EFT results in the top sector with the ATLAS detector

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On behalf of the ATLAS Collaboration

Where is all the BSM?

Where is all the BSM?

- **Community currently focused on the next collider, to measure Higgs couplings with precision.**
- **Easy to forget that we haven't even done half of the top ones** (and those we have still giving surprises)**!**

γ g Z

b t H

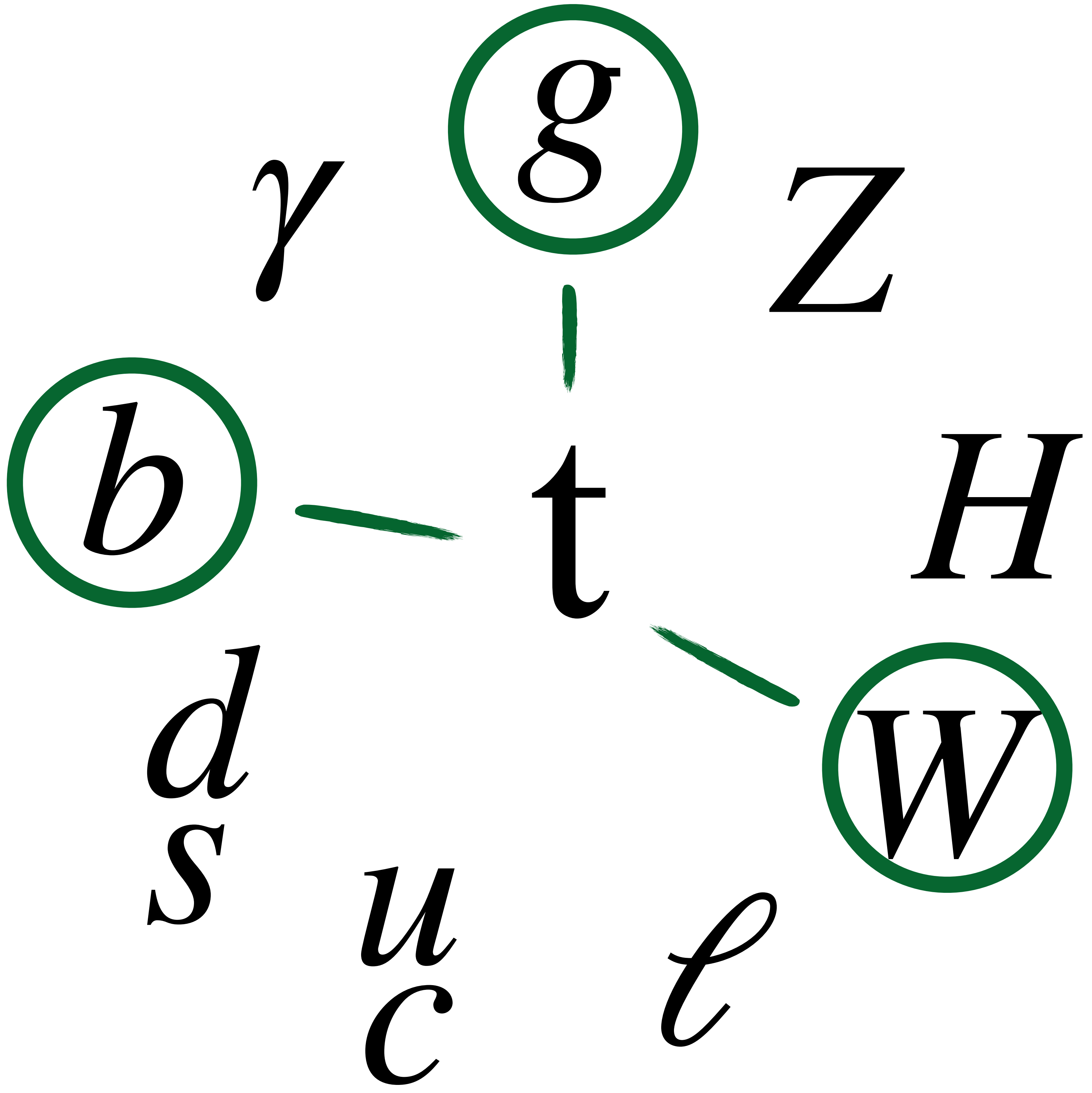
d W

s u ℓ

c

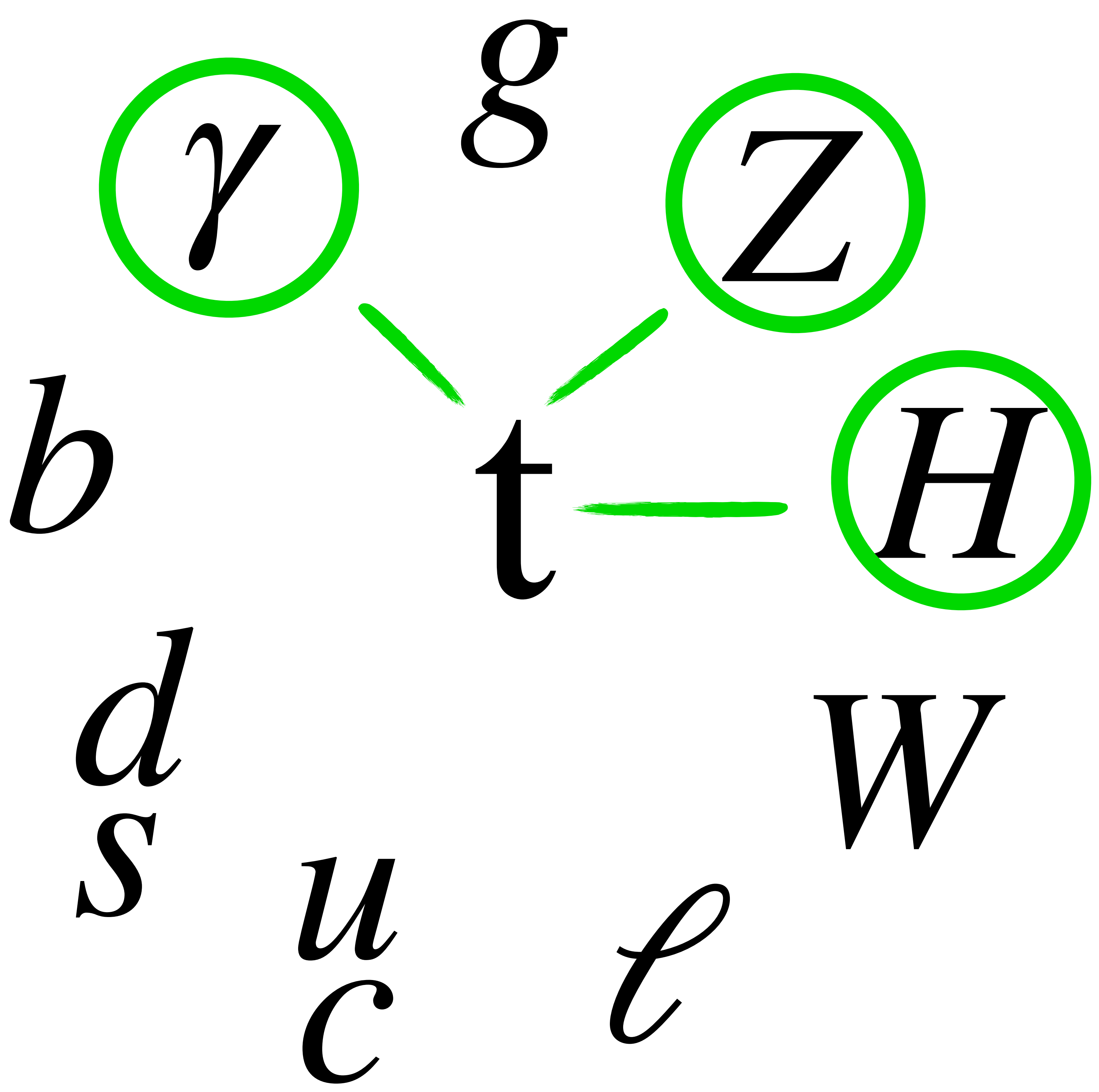
Where is all the BSM?

- **We have probed the top's interactions with some particles in great detail.**
- **However, surprises still happen at high precision!** (See topponium for a timely example of top-gluon surprises)**.**



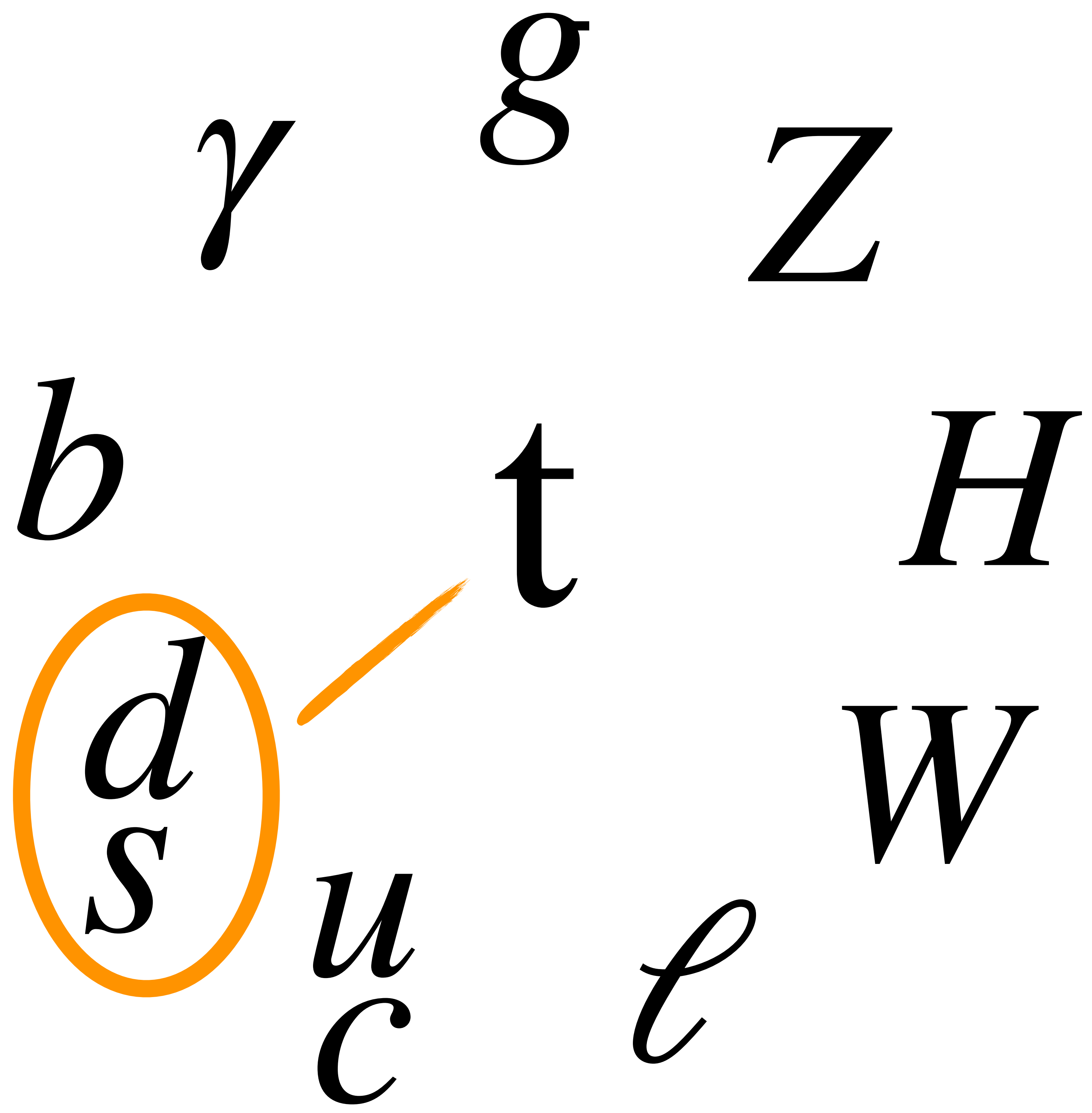
Where is all the BSM?

- Some couplings we have only just begun to access and understand relatively poorly.
- These are excellent avenues to probe for new Physics and exploring them will be a key exploit of the HL-LHC.



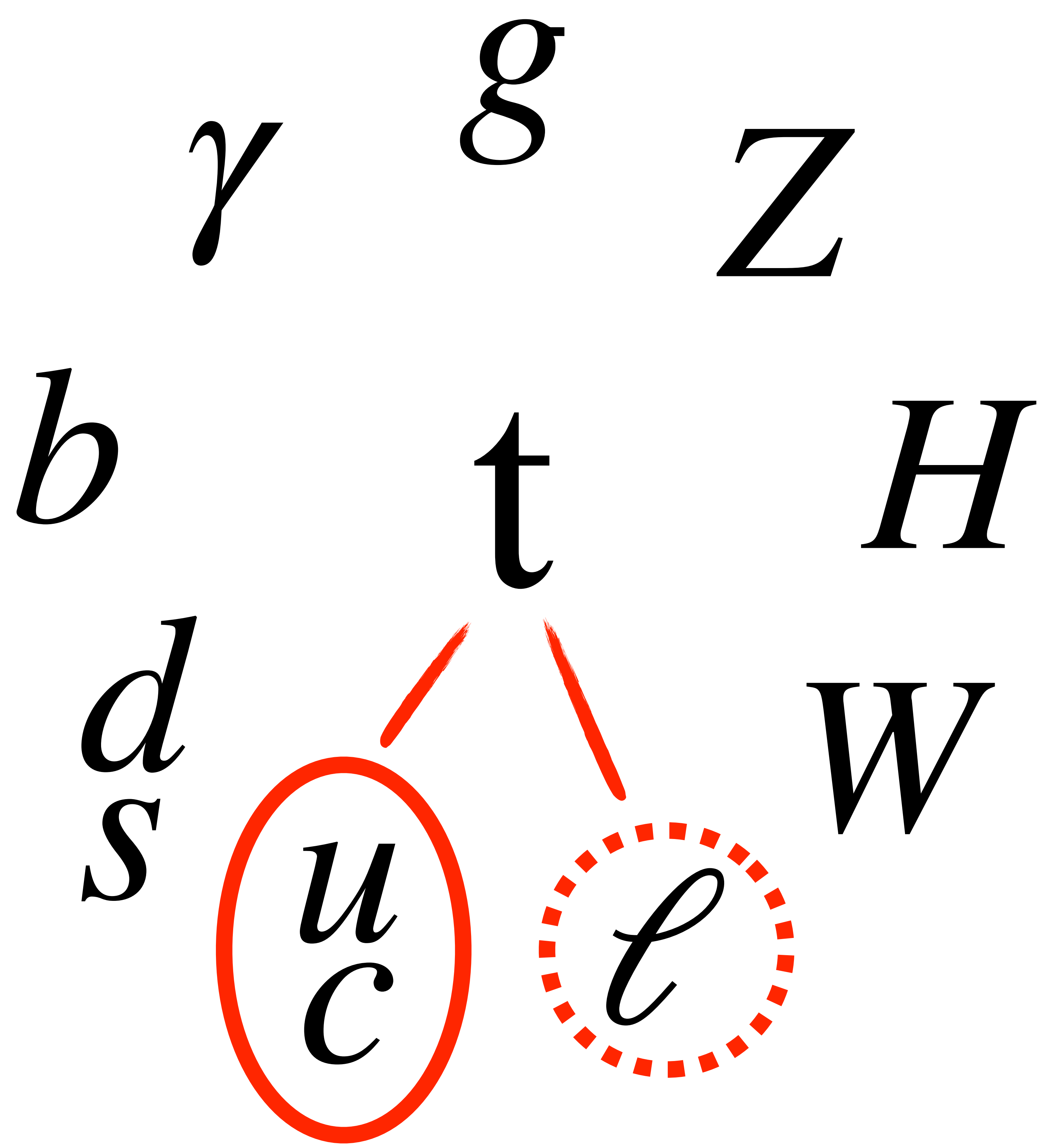
Where is all the BSM?

- Even with the HL-LHC, some will test our experimental abilities to the limits to even observe!



