Direct Probes of CP Violation in the Higgs Sector

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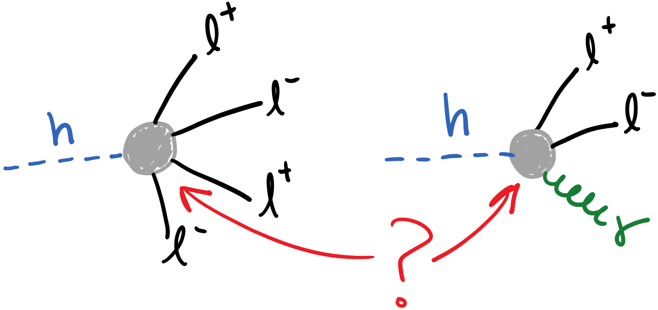
Standard Disclaimer: Not a comprehensive review of direct probes of CPV in Higgs sector

I will attempt to briefly mention various possibilities, but will mainly focus on CPV in:



Probes Higgs couplings to $ZZ, Z\gamma$, and $\gamma\gamma$ pairs, but little to say about CPV in hWW couplings

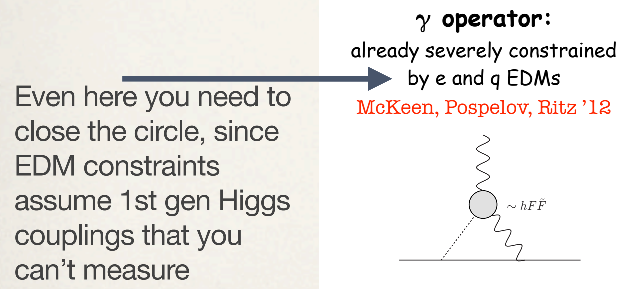
(see for example: H. de Sandes, C. Delaunay, G. Perez, W. Skiba: 1308.4903)

Many studies of direct probes of CPV in Higgs sector before and after discovery...Considered CPV observables at LHC and lepton colliders

A. Soni, R. Xu**9301225**
B. Grzadkowski, J. Gunion: **9501339**
B. Grzadkowski, J. F. Gunion, X. He: **9605326**
B. Grzadkowski, J. F. Gunion, J. Kalinowski: **9902308**
R. M. Godbole, D. Miller, M. Muhlleitner: **0708.0458**
Q.-H. Cao, C. Jackson, W.-Y. Keung, I. Low, and J. Shu: **0911.3398**
Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, et. al.: **1001.5300**
C. Englert, C. Hackstein, and M. Spannowsky: **1010.0676**
N. Desai, D. K. Ghosh, and B. Mukhopadhyaya: **1104.3327**
A. Y. Korchin, V. A. Kovalchuk: **1303.0365**
R. Godbole, D. J. Miller, K. Mohan, and C. D. White: **1306.2573**
R. Harnik, A. Martin, T. Okui, R. Primulando, and F. Yu: **1308.1094**
H. de Sandes, C. Delaunay, G. Perez, W. Skiba: **1308.4930**
D. Gao, Y. Sun, X. Wang: **1309.4171**
I. Anderson, S. Bolognesi, F. Caola, Y. Gao, et. al.: **1309.4819**
F. Bishara, Y. Grossman, R. Harnik, D. J. Robinson, J. Shu: **1312.2955**
M. Farina, Y. Grossman, D. J. Robinson: **1503.06470**
S. Dwivedi, D. K. Ghosh, B. Mukhopadhyaya, A. Shivaji: **1505.05844**
G. Li, H. Wang, S. Zhu: **1506.06453**
K. Hagiwara, K. Ma, H. Yokoya: **1506.06453**
+ **many others** as well as **various ATLAS and CMS studies**

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



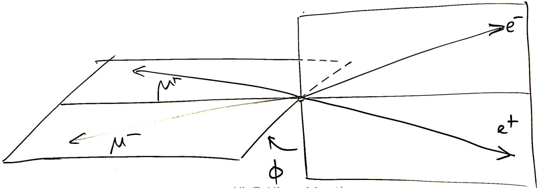
(figure stolen from Joe Lykken Madrid Higgs workshop talk)

- Crucial to have direct probes of CPV free of these assumptions

'Conventional' CP Violation via Triple Products

- Typically rely on constructing a CP-odd triple products
- 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 $h \to \tau\tau$

