Study of the Tensor Structure of Higgs Boson Couplings with the $H \rightarrow ZZ^{*} \rightarrow 4\ell$ Decay Channel with the ATLAS Detector

IMPRS Young Scientist Workshop at Ringberg Castle

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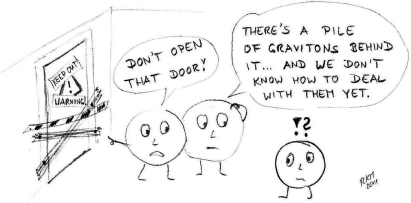
The Standard Model is not the End of the Story...

- Open questions:
  - General relativity
  - Neutrino oscillations
  - Nature of dark matter and dark energy
  - Matter - antimatter asymmetry



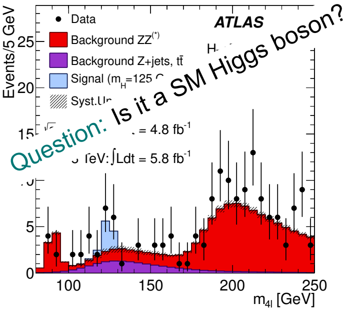
- Theories beyond the Standard Model:
  - Supersymmetry, string theory, M-theory and extra dimensions
- Experimental search for physics beyond the Standard Model in pp collisions:
  1. Direct searches: search for new particles (heavy resonances, SUSY particles, dark matter ...)
  2. Indirect searches: precise measurements of known particles of the SM - search for deviations from the prediction of the SM

     $\Rightarrow$ Search for anomalous Higgs boson couplings

The Higgs Boson in the Standard Model

- 2012: discovery of the Higgs boson
- SM prediction: scalar CP-even particle (J^P=0^+)

	CP-even scalar
Conjugation	
Spin: J	0
Charge: C	$+1$
Parity: P	$+1$
J^P	0^+
	SM Higgs boson

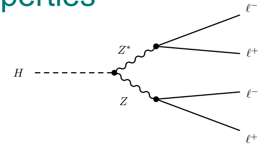


- Spin 0^+ hypotheses preferred by the Run I data

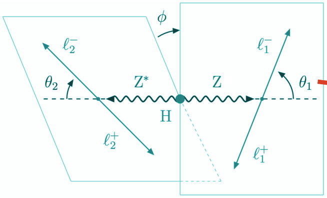
- But: small admixtures of 0^- state to 0^+ are still possible (Beyond SM):

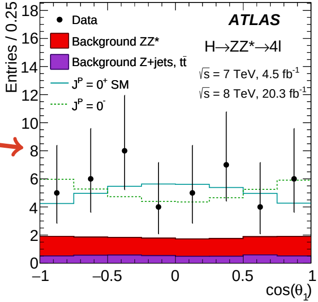
$$|H_{BSM}\rangle = \cos(\alpha)|0^+\rangle + \sin(\alpha)|0^-\rangle$$

Measurement of the Higgs Boson CP Properties



1. Decay Channel for CP properties measurement:
2. Observable to study CP properties:





$\Rightarrow$ Statistics very low: using event rates

3. Approach to account for BSM contributions: effective field theory

Measurement of Anomalous Couplings

- Effective field theory assumption:
  - Physics beyond the SM appears at energy scale $\Lambda \gg$ E

$\Rightarrow$ Point-like interaction can be assumed

SM CP-even

$$\mathcal{L}_0^V = \left\{ \underline{\kappa_{SM} \cos\alpha \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right]} \right.$$

$$- \frac{1}{4}\left[\underline{\kappa_{Hgg} \cos\alpha\, g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu}} \right]$$

$$\left.\right\} \mathcal{X}_0$$

Measurement of Anomalous Couplings

- Effective field theory assumption:
  - Physics beyond the SM appears at energy scale $\Lambda \gg E$

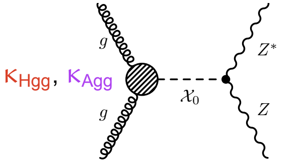
$\Rightarrow$ Point-like interaction can be assumed

SM CP-even

anomalous (BSM) CP-odd

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

1. non-SM coupling to gluons



Measurement of Anomalous Couplings

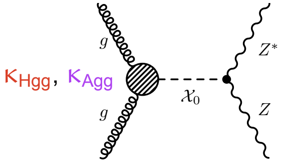
- Effective field theory assumption:
  - Physics beyond the SM appears at energy scale $\Lambda \gg$ E

$\Rightarrow$ Point-like interaction can be assumed

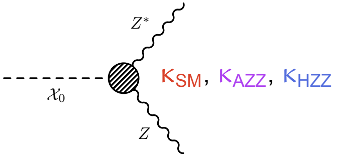
SM CP-even
anomalous (BSM) CP-even
anomalous (BSM) CP-odd

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

1. non-SM coupling to gluons



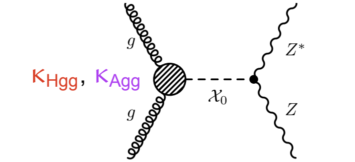
2. non-SM coupling to vector bosons



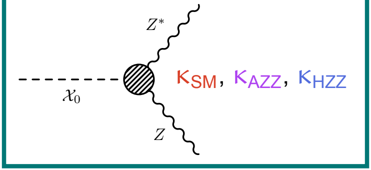
Analysis Strategy

- Too low statistics to use the information from angular distributions
  $\Rightarrow$ Event rates
- Approach: effective field theory
- Too low statistics to measure all predicted couplings simultaneously
  $\Rightarrow$ Test two different models with different assumptions:

1. non-SM coupling to gluons



2. non-SM coupling to vector bosons

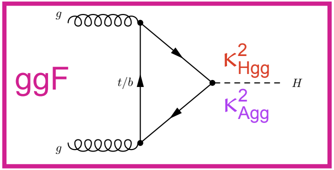


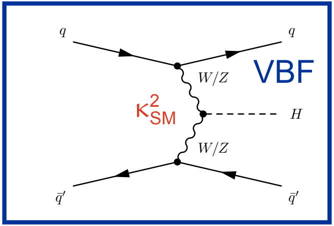
All other couplings are set to the SM value

1. Measurement of Hgg Tensor Coupling

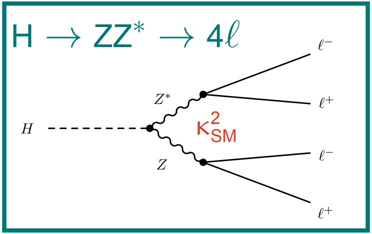
- Production and decay rates are dependent on the anomalous couplings:

Production:





Decay:



