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

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20.10.2015

MPP Higgs Meeting

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Part I: (SM) Higgs boson CP properties

Part II: Signal model construction *Morphing method*

Introduction: CP?

- CP measurement within the assumption of an scalar (spin 0) particle (from Run1 measurements)
- CP: Combination of charge conjugation and parity
- Charge conjugation is conserved in terms of neutral systems

	scalar	pseudoscalar	vector	pseudovector
Spin: J	0	0	1	1
Parity: $P\|X\rangle$	+1	-1	-1	+1
J^P	0^+	0^-	1^-	1^+
Example	SM Higgs boson	π, K, η, η'	Z, W, γ, g	pseudovector mesons

- CP is conserved in the SM Higgs sector, example HZZ decay:
- $CP|ZZ\rangle = |ZZ\rangle$
- $CP|H\rangle = |H\rangle$

Introduction: CP violation

- Pure pseudoscalar state 0^- for discovered boson has been excluded in Run-1
- BUT it is still possible that we have a mixed state of 0^- and 0^+

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

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

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

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

CP measurement ⇔ Tensor structure measurement

- Why is CP measurement often described as tensor structure measurement?
- Because CP properties of the Higgs boson are determined by studying the coupling structure (tensor structure) of the coupling of the Higgs boson to SM particles, for example HZZ coupling

SM CP-even
BSM CP-even
BSM CP-odd

$$\mathcal{L}_0^V = \underline{\left\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu\right]\right.} - \underline{-\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu}\right.} + \underline{\left.\left.\sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]\right\}} X_0$$

- Upper limits on beyond the SM (BSM) CP-even $\boxed{\kappa_{HZZ}\kappa_{SM}}$ and BSM CP-odd $\boxed{\kappa_{AZZ}\kappa_{SM}}$ contributions

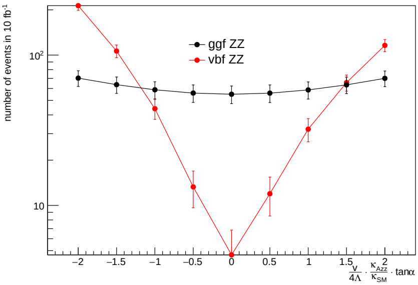
How can we experimentally measure different admixtures in HZZ couplings?

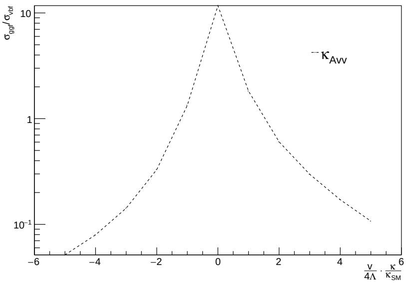
1. Production: Total cross section and production system kinematic distributions
2. Decay: Decay system kinematic distributions

Production:Cross section

- Benefit from increase of VBF rate in case of BSM couplings:

