Strong Electroweak Phase Transition in the MSSM-like parameter space

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DESY THEORY WORKSHOP 2013

Based on:

M. Carena, G.N., M. Quirós, C.E.M. Wagner
arXiv:0806.4297; arXiv:0809.3760; arXiv:1207.6330.

M. Laine, G.N., K. Rummukainen
arXiv:1211.7344.

Outline

1. EWBG Introduction
2. MSSM Light Stop Scenario
3. EWPT and Baryogenesis at $m_h = 126$ GeV
   - 4d $T \neq 0$ eff. potential approach
   - 3d dimensionally reduced eff. potential
4. Conclusions
   - LHC and EWBG in the Light Stop Scenario

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 number?

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

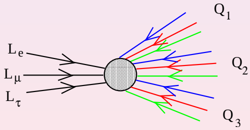
An answer: EWBG in the SM Kuzmin et al.,85; ...

Kuzmin, Rubakov and Shapshnikov, Phys.Lett.B155:36,1985;
....

Some EWBG reviews:
A. Riotto, hep-ph/9807454
M. Quirós, hep-ph/9901312
J. Cline, hep-ph/0609145
T. Konstandin, 1302.6713

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 violation
3. EWPT (when of 1^{st} order) proceeds by bubble nucleation. Expanding bubbles break the thermal equilibrium.



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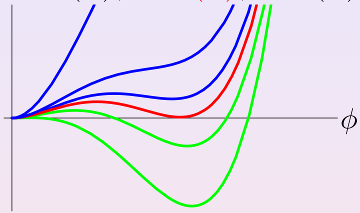
Kuzmin et al.,85; ...

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



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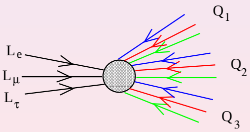

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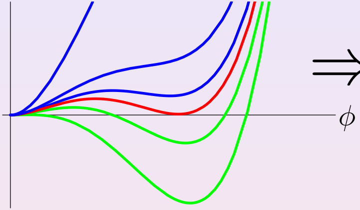
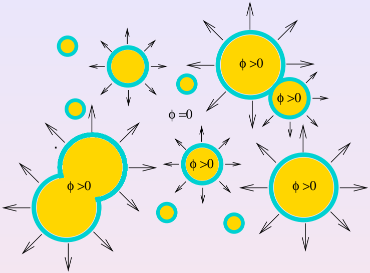
An answer: EWBG in the SM

Kuzmin et al.,85; ...

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



$\Rightarrow$



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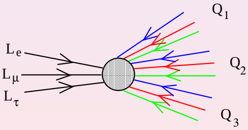

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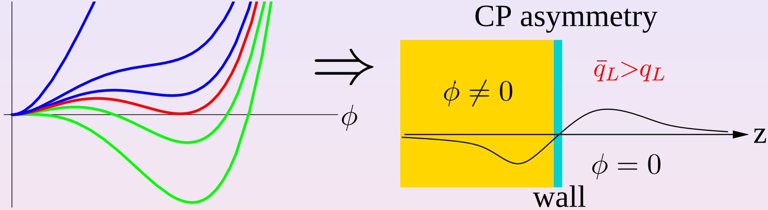

In front of the wall CP asymm. generates temporally $\bar{q}_L > q_L$
$\Rightarrow$ There are more sphalerons $B\uparrow$ than those $B\downarrow$
$\Rightarrow$ Temporally B asymm. is present beyond the wall $\Rightarrow$ The wall expansion accumulates $B > 0$ inside the bubble, where

If broken-phase sphalerons are in therm. equilibrium, $B \to 0$.
Otherwise *(strong EWPT)* WE HAVE PRODUCED $B \neq 0$.

An answer: EWBG in the SM

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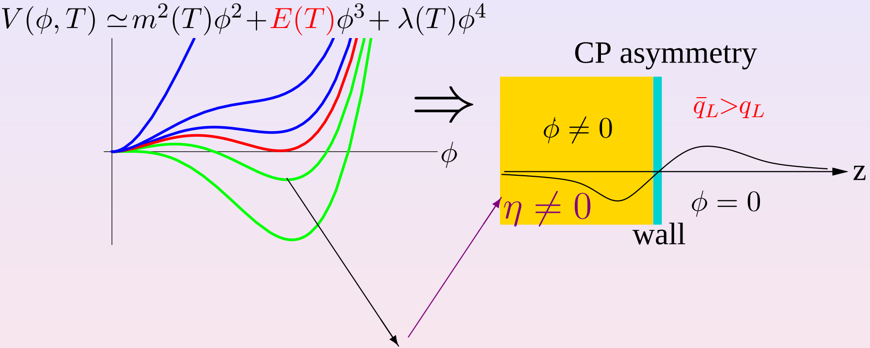


$$\frac{v(T_n)}{T_n} \gtrsim 1$$

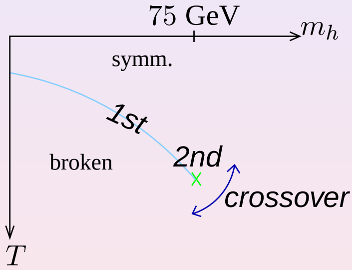
[with $v(T=0) = 246$ GeV]

