Higgs CP violation

some remarks

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Workshop on the CP nature of the Higgs boson
ACFI, 2015
14 talks + 3 discussions

Topics from theory to experiment frontiers

theories — 2HDM, MSSM, etc

colliders — Higgs production & decays, new particles

low energy — electric dipole moments

cosmology — electroweak baryogenesis
The CP nature of \( h_{125} \)

Higgs boson from Geneva to Particle data group

June 4, 2012

no description about CP yet
motivation from cosmology

Necessary conditions

1) CP violation
2) B violation
3) Non equilibrium

Sakharov, 1967

Electroweak baryogenesis

Kuzmin, Rubakov, Shaposhnikov, 1985; Morrissey, Ramsey-Musolf, arxiv:1206.2942

talks by Liu, Ovanesyan and Shu
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Interact w. Higgs background in a CP violating way

Final baryon asymmetry:

\[ \frac{n_b}{n_\gamma} \sim \frac{\alpha^4_w}{g_*} \Delta \theta(T_c) \sim 10^{-8} \Delta \theta(T_c) \]

\[ \Delta \theta(T_c) \gtrsim 0.01 \]

How \( \Delta \theta(T_c) \) in early universe implies Higgs CP mixture today

talks by Liu, Ovanesyan and Shu
motivation from theory

We know theories that can violate CP

2HDM

\[ V(\phi_1, \phi_2) = \cdots + m_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \]

Glashow, Weinberg, 1977

\[ \mathcal{L}_Y = Y_u \bar{Q} \phi_1 u_R \]

\[ + Y_d \bar{Q} \phi_2 d_R \]

Type II

talk by Chen, Inoue and Liu
motivation from theory

We know theories that can violate CP

\[ V(\phi_1, \phi_2) = \cdots + m_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \]

\[ \mathcal{L}_Y = Y_u \bar{Q} \tilde{\phi}_1 u_R \]
\[ + Y_d \bar{Q} \phi_1 d_R \]

Glashow, Weinberg, 1977

Type I

talk by Chen, Inoue and Liu
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Glashow, Weinberg, 1977

Type I

If explicit break CP

All CP observables depend on \[ \text{Im}[\lambda_5^*(m_{12}^2)^2] \]

\[ \Rightarrow h(c_f\bar{f}f + \bar{c}_f\bar{f}i\gamma_5f) \]

\[ \Rightarrow hZ\bar{Z} + \cdots \]

talk by Chen, Inoue and Liu
motivation from theory

A theoretical motivation:

**2HDM**

\[ V(\phi_1, \phi_2) = \cdots + m_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \]

\[ + \left[ \lambda_6 (\phi_1^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + \text{h.c.} \right] \]

\[ \mathcal{L}_Y = Y_u \bar{Q} \phi_1 u_R + Y_u' \bar{Q} \phi_2 u_R \]

\[ + Y_d \bar{Q} \phi_1 d_R + Y_d' \bar{Q} \phi_2 d_R \]

*General* alignment, MFV …
motivation from theory

A theoretical motivation:

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\[ \mathcal{L}_Y = Y_u \bar{Q} \phi_1 u_R + Y'_u \bar{Q} \phi_2 u_R \]

\[ + Y_d \bar{Q} \phi_1 d_R + Y'_d \bar{Q} \phi_2 d_R \]

General alignment, MFV ...

Spontaneous CP violation

Start from real Lagrangian, reach complex vevs

\[ \Rightarrow \text{CP phase in CKM matrix} \quad O(1) \text{ CP mixture?} \]

Must have: \( Y_u, Y'_u, Y_d, Y'_d \) all nonzero \quad tree level FCNC?

