Mining the Golden Channel:

Searching for New Physics in $h \to 4\ell$

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(In collaboration with Yi Chen, Adam Falkowski, Roni Harnik, and Daniel Stolarski)

Physics Possibilities in $h \to 4\ell$ 'Golden Channel'

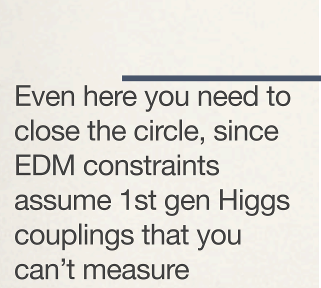
- Measuring/constraining 'anomalous' hVV Couplings
- Establishing CP properties $\Rightarrow$ searching for CP violation (CPV)
- Constraining 'Wilson coefficients' in EFT
- Exotic Higgs decays
- Probing loop effects in hVV couplings
- Performing multi-parameter extraction at LHC
- Also possibilities in closely related $h \to 2\ell\gamma$

(In collaboration with: Adam Falkowski, Roni Harnik, Ian Low, Joe Lykken, Daniel Stolarski

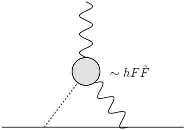
and CMS experimentalists Yi Chen, Emanuele DiMarco, Maria Spiropulu, Si Xie)

Need for Direct Probes of hVV CP Properties

- Many indirect constraints on CP properties:
  - Constraints from EWPD
  - Measurements of $h \to SM$ decay rates
  - The most severe constraints come from EDMs
- These are indirect and rely on model dependent assumptions



γ operator:
already severely constrained by e and q EDMs
McKeen, Pospelov, Ritz '12

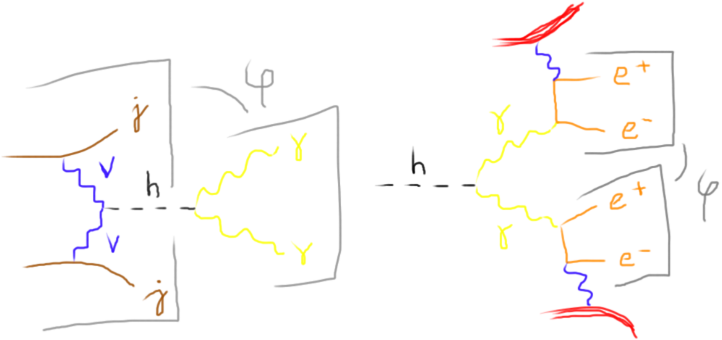


(figure stolen from Joe Lykken Madrid Higgs workshop talk)

- Can not establish overall signs even with theory assumptions
- Direct probes of CP are needed free of these assumptions

Proposals for Direct Probes of $h\gamma\gamma$ CP Properties

- Can we directly probe the CP nature of $h - \gamma\gamma$ couplings?
- Recent proposals include:
  - Measuring correlations in $VBF \to \gamma\gamma$ (M. Buckley, M. Ramsey-Musolf: 1208.4840)
  - Measuring correlations between photons which convert in detector (F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J.Shu, J. Zupan: 1312.2955)



- Interesting, but experimentally very challenging measurements

Many Studies of hZZ Couplings in $h \to 4\ell$

Many studies dedicated to via *tree level hZZ* coupling

Strategies for studying the hZZ CP properties also were proposed

R. M. Godbole, D. Miller, M. Muhlleitner: **0708.0458**
Q. Cao, C. Jackson, W.Y. Keung, I. Low: **0911.3398**
Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
J. Gainer, K. Kumar, I. Low, RVM: **1108.2274**
S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, et. al: **1208.4018**
R. Boughezal, T. LeCompte, F. Petriello: **1208.4311**
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, et. al: **1210.0896**
J.M. Cambell, W.T. Giele, C. Williams: **1205.3434**
J.M. Cambell, W.T. Giele, C. Williams: **1204.4424**
Sun, Yi and Wang, Xian-Fu and Gao, Dao-Neng: **1309.4171**
J. Gainer, J. Lykken, et. al.: **1304.4936**
P. Artoisenet, P. de Aquino, F. Demartin, F. Maltoni, et. al: **1306.6464**
T. Chen, J. Gainer, et. al.: **1310.1397**
J. Gainer, J. Lykken, et. al.: **1208.4018**
Gonzales-Alonso, Isidori: **1403.2648**
+ **many others...**

ATLAS and CMS discovered Higgs and begun studies of *hZZ* CP properties

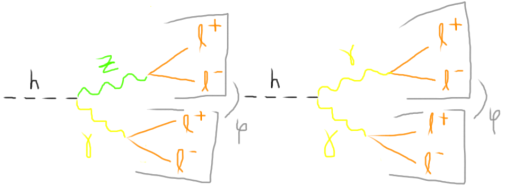
However, golden channel not only $h \to ZZ \to 4\ell$!

New Direct Probes of $h\gamma\gamma$ *and* $hZ\gamma$ CP Properties

- Interference effects in $h \to 4\ell$ give access to CP of hVV couplings

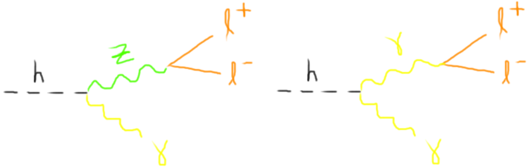
  (Y. Chen, RVM: 1310.2893, Y. Chen, R. Harnick, RVM: 1404.1336, 1503.05855)

  - Sensitivity driven by interference with *tree level ZZ* amplitude



- Can also probe CP in $h \to 2\ell\gamma$ (Y. Chen, A. Falkowski, I. Low, RVM: 1405.6723)
  - Relies on 'strong phase - weak phase' interference which allows for CPV observables even in 3-body decays (Berger, Blanke, Grossman: 1105.0672)

