# Measurement of the HVV tensor structure in $pp \to H \to ZZ^* \to 4\ell$ decays with the ATLAS detector

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Bundesministerium
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und Forschung

FSP 103
ATLAS

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

# CP-properties of the Higgs boson

1. **Spin-0:** Boson is scalar particle, as predicted by the Standard Model (LHC Run-I).
   ATLAS: Eur. Phys. J. C75 (2015) 476
   CMS: Phys. Rev. D 92, 012004
2. **CP properties of the discovered boson?**
   CP: Combination of parity and charge conjugation.
   - CP even eigenstate $0^+$? SM
   - Pure pseudoscalar state $0^-$ for discovered boson has been excluded in Run-I
   - BUT it is still possible that we have a mixed state of $0^-$ and $0^+$

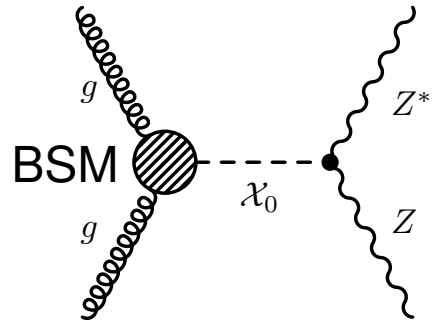
$\Rightarrow$ Additional, non-SM couplings in HVV-vertex?

$\Rightarrow$ CP violation in the Higgs sector, possible explanation for baryon/antibaryon asymmetry

# Theoretical description

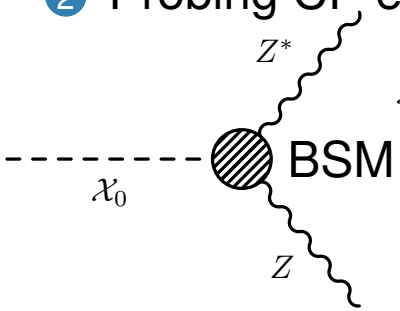
## Effective Lagrangian of the Higgs characterization model (arXiv:1306.6464)

1. Probing CP-odd BSM coupling in ggH vertex:
   (talk by Verena Walbrecht)




POI: $s_\alpha \kappa_{\text{Agg}}$

2. Probing CP-even and CP-odd BSM couplings in HVV-vertex (this talk):




$$\mathscr{L} = \Big\{ c_\alpha \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu} \right] - \frac{1}{4} \left[ c_\alpha \kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} \right] - \frac{1}{4} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \Big\} \mathcal{X}_0$$

SM CP-even,tree-level
BSM CP-even
BSM CP-odd

$\alpha =$ CP mixing angle
$\kappa =$ HC coupling parameter
$g =$ coupling strength SM or MSSM
$\Lambda =$ cut-off energy
$c_\alpha = \cos(\alpha)$
$s_\alpha = \sin(\alpha)$

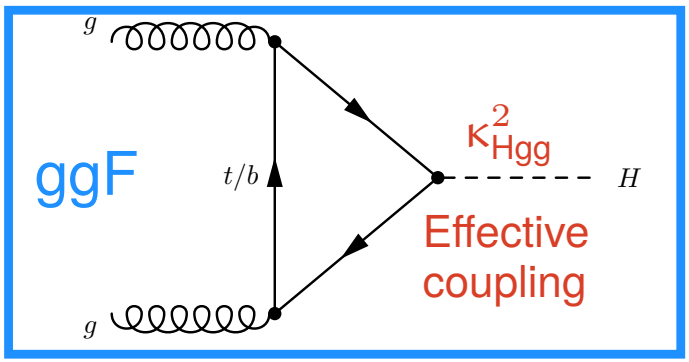
POIs: $s_\alpha \kappa_{\text{Avv}}$, $c_\alpha \kappa_{\text{Hvv}}$, $c_\alpha \kappa_{\text{SM}}$

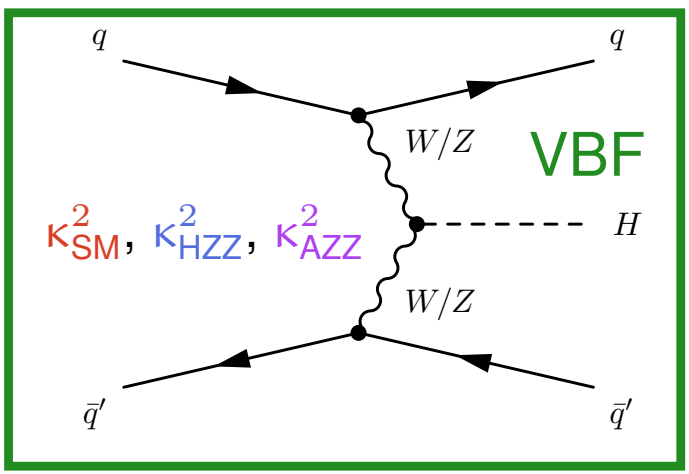
- Additional higher order BSM couplings not considered in analysis.

