Strong phase transition in two-Higgs-doublet models

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- Not satisfied in SM unless $m_h \lesssim m_W$, which is not the case.
- CP violation from CKM matrix too small.

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- Correct BAU can be obtained for simplified cases and for particular combinations of parameters.
- But what happens in the general case?

2HDM

- Avoid FCNC $\Rightarrow \mathbb{Z}_2$ symmetry: $\Phi_1 \to -\Phi_1,\ \Phi_2 \to \Phi_2$.

	u_R	d_R	e_R
Type I	+	+	+
Type II	+	−	−
Type X	+	+	−
Type Y	+	−	+

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- For PT, only top-quark needs to be considered.
Then models differ only in phenomenological constraints on their parameter space. These come mainly from B-physics, so

$$\text{Type I} \sim \text{Type X},$$
$$\text{Type II} \sim \text{Type Y}.$$

2HDM

- For simplicity, consider CP conserving case only.

$$V_{tree}(\Phi_1,\Phi_2) = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}\left(\Phi_1^\dagger\Phi_2 + H.c.\right) + \\ + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \\ + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right].$$

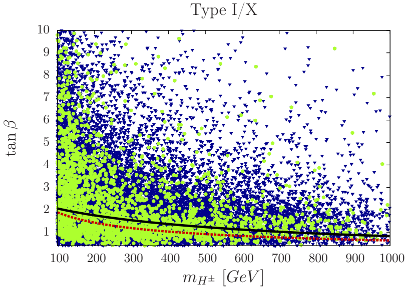
- EW minimum: $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}, \ \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta \end{pmatrix}.$
- Physical parameters:
  - $v \approx 174$ GeV and $M \equiv \frac{\mu}{\sqrt{\sin(2\beta)}}$.
  - Masses: $m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}$.
  - β is the mixing angle between (G^+, H^+) and between (G^0, A^0).
  - Likewise, α is the mixing angle between (h^0, H^0). It is here defined such that $\alpha = \beta \iff h^0 = h_{SM}$.

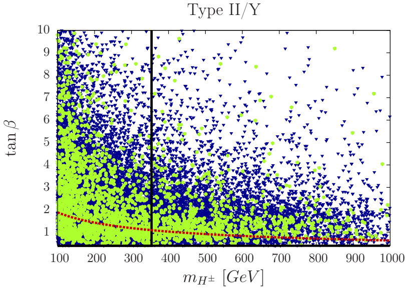
$$V = V_{tree} + V_{CW} + V_{CT} + V_T.$$

- Fix $m_{h^0} = 125$ GeV

$$0.4 \leq \tan\beta \leq 10\ ,$$
$$-\frac{\pi}{2} < \alpha \leq \frac{\pi}{2}\ ,$$
$$0 \text{ GeV} \leq \mu \leq 1 \text{ TeV},$$
$$100 \text{ GeV} \leq m_{A^0},\ m_{H^\pm} \leq 1 \text{ TeV},$$
$$150 \text{ GeV} \leq m_{H^0} \leq 1 \text{ TeV}.$$

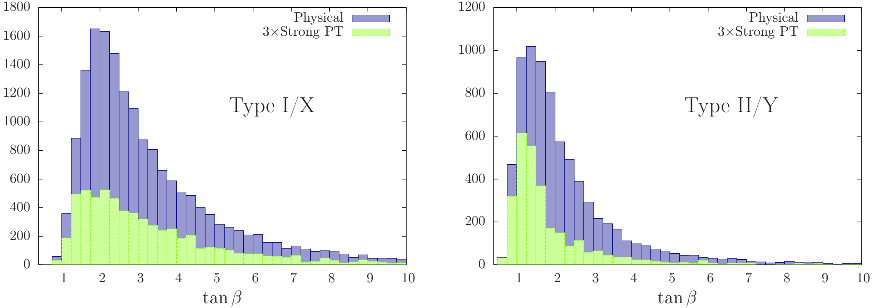
- Constraints:
  - EW precision: $\rho - 1 \approx 0$;
  - $\lambda_i < 4\pi$;
  - metastability;
  - $B^0 - \bar{B}^0$ (red/dashed) and $\bar{B} \to X_s\gamma$ (black/full).





