Cornering Spontaneous CP Violation with Charged-Higgs Searches

[arXiv: 1912.11501]

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Motivation

1964: Observation of $K_L \to \pi\pi$:

CP violation (CPV)

$\swarrow$ 1973 $\searrow$

Kobayashi and Maskawa:
i.a. third quark generation
$\to$ explicit CPV

T.D. Lee:
second Higgs doublet
$\to$ spontaneous CPV

- Despite success of KM mechanism
  explicit $\leftrightarrow$ spontaneous CP violation (SCPV) still unresolved

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Question: *Is it possible to exclude SCPV with current data?*

Model

Higgs Sector I: Potential

$$
\begin{aligned}
V = {} & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - (m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}) \\
& + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\
& + \left[\phi_1^\dagger \phi_2 \left(\frac{\lambda_5}{2} \phi_1^\dagger \phi_2 + \lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2) \right) + \text{h.c.} \right],
\end{aligned}
$$

Here: all parameters real and

$$
\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v c_\beta \end{pmatrix}, \qquad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v s_\beta e^{i\xi} \end{pmatrix}.
$$

Theoretical constraints on V:

- bounded from below [Ivanov, 06]
- perturbativity [Ginzburg et al., 05; Murphy, 17]
- metastable minimum [Ivanov, 07; Ivanov et al., 15]

Higgs Sector II: Mass Spectrum

- Vacuum conditions:

$$\left.\begin{aligned} \mathrm{Re}\left(\left.\frac{\partial V(\phi_1,\phi_2)}{\partial \phi_1}\right|_{\phi_i=\langle\phi_i\rangle}\right) &= 0 \\ \mathrm{Im}\left(\left.\frac{\partial V(\phi_1,\phi_2)}{\partial \phi_1}\right|_{\phi_i=\langle\phi_i\rangle}\right) &= 0 \\ \mathrm{Re}\left(\left.\frac{\partial V(\phi_1,\phi_2)}{\partial \phi_2}\right|_{\phi_i=\langle\phi_i\rangle}\right) &= 0 \end{aligned}\right\}$$

solve m_{11}^2, m_{22}^2 and m_{12}^2 for v, β and ξ
$\Rightarrow$ all three mass scales of $\mathcal{O}(v)$, i.e. *no* decoupling limit (not even for $\xi \to 0$!)

- Mass spectrum:

$$(M_H^2)_{ij} = \left.\frac{\partial V(\phi_1,\phi_2)}{\partial \varphi_i \partial \varphi_j}\right|_{\varphi_k=0}$$

$$m_{H^\pm}^2 = v^2\,(\lambda_5 - \lambda_4)$$

$$\det(M_H^2) \propto s_{2\beta}^2 s_\xi^2$$

Higgs Sector III: Upper Bound on Higgs Masses

- Requiring *NLO* perturbative unitarity for the couplings λ_i:

$$m_{H^\pm} \lesssim 435\,\mathrm{GeV}$$
$$m_{H_2} \lesssim 485\,\mathrm{GeV}$$
$$m_{H_3} \lesssim 545\,\mathrm{GeV}$$

Unitarity:

$$SS^\dagger = 1 \Rightarrow \left| a_j - \frac{1}{2}\mathrm{i} \right| \leq \frac{1}{2}$$

Perturbativity:

$$\left| \frac{a_j^{\mathrm{NLO}}}{a_j^{\mathrm{LO}}} \right| < 1$$

Yukawa Sector I: Mass Terms

$$\mathcal{L}_{\rm yuk} = -\overline{Q}_L \left(Y_{u1}\tilde{\phi}_1 + Y_{u2}\tilde{\phi}_2 \right) u_R - \overline{Q}_L \left(Y_{d1}\phi_1 + Y_{d2}\phi_2 \right) d_R + \text{h.c.}$$

After symmetry breaking

$$\frac{M_u}{v} = Y_{u1} c_\beta + Y_{u2} e^{-i\xi} s_\beta \,, \qquad \frac{M_d}{v} = Y_{d1} c_\beta + Y_{d2} e^{i\xi} s_\beta$$

$\Rightarrow$ KM phase can only be induced if ξ remains physical

- Jarlskog invariant $J \neq 0 \Rightarrow$ at least the pair $\{Y_{u1}, Y_{u2}\}$ or $\{Y_{d1}, Y_{d2}\}$ cannot be diagonal in same flavour basis

$\Longrightarrow$ flavour violating (FV) couplings necessary

- since FCNC couplings in down sector severely constrained: consider limit where Y_{d_1} and Y_{d_2} diagonal in same flavour basis

