Measurement of the Tensor Structure of the Higgs Boson Coupling to Z Bosons with the ATLAS Detector at $\sqrt{s}$ =13 TeV

36th IMPRS Workshop

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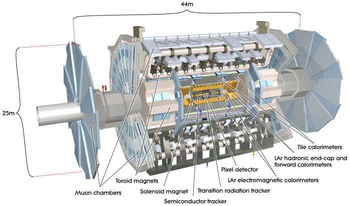
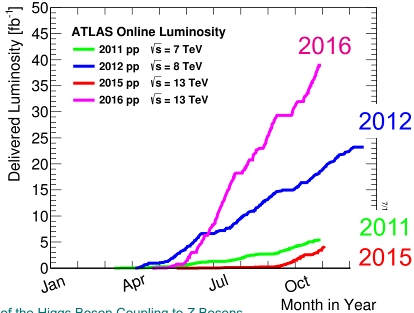
pp Collision Data Recorded with the ATLAS Detector



- 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: $\mathcal{L} \approx$ 35 fb^{-1}
- This study:

  Run II pp collision data recorded until August 2016, $\mathcal{L}$= 14.78 fb^{-1}

- Delivered luminosity:



Run I Measurement of the Higgs Boson CP Properties

- SM predicts a scalar CP-even particle ($J^P = 0^+$)
- Spin 0^+ hypotheses preferred by the Run I data compared to 0^- $1^\pm$ or $2^\pm$
- But: Small admixtures of 0^- state to 0^+ are still possible (Beyond SM):

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

  - $CP|0^\pm\rangle = \pm|0^\pm\rangle$

  $\rightarrow CP|H_{BSM}\rangle \neq \pm|H_{BSM}\rangle$

  $\Rightarrow$ CP violation

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

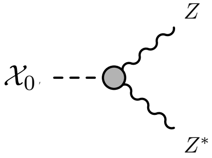
- This study: Effective field theory approach to account for BSM contributions

Measurement of Anomalous Couplings

- Effective field theory assumption:
  New physics appear at energy scale Λ much larger than the interaction energy E $\ll \Lambda$

$\Rightarrow$ Point-like HZZ interaction can be assumed

- This study: Cut-off energy Λ=1 TeV



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

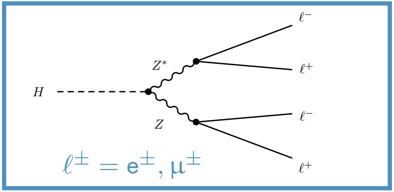
SM CP-even (κ_{SM})
anomalous CP-even (κ_{HZZ})
anomalous CP-odd (κ_{AZZ})

$g =$ coupling strength SM
$\kappa =$ coupling parameter
$c_\alpha = \cos(\alpha)$, $s_\alpha = \sin(\alpha)$
$\mathcal{X}_0 =$ Spin 0 field
$\tilde{V}^{\mu\nu} = 1/2\epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$

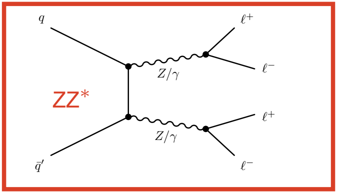
- Assumption: $\kappa_{XZZ} = \kappa_{XWW}$

Study of the H $\rightarrow$ ZZ $\rightarrow$ 4ℓ Decay Channel

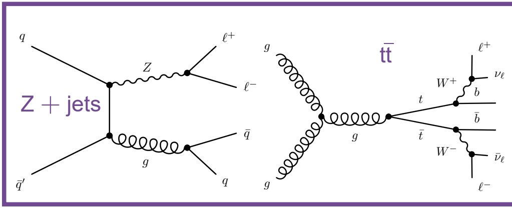
- Signal:



- Irreducible background:



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

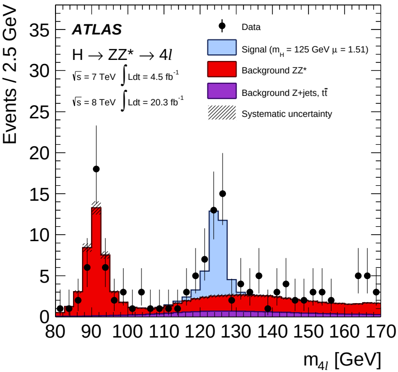


- Estimated in dedicated control data ($Z+\ell\ell$)
- Background enriched and signal depleted
- Cross checks in $Z+\mu$ data

Result of the Event Selection

- Run I: (2011+2012)

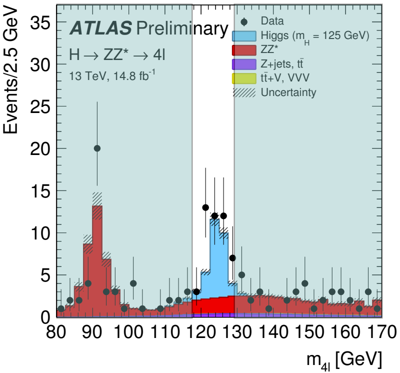
Phys. Rev. D 91, 012006 (2015)l



- Run II: (2015+2016) n_{exp}=32.0 ± 3.2

n_{obs}=44

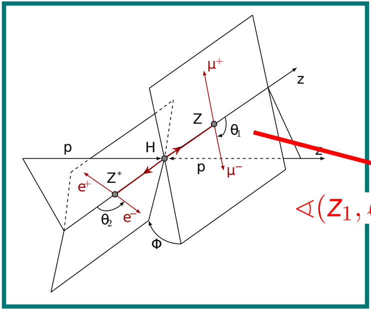
ATLAS-CONF-2016-079



Re-observation of the Higgs boson with Run II

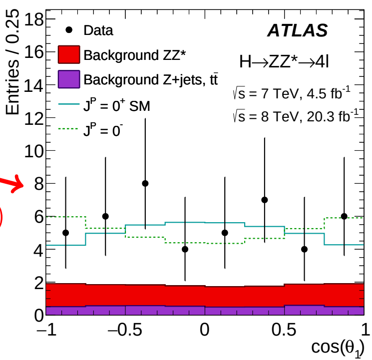
Measurement of the HZZ Tensor Coupling

- CP-sensitive kinematic discriminants in the decay system :



$\cos(\theta_1)$, $\cos(\theta_2)$, ϕ

Eur. Phys. J. C75 (2015) 476

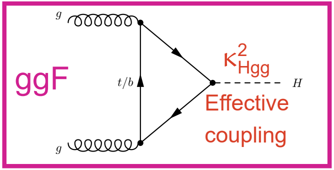


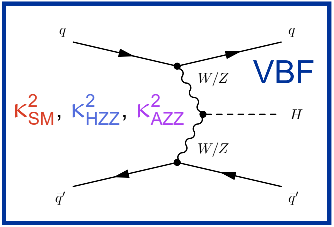
Information from kinematic distributions (used in Run-1)

Measurement of the HZZ Tensor Coupling

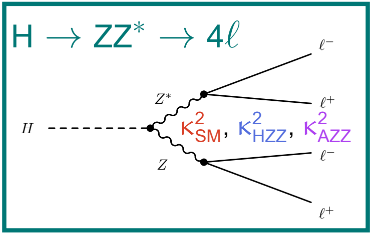
- Production and decay rates are dependent on the anomalous couplings

