Development of Morphing for Studies of HEFT with ATLAS

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PRISMA Cluster of Excellence

FSP 101 ATLAS

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Outline

- Theoretical framework and analysis prospects
- Morphing method
- Example: VBF H→WW
- VBF vertex study

Introduction

- Signal strength and kinematics depend on **many parameters**
- Parameters do not factorize trivially into individual observables
- Necessary to build a signal model taking **all parameters** into account **simultaneously** & modelling all interference effects → **Morphing**
- Use effective Lagrangian as an example, but can apply same techniques to many other BSM model with large sets of parameters

Effective field theory framework implemented in Higgs Characterisation model

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

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

🟦 Used in Run 1

🟥 Plan Run 2

- Implemented in MadGraph5_aMC@NLO
- $\Lambda = 1\,\text{TeV}$, $\cos\alpha = \frac{1}{\sqrt{2}}$ fixed
- Define full coupling parameter as g_x (e.g. $g_{AWW} = s_\alpha \kappa_{AWW} / \Lambda$)

Analyses overview and plans in ATLAS

Effective Langrangian analyses in Run 1

- Only **small subset** of parameters considered
- Influences of parameters in the matrix element studied **in isolation**
- Cross-section (rate) and kinematics (shape) studied **separately**
- Couplings measurement: `arXiv:1507.04548`
  Spin & parity measurement: `arXiv:1506.05669`

Plans for Run 2

- Perform combined studies of **many (all) parameters** in the matrix element
- Take **all correlations** between different operators into account
- Use constraining power from **rate & shape information**
- Combine results from different channels

→ Challenge: **large parameter space** (e.g. VBF H→VV 13 free parameters)

→ New method to construct predictions for signal cross section and distributions

Morphing

Comparison of methods

- **Needed:** MC samples covering wide range of values for coupling parameters
- Run 1 HWW and HZZ analyses: **Matrix Element Reweighting**
  (Event by event matrix element reweighting of one source MC sample with large statistics)

$$w(\vec{g}_{target}) = w(\vec{g}_i)\frac{|\mathcal{M}(\vec{g}_{target})|^2}{|\mathcal{M}(\vec{g}_{source})|^2}$$

ME Reweighting

For every configuration point

- rerun analysis
- write event weights to disk
- additional interpolation

Morphing

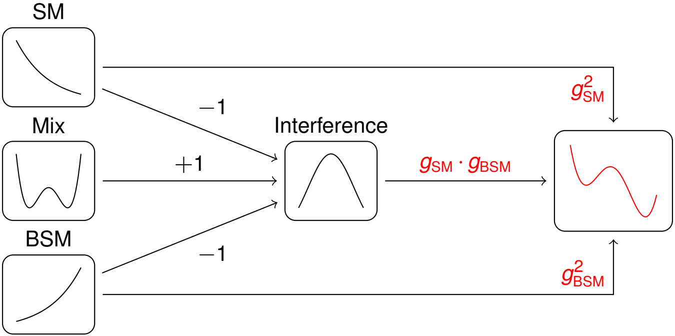
- only calculates linear sums of coefficients
- all other inputs are pre-computed once
- computationally fast & convenient tool

- **Morphing function:** Instead of “matrix element reweighting” use morphing to obtain a distribution with arbitrary coupling parameters
- 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** coupling parameters to data & derive limits

Signal model construction in Run 2: Morphing

- **Morphing function** for an observable T_{out} at any coupling point $\vec{g}_{target}$ constructed from weighted sum of input samples T_{in} at fixed coupling points $\vec{g}_i$

$$T_{out}(\vec{g}_{target}) = \sum_{i=1}^{N_{input}} w_i(\vec{g}_{target}; \vec{g}_i) \cdot T_{in}(\vec{g}_i) \qquad \text{e.g. } T = \Delta\phi_{jj}$$



Example for 2 free parameters in one vertex

- Process with **two parameters** applied in **one vertex**: g_{SM} and g_{BSM}
- Matrix element can be **factorized**:

$$\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}}) = g_{\text{SM}} \mathcal{O}_{\text{SM}} + g_{\text{BSM}} \mathcal{O}_{\text{BSM}}$$
$$|\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2 = g_{\text{SM}}^2 |\mathcal{O}_{\text{SM}}|^2 + g_{\text{BSM}}^2 |\mathcal{O}_{\text{BSM}}|^2 + 2 g_{\text{SM}} g_{\text{BSM}} \mathcal{R}(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}})$$

- **Distribution** of a kinematic observable **proportional to the matrix element squared**

$$T(g_{\text{SM}}, g_{\text{BSM}}) \propto |\mathcal{M}(g_{\text{SM}}, g_{\text{BSM}})|^2$$

- **3 generated distributions** needed to obtain distribution with arbitrary parameters
- E.g. generate MC events for $T(1,0)$, $T(0,1)$, $T(1,1)$

$$T_{in}(1,0) \propto |\mathcal{O}_{\text{SM}}|^2$$
$$T_{in}(0,1) \propto |\mathcal{O}_{\text{BSM}}|^2$$
$$T_{in}(1,1) \propto |\mathcal{O}_{\text{SM}}|^2 + |\mathcal{O}_{\text{BSM}}|^2 + 2\mathcal{R}(\mathcal{O}_{\text{SM}}^* \mathcal{O}_{\text{BSM}})$$

