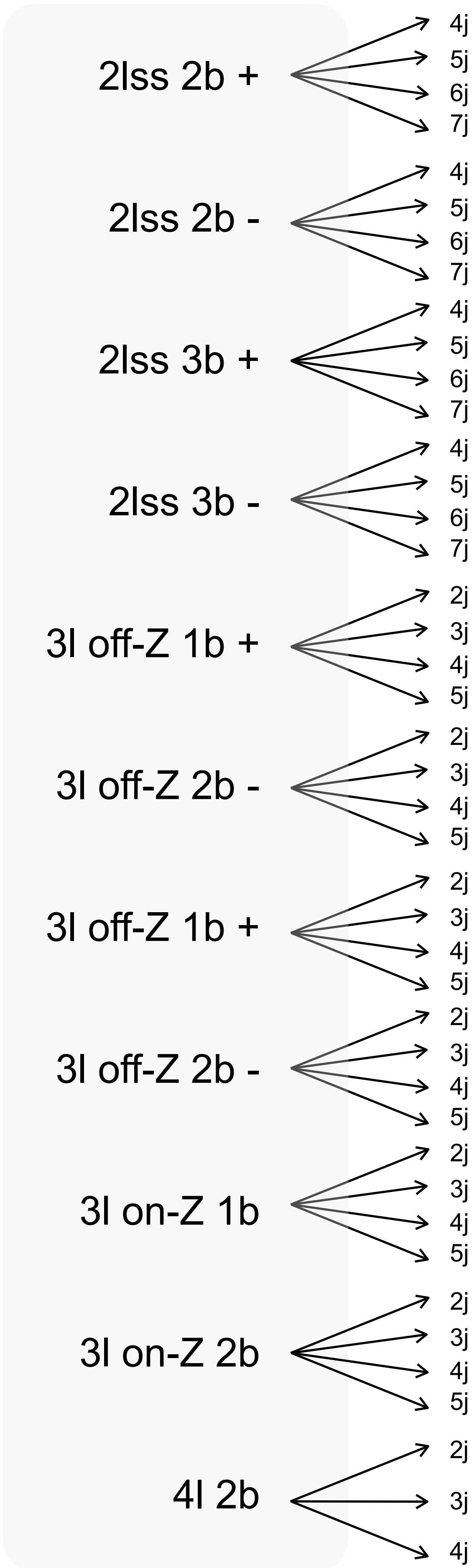
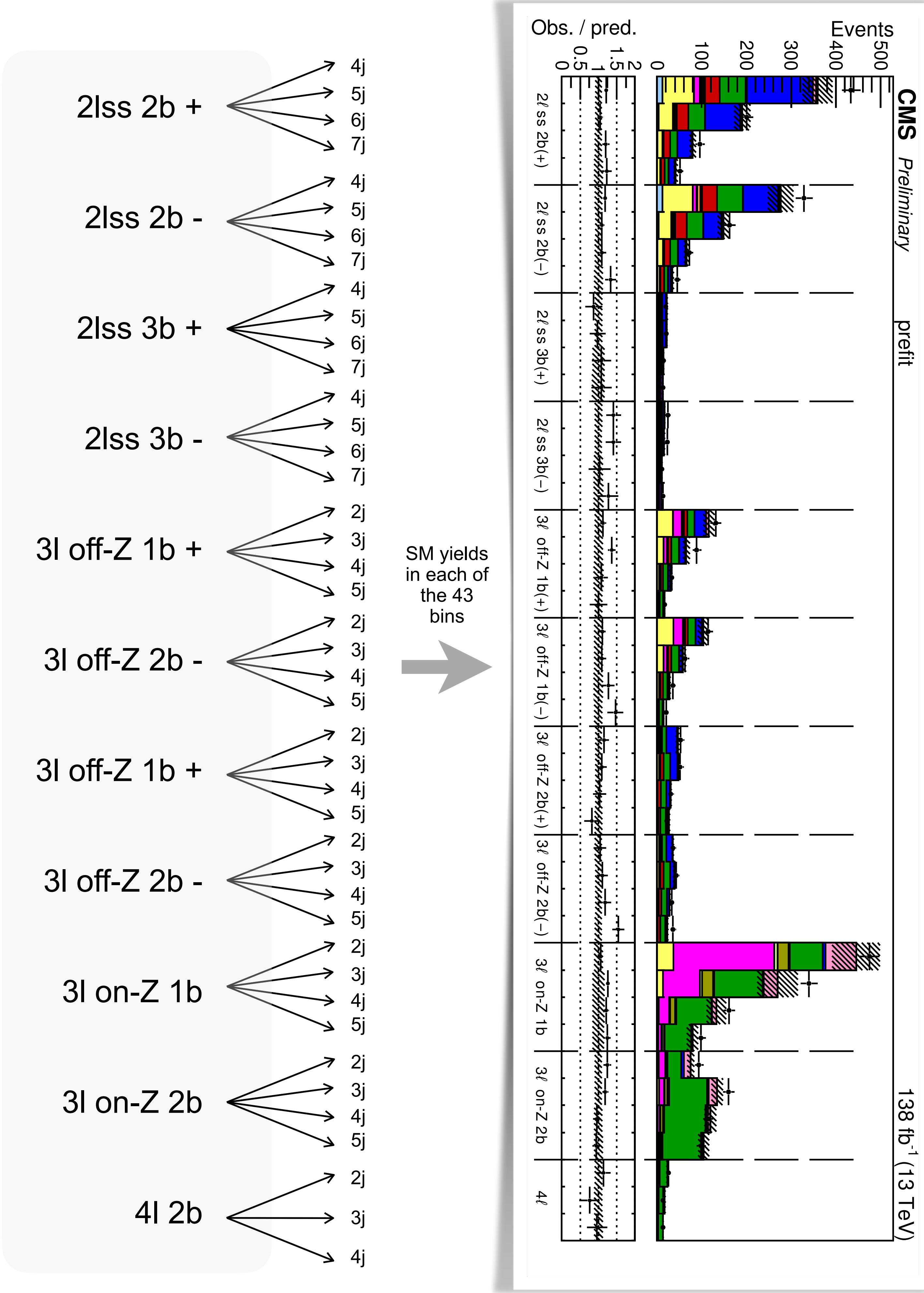
Signal region categories

- The event selection results in 43 total signal-region categories



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



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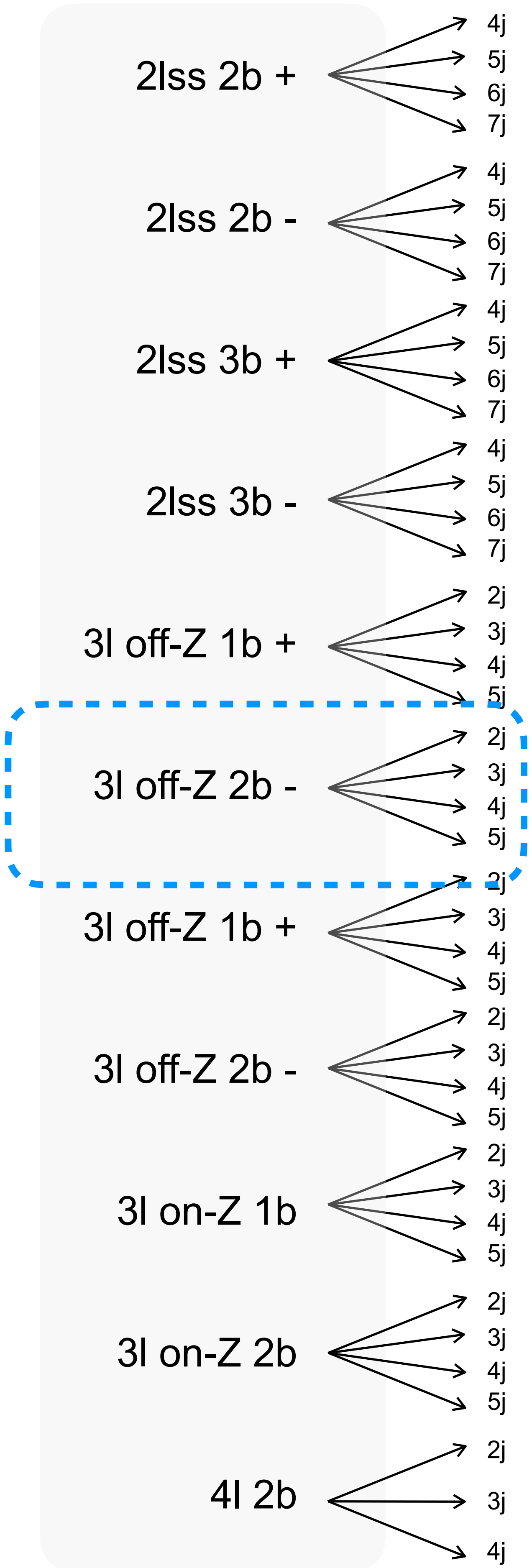
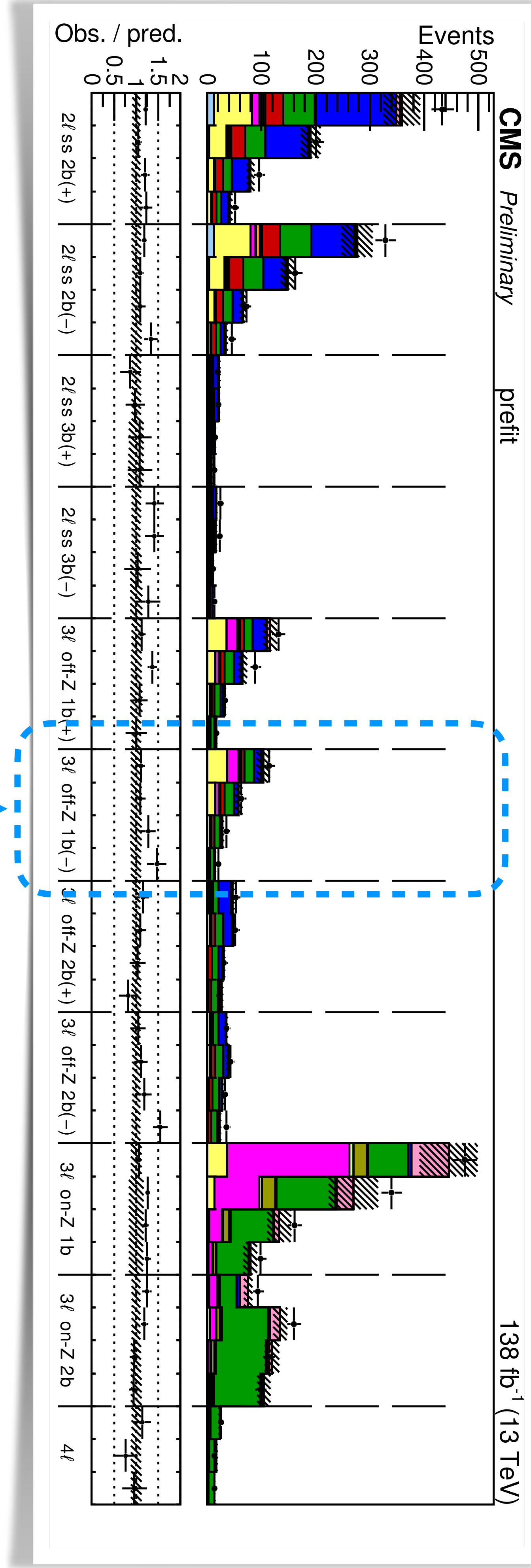
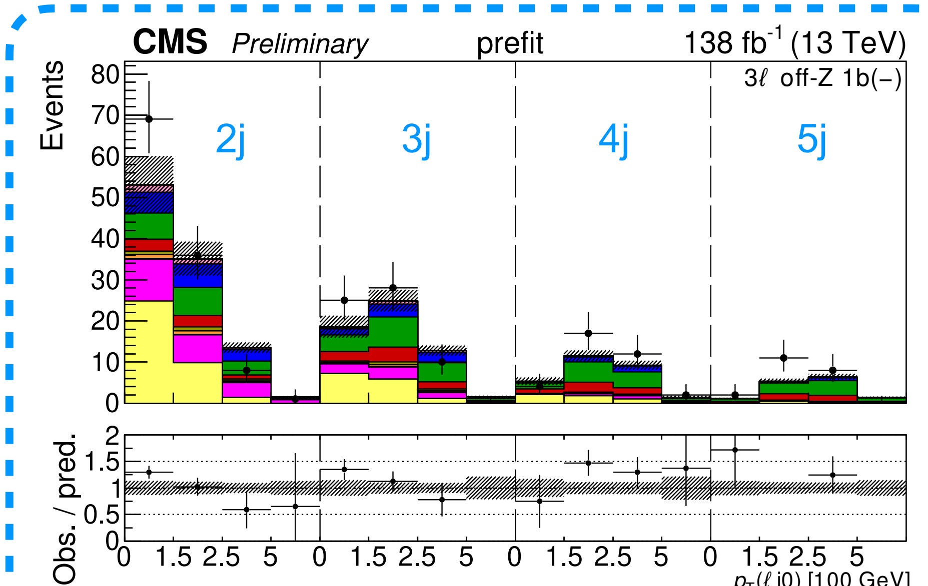




