(Anomalous) Higgs Couplings and CP Violation in $h \to 4\ell$

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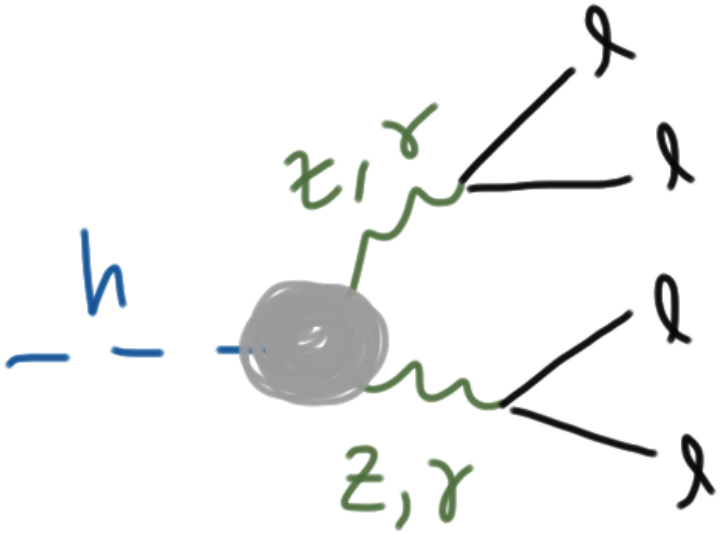
(In collaboration with Yi Chen, Adam Falkowski, Roni Harnik, and Daniel Stolarski)

Many recent studies dedicated to Higgs couplings in $h \to 4\ell$...

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**
J. Gainer, J. Lykken, et. al.: **1304.4936**
P. Artoisenet, P. de Aquino, F. Demartin, F. Maltoni, et. al: **1306.6464**
Sun, Yi and Wang, Xian-Fu and Gao, Dao-Neng: **1309.4171**
Anderson, S. Bolognesi, F. Caola, Y. Gao, A. V. Gritsan, et al.: **1309.4819**
T. Chen, J. Gainer, et. al.: **1310.1397**
Gonzales-Alonso, Isidori: **1403.2648**
J. Gainer, J. Lykken, K. T. Matchev, S. Mrenna, M. Park: **1403.4951**
M. Beneke, D. Boito, Y. Wang: **1406.1361**
M. Gonzalez-Alonso, A. Greljo, G. Isidori, D. Marzocca**1412.6038**
M. Gonzalez-Alonso, A. Greljo, G. Isidori, and D. Marzocca: **1504.04018**
M. Bordone, A. Greljo, G. Isidori, D. Marzocca, A. Pattori: **1507.02555**
+ **many others** as well as **various ATLAS and CMS studies**

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

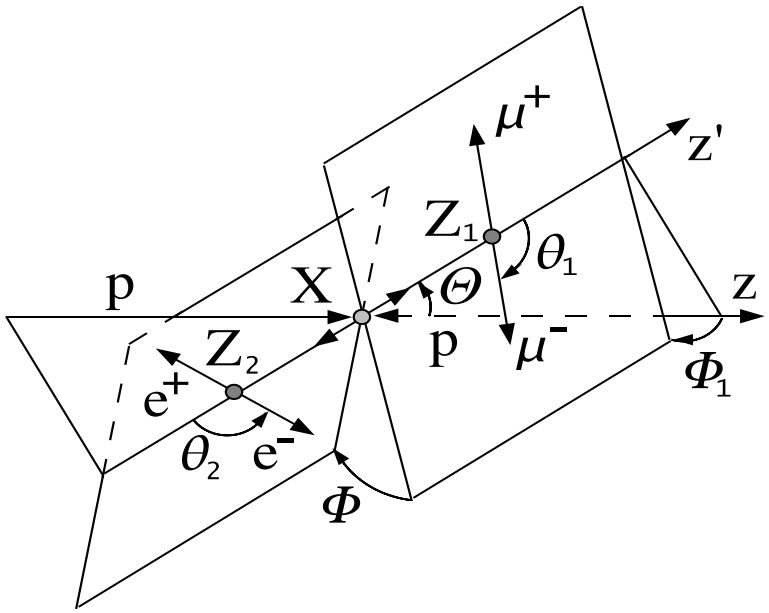
$$\begin{aligned}\mathcal{L} \supset\ & \frac{h}{4v}\Big(2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \widetilde{Z}_{\mu\nu} + 4A_4^{ZZ} Z_\mu \partial_\nu Z^{\mu\nu} \\ +\ & 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \widetilde{Z}_{\mu\nu}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