# Probing BSM couplings in the HVV-vertex

- Production and decay rates are dependent on the anomalous couplings

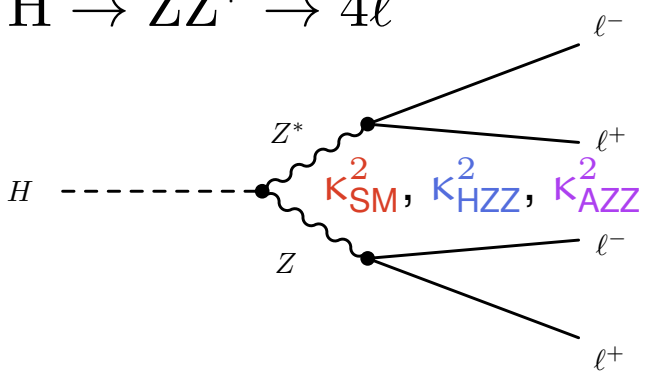
Production:




Decay:

$$H \to ZZ^* \to 4\ell$$



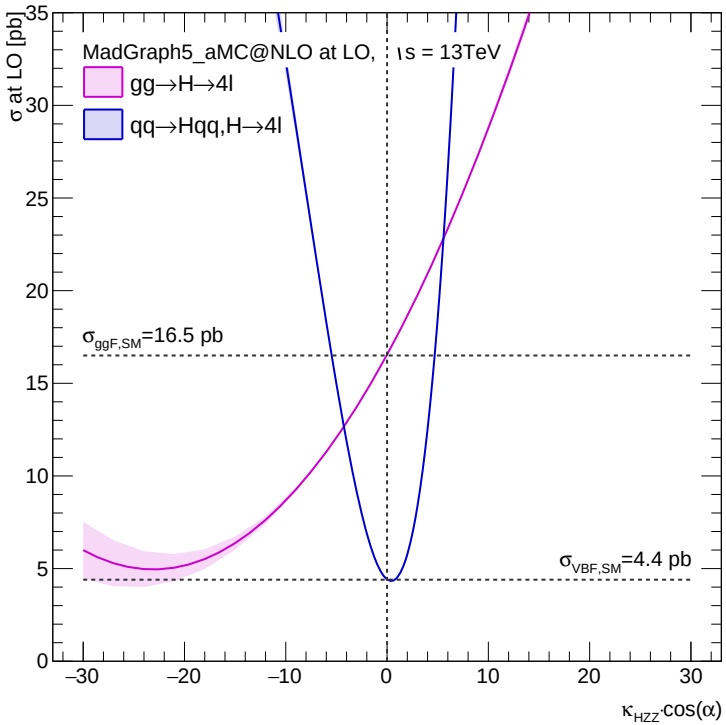

Dependence:

