Looking for strong EW phase transitions

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Electroweak Phase Transition

Based on works done with
M. Carena, M. Quirós, C. Wagner, A. Wulzer

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?

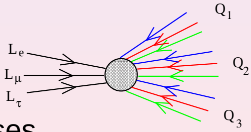
Possible mechanisms attempting to produce η must contain the ingredients [Sakharov,1967]

1. B violation
2. C and CP violation
3. Departure form 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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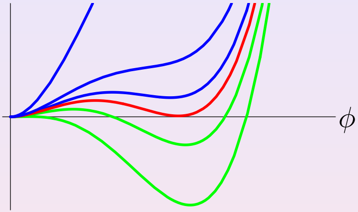
$$V(\phi, T) \simeq m\phi^2 + E\phi^3 + \lambda\phi^4$$



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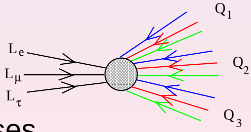

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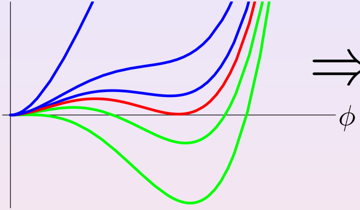

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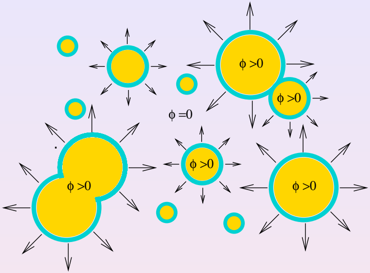

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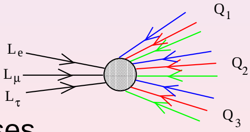

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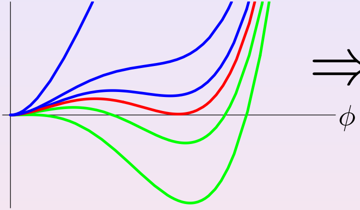

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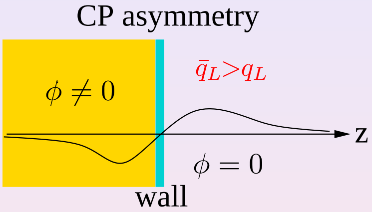

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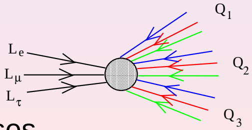

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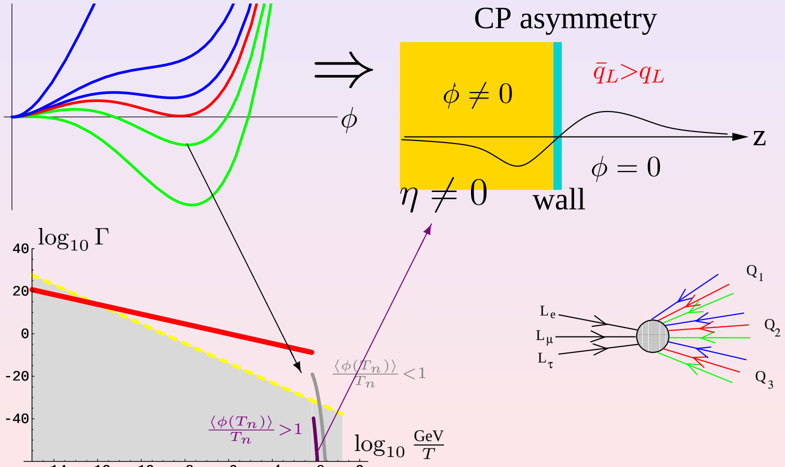
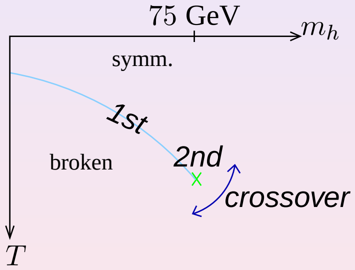


Another answer: EWBG in the MSSM

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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Thesis 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 $M_Q \simeq m_A \simeq ... \equiv \tilde{m} \gg few\, TeV$
- $A_t \ll \widetilde{m}$ (motivated by the strength of the EWPT)

(A sort of light-stop scenario in SS)