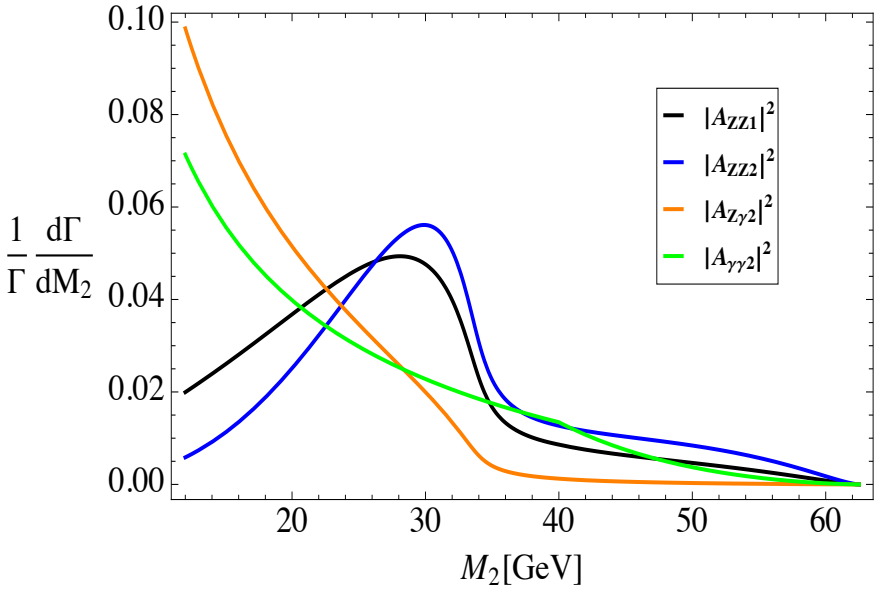
- SM $h \to 4\ell$ rate dominated by tree level A_1^{ZZ} operator (treat as 'BG')

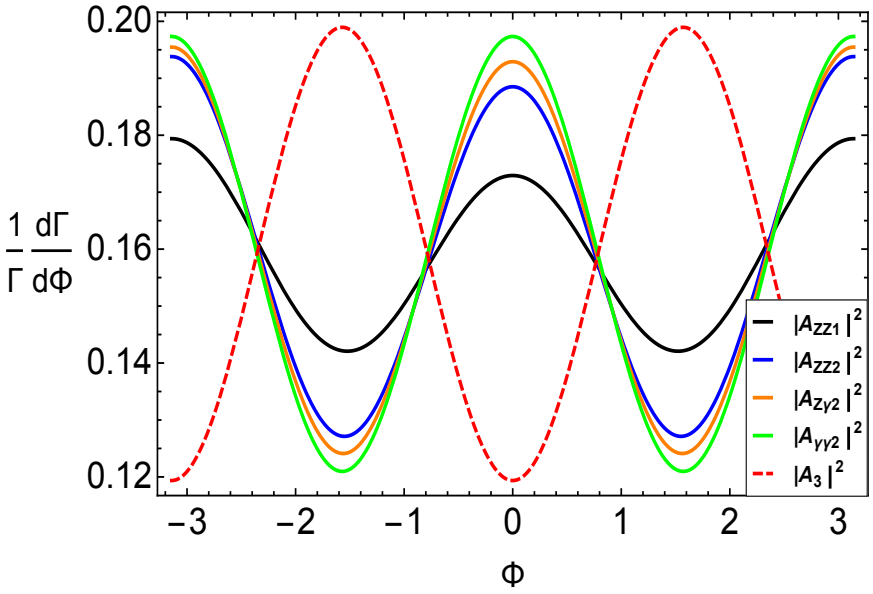
Kinematic Distributions in $h \to 4\ell$ Decay

Sensitivity to Higgs couplings comes from the many kinematic (eight) distributions and their correlations

They contain information about CP properties and tensor structure of Higgs couplings to $ZZ, Z\gamma, \gamma\gamma$



