EWBG in the MSSM

Towards higher scales of SUSY-breaking

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In occasion of

Baryogenesis Confronts Experiments

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Outline

Main motivation

In the MSSM the light–stop scenario is required by EWBG [Carena et al.,98] .

In the case of large m_A (SM-like Higgs), the requirement of a strong enough 1^{st} order phase transition ($v(T)/T \gtrsim 1$) can be translated in a window of $m_{\tilde{t}_R}$ versus m_h.

Some considerations about that window are relevant:

- If M_Q is a few TeV, the window is jeopardized by the Higgs experimental bound ($m_h > 114.7$ GeV).
- m_h was calculated in the 1–loop approximation.

$$\Downarrow$$

More precision in the m_h calculation? Larger M_Q?

Framework

The main features of the SUSY spectrum are:

- Fermions are at the EW scale
- The $\tilde{t}_R$ is lighter than the top quark
- The other scalars $m_Q \simeq m_A \simeq ... \equiv \tilde{m} \gtrsim$ *few TeV*
- $A_t \ll \widetilde{m}$ (motivated by the strength of the EWPT)

(A sort of light-stop scenario in SS)

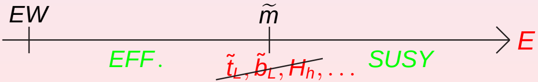
$$\Downarrow$$

LOW ENERGY EFFECTIVE THEORY

LE Lagrangian

The effective Lagrangian is

$$
\begin{aligned}
\mathcal{L}_{\rm eff} \; = \; & m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - h_t\left[\bar{q}_L \epsilon H^* t_R\right] + Y_t\left[\bar{\tilde{H}}_u \epsilon q_L \tilde{t}^*_R\right] \\
& -\sqrt{2}G\;\tilde{t}_R \tilde{g}^a \overline{T}^a \bar{t}_R + \sqrt{2}J\;\tilde{t}^*_R \tilde{B} t_R - \frac{1}{6}K \tilde{t}^*_{R_\omega}\tilde{t}_{R_\omega}\;\tilde{t}^*_{R_\gamma}\tilde{t}_{R_\gamma} - Q\;\left|\tilde{t}_R\right|^2 \left|H\right|^2 \\
& + \frac{H^\dagger}{\sqrt{2}}\left(g_u \sigma^a \tilde{W}^a + g'_u \tilde{B}\right)\tilde{H}_u + \frac{H^T \epsilon}{\sqrt{2}}\left(-g_d \sigma^a \tilde{W}^a + g'_d \tilde{B}\right)\tilde{H}_d + \text{h.c.} \\
& - \frac{M_3}{2}\tilde{g}^a \tilde{g}^a - \frac{M_2}{2}\tilde{W}^A \tilde{W}^A - \frac{M_1}{2}\tilde{B}\tilde{B} - \mu \tilde{H}_u^T \epsilon \tilde{H}_d - M_U^2\;\tilde{t}^*_R \tilde{t}_R
\end{aligned}
$$



Matching conditions at $\widetilde{m}$

(*One–loop:* $\overline{MS}$ *- dim. regular. - Landau gauge -* g_3, λ_t)

$$\lambda(\tilde{m}) - \Delta\lambda = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{4} \cos^2 2\beta \left(1 - \frac{1}{2}\Delta Z_\lambda\right)$$

$$h_t(\tilde{m}) - \Delta h_t = \lambda_t(\tilde{m}) \sin\beta \left(1 - \frac{1}{2}\Delta Z_{h_t}\right)$$

$$Q(\tilde{m}) - \Delta Q = \left(\lambda_t^2(\tilde{m}) \sin^2\beta - \frac{1}{3} g'^2 \cos 2\beta\right) \left(1 - \frac{1}{2}\Delta Z_Q\right)$$

$$Y_t(\tilde{m}) - \Delta Y_t = \lambda_t(\tilde{m}) \left(1 - \frac{1}{2}\Delta Z_{Y_t}\right)$$