$$\sigma_{ggF} \propto \kappa^2_{XZZ}$$

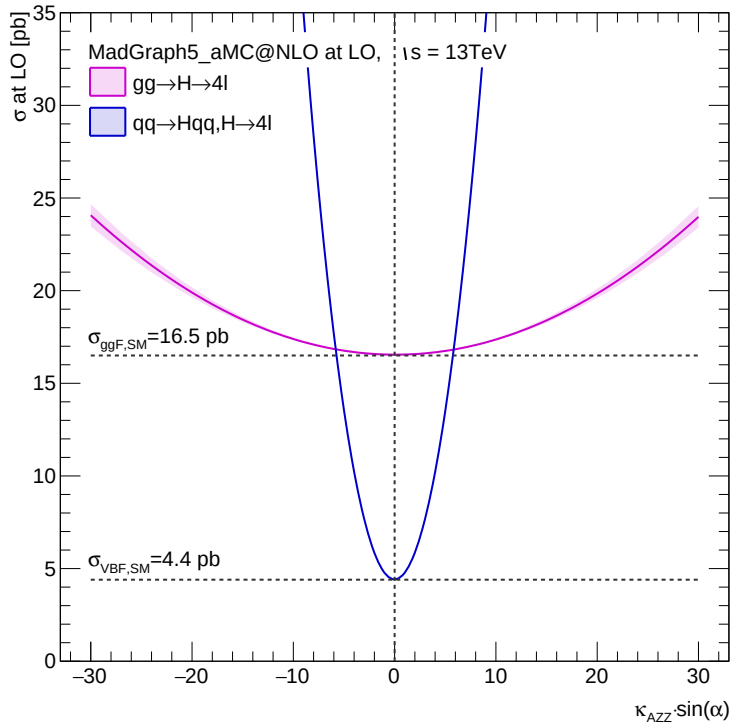
$$\sigma_{VBF} \propto \kappa^4_{XZZ}$$

# CP-sensitive observable: Total cross-section

## BSM CP-even



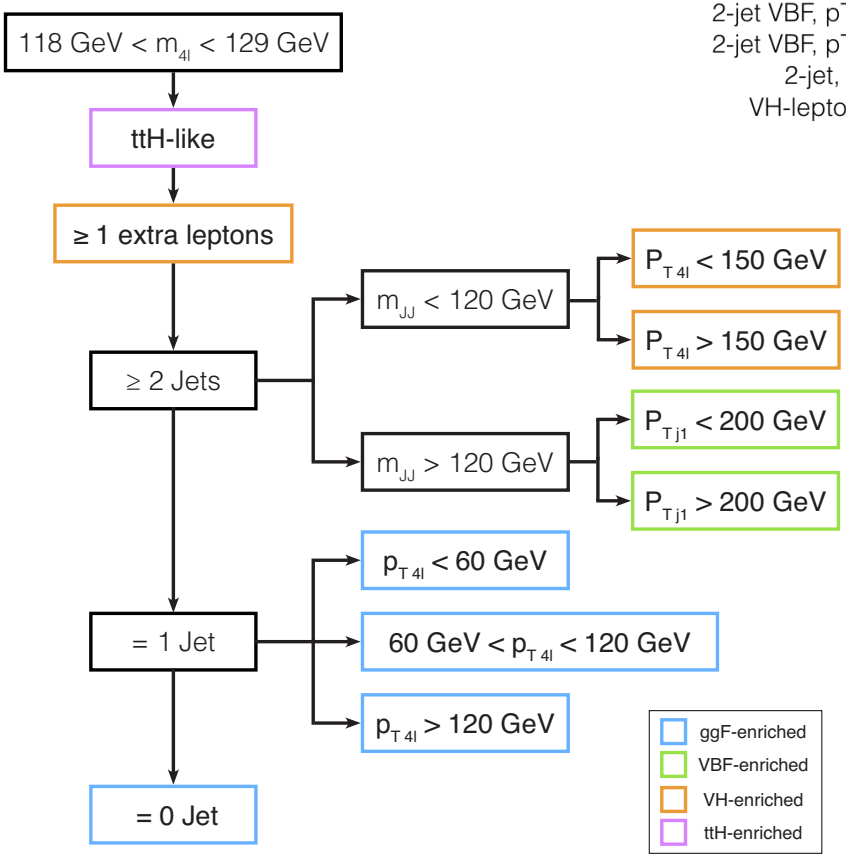

## BSM CP-odd

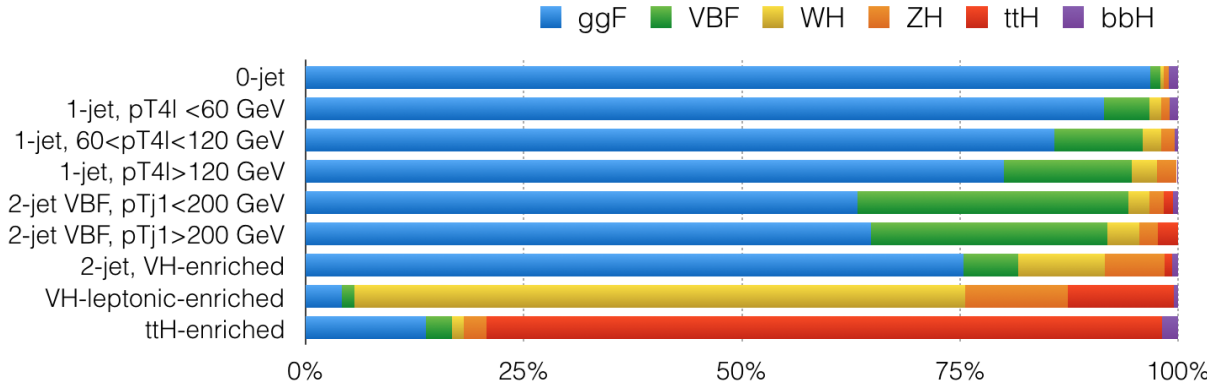



*Plots produced using MadGraph5_aMC@NLO standalone code.