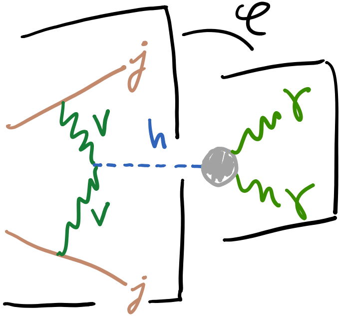
$$\cos\phi = \frac{(\vec{p}_1 \times \vec{p}_2) \cdot (\vec{p}_3 \times \vec{p}_4)}{|\vec{p}_1 \times \vec{p}_2| \, |\vec{p}_3 \times \vec{p}_4|}$$

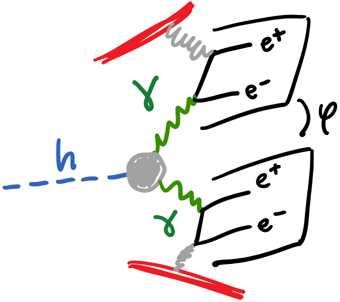


- For this type of CPV only need distinct 'weak phases' (phases that change sign under CP) in amplitudes which are interfering

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)



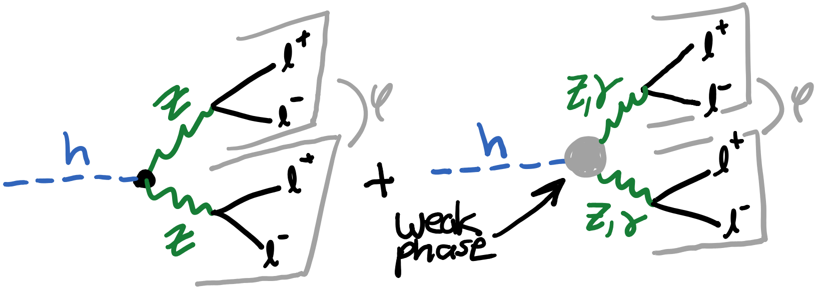


- Interesting possibilities...experimentally challenging to measure

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

- Sensitivity driven by interference between tree level ZZ 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)



- Effective couplings to VV provide the potential weak phases
- BUT...CPV 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

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

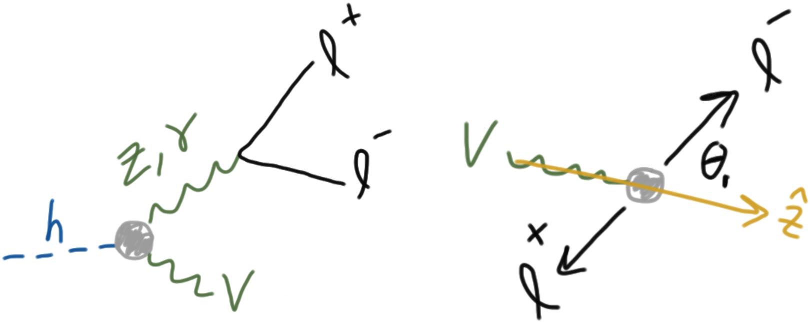
- Note also that last condition requires $\mathcal{M}_F \neq CP(\mathcal{M}_F) \equiv \mathcal{M}_{\bar{F}}$
- What kind of physics/processes can satisfy these conditions?

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 asymmetry in polar angle of final state lepton ℓ^-



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

CP Violation in $h \to 2\ell\gamma$ Decays

- **We can parametrize the $hZ\gamma$ and $h\gamma\gamma$ couplings as,**

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

- **Can gain insight into CPV by examining helicity amplitudes**

$$\lambda_{\pm 1}^{V} = \mp g_{V,\lambda}\frac{(A_2^{V\gamma} \pm iA_3^{V\gamma})M_1(m_h^2 - M_1^2)}{2\sqrt{2}v(M_1^2 - m_V^2 + im_V\Gamma_V)}\left(1 \mp \kappa\cos\theta_1\right), \quad \lambda = R, L$$

- **See that conditions for CPV are satisfied by amplitudes**
  - Two different intermediate particles, Z and γ, contribute to the same amplitudes.
  - $\text{Arg}(A_2^{V\gamma} + iA_3^{V\gamma})$,$V = Z, \gamma$, provide different weak phases.
  - $\text{Arg}(M_1^2 - m_V^2 + im_V\Gamma_V)$, $V = Z, \gamma$, give distinct strong phases.