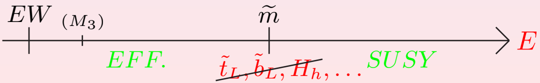
$$\Downarrow$$

LOW ENERGY EFFECTIVE THEORY

LE Lagrangian

The effective Lagrangian is

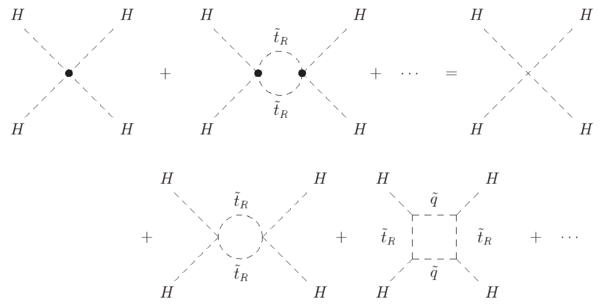
$$
\begin{aligned}
\mathcal{L}_{eff} = \; & m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - h_t\left[\bar{q}_L \epsilon H^* t_R\right] + Y_t\left[\overline{\tilde{H}}_u \epsilon q_L \tilde{t}_R^*\right] \\
& - \sqrt{2} G\, \Theta_{\tilde{g}}\, \tilde{t}_R \tilde{g}^a \overline{T}^a \bar{\tilde{t}}_R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

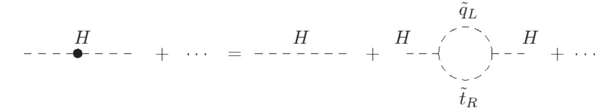


Matching conditions at $\widetilde{m}$

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

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

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

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

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

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

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

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

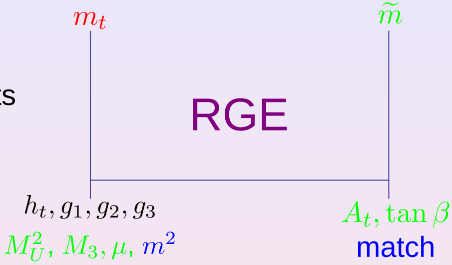
$$
\begin{aligned}
(4\pi)^2\beta_{M_1} &= 0 \\
(4\pi)^2\beta_{M_2} &= 0 \\
(4\pi)^2\beta_{m} &= -6Q\, m_U^2 + 6m^2 h_t^2 \\
(4\pi)^2\beta_{\mu} &= \frac{3}{2}\,\mu\, Y_t^2 \\
(4\pi)^2\beta_{M_3} &= M_3\left(-18g_3^2 + G^2\right) \\
(4\pi)^2\beta_{M_U^2} &= M_U^2\left(\frac{8}{3}K + 4Y_t^2 + \frac{16}{3}G^2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

- Checked by the SUSY and SS limits

Higgs mass calculation

INPUTS:

- Experimental LE inputs
- Theoretical inputs
- Free parameters



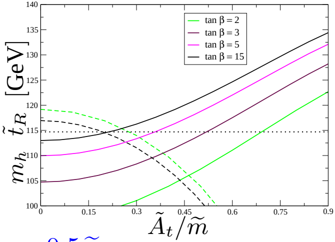
HIGGS MASS:

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



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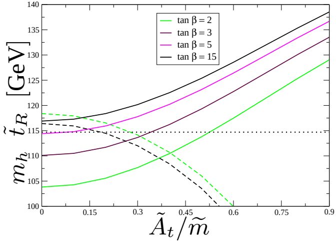
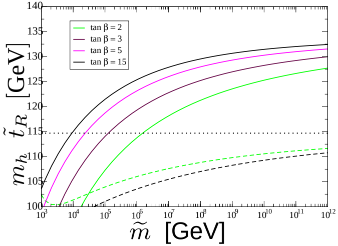


$\tilde{A}_t = 0.5\widetilde{m}$



$m_h \lesssim 133$ GeV

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

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

Why $M_U^2 < 0$? Basic idea [Carena et al.,96]

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

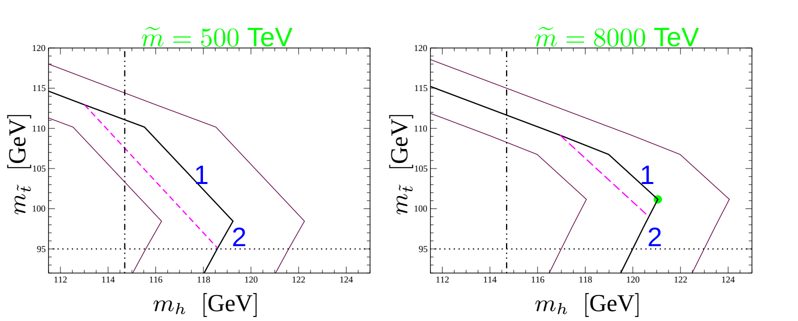
At $T \neq 0$ we consider the 2-loop effective potential in the LE theory taking into account only the effective couplings $\sim g_3, \lambda_t$.