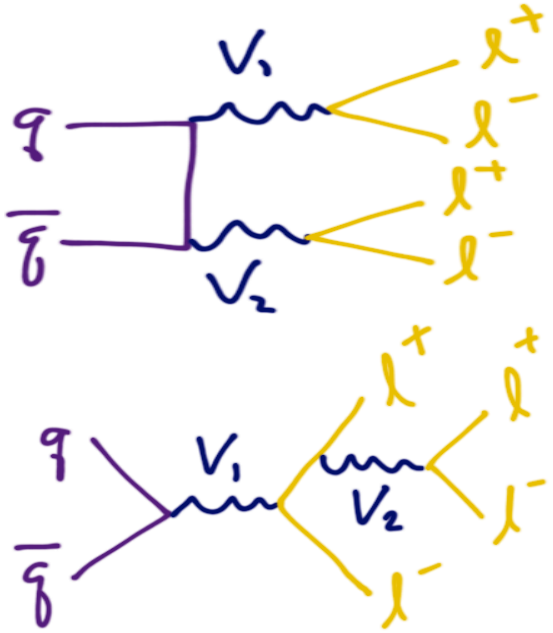




(Y. Chen, R. Harnik, RVM: 1404.1336)

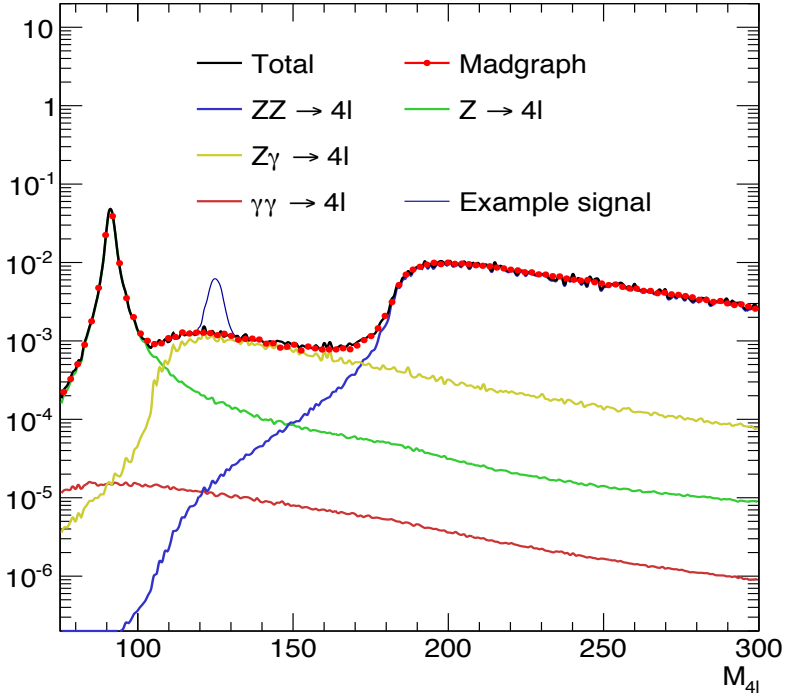
The 'non Higgs' Background

Dominant irreducible background is primarily $q\bar{q} \to 4\ell$ $(V_1, V_2 = Z, \gamma)$ which includes both t & s channel



Enters primarily as a resolution effect which 'widens' the signal region

Different components dominate in different regions of $M_{4\ell}$, but t-channel $Z\gamma$ dominates around signal region of $M_{4\ell} = 125$ GeV.



Since kinematic distributions largely dominated by pole structure, implies Higgs couplings to $Z\gamma$ will be most affected by presence of $q\bar{q} \to 4\ell$ BG

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

Matrix Element Method (MEM) Analysis

- We use all decay observables to construct a MEM analysis using normalized (analytic) fully differential cxns for $h \to 4\ell$ & $q\bar{q} \to 4\ell$
- Pseudo experiments are performed to examine sensitivity to hVV loop induced couplings as a function of number of events (or luminosity)
- Fix $A_1^{ZZ} = 2$ and perform 8D parameter fit to 'anamolous' couplings:

$$\vec{A} = (A_2^{ZZ}, A_3^{ZZ}, A_4^{ZZ}, A_2^{Z\gamma}, A_3^{Z\gamma}, A_4^{Z\gamma}, A_2^{\gamma\gamma}, A_3^{\gamma\gamma})$$

(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)

