The Light Stop Scenario and its Strong First Order Phase Transition

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U L B

[arXiv:0806.4297]   [arXiv:0809.3760]

in collaboration with M. Carena,M. Quirós,C. Wagner

Outline

The Question: Why this asymmetry?

The Universe is matter dominated. Natural $\bar{p}$ in the cosmic rays, but compatible with secondary production.
BBN and CMB furnish independently:

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

Why this strange number? Why not zero?

Possible mechanisms attempting to produce η must contain the ingredients [Sakharov,1967]

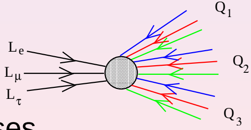
1. B violation
2. C and CP violation
3. Departure from thermal equilibrium

An answer: EWBG in the SM

Kuzmin et al.,85; ...

The SM contains the Sakharov conditions:

1. B number is non-perturbative violated at $T \neq 0$ (sphalerons) ['t Hooft,76]



2. CKM matrix contains CP violating phases
3. EWPT (when of 1^{st} order) proceeds by bubble nucleation. Expanding bubbles break the thermal equilibrium.

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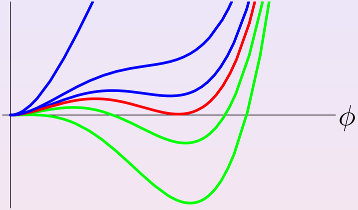
$$V(\phi, T) \simeq m\phi^2 + E\phi^3 + \lambda\phi^4$$



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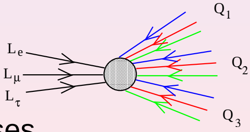

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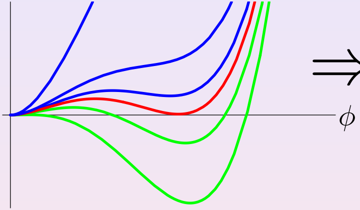

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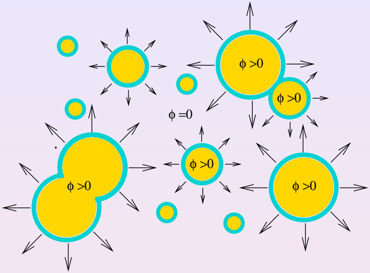

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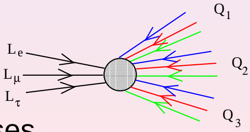

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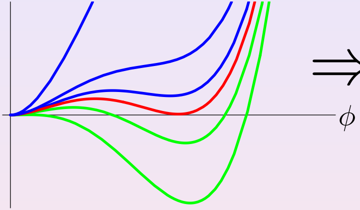

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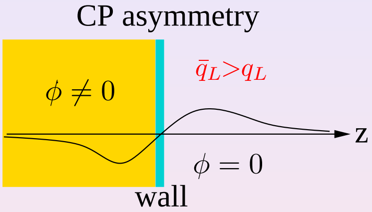

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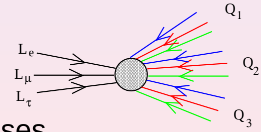

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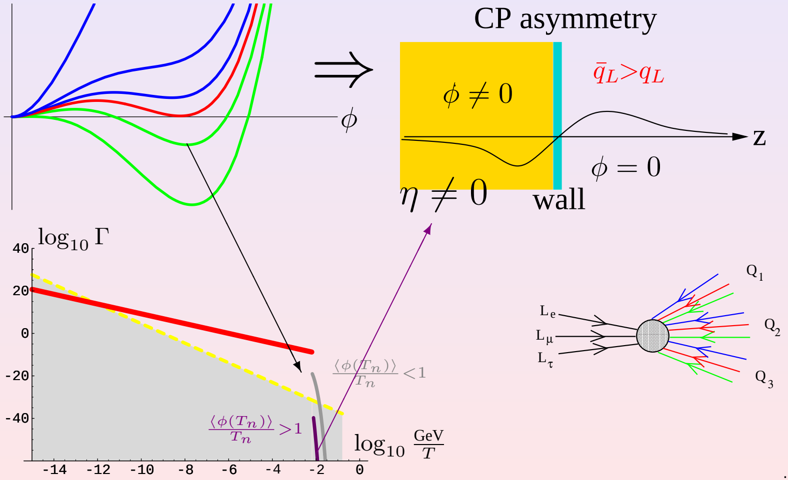
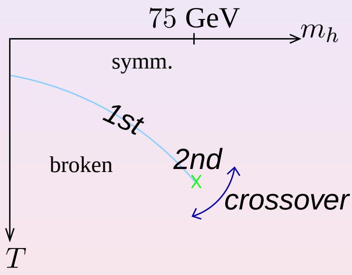


Another answer: EWBG in the MSSM

Unluckily, EWBG in the SM does not work: the EWPT is not strong enough ($\frac{\langle\phi(T_n)\rangle}{T_n} < 1$) since $m_h > 114.4$ GeV [LEP].