Signal region categories

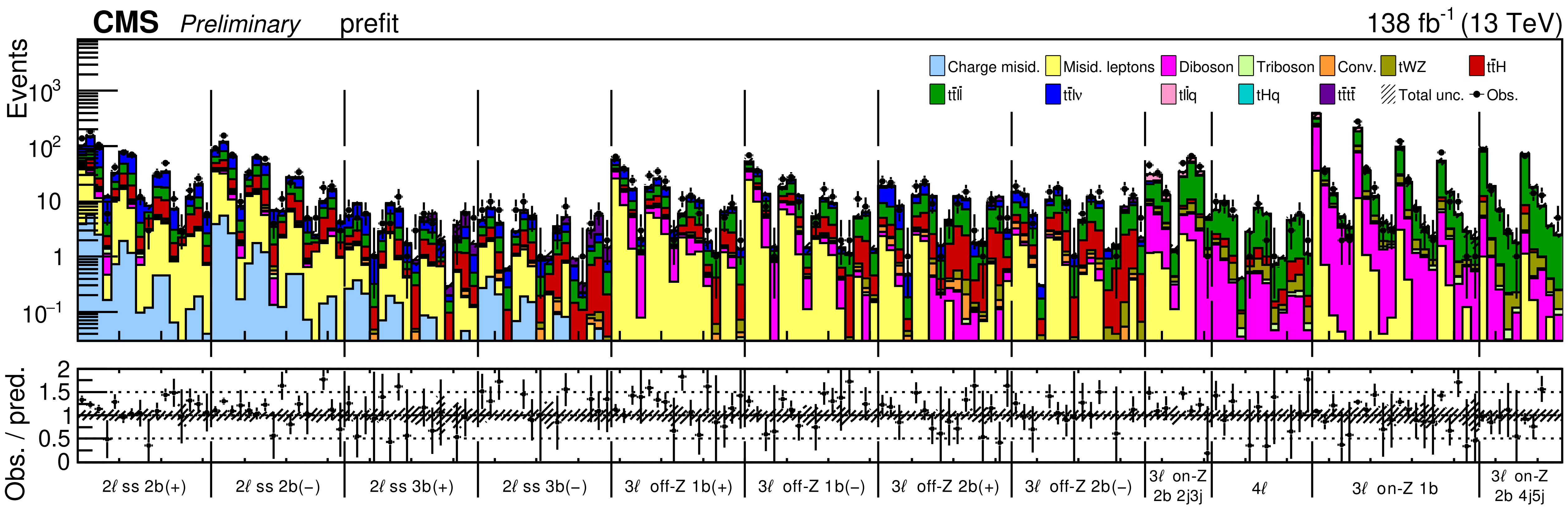
- The event selection results in 43 total signal-region categories
- To improve sensitivity to EFT, further bin events in each category according to a kinematic distribution



E.g. the "3l off-Z 1b -" category

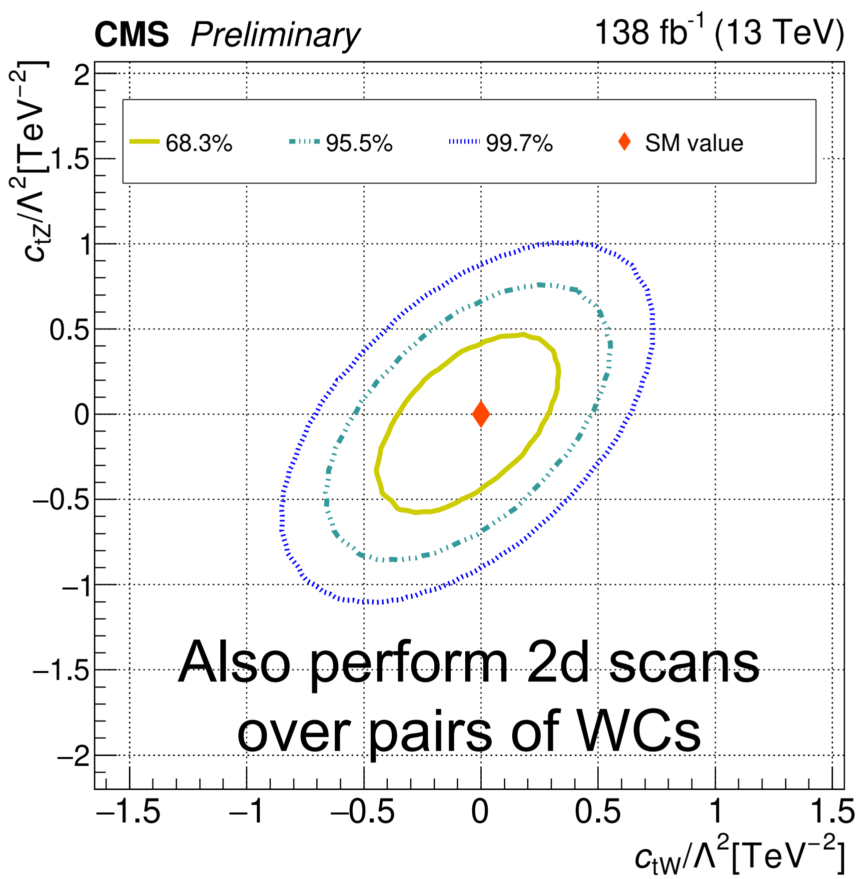
Summary of event selection and categorization

- Binning the 43 categories with these kinematical distributions → 178 total bins
- The predicted yield in each bin depends quadratically on the 26 WCs
- Perform a likelihood fit (where the WCs are the POIs) to extract the confidence intervals for WCs simultaneously
    - Systematic uncertainties are accounted for
    - Backgrounds (mainly dibosons and misidentified leptons) also contribute

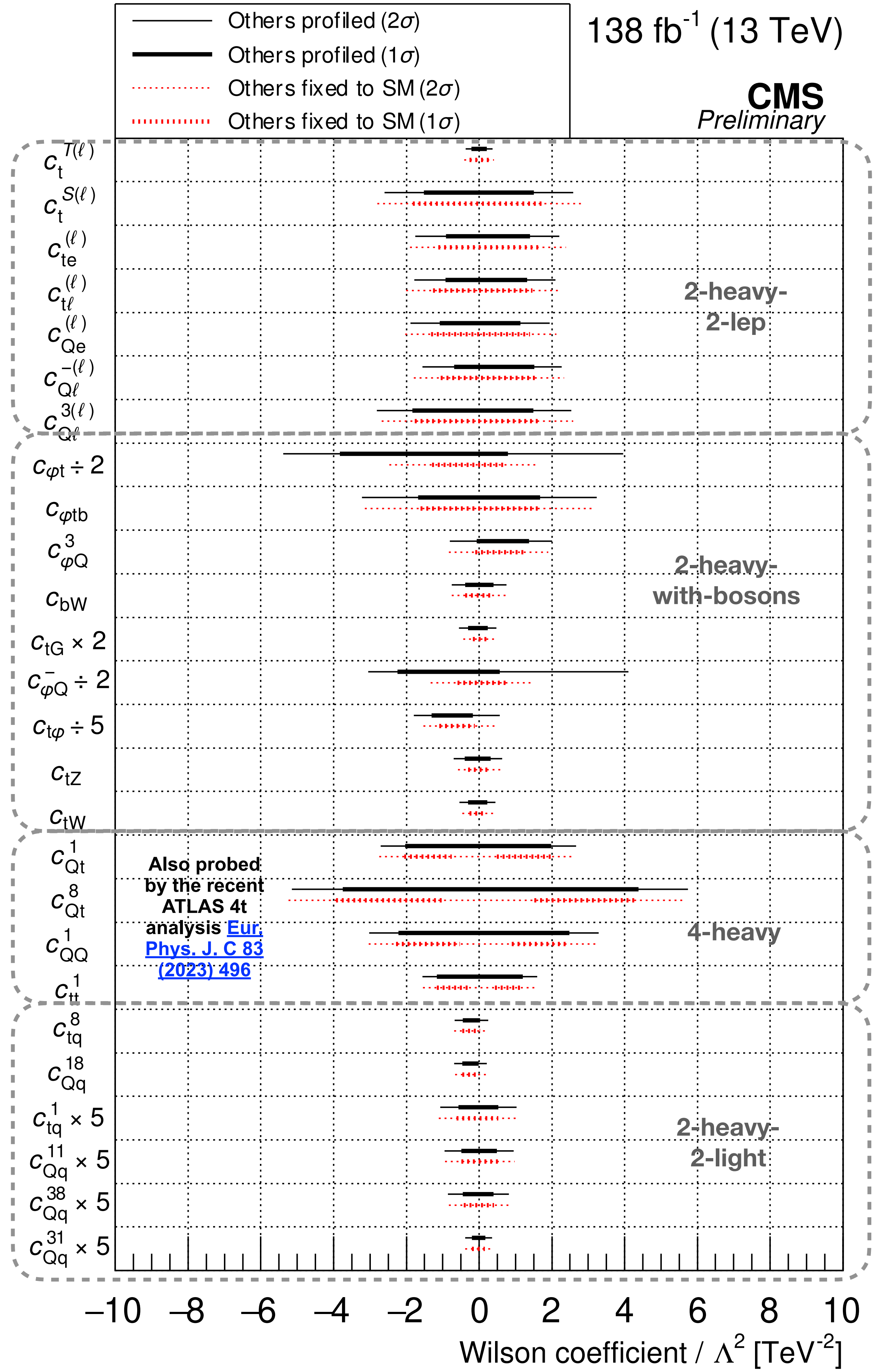


Results

- Extract the 1σ and 2σ confidence intervals for the WCs where other WCs are fixed to the SM (red) or **profiled (black)**
- Results are consistent with SM
- For most of the WCs, sensitivity is limited by statistics

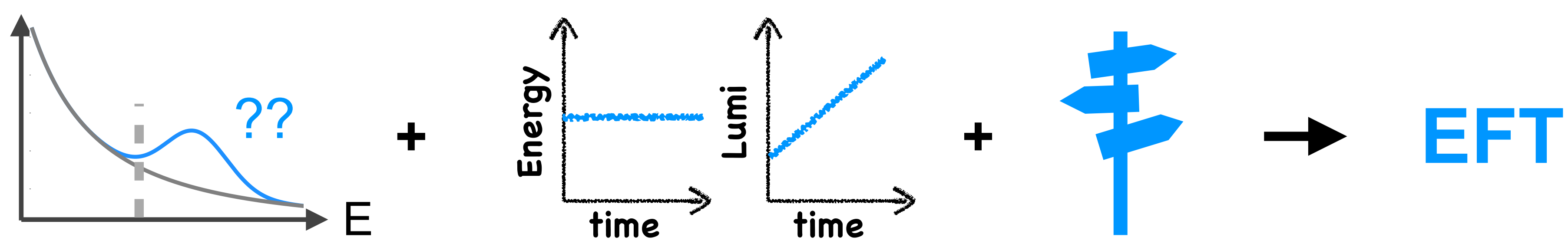


Also perform 2d scans over pairs of WCs



Summary and outlook

- SM EFT provides a systematic and relatively model independent framework to describe the effects of potential heavy new physics across sectors at the LHC



- CMS and ATLAS cover many aspects of possible new physics effects impacting TOP
    - Different EFT approaches used (direct and indirect), pros and cons to each
    - Most of the WCs involving tops are probed, primary exceptions are t-t-b-b

- But still many new directions to improve and expanded, combinations will be especially interesting (though care will need to be taken):
    - More data
    - Improvements in EFT modeling
    - Combinations within TOP
    - Combinations across sectors

} Hopefully leading to new physics discoveries!

