University of Glasgow

Effective Field Theory (EFT) limits from ATLAS and CMS

Mark Owen
On behalf of ATLAS & CMS
The University of Glasgow

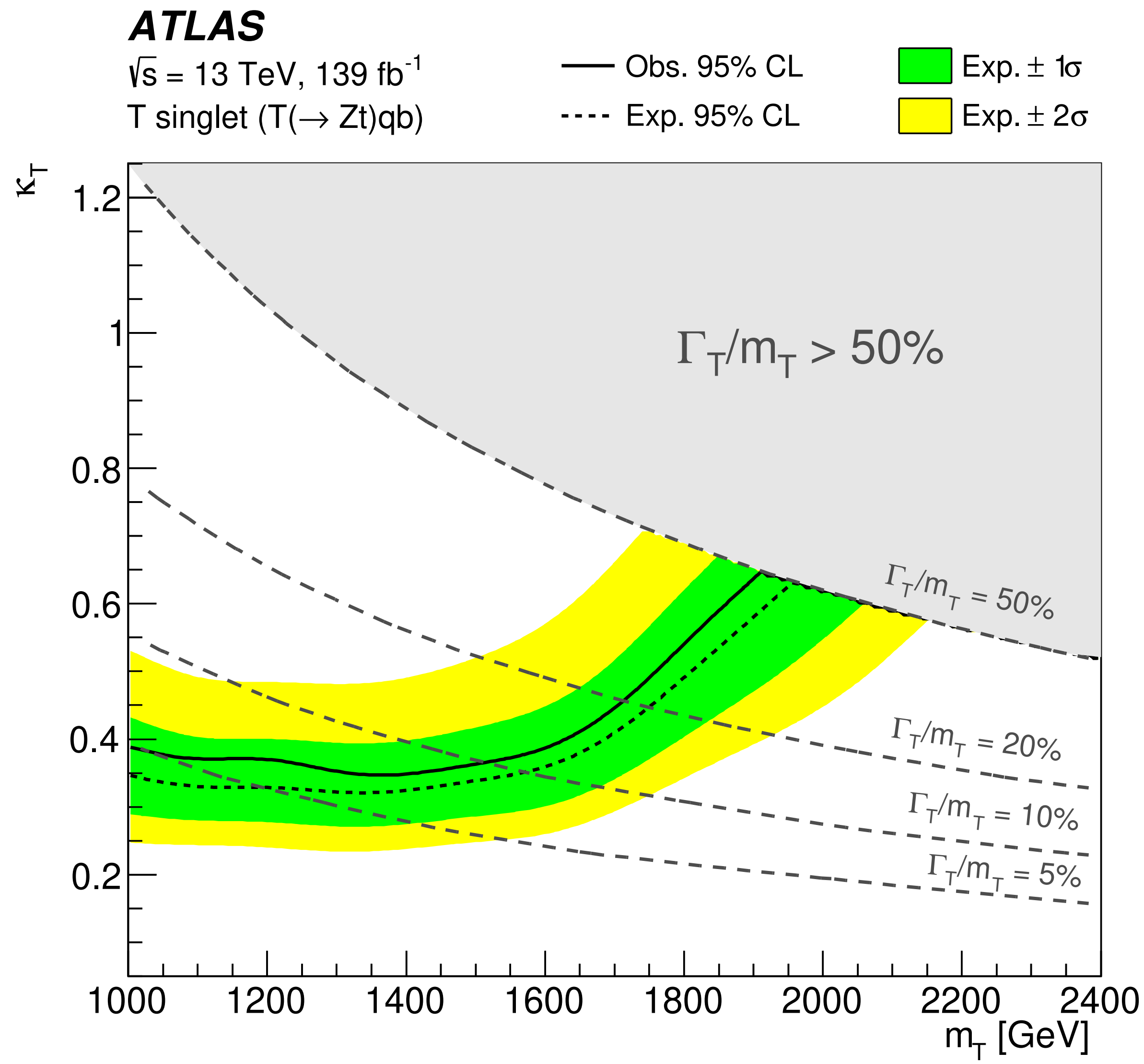
Moriond EW 2024

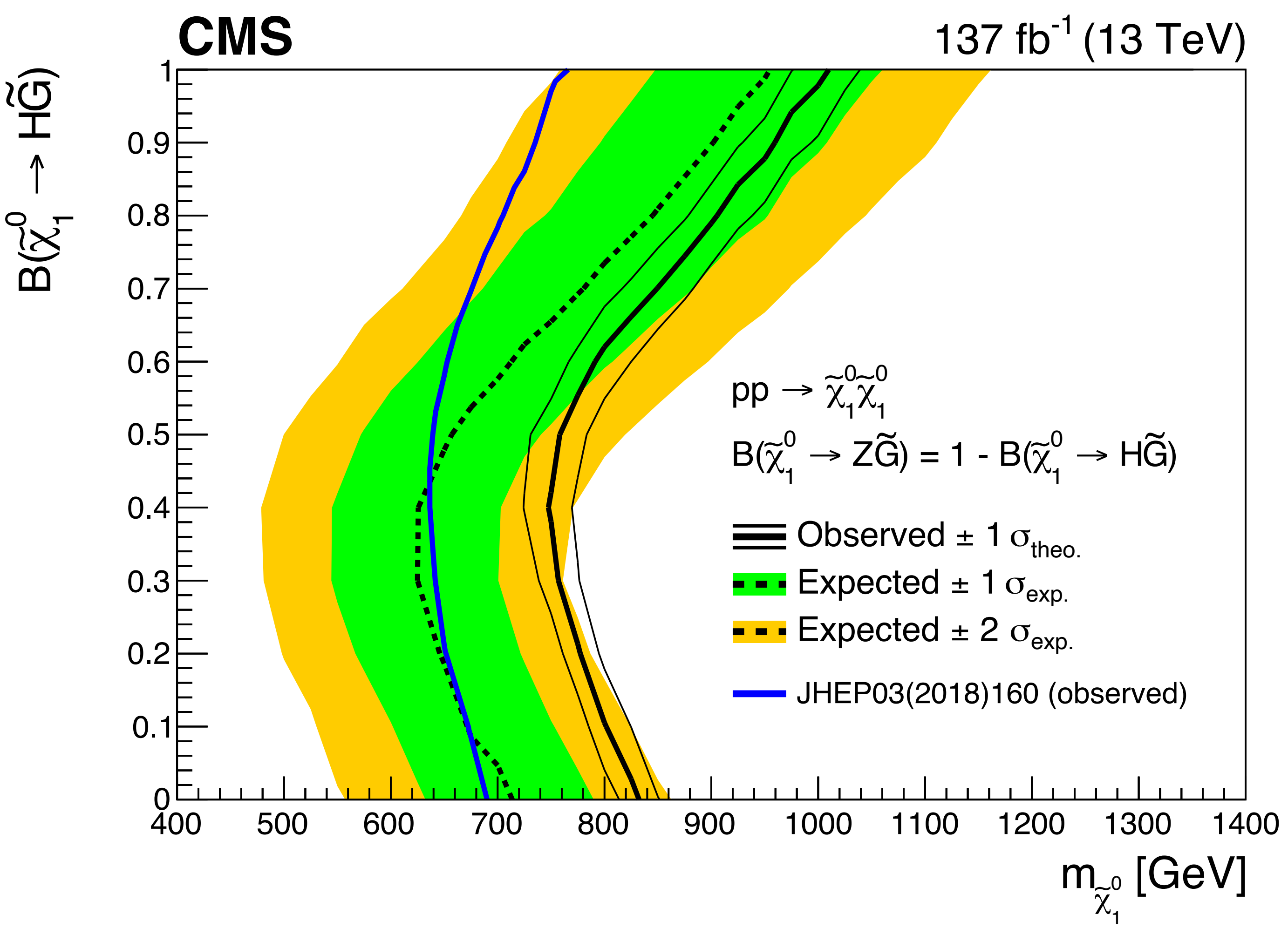
Outline

- Why (SM)EFT for ATLAS and CMS?
- Highlights of recent SMEFT limits:
  - CMS $\gamma\gamma \to \tau\tau$
  - ATLAS WWjj
  - ATLAS $hh \to bb\gamma\gamma$
  - ATLAS $t\bar{t}Z + t\bar{t}\gamma$
  - CMS tt + leptons
- Summary

New physics limits at the LHC

- Huge programme of dedicated searches for new particles / forces:





SM Effective field theory

- New physics could be at such a high energy scale that we cannot see the new resonances at the LHC.
- New particles will still impact LHC measurements - parameterise this with an effective field theory:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots .$$

$O_i^{(n)}$: operator of dimension n (obeying SM symmetries)

$c_i^{(n)}$: Wilson coefficient for $O_i^{(n)}$

Λ: energy scale of new physics

SM Effective field theory

- New physics could be at such a high energy scale that we cannot see the new resonances at the LHC.
- New particles will still impact LHC measurements - parameterise this with an effective field theory:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots .$$

$O_i^{(n)}$: operator of dimension n (obeying SM symmetries)

$c_i^{(n)}$: Wilson coefficient for $O_i^{(n)}$

Λ: energy scale of new physics

- If $\Lambda \gg E$, can truncate series at e.g. n=6.
- One n=5 operator violates L conservation and can generate neutrino mass - not relevant for LHC studies.
- For n=6, Warsaw basis [JHEP 10 (2010) 085] often used to define a complete set of independent operators - 59 operators for CP-even and restricted-flavour scenario.

Effect on observables

$$\sigma = |\mathcal{A}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

Effect on observables

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2{\rm Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM

Effect on observables

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2{\rm Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM

Interference of SM and NP

Effect on observables

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_j^{(6)*}\right)$$

SM

Interference of SM and NP

Pure NP

Effect on observables

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM

Interference of SM and NP

Pure NP

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} p_i + \sum_i \frac{c_i^2}{\Lambda^4} p_{2,i} + \sum_{i<j} \frac{c_i c_j}{\Lambda^4} p_{ij}$$

Effect on observables

$$\sigma = |\mathcal{A}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM

Interference of SM and NP

Pure NP

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} p_i + \sum_i \frac{c_i^2}{\Lambda^4} p_{2,i} + \sum_{i<j} \frac{c_i c_j}{\Lambda^4} p_{ij}$$

- Just need quadratic parameterisation in $\frac{c_i}{\Lambda^2}$ & a measurement can be used to constrain c_i.
- Want observables that: (i) have large p_i/σ_{SM} (ii) we can measure precisely.
- Caveat: dimension 8 operators also enter at $\frac{1}{\Lambda^4}$, but are often neglected.

Effect on observables

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j}\frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_j^{(6)*}\right)$$

SM

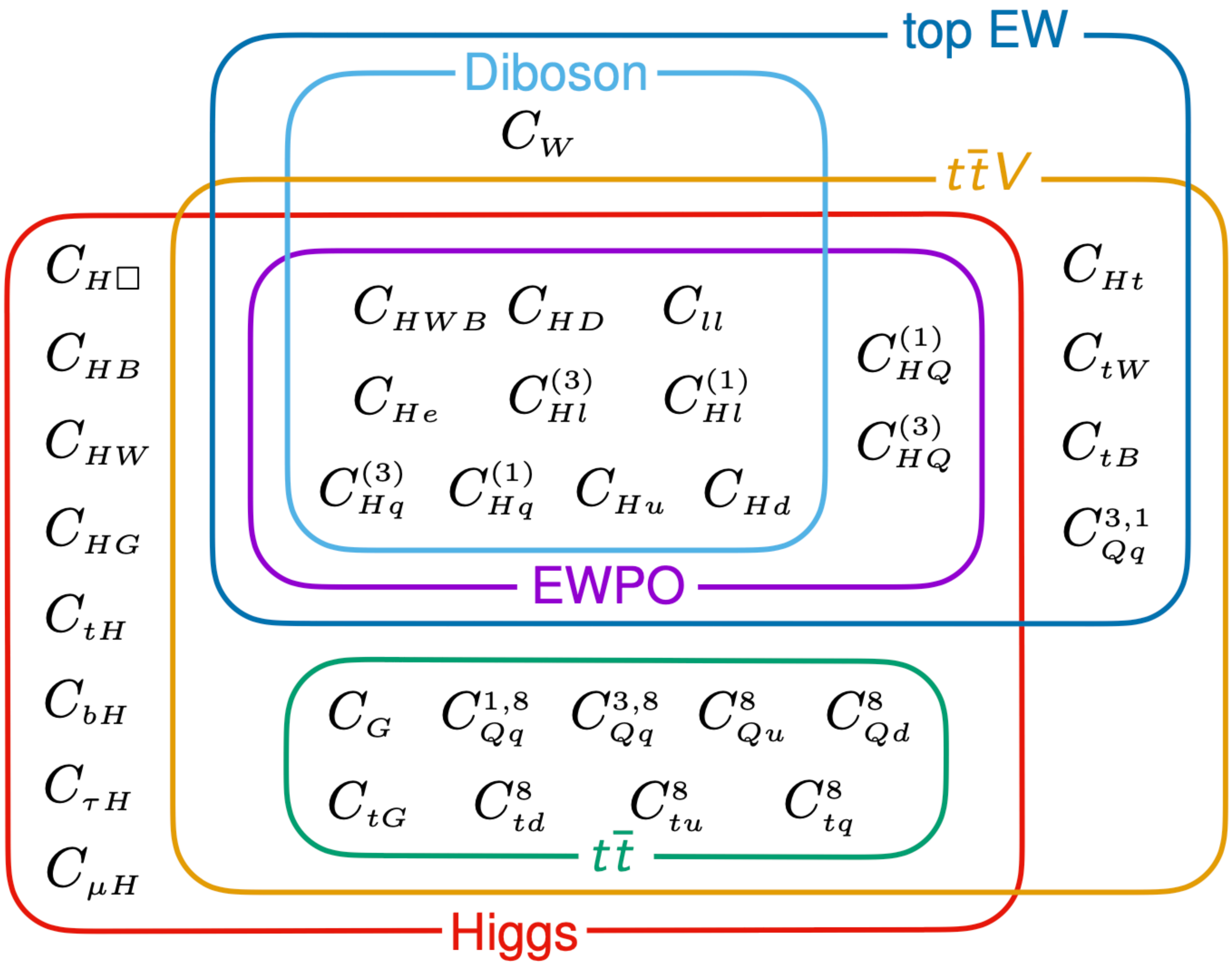
Interference of SM and NP

Pure NP

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} p_i + \sum_i \frac{c_i^2}{\Lambda^4} p_{2,i} + \sum_{i<j} \frac{c_i c_j}{\Lambda^4} p_{ij}$$

- Just need quadratic parameterisation in $\frac{c_i}{\Lambda^2}$ & a measurement can be used to constrain c_i.
- Want observables that: (i) have large $p_i/\sigma_{\rm SM}$ (ii) we can measure precisely.
- Caveat: dimension 8 operators also enter at $\frac{1}{\Lambda^4}$, but are often neglected.
- Aim for global fits of many operators with many input physics measurements.

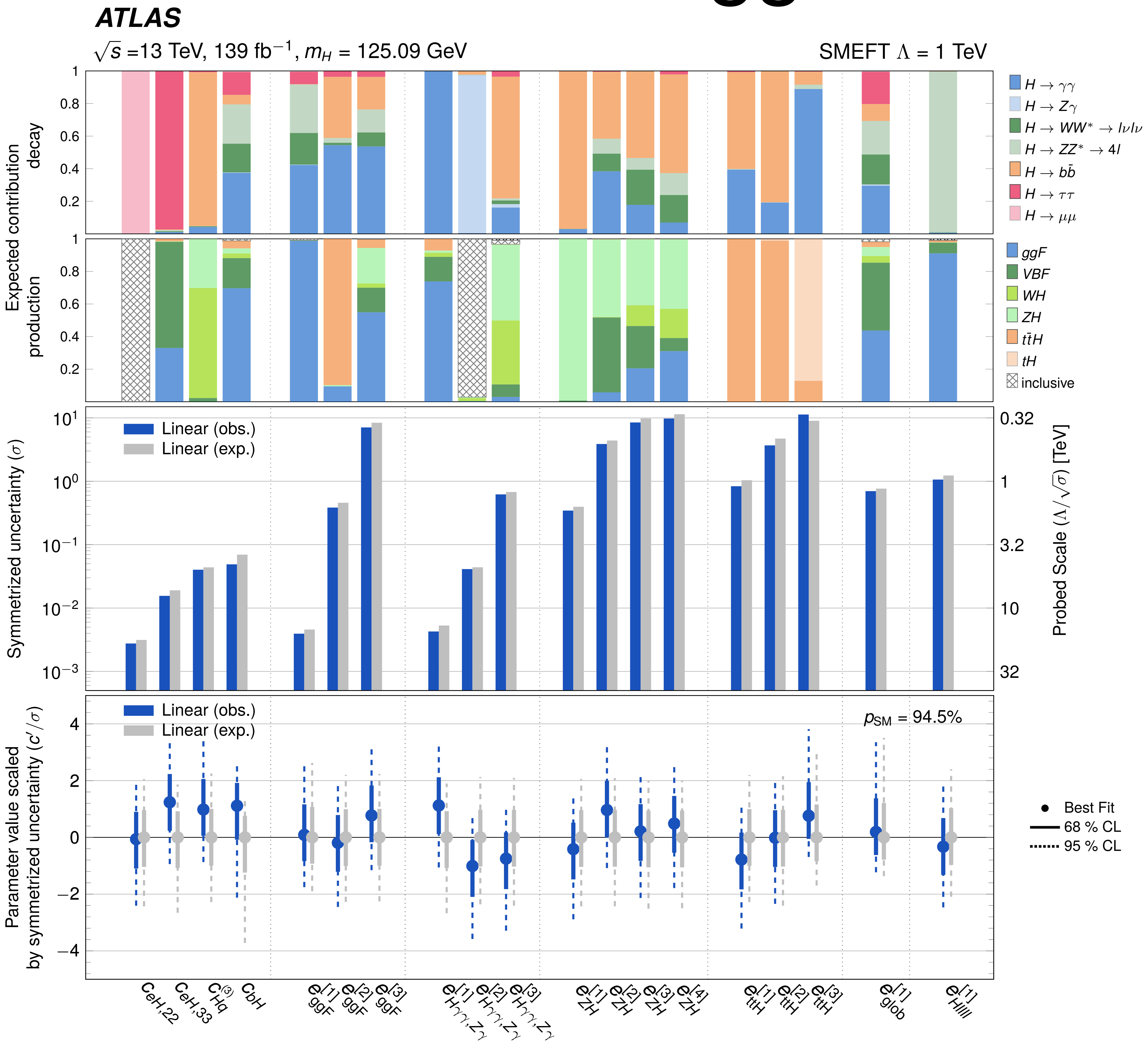
Effect on observables



- Aim for global fits of many operators with many input physics measurements.

