Combined effective field theory interpretation of VBS measurements with ATLAS

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On behalf of the analysis team

ATLAS

- arXiv:2603.18630

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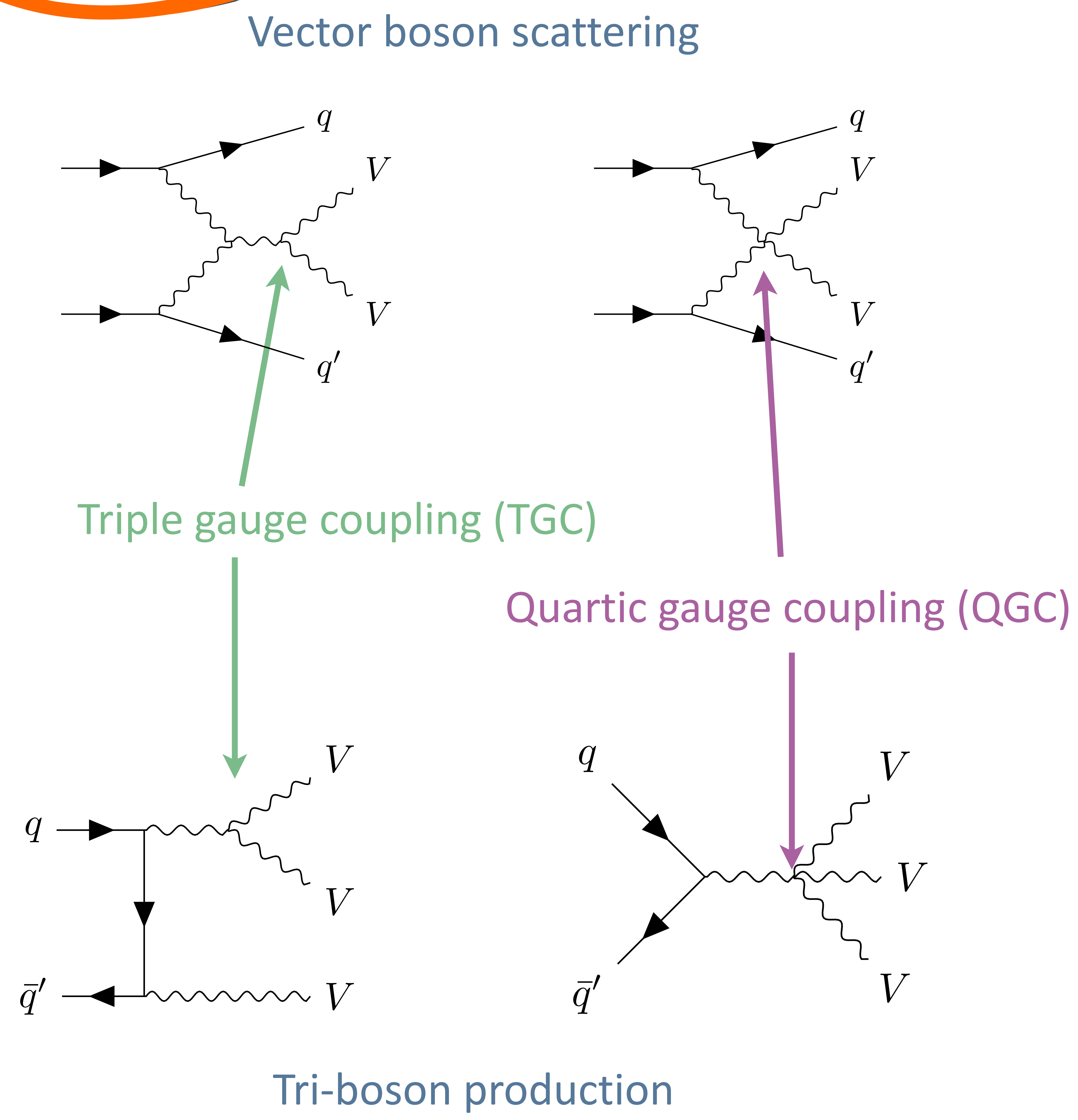
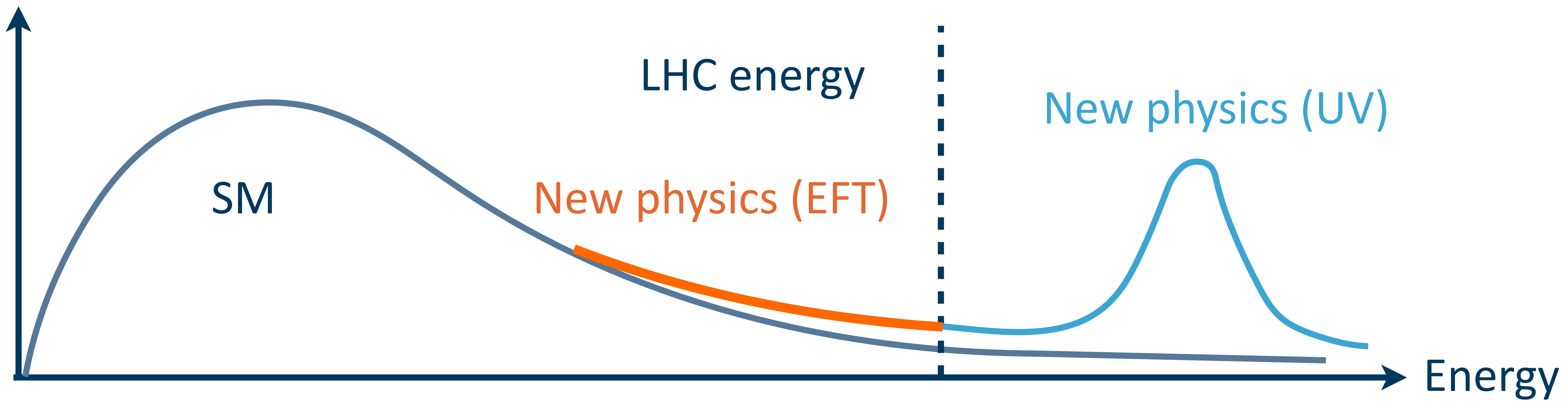
Vector boson scattering and tri-boson productions



- Vector boson scattering (VBS) and tri-boson production processes probe many different kinds of gauge couplings
- Special interest in VBS and tri-boson: anomalous QGCs (aQGCs)
  - Many BSM models predict direct aQGCs or resonances at beyond TeV scale that could be experimentally measured as aQGCs
  - Can be studied in the SM Effective Field Theory (SMEFT) framework



Standard Model Effective Field Theory

Violating Lepton and Baryon numbers

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i^{N_5} \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i^{N_6} \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i^{N_7} \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i^{N_8} \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

Dimension-6 Dimension-8

- Taylor expansion of the SM Lagrangian into local operators with mass dimension > 4
  - Λ: scale of new physics
  - $\mathcal{O}_i^{(n)}$: operators that introduce new interaction vertices
  - $c_i^{(n)}$: coefficients that indicate the strength of the couplings

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Dimension-6

Constrained by many other analyses

Dimension-8

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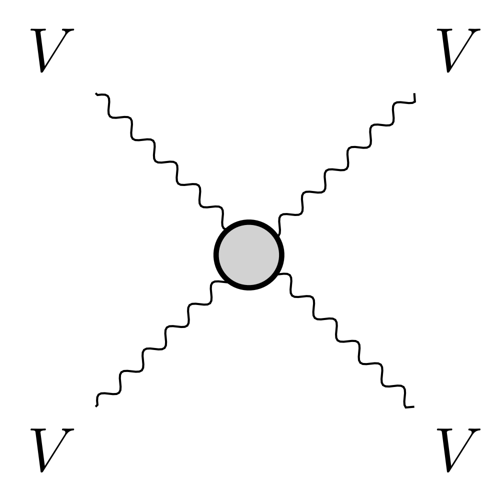
  - Λ: scale of new physics
  - $\mathscr{O}_i^{(n)}$: operators that introduce new interaction vertices
  - $c_i^{(n)}$: coefficients that indicate the strength of the couplings
- Pure aQGC: first appear at dimension-8
  - Existing dimension-6 measurements cannot constrain aQGC strongly
  - Dedicated dimension-8 SMEFT interpretations are needed



$$\mathscr{L}_{SMEFT} \sim \mathscr{L}_{SM} + \sum_j^{N_8} \frac{f_j^{(8)}}{\Lambda^4}\mathscr{O}_j^{(8)}$$

Dimension-8 and Éboli model

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Éboli basis
C-even P-even operators predicting aQGCs

- **S**calar operators: containing only derivatives of the Higgs field (O_{S0}, O_{S1}, O_{S2})
- **T**ensor operators: containing only EW boson field strengths ($O_{T0}, \ldots, O_{T9}$)
- **M**ixed operators: mixture of the derivatives and field strengths ($O_{M0}, \ldots, O_{M7}$)

Vertices impacted by the operators

	WWWW	WWZZ	WWγZ	WW$\gamma\gamma$	ZZZZ	ZZZγ	ZZ$\gamma\gamma$	Z$\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$O_{S,0}, O_{S,1}, O_{S,2}$	√	√			√				
$O_{M,0}, O_{M,1}, O_{M,7}$	√	√	√	√	√	√	√		
$O_{M,2}, O_{M,3}, O_{M,4}, O_{M,5}$		√	√	√	√	√	√		
$O_{T,0}, O_{T,1}, O_{T,2}, O_{T,3}$	√	√	√	√	√	√	√	√	√
$O_{T,4}, O_{T,5}, O_{T,6}, O_{T,7}$		√	√	√	√	√	√	√	√
$O_{T,8}, O_{T,9}$					√	√	√	√	√

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$O_{M,2}, O_{M,3}, O_{M,4}, O_{M,5}$		√	√	√	√	√	√		
$O_{T,0}, O_{T,1}, O_{T,2}, O_{T,3}$	√	√	√	√	√	√	√	√	√
$O_{T,4}, O_{T,5}, O_{T,6}, O_{T,7}$		√	√	√	√	√	√	√	√
$O_{T,8}, O_{T,9}$					√	√	√	√	√