$$K(\tilde{m}) - \Delta K = \left(g_3^2(\widetilde{m}) + \frac{4}{3} g'^2(\widetilde{m})\right) \left(1 - \frac{1}{2}\Delta Z_K\right)$$

$$G(\tilde{m}) - \Delta G = g_3(\tilde{m}) \left(1 - \frac{1}{2}\Delta Z_G\right)$$

$$J(\tilde{m}) = \frac{2}{3} g'(\tilde{m}) \,, \qquad g_u(\widetilde{m}) = g(\widetilde{m}) \sin\beta \,, \qquad g_d(\widetilde{m}) = g(\widetilde{m}) \cos\beta \,,$$

$$g'_u(\widetilde{m}) = g'(\widetilde{m}) \sin\beta \,, \qquad g'_d(\widetilde{m}) = g'(\widetilde{m}) \cos\beta$$

RGE

For the adimensional couplings...

$$(4\pi)^2\beta_\lambda = 12\lambda^2+6Q^2 - 12h_t^4 + 12h_t^2\lambda$$

$$(4\pi)^2\beta_{h_t} = h_t\left(\frac{9}{2}h_t^2+\frac{1}{2}Y_t^2 + \frac{4}{3}G^2 - 8g_3^2\right)$$

$$(4\pi)^2\beta_Q = -\frac{32}{3}G^2h_t^2 - 4Y_t^2h_t^2 + Q\left(K + 3\lambda + 4Q + 6h_t^2 + 4Y_t^2 + \frac{16}{3}G^2 - 8g_3^2\right)$$

$$(4\pi)^2\beta_{Y_t} = \frac{1}{2}Y_t\left(h_t^2 + 8Y_t^2 + \frac{16}{3}G^2 - 8g_3^2\right)$$

$$(4\pi)^2\beta_K = 12Q^2 + 13g_3^4 - \frac{88}{3}G^4 - 24Y_t^4 + K\left(\frac{14}{3}K + 8Y_t^2 + \frac{32}{3}G^2 - 16g_3^2\right)$$

$$(4\pi)^2\beta_G = \frac{1}{2}G\left(9G^2 + 2h_t^2 - 26\,g_3^2 + 4Y_t^2\right)$$

$$(4\pi)^2\beta_J = J\left(h_t^2 + 2Y_t^2 + \frac{12}{3}G^2 - 4g_3^2\right)$$

$$(4\pi)^2\beta_{g_u(')} = g_u(')\left(3h_t^2+\frac{3}{2}Y_t^2\right)\ ,\quad (4\pi)^2\beta_{g_d(')} = 3\,g_d(')\,h_t^2\ ,$$

RGE

... and for the mass terms

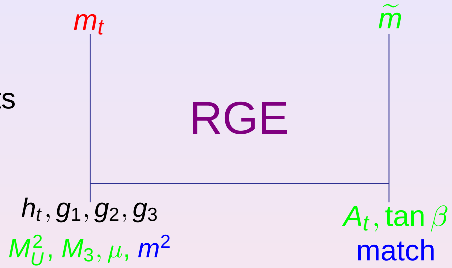
$$
\begin{aligned}
(4\pi)^2\beta_{M_1} &= 0\\
(4\pi)^2\beta_{M_2} &= 0\\
(4\pi)^2\beta_{m} &= -6Q\, m_U^2 + 6m^2 h_t^2\\
(4\pi)^2\beta_{\mu} &= \frac{3}{2}\,\mu\, Y_t^2\\
(4\pi)^2\beta_{M_3} &= M_3\left(-18g_3^2 + G^2\right)\\
(4\pi)^2\beta_{M_U^2} &= M_U^2\left(\frac{8}{3}K + 4Y_t^2 + \frac{16}{3}G^2 - 8g_3^2\right) - \frac{32}{3}M_3^2G^2 - 4m^2Q - 4Y_t^2\mu^2
\end{aligned}
$$

