# STATUS OF NEGATIVE COUPLING MODIFIERS FOR EXTENDED HIGGS SECTORS

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# OUTLINE

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- Custodial Symmetry in BSM
- Accidentally Custodial triplet
- Generalization for different multiplets
- Scans
- 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!
  - In this work we focus on the ratio of coupling modifier $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$.
  - This observable probes custodial violation on the Higgs sector.
  - Current CMS fits* gives a preference for **negative** $\lambda_{WZ}$.

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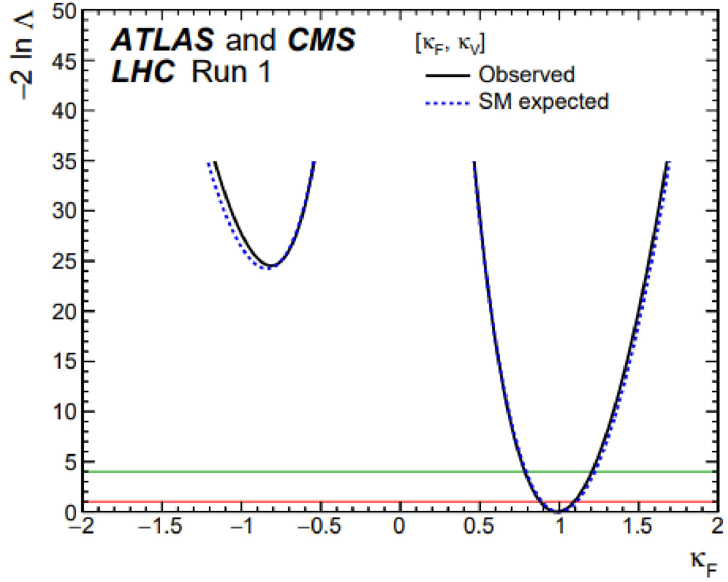



*CMS-HIG-17-031 **CERN-EP-2016-100

# CUSTODIAL SYMMETRY IN BSM

- Custodial symmetry is an accidental global SU(2) × SU(2) symmetry of the Higgs sector.
- In the SM we have the $\lambda_{WZ} = 1$ and there is also the ρ parameter: $\rho = \frac{m_W^2}{c_W^2 m_Z^2}$.
- Naively one would think that both observables are connected in any model, which is not true.
- $\rho$ is connected to the vacuum while $\lambda_{WZ}$ is connected to the potential.
- We can have custodial symmetric vacuum with custodial violating potentials (Accidentally custodial models)!

# CUSTODIAL SYMMETRY IN BSM

- If we assume that the vacuum preserves the symmetry, the custodial violation inside $\lambda_{WZ}$ comes only from the diagonalization of the different multiplets:
- $h = R_0 \varphi_0^R + R_1 \psi_1^R + R_2 \psi_2^R + \cdots$
- The kappas have the form:
- $\kappa_V^h = R_0 \kappa_V^{doublet} + R_1 \kappa_V^{multiplet\ 1} + R_2 \kappa_V^{multiplet\ 2} + \cdots$
- If we want to explore if a region is excluded, we do not need to resolve the source of $\vec{R}$ in terms of the potential, we can treat them as random variables and independent of the vevs!

# ACCIDENTALLY CUSTODIAL TRIPLET

- The simplest model* that can generate negative $\lambda_{WZ}$ involves two triplets: We have the usual Higgs doublet $(\varphi^+, \varphi^0)$ with $Y = 1$, a complex triplet $(\chi^{++}, \chi^+, \chi^0)$ with $Y = 2$ and a real triplet $(\xi^+, \xi^0, \xi^-)$ with $Y = 0$.

