THE WIDE WORLD OF CP VIOLATION AT HL-LHC AND HE-LHC

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CP Violation – Motivated and Required

We think, ergo CP violation

R. Descartes (?)

- 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

CP Violation – Motivated and Required

• Many CP puzzles remain outstanding
  – Leading SM CPV comes from CKM phase
  – $\Theta$-parameter of QCD constrained to be $< 10^{-10}$
  – Possible Dirac and Majorana phases of PMNS matrix are next targets of neutrino experiments

• SM predicts no tree-level CPV in Higgs couplings
  – Attractive possibility to use first-order electroweak phase transition + CP violation in Higgs couplings to generate the baryon asymmetry

See, e.g. Konstandin [1302.6713]
CP and the Higgs

• Higgs couplings can naturally have CP phases: distinct UV origins
  – scalar-pseudoscalar admixture
    • e.g. scalar potential has imaginary phase in 2HDM bilinear
    • readily (naïvely) tested via rate suppression
Higgs couplings can naturally have CP phases: distinct UV origins

- scalar-pseudoscalar admixture
- couplings to gauge bosons (e.g. bosonic CPV)

\[ \mathcal{L} = \frac{m_Z^2}{v} h Z_\mu Z^\mu + c_{ZZ} \frac{h}{\Lambda} Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} \frac{h}{\tilde{\Lambda}} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \]

- Many results and constraints
- For example, tested via acoplanarity measurement in \( h \to ZZ^* \to 4l \) (see talk by Y. Chen next)
CP and the Higgs

• Higgs couplings can naturally have CP phases: distinct UV origins
  – scalar-pseudoscalar admixture
  – couplings to gauge bosons (e.g. bosonic CPV)
  – couplings to fermions (e.g. fermionic CPV)

\[ \mathcal{L} = -m_f \bar{f} f - \frac{y_f}{\sqrt{2}} h \bar{f} (\cos \Delta + i\gamma_5 \sin \Delta) f \]

• \( \Delta = 0 \) is predicted in the SM (purely CP-even)
• \( \Delta = \pi/2 \) is pure CP-odd (and CP conserving)
• \( \Delta = \pm \pi/4 \) is maximally CP-violating
Yukawa CP phases

\[ \mathcal{L} = - \left( \alpha_{ij} + \beta_{ij} \frac{H^\dagger H}{\Lambda^2} \right) H \bar{f}^i f^j \]

– In dim-6 SMEFT, can readily generate BSM Yukawa couplings including
  • Enhanced/suppressed diagonal flavor couplings
  • New off-diagonal flavor-violating couplings
  • CP phases in diagonal or off-diagonal couplings
– \( \alpha \) and \( \beta \) are generally complex matrices – must have flavor symmetry in UV physics to ensure they are aligned

• In EW broken phase, one combination gives known fermion masses, other generally leads to complex Yukawa matrices

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Yukawa CP phases

– Curious fact: Suppressing Yukawa CP phases in SMEFT requires parametrically (chirally) large scale separation

\[
\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y_u' \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_\ell \bar{L} H \ell_R + y_\ell' \frac{H^\dagger H}{\Lambda^2} \bar{L} H \ell_R \\
+ y_d \bar{Q}_L H d_R + y_d' \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{h.c.}
\]

– Flavor symmetries diagonalize and remove phases in mass matrices

\[
m_f = \frac{y_f v}{\sqrt{2}} + \frac{y_f' v^3}{2\sqrt{2} \Lambda^2}
\]

– Yukawa phases can be chirally enhanced for light fermions

\[
\frac{y_f, \text{ eff}}{\sqrt{2}} = \frac{y_f v}{\sqrt{2}} + \frac{3y_f' v^2}{2 \sqrt{2} \Lambda^2} = \frac{m_f}{v} + \frac{2y_f' v^2}{2 \sqrt{2} \Lambda^2}
\]

• (Bluntly, fine-tune mass generation ↔ large BSM effects)
Complementarity with EDMs

• Top CPV phase naively constrained by electron EDM
  Brod, Haisch, Zupan [1310.1385]
  • Indirect probe, still important to perform direct tests at LHC
    See Buckley, Goncalves [1507.07926],
    Mileo, Kies, Szynkman, Crane, Gegner [1603.03632],
    cf. F. Maltoni slides from yesterday

• Light quark CPV phases confront neutron EDM
  Chien, Cirigliano, Dekens, de Vries, Mereghetti [1510.00725]