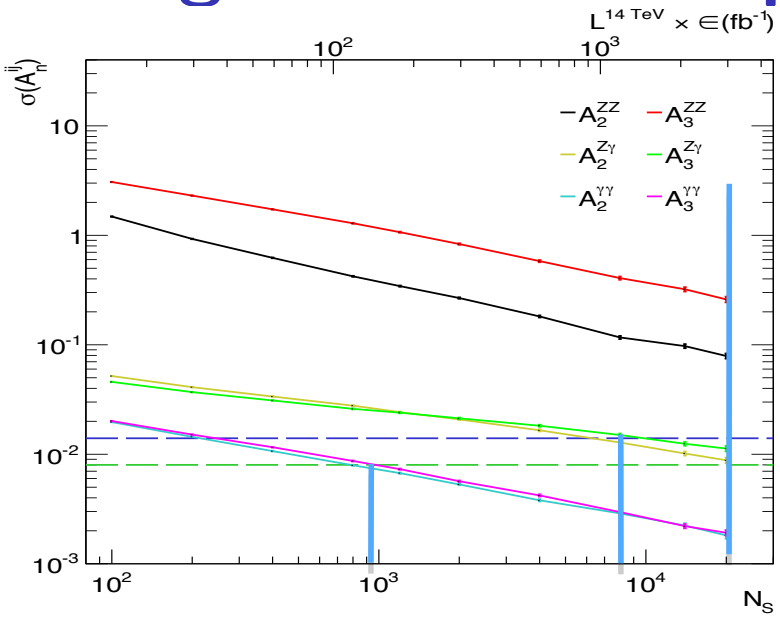
- All couplings floated independently and all correlations included
- As test statistic we define 'average error' on best fit value:

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

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

- Consider two sets of cuts ('CMS-like' and 'Relaxed'):
  - $p_{T\ell} > 20, 10, 7, 7$ GeV, $|\eta_\ell| < 2.4$, 40 GeV $\leq M_1$, 12 GeV $\leq M_2$
  - $p_{T\ell} > 20, 10, 5, 5$ GeV, $|\eta_\ell| < 2.4$, 4 GeV $\leq M_{1,2} \notin (8.8, 10.8)$ GeV