Necessary requirement to have $\eta \neq 0$

Another answer: EWBG in the MSSM

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

[Kajantie et al.,97]



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

MSSM Light Stop Scenario

[Carena et al.,96;Delepine et al.,96; De Carlos et al.,97; Cline et al.,98; Carena et al.,98] showed that the Light Stop Scenario (LSS) is the most favorable MSSM framework to get a strong EWPT.

By the (4d) finite-temperature effective potential they found a MSSM parameter window (for $m_Q \sim 1$ TeV) where the EWPT is strongly first order when $m_h \lesssim 105$ GeV.

The same conclusion was reached in the (3d) dimensionally reduced effective theory by means of perturbation theory and lattice simulations [Laine,96; Losada,96; Cline et al.,98; Laine et al.,98].

KEY POINT: $M_U^2 < 0$! Why? [Carena et al.96;Delepine 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 the LSS right-handed stops can strengthen the EW transition. Its spurious cubic term appears as

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

$$\Downarrow$$

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

$$\Downarrow$$

Light Right-Handed Stop

$$m_{\tilde{t}_1} = \sqrt{M_U^2 + \frac{Q}{2}v^2} \sim \sqrt{M_U^2 + m_t^2} < m_t \quad \text{[for } A_t \sim 0\text{]}$$

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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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Requirement [Cline et al.99]:

$T_n^{\text{CB}} < T_f^{\text{EWB}} < T_n^{\text{EWB}}$ (no 2-step EWPT)

DELICATE PROBLEM

- Very very roughly: $v(T_n)/T_n \sim 2E/\lambda$ (to be precisely calculated numerically from $V(\phi, T)$)
- λ is very sensitive to m_h, which is sensitive to loop corrections
- $V(\phi, T_n)$ strongly depends on high loop corrections (e.g. HTL resummations are required)
- EWB and CB phase trans. compete $\Rightarrow$ precise calculation of $V(U_{\tilde{t}_R}, T)$ is needed
- In $V(U_{\tilde{t}_R}, T)$ the large α_s makes the potential less perturbative
- Any $V(T \neq 0)$ has non-perturbative infrared problems (at Landau scale) $\Rightarrow$ lattice simulations

Requirement [Cline et al.99]:

$$T_n^{\mathrm{CB}} < T_f^{\mathrm{EWB}} < T_n^{\mathrm{EWB}}$$ (no 2-step EWPT)

Strong EWPT at $m_h \simeq 126$ GeV?

For $A_t \ll m_Q$, $M_U^2 < 0$, $m_Q \sim 1$ TeV

the MSSM EWPT is strong at $m_h \lesssim 105$ GeV

For other MSSM parameter regions ($m_Q \gg 1$ TeV)

can we obtain a strong EWPT with $m_h \simeq 126$ GeV?

As in the past, we will answer by two approaches:

1. 4d finite-temperature eff. potential
   [Carena,GN,Quiros,Wagner 08;09;12]
2. 3d (dimensionally reduced) eff. theory + lattice simulations
   [Laine,GN,Rummukainen 12]

4d finite-temperature eff. potential

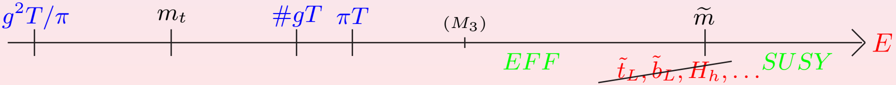
[Carena,GN,Quiros,Wagner 08;09;12]

4d $T \neq 0$ eff. potential [Carena,GN,Quiros,Wagner 08;09;12]

Optimal MSSM setting for EWBG:

- Fermions are at the EW scale (gluino a bit heavier)
- The $\tilde{t}_R$ is lighter than the top quark
- The other scalars $m_Q \simeq m_A \simeq ... \equiv \tilde{m} \gg few\ TeV$
- $A_t \ll m_Q$ (motivated by the strength of the EWPT)
- $\tan\beta \lesssim 15$ (motivated by EDM and BAU)

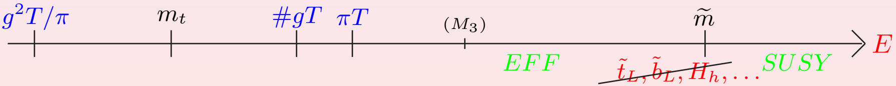
(A sort of light-stop scenario in SS)



4d $T \neq 0$ eff. potential [Carena,GN,Quiros,Wagner 08;09;12]