• Open room for $\tau$ Yukawa phase – HL-LHC and HE-LHC could provide leading sensitivity
  Harnik, Martin, Okui, Primulando, FY [1308.1094]
  Berge, Bernreuther, Kirchner [1510.03850]
CP phase in Tau Yukawa

\[ \mathcal{L} = -m_\tau \bar{\tau} \tau - \frac{y_\tau}{\sqrt{2}} h \bar{\tau} (\cos \Delta + i \gamma_5 \sin \Delta) \tau \]

- eEDM probes currently leave $\Delta$ unconstrained
CP phase in Tau Yukawa

\[ \mathcal{L} = -m_\tau \bar{\tau} \tau - \frac{y_\tau}{\sqrt{2}} h \bar{\tau} (\cos \Delta + i \gamma_5 \sin \Delta) \tau \]

- eEDM probes currently leave \( \Delta \) unconstrained

Signal strengths only constrain the quadrature sum

Must use differential distributions to test CP

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Brod, Haisch, Zupan [1310.1385]
Basic CPV collider phenomenology

• NP CPV sources generally affect inclusive rates
  – Normalized differential distributions fold out rate information (by construction)
  – Need statistics (=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
Review: Angular observables

- X decays to $V_1 V_2$, decays to 4 fermions
- Characterize by five angles, two masses (+X mass if unknown)

$$
\cos \theta_{p_1} = -\hat{p}_{p_1} \cdot \hat{p}_{V_2}
$$
$$
\cos \theta_{p_3} = -\hat{p}_{p_3} \cdot \hat{p}_{V_1}
$$
$$
\cos \theta^* = \hat{p}_{V_1} \cdot \hat{z}_{\text{beam}}
$$
$$
\Phi_{V_1} = \frac{\hat{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_{sc})}{|\hat{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_{sc})|} \arccos(\hat{n}_1 \cdot \hat{n}_{sc})
$$
$$
\Phi = \frac{\hat{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_2)}{|\hat{p}_{V_1} \cdot (\hat{n}_1 \times \hat{n}_2)|} \arccos(-\hat{n}_1 \cdot \hat{n}_2)
$$
Extracting the phase in Higgs decays to taus

• Tau Yukawa CPV is imprinted on the tau polarizations relative to each other
  – Tau polarizations then get imprinted on the $\nu$ and $\rho$, $\rho$ polarization is imparted to the $\pi$s

• Simplest observable (appropriate for LHC) is $\rho^+\rho^-$ acoplanarity angle
  • [New, better observable (appropriate for $e^+e^-$ collider) is $\Theta$]

$$
\begin{align*}
  h &\rightarrow \tau^- \tau^+ \\
  &\rightarrow \rho^- \nu_\tau \rho^+ \bar{\nu}_\tau \\
  &\rightarrow \pi^- \pi^0 \nu_\tau \pi^+ \pi^0 \bar{\nu}_\tau
\end{align*}
$$

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Ideal situation

$\Theta$ is an optimal reconstructable angular variable sensitive to CPV in $h \rightarrow \tau \tau$

Note MC Z background is flat

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LHC prospects

• Consider h+j events ("boosted" $\tau_{\text{had}}\tau_{\text{had}}$ sample)

• At the LHC, need to approximate neutrino momenta
  – Have (8-2-2-2=) 2 unknown four-momentum components
  – Will use collinear approximation for neutrino momenta
    • In this approximation, $\Theta$ is identical to $\rho\rho$ acoplanarity angle
    • Other approximations considered tended to wash out or distort the sinusoidal shape of the $\Theta$ distribution
  – First proposal to measure $\Delta$ at the LHC with prompt tau decays and kinematics
Collinear amplitude is about 25% of the truth $\Theta$ amplitude.
LHC14 simulation details

- Use MadGraph5 for h+j and Z+j events at LHC14
  - Mimic cuts for 1-jet, hadronic taus Higgs search category
  - Impose preselection of $p_T(j) > 140$ GeV, $|\eta(j)| < 2.5$
  - Normalize to MCFM NLO $\sigma(h+j)=2.0$ pb, $\sigma(Z+j)=420$ pb
  - No pileup or detector simulation, aside from tau-tagging efficiencies
    - Pileup degrades primary vertex determination for charged pion tracks and adds ECAL deposits that reduce neutral pion resolution
    - Tracking and detector resolution will clearly smear the $\Theta$ distribution
Yields for 3 ab$^{-1}$ LHC

- **Signal region:**
  \[ \text{MET} > 40 \text{ GeV}, \ p_T(\rho) > 45 \text{ GeV}, \ |\eta(\rho)| < 2.1, \ m_{\text{coll}} > 120 \text{ GeV} \]

- Inject an additional 10% contribution to (flat) Zj background to account for QCD multijets