JHEP 04 (2021) 279

Combined Higgs fit



arXiv:2402.05742

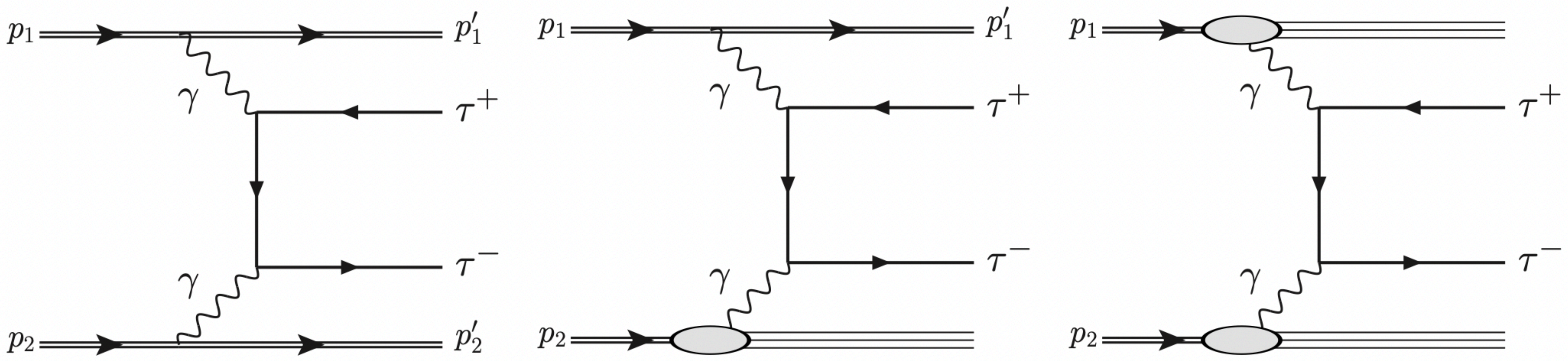
CMS $pp(\gamma\gamma) \rightarrow \tau\tau$

Other recent exclusive studies:
CMS $\gamma\gamma \rightarrow WW/ZZ$ JHEP 07 (2023) 229
ATLAS and CMS $\mathrm{PbPb}(\gamma\gamma) \rightarrow \tau\tau$ PRL 131 (2023) 151802, PRL 131 (2023) 151803

CMS-PAS-SMP-23-005

CMS $\gamma\gamma \to \tau\tau$

- Use LHC as a photon collider:



- The process probes the magnetic (a_τ) and electric (d_τ) dipole moments of the tau lepton, which are related to SMEFT operators:

$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Re}\left[C_{\tau\gamma}\right]$$

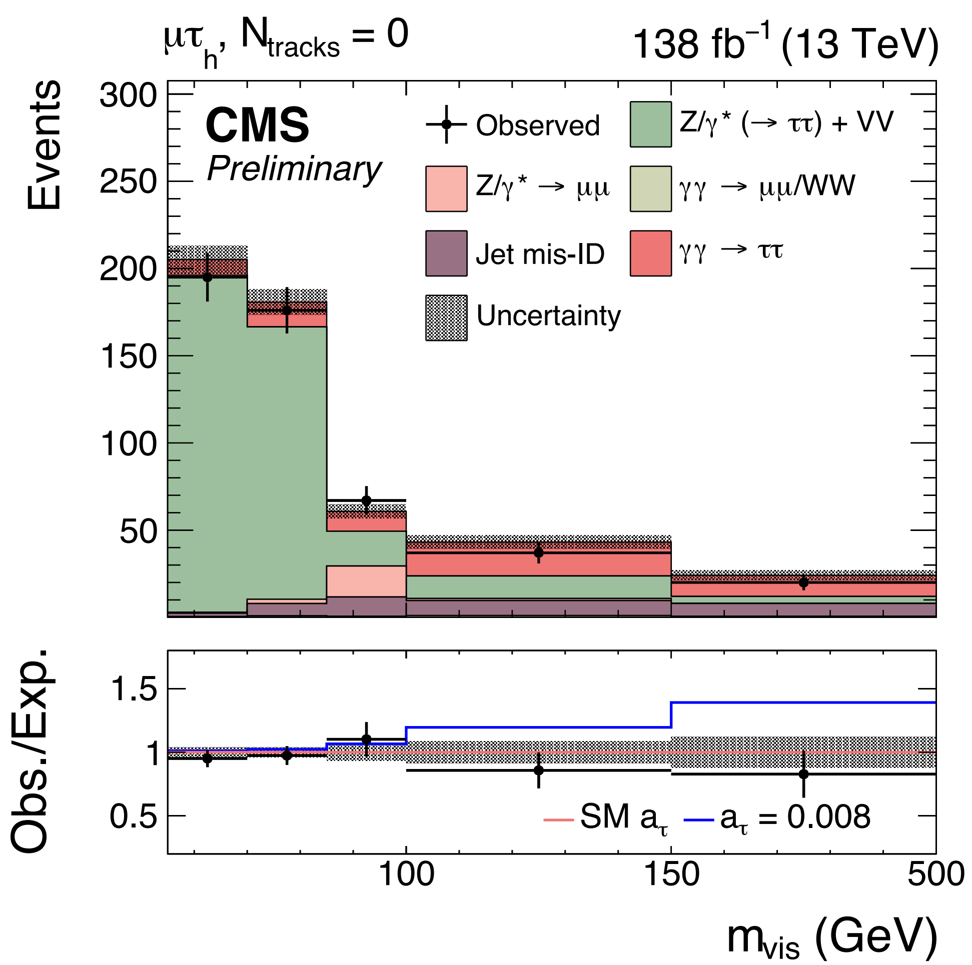
$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Im}\left[C_{\tau\gamma}\right]$$

$$C_{\tau\gamma} = \left(cos\theta_W C_{\tau B} - \sin\theta_W C_{\tau W}\right)$$

CMS-PAS-SMP-23-005

CMS $\gamma\gamma \rightarrow \tau\tau$

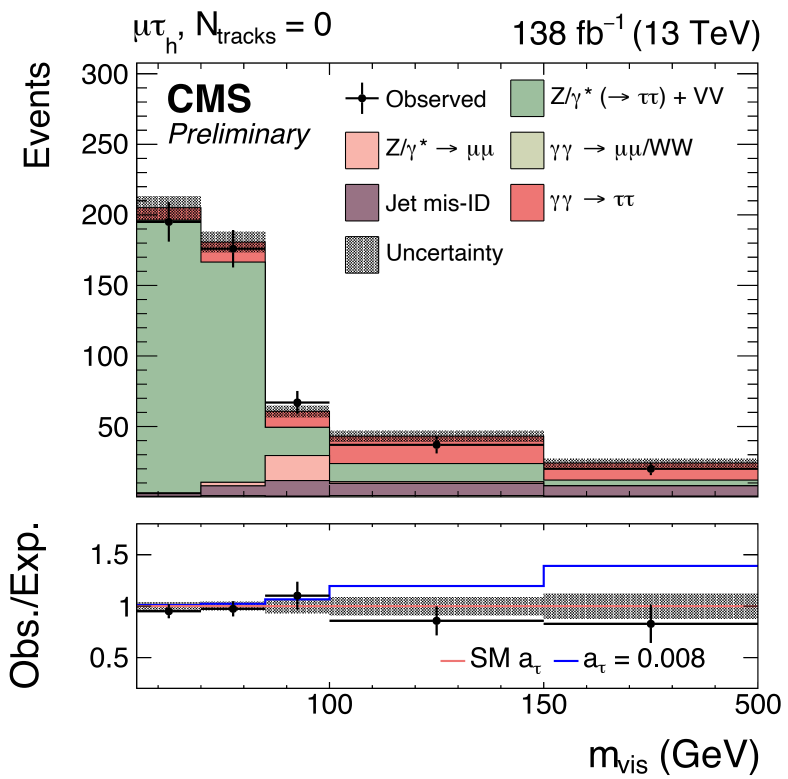
- Search for $e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$ channels.
- "Exclusivity" requirement of maximum 1 track close to the tau decay products is crucial to select di-photon production.
- Invariant mass of tau decay products provides observable sensitive of new physics:

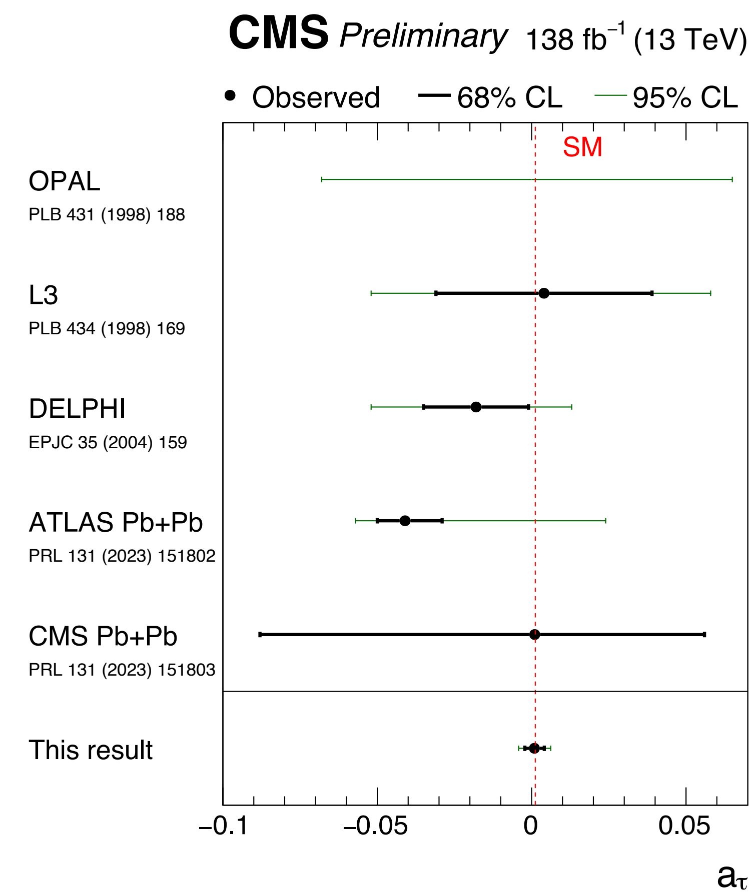


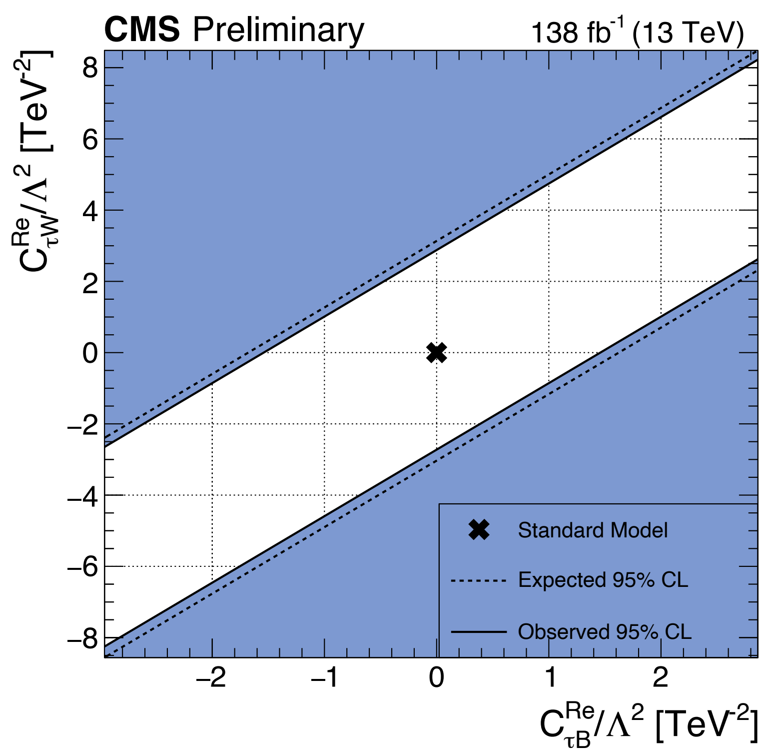
First observation (5.3σ) of $pp(\gamma\gamma) \rightarrow \tau\tau$.

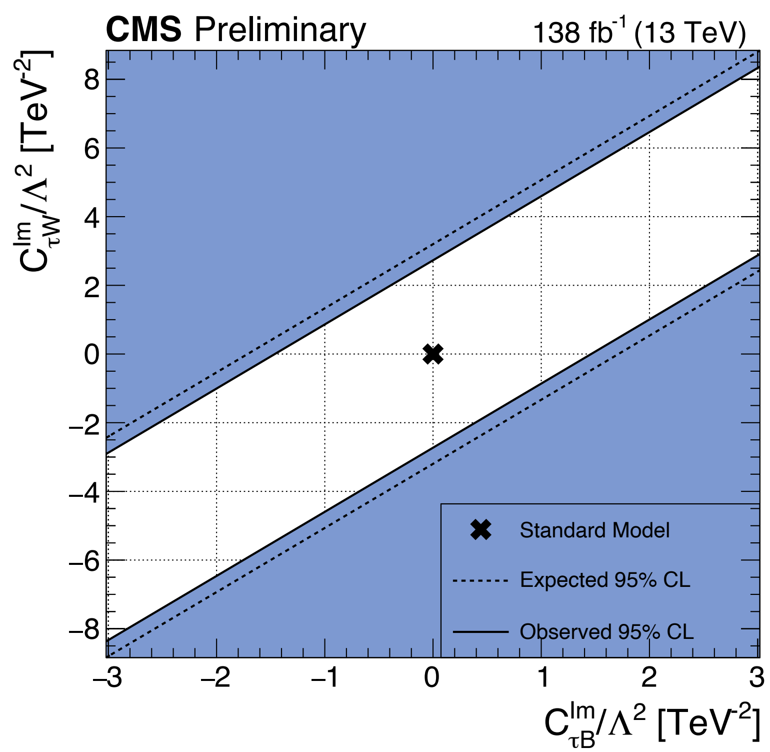
CMS-PAS-SMP-23-005

CMS $\gamma\gamma \to \tau\tau$ limits









CMS-PAS-SMP-23-005

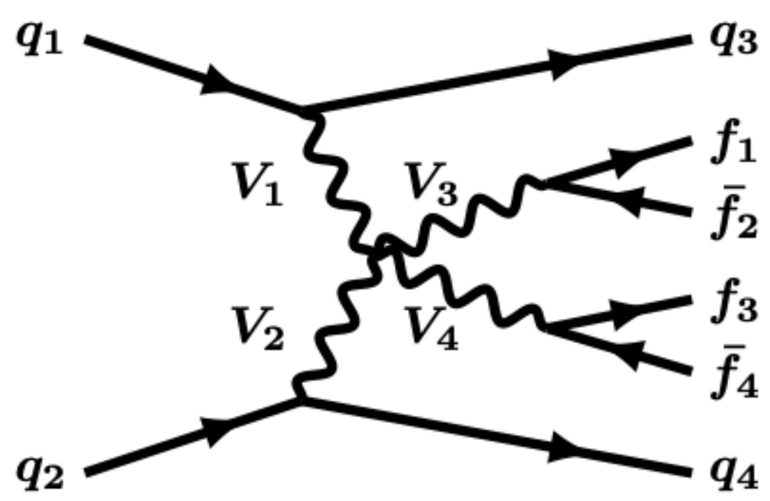
ATLAS $W^{\pm}W^{\pm}jj$

Other recent diboson EFT studies:
ATLAS $W\gamma jj$ arXiv:2403.02809
ATLAS WZjj arXiv:2403.15296
ATLAS ZZ arXiv:2310.04350
CMS $W\gamma jj$ PRD 108 (2023) 032017
CMS exclusive WW, ZZ JHEP 07 (2023) 229