The $T = 0$ effective Lagrangian is

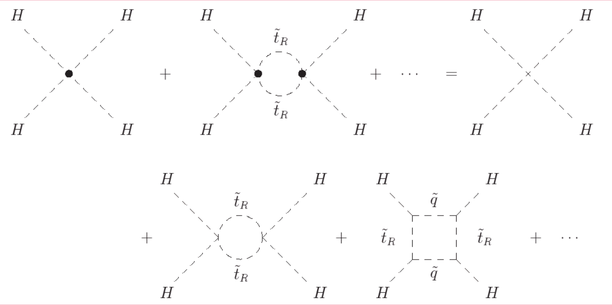
$$
\begin{aligned}
\mathcal{L}_{eff} = \; & m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - h_t \left[\bar{q}_L \epsilon H^* t_R\right] + Y_t \left[\bar{\tilde{H}}_u \epsilon q_L \tilde{t}_R^*\right] \\
& -\sqrt{2} G \, \Theta_{\tilde{g}} \, \tilde{t}_R \tilde{g}^a \overline{T}^a \bar{t}_R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

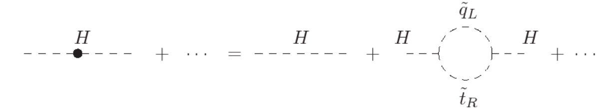


Matching conditions at $\widetilde{m}$

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

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

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

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

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

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

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

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

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

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

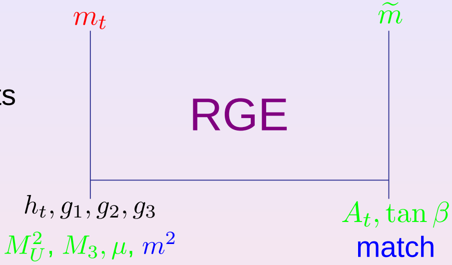
... and for the mass terms

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

Higgs mass calculation

INPUTS:

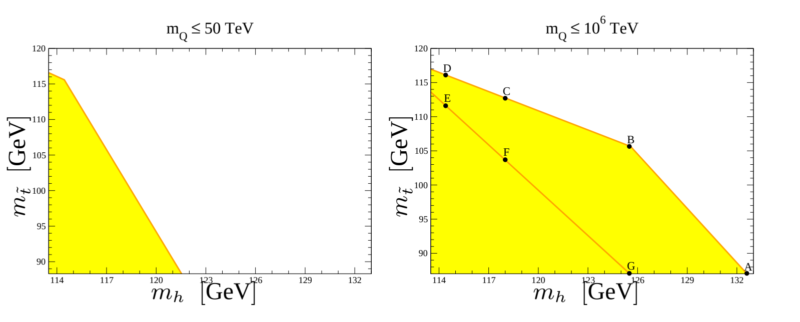
- Experimental LE inputs
- Theoretical inputs
- Free parameters



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-Stop window $\langle\phi(T_n)\rangle/T_n > 1$ ($\mu = 100, M_3 = 800$ GeV)



Based on effect. parameters. 2-loops $T \neq 0$ eff. pot. in the g_3, h_t approx

EWBG bounds (for $m_h \approx 126$ GeV):

$m_{\tilde{t}_L} \gg 50$ TeV $\qquad$ $m_{\tilde{t}_R} \lesssim 110$ GeV

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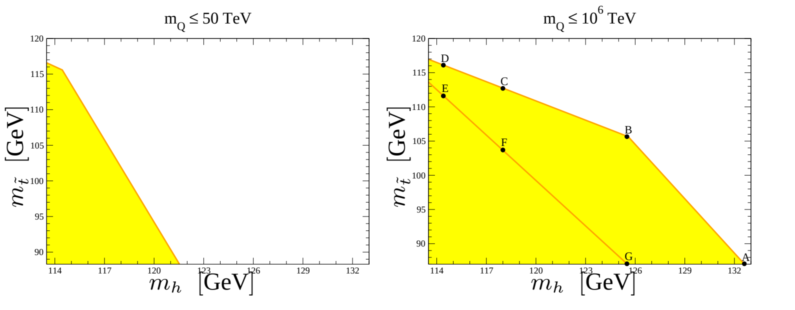
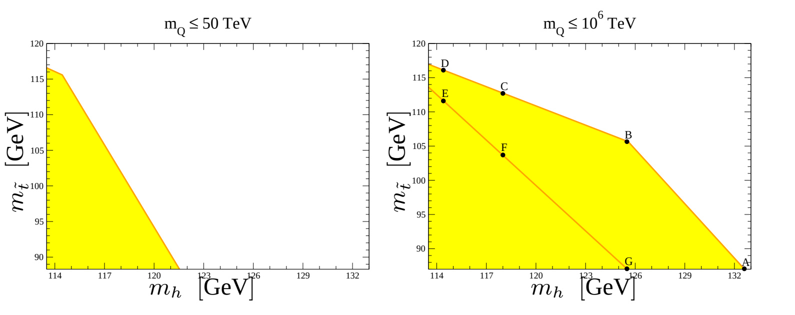