Production:





Decay:



Dependence:

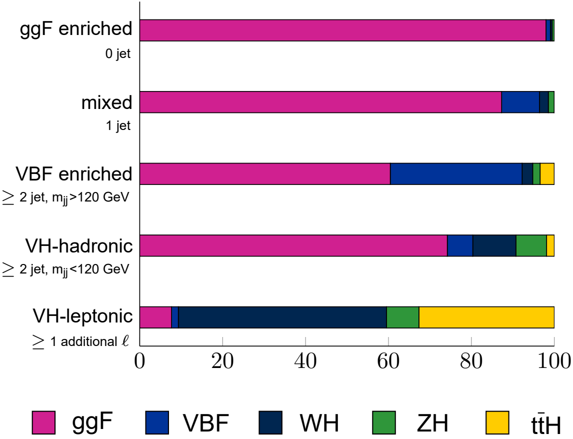
$$\sigma_{\mathrm{ggF}} \propto \kappa^2_{\mathrm{XZZ}}$$

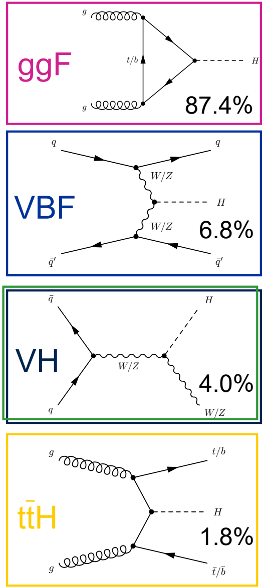
$$\sigma_{\mathrm{VBF}} \propto \kappa^4_{\mathrm{XZZ}}$$

Production rate information sensitive to BSM contributions

Event Categorisation

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





Signal Modelling via Morphing Method

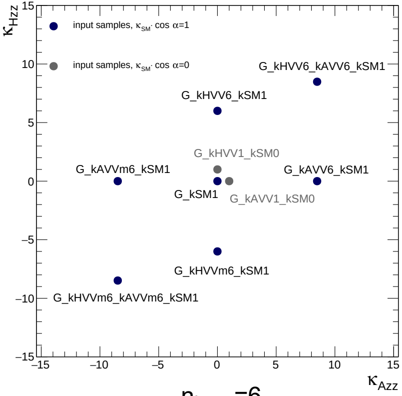
- Continuous signal model to describe signal expectation in dependence on BSM couplings $(\kappa_{HZZ}, \kappa_{AZZ})$
- Predicts kinematic distributions and cross-sections at every parameter point based on a discrete set of simulated input samples

$$\underbrace{N_{out}(\vec{\kappa}_{out})}_{\text{Output distribution}} = \sum_{i=1}^{N_{input}} \underbrace{w_i(\vec{\kappa}_{out}; \vec{\kappa}_i)}_{\text{weight}} \cdot \underbrace{N_i(\vec{\kappa}_i)}_{\text{Input distribution}} \qquad \vec{\kappa} = (\kappa_{SM}, \kappa_{HZZ}, \kappa_{AZZ})$$

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

Optimizing the Set of Input Samples for Modelling ggF production

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



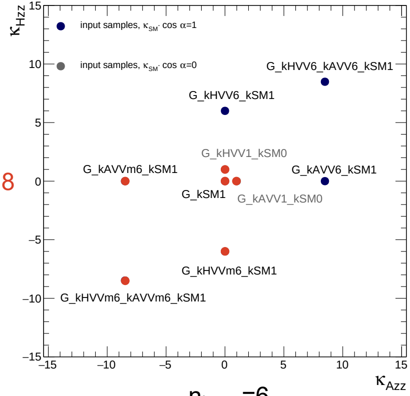
$n_{input}=6$

- Comparing number of expected events predicted by signal model and obtained from validation sample
- Input sample set with smallest statistical uncertainty
- Checking predicted distribution

Optimizing the Set of Input Samples for Modelling ggF production

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

Set 8



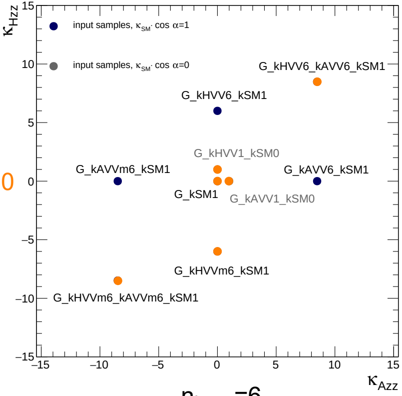
$n_{input}=6$

- Comparing number of expected events predicted by signal model and obtained from validation sample
- Input sample set with smallest statistical uncertainty
- Checking predicted distribution

Optimizing the Set of Input Samples for Modelling ggF production

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

Set 10

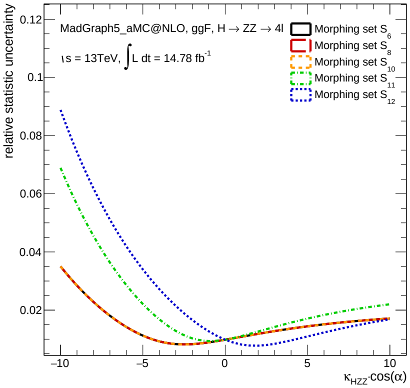


n_{input}=6

- Comparing number of expected events predicted by signal model and obtained from validation sample
- Input sample set with smallest statistical uncertainty
- Checking predicted distribution

Optimizing the Set of Input Samples for Modelling ggF production

Relative statistical uncertainty:

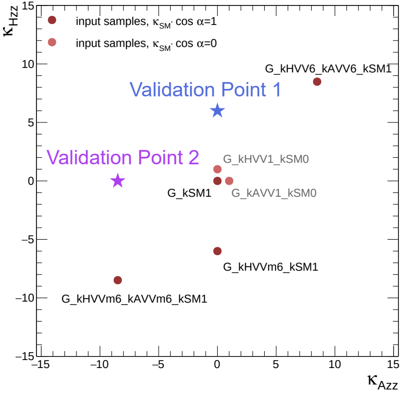


- Comparing number of expected events predicted by signal model and obtained from validation sample
- Input sample set with smallest statistical uncertainty
- Checking predicted distribution

Optimizing the Set of Input Samples for Modelling

ggF production

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

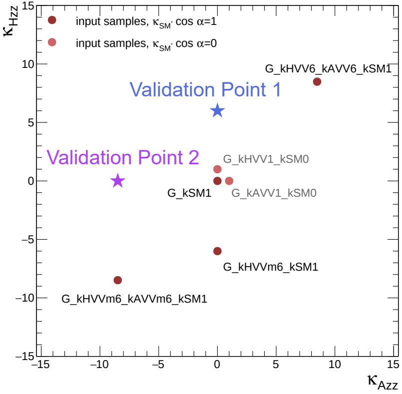


- Comparing number of expected events predicted by signal model and obtained from validation sample
- Input sample set with smallest statistical uncertainty
- Checking predicted distribution

