$\mathcal{CPV}$ and Higgs Physics

Generalities and a Specific Example

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$\mathcal{CPX}$ work with M. Carena, J. Ellis, A. Pilaftsis, C.E.M. Wagner (NPB659, hep-ph/0211467)

$\mathcal{CPV}$ Phenomenon

- rare (weak) effect in K and $B(?)$ meson decays
- necessary condition for baryogenesis
- not necessarily related

Origin Unclear: most scenarios focus on Higgs sector

$$\mathcal{L}_{\text{Yuk}} = Y_{ij} Q_{Li} \Phi_1 U_{Rj} + \widetilde{Y}_{ij} Q_{Li} \Phi_2 D_{Rj} + h.c.$$

$$Y_{ij} \neq Y_{ij}^\dagger \quad \widetilde{Y}_{ij} \neq \widetilde{Y}_{ij}^\dagger \quad \text{Explicit}$$
$$\langle \Phi_1 \rangle = v_1 \quad \langle \Phi_2 \rangle = v_2 e^{i\xi} \quad \text{Spontaneous}$$

Higgs physics beyond the SM may use either source

- *focus here on Explicit $\mathcal{CPV}$*

Lessons of SM $\mathcal{CPV}$

1. SM has Explicit breaking
2. $\mathcal{CPV}$ occurs in charged current
3. FCNC related to $\mathcal{CPV}$
4. single source ($\delta_{\rm CKM}$)
   - $\delta_{\rm CKM} \sim \mathcal{O}(1)$
   - weakness related to small mixing angles
5. SM alone cannot explain EW-Baryogenesis

BSM Physics may or may not follow this pattern

- there may be (will be?) multiple sources of $\mathcal{CPV}$
- Spontaneous $\mathcal{CPV}$ requires an extended Higgs sector
  - suppress FCNC $\Rightarrow$ $\mathcal{CPV}$ at loop-level $\Rightarrow$ light scalar

More Specific: 2HDM

$$V = V_2 + V_4$$

$$\begin{aligned} V_2 &= \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + m_{12}^2(\Phi_1^\dagger\Phi_2) + m_{12}^{*2}(\Phi_2^\dagger\Phi_1) \\ V_4 &= \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2\, \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ &\quad \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.] + \\ &\quad \{[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + h.c.\} \end{aligned}$$

Suppress FCNC & $\mathcal{CP}\!\!\!\!/\,\mathcal{V}$ $\Rightarrow \Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

- $\lambda_6 = \lambda_7 = m_{12}^2 = 0$
- *soft violation*: $m_{12}^2 \neq 0$

Tadpole $\langle \frac{\partial \mathcal{L}_V}{\partial a} \rangle = 0$ relates sources of phases

$$\mathrm{Im}(m_{12}^2) = \mathrm{Im}(\lambda_5) v_1 v_2 + \frac{1}{2}[\mathrm{Im}(\lambda_6) v_1^2 + \mathrm{Im}(\lambda_7) v_2^2]$$

Loop-Level $\mathcal{CPV}$

Complex m_{12}^2, λ_i can be generated at loop-level

Hard to address without explicit models

- SUSY can have complex soft-breaking parameters

In general, will be correlated with loop-level $\mathcal{CPV}$ amplitudes

- In SUSY, different flavor structure

Main effect on Higgs sector may not result in a $\mathcal{CPV}$ observable

- concentrate on neutral Higgses, particularly light ones

Of course, there *are* direct $\mathcal{CPV}$ effects

- $\Gamma(H^+) \neq \Gamma(H^-)$ (CC)
- anomalous increase in $h \to d\bar{d}$ (Demir)

Higgs Phenomenology in the MSSM

- Supersymmetry fixes the particle content and interactions
  - At tree level, $\lambda_{5,6,7} = 0 \Rightarrow$ no $\not{\mathcal{CP}}$
- (soft) Susy breaking (SSB) induces particle-sparticle mass splittings
  - terms of dimension mass (μ, A, m_0, M_i)
- SM Higgs $\longrightarrow$ 2HDM with 3 neutral, 1 charged scalar
  - $m_h^2 \sim |M_Z \cos(2\beta)|^2 +$ (stuff $\propto$ SSB)
- "Always" known that SSB terms could be complex
  - $\mathcal{O}(40)$ phases possible
  - Some phases can be rotated away
  - Relative phases (e.g. $\arg(A_{top}\mu^*), \arg(M_{\tilde{g}}\mu^*)$) remain