$$\Downarrow$$

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 $T_h^c \geq T_{\tilde{t}}^c + 1.6$ 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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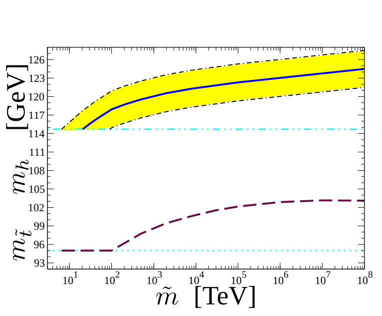

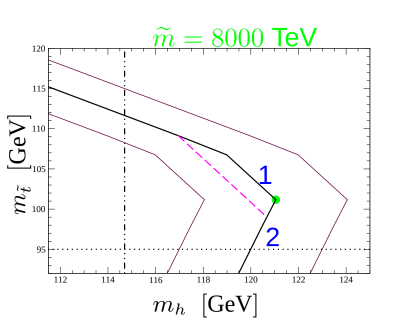

EWBG bounds (upper uncertainty):

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

$\tilde{m} \gtrsim 7$ TeV

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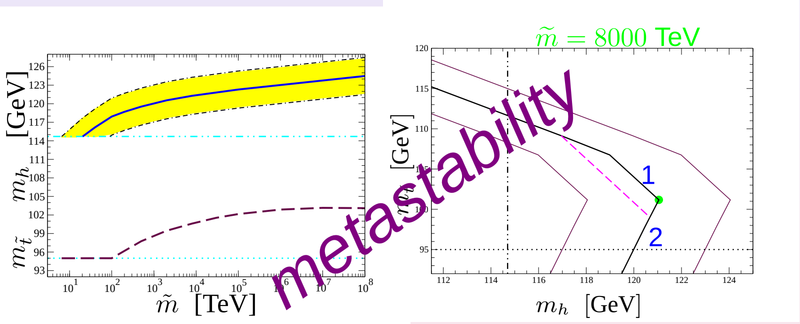

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Condition 1: $\tan\beta \leq 15$

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

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

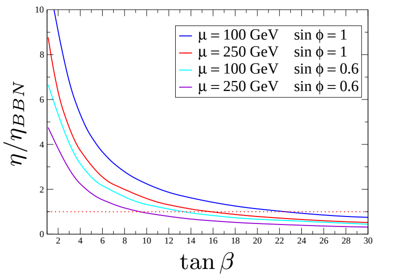
- BAU: fixing $\langle h\rangle_{T_n}/T_n = 1$ [Carena et al.,01]