Key eff. parameters: $m_h, m_U^2, Q, \lambda, K$

Maybe LSS is the effective theory of non-MSSM and m_Q can be much smaller [A.Delgado,G.N.,M.Quiros,12]

Higgs-Stop window $\langle\phi(T_n)\rangle/T_n > 1$ $(\mu = 100, M_3 = 800$ GeV)



Point	A	B	C	D	E	F	G
$\vert A_t/m_Q\vert$	0.5	0	0	0	0.3	0.4	0.7
$\tan\beta$	15	15	2.0	1.5	1.0	1.0	1.0

3d dimensionally reduced eff. potential

[Laine,GN,Rummukainen 12]

3d dim. reduced eff. potential [Laine,GN,Rummukainen 12]

Conservative MSSM setting for EWBG:

- Fermions are at the EW scale (light gluino)
- The $\tilde{t}_R$ is lighter than the top quark
- The other scalars $m_Q \simeq m_L \simeq ... \equiv \tilde{m} \gg few\ TeV$ but $m_A = 150$ GeV
- $A_t \ll m_Q$ (motivated by the strength of the EWPT)
- $\tan\beta \lesssim 15$ (motivated by EDM and BAU)

(In blue the differences with the previous setting)

3d dim. reduced eff. potential [Laine,GN,Rummukainen 12]

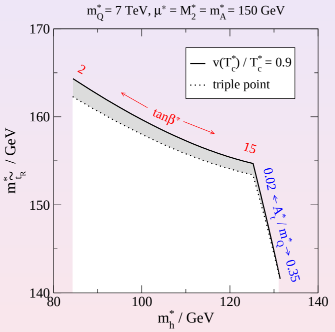
Procedure: [Laine 96, Losada 96, Laine et al. 99]

1. At $T = 0$ integration out heavy scalars (1-loop)
2. Dim. reduction matching 3d and 4d theories (1-loop).
3. Relation between 4d $\overline{MS}$ parameters and phys. observables ($\mu \approx T$, 1-loop)
4. Effect. potential in 3d theory (2-loop) / Lattice simulations

3d dim. reduced eff. potential [Laine,GN,Rummukainen 12]

Phase diagram from 2-loop eff. potential

- Strong EWPT at $m_h \approx 126$ GeV
- $m_{\tilde{t}_R} \approx 155$ GeV !!!
- UV uncertainties (is it MSSM ?)
- Band size strongly depends on K



Valid for any theory with similar $(m_U^2, Q, \lambda, K)_{3d}$

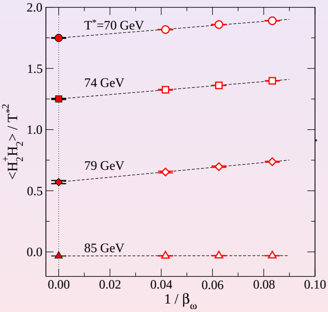
3d lattice simulations

[Laine,GN,Rummukainen 12]

Lattice spacings $\beta_w = 4/(g_w^2 Ta)$ and volumes

T dependence in the continuum limit

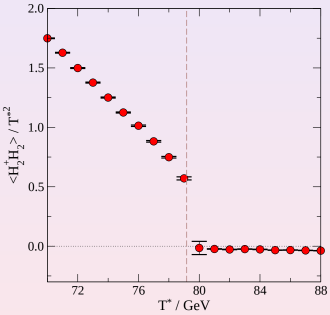
β_w	volumes
8	12^3, 16^3
10	16^3
12	16^3, 20^3, 32^3, $12^2 \times 36$, $20^2 \times 40$
14	24^3, $14^2 \times 42$, $24^2 \times 48$
16	24^3, $16^2 \times 48$, $20^2 \times 60$, $24^2 \times 72$
20	32^3, $20^2 \times 60$, $26^2 \times 72$, $32^2 \times 64$
24	24^3, 32^3, 48^3, $24^2 \times 78$, $30^2 \times 72$
30	48^3

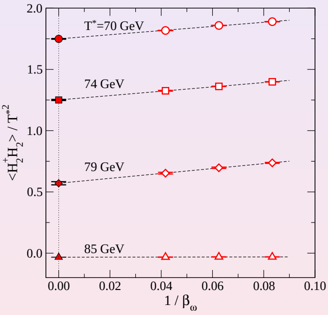


3d lattice simulations

[Laine,GN,Rummukainen 12]