Dependence:

$$\boxed{\sigma_{ggF} \propto \kappa_{Agg}^2}$$

$$\boxed{\sigma_{VBF} = \text{const}}$$

Production rate information sensitive to BSM contributions

1. Measurement of Hgg Tensor Coupling

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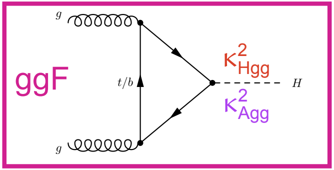
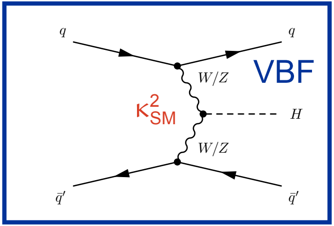
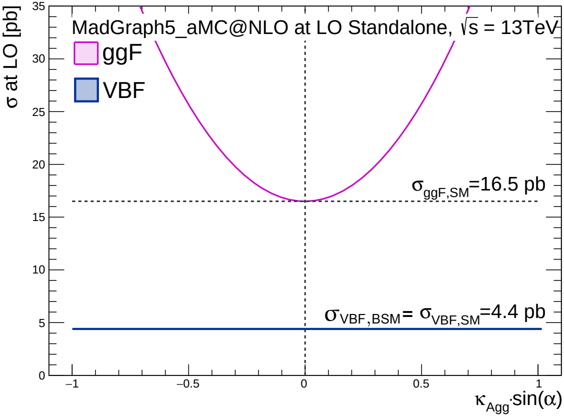
Production:





Dependence:



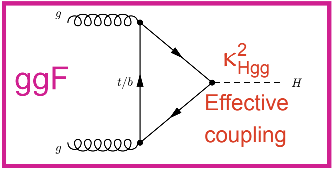
Production rate information sensitive to BSM contributions

2. Measurement of the HZZ Tensor Coupling

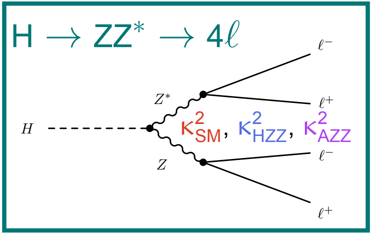
- Production and decay rates are dependent on the anomalous couplings:

Production:

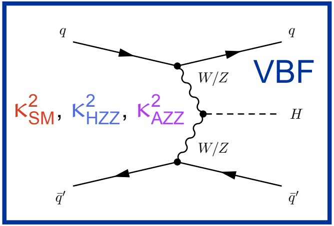
Dependence:



Decay:



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



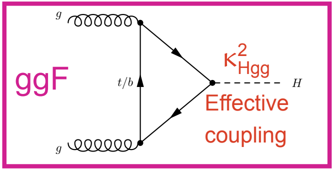
$\sigma_{VBF} \propto \kappa^4_{XZZ}$

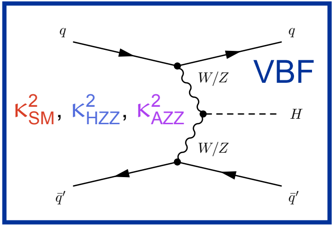
Production rate information sensitive to BSM contributions

2. Measurement of the HZZ Tensor Coupling

- Production and decay rates are dependent on the anomalous couplings:

Production:





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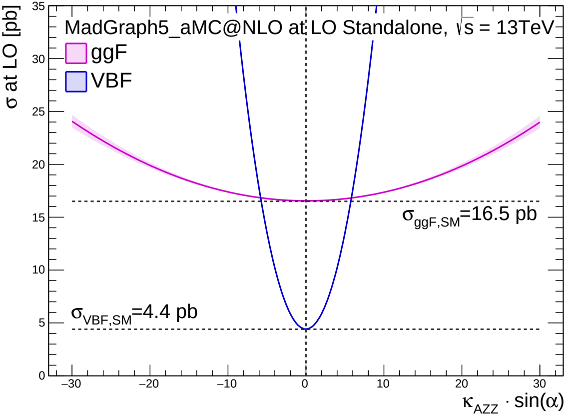
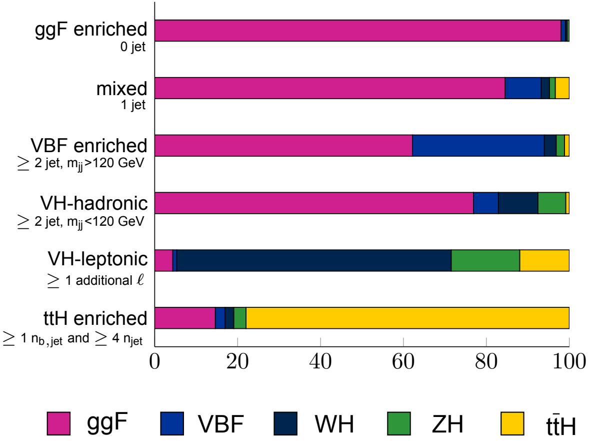
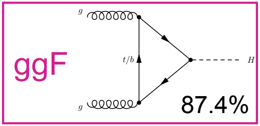


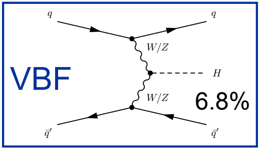
Production rate information sensitive to BSM contributions

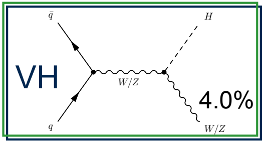
Event Categorisation

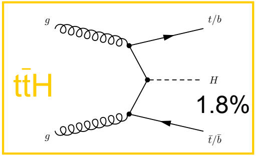
- Production mode splitting for the SM Higgs boson for $m_H = 125$ GeV:









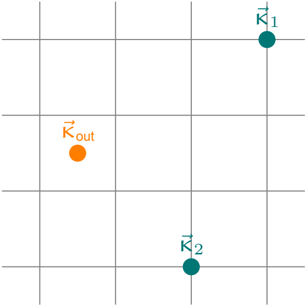


Signal Modelling

- Continuous signal model to describe signal expectation in dependence on BSM couplings $(\kappa_{Agg}, \kappa_{HZZ}, \kappa_{AZZ})$
- Predicts number of expected events at every parameter point based on a discrete set of simulated input samples

Output distribution　　weight　　Input distribution

$$N_{out}(\vec{\kappa}_{out}) = \sum_{i=1}^{N_{input}} w_i(\vec{\kappa}_{out}; \vec{\kappa}_i) \cdot N_i(\vec{\kappa}_i)$$



1. Hgg Tensor Coupling: $\vec{\kappa} = (\kappa_{Hgg}, \kappa_{Agg})$
2. HZZ Tensor Coupling: $\vec{\kappa} = (\kappa_{SM}, \kappa_{HZZ}, \kappa_{AZZ})$