Backup

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.

More info on the CMS analyses

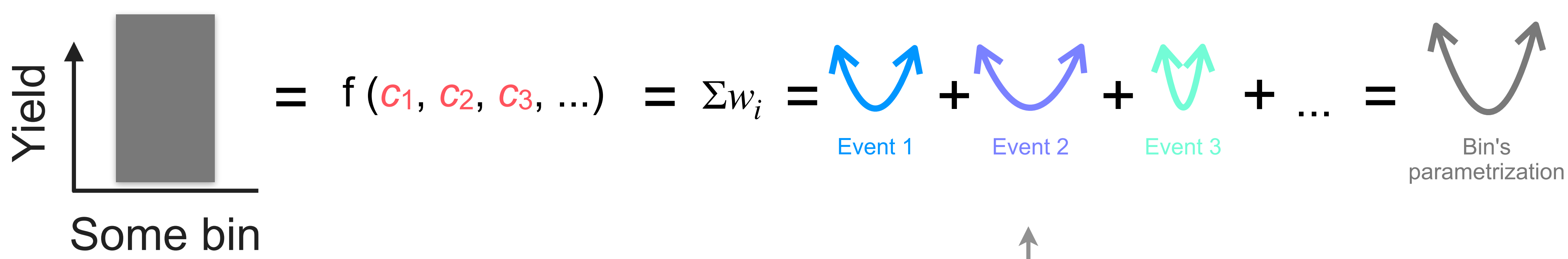
Modeling the signal contribution (TOP-22-006)

- We generate MC samples for our six signal processes (ttH, ttlnu, ttll, tllq, tHq, tttt) using MG with the dim6top model (arxiv 1802.07237) to incorporate the relevant EFT effects in the event weights of the simulated events
  - The dim6top model is LO, so we include an extra jet in the matrix element (when possible) to improve modeling and avoid inadvertently missing relevant EFT impacts (arxiv 2012.06872)
  - Include 26 WCs (all WCs from dim6top that significantly impact the data sets included in the analysis)

Operator category	WCs
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)	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

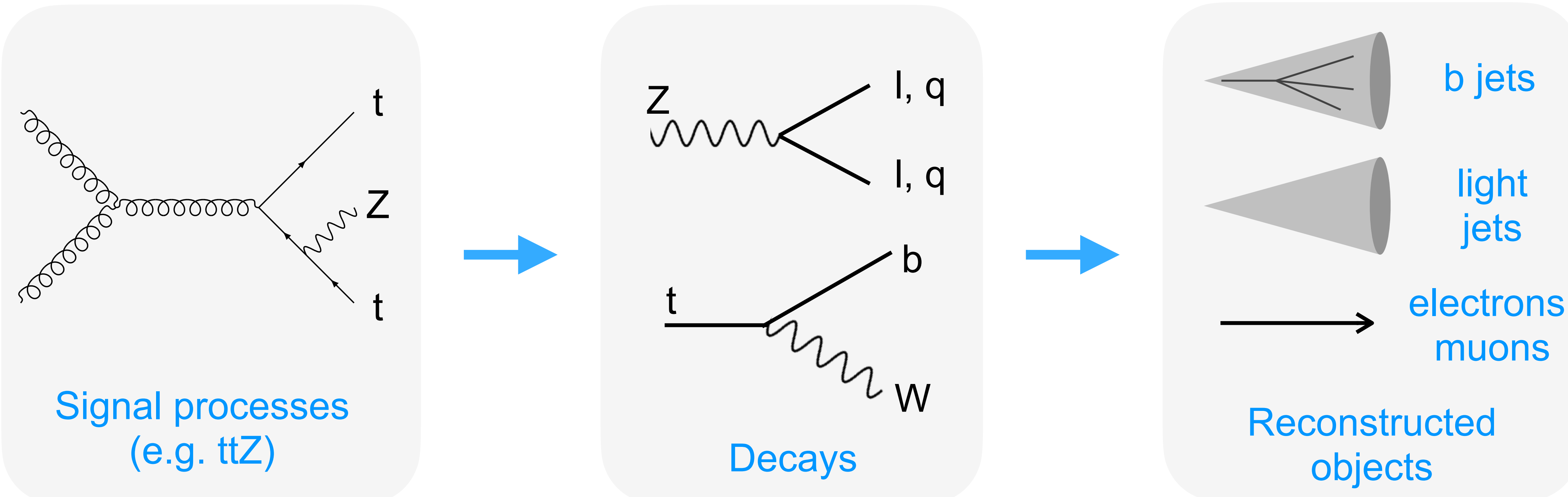
Strategy for multilepton EFT analysis (TOP-22-006)

- Make use of the fact that the yield depends quadratically on the WCs
  - EFT effects linear in amplitude: $\mathscr{M} = \mathscr{M}_{SM} + \sum_i c_i \mathscr{M}_i$ ← c_i are the WCs
  - So σ depends quadratically: $d\sigma(c_1) \propto |\mathscr{M}_{SM} + c_1 \mathscr{M}_1|^2 \propto s_0 + s_1 c_1 + s_2 c_1^2$ (SM: s_0; Interference with SM: $s_1 c_1$; Pure NP: $s_2 c_1^2$)
  - Each generated event's weight will also depend quadratically, find the functional dependence via MG reweighing procedure

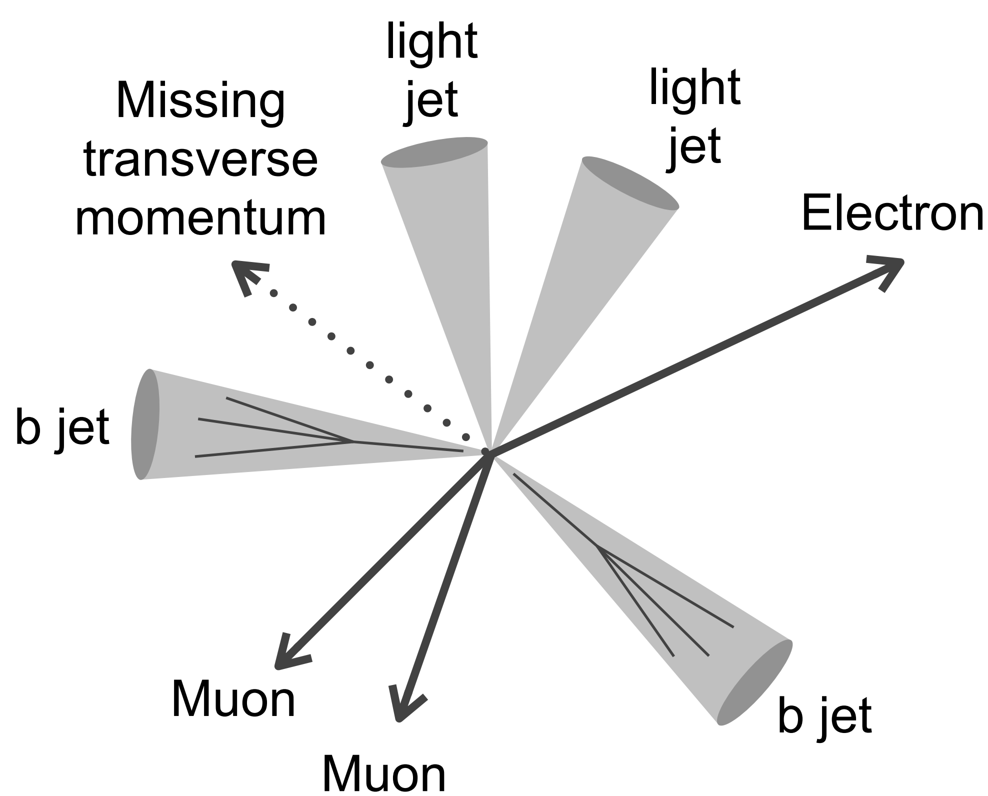


Note: These are actually n-dimensional quadratics for each even, where n = number of WCs (so 26d for TOP-22-006)

Experimental signatures (TOP-22-006)



