Status of negative coupling modifiers for extended Higgs sectors

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Based on work with Daniel Stolarski and Yongcheng Wu

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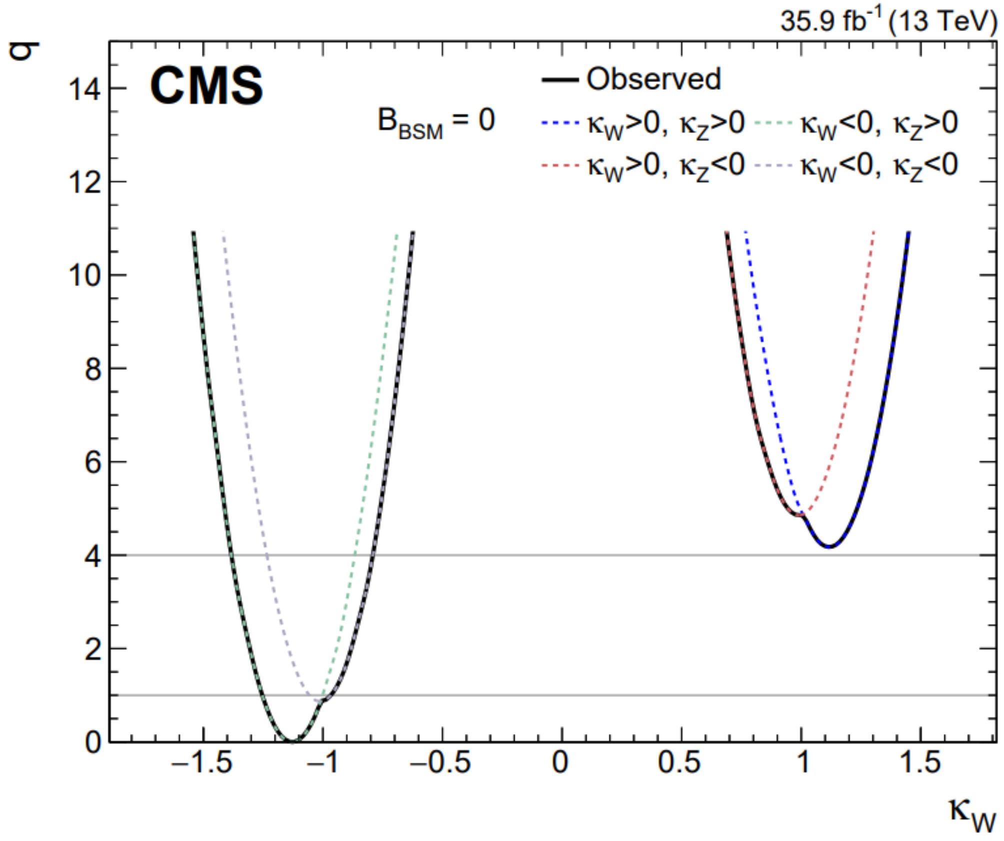
- Accidentally Custodial triplets
- Generalization for different multiplets
- Experimental bounds from Higgs precision measurements
- Conclusion

Introduction

- The LHC shows that corrections from new physics appear to be small.
- This could be an artifact of the way we are accessing information. Lose information on the sign of couplings!
- The CMS* fits for ratios of coupling modifiers prefers negative λ_{WZ} !
- What if we take this result seriously. What models can generate $\lambda_{WZ} = {}^{\kappa_W}/_{\kappa_Z} \sim -1$?
- $\lambda_{WZ} = {}^{\kappa_W}/_{\kappa_Z} \sim -1$ implies large custodial violation!



*CMS-HIG-17-031 *CERN-EP-2016-100

Custodial Symmetry in the SM and BSM

- Custodial symmetry is an accidental global $SU(2)_L \times SU(2)_R$ symmetry of the Higgs sector.
- Softly broken by hypercharge and Yukawa.
- The ratios of charged and neutral currents are equal at tree-level in the SM:

$$\rho = \frac{m_W^2}{c_W^2 m_Z^2} = 1$$

- New scalars contributing to the EWSB can affect the ρ parameter at tree-level:

$$\rho = \frac{\sum_i \left(t_i(t_i+1) - t_{3\,i}^2\right) v_i^2}{2\sum_i t_{3\,i}^2 v_i^2}$$

t_i is the weak isospin
$t_{3\,i}$ is the third component of $SU(2)_L$
v_i the vacuum expectation value of the representation i.