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

$\Downarrow$

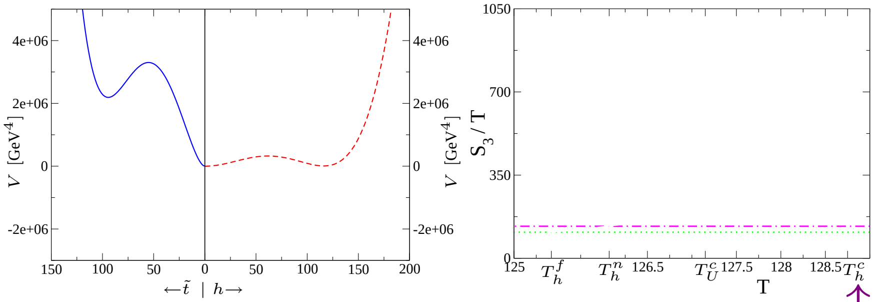
Good choice: $\tan\beta \leq 15$

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



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

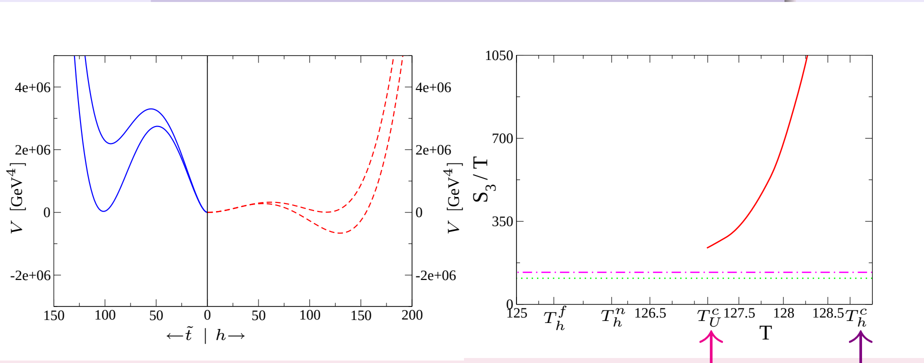
Nucl: $S_3/T \approx 135$ End: $S_3(T_f)/T_f \approx 110$



- At $T = T_c^{EWB} = 128.7\,\mathrm{GeV}$: $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite
-
-
-

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

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



- At $T = T_c^{EWB} = 128.7\,\text{GeV}$: $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite
- At $T = T_c^{CB} = 127.1\,\text{GeV}$: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite
-
-

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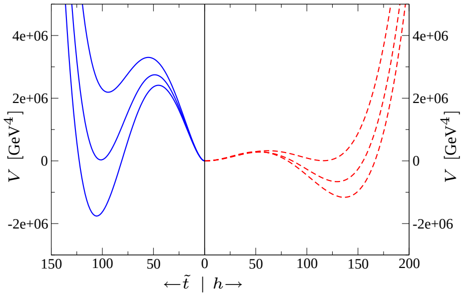

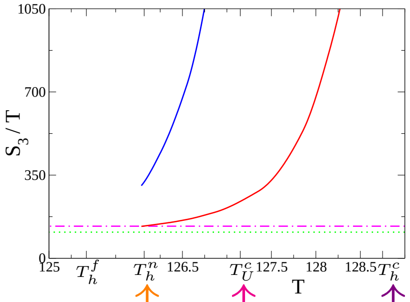

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-

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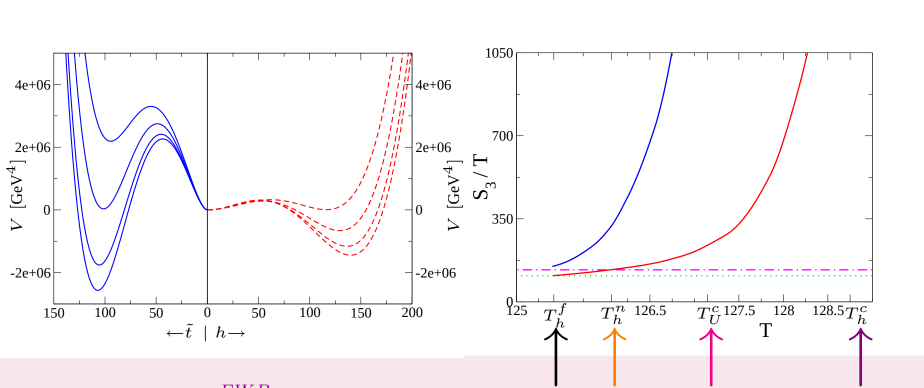

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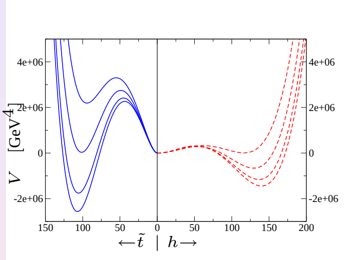
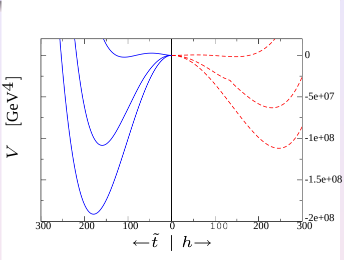
- At $T = T_f = 125.4\,\text{GeV}$: $S_{SP\to EWB} = 110$ and $S_{SP\to CB} > 135$

Metastability

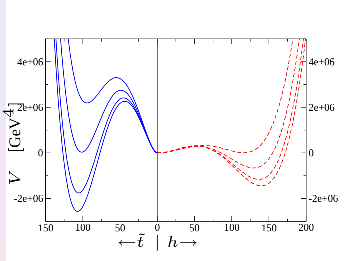
Is the transition EWB→CB possible ?