- Distribution with **arbitrary parameters** $(g_{\text{SM}}, g_{\text{BSM}})$

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

Propagation of statistical uncertainties

- Morphing function for a bin in distribution

$$T_{out}^{bin}(\vec{g}_{target}) = \sum_i w_i(\vec{g}_{target}; \vec{g}_i)\, T_{in}^{bin}(\vec{g}_i)$$

- For one input distribution, the bin content is calculated as follows

$$T_{in}^{bin}(\vec{g}_i) = N_{MC,in}^{bin}(\vec{g}_i) \cdot \sigma_{in}(\vec{g}_i)\mathcal{L}/N_{\mathrm{MC,in}}$$

- The uncertainty on that bin is $\sqrt{N_{MC,in}^{bin}(\vec{g}_i)}$
- The propagated statistical uncertainty is

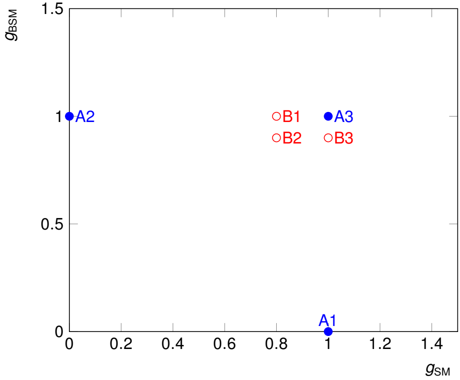
$$\Delta T_{out}^{bin} = \sqrt{\sum_i w_i^2(\vec{g}_{target}; \vec{g}_i) N_{MC,in}^{bin}(\vec{g}_i) \cdot (\sigma_{in}(\vec{g}_i)\mathcal{L}/N_{\mathrm{MC,in}})^2}$$

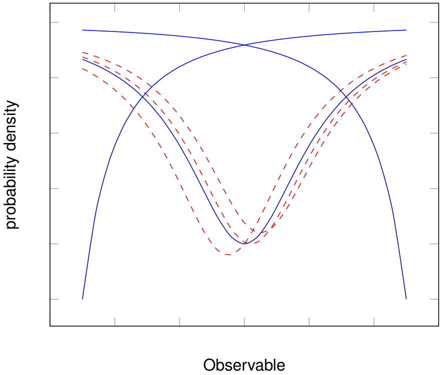
- Highly **dependent** on
  - **input parameters** $\vec{g}_i$
  - desired **target parameters** $\vec{g}_{target}$

Choice of input parameters

- So far fixed parameters for input distributions: $T_{in}(1,0)$, $T_{in}(0,1)$, $T_{in}(1,1)$
- Aim to **generalize morphing** to have arbitrary g_i

→ Can be chosen to **reduce statistical uncertainty**





Example for 2 free parameters in one vertex: generalization of input parameter

- Generalize to **arbitrary input parameters** $\vec{g}_i$ used to generate input distributions $T_{in}(\vec{g}_i)$

$$T_{in}(g_{\mathrm{SM},i}, g_{\mathrm{BSM},i}) \propto {g_{\mathrm{SM},i}}^2 |\mathcal{O}_{\mathrm{SM}}|^2 + {g_{\mathrm{BSM},i}}^2 |\mathcal{O}_{\mathrm{BSM}}|^2 + 2 g_{\mathrm{SM},i} g_{\mathrm{BSM},i} \mathcal{R}(\mathcal{O}^*_{\mathrm{SM}} \mathcal{O}_{\mathrm{BSM}}), \qquad i = 1, \ldots 3$$

- Ansatz for **output distribution**

$$\begin{aligned} T_{out}(g_{\mathrm{SM}}, g_{\mathrm{BSM}}) = & \underbrace{(a_{11} {g_{\mathrm{SM}}}^2 + a_{12} {g_{\mathrm{BSM}}}^2 + a_{13} g_{\mathrm{SM}} g_{\mathrm{BSM}})}_{w_1} T_{in}(g_{\mathrm{SM},1}, g_{\mathrm{BSM},1}) \\ & + \underbrace{(a_{21} {g_{\mathrm{SM}}}^2 + a_{22} {g_{\mathrm{BSM}}}^2 + a_{23} g_{\mathrm{SM}} g_{\mathrm{BSM}})}_{w_2} T_{in}(g_{\mathrm{SM},2}, g_{\mathrm{BSM},2}) \\ & + \underbrace{(a_{31} {g_{\mathrm{SM}}}^2 + a_{32} {g_{\mathrm{BSM}}}^2 + a_{33} g_{\mathrm{SM}} g_{\mathrm{BSM}})}_{w_3} T_{in}(g_{\mathrm{SM},3}, g_{\mathrm{BSM},3}) \end{aligned}$$

Example for 2 0perators in one vertex

- T_{out} should be equal to T_{in} for $\vec{g}_{target} = \vec{g}_i$

$$\begin{aligned} 1 &= a_{11} g_{\mathrm{SM},1}{}^2 + a_{12} g_{\mathrm{BSM},1}{}^2 + a_{13} g_{\mathrm{SM},1} g_{\mathrm{BSM},1} \\ 0 &= a_{21} g_{\mathrm{SM},1}{}^2 + a_{22} g_{\mathrm{BSM},1}{}^2 + a_{23} g_{\mathrm{SM},1} g_{\mathrm{BSM},1} \\ \dots \end{aligned}$$