Custodial Symmetry in the SM and BSM

- Scalar extensions of the SM can preserve ρ at tree-level if they are representations of $SU(2)_L \times SU(2)_R$.
- We can include any number of doublets and for higher representations we have the Georgi-Machacek model and its extensions:

$$(\chi^{++},\, \chi^{+},\, \chi^{0}) \qquad (\xi^{+},\, \xi^{0},\, \xi^{-})$$

$$Y = 2 \qquad Y = 0$$

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

$$\begin{aligned} V(\Phi, X) = {} & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\ & +\lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ & -M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}. \end{aligned}$$

$$Q = T^3 + Y/2$$

Custodial Symmetry in the SM and BSM

- Custodial preserving models avoid the strong bounds on ρ, but at the same time we have $\lambda_{WZ} = 1$.
- In general, any contribution for $\kappa_W$and κ_V comes from the diagonalization of the different multiplets:

$$h = R_0 \varphi_0^R + R_1 \psi_1^R + R_2 \psi_2^R + \cdots$$

$$\kappa_V^h = R_0 \kappa_V^{doublet} + R_1 \kappa_V^{multiplet\ 1} + R_2 \kappa_V^{multiplet\ 2}$$

- If we want a custodial violating relation for the coupling modifiers, we need custodial violation in the **potential**. If we want $\rho = 1$ we need custodial preserving **vacuum**. We can have both!

Accidentally Custodial triplets

- The vector $\vec{R}$ comes from the diagonalization matrix and is a real unit vector. We can treat this in a "model-independent" way if we assume that $\vec{R}$ is a random unit vector and the vevs also live in a random vector which is normalized to be the EW vacuum: $v^2 = v_\varphi^2 + 8v_X^2$
- Parameter point → V(point) → $\vec{R}$
- A random $\vec{R}$ may or not be realized in the model, but for every parameter point we have one specific $\vec{R}$.
- If we exclude every $\vec{R}$ then this region of parameter space is also excluded in the model. If there is a region of $\vec{R}$ allowed, then we need to perform model-dependent calculations to check if this region is populated in the model.

*arXiv:1807.11511

Generalization for different multiplets

- Any model with a custodial limit can contribute to λ_{WZ} while avoiding the ρ parameter.
- The particle content of those models can be constructed from the generalized Georgi-Machacek models*, which we can break down into SU(2) x U(1) quantum numbers:
- **AC triplets**: one field with **(1,2)** and one with **(1,0)**
- **AC quartets**: one field with **(3/2,3)** and one with **(3/2,1)**
- **AC pentets**: one field with **(2,4)**, one with **(2,2)** and one with **(2,0)**
- **AC sextets**: one field with **(5/2,5)**, one with **(5/2,3)** and one with **(5/2,1)**

*arXiv:1502.01275

Generalization for different multiplets

- Perturbative unitarity constraints the number of allowed models, assuming one doublet we can have 4487 possibilities.

$$a_0(T) = \frac{g^2}{16\pi}\frac{\sqrt{n}(n^2-1)}{2\sqrt{3}}$$

- From these combinations, we can only have at most one **AC sextet**, four **AC pentets**, 23 **AC quartets**, or 145 **AC triplets**.
- Non-trivial contributions occurs only with multiplets which contribute for the EWSB. In the cases with a lot of multiplets, the strongest contribution comes from when all the multiplets have nearly degenerated vevs.

Bounds from Higgs precision measurements

- We perform random numerical scans for each possible model where we fixed λ_{WZ} to be negative and conservatively allow it to be within the 5σ allowed region:

$$-1.44 \leq \lambda_{WZ} \leq -0.69$$

- We use ATLAS data since they provide correlations, but the same conclusions applies for the uncorrelated CMS data.

$$\kappa_{fZ} = \frac{\kappa_f \kappa_Z}{\kappa_h} \qquad \lambda_{fZ} = \frac{\kappa_f}{\kappa_Z}$$

$$\kappa_h = \sqrt{0.75\kappa_f^2 + 0.22\kappa_W^2 + 0.03\kappa_Z^2}$$

ATLAS FIT:

$$(\lambda_{fZ}, \kappa_{fZ}) = (0.99, 0.98)$$

$$COV = \begin{pmatrix} 0.0093 & -0.00054 \\ -0.00054 & 0.0020 \end{pmatrix}$$

CMS FIT (UNCORRELATED):