<table>
<thead>
<tr>
<th></th>
<th>$h\ j$</th>
<th>$Z\ j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive $\sigma$</td>
<td>2.0 pb</td>
<td>420 pb</td>
</tr>
<tr>
<td>$\text{Br}(\tau^+\tau^- \text{ decay})$</td>
<td>6.1%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$\text{Br}(\tau^- \rightarrow \pi^-\pi^0\nu)$</td>
<td>26%</td>
<td>26%</td>
</tr>
<tr>
<td>Cut efficiency</td>
<td>18%</td>
<td>0.24%</td>
</tr>
<tr>
<td>$N_{\text{events}}$</td>
<td>1100</td>
<td>1800</td>
</tr>
</tbody>
</table>

$N_{\text{events}}$ for 3 ab$^{-1}$ with $\tau$-tagging 50% efficiency
Yields for 3 ab\(^{-1}\) LHC

- Consider \(\tau\) tagging efficiency benchmarks of 50\% and 70\%, use likelihood analysis testing different \(\Delta\)

<table>
<thead>
<tr>
<th>(\tau_t) efficiency</th>
<th>50%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(\sigma)</td>
<td>(L = 550 \text{ fb}^{-1})</td>
<td>(L = 300 \text{ fb}^{-1})</td>
</tr>
<tr>
<td>5(\sigma)</td>
<td>(L = 1500 \text{ fb}^{-1})</td>
<td>(L = 700 \text{ fb}^{-1})</td>
</tr>
<tr>
<td>Accuracy ((L = 3 \text{ ab}^{-1}))</td>
<td>11.5(^\circ)</td>
<td>8.0(^\circ)</td>
</tr>
</tbody>
</table>

- Discriminating pure scalar vs. pure pseudoscalar at 3\(\sigma\) requires 550 (300) \(\text{fb}\^{-1}\) with 50\% (70\%) \(\tau\) tagging efficiency
  - For 5\(\sigma\), require 1500 (700) \(\text{fb}\^{-1}\) with 50\% (70\%) \(\tau\) tagging efficiency
  - Again, detector effects and pileup are neglected
Updated Delphes analysis

Askew, Jaiswal, Okui, Prosper, Sato [1501.03156]

– Collinear approx. at LHC is likely a hard limit
– Angular resolution negligibly (4%) degrades $\Theta$ distribution
– MET resolution most significantly affects contamination from irreducible $Z$ background

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### Hadronic τ Reconstruction

#### Single prong decay also important if impact parameter information is used

Berge, Bernreuther, Niepelt, Spiesberger [1108.0670]

Zanzi for ATLAS and CMS [1703.10259]

See also poster by M. L. Ojeda with 1-prong and 3-prong p<sub>T</sub> dependence

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<table>
<thead>
<tr>
<th>Generated decay mode</th>
<th>ATLAS Simulation Tau Particle Flow</th>
<th>Purity Matrix Z/γ*→ττ</th>
</tr>
</thead>
<tbody>
<tr>
<td>h&lt;sup&gt;±&lt;/sup&gt;</td>
<td>70.4</td>
<td>0.1</td>
</tr>
<tr>
<td>h&lt;sup&gt;±&lt;/sup&gt;π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>24.5</td>
<td>0.9</td>
</tr>
<tr>
<td>h&lt;sup&gt;±&lt;/sup&gt;≥2π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>2.2</td>
<td>0.4</td>
</tr>
<tr>
<td>h&lt;sup&gt;±&lt;/sup&gt;≥1π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>0.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

| h<sup>±</sup>π<sup>0</sup> | 73.5                              | 0.4                   |
| h<sup>±</sup>≥2π<sup>0</sup> | 18.4                              | 0.1                   |
| h<sup>±</sup>≥1π<sup>0</sup> | 15.7                              | 0.4                   |

| h<sup>±</sup>π<sup>0</sup> | 4.8                               | 12.9                  |
| h<sup>±</sup>≥2π<sup>0</sup> | 1.2                               | 58.8                  |
| h<sup>±</sup>≥1π<sup>0</sup> | 0.7                               | 16.5                  |

**Note:** The table above shows the purity matrix for different decay modes, with entries indicating the purity of each mode.
HE-LHC (first look)

- Higgs+jet rates will give $3.5 \times$ increase in signal statistics

<table>
<thead>
<tr>
<th>$p_T$ cut (GeV) on h+j for</th>
<th>NLO cross section for 27 TeV pp collider (MCFM 8.0)</th>
<th>Signal enhancement compared to 14 TeV, $p_T &gt; 140$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>12.1 pb</td>
<td>6.05×</td>
</tr>
<tr>
<td>140</td>
<td>6.96 pb</td>
<td>3.48× [Our original working point]</td>
</tr>
<tr>
<td>150</td>
<td>6.12 pb</td>
<td>3.06×</td>
</tr>
<tr>
<td>200</td>
<td>3.43 pb</td>
<td>1.72×</td>
</tr>
<tr>
<td>250</td>
<td>2.08 pb</td>
<td>1.04×</td>
</tr>
</tbody>
</table>