- Checked by the SUSY limit

Higgs mass calculation

INPUTS:

- Experimental LE inputs
- Theoretical inputs
- Free parameters



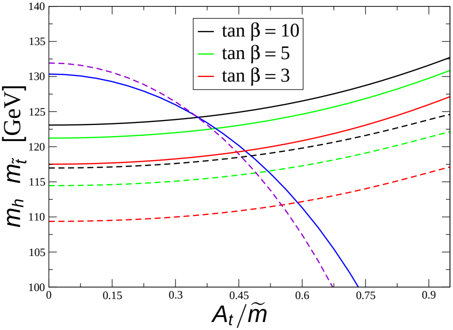
HIGGS MASS:

by the 1-loop effective potential in the LE theory improved by the 1-loop RGE resummation (necessary to resum large logs for large values of M_Q)

Higgs and stop mass

$M_U^2 = -(100GeV)^2 \quad \mu = 100GeV \quad M_3 = 600GeV$

$m_{\tilde{t}}^2 = M_U^2 + \frac{Q}{2} v_{246}^2$



$\widetilde{m} = 100TeV$

$\widetilde{m} = 10TeV$

- The shape of m_h is similar to the familiar one, even if now it is a combination of several threshold contributions
- Typically $m_{\tilde{t}} \lesssim 135GeV$

Prophecy: ($\widetilde{m} < 10TeV$ + $\tan\beta < 5$ + EWBG) difficult

Application to EWBG

Why $M_U^2 < 0$? Basic idea

To obtain a strong 1^{st} order EW transition, the Higgs potential has to develop a large barrier, typically generated by a "cubic term" which can be produced only by bosons.

Unlike in the SM (developing a small cubic term), in our LE theory the Stop could strengthen the EW transition. Its spurious cubic term appears as

$$\left[M_U^2 + \frac{Q}{2}h^2 + \Pi(T)\right]^{3/2}$$

$$\Downarrow$$

To strengthen the transition $M_U^2 \approx -\Pi(T_c)$

$$\Downarrow$$

The theory then has two minima!

EWB	CB
$\langle h, \tilde{t} \rangle = (v, 0)$	$\langle h, \tilde{t} \rangle = (0, u)$

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EWB $\langle h, \tilde{t} \rangle = (v, 0)$

CB $\langle h, \tilde{t} \rangle = (0, u)$

Potentials and possible transitions

Starting from the symmetric phase (SP), since $M_U^2 < 0$:

- If $(T^n_{SP\to CB} > T^n_{SP\to EWB})$ + $(\langle V_h\rangle > \langle V_{\tilde{t}}\rangle)$ NO
- If $(T^n_{SP\to CB} > T^n_{SP\to EWB})$ + $(\langle V_h\rangle < \langle V_{\tilde{t}}\rangle)$ NO[Cline et al,99]
- If $(T^n_{SP\to CB} < T^n_{SP\to EWB})$ + $(\langle V_h\rangle < \langle V_{\tilde{t}}\rangle)$ OK
- If $(T^n_{SP\to CB} < T^n_{SP\to EWB})$ + $(\langle V_h\rangle > \langle V_{\tilde{t}}\rangle)$?

At $T \neq 0$ we consider the 2-loop effective potential in the LE theory taking into account only the effective couplings $\sim g_3, \lambda_t$.

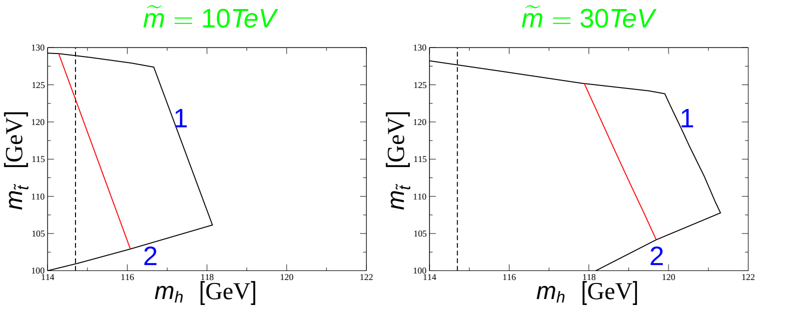
$$\Downarrow$$

tree-level: $m_H, m_{\tilde{t}}, m_U^2$ (Q, λ)