(Note: we also needed $\mathcal{M}(h \to 2\ell\gamma) \neq CP[\mathcal{M}(h \to 2\ell\gamma)]$)

- **Fully differential cross section can be written as $CPC + CPV$**

$$\frac{d\Gamma}{dM_1^2 d\cos\theta_1} = \left(1 + \cos^2\theta_1\right)\frac{d\Gamma_{\text{CPC}}}{dM_1^2} + \cos\theta_1\frac{d\Gamma_{\text{CPV}}}{dM_1^2}$$

(We see directly that any asymmetry implies CPV!)

CP Violation in $h \to 2\ell\gamma$ Decays

- Can compute the total *integrated* forward-backward asymmetry

$$\bar{A}_{\rm FB} \equiv \frac{3\int_{M_0}^{m_h} dM_1\, M_1 \frac{d\Gamma_{\rm CPV}}{dM_1}}{8\int_{M_0}^{m_h} dM_1\, M_1 \frac{d\Gamma_{\rm CPC}}{dM_1}}$$

- In narrow width approx. can get estimate for total asymmetry

$$\bar{A}_{\rm FB} \approx \frac{\Gamma_Z}{m_Z} \frac{A_2^{Z\gamma}A_3^{\gamma\gamma} - A_2^{\gamma\gamma}A_3^{Z\gamma}}{(A_2^{Z\gamma})^2 + (A_3^{Z\gamma})^2} \frac{3e(g_{Z,R} - g_{Z,L})}{2(g_{Z,R}^2 + g_{Z,L}^2)} \approx 0.07 \frac{A_2^{Z\gamma}A_3^{\gamma\gamma} - A_2^{\gamma\gamma}A_3^{Z\gamma}}{(A_2^{Z\gamma})^2 + (A_3^{Z\gamma})^2}$$

- Can estimate final asymmetry assuming $\sigma_{h\to 2\ell\gamma}/\sigma_{BG} \sim 1/60$

$$\frac{S}{\sqrt{B}} \sim \left(\frac{\bar{A}_{\rm FB}}{0.1}\right)\sqrt{\frac{L}{3000\ {\rm fb}^{-1}}}$$

- LHC should have chance to observe $\bar{A}_{FB}$ in HL phase!
- Sensitivity can be improved with full MEM analysis (ongoing!)

CP Violation in $h \to 2\ell Z$ Decays

- Can also probe CPV in $h \to 2\ell Z$ for $hZ\gamma$ and hZZ couplings

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

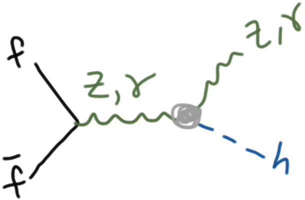
- Now have tree level A_1^{ZZ} coupling which dominates CPC part
- Total FB asymmetry given parametrically by

$$\bar{A}_{\rm FB}(h \to \ell^- \ell^+ Z) \sim \frac{\Gamma_Z}{m_Z} \frac{A_3^{Z\gamma}}{A_1^{ZZ}} \lesssim 10^{-3}$$

- Difficult to observe at LHC, but perhaps at 100 TeV
- Again full MEM will help boost the sensitivity (more to follow)
- Also part of $h \to 4\ell$ decay which includes $h\gamma\gamma$ couplings

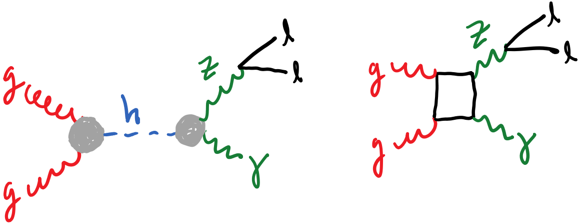
CP Violation in 2-to-2 Scattering

- Crossing symmetry implies $f\bar{f} \to Z/\gamma \to hV$ can also be utilized



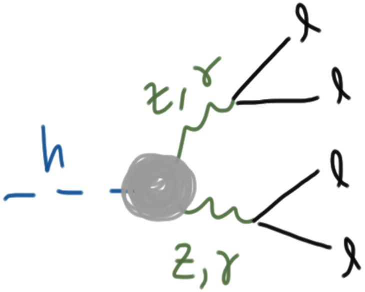
- Can use signal/background interference to probe CPV

(M. Farina, Y. Grossman, D. J. Robinson: 1503.06470)



- These are difficult to observe at LHC, but could be very interesting at future e^+e^- machine or 100 TeV hadron collider

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)