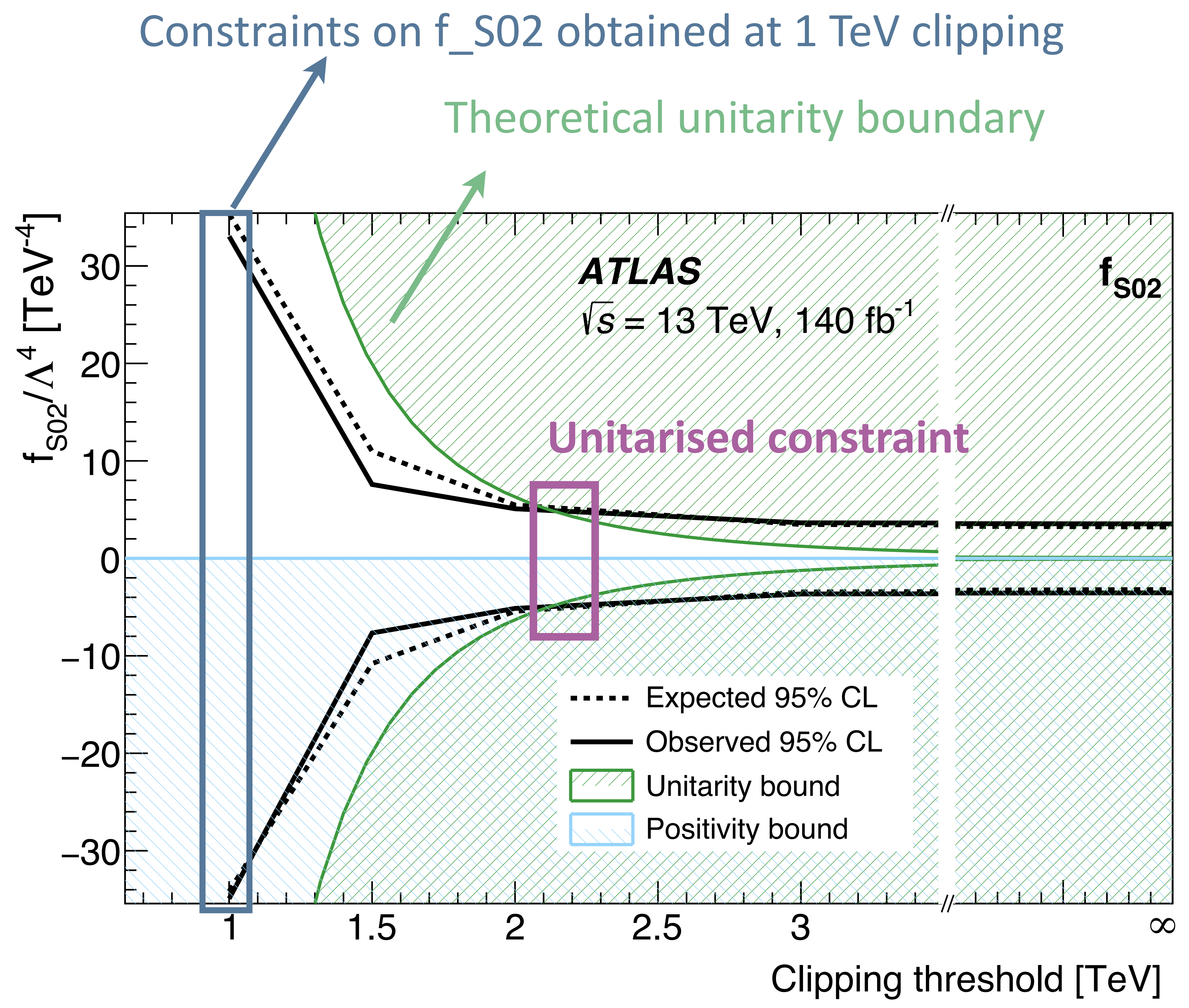
- Experimentally: we focus on a set of C-even P-even operators giving rise to aQGCs, the Éboli basis operators
- The effect of these operators: modifying the cross-sections → Given the measured cross-sections, we can set constraints on the coefficients of these operators

Pure SM — EFT-SM interference (linear) — Pure EFT, single operator or cross-terms (quadratic)

$$\mathscr{A}^2 = |\mathscr{A}_{SM}|^2 + 2\sum_i \frac{c_i}{\Lambda^4}\Re(\mathscr{A}_i^* \mathscr{A}_{SM}) + \sum_i \frac{c_i^2}{\Lambda^8}|\mathscr{A}_i|^2 + 2\sum_{i\neq j}\frac{c_i c_j}{\Lambda^8}\Re(\mathscr{A}_i^*\mathscr{A}_j)$$

Theoretical boundaries

- Unitarity violation and clipping methods
  - Theoretically: require that perturbative partial-wave unitarity satisfied
  - Experimentally: ad-hoc unitarisation procedure — introducing a cut-off scale (clipping threshold), beyond which the coefficient is set to zero
  - In practice: a scan over several chosen clipping thresholds, at each threshold, obtain a constraint on the coefficient. The final unitarised constraint is taken from the intersection between the unitarity bound and the scan



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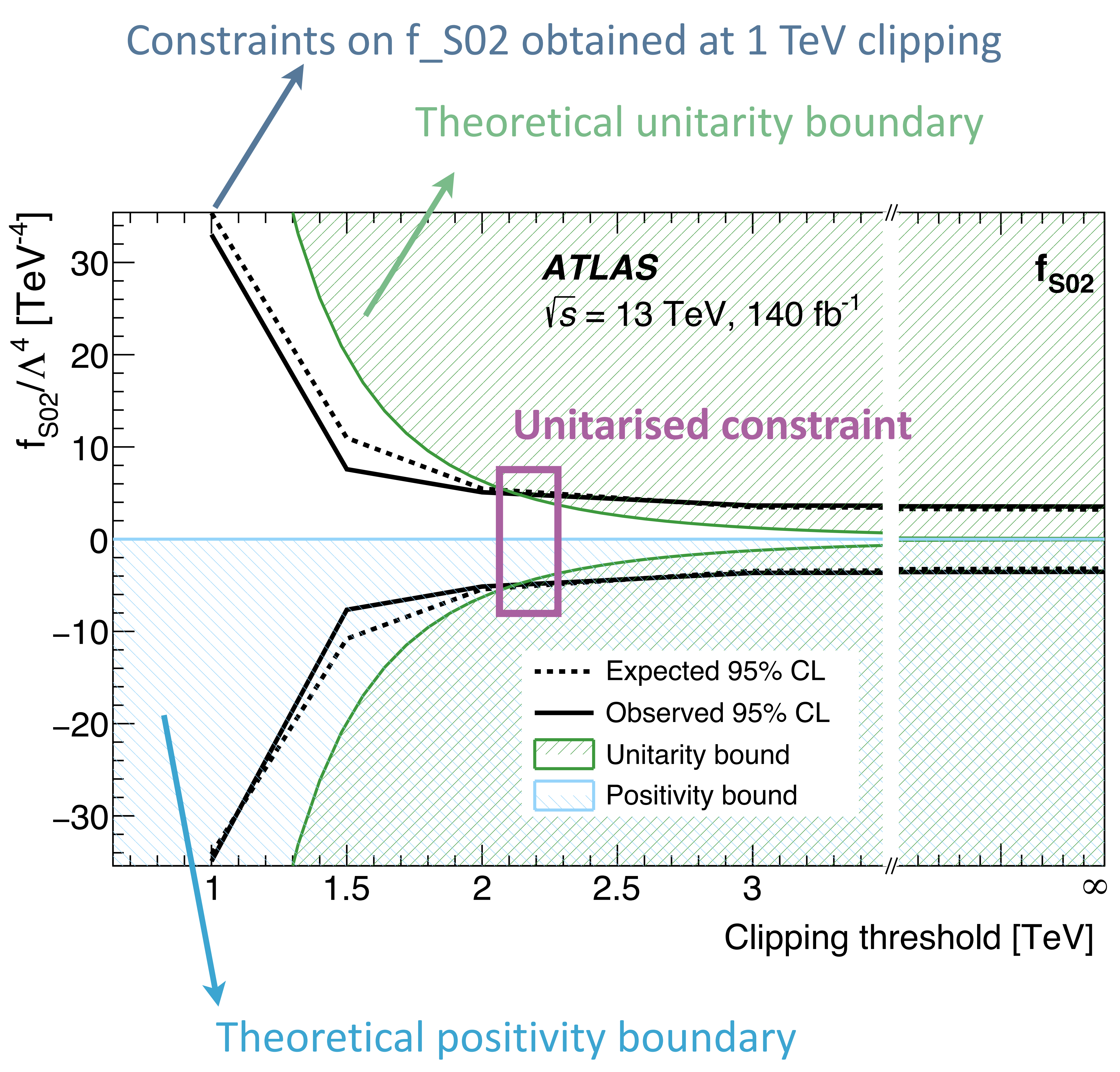
- Positivity boundaries
  - UV theories assumed to obey the low-scale principles of unitarity, locality and causality
  - Positive definite cross-sections on the helicity-amplitude



Input analyses

- 7 VBS analyses + 1 tri-boson analysis → constraints on coefficients of 17 Éboli basis operators — probe all gauge boson quartic vertices

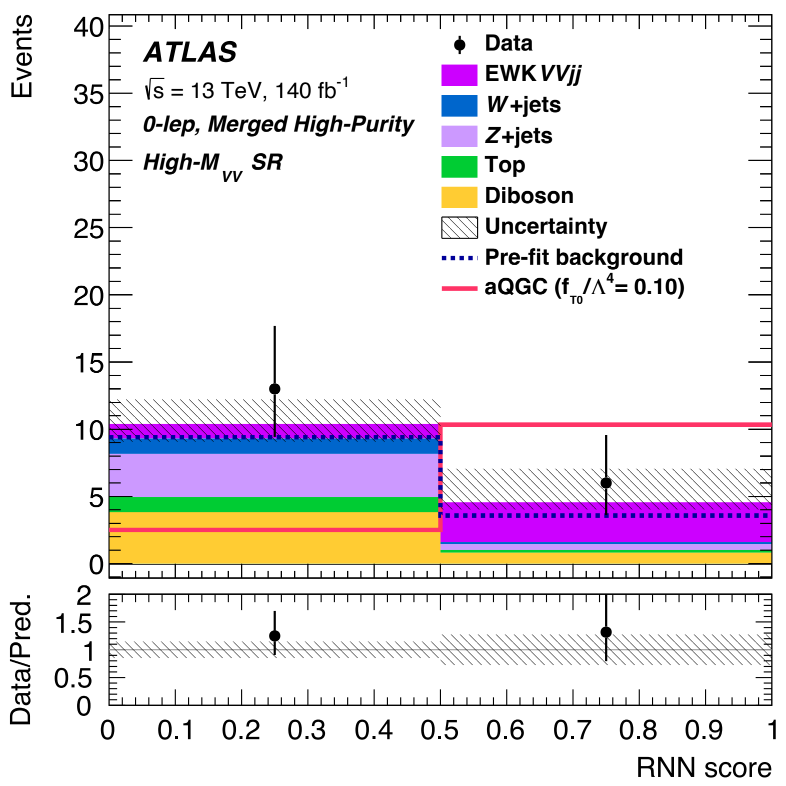
VBS analyses

- Semileptonic $VVjj$ (2503.17461)
- $WZjj$ (2403.15296), $WWjj$ (2312.00420), $ZZ(4l)jj$ (2308.12324)
- $W\gamma jj$ (2403.02809), $Z(\nu\nu)\gamma jj$ (2208.12741), $Z(ll)\gamma jj$ (2305.19142)