Explicit $\mathcal{CPV}$

Complex Soft SUSY-Breaking parameters $\Rightarrow \mathcal{CPV}$

- $\mathcal{CP}$ no longer labels Higgs mass eigenstates
  - Higgses have scalar and pseudoscalar components
  - Different couplings, mixings, and mass relations
- Phases will affect other observables
  - Electric Dipole Moments (EDMs) of electron/neutron
  - Several ways to avoid contradictions with data
    - Heavy ($M > 1$ TeV) Squarks for $1^{\rm st} - 2^{\rm nd}$ generations
    - Cancellations between different contributions
  - $3^{\rm rd}$ generation alone can yield observable contributions
    - Cancellations are also possible here
- Effects considered here are not $\mathcal{CPV}$, but a consequence of $\mathcal{CPV}$ in the full theory

References

Incomplete list

- Pilaftsis and Wagner [hep-ph/9902371]
- Carena, Ellis, Pilaftsis, and Wagner [hep-ph/0003180]
- CEPW [hep-ph/0009212]
- Choi, Hagiwara, Lee, Drees, Song(s): Some phenomenology
- Gunion, Kalinowski, Grzadkowski: Generic 2HDM models
- Demir; Ibrahim-Nath: Neutral decays
- Heinemeyer-Weiglein: Diagrammatic approach

Mass^2 Matrix $(2\times 2\oplus 1\times 1\to 3\times 3)$

Diagonalization yields mass eigenstates and mixing

- Most important parameter is still Stop Mixing
  - $|X_{top}| = |A_{top} - \mu^*/\tan\beta|$
- Mixing between Even/Odd $\mathcal{CP}$ is One-Loop phenomena
  - Important when some Even components are small
  - Requires large μ, A and sizeable phases $\phi_A = \arg(A_{top}\mu^*)$

$$\mathcal{M}^2 = \begin{pmatrix} ee & ee & eo(1) \\ ee & ee & eo(2) \\ eo(1) & eo(2) & oo \end{pmatrix}$$

$$eo(1) \sim v^2 \frac{3}{192\pi^2}\bar{\mu}^2 \sin 2\phi_A$$

$$eo(2) \sim v^2 \frac{3}{192\pi^2}\bar{\mu}\bar{A}(6-\bar{A}^2)\sin\phi_A$$

$\mathcal{CPX}$ Benchmark

$|\mu| : |A| : M_{\rm SUSY} = 4 : 2 : 1$

Large Hierarchy

Not a high-scale prediction

Couplings

- $\sin\alpha, \cos\alpha \to O_{IJ} \quad (I, J = 1, 2, 3)$
- $hZZ, HZZ \to$ Three Higgses share W/Z coupling at tree level
- $ZhA \to ZH_IH_J$ couplings for all I, J
- $Af\bar{f} \to$ All Higgses can have a pseudoscalar coupling to fermions
  - Threshold is β instead of β^3 suppressed

$$\begin{aligned}
g_{H_iZZ} &= O_{1i}\cos\beta + O_{2i}\sin\beta \\
g^S_{H_idd} &= O_{1i}/\cos\beta(1+\Delta)^{-1} \\
g^P_{H_idd} &= -O_{3i}\tan\beta(1+\Delta)^{-1} \\
g^S_{H_iuu} &= O_{2i}/\sin\beta \\
g^P_{H_iuu} &= -O_{3i}/\tan\beta
\end{aligned}$$