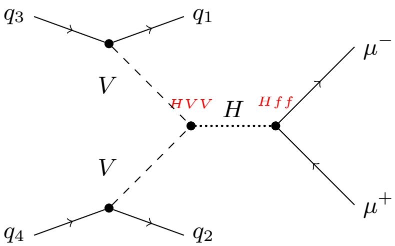
$\sigma_{ggf}/\sigma_{vbf}$



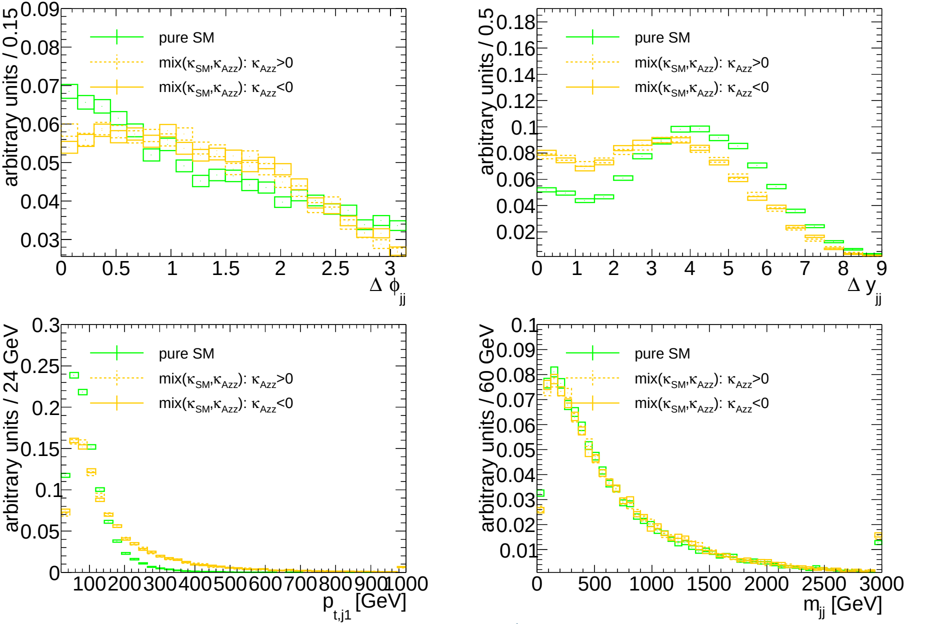


- $g_{SM} = \kappa_{SM} \cdot \cos(\alpha)$ = 1. and $\kappa_{XVV \neq AZZ} = 0$

Production: Distributions in VBF production

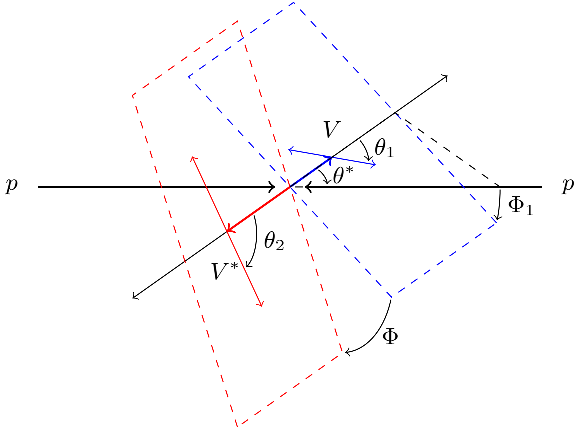


Production: Kinematic distributions in VBF production

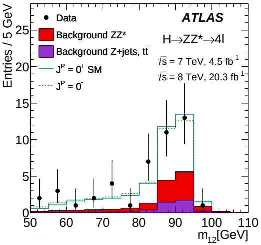


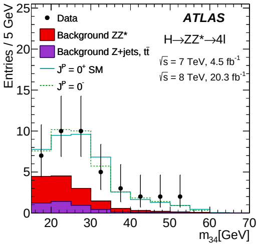
Decay: Kinematic decay distributions

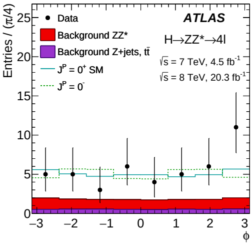
- Higgs boson scalar particle $\rightarrow$ Angular distribution of ZZ is isotropic
- Information about CP of Higgs boson only in decay of the Z-bosons (for example $ZZ \rightarrow 4\ell$), as it is extracted by the polarisation of the Z bosons

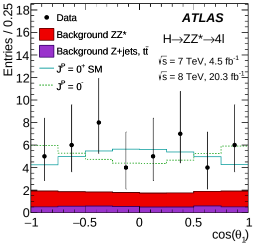


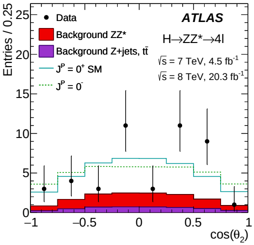
Example decay distributions











Outlook

- Effective Lagrangian for the interaction of scalar and pseudo-scalar states with vector bosons:

Done in Run 1

Plan Run 2

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

- Plan Run 2: Include large set of EFT parameters, to take all correlations into account. (Run 1: including only 1-2 anomalous couplings, with all others set to zero.)

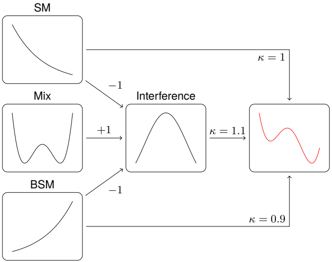
Part I: (SM) Higgs boson CP properties

Part II: Signal model construction *Morphing method*

Signal model construction: Morphing

- Analytical morphing is a method to construct a continuous signal model describing Higgs boson couplings with BSM contributions

$$T_{target}(g_{SM}, g_{BSM}) = \sum_{i=1}^{N_{input}} w_i(g_{SM}, g_{BSM}) \cdot T_i$$



- Prediction of:
  1. Cross section
  2. Kinematic distributions

Calculation of the weights: An example

- Weights are calculated based on Matrix Elements:

$$ME^2_{target} = (g_{SM} \cdot ME_{SM} + g_{BSM} \cdot ME_{BSM})^2$$

$$T_{target} \propto ME^2_{target}$$

$$\Rightarrow \{w_{SM}, w_{Interfernce}, w_{BSM}\} = \{g^2_{SM}, g_{SM} \cdot g_{BSM}, g^2_{BSM}\}$$

- Choose configuration of three input samples $S(g_{SM}, g_{BSM})$: Can be arbitrary but weights of samples have to be linear independet $S_1(1,0)$, $S_2(1,1)$, $S_3(0,1)$

$$\begin{matrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{matrix}$$

- Final weights can be extracted by inverting this matrix

$$\{w_{S1}, w_{S2}, w_{S3}\} = \{(g^2_{SM} - g_{SM}g_{BSM}), g_{SM} \cdot g_{BSM}, (g^2_{BSM} - g_{SM}g_{BSM})\}$$

Signal model construction: Morphing, why?

