Framework for Extracting (Effective) Higgs Couplings in $h \to 4\ell$

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Parametrization of Effective Couplings

- Can consider the following $d \lesssim 5$ Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset & \frac{1}{4v}\Big(2A_1^{ZZ} m_Z^2 h Z^\mu Z_\mu + A_2^{ZZ} h Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} h Z^{\mu\nu} \widetilde{Z}_{\mu\nu} \\
- & 4A_4^{ZZ} h Z_\mu \Box Z^\mu - 2A_5^{ZZ} (\frac{m_Z}{m_h})^2 \Box h Z_\mu Z^\mu \\
+ & 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu}\Big)
\end{aligned}
$$

- In 1-to-1 mapping to usual $d = 6$ operators using Higgs doublet
- Leads to the vertex structures,

$$
\begin{aligned}
\Gamma_i^{\mu\nu} = & \frac{i}{v}\Big((A_1^i + A_4^i(\frac{k_1^2 + k_2^2}{m_Z^2}) + A_5^i(\frac{\hat{s}}{m_h^2}))m_Z^2 g^{\mu\nu} \\
+ & A_2^i(k_1^\nu k_2^\mu - k_1 \cdot k_2 g^{\mu\nu}) + A_3^i \epsilon^{\mu\nu\alpha\beta} k_{1\alpha} k_{2\beta}\Big)
\end{aligned}
$$

(where $A_1^{Z\gamma,\gamma\gamma} = A_4^{Z\gamma,\gamma\gamma} = A_5^{Z\gamma,\gamma\gamma} = 0$)

- Note that only sensitive to A_5^{ZZ} for off-shell Higgs decays
- Need framework which can extract these couplings simultaneously

Constructing 'Sensitivity Curves'

- Let us start by examining 'sensitivity curves' for the hVV' loop induced couplings as a function of number of events (or luminosity)
- Consider a (slightly) simplified parametrization (fixing $A_1^{ZZ} = 2$):

$$\mathcal{L} \supset \frac{h}{4v}\Big(2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \widetilde{Z}_{\mu\nu} + 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu}\Big)$$

- We perform a 6D parameter fit to the 6 loop induced couplings:

$$\vec{A} = (A_2^{ZZ}, A_3^{ZZ}, A_2^{Z\gamma}, A_3^{Z\gamma}, A_2^{\gamma\gamma}, A_3^{\gamma\gamma})$$

(In SM A_2^i generated at 1-loop and $\mathcal{O}(10^{-2} - 10^{-3})$ while A_3^i only appear at 3-loop)

- All couplings floated simultaneously to keep all correlations
- We plot the 'average error' as function of number of events:

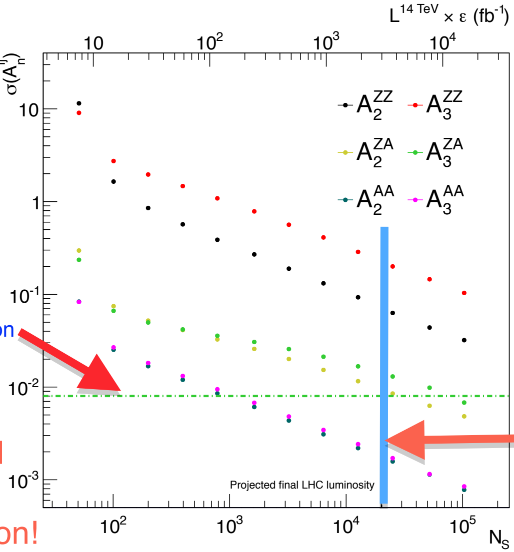
$$\sigma = \sqrt{\frac{\pi}{2}} \langle |\hat{A} - \vec{A}_o| \rangle$$

($\hat{A}$ is best fit point, $\vec{A}_o$ is'true' value, and average taken over large set of PE)

Sensitivity Projections for Couplings: $\vec{A}_o = (0, 0, 0, 0, 0, 0)$

For low numbers of events can float the coupling individually and achieve better sensitivity. Can put a meaningful constraint on all couplings and serves as consistency check with other direct measurements.

(Y. Chen, R. Harnik, RVM: arXiv:1404.1336)



All possible interference effects between intermediate states as well as identical final states in case of 4e/4mu are included.

SM value for CP even photon coupling

Approximate end of HL LHC running (3000/fb)

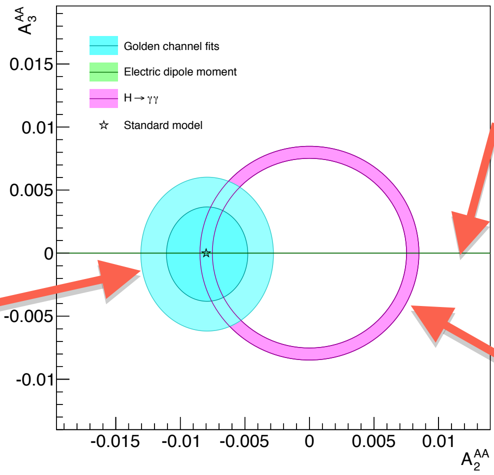
We have applied `CMS-like' cuts and reconstruction!