- Constraints in **matrix form**

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} g_{\mathrm{SM},1}{}^2 & g_{\mathrm{SM},2}{}^2 & g_{\mathrm{SM},3}{}^2 \\ g_{\mathrm{BSM},1}{}^2 & g_{\mathrm{BSM},2}{}^2 & g_{\mathrm{BSM},3}{}^2 \\ g_{\mathrm{SM},1} g_{\mathrm{BSM},1} & g_{\mathrm{SM},2} g_{\mathrm{BSM},2} & g_{\mathrm{SM},3} g_{\mathrm{BSM},3} \end{pmatrix} = \mathbb{1}$$

$$\Leftrightarrow \qquad A \cdot G = \mathbb{1}$$

- **Definite solution** $A = G^{-1}$ requires the samples to have parameters such that $\det(G) \neq 0$
- Very flexible in choosing the parameters for the input distributions

→ Can be chosen to **reduce statistical uncertainty** in considered parameter space

General morphing and number of input distributions

- More complicated when processes share parameters between **production and decay**, for example VBF $H \to VV$
- General matrix element squared at **LO** & assuming **narrow-width-approximation** (ignoring the effect on the total width)
  ⇒ **polynomials** of 2nd order in production and 2nd order in decay

$$T(\vec{g}) \propto |\mathcal{M}(\vec{g})|^2 = \underbrace{\left(\sum_{i=1}^{n_p+n_s} g_i O_i\right)^2}_{\text{production vertex}} \cdot \underbrace{\left(\sum_{j=1}^{n_d+n_s} g_j O_j\right)^2}_{\text{decay vertex}}$$

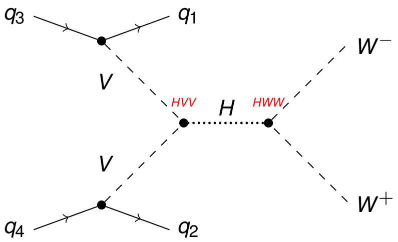
with number of parameters in **production vertex** (n_p), **decay vertex** (n_d) and **shared in vertices** (n_s)

- **Number of required input distributions** equal to number of different terms in expanded matrix element squared
  → dependent on process and considered parameters
  → N_{input} function of n_p, n_d and n_s
- Example: 13 free parameters for VBF H→ZZ process:
  - $n_p = 4$ parameters in production: $g_{\mathrm{HWW}}, g_{\mathrm{AWW}}, g_{\mathrm{H\partial WR}}, g_{\mathrm{H\partial WI}}$
  - $n_s = 9$ parameters in both vertices: $g_{\mathrm{SM}}, g_{\mathrm{HZZ}}, g_{\mathrm{AZZ}}, g_{\mathrm{H\partial Z}}, g_{\mathrm{H\gamma\gamma}}, g_{\mathrm{A\gamma\gamma}}, g_{\mathrm{HZ\gamma}}, g_{\mathrm{AZ\gamma}}, g_{\mathrm{H\partial\gamma}}$
  - $n_d = 0$, no parameters only in decay

→ **1605 samples** needed!

→ Reduction of considered operators favourable → see VBF study

VBF H→WW example



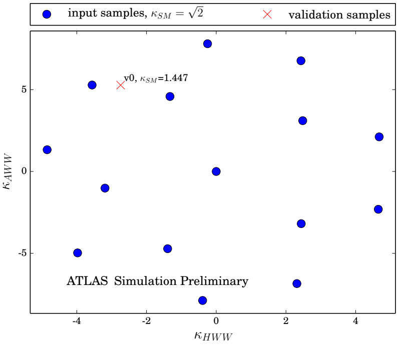
- VBF H→WW process with **SM** (g_{SM}) and **2 BSM** operators (g_{HWW}, g_{AWW})

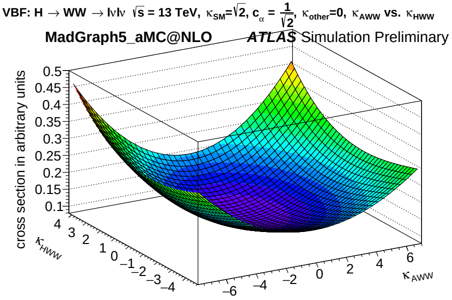
→ **15 samples** with different parameters needed

- 50k events generated for each sample
- Only signal considered
- Kinematic observable used: $\Delta\phi_{jj}$

VBF H→WW example: Samples

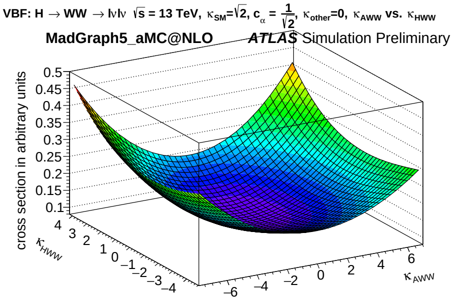
- Expect only **small deviations from SM**
  - → $g_{SM} = 1$ for all input samples ($\Lambda = 1\,\mathrm{TeV}$, $\cos\alpha = \frac{1}{\sqrt{2}}$)
  - → BSM parameter limits chosen such that $\sigma_{\text{pure BSM}} \sim \sigma_{SM}$
  - → all other BSM parameters set to 0
- Scatter plot shows blue points in (g_{AWW},g_{HWW}) space used to generate **input samples**
- A **validation sample** is produced at the red cross for cross-check
  - → **morphing** can reproduce the distribution there
  - → **fit** can reproduce the parameters from the validation sample