arXiv:2312.00420

ATLAS $W^{\pm}W^{\pm}jj$

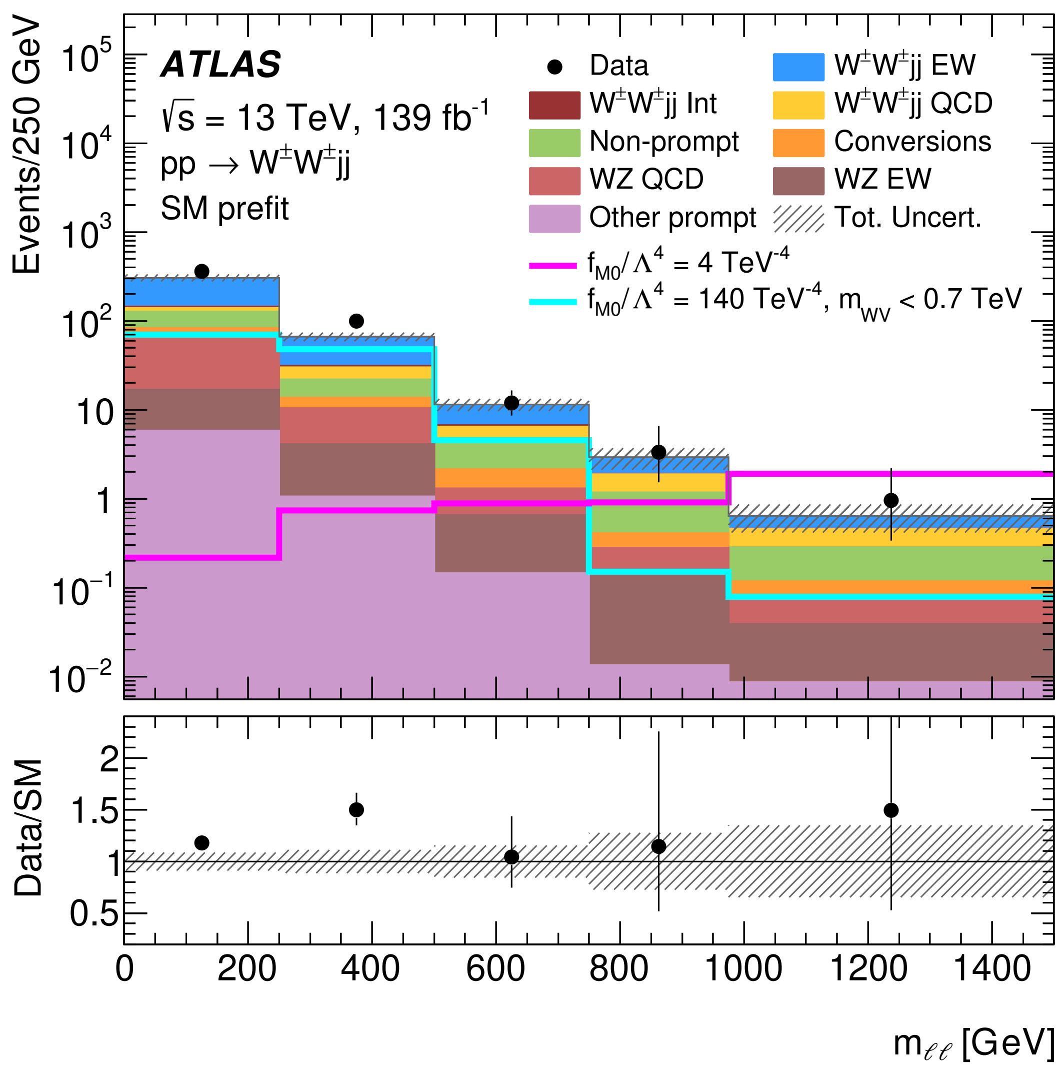
- Same-sign W boson production possible in SM via triple & quartic gauge boson vertices and Higgs exchange.
- Contributions to quartic vertex (and not triple vertex) appear first at dimension 8 in SMEFT.

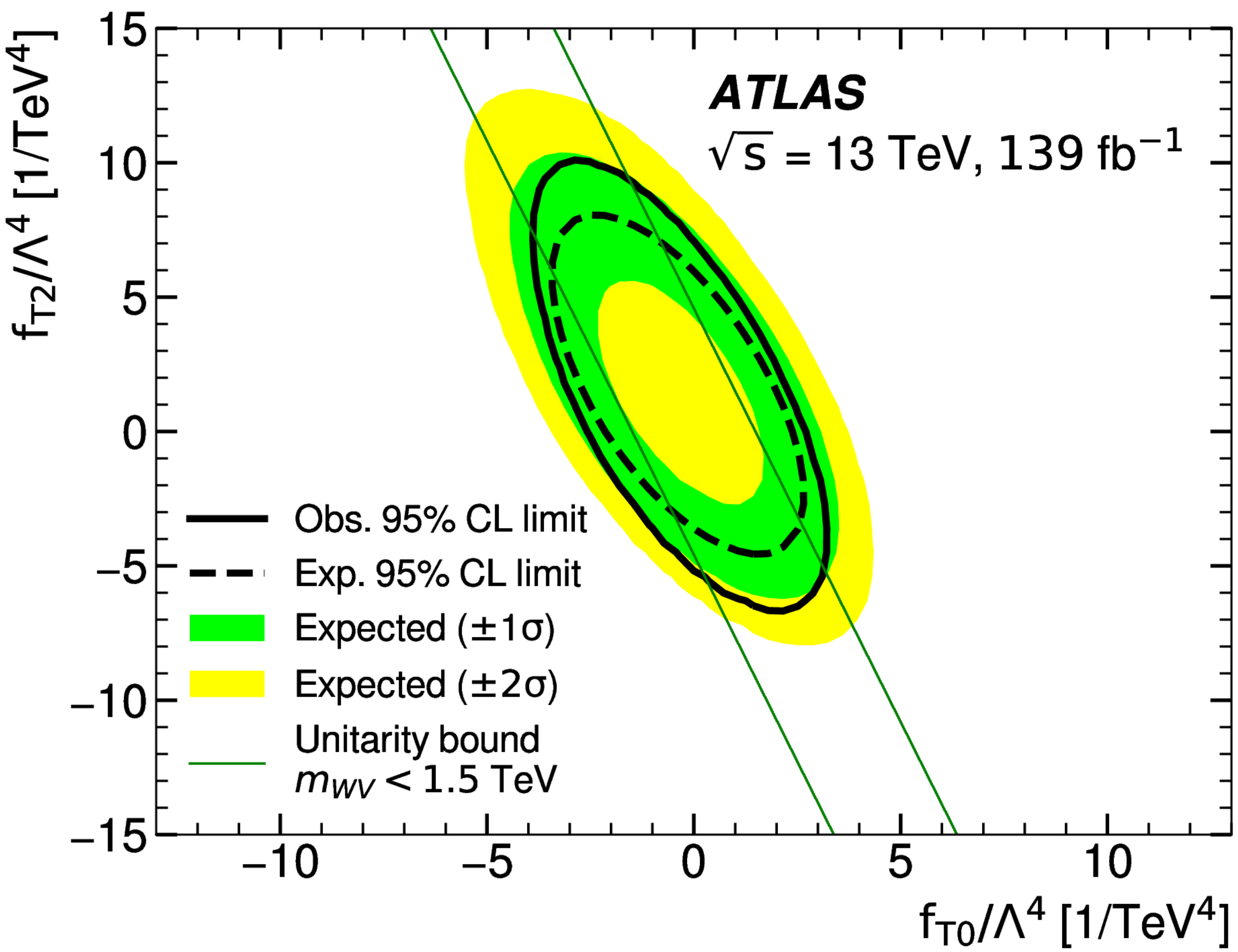


- Analysis selects $\ell^{\pm}\ell^{\pm}jj$ events consistent with vector-boson scattering - high $m(jj)$, large $\Delta y(jj)$.
- Differential cross-section are measured in the paper, but EFT limits done by direct fit to the reconstructed $m(\ell\ell)$ distribution and two control regions.
- 8 operators considered, either in 1D or 2D fits.

arXiv:2312.00420

ATLAS $W^{\pm}W^{\pm}jj$





- EFT predictions can violate unitarity - this is implemented in the limits by applying a WV invariant mass requirement on the signal which varies according to the sensitivity.
- Competitive limits with earlier CMS measurement [PLB 809 (2020) 135710].

arXiv:2312.00420

ATLAS $hh \to bb\gamma\gamma$

JHEP 01 (2024) 066

ATLAS $hh \to bb\gamma\gamma$

- Not yet at SM sensitivity for hh, but can probe non-SM contributions.

- Interesting case, where alternate HEFT Lagrangian formalism is used, in addition to SMEFT interpretation.

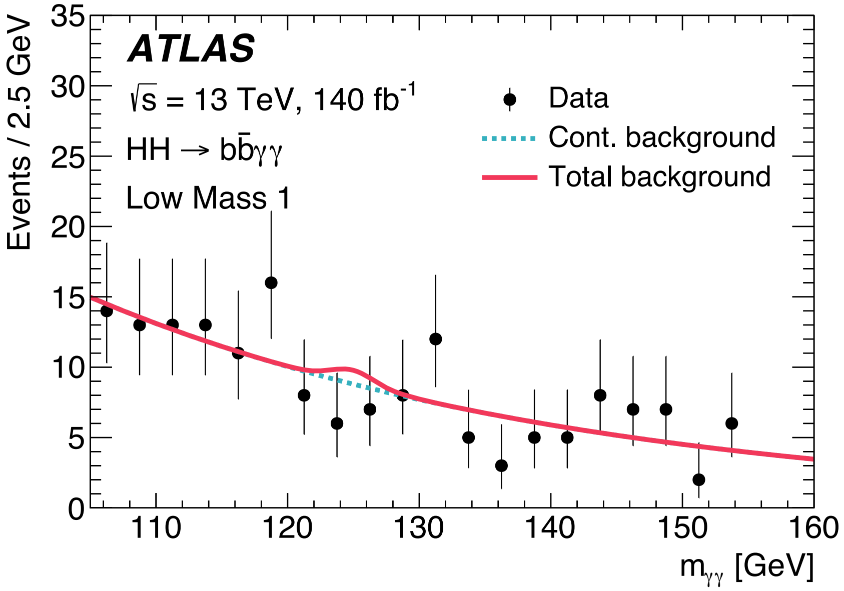
  - Couplings of HH to fermions / gluons decoupled from H to fermions / gluons, test c_{hhh}, c_{tthh} and c_{gghh}.

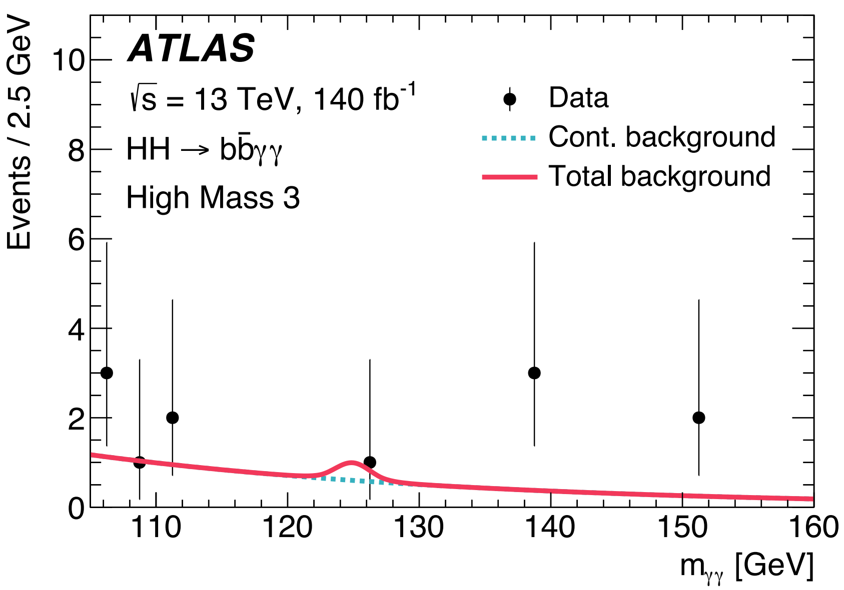
- Analysis separates events by $m^*(bb\gamma\gamma)$ - different operators contribute to different regions.

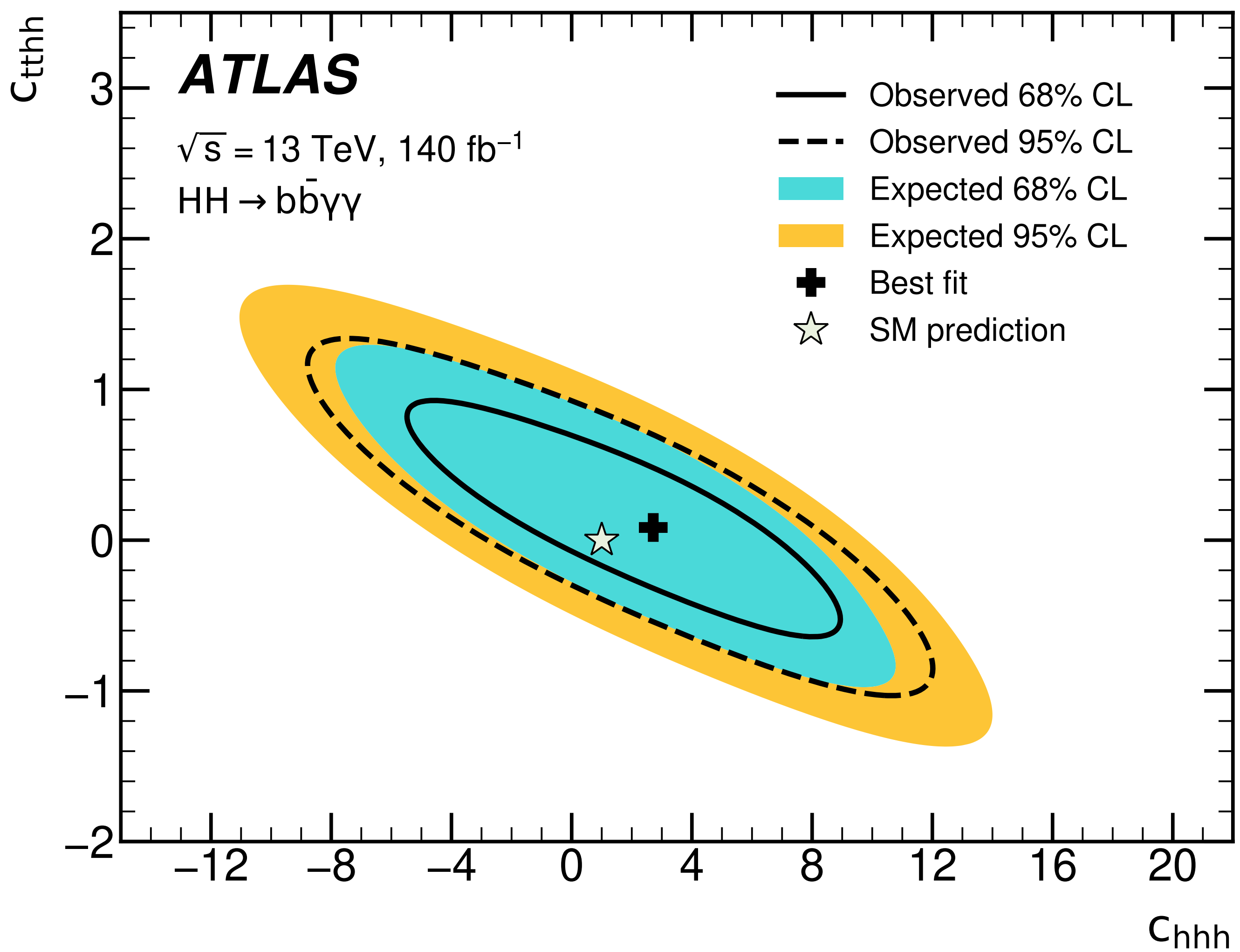
$$m^*(bb\gamma\gamma) = m(bb\gamma\gamma) - \left(m(bb) - m_H\right) - \left(m(\gamma\gamma) - m_H\right)$$

JHEP 01 (2024) 066

ATLAS $hh \to bb\gamma\gamma$







- No deviation from SM.

