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

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Properties of the Higgs boson

1. Spin-0: Boson is scalar particle, as predicted by the Standard Model (SM).

   ATLAS: Physics Letters B 726 (2013) 120–144

   and CMS: CMS PAS HIG-14-014

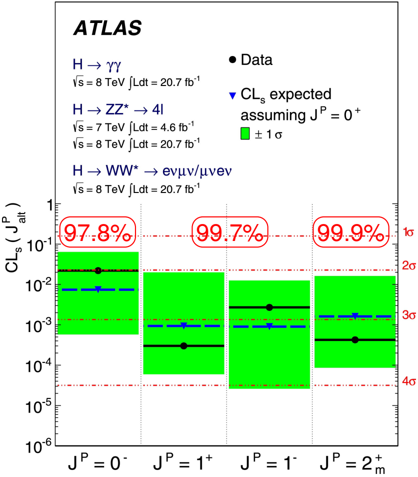
2. CP properties of the discovered boson?

   CP: Combination of parity and charge conjugation.

- CP even eigenstate CP^+? SM
- No CP eigenstate? Mixture of CP even and CP odd.

→ CP violation in Higgs sector could be explanation for matter antimatter asymmetrie.

Eur. Phys. J. C75 (2015) 476



- Additional, non-SM couplings in HVV vertex?

CP measurement in the $H \to ZZ^* \to 4\ell$ channel

- Theoretical basis: Effective field theory (EFT) implemented in Higgs characterisation model (arXiv:1306.6464).
- Effective Lagrangian for the interaction of scalar and pseudo-scalar states with vector bosons:

Done in Run 1

$$
\begin{aligned}
\mathcal{L}_0^V = & \Big\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W} (W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.) \right] \Big\} \mathcal{X}_0
\end{aligned}
$$

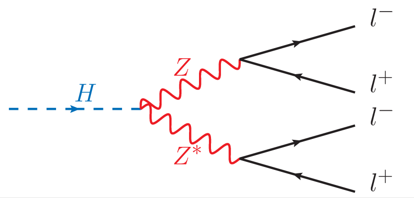
- CP violation: Mixture of CP even and CP odd.

⇒ Search for non-SM admixtures in $H \to ZZ^* \to 4\ell$ decays.

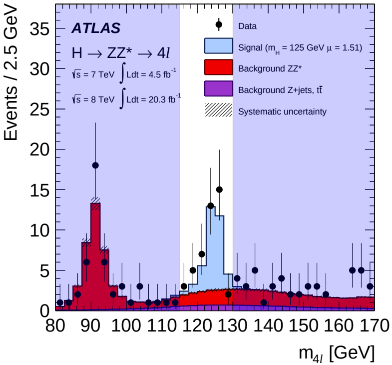
The $H \to ZZ^* \to 4\ell$ decay channel

- Small branching ratio, but clean signal.

Event signature $H \to ZZ^* \to 4\ell$ with $\ell = e, \mu$:

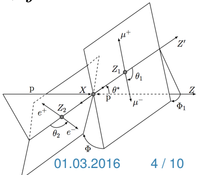


Phys. Rev. D 91, 012006 (2015)



- Backgrounds:
  1. Irreducible SM ZZ^*.
  2. Reducible $Z + jets$.

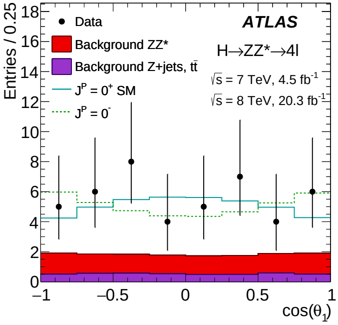
- Four final state leptons can be fully reconstructed by the detector: $\Rightarrow H \to ZZ^* \to 4\ell$ suited for property measurements.



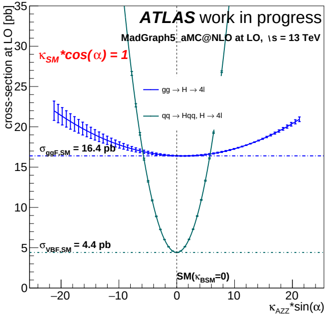
Observables sensitiv to BSM admixtures in $H \to ZZ^* \to 4\ell$

Shape information (used in Run-1)

Eur. Phys. J. C75 (2015) 476



Production rate information (planned to be added in Run-2):
$\sigma_{\text{ggF}} \propto \kappa^2_{\text{BSM}}$; $\sigma_{\text{VBF}} \propto \kappa^4_{\text{BSM}}$

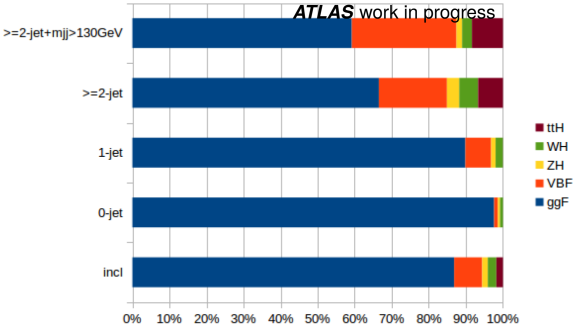


- $H \to ZZ^* \to 4\ell$ statistically limited: Which observables are available at the ATLAS expected dataset in 2016 - $\mathcal{L} \approx 30$ fb^{-1} at $\sqrt{s} = 13$ TeV?