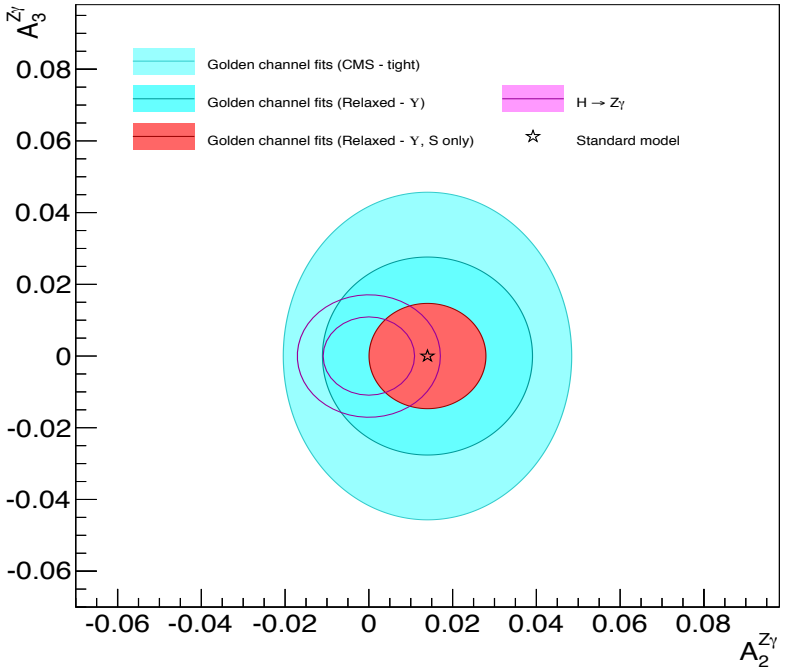
Probing Effective Couplings at LHC

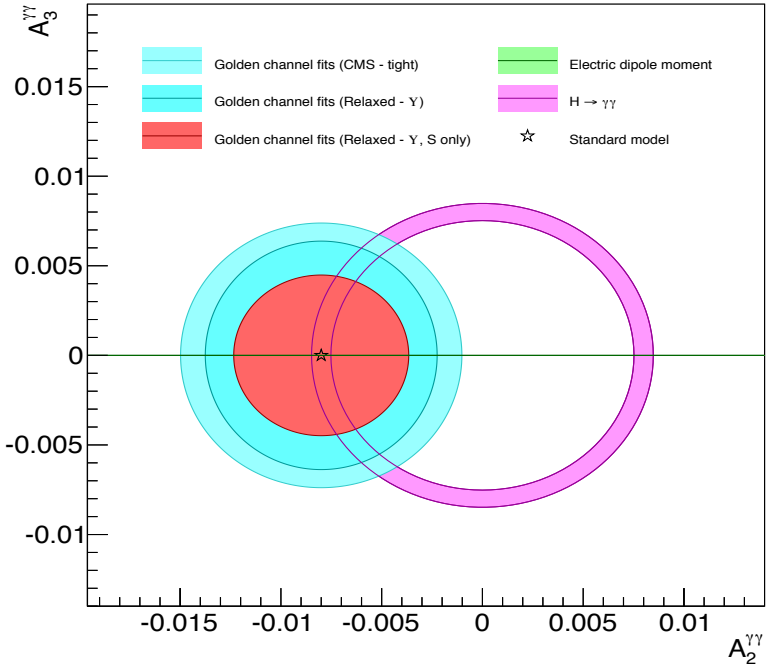


Assuming SM production and BR and 'true point' near SM prediction we see much stronger sensitivity to $Z\gamma$ and $\gamma\gamma$ effective couplings

Can potentially probe $Z\gamma$ and $\gamma\gamma$ CP properties at high luminosity LHC

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





Wilson Coefficients in Linearly Realized EFT

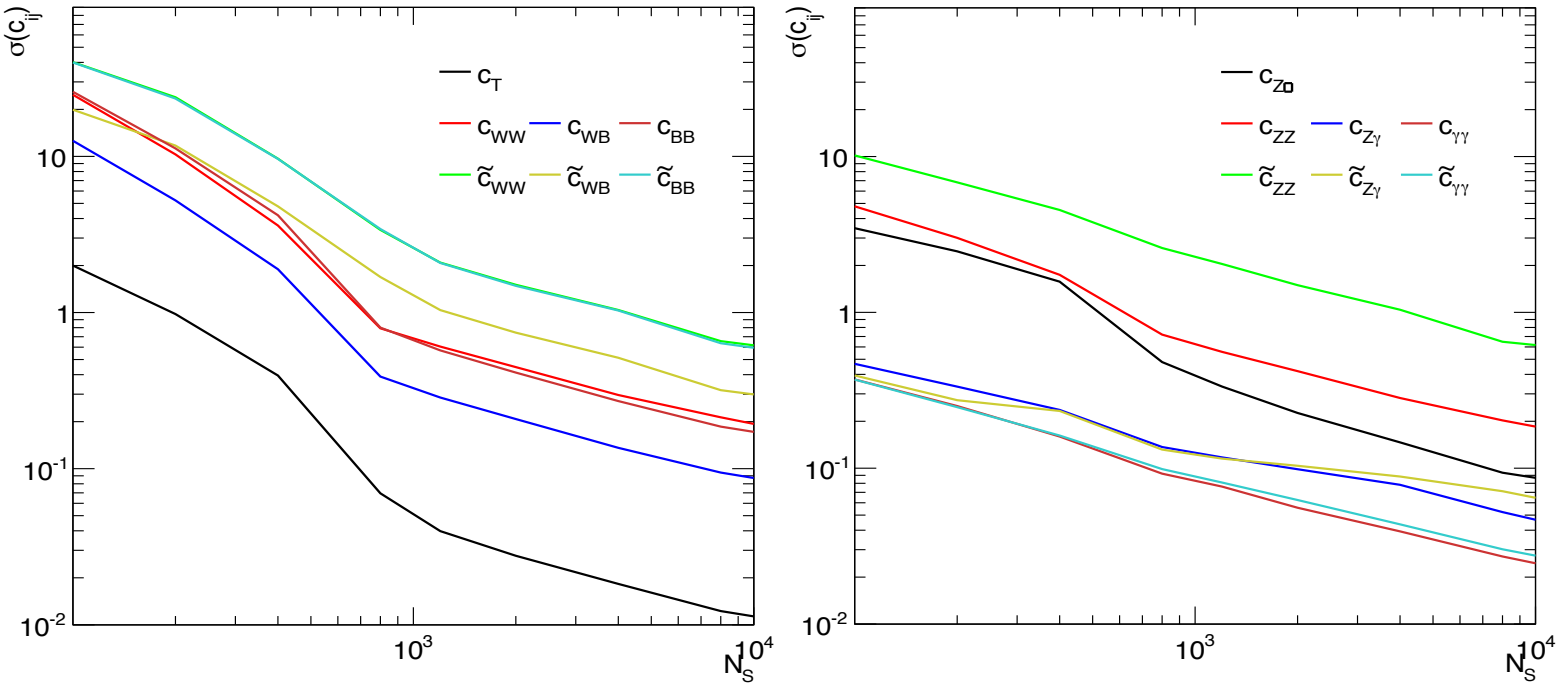
- Can also perform fits in the context of SM + D6 EFT assuming EW doublet
- Constrains Wilson coefficients in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ invariant theory