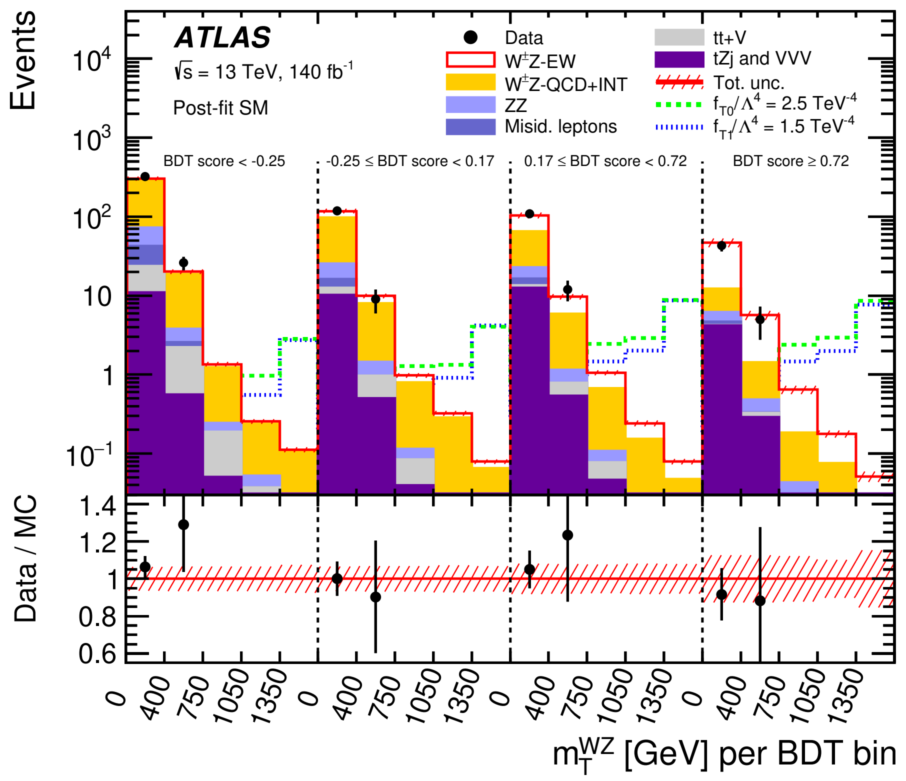
Tri-boson analysis

- $W\gamma\gamma$ (2308.03041)