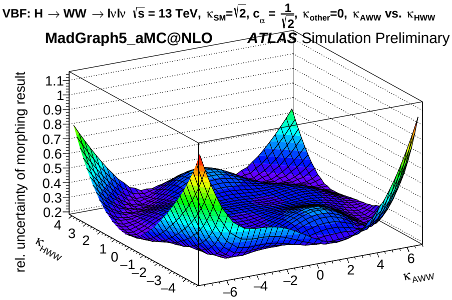




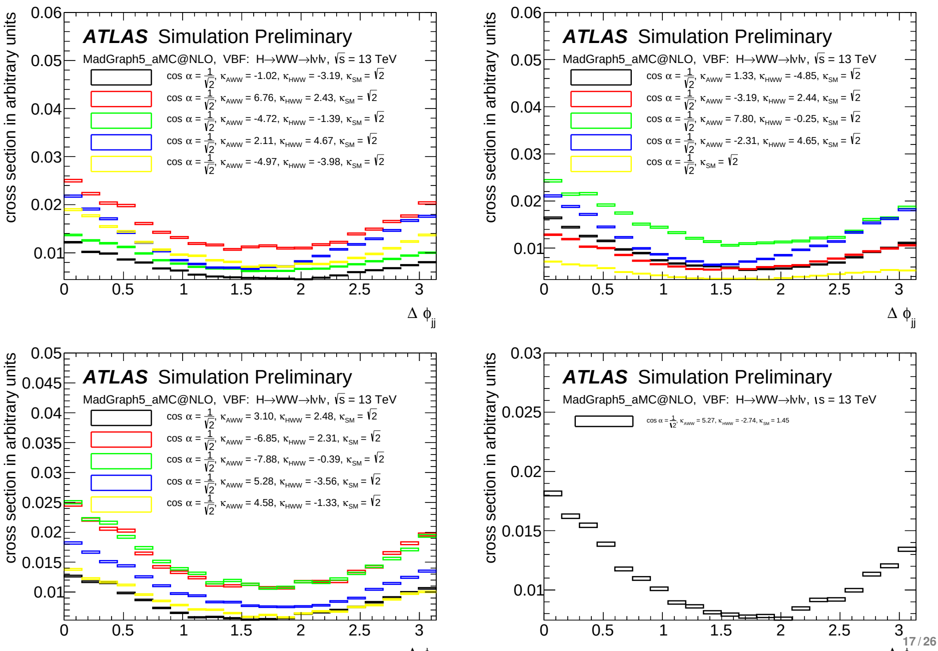
VBF H→WW example: Rel. uncertainty on number of expected events

- Dependence of **stat. uncertainty** propagated in morphing function on generated input parameter grid
- Distribution of samples in parameter space **reduces** stat. uncertainty





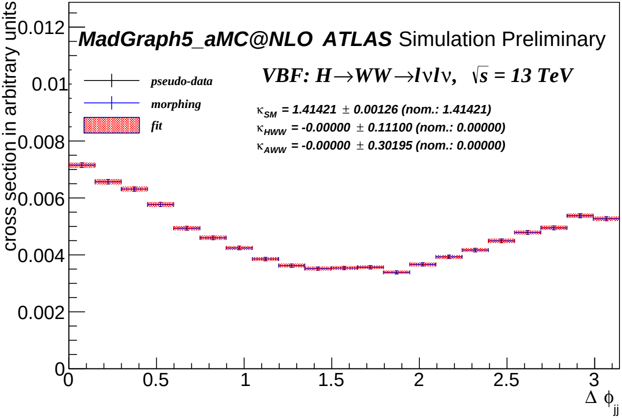
VBF H→WW example: Input and validation distributions



VBF H→WW example: Morphing and fit to SM input sample

- Morphing and fit to SM input distribution (pseudo-data)
- MC stat. uncertainty used
- Input and morphed distribution stat. dependent
  - perfect agreement in morphing
  - Post-fit parameters match exact nominal values
- **Correlations** at SM point in table

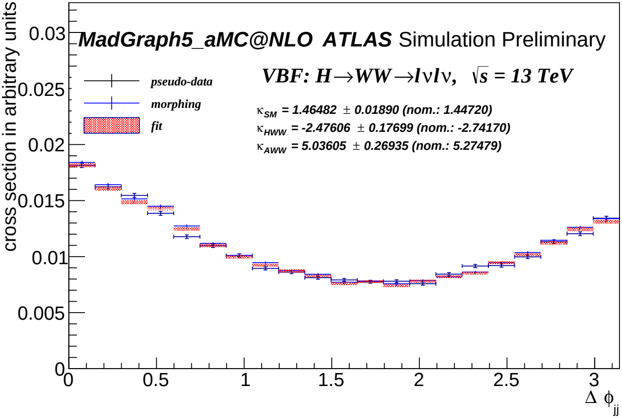
	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.15	-0.23
κ_{HWW}	0.15	1.00	0.36
κ_{AWW}	-0.23	0.36	1.00