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



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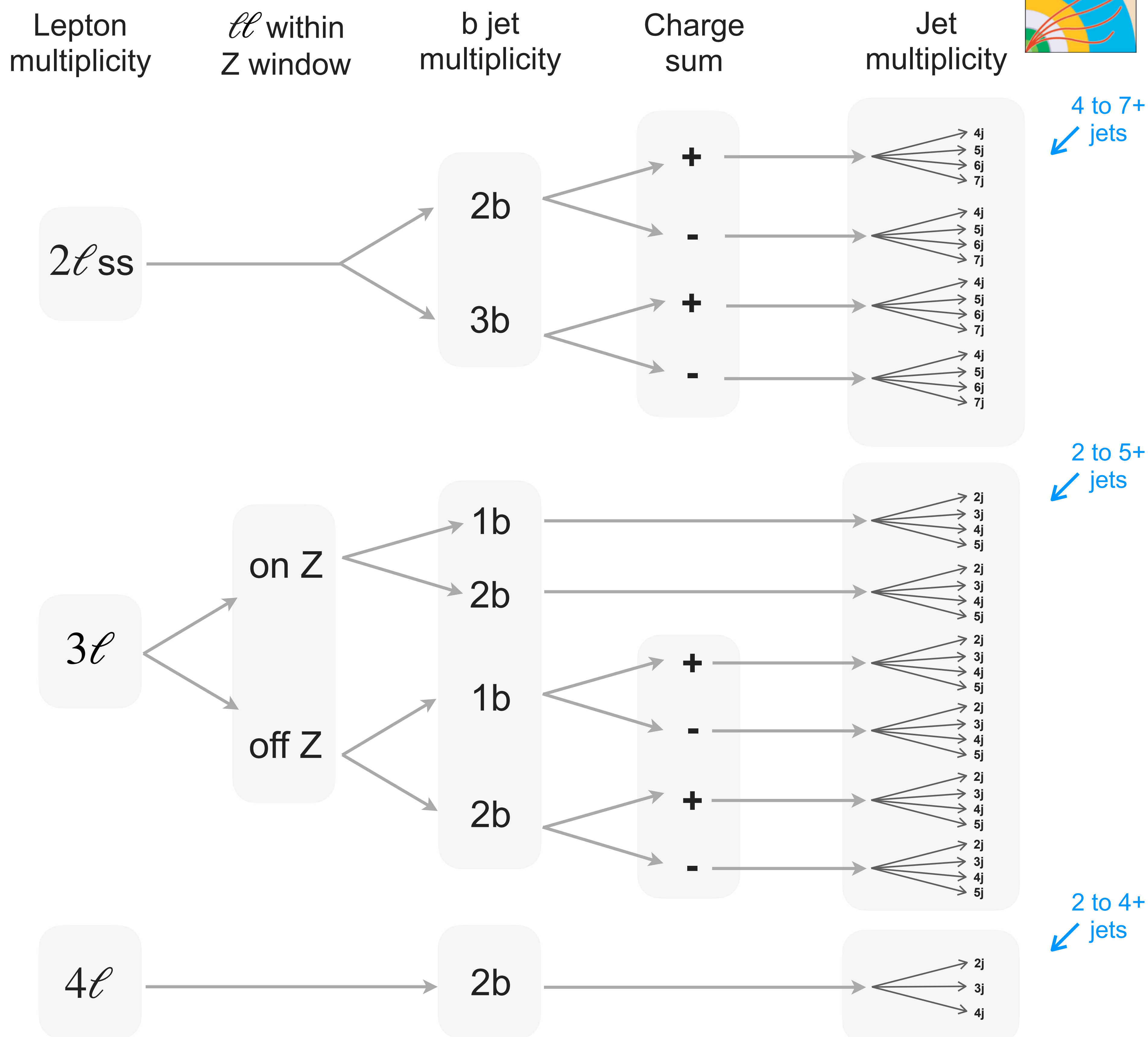
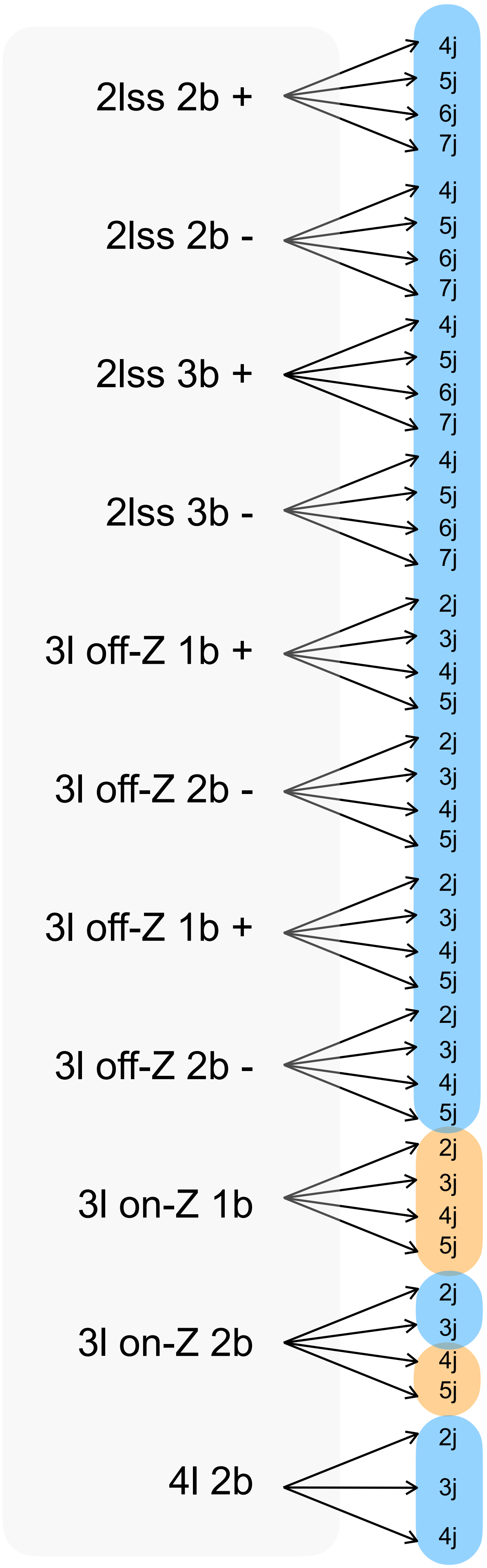
Event selection summary TOP-22-006

We're interested in leptonic decays of associated top processes

The categorization aims to differentiate between processes as much as possible (since EFT impacts them differently

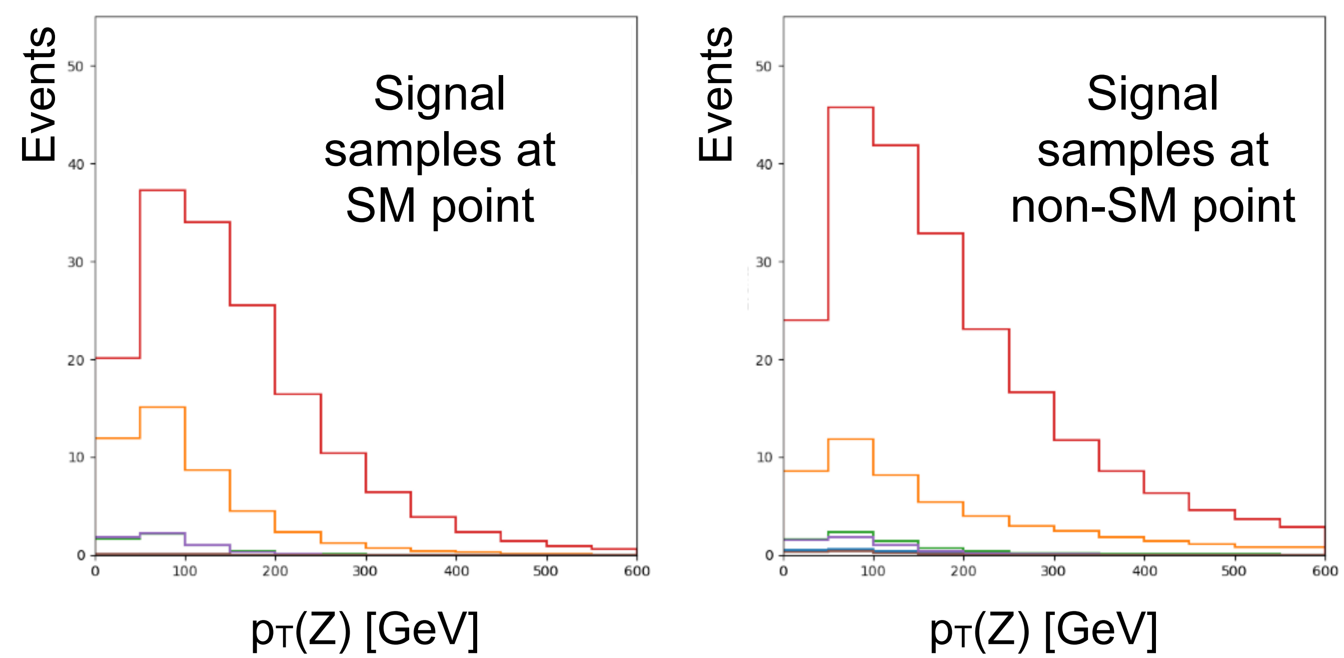


(Note: All highest multiplicity categories (for lep and jets) are inclusive)



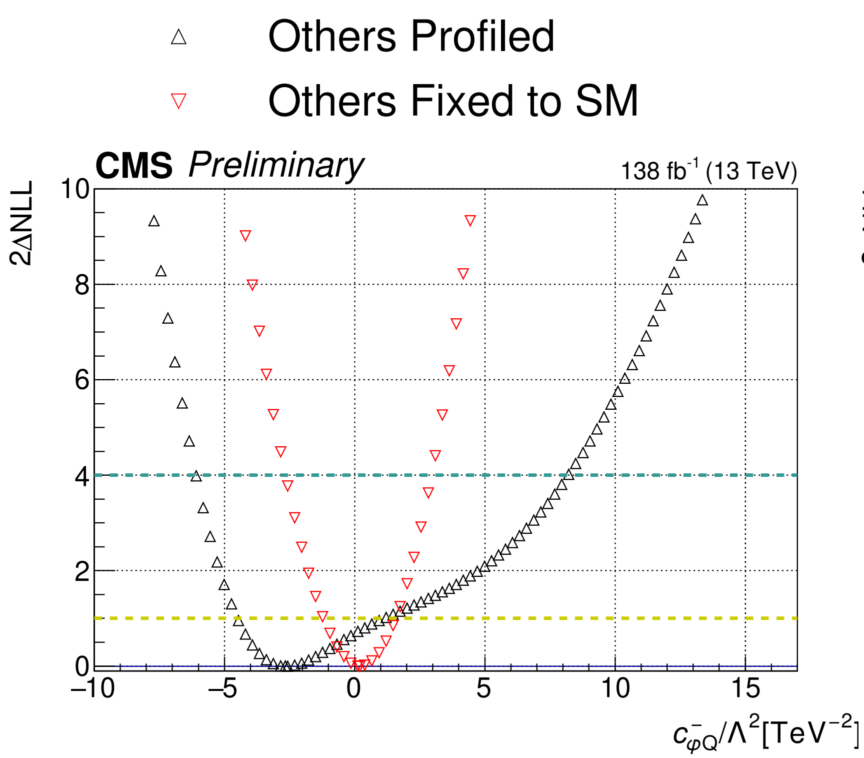
The kinematic distributions used in TOP-22-006

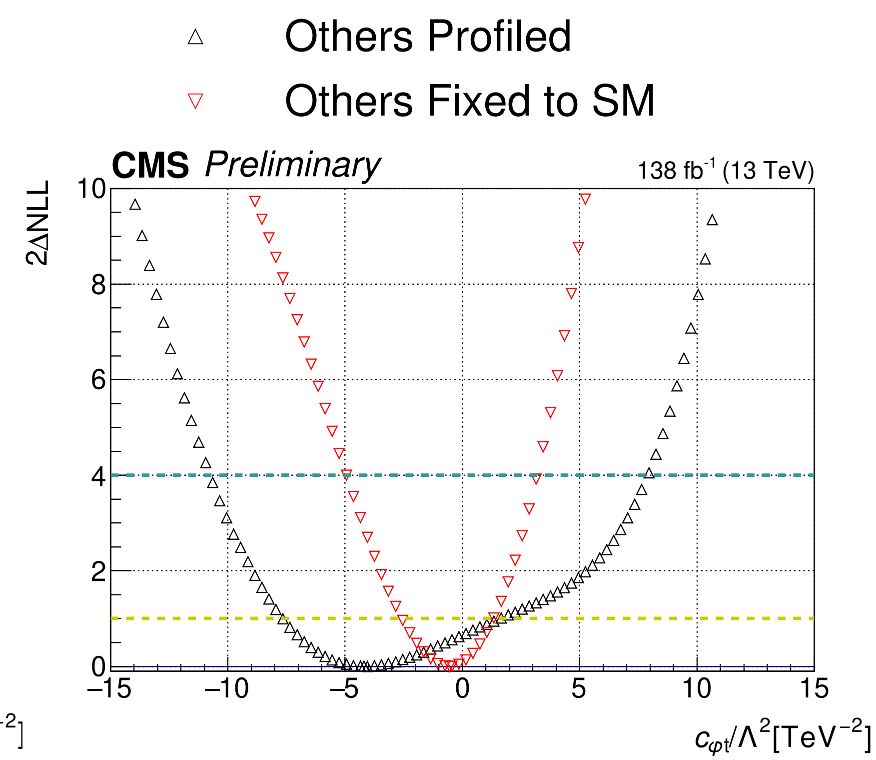
- In order to improve sensitivity, we fit a differential kinematic distribution for each of the 43 categories
- Use different variables ($p_T(lj)_0$, $p_T(Z)$) in different regions to optimize sensitivity to EFT effects