# Event categorization: Entangling production modes

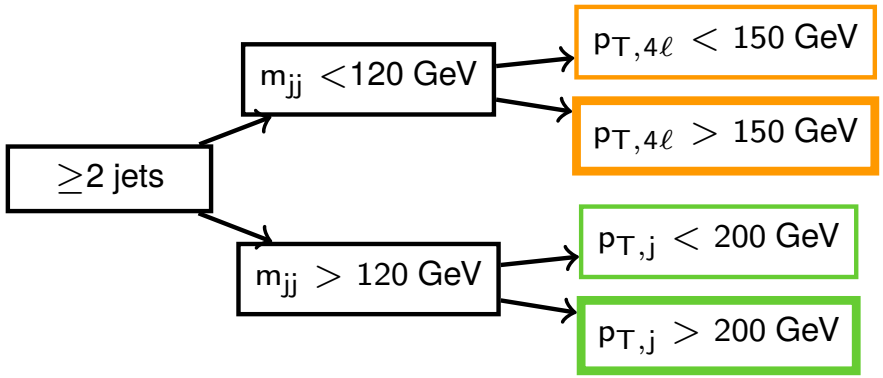
- Apply common H4l$\ell$ selection and categorize events in a mass range of $m_{4\ell} = [118, 129]$ GeV