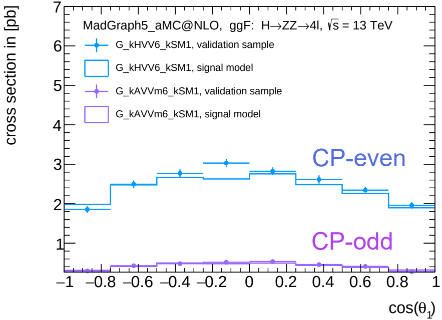
Optimizing the Set of Input Samples for Modelling

ggF production

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



Validation of the input sample set:



Good agreement between prediction and validation point

Results of the HZZ Tensor coupling measurement

- Measuring κ_{AZZ} and κ_{HZZ}:

  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	Total
Signal	11.37±0.04	6.49±0.03	1.38±0.02	2.91±0.03	0.08±0.01	22.23±0.13
ZZ^*	6.10±0.02	1.63±0.01	0.17±0.01	0.22±0.01	0.02±0.01	8.14±0.04
Z+jets,$t\bar{t}$	0.84±0.12	0.44±0.07	0.09±0.01	0.24±0.11	0.01±0.01	1.62±0.07
Expected	18.4±0.4	8.6±0.1	1.6±0.1	3.4±0.1	0.17±0.01	32.0±0.5
Observed	21	12	2	9	0	44

- Test statistic:

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

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

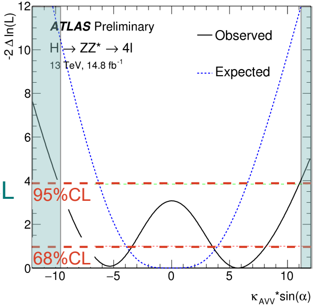
Results of the HZZ Tensor Coupling Measurement

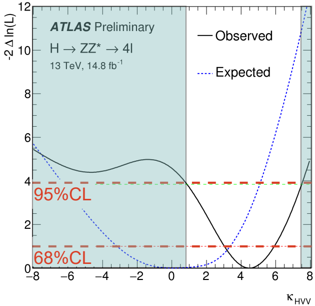
- Expected and observed distributions of the test statistic q for fits of ...

... $\kappa_{AZZ} \cdot \sin(\alpha)$ (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
$\kappa_{AZZ} \cdot \sin(\alpha)$	5.2	[-6.3,6.5]	[-9.7,11.0]
κ_{HZZ}	4.5	[-6.2,5.1]	[0.9,7.5]

$\Rightarrow$ Compatible with the SM prediction within 1.8 and 2.1 standard deviations

Summary

- Re-observation of the Higgs boson with Run II in the $H \to ZZ^* \to 4\ell$ decay channel

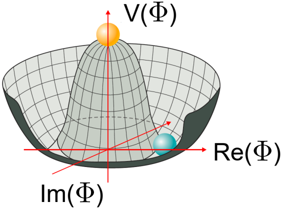
- Measurement of the anomalous H to ZZ couplings:
  - More events observed in each category than expected
  - Allowed regions at 95% confidence level:
    $-9.7 \leq \kappa_{AZZ} \cdot \sin(\alpha) \leq 11.0$
    $0.9 \leq \kappa_{HZZ} \leq 7.5$
  - No significant deviation from the SM prediction yet with 14.78 fb^{-1}

BACKUP

The Higgs Mechanism in the Standard Model

- Lagrangian for the scalar Higgs field, $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$:

$$\mathcal{L}_{\text{scalar}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \underbrace{(\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2)}_{=V(\Phi)}$$



- μ^2<0: non vanishing vacuum expectation value, $v = \sqrt{-\mu^2/\lambda}$
- Possible choice of ground state: $\langle \Phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$
- Particular choice $\Rightarrow$ breaks gauge symmetry spontaneously
- Invariance under $U(1)_Q$ still preserved

$\Rightarrow$ Weak bosons acquire mass

- Masses of fermions are obtained by introducing Yukawa interactions

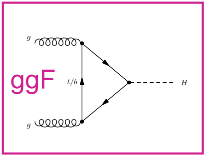
$\Rightarrow$ Resulting particle: Higgs boson

- 2012: Discovery of the Higgs boson with a mass of $m_H = 125$ GeV

  Phys. Lett. B 716 (2012) 1-29 and Phys. Lett. B 716 (2012) 30-61

Production and Decay of the Higgs Boson at the LHC

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



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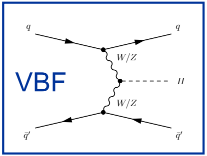

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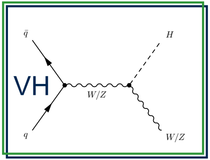

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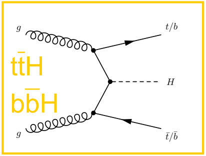
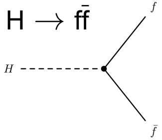
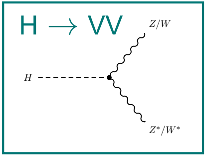
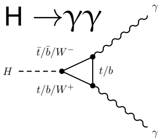


1.8%

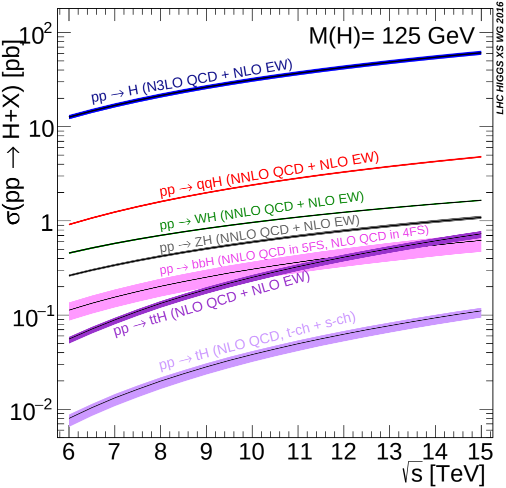
- Decay of the SM Higgs boson:



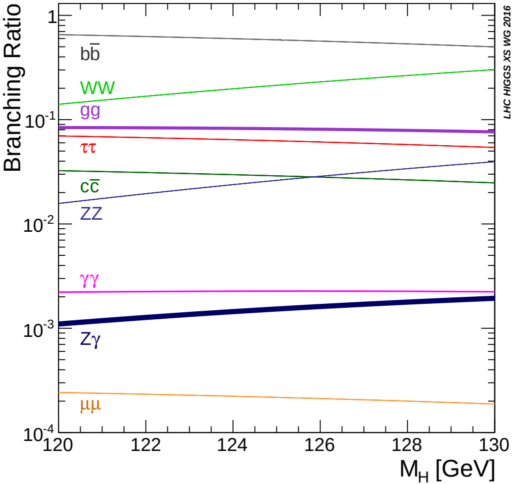




SM Higgs Boson Production Cross Section



Branching Ratios of the SM Higgs Boson



CP-Violation in the 2HDM

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

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

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

CP-Violation in the 2HDM

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

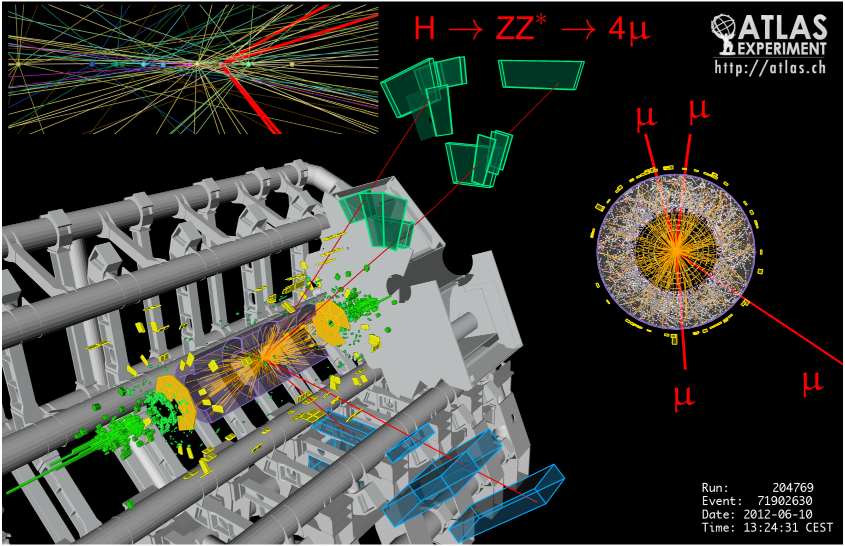
$$\phi_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 e^{i\xi} \end{pmatrix}$$

- Relation: $\mathrm{Im}\left(\mathrm{m}_{12}^2 e^{i\xi}\right) = \mathrm{Im}\left(\lambda_5 e^{2i\xi}\right) v_1 v_2$
  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



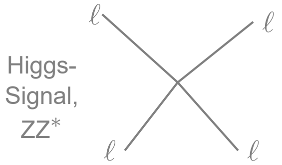
H → ZZ* → 4μ
ATLAS EXPERIMENT
http://atlas.ch
μ
μ
μ
μ
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

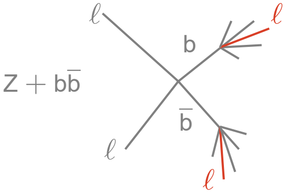
$H \rightarrow ZZ^{*} \rightarrow 4\ell$ Event Selection

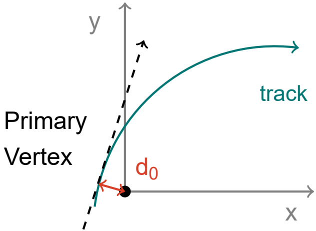
- 2 pairs opposite electric charge, same flavour
- Cut on invariant masses:
  - Leading lepton pair: $50\ \text{GeV} < m_{12} < 106\ \text{GeV}$
  - Off-shell Z: $m_{threshold} < m_{34} < 115\ \text{GeV}$

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

- 2 pairs opposite electric charge, same flavour
- Cut on invariant masses:
  - Leading lepton pair: $50\ \text{GeV} < m_{12} < 106\ \text{GeV}$
  - Off-shell Z: $m_{\text{threshold}} < m_{34} < 115\ \text{GeV}$
- 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: $|d_0/\sigma_{d_0}| < 5.0$







Full Event Selection

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

LEPTON REQUIREMENTS	
Electrons	$E_T > 7$ GeV and $\lvert\eta\rvert < 2.47$ $z_0 \cdot \sin(\theta) < 5$ mm
Muons	$p_T > 5$ GeV and $\lvert\eta\rvert < 2.7$ $p_T > 15$ GeV and $\lvert\eta\rvert < 0.1$ (CT muons) $z_0 \cdot \sin(\theta) < 5$ mm $\lvert d_0\rvert < 1$ 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 ($\Delta R = 0.2$): $I_e^{calo} < 0.20$ $\lvert d_0/\sigma_{d_0}\rvert < 3(5)$ 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

Reducible Background

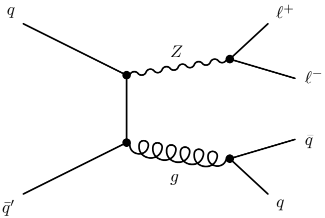
- Estimated using control data enhanced in background and depleted in signal
- Dominant contribution: Z+jets

  $\ell\ell$+ee final state:

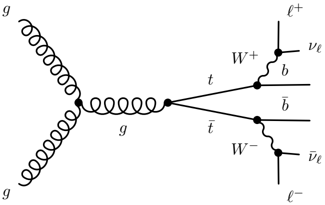
  - photon conversion
  - misidentified light flavour jets

  $\ell\ell + \mu\mu$ final state:

  - semileptonic b/c- decays (Z+HF jets)
  - in-flight π/K- decays (Z+LF jets)



- $t\bar{t}$ production:
  - $\ell\ell + \mu\mu$ and $\ell\ell$+ee final states
  - non-isolated leptons from W boson and b-quark decays



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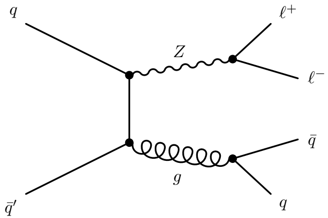

- $t\bar{t}$ production:
  - $\ell\ell + \mu\mu$ and $\ell\ell$+ee final states
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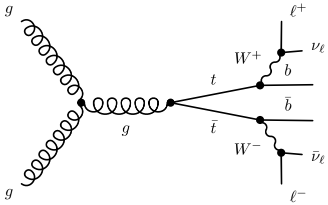


Estimation of the Reducible $\ell\ell + \mu\mu$ Background

- Evaluation of the contribution in background-enriched control regions
- Built by relaxing or inverting the lepton selection criteria

Control Region:

Signal Region:	Z+HF:	Z+LF:	$t\bar{t}$: $e\mu+\mu\mu$
$\|d_0/\sigma_{d_0}\|$ ✓	invert. $\|d_0/\sigma_{d_0}\|$	$\|d_0/\sigma_{d_0}\|$ ✓	$\|d_0/\sigma_{d_0}\|$ ✗
I_μ ✓	invert. I_μ	invert. I_μ	I_μ ✗

Estimation of the Reducible $\ell\ell + \mu\mu$ Background

- Evaluation of the contribution in background-enriched control regions
- Built by relaxing or inverting the lepton selection criteria

Signal Region:

$|d_0/\sigma_{d_0}|$ ✓

I_μ ✓

Fake Factor

$F_{HF} = \frac{\epsilon^{\mu\mu}_{\text{iso\&}d_0}}{1-\epsilon^{\mu\mu}_{\text{iso\&}d_0}}$

$F_{LF} = \frac{\epsilon^{\mu\mu}_{\text{iso}}}{1-\epsilon^{\mu\mu}_{\text{iso}}}$

$F_{t\bar{t}} = \frac{\epsilon^{\mu\mu}_{\text{iso\&}d_0} \cdot \epsilon_{\ell\ell}}{\epsilon_{e\mu}}$

Control Region:

Z+HF:
invert. $|d_0/\sigma_{d_0}|$
invert. I_μ

Z+LF:
$|d_0/\sigma_{d_0}|$ ✓
invert. I_μ

$t\bar{t}$: $e\mu+\mu\mu$
$|d_0/\sigma_{d_0}|$ ✗
I_μ ✗

Estimation of the Reducible $\ell\ell + \mu\mu$ Background

- Evaluation of the contribution in background-enriched control regions
- Built by relaxing or inverting the lepton selection criteria

Signal Region:

$|d_0/\sigma_{d_0}|$ ✓

I_μ ✓

Fake Factor

Control Region:

Z+HF:
invert. $|d_0/\sigma_{d_0}|$
invert. I_μ

$$F_{HF} = \frac{\epsilon^{\mu\mu}_{\text{iso\&}d_0}}{1-\epsilon^{\mu\mu}_{\text{iso\&}d_0}}$$

Z+LF:
$|d_0/\sigma_{d_0}|$ ✓
invert. I_μ

$$F_{LF} = \frac{\epsilon^{\mu\mu}_{\text{iso}}}{1-\epsilon^{\mu\mu}_{\text{iso}}}$$

$t\bar{t}$: $e\mu$+$\mu\mu$
$|d_0/\sigma_{d_0}|$ ✗
I_μ ✗

$$F_{t\bar{t}} = \frac{\epsilon^{\mu\mu}_{\text{iso\&}d_0} \cdot \epsilon_{\ell\ell}}{\epsilon_{e\mu}}$$

- Efficiencies determined in Monte-Carlo simulation

$\Rightarrow$ Cross checks of single lepton selection efficiencies in Z+μ data

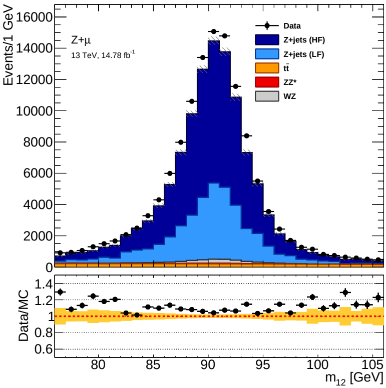
- $\epsilon^{\mu\mu}_{\text{iso}}$ from Z+HF also applied on light flavour jets (due to low Z+LF statistic)

$\Rightarrow$ Cross check in Z+μ data

Selection of Z ($\to e^+e^-, \mu^+\mu^-$) + μ Events

- Z-Candidate:
  - Lepton identification criteria, isolation- and d_0-cuts
  - $p_T^1 > 20$ GeV, $p_T^2 > 15$ GeV
  - $|m_{ll} - M_Z^{PDG}| < 15$ GeV
- Additional muon:
  - Exactly one additional reconstructed combined muon with $p_T^\mu > 5$ GeV
  - no cut on d_0-significance
  - no isolation criteria

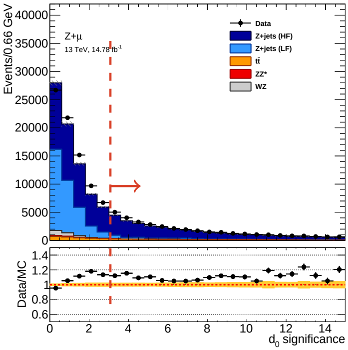
Z-Candidate after event selection:



Shape of the distribution in good agreement

Investigation of the additional muon

Muons from c/b decays:



$$\left|d_0/\sigma_{d_0}\right| > 3.0$$

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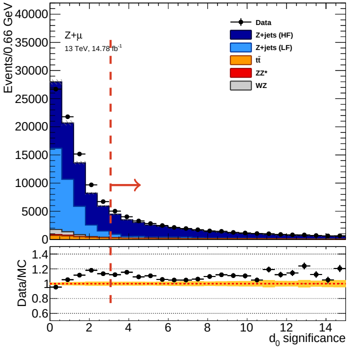
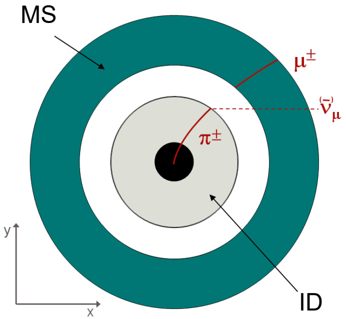


$$\left|d_0/\sigma_{d_0}\right| > 3.0$$

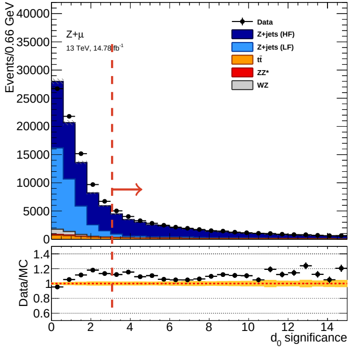
Muons from π/K decays:



$$p_T\text{-Balance: } \frac{\Delta p_T}{p_T} = \frac{p_T^{ID} - p_T^{MS}}{p_T^{ID}} > 0.1$$

Investigation of the additional muon

Muons from c/b decays:



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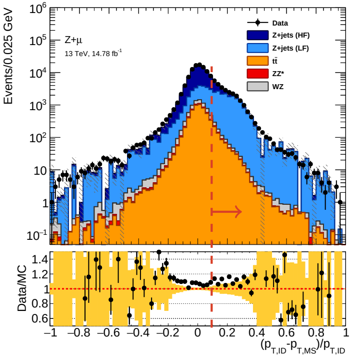
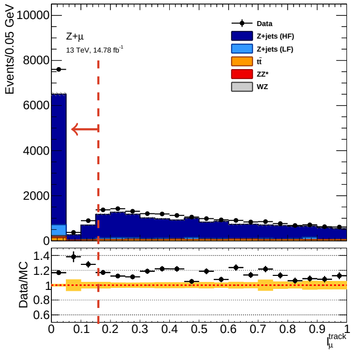
Muons from π/K decays:



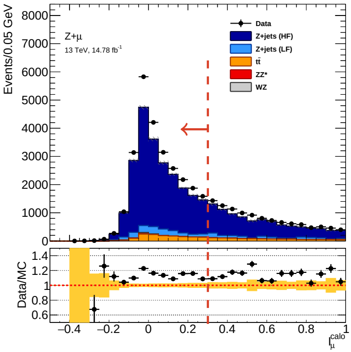
$$p_T\text{-Balance: } \frac{\Delta p_T}{p_T} = \frac{p_T^{ID} - p_T^{MS}}{p_T^{ID}} > 0.1$$

Muons from b/c-decays (Z+HF): $\left|d_0/\sigma_{d_0}\right|>3.0$

Track-based isolation:



Calorimeter-based isolation:



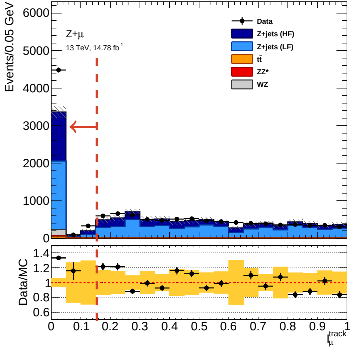
$\Rightarrow$ Shapes of the distributions are in agreement

$$\boxed{\epsilon^{\mu}_{\mathrm{Iso}} = \frac{N_{\mu}(\text{after cut})}{N_{\mu}(\text{before cut})}}$$

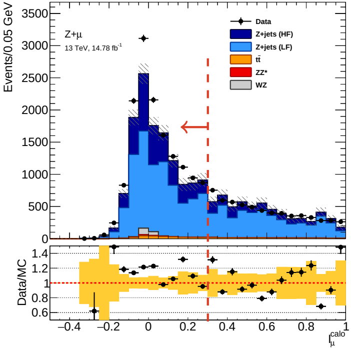
$$N_{\mu} = N^{\text{total}}_{\mu} - N^{\text{MC}}_{\mu,(\text{WZ, ZZ})}$$

