Electroweak Baryogenesis after LHC8

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What NExT?
Southampton – November 27, 2013

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    - ✓expansion of Universe;
    - ✓EW phase transition.

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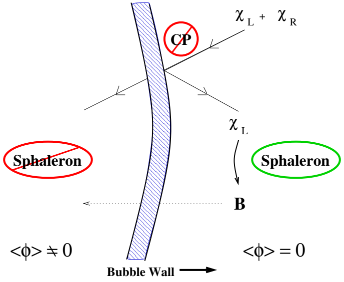
- Successful baryogenesis requires a strong first order phase transition:

$$\frac{v_c}{T_c} \gtrsim 1.$$



Morrissey, Ramsey-Musolf [arXiv:1206.2942]

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  - MSSM, NMSSM;
  - 2HDM.

EWBG in the MSSM

MSSM Higgs sector $\Rightarrow$ two $SU(2)_L$ scalar doublets $\Phi_1,\ \Phi_2$:

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

$$V_{\text{tree}}^{\text{MSSM}} = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}\left(\Phi_1^\dagger\Phi_2 + H.c.\right) + \\ + \frac{g^2+g'^2}{8}\left(\Phi_1^\dagger\Phi_1 - \Phi_2^\dagger\Phi_2\right)^2 + \frac{g^2}{2}\left|\Phi_1^\dagger\Phi_2\right|^2.$$

EW minimum: $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}, \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta \end{pmatrix}.$

Mass eigenstates: $\underbrace{G^0,\ G^\pm}_{\text{Goldstone bosons}} + \underbrace{h^0,\ H^0,\ A^0,\ H^\pm}_{\text{physical Higgs states}}.$

EWBG in MSSM (?)

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- This scenario allows for rather definite predictions on SM Higgs production and branching ratios, with severe tension with experimental data! [Curtin, Jaiswal, Meade, arXiv:1203.2932]
- Could be alleviated if light neutralino has mass $\lesssim 60$ GeV. [Carena, Nardini, Quiros, Wagner, arXiv:1207.6330]

2HDM

- Two-Higgs-doublet models are the minimal SM extension able to account for BAU.
- Generalization of the MSSM Higgs sector.
- Extra heavy bosons ($h^0,\ H^0,\ A^0,\ H^\pm$) may strengthen the EW phase transition.
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  [Fromme, Huber, Seniuch, hep-ph/0605242]
- But what happens in the general case?

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- General fermionic couplings:

$$\mathcal{L}_{\text{Yukawa}} = -\overline{Q}_L \left(\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2\right) n_R + \ldots$$

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$$\mathcal{L}^{FCNC} = -\overline{d}_L \widetilde{\Gamma}_1 \varphi_1^0 d_R + \dots$$

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- Avoid this with $\mathbb{Z}_2$ 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	+	−	+

Only top-quark is significant for phase transition.
Then models differ only in phenomenological constraints on their parameter space. These come mainly from B-physics, so

Type I $\sim$ Type X,
Type II $\sim$ Type Y.

2HDM

- For simplicity, consider CP conserving case only.

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

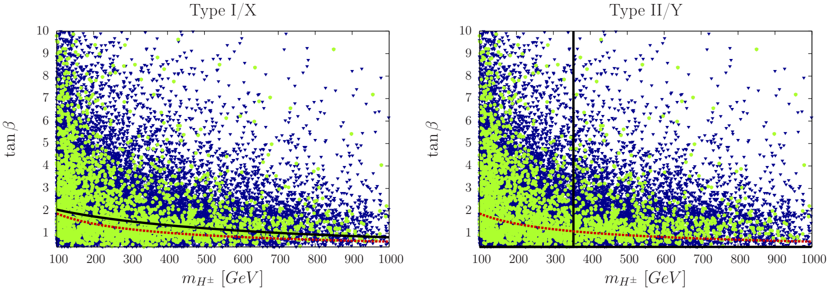
- EW minimum: $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}$, $\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta \end{pmatrix}$.
- Physical parameters:
  - $v \approx 174$ GeV and $M \equiv \frac{\mu}{\sqrt{\sin(2\beta)}}$.
  - Masses: $m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}$.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

