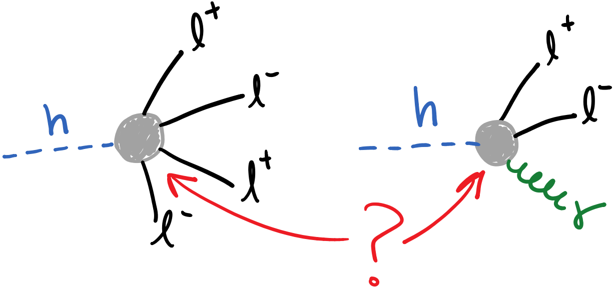
The Higgs Boson in $h \to 4\ell$ and $h \to 2\ell\gamma$



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HEP Seminar: SMU

March 21, 2016

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

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

Many studies of $h \to 4\ell$ and $h \to 2\ell\gamma$ decays before and after discovery...

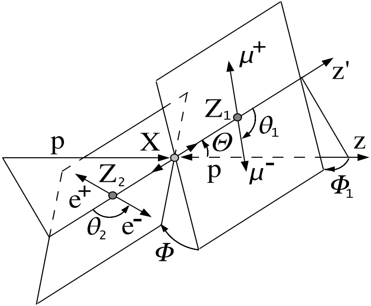
R. M. Godbole, D. Miller, M. Muhlleitner: **0708.0458**
Q. Cao, C. Jackson, W.Y. Keung, I. Low: **0911.3398**
Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
J. Gainer, K. Kumar, I. Low, RVM: **1108.2274**
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**

Physics Possibilities in $h \to 4\ell$ and $h \to 2\ell\gamma$

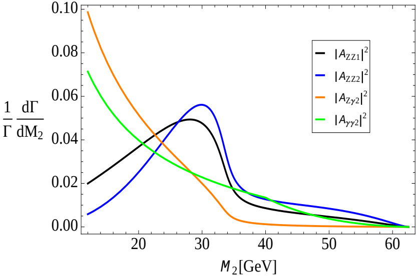
- Hypothesis testing and multi-parameter extraction at LHC
- Establishing CP properties $\Rightarrow$ searching for CP violation (CPV)
- Measuring/constraining 'anomalous' hVV Couplings
- Testing $SU(2)_L \otimes U(1)_Y$ gauge invariance and EFT
- Probing top Yukawa CP properties
- Testing Custodial symmetry
- Exotic Higgs decays

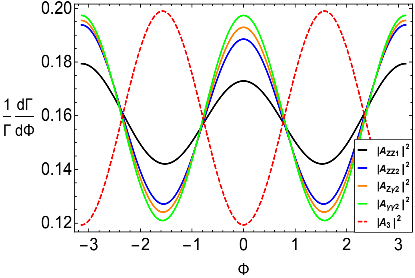
ID-ing the Higgs with Kinematic Distributions

- Sensitivity to Higgs couplings and underlying loop effects comes from the many kinematic differential distributions and their correlations
- They contain information about CP properties and tensor structure of Higgs couplings



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





Constructing a MEM 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)

- For $pp \to h \to 4\ell$ we construct the pdf from the differential cxn:

$$P(\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega}|\vec{A}) =$$

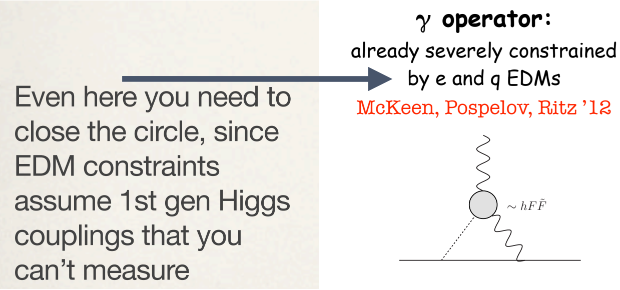
$$W_{\mathrm{prod}}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(\hat{s}, M_1, M_2, \vec{\Omega}|\vec{A})}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

- Construct ratios $\Lambda = L(A_a)/L(A_b) \Rightarrow$ hypothesis testing
- Perform parameter extraction via maximization of the likelihood

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

Searching for CP Violation in *hVV* Couplings

- 'Smoking gun' of BSM physics which could perhaps be connected with baryogenesis $\Rrightarrow$ matter/anti-matter asymmetry
- Many indirect constraints of CP violation:
  - 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