- The EW symmetry breaking has the form:

$$\varphi^0 = \frac{v_\varphi}{\sqrt{2}} + \frac{1}{\sqrt{2}}(\varphi_R^0 + i\varphi_I^0),\ \xi^0 = v_\xi + \xi_R^0\ ,\ \chi^0 = v_\chi + \frac{1}{\sqrt{2}}(\chi_R^0 + i\chi_I^0)\ .$$

- The $\rho$ parameter in this model is:

$$\rho = \frac{m_W^2}{c_W^2 m_Z^2} = \frac{v_\varphi^2 + 4v_\chi^2 + 4v_\xi^2}{v_\varphi^2 + 8v_\chi^2}$$

- $v_\xi = v_\chi \rightarrow$ vacuum custodially symmetric

*arXiv:1807.11511

# ACCIDENTALLY CUSTODIAL TRIPLET

- $h = R_0 \varphi_R^0 + R_1 \chi_R^0 + R_2 \xi_R^0$
- $\lambda_{WZ} = \frac{2\sqrt{2}\nu_\chi R_1 + 4\nu_\chi R_2 + \nu_\varphi R_0}{4\sqrt{2}\nu_\chi R_1 + \nu_\varphi R_0}$
- Assume $\lambda_{WZ} = -1$,write the other observables:

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

- Then, solve for $\vec{R}$, if we assume $\lambda_{fZ} = \pm 1$we get:

$$\kappa_{fZ} = R_0 \frac{\nu_\varphi}{\nu} \text{ for } \lambda_{fZ} = 1$$

$$\kappa_{fZ} = -1.39 R_0 \frac{\nu_\varphi}{\nu} \text{ for } \lambda_{fZ} = -1$$

# GENERALIZATION FOR DIFFERENT MULTIPELTS

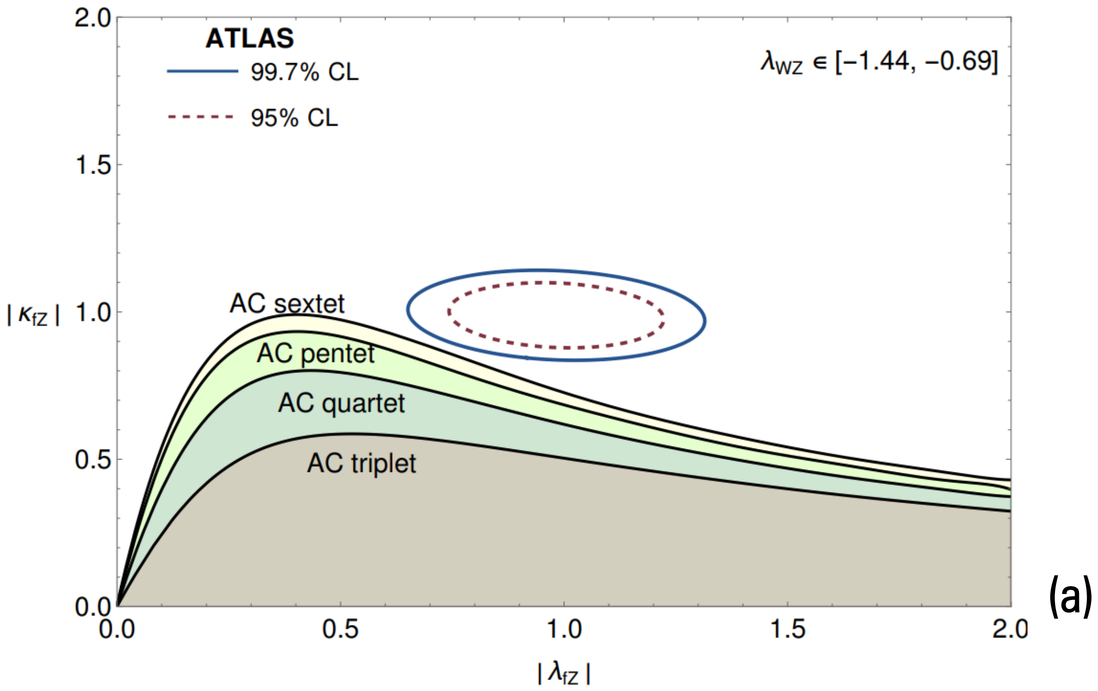
- Any model with a custodial limit can contribute to $\lambda_{WZ}$ while avoiding the $\rho$ parameter.
- The particle content of those models can be constructed from the generalized Georgi-Machacek models*, which we can break down into SU(2) x U(1) quantum numbers:
- AC triplets:  one field with (1,2) 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