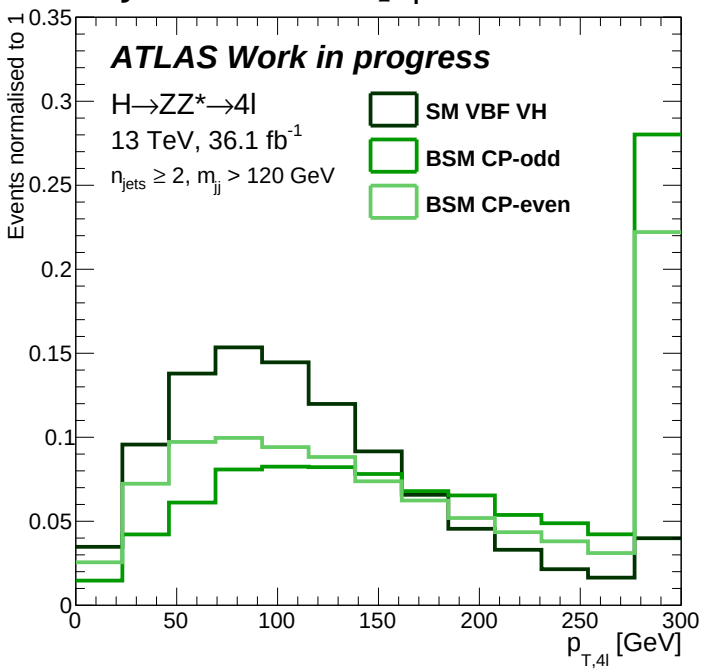



# Event categorization: Entangling SM from BSM

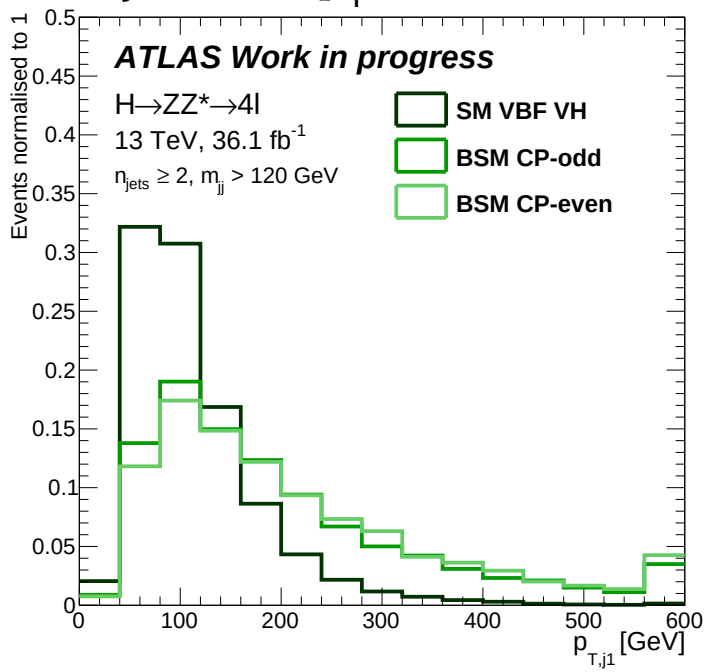
- Dedicated SM/BSM bins




2-jet, VHhad, $p_T^{4l} > 150$ GeV




2-jet, VBF, $p_T^{j1} > 200$ GeV



# Observable: Number of expected events for 36.1 fb$^{-1}$ run-2 data

- Cut and count in all categories

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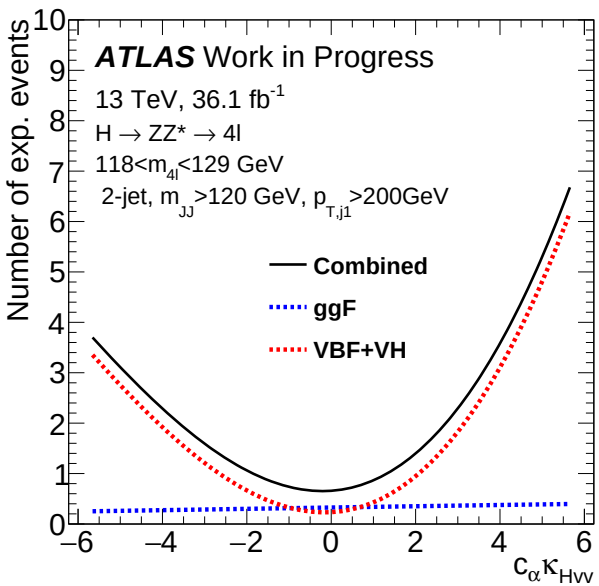
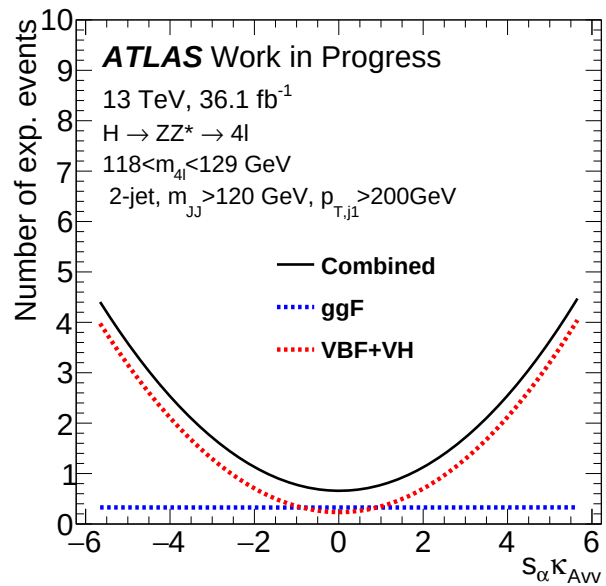
| Analysis category | Signal ggF+bbH+ttH | Signal VBF+VH | Background ZZ | Background Z+jets+tt, ttV+VVV | Total Expected |
|---|---|---|---|---|---|
| $m_{4\ell} \in$ [118,129] GeV | 47.1 | 6.1 | 19.2 | 3.7 | 76.2 |
| ttH | 0.4 | 0.0 | 0.0 | 0.1 | 0.4 |
| VH-leptonic | 0.1 | 0.3 | 0.1 | 0.0 | 0.4 |
| ggF enriched | 26.0 | 0.5 | 13.5 | 2.2 | 42.3 |
| 1-jet, $p_{T,H}$<60 GeV | 8.0 | 0.7 | 2.9 | 0.5 | 12.2 |
| 1-jet, $p_{T,H} \in$[60,120] GeV | 4.5 | 0.9 | 0.9 | 0.4 | 6.6 |
| 1-jet, $p_{T,H}$>120 GeV | 1.1 | 0.4 | 0.1 | 0.0 | 1.6 |
| VH-hadronic, $p_{T,H}$<150 GeV | 2.3 | 0.6 | 0.7 | 0.2 | 3.8 |
| VH-hadronic, $p_{T,H}$>150 GeV | 0.4 | 0.2 | 0.0 | 0.0 | 0.7 |
| VBF enriched, $p_{T,J1}$<200 GeV | 4.0 | 2.3 | 1.0 | 0.3 | 7.5 |
| VBF enriched, $p_{T,J1}$>200 GeV | 0.3 | 0.2 | 0.0 | 0.1 | 0.6 |

## BSM CP-even




## BSM CP-odd



# Statistical evaluation

- Parameters of interest $\kappa$ are extracted by a fit to the observed data simultaneously in all categories:

$$L(n_{\text{data}}|\kappa,\theta) = \prod_{c=1}^{N_{\text{cat}}=10} \text{Poisson}\left(n_c|\nu_c(\kappa)\right) \times A_c(\theta)$$

  with $n_c$ the number of observed and $\nu_c(\kappa)$ the number of predicted events in each category.
- Systematic uncertainties represented by nuisance parameters $\theta$ are constrained by auxiliary measurements $A$.
- Experimental and theoretical uncertainties covering lepton and jet uncertainties, as well as uncertainties on the total and differential cross-sections are added.
- Test statistic $t$ evaluated under asymptotic approximation in order to evaluate 68 % and 95 % CL limits:

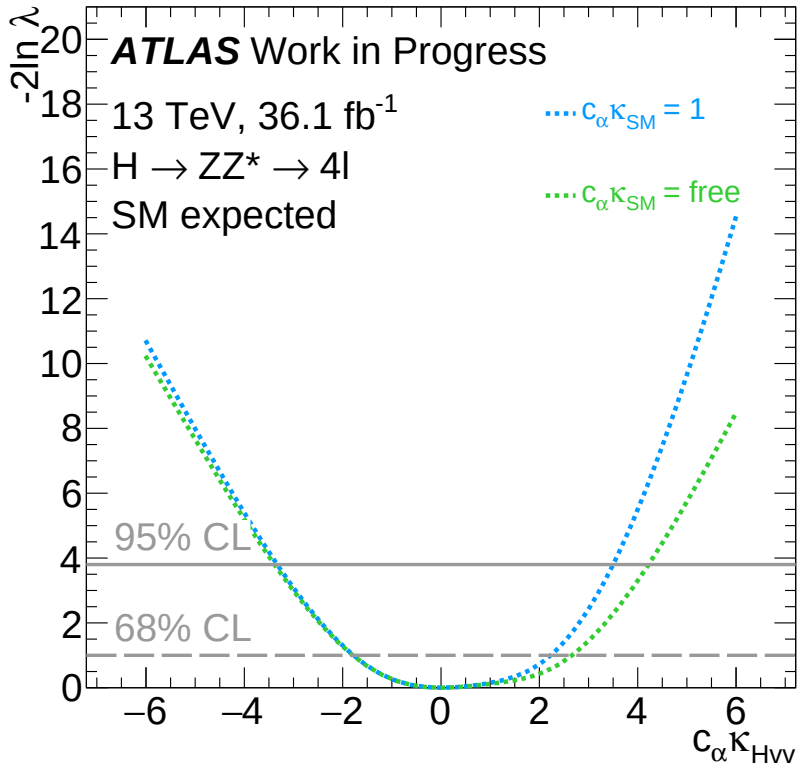
$$t = -2\ln\frac{L(\kappa,\hat{\hat{\theta}})}{L(\hat{\kappa},\hat{\theta})}$$

best-fit $\hat{\kappa},\hat{\theta}$

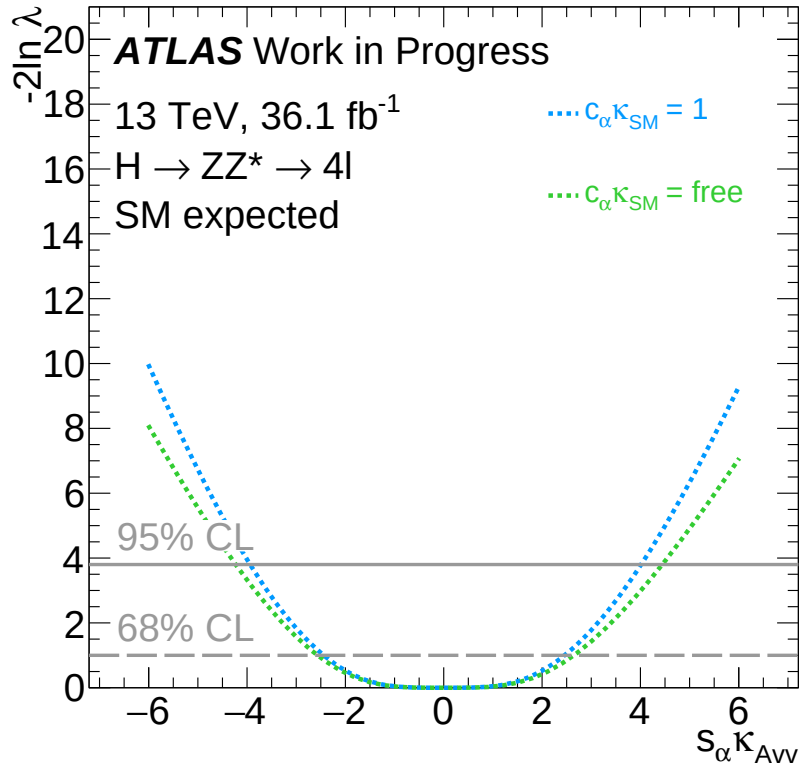
best-fit $\hat{\hat{\theta}}$ for fixed $\kappa$