radiative: other couplings

Higgs-Stop window $\langle h \rangle_{T_c}/T_c > 1$ $(\mu = 100, M_3 = 600)$

Condt. 1: $\tan\beta \lesssim 10$ good for EDM and BAU.
Condt. 2: If $T^c_h \geq T^c_{\tilde{t}} + 2\ GeV \;\Rightarrow\; T^n_{SP\to CB} < T^n_{SP\to EWB}$



In light stop SS up to $m_h \approx 127$ GeV!!!

Condt. 1 strongly restricts the window, but the same $(m_h, m_{\tilde{t}}, M_U^2)$ can be often obtained by lower $\tan\beta$ in a higher $\tilde{m}$ scenario where only less important couplings are different

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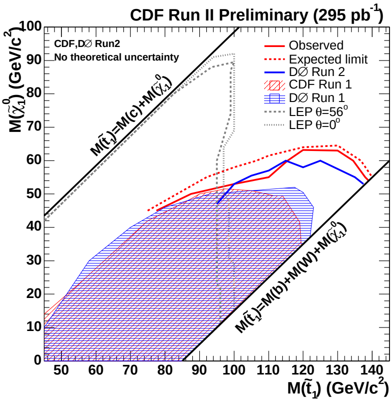
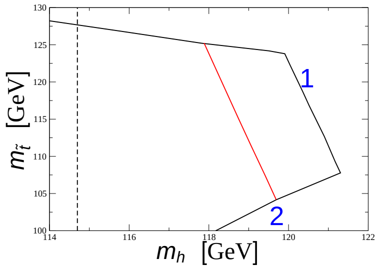


$\widetilde m = 30TeV$



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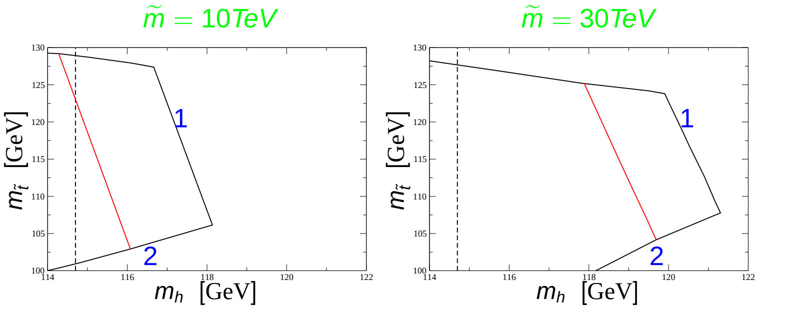

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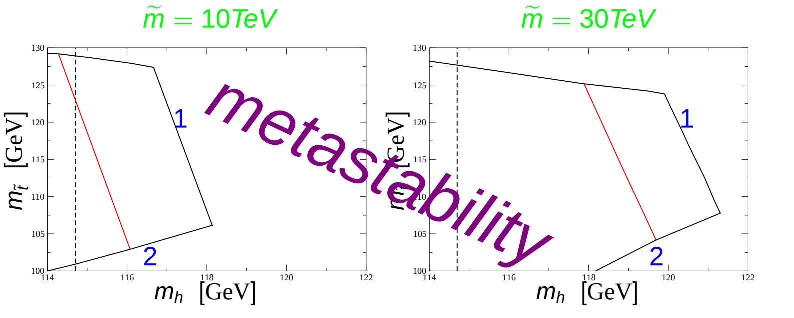

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Condition 1: $\tan\beta \leq 10$