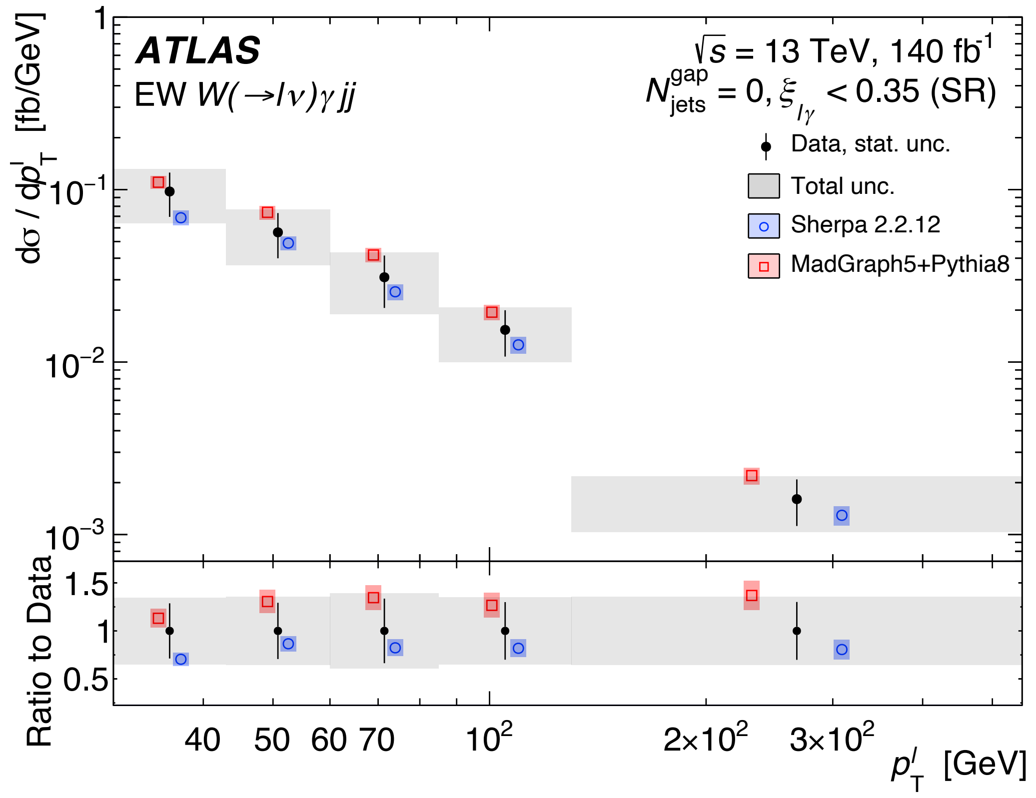
Semileptonic $VVjj$



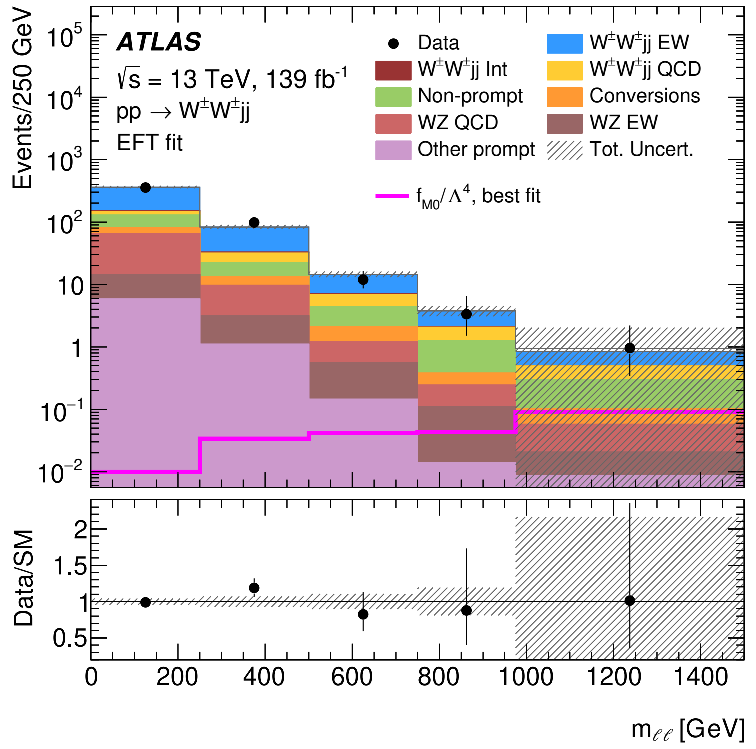
$WZjj$



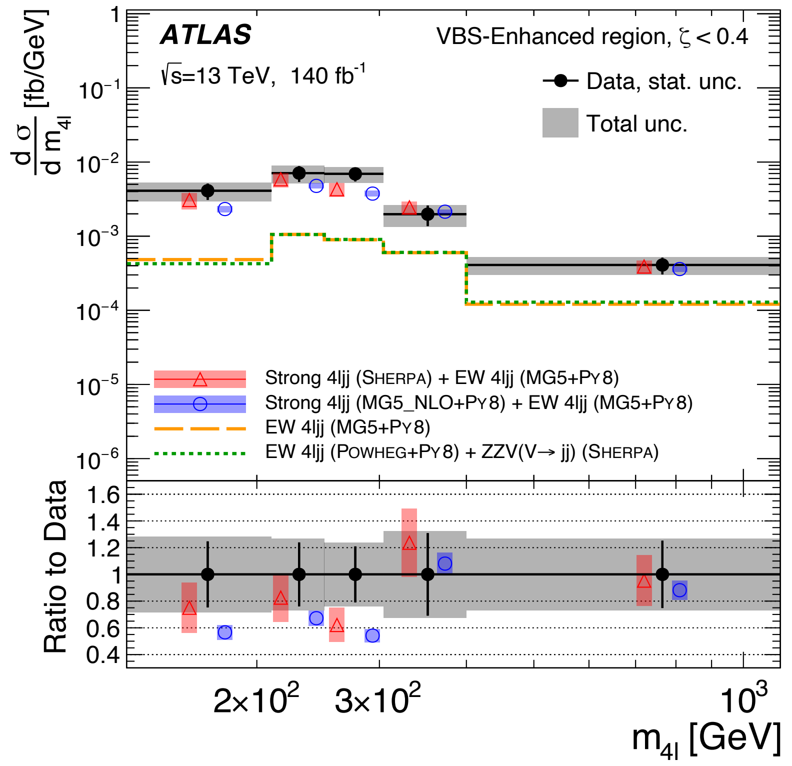
$W\gamma jj$



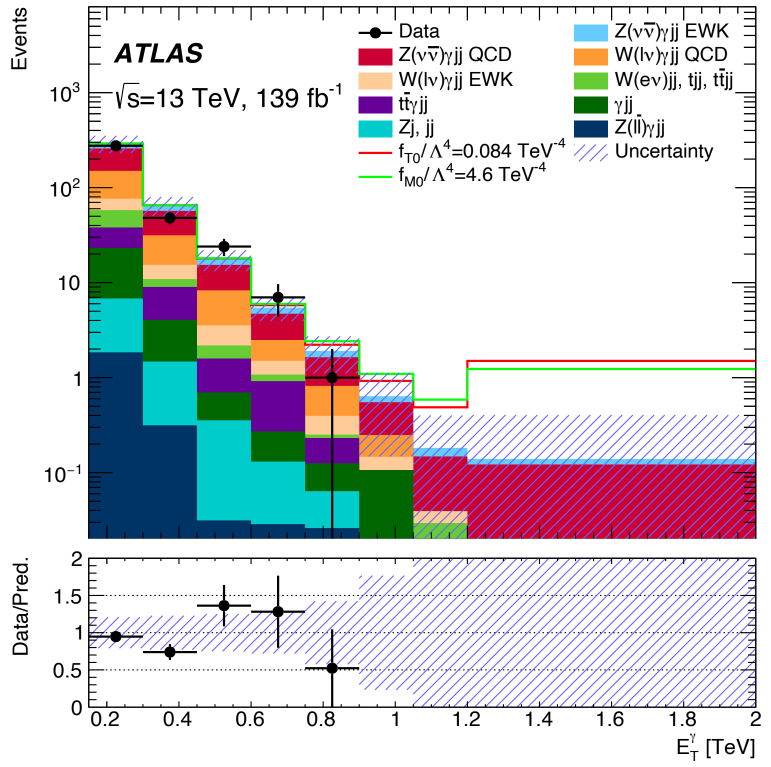
$WWjj$



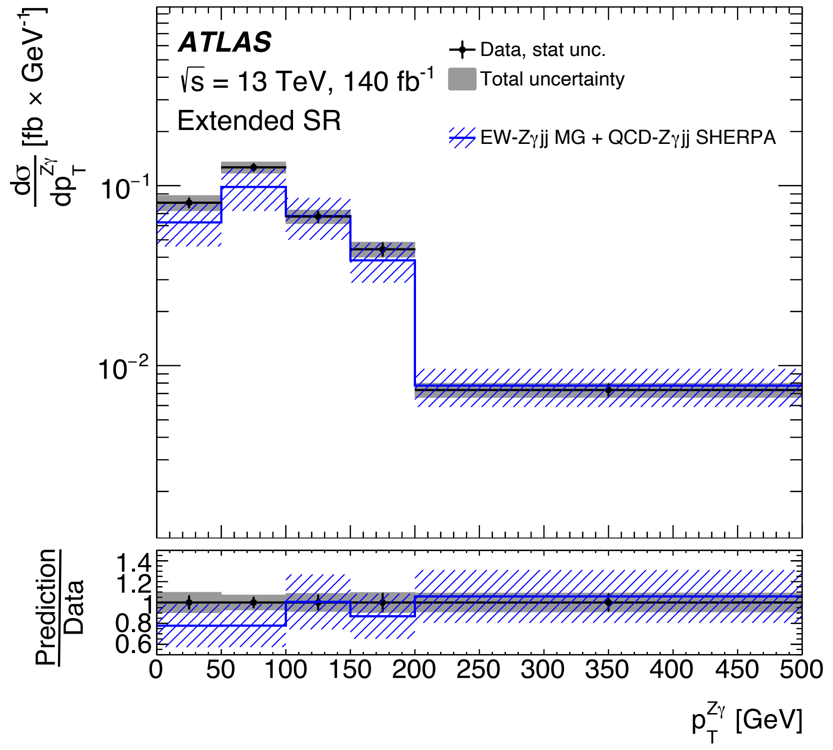
$ZZ(4l)jj$



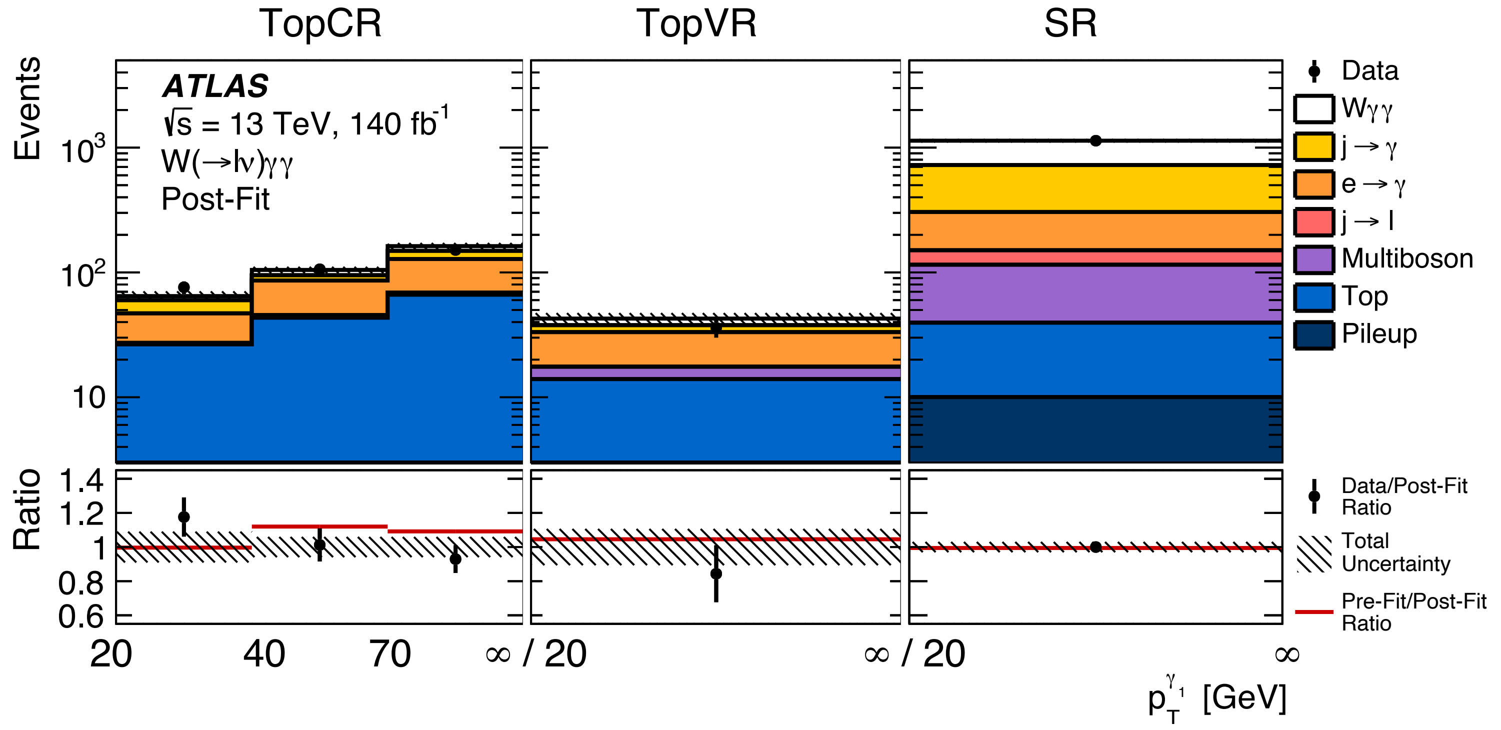
$Z(\nu\nu)\gamma jj$



$Z(ll)\gamma jj$



$W\gamma\gamma$



Modifications to the input analyses

- Overlapped phase spaces
  - No significant overlap in signal sample; for background, some overlaps appear, but mostly negligible statistical effect
  - Exception: one $WWjj$ control region overlap with $WZjj$ signal region. Removing this CR changes the constraints on operators at ~0.5% level → control region removed

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- Fitted distribution changes
  - $Z(\nu\nu)\gamma jj$: additional observable bins for probing more operators simultaneously
  - $W\gamma\gamma$: finer observable bins to improve the constraints (around 40% better)
  - $W\gamma jj$: unify the observable used for EFT interpretations (up to 20% better constraints)

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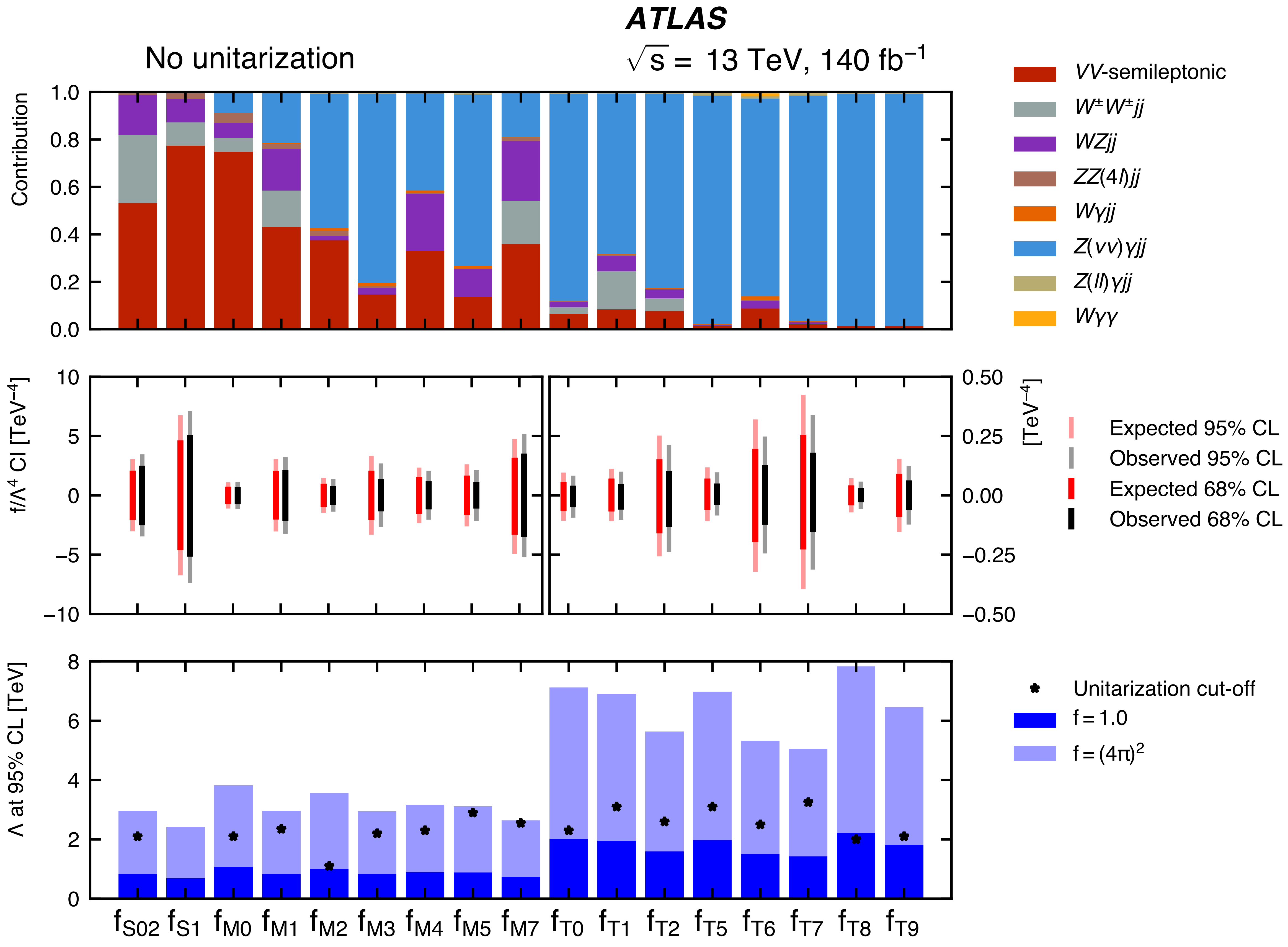
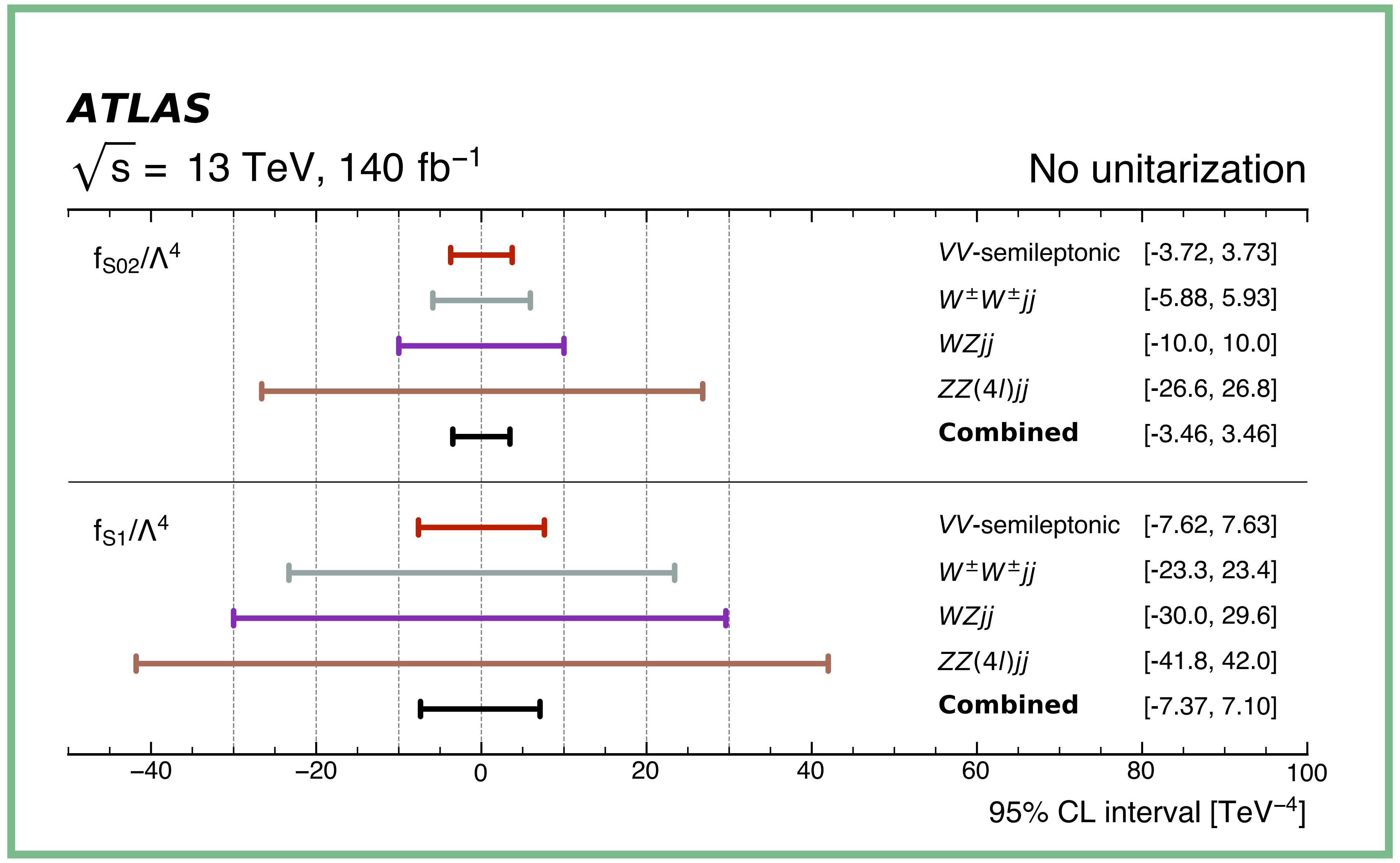
- Complementary / added EFT interpretations
  - $Z(ll)\gamma jj$, $ZZ(4l)jj$, $W\gamma\gamma$: no Éboli model interpretations in publication, newly added in this combination
  - $Z(\nu\nu)\gamma jj$, $WZjj$: extended interpretations in more operators
  - Cross-term effects are considered in this combination