Evolution	T dependence in the continuum limit

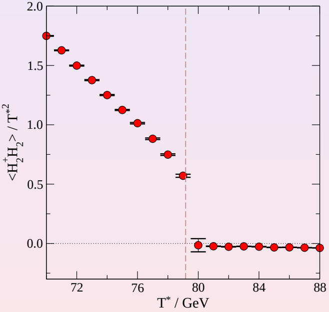


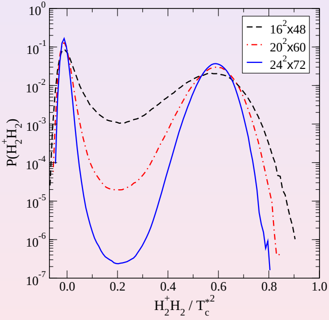


3d lattice simulations

[Laine,GN,Rummukainen 12]

Evolution	Lattice definition of T_c

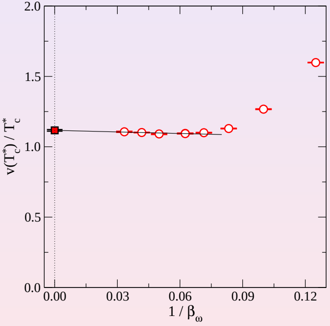


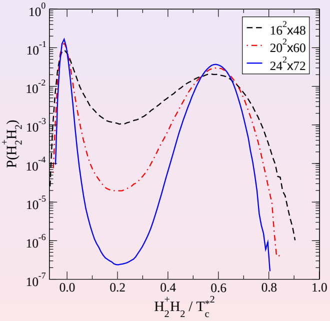


3d lattice simulations

[Laine,GN,Rummukainen 12]

Strength	Lattice definition of T_c





Comparison: $\left(\frac{v(T_c)}{T_c}\right)_{latt} = 1.12$ $\left(\frac{v(T_c)}{T_c}\right)_{pert} = 0.9$

3d lattice simulations

[Laine,GN,Rummukainen 12]

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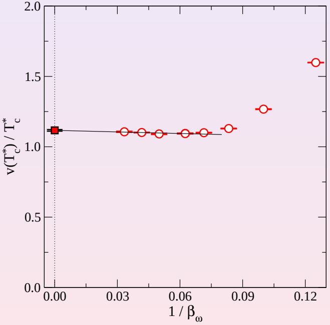
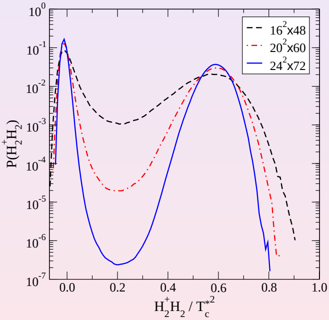




Comparison: $\left(\frac{v(T_c)}{T_c}\right)_{latt} = 1.12 \qquad \left(\frac{v(T_c)}{T_c}\right)_{pert} = 0.9$

Conclusions

We used two approaches:

1. 4d finite-temperature eff. potential
   +) Resum. large logs;
   -) Non-perturb. effects (magnetic scale, stop direction...);
2. 3d (dimensionally reduced) eff. theory + lattice simulations
   +) Non-perturb. effects included
   -) Large logs;

In both cases

there exists a parameter window providing strong EWPT with $m_h \simeq 126$ GeV (requirement to explain BAU via EWBG)

Conclusions

4d and 3d $T \neq 0$ perturbative calculation prove the existence of strong EWPT driven by stops in MSSM-like models

Lattice simulations show that perturbative calculations underestimate the EWPT strength

More work is needed to understand whether discrepancies (mostly absorbed into $m_{\tilde{t}_R}$) are only due to UV corrections

There exists a class of models having the considered 3d theory with strong EWPT at $m_{\tilde{t}_R} \approx 155$ GeV and $m_h \approx 126$ GeV

In this class of models the tension between EWBG and the LHC Higgs results is relaxed and there might be no (less) need of Higgs invisible width

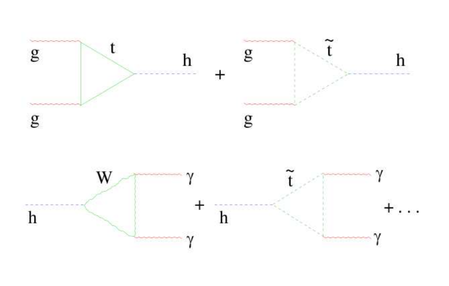
BACKUP

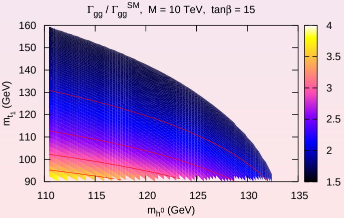
LSS and LHC

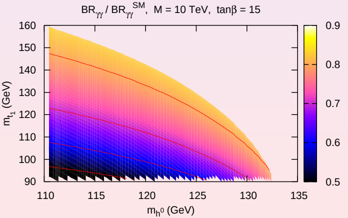
(in Higgs searches)