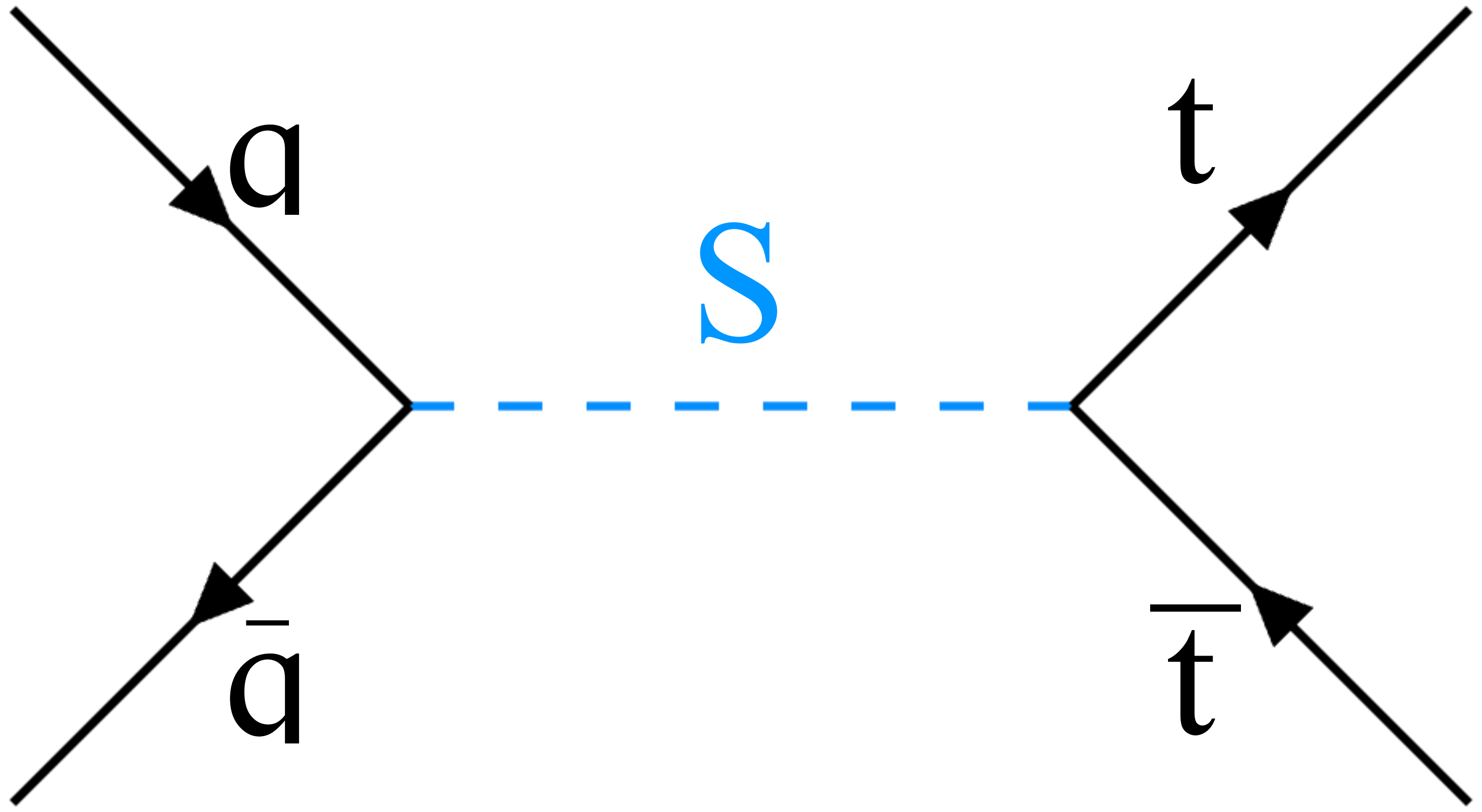
Where is all the BSM?

- **And some can only exist with FCNC** (loop, CKM, and GIM suppressed, unless BSM) **or more exotic signatures** (making them excellent avenues to probe for BSM)

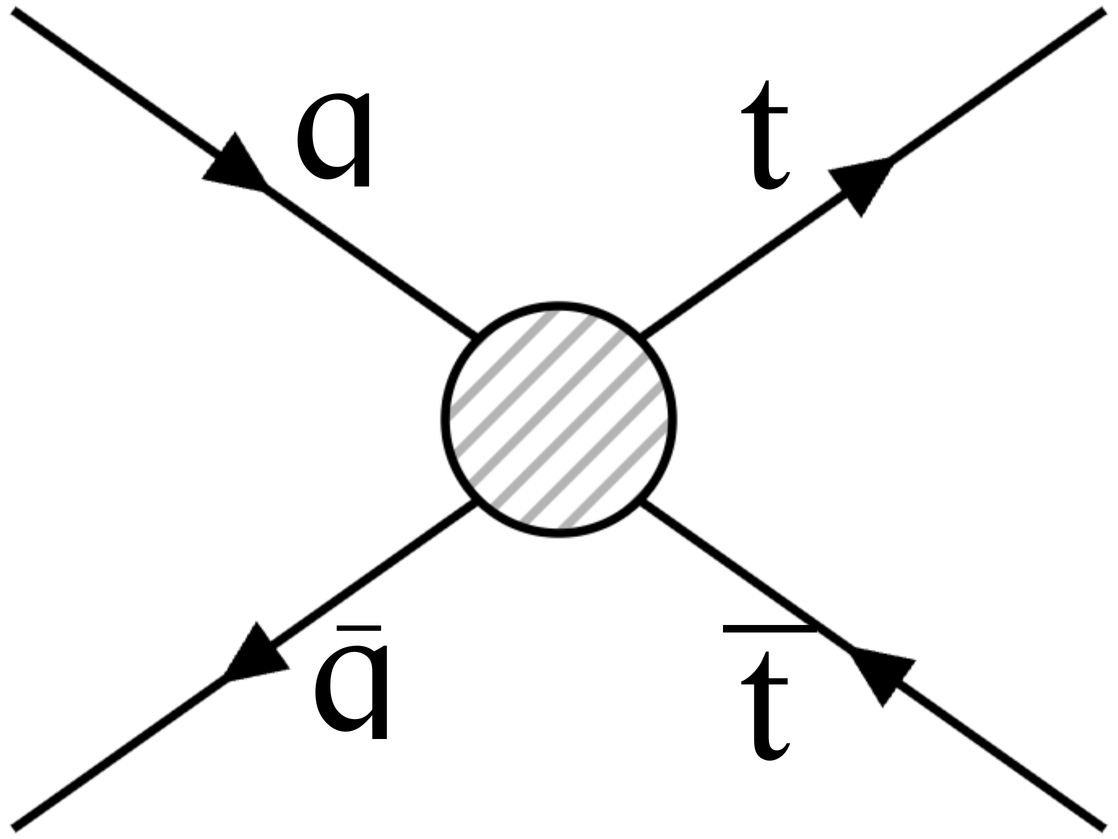


EFT vs UV Complete

- **EFT's are a convenient way to describe deviations and probe sensitivity** (but are not BSM models)**.**



$m(S),\ \Gamma(S),\ \alpha_S$



$C_{qu}^{(1)33ii}$ $C_{qd}^{(1)33ii}$ $C_{qd}^{(1)ii33}$

$C_{qu}^{(8)33ii}$ $C_{qd}^{(8)33ii}$ $C_{qd}^{(8)ii33}$

- **UV complete models described by multiple EFT operators.**

Top EFT

Top EFT

$t\bar{t}$ is the most prevalent form of top production at the LHC. Operators are related to the gluon or quark initiated production.

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\,\bar{t}$

Top EFT

C_{HWB} C_{HD} C_{ll} $C_{HQ}^{(1)}$

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$ $C_{HQ}^{(3)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

EWPO

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

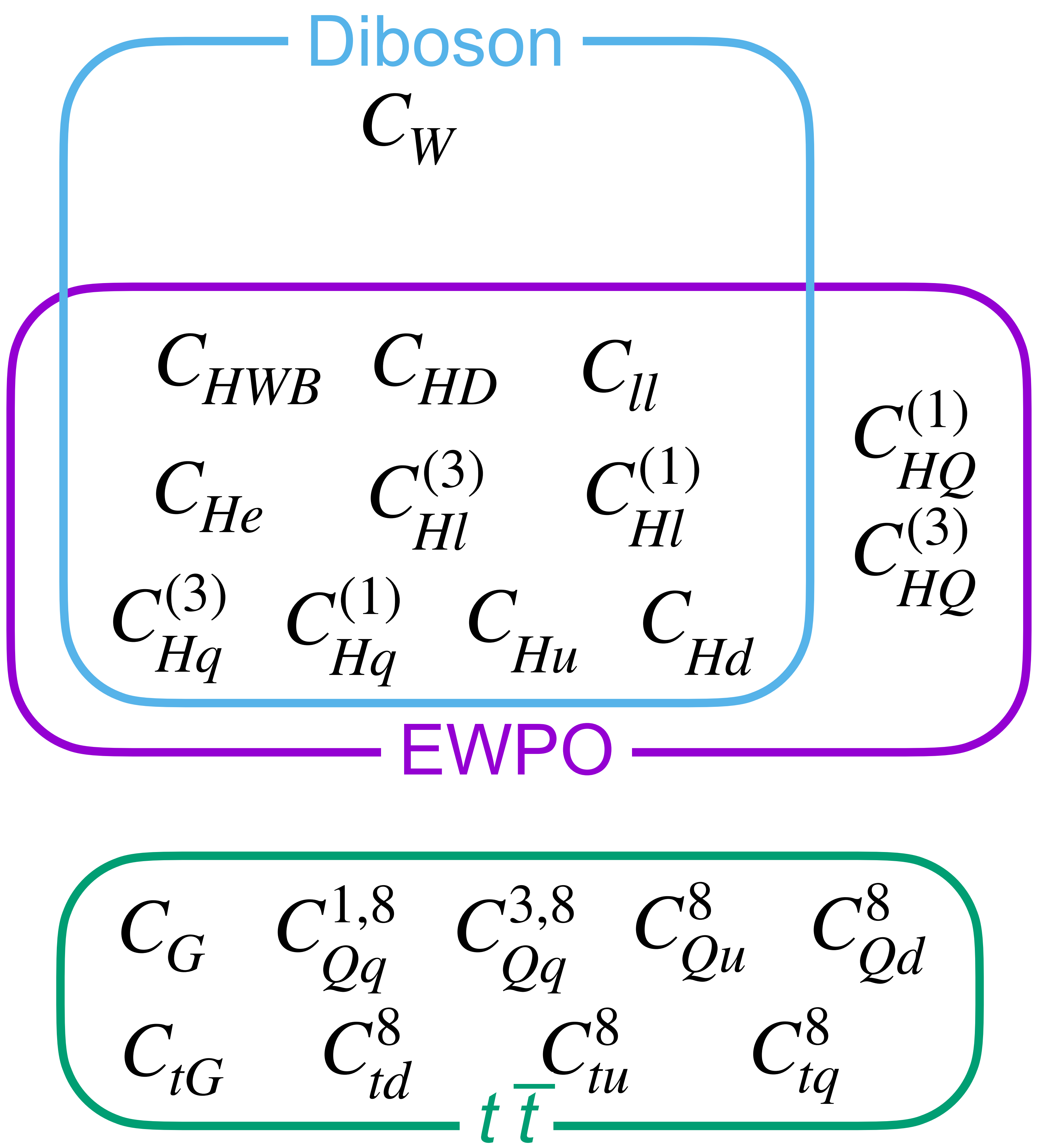
C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\,\bar{t}$

EWPO observations also appear, mostly in the decays of the top.