Results: 1-dimensional constraints

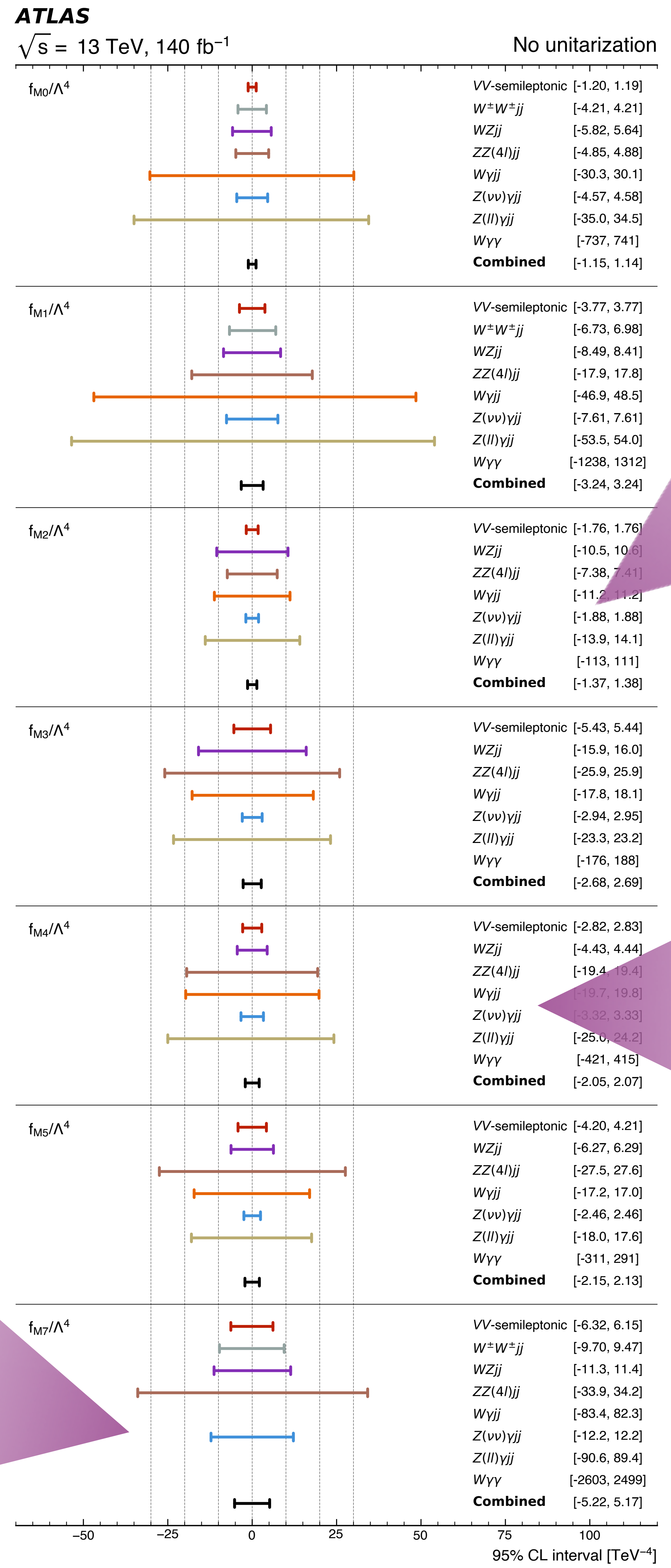


- Main contribution: semileptonic $VVjj$ and $Z(\nu\nu)\gamma jj$
- Non-unitarised constraints
  - Current best constraints on T5, T6, T7, T8 and T9 across experiments
  - Compared to individual analyses: scalar and mixed-type operators get up to 30% tighter constraints, tensor-type operators have similar constraints as $Z(\nu\nu)\gamma jj$
- Probed energy scale given illustrative values of Wilson coefficients

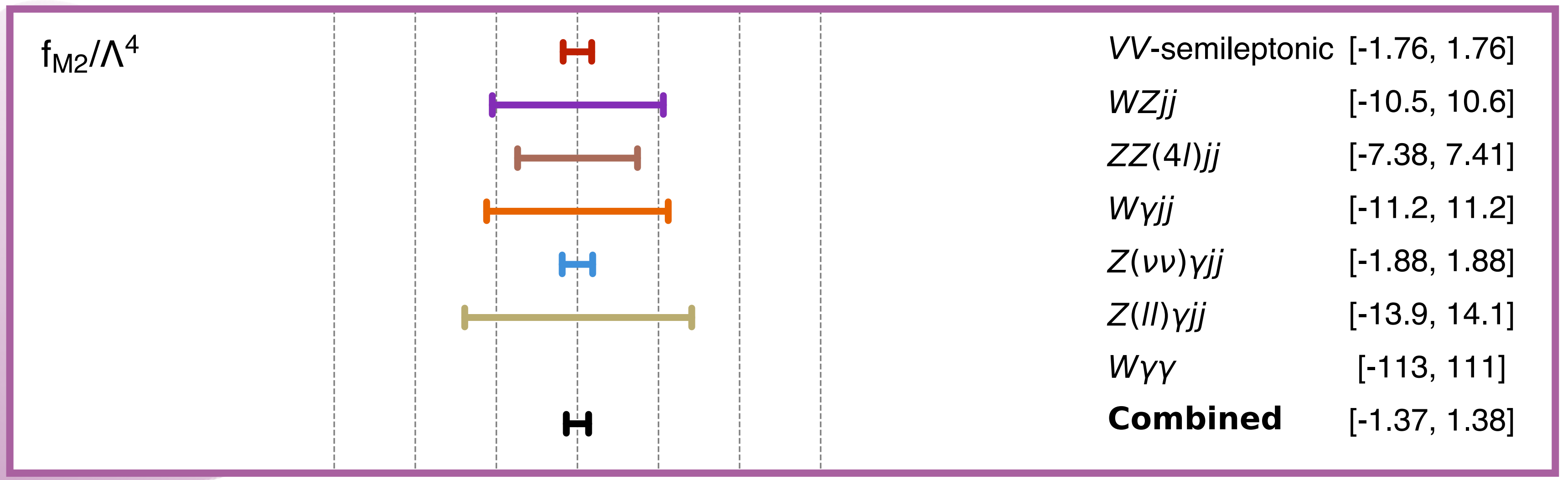
Results: 1-dimensional constraints



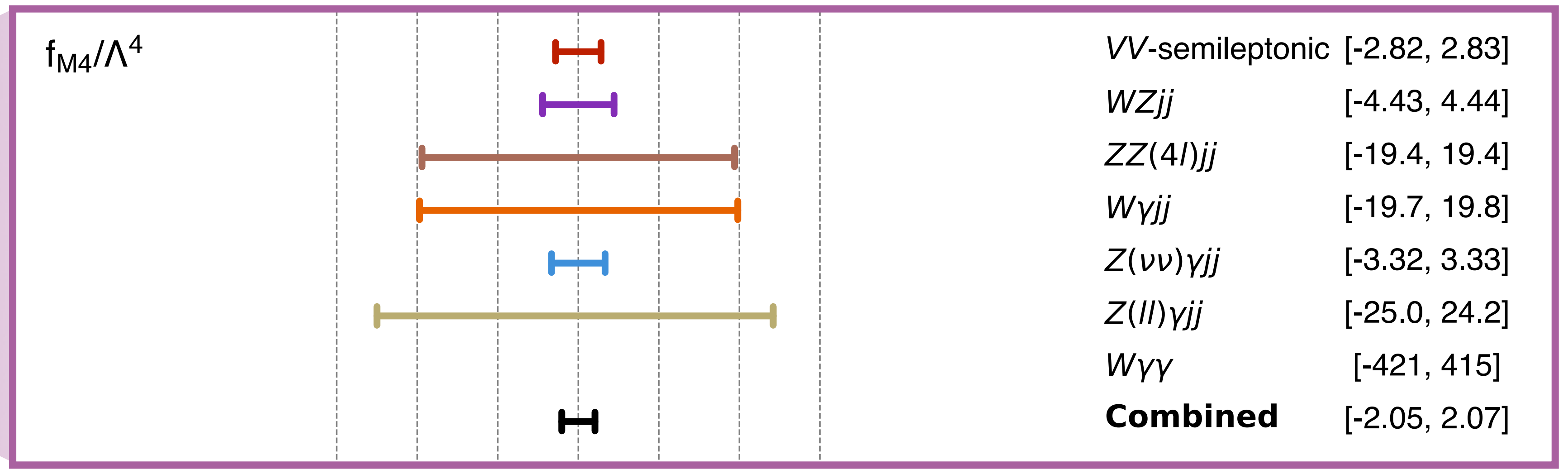
Scalar operators: around 5% better w.r.t. individual analyses



