Effective Field Theory interpretation of the $pp \rightarrow H \rightarrow 4\ell$ Higgs boson decay measurements with the ATLAS detector

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Standard Model Effective Field Theory

- Effective Field Theories assume that new physics occurs at an energy scale, Λ, much greater than the interaction energy $E << \Lambda$
- SMEFT extends the Standard Model (SM) Lagrangian by introducing higher-dimensional operators:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \dots$$

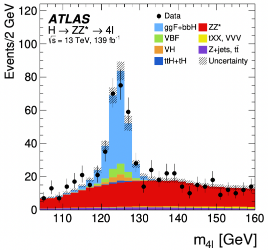
$$\text{where} \quad \mathcal{L}^{(D)} = \sum_i \frac{C_i^{(D)}}{\Lambda^{D-4}} O_i^{(D)}$$

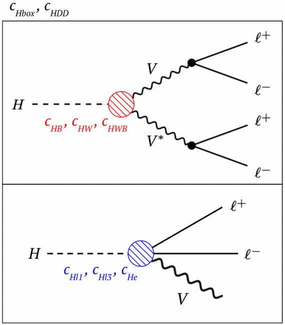
- The leading contributions to new physics are from the dimension-6 operators:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i = \mathcal{L}_{SM} + \sum_i c_i O_i$$

$H \to 4\ell$ Decay Channel

arxiv.org/pdf/2004.03447.pdf

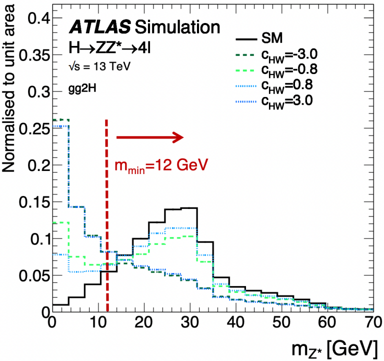




- The $H \to 4\ell$ decay channel has a clear Higgs boson signature and a high signal-to-background ratio
- Generate events with a Higgs boson decaying into two pairs of oppositely charged leptons
- Wilson Coefficients, c_i, associated with the couplings between the Higgs boson and its decay products
- 8 Wilson Coefficients are considered:
  - c_{Hbox}, c_{HDD}
  - c_{HB}, c_{HW}, c_{HWB}
  - c_{Hl1}, c_{Hl3}, c_{He}

$H \to 4\ell$ Decay Channel

- There are several observables which are strongly dependent on some of the Wilson Coefficients, c_i
- The strongest BSM dependence is in the invariant mass of the off-shell Z-boson (m_{Z*})
- An event selection cut of $m_{Z*} > 12 GeV$ is introduced to suppress the background



arxiv.org/pdf/2004.03447.pdf

Acceptance Corrections

- Signal Acceptance:

$$A^{BSM} = \frac{N^{BSM}_{fiducial}}{N^{BSM}_{total}} \Rightarrow \frac{A^{BSM}}{A^{SM}} \propto \frac{\sigma^{BSM}_{fid}(c_i)/\sigma^{SM}_{fid}}{\sigma^{BSM}_{tot}(c_i)/\sigma^{SM}_{tot}}$$

- The cross section can be parametrised in terms of the Wilson Coefficients, c_i:

$$\frac{\sigma^{BSM}(c_{ij})}{\sigma^{SM}} = 1 + \sum_i \alpha_i c_i + \sum_{i,j} \beta_{ij} c_i c_j$$

- For one coupling, the acceptance can be approximated using a Taylor expansion:

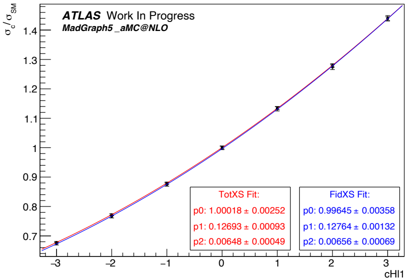
$$\frac{A^{BSM}}{A^{SM}} = \frac{1 + a_{fid} c_i + b_{fid} c_i^2}{1 + a_{tot} c_i + b_{tot} c_i^2}$$

$$\approx 1 + (a_{fid} - a_{tot}) c_i + (b_{fid} - b_{tot} - a_{fid} a_{tot}) c_i^2 + \ldots$$

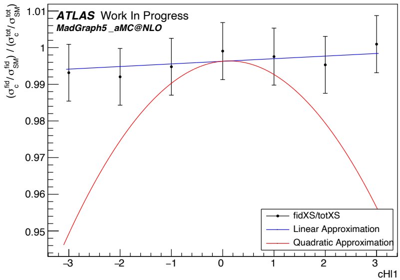
Acceptance Example - c_{Hl1}

- Signal samples with 200,000 events were generated using MadGraph5 at NLO, for different c_i values for each of the 8 the Wilson coefficients considered
- An example for c_{Hl1} :

Cross Section



Acceptance



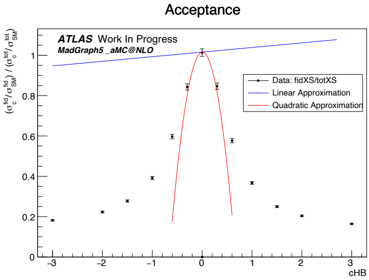
$$\Rightarrow \frac{A^{BSM}}{A^{SM}} \approx 0.9966 + 0.0012 c_{Hl1} - 0.0161 c_{Hl1}^2$$

Acceptance Parametrisation

- The acceptance was calculated for the 8 couplings, in the quadratic approximation, when all other Wilson coefficients are set to zero:

ATLAS Work in Progress

	Quadratic Approximation
c_{Hbox}	$0.997 + 0.002c_{Hbox} - 0.015(c_{Hbox})^2$
c_{HDD}	$0.998 + 0.003c_{HDD} - 0.001(c_{HDD})^2$
c_{Hl1}	$0.996 + 0.002c_{Hl1} - 0.016(c_{Hl1})^2$
c_{Hl3}	$0.998 - 0.001c_{Hl3} - 0.055(c_{Hl3})^2$
c_{He}	$0.998 + 0.001c_{He} - 0.010(c_{He})^2$
c_{HWB}	$1.018 - 0.164c_{HWB} - 0.707(c_{HWB})^2$
c_{HW}	$1.014 + 0.167c_{HW} - 0.649(c_{HW})^2$
c_{HB}	$1.014 + 0.025c_{HB} - 2.339(c_{HB})^2$



- The largest quadratic terms are observed for the Wilson Coefficients defining the coupling between the Higgs and vector bosons, c_{HWB}, c_{HW} and c_{HB}

Quadratic Approximation - Mixed Terms

- To include the quadratic terms in the acceptance, the mixing between the couplings must also be considered
- For two couplings:

$$\frac{\sigma^{BSM}(c_1, c_2)}{\sigma^{SM}} = 1 + \alpha_1 c_1 + \beta_1 c_1^2 + \alpha_2 c_2 + \beta_2 c_2^2 + \gamma_{12} c_1 c_2$$

- Two ways to calculate the mixed terms:
  1. Three Point Calculation - The mixed term is calculated from the following approximation:

     $$\sigma_{(c_1=1, c_2=1)} = \gamma_{12} c_1 c_2 + \sigma_{(c_1=1, c_2=0)} + \sigma_{(c_1=0, c_2=1)} - 1$$

  2. 2D Fit - Calculate the acceptance for large number of coupling combinations and extract the mixed term using a two dimensional fit

Mixed Terms Comparison

- From 8 couplings, there are 28 combinations of two couplings
- A selection of the mixed terms are shown below, focusing on the coupling combinations with the largest mixed terms:

ATLAS Work in Progress

	Total Cross Section		**Fiducial Cross Section**	
Couplings:	**Three Points**	**2D Fit**	**Three Points**	**2D Fit**
cHl1, cHe	-0.0031 ± 0.0079	-0.0010 ± 0.0002	-0.0017 ± 0.0113	-0.0011 ± 0.0002
cHl1, cHl3	-0.0094 ± 0.0073	-0.0099 ± 0.0002	-0.0082 ± 0.0104	-0.0102 ± 0.0002
cHW, cHDD	0.06783 ± 0.0111	0.06715 ± 0.0007	0.04187 ± 0.0128	0.04696 ± 0.0006
cHB, cHW	-0.0305 ± 0.0250	-0.0329 ± 0.0030	-0.0596 ± 0.018	-0.0607 ± 0.0015
cHW, cHWB	-1.3105 ± 0.0124	-1.3106 ± 0.0015	-0.1512 ± 0.0132	-0.1537 ± 0.0009
cHB, cHWB	-1.4263 ± 0.0228	-1.4264 ± 0.0030	-0.2048 ± 0.0173	-0.1857 ± 0.0015

- 2D fit provides an error on the mixed terms which is ~ 10x smaller than the three point calculation

2D Acceptance

- Mixed terms largest for (c_{HB}, c_{HWB}):

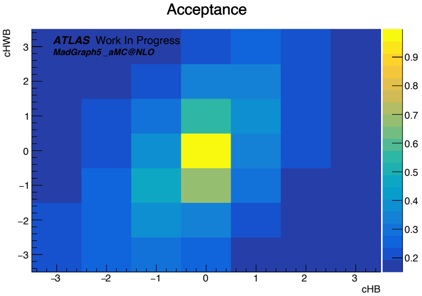
  Fiducial Cross Section (2D fit):

  $0.998 - 0.084c_{HB} + 0.020c_{HWB} + 0.364c_{HB}^2 + 0.100c_{HWB}^2 - 0.186c_{HB}c_{HWB}$

  Total Cross Section (2D fit):

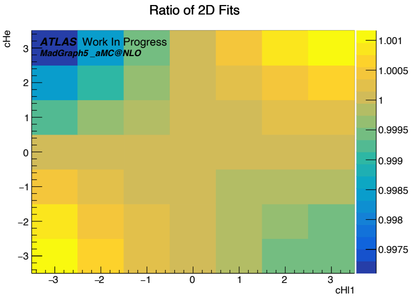
  $0.999 - 0.112c_{HB} + 0.180c_{HWB} + 2.658c_{HB}^2 + 0.791c_{HWB}^2 - 1.426c_{HB}c_{HWB}$

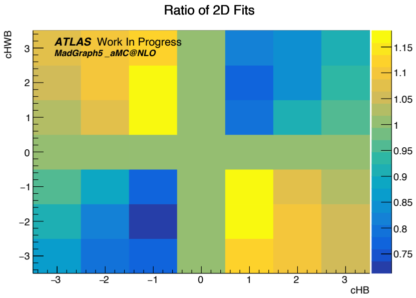
- Acceptance for two couplings is approximated by the ratio of the 2D fitting functions of the fiducial and total cross section:



Impact of Mixed Terms

- Taking the ratio of the acceptance approximations with and without the mixed terms shows the mixed terms can contribute up to $\sim 15\%$ to the overall acceptance:





Conclusions

- Effect of the Standard Model Effective Field Theory on the $H \to 4\ell$ decay channel was investigated, with a focus on calculating the acceptance corrections
- For some Wilson coefficients, the contribution of the quadratic terms to the acceptance is large
- To include the quadratic terms when determining the acceptance, one also must include the mixed terms
- The mixed terms are largest for the Wilson Coefficients associated with the coupling of the Higgs boson to the vector bosons and these terms can contribute up to $\sim 15\%$ of the overall acceptance