JHEP 01 (2024) 066

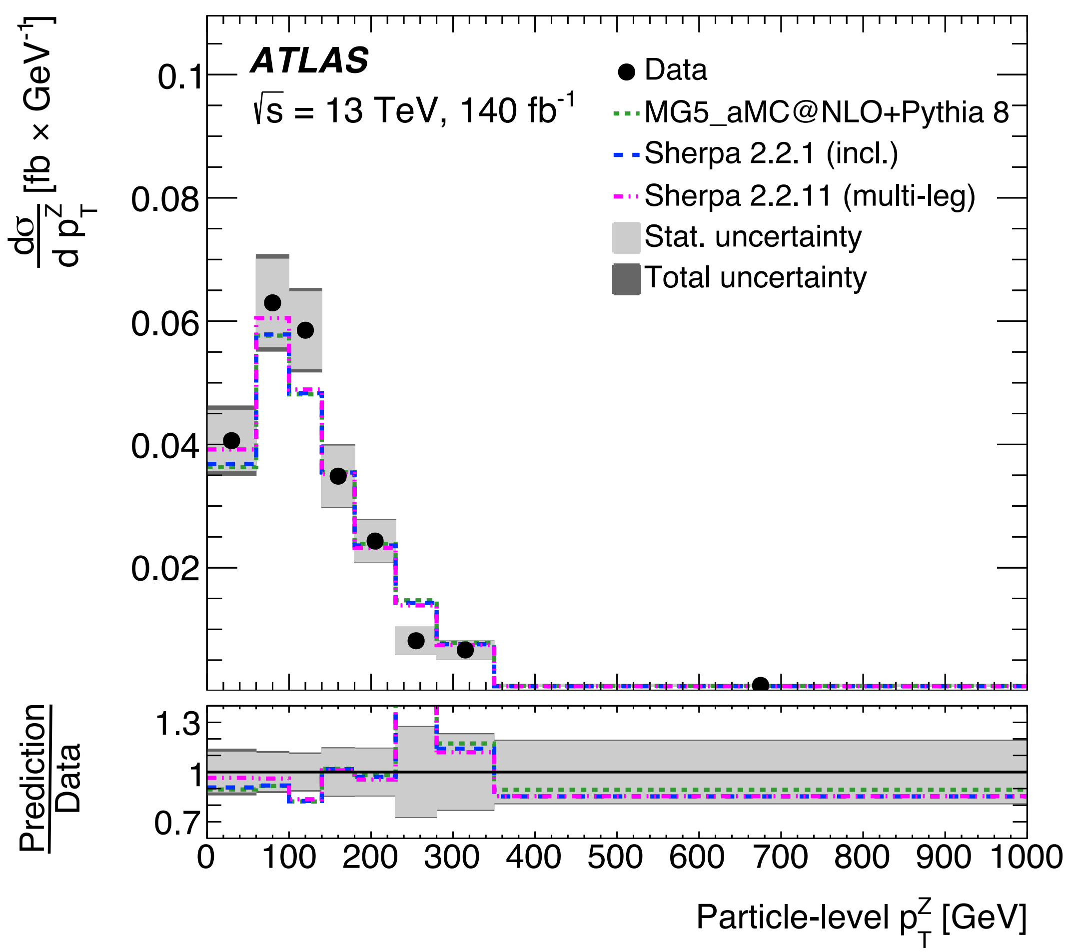
ATLAS $t\bar{t}Z + t\bar{t}\gamma$

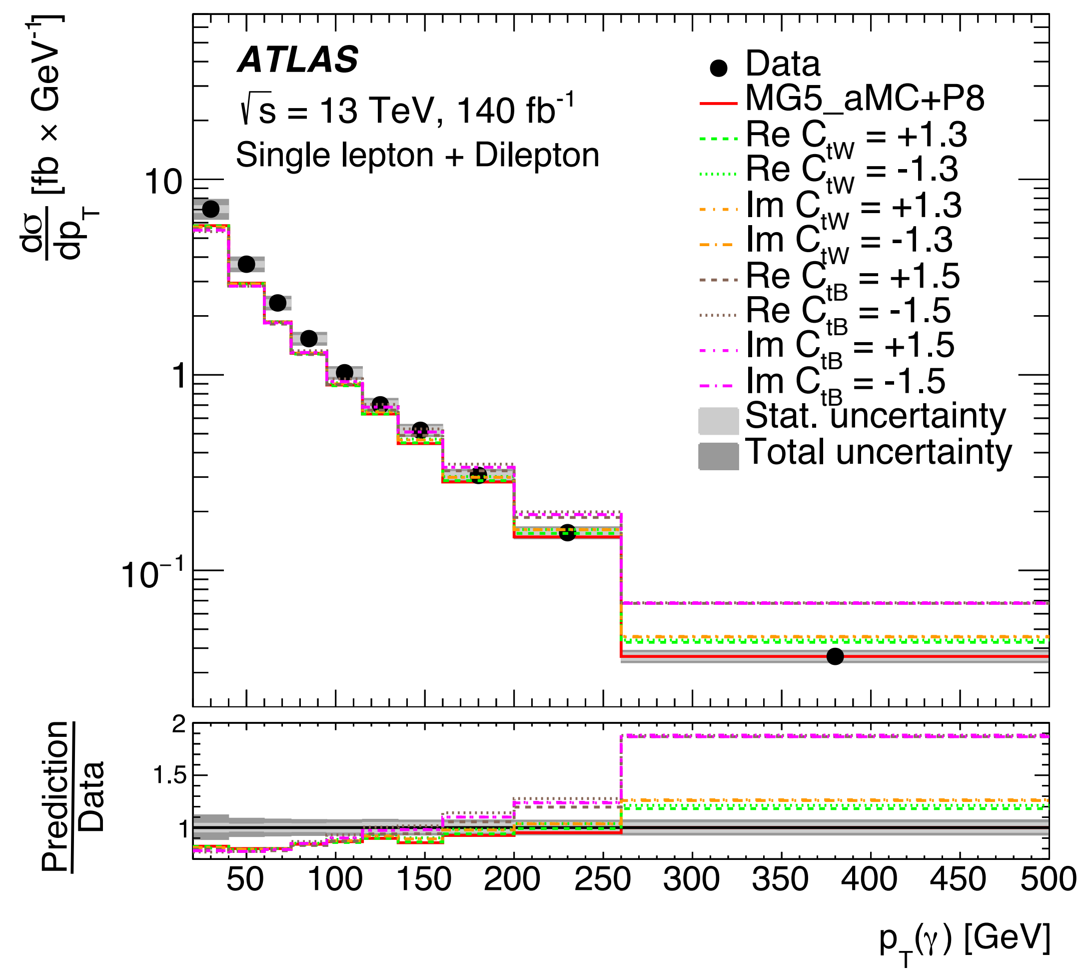
arXiv:2403.09452

arXiv:2312.04450

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

- Recent differential cross-section measurements of $t\bar{t}Z$ and $t\bar{t}\gamma$ production:





Simultaneous EFT fit to the two distributions, with two complex WC: $C_{tZ}, C_{t\gamma}$

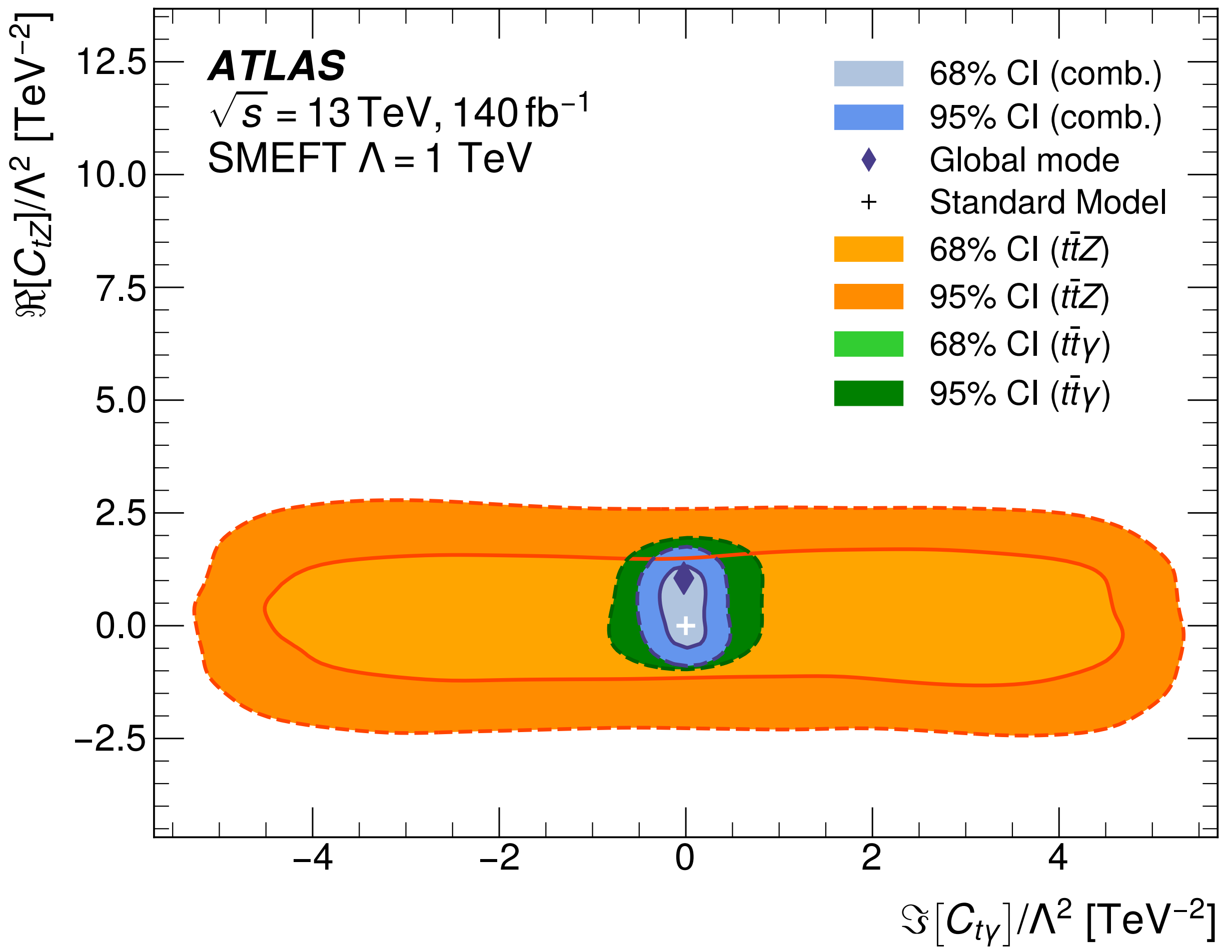
$$C_{tZ} = \cos\theta_W C_{tW} - \sin\theta_W C_{tB}$$
$$C_{t\gamma} = \sin\theta_W C_{tW} + \cos\theta_W C_{tB}$$

arXiv:2312.04450

arXiv:2403.09452

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

- Example limit (other WC are marginalised over):



Combination of measurements significantly improves sensitivity.

arXiv:2403.09452

CMS tt + leptons

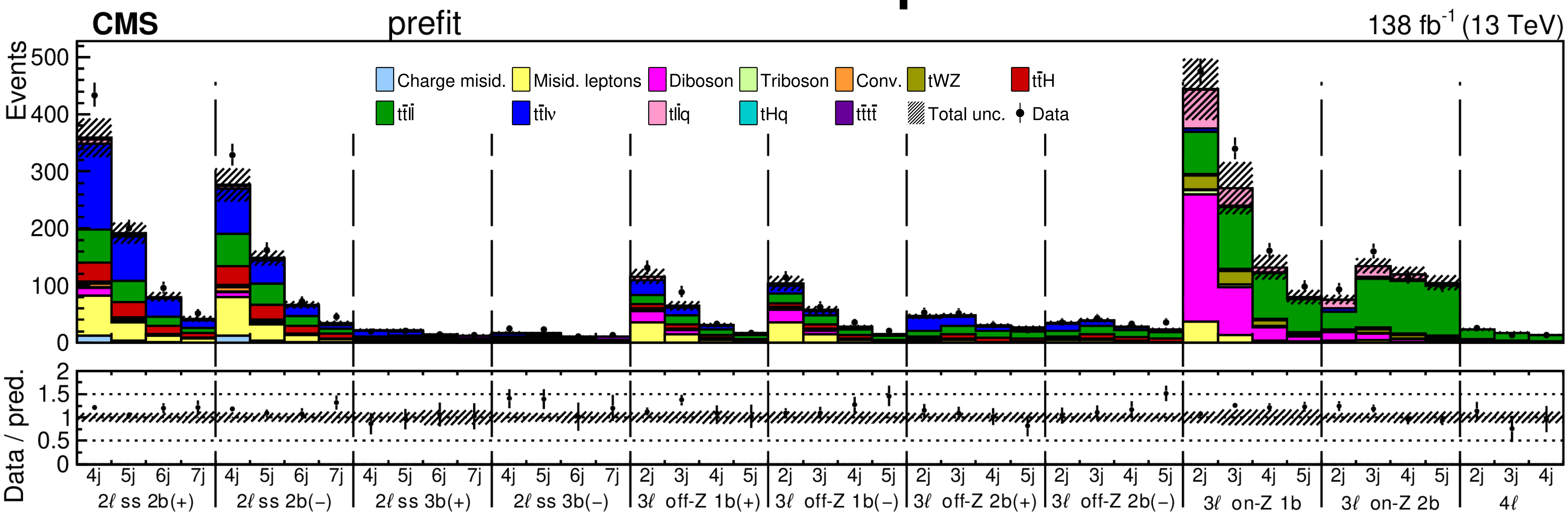
JHEP 12 (2023) 068

CMS tt + leptons

- Multiple physics processes can lead to $t\bar{t}$ + additional leptons: $t\bar{t}H, t\bar{t}Z, t\bar{t}W, t\bar{t}t\bar{t}, tZq, tHq$.
  - Single SMEFT operator can affect many of the processes.
- Analysis looks at events with 2 (same charge), 3 or 4 leptons, at least 2 jets (1 b-jet).
  - Events are subdivided according to number of jets, b-jets and lepton charge.
- Observables:
  - Most ttZ like events: $p_T(Z \to \ell^+\ell^-)$.
  - Others: p_T of pair of jet / lepton 4-vectors with highest p_T.

JHEP 12 (2023) 068

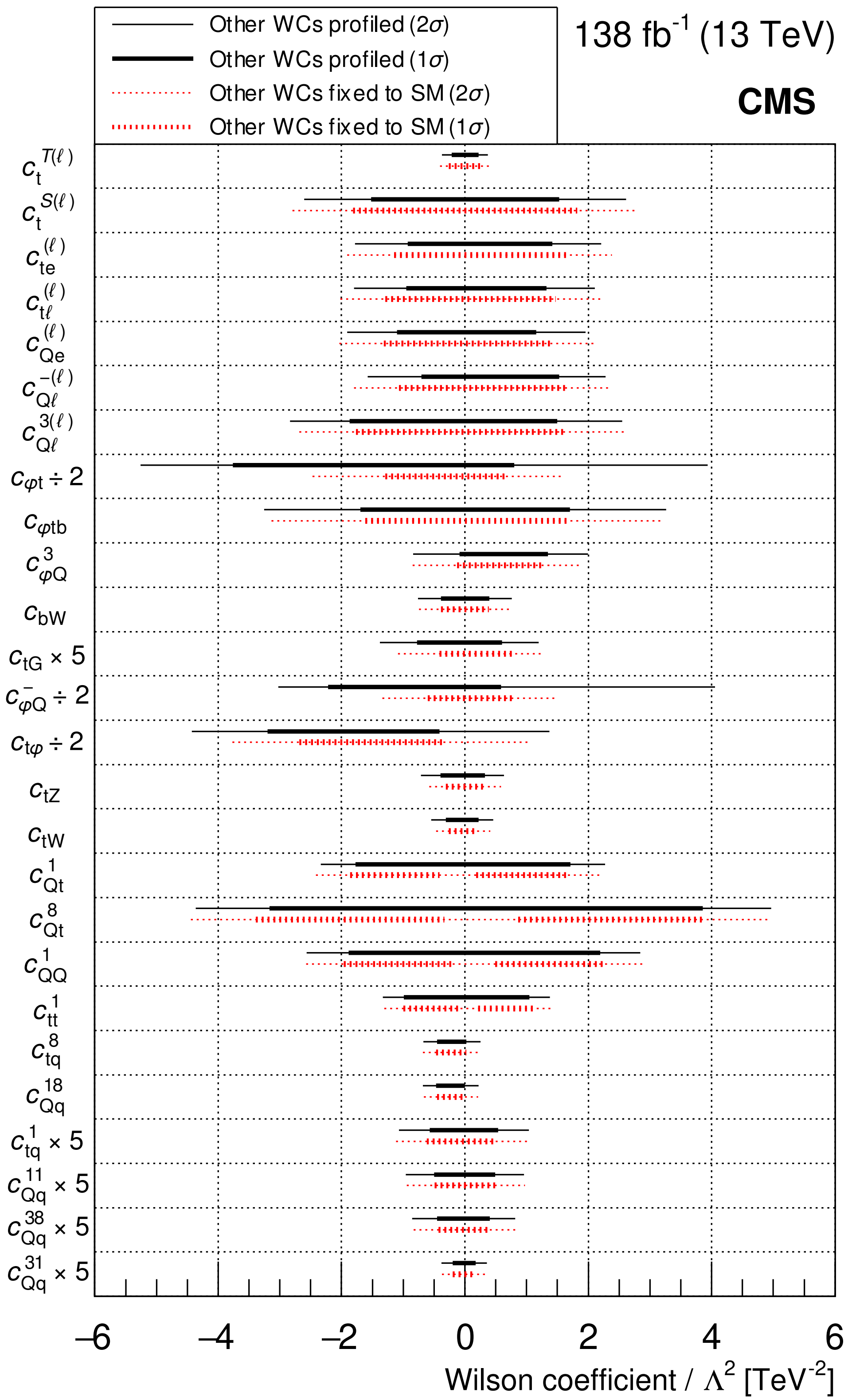
CMS tt + leptons



- EFT fits to reconstructed level data, 26 EFT operators are considered.
- Fits done with either:
  - All Wilson coefficients free-floating (profiled)
  - Only one / two are free and others are fixed to 0.