Golden Channel vs. $h \to \gamma\gamma$ and EDMs: $\vec{A}_o = (0, 0, 0, 0, -0.008, 0)$

- What can be done with $\sim 3000 fb^{-1}$ in golden channel vs. $h \to \gamma\gamma$?

(Y. Chen, R. Harnik, RVM: arXiv:1404.1336)

EDM constraint assuming SM Higgs couplings to 1st gen fermions and 1TeV NP scale



68% and 95% confidence interval from golden channel

The 1 sigma confidence interval from Higgs to di-photon decay

LHC should directly establish CP nature of Higgs couplings to photons!

‘Detector level’ Likelihood

- Of course what we really want is to do all of this at ‘detector level’
- Need a likelihood that takes *reconstructed* observables as input
- This can be done by a convolution of the *analytic* ‘generator level’ *pdf* with a transfer function $T(\vec{X}^R|\vec{X}^G)$ over generator level observables

$$P(\vec{X}^{\mathrm{R}}|\vec{A}) = \int P(\vec{X}^{\mathrm{G}}|\vec{A})T(\vec{X}^{R}|\vec{X}^{G})d\vec{X}^{\mathrm{G}}$$

$$\vec{X} \equiv (\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega})$$

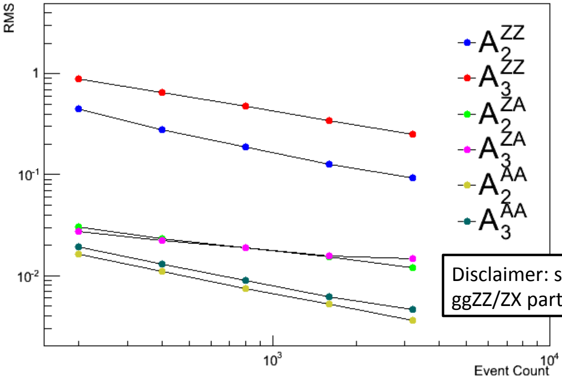
Note: Not done by MC integration $\Rightarrow$ done via C.O.V. and numerical techniques

- $T(\vec{X}^R|\vec{X}^G)$ represents probability to observe $\vec{X}^R$ given $\vec{X}^G$
- Can be optimized for specific detector and included in convolution
- This integration takes us from generator level observables ($\vec{X}^G$) to detector level (reconstructed) observables ($\vec{X}^R$)
- Conceptually simple, but requires a number of steps to perform (and massive computing) details in arXiv:1401.2077 and technical note to appear soon
- We have performed this 12-D convolution for signal and background

The 6D Fit at *Detector Level*: $\vec{A}_o = (0, 0, 0, 0, 0, 0)$

- We perform same 'toy' 6D fit as in generator (signal only) case
- Includes detector as well as (most) background and production effects
  - All ratios are fitted simultaneously

Very preliminary!



Absolute scale is related to the pure term cross section. Will be clearer once we convert to fa3-like quantites

Disclaimer: systematics not included ggZZ/ZX parts needs to be finalized!

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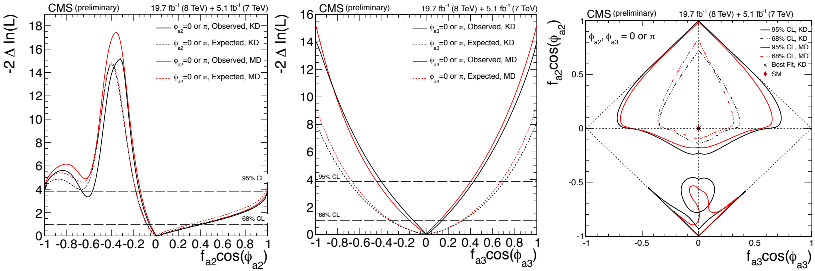
- We see very similar sensitivity to 'generator level' analysis

- Used in recent CMS study of anomalous hVV couplings in $h \to 4\ell$



- Used in a limited scope so as validate with other other frameworks
- Performance in these cases was found to be similar
- Can begin utilizing full power of framework in future studies
- A simultaneous extraction of all effective Higgs couplings!

Summary

- Can use $h \to 4\ell$ to extract Higgs couplings to $ZZ, Z\gamma$, and $\gamma\gamma$
- For anomalous couplings strongest sensitivity will be for $\gamma\gamma$
- We have built a complete framework which can extract all couplings simultaneously and at 'detector level' in short computing time
- Independent of parametrization and easily adapted to whichever parametrization is most convenient at a given time
- Also can be used to search for other NP like exotic Higgs decays
- Framework is also easily adapted to $h \to 2\ell\gamma$ and $h \to \gamma\gamma$

THANKS!