(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)

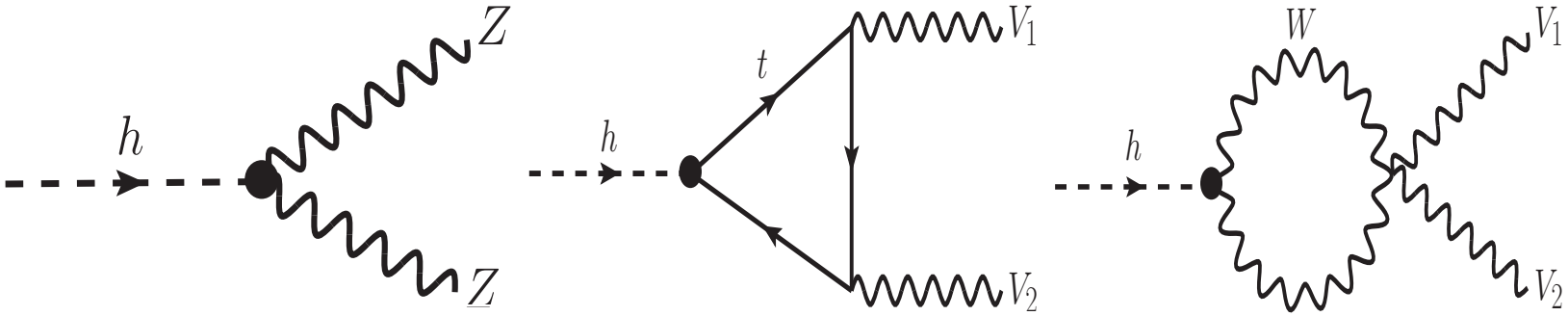
(Y. Chen, A. Falkowski, R. Harnik, RVM: PRELIMINARY)



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

Probing Loop Effects in $h \to 4\ell$

- Everything discussed so far is from an 'EFT perspective'
- Can also use $h \to 4\ell$ to probe underlying loop effects
- In SM, W and top loops contribute to effective hVV couplings



- Can search for deviations in coupling of Higgs to top and W

$$\mathcal{L}_{ZW} \supset \frac{h}{v}\left(\frac{1}{2} g_{ZZ} m_Z^2 Z^\mu Z_\mu + g_{WW} m_W^2 W^{+\mu} W_\mu^-\right)$$