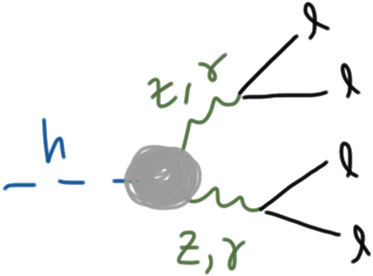
Also a well known effect in B physics



  - Less promising for probing CPV, but *might* be possible at LHC

Anomalous Higgs Couplings in $h \to 4\ell$

- Refers to $h \to VV \to 4\ell$ decay where $4\ell = 2e2\mu, 4e, 4\mu$ and $VV = ZZ, Z\gamma, \gamma\gamma$ (where Z, γ are in general off-shell)



- Can parametrize the hVV couplings with following Lagrangian

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

(For SM at tree level we have $A_1^{ZZ} = 2$ and all others zero)

- In SM, $h \to 4\ell$ rate dominated by tree level A_1^{ZZ} operator

hVV: Measurements

* The SM-like rate to 4ℓ + "scalar evidence" imply that the Higgs is SM-like.
* It is worth emphasizing what we do **not** know:
  - Don't know the sign of the $h\gamma\gamma$ vertex.
  - Don't know its phase w/o assumptions.
  - Constraints on $Z\gamma$ and ZZ high-dim operators are very poor, and will remain so for a while.

Can the golden channel shed light on the small dim-5 operators? which ones?

(Slide stolen from Roni Harnik talk at NPKI, Jeju)

Fully Differential Cxn and Tree Level Higgs 'BG'

- We treat tree level SM operator as 'background' and fix $A_1^{ZZ} = 2$

$$\mathcal{L} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

Background

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Signal

$$+ A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\Big)$$

(Again stolen from Roni Harnik talk at NPKI, Jeju)

- The $h \to 4\ell$ fully differential decay width is computed analytically
- It can be written schematically as:

$$\frac{d\Gamma_{h\to 4\ell}}{d\mathcal{O}} \sim \sum A_n^i A_m^{j*} \times \frac{d\hat{\Gamma}_{nm}^{ij}}{d\mathcal{O}}$$

(Where $i, j = ZZ, Z\gamma, \gamma\gamma$ and $n, m = 1, 2, 3$ and treated at fixed $\hat{s} = m_h^2$)

- Various projections and total width obtained by integration over $\mathcal{O}$
- How well can differential 'sub-widths' be distinguished from SM?
- Can examine total partial widths to get an idea...OR

Total Integrated Magnitudes

- A better indicator of relative sensitivity is to look at 'integrated magnitudes' which we define as the following:

$$\Pi^{ij}_{nm} = A^i_n A^{j*}_m \times \int \left| \frac{d\hat{\Gamma}^{ij}_{nm}}{d\mathcal{O}} \right| d\mathcal{O}$$

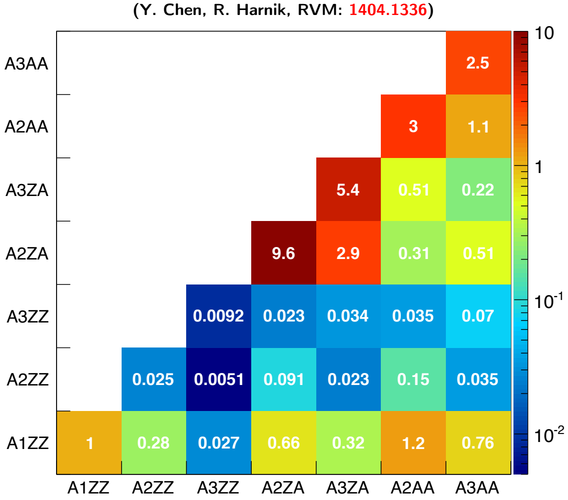
- These are strictly non-zero even in case of CP violation
- Contain some information about shapes of differential spectra
- Give better indication of size of interference effects
- These interference effects give $h \to 4\ell$ sensitivity to CP
- Lets examine for 'CMS-like' cuts setting $A^{ZZ}_1 = 2$ and other $A^i_n = 1$

  We will normalize to tree level SM where $A^{ZZ}_1 = 2$ and all others zero

$$\Pi^{ij}_{nm}/\Gamma^{SM}_{4\ell}$$

Integrated Magnitudes: $\Pi^{ij}_{nm}/\Gamma^{SM}_{4\ell}$ ($A^{ZZ}_1 = 2$, $A^i_n = 1$)

- Integrating over variables we find all the integrated magnitudes

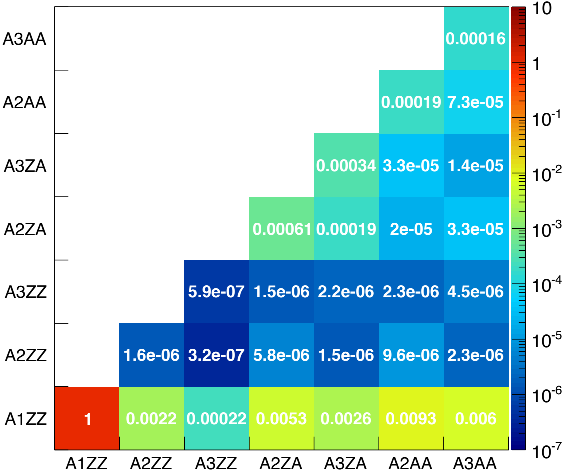


- We see many of the interference terms give sizable contribution

Integrated Magnitudes: $\Pi^{ij}_{nm}/\Gamma^{SM}_{4\ell}$ $(A^{ZZ}_1 = 2,\ A^i_n = 0.008)$

- Of course in SM and most BSM we expect $A^i_n \lesssim \mathcal{O}(10^{-2})$

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



- For points near SM, interference with A^{ZZ}_1 give largest contributions

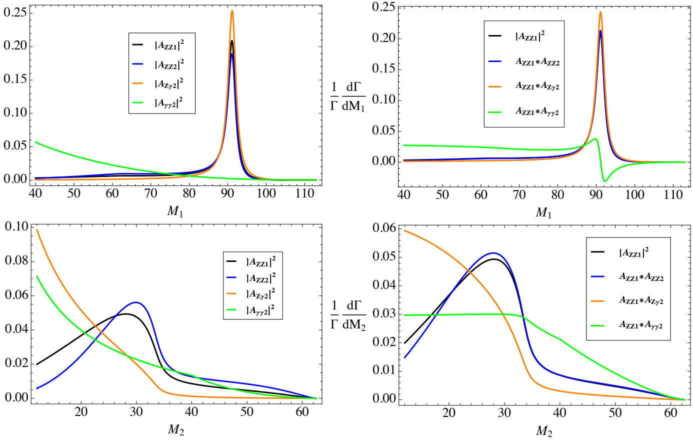
The M_1, M_2 Differential Mass Spectra

- To gain further insight we examine the M_1, M_2 differential spectra

We show $|A_2^i|^2$ on the left and $A_1^{ZZ} * A_2^i$ on the right plotted on top of $|A_1^{ZZ}|^2$ 'BG' (Black)

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

Of course angles help in discrimination as well!