$$\kappa_{fZ} = 1.03 \pm 0.09$$

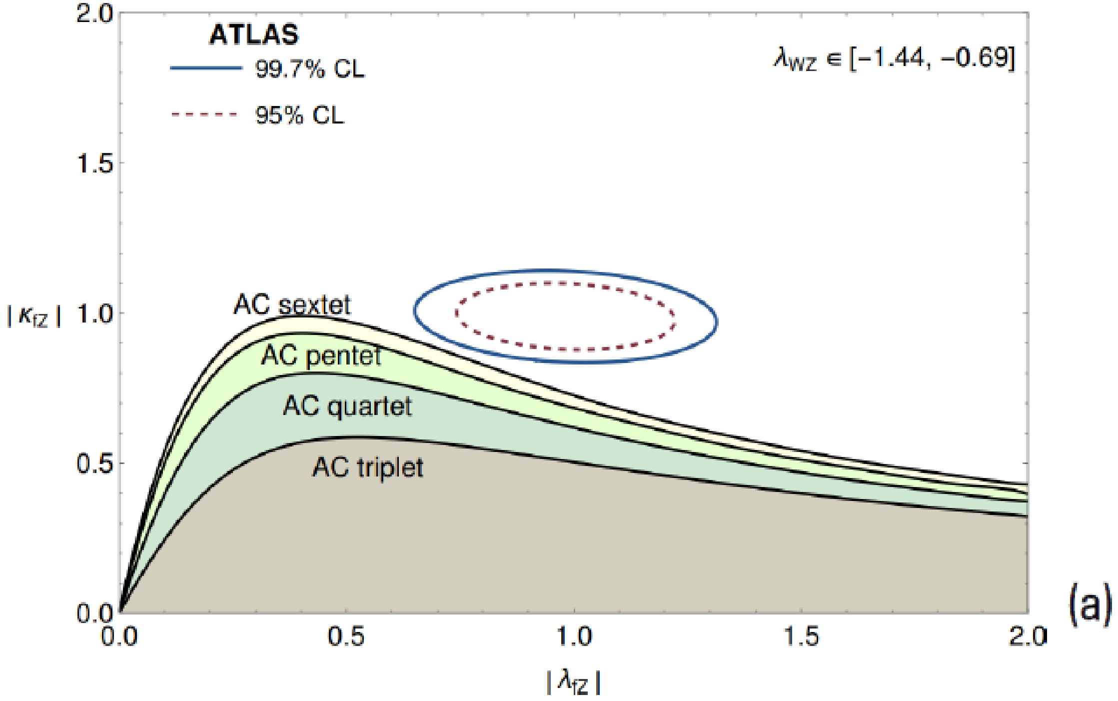
$$\lambda_{fZ} = 1.10 \pm 0.11$$

$$\lambda_{WZ} = -1.13^{+0.10}_{-0.11}$$

- We also performed scans allowing for custodial violation from the vacuum, again in a conservatively 5σ allowed region:

$$0.99944 \leq \rho \leq 1.00134$$

Bounds from Higgs precision measurements



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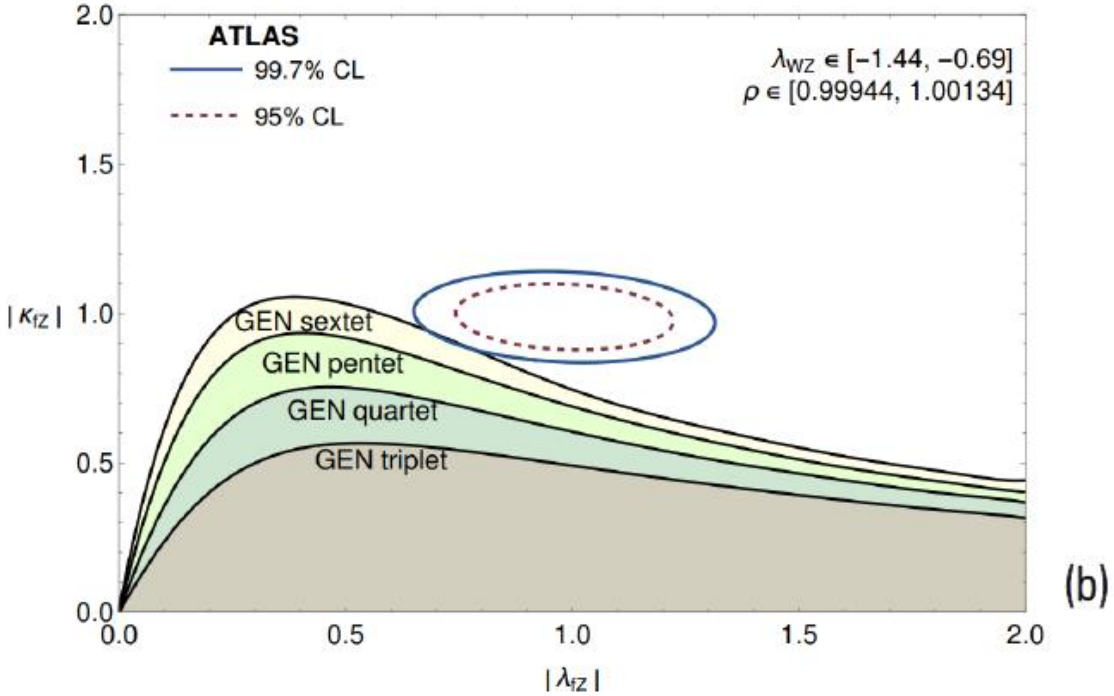
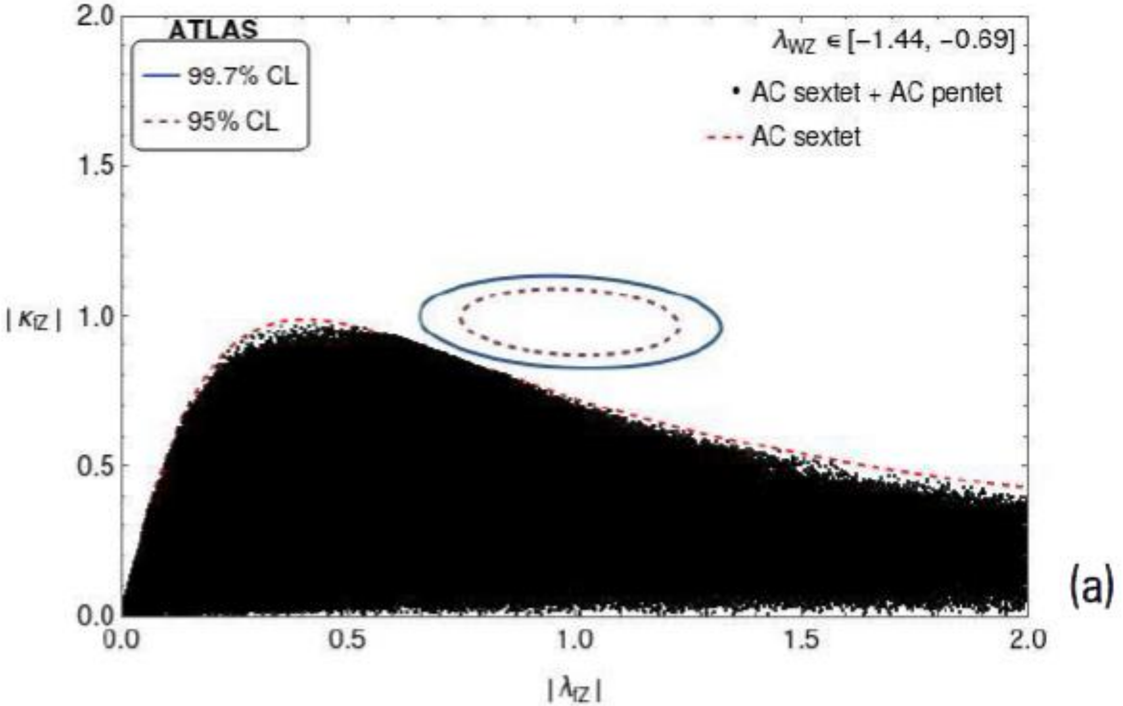
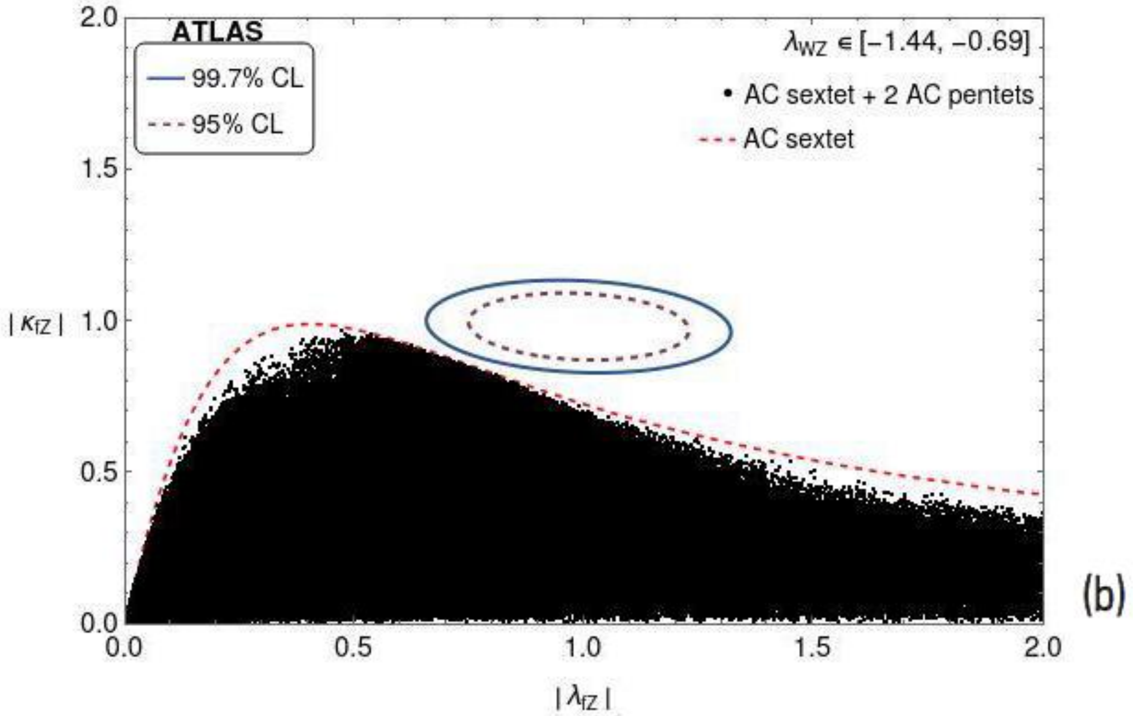