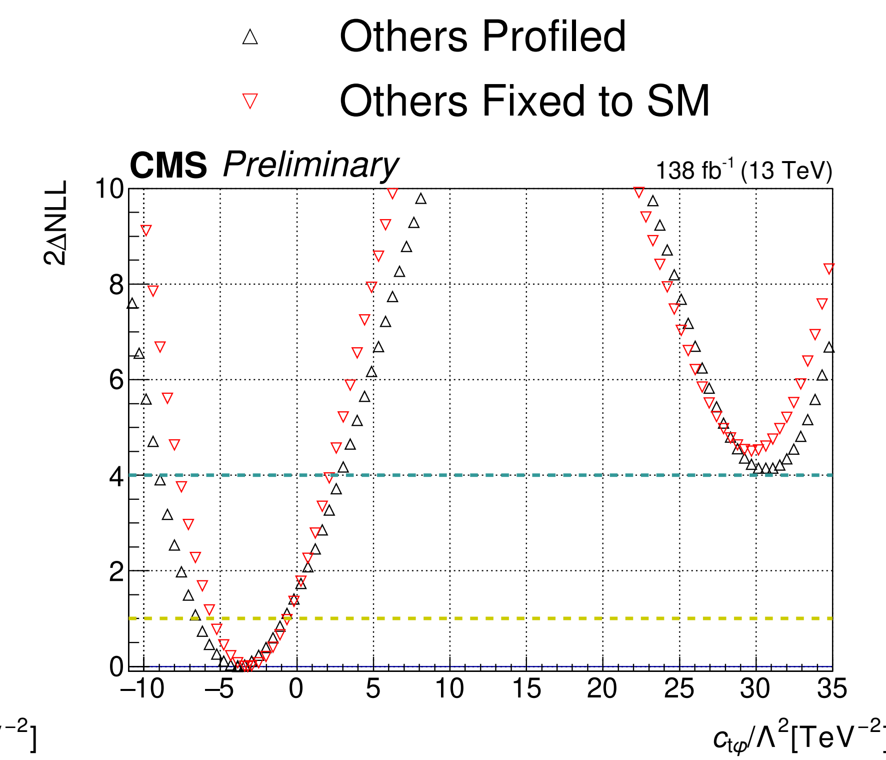


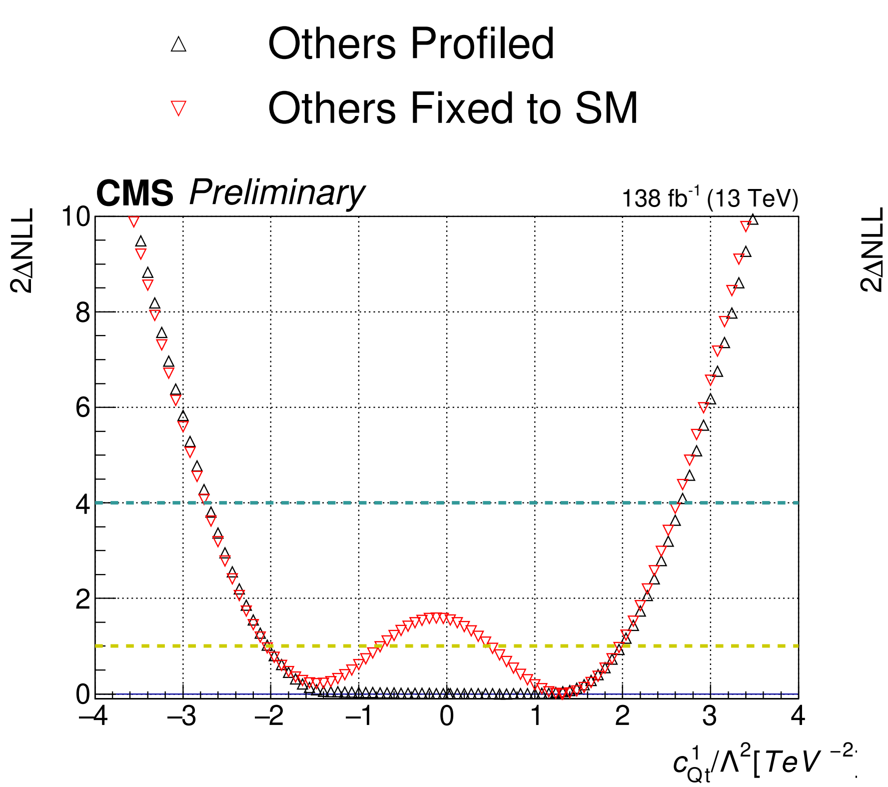
When we reweight to a non-SM point, we can see the shape and normalization of the distribution changes

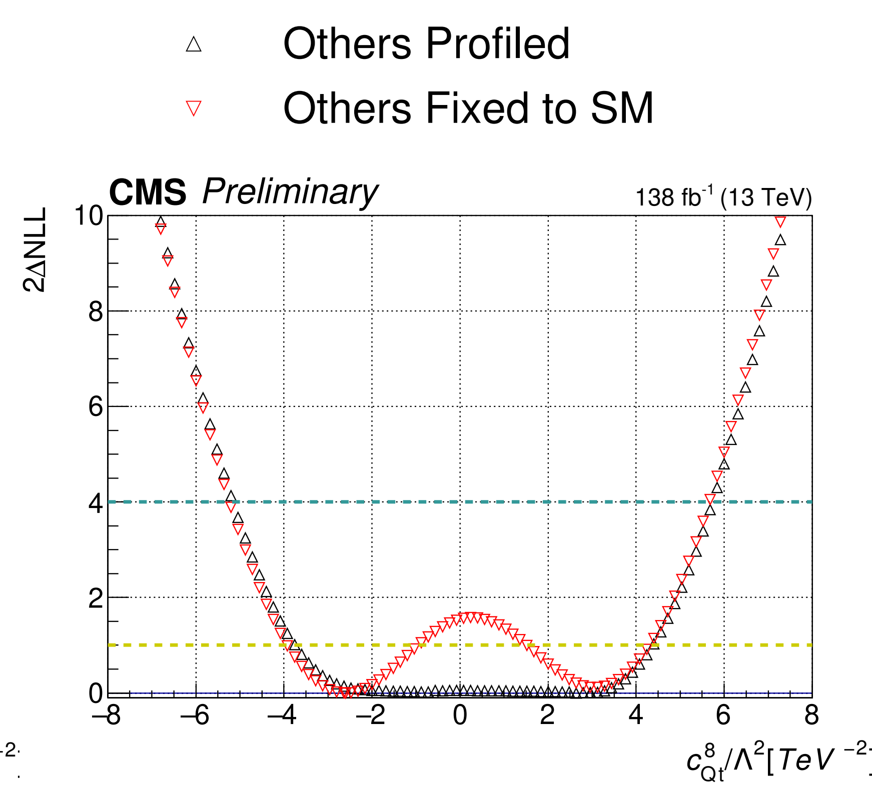
Example one-dimensional scans TOP-22-006

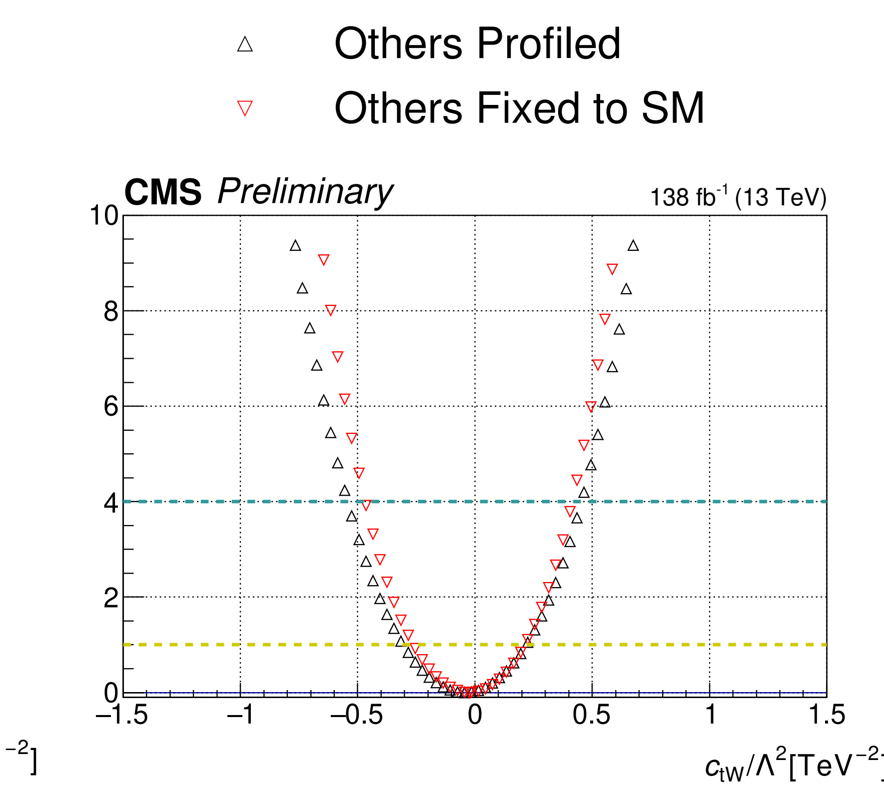












Interpretation of sensitivity TOP-22-006

- The sensitivity to most of the WCs comes from a wide range of bins across all selection 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