Results of the Tensor Coupling Measurement

- Measuring BSM coupling parameter:
  Comparison of observed number of events in each category with the one predicted by signal model
- 118 GeV<$m_{4\ell}$<129 GeV (for SM Signal):

Event Category	ggF enriched	mixed	VH-hadronic	VBF enriched	VH-leptonic	ttH-enriched
Signal	26.80 ± 2.50	15.67 ± 1.33	3.54 ± 0.51	6.87 ± 0.81	0.32 ± 0.02	0.39 ± 0.04
ZZ^*	13.70 ± 1.00	4.12 ± 0.42	0.66 ± 0.16	1.17 ± 0.32	0.05 ± 0.01	0.01 ± 0.01
Z+jets,$t\bar{t}$	2.23 ± 0.31	0.96 ± 0.42	0.02 ± 0.02	0.45 ± 0.04	0.01 ± 0.00	0.07 ± 0.04
Expected	42.70 ± 2.70	20.85 ± 1.41	4.39 ± 0.51	8.42 ± 0.91	0.38 ± 0.02	0.47 ± 0.05
Observed	49	24	3	19	0	0

- Test statistic:

$$q = -2\ln\frac{L(\kappa)}{L(\hat{\kappa})} = -2\ln(\lambda)$$

- $L(\hat{\kappa})$: is the maximum of the likelihood

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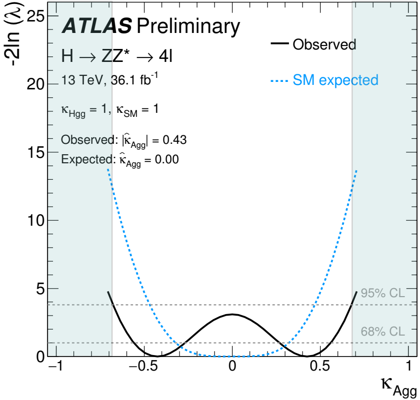
Results of the Hgg Tensor Coupling Measurement

- Expected and observed distributions of the test statistic q for fits of κ_{Agg}:

Regions excluded at 95% CL



$\kappa_{SM} \cdot \cos\alpha = 1$

$\kappa_{Hgg} \cdot \cos\alpha = 1$

BSM coupling parameter	Best fit	Allowed range at 95% confidence level (CL) expected for SM	observed
κ_{Agg}	$\pm$0.43	[-0.47,0.47]	[-0.68,0.68]

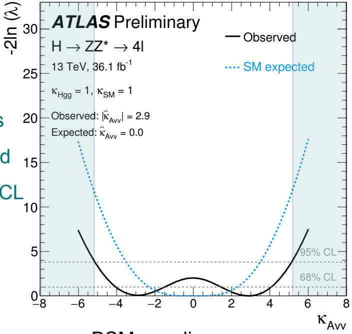
$\Rightarrow$ Compatible with the SM prediction within 1.8 standard deviations

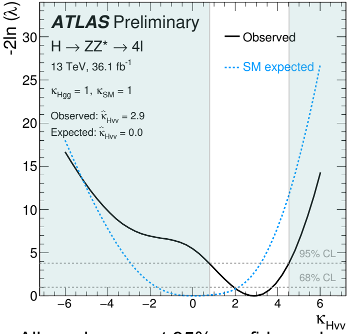
Results of the HZZ Tensor Coupling Measurement

- Expected and observed distributions of the test statistic q for fits of...

... κ_{AZZ} (κ_{HZZ}=0) ... κ_{HZZ} (κ_{AZZ}=0) $\kappa_{SM} \cdot \cos\alpha=1$

Regions excluded at 95% CL





BSM coupling parameter	Best fit	Allowed range at 95% confidence level (CL) expected for SM	observed
κ_{AZZ}	±2.9	[-3.5,3.5]	[-5.2,5.2]
κ_{HZZ}	2.9	[-2.9,3.2]	[0.8,4.5]

⇒ Compatible with the SM prediction within 1.4 and 2.3 standard deviations

Summary

- Measurement of the anomalous couplings :

– More events observed in each category then expected

– Too low statistic to observe a significant deviation from the SM predication

– Excluded regions at 95% confidence level:

1. non-SM coupling to gluons

$\kappa_{Agg} < -0.68$ and $\kappa_{Agg} > 0.68$

2. non-SM coupling to vector bosons

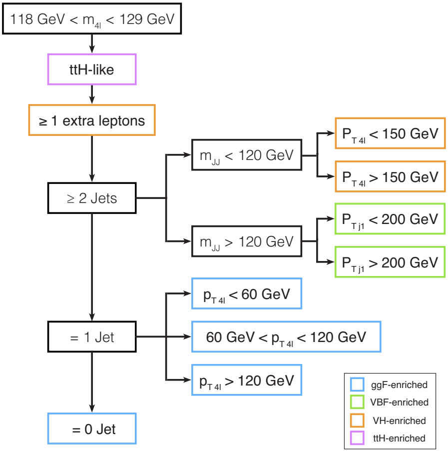
$\kappa_{AZZ} < -5.2$ and $\kappa_{AZZ} > 5.2$

$\kappa_{HZZ} < 0.8$ and $\kappa_{HZZ} > 4.5$

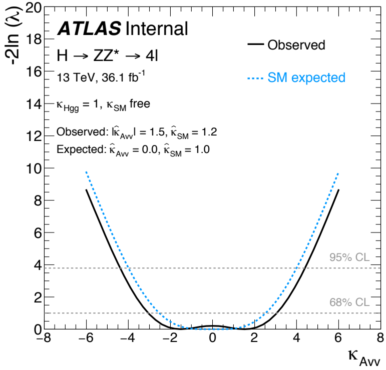
- Outlook: Combine event yield and angular distribution information