EXCLUDED AT 99.7%CL

*ATLAS-CONF-2020-027

Bounds from Higgs precision measurements





More multiplets is not better! Same behavior as the largest multiplet.

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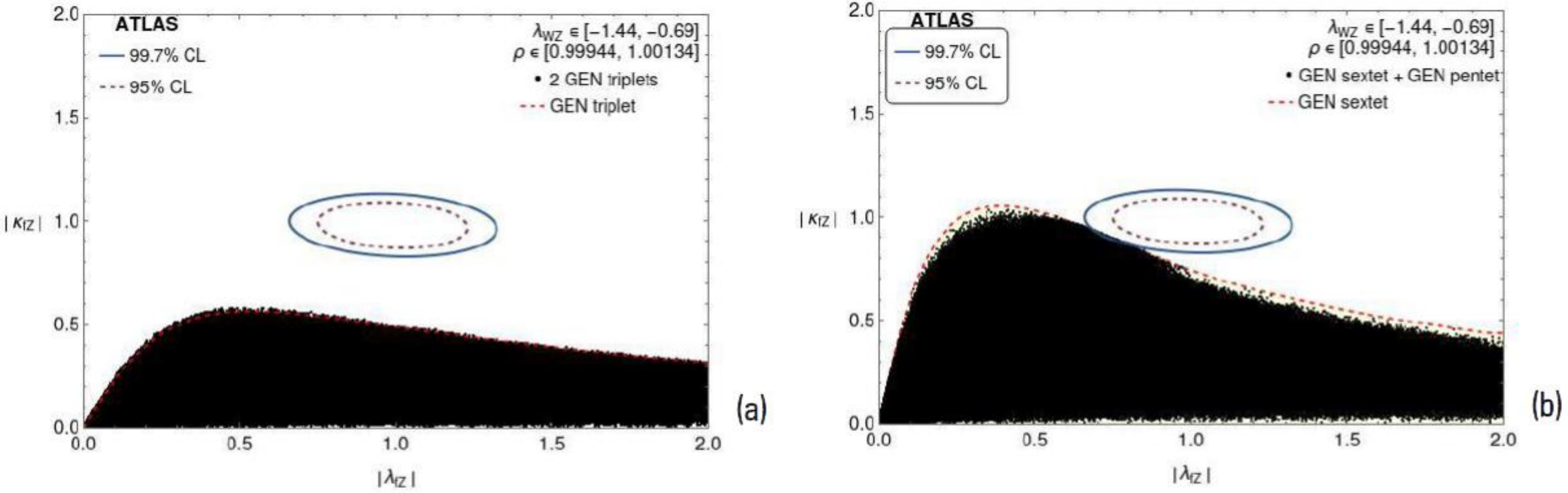
Bounds from Higgs precision measurements



General vevs also do not help, ρ bound is too strong even at 5σ.