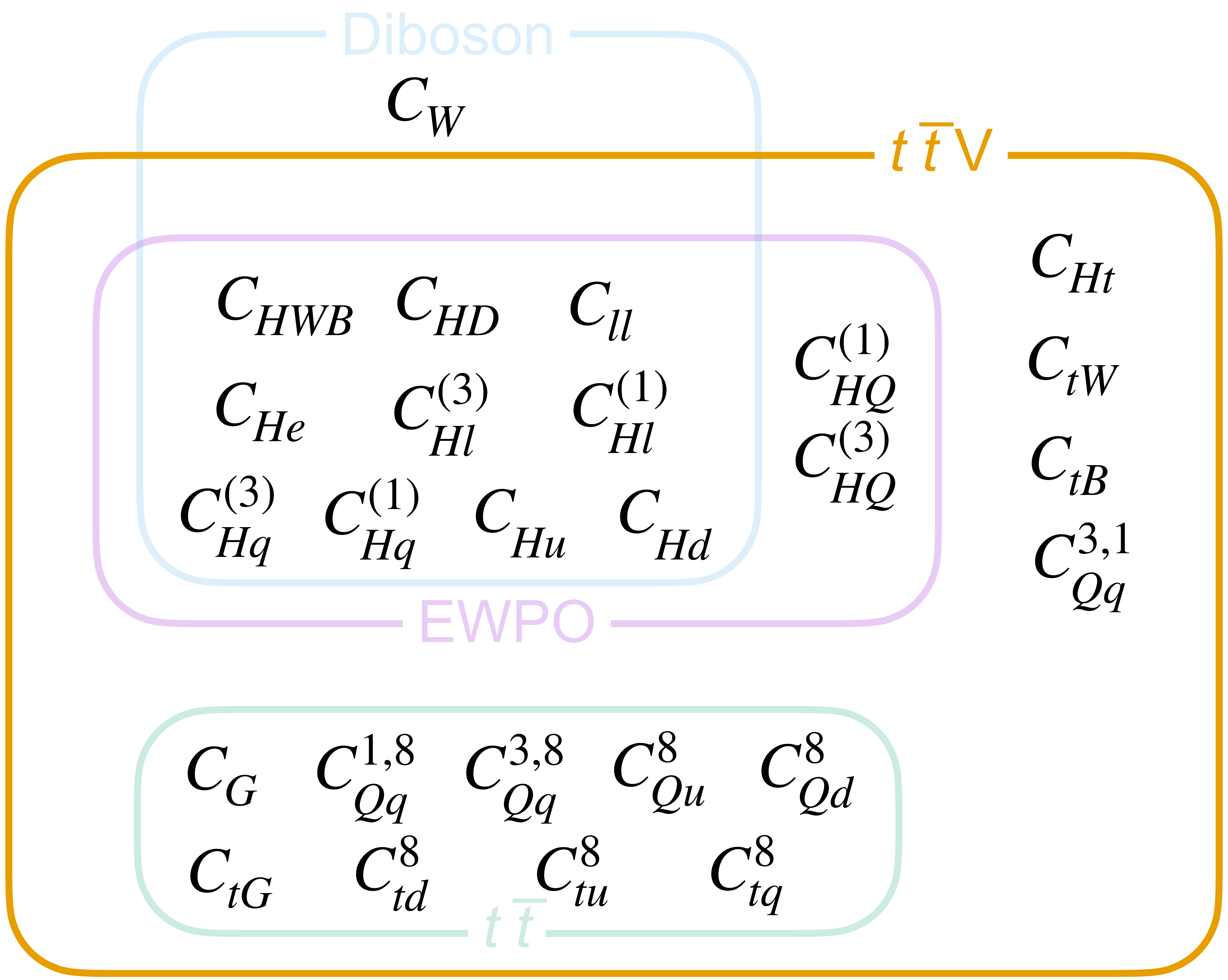
Top EFT

As well as some operators seen more commonly in Diboson signatures



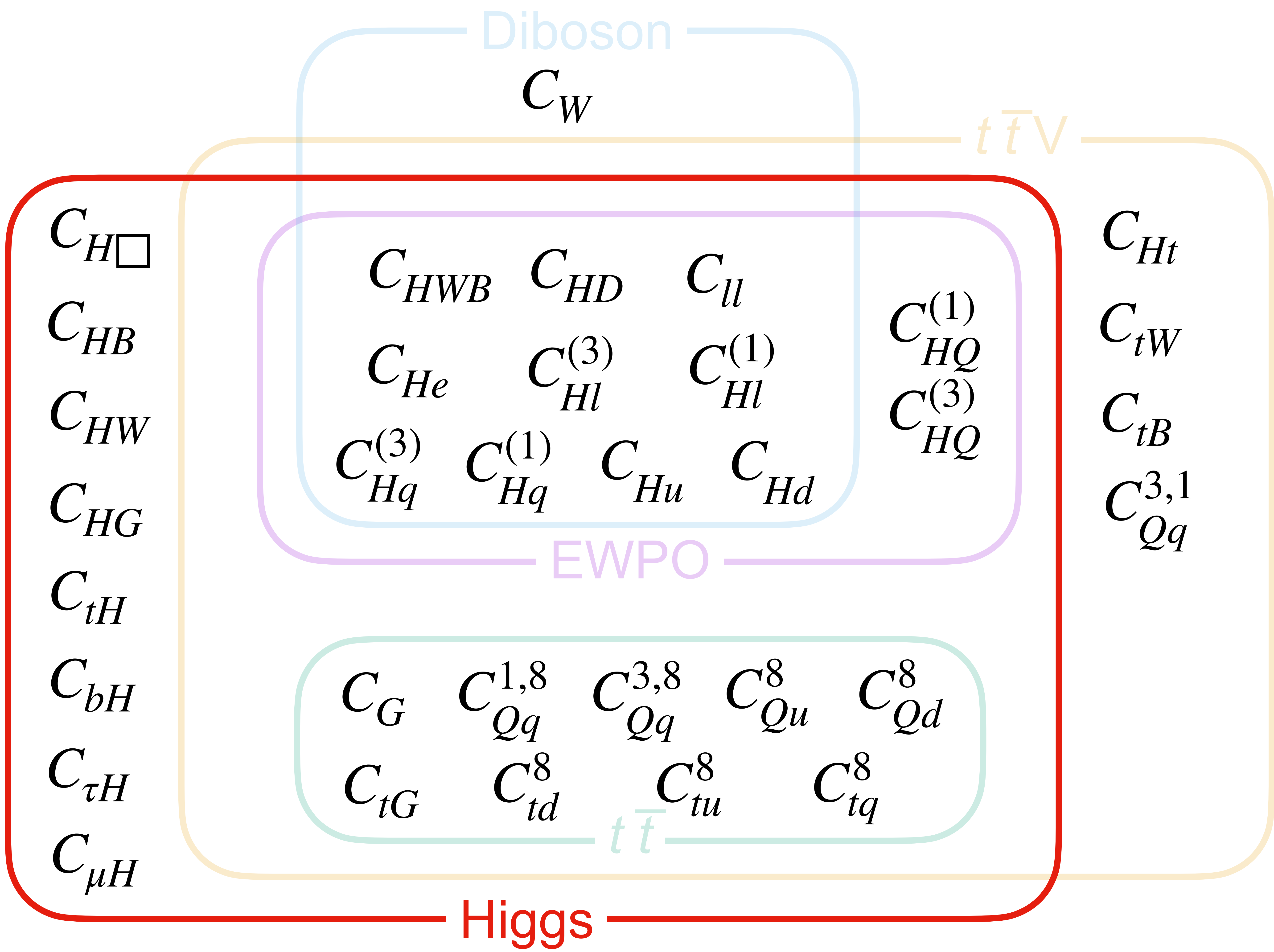
Top EFT

In top-pair + Boson signatures we pick up sensitivity to top-EW-Boson couplings



Top EFT

And finally, we get some Higgs sensitivity as well



Top EFT

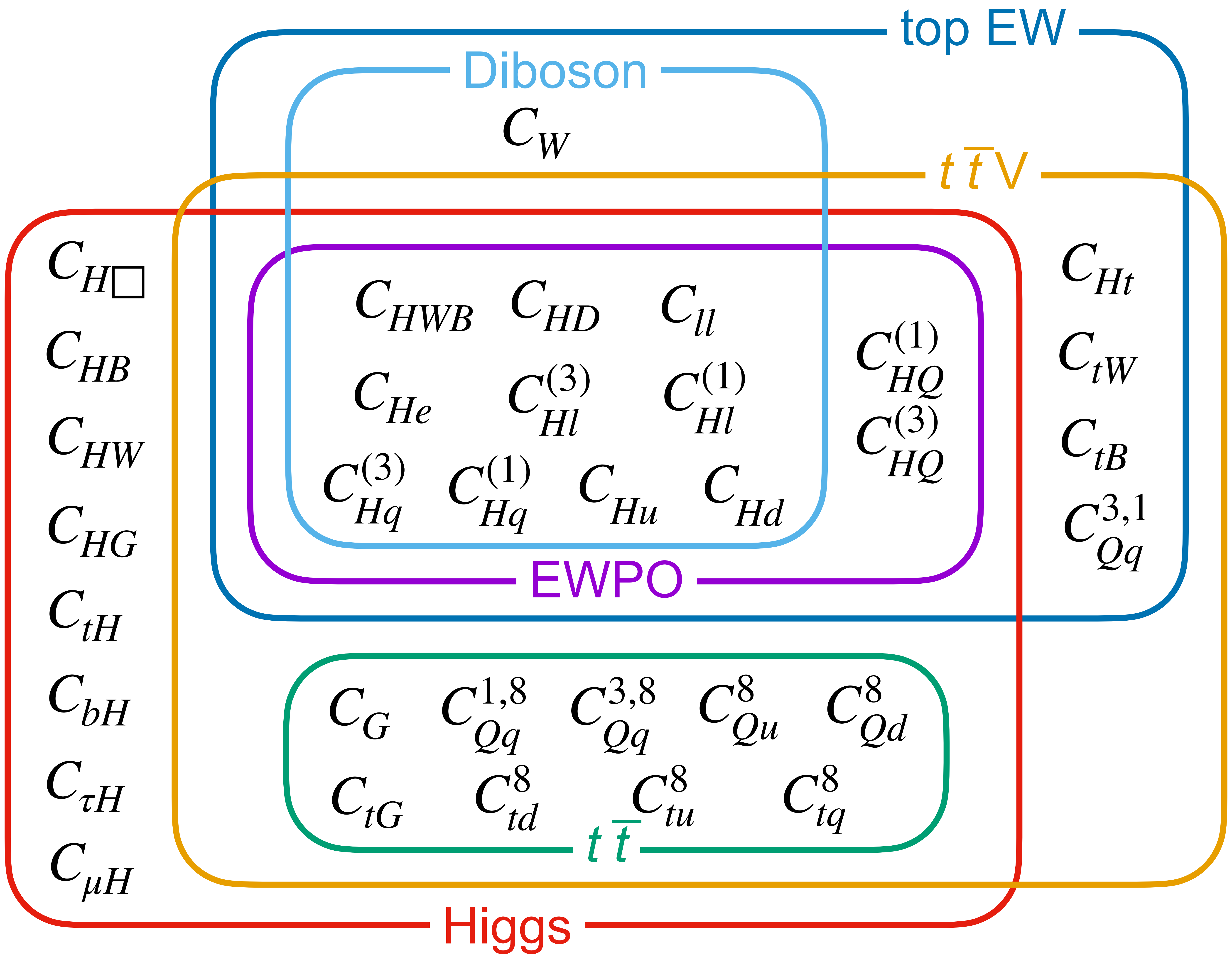


Figure from Ellist, Madigan, Mimasu, Sanz, You, JHEP 04 (2021) 279

tops and bosons

- **As some of the heaviest processes at the LHC, top + Boson signatures are ideal places to search for BSM.**

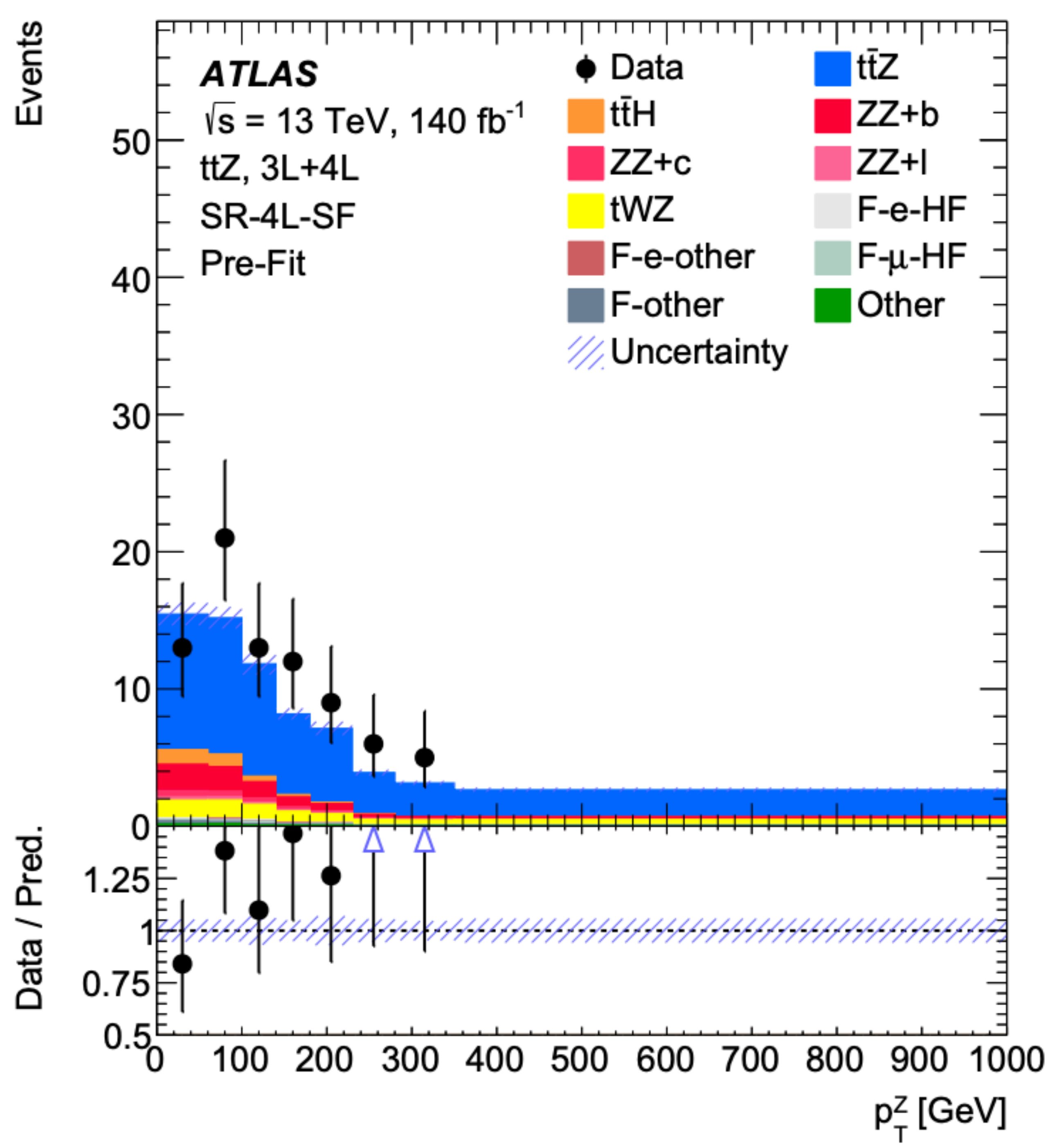
$$\text{tops and gluons}\ \left\{ C_{tG}\ \underbrace{C_{tW}\ \overbrace{\ C_{tB}}^{\text{tops and photons}}}_{\text{tops and Z's}}\ C_{t\phi} \right\}\ \text{tops and Higgs}$$

tops and Z's
(C_{tZ})

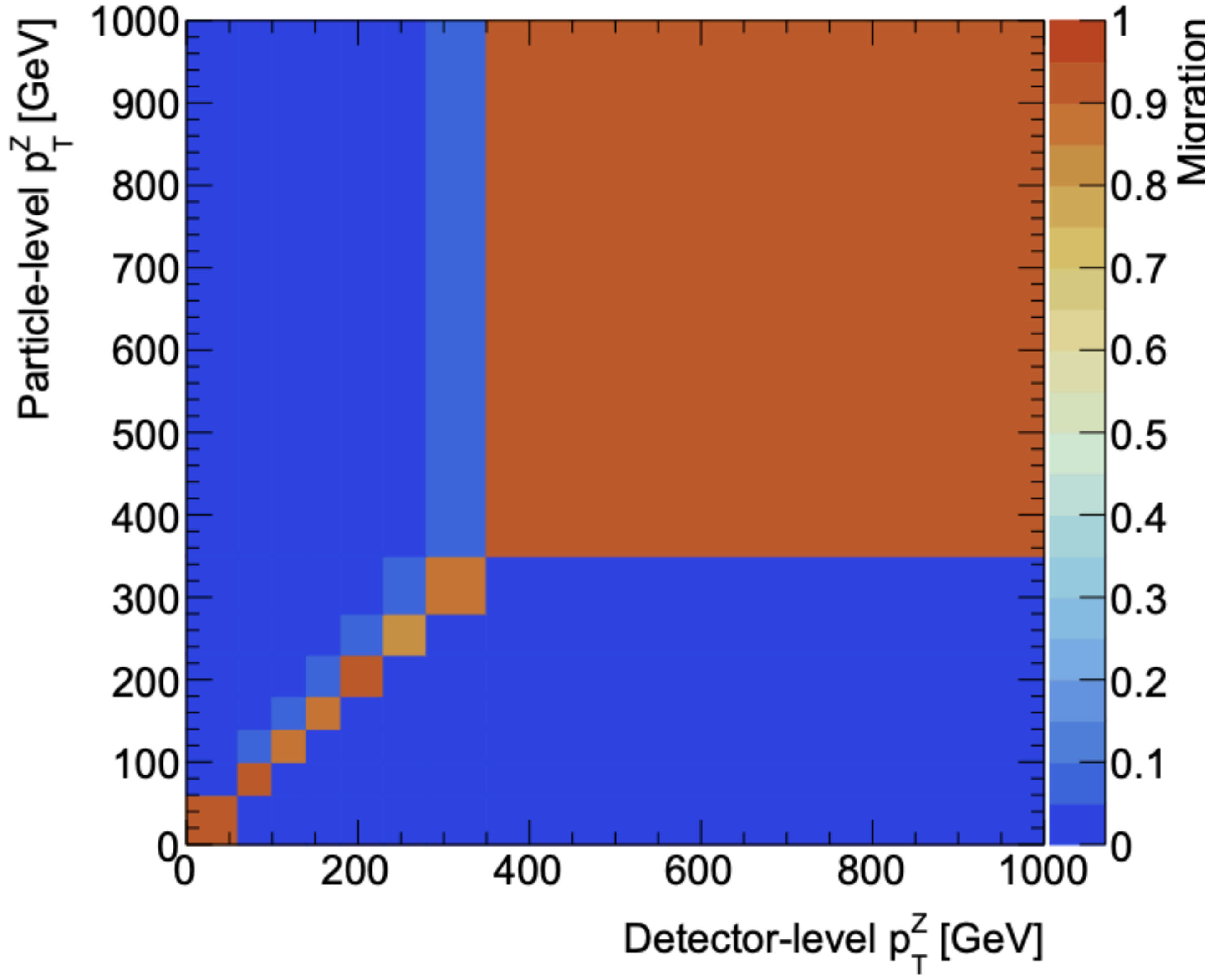
$t\bar{t}Z$

JHEP 07 (2024) 163

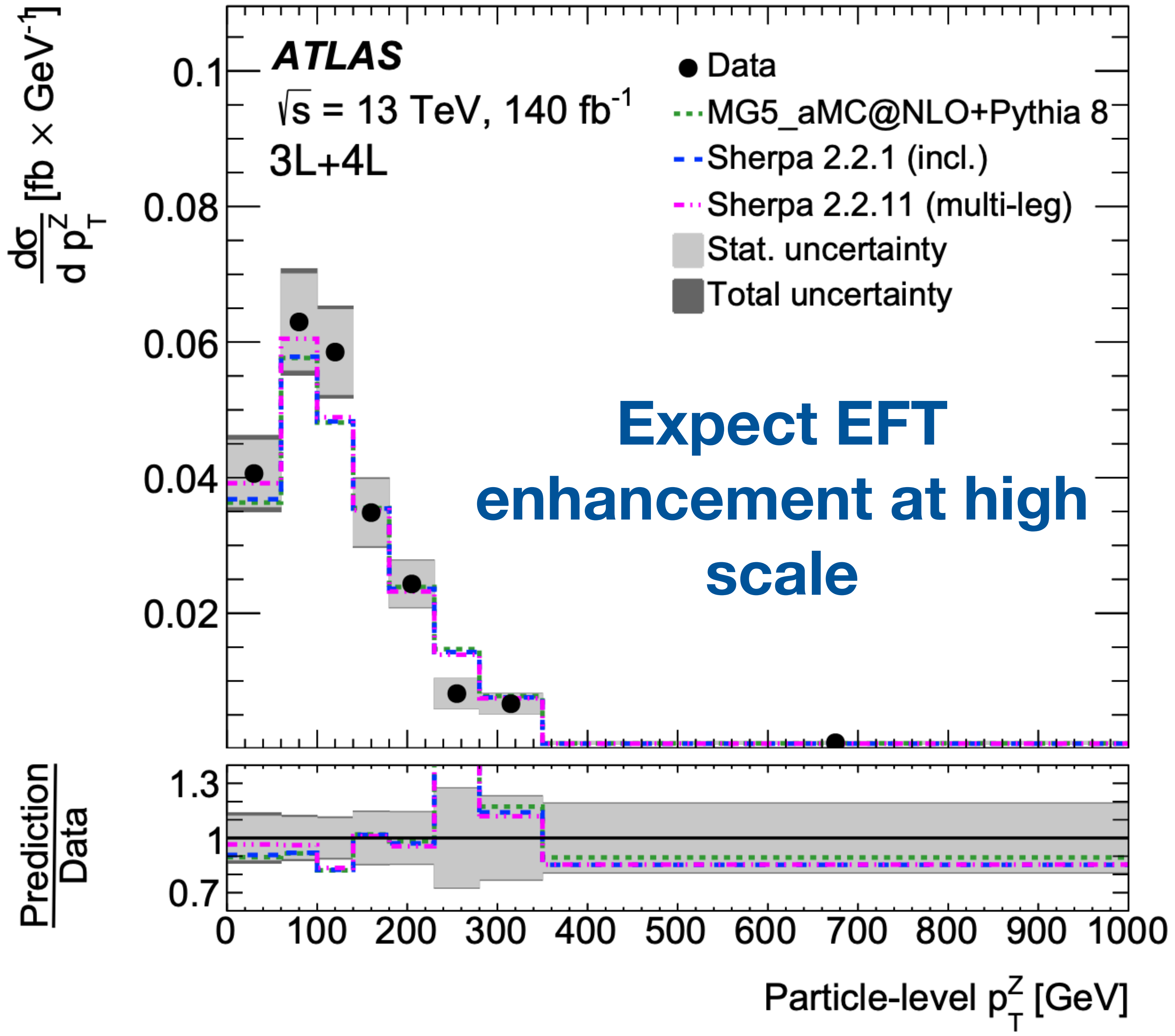
Detector Level



Migration Matrix



Unfolded Particle Level

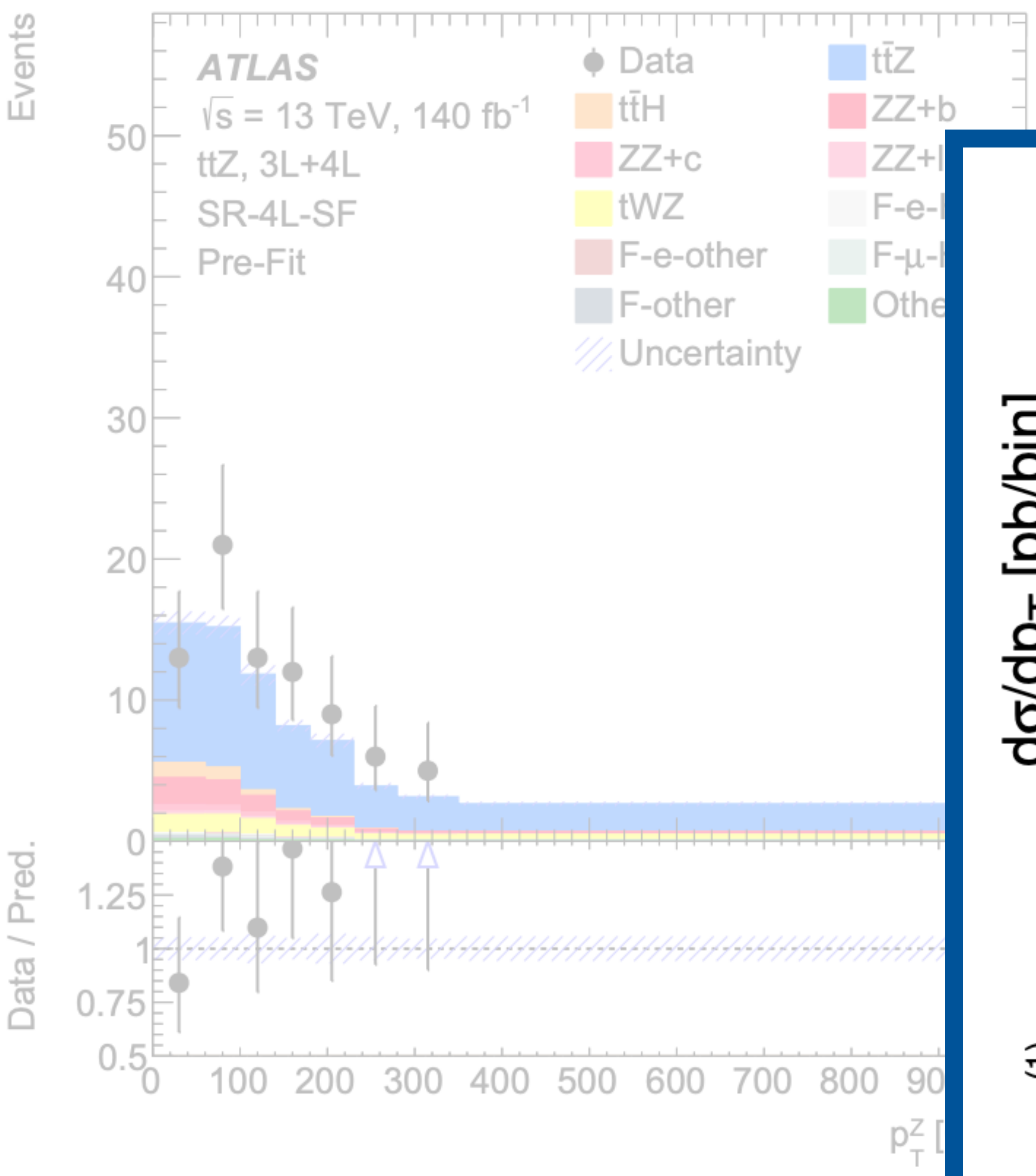


- **Measurement uses 3L + 4L final states and a profile-likelihood based unfolding on full Run2 data** (on multiple observables)**.**
- **EFT limits set using unfolded results.**