VBF H→WW example: Morphing and fit to validation sample

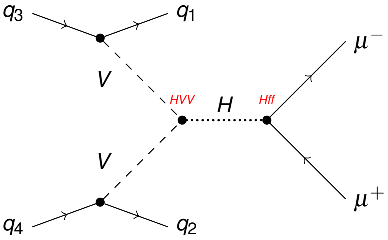
- Morphing and fit to validation distr. (pseudo-data)
- Validation and morphed distribution stat. independent
    - Agreement in morphing within MC stat. uncertainty
    - Fit results match nominal values within fit uncertainties
- **Correlations** vary at different parameter point

	κ_{SM}	κ_{HWW}	κ_{AWW}
κ_{SM}	1.00	0.20	-0.95
κ_{HWW}	0.20	1.00	0.09
κ_{AWW}	-0.95	0.09	1.00



Study of the VBF vertex

- Many operators enter VBF
- Goal: **neglect operators** without losing generality to **minimize number of needed samples**

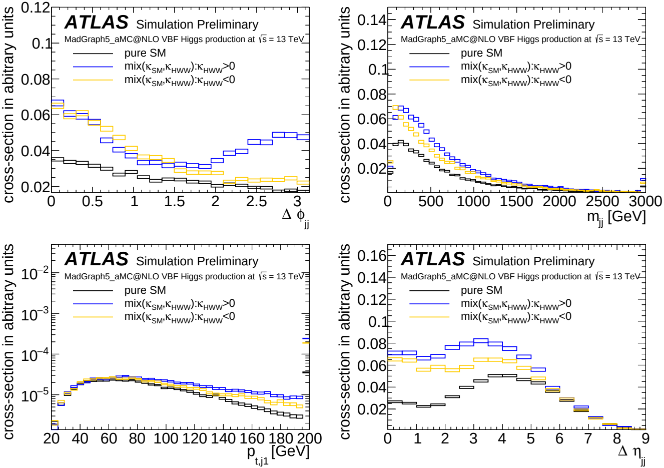


- Technical choice of H→ $\mu\mu$ decay: no crossover between production and decay
- Full set of 13 VBF prod. op. leads to **91 samples** to produce: still manageable
- Generator level, signal only samples used with 30k events each
- Setup **fit to SM input sample**
  - Learn **correlations** between operators
  - Explore **sensitivity**
  - uses observables: $\Delta\phi_{jj}$, p_T^{j1}, m_{jj}, $\Delta\eta_{jj}$
  - Understand which operators have negligible influence on VBF

Cross sections and shapes depending on VBF couplings

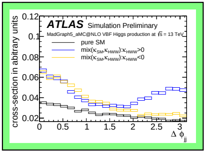
- BSM coupling parameters chosen such that one-operator pure BSM samples correspond to SM VBF cross section

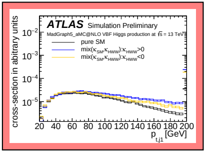
κ_{SM}	1
$\kappa_{\mathrm{H}\gamma\gamma}$	203.22
$\kappa_{\mathrm{A}\gamma\gamma}$	408.62
$\kappa_{\mathrm{HZ}\gamma}$	109.13
$\kappa_{\mathrm{AZ}\gamma}$	986.88
κ_{HZZ}	5.75
κ_{AZZ}	6.96
κ_{HWW}	3.36
κ_{AWW}	3.92
$\kappa_{\mathrm{H}\partial\mathrm{WR}}$	0.76
$\kappa_{\mathrm{H}\partial\mathrm{WI}}$	0.84
$\kappa_{\mathrm{H}\partial\mathrm{A}}$	1.77
$\kappa_{\mathrm{H}\partial\mathrm{Z}}$	1.37

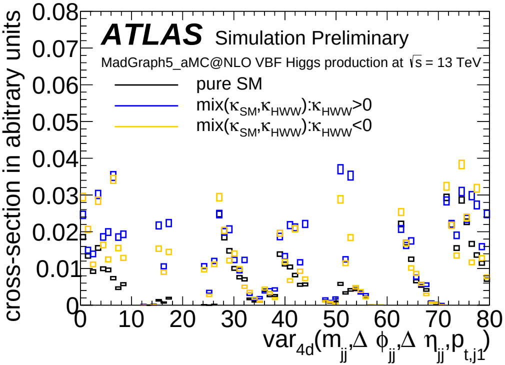


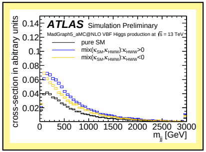
- Production of 91 samples ($\Lambda = 1000\,\mathrm{GeV}$, $\cos\alpha = 1/\sqrt{2}$, $\kappa_{\mathrm{SM}} = \sqrt{2}$)
  - 1 pure SM sample
  - 24 samples with SM + 1 BSM ($\pm\kappa_{\mathrm{BSM}}$)
  - 66 samples with SM + 2 BSM ($+\kappa_{\mathrm{BSM}}$)

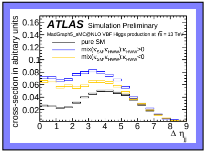
Combined distribution of four observables