JHEP 12 (2023) 068

CMS tt + leptons



- Powerful analysis - limits not degrading going from individual (red) to profiled (black) fits.
- Direct comparisons to ATLAS result challenging due to operator definitions / sets.

JHEP 12 (2023) 068

Summary

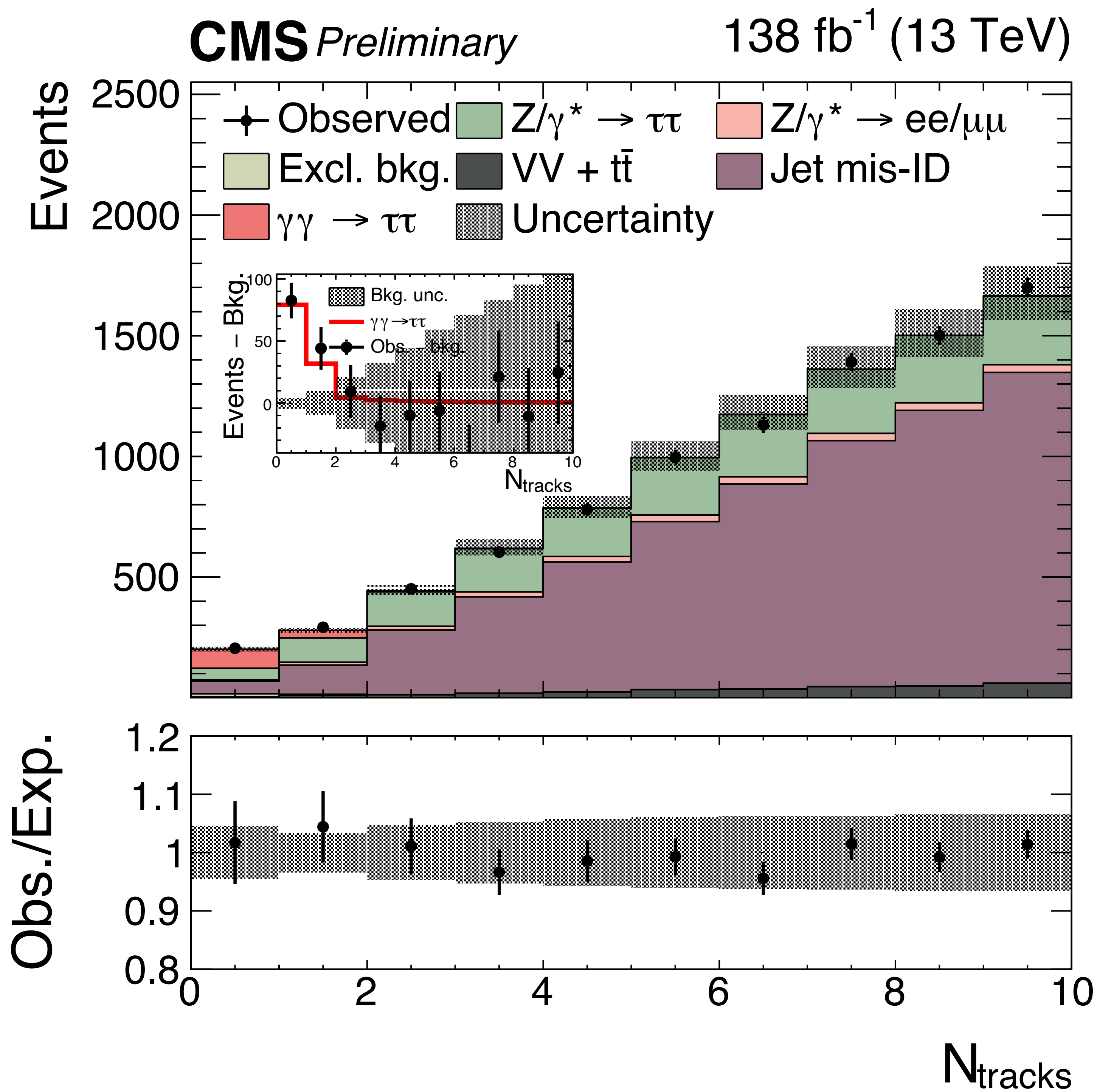
- No discovery of resonant new physics at the LHC - (SM)EFT is tool of choice for parameterising effects of heavy new physics on our measurements.
- EFT limits produced from a diverse range of analyses.
  - Number / choice of operators still a challenge.
  - Both strategies of fitting directly reconstructed level data vs fitting measured cross-section have been deployed.
- EWPO + Higgs + diboson global EFT fit done by ATLAS in 2022.
  - Many new results since then -> stay tuned!

University of Glasgow

Backup

CMS $\gamma\gamma \to \tau\tau$

- N(tracks) distribution without selection, but with $m_{\text{vis}} > 100$ GeV:



CMS-PAS-SMP-23-005

CMS tt + leptons

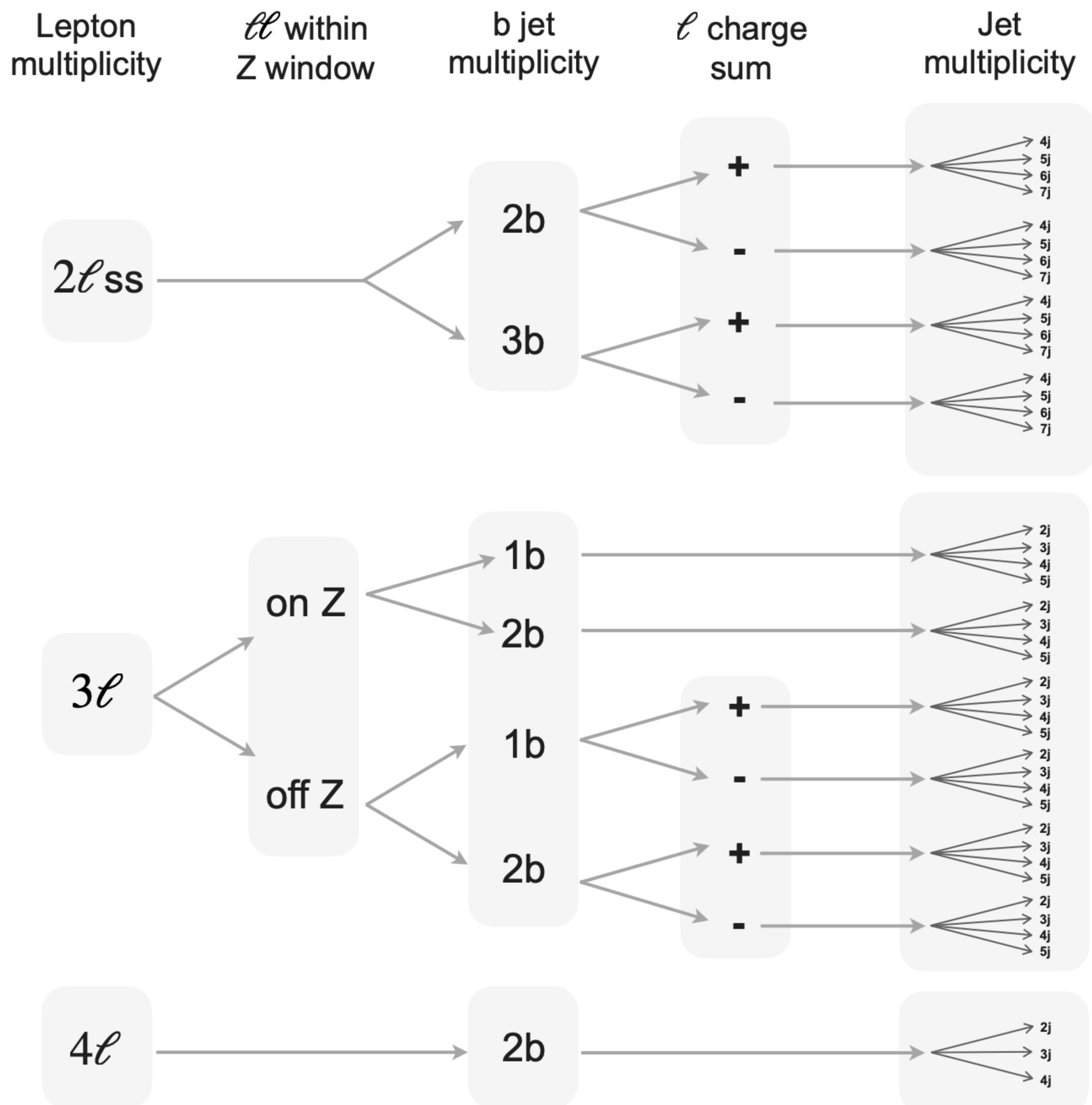
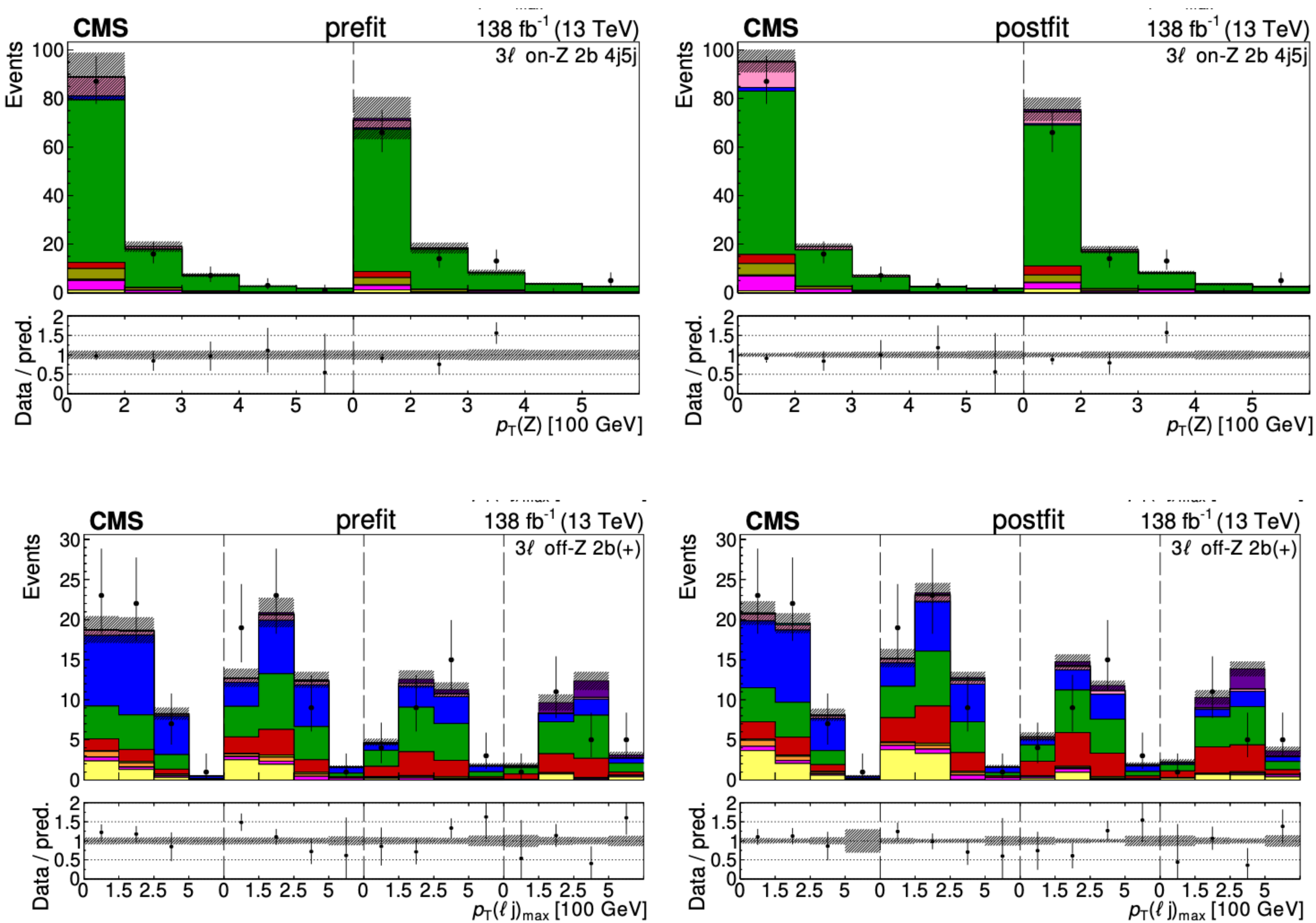


Figure 2: Summary of the event selection categorization. The details for the selection requ
ments are described in Sections 5.1–5.3.