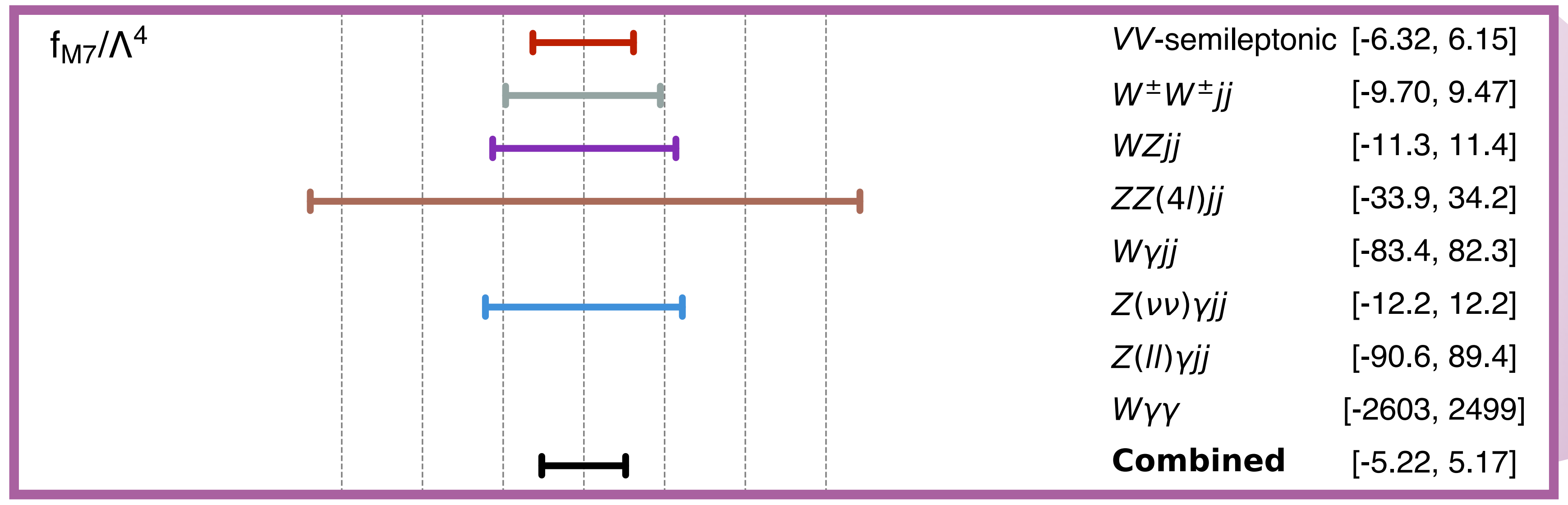
M2: 22% better w.r.t. individual analyses



M4: 27% better w.r.t. individual analyses

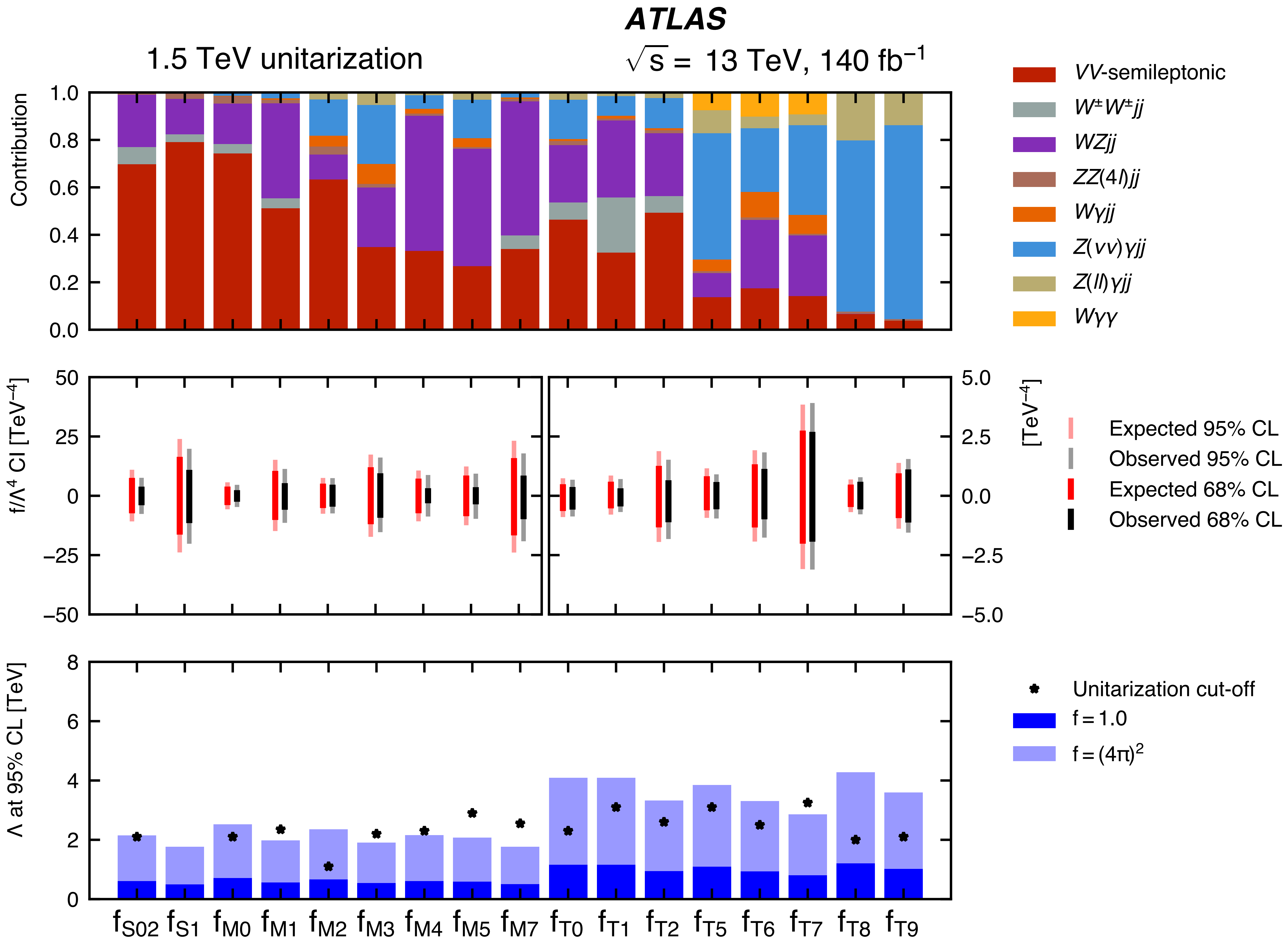


M7: 17% better w.r.t. individual analyses

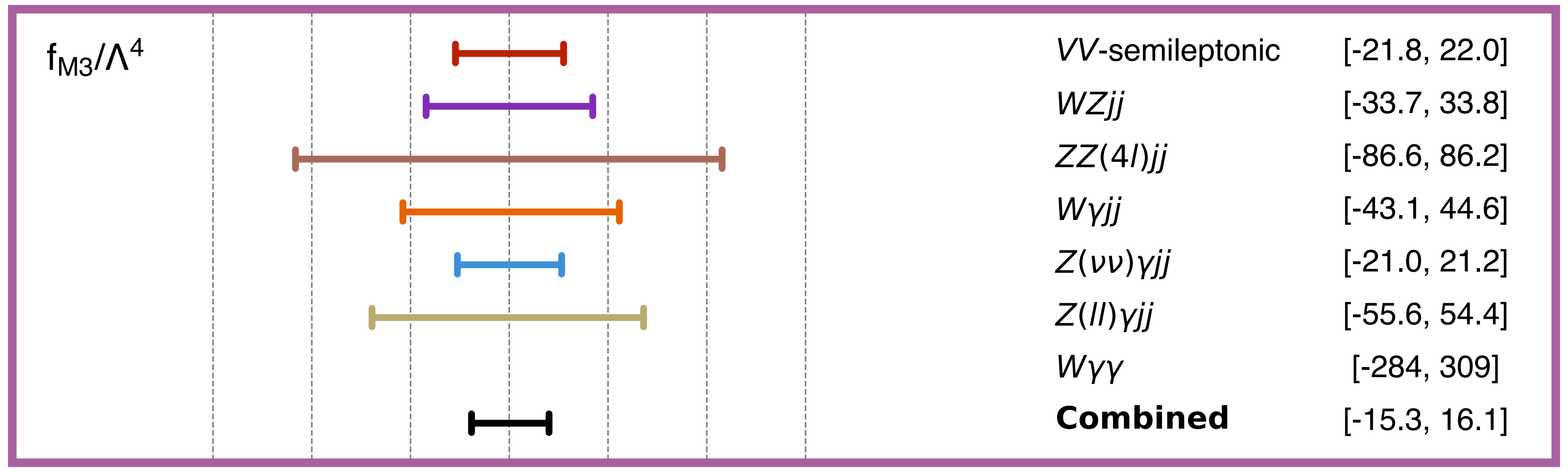


Results: 1-dimensional constraints with clipping

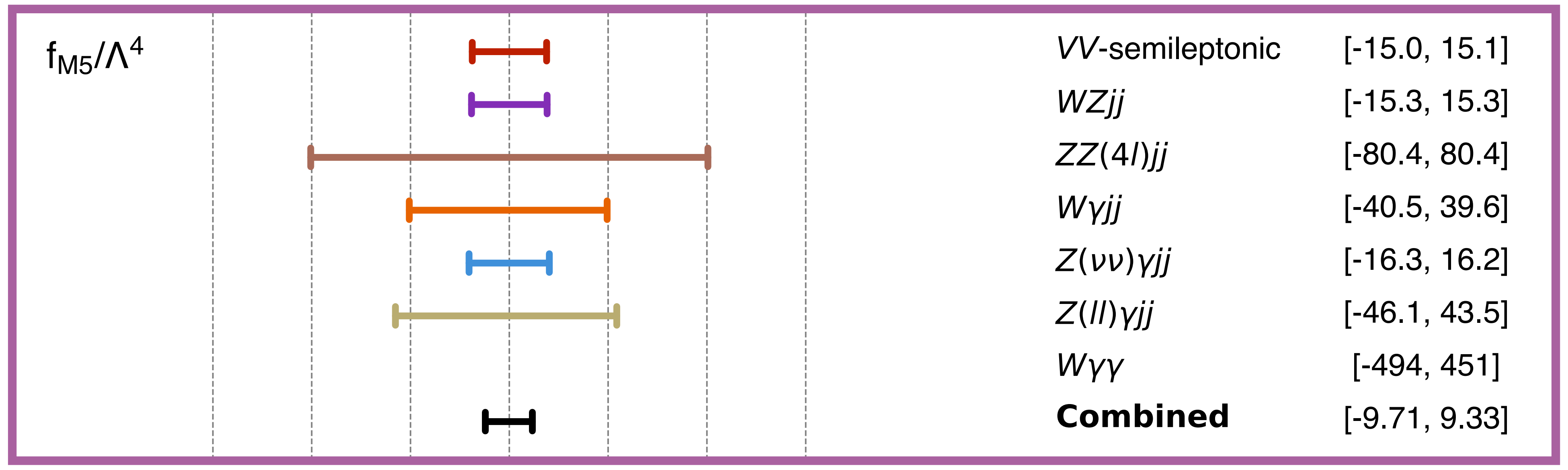
- At 1.5 TeV clipping: more even contribution from different analyses