Muons from π/K- decays (Z+LF): $\frac{\Delta p_T}{p_T} = \frac{p_T^{ID} - p_T^{MS}}{p_T^{ID}} > 0.1$

Track-based isolation:



Calorimeter-based isolation:



$\Rightarrow$ Low Monte-Carlo statistic, agreement with data

$$\boxed{\epsilon_{Iso}^{\mu} = \frac{N_\mu\,(\text{after cut})}{N_\mu\,(\text{before cut})}} \qquad N_\mu = N_\mu^{total} - N_{\mu,(WZ,\,ZZ)}^{MC}$$

Isolation Efficiencies

1. Comparison of $\epsilon^{\mu}_{\mathrm{Iso}}$ in Z+HF jet region:

- Muons from b/c-decays: Simulation: $(16.4 \pm 0.3)\%$ Data: $(17.0 \pm 0.2)\%$

- $\epsilon^{\mu}_{\mathrm{Iso}}$ in data and simulation agree well for muons from b/c- decays
- Relative discrepancy below 4%

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2. Comparison of $\epsilon^{\mu,\mathrm{Data}}_{\mathrm{Iso}}$ in Z+LF jet region with $\epsilon^{\mu,\mathrm{MC}}_{\mathrm{Iso}}$ in Z+HF jet region:

- Muons from π/K-decays:

Simulation:	$(11.6 \pm 0.9)\%$
Data:	$(\mathbf{15.1 \pm 0.3})\%$

- $\epsilon^{\mu}_{\mathrm{Iso}}$ agree within 10% between muons from π/K- and b/c- decays

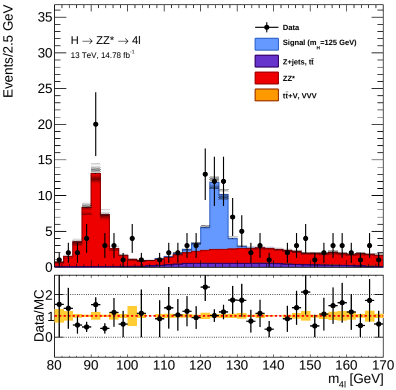
$\Rightarrow$ $\epsilon^{\mu}_{\mathrm{Iso}}$ in Z+HF also applies for light flavour jets

- Discrepancy between data and simulation $\Rightarrow$ systematic uncertainty for the fake factor

Results of the Event Selection

- Data and simulation in good agreement
- Observed and expected number of events in 118 GeV$<m_{4\ell}<$129 GeV:

Signal	22.2	$\pm$ 2.1
ZZ^*	8.2	$\pm$ 0.8
Z+jets, $t\bar{t}$, WZ	1.6	$\pm$ 0.2
Total Expected	32.0	$\pm$ 3.2
Total Observed	44	



- Deviation from the SM expectation is below 2 standard deviation
- Higgs boson rediscovered with Run II

Additional Muon

Table: Efficiency of muon selection after the d_0 significance and isolation cuts for an additional muon in $Z + \mu$ events.

Selection applied	Data [%]	MC [%]
d_0 significance	63.5 ± 0.4	65.2 ± 1.4
isolation	18.7 ± 0.2	15.8 ± 0.5
d_0 significance + isolation	11.8 ± 0.2	10.3 ± 0.3

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

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

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

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

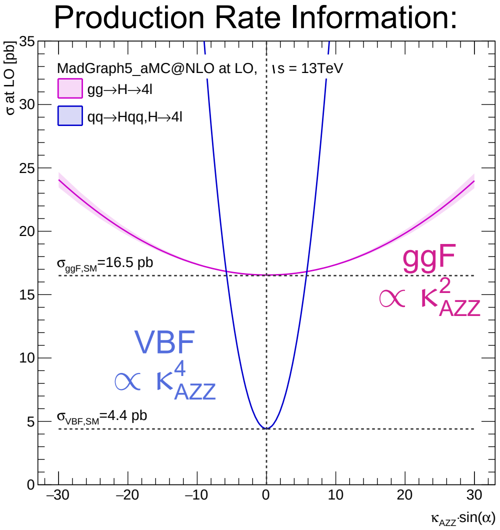
$\Lambda =$ cut-off energy

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

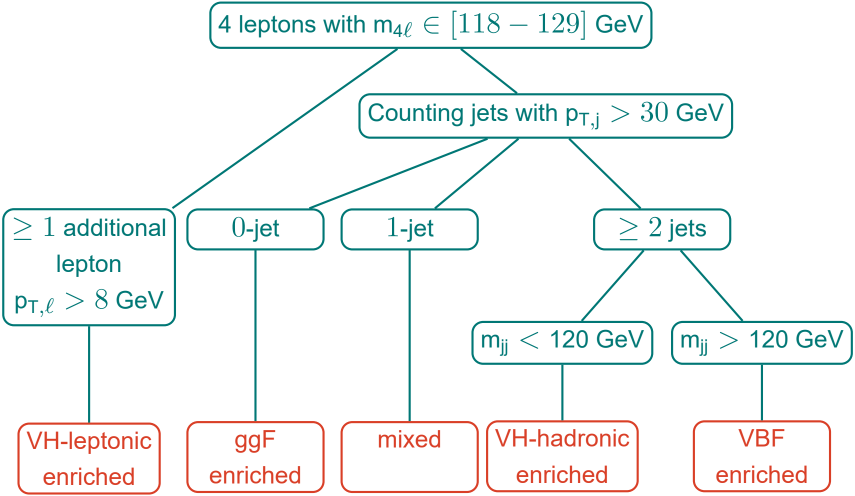
$s_\alpha = \sin(\alpha)$

- CP violation: Mixture of CP even and CP odd

Measurement of the HZZ Tensor Coupling



Event Categorisation



BSM Monte Carlo Samples ggF

Sample name	κ_{HZZ}	κ_{AZZ}	κ_{SM}	$\cos(\alpha)$	σ_{ggF} [pb]
G_kSM1	0	0	1	1	32.910
G_kHVV1_kSM0	1	0	0	1	0.3732
G_kHVV6_kSM1	6	0	1	1	46.494
G_kHVVm6_kSM1	-6	0	1	1	22.436
G_kAVV1_kSM0	0	1	0	$1/\sqrt{2}$	0.0043
G_kAVV6_kSM1	0	6	1	$1/\sqrt{2}$	8.4040
G_kAVVm6_kSM1	0	-6	1	$1/\sqrt{2}$	8.3872
G_kHVV6_kAVV6_kSM1	6	6	1	$1/\sqrt{2}$	11.764
G_kHVVm6_kAVVm6_kSM1	-6	-6	1	$1/\sqrt{2}$	5.7936