$t\bar{t}Z$

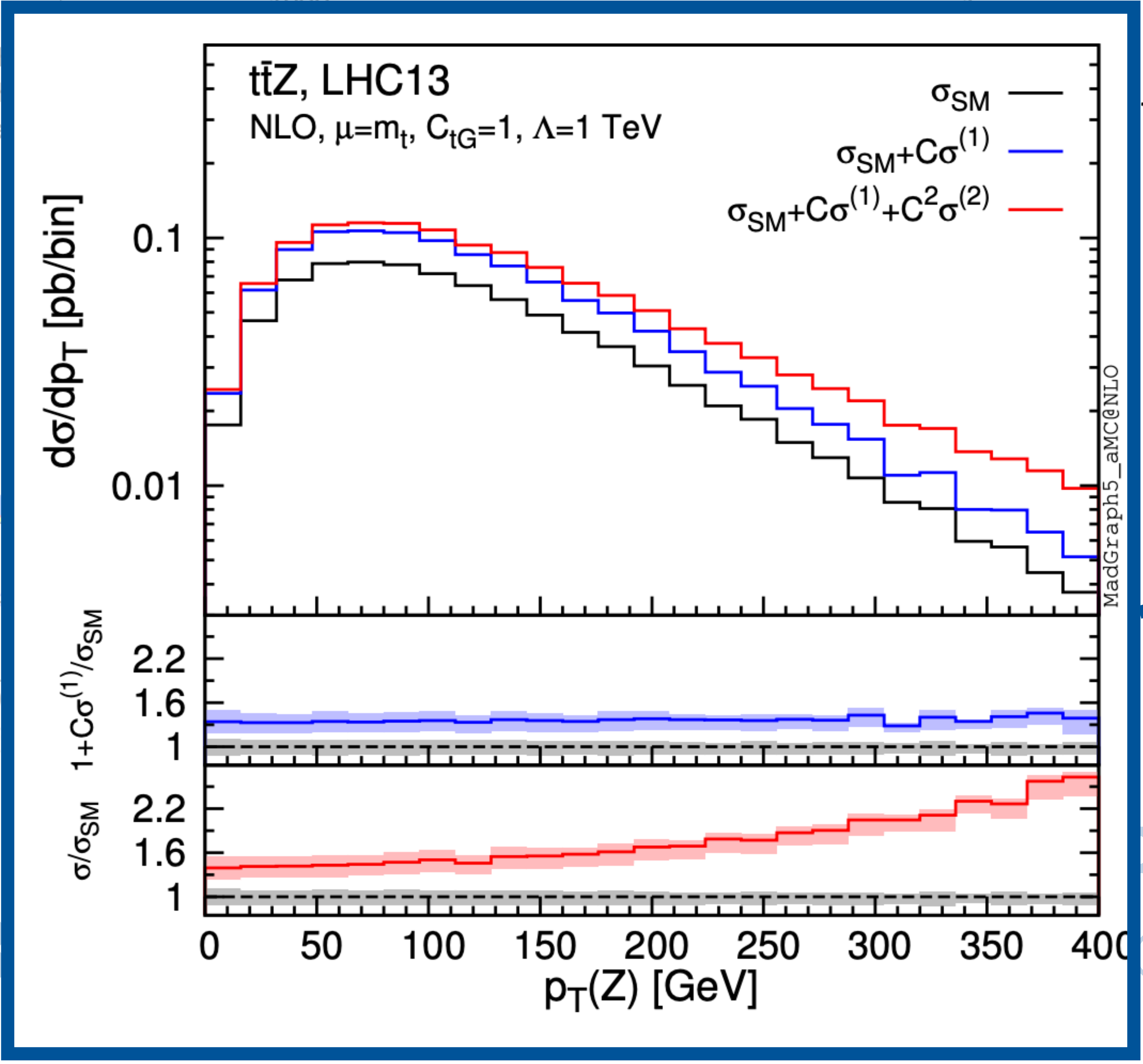
JHEP 07 (2024) 163

Detector Level

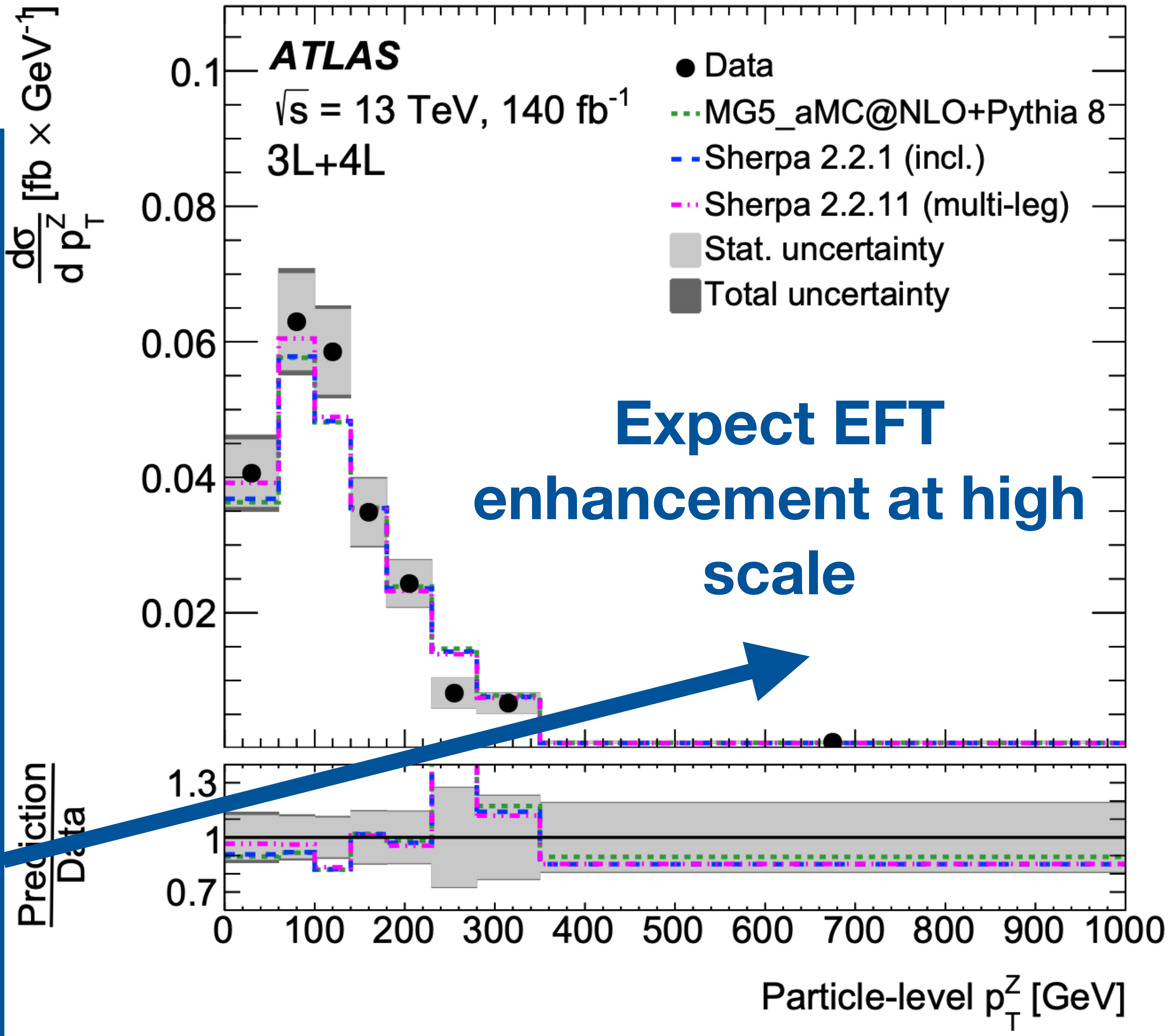


Migration Matrix

Bylund, Maltoni, Tsinikos, Vryonidoub, Zhang
JHEP 05 (2016) 052



Unfolded Particle Level

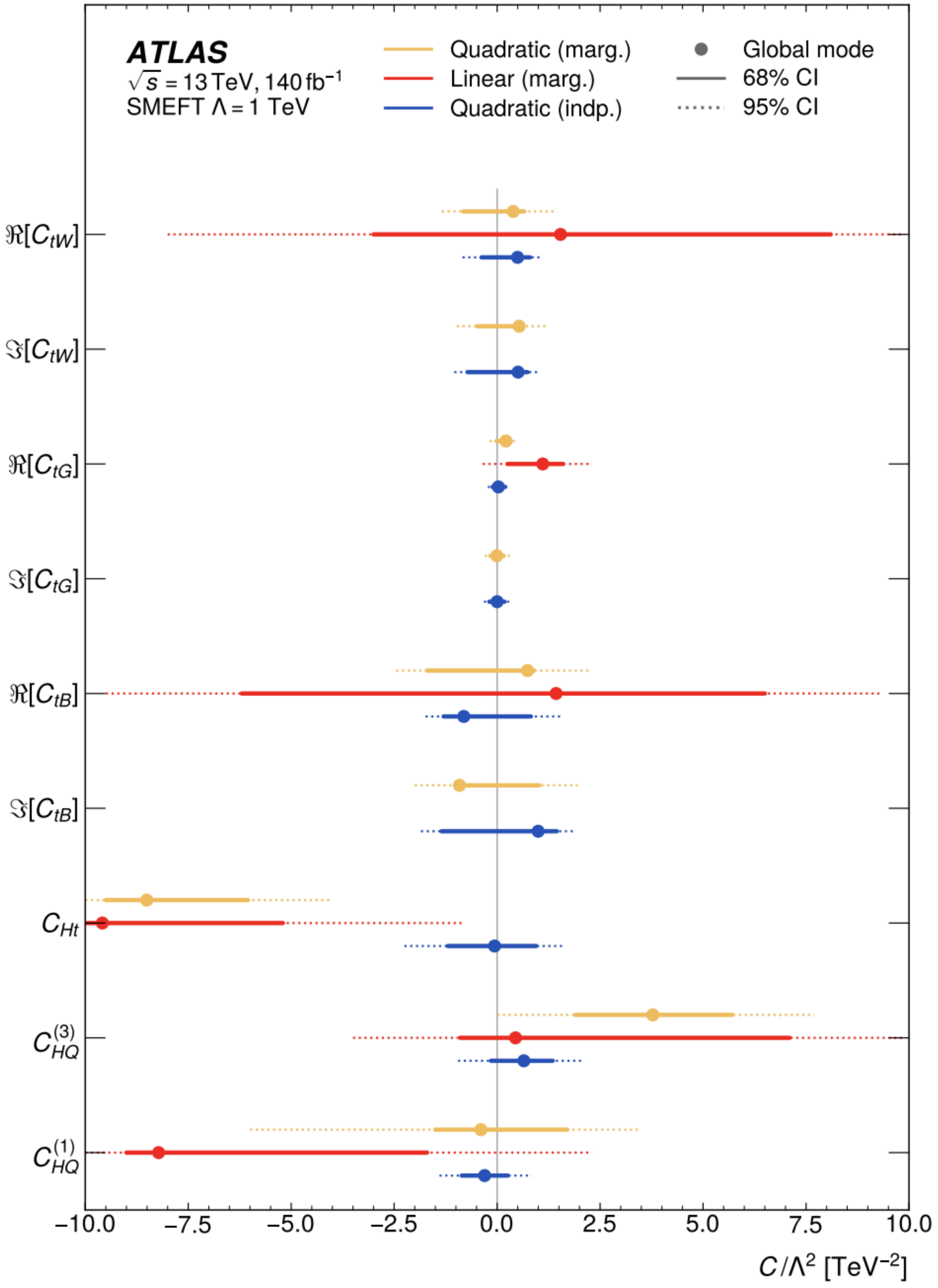


- Measurement use... profile-likelihood based unfolding on full R... ...ples).
- EFT limits set using unfolded results.

JHEP 07 (2024) 163

- **Limits set on top-boson and 4-fermion operators.**
- **EFT fit to both linear and linear+quadratic dim. 6 operators.**
- **Many of the operators have strong quadratic effects** (leading to stronger constraints on operators in the fit)

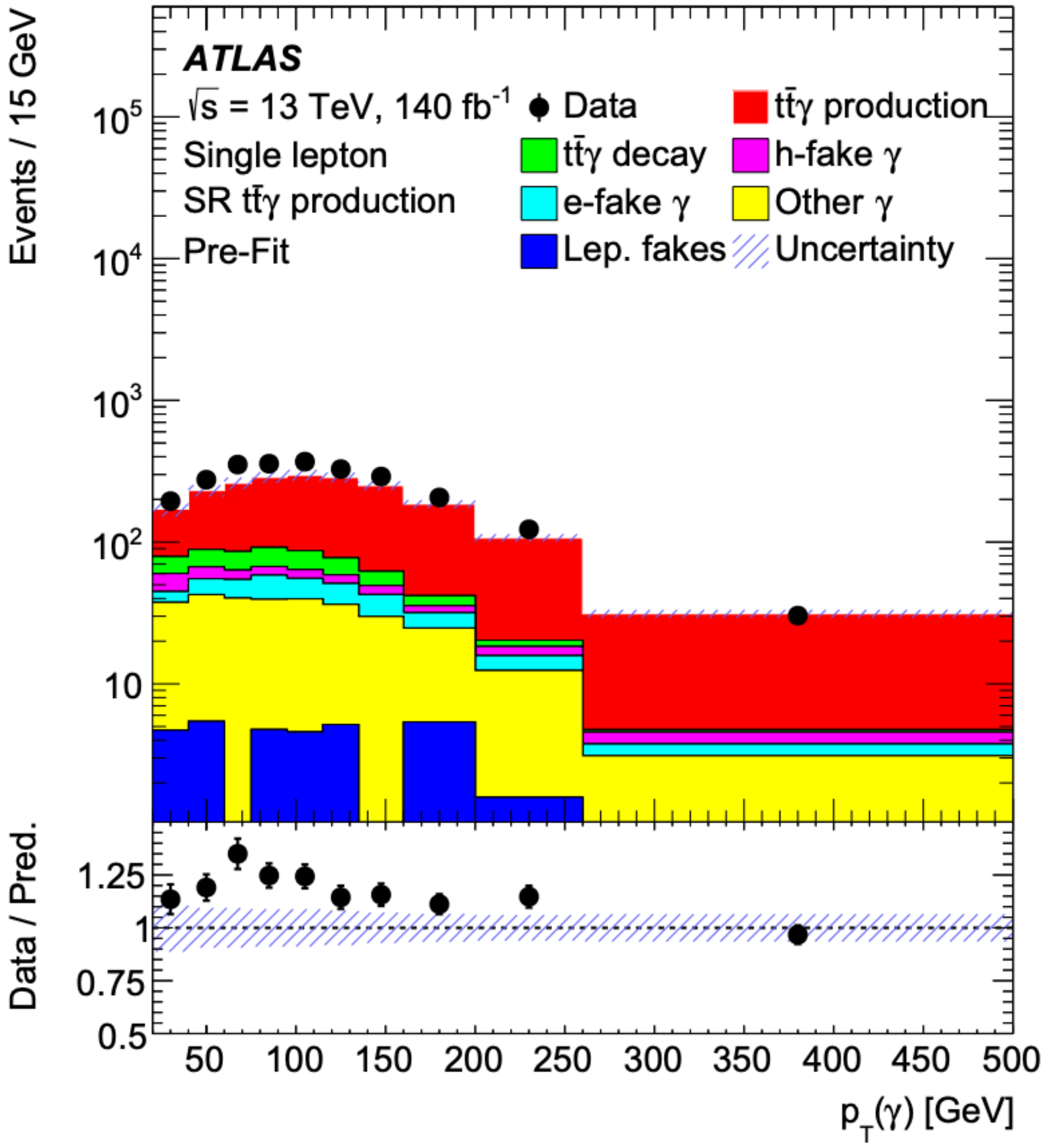
➡ **But that means dim. 8 may also need to be considered.**