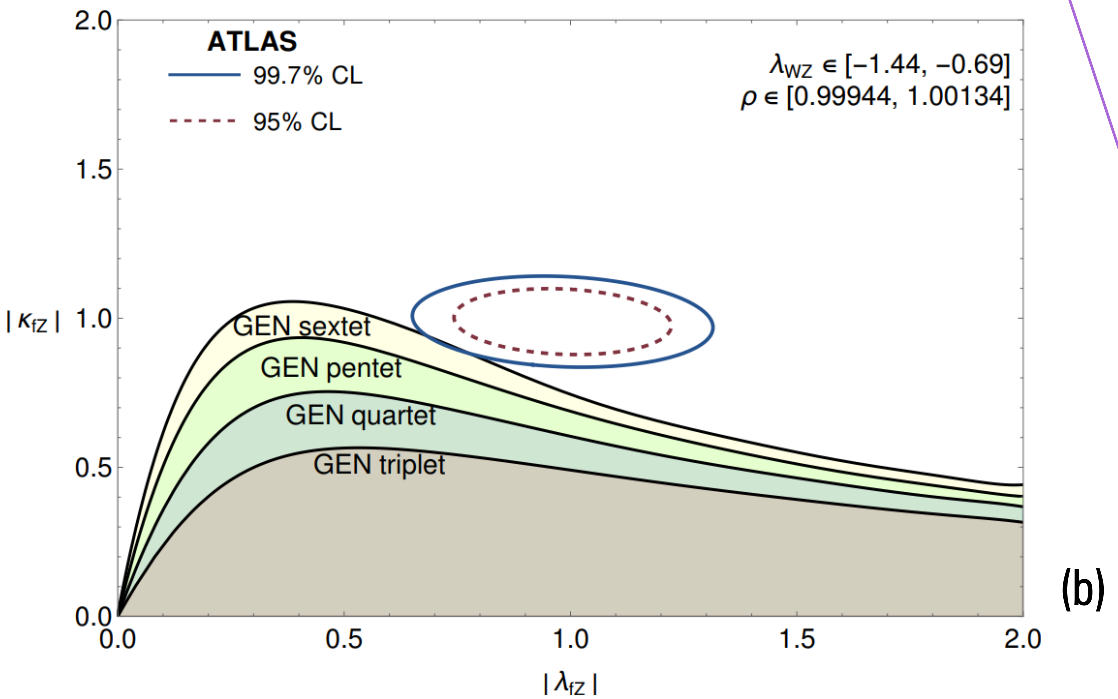
# GENERALIZATION FOR DIFFERENT MULTIPELTS

- Perturbative unitarity constraints the number of allowed models, assuming one doublet we can have 4487 possibilities.
- From these combinations, we can only have at most one AC sextet, four AC pentets, 23 AC quartets, or 145 AC triplets.
- The models that we study here are AC triplet, AC quadruplet, AC pentet, AC sexplet, 2 AC triplets, AC pentet + AC sexplet, and two AC pentet + AC sexplet. Additionally, we also explore the case with general vev's for each of these models.
- We also explore the limiting cases of four AC pentets, 23 AC quartets, and 145 AC triplets.