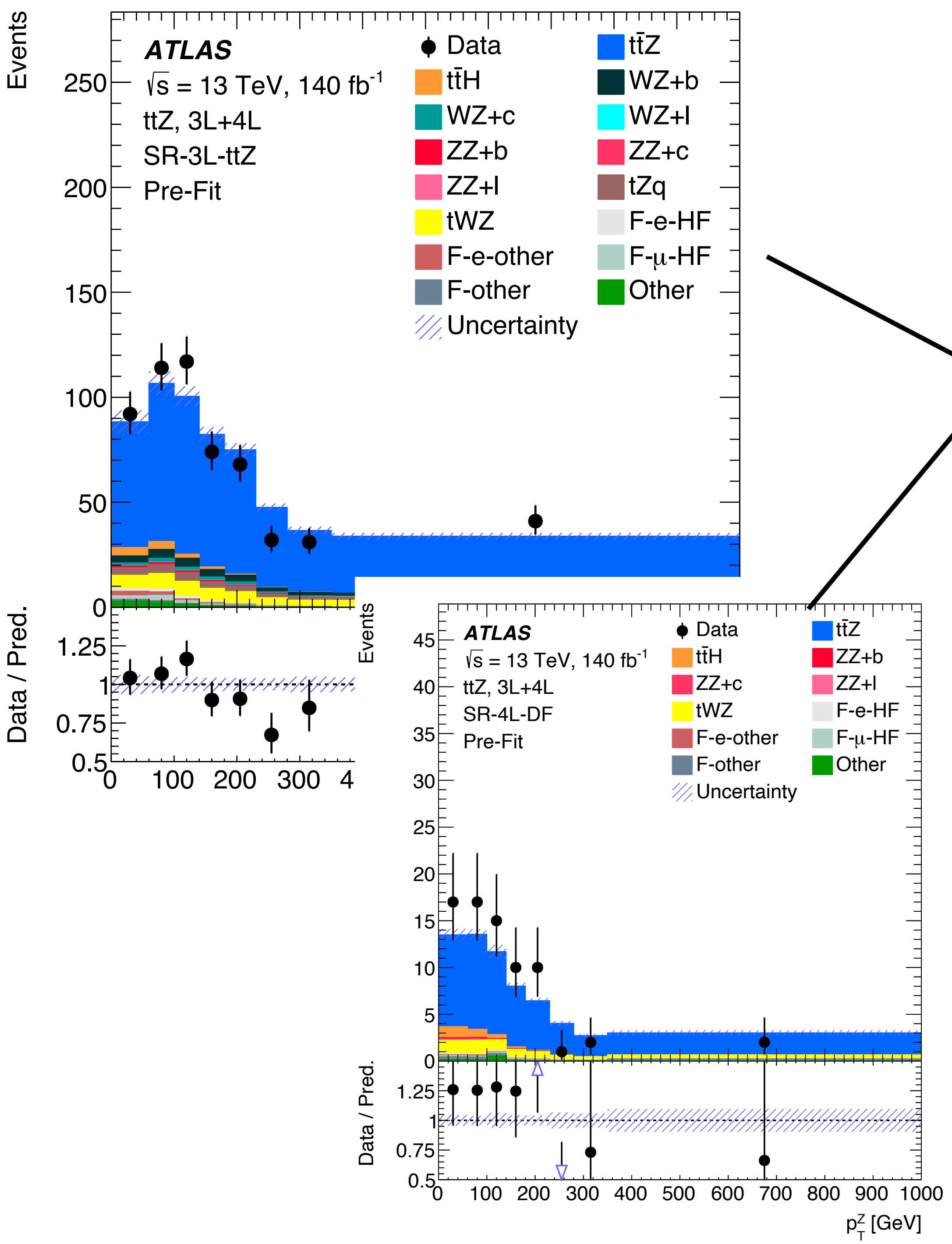
CMS tt + leptons

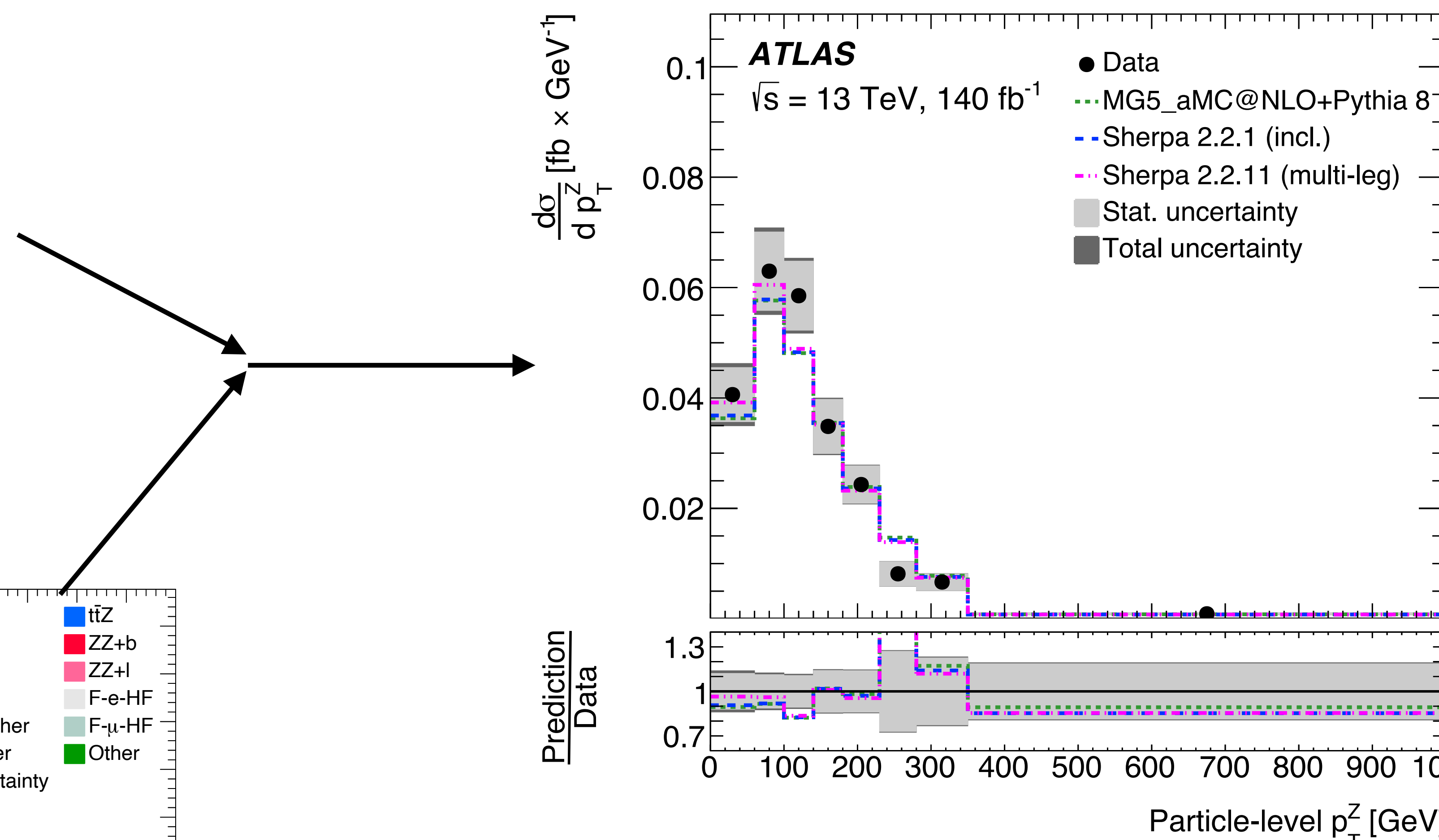


JHEP 12 (2023) 068

ATLAS ttZ measurement

- Recent differential cross-section of $t\bar{t}Z$ production:

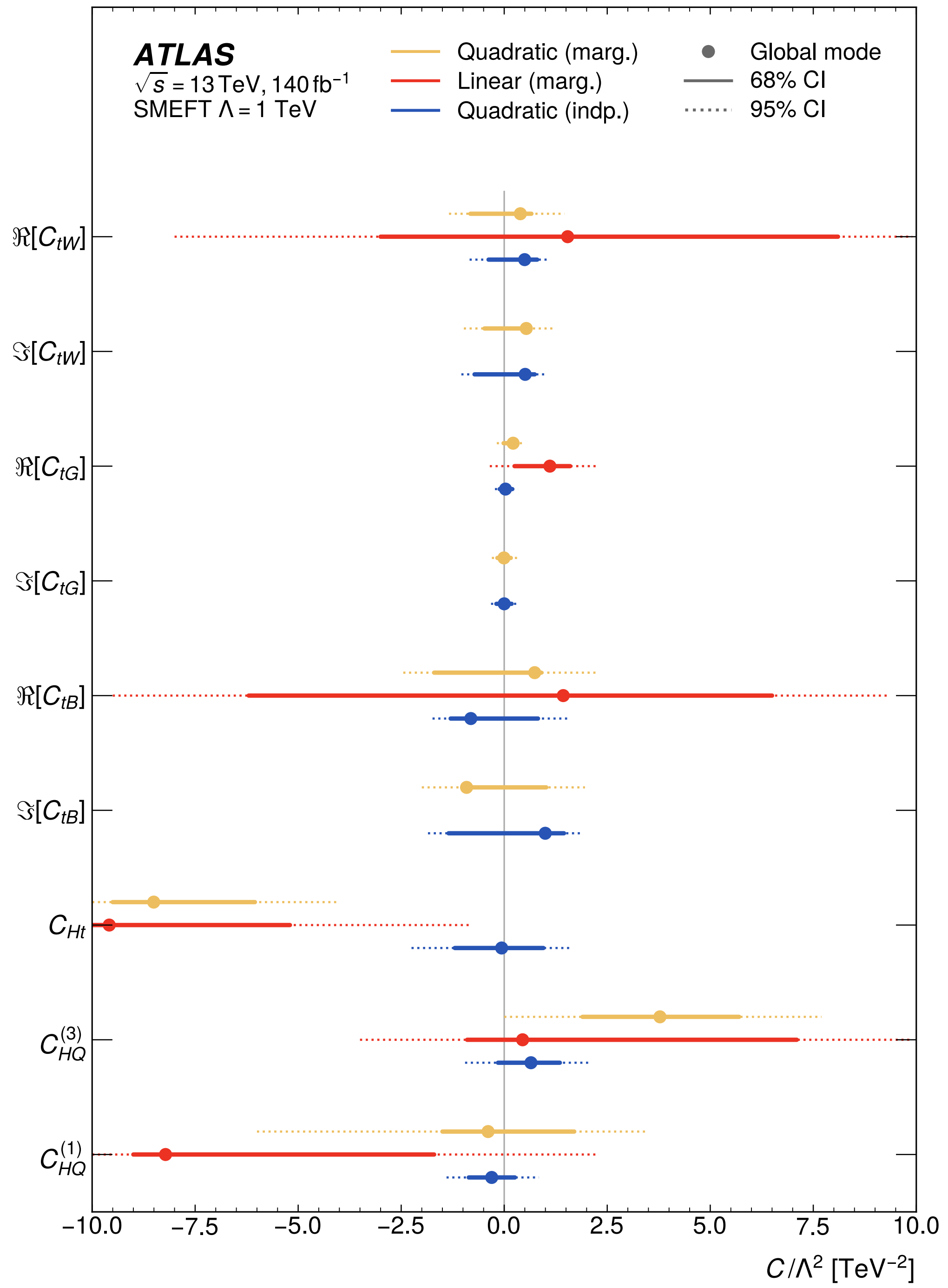




Simultaneous EFT fit to four differential distributions, considering either 6 top-boson, or 14 four-quark operators

ATLAS ttZ measurement

- Results for top-Boson operators:

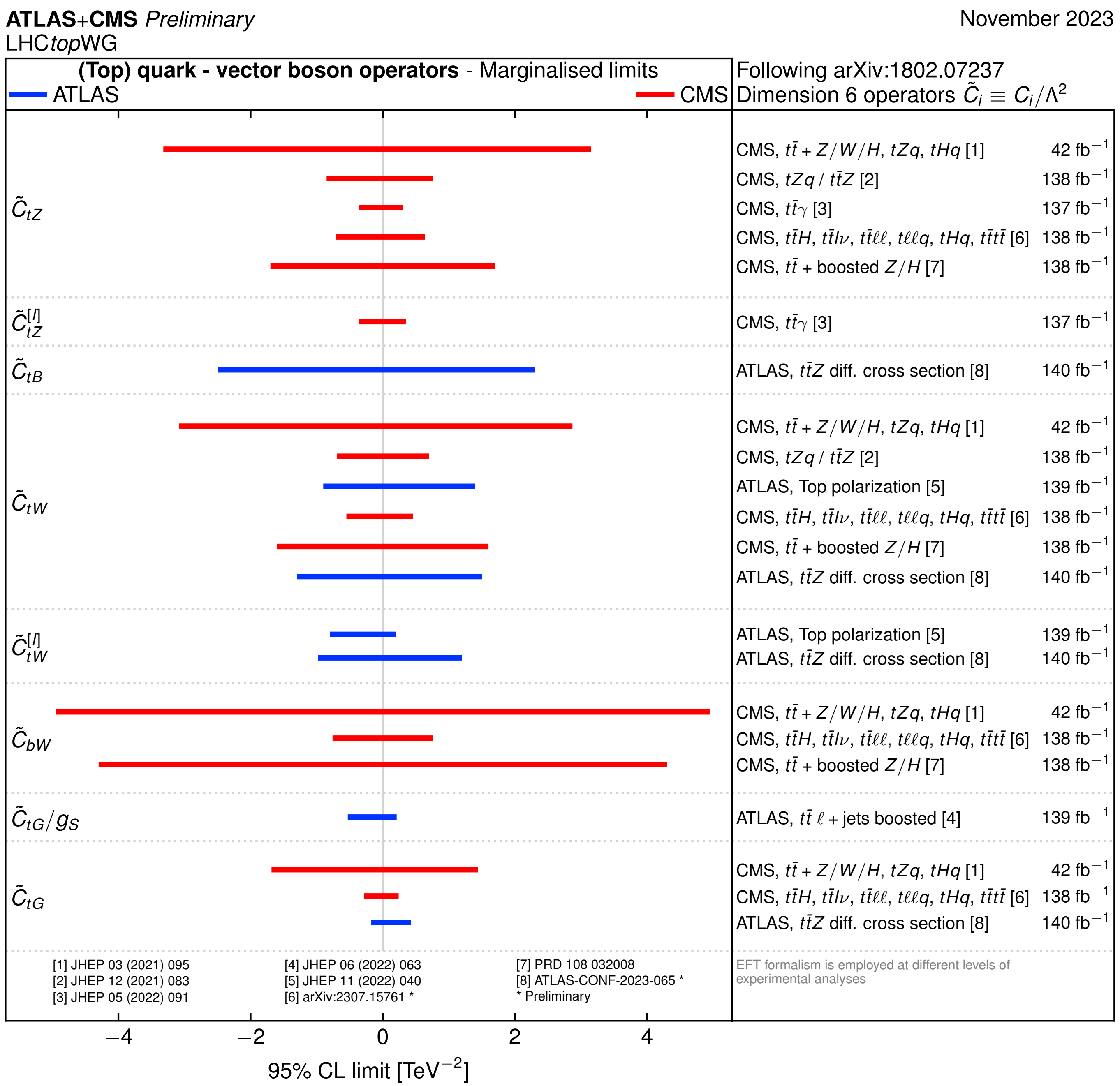


Strong constraints when allowing only one operator to be non-zero (independent, blue).

Weaker constraints once all operators are non-zero (marginalised, yellow).

Comparing ATLAS and CMS for ttZ

- Very different analysis strategies - would like to compare:



- Unfortunate difference between ATLAS and CMS for definition of top-Z operators:

$$c_{tZ} = -\sin\theta_W C_{tB} + \cos\theta_W C_{tW},$$

$$c^{-}_{\varphi Q} = C^{(1)}_{HQ} - C^{(3)}_{HQ},$$

- Would be good to harmonise.