Stops in the Higgs searches [Menon et al.,09]

$\sigma(gg \to h^0)$ and $\Gamma(h^0 \to \gamma\gamma)$

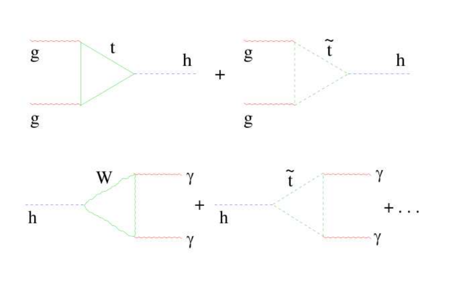


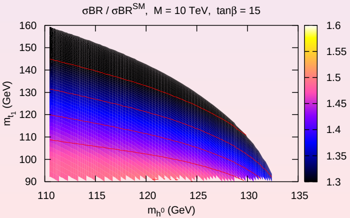




Stops in the Higgs searches [Menon et al.,09]

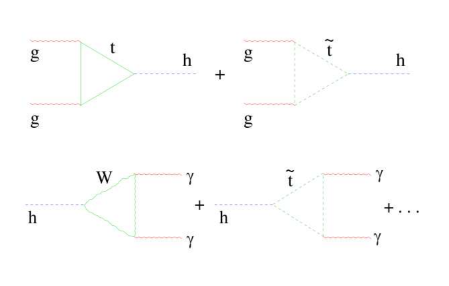
...and $\sigma(gg \to h^0) \times \Gamma(h^0 \to \gamma\gamma)$

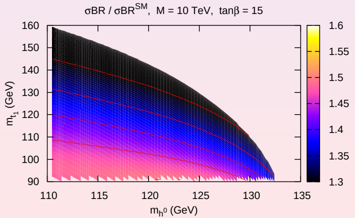




Stops in the Higgs searches [Menon et al.,09]

...and $\sigma(gg \to h^0) \times \Gamma(h^0 \to \gamma\gamma)$, BUT $\sigma(gg \to h^0) \times \Gamma(h^0 \to WW)$?





Stops in the Higgs searches [Curtin et al.,12, Cohen et al.,12]

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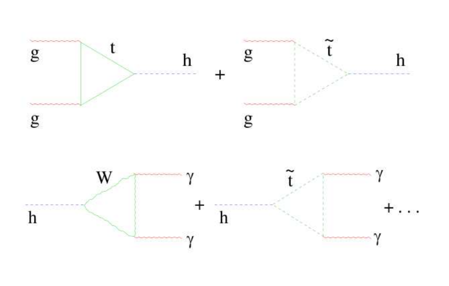
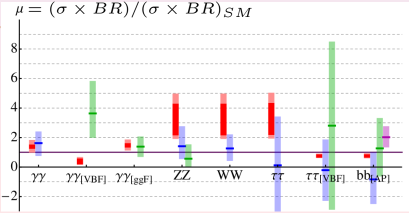


$A_t = 0$, $m_h = 125$ GeV
$80 < m_{\tilde{t}}/\text{GeV} < 115$
$\tan\beta = 15$
LHC data < 5 fb^{-1}



Stops and Light Neutralinos [Carena,G.N.,Quiros,Wagner,12]

Overproduction of weak boson vectors. Tension with data...
...but only under the assumption $\Gamma(h \to \mathrm{inv}) \simeq 0$!!!!

In the MSSM indeed $m_{\chi_1^0} < m_h/2 \Rightarrow \Gamma(h \to \mathrm{inv}) > 0$

$m_{\chi_1^0} \gtrsim \mathcal{O}(1\,GeV)$ is allowed [H.K. Dreiner et al.,09,12]

Lightest-Higgs invisible decay

$$\Gamma(h \to \chi_1^0 \chi_1^0) = \frac{G_F m_W^2}{2\sqrt{2}\pi}\, m_h \left(1 - \frac{4 m_{\chi_1^0}^2}{m_h^2}\right)^{3/2} g_{h11}^2$$

$$g_{h11} = (N_{12} - \tan\theta_W N_{11})(\sin\beta N_{1u} - \cos\beta N_{1d})$$

$\mathrm{BR}_{95\%\mathrm{CL}}(h \to \chi_1^0 \chi_1^0) \lesssim 0.85(0.65)$ [Djouadi et al.,12; Espinosa et. al.,12; atlas-conf-2012-170]

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Z invisible decay

$$\Gamma(Z \to \chi_1^0 \chi_1^0) = \frac{G_F}{\sqrt{2}\, 6\pi} m_Z^3 \left(1 - \frac{4 m_{\chi_1^0}^2}{m_Z^2}\right)^{3/2} g_{Z11}^2$$
$$g_{Z11} = \frac{1}{2}\left(|N_{1u}|^2 - |N_{1d}|^2\right)$$

