PROSPECTS FOR MEASURING HIGGS CP VIOLATION AT FUTURE COLLIDERS

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The CP Nature of the Higgs Boson, May 1, 2015
CP Violation – Motivated and Required

• Sakharov’s three conditions for baryogenesis motivate searches for new sources of CP violation
  – Need B violation
  – Need C and CP violation
  – Need interactions to happen out of thermal equilibrium

• Our picture of baryogenesis is embarrassingly incomplete
  – SM EW baryogenesis is insufficient
  – Strongly motivates new sources of CPV
A natural place to test for CP violating phases is with Higgs physics: distinct NP sources

- scalar-pseudoscalar admixture (e.g. scalar potential)
  - naïvely tested via rate suppression

- couplings to gauge bosons (e.g. bosonic CPV)
  - for example, tested via acoplanarity measurement in \( h \to ZZ^* \to 4l \)

- couplings to fermions (e.g. fermionic CPV)
  - tomorrow: test via \( h \to \tau^+ \tau^- \to (\rho^+\nu) (\rho^-\nu) \to (\pi^+\pi^0)\nu (\pi^-\pi^0)\nu \)

Throughout, will focus on spin-0 Higgs

- ATLAS and CMS (see talk by Whitbeck and e.g. CMS [1411.3441]) have excluded other spin possibilities
Current Higgs proportionality measurements

- These rate measurements only tell half of the story
  - Must also test phases (and higher order moments via Higgs EFT)

ATLAS-CONF-2015-007
CMS [1412.8662]
CP and the Higgs

- Precision Higgs physics is a central tenet of the LHC/HL-LHC program
  - Much effort is justifiably concentrated on coupling extractions
  - In order to be sensitive to deviation $\delta$, should measure to $\delta/3$ or $\delta/5$ precision
    - Motivates a dedicated Higgs factory (ILC, FCCee, CEPC)
- Will summarize available CPV study prospects at future machines
  - Inherently different levels of rigor
  - Emphasize how different machines enable new search channels and tests of Higgs couplings
    - Also complementary to indirect tests (EDMs)
Machines

- $e^+e^-$ collider
  - ILC: Linear collider has polarized beams, much less instantaneous luminosity
  - FCC-ee, CEPC: Circular collider has unpolarized beams, much better instantaneous luminosity

- $pp$ collider
  - LHC & HL-LHC, FCC-hh, SPPC

- (Muon collider)
- (γγ collider)
Outline

• Studied channels
  – ZZ, WW (A. Whitbeck)
  – gg (M. Dolan)
  – Zγ (M. Farina)
  – ττ (FY)

• The unlikely/impossible SM decay channels (w/o a unique collider)
  – ee, μμ, γγ, qq (q = u, d, s, c)

• Prospective channels
  – bb, tt (T. Liu)

• Open questions and summary
Basic CPV collider phenomenology

• NP CPV sources generally affect inclusive rates
  – Normalized differential distributions fold out rate information (by construction)
  – Need to have rates (=inclusive distributions=integrated luminosity) before asymmetry variables or differential distributions are meaningful

• Canonical observables
  – triple product of 3-vectors – CP-odd, T-odd combination
    • \( p_1 \cdot (p_2 \times p_3) \)
  – angular distributions – uses decays of polarized intermediate particles
    • acoplanarity in \( h \rightarrow ZZ^* \rightarrow 4 \) leptons
Testing CPV in Higgs decays to (electroweak) gauge bosons

- For ZZ*, measure acoplanarity angle $\Phi$ (angle between $Z_1$ and $Z_2$ decay planes)
- Golden channel
  - everything measureable, can reconstruct the Higgs rest frame and appropriate decay planes
Testing CPV in Higgs decays to ZZ* 

Final state observables

- Four-vectors of the final state particles give access to boson decay planes and to the tensor structure.
- Easier in ZZ* → 4l case, harder in WW → lvlv case.
- Reasonable target: 10% CP-odd admixture corresponds to f_{CP} < 10^{-5} in VV decays. (Snowmass)
Testing CPV in Higgs production

- VBF production
  - CP even is pure $W_{\mu\nu}W^{\mu\nu}$
  - CP odd is pure $W_{\mu\nu}\tilde{W}^{\mu\nu}$
  - Shape is influenced by VBF cuts
Testing CPV in Higgs production

• VH Production is equivalent physics to decay because of crossing symmetry
  – More sensitive to momentum form factors
  – Use ZH production, Z to leptons, Higgs to bottoms

Anderson, et. al. [1309.4819]
Testing CPV in Higgs production

• VH Production is equivalent physics to decay because of crossing symmetry
  – At lepton collider

Anderson, et. al. [1309.4819]
Testing CPV in Higgs production

- LHC ZH production

Red: SM
Blue: pseudoscalar
Green: \( f_{a3} = 0.5, \phi_{a3} = 0 \)
Magenta: \( f_{a3} = 0.5, \phi_{a3} = \pi/2 \)

Anderson, et. al. [1309.4819]
CPV in HVV interactions

- Build kinematic discriminant and extrapolate sensitivity
  - Extrapolation will be systematics limited
  - Form factors in production also change kinematics (interpretation is not model independent)

Anderson, et. al. [1309.4819]
Other channels and representative work

• $Z\gamma, Z \rightarrow l^+l^-$ (M. Farina and collaborators, 1503.06470)
  – Take advantage of interference between continuum background and signal from gluon initiated events