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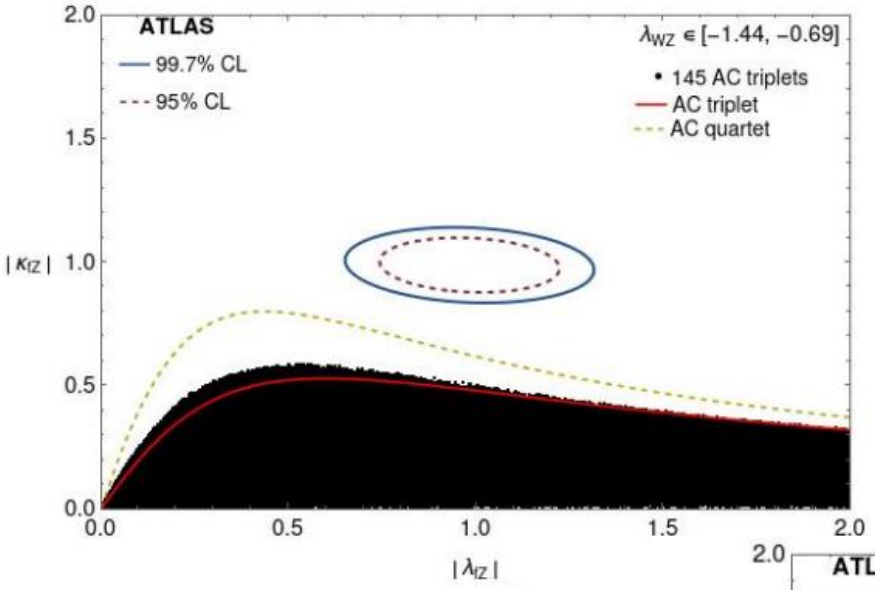
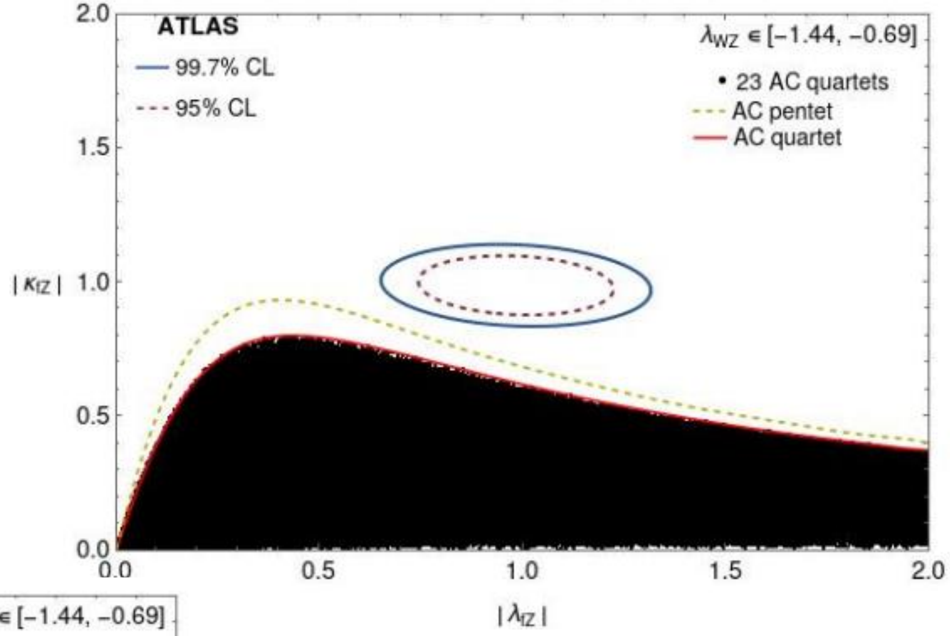
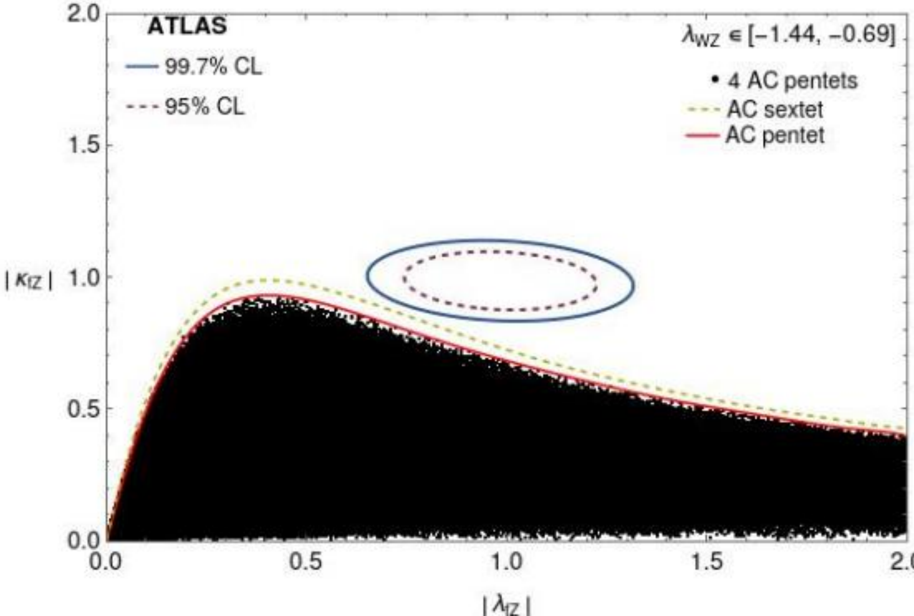
Bounds from Higgs precision measurements