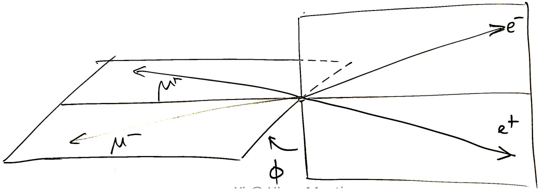
(figure stolen from Joe Lykken Madrid Higgs workshop talk)

- Direct probes of CP are needed free of these assumptions

‘Conventional’ CP Violation via Triple Products

- Typically rely on constructing a CP-odd triple product asymmetry
- Need four visible 4-momenta to construct CPV observable
- One example is the azimuthal angle between decay planes of a four-body Higgs decay such as in $h \to 4\ell$ or $h \to \tau\tau$

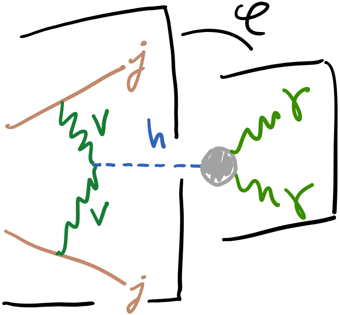
$$\cos\phi = \frac{(\vec{p}_1 \times \vec{p}_2)\cdot(\vec{p}_3 \times \vec{p}_4)}{|\vec{p}_1 \times \vec{p}_2|\;|\vec{p}_3 \times \vec{p}_4|}$$

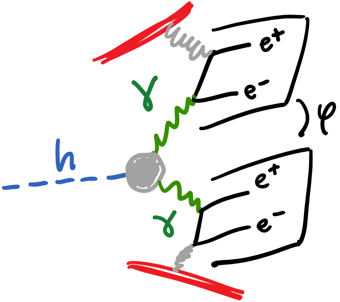


- For this type of CPV only need distinct ‘weak phases’ (phases that change sign under CP) in amplitudes which are interfering

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)



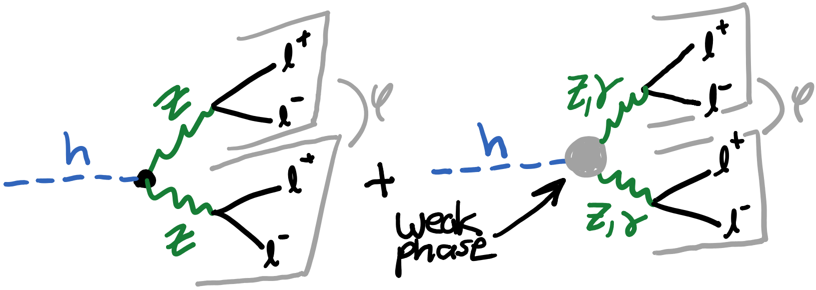


- Interesting possibilities...experimentally challenging measurements

Probing CPV in hZZ and $hV\gamma$ with $h \to 4\ell$

- Sensitivity is driven by interference between tree level ZZ mediated amplitude and the 1-loop $VV = ZZ, Z\gamma, \gamma\gamma$ mediated decays

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



- The effective couplings to VV provide the potential weak phases
- BUT...CPV observables also possible without 4 visible momenta!

CP Violation Without Triple Products

- Consider decay into CP conjugate final states F and $\bar{F}$
- Conditions necessary for CPV without triple products:
  - Interference between different amplitudes

$$\mathcal{M}_F = \mathcal{M}_1 + \mathcal{M}_2$$

  - Distinct strong and weak phases for $\mathcal{M}_1$ and $\mathcal{M}_2$

$$\mathcal{M}_i = |c_i| e^{i(\delta_i + \phi_i)}$$

(where $\delta_i \to \delta_i$ and $\phi_i \to -\phi_i$ under CP)

  - Need a CP violating observable such as an asymmetry

$$A_{\rm CP} = \frac{d\Gamma_F - d\Gamma_{\bar{F}}}{d\Gamma_F + d\Gamma_{\bar{F}}} \propto |c_1||c_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

- Note also that last condition requires $\mathcal{M}_F \neq CP(\mathcal{M}_F) \equiv \mathcal{M}_{\bar{F}}$
- What kind of physics/processes can satisfy these conditions?