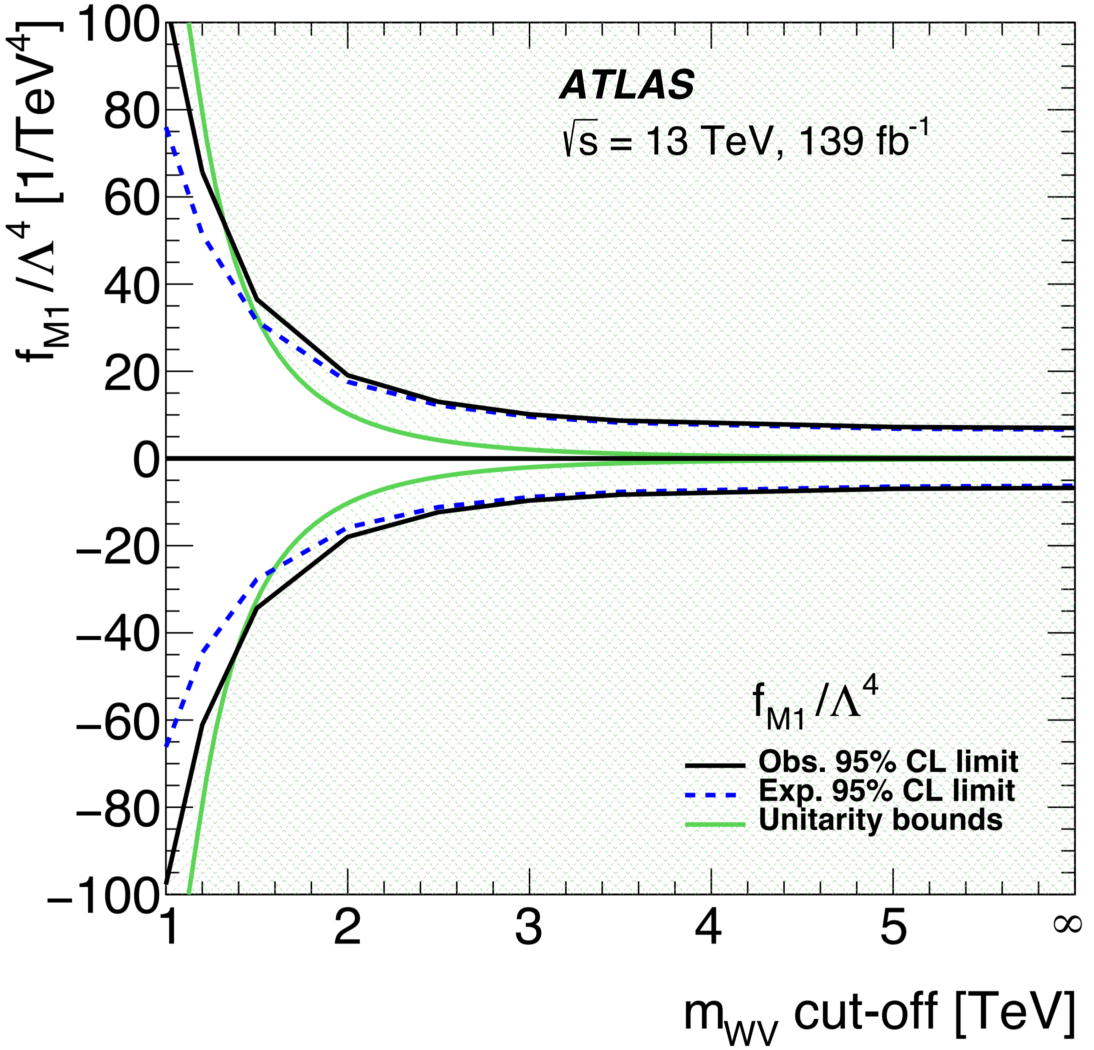
ATLAS $W^{\pm}W^{\pm}jj$

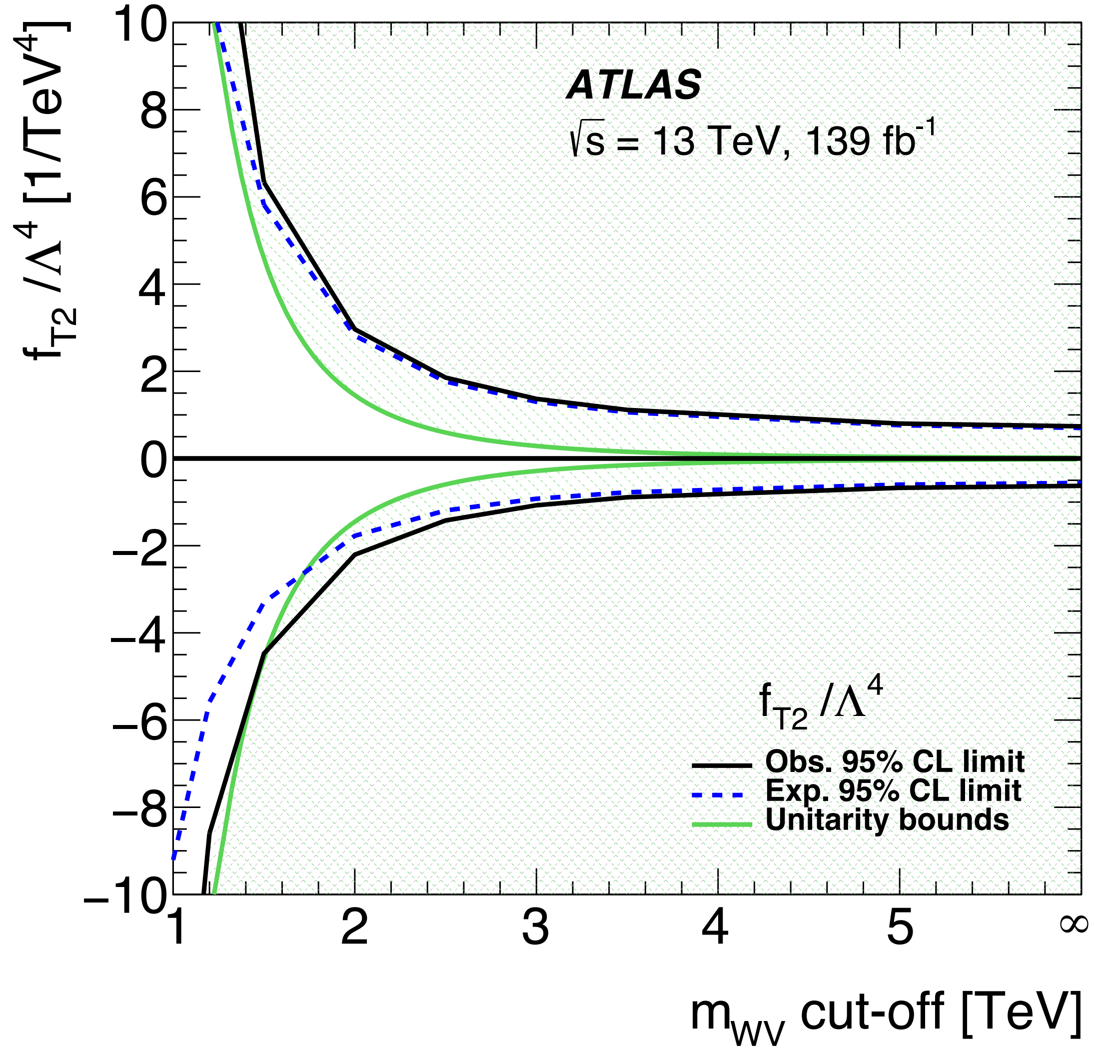
- Operators:
  - $O_{S0,1,2}$: four covariant derivatives of the Higgs field.
  - $O_{M0,1,7}$: two Higgs field covariant derivatives, two field-strength tensors.
  - $O_{T0,1,2}$: four field-strength tensors.
  - O_{S0}, O_{S2} are hermitian conjugate, so assume $f_{S0} = f_{S2} = f_{S02}$

arXiv:2312.00420

ATLAS $W^{\pm}W^{\pm}jj$

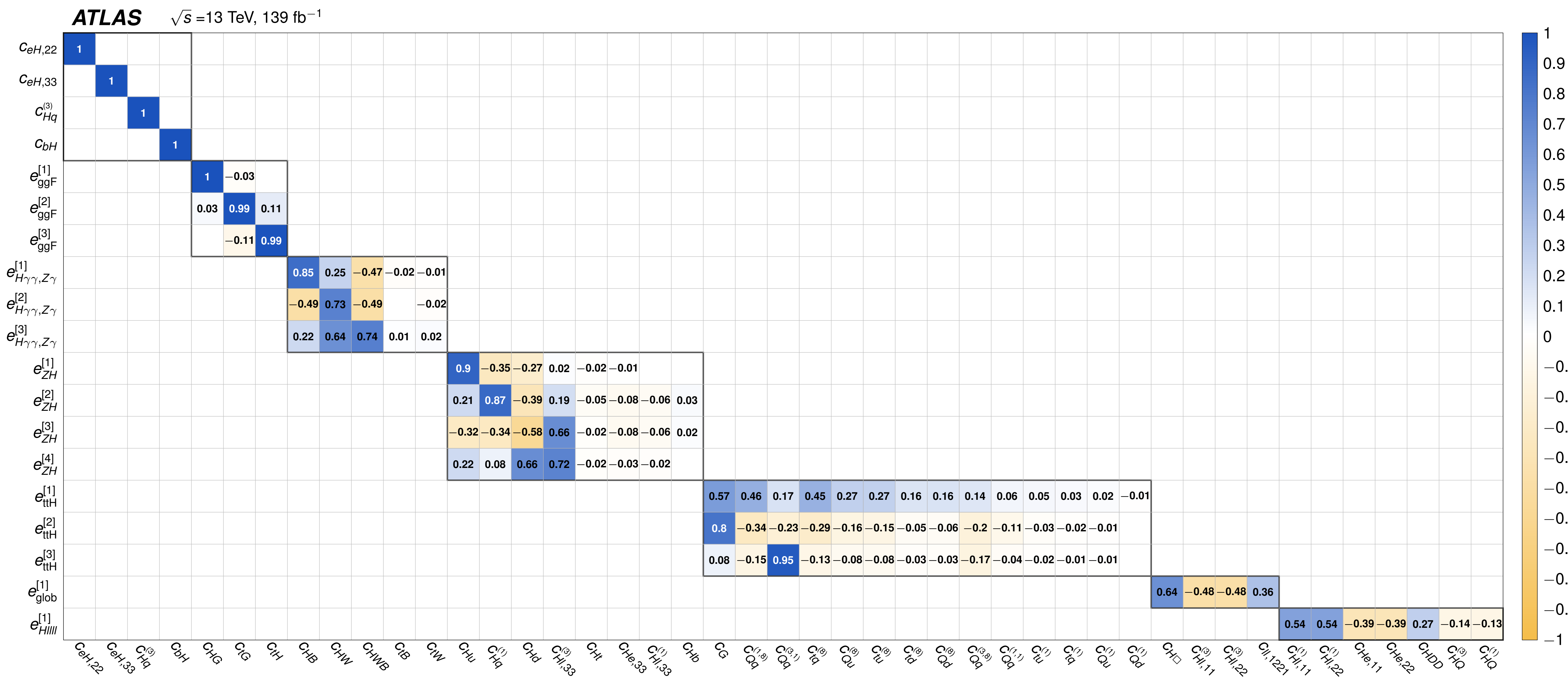
- Unitarity bounds:





ATLAS Higgs EFT

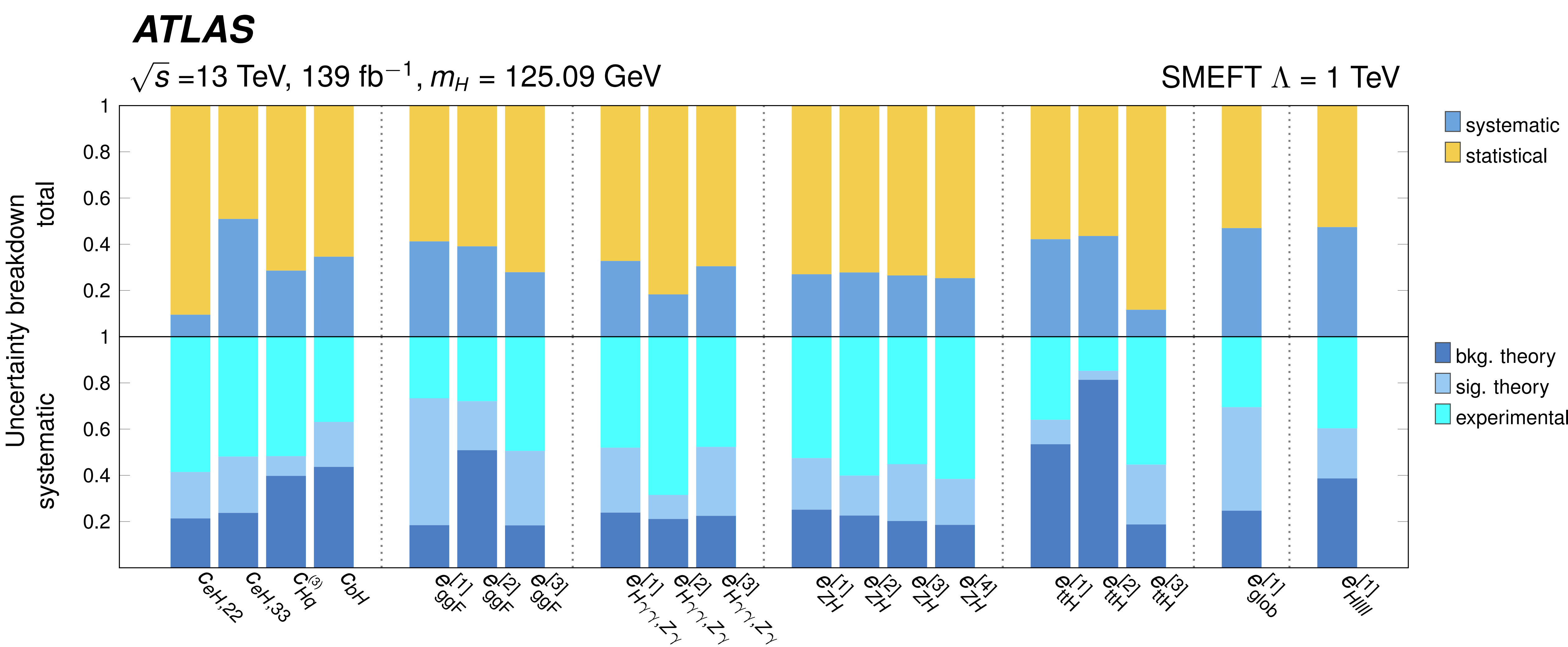
- Eigen-vector basis:



arXiv:2402.05742

ATLAS Higgs EFT

- Relative importance of statistical and systematic uncertainties:

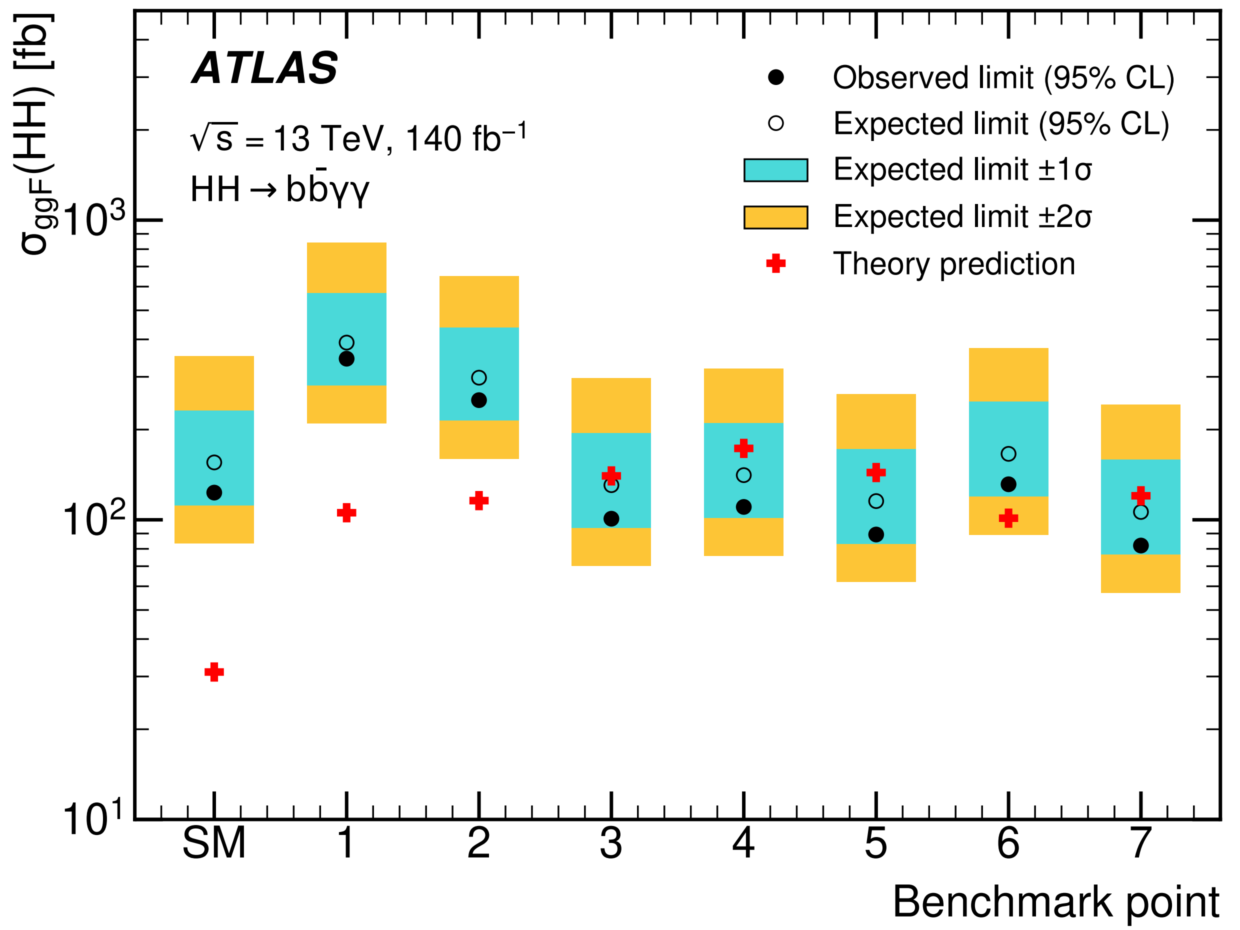


arXiv:2402.05742

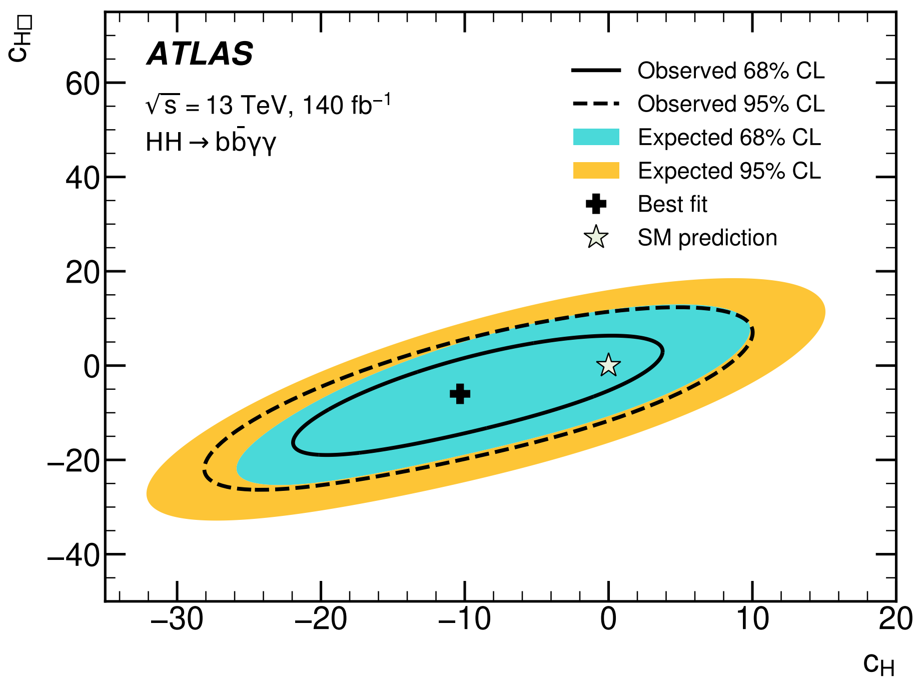
ATLAS $hh \to bb\gamma\gamma$

- Limits on benchmark HEFT points:

Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	−1/3	0	1/6
3	2.21	1.05	1/2	1/2	−1/3
4	2.79	0.90	−1/3	−1/2	−1/6
5	3.95	1.17	1/6	−1/2	−1/3
6	−0.68	0.90	1/2	1/4	−1/6
7	−0.10	0.94	1/6	−1/6	1