T.D. Lee, 1973
motivation from theory

If you believe in Supersymmetry

**MSSM**  no CP violation at tree level

\[ V(\phi_1, \phi_2) = \cdots + m_{12}^2 (\phi_1^\dagger \phi_2) + \lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.} \]

\[ B_\mu \quad 0 \]

CPV from radiative corrections:

\[ \mathcal{L} \ni \tilde{t}_L^* (A_t \phi_1 - \mu y_t \phi_2^*) \tilde{t}_R \]

\[ \lambda_5, \lambda_6, \lambda_7 \sim \frac{1}{16\pi^2} \]

*recent work by Wagner, 1502.02210*
motivation from theory

Effective operators

\[
\begin{array}{c|cc}
\text{Operator} & \text{Mass term} & \text{Higgs-fermion coupling} \\
\hline
y_t(\bar{Q}_L t_R H^c) + \text{h.c.} & m_t = \frac{\nu \sqrt{2}}{\Lambda} & \frac{\nu}{\sqrt{2}} \\
\frac{H^+ H}{\Lambda^2} (\bar{Q}_L t_R H^c) + \text{h.c.} & \delta m_t \propto \frac{(\nu / \sqrt{2})^3}{\Lambda^2} & \delta y_t \propto \frac{3 (\nu / \sqrt{2})^2}{\Lambda^2} \\
\end{array}
\]

\[
\Rightarrow h(c_f \bar{f} f + \tilde{c}_f \bar{f} i\gamma_5 f)
\]

More possibilities:

scalar singlet, vector-like fermions, models for neutrino mass

talk by Brod and Yu
Experimental tests

Instead of telling Nature what to do, listen what Nature really does

Experimentally, how large can CPV be? where to look for?

But, break CP at weak scale,

Severe constraints from EDM?

For example \( d_e \sim e \frac{m_e \theta_{CPV}}{(16\pi^2)^2 \Lambda_{EW}^2} \sim 10^{-26} \theta_{CPV} \ e \ cm \)

\( \lesssim 10^{-28} \ e \ cm \ (ACME) \)

(for two-loop diagram)

Barr, Zee, 1990

c.f. \( \Delta \theta(T_c) \gtrsim 0.01 \) from genesis
EDM

Can be powerful, but interpretation need great care. (indirect)

Other sources: SUSY, Left-right models, etc.

Even for CPV involving Higgs itself: an example: eEDM

1) cancelation occurs if

\[ c_t \tilde{c}_e \approx c_e \tilde{c}_t \approx a \tilde{c}_e \]

J. Shu, Y.Z., arxiv:1304.0773
Inoue, Ramsey-Musolf, Y.Z., 1403.4257

2) strong constraints on \( \tilde{c}_t \) if

\[ \tilde{c}_e = 0 \] talk by Brod

Brod, Haisch, Zupan, 1310.1385
Distinguish scenarios?

Directly measure CPV in Higgs and electron coupling seems hard..

Measure Higgs CPV at colliders if we see them, possibly from heavy flavor

The inverse problem $\Rightarrow h(c_t \bar{t} t + \bar{c}_t \bar{t} i \gamma_5 t)$