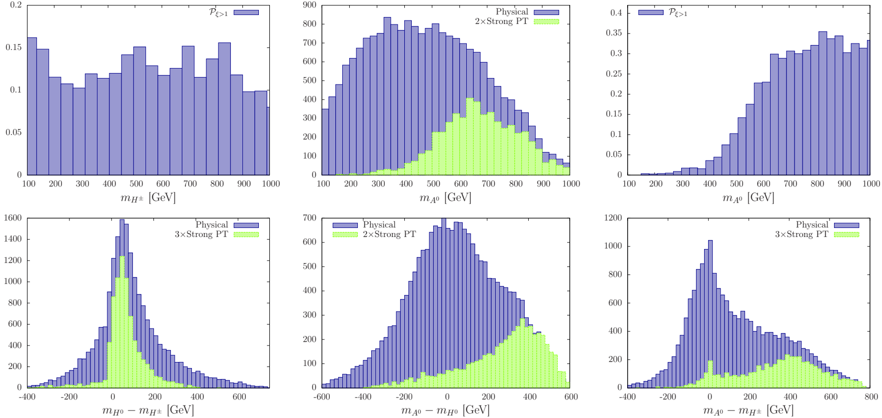
Type II/Y: $m_{H^\pm} \geq 360$ GeV [Hermann et al., arXiv:1208.2788].

Results: $\tan\beta$

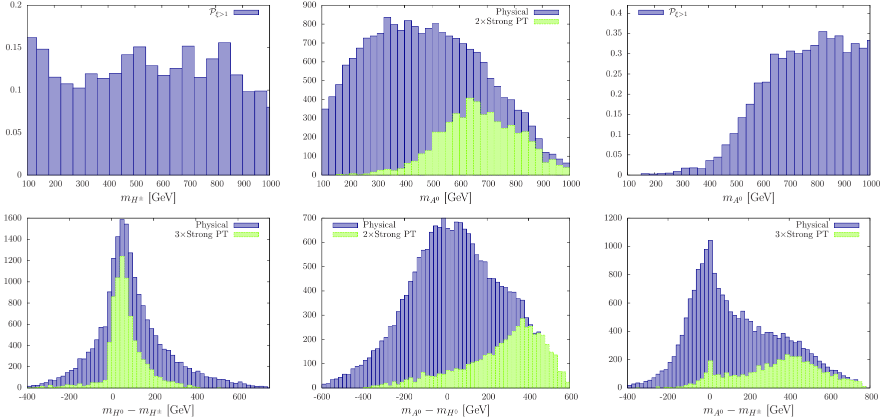


Preference for $\tan\beta \lesssim 3$ is excellent for baryogenesis, since $n_B \sim (\tan\beta)^{-2}$.

Results: Masses



$m_{H^\pm}$ hardly influences the phase transition.



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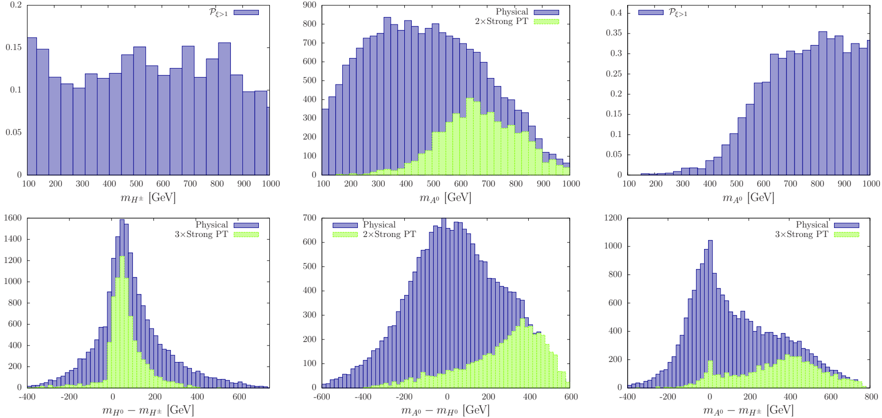