# SCANS



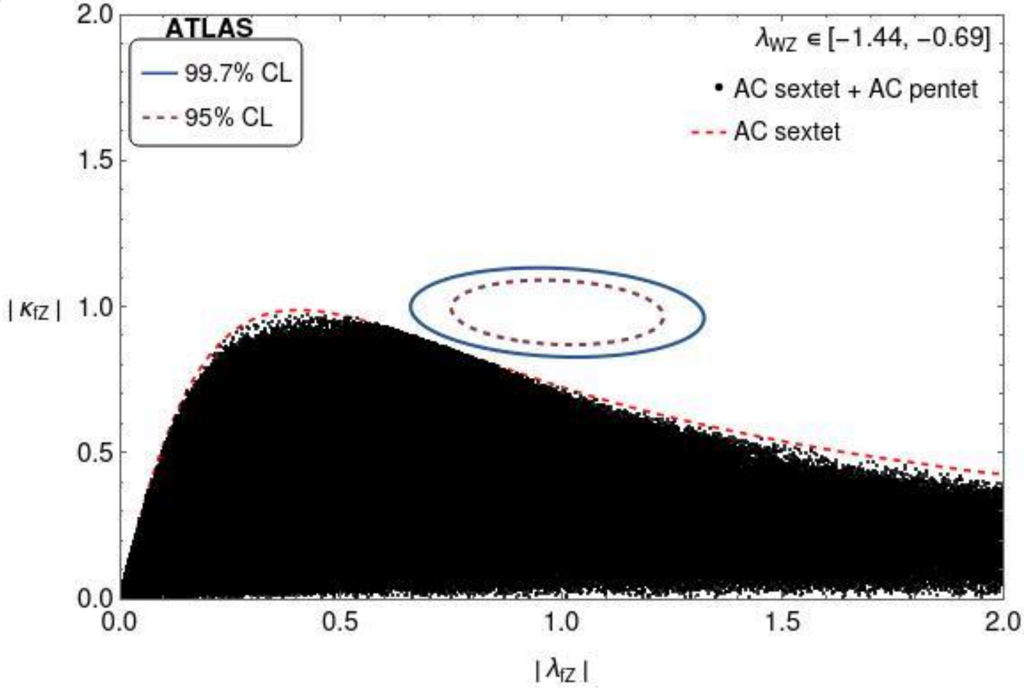

EXCLUDED AT 99.7%CL



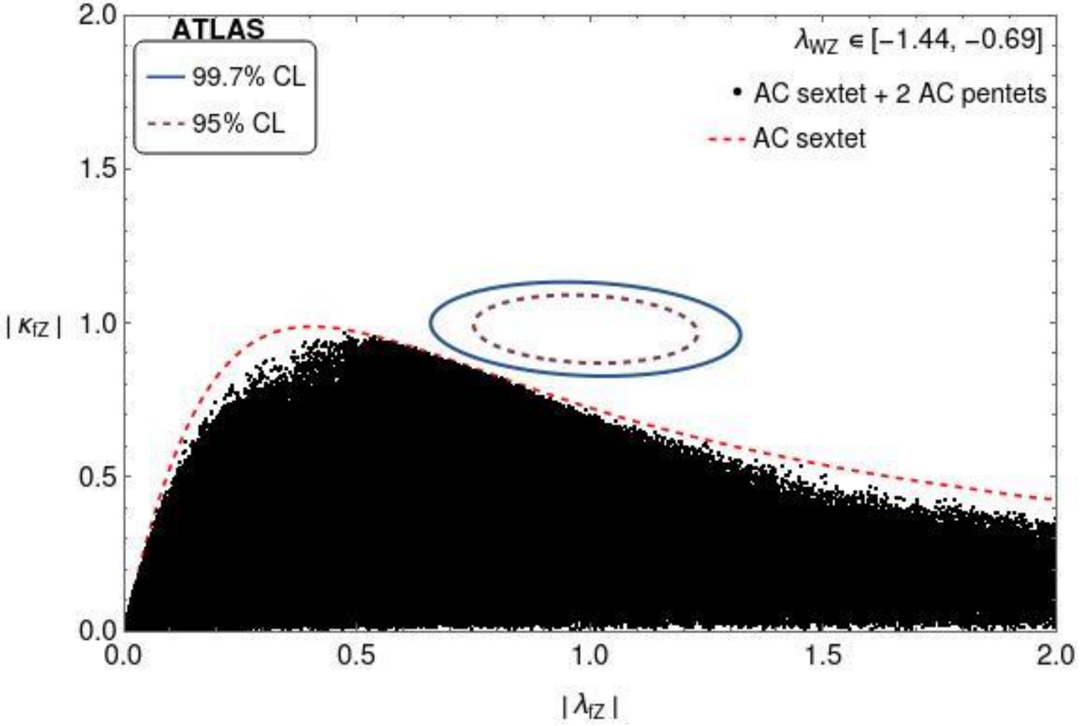

EXCLUDED AT 99.5%CL

*ATLAS-CONF-2020-027

# SCANS




(a)