Kelci Mohrman, University of Notre Dame

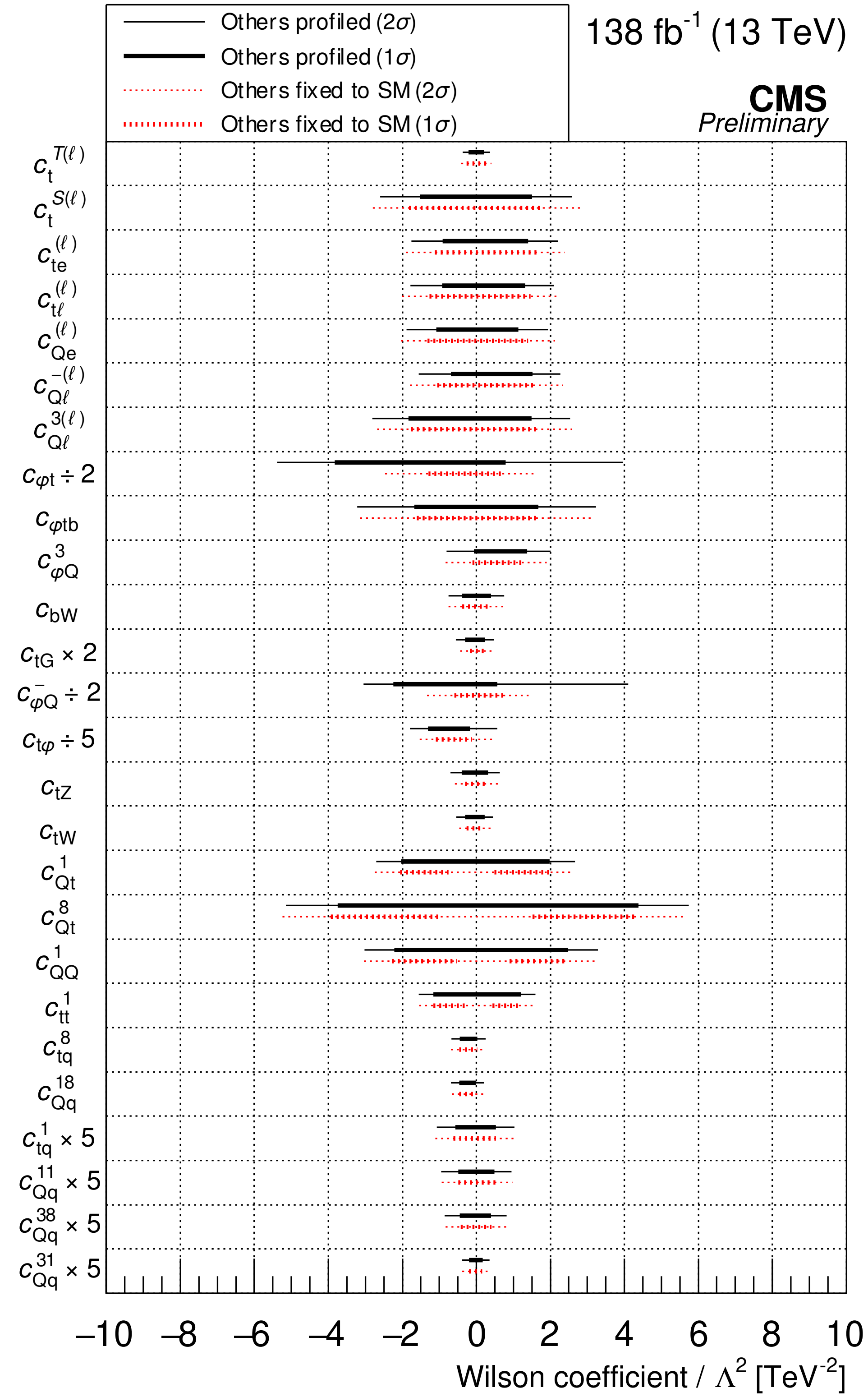
CMS PAS TOP-22-006 limits

WC/Λ^2 [TeV^{-2}]	2σ Interval (others profiled)	2σ Interval (others fixed to SM)
$c_{t}^{T(\ell)}$	[-0.37, 0.37]	[-0.40, 0.40]
$c_{t}^{S(\ell)}$	[-2.60, 2.59]	[-2.80, 2.80]
$c_{te}^{(\ell)}$	[-1.76, 2.20]	[-1.90, 2.39]
$c_{t\ell}^{(\ell)}$	[-1.78, 2.10]	[-2.01, 2.20]
$c_{Qe}^{(\ell)}$	[-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]
$c_{\varphi t}$	[-10.76, 7.91]	[-4.95, 3.19]
$c_{\varphi tb}$	[-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_{tG}	[-0.27, 0.24]	[-0.22, 0.25]
$c_{\varphi Q}^{-}$	[-6.09, 8.20]	[-2.66, 2.95]
$c_{t\varphi}$	[-8.98, 2.85]	[-7.68, 2.15]
c_{tZ}	[-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]

Kelci Mohrman, University of Notre Dame

Summary: CMS PAS TOP-22-006

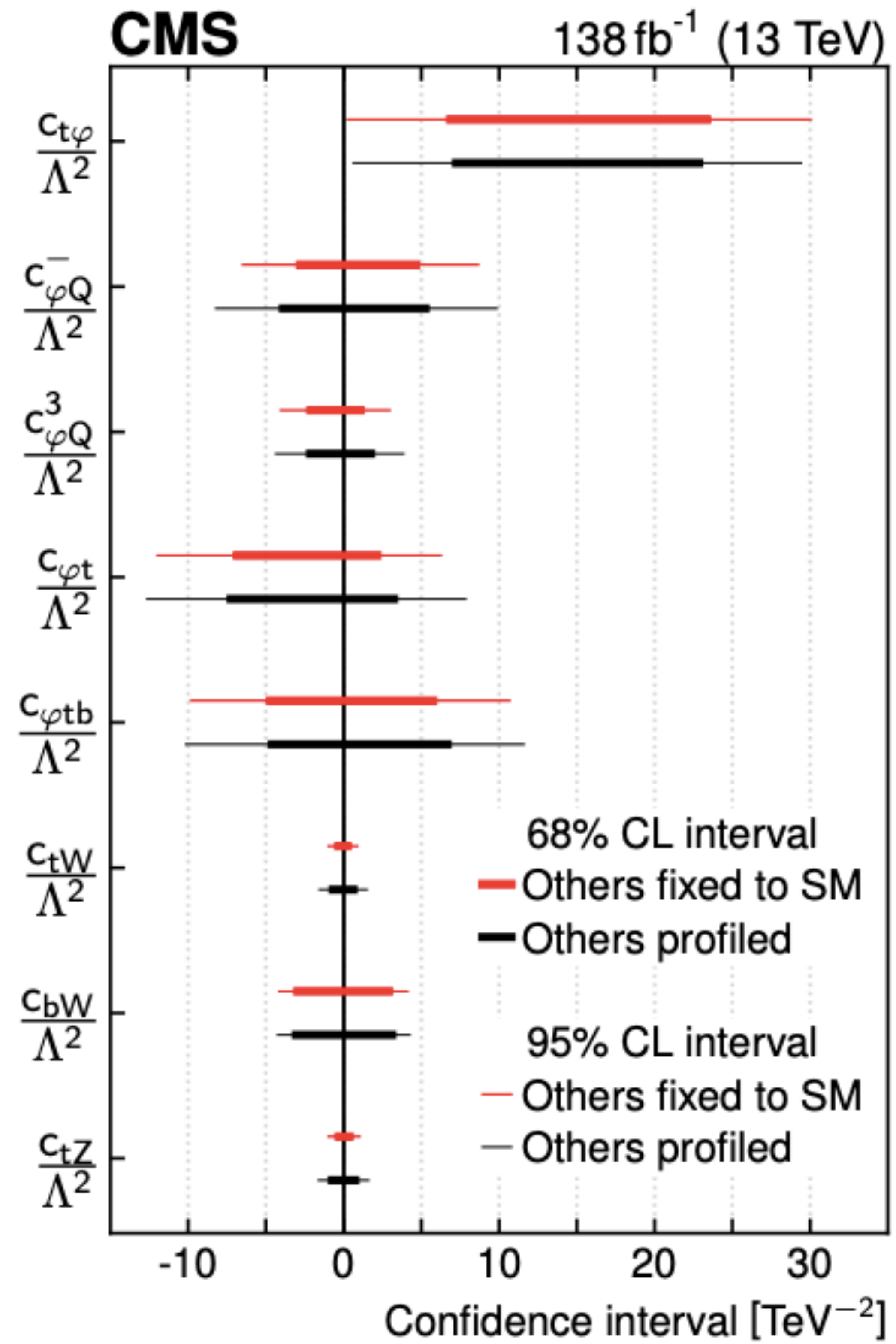
- "Search for new physics in top quark production with additional leptons in the context of effective field theory using 138 fb−1 of proton-proton collisions at √s = 13 TeV"
    - Signal processes: ttH, ttll, ttlnu, tllq, tHq, tttt
    - Multilepton final states (2 same-sign leptons or 3 or more leptons)
- EFT modeling:
    - Parameterize event weights as 26-dimensional quadratics in terms of the WCs in order to target the EFT effects directly at detector level
    - Fit 26 WCs individually and profiled



Summary: CMS TOP-21-003

- "Search for new physics using effective field theory in 13 TeV pp collision events that contain a top quark pair and a boosted Z or Higgs boson"
    - Target ttZ/H where the Z/H is boosted
    - Single lepton signatures

- EFT modeling:
    - Detector level approach (parameterize event weights in terms of the WCs in order to obtain detector level yields as a function of the WCs)
    - Fit 8 WCs (2heavy-with-bosons) individually and profiled



Summary: CMS TOP-21-004

- "Measurement of the inclusive and differential ttγ cross sections in the dilepton channel and effective field theory interpretation in proton-proton collisions at $\sqrt{s}$ = 13 TeV"
  - Target leptonic decays of $t\bar{t}\gamma$
  - Final states: Opposite sign leptons and a photon
- EFT modeling:
  - Studied in bins of photon pt
  - Model operator effects using gen-sample reweighting to estimate the expected SMEFT modifications at the reconstructed level
  - Real and imaginary part of ctZ is studied

	Wilson coefficient		Dilepton result 68% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton result 95% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton & ℓ+jets combination 68% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton & ℓ+jets combination 95% CL interval $[(\Lambda/\mathrm{TeV})^2]$
Expected	c_{tZ}	$c^{I}_{tZ} = 0$	$[-0.28, 0.35]$	$[-0.42, 0.49]$	$[-0.15, 0.19]$	$[-0.25, 0.29]$
		profiled	$[-0.28, 0.35]$	$[-0.42, 0.49]$	$[-0.15, 0.19]$	$[-0.25, 0.29]$
	c^{I}_{tZ}	$c_{tZ} = 0$	$[-0.33, 0.30]$	$[-0.47, 0.45]$	$[-0.17, 0.18]$	$[-0.27, 0.27]$
		profiled	$[-0.33, 0.30]$	$[-0.47, 0.45]$	$[-0.18, 0.18]$	$[-0.27, 0.27]$
Observed	c_{tZ}	$c^{I}_{tZ} = 0$	$[-0.43, -0.09]$	$[-0.53, 0.52]$	$[-0.30, -0.13]$	$[-0.36, 0.31]$
		profiled	$[-0.43, 0.17]$	$[-0.53, 0.51]$	$[-0.30, 0.00]$	$[-0.36, 0.31]$
	c^{I}_{tZ}	$c_{tZ} = 0$	$[-0.47, -0.03] \cup [0.07, 0.38]$	$[-0.58, 0.52]$	$[-0.32, -0.13] \cup [0.16, 0.29]$	$[-0.38, 0.36]$
		profiled	$[-0.43, 0.33]$	$[-0.56, 0.51]$	$[-0.28, 0.23]$	$[-0.36, 0.35]$

Summary: CMS TOP-21-001

- "Probing effective field theory operators in the associated production of top quarks with a Z boson in multilepton final states at $\sqrt{s}$ = 13 TeV"
    - Target ttZ and tZq
    - Multilepton final states (3 or 4 leptons)
- EFT modeling:
    - Detector level approach (parameterize event weights in terms of the WCs in order to obtain detector level yields as a function of the WCs)
    - Probe 5 WCs, fit individually and profiled

WC/Λ^2 $[\mathrm{TeV}^{-2}]$	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}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^{3}_{\varphi\mathrm{Q}}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^{-}_{\varphi\mathrm{Q}}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi\mathrm{t}}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

Summaries of the ATLAS analyses

ATLAS-CONF-2023-001

- "Search for charged-lepton-flavour violating $\mu\tau qt$ interaction in top-quark production and decay with the ATLAS detector at the LHC"
  - The analysis targets events containing two muons, a hadronically decaying tau lepton and at least one jet, with exactly one b-tagged jet, produced by a $\mu\tau qt$ interaction in top-quark production or decay
  - No excess above the Standard Model background is observed

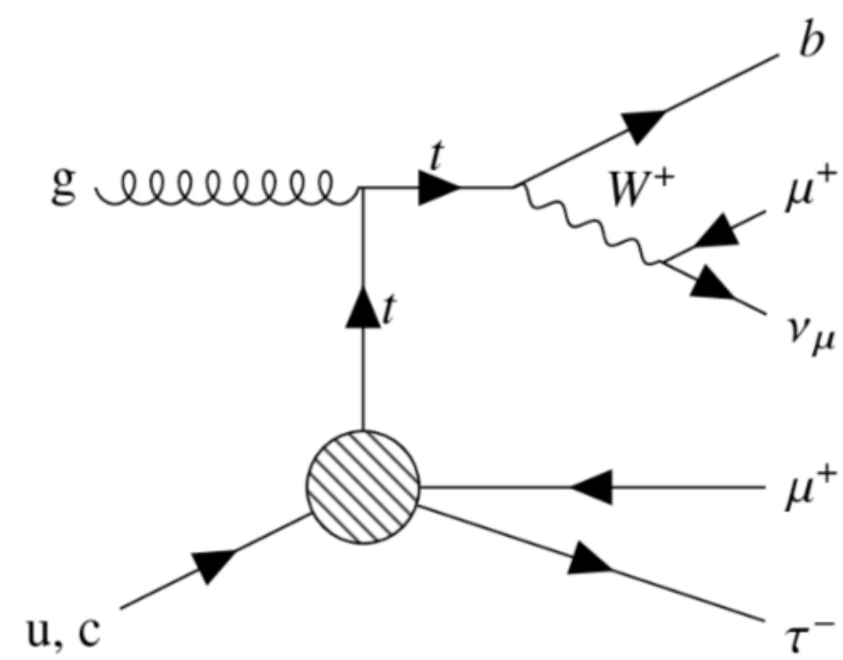


Table 7: Expected and observed 95% CL upper limits on Wilson coefficients corresponding to 2Q2L EFT operators which could introduce cLFV top decay in the $\mu\tau$ channel, and existing limits from Ref. [22] (previous). Results are shown separately for $\mu\tau ut$ and $\mu\tau ct$ interactions. The lepton generations are denoted by $i, j = 2, 3$ for μ and τ (where $i \neq j$) and the quark generations are denoted by $k = 1, 2$ for u and c, respectively.