- Easy to see $\gamma\gamma$ most easily distinguished from A_1^{ZZ} 'background'

Constructing ‘Sensitivity Curves’

- Of course in the end we use all (decay) observables available
- Let us examine ‘sensitivity curves’ for the *hVV* loop induced couplings as a function of number of events (or luminosity)
- 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 independently and all correlations included
- We plot the ‘average error’ as function of number of events:

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

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

- We fit to a ‘true’ point of $\vec{A}_o = (0, 0, 0, 0, 0, 0)$ (tree level SM)
- Apply current CMS-like cuts: $p_{T\ell} > 20, 10, 7, 7$ GeV for lepton p_T ordering, $|\eta_\ell| < 2.4$, and 40 GeV $\leq M_1$, 12 GeV $\leq M_2$, $M_1 > M_2$

Sensitivity Projections for Effective Couplings

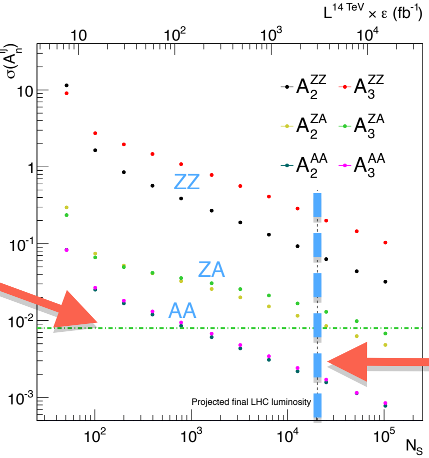
We consider $\sigma(A)$ vs. N_S and $\mathcal{L} \times \epsilon$ for the six ‘anomalous’ couplings

At this point we consider a pure signal sample, i.e. no non-Higgs BG.

SM value for CP even photon coupling

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

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



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

Approximate end of HL LHC running (3000/fb)

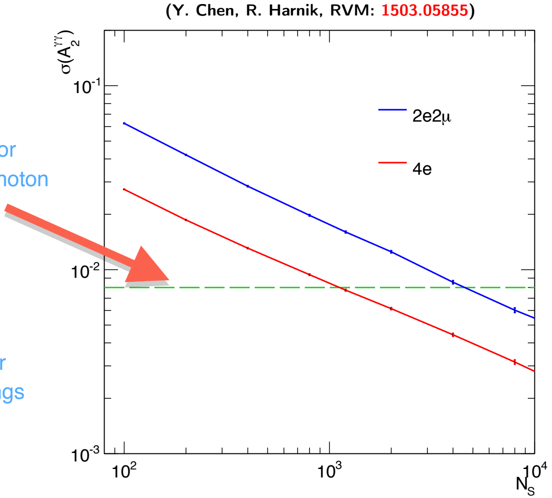
Is there any room for improvement? Should we expect there to be?

Comparing Sensitivity in $2e2\mu$ vs. $4e$ for CMS Cuts

Let us examine sensitivity to $h\gamma\gamma$ couplings in separate channels

SM value for CP even photon coupling

Similar story for CP odd couplings



Sensitivity to Higgs couplings to photons is driven by 4e when using CMS cuts

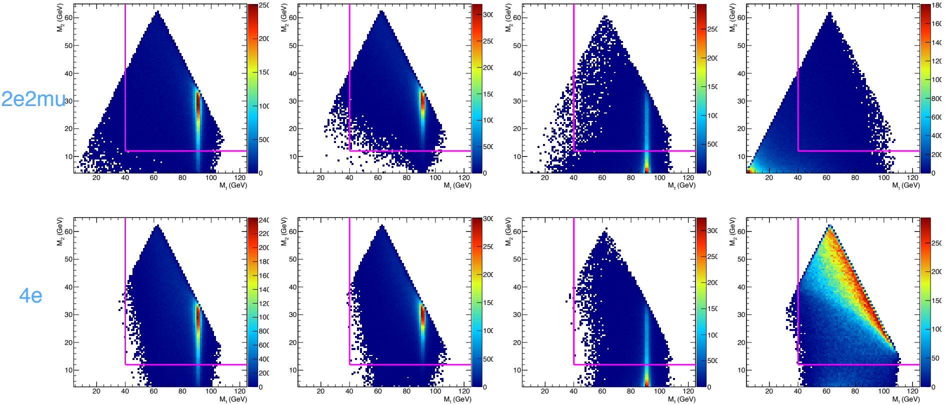
Note we use 4e and 4mu interchangeably in massless limit.

We see dramatically stronger sensitivity in $4e$ than in $2e2\mu$...why?