Background

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

Signal

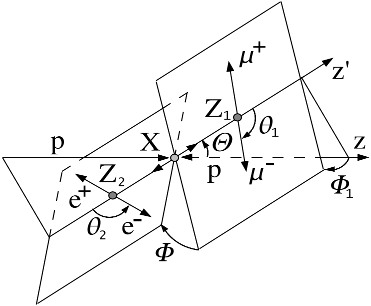
$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

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

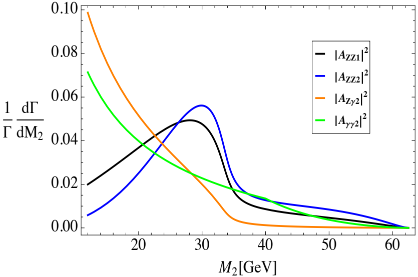
$$+ 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\Big)$$

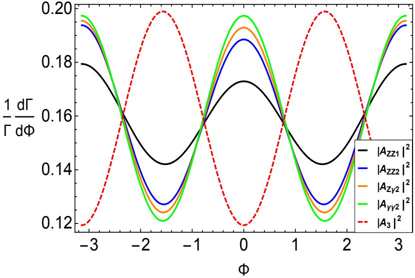
ID-ing the Higgs with Kinematic Distributions

- Sensitivity to Higgs couplings and underlying loop effects comes from the many kinematic observables
- Contain information about CP properties and tensor structure of hVV 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)

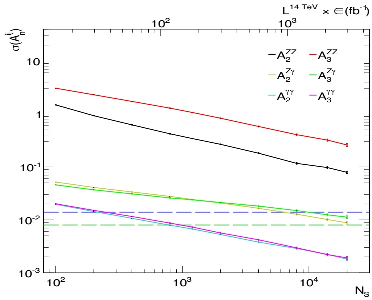
- For $pp \to h \to 4\ell$ we construct the pdf from the differential cxn:

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

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

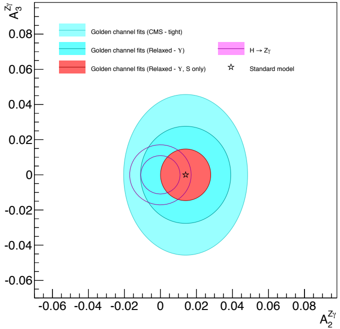
$$\frac{\partial L(\vec{A})}{\partial \vec{A}}\Big|_{\vec{A}=\hat{A}} = 0$$

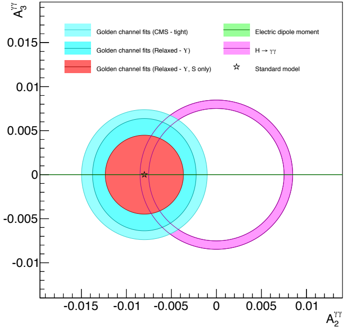
Probing Anomalous Couplings at the LHC



(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

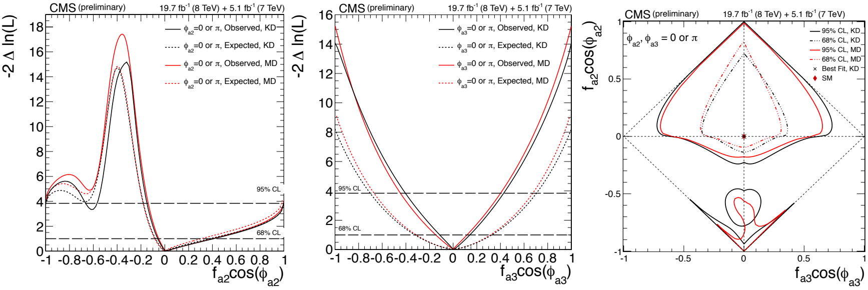
CMS PAS HIG-14-014, arXiv: 1411.3441

- 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 hVV couplings in $h \to 4\ell$

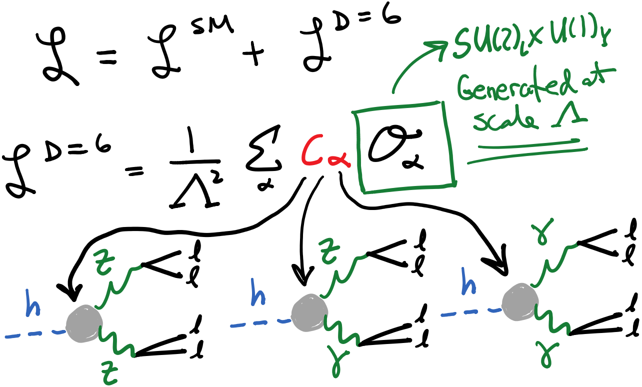


- Used in a limited scope and validated with other frameworks
- Can begin utilizing full power of framework in future studies