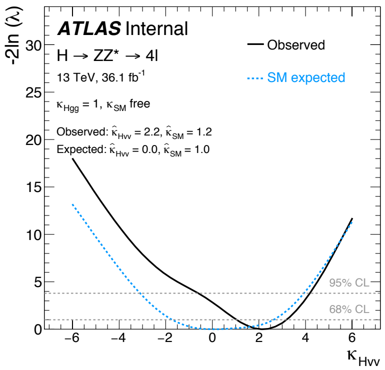
BACKUP

Full Categorization

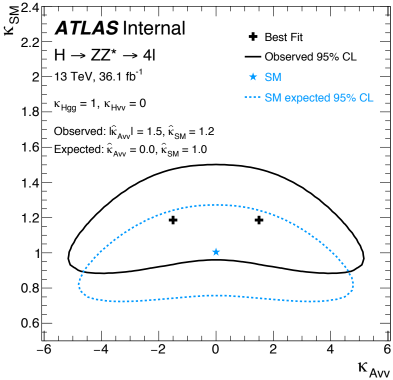


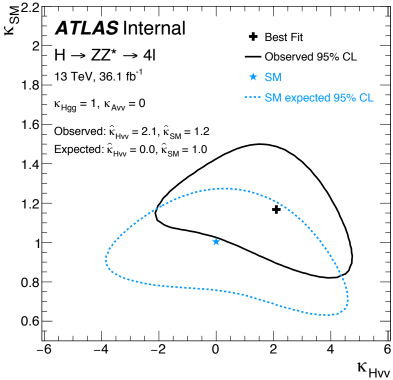
κ_{SM} free



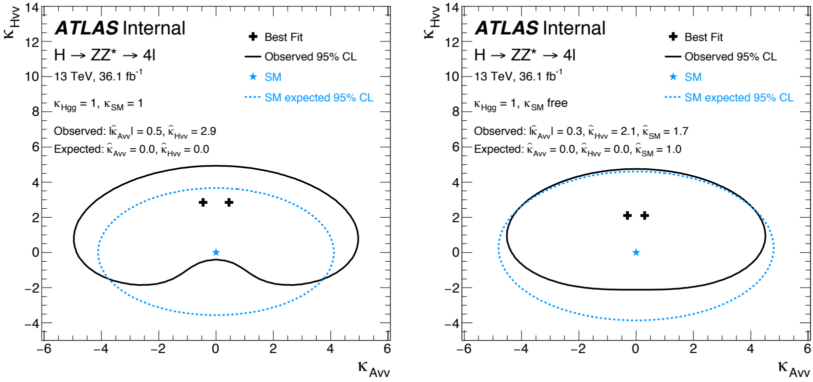


2D scans

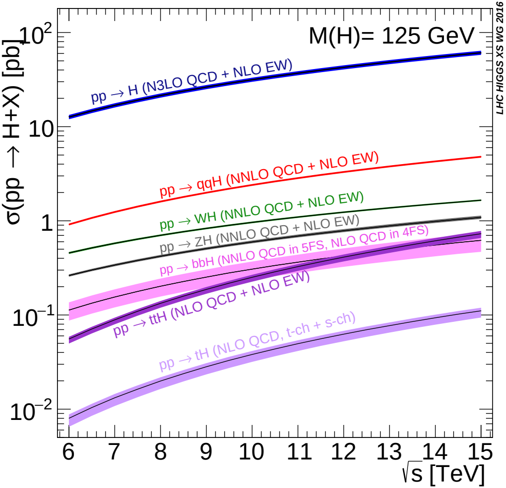

ATLAS Internal
H → ZZ* → 4l
13 TeV, 36.1 fb^{-1}
$\kappa_{Hgg} = 1$, $\kappa_{Hvv} = 0$
Observed: $|\hat{\kappa}_{Avv}| = 1.5$, $\hat{\kappa}_{SM} = 1.2$
Expected: $\hat{\kappa}_{Avv} = 0.0$, $\hat{\kappa}_{SM} = 1.0$
Best Fit
Observed 95% CL
SM
SM expected 95% CL
κ_{SM}
κ_{Avv}


ATLAS Internal
H → ZZ* → 4l
13 TeV, 36.1 fb^{-1}
$\kappa_{Hgg} = 1$, $\kappa_{Avv} = 0$
Observed: $\hat{\kappa}_{Hvv} = 2.1$, $\hat{\kappa}_{SM} = 1.2$
Expected: $\hat{\kappa}_{Hvv} = 0.0$, $\hat{\kappa}_{SM} = 1.0$
Best Fit
Observed 95% CL
SM
SM expected 95% CL
κ_{SM}
κ_{Hvv}

2D scans


ATLAS Internal
H → ZZ* → 4l
13 TeV, 36.1 fb^{-1}
$\kappa_{Hgg} = 1$, $\kappa_{SM} = 1$
Observed: $|\hat{\kappa}_{Avv}| = 0.5$, $\hat{\kappa}_{Hvv} = 2.9$
Expected: $\hat{\kappa}_{Avv} = 0.0$, $\hat{\kappa}_{Hvv} = 0.0$
Best Fit
Observed 95% CL
SM
SM expected 95% CL
κ_{Hvv}
κ_{Avv}
ATLAS Internal
H → ZZ* → 4l
13 TeV, 36.1 fb^{-1}
$\kappa_{Hgg} = 1$, κ_{SM} free
Observed: $|\hat{\kappa}_{Avv}| = 0.3$, $\hat{\kappa}_{Hvv} = 2.1$, $\hat{\kappa}_{SM} = 1.7$
Expected: $\hat{\kappa}_{Avv} = 0.0$, $\hat{\kappa}_{Hvv} = 0.0$, $\hat{\kappa}_{SM} = 1.0$
Best Fit
Observed 95% CL
SM
SM expected 95% CL
κ_{Hvv}
κ_{Avv}

SM Higgs Boson Production Cross Section



CP-Violation in the 2HDM

- Additional SU(2) doublet
  $\rightarrow$ two neutral scalars (h,H), a pseudoscalar (A), two charged (H$^{\pm}$)
- 2HDM potential:

$$V = \frac{1}{2}\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right)$$
$$+ \frac{1}{2}\left[\lambda_5\left(\phi_1^\dagger\phi_2\right)^2 + h.c.\right] + \left\{\left[\lambda_6\left(\phi_1^\dagger\phi_1\right)^2 + \lambda_7\left(\phi_2^\dagger\phi_2\right)^2\right]\left(\phi_1^\dagger\phi_2\right) + h.c.\right\}$$
$$- \left\{m_{11}^2\left(\phi_1^\dagger\phi_1\right) + \left[m_{12}^2\left(\phi_1^\dagger\phi_2\right) + h.c.\right] + m_{22}^2\left(\phi_2^\dagger\phi_2\right)\right\}$$

- no CP violation in the Higgs sector and no FCNC if:
  $\lambda_6 = \lambda_7 = m_{12}^2 = 0$ (Z_2 Symmetry)

CP-Violation in the 2HDM

- Simplest case of CP violation in the Higgs sector:
  $\lambda_6 = \lambda_7 = 0$ and $m_{12}^2 \neq 0$
- Parametrization of the minimum of the potential:

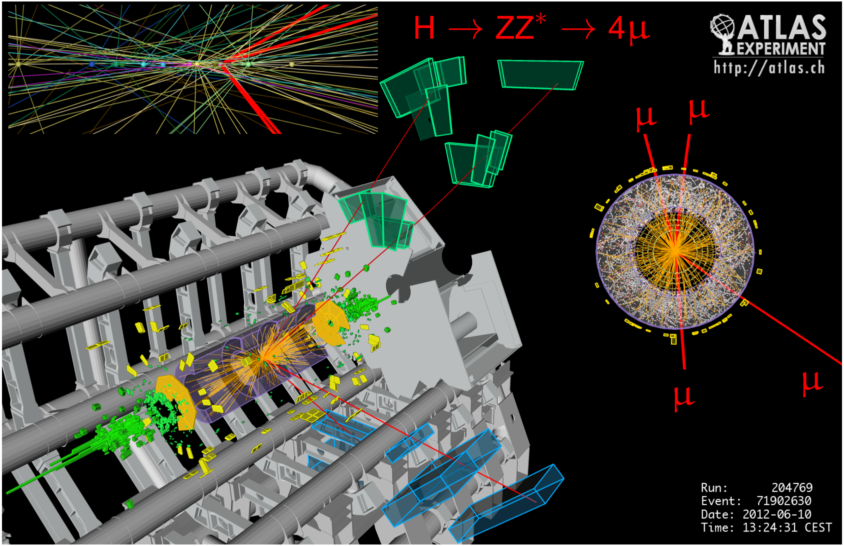
$$\phi_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 e^{i\xi} \end{pmatrix}$$

- Relation: $\mathrm{Im}\left(m_{12}^2 e^{i\xi}\right) = \mathrm{Im}\left(\lambda_5 e^{2i\xi}\right) v_1 v_2$
  rephasing invariance $\Rightarrow \xi = 0$
- Mass squared matrix of the neutral sector:

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 & -\frac{1}{2}\mathrm{Im}\lambda_5 v^2 \sin\beta \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 & -\frac{1}{2}\mathrm{Im}\lambda_5 v^2 \cos\beta \\ -\frac{1}{2}\mathrm{Im}\lambda_5 v^2 \sin\beta & -\frac{1}{2}\mathrm{Im}\lambda_5 v^2 \cos\beta & \mathcal{M}_{33}^2 \end{pmatrix}$$

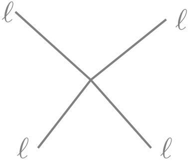
- $\lambda_5 \neq 0$: three neutral Higgs state mix $\Rightarrow$ CP-violation

Backup


$H \rightarrow ZZ^* \rightarrow 4\mu$
ATLAS EXPERIMENT
http://atlas.ch
μ
μ
μ
μ
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

$H \rightarrow ZZ^* \rightarrow 4\ell$ Event Selection

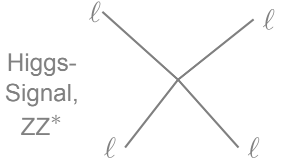
Higgs-Signal, ZZ^*

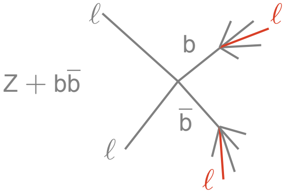


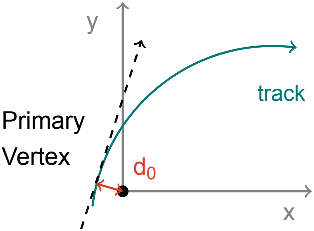
- 2 pairs opposite electric charge, same flavour
- Cut on invariant masses:
  - Leading lepton pair: 50 GeV < m_{12} < 106 GeV
  - Off-shell Z: $m_{threshold}$ < m_{34} < 115 GeV

$H \rightarrow ZZ^* \rightarrow 4\ell$ Event Selection

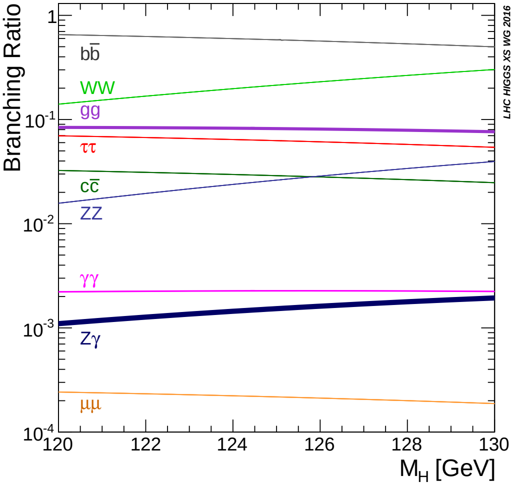
- 2 pairs opposite electric charge, same flavour
- Cut on invariant masses:
  - Leading lepton pair: 50 GeV < m_{12} < 106 GeV
  - Off-shell Z: $m_{\text{threshold}} < m_{34}$ < 115 GeV
- Muon (electron) isolation:
  - Track-based isolation: $I^{\text{track}}_{\mu(e)} = \left(\sum p_T^{\text{track}}\right)/p_T^{\ell}(E_T^{\ell}) < 0.15\ (0.15)$
  - Calorimeter-based isolation: $I^{\text{calo}}_{\mu(e)} = \left(\sum E_T^{\text{cluster}}\right)/p_T^{\ell}(E_T^{\ell}) < 0.30\ (0.20)$
- d_0-significance:
  - Muons: $|d_0/\sigma_{d_0}| < 3.0$
  - Electrons: $|d_0/\sigma_{d_0}| < 5.0$







Branching Ratios of the SM Higgs Boson



pp Collision Data Recorded with the ATLAS Detector

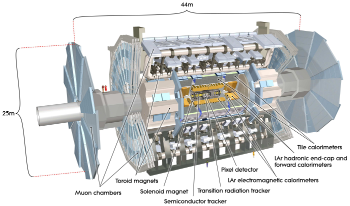
- Number of expected pp collisions:

$$N_{exp} = \mathcal{L} \cdot \sigma = \int dt\, \mathscr{L} \cdot \sigma$$

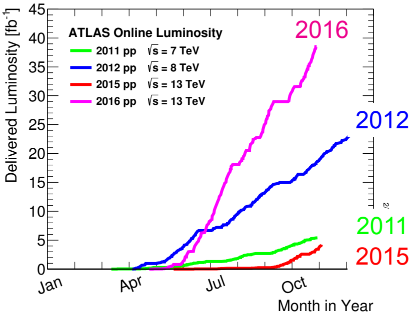
$$\mathscr{L} \propto n_b \cdot N_b^2 \cdot f_{rev}$$

- Run I (2011+2012):
  - $\sqrt{s}$ = 7 TeV: $\mathcal{L}$= 4.6 fb^{-1}
  - $\sqrt{s}$ = 8 TeV: $\mathcal{L}$= 20.7 fb^{-1}
- Run II (since 2015):
  - $\sqrt{s}$ = 13 TeV: $\mathcal{L}$= 36.1 fb^{-1}
- This study:

  Run II pp collision data $\mathcal{L}$= 36.1 fb^{-1}

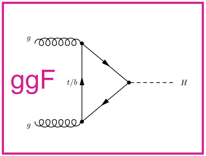


- Delivered luminosity:

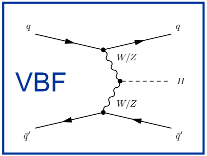


Production and Decay of the SM Higgs Boson at the LHC

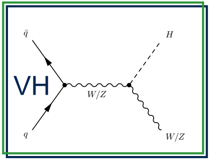
- Production of the SM Higgs boson with a mass of 125 GeV at $\sqrt{s}$=13 TeV:



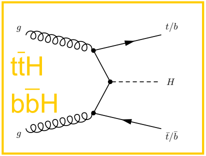
87.4%



6.8%



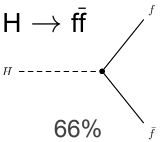
4.0%



1.8%

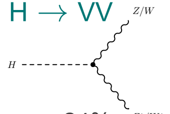
- Decay of the SM Higgs boson:

$H \rightarrow f\bar{f}$



66%

$H \rightarrow VV$

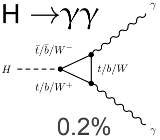


24%

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

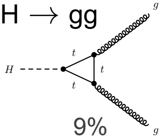
0.0124%

$H \rightarrow \gamma\gamma$



0.2%

$H \rightarrow gg$



9%

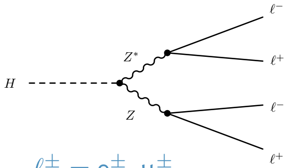
Full Event Selection

Table: Event selection criteria applied in the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis [?].

	Lepton Requirements
Electrons	$E_T > 7$ GeV and $\|\eta\| < 2.47$ $z_0 \cdot \sin(\theta) < 5$ mm
Muons	$p_T > 5$ GeV and $\|\eta\| < 2.7$ $p_T > 15$ GeV and $\|\eta\| < 0.1$ (CT muons) $z_0 \cdot \sin(\theta) < 5$ mm $\|d_0\| < 1$ mm
	Event selection
Higgs Boson Candidate	Two lepton pairs of same-flavour and opposite-charge $p_T > 20, 15, 10$ GeV for the three highest-p_T leptons $\Delta R(\ell, \ell') > 0.10\ (0.20)$ for same- (different-) flavour leptons $m_{\ell\ell} > 5$ GeV for same-flavour opposite-charge di-lepton pairs 50 GeV $< m_{12} < 106$ GeV $m_{\text{threshold}} < m_{12} < 115$ GeV
Lepton Isolation	Muon track isolation ($\Delta R \leq 0.3$): $I_\mu^{track} < 0.15$ Muon calorimeter isolation ($\Delta R = 0.2$): $I_\mu^{calo} < 0.30$ Electron track isolation ($\Delta R \leq 0.2$): $I_e^{track} < 0.15$ Electron calorimeter isolation ($\Delta R = 0.2$): $I_e^{calo} < 0.20$ $\|d_0/\sigma_{d_0}\| < 3(5)$ for muons (electrons)
Vertex Selection	$\chi^2/N_{\text{dof}} < 6$ for 4μ candidates $\chi^2/N_{\text{dof}} < 9$ for $2e2\mu$, $2\mu2e$, $4e$ candidates

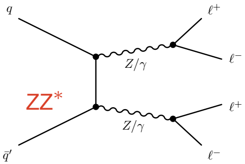
The H $\rightarrow$ ZZ $\rightarrow$ 4ℓ Decay Channel

- Signal:



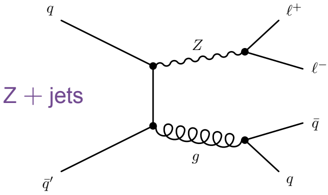
$\ell^\pm = \mathrm{e}^\pm, \mu^\pm$

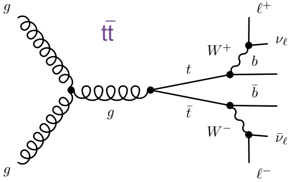
- Irreducible background:



Estimated with Monte Carlo Simulation

- Reducible background: at least one lepton originates from a gluon or jet



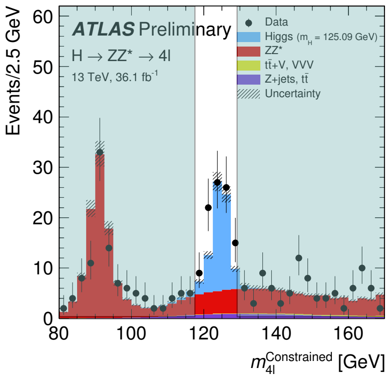


Data driven estimation

Results of the Event Selection

- Invariant mass spectrum after event selection:
- Good agreement between data and simulation
- Observed and expected number of events in $118\ \text{GeV} < m_{4\ell} < 129\ \text{GeV}$:

Signal	54.0	$\pm$ 4
ZZ^*	19.7	$\pm$ 1.5
Z+jets, $t\bar{t}$	3.9	$\pm$ 0.5
Total Expected	77.0	$\pm$ 4
Total Observed	95	



CP measurements in the H $\rightarrow ZZ^* \rightarrow 4\ell$ channel

- Effective field theory (EFT) implemented in the so called Higgs characterisation model (arXiv:1306.6464)

Bosons

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

Fermions

$$
\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar{\psi}_f \left(c_\alpha \kappa_{Hff} g_{Hff} + i \sin(\alpha) \kappa_{Aff} g_{Aff} \gamma_5\right) \psi_f \mathcal{X}_0
$$

Done in Run 1

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

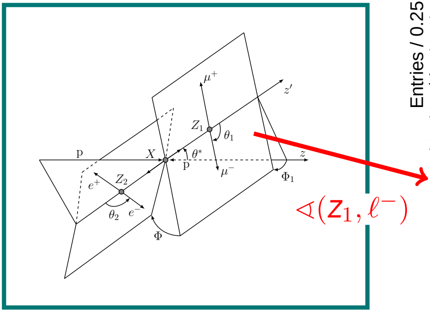
$c_\alpha = \cos(\alpha)$

$s_\alpha = \sin(\alpha)$

- CP violation: Mixture of CP even and CP odd

Measurement of the HVV Tensor Coupling

- CP-sensitive kinematic discriminants in the decay system :



m_{12}, m_{34}, $\cos(\theta_1)$, $\cos(\theta_2)$, ϕ, ϕ_1, θ^*

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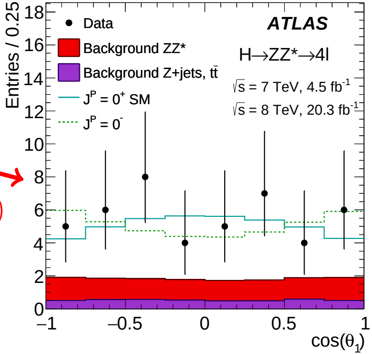