# Expected limits on $c_\alpha \kappa_{\text{Hvv}}$ and $s_\alpha \kappa_{\text{Avv}}$ using 36.1 fb$^{-1}$

## BSM CP-even




## BSM CP-odd

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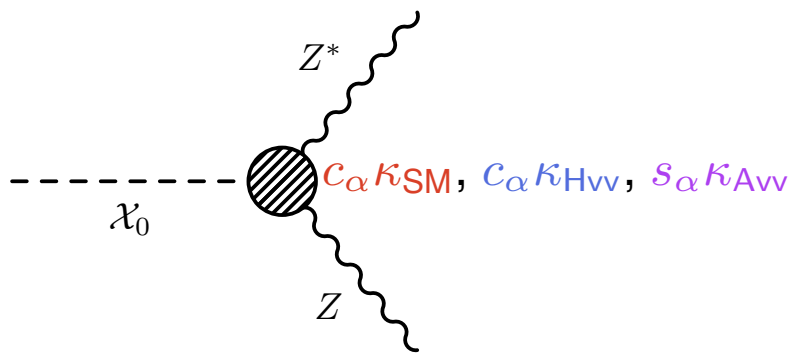
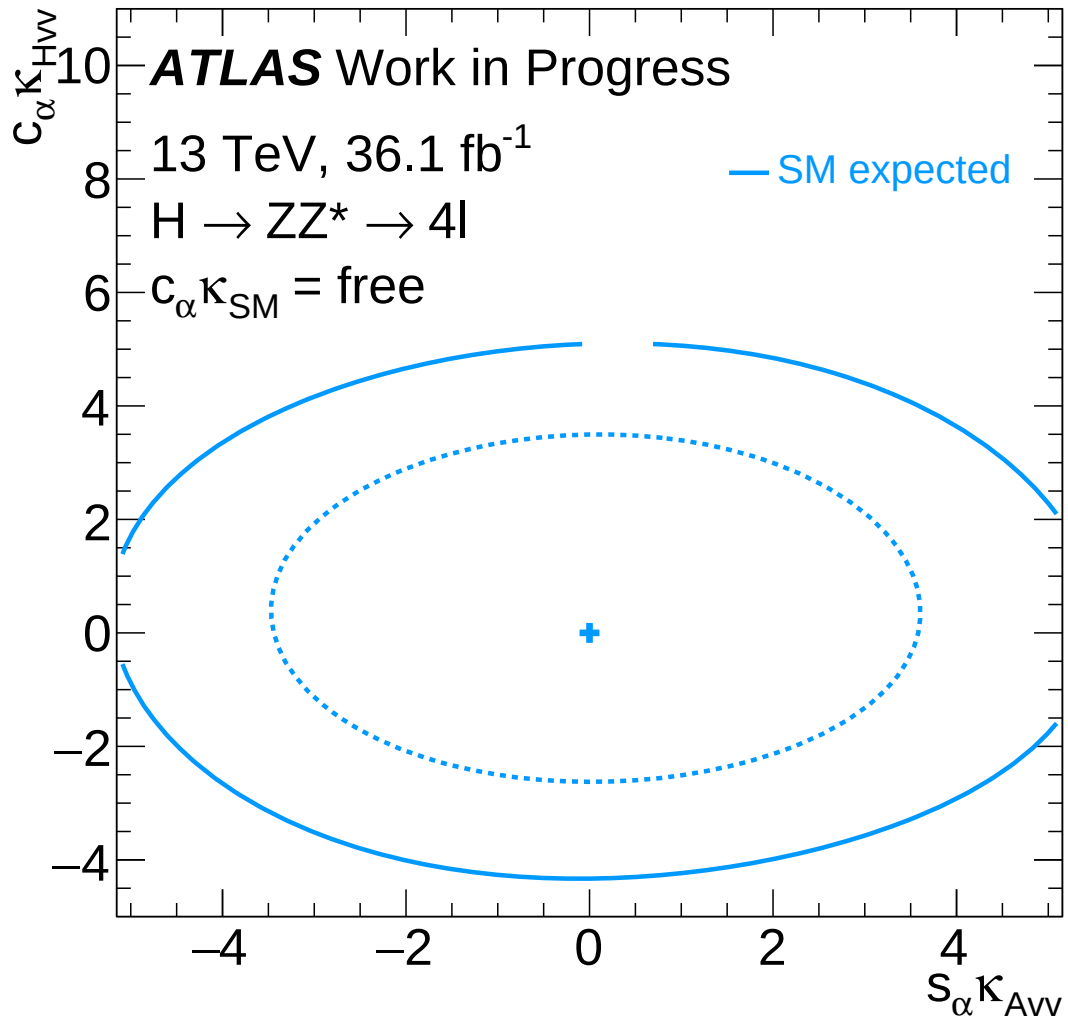
| $95\% CL$ | $c_\alpha \kappa_{\text{Hvv}}$ | $s_\alpha \kappa_{\text{Avv}}$ |
|---|---|---|
| $c_\alpha \kappa_{\text{SM}} = 1$ | $[-3.35, 3.51]$ | $[-3.95, 4.03]$ |
| $c_\alpha \kappa_{\text{SM}} =$ free | $[-3.41, 4.24]$ | $[-4.25, 4.47]$ |