$M_1 - M_2$ Differential Mass Spectra and CMS Cuts

Let us examine $M_1 - M_2$ spectra for $|A_1^{ZZ}|^2, |A_2^{ZZ}|^2, |A_2^{Z\gamma}|^2, |A_2^{\gamma\gamma}|^2$

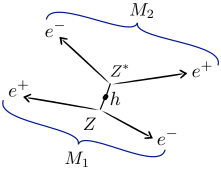
(Y. Chen, R. Harnik, RVM: 1503.05855)



Much larger acceptance in $4e$ (bottom) vs. $2e2\mu$ (top) for CMS cuts (pink line)

The ‘Wrong’ Lepton Pairing in $4e$ (or 4μ)

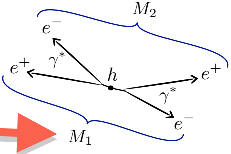
- CMS cuts/pairings optimized for Higgs *discovery* via tree level hZZ coupling
- In particular, one opposite charge same flavor pair near M_Z is required
- Assumes implicitly (nearly) on-shell Z is mediating the process
- However, this assumption does not hold in processes mediated by $\gamma\gamma$



By convention M1 is chosen to be the pair closest to MZ

—or—

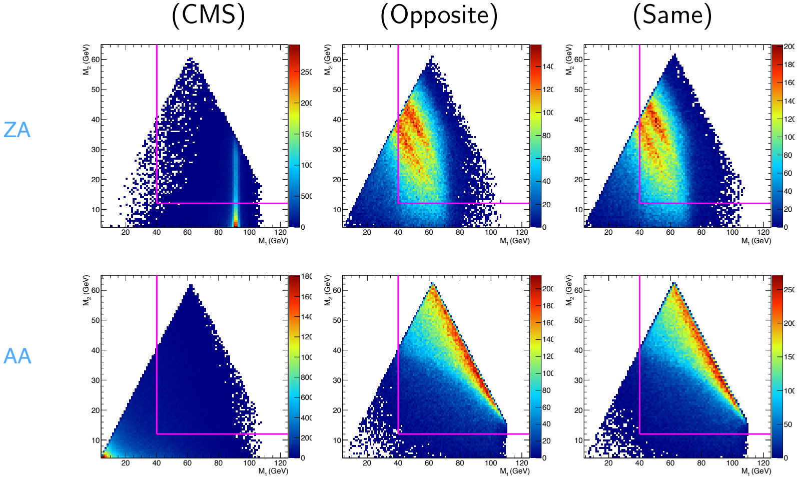
Lepton pair which is chosen to make up M1 do not come from same photon!



- This gives CMS cuts an ‘accidentally’ high efficiency for ‘$\gamma\gamma$-like’ events!
- In $2e2\mu$, ‘$\gamma\gamma$-like’ events do not pass cut since same flavor pairs are required

Enhancing the $Z\gamma$ and $\gamma\gamma$ Components in $2e2\mu$

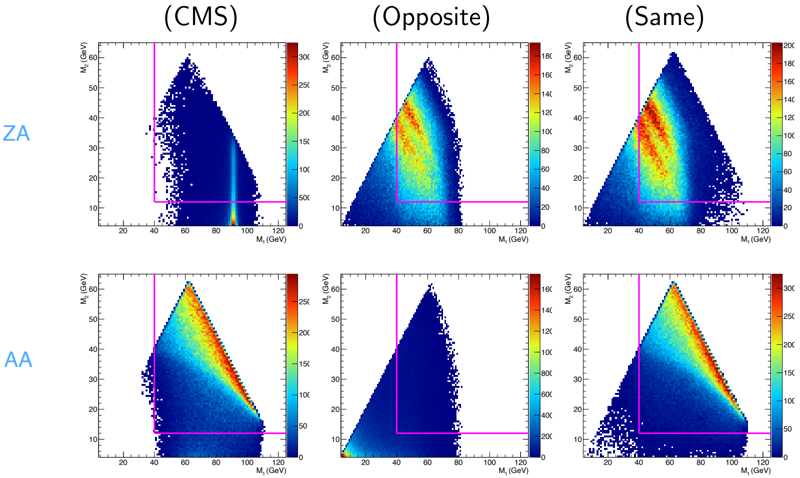
Can enhance acceptance for $|A_2^{Z\gamma}|^2$ (top) and $|A_2^{\gamma\gamma}|^2$ (bottom)-like events by employing 'alternative' lepton instead of standard CMS (or ATLAS) pairings



Both 'Opposite' and 'Same' pairings perform better than current CMS choice

Squeezing More out of the $4e$ (and 4μ) Channel

We see (Same) pairing is optimal for *both* $|A_2^{Z\gamma}|^2$ (top) and $|A_2^{\gamma\gamma}|^2$ (bottom)



- Of course if we take the entire 4ℓ phase space then all pairings are equivalent
- In this case $2e2\mu$, $4e$, and 4μ all perform similarly in terms of sensitivity
- Implies acceptance can also be enhanced just by lowering M_1, M_2 with standard pairing
- This is perhaps more intuitive though not equivalent to considering alternative pairings

Alternative Cuts and Lepton Pairings

- We consider a number of alternative cuts and lepton pairings

(Y. Chen, R. Harnik, RVM: 1503.05855)

Name	Lepton Pairing	Lepton Selection	Mass Selection
CMS - tight	$(e^-e^+)(\mu^-\mu^+), (e^-e^+)(e'^-e'^+)$	$p_T > (20, 10, 7, 7), \|\eta\| < 2.4$	$M_1 > 40, M_2 > 12, M_{\ell\ell} > 4$
CMS - loose	$(e^-e^+)(\mu^-\mu^+), (e^-e^+)(e'^-e'^+)$	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_1 > 40, M_2 > 12, M_{\ell\ell} > 4$
Opposite	$(e^-\mu^+)(\mu^-e^+), (e^-e'^+)(e'^-e^+)$	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_1 > 40, M_2 > 12, M_{\ell\ell} > 4$
Same	$(e^-\mu^-)(e^+\mu^+), (e^-e'^-)(e^+e'^+)$	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_1 > 40, M_2 > 12, M_{\ell\ell} > 4$
Combined	all 3 pairings combined	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_1 > 40, M_2 > 12, M_{\ell\ell} > 4$
Relaxed	$(e^-e^+)(\mu^-\mu^+), (e^-e^+)(e'^-e'^+)$	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_{\ell\ell} > 4$
Relaxed $-\Upsilon$	$(e^-e^+)(\mu^-\mu^+), (e^-e^+)(e'^-e'^+)$	$p_T > (20, 10, 5, 5), \|\eta\| < 2.4$	$M_{\ell\ell} > 4, M_{\ell\ell} \notin (8.8, 10.8)$