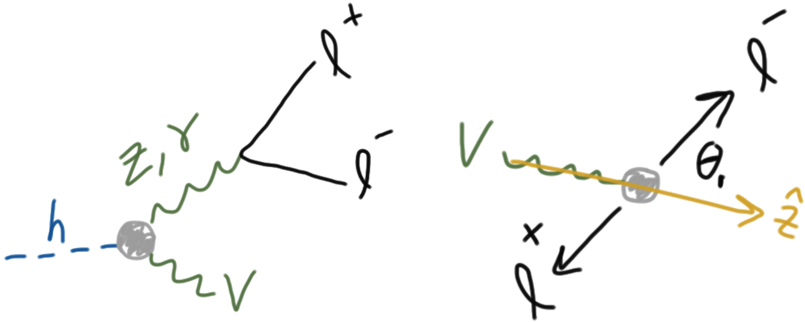
A well known effect in flavor physics and studied in BSM context by J. Berger, et al: 1105.0672

New Observables for CPV in Higgs Decays

- Our primary example of this type of CPV is $h \to 2\ell V$ $(V = \gamma, Z)$

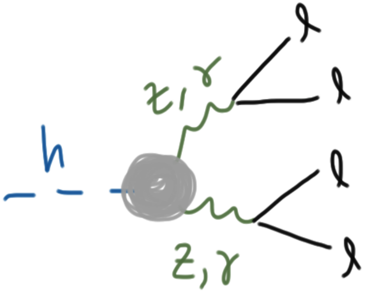
  (see Y. Chen, A. Falkowski, I. Low, RVM: 1405.6723 for other examples of this type of CPV)

- Observable as an asymmetry in polar angle of final state lepton ℓ^-



- Note generally asymmetry $\neq$ CPV (e.g. $e^+e^- \to f\bar{f}, WW$ @ LEP)
- Also need C violation since individual polarizations not measured
- Of course this type of CPV also possible in $h \to 4\ell$ decays

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



- We consider $h \to VV \to 4\ell$ where $4\ell \equiv 2e2\mu, 4e, 4\mu$ and $VV = ZZ, Z\gamma, \gamma\gamma$
- Can parametrize the hVV couplings with an effective Lagrangian (up to D = 5)

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

Background

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

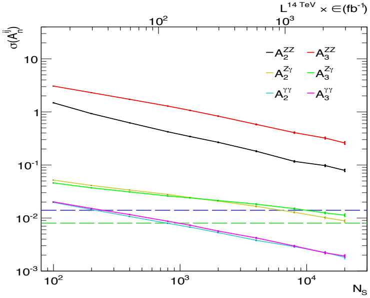
Signal

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

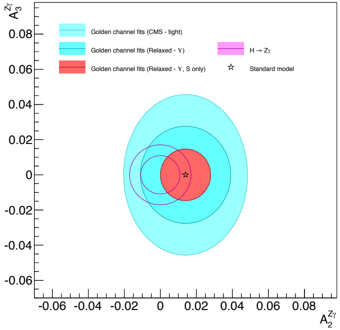
$$\left. + 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\right)$$

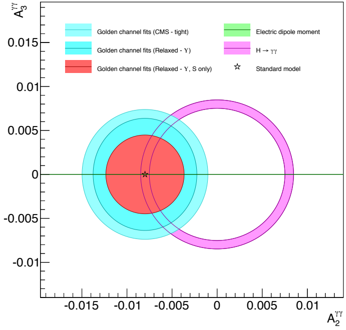
Probing Anomalous Couplings at the LHC

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



- **Perform 6D fit** to $ZZ, Z\gamma$, $\gamma\gamma$ 'anomalous' effective Higgs couplings
- Stronger sensitivity to $Z\gamma$ and $\gamma\gamma$ effective couplings
- Can **probe $Z\gamma$ and $\gamma\gamma$ CP properties** at HL-LHC