(b)

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

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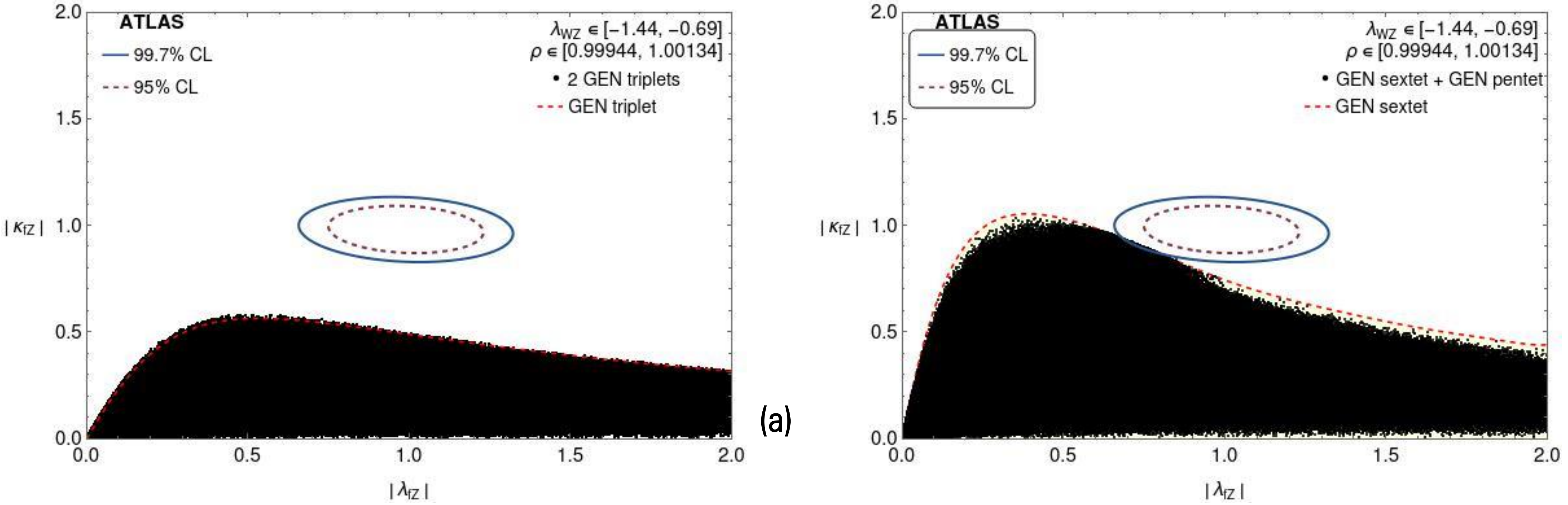
# SCANS




General vevs also does not help. $\boldsymbol{\rho}$ parameter constraint is too strong, even at 5 $\boldsymbol{\sigma}$.
Same behaviour as the situation with only the largest multiplet