what if we see CPV at colliders but not in EDM

Wait and see what Nature dictates
Many EDMs

Complementary bounds

Beware of hadronic uncertainties

Quite a few observables

<table>
<thead>
<tr>
<th>System</th>
<th>Year/ref</th>
<th>Result</th>
<th>Coeff</th>
<th>Best value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>1989 [37]</td>
<td>$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ e cm</td>
<td>$\alpha_d$</td>
<td>0.002</td>
<td>$(0.0005 - 0.0004)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_e = (-1.5 \pm 5.6) \times 10^{-26}$ e cm</td>
<td>$\alpha_l$</td>
<td>0.002</td>
<td>$(0.0005 - 0.0004)$</td>
</tr>
<tr>
<td>Tl</td>
<td>2002 [9]</td>
<td>$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ e cm</td>
<td>$\beta_1$</td>
<td>$4 \times 10^{-4}$</td>
<td>$(1 - 10) \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_e = (6.9 \pm 7.4) \times 10^{-28}$ e cm</td>
<td>$\alpha_1$</td>
<td>$8 \times 10^{-4}$</td>
<td>$(2 - 18) \times 10^{-4}$</td>
</tr>
<tr>
<td>YbF</td>
<td>2011 [8]</td>
<td>$d_e = (-2.4 \pm 5.9) \times 10^{-28}$ e cm</td>
<td>$\beta_2$</td>
<td>$-0.35$</td>
<td>$(-0.09 - 0.9)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_l = -0.7$</td>
<td>$\alpha_2$</td>
<td>$-0.2 - 1.8$</td>
<td></td>
</tr>
<tr>
<td>ThO</td>
<td>2014 [7]</td>
<td>$\omega^{NEE} = 2.6 \pm 5.8$ mrad/s</td>
<td>$\delta_1$</td>
<td>$8.2 \times 10^{-9}$</td>
<td>$(2 - 20) \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e cm</td>
<td>$\alpha_3$</td>
<td>$16.3 \times 10^{-9}$</td>
<td>$(4 - 40) \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_S = (-1.3 \pm 3.0) \times 10^{-9}$</td>
<td>$\alpha_4$</td>
<td>$0.4 \times 10^{-3}$</td>
<td>$(0.2 - 0.6) \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\alpha_5$</td>
<td>$-1.6 \times 10^{-3}$</td>
<td>$(-0.8 - 2.4) \times 10^{-3}$</td>
</tr>
<tr>
<td>ThO</td>
<td>2014 [7]</td>
<td>$\omega^{NEE} = 2.6 \pm 5.8$ mrad/s</td>
<td>$\delta_2$</td>
<td>$-0.35$</td>
<td>$(0.17 - 0.52)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$d_e = (-2.1 \pm 4.5) \times 10^{-29}$ e cm</td>
<td>$\alpha_6$</td>
<td>$1.4$</td>
<td>$0.7 - 2.1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C_S = (-1.3 \pm 3.0) \times 10^{-9}$</td>
<td>$\delta_3$</td>
<td>$8.2 \times 10^{-9}$</td>
<td>$(4 - 12) \times 10^{-9}$</td>
</tr>
<tr>
<td>d$_{199}$Hg</td>
<td>2009 [5]</td>
<td>$d_A = (0.49 \pm 1.5) \times 10^{-29}$ e cm</td>
<td>$\beta_1$</td>
<td>$3 \times 10^{-8}$</td>
<td>$(1 - 10) \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>2001 [38]</td>
<td>$d_A = (0.7 \pm 3) \times 10^{-27}$ e cm</td>
<td>$\beta_2$</td>
<td>$40 \times 10^{-7}$</td>
<td>$(10 - 80) \times 10^{-7}$</td>
</tr>
<tr>
<td>TlF</td>
<td>2000 [39]</td>
<td>$d = (-1.7 \pm 2.9) \times 10^{-23}$ e cm</td>
<td>$g_S$</td>
<td>12.7</td>
<td>$11 - 14.5$</td>
</tr>
<tr>
<td>neutron</td>
<td>2006 [4]</td>
<td>$d_n = (0.2 \pm 1.7) \times 10^{-26}$ e cm</td>
<td>$g_S^{(1)}$</td>
<td>0.9</td>
<td>$0.6 - 1.2$</td>
</tr>
</tbody>
</table>

*beware of hadronic uncertainties*
new EDM experiments

- ThO, current limit on eEDM: $10^{-28}$ e-cm, next $\times 10$ improvement.
  - $^{199}$Hg EDM $<10^{-29}$ e-cm sensitivity, imminent
  - nEDM at PSI $10^{-26}$ e-cm sensitivity, 2015 - 2017
  - nEDM at PSI $10^{-27}$ e-cm sensitivity, 2018 - ...
  - nEDM at SNS $\sim 2 \times 10^{-28}$ e-cm starting data taking 2021