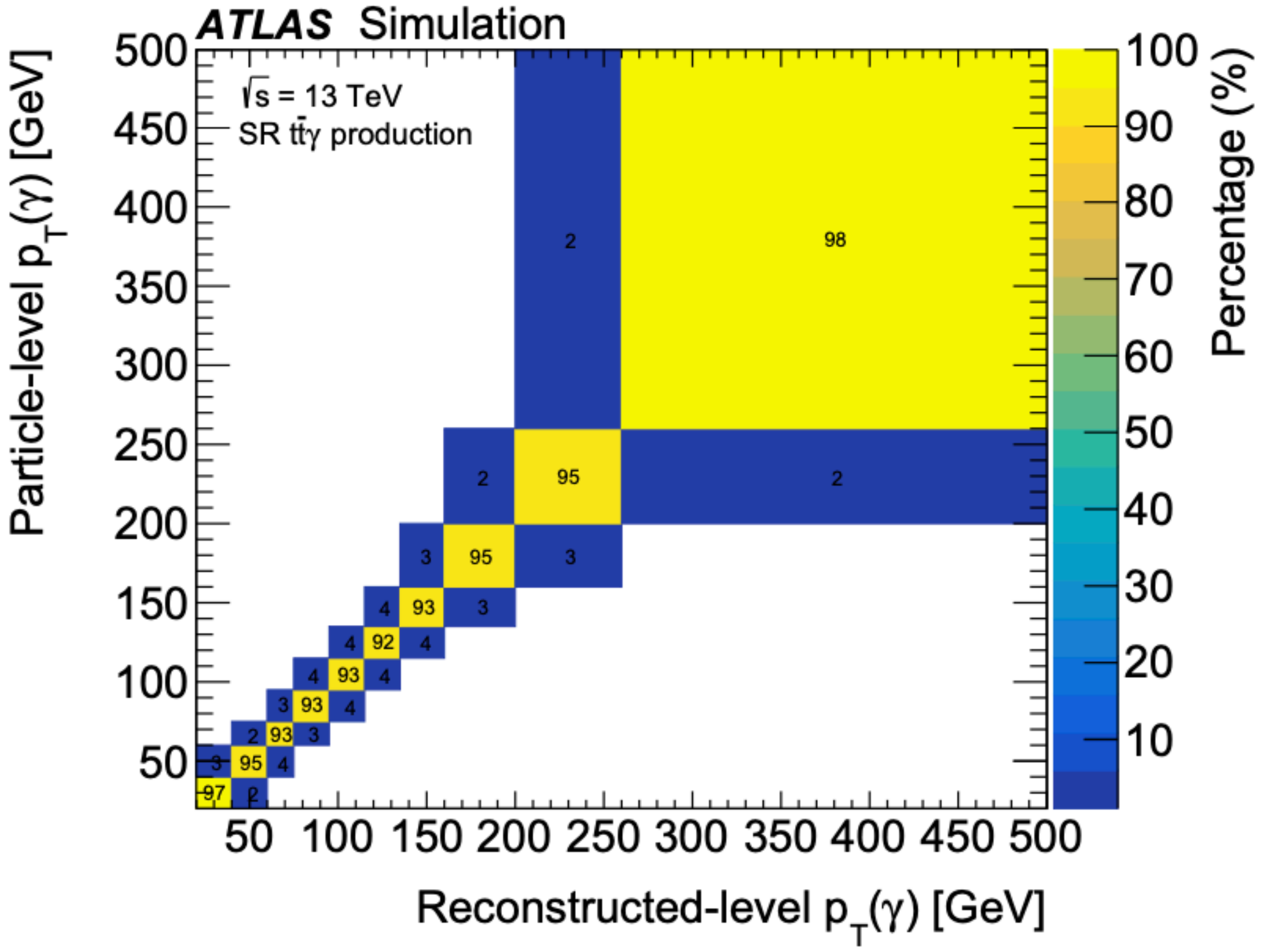
[JHEP 10 (2024) 191]

$t\bar{t}\gamma$

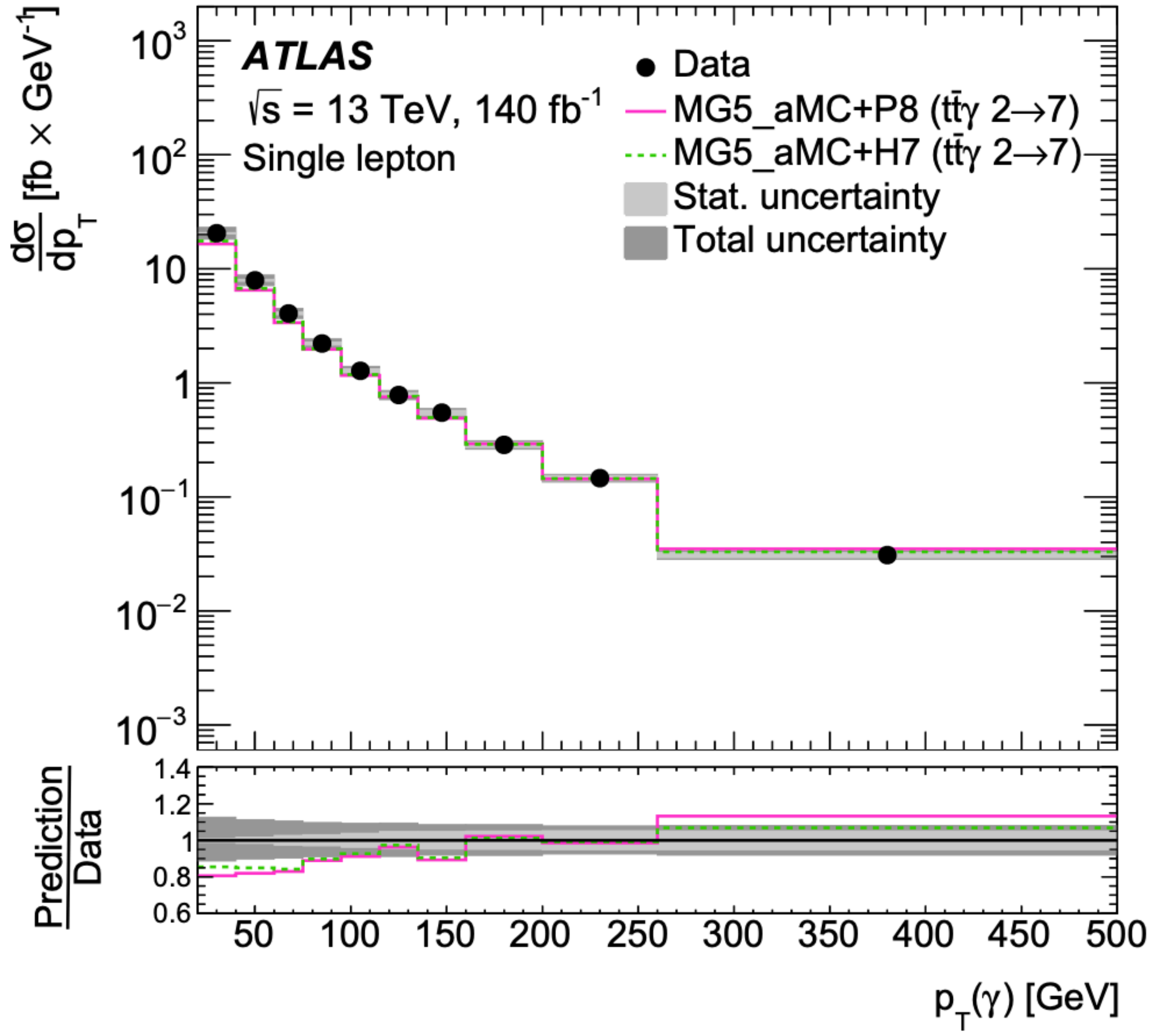
Detector Level



Migration Matrix



Unfolded Particle Level

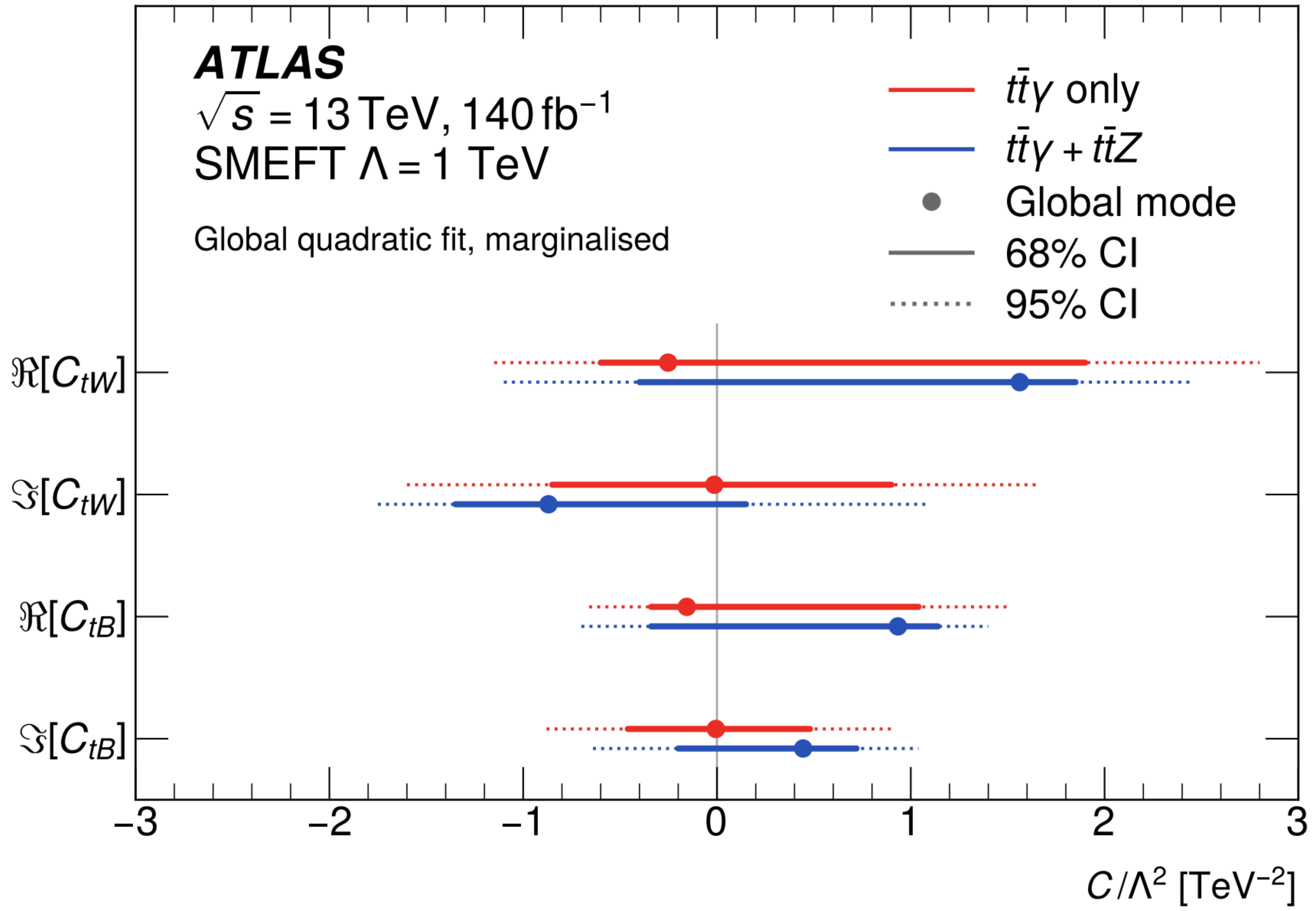


- **Very similar procedure for $t\bar{t}\gamma$** (now using 1L and 2L channels)**.**
- **Again, multiple top and γ-related observables fit simultaneously in EFT interpretation.**

$t\bar{t}Z + t\bar{t}\gamma$

[JHEP 10 (2024) 191](#)

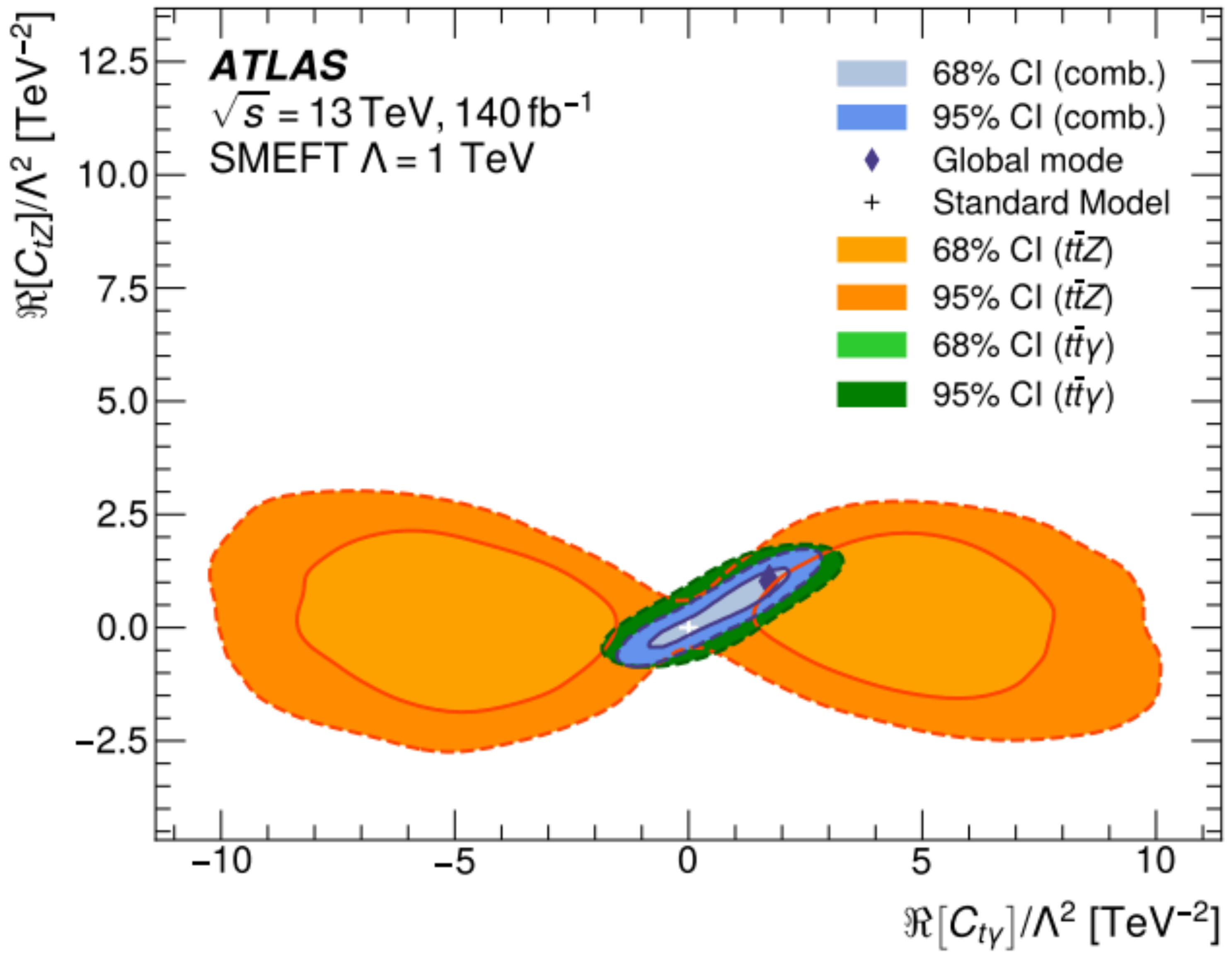
[JHEP 07 (2024) 163](#)



Rotation

$$C_{tZ} = \cos\theta_W \cdot C_{tW} - \sin\theta_W \cdot C_{tB}$$

$$C_{t\gamma} = \sin\theta_W \cdot C_{tW} + \cos\theta_W \cdot C_{tB}$$



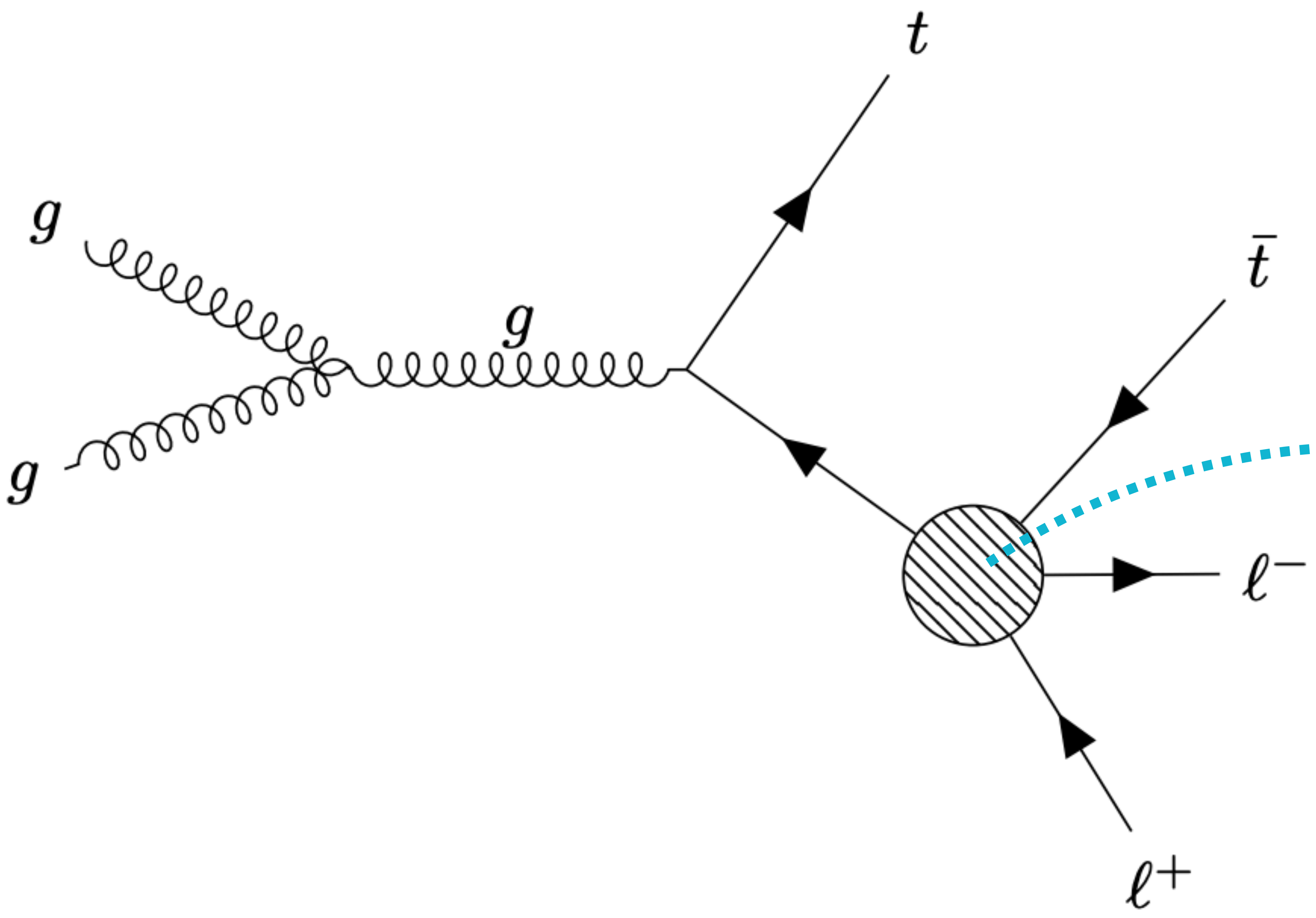
- **Combining the two results helps to maximise the power of the Run2 dataset to constrain operators.**

- **All results compatible with no deviation and set limits on scale of BSM allowed in these processes.**

$t\bar{t}ll$ NEW!