$\Gamma_{95\%\mathrm{CL}}(Z \to \chi_1^0 \chi_1^0) \lesssim 0.5\,\text{MeV}$ [LEP]

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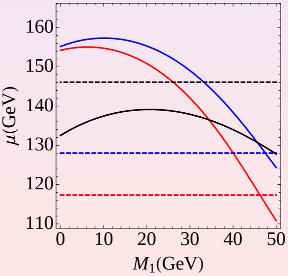
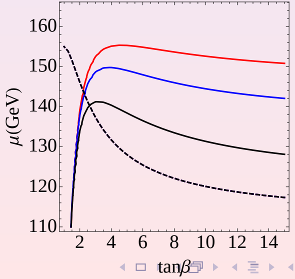
Z invisible decay

$M_2 = 200$ GeV, $\tan\beta = 15,5,2$



$M_2 = 200$ GeV, $M_1 = 20,30,40$ GeV



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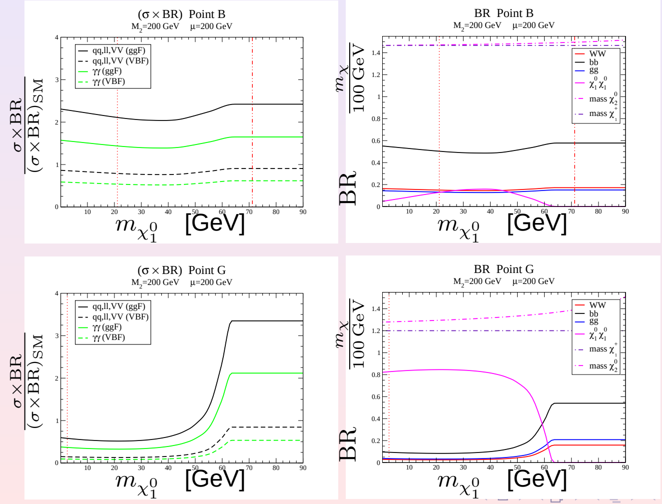

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Overproduction of weak boson vectors. Tension with data...
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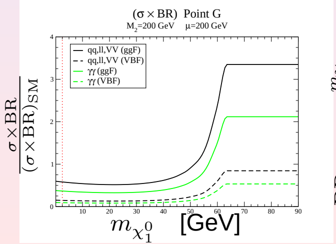
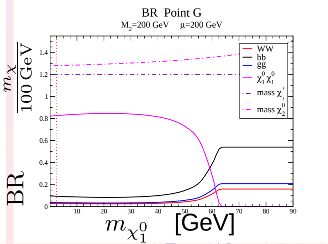
With light neutralino the LSS predictions are less restrictive

Some general predictions are still possible:

- The ratios between the LSS channels are (almost) invariant
- Diphoton channel through weak vector fusion is smaller than SM



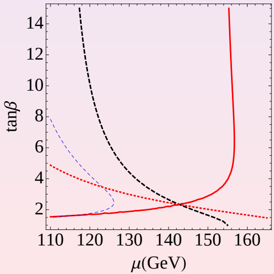


Light Neutralinos as DM [Carena,G.N.,Quiros,Wagner,12]

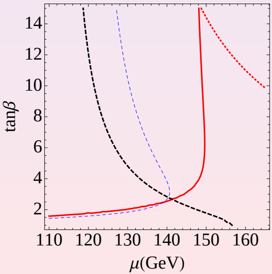
For $m_{\chi_1^0} = 35 - 40$ GeV and $g_{Z11} \approx 0.05$ lightest neutralino provides correct DM abundance [Menon et al.,04]. In such a case (with $M_2 = 200$ GeV) the LSS prediction is stronger:

$m_{\chi_1^+} > 95$ GeV $\quad \Gamma_{95\%\text{CL}}(Z \to \chi_1^0 \chi_1^0) \lesssim 0.5$ MeV

$M_1 = 55$ GeV



$M_1 = 40.6$ GeV



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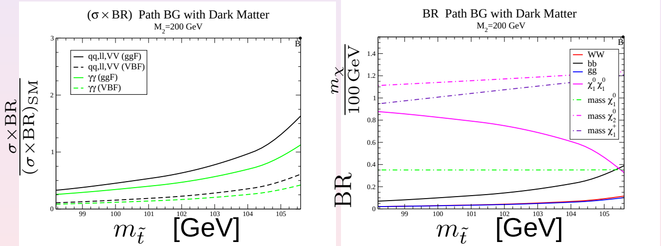


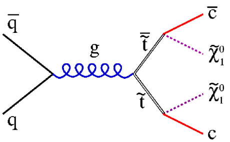
In this specific case LHC data favor $m_{\tilde{t}_R} \approx 104$ GeV