[Kajantie et al.,97]



$\Rightarrow$ New physics to modify the $V(\phi, T)$.
Well motivated possibility: EWBG in the MSSM.

State of the art (< 2008)

In the MSSM the EWPT was strong enough in the Light Stop Scenario ($m_{\tilde{t}_R} < m_t$) [Carena et al.,96;Delepine et al.,96;Cline et al.,98], but the analysis was performed for $m_h \gtrsim 65$ GeV.

In the case of large m_A (SM-like Higgs), the parameter region useful for $v(T)/T \gtrsim 1$ 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 present Higgs experimental bound ($m_h > 114.4$ GeV).
- m_h was calculated in the 1–loop approximation.

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Talk aim: what happens whether

More precision in the m_h calculation? Larger M_Q?

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LSS Framework

The main features of the LSS spectrum are:

- Fermions are at the EW scale (gluino may be a bit heavy)
- The $\tilde{t}_R$ is lighter than the top quark
- The other scalars $M_Q \simeq m_A \simeq ... \equiv \tilde{m} \gg few\, TeV$
- $A_t \ll \tilde{m}$ (motivated by the strength of the EWPT)

(A sort of light-stop scenario in SS)

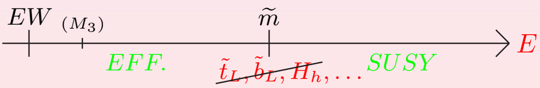
$$\Downarrow$$

LOW ENERGY EFFECTIVE THEORY

LE Lagrangian

The effective Lagrangian is

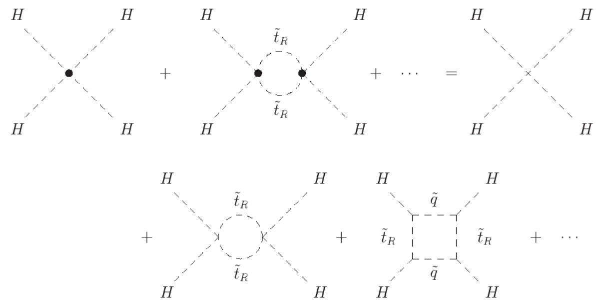
$$
\begin{aligned}
\mathcal{L}_{eff} = & \; m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - h_t\left[\bar{q}_L \epsilon H^* t_R\right] + Y_t\left[\overline{\tilde{H}}_u \epsilon q_L \tilde{t}_R^*\right] \\
& -\sqrt{2} G\, \Theta_{\tilde{g}}\, \tilde{t}_R \tilde{g}^a \overline{T}^a \bar{t}_R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

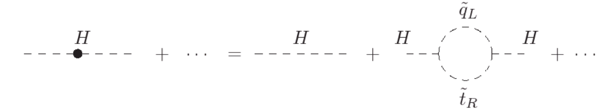


Matching conditions at $\widetilde{m}$

(*One–loop:* $\overline{MS}$ *- dim. regular. - Landau gauge - 4-dim. ops.*)

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





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

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

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

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

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

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

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

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

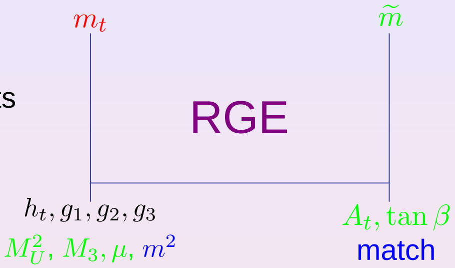
$$(4\pi)^2\beta_{M_1} = 0$$
$$(4\pi)^2\beta_{M_2} = 0$$
$$(4\pi)^2\beta_{m} = -6Q\, m_U^2 + 6m^2 h_t^2$$
$$(4\pi)^2\beta_{\mu} = \frac{3}{2}\,\mu\, Y_t^2$$
$$(4\pi)^2\beta_{M_3} = M_3\left(-18g_3^2 + G^2\right)$$
$$(4\pi)^2\beta_{M_U^2} = M_U^2\left(\frac{8}{3}K + 4Y_t^2 + \frac{16}{3}G^2 - 8g_3^2\right)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