Submitted to EPJC

- **Searching for lepton flavour violation and focusing on 4-fermion operators in off-shell $t\bar{t}ll$ production ($|m(\ell\ell) - m(Z)| > 10\ GeV$).**



- **Unlike the other measurements, here a profile likelihood fit at detector level is performed to test six four-fermion operators:**

$$C_{tl},\ C_{te},\ C_{Qe},\ C_{Ql}^{-},\ (C_{Ql}^{1} - C_{Ql}^{3})\ C_{leQt}^{1}\ C_{leQt}^{3}$$

- **Also considering flavour split scenario** (i.e. ee and μμ separately)**.**

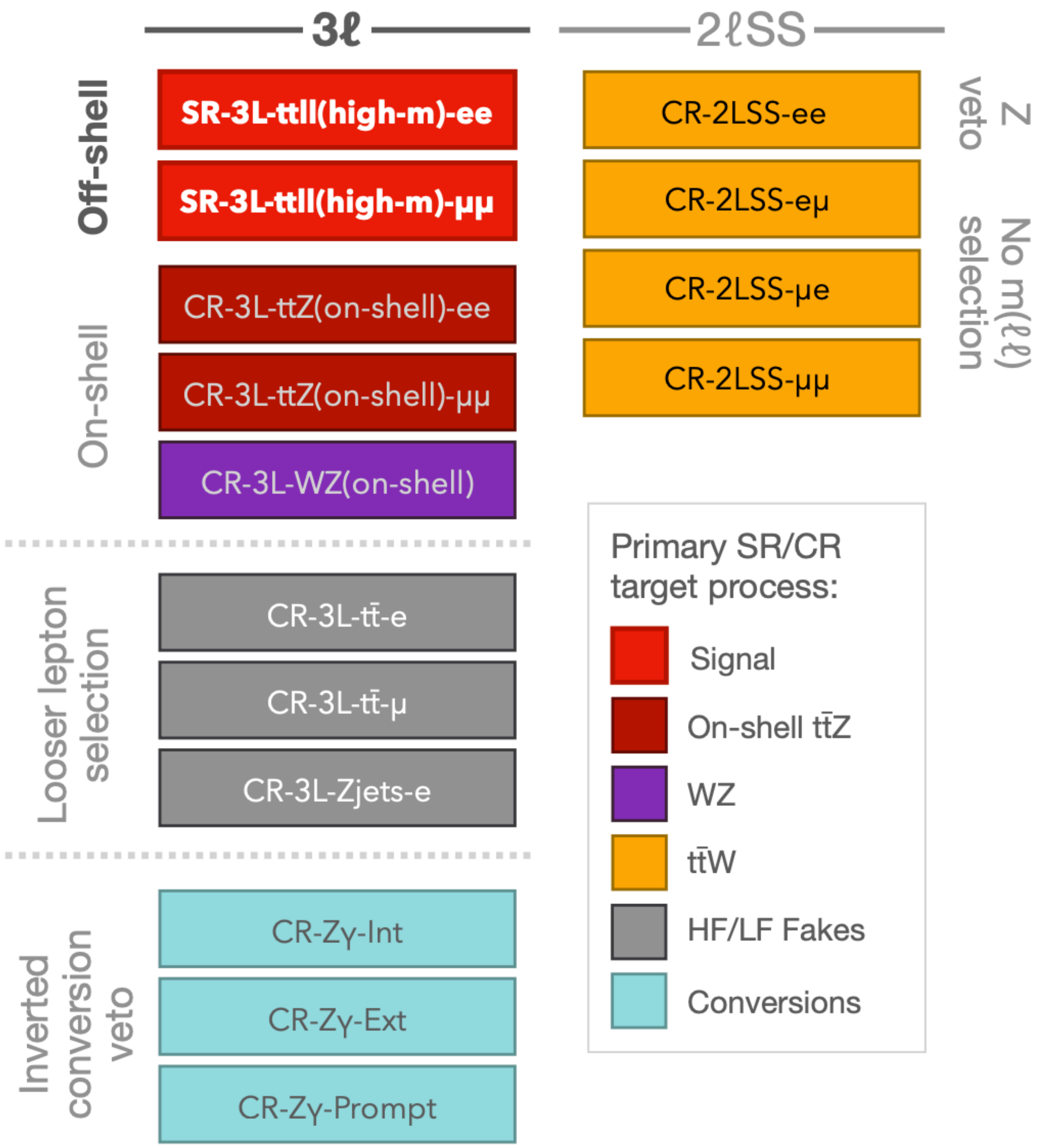
tt̄ll NEW!

Submitted to EPJC

- **Signal region focuses on the 3-lepton high m(ll) region as this is the highest purity phase-space that can be accessed.**

Signal Region is the off-shell Z/γ* region

on-shell tt̄Z 3L used as control region



- **Main sources of background come from SM processes with same or similar final state, and from misidentified leptons.**

- **Complex selection to isolate control regions to control these backgrounds** (very good control of backgrounds post-fit).

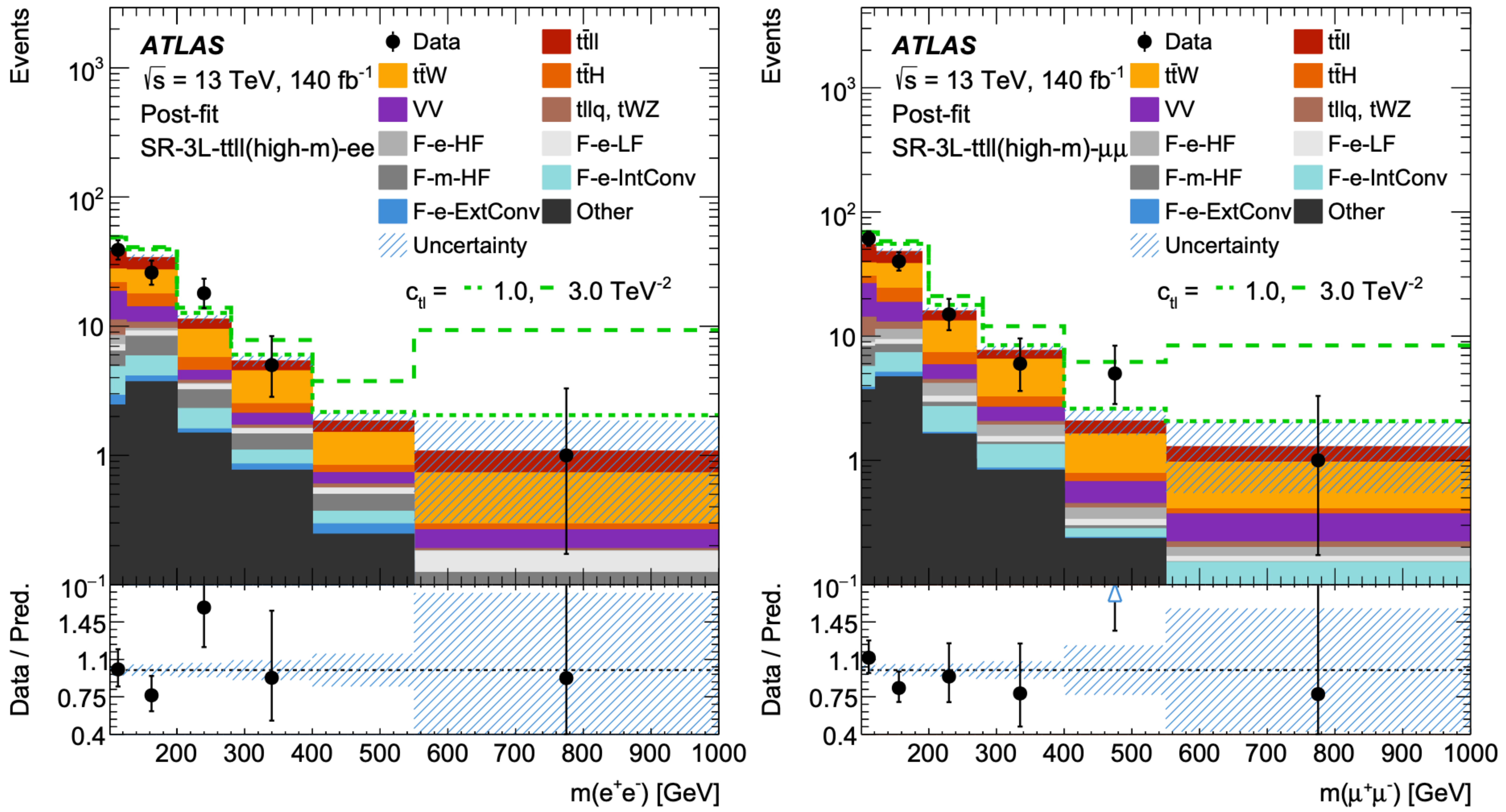
University of Glasgow

ttll NEW!