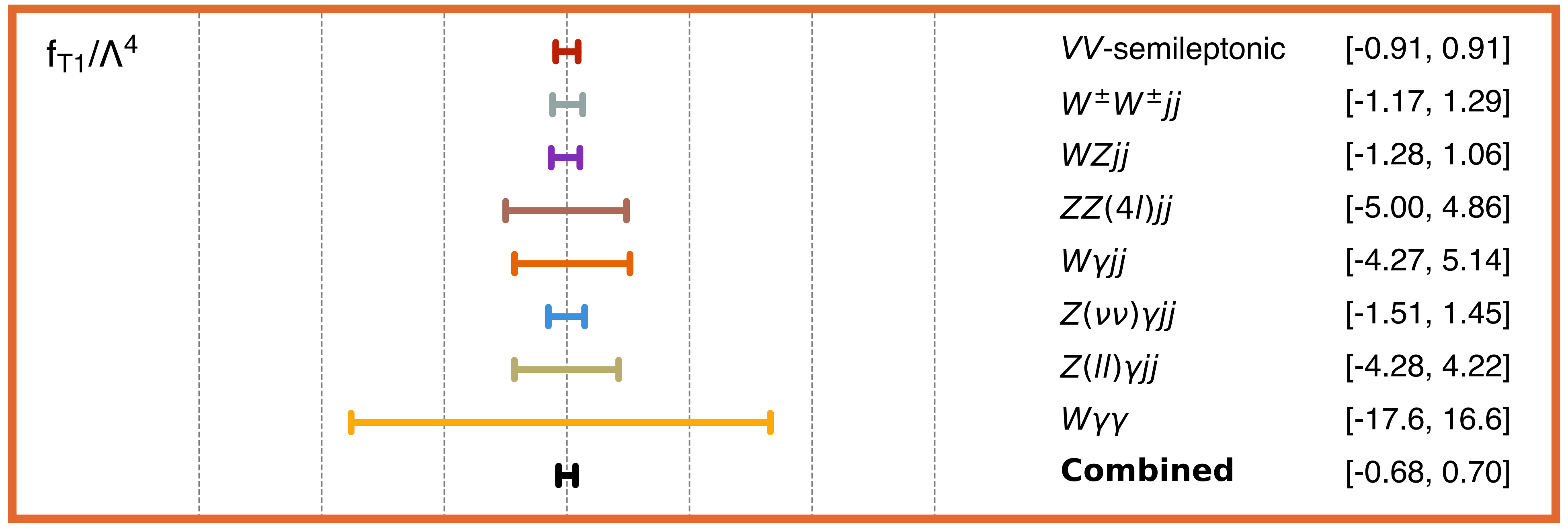
M3: 26% better w.r.t. individual analyses



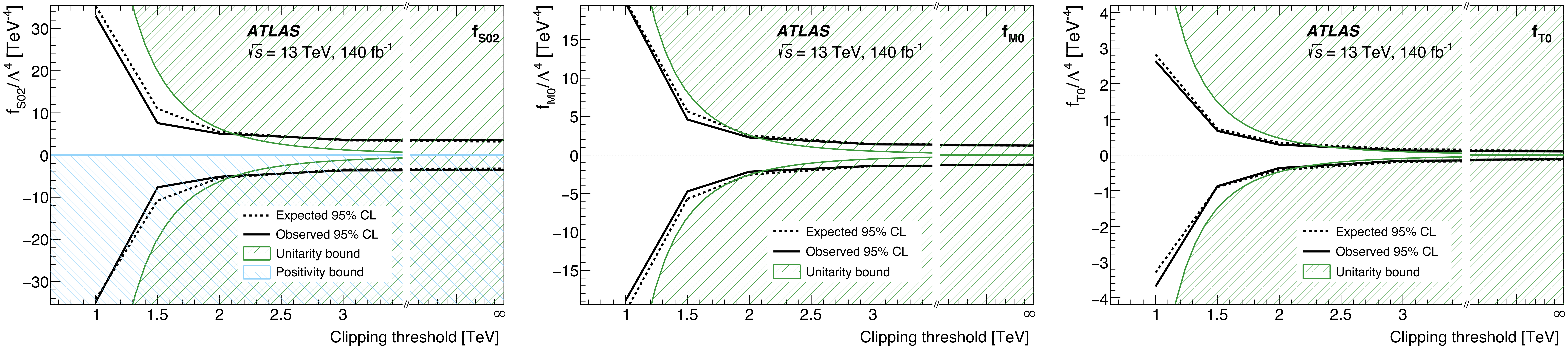
M5: 37% better w.r.t. individual analyses



T1: 24% better w.r.t. individual analyses



Results: unitarised constraints



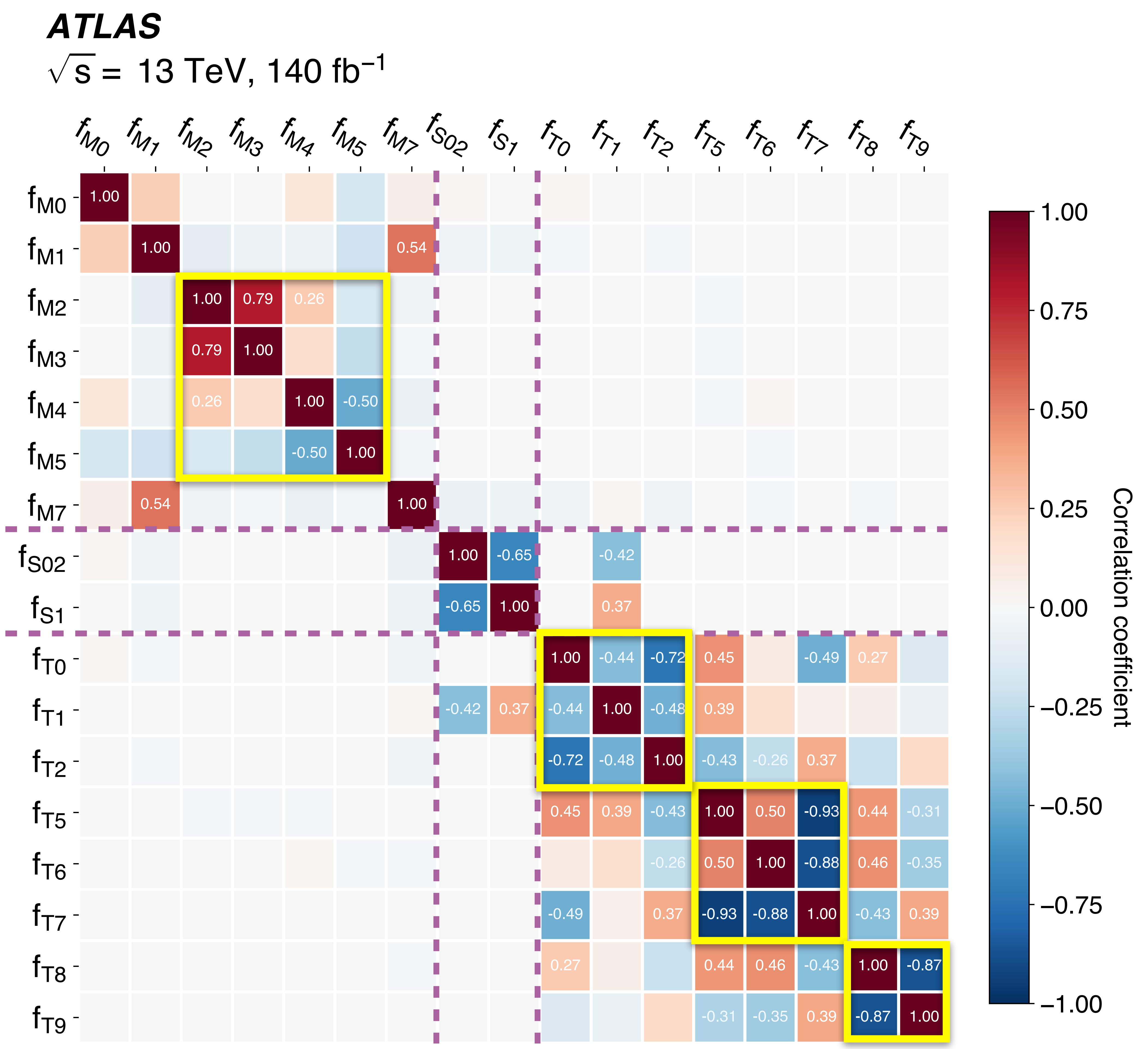
- The unitarisation cut-offs are usually around 2-3 TeV
- No unitarisation cut-off found for S1, as the theory bound set better constraints than the experimental interval
- Unitarised confidence intervals: 17-96% improvements compared to the published results

Cross-terms between operators

$$\mathscr{A}^2 = |\mathscr{A}_{SM}|^2 + 2\sum_i A_i \frac{c_i}{\Lambda^4} + \sum_i B_i \frac{c_i^2}{\Lambda^8} + 2\sum_{i\neq j} \frac{c_i c_j}{\Lambda^8} \Re(\mathscr{A}_i^* \mathscr{A}_j)$$