Yukawa Sector II: Higgs-Quark Couplings

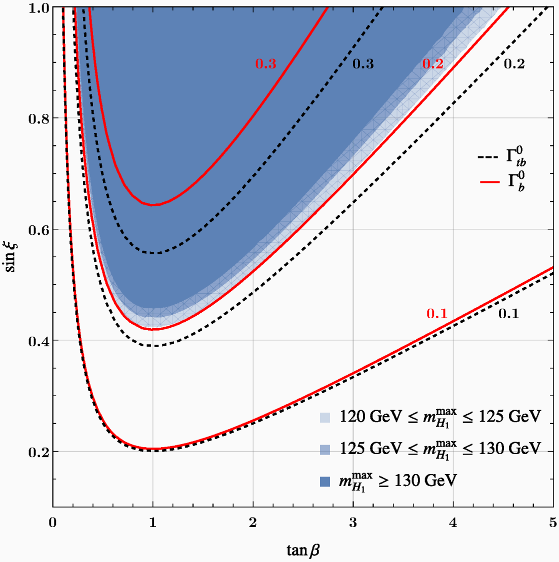
$$\mathcal{L}_{\mathrm{H}} = \overline{u}_{L,f}\, H_k^0\, \Gamma_{u_f u_i}^{LRH_k^0}\, u_{R,i} + \overline{d}_{L,i}\, H_k^0\, \Gamma_{d_i d_i}^{LRH_k^0}\, d_{R,i}$$
$$+ \overline{u}_f H^+ \left(\Gamma_{u_f d_i}^{LRH^+} P_R + \Gamma_{u_f d_i}^{RLH^+} P_L \right) d_i$$
$$+ \mathrm{h.c.}$$

Sum rule for charged-Higgs couplings to bottom quarks:

$$\sum_{i=u,c,t} |\Gamma_{ib}^{RL}|^2 = \frac{m_t^2}{v^2} + \frac{2m_t}{v s_{2\beta}} \left(c_{2\beta}^2 \mathrm{Re}\Gamma_{tb}^{RL} - \frac{\mathrm{Im}\Gamma_{tb}^{RL}}{t_\xi} \right)$$
$$+ \mathcal{O}\left(|V_{cb}| \frac{m_c}{m_t} \right)$$

$$\max\{|\Gamma_{ub}^{RL}|, |\Gamma_{cb}^{RL}|, |\Gamma_{tb}^{RL}|\} \geq 0.20$$

Yukawa Sector III: Lower Bound on Charged-Higgs Couplings



$$\det(M_H^2) \propto s_{2\beta}^2 s_\xi^2$$

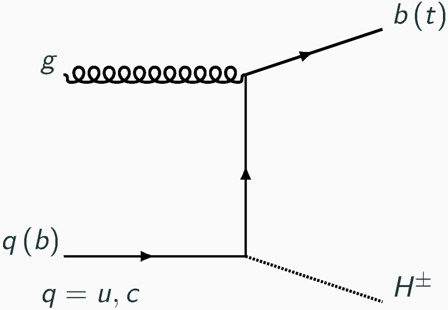
$$\Gamma_b^0 = \max\{|\Gamma_{ub}^{RL}|, |\Gamma_{cb}^{RL}|, |\Gamma_{tb}^{RL}|\}$$

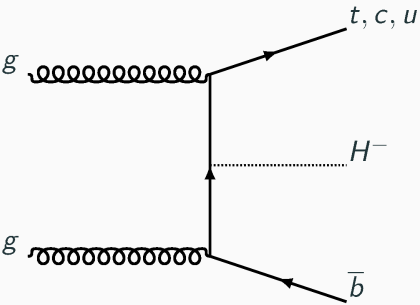
Phenomenology

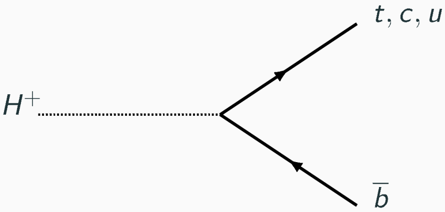
Phenomenology I: General Aspects

- 17 free parameters:
  - 3 heavy Higgs masses $m_{H_2}, m_{H_3}, m_{H^\pm}$
  - 2 vacuum angles β, ξ
  - 3 neutral Higgs mixing angles s_{12}, s_{13}, s_{23}
  - 3 angles and 6 phases determining the FV Higgs couplings
- despite large effects in flavour observables (EDMs, $B \to X_s\gamma$, neutral meson mixing, ...) possible, model is far from being ruled out
- same for collider searches, however:
  due to sum rule sizeable charged-Higgs couplings guaranteed

Phenomenology II: Collider Signatures







Conclusion

Conclusion

- no decoupling limit $\rightarrow$ upper limits on heavy Higgs masses

$\rightarrow$ compact parameter space allows ruling out spontaneous CP violation

- negligible FV couplings in down quark sector yields lower limits on charged-Higgs couplings