Expected Yields for a SM Higgs boson with $m_H = 125$ GeV in $H \to ZZ^* \to 4\ell$ with $\mathcal{L} = 30\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

****Events exp. all production modes****

	all
1 - Full selection, full mass range	47
2 - $m_{4\ell}$: [115-130] GeV	44
3 - 0-jet	18
4 - 1-jet	15
5 - $>$=2-jet	10
6 - $>$=2-jet+mjj$>$130GeV	7



Fit model for high and low luminosities

1. High luminosity (100-300 fb^{-1}):
   - Expected number of events (in each bin of a discriminant kinematic distribution) can be predicted for any configuration of BSM parameters:

$$N_{\text{ggF}}^{\text{Bin i}} = f_{\text{ggF}}(\cos(\alpha), \kappa_{\text{Hgg}}, \kappa_{\text{Agg}}, \kappa_{\text{SM}}, \kappa_{\text{HZZ}}, \kappa_{\text{AZZ}}, \kappa_{\text{H}\gamma\gamma}, \kappa_{\text{A}\gamma\gamma}, \kappa_{\text{HZ}\gamma}, \kappa_{\text{AZ}\gamma}, \kappa_{\text{H}\partial\gamma}, \kappa_{\text{H}\partial\text{Z}})$$

$$N_{\text{VBF}}^{\text{Bin i}} = f_{\text{VBF}}(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{HZZ}}, \kappa_{\text{AZZ}}, \kappa_{\text{HWW}}, \kappa_{\text{AWW}}, \kappa_{\text{H}\gamma\gamma}, \kappa_{\text{A}\gamma\gamma}, \kappa_{\text{HZ}\gamma}, \kappa_{\text{AZ}\gamma}, \kappa_{\text{H}\partial\gamma}, \kappa_{\text{H}\partial\text{Z}}, \kappa_{\text{H}\partial\text{W}})$$

   - The predictions are obtained via analytic morphing procedure (see next slide).
   - The fit to the observed data is performed simultaneously in the 0-jet and the 2-jet category.

$$\mathcal{L}(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}}) = \prod_{c=1}^{n_{\text{cat}}=2} \prod_{i=1}^{n_{\text{bins}}} \text{Poisson}\left(n_i | \nu_i(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}})\right)$$

   with n_i the number of observed and $\nu_i(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{BSM}})$ the number of predicted events in each bin.

2. Simplifications for low luminosity ($\sim$30 fb^{-1})
   - Statistics too small for the study of kinematic distributions, thus fitting only the expected total rates of events (simultaneously for 0-jet and 2-jet categories).
   - Reducing the number of free BSM parameters in the fit, studying one parameter at a time.

Creating signal model with morphing method

- Model: Mixing of SM with one additional BSM operator; here: BSM CP-odd κ_{AZZ}.
- Morphing method (see talk by Carsten Burgard) utilized to create signal model for N_{ggF} and N_{VBF}.

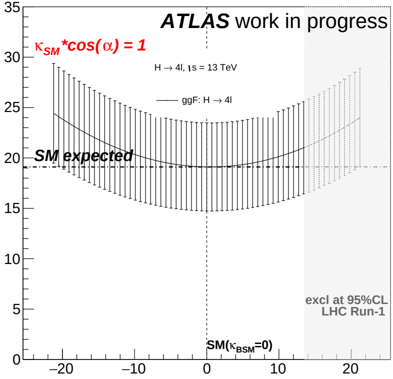
$$N_{\text{ggF}} = f_{\text{ggF}}(\cos(\alpha), \kappa_{\text{Hgg}}, \kappa_{\text{SM}}, \kappa_{\text{Azz}})$$
$$N_{\text{VBF}} = f_{\text{VBF}}(\cos(\alpha), \kappa_{\text{SM}}, \kappa_{\text{Azz}}, \kappa_{\text{Aww}})$$

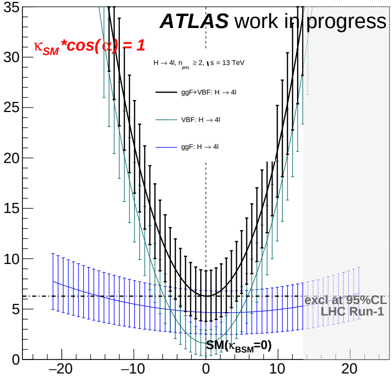
- Generator: MadGraph5 (at LO), interfaced to Pythia8 for showering.
- Assumption: For VBF production BSM CP-odd coupling to Z and W-Bosons is correlated

ggF	κ_{Hgg}	κ_{SM}	κ_{Azz}	$\cos\alpha$
hggsm	1.0	1.0	0.0	1.0
hggazz	$\sqrt{2}$	1.0	13.938	$\frac{1}{\sqrt{2}}$
hggsmazz	$\sqrt{2}$	$\sqrt{2}$	13.938	$\frac{1}{\sqrt{2}}$

VBF	κ_{SM}	$\kappa_{Azz} = \kappa_{Aww}$	$\cos\alpha$
sm	1.0	0.0	1.0
smkavvm1	1.0	-32.5203	0.447214
smkavv1	1.0	15.0	$\frac{1}{\sqrt{2}}$
smkavv2	1.0	5.0	$\frac{1}{\sqrt{2}}$
smkavvm2	1.0	-2.5	$\frac{1}{\sqrt{2}}$

Number of expected events of $H \to ZZ^* \to 4\ell$ decays in 0-jet and 2-jet categories for 30 fb^{-1} at $\sqrt{s} = 13$ TeV





Summary

- Tensor structure measurement has information available from shape and rate predictions
- Simplified model shown in order to extract BSM parameter in the $H \to ZZ^* \to 4\ell$ channel with an available dataset of $\mathcal{L} = 30\,\text{fb}^{-1}$
- Only rate information used so far and backgrounds neglected
- Plan: Use model in order to extract sensitivity to different BSM parameters in $H \to ZZ^* \to 4\ell$