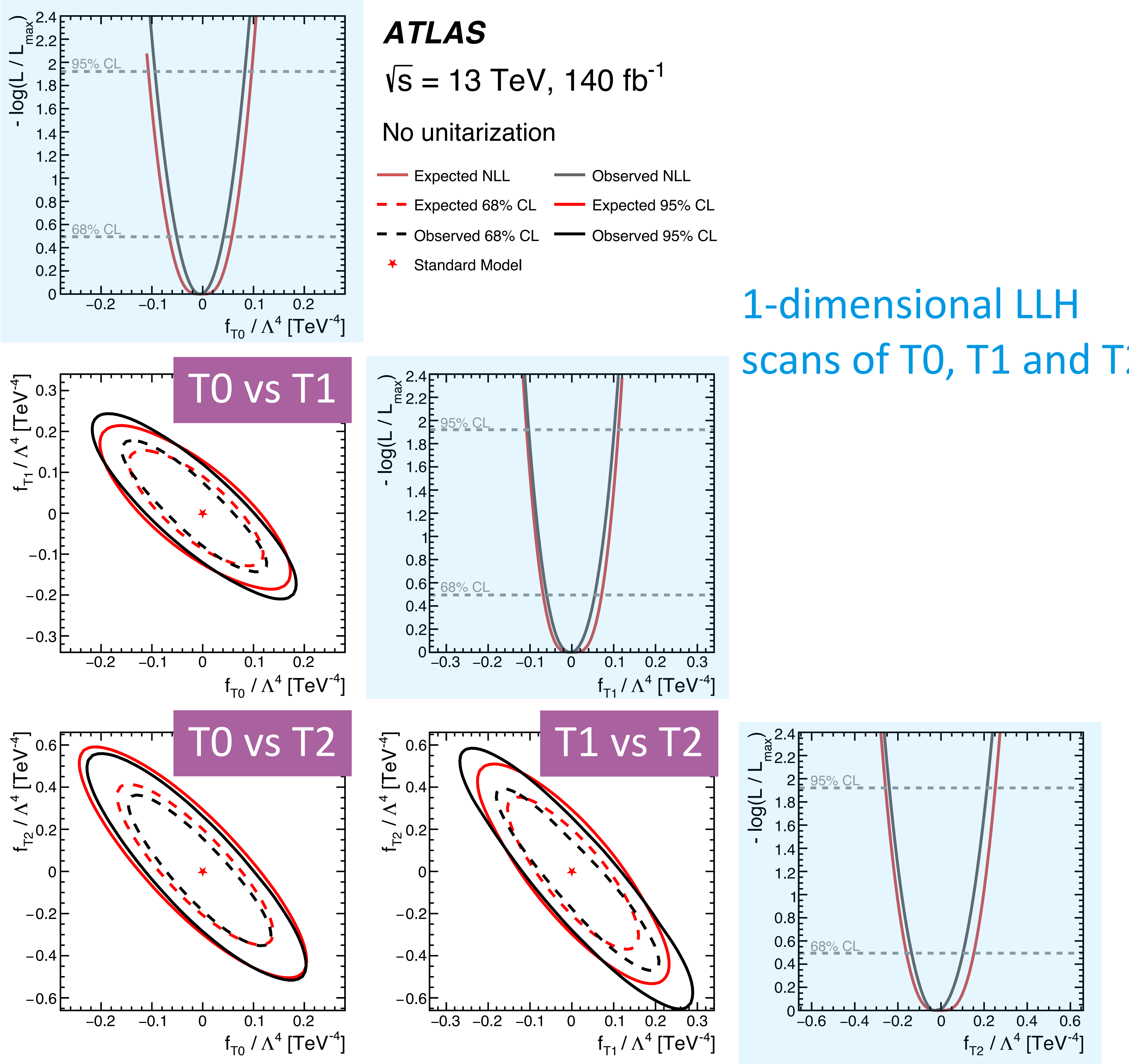
Pure SM — Linear term — EFT cross-terms (quadratic)

- Correlation structure of the Éboli operators affect the sizes of cross-terms:
  - Between different operator families (mixed, scalar or tensor), the cross-terms are highly suppressed
  - Within each family, the several blocks are formed:
    - f_{M0}, f_{M1}, f_{M7} / $f_{M2}, f_{M3}, f_{M4}, f_{M5}$
    - f_{S02}, f_{S1}
    - f_{T0}, f_{T1}, f_{T2} / f_{T5}, f_{T6}, f_{T7} / f_{T8}, f_{T9}



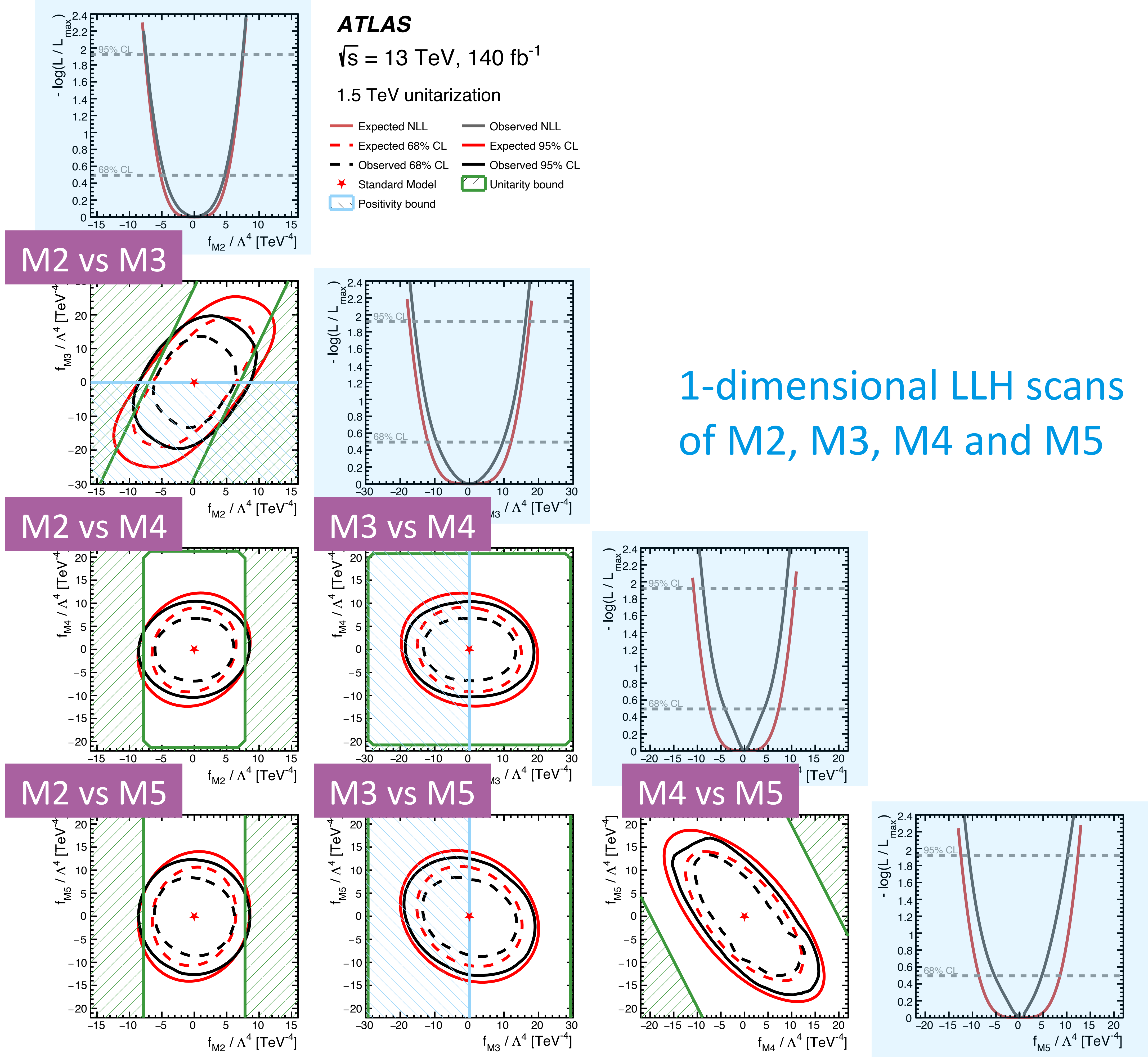
Results: 2-dimensional constraints

No unitarisation cut-off applied, T0, T1 & T2



1-dimensional LLH scans of T0, T1 and T2

Unitarisation cut-off applied at 1.5 TeV, M2, M3, M4 & M5



1-dimensional LLH scans of M2, M3, M4 and M5

Results: from one-at-a-time constraints to profiled constraints

- Profiled constraints:
  - Obtained through likelihood scans for each operator, allowing other operators to freely float
  - Enable interpretation with models predicting simultaneously changing coefficients

Coefficient	Profiled expected confidence intervals [TeV $^{-4}$]	Profiled observed confidence intervals [TeV $^{-4}$]
f_{S02}/Λ^4	[-4.06, 4.08]	[-4.87, 4.88]
f_{S1}/Λ^4	[-8.72, 8.73]	[-9.82, 9.82]
f_{M0}/Λ^4	[-1.67, 1.68]	[-1.68, 1.65]
f_{M1}/Λ^4	[-8.13, 7.52]	[-9.05, 8.58]
f_{M2}/Λ^4	[-1.91, 1.91]	[-1.97, 1.99]
f_{M3}/Λ^4	[-4.16, 4.16]	[-3.89, 3.92]
f_{M4}/Λ^4	[-3.15, 3.15]	[-2.55, 2.56]
f_{M5}/Λ^4	[-3.48, 3.49]	[-2.77, 2.77]
f_{M7}/Λ^4	[-16.6, 15.7]	[-12.4, 12.9]
f_{T0}/Λ^4	[-0.33, 0.24]	[-0.34, 0.22]
f_{T1}/Λ^4	[-0.199, 0.211]	[-0.254, 0.283]
f_{T2}/Λ^4	[-0.578, 0.639]	[-0.665, 0.599]
f_{T5}/Λ^4	[-0.405, 0.384]	[-0.319, 0.289]
f_{T6}/Λ^4	[-0.658, 0.642]	[-0.490, 0.370]
f_{T7}/Λ^4	[-1.51, 1.58]	[-1.17, 1.13]
f_{T8}/Λ^4	[-0.196, 0.181]	[-0.163, 0.147]
f_{T9}/Λ^4	[-0.360, 0.384]	[-0.281, 0.280]

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- Compared to normal 1 dimensional scan:
  - Operators having smaller cross-terms with others are not much affected (~ a few percents)
  - Higher cross-terms — significant changes

Summary

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i^{N_5} \frac{c_i^{(5)}}{\Lambda}\mathscr{O}_i^{(5)} + \sum_i^{N_6} \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_i^{N_7} \frac{c_i^{(7)}}{\Lambda^3}\mathscr{O}_i^{(7)} + \sum_i^{N_8} \frac{c_i^{(8)}}{\Lambda^4}\mathscr{O}_i^{(8)} + \ldots$$

Dimension-6 Dimension-8

- The first combination paper focusing on dimension-8 EFT operators that induce aQGCs
  - Many modifications to input analyses to facilitate the combination
  - 1-dimensional, 2-dimensional and profiled constraints on 17 Éboli basis operators are obtained, with different unitarisation bounds considered
  - Competitive results with the CMS collaboration. For several operators, this combination provides the most sensitive constraints to date
- Future: more multi-boson analyses to be included, optimisation of analysis designs for EFT interpretation, a larger set of EFT operators… — a very exciting field to explore!

Related CMS papers on aQGC operators

$ZZ(4l)jj$ 2008.07013, $Z\gamma jj$ 2106.11082, $W/Z\gamma\gamma$ 2105.12780, leptonic WZ/WW 2005.01173, semileptonic VV 2510.00118, high-mass $\gamma\gamma \rightarrow WW/ZZ$ 2211.16320

Back-up