Submitted to EPJC

ATLAS EXPERIMENT

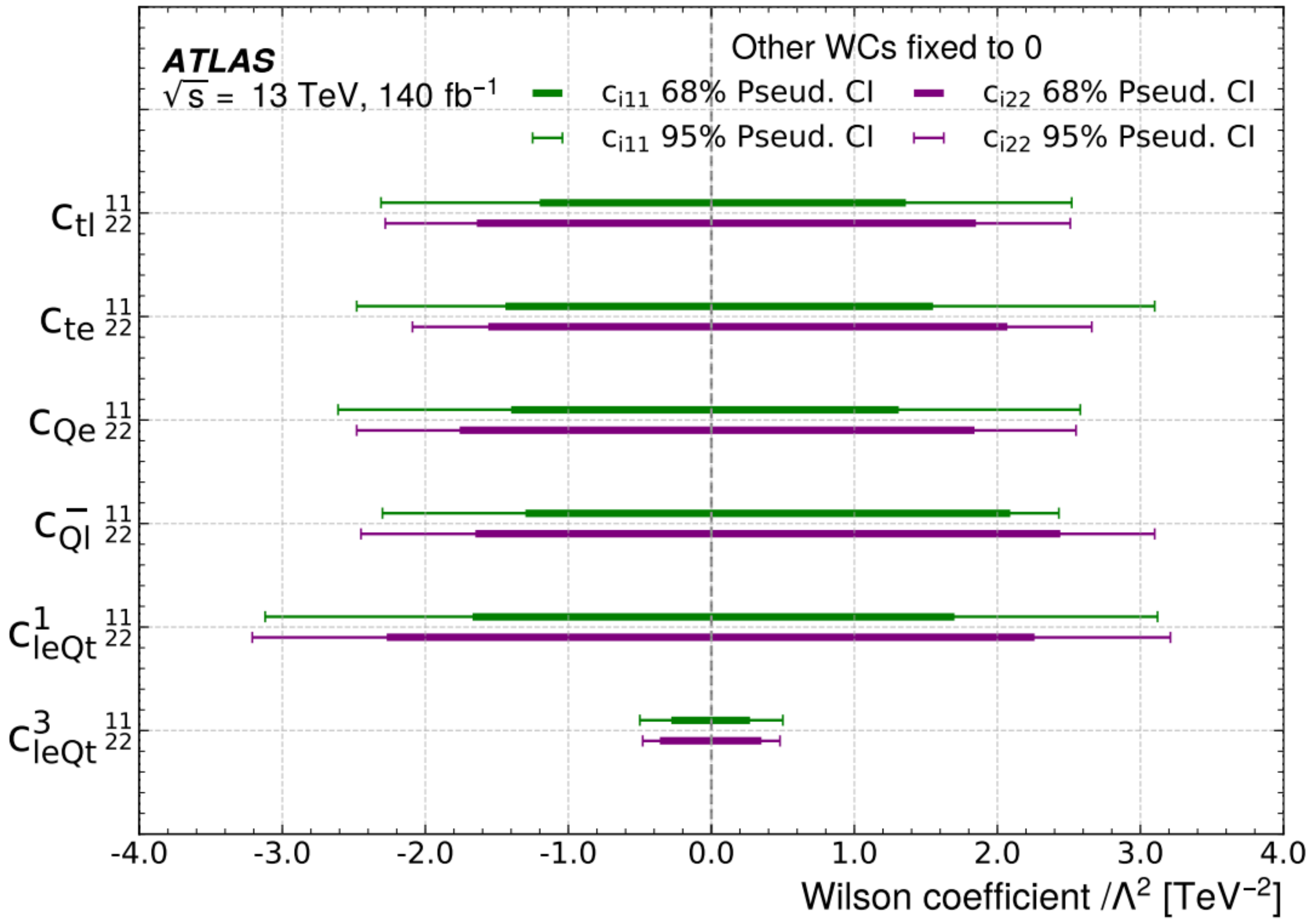
THE ROYAL SOCIETY

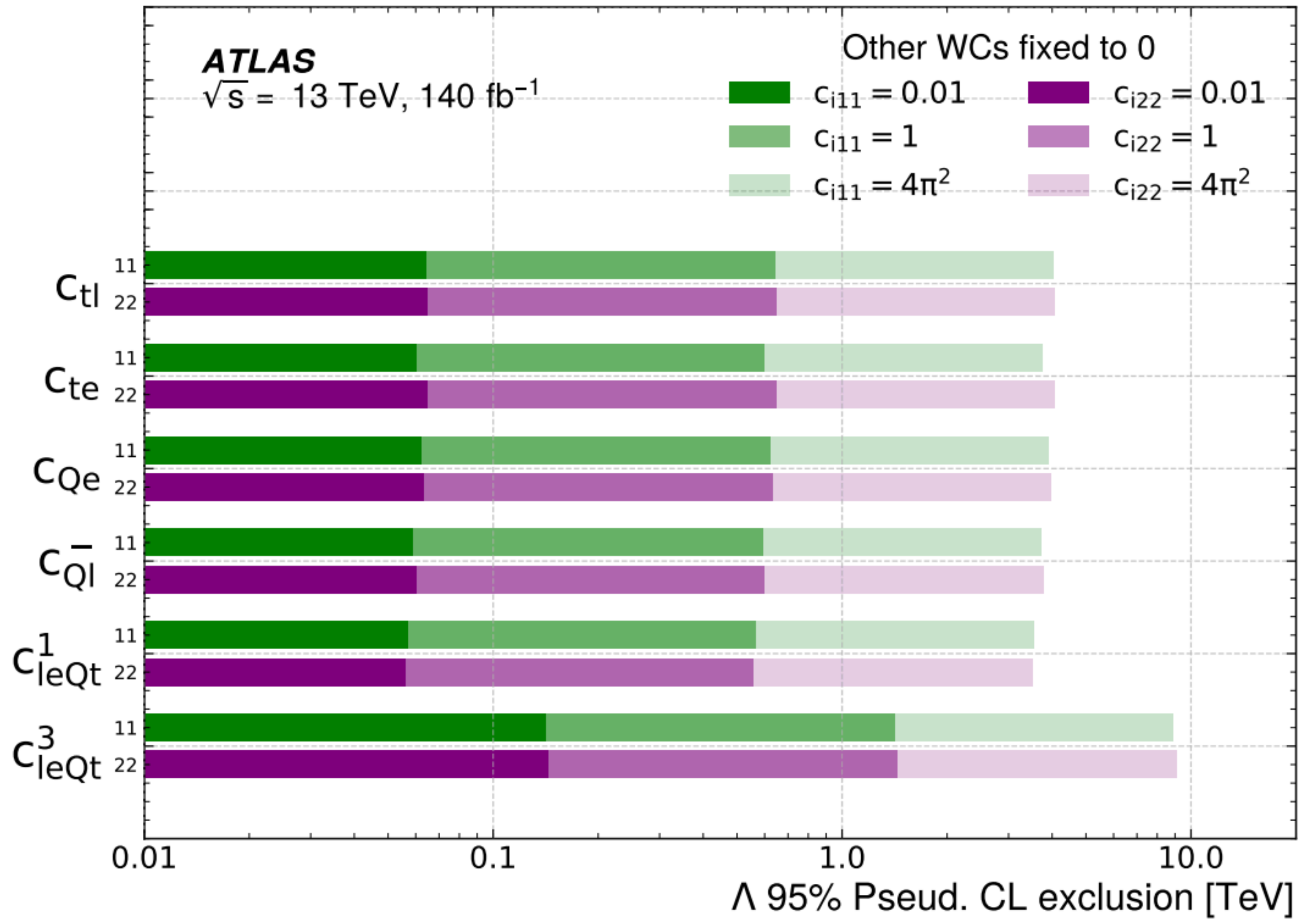


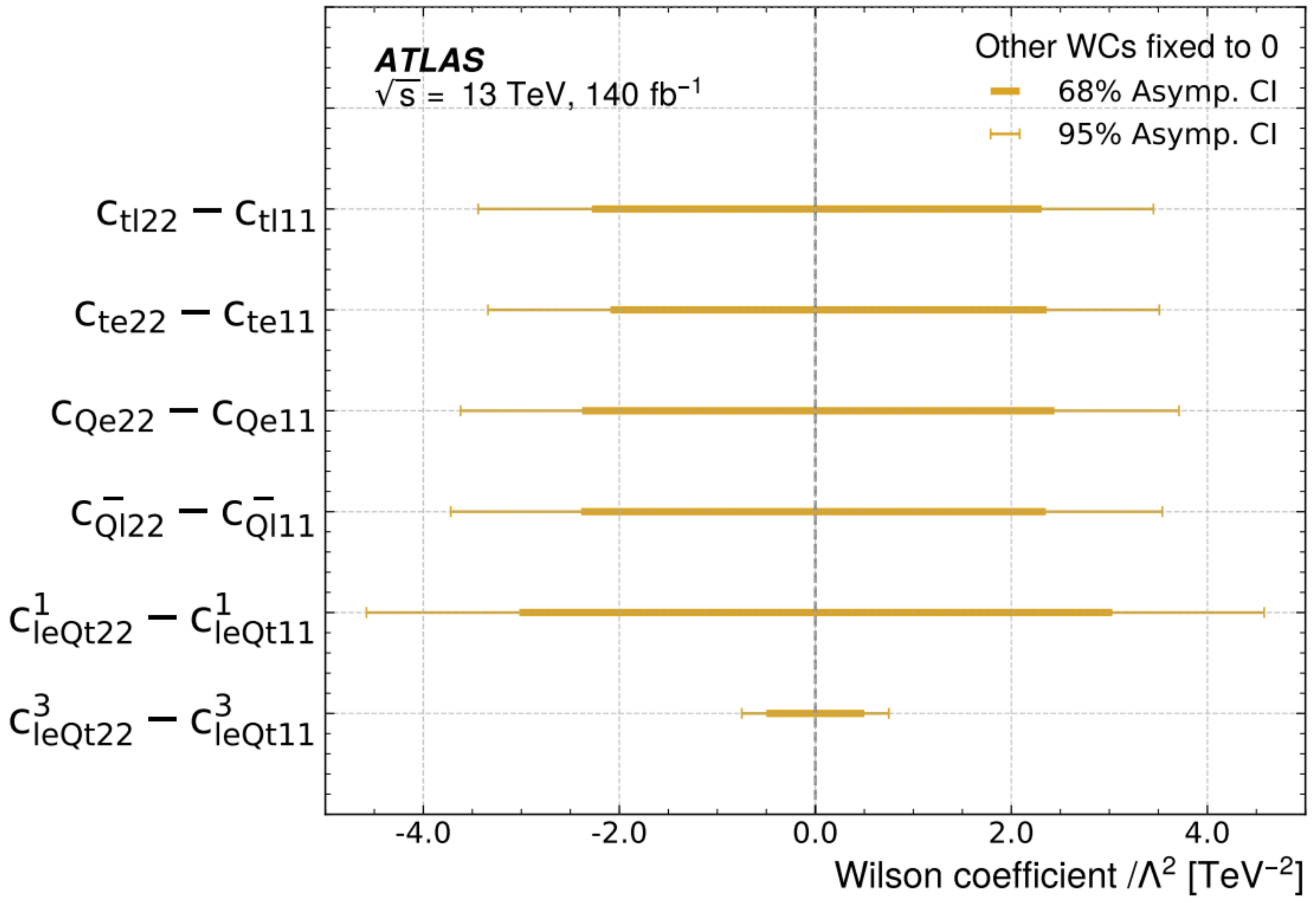
- **EFT effects are expected to be strongest a high m(ll) but also induce a general cross-section enhancement across the phase-space.**
  Evidence for off-shell $t\bar{t}ll$ production at significance of 2.9σ.

ttll NEW!

Submitted to EPJC



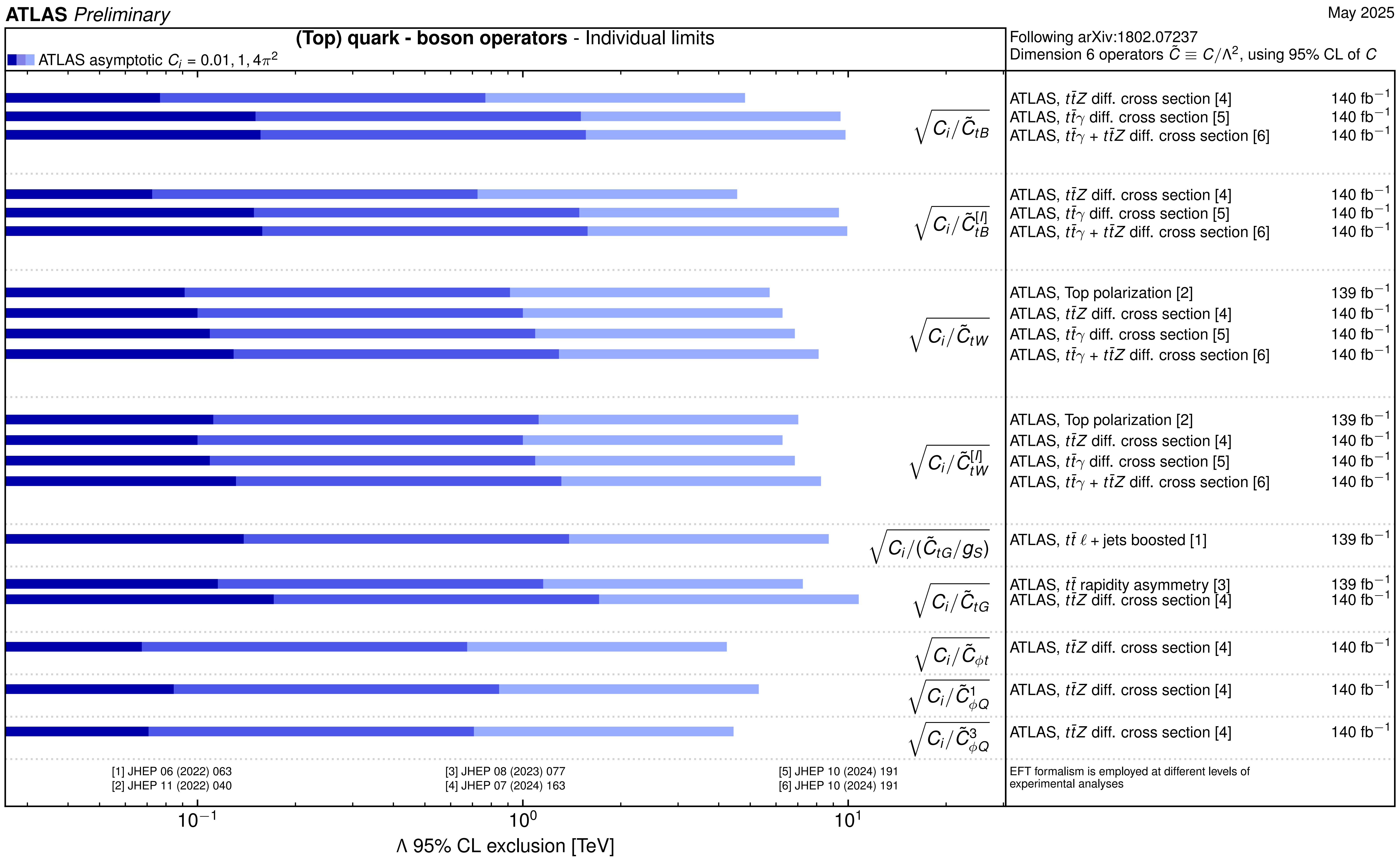




- **Limits improve upon previous searches but are still statistically limited** (Run3 data will bring significant improvements)**.**
- **Fits use pseudo-data to address possible loss of coverage due to dominant quadratic effects in EFT parameterisation.**
- **Results show no evidence of lepton flavour violating effects.**

Summary

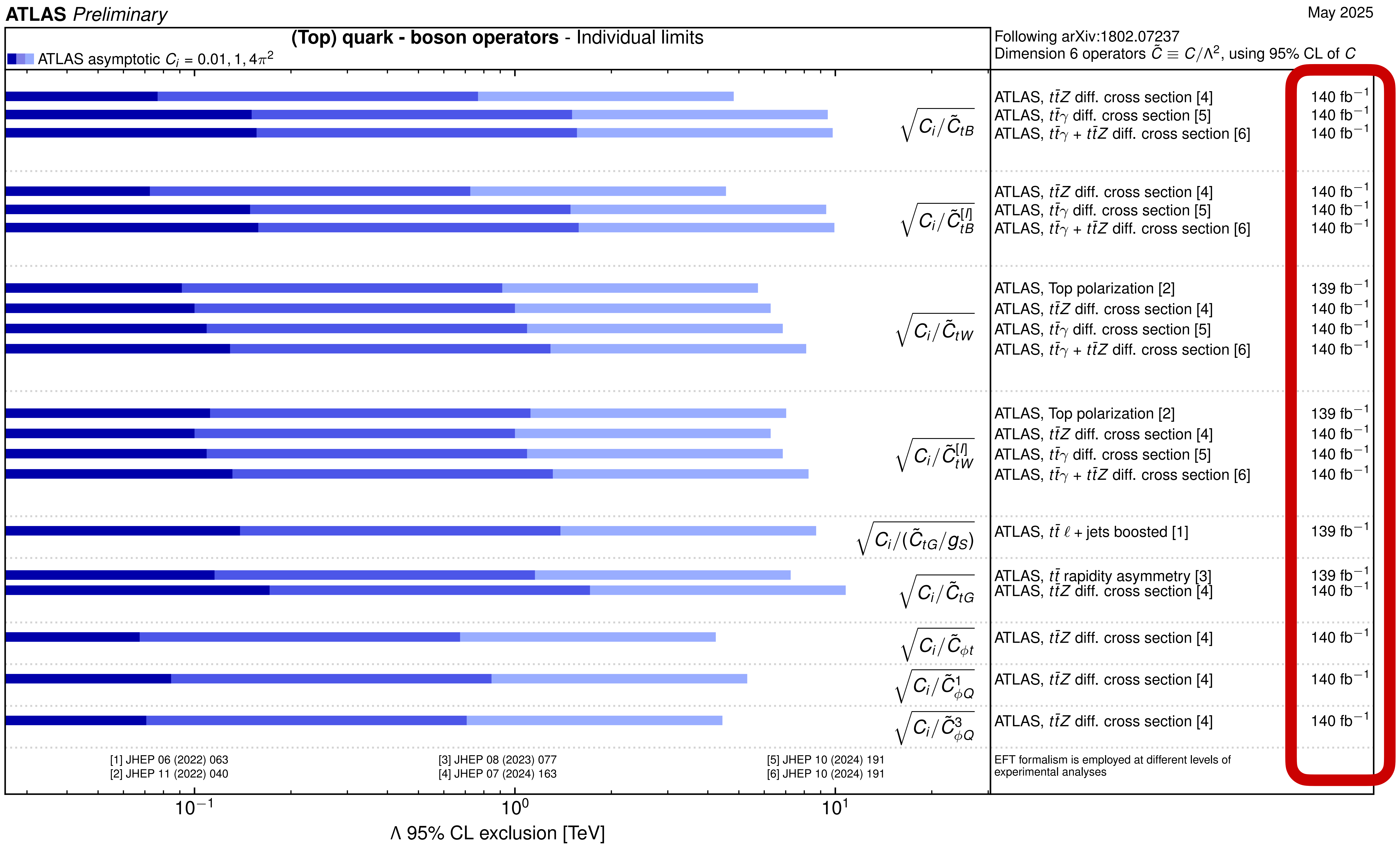
ATL-PHYS-PUB-2025-028



Summary

ATL-PHYS-PUB-2025-028

- **ATLAS has fully exploited the Run2 data for EFT interpretations!**
- **Novel analyses in ultra rare processes** (all of them looking at more than just EFT)**.**

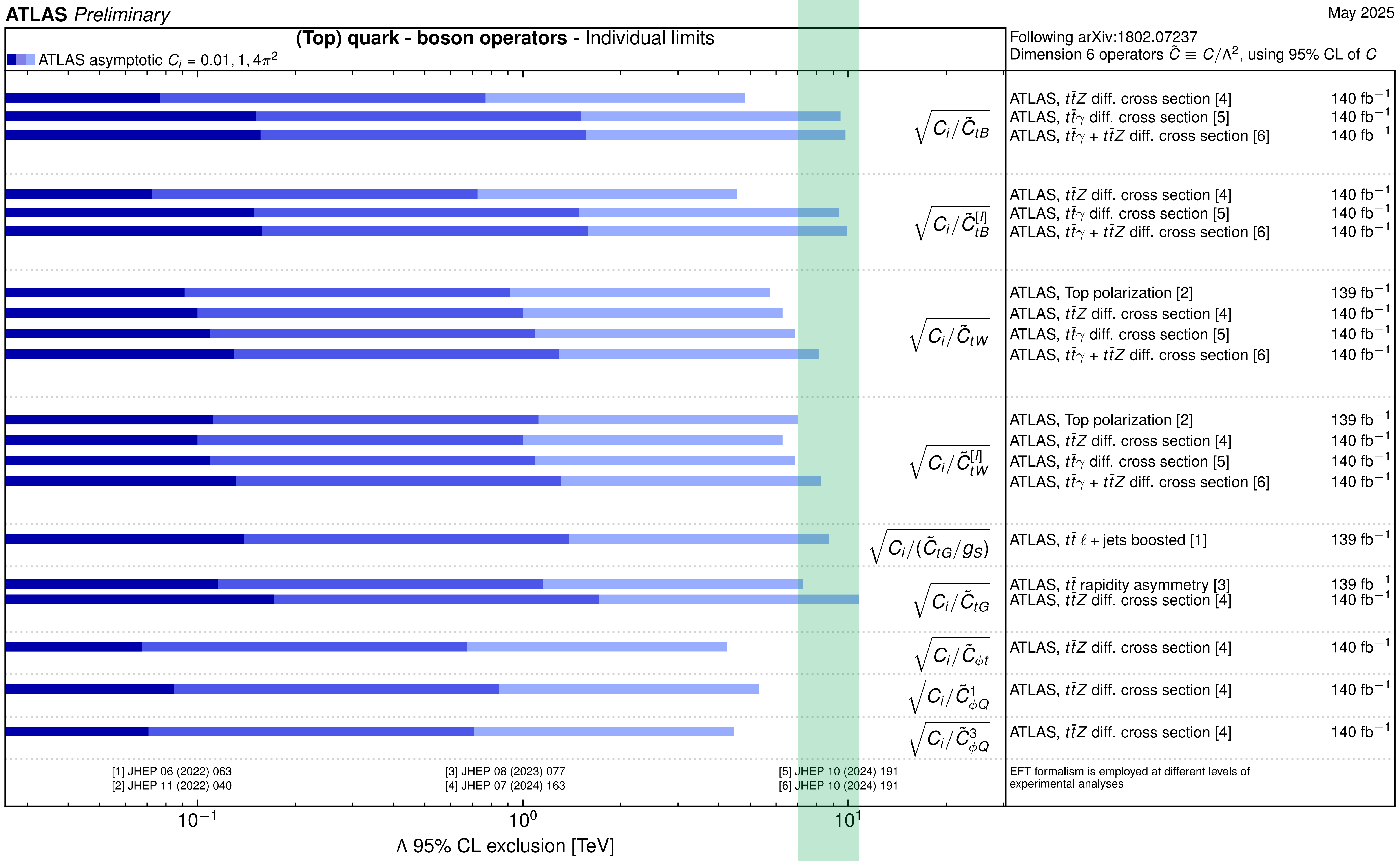


Summary

[ATL-PHYS-PUB-2025-028]

- **Very strong BSM effects can be excluded into the many-TeV range, even up to 10 TeV.**
- **Safe to say that strongly coupling, multi-TeV new bosons or loop modifications not favoured by data.**

$C_i = 4\pi^2$
(strong)