Framework in CMS Analysis

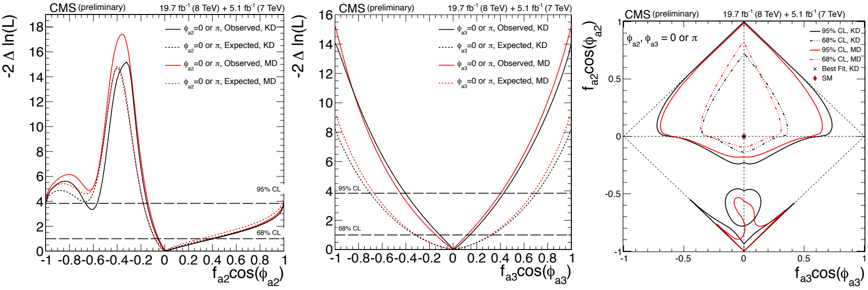
CMS PAS HIG-14-014, arXiv: 1411.3441

- A multi-dimensional Higgs couplings extraction framework

  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, arXiv:1410.4817

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



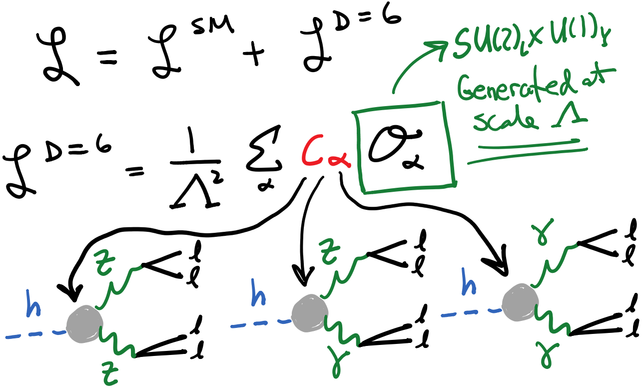
- Used in a limited scope and validated with other frameworks
- Can begin utilizing full power of framework in future LHC studies

Testing $SU(2)_L \otimes U(1)_Y$ Gauge Invariance and EFT

- Wilson coefficients in $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ invariant theory are generated at some high scale Λ and RG evolved down to weak scale

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

- Construct SM + D6 EFT and perform fits to Wilson coefficients



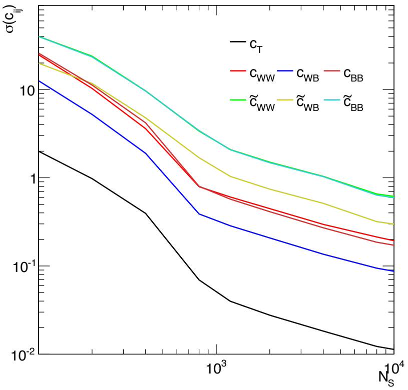
- Gauge invariance implies correlations among different 4ℓ components

Extracting Wilson Coefficients at LHC

- Can fit in any basis such as in ‘Warsaw’ or ‘Higgs’ basis

  (B. Grzadkowski, et. al.: 1008.4884, R. S. Gupta, A. Pomarol, F. Riva: 1405.0181)

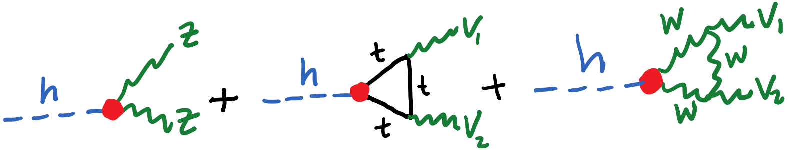
(Y. Chen, A. Falkowski, R. Harnik, RVM: PRELIMINARY)



- Wilson coefficients give a more direct connection with UV theories

Probing top and W Loop Effects in $h \to 4\ell$

- The *W* and top loops contribute to effective hVV couplings



- Can study the nature of the top and W couplings to the Higgs

$$\mathcal{L}_{ZW} \supset \frac{h}{v}\Big(g_Z m_Z^2 Z^\mu Z_\mu + 2 g_W m_W^2 W^{\mu+} W_\mu^-\Big)$$

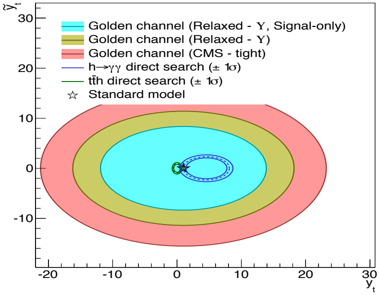
$$\mathcal{L}_t \supset \frac{m_t}{v} h\bar{t}(y_t + i\tilde{y}_t\gamma^5)t$$

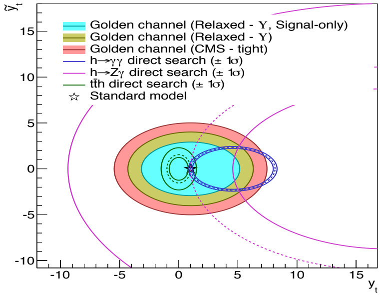
- Interference between tree level hZZ amplitude and top loop diagram allows us to probe top CP properties and searching for CP violation

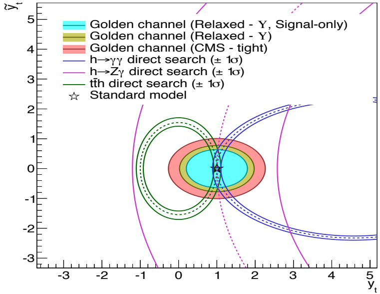
Probing Top Yukawa CP Properties in $h \to 4\ell$

- Compare with other probes such as $h \to \gamma\gamma$, $h \to Z\gamma$, and tth
- Qualitatively different probe of the top Yukawa CP properties