Δ is one-loop [gluino-sbottom,higgsino-stop] but can be $\mathcal{O}(1)$

Sum Rules

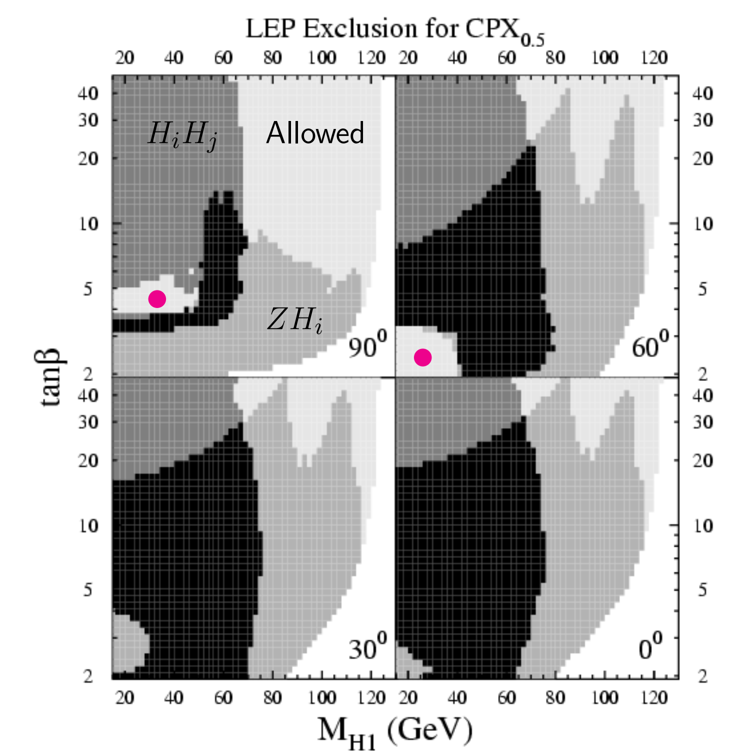
Couplings are inter-related

- Really radical behavior not possible
- SM-like Higgs must have some scalar coupling to U,D
- Pseudoscalar coupling to Top suppressed
- Cannot suppress U and D couplings at once
- Relations between ZZH_k and ZH_iH_j couplings

$$
\begin{aligned}
g_{H_iZZ} &= \cos^2\beta g_D^S(1+\Delta) + \sin^2\beta g_U^S = \epsilon_{ijk} g_{ZH_jH_k} \\
g_D^P &= g_U^P \tan^2\beta(1+\Delta)^{-1} \\
1 &= \cos^2\beta(1+\Delta)^2[(g_D^S)^2 + (g_D^P)^2] + \sin^2\beta[(g_U^S)^2 + (g_U^P)^2]
\end{aligned}
$$

