

# Possibilities in $h \rightarrow 4\ell$ at 100 TeV

Roberto Vega-Morales

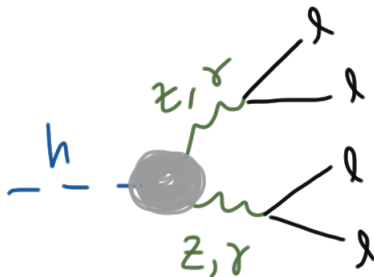
**Laboratoire de Physique Théorique d'Orsay**  
(Work Supported by ERC Advanced Grant Higgs@LHC)

FCC Higgs EWSB Working Group Discussion  
CERN: February 25, 2015

(In collaboration with: Adam Falkowski, Roni Harnik, Ian Low, Joe Lykken, Daniel Stolarski  
and CMS experimentalists Yi Chen, Emanuele DiMarco, Maria Spiropulu, Si Xie)

## Anomalous Higgs Couplings in the Golden Channel

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



- Can parametrize the  $hVV'$  couplings with following Lagrangian

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

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

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

## Constructing 'Sensitivity Curves' with MEM

- ▶ 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)

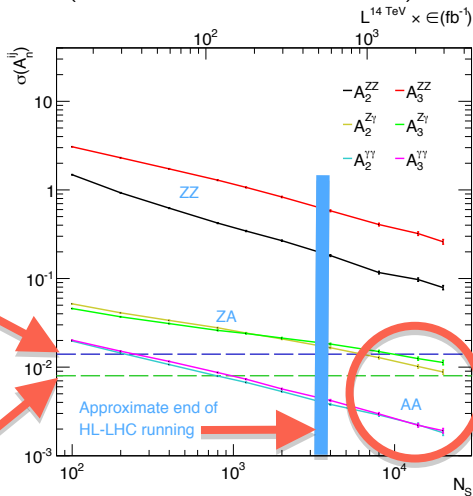
- ▶ We fit to a 'true' point of  $\vec{A}_o = (0, 0, 0, 0, 0, 0)$  (tree level SM)
- ▶ Apply optimized  $h \rightarrow 4\ell$  cuts:  $p_{T\ell} > 20, 10, 5, 5$  GeV for lepton  $p_T$ ,  $|\eta_\ell| < 2.4$ , and  $4 \text{ GeV} \leq M_{1,2}$ ,  $M_1 > M_2$  (Y. Chen, R. Harnik, RVM: to appear)

# Sensitivity Projections With Optimized Cuts

We can now attempt to give an estimate of sensitivity

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

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



Note this is luminosity x efficiency

100 TeV collider should allow us to probe CP even couplings well below SM values!

These include the dominant qq BG and detector energy 'resolution effects'

Should also be able to put strong constraints on CP odd couplings.

SM value for CP even ZA coupling

SM value for CP even AA coupling

Approximate end of HL-LHC running

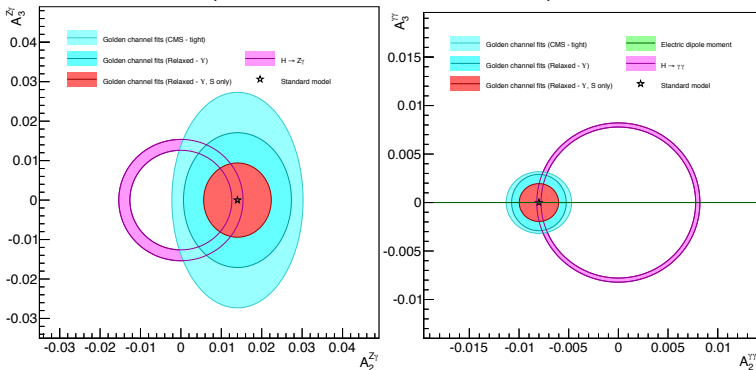
100 TeV territory

# Directly Probing $Z\gamma$ and $\gamma\gamma$ CP Properties at 100 TeV

Can we overall sign of  $hZ\gamma$  and  $h\gamma\gamma$  with 20,000 events?

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

(Y. Chen, R. Harnik, RVM: **PRELIMINARY**)

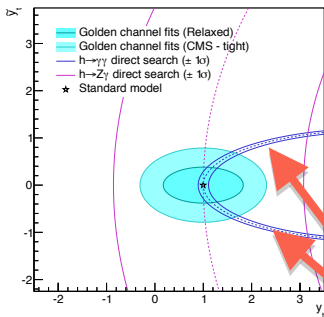


See  $h \rightarrow 4\ell$  useful for probing 'blind' directions in  $h \rightarrow V\gamma$  two body decays  
Improvement in sensitivity with optimized cuts (see: Y. Chen, R. Harnik, RVM: [to appear](#))  
With 20k events could establish overall sign of  $hZ\gamma$  and  $h\gamma\gamma$  in  $h \rightarrow 4\ell$  alone

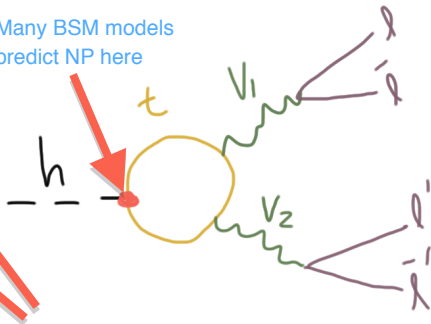
# Probing the Top Yukawa in $h \rightarrow 4\ell$ at 100 TeV

- ▶ Can  $h \rightarrow 4\ell$  also probe underlying loop processes with 20k events?
- ▶ Investigating if we can probe  $ht\bar{t}$  and other BSM possibilities

(Y. Chen, D. Stolarski, RVM: [work in progress](#))



Many BSM models predict NP here



Can potentially uncover CPV in top sector here which would be 'blind' to two body decays

- ▶ 100 TeV collider would aid in lifting degeneracies in  $h \rightarrow Z\gamma, \gamma\gamma$
- ▶ Could discover CPV in top sector in LHC 'blind' regions

## Summary

- ▶  $h \rightarrow 4\ell$  an indispensable tool to study Higgs and search for BSM
- ▶ Can use  $h \rightarrow 4\ell$  to study Higgs couplings to  $ZZ$ ,  $Z\gamma$ , and  $\gamma\gamma$
- ▶ It is a direct and unique probe of CP properties of these couplings
- ▶ Serves as complementary, but qualitatively different measurement to  $h \rightarrow Z\gamma$  and  $h \rightarrow \gamma\gamma$  on-shell (two body) decays
- ▶ Can also use golden channel to search for exotic Higgs decays and underlying loop effects which generate effective Higgs couplings
- ▶ Limited mainly by statistics making 100 TeV collider the ideal tool to maximize the information in the  $gg \rightarrow h \rightarrow 4\ell$  process
- ▶ Similar statements apply (to a lesser extent) to  $h \rightarrow 2\ell\gamma$  channel

# 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](#)

Yi Chen PhD thesis: [CERN-THESIS-2014-201](#)

Also in near future see:

Y. Chen, R. Harnick, RVM: [to appear](#),

Y. Chen, D. Stolarski, RVM: [to appear](#)