N copies of equal size vevs

Extremal cases are also excluded with more than 99.7%CL



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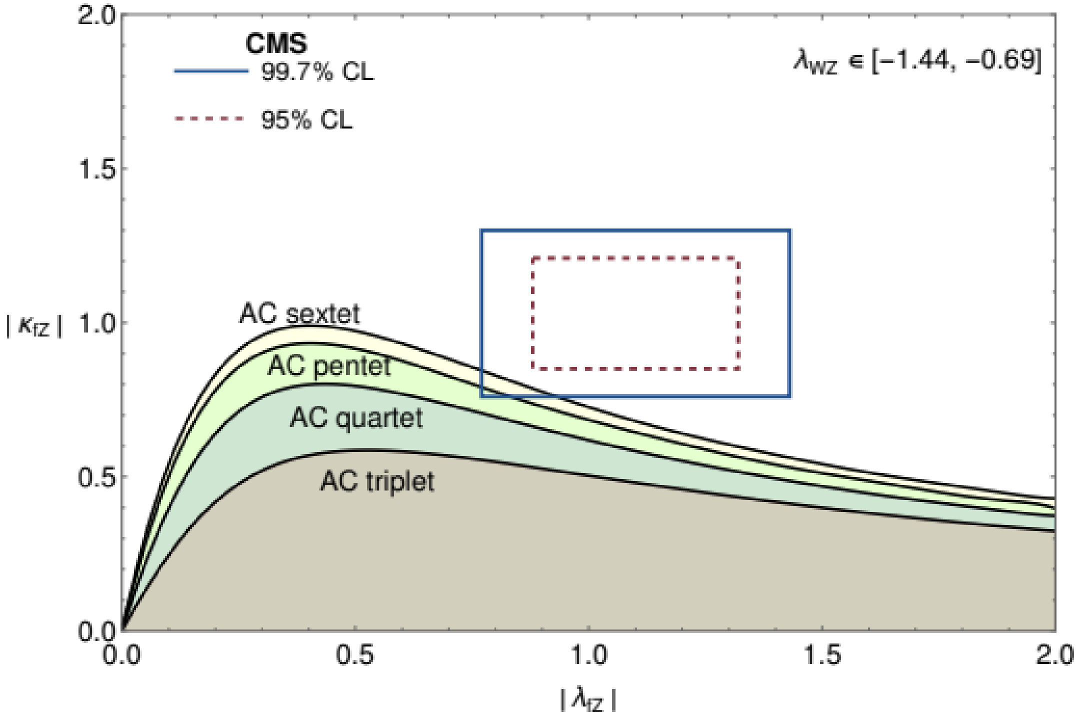
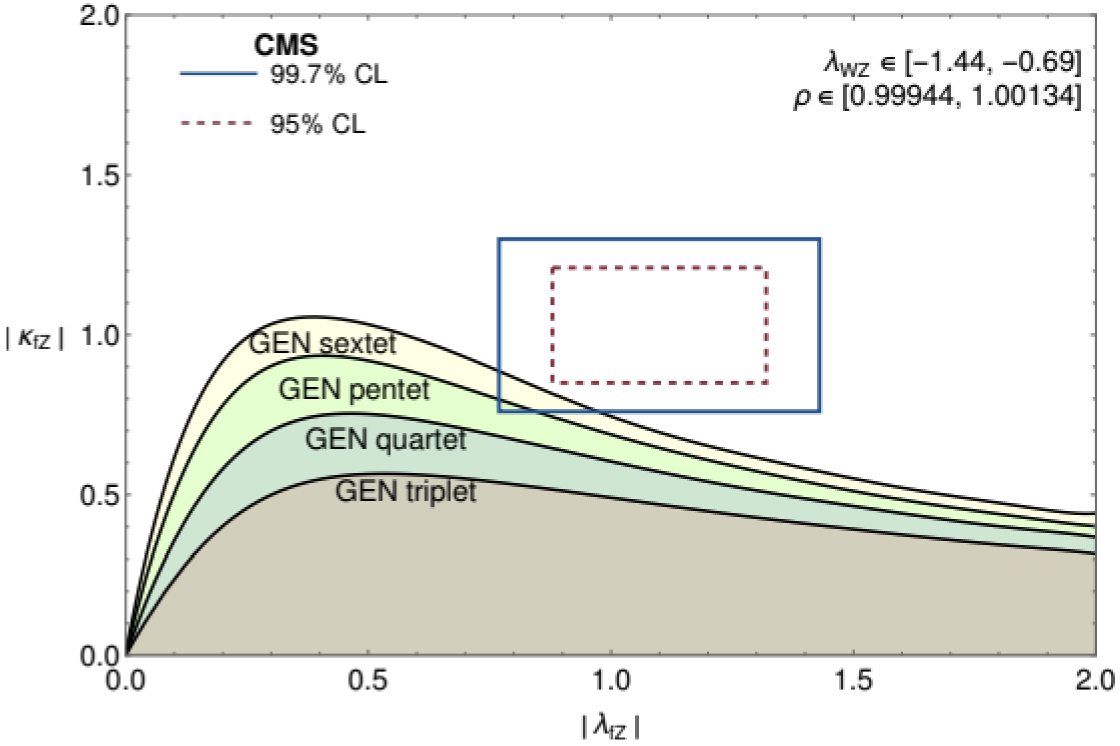
Conclusion