- EDM: one-loop predominates ($\widetilde{m} \gtrsim 10 TeV$), roughly [Pilaftsis,02]

$$d_e \lesssim d_e^{exp} \tan\beta/10$$

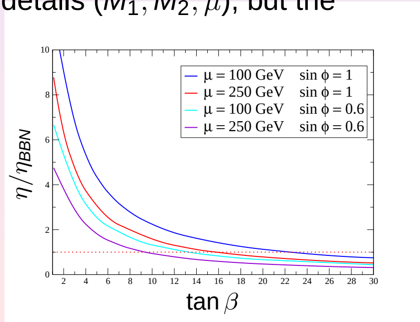
- BAU: fixing $\langle h \rangle_{T_c}/T_c = 1$ [Carena et al.,01]

Calculation strongly depends on details (M_1, M_2, μ), but the windows do weakly depend

$\Downarrow$

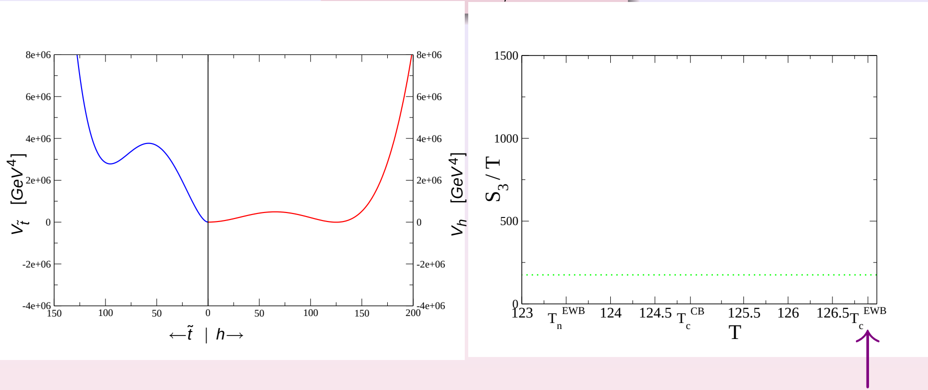
Good choice: $\tan\beta \leq 10$

Very conservative: $\tan\beta \leq 5$



Condition 2: $T_h^c \geq T_{\tilde{t}}^c + 2\ GeV \Rightarrow T^n_{SP\to CB} < T^n_{SP\to EWB}$

Nucleation $S_3/T \approx 140$



- At $T = T_c^{EWB} = 126.9 GeV$ the actions $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite

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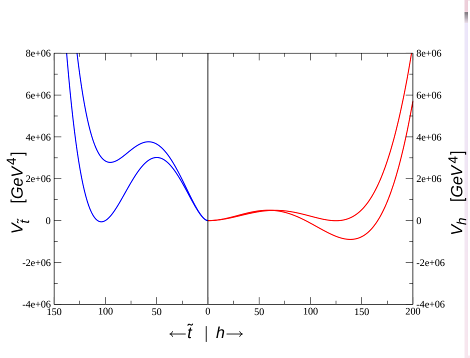

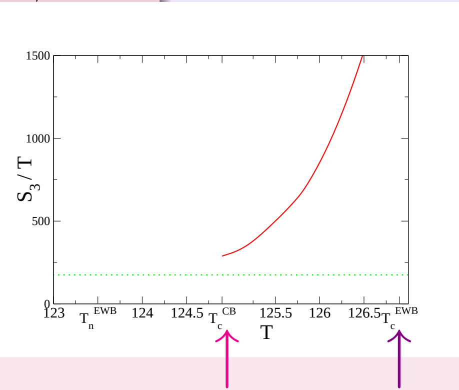

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- At $T = T_c^{CB} = 124.9 GeV$ the action $S_{SP\to CB}$ is infinite and $S_{SP\to EWB}$ is still too large