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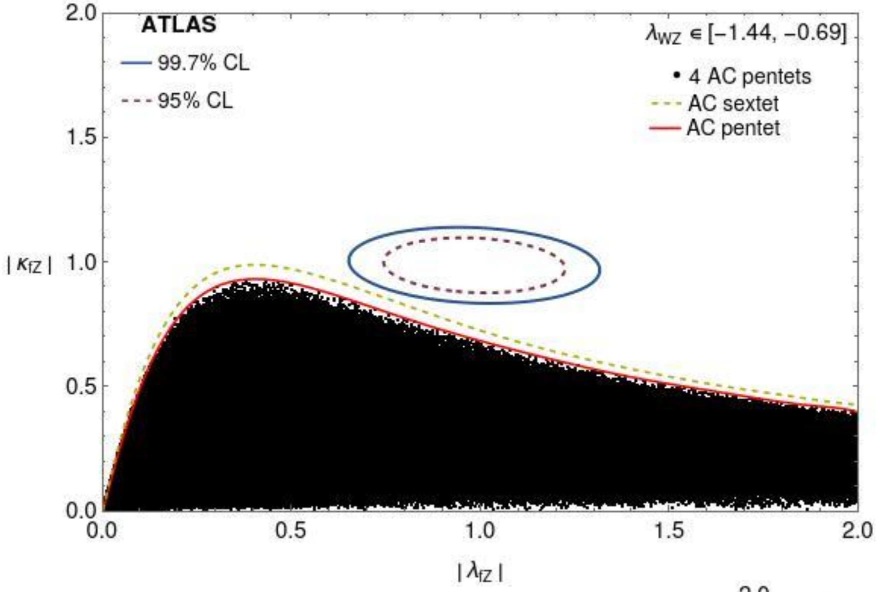
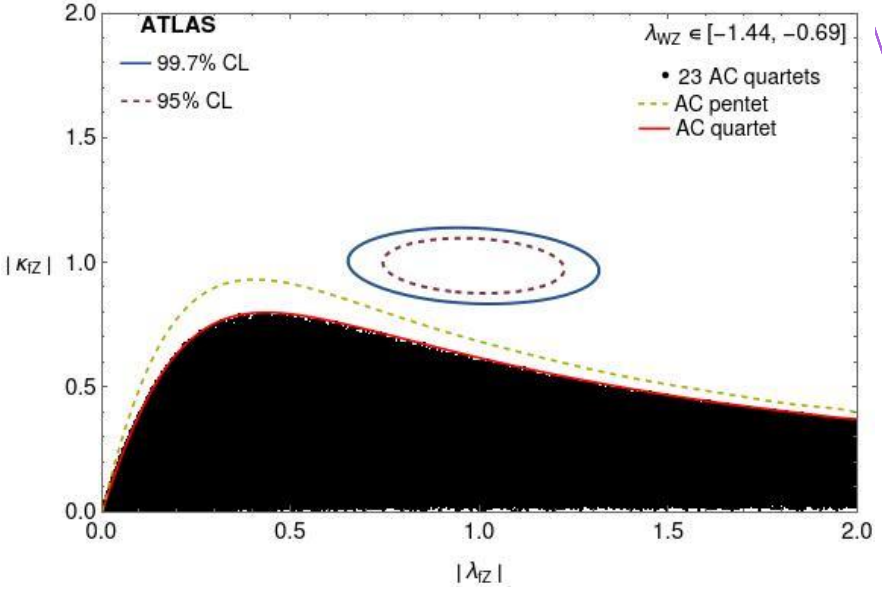
# SCANS

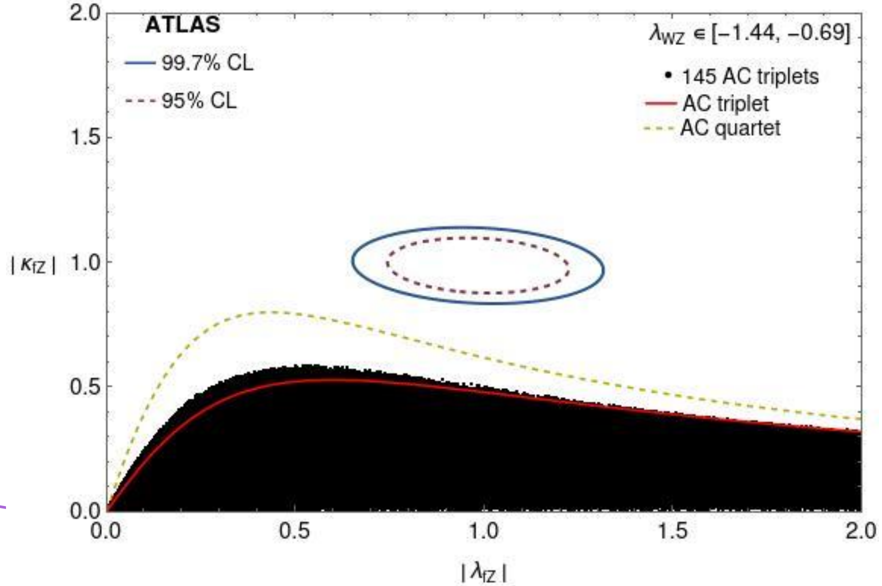



(a)




(b)

Extremal cases are also excluded with more than 99.7%CL!