- Checked by the SUSY and SS limits

Higgs mass calculation

INPUTS:

- Experimental LE inputs
- Theoretical inputs
- Free parameters



HIGGS MASS:

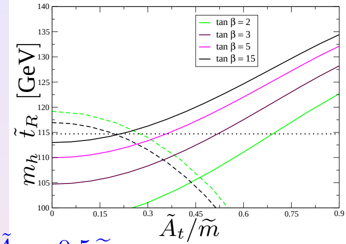
by the 1-loop effective potential in the LE theory improved by the 1-loop RGE resummation (necessary to resum large logs for large values of M_Q)

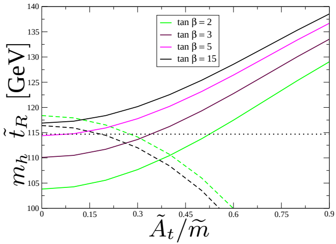
Higgs and stop mass

$M_U^2 = -(100)^2$ GeV^2

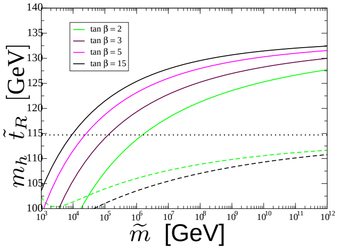
$\widetilde{m} = 100$ TeV

$\widetilde{m} = 1000 TeV$





$\tilde{A}_t = 0.5\widetilde{m}$



$m_h \lesssim 133$ GeV

$m_{\tilde{t}_R} \lesssim 120$ GeV

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

Why $M_U^2 < 0$? Basic idea

To obtain a strong 1^{st} order EW transition ($\langle\phi(T_n)\rangle > T_n$), the Higgs potential ($V(\phi,T) \simeq m\phi^2 + E\phi^3 + \lambda\phi^4$) has to develop a large barrier ($E\uparrow$), increased by the "cubic term" produced 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

$$\left[M_U^2 + \frac{Q}{2}\phi^2 + \Pi(T)\right]^{3/2} \qquad Q \sim (1 - \tilde{A}_t/\widetilde{m})$$

$$\Downarrow$$

To strengthen the transition $M_U^2 \approx -\Pi(T_c)$ so that $[\cdots]^{3/2} \sim E\phi^3$

$$\Downarrow$$

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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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 $(T^n_{SP\to CB} < T^n_{SP\to EWB})$ + $(\langle V_h\rangle > \langle V_{\tilde t}\rangle)$?

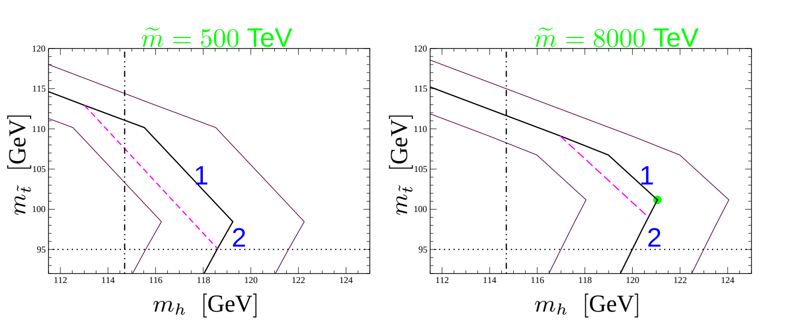
At $T \neq 0$ we consider the 2-loop effective potential in the LE theory taking into account only the effective couplings $\sim g_3, \lambda_t$.

$$\Downarrow$$

tree-level: $m_h, m_{\tilde t}, m_U^2$ (Q, λ)
radiative: other couplings

Higgs-Stop window $\langle\phi(T_c)\rangle/T_c > 0.9$ $(\mu = 100, M_3 = 500)$

Condt. 1: $\tan\beta \lesssim 15$ good for EDM and BAU.
Condt. 2: If $T^c_h \geq T^c_{\tilde{t}} + 1.6$ GeV $\Rightarrow$ $T^n_{SP\to CB} < T^f_{SP\to EWB}$