- TUM nEDM effort, making progress in B-field shielding, met B-field specs. It moves to ILL in 2015, goal: $10^{-28}$ e-cm, staged approach, starting in 2016.
  - $^{225}$Ra EDM, $\sim 5 \times 10^{-22}$ e-cm now, $\sim 3 \times 10^{-28}$ e-cm w/ FRIB

- Storage ring EDM: pEDM first goal $10^{-29}$ e-cm, start taking data early 2020’s. Strength: statistics

*talk by Semertzidis*
Direct tests

Make the Higgs boson, and watch

1) the shape of its decay products

2) shape of particles produced in association with Higgs
Direct tests

\[ H \to ZZ \to 4\ell \]

Probes the presence of

\[ a_3 \frac{h}{\nu} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \]

Future LHC reach

\[ f_{a_3} \sim \frac{|a_3|^2}{|a_1|^2} < 0.13(0.04) \quad 300 \text{ (3000) /fb} \]

Models: competing loop with tree

\[ a_3 \sim \frac{1}{16\pi^2} \quad (a_1 \sim 1) \]

talk by Whitbeck
Direct tests

VFB and VF production

talks by Dolan and Yu

\[ h(\cos \theta_{\text{CPV}} \bar{t}t + \sin \theta_{\text{CPV}} \bar{t}\gamma_5 t) \]

Snowmass Higgs, 1310.8361

\[ \theta_{\text{CPV}} \]

\[ hVV \text{ decay} \]

\[ hV \text{ prod} \]

\[ \text{VBF prod} \]
Direct tests

ggh with forward jets

talk by Dolan

both CP even and odd processes go via loop

can better understand QCD multi jet events
Direct tests

talk by Yu

not loop suppressed

could be probed at both e+e- and hadron colliders

\[
\frac{m_\tau}{v} h (\cos \theta_{\text{CPV}} \tau + \sin \theta_{\text{CPV}} i \gamma_5 \tau)
\]

<table>
<thead>
<tr>
<th>Colliders</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC (1 ab(^{-1}))</th>
<th>FCCee/CEPC (1 ab(^{-1}))</th>
<th>FCCee/CEPC (5 ab(^{-1}))</th>
<th>FCCee/CEPC (10 ab(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy(1(\sigma))</td>
<td>25°</td>
<td>8.0°</td>
<td>4.4°</td>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
<tr>
<td>(\theta_{\text{CPV}})</td>
<td>0.4</td>
<td>0.14</td>
<td>0.08</td>
<td>0.1</td>
<td>0.04</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Direct tests

\[ pp \rightarrow t\bar{t}h \]

Still need a roadmap

talk by Liu and Yu

\[ h \rightarrow \gamma\gamma \quad h \rightarrow Z\gamma \]

measure photon polarization

interference with background, on the Higgs pole

talk by Marco and Yu
More tests

Higgs CPV means something not decoupled

(in 2HDM, heavy scalars)

Some decay channels more sensitive to CPV

apply the LHC heavy Higgs search data

*talk by Chen*
More tests

\[ p\bar{p} \rightarrow Zh \rightarrow \ell\ell bb \]

Again, $\mu_0$—typically loop suppressed

\[ p\bar{p} \rightarrow Wh \rightarrow \ell\nu bb \]

Ellis, Hwang, Sanz, You, 1208.6002
CDF+D0, 1502.00967
Summary

Higgs boson has been discovered

One next task is to reveal its CP nature

Well motivated: theoretically and experimentally

already have several handles to this question

Develop new observables; further explore their interplays

Exciting discovery awaits us!
talk by Dolan

Maybe cooler if
talk by Dolan

Maybe cooler if

\[
\begin{align*}
h^0(125) \\
h^0(400) \\
h^0(425) \\
h^{\pm}(450)
\end{align*}
\]
Maybe cooler if

- $h^0(125)$
- $h^0(400)$
- $h^0(425)$
- $h^\pm(450)$