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

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

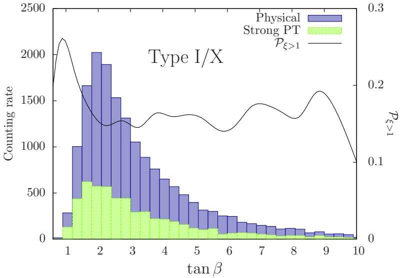
$$0.4 \le \tan\beta \le 10\ ,$$
$$-\tfrac{\pi}{2} < \alpha \le \tfrac{\pi}{2}\ ,$$
$$0\ \text{GeV} \le \mu \le 1\ \text{TeV},$$
$$100\ \text{GeV} \le m_{A^0}, m_{H^\pm} \le 1\ \text{TeV},$$
$$150\ \text{GeV} \le m_{H^0} \le 1\ \text{TeV}.$$

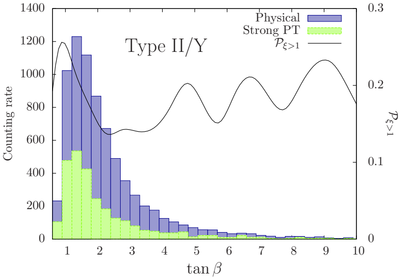
- Constraints:
  - EW precision: $\rho - 1 \approx 0$;
  - $\lambda_i < 4\pi$;
  - metastability;
  - $B^0 - \bar{B}^0$ (red/dashed) and $\bar{B} \to X_s\gamma$ (black/full).



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

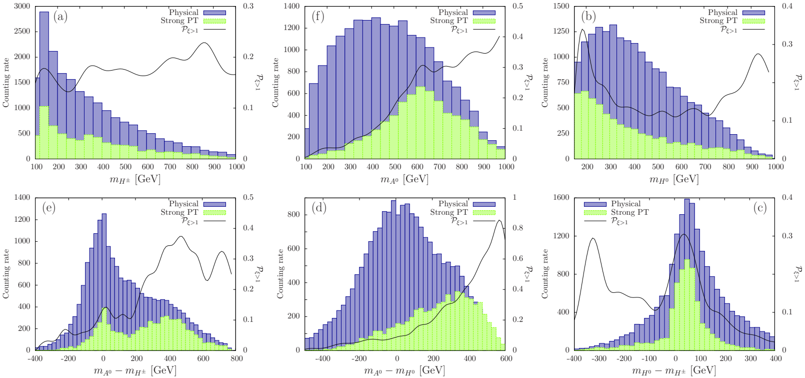
Results: $\tan\beta$





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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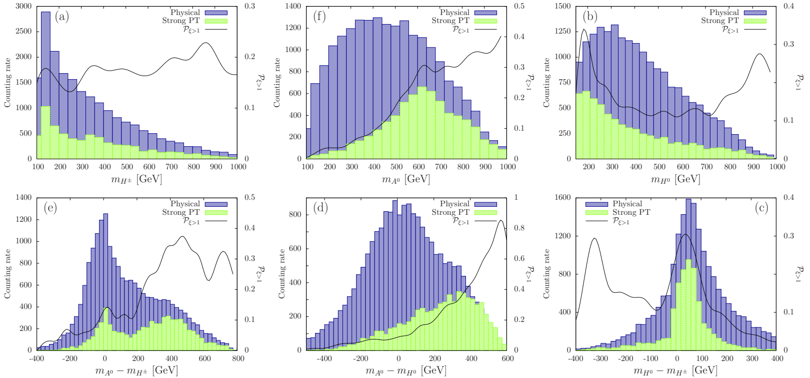

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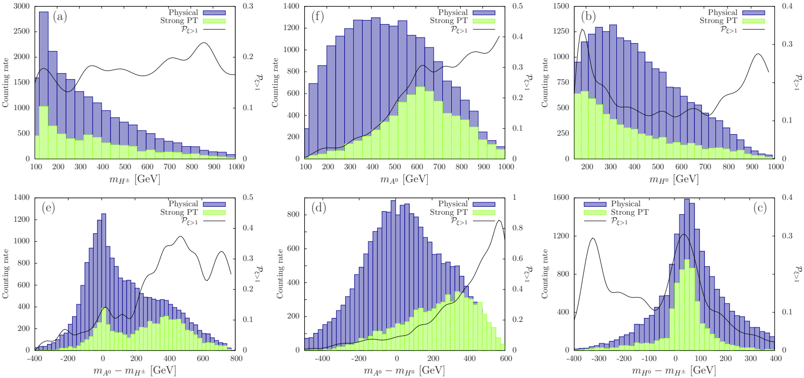