Only effect. parameters are important

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

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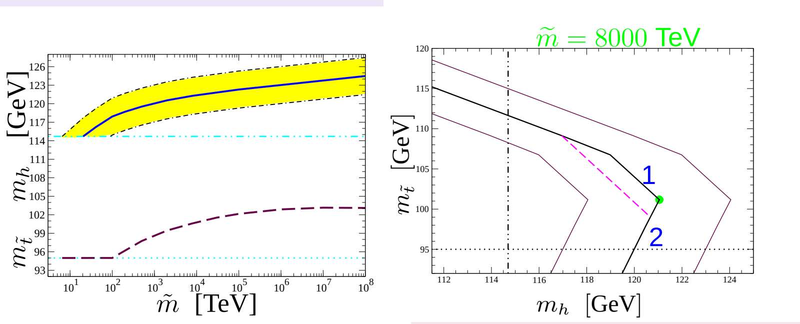

EWBG bounds (upper uncertainty):

$m_h \lesssim 127$ GeV $\quad$ $m_{\tilde{t}_R} \lesssim 120$ GeV

$\tilde{m} \gtrsim 7$ TeV

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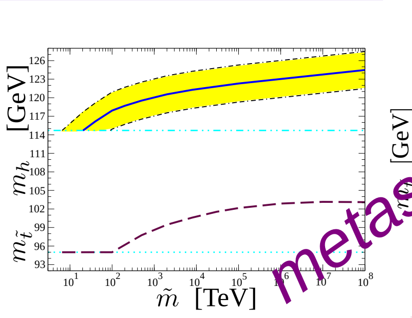

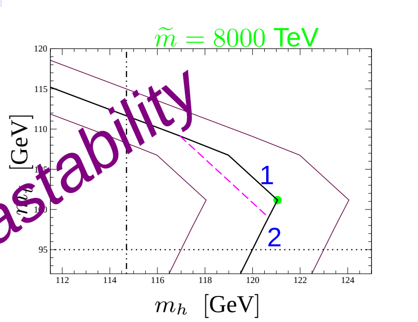

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Condition 1: $\tan\beta \le 15$

- EDM: one-loop predominates ($\widetilde{m} \gtrsim 10\,$TeV), roughly [Chang et al.,99]

$$d_e \lesssim d_e^{exp}\ \tan\beta/15 \qquad (\widetilde{m} \approx 10\,\text{TeV})$$

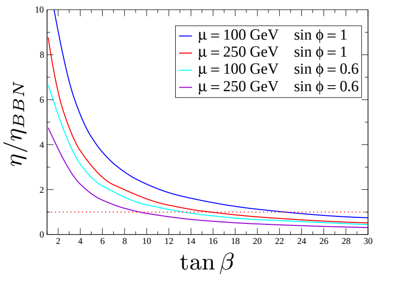
- BAU: fixing $\langle h\rangle_{T_n}/T_n = 1$ [Carena et al.,01]

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

$\Downarrow$

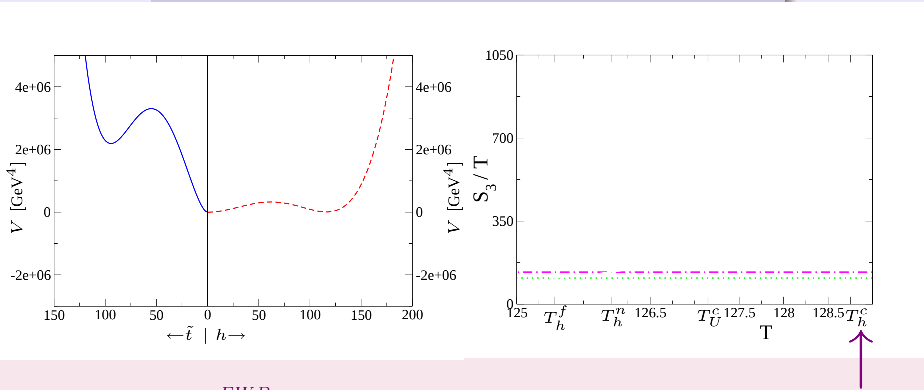
Good choice: $\tan\beta \le 15$

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



Condition 2: $T_h^c \geq T_{\tilde{t}}^c + 1.6$ GeV $\Rightarrow T^n_{SP\to CB} < T^f_{SP\to EWB}$