Information from kinematic distributions (used in Run-1)

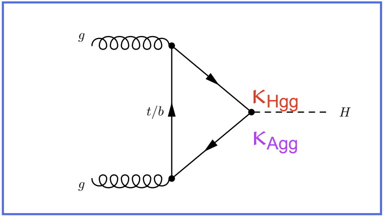
Signal Modelling via Morphing Method

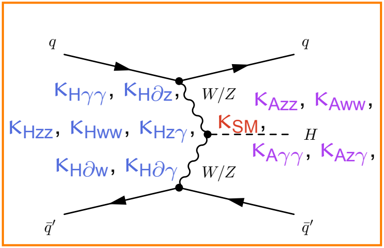
- Number of input samples T_i is dependent on the number of couplings one wants to model

$$
\begin{aligned}
\mathrm{N} = \; & \frac{\mathrm{n_p}\left(\mathrm{n_p}+1\right)}{2} \cdot \frac{\mathrm{n_d}\left(\mathrm{n_d}+1\right)}{2} + \binom{4+\mathrm{n_s}-1}{4} + \left(\mathrm{n_p}\cdot\mathrm{n_s} + \frac{\mathrm{n_s}\left(\mathrm{n_s}+1\right)}{2}\right) \\
& \cdot \frac{\mathrm{n_d}\left(\mathrm{n_d}+1\right)}{2} + \left(\mathrm{n_d}\cdot\mathrm{n_s} + \frac{\mathrm{n_s}\left(\mathrm{n_s}+1\right)}{2}\right) \cdot \frac{\mathrm{n_p}\left(\mathrm{n_p}+1\right)}{2} \\
& + \frac{\mathrm{n_s}\left(\mathrm{n_s}+1\right)}{2} \cdot \mathrm{n_p} \cdot \mathrm{n_d} + \left(\mathrm{n_p}+\mathrm{n_d}\right)\binom{3+\mathrm{n_s}-1}{3}
\end{aligned}
$$

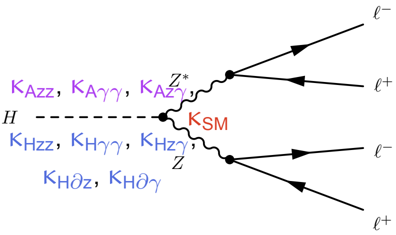
Relevant couplings in ggF/VBF production in H4ℓ channel

Production: ggF,VBF





Decay: $H \to 4\ell$



Signal Modelling via Morphing Method

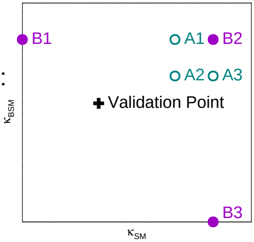
- Statistical uncertainty of output distribution:

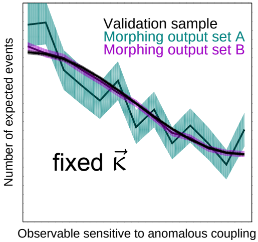
$$\Delta T_{\mathrm{out}}^{\mathrm{bin}} = \sqrt{\sum_i w_i\left(\vec{\kappa}_{\mathrm{out}};\vec{\kappa}_i\right) N_{\mathrm{MC},i}^{\mathrm{bin}}\left(\vec{\kappa}_i\right)\cdot\left(\frac{\sigma_i\left(\vec{\kappa}_i\right)\mathcal{L}}{N_{\mathrm{MC},i}\left(\vec{\kappa}_i\right)}\right)^2}$$

Set of input samples:

○ A1, ○ A2,○ A3

● B1, ● B2,● B3

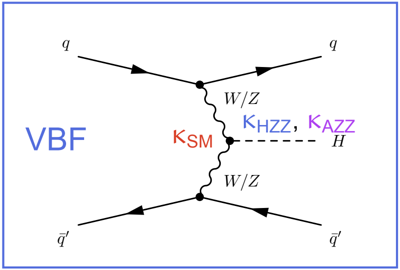


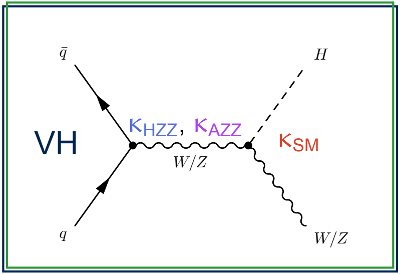


- Different choice of input samples ⇒ different statistical uncertainties
- In addition, require that predicted value of the observable agrees with validation value

Set of Input Samples for Modelling VBF and VH production

- VBF and VH production have the same coupling structure:

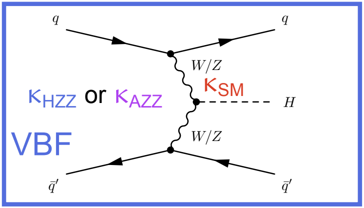


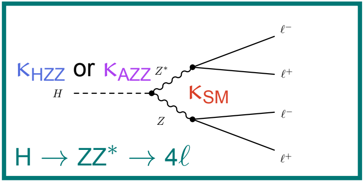


$\Rightarrow$ VBF and VH production are combined

- Assumption: $\kappa_{XZZ} = \kappa_{XWW}$, where X = H,A
- Separate model for κ_{AZZ} and κ_{HZZ}

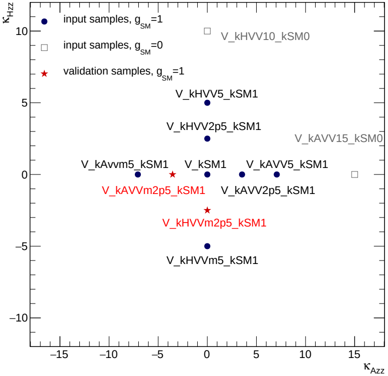
Set of Input Samples for Modelling VBF and VH production



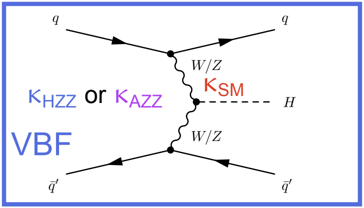


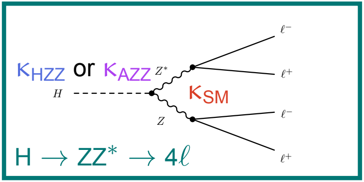
Production mode	n_p	n_d	n_s	N
VBF+VH	0	0	2	5

Input samples in κ_{AZZ}-κ_{HZZ} plane:



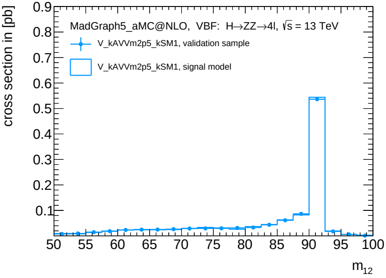
Set of Input Samples for Modelling VBF and VH production





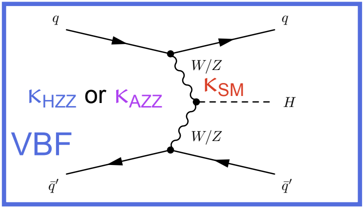
Production mode	n_p	n_d	n_s	N
VBF+VH	0	0	2	5

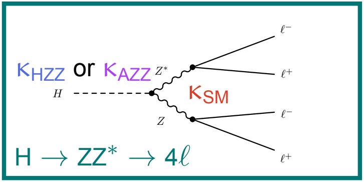
Validation of the input sample set: κ_{AZZ}



Good agreement between prediction and validation point

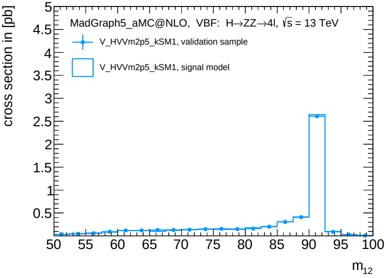
Set of Input Samples for Modelling VBF and VH production





Production mode	n_p	n_d	n_s	N
VBF+VH	0	0	2	5

Validation of the input sample set: κ_{HZZ}



Good agreement between prediction and validation point

CP sensitive discriminants in the decay system

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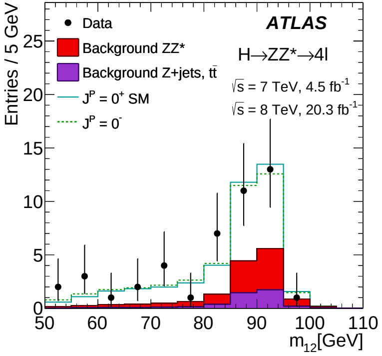

CP sensitive discriminants in the decay system

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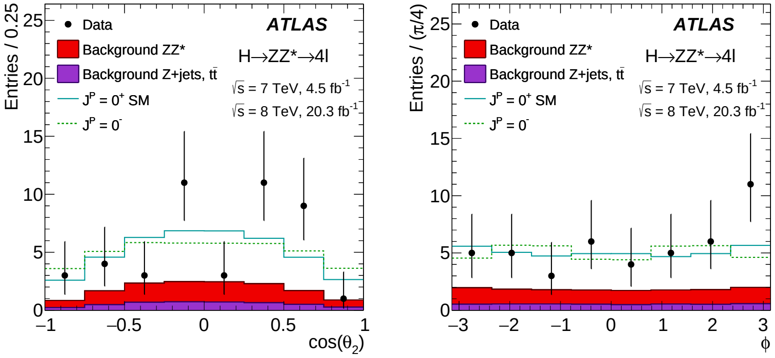


Signal Modelling via Morphing Method

- Continuous signal model to describe signal expectation in dependence on BSM couplings
- Predicts kinematic distributions and cross-sections at every parameter point

$$\underbrace{T_{out}(\vec{\kappa}_{out})}_{\text{Output distribution}} = \sum_{i=1}^{N_{input}} \underbrace{w_i(\vec{\kappa}_{out}; \vec{\kappa}_i)}_{\text{weight}} \cdot \underbrace{T_{in}(\vec{\kappa}_i)}_{\text{Input distribution}} \qquad \vec{\kappa} = \left(\kappa_{SM}, \kappa_{BSM}^1, \ldots, \kappa_{BSM}^n\right)$$

- Assumption:

$$T(\vec{\kappa}) \propto |\mathcal{M}(\vec{\kappa})|^2 = \underbrace{\left(\sum_{\alpha \in p,s} \kappa_\alpha \mathcal{O}(\kappa_\alpha)\right)^2}_{\text{production}} \cdot \underbrace{\left(\sum_{\alpha \in d,s} \kappa_\alpha \mathcal{O}(\kappa_\alpha)\right)^2}_{\text{decay}}$$

p: production
d: decay
s: shared in both

- Challenge: Find the set of input samples which gives the lowest statistical uncertainty

Morphing: Calculation of weights functions

$$T_{out}(\vec{g}_{out}) = \sum_{i=1}^{N_{input}} w_i(\vec{g}_{out}; \vec{g}_i) \cdot T_{in}(\vec{g}_i) \qquad \text{e.g. } T = \sigma \cdot BR,\ T = \cos\theta_1$$

- Ansatz for morphing weights:

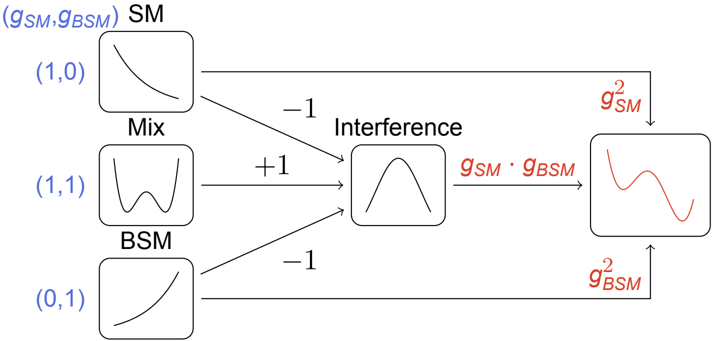
$$w_i = \left(a_{i1} g_{\mathrm{SM}}{}^2 + a_{i2} g_{\mathrm{BSM}}{}^2 + a_{i3} g_{\mathrm{SM}} g_{\mathrm{BSM}}\right)$$

- Requirement for calculation of constants:

$$w_i = 1 \quad \text{and} \quad w_{j\neq i} = 0 \quad \text{if} \quad \vec{g}_{out} = \vec{g}_i$$

$\Rightarrow$ Linear system of equations, solveable through matrix inversion

Morphing: Specific example



- Morphing function for this specific example:

$$T_{out}(g_{\rm SM}, g_{\rm BSM}) = \underbrace{({g_{\rm SM}}^2 - g_{\rm SM}g_{\rm BSM})}_{=w_1} T_{in}(1,0) + \underbrace{({g_{\rm BSM}}^2 - g_{\rm SM}g_{\rm BSM})}_{=w_2} T_{in}(0,1) + \underbrace{g_{\rm SM}g_{\rm BSM}}_{=w_3} T_{in}(1,1)$$

$\Rightarrow$ Set of input samples can be arbitrarily chosen as long as linear system of equations can be solved