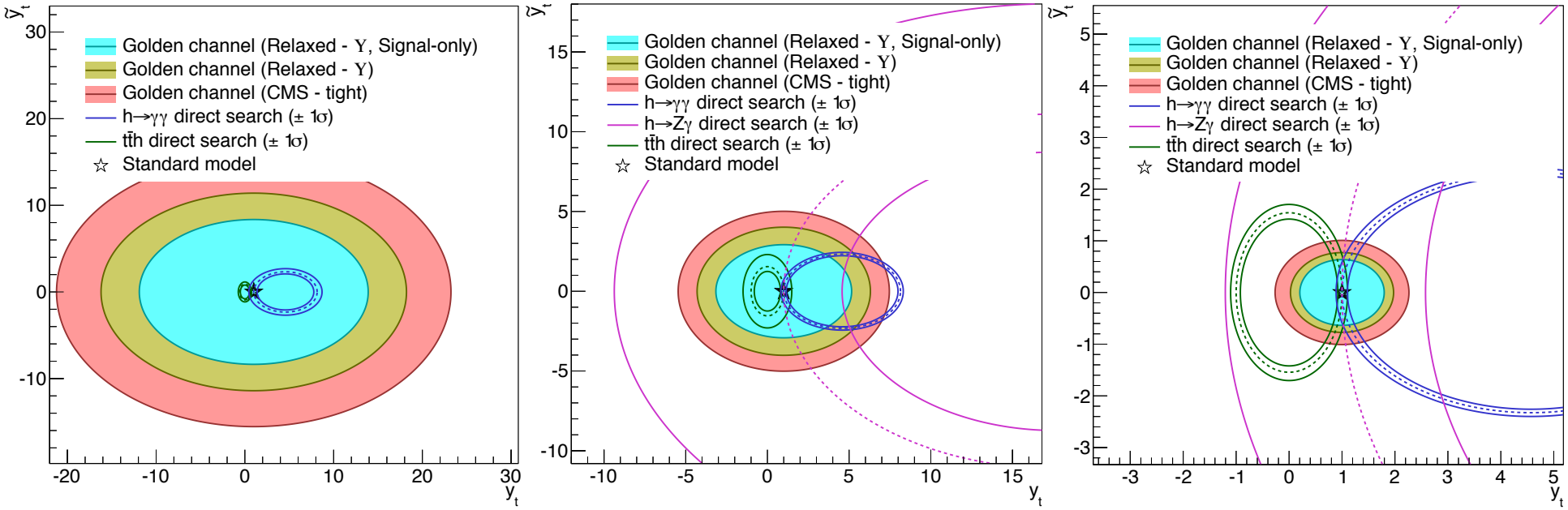
$$\mathcal{L}_t \supset \frac{m_t}{v} h \bar{t}(y_t + i\tilde{y}_t \gamma^5) t$$

- Interference between tree level hZZ amplitude and top loop diagram allows us to probe top CP properties and search for CPV

Probing the Top Yukawa CP Properties

- We first examine the ability to probe the top-Higgs interactions in $h \to 4\ell$
- Fix $g_{WW,ZZ}$ couplings to SM, but allow 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)



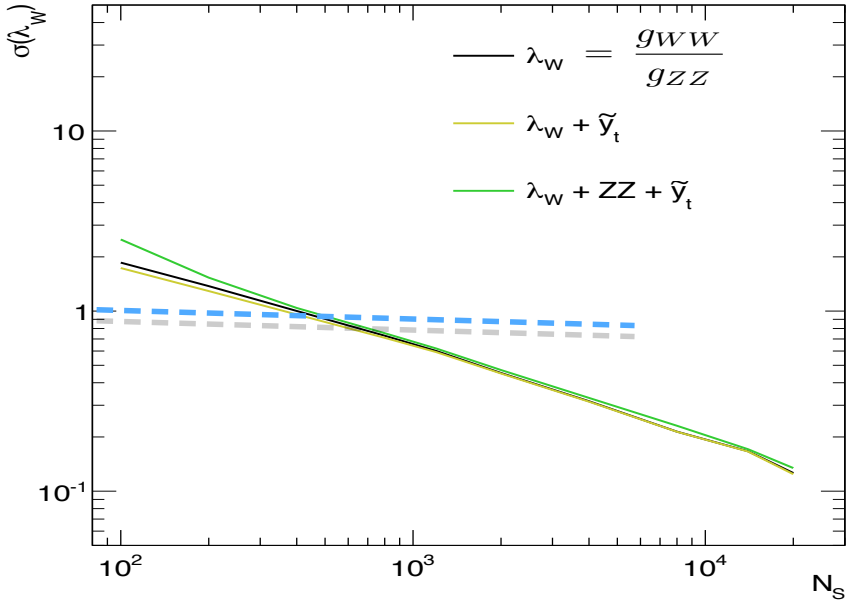
- The golden channel should be a useful and qualitatively different channel for probing the top Yukawa CP properties at the LHC and future colliders