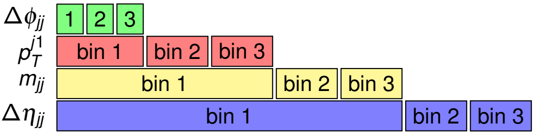












Fit result sensitivity on VBF couplings

parameter	post-fit value	$+$	$-$
Λ	1000.		
$\cos\alpha$	0.71		
$\kappa_{\mathrm{H}\ell\ell}$	1.41		
$\kappa_{\mathrm{A}\gamma\gamma}$	0	$+219$	-441
κ_{AWW}	0	$+3$	-2.6
$\kappa_{\mathrm{AZ}\gamma}$	0	$+441$	-398
κ_{AZZ}	0	$+2.7$	-1.3
$\kappa_{\mathrm{H}\gamma\gamma}$	0	$+236$	-91
$\kappa_{\mathrm{H}\partial\gamma}$	0	$+0.3$	-0.6
$\kappa_{\mathrm{H}\partial\mathrm{Wl}}$	0	$+1.6$	-0
$\kappa_{\mathrm{H}\partial\mathrm{WR}}$	0	$+0.5$	-0.3
$\kappa_{\mathrm{H}\partial\mathrm{Z}}$	0	$+1.2$	-0.5
κ_{HWW}	0	$+1.5$	-3
$\kappa_{\mathrm{HZ}\gamma}$	0	$+38$	-49
κ_{HZZ}	0	$+8$	-2.5
κ_{SM}	1.41	$+0.22$	-0.11

- Simultaneously to all parameters to SM distribution
- Assuming 8% VBF cross section uncertainty
- **Fit uncertainties** give information on **sensitivity**
- Sensitvity on $\gamma\gamma$ and Zγ couplings small
- Close to the SM, 4 couplings (H$\gamma\gamma$, A$\gamma\gamma$, HZγ, AZγ) can be ignored for VBF without loss of generality
- Other measurements will limit this operator to far smaller values
- To be tested that the $\gamma\gamma$ and Zγ operators don't influence any other VBF observable

Fit result correlations of VBF couplings

	$\kappa_{\mathrm{A}\gamma\gamma}$	κ_{AWW}	$\kappa_{\mathrm{AZ}\gamma}$	κ_{AZZ}	$\kappa_{\mathrm{H}\gamma\gamma}$	$\kappa_{\mathrm{H}\partial\gamma}$	$\kappa_{\mathrm{H}\partial\mathrm{WI}}$	$\kappa_{\mathrm{H}\partial\mathrm{WR}}$	$\kappa_{\mathrm{H}\partial\mathrm{Z}}$	κ_{HWW}	$\kappa_{\mathrm{HZ}\gamma}$	κ_{HZZ}	κ_{SM}
$\kappa_{\mathrm{A}\gamma\gamma}$	1.000	0.101	-0.093	0.045	0.113	-0.348	-0.046	0.132	-0.118	-0.167	0.058	0.062	-0.171
κ_{AWW}	0.101	1.000	0.306	-0.377	-0.355	0.220	-0.151	-0.573	0.747	0.282	0.143	-0.245	-0.130
$\kappa_{\mathrm{AZ}\gamma}$	-0.093	0.306	1.000	-0.089	0.170	-0.044	-0.056	0.106	0.008	-0.026	0.208	-0.092	-0.056
κ_{AZZ}	0.045	-0.377	-0.089	1.000	-0.222	0.165	0.415	0.240	-0.326	0.316	0.147	-0.449	0.093
$\kappa_{\mathrm{H}\gamma\gamma}$	0.113	-0.355	0.170	-0.222	1.000	-0.122	-0.201	0.174	-0.262	-0.457	-0.018	0.249	0.004
$\kappa_{\mathrm{H}\partial\gamma}$	-0.348	0.220	-0.044	0.165	-0.122	1.000	-0.151	-0.380	0.369	0.231	0.299	-0.314	0.199
$\kappa_{\mathrm{H}\partial\mathrm{WI}}$	-0.046	-0.151	-0.056	0.415	-0.201	-0.151	1.000	0.090	-0.101	0.247	-0.156	-0.180	-0.002
$\kappa_{\mathrm{H}\partial\mathrm{WR}}$	0.132	-0.573	0.106	0.240	0.174	-0.380	0.090	1.000	-0.944	-0.116	-0.331	0.208	0.019
$\kappa_{\mathrm{H}\partial\mathrm{Z}}$	-0.118	0.747	0.008	-0.326	-0.262	0.369	-0.101	-0.944	1.000	0.193	0.294	-0.191	0.081
κ_{HWW}	-0.167	0.282	-0.026	0.316	-0.457	0.231	0.247	-0.116	0.193	1.000	-0.136	-0.747	-0.065
$\kappa_{\mathrm{HZ}\gamma}$	0.058	0.143	0.208	0.147	-0.018	0.299	-0.156	-0.331	0.294	-0.136	1.000	-0.399	0.230
κ_{HZZ}	0.062	-0.245	-0.092	-0.449	0.249	-0.314	-0.180	0.208	-0.191	-0.747	-0.399	1.000	0.029
κ_{SM}	-0.171	-0.130	-0.056	0.093	0.004	0.199	-0.002	0.019	0.081	-0.065	0.230	0.029	1.000