For more information see:

Y. Chen, N. Tran, RVM: arXiv:1211.1959,
Y. Chen, RVM: arXiv:1310.2893,
Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, RVM, S. Xie: arXiv:1401.2077,
Y. Chen, R. Harnick, RVM: arXiv:1404.1336,
CMS Collaboration: CMS PAS HIG-14-014

Extra Slides

The Full *PDF*

- We need a function for the 'production' spectrum to form full pdf

$$P(\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega}|\vec{A}) =$$
$$W_{\rm prod}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(\hat{s}, M_1, M_2, \vec{\Omega}|\vec{A})}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

Note decay part treated at fixed $\hat{s}$

- For signal W_{prod} includes NLO $gg \to h$ process (can include VBF)
- For BG NLO $q\bar{q} \to 4\ell, gg \to 4\ell, qg, q\bar{q} \to 4\ell + j$ (and $Z + X$)
- Of course W_{prod} also includes parton distribution functions
- Several options for obtaining W_{prod}:
  - Compute as much analytically as possible
  - Can construct 'analytic parametrizations' of W_{prod}
  - Use 'look up' tables and boost events accordingly
  - A 'hybrid method' of these approaches
- Since we ultimately fit to ratios of parameters and average over $(\vec{p}_T, Y, \phi)$, analysis largely insensitive to 'production effects'
- Enters mainly as an acceptance effect due to detector

Constructing a Maximum Likelihood Analysis

- A likelihood can be formed out of probability density functions (*pdfs*) using some set of observables as follows

$$L(\vec{A}) = \prod_{\mathcal{O}}^{N} \mathcal{P}(\mathcal{O}|\vec{A})$$

(where $\mathcal{O}$ is set of observables and $\vec{A}$ a set of undetermined parameters)

- $\mathcal{P}(\mathcal{O}|\vec{A})$ built out of fully differential cross section for observables
- The *pdf* takes in the set observables $\mathcal{O}$ as its input
- $L(\vec{A})$ is a function of undetermined parameters and represents the likelihood for observing a given data set (N events of $\mathcal{O}$)
- With this one can go on to do direct parameter extraction of $\vec{A}$

Parameter Extraction From Maximum Likelihood

- This is done by maximizing the likelihood with respect to $\vec{A}$

$$\frac{\partial L(\vec{A})}{\partial \vec{A}}\bigg|_{\vec{A}=\hat{A}} = 0$$

- For a given data set of N events $\hat{A}$ gives the value of the parameter which maximizes the likelihood OR the most likely value of $\vec{A}$
- To estimate error repeat for a large set of $\mathcal{N}$ pseudo-experiments and obtain a distribution for $\hat{A}$ with a given spread and average value $\bar{A}$
- The true value $\vec{A}_o$ will sit in some interval around $\bar{A}$
- In the limit as $\mathcal{N} \to \infty$ one will find $\bar{A} \to \vec{A}_o$
- Conceptually straightforward, but technically challenging...

Summary of Framework for Parameter Extraction

Extracting of Effective Higgs Couplings in Golden Channel

- Obtain analytic generator level pdf $P(\vec{X}^G|\vec{A})$ (i.e. fully diff cxn)
- Perform convolution with transfer function over 12 CM variables

$$P(\vec{X}^{\mathrm{R}}|\vec{A}) = \int P(\vec{X}^{\mathrm{G}}|\vec{A}) T(\vec{X}^R|\vec{X}^G) d\vec{X}^{\mathrm{G}}$$

- Normalize over $\vec{X}^R$; build detector level likelihood as function of $\vec{A}$

$$L(\vec{A}) = \prod_{\vec{X}^R}^{N} \mathcal{P}(\vec{X}^R|\vec{A})$$

- Maximize likelihood with respect to undetermined parameters

$$\frac{\partial L(\vec{A})}{\partial \vec{A}}\Big|_{\vec{A}=\hat{A}} = 0$$

- Obtain $\hat{A}$ for data set of N observables $\Rightarrow$ Extract Higgs couplings

Advantages of Framework for Parameter Extraction

- Speed, Stability, and Precision:
  - Because final likelihood is an 'analytic' (simple quadratic) function of parameters $\vec{A}$, once likelihood is built, parameter fitting extremely fast
  - Even for large number of events or multi-dimensional parameter fits
  - Maximum of the likelihood is always found with very high convergence rate ($> 99\%$) $\Rightarrow$ accurate and precise extraction of parameters
- Flexibility and Generality:
  - One can easily perform any combination of parameter fits desired
  - Trivial to perform reparametrizations of parameters for more intuitive interpretation or to avoid degeneracies in parameter space
  - Allows us to account for potential correlations between parameters
  - Can incorporate different transfer functions to include detector effects
  - Easy to include other exotic Higgs interactions, i.e. $Z's$, VLLs, etc.
- Intuitiveness and Transparency of Physics:
  - Conceptually straightforward: we simply maximize the likelihood, no hypothesis testing or construction of descriminants
  - Interpretation of physics is straightforward and transparent
- Likelihood is (mostly) un-binned and uses all 8 decay observables!