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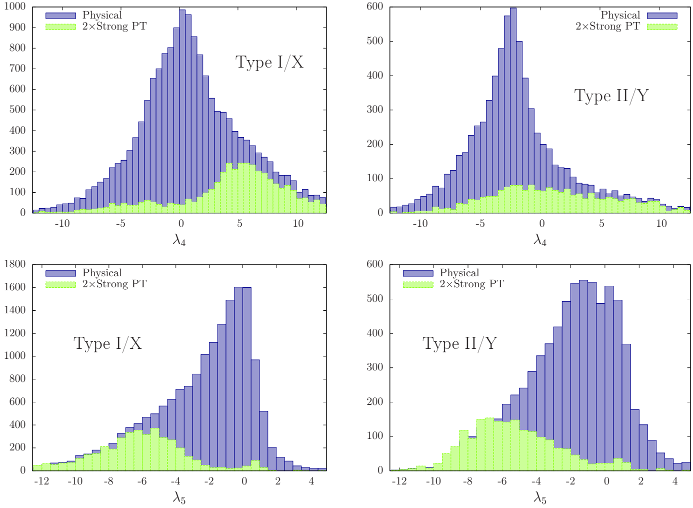
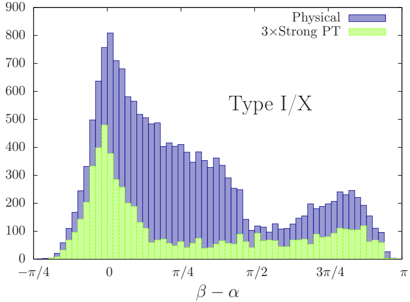
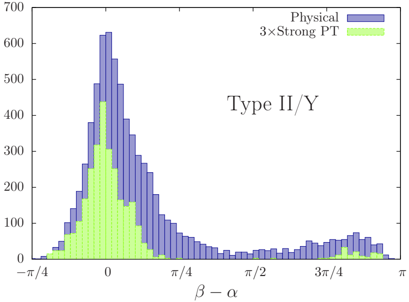
Strong PTs also prefer hierarchy $m_{A^0} > m_{H^0} \gtrapprox m_{H^\pm}$.

Results: Couplings

$$\lambda_4 = \frac{1}{2v^2}\left(M^2 + m_{A^0}^2 - 2m_{H^\pm}^2\right), \quad \lambda_5 = \frac{1}{2v^2}\left(M^2 - m_{A^0}^2\right).$$

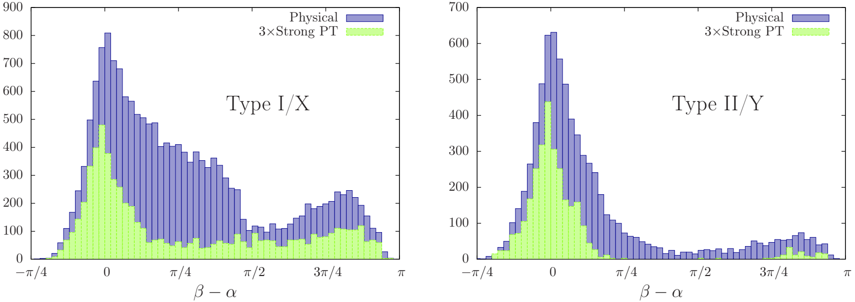






A strong PT favours a SM-like h^0.