Nucl: $S_3/T \approx 135$ End: $S_3(T_f)/T_f \approx 110$



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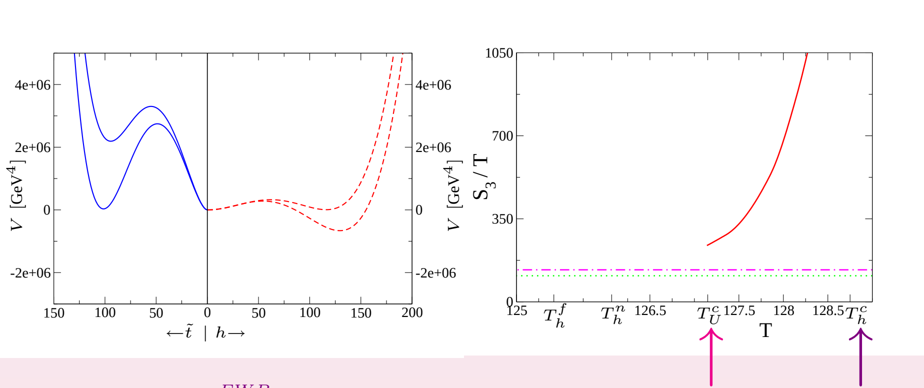

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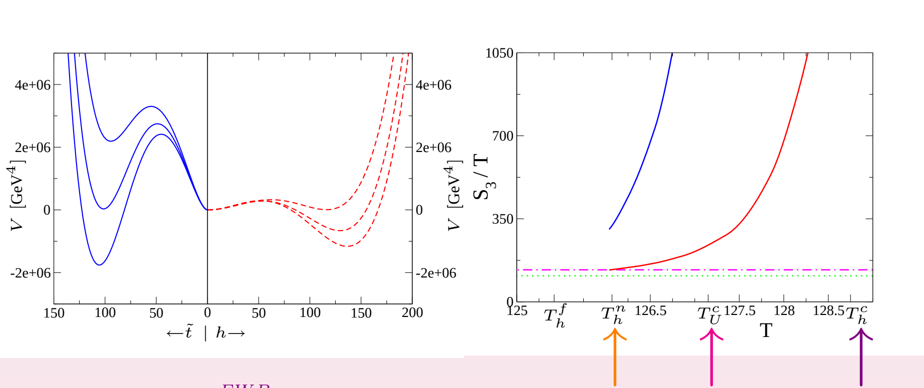
- At $T = T_c^{CB} = 127.1\,\text{GeV}$: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite

Condition 2: $T_h^c \geq T_{\tilde{t}}^c + 1.6\ \mathrm{GeV} \Rightarrow T^n_{SP\to CB} < T^f_{SP\to EWB}$

Nucl: $S_3/T \approx 135$ End: $S_3(T_f)/T_f \approx 110$



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- At $T = T_c^{CB} = 127.1\,\mathrm{GeV}$: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite
- At $T = T_n = 126.0\,\mathrm{GeV}$: $S_{SP\to EWB} = 135$ and $S_{SP\to CB}$ too large
-

Condition 2: $T_h^c \geq T_{\tilde{t}}^c + 1.6\ \text{GeV} \Rightarrow T^n_{SP\to CB} < T^f_{SP\to EWB}$

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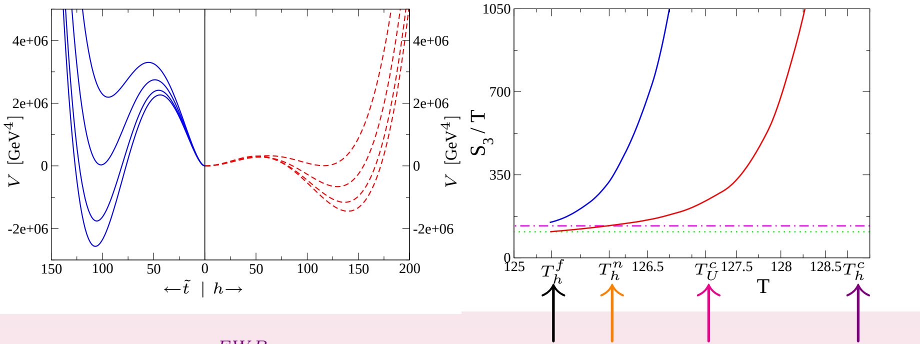