	95% CL upper limits on Wilson coefficients c/Λ^2 [TeV^{-2}]							
	$c_{lq}^{-(ijk3)}$	$c_{eq}^{(ijk3)}$	$c_{lu}^{(ijk3)}$	$c_{eu}^{(ijk3)}$	$c_{lequ}^{1(ijk3)}$	$c_{lequ}^{1(ij3k)}$	$c_{lequ}^{3(ijk3)}$	$c_{lequ}^{3(ij3k)}$
Previous (u) [22]	12	12	12	12	26	26	3.4	3.4
Expected (u)	0.47	0.44	0.43	0.46	0.49	0.49	0.11	0.11
Observed (u)	0.49	0.47	0.46	0.48	0.51	0.51	0.11	0.11
Previous (c) [22]	14	14	14	14	29	29	3.7	3.7
Expected (c)	1.6	1.6	1.5	1.6	1.8	1.8	0.35	0.35
Observed (c)	1.7	1.6	1.6	1.6	1.9	1.9	0.37	0.37

ATLAS: Eur. Phys. J. C 83 (2023) 496

- "Observation of four-top-quark production in the multilepton final state with the ATLAS detector"
  - $t\bar{t}t\bar{t}$ in multilepton final states (2lss or 3 or more leps)
- EFT approach:
  - Parameterizing the 4t yield in each bin of the GNN score distribution as a quadratic function of the coefficient of the corresponding EFT operator and performing the fit to data
  - Probe 4 WCs (of the 4heavy WC category)
  - Perform the fit individually (on WC at a time)

Table 8: Expected and observed 95% CL intervals on EFT coupling parameters assuming one EFT parameter variation in the fit.

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

ATLAS: Eur. Phys. J. C 83 (2023) 496

- Comparison with limits from TOP-22-006 for the 4heavy operators

Table 8: Expected and observed 95% CL intervals on EFT coupling parameters assuming one EFT parameter variation in the fit.

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

ATLAS 2303.15061

(Note, the WCs are in different orders!)

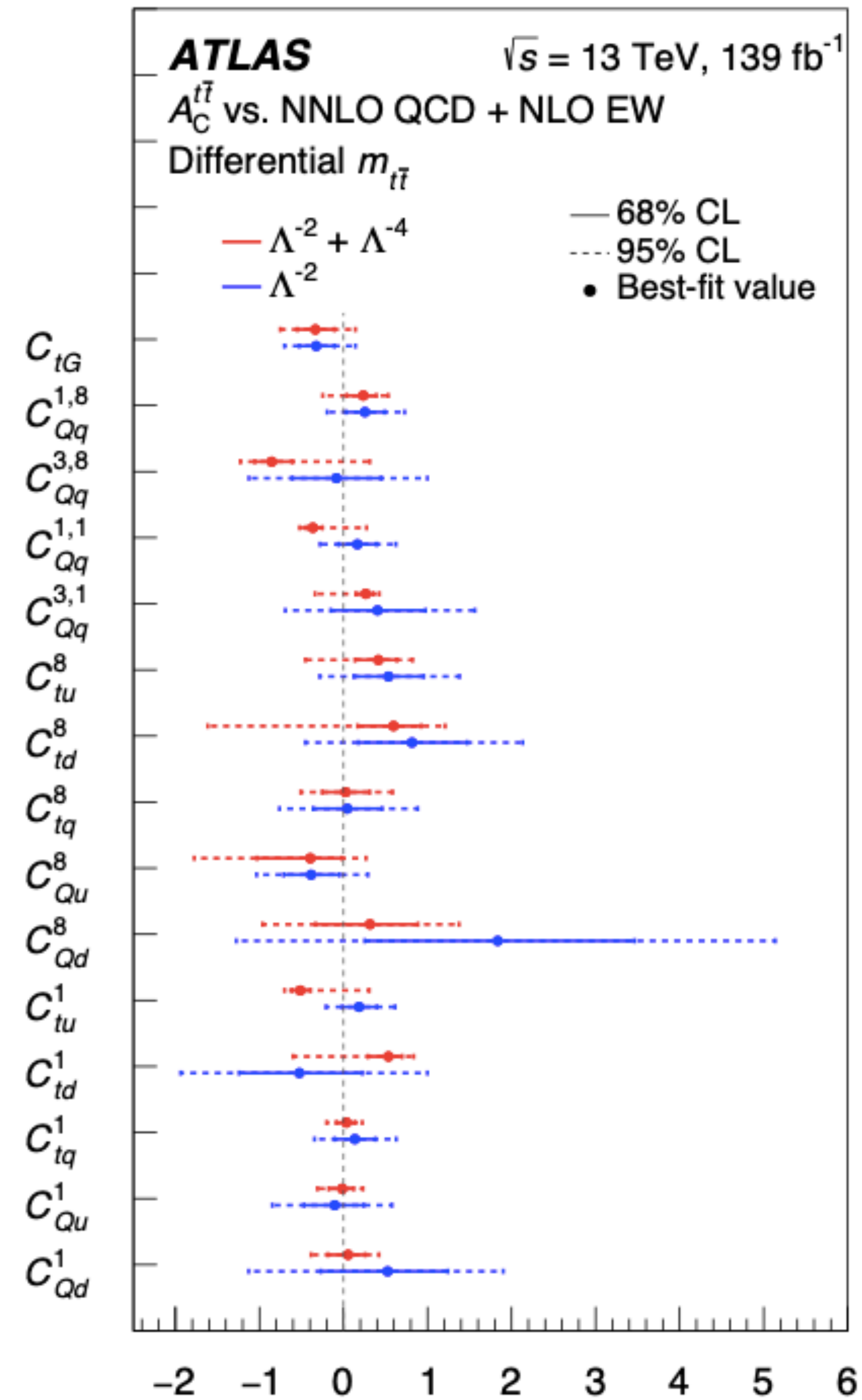
Table 4: The 2σ uncertainty intervals extracted from the likelihood fits described in Section 7. The intervals are shown for the case where the other WCs are profiled, and the case where the other WCs are fixed to their SM values of zero.

WC/Λ^2 [TeV^{-2}]	2σ Interval (others profiled)	2σ Interval (others fixed to SM)
c^1_{Qt}	[-2.71, 2.66]	[-2.75, 2.62]
c^8_{Qt}	[-5.15, 5.74]	[-5.24, 5.66]
c^1_{QQ}	[-3.03, 3.28]	[-3.04, 3.28]
c^1_{tt}	[-1.56, 1.60]	[-1.54, 1.63]

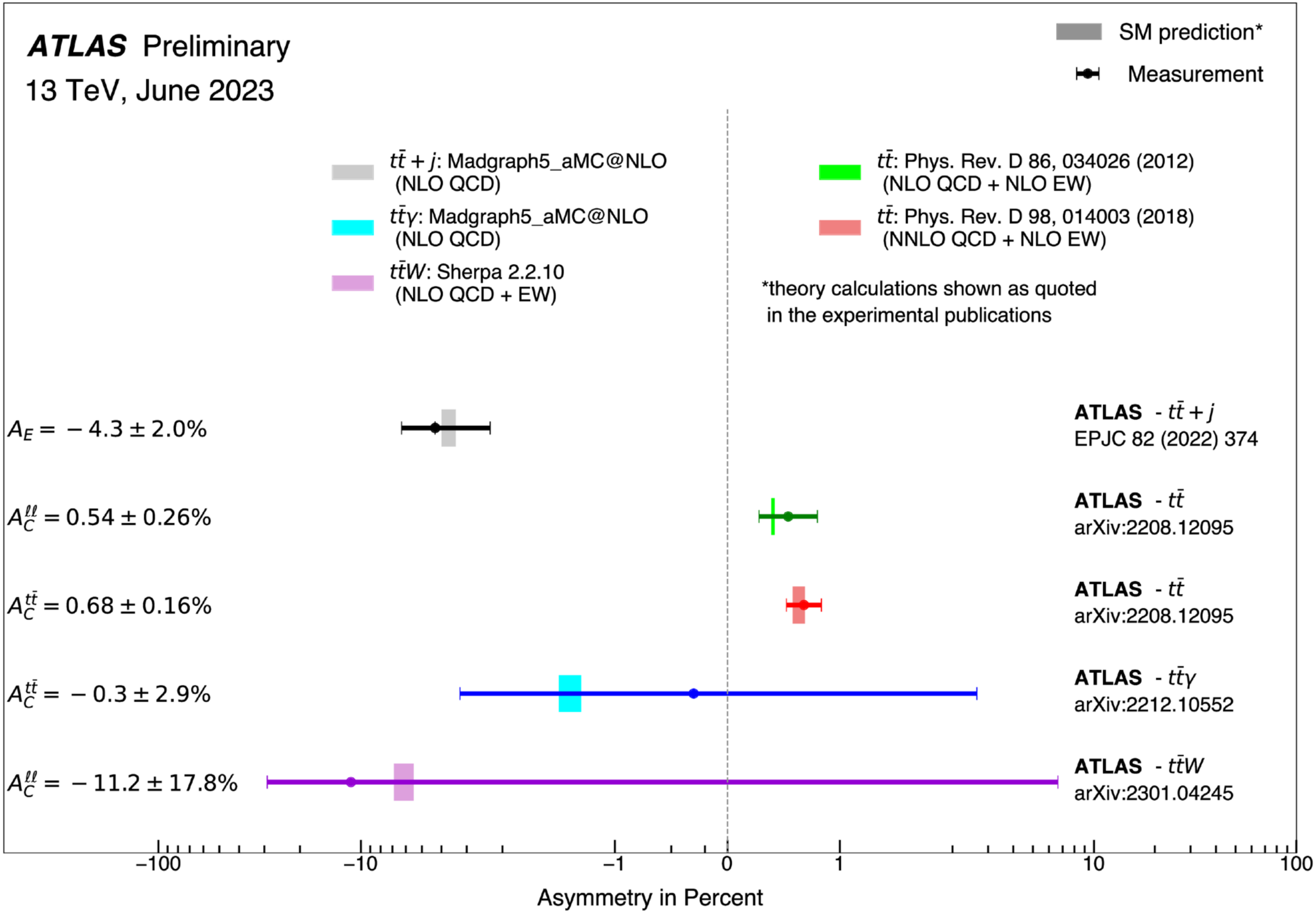
CMS TOP-22-006

ATLAS: 2208.12095

- "Evidence for the charge asymmetry in $p\,p \to t\,t$ production at $\sqrt{s}$ = 13 TeV with the ATLAS detector"
  - Single- and di-lepton $t\bar{t}$ charge asymmetry
  - Unfolding performed to correct for detector resolution and acceptance effects
  - Single-lepton and dilepton channels, both resolved and boosted topologies
- EFT approach:
  - Study 15 WCs
  - The WCs are fit individually and in pairs, to $A_c^{t\bar{t}}$ vs $m_{t\bar{t}}$