- In this work, we studied the current status of negative coupling modifiers in the extended Higgs sector, with the focus on the observable λ_{WZ}.
- We present the analysis for the simplest case of AC triplets, and then we show how to generalize the procedure to different multiplets.
- The possibility of exploring this wide range of models lies in the fact that the coupling modifiers, in the end, depend only on the diagonalization matrix and the vevs.
- Under the analysis done we can see that all the models with one or more AC multiplets studied here are **excluded** under ATLAS results at 99.7%CL (99.5%CL for GEN sextet).
- What does this mean for negative λ_{WZ}?
- We can then say that this region of parameter space is heavily disfavored for any weakly coupling extended scalar sector.
- In contrast, if the measured value for CMS stays to be negative and different experiments confirm this, we would not be able to describe the new physics using the current methods.

Backup


CMS
99.7% CL
95% CL
$\lambda_{WZ} \in [-1.44, -0.69]$
AC sextet
AC pentet
AC quartet
AC triplet
$|\kappa_{fZ}|$
$|\lambda_{fZ}|$
0.0
0.5
1.0
1.5
2.0


CMS
99.7% CL
95% CL
$\lambda_{WZ} \in [-1.44, -0.69]$
$\rho \in [0.99944, 1.00134]$
GEN sextet
GEN pentet
GEN quartet
GEN triplet
$|\kappa_{fZ}|$
$|\lambda_{fZ}|$
0.0
0.5
1.0
1.5
2.0

Backup

- The scan for models with too many multiplets can be difficult, since we need to populate the surface of a multi-dimensional sphere.
- However, since there are a limited number of possible multiplets, we can use the Cauchy–Schwarz inequality to re-write the vector R which lives in a sphere to a vector $\tilde{R}$ which lives inside an ellipses:

$$\kappa_V^h = R_1 \kappa_V^{\text{doublet}} + \left(R_2 \kappa_V^{\text{multiplet 1}} + R_3 \kappa_V^{\text{multiplet 2}} \right) + \left(R_4 \kappa_V^{\text{multiplet 1}} + R_5 \kappa_V^{\text{multiplet 2}} \right) + \ldots =$$
$$= R_1 \kappa_V^{\text{doublet}} + \left(R_2 + R_4 + \ldots \right) \kappa_V^{\text{multiplet 1}} + \left(R_3 + R_5 + \ldots \right) \kappa_V^{\text{multiplet 2}} =$$
$$= R_1 \kappa_V^{\text{doublet}} + \tilde{R}_2 \kappa_V^{\text{multiplet 1}} + \tilde{R}_3 \kappa_V^{\text{multiplet 2}}$$

- Using these relations, we can simplify the parameter space and obtain the maximal contributions for the observables without having to resolve the degeneracy.

$$R_1^2 + \frac{\tilde{R}_2^2}{N} + \frac{\tilde{R}_3^2}{N} \leq 1 \,,$$
$$\left| \tilde{R}_2 \right| \leq \sqrt{N} \,, \; \left| \tilde{R}_3 \right| \leq \sqrt{N} \,.$$