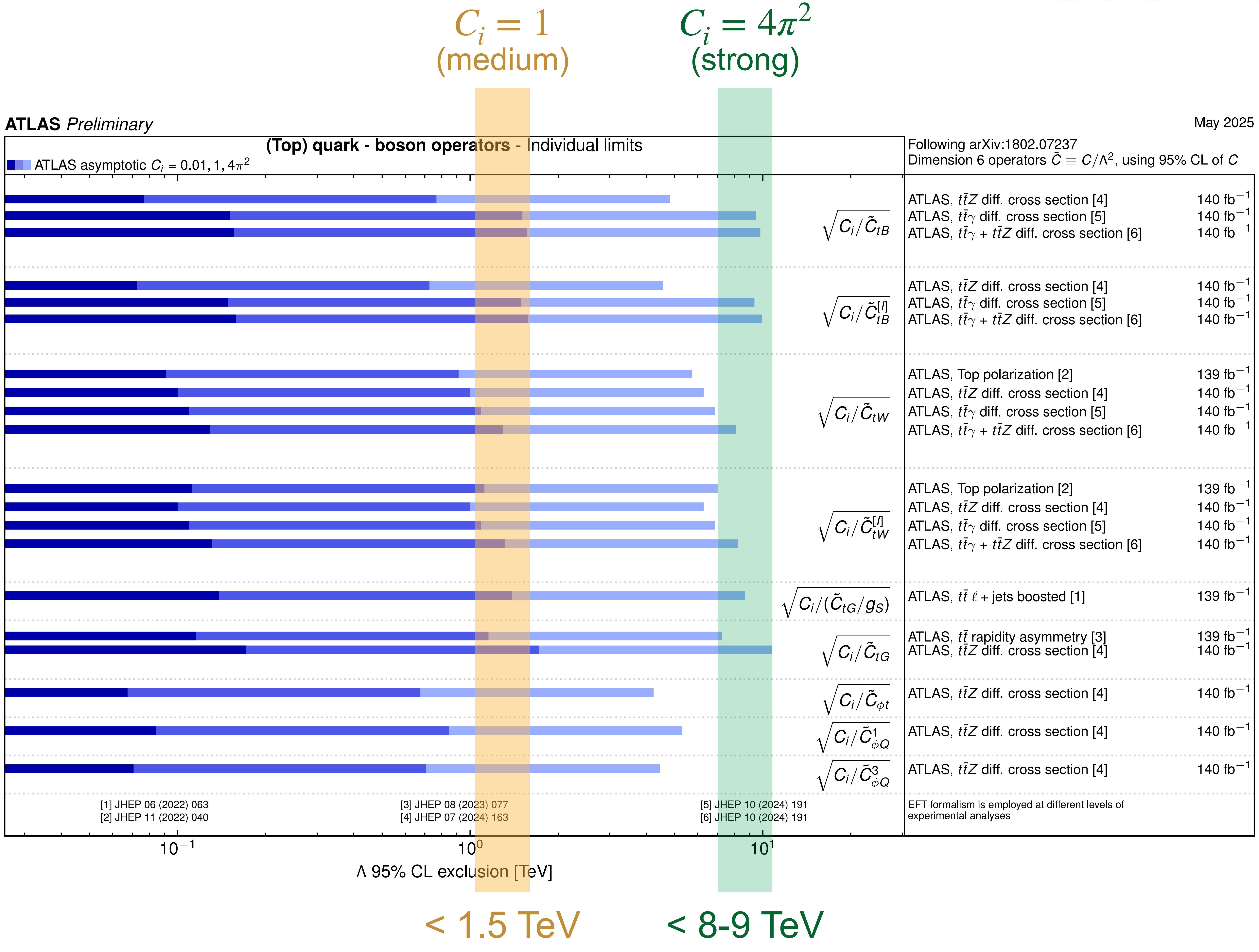


< 8-9 TeV

Summary

ATL-PHYS-PUB-2025-028

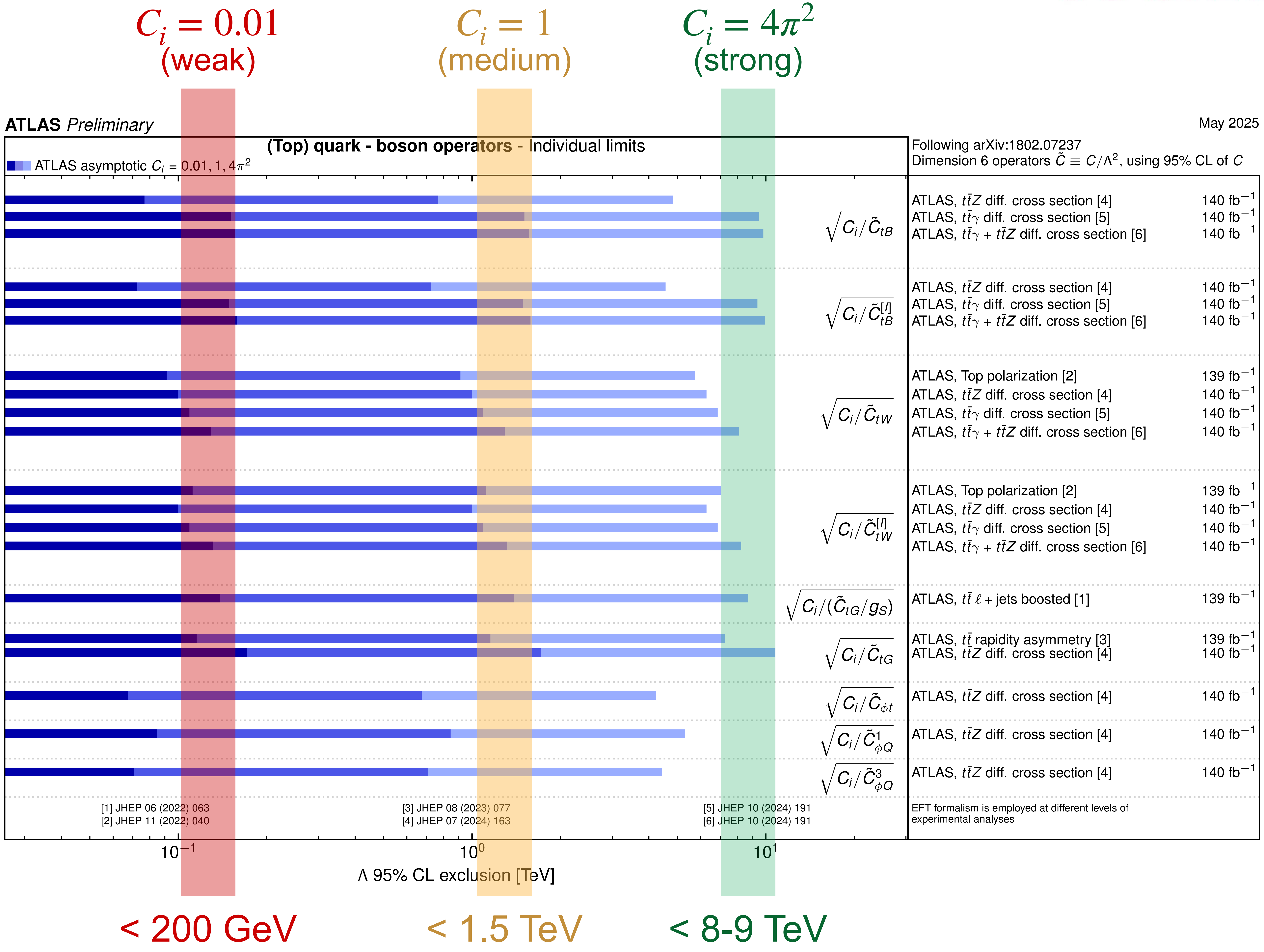
- **Even moderately strong BSM effects are excluded at the TeV level by multiple different analyses.**



Summary

ATL-PHYS-PUB-2025-028

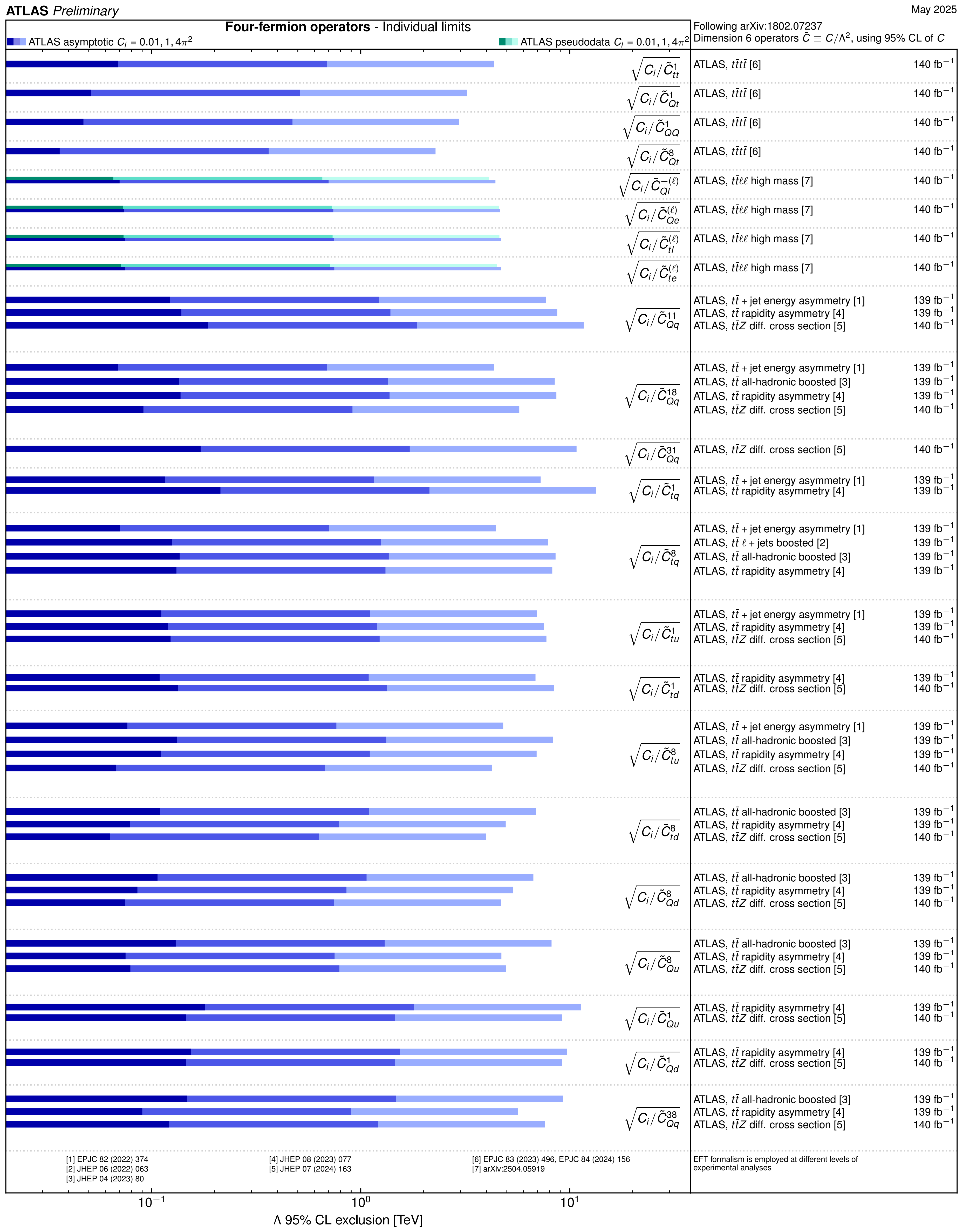
- **The subtlest physics would struggle to hide at the EW scale, highlighting the impressive power of these measurements.**



Summary

ATL-PHYS-PUB-2025-028

- **No time to talk about the other types of operators, but the story is similar** (constraints a little weaker in places).
- **So, is there no new physics in the top sector?**
  - ➡ Not necessarily, but it is clear that it is well hidden.
  - ➡ EFT is a guide, and it is telling us to look more closely and carefully. BSM isn't going to make itself easy to find.
- **Next generation of Run3 measurements will start to appear soon, looking in more places, with more observables, to leave nowhere for BSM to hide!**



Backup

Presenting Results

- **There are two ways to use EFT results to make statements about where BSM could be hiding based on E and C_i.**

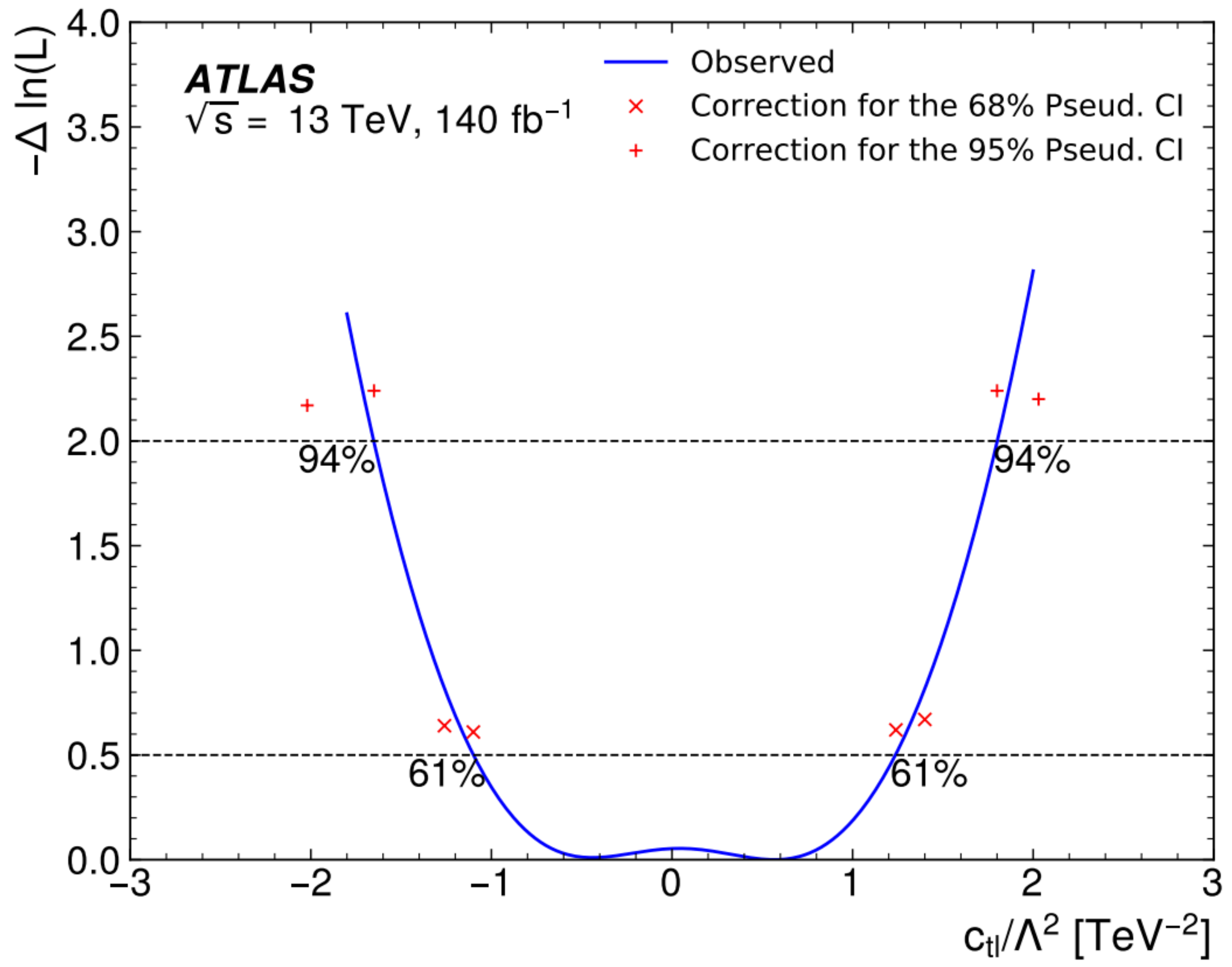
Limits on Energy Scale (E)
(for various coefficient values)

C = 0.01 ('weak'), BSM excluded below X GeV

C = 1.00 ('strong'), BSM excluded below Y GeV

C = $4\pi^2$ (' very strong '), BSM excluded below Z GeV

Limits on Coefficients (C_i)
(at fixed scale, usually $\Lambda^2 = 1$ TeV)



- **We usually present results both ways.**

Presenting Results

Operator	Definition	Description
O_{te}	$(\bar{e}_p \gamma_\mu e_r)(\bar{t}\gamma^\mu t)$	R-handed leptons and R-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex
O_{Qe}	$(\bar{Q}\gamma_\mu Q)(\bar{e}_p \gamma^\mu e_r)$	R-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices
O_{tl}	$(\bar{l}_p \gamma_\mu l_r)(\bar{t}\gamma^\mu t)$	L-handed leptons and R-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex
O^1_{Ql}	$(\bar{l}_p \gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$	L-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, weak-singlet
O^3_{Ql}	$(\bar{l}_p \sigma^i \gamma_\mu l_r)(\bar{Q}\sigma^i \gamma^\mu Q)$	L-handed leptons and L-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, weak-triplet
O^1_{leQt}	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{Q}^k t)$	Mixed L-/R-handed quarks and leptons in the $t\bar{t}\ell^+\ell^-$, $t\bar{b}\ell^+\ell^-$ and $b\bar{b}\ell^+\ell^-$ vertices, scalar
O^3_{leQt}	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{Q}^k \sigma^{\mu\nu} t)$	Mixed L-/R-handed quarks and leptons in the $t\bar{t}\ell^+\ell^-$, $t\bar{b}\ell\nu$, $\bar{t}b\ell\nu$ and $b\bar{b}\ell^+\ell^-$ vertices, tensor

Presenting Results

	SR-3L-ttll(high-m)	
Process	ee	$\mu\mu$
$t\bar{t}\ell^+\ell^-$	19.4 ± 1.4	27.4 ± 1.2
$t\bar{t}W$	19.9 ± 1.9	27.5 ± 3.5
$t\bar{t}H$	8.6 ± 0.8	11.9 ± 1.1
WZ	12 ± 5	20 ± 8
ZZ	1.4 ± 0.6	2.4 ± 1.0
$t\ell^+\ell^- q$, tWZ	4.2 ± 0.8	6.5 ± 1.2
F-e-ExtConv	1.2 ± 1.1	0.67 ± 0.04
F-e-IntConv	4.9 ± 1.1	6.2 ± 2.6
F-e-HF	2.1 ± 1.5	4.5 ± 0.7
F-e-LF	2.4 ± 0.7	2.0 ± 0.5
F-m-HF	5.8 ± 1.5	4.2 ± 0.5
Other (fakes)	4.4 ± 2.1	6 ± 4
Other (non-fakes)	4.6 ± 1.6	5.7 ± 1.9
Total	91 ± 7	124 ± 9

Presenting Results