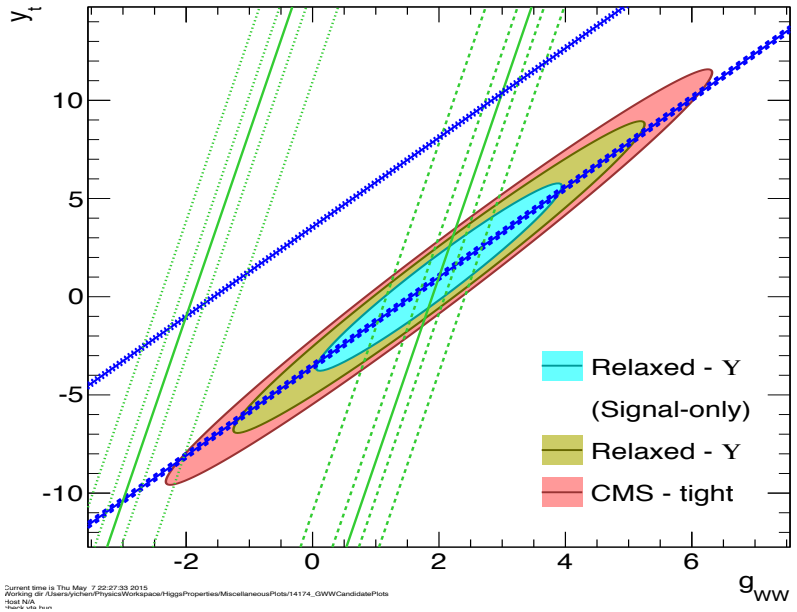
Top and W Couplings and Custodial Symmetry

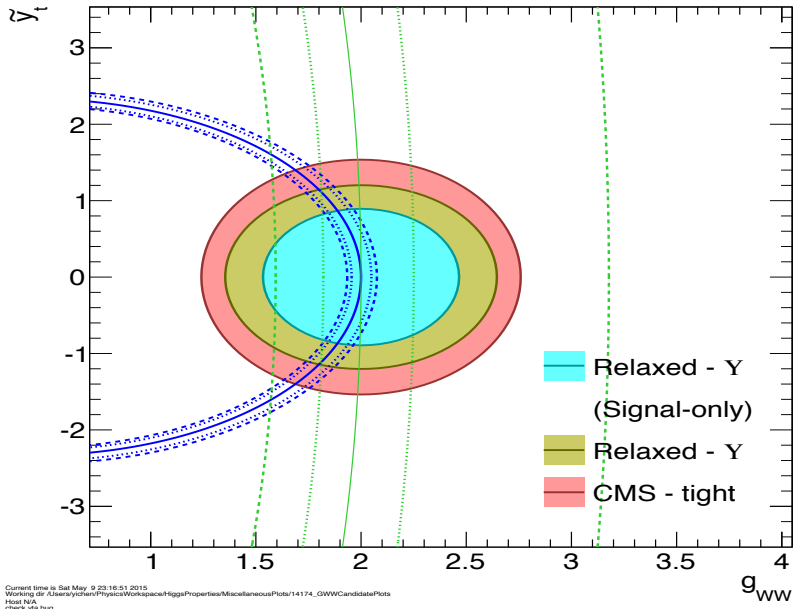
We can also examine allowing W coupling to float as well and examine g_{WW} vs y_t and g_{WW} vs $\tilde{y}_t$ planes

Another possibility is to probe custodial symmetry through the ratio of couplings $\lambda_W = g_{WW}/g_{ZZ}$

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







Ongoing Work and Conclusions

- As part of ongoing work we are also exploring:

  Work in progress with Y. Chen, A. Falkowski, D. Stolarski

  - Sensitivity to Higgs quartic coupling
  - Other NP contributions to loops (squarks, charginos, etc.)
  - Using priors from other measurements with $h \to 4\ell$ MEM analysis
  - Examine effective couplings in loop processes (i.e. NLO EFT)

- Conclusions:
  - $h \to 4\ell$ 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 $\gamma\gamma$ and couplings to top, W, and Z in underlying loop processes
  - It is a direct probe of CP properties of these couplings
  - $h \to 4\ell$ serves as complementary, but qualitatively different measurement to $h \to Z\gamma$ and $h \to \gamma\gamma$ on-shell decays

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, R. Harnik, RVM: arXiv:15XX.YYYYY,
Y. Chen, D. Stolarski, RVM: arXiv:15XX.ZZZZZ