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 high scale Λ and RG evolved 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 WCs

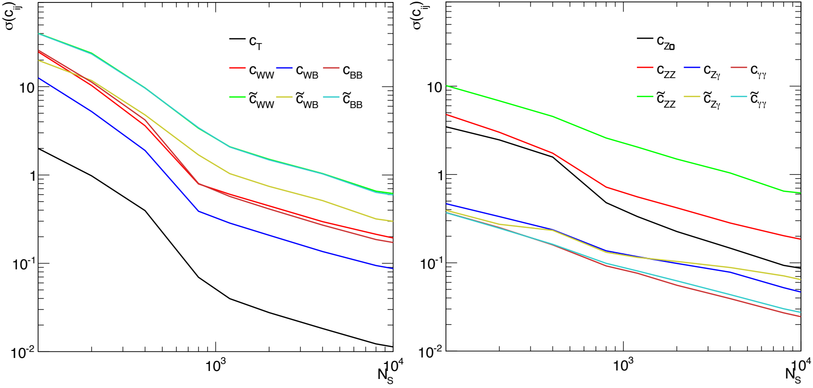


- **Gauge invariance implies correlations** among 4ℓ components

Extracting Wilson Coefficients at LHC (ongoing)

- WCs give a more direct connection with UV theories

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

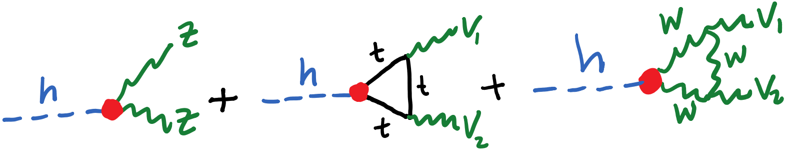


- Can fit in any basis such as in 'Warsaw' or 'Higgs' basis

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

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

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



- Can study the CP nature of the top couplings to the Higgs

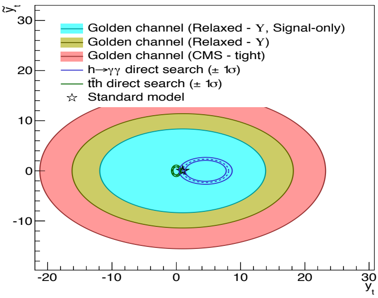
$$\mathcal{L}_t \supset \frac{m_t}{v} h\bar{t}(y_t + i\tilde{y}_t\gamma^5)t$$

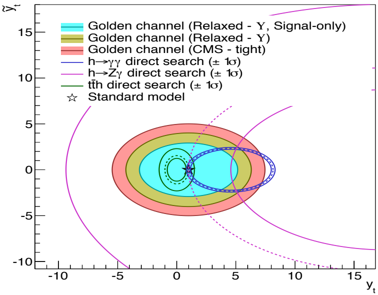
- Interference between tree level *hZZ* amplitude and top loop diagram gives sensitivity to CPV

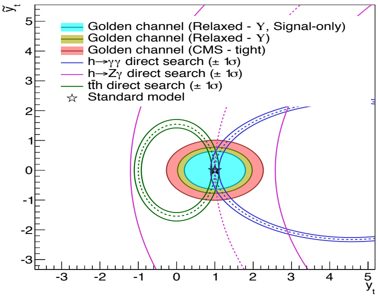
Probing Top Yukawa CP Properties in $h \to 4\ell$

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

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







- Not yet sensitive, but should become at HL-LHC

Summary

- Direct probes of CPV in the Higgs sector are crucial and complementary to indirect searches (EDMs, decay rates,...)
- Can construct a number of CPV violating observables in processes involving Higgs boson production and decay
- Higgs decays in $h \to 4\ell$ and $h \to 2\ell\gamma$ are particularly promising for probing CP properties of $hV\gamma$ couplings
- Especially useful when utilizing all observables in a fully differential matrix element method analysis
- Can also probe underlying loop effects to search for CPV in top quark Yukawa sector for example
- These channels will become especially important at HL-LHC
- Other direct probes would also be very interesting at future linear e^+e- machine or 100 TeV hadron collider

THANKS!

(and let me know if interested in football!)

Extra Slides

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