# Multidimensional fit

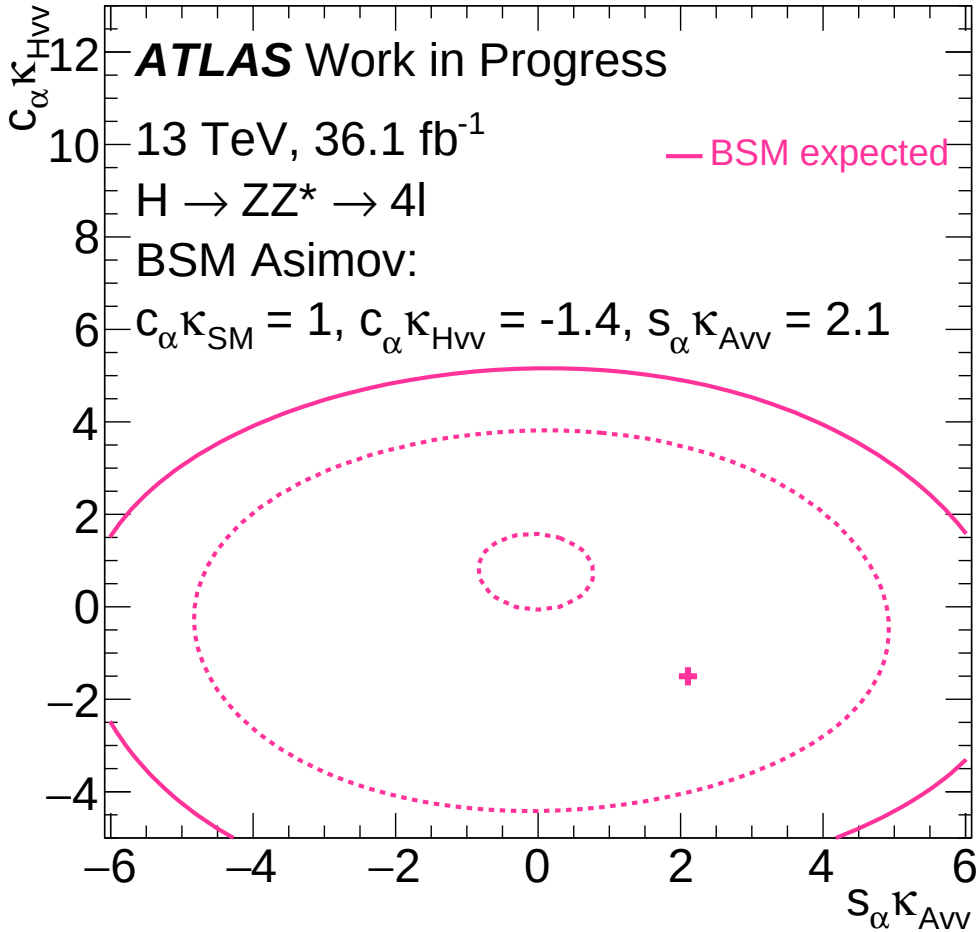
- So far, we assumed that any difference from the expected SM cross-section is coming from one BSM parameter
- ... but what if we consider variations from both BSM couplings and the SM coupling simultaneously?



# Expected multidimensional limit with free SM contribution using 36.1 $fb^{-1}$



# What if ... we had a BSM signal?

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| $s_\alpha \hat{\kappa}_{Avv}$ | $c_\alpha \hat{\kappa}_{Hvv}$ | $c_\alpha \hat{\kappa}_{SM}$ | $\sigma_{SM,excl}$ |
|---|---|---|---|
| $2.1$ | $-1.5$ | fixed | $1.0$ |

# Summary

- Probing BSM CP-even and BSM CP-odd couplings entering in the HVV vertex with the $H \to ZZ^* \to 4\ell$ decay channel
- Observable sensitive to the presence of BSM couplings is the total production rate
- Previous measurements: Run-1 (different method based on differential distributions only) and run-2 based on $14.8\text{fb}^{-1}$
- First run-2 measurement already exceeds run-1 limits by a factor $\sim$10 :

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| $95\% CL$ | $c_\alpha \kappa_{\text{Hvv}}$ | $s_\alpha \kappa_{\text{Avv}}$ | |
|---|---|---|---|
| $c_\alpha \kappa_{\text{SM}} = 1$ | $[0.9, 7.5]$ | $[-9.7, 11]$ | $14.8\text{fb}^{-1}$ (observed) |

- Expected 68 % and 95 % CL limits based on $36.1\text{fb}^{-1}$ run-2 data

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| $95\% CL$ | $c_\alpha \kappa_{\text{Hvv}}$ | $s_\alpha \kappa_{\text{Avv}}$ | |
|---|---|---|---|
| $c_\alpha \kappa_{\text{SM}} = 1$ | $[-6.3, 5.1]$ | $[-6.3, 6.5]$ | $14.8\text{fb}^{-1}$ (expected) |
| $c_\alpha \kappa_{\text{SM}} = 1$ | $[-3.35, 3.51]$ | $[-3.95, 4.03]$ | $36.1\text{fb}^{-1}$ (expected) |
| $c_\alpha \kappa_{\text{SM}} =$ free | $[-3.41, 4.24]$ | $[-4.25, 4.47]$ | $36.1\text{fb}^{-1}$ (expected) |