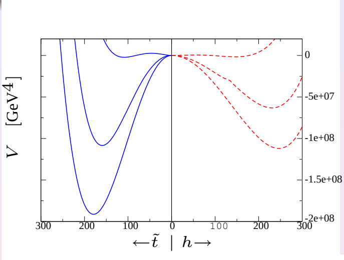




Metastability

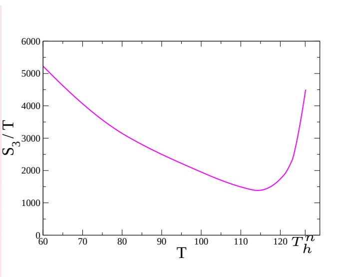
Is the transition EWB→CB possible ? NO





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

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?

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

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

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

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

m_Z

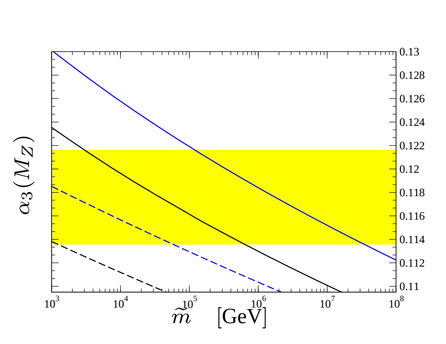
$\widetilde{m}$

M_{GUT}

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 first part

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 $m_h \lesssim 133$ 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.

Another possibility

If we are not able to modify the barrier of the Higgs effective potential...

...we try to change the nucleation temperature of the EWPT !

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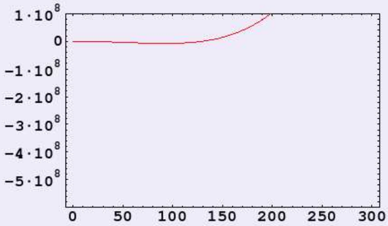
...if there would be a supercooling...

If supercooling is efficient, in the SM $\langle\phi(T)\rangle \to v$ when $T \ll T_{EWPT}$ and easily $\langle\phi(T)\rangle/T \gg 1$.

At one-loop with $m_H = 250GeV$, $T \simeq 305GeV$ and $\langle\phi(T)\rangle/T \sim 0.3$



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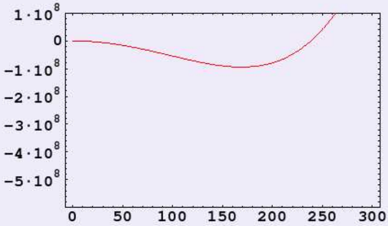
At one-loop with $m_H = 250GeV$, $T \simeq 250GeV$ and $\langle\phi(T)\rangle/T \sim 0.7$



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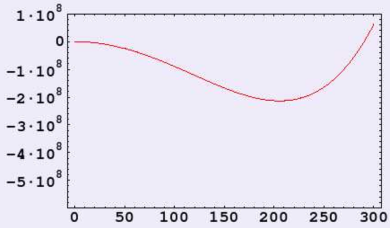
At one-loop with $m_H = 250GeV$, $T \simeq 200GeV$ and $\langle\phi(T)\rangle/T \sim 1$



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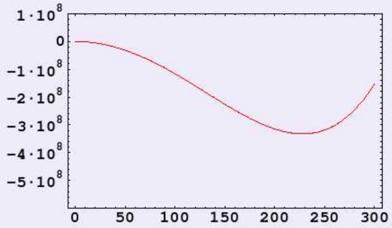
At one-loop with $m_H = 250GeV$, $T \simeq 150GeV$ and $\langle\phi(T)\rangle/T \sim 1.5$



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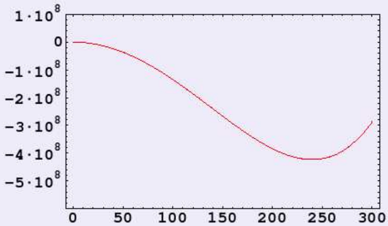
At one-loop with $m_H = 250 GeV$, $T \simeq 100 GeV$ and $\langle\phi(T)\rangle/T \sim 2.4$