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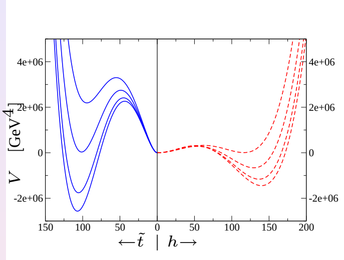
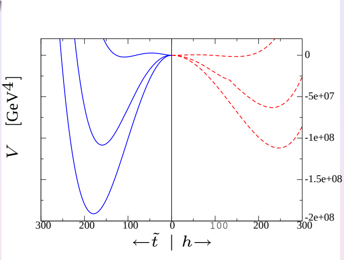
- At $T = T_n = 126.0\,\text{GeV}$: $S_{SP\to EWB} = 135$ and $S_{SP\to CB}$ too large
- At $T = T_f = 125.4\,\text{GeV}$: $S_{SP\to EWB} = 110$ and $S_{SP\to CB} > 135$

Metastability

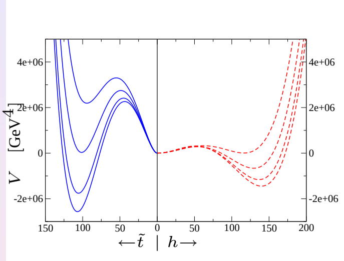
Is the transition EWB→CB possible ?

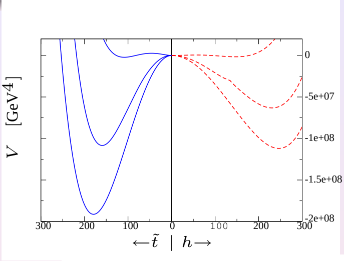




Metastability

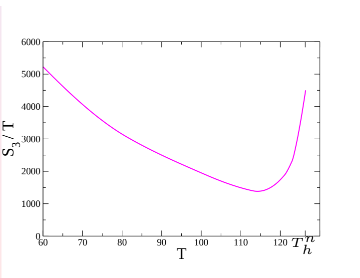
Is the transition EWB→CB possible ? NO





$$S_{EWB \rightarrow CB} \gg 135$$

IT DOESN'T DECAY !



Gauge Coupling Unification

EWBG suggests $\widetilde{m} \gg$ TeV. Large modif. from the usual parameter region of the MSSM, which unifies.

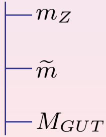
EWBG compatible with unification?

$$g_1^2 = (5/3)g'^2$$

$$(4\pi)^2 \frac{d}{dt} g_i = g_i^3 b_i + + \frac{g_i^3}{(4\pi)^2} \left[\sum_{j=1}^{3} B_{ij} g_j^2 - d_i^u h_t^2 - d_i^G G^2 - d_i^J J^2 - \cdots \right]$$

$$\boxed{b^{LSS} = \left(\frac{143}{30}, -\frac{7}{6}, -\frac{41}{6} + 2\Theta_{\tilde{g}}\right)}$$

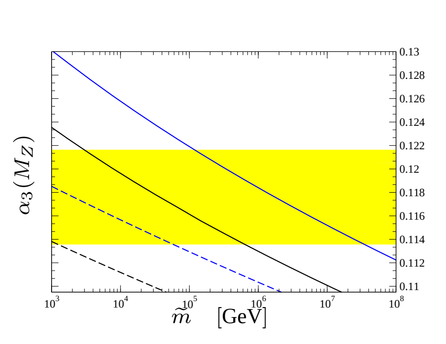
$$\boxed{b^{SUSY} = \left(\frac{33}{5}, -2, -3\right)}$$



Gauge Coupling Unification

EWBG suggests $\tilde{m} \gg$ TeV. Large modif. from the usual parameter region of the MSSM, which unifies.

EWBG compatible with unification? YES



1-σ prediction:

$M_3 = 500$ GeV:
$\tilde{m} = 10^{3.3\pm0.6}$ TeV

$M_3 = 150$ GeV:
$\tilde{m} = 10^{1.6\pm0.6}$ TeV

Conclusions

Effective Theory

- By using appropriate RGE and matching conditions, we have computed the LE effective theory in the LSS in a reliable manner for very high $\widetilde{m}$.
- We have calculated m_h using the effective potential improved by the RGE and we find $m_h \lesssim 150(133)$ GeV for $M_U^2 > (<) 0$.

EWBG

- We have improved 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 $\widetilde{m} \gtrsim 7$ TeV the window is in agreement with BAU.
- The parameters for EWBG imply an EW metastable vacuum that we have checked not to decay.
- Bounds: $m_h \lesssim 127$ GeV and $m_{\tilde{t}_R} \lesssim 120$ GeV.
- EWBG in the LSS compatible with GUT.