BACKUP

SMEFT Operators - $H \to 4l$

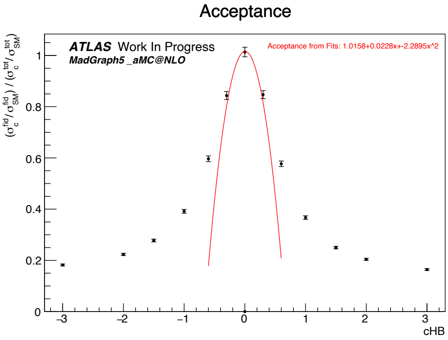
Wilson Coefficient	Operator
c_{Hbox}	$(H^\dagger H)\Box(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
c_{Hl1}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
c_{Hl3}	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$

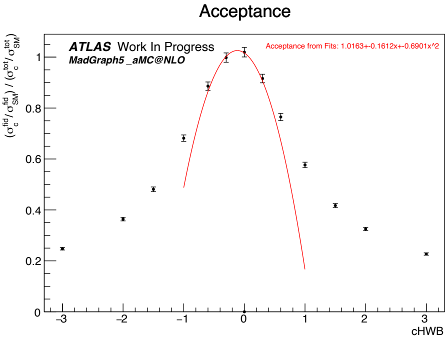
Acceptance - Full Taylor Expansion

$$\frac{A^{BSM}}{A^{SM}} = \frac{a_{fid} + b_{fid} c_i + c_{fid} c_i^2}{a_{tot} + b_{tot} c_i + c_{tot} c_i^2}$$

$$\approx a_{fid} a_{tot} + (a_{tot} b_{fid} - a_{fid} b_{tot}) c_i + (a_{tot} c_{fid} - a_{fid} c_{tot} - b_{fid} b_{tot}) c_i^2 + \ldots$$

Acceptance Parametrisation





Acceptance Parametrisation (Linear Approximation):

$$1 + 0.163c_{HW} + 0.023c_{HB} - 0.161c_{HWB}$$

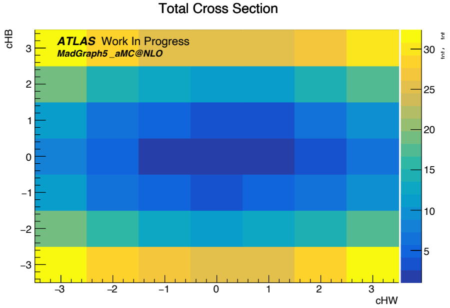
Cross Sections

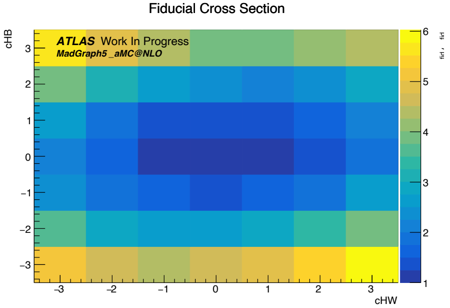
	Fiducial Fit:	Total Fit:
cHbox	$0.997 + 0.122c_{Hbox} + 0.004(c_{Hbox})^2$	$1.000 + 0.120c_{Hbox} + 0.004(c_{Hbox})^2$
cHe	$0.998 - 0.101c_{He} + 0.006(c_{He})^2$	$1.000 - 0.102c_{He} + 0.006(c_{He})^2$
cHl1	$0.0996 + 0.128c_{Hl1} + 0.007(c_{Hl1})^2$	$1.000 + 0.127c_{Hl1} + 0.007(c_{Hl1})^2$
cHl3	$0.998 - 0.236c_{Hl3} + 0.016(c_{Hl3})^2$	$1.000 - 0.235c_{Hl3} + 0.016(c_{Hl3})^2$
cHDD	$0.998 + 0.008c_{HDD} + 0.018(c_{HDD})^2$	$1.000 + 0.005c_{HDD} + 0.019(c_{HDD})^2$
cHWB	$1.017 + 0.019c_{HWB} + 0.101(c_{HWB})^2$	$1.001 + 0.180c_{HWB} + 0.791(c_{HWB})^2$
cHW	$1.014 - 0.037c_{HW} + 0.121(c_{HW})^2$	$1.000 - 0.200c_{HW} + 0.752(c_{HW})^2$
cHB	$1.015 - 0.089c_{HB} + 0.368(c_{HB})^2$	$0.999 - 0.112c_{HB} + 2.657(c_{HB})^2$

Linear Approximation of the Acceptance:

$$1.029 + 0.002c_{Hbox} - 0.001c_{He} + 0.001c_{Hl1} - 0.001c_{Hl3} + 0.003c_{HDD} - 0.161c_{HWB} + 0.163c_{HW} + 0.023c_{HB}$$

2D Cross Section - cHW, cHB





2D Fit: $1.000 - 0.201x - 0.114y$

$-0.033xy + 0.752x^2 + 2.66y^2$

Mixed term from 1D fits:

$-0.031xy$

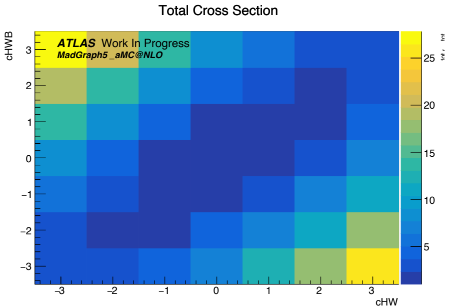
2D Fit: $1.000 - 0.040x - 0.089y$

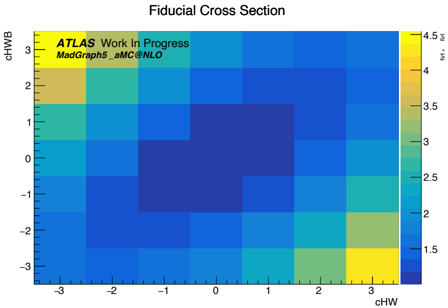
$-0.061xy + 0.118x^2 + 0.363y^2$

Mixed term from 1D fits:

$-0.058xy$

2D Cross Section - cHW, cHWB





2D Fit: $1.000 - 0.199x + 0.180y$

$-1.311xy + 0.751x^2 + 0.791y^2$

Mixed term from 1D fits:

$-1.309xy$

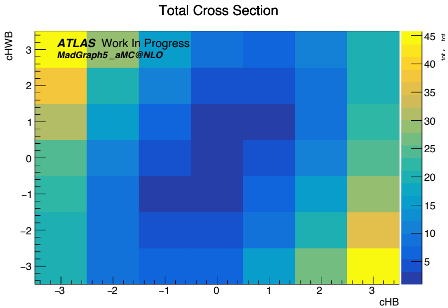
2D Fit: $1.000 - 0.039x + 0.020y$

$-0.154xy + 0.118x^2 + 0.101y^2$

Mixed term from 1D fits:

$-0.156xy$

2D Cross Section - cHB, cHWB

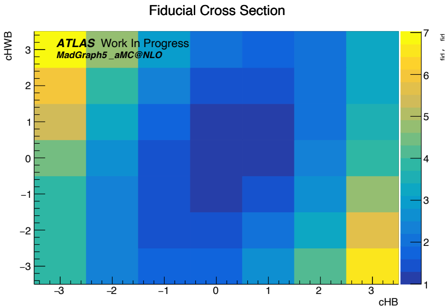


2D Fit: $0.999 - 0.112x + 0.180y$

$-1.426xy + 2.658x^2 + 0.791y^2$

Mixed term from 1D fits:

$-1.427xy$



2D Fit: $0.998 - 0.084x + 0.020y$

$-0.186xy + 0.364x^2 + 0.100y^2$

Mixed term from 1D fits:

$-0.200xy$

2D Acceptance