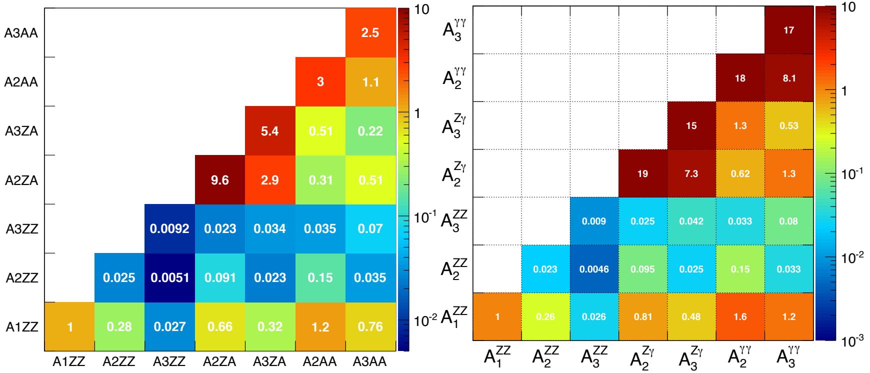
- Will each have different efficiencies and sensitivities
- We expect largest phase space (Relaxed) to have best sensitivity
- When $M_{1,2} \lesssim 10$ GeV, must worry about QCD resonances

  (see Gonzalez-Alonso, Isidori: 2014.2648)
- Can 'cut-out' phase space where they are expected (Relaxed$-\Upsilon$)

Integrated Magnitudes with Relaxed$-\Upsilon$ Cuts

Compare integrated magnitudes for CMS-tight (left) vs. Relaxed$-\Upsilon$ (right)

(Y. Chen, R. Harnik, RVM: 1503.05855)

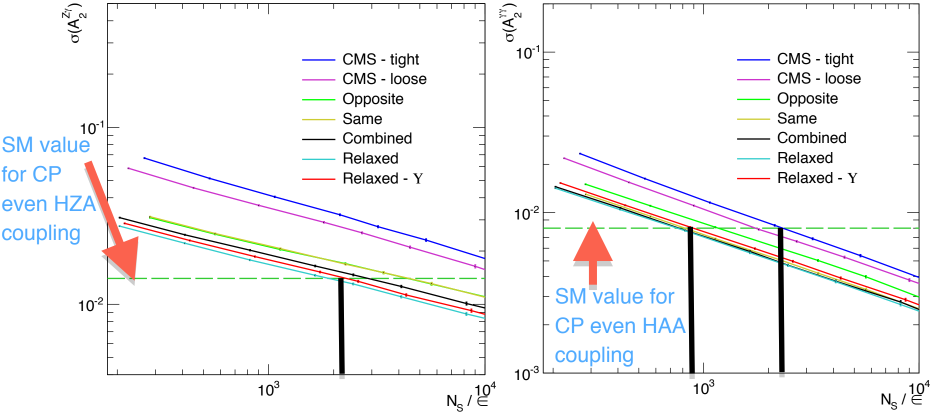


We see $\sim 15 - 60\%$ enhancement in size of interference between the higher dimensional $\gamma\gamma$ and $Z\gamma$ couplings with tree level A_1^{ZZ} coupling (bottom row)

Comparison of Cuts and Lepton Pairings

We compare $\sigma(A)$ vs. N_S/ϵ for the various cuts and lepton pairings
Fit to a 'true' point of $\vec{A}_o = (0,0,0,0,0,0)$ and pure signal sample

(Y. Chen, R. Harnik, RVM: 1503.05855)



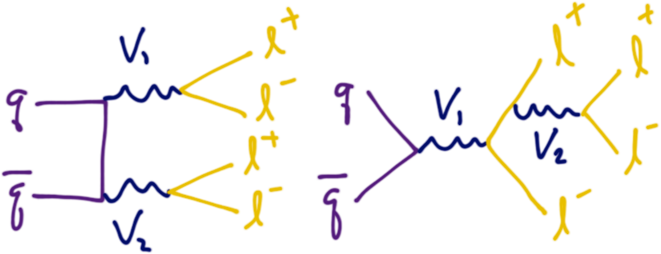
Dramatic enhancements for $Z\gamma$ and $\gamma\gamma$ couplings compared to current cuts
With perfect detector resolution this would reflect an accurate picture of sensitivity
Detector resolution introduces 'non-Higgs' BG into the signal region which affects sensitivity

The ‘non-Higgs’ Background

How does the story change in the presence of non-Higgs background?

- Dominant irreducible background is primarily $q\bar{q} \to 4\ell$
- This includes both the t-channel and s-channel process

Also computed analytically

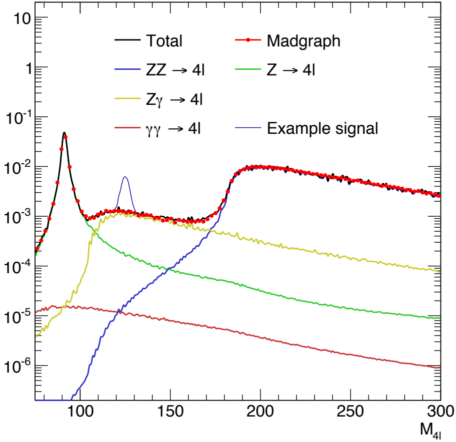


- Has other smaller contributions from higher order processes and fakes
- Again $V_1, V_2 = Z, \gamma$ (and can be off-shell) and $\ell = e, \mu$
- A rich interference structure between various intermediate states as well as between s and t-channel and identical final states for $4e/4\mu$
- Different components dominate in different regions of $M_{4\ell}$

Signal Plus Background $M_{4\ell}$ Spectrum

We examine size of different $q\bar{q} \to 4\ell$ components as function of $M_{4\ell}$

(Y. Chen, R. Harnik, RVM: 1503.05855)



We have included a 2 GeV width gaussian for the signal to model detector resolution.