BSM Monte Carlo Samples VBF+VH

Sample name	κ_{Hvv}	κ_{Avv}	κ_{SM}	cos (α)	σ_{VBF+VH} [pb]
V_kSM1	0	0	1	1	4.9392
V_kHVV10_kSM0	10	0	0	1	8.0489
V_kHVV5_kSM1	5	0	1	1	22.073
V_kHVV2p5_kSM1	2.5	0	1	1	7.3994
V_kHVVm5_kSM1	-5	0	1	1	20.501
V_kHVVm2p5_kSM1	-2.5	0	1	1	10.432
V_kAVV15_kSM0	0	15	0	$1/\sqrt{2}$	10.320
V_kAVV5_kSM1	0	5	1	$1/\sqrt{2}$	4.2259
V_kAVV2p5_kSM1	0	2.5	1	$1/\sqrt{2}$	1.9750
V_kAVVm5_kSM1	0	-5	1	$1/\sqrt{2}$	4.2366
V_kAVVm2p5_kSM1	0	-2.5	1	$1/\sqrt{2}$	1.9752

Scale Factor

The scale factor for each bin j is therefor given as

$$\mathrm{SF}_j(\mathrm{ggF}) = \frac{N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{ggF}) + N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{t\bar{t}H}) + N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{b\bar{b}H})}{N^{\mathrm{exp},j}_{\mathrm{MG5,SM}}(\mathrm{ggF})} \tag{1}$$

for the ggF production mode and

$$\mathrm{SF}_j(\mathrm{VBF}+\mathrm{VH}) = \frac{N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{VBF}) + N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{WH}) + N^{\mathrm{exp},j}_{\mathrm{Powheg,SM}}(\mathrm{ZH})}{N^{\mathrm{exp},j}_{\mathrm{MG5,SM}}(\mathrm{VBF{+}VH_{had}}) + N^{\mathrm{exp},j}_{\mathrm{MG5,SM}}(\mathrm{VH_{lep}})} \tag{2}$$

for the VBF and VH production.

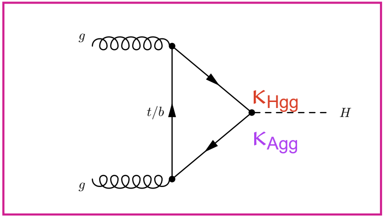
Signal Modelling via Morphing Method

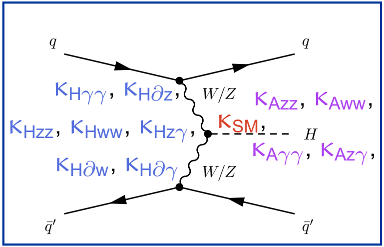
- Number of input samples T_i is dependent on the number of couplings one wants to model

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

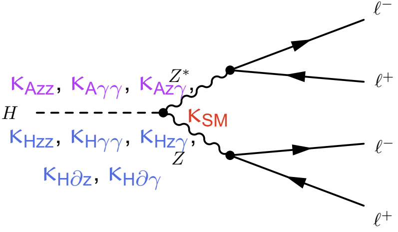
Relevant couplings in ggF/VBF production in H4ℓ channel

Production: ggF,VBF





Decay: $H \rightarrow 4\ell$



Signal Modelling via Morphing Method

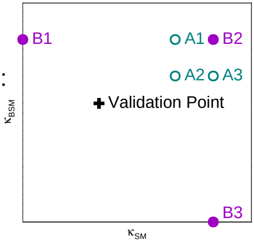
- Statistical uncertainty of output distribution:

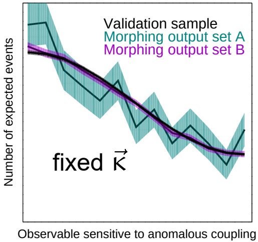
$$\Delta T_{\mathrm{out}}^{\mathrm{bin}} = \sqrt{\sum_i w_i\left(\vec{\kappa}_{\mathrm{out}};\, \vec{\kappa}_i\right) N_{\mathrm{MC},i}^{\mathrm{bin}}\left(\vec{\kappa}_i\right) \cdot \left(\frac{\sigma_i\left(\vec{\kappa}_i\right)\mathcal{L}}{N_{\mathrm{MC},i}\left(\vec{\kappa}_i\right)}\right)^2}$$

Set of input samples:

○ A1, ○ A2,○ A3

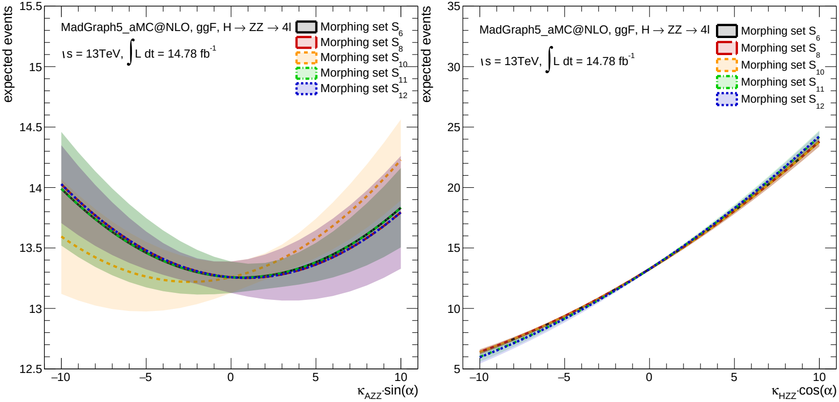
● B1, ● B2,● B3



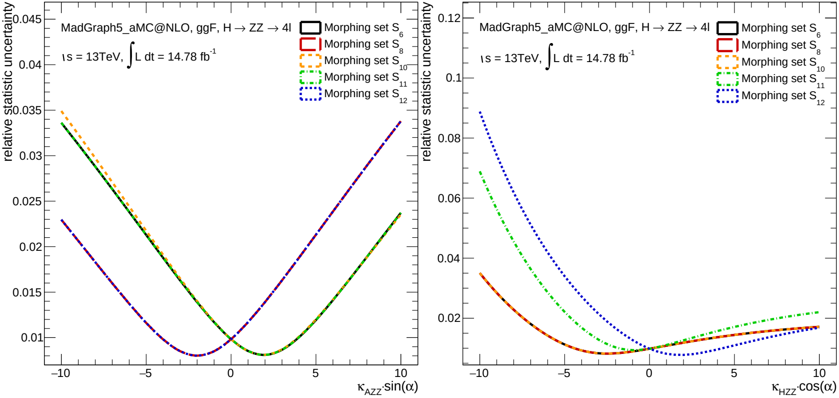


- Different choice of input samples $\Rightarrow$ different statistical uncertainties
- In addition, require that predicted value of the observable agrees with validation value

Set of Input Samples for Modelling ggF production



Set of Input Samples for Modelling ggF production



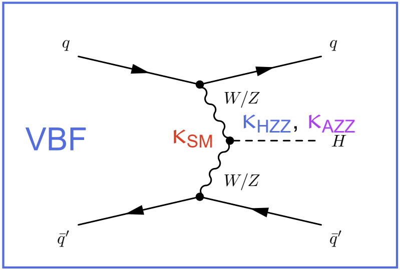
Size of Weights for Modelling ggF production

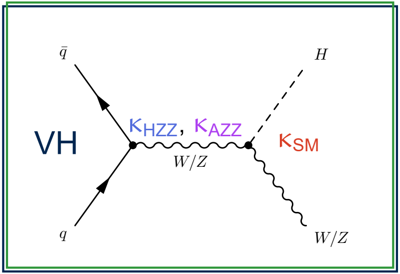
Table: Range of weight values obtained with a given tested ggF morphing input set (S_6, S_8, S_{10}, S_{11} and S_{12}) from a scan in the $\kappa_{AZZ} \cdot \sin(\alpha)$ and $\kappa_{HZZ} \cdot \cos(\alpha)$ parameter space.