- Some **large correlations** present **close to the standard model**
- Can likely neglect 1-2 more parameters after rotating into a parameter basis diagonal in this correlation matrix by principle component analysis
- E. g. anti-correlated component between $\kappa_{\mathrm{H}\partial\mathrm{Z}}$ and $\kappa_{\mathrm{H}\partial\mathrm{WR}}$
- Correlations may change away from SM

Generality of the method

- Morphing only requires that any differential cross section can be expressed as **polynomial in BSM couplings**
- Method can be used on **any generator** that allows one to vary input couplings
- Works on **generator** and **reco-level** distributions
- **Independent of physics process**
- Works on distributions and cross sections

Summary

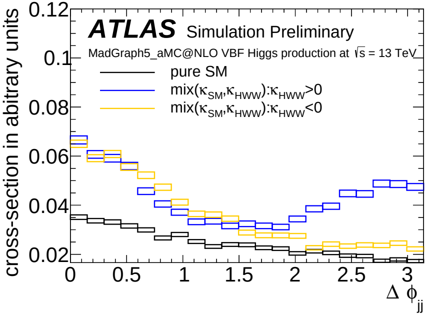
- Plan for Run 2: **Higgs coupling measurements**
- Combine **rate and shape information** within effective Lagrangian framework
- New method for modelling BSM effects
  - continuous
  - analytical
  - fast
- First application: detailed and complete study of **VBF production**
- Next steps
  - Similar study of WH, ZH and $H \to VV$
  - First look into most complex cases of VBF, VH or $H \to VV$
- Pub note: ATL-PHYS-PUB-2015-047

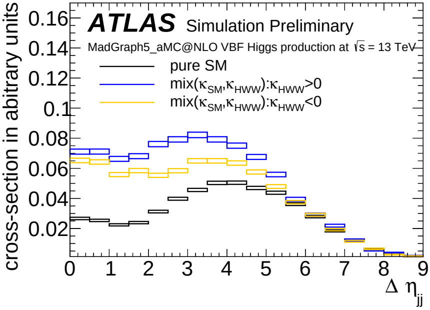
Backup

Number of input distributions

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

with number of parameters in **production vertex** (n_p), **decay vertex** (n_d) and **shared in vertices** (n_s)