These spectra include gg and qq PDFs at a 14 TeV LHC

We see around $M_{4\ell} \sim 125$ GeV the $q\bar{q} \to Z\gamma$ component dominates

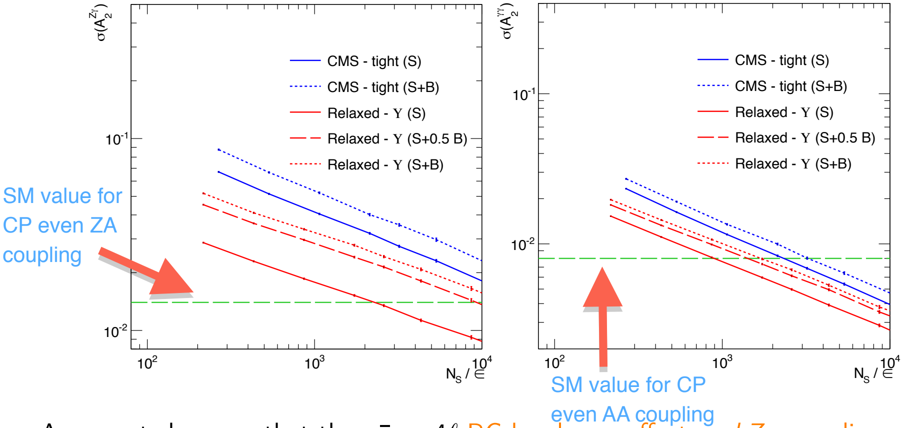
We thus expect $q\bar{q} \to 4\ell$ BG mostly affects sensitivity to $hZ\gamma$ couplings

Comparison of Sensitivity: Signal vs. Signal + BG

Let us examine how sensitivity changes once non-Higgs BG is included

We perform this comparison for CMS-like cuts and Relaxed$-\Upsilon$ cuts

(Y. Chen, R. Harnik, RVM: 1503.05855)



As expected we see that the $q\bar{q} \to 4\ell$ BG has larger effect on $hZ\gamma$ coupling

Effect of BG larger for Relaxed$-\Upsilon$, but sensitivity is still improved *wrt* CMS

Sensitivity to $h\gamma\gamma$ also affected, but not as drastically and similar for both cuts

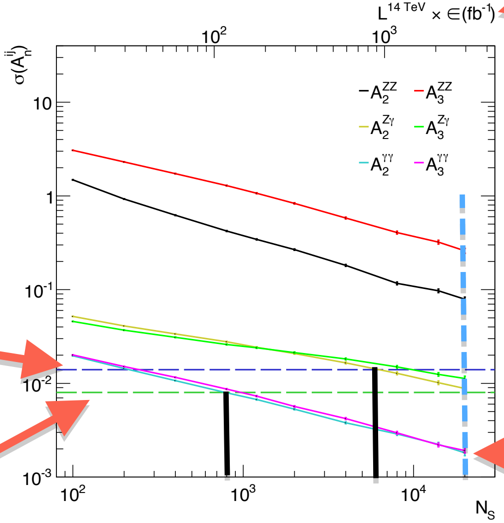
Sensitivity Projections at LHC: Optimized Cuts

Can now attempt to give an estimate of sensitivity at 14 TeV LHC and beyond

Fit to 'true' point of $\vec{A} = (0,0,0,0,0,0)$ and assume SM production and BR

Very good prospects for probing couplings to photons for order SM values. Will need a little luck to really probe ZA couplings. Prospects for ZZ couplings are less promising.

(Y. Chen, R. Harnik, RVM: 1503.05855)



Note this is luminosity X efficiency

These include the dominant qq BG and detector resolution effects

Again all couplings are floated indepedently keeping all correlations.

SM value for CP even ZA coupling

SM value for CP even AA coupling

Approximate end of HL LHC running (3000/fb)

Directly Probing $Z\gamma$ and $\gamma\gamma$ CP Properties

Can LHC establish overall sign of $hZ\gamma$ and $h\gamma\gamma$ with $\sim 3000 fb^{-1}$ of data?

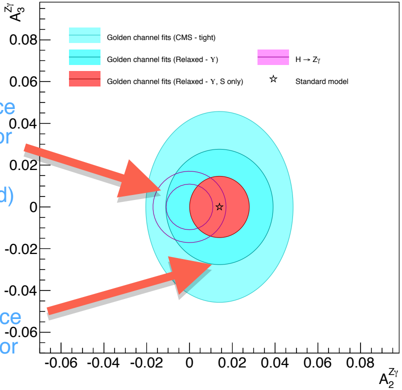
Fit to 'true' point of $\vec{A} = (0, 0, 0.014, 0, -0.008, 0)$ (SM values for $A_2^{Z\gamma}, A_2^{\gamma\gamma}$)

We also compare CMS cuts versus the optimized cuts

(Y. Chen, R. Harnik, RVM: 1503.05855)

The 68% confidence interval for H to ZA (projected)

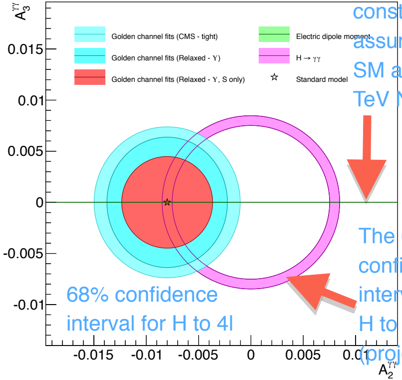
Th 68% confidence interval for H to 4l



EDM constraint assuming SM and 1 TeV NP

68% confidence interval for H to 4l

The 68% confidence interval from H to AA (projected)



Prospects for $h\gamma\gamma$ are very promising while for $hZ\gamma$ it will be more difficult, but still $h \to 4\ell$ serves as a useful and complementary probe to $h \to Z\gamma$

We also see the large improvement in sensitivity by utilizing Relaxed$-\Upsilon$ cuts

Constraining Couplings in Linearly Realized EFT

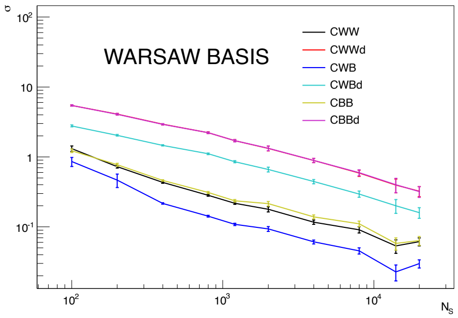
Can also perform fits in the context of SM + D6 EFT assuming EW doublet
Constrains Wilson coefficients in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ invariant theory