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





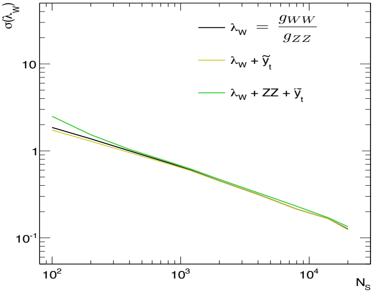


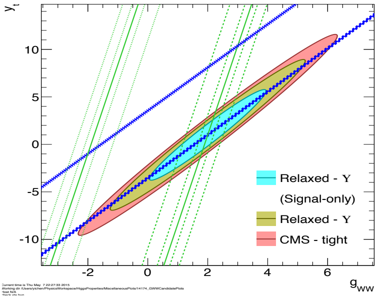
- Not yet sensitive, but should become at high luminosity LHC

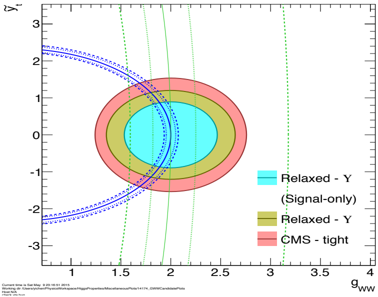
Custodial Symmetry *and* Top CP Properties

- Another possibility is to probe custodial symmetry through the ratio of couplings $\lambda_W = g_W / g_Z$

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

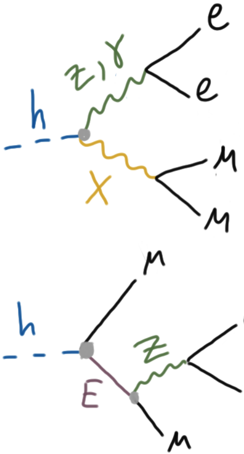






- Examining possibility of probing custodial symmetry and top CP quark properties simultaneously

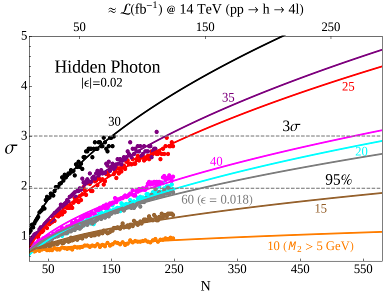
Exotic Higgs Decays in the Golden Channel



- Can use $h \to 4\ell$ to search for exotic Higgs decays to BSM particles (D. Curtin, et. al: arXiv:1312.4992)

- Can probe parameter space of models with new vector bosons in mass range 10 – 65 GeV

(A. Falkowski, RVM: arXiv:1404.1095)



- VL leptons below ~ 110 GeV
- Useful probe even if total $h \to 4\ell$ is close to SM value

Ongoing Work and Conclusions

- As part of ongoing work we are also exploring:

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

  - Sensitivity to Higgs quartic coupling
  - Other NP contributions to loops (squarks, charginos, etc.)
  - Examining using priors with $h \to 4\ell$ and $h \to 2\ell\gamma$ MEM studies
  - Probing effective couplings in loop processes (i.e. NLO EFT)

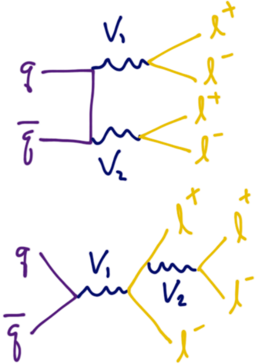
- Conclusions:
  - $h \to 4\ell$ an indispensable tool to study Higgs and search for BSM
  - Can use $h \to 4\ell$ to study Higgs couplings to $ZZ, Z\gamma$, and $\gamma\gamma$ and couplings to top, W, and Z in underlying loop processes
  - It is a direct probe of CP properties of these couplings
  - $h \to 4\ell$ serves as complementary, but qualitatively different measurement to $h \to Z\gamma$ and $h \to \gamma\gamma$ on-shell decays
  - Can be used to search for exotic Higgs decays

THANKS!

Extra Slides

The 'non Higgs' Background

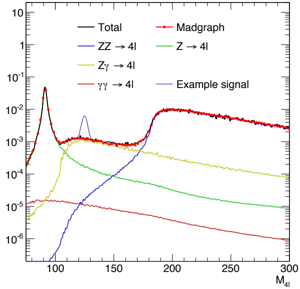
- Dominant irreducible background is $q\bar{q} \to 4\ell$ ($V_1, V_2 = Z, \gamma$) which includes both t & s channel



- Enters largely as a resolution effect due to detector smearing

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

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

(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
- 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

‘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