Δ expected to be largest for 3rd generation

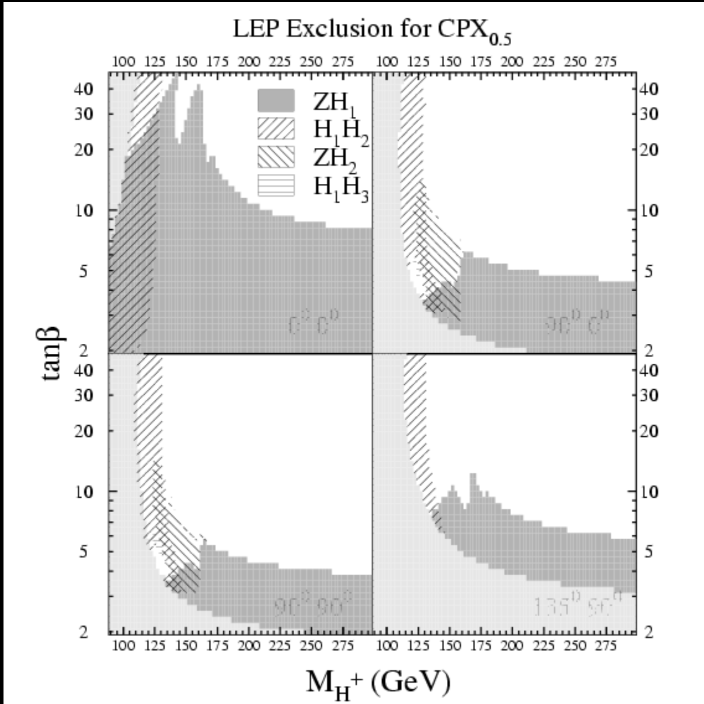
LEP Results for $\mathcal{CPX}$



- $H_1 < H_2 < H_3$
- $Z^* \to ZH_2$ is dominant production mechanism
- $H_2 \to H_1H_1$ can be dominant decay mode
- Allowed
- $e^+e^- \to ZH_i$
- $Z^* \to H_iH_j \to 4b$
  - No dedicated 6 b analysis (OPAL)
- Black = overlap

LEP Results for $\mathcal{CPX}$

A°, M°=[0 0] **[90 0]**

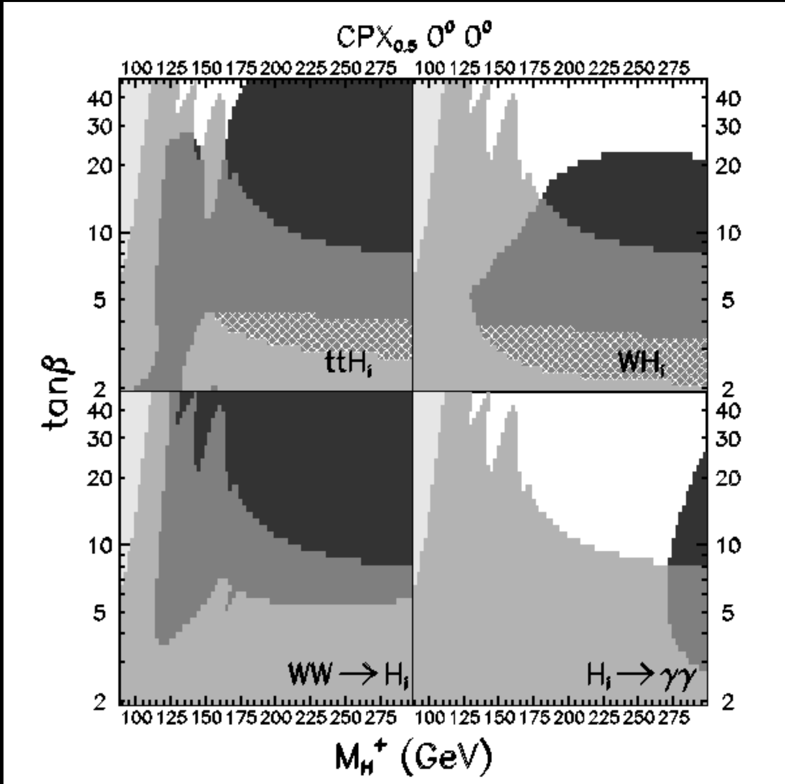


[90 90] **[135 90]**

- Large Phase $\arg(A) \sim \frac{\pi}{2}$ responsible for holes
- Light $M_{H^\pm} \sim 125$ GeV
- Smallish $\tan\beta \sim 4-5$
- $\arg(M)$ less important
- Generally less coverage than w/o $\mathcal{CPV}$

$\mathcal{CPX}$ with NO phases

[tth 100/30] [W/Zh 3σ 5/2]