(c)

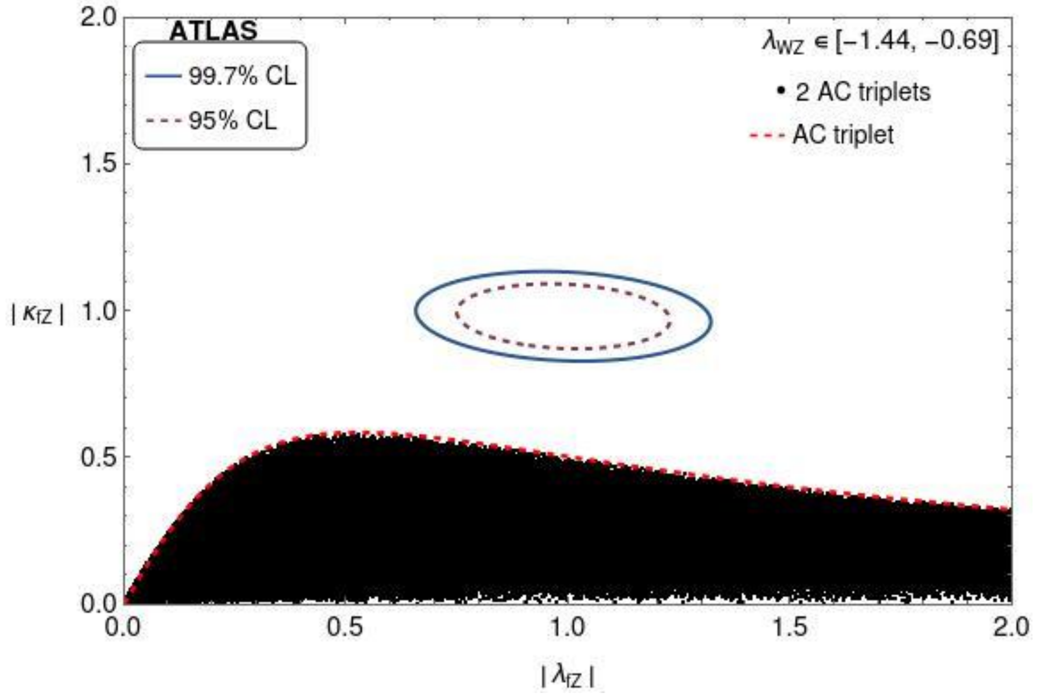
Equal small vevs ~ N copies

*ATLAS-CONF-2020-027

# CONCLUSION

- In this work, we studied the current status of negative coupling modifiers in the extended Higgs sector, with the focus on the observable $\lambda_{WZ}$.
- 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 $\lambda_{WZ}$?
- 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.
- It may be that new physics is hiding in plain sight, after all, only future experiments can tell.

# BACKUP



ATLAS
99.7% CL
95% CL
$\lambda_{WZ} \in [-1.44, -0.69]$
2 AC triplets
AC triplet
$|\kappa_{fZ}|$
$|\lambda_{fZ}|$
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0

# BACKUP

Observables used:

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

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$

$$\lambda_{fZ} = \frac{\kappa_f}{\kappa_Z}$$

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

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):

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

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

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

# BACKUP

Coupling modifiers for different multiplets:

DOUBLET:

$\kappa_f^{(\frac{1}{2},1)} = \frac{v_{(\frac{1}{2},1)}}{v}$, $\kappa_W^{(\frac{1}{2},1)} = \frac{v_{(\frac{1}{2},1)}}{v}$ $\kappa_Z^{(\frac{1}{2},1)} = \frac{v_{(\frac{1}{2},1)}}{v}$