Results: $\beta - \alpha$



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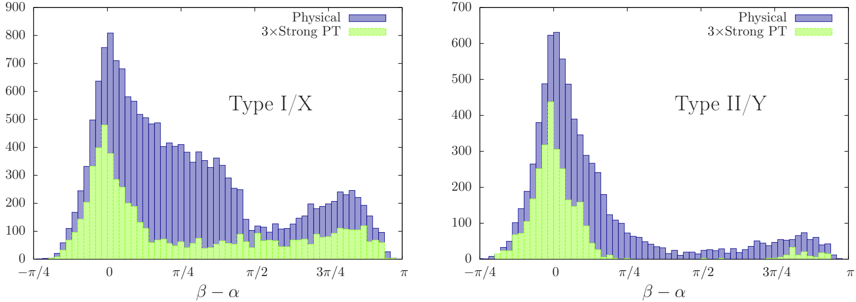

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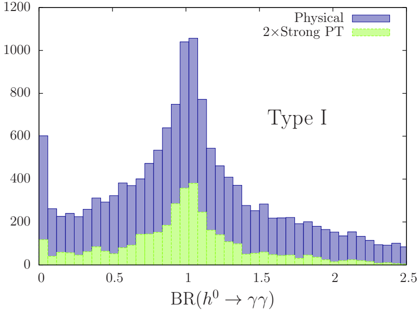
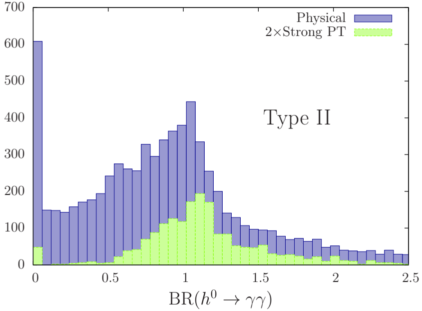
Moreover, $\alpha \lessapprox \beta$ is slightly preferred.

Results: $h^0 \to \gamma\gamma$





Coupling of h^0 to b and τ:

$$\text{Type I: } \frac{\sin\alpha}{\sin\beta}\,, \qquad \text{Type II: } \frac{\cos\alpha}{\cos\beta}\,.$$

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Thank you!

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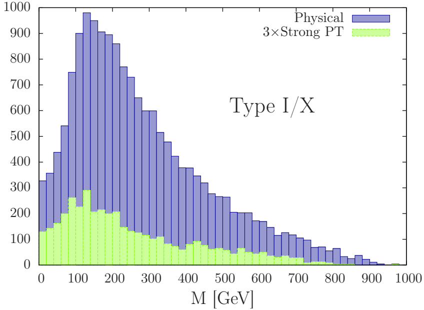

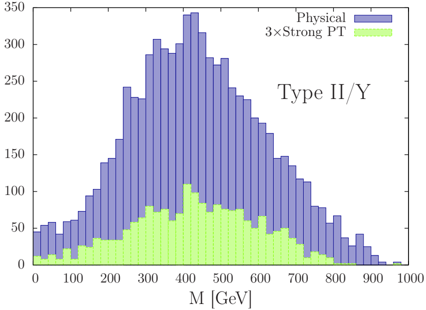

Type II/Y: $m_{H^\pm} \geq 360$ GeV.

Appendix

- Surviving points after each step of tests:

	Total	EW precision	$\lambda_i < 4\pi$	Metastability	Strong PT
Absolute	$6.3 \cdot 10^6$	$1.2 \cdot 10^6$	$1.4 \cdot 10^5$	$2.6 \cdot 10^4$	$3.7 \cdot 10^3$
Relative	100%	19.1%	2.3%	0.41%	0.059%

- Physical fields:

$$
\begin{aligned}
G^+ &= \cos\beta\ \varphi_1^+ + \sin\beta\ \varphi_2^+ && \text{(charged Goldstone)},\\
H^+ &= -\sin\beta\ \varphi_1^+ + \cos\beta\ \varphi_2^+ && \text{(charged scalar)},\\
G^0 &= \cos\beta\ \eta_1 + \sin\beta\ \eta_2 && \text{(neutral Goldstone)},\\
A^0 &= -\sin\beta\ \eta_1 + \cos\beta\ \eta_2 && \text{(pseudo-scalar)},\\
h^0 &= \cos\alpha\ h_1 + \sin\alpha\ h_2 && \text{(lightest scalar)},\\
H^0 &= -\sin\alpha\ h_1 + \cos\alpha\ h_2 && \text{(heaviest scalar)}.
\end{aligned}
$$

where
$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ h_i + i\eta_i \end{pmatrix}.$$