- Remark: Boosted Higgs studies will gain significantly by going to HE-LHC
  - Important for exotic Higgs decays with jet substructure
Many more Higgs modes to study

- **EW dibosons**
  - Probe in both decays and production, especially VBF and VH (using crossing symmetry)
  - Part of general study of differential distributions to test momentum-dependent form factors

- **ttH**
  - Dileptonic tt final state with H→bb jet substructure

- **Zγ**
  - Take advantage of interference between continuum background and signal from gluon initiated events

- **gg**
  - Use associated jets for angular analysis

- **γγ**
  - Require converted photons (detector material) and angular resolution on leptonic opening angles

- **bb, cc, etc.**
  - Can possibly overcome QCD wash-out of quark polarization

See, e.g. Anderson, et al. [1309.4819]
See, e.g. Buckley, Goncalves [1507.07926]
Farina, Grossman, Robinson [1503.06470]
Dolan, Harris, Jankowiak, Spannowsky [1406.3322]
Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]
Galanti, Giammanco, Grossman, Kats, Stamou, Zupan [1505.02771]

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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

• Straw man NP models for precision Higgs physics
  – 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

• Each measured Higgs coupling can be a test bed for CPV
  – No tree-level CPV expected in any Higgs coupling
  – Yukawa phases should up at dimension-4 in EW broken phase
  – $h \rightarrow \tau \tau$ is a promising first channel to study at HL-LHC and HE-LHC
  – Direct tests at colliders still strongly motivated even though EDM results are null
  – Post-(pre?-)discovery model building needed to connect directly CP phases to EW baryogenesis
TABLE III: List of $f_{CP}$ values in HVV couplings expected to be observed with 3σ significance and the corresponding uncertainties $\delta f_{CP}$ for several collider scenarios, with the exception of $V^* \to VH$ mode at $pp$ 300 fb$^{-1}$ where the simulated measurement does not quite reach 3σ. Numerical estimates are given for the effective couplings $Hgg$, $H\gamma\gamma$, $HZ\gamma$, $HZZ/HWW$, assuming custodial $Z/W$ symmetry and using $HZZ$ couplings as the reference. The $\checkmark$ mark indicates that a measurement is in principle possible but is not covered in this study.

<table>
<thead>
<tr>
<th>collider energy GeV</th>
<th>$\mathcal{L}$ fb$^{-1}$</th>
<th>$H \to VV^*$ $f_{CP}$ $\delta f_{CP}$</th>
<th>$V^* \to VH$ $f_{CP}$ $\delta f_{CP}$</th>
<th>$V^<em>V^</em> \to H$ $f_{CP}$ $\delta f_{CP}$</th>
<th>$gg \to H$ $f_{CP}$ $\delta f_{CP}$</th>
<th>$H \to Z\gamma$ $\gamma\gamma \to H$</th>
<th>$H \to \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>14000 300</td>
<td>0.18 0.06</td>
<td>$6 \times 10^{-4}$ $4 \times 10^{-4}$</td>
<td>$18 \times 10^{-4}$ $7 \times 10^{-4}$</td>
<td>$-0.50$ 0.16</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>pp</td>
<td>14000 3000</td>
<td>0.06 0.02</td>
<td>$3.7 \times 10^{-4}$ $1.2 \times 10^{-4}$</td>
<td>$4.1 \times 10^{-4}$ $1.3 \times 10^{-4}$</td>
<td>$-0.50$ 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>250 250</td>
<td>$\checkmark$</td>
<td>$21 \times 10^{-4}$ $7 \times 10^{-4}$</td>
<td>$\checkmark$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>350 350</td>
<td>$\checkmark$</td>
<td>$3.4 \times 10^{-4}$ $1.1 \times 10^{-4}$</td>
<td>$\checkmark$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>500 500</td>
<td>$\checkmark$</td>
<td>$11 \times 10^{-5}$ $4 \times 10^{-5}$</td>
<td>$\checkmark$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>1000 1000</td>
<td>$\checkmark$</td>
<td>$20 \times 10^{-6}$ $8 \times 10^{-6}$</td>
<td>$\checkmark$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>125</td>
<td>$\checkmark$</td>
<td></td>
<td></td>
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</tbody>
</table>

Anderson, et. al. [1309.4819]