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

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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^+

$$|H_{BSM}\rangle = \cos(\alpha)|0^+\rangle + \sin(\alpha)|0^-\rangle$$

⇒ Additional, non-SM couplings in HVV vertex?

⇒ CP violation in the Higgs sector, possible explanation for baryon/antibaryon asymmetry

BSM analysis: Theoretical description

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

1. Probing CP-even and CP-odd BSM couplings in HVV vertex:

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

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

$\alpha =$ 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: $s_\alpha \kappa_{\mathrm{Avv}}$, $c_\alpha \kappa_{\mathrm{Hvv}}$, $c_\alpha \kappa_{\mathrm{SM}}$

2. Probing CP-odd BSM coupling in ggH vertex (Verena Walbrecht):

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

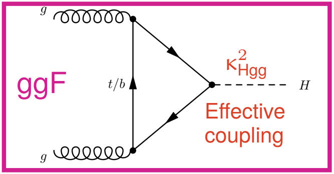
POI: $s_\alpha \kappa_{\mathrm{Agg}}$

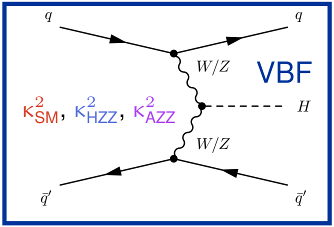
- Additional higher order BSM couplings not considered in analysis.

Measurement of the HZZ Tensor Coupling

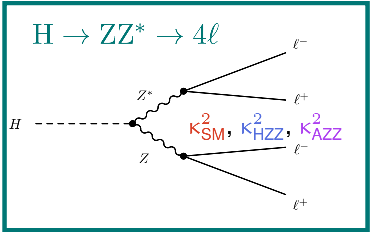
- Production and decay rates are dependent on the anomalous couplings

Production:





Decay:



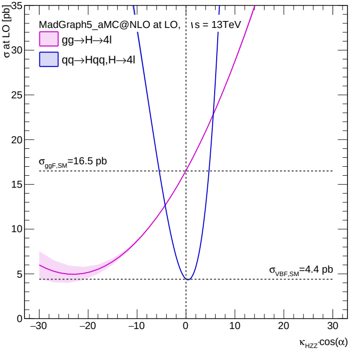
Dependence:

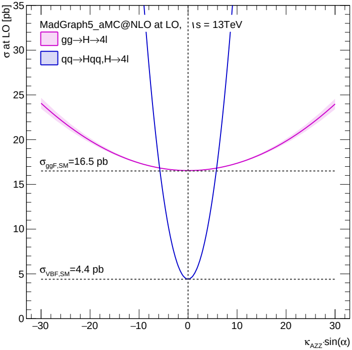
$$\sigma_{\mathrm{ggF}} \propto \kappa_{XZZ}^2$$

$$\sigma_{\mathrm{VBF}} \propto \kappa_{XZZ}^4$$

Production rate information sensitive to BSM contributions

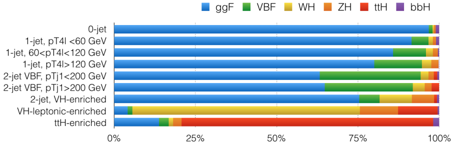
CP-sensitive observable: Total cross-section

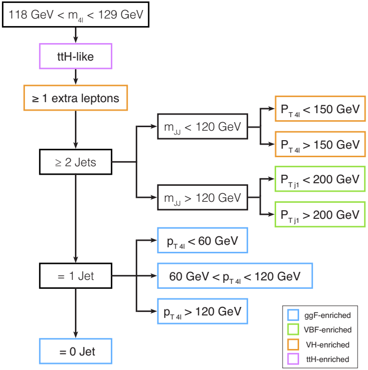




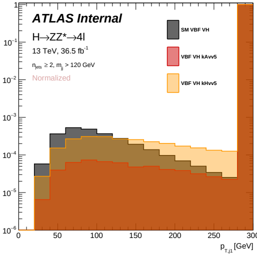
Analysis strategy: Event categorization

- Apply common H4ℓ selection and categorize events in a mass range of $m_{4\ell} = [118, 129]$ GeV
- Separate different production modes and SM from BSM





- Dedicated SM/BSM bins

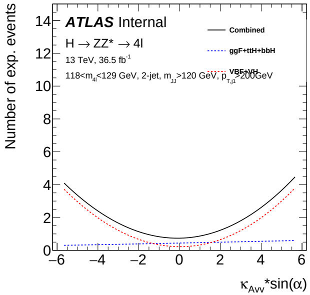


Analysis strategy: Discriminants

- Cut and count in all categories

Analysis category	Signal ggF+bbH+ttH	VBF+VH	Background ZZ	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, $p_{T,H}$ ∈[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

- Most sensitive categories: Large content of VBF+VH signals.