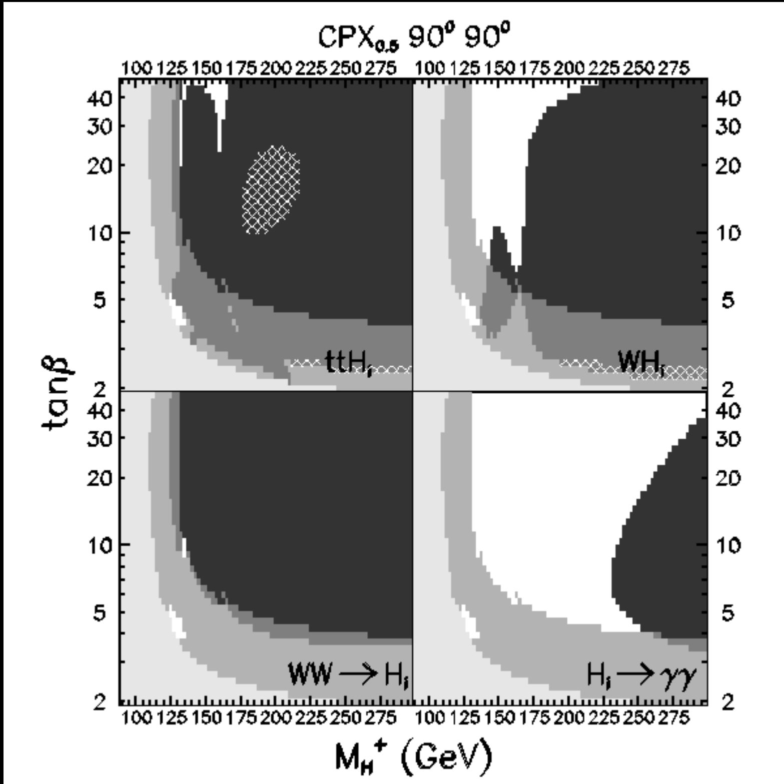


[WW→ h 30] [h→ $\gamma\gamma$ 100/30]

- 5σ (LHC)
  3σ (FNAL)
- Large Stop Mixing
- $WW \to h \to \tau\tau$ important
- high $\int dt\mathcal{L}$ needed
- LHC coverage "guaranteed"

$\mathcal{CPX}$ with Sizeable Phases

[tth 100/30] [W/Zh 3σ 5/2]

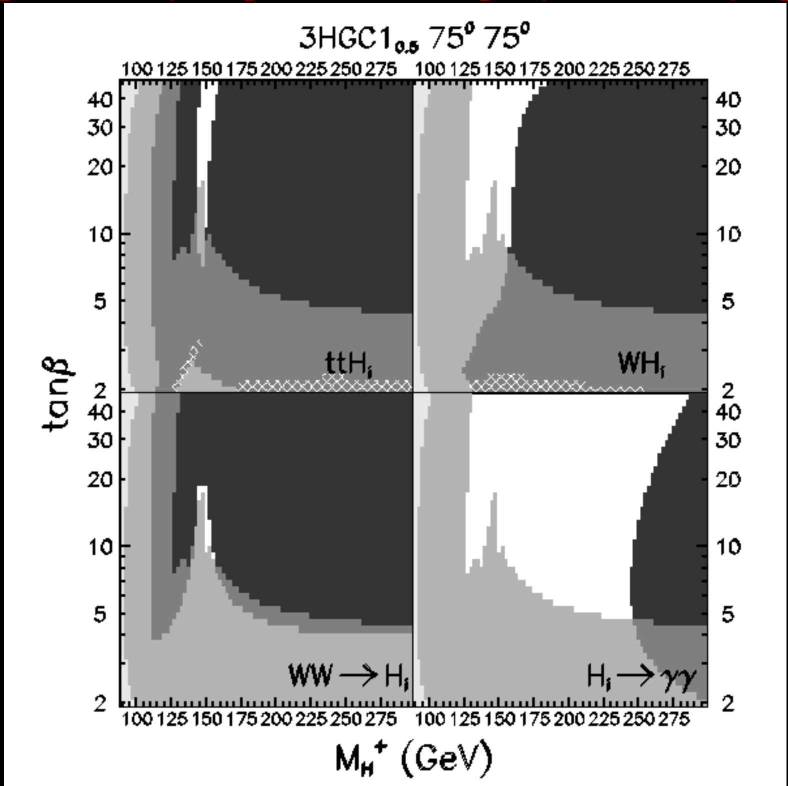


[WW→h 30] [h→ $\gamma\gamma$ 100/30]

- $\phi_A = 90^\circ$
- LEP coverage greatly reduced
- tth coverage limited for 30 fb^{-1}
- $\gamma\gamma$ not very constraining
- Uncovered region persists!