• $gg$ (M. Dolan and collaborators, 1406.3322)
  – Use associated jets for angular analysis

• $\tau\tau$ (FY and collaborators, 1308.1094)
  – At LHC or other proton machines, reconstruct acoplanarity from rho meson decays
  – At lepton colliders, can fully reconstruct Higgs rest frame and neutrino momenta (up to two-fold ambiguity)

  • See also Berge, et. al. [1308.2674] and refs. therein
Other channels

- $\gamma\gamma$ (F. Bishara, *et. al.*, 1312.2955)
  - Require converted photons (detector material) and angular resolution on leptonic opening angles
Other channels

• $\gamma\gamma$ (F. Bishara, et. al., 1312.2955)

  – Require converted photons (detector material) and angular resolution on leptonic opening angles

<table>
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<tr>
<th>$\sqrt{s}$</th>
<th>$\mathcal{L}$ [fb$^{-1}$]</th>
<th>$\sigma \times \text{BR}(h \rightarrow \gamma\gamma)$ [fb]</th>
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Table 1. Expected number of events after the application of $S$ or $T$ cuts with $\theta_{\ell\ell} > 10^{-4}$ to obtain $\langle B \rangle/\langle A \rangle \sim 20\%$. The Higgs production cross section includes the gluon fusion and VBF channels only and is taken from [55].

  – Would be trivial (!) at $\gamma\gamma$ collider
Other channels

• $\mu\mu$
  – Not possible in Higgs decay
  – Polarize beams at muon collider

• $ee$
  – Not possible in Higgs decay
  – Polarize beams at electron collider, push energy resolution to $R = 0.01\%$ or less
First generation couplings

- **s-channel Higgs production**
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; $\sigma(\text{ee} \rightarrow \text{H}) = 1.6 \text{ fb}$; 7 Higgs decay channels studied

**Preliminary Results**

$L = 10 \text{ ab}^{-1}$

$k_e < 2.2$ at $3\sigma$

- **Work in progress**
  - How large are loop induced corrections? How large are BSM effects?
  - Do we need an energy scan to find the Higgs?
  - How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?
  - Can polarization increase sensitivity?
Other channels

- $\mu\mu$
  - Not possible in Higgs decay
  - Polarize beams at muon collider
- $ee$
  - Not possible in Higgs decay
  - Polarize beams at electron collider, push energy resolution to $R = 0.01\%$ or less
- $qq$ ($q = u, d, s, c$)
  - Only recent work addressed extracting second generation Yukawas from $h \rightarrow J/\Psi \gamma$
    - See Kagan, et. al. (1406.1722), Grossman, et. al. (1501.06569)
    - Needs full luminosity HL-LHC
    - No study of CPV prospects in these decays
    - May have complementarity with meson CPV probes
Other channels

- **bb**
  - Without 2HDM $\tan \beta$ enhancement, could only use Higgs decay and not $bbH$ production
  - Some work in progress by Yevgeny Kats and collaborators about how bottom spin is retained in hadronization and subsequent decay
    - See Y. Kats, “$b$ polarization as a probe of new physics”, 2nd NPKI Workshop, Physics from Run 2 of the LHC
  - Would require dedicated analysis for constructing appropriate CPV observable in $bb$ decay channel
Other channels

- \( tt \) (see talk by T. Liu)
  - Independent measurement from \( gg \) production, \( \gamma Z \) and \( \gamma\gamma \) decay
  - Probed via \( ttH \) production
  - EDM constraints require non-trivial flavor construction if we have positive signal in \( ttH \) and null results in EDM

Brod, Haisch, Zupan [1310.1385]
ttH production – pp collider
$t\bar{t}H$ production – (high energy) $e^+e^-$ collider

Moortgat-Pick (ed.), et. al. ILC physics study, 1504.01726
ttH production at lepton collider

- Need to capture top polarization
- No modern complete pheno studies

FIG. 3: The top quark polarization in the process $e^+e^- \rightarrow t\bar{t}\Phi$ for a scalar and a pseudoscalar Higgs boson as a function of $\sqrt{s}$ for two masses $M_\Phi = 120$ and 150 GeV (left) and with unpolarized and polarized $e^\pm$ beams as a function of the parameter $b$ at $\sqrt{s} = 800$ GeV for $M_\Phi = 120$ GeV (right).

Dev, et. al. [0707.2878]
ttH production at lepton collider

- Sensitivity to pseudoscalar coupling

![Graph showing sensitivity to pseudoscalar coupling](image)

**FIG. 4:** The sensitivity of the cross section (left) and the top quark polarization (right) on the parameter $b$ for $M_\Phi = 120$ at $\sqrt{s} = 800$ with $\mathcal{L} = 500$ fb$^{-1}$.

Dev, et. al. [0707.2878]
Open issues

• Post-discovery: what Lagrangian CPV source is responsible in the case of a positive measurement?

• Targets for CPV sensitivity
  – Tree-level operator (Yukawa) vs. loop-induced
  – How to include rate effects

• Precision Higgs physics NP models
  – Real coefficients induce unitarity violation in scattering
    • Imply a NP scale for UV completion
  – Imaginary coefficients – any guiding principle for size of effects?
Summary

• New CP phases are motivated from general baryogenesis arguments
• Many physics studies are needed to motivate the physics case of future machines
• Each measured Higgs coupling can be a test bed for CPV
  – New dimension 4 couplings (for example, FV couplings) are also possible and immediately go beyond SM
CPV in HVV interactions

• Comparison for $e^+e^-$ and pp

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