AC TRIPLET:

$\kappa_f^{(1,2)} = 0$, $\kappa_W^{(1,2)} = 2\sqrt{2}\frac{v_{(1,2)}}{v}$ $\kappa_Z^{(1,2)} = 4\sqrt{2}\frac{v_{(1,2)}}{v}$

$\kappa_f^{(1,0)} = 0$, $\kappa_W^{(1,0)} = 4\frac{v_{(1,0)}}{v}$ $\kappa_Z^{(1,0)} = 0$

AC QUARTET:

$\kappa_f^{(\frac{3}{2},3)} = 0$, $\kappa_W^{(\frac{3}{2},3)} = 3\sqrt{2}\frac{v_{(\frac{3}{2},3)}}{v}$ $\kappa_Z^{(\frac{3}{2},3)} = 9\sqrt{2}\frac{v_{(\frac{3}{2},3)}}{v}$

$\kappa_f^{(\frac{3}{2},1)} = 0$, $\kappa_W^{(\frac{3}{2},1)} = 7\sqrt{2}\frac{v_{(\frac{3}{2},1)}}{v}$ $\kappa_Z^{(\frac{3}{2},1)} = \sqrt{2}\frac{v_{(\frac{3}{2},1)}}{v}$

AC PENTET:

$\kappa_f^{(2,4)} = 0$, $\kappa_W^{(2,4)} = 4\sqrt{2}\frac{v_{(2,4)}}{v}$ $\kappa_Z^{(2,4)} = 16\sqrt{2}\frac{v_{(2,4)}}{v}$

$\kappa_f^{(2,2)} = 0$, $\kappa_W^{(2,2)} = 10\sqrt{2}\frac{v_{(2,2)}}{v}$ $\kappa_Z^{(2,2)} = 4\sqrt{2}\frac{v_{(2,2)}}{v}$

$\kappa_f^{(2,0)} = 0$, $\kappa_W^{(2,0)} = 12\frac{v_{(2,0)}}{v}$ $\kappa_Z^{(2,0)} = 0$

AC SEXTET:

$\kappa_f^{(\frac{5}{2},5)} = 0$, $\kappa_W^{(\frac{5}{2},5)} = 5\sqrt{2}\frac{v_{(\frac{5}{2},5)}}{v}$ $\kappa_Z^{(\frac{5}{2},5)} = 25\sqrt{2}\frac{v_{(\frac{5}{2},5)}}{v}$

$\kappa_f^{(\frac{5}{2},3)} = 0$, $\kappa_W^{(\frac{5}{2},3)} = 13\sqrt{2}\frac{v_{(\frac{5}{2},3)}}{v}$ $\kappa_Z^{(\frac{5}{2},3)} = 9\sqrt{2}\frac{v_{(\frac{5}{2},3)}}{v}$

$\kappa_f^{(\frac{5}{2},1)} = 0$, $\kappa_W^{(\frac{5}{2},1)} = 17\frac{v_{(\frac{5}{2},1)}}{v}$ $\kappa_Z^{(\frac{5}{2},1)} = \sqrt{2}\frac{v_{(\frac{5}{2},1)}}{v}$

# BACKUP

N copies limit:

$$\kappa_V^h = R_0\kappa_V^{doublet} + \left(R_1\kappa_V^{mult\,1} + R_2\kappa_V^{mult2}\right) + \left(R_3\kappa_V^{mult\,1} + R_4\kappa_V^{mult2}\right) + \cdots =$$

$$= R_0\kappa_V^{doublet} + (R_1 + R_3 + \cdots)\,\kappa_V^{mult\,1} + (R_2 + R_4 + \cdots)\kappa_V^{mult\,2} =$$

$$= R_0\,\kappa_V^{doublet} + \widetilde{R_1}\kappa_V^{mult\,1} + R_2\widetilde{\kappa_V^{mult\,2}}$$

Cauchy inequality:

$$R_0^2 + \frac{\widetilde{R_1}^2}{N} + \frac{\widetilde{R_2}^2}{N} \leq 1$$