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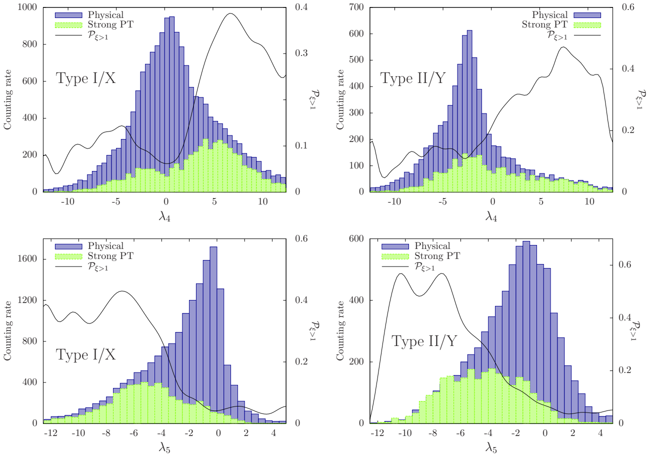
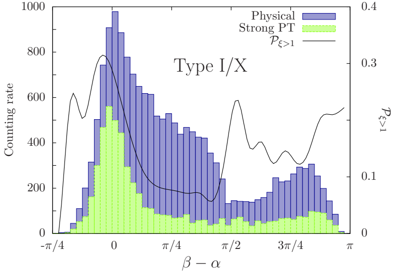
Strong PTs also prefer hierarchy $m_{A^0} > m_{H^0} \gtrapprox m_{H^\pm}$.

Results: Couplings

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



Results: $\beta - \alpha$



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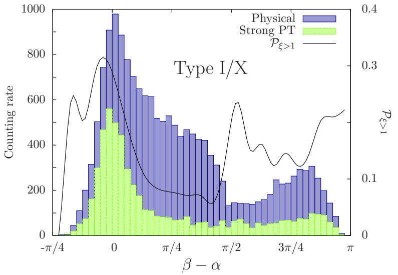

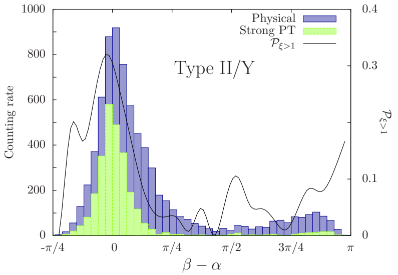

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Put another way, the observation of a SM-like h^0 constrains the parameter space of 2HDMs in favour of strong PTs.

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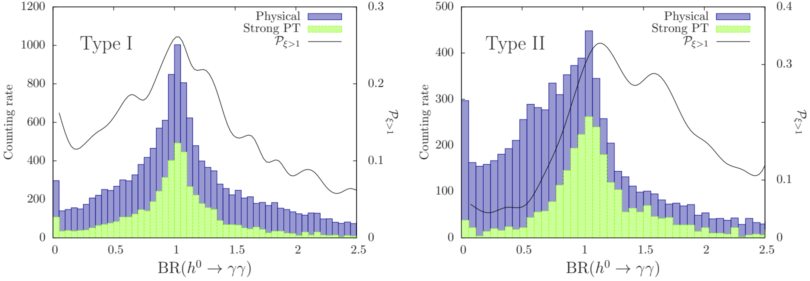
Thank you!

Appendix – $h^0 \to \gamma\gamma$

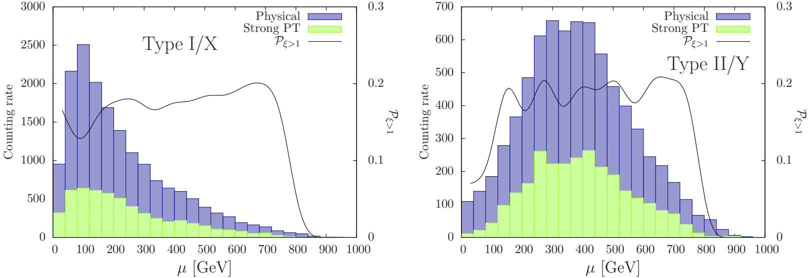


Coupling of h^0 to b and τ:

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

Appendix – μ parameter

$$V_{\text{tree}} \supset -\frac{\mu^2}{2}\left(\Phi_1^\dagger \Phi_2 + H.c.\right)$$



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	6.3×10^6	1.2×10^6	1.4×10^5	2.6×10^4	4.3×10^3
Relative	100%	19.1%	2.3%	0.41%	0.069%

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