A_{top}:μ:M_S :: 2:−2:1

[tth 100/30] [W/Zh 3σ 5/2]

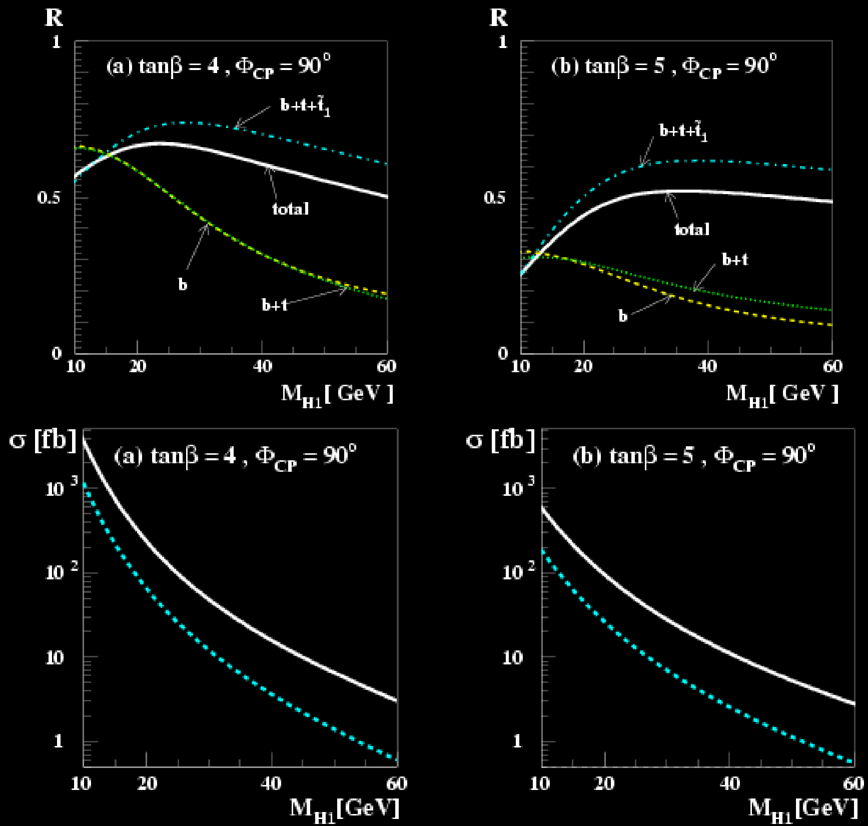


[WW→h 30] [h→ $\gamma\gamma$ 100/30]

- Again, not a High-Scale prediction
- All 3 Higgses can evenly share the coupling to W/Z
- Ignores complications of nearby signal
- Effects for larger $M_{H^\pm}$, $\tan\beta$

Diffractive Production $p\bar{p} \rightarrow p\bar{p}H$

Cox, Forshaw, Lee, Monk, Pilaftsis [hep-ph/0303206]



Concluding Remarks on $\mathcal{CPV}$

- MSSM Higgs sector with explicit $\mathcal{CPV}$ may be challenging
  - Light scalars consistent with data
- Studied several benchmarks (focussed on SM-like signatures)
- ttH and VV→H afford most coverage
  - Uncovered regions remain
  - These results may be too optimistic
  - Signals are the least studied (though not neglected)
  - No studies of effects of nearby signals
- $H_i \to \gamma\gamma$ not very significant
- $gg \to H_i \to Z^* Z^*$ never relevant in our benchmarks

- Do any high-scale models predict $\mathcal{CPX}$ behavior?
  - Do some high-scale constraints need to be relaxed?
- How will we really know $\mathcal{CPV}$ is affecting the Higgs sector?
  - Correlate with other observables (Muryama,Pierce $\longrightarrow$ hard)?
  - Measure ϕ_μ at a LC?
- Effects on Heavy Higgses needs more work
- Not much correlation with other $\mathcal{CPV}$ observables

Phenomena	Most Important Sparticle
Higgs Sector	$\widetilde{t}$
K, B mesons	$\widetilde{b}$
EW-Baryogenesis	$\widetilde{C}_i$