ATLAS Simulation Preliminary
MadGraph5_aMC@NLO VBF Higgs production at √s = 13 TeV
pure SM
mix(κ_SM,κ_HWW):κ_HWW>0
mix(κ_SM,κ_HWW):κ_HWW<0
cross-section in abitrary units
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
Δ ϕ_jj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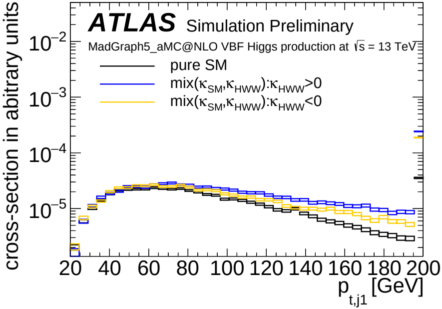
mix(κ_SM,κ_HWW):κ_HWW<0
cross-section in abitrary units
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1
2
3
4
5
6
7
8
9
Δ η_jj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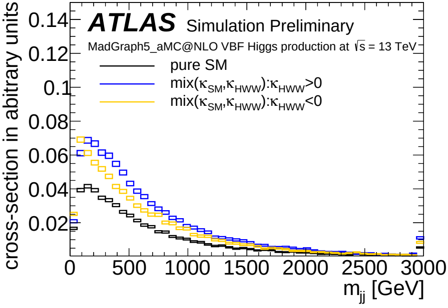
cross-section in abitrary units
10^-2
10^-3
10^-4
10^-5
20
40
60
80
100
120
140
160
180
200
p_t,j1 [GeV]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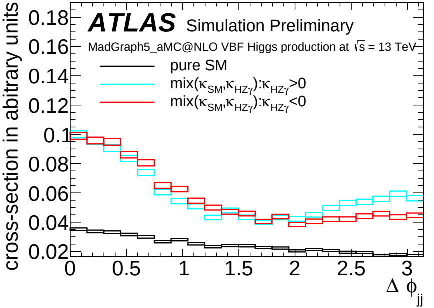
cross-section in abitrary units
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
500
1000
1500
2000
2500
3000
m_jj [GeV]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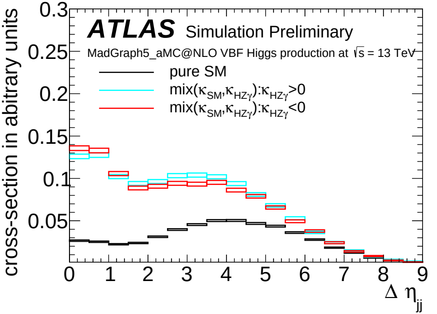
cross-section in abitrary units
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0
0.5
1
1.5
2
2.5
3
$\Delta\phi_{jj}$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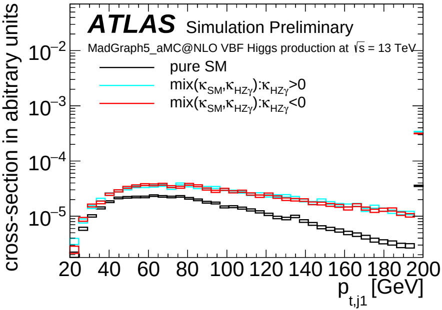
cross-section in abitrary units
0.05
0.1
0.15
0.2
0.25
0.3
0
1
2
3
4
5
6
7
8
9
$\Delta\eta_{jj}$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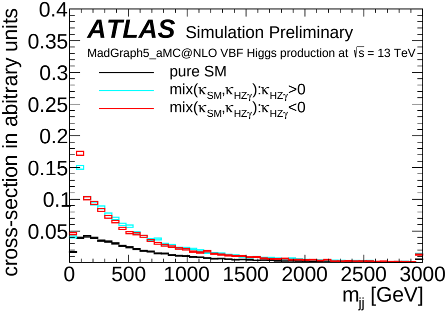
cross-section in abitrary units
10^{-5}
10^{-4}
10^{-3}
10^{-2}
20
40
60
80
100
120
140
160
180
200
$p_{t,j1}$ [GeV]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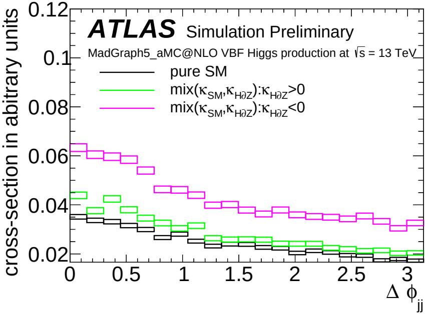
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
500
1000
1500
2000
2500
3000
m_{jj} [GeV]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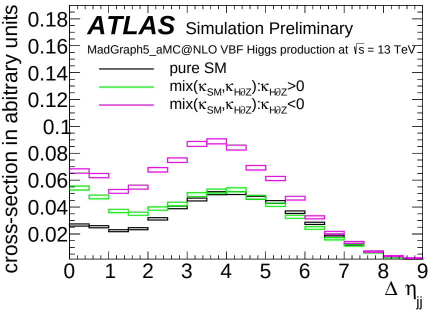
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
Δ φjj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0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
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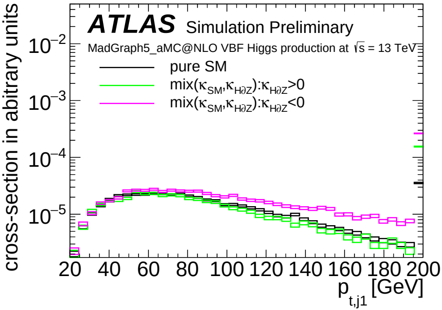
Δ ηjj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10−2
10−3
10−4
10−5
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40
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80
100
120
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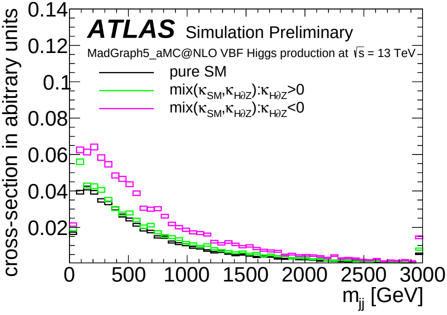
160
180
200
pt,j1 [GeV]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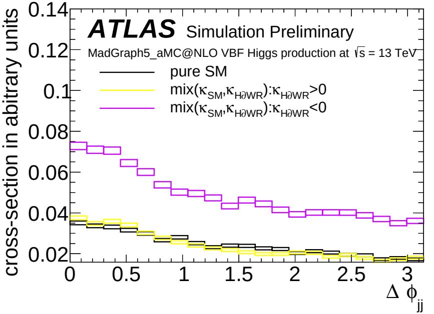
0.1
0.08
0.06
0.04
0.02
0
500
1000
1500
2000
2500
3000
mjj [GeV]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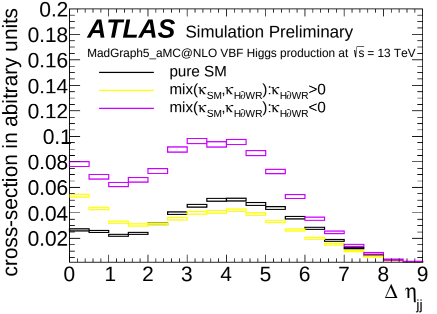
1.5
2
2.5
3
Δ φjj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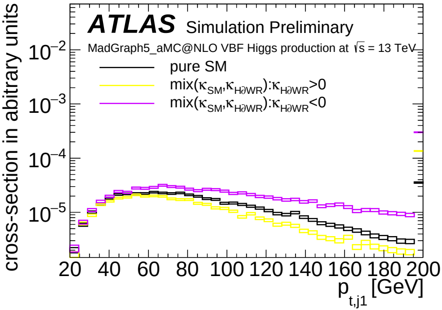
Δ ηjj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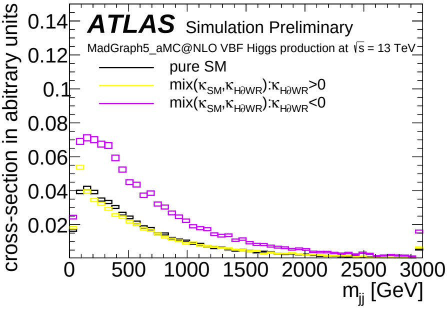
180
200
pt,j1 [GeV]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