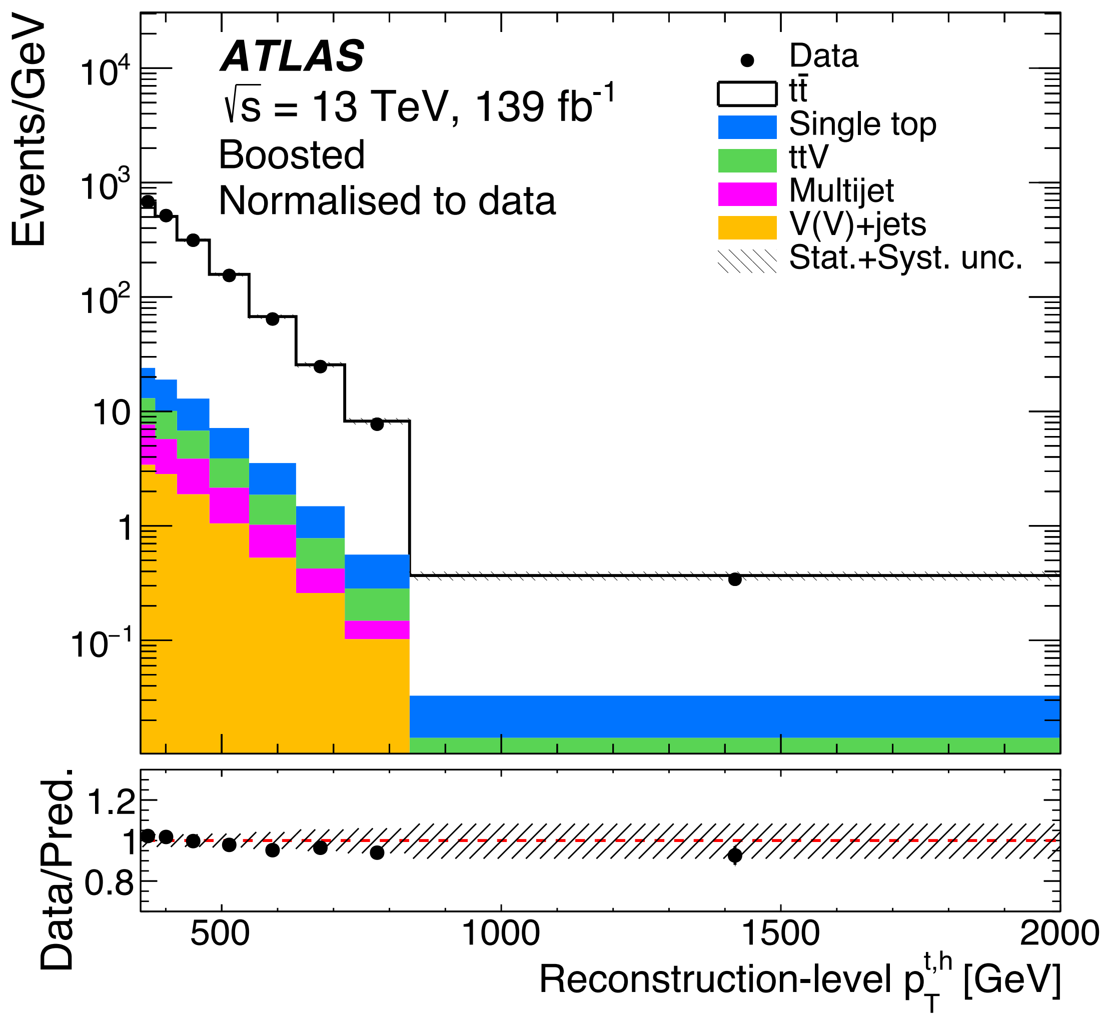
- Limits on benchmark SMEFT:

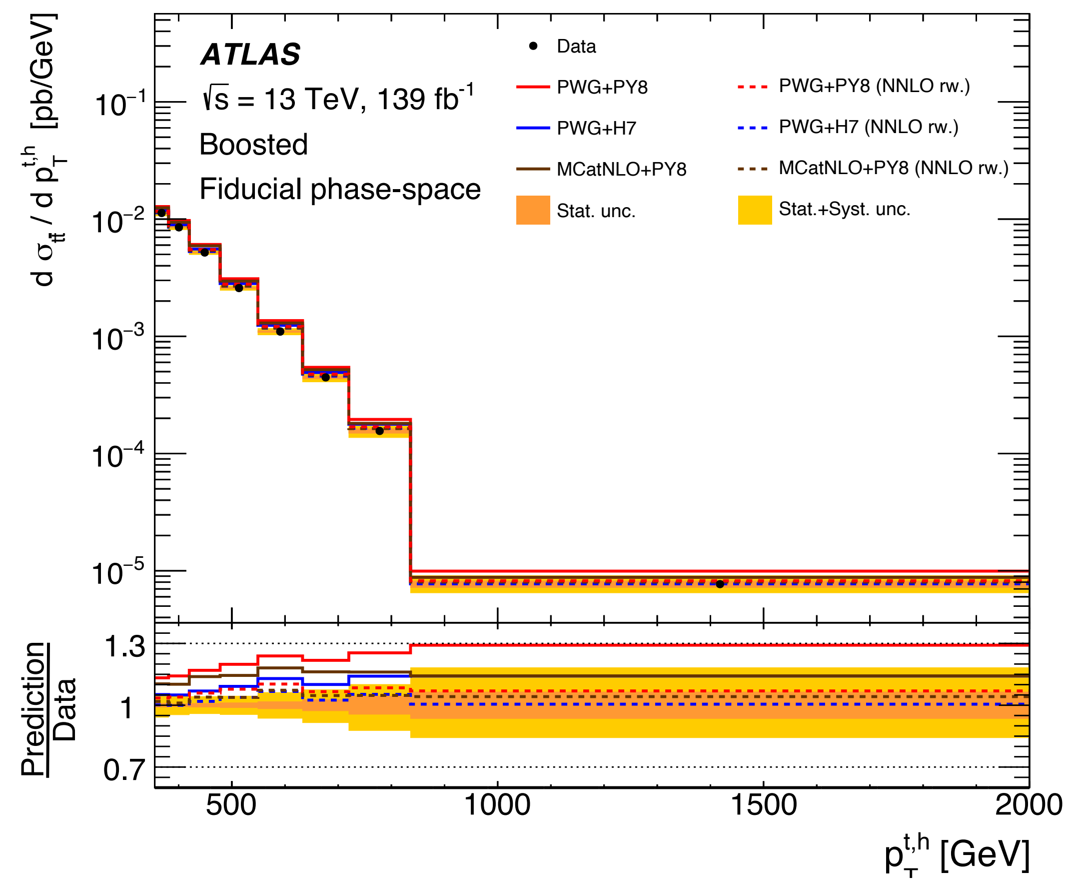


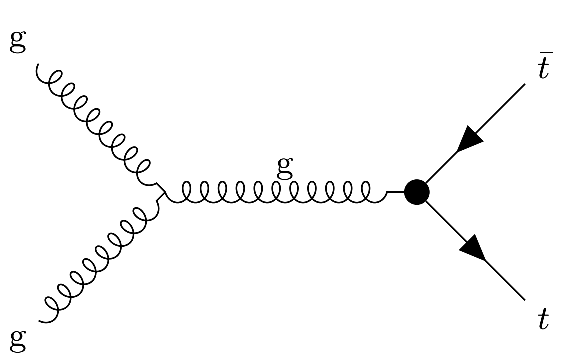
JHEP 01 (2024) 066

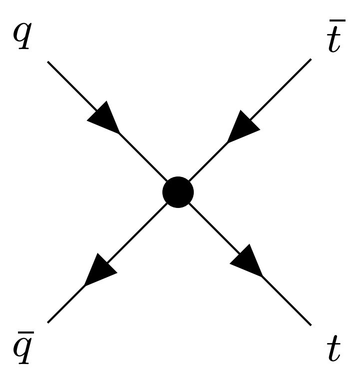
ATLAS Boosted top

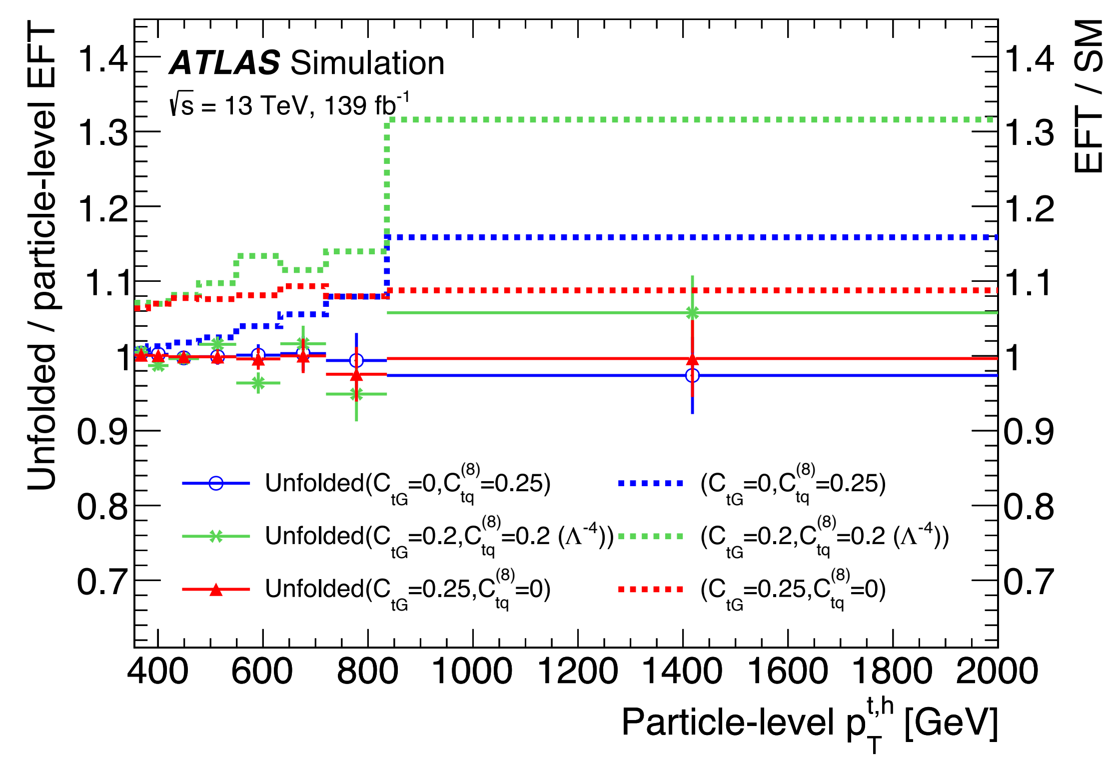
- Example of closure test with EFT injection:







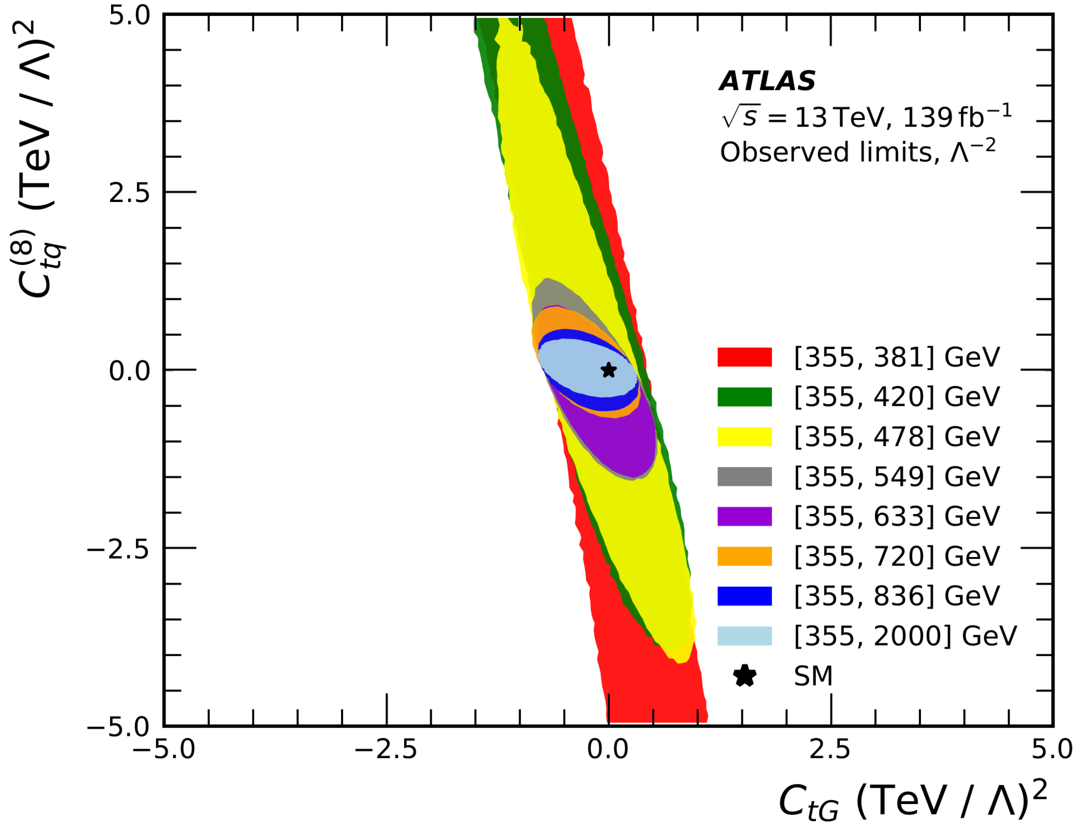


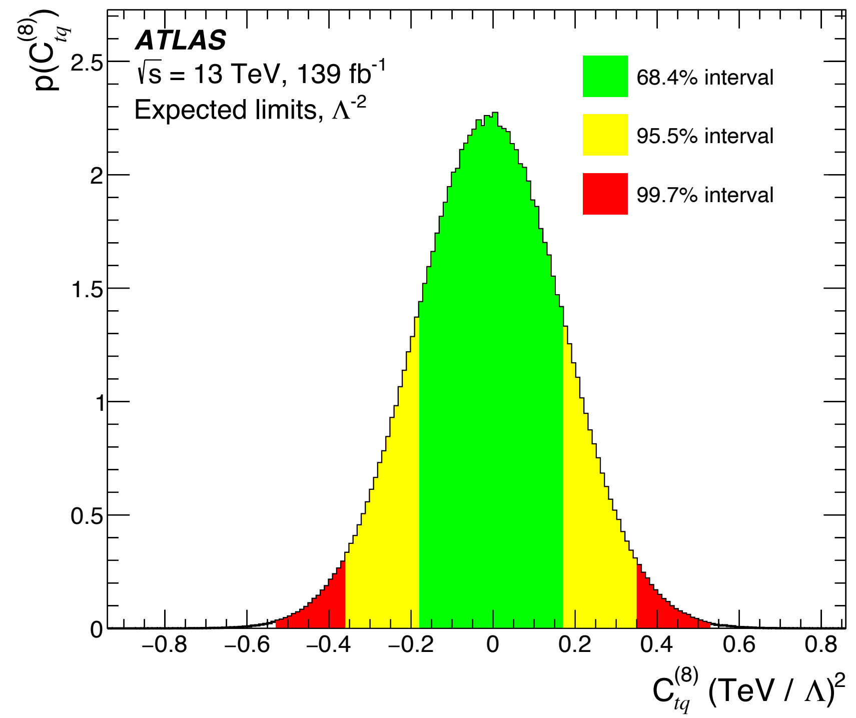


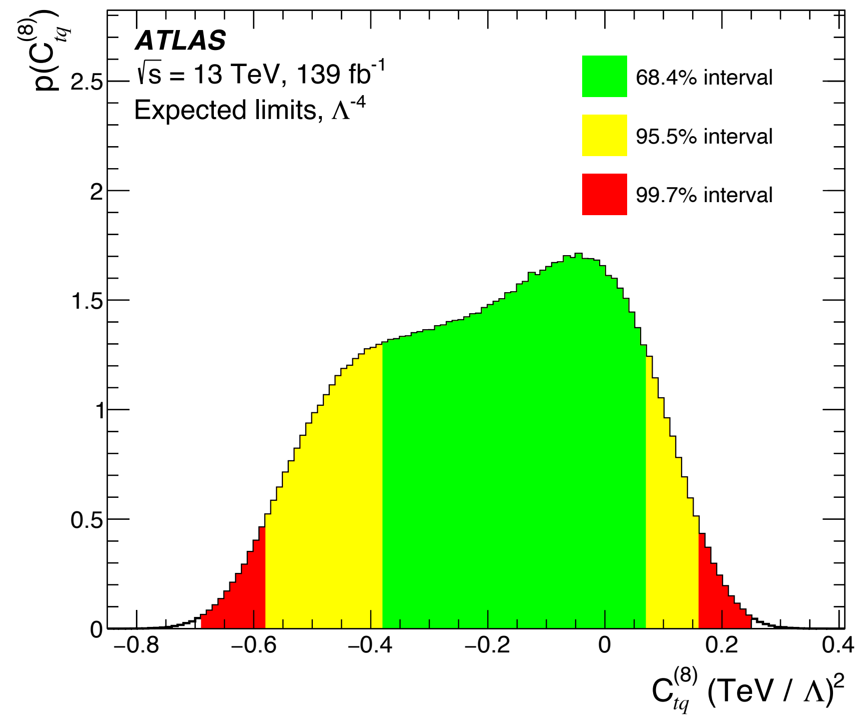
JHEP 06 (2022) 063

ATLAS Boosted top

- Importance of differential information and difference between linear / quadratic terms:







JHEP 06 (2022) 063