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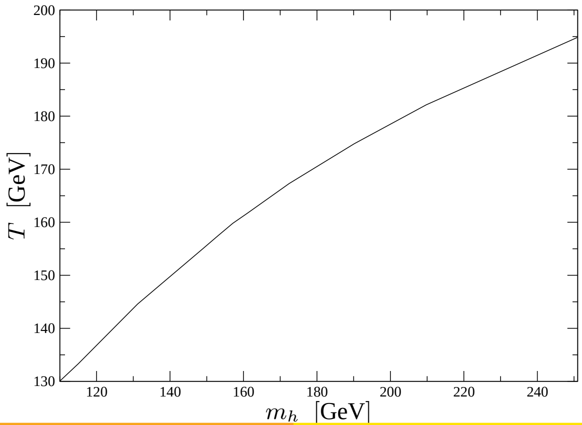

AdS-S/RS phase transition

Another possibility appears in warped spaces with the Higgs localized in the IR brane

- The radion $\mu(x)$ VEV which fixes the distance between the UV and IR branes will play a major role in the phase transition
- At high temperatures ($\mu \sim 0$) the space is AdS and the IR brane is replaced by a black hole horizon (AdS-S) [Witten,98]

AdS/CFT correspondence

At high T IR brane does not exist $\Leftrightarrow$ Deconfined (phase) Higgs [$\sim h$ does not exist]

- At temperature T_n ($\mu \neq 0$) the IR brane is nucleated from the horizon and the space is RS

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For earlier studies of the radion phase transition see [1]

Essential observation

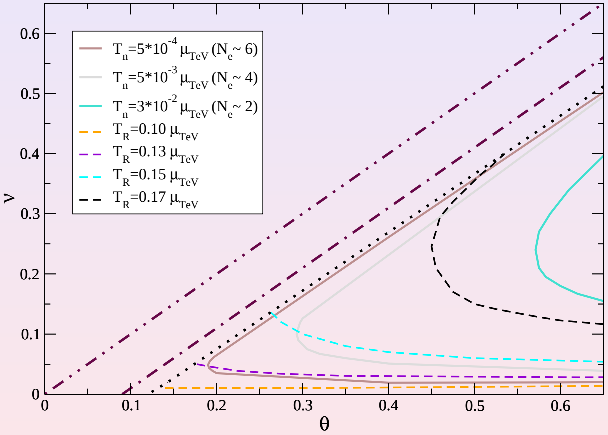
At the typical nucleation temperatures T_n the SM potential is a little perturbation of the radion potential and should not alter the bounce solution and the corresponding Euclidean action that governs the radion phase transition.

The radion potential has a large barrier and its transition transition is supercooled $T_n \ll T_c \lesssim \mu_{TeV}$.

Since $T_n < T_{EW}$, the Higgs "appears" when $\langle\phi(T)\rangle > T$. The EWPT is supercooled!

[1] Creminelli et al.,01; Randall et al.,06; Kaplan et al., 06.

Example: parameter region for N=3



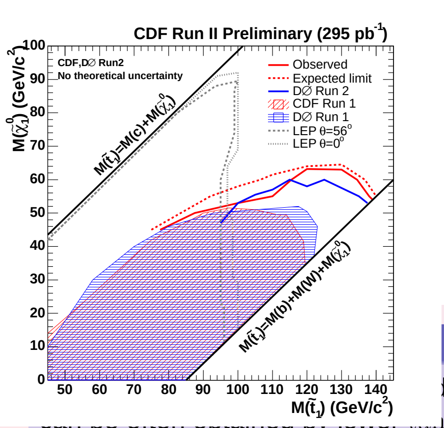
Conclusion second part

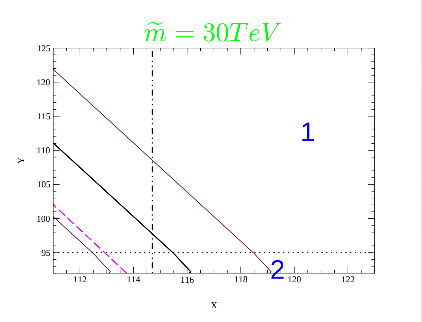
- Supercooling strenghtens the EWPT appreciably
- In RS (with GW) the EWPT is strong
- ...more details during the discussion of the next week or privately

Higgs-Stop window $\langle h \rangle_{T_c}/T_c > 1$ $(\mu = 100, M_3 = 500)$

Condt. 1: $\tan\beta \lesssim 10$ good for EDM and BAU.

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





to $m_h \approx 127$ GeV!!!

…low, but the same $(m_h, m_{\tilde t}, M_U^2)$ … β in a higher $\widetilde{m}$ scenario where only less important couplings are different

THANKS FOR
THE
ATTENTION