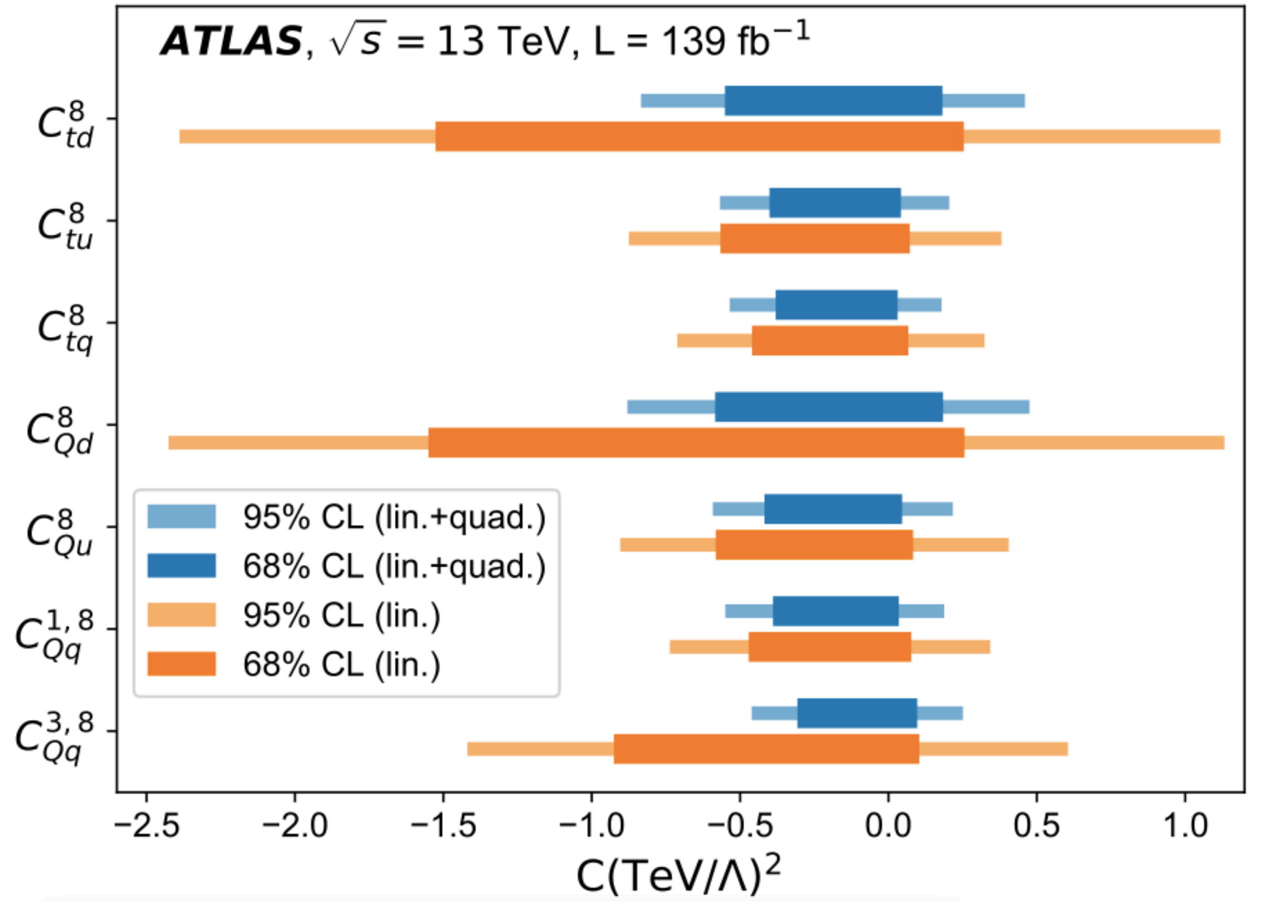
ATLAS: 2208.12095



ATLAS: JHEP 04 (2023) 80

- "Differential tt cross-section measurements using boosted top quarks in the all-hadronic final state with 139 fb^{-1} of ATLAS data"
  - Hadronic, $t\bar{t}$
  - The observed data are unfolded to remove detector effects

- EFT approach:
  - Fit to the $p_T^{t,1}$ distribution (pt of leading top jet)
  - Limits on 7 WCs (2light-2heavy) individually and in pairs (ctG also included in one pair)



ATLAS: 2202.12134

- "Measurements of differential cross-sections in top-quark pair events with a high transverse momentum top quark and limits on beyond the Standard Model contributions to top-quark pair production with the ATLAS detector at $\sqrt{s}$ = 13 TeV"
    - Semi-leptonic, $t\bar{t}$
    - Data is unfolded
- EFT approach:
    - Fit the top quark pt distribution
    - Study two WCs: ctG and ctq8
    - WCs are fit individually and together

Model	$C_i\ (\Lambda/\text{TeV})^2$	Marginalised 95% intervals Expected	Marginalised 95% intervals Observed	Individual 95% intervals Expected	Individual 95% intervals Observed	Global fit 95% limits [111]
Λ^{-4}	C_{tG}	[−0.44, 0.35]	[−0.53, 0.21]	[−0.44, 0.28]	[−0.52, 0.15]	[0.006, 0.107]
	$C_{tq}^{(8)}$	[−0.57, 0.17]	[−0.60, 0.13]	[−0.57, 0.18]	[−0.64, 0.12]	[−0.48, 0.39]
Λ^{-2}	C_{tG}	[−0.44, 0.44]	[−0.68, 0.21]	[−0.41, 0.42]	[−0.63, 0.20]	[0.007, 0.111]
	$C_{tq}^{(8)}$	[−0.35, 0.35]	[−0.30, 0.36]	[−0.35, 0.36]	[−0.34, 0.27]	[−0.40, 0.61]

ATLAS: [2202.11382]

- "Measurement of the polarisation of single top quarks and antiquarks produced in the t-channel at $\sqrt{s}$ = 13 TeV and bounds on the tWb dipole operator from the ATLAS experiment"
  - Study t channel single-top
  - Leptonic
  - The top-quark and top-antiquark polarisation vectors are measured from the distributions of the direction cosines of the charged-lepton momentum in the top-quark rest frame
- EFT approach:
  - Perform an interpretation of the unfolded normalised differential angular distributions in an EFT context
  - The angular differential cross-sections are used, the unfolded and normalised distributions of $\cos\theta_{\ell x'}$ and $\cos\theta_{\ell y'}$ (cos of the charged lepton momentum in the top rest frame)
  - Study two WCs: The real and imaginary part of ctW

	C_{tW}		C_{itW}	
	68% CL	**95% CL**	**68% CL**	**95% CL**
All terms	$[-0.3, 0.8]$	$[-0.9, 1.4]$	$[-0.5, -0.1]$	$[-0.8, 0.2]$
Order $1/\Lambda^4$	$[-0.3, 0.8]$	$[-0.9, 1.4]$	$[-0.5, -0.1]$	$[-0.8, 0.2]$
Order $1/\Lambda^2$	$[-0.3, 0.8]$	$[-0.8, 1.5]$	$[-0.6, -0.1]$	$[-0.8, 0.2]$

ATLAS: [2202.11382]

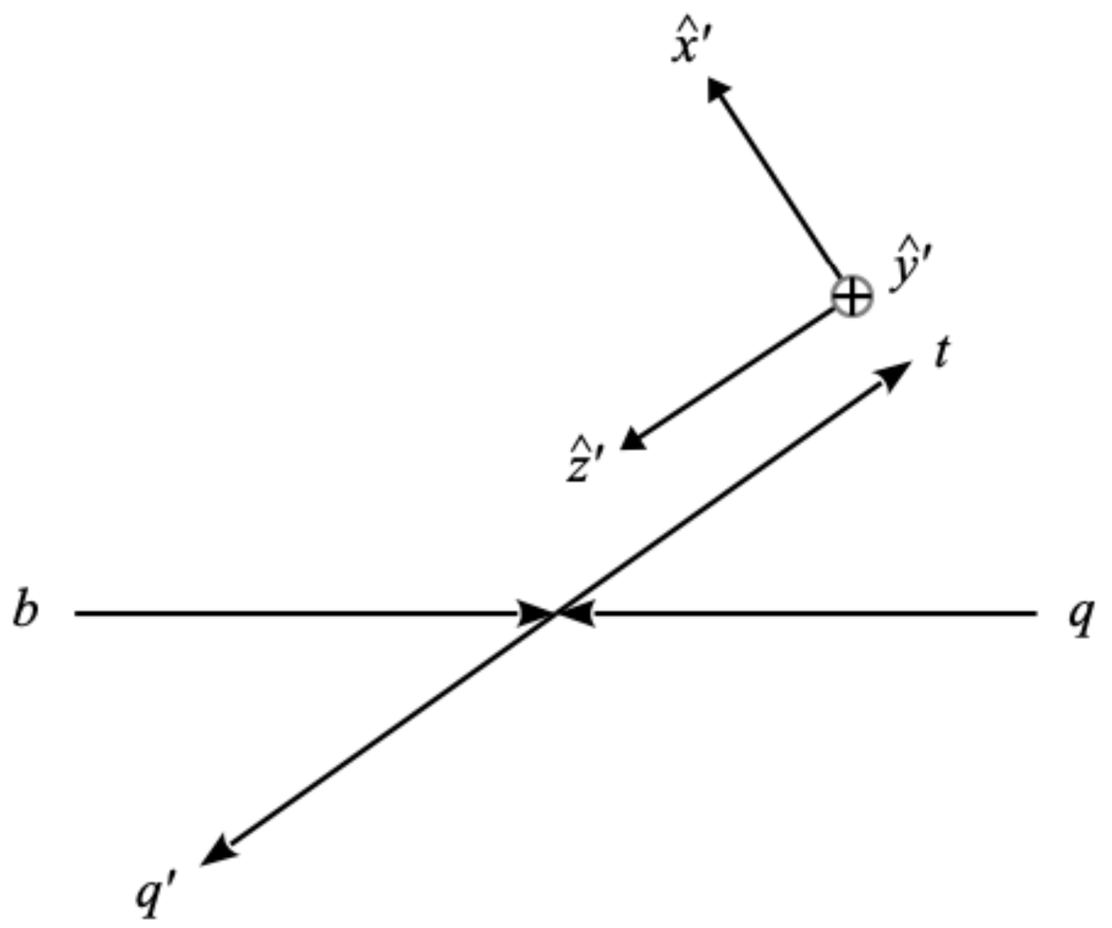


Figure 2: Diagram illustrating the three orthogonal directions $\hat{x}'$, $\hat{y}'$ and $\hat{z}'$ used in this analysis, as seen in the zero-momentum frame of the initial-state quarks. The $\hat{z}'$ direction is that of the spectator quark in the top-quark rest frame. The $\hat{x}'$ direction lies in the production plane, while the $\hat{y}'$ direction is perpendicular to the production plane.