LSS and LHC

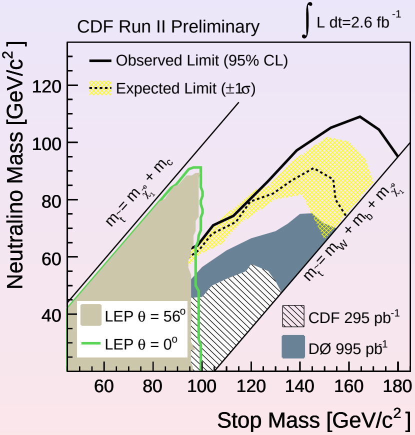
(in stop searches)

Looking for stops at LHC (with $m_{\chi_1^0} \gtrsim 65$ GeV)

- stop-neutralino coannihilation:



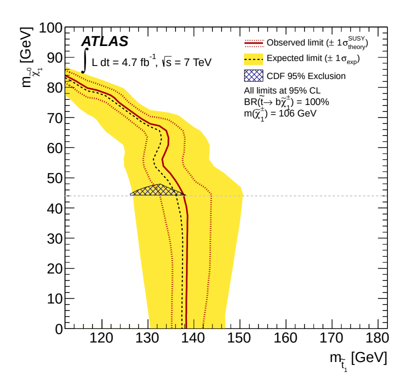
$$\Gamma_{\tilde{t}} \sim \frac{m_{\tilde{t}}}{16\pi^2} \mathcal{O}\left(\frac{m_t A_b}{m_Q^2}, \frac{m_t A_t}{m_Q^2}\right)$$

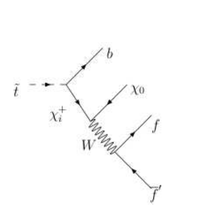


- light gluino (already disfavored by EWPT) are excluded

Looking for stops at LHC (with $m_{\chi_1^0} < 65$ GeV)

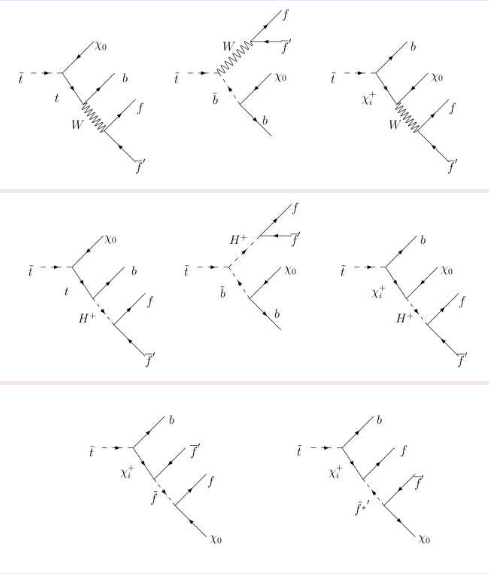
- on-shell chargino $m_{\chi_1^+} = 106$ GeV, 2 opposite-sign e/μ events $\tilde{t} \to b\chi_0^+ (W^* \chi_1^0)$ [arXiv:1208.4305]:





But in the LSS, charginos are typically off-shell ($m_{\tilde{t}} < m_{\chi_1^+}$)

Looking for stops at LHC (with $m_{\chi_1^0} < 65\,$GeV)



Looking for stops at LHC (model dependent)

For $m_{\chi_1^+} < m_{\tilde{t}_R}$:

- $\tilde{t} \to b\chi_1^+(W\chi_1^0)$ rules out $m_{\tilde{t}_R} \lesssim 130\#$ GeV
- $\tilde{t} \to b\chi_1^+(\tau\nu_\tau\chi_1^0)$ (via light $\tilde{\tau}/\tilde{\nu}_\tau$) Allowed

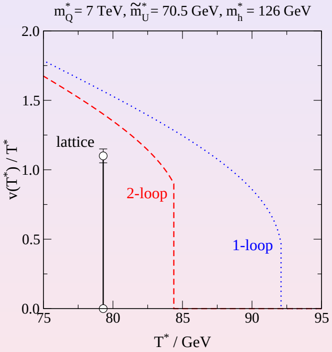
For $m_{\chi_1^+} > m_{\tilde{t}_R}$:

- as above but with χ_1^+ off-shell. Allowed
- $\tilde{t} \to c\chi_1^0$ (disfavored by Higgs searches)

If different channels have similar widths, more difficult

Open questions (1)

In lattice simulations the phase transition is stronger than in perturbation theory [Laine,GN,Rummukainen, to appear]

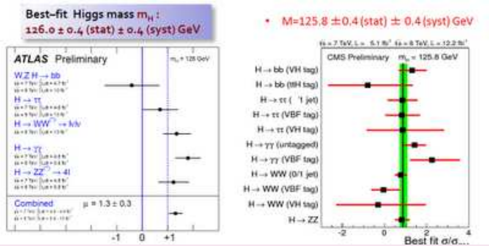


The