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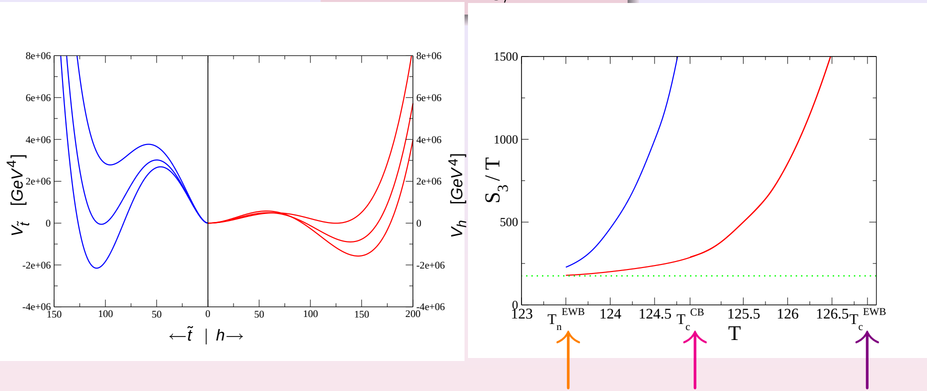
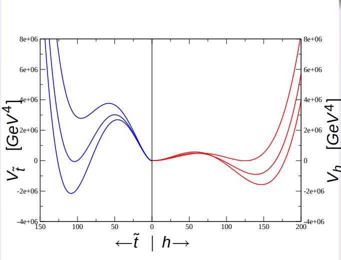
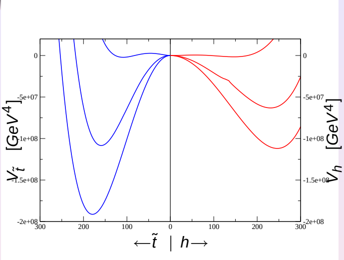


- At $T = T_c^{EWB} = 126.9 GeV$ the actions $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite
- At $T = T_c^{CB} = 124.9 GeV$ the action $S_{SP\to CB}$ is infinite and $S_{SP\to EWB}$ is still too large
- At $T = T_n = 123.5$ the action $S_{SP\to EWB}$ gets to ~ 140, thus the new phase is EWB

Metastability

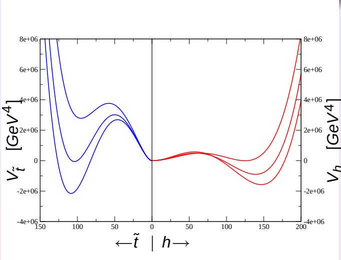
Is the transition EWB→CB possible ?

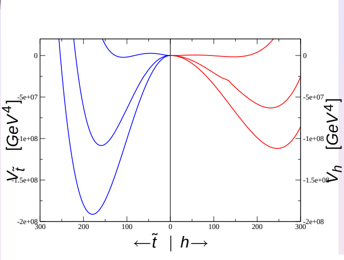




Metastability

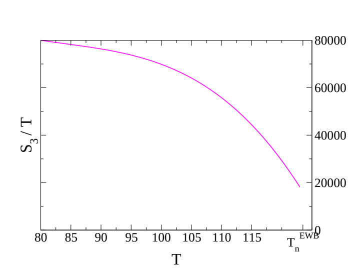
Is the transition EWB→CB possible ? NO





$$S_{EWB \to CB} \gg 140$$

IT DOESN'T DECAY !



Conclusions

Effective Theory

- By using appropriate RGE and matching conditions, we have computed the LE effective theory in the light stop scenario in a reliable manner for very high $\widetilde{m}$.
- As an immediate application we calculate the light Higgs mass using the effective potential improved by the RGE.

EWBG

- We improve on the determination of the $m_h - m_{\tilde{t}}$ strong-transition window that permits to explore higher scales $\widetilde{m}$.
- We observe that for $\widetilde{m} \gtrsim 10$ TeV the window is in agreement with BAU.
- The parameters for EWBG imply an EW metastable vacuum that we have checked not to decay.