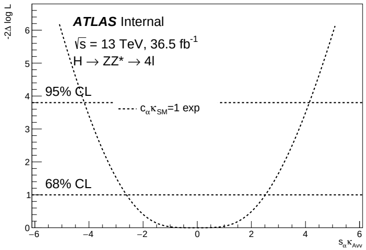
Statistical evaluation

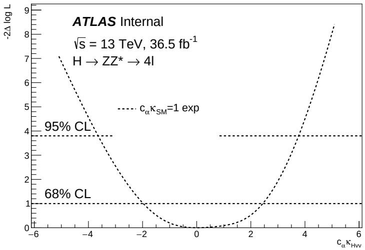
- The fit to the observed data is performed simultaneously in all categories.

$$\mathcal{L}(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}}) = \prod_{c=1}^{n_{\text{cat}}=10} \text{Poisson}\left(n_c | \nu_c(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}})\right) \mathcal{L}(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}})$$

  with n_c the number of observed and $\nu_c(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}})$ the number of predicted events in each category.
- 68 % and 95 % CL limits evaluated under asymptotic approximation.
- Experimental and theoretical uncertainties covering lepton and jet uncertainties, as well as uncertainties on the total and differential cross-sections are added.

1D scans – $c_\alpha \kappa_{\mathrm{SM}}$=1 fixed

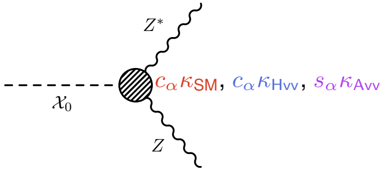




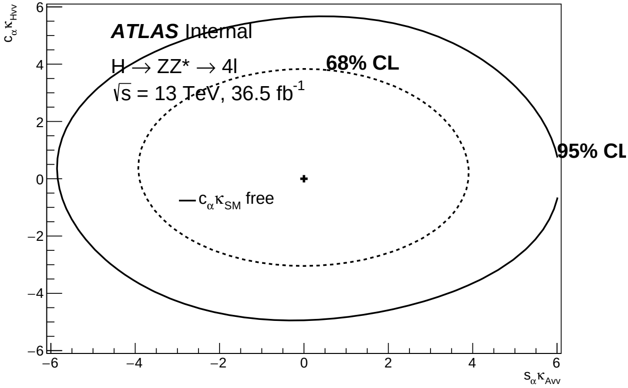
$s_\alpha \kappa_{\mathrm{Avv}}$		$c_\alpha \kappa_{\mathrm{Hvv}}$	
$68\% CL$	$95\% CL$	$68\% CL$	$95\% CL$
$[-2.5, 2.5]$	$[-4.1, 4.1]$	$[-1.8, 2.4]$	$[-3.4, 3.8]$

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?

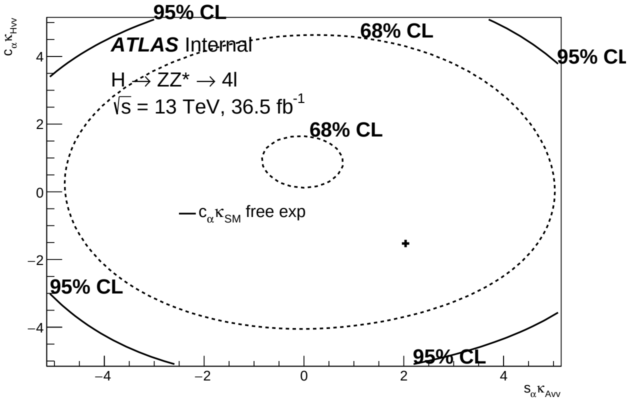


2D $s_\alpha \kappa_{\mathrm{Avv}}$ vs $c_\alpha \kappa_{\mathrm{Hvv}}$ – $c_\alpha \kappa_{\mathrm{SM}}$ free



What if ... we had a BSM signal?

- BSM signal injected with: κ_{Hvv} = -2 , κ_{Avv} = 3, $\kappa_{\text{SM}} = \sqrt{2}$ and $\cos(\alpha) = \frac{1}{\sqrt{2}}$



Summary

- Measurement of the HZZ tensor structure using the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel
- BSM CP-even $c_\alpha \kappa_{\text{Hvv}}$ and CP-odd $s_\alpha \kappa_{\text{Avv}}$ parameters are entering in the HVV vertex
- Expected 68 % and 95 % CL limits based on 36.1fb^{-1} run-2 data

$s_\alpha \kappa_{\text{Avv}}$		$c_\alpha \kappa_{\text{Hvv}}$	
$68\% CL$	$95\% CL$	$68\% CL$	$95\% CL$
$[-2.5, 2.5]$	$[-4.1, 4.1]$	$[-1.8, 2.4]$	$[-3.4, 3.8]$