$\Rightarrow$ sizeable cross sections in channels that have not been explored yet

$\Rightarrow$ strong motivation for non-standard Higgs searches

Backup

Backup I: Mass Invariants

$$\frac{1}{2v^2}\sum_{i=1}^{3} m_{H_i}^2 = s_{2\beta}c_\xi\left(\lambda_6+\lambda_7\right)+\lambda_2 s_\beta^2+\lambda_1 c_\beta^2+\lambda_5\,,$$

$$\frac{1}{2v^6}\prod_{i=1}^{3} m_{H_i}^2 = s_{2\beta}^2 s_\xi^2 \times\left(-\lambda_2\lambda_6^2+\lambda_{345}\left(-\lambda_{345}\lambda_5+2\lambda_6\lambda_7\right)+\lambda_1\left(\lambda_2\lambda_5-\lambda_7^2\right)\right)\,,$$

$$\frac{1}{2v^4}\sum_{i=1,j>i}^{3} m_{H_i}^2 m_{H_j}^2 = \ldots\,,$$

with $\lambda_{345}=\lambda_3+\lambda_4-\lambda_5$.

Backup II: Higgs-Fermion-Fermion Vertices $\Gamma^{LRH}_{q_f q_i}$ for $Y_{d2} = 0$

$$\Gamma^{LRH_k^0}_{u_f u_i} = x_u^k \left(\frac{m_{u_i}}{v s_\beta} \delta_{fi} - \frac{\epsilon^u_{fi}}{t_\beta} \right) + x_d^{k*} \epsilon^u_{fi} \,,$$

$$\Gamma^{LRH_k^0}_{d_f d_i} = x_d^k \frac{m_{d_i}}{v c_\beta} \delta_{fi} \,,$$

$$\Gamma^{LRH_k^\pm}_{u_f d_i} = s_\beta V_{fj} \frac{m_{d_i}}{v c_\beta} \delta_{ji} \,,$$

$$\Gamma^{LRH_k^\pm}_{d_f u_i} = c_\beta V^*_{jf} \left[\frac{m_{u_i}}{v s_\beta} \delta_{ji} - \frac{\epsilon^u_{ji}}{s_\beta c_\beta} \right] \,,$$

$$x_u^k = \frac{1}{\sqrt{2}} \left(-O_{2k} + i c_\beta O_{3k} \right) \,, \qquad x_d^k = \frac{1}{\sqrt{2}} \left(-O_{1k} + i s_\beta O_{3k} \right) \,,$$

$$\Gamma^{RLH}_{q_f q_i} = \Gamma^{LRH*}_{q_i q_f} \,.$$

Backup III: Benchmark Points (BPs)

	BP1	BP2	BP3	BP4	BP5	BP6
m_{H_2} (GeV)	170	335	215	320	160	135
m_{H_3} (GeV)	245	355	245	335	190	335
$m_{H^\pm}$ (GeV)	180	375	170	325	165	350
t_β	0.38	0.84	0.43	0.67	0.36	0.37
ξ	1.95	1.96	1.59	1.59	2.04	1.32
$\lvert s_{13}\rvert \times 10^2$	4.4	1.3	0.12	0.081	7.5	1.2
$\lvert s_{12}\rvert \times 10^2$	2.3	1.6	0.32	0.095	2.8	3.4
$\lvert s_{23}\rvert$	0.23	1.00	0.18	0.99	0.42	0.21
$\lvert\Gamma_{tb}^{RLH^\pm}\rvert$	0.38	0.58	0.16	1.17	0.35	0.32
$\lvert\Gamma_{cb}^{RLH^\pm}\rvert$	$< 10^{-3}$	0.76	0.76	0.70	$< 10^{-2}$	0.37
$\lvert\Gamma_{ub}^{RLH^\pm}\rvert$	$< 10^{-6}$	0.45	$< 10^{-4}$	$< 10^{-5}$	$< 10^{-4}$	$< 10^{-7}$
$\sigma_{\rm prod}^{14\ \rm TeV}(pp \to qbH^\pm)$ (pb)	≈ 0	190	520	36	≈ 0	7.9
$\sigma_{\rm prod}^{14\ \rm TeV}(pp \to tbH^\pm)$ (pb)	0.62	0.28	0.13	1.6	0.71	0.10
$\sigma_{\text{Drell-Yan}}^{14\ \rm TeV}(pp \to H^\pm H^\mp)$ (fb)	35	2.0	44	3.7	49	3.5
Main decay channel of $H^\pm$	tb 99%	cb 58%	cb 100%	tb 59%	cb 89%	$WH_2(\to c\bar{c}, b\bar{b})$ 62%