- Needed: MC samples covering wide range of values for mixing parameters
- Run 1 HZZ and HWW analyses: Matrix Element Reweighting:

$$event\_weight = |ME_{Target}|^2/|ME_{Source}|^2$$

- One source MC sample with large statistics is reweighted to target sample with arbitrary configuration of mixing parameters

- Morphing function: Instead of "Matrix Element Reweighting" use morphing between SM and BSM CP-sensitive distributions to produce an arbitrarily mixed distribution

  $\rightarrow$ Moving from event level to distribution level

+ Continuous description of distributions in terms of mixing parameters
+ More flexible when adding additional operators to EFT Lagrangian

Signal model construction: Morphing, why?

- computationally fast & convenient tool

Morphing

- only calculates linear sums of coefficients
- all other inputs are pre-computed once

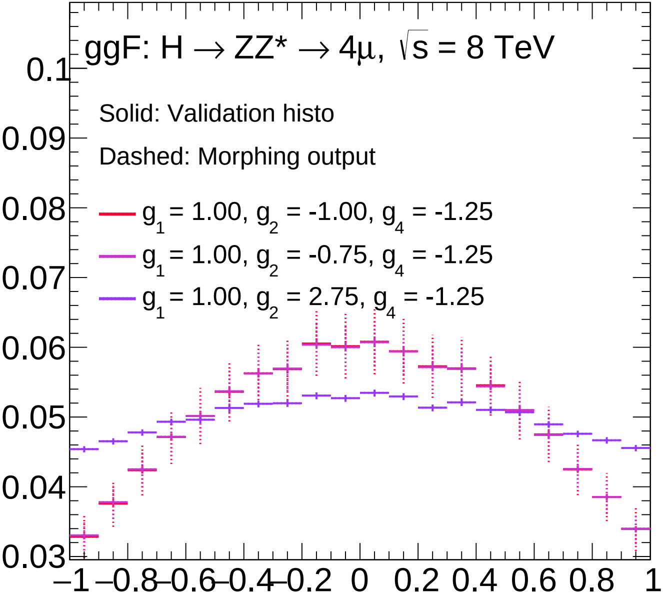
ME Reweighting

For every configuration point

- write events to disk
- rerun analysis
- additional interpolation

- can be applied directly and without change to
  - cross sections
  - distributions (before or after detector simulation)
  - MC events
- exact continuous analytical description of rates and shapes
- even possible to **fit** κs to data & derive limits

Morphing validation: MC12 $ZZ\ 4\mu$



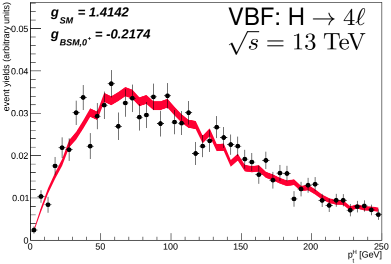
Outlook: Difficulties of morphing method

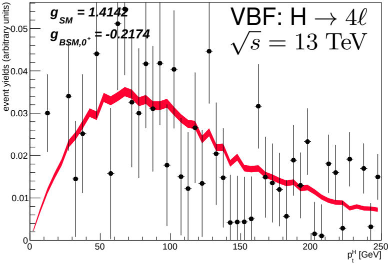
- N_{input} (=Number of input samples T_i) is fixed for a given number of couplings N_{coup}, for example:

$$\text{ggF: } N_{input} = N_{coup,prod} \cdot \frac{N_{coup,prod}+1}{2} \cdot N_{coup,dec} \cdot \frac{N_{coup,dec}+1}{2}$$

$$\text{VBF: } N_{input} = \binom{4 + N_{coup} - 1}{4}$$

- Full VBF BSM $H \to ZZ \to 4\ell$ process: 1605 samples
- Configuration of input samples T_i is free as long as they are pairwise independent
- Morphing to same sample with 'good choice' (left) and 'bad choice' (right) of input:





- Increase of statistical error when parameter configuration of target sample is not well represented by the input samples

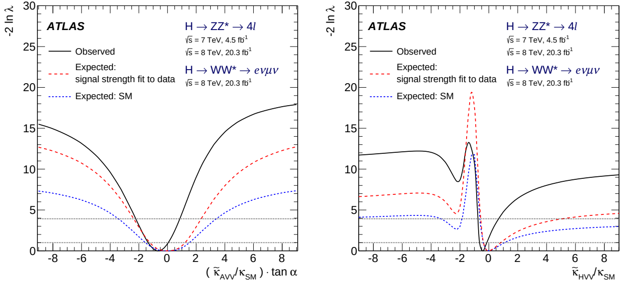
Summary morphing method

- Morphing method is well advanced and validated
- Draft of ATLAS PUB note describing the morphing: https://cds.cern.ch/record/2018491
- One of our colleague will give a talk at the HEFT2015 in Chicago (4.-6. Nov)

$\rightarrow$ Plan is to have a first version of the note until then

Backup

Result combination tensor structure measurement



Coupling ratio Combined	Best-fit value Observed	95% CL Exclusion Regions Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$