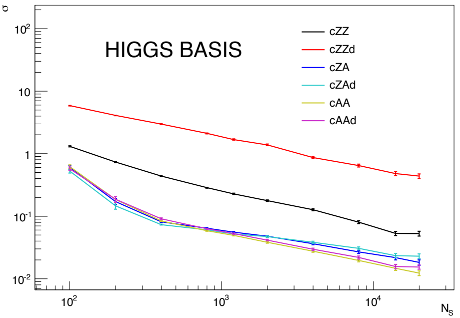
(LHC Higgs Cross Section Working Group 2: LHCHXSWG-INT-2015-001 cds.cern.ch/record/2001958)

Easily perform fits in any basis such as in Warsaw (left) or Higgs (right)

(B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek: 1008.4884, R. S. Gupta, A. Pomarol, F. Riva: 1405.0181)

(Y. Chen, A. Falkowski, RVM: PRELIMINARY)



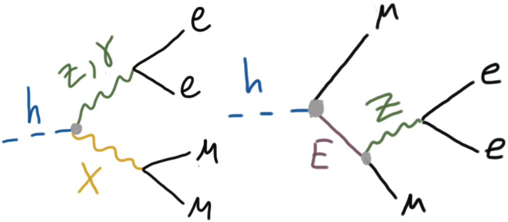


Also exploring fits with priors derived from other Higgs measurements at LHC

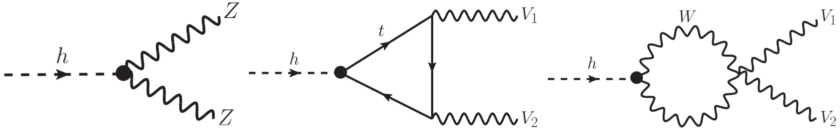
Other BSM Possibilities and Ongoing Work

- Everything discussed so far is from an 'EFT perspective'
- Can also use $h \to 4\ell$ to search for exotic particles like vector like leptons or new vector bosons (A. Falkowski, RVM: 1404.1095, D. Curtin, et al: 1312.0663)

Also see Curtin, et. al. (1312.4992) for a general and comprehensive review of exotic Higgs decays



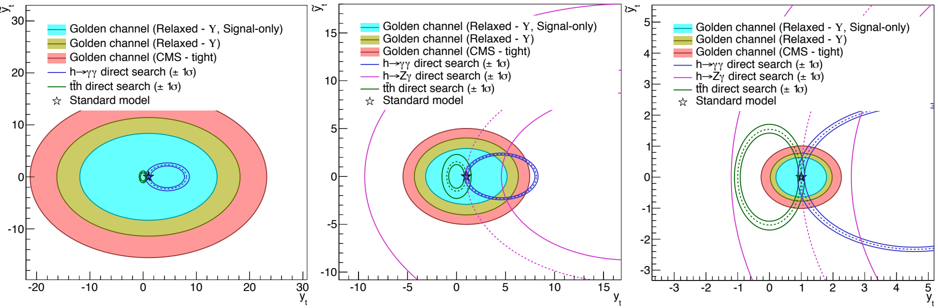
- The sensitivity to $hZ\gamma$ and $h\gamma\gamma$ effective couplings leads us to ask can we probe underlying loop processes?



Probing the Top Yukawa CP Properties

We first examine the ability to probe the top-Higgs interactions in $h \to 4\ell$
Assume fixed g_{WW} coupling, but allow for general CP mixture of top Yukawa
We can also compare sensitivity to $h \to \gamma\gamma$, $h \to Z\gamma$, and tth channels

(Y. Chen, D. Stolarski, RVM: 1505.01168)



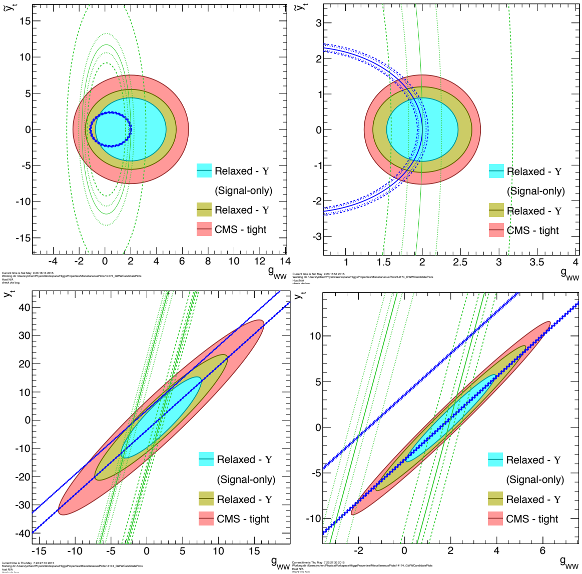
The golden channel should be a useful and qualitatively different channel for probing the top Yukawa CP properties at the LHC and future colliders

Probing Tree Level Couplings to WW and top

(Y. Chen, D. Stolarski, RVM: PRELIMINARY)

CP odd top Yukawa vs. gWW

CP even top Yukawa vs. gWW



Can use h -> 4l to lift degeneracies in h -> AA and h -> ZA

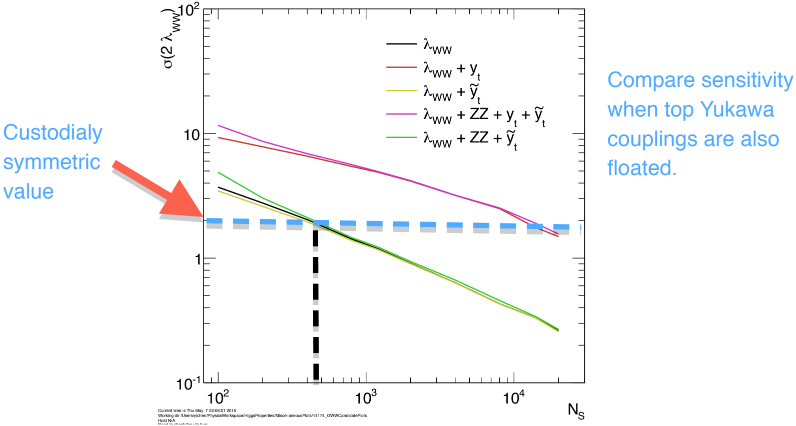
Non-trivial correlations between gWW and CP even top Yukawa