Morphing set	Weight for values $[w_i^{min}, w_i^{max}]$ for	
	$\kappa_{AZZ} \cdot \sin(\alpha) \in [-10, 10]$	$\kappa_{HZZ} \cdot \cos(\alpha) \in [-10, 10]$
S_6	$[-40, 640]$	$[-10, 160]$
S_8	$[-40, 640]$	$[-10, 160]$
S_{10}	$[-50, 400]$	$[-10, 160]$
S_{11}	$[-40, 640]$	$[-240, 240]$
S_{12}	$[-40, 640]$	$[-240, 240]$

Set of Input Samples for Modelling VBF and VH production

- VBF and VH production have the same coupling structure:

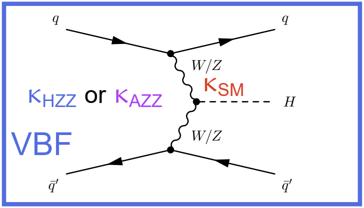


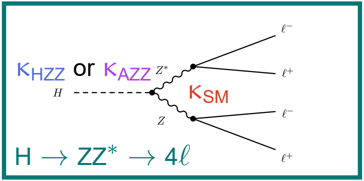


$\Rightarrow$ VBF and VH production are combined

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

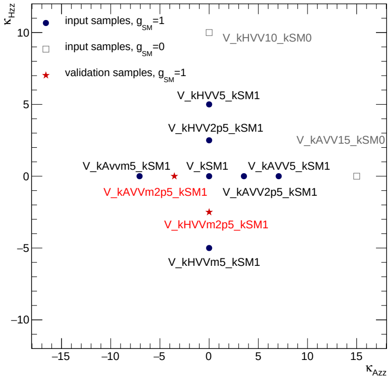
Set of Input Samples for Modelling VBF and VH production



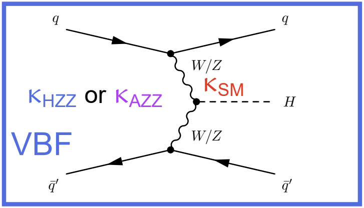


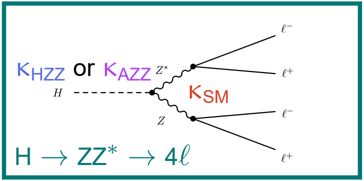
Production mode	n_p	n_d	n_s	N
VBF+VH	0	0	2	5

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



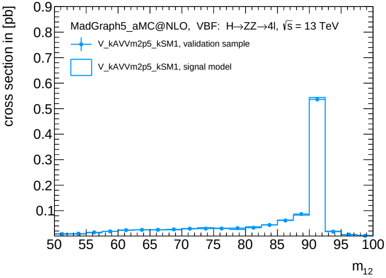
Set of Input Samples for Modelling VBF and VH production





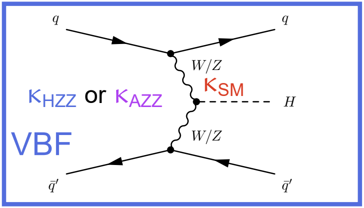
Production mode	n_p	n_d	n_s	N
VBF+VH	0	0	2	5

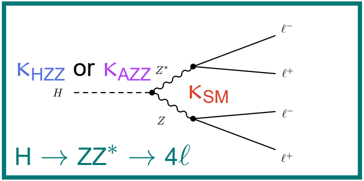
Validation of the input sample set: κ_{AZZ}



Good agreement between prediction and validation point

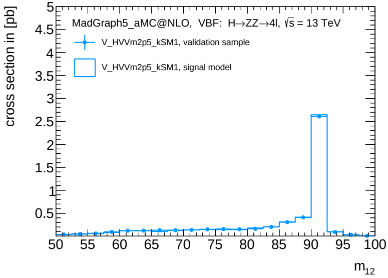
Set of Input Samples for Modelling VBF and VH production





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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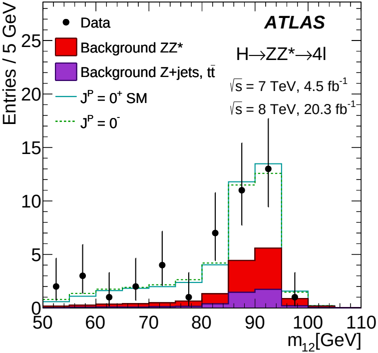

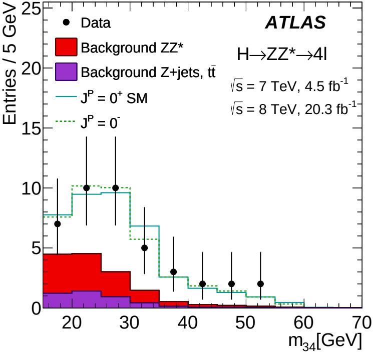

CP sensitive discriminants in the decay system

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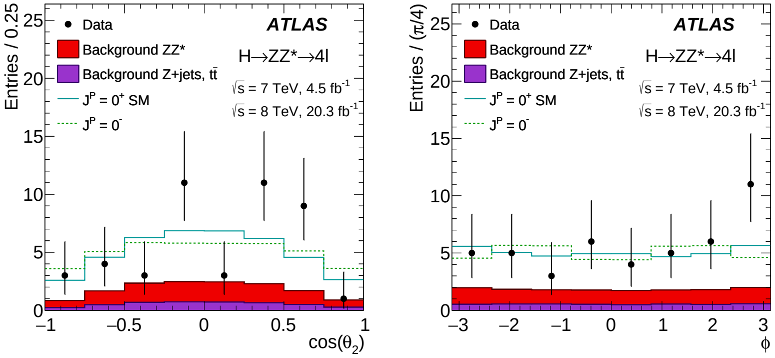


Signal Modelling via Morphing Method

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

Output distribution, weight, Input distribution

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

- 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:

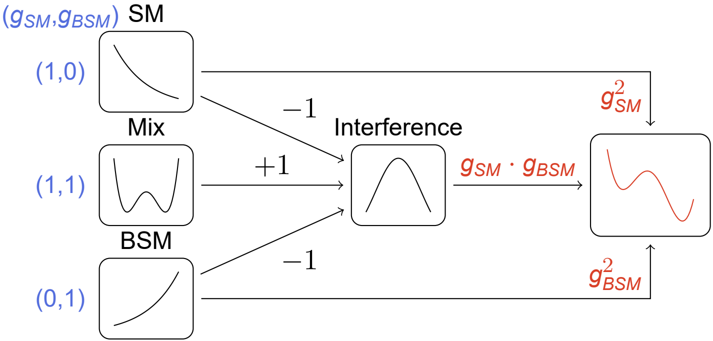
$$w_i = \left(a_{i1} g_{\mathrm{SM}}{}^2 + a_{i2} g_{\mathrm{BSM}}{}^2 + a_{i3} g_{\mathrm{SM}} g_{\mathrm{BSM}}\right)$$

- 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:

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

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