Probing Custodial Symmetry

Implies sensitivity to the ratio of hWW/hZZ tree level couplings

Measure of custodial symmetry and can deviate from one at tree level even with $\rho = 1$ at tree level **(e.g. M. Garcia-Pepin, S. Gori, M. Quiros, R. Vega, RVM, T. Yu: 1409.5737)**

(Y. Chen, D. Stolarski, RVM: PRELIMINARY)



The golden channel should be able to establish overall sign of at LHC

Probably need a 100 TeV hadron collider for high precision tests

Comments on Parameter Extraction Framework

- We have built a complete and flexible framework which can perform multidimensional parameter fits with high precision in $h \to 4\ell$
- Based primarily on analytic calculations of $h \to 4\ell$ and $q\bar{q} \to 4\ell$ which are incorporated into a maximum likelihood framework

  (Y. Chen, N. Tran, RVM: 1211.1959, Y. Chen, RVM: 1310.2893)
- Not dependent on a particular parametrization and easily adapted to whichever parametrization is most convenient at a given time
- Easily adapted to study exotic Higgs decays, loop effects, EFTs, etc.
- This framework has also been realized at 'detector level' and can be used in experimental analyses at the LHC or future colliders

  (Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, RVM, S. Xie: 1401.2077, 1410.4817)
- Recently used by CMS in $h \to 4\ell$ studies of hVV couplings

  (CMS Collaboration: CMS-HIG-14-018, 1411.3441)
- Framework is also easily adapted to $h \to 2\ell\gamma$ and $h \to \gamma\gamma$

Summary

- $h \to 4\ell$ an indispensable tool to study Higgs and search for BSM
- Can use $h \to 4\ell$ to study Higgs couplings to $ZZ, Z\gamma$, and $\gamma\gamma$
- It is a direct and unique probe of CP properties of these couplings
- Current CMS (and ATLAS) cuts optimized for Higgs discovery via the hZZ tree level coupling, but sensitivity to $Z\gamma$ and $h\gamma\gamma$ is greatly enhanced by relaxing cuts (or alternative lepton pairings)
- LHC should establish overall sign of $h\gamma\gamma, hZ\gamma$ and put meaningful constraints on CP properties in the golden channel
- $h \to 4\ell$ serves as complementary, but qualitatively different measurement to $h \to Z\gamma$ and $h \to \gamma\gamma$ on-shell decays
- Can also use golden channel to search for exotic Higgs decays and underlying loop effects which generate effective Higgs couplings
- Similar statements apply (to a lesser extent) to $h \to 2\ell\gamma$ channel
- Analysis framework fully equipped to perform studies at LHC

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,
A. Falkowski, RVM: arXiv:1404.1095,
Y. Chen, R. Harnick, RVM: arXiv:1404.1336,
Y. Chen, A. Falkowski, I. Low, RVM: arXiv:1405.6723,
Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, RVM, S. Xie: arXiv:1410.4817,
CMS Collaboration: CMS PAS HIG-14-014,
CMS Collaboration: arXiv:1411.3441,
Y. Chen, R. Harnick, RVM: arXiv:1503.05855,
Y. Chen, D. Stolarski, RVM: arXiv:1505.01168

Also in near future see:

Y. Chen, A. Falkowski, RVM: arXiv:15XX.YYYYY,
Y. Chen, D. Stolarski, RVM: arXiv:15XX.ZZZZZ

Extra Slides

‘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 ⇒ done via C.O.V. and numerical techniques

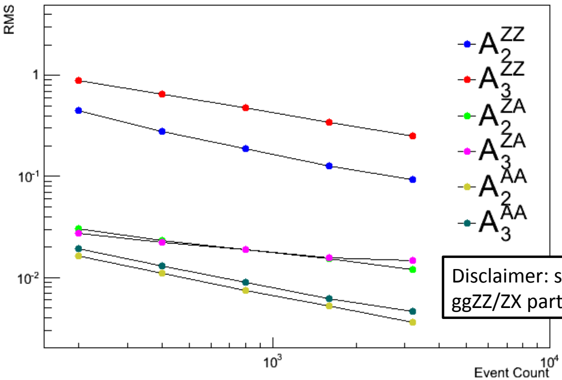
- $T(\vec{X}^R|\vec{X}^G)$ represents probability to observe $\vec{X}^R$ given $\vec{X}^G$
- Can be optimized for specific detector and included in convolution
- This integration takes us from generator level observables ($\vec{X}^G$) to detector level (reconstructed) observables ($\vec{X}^R$)
- Conceptually simple, but requires a number of steps to perform (and massive computing) details in arXiv:1401.2077 and technical note arXiv:1410.4817
- 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 6D fit as done at generator level
- Includes detector as well as (most) BG and production effects
  - All ratios are fitted simultaneously

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

Very preliminary!



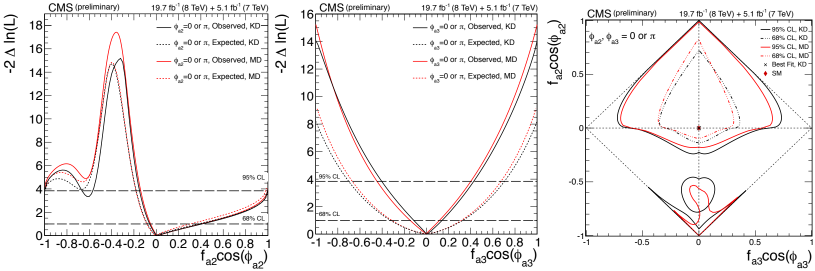
Disclaimer: systematics not included
ggZZ/ZX parts needs to be finalized!

- We see very similar sensitivity to ‘generator level’ analysis

Framework in CMS Analysis:

CMS PAS HIG-14-014, 1411.3441

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



- Used in a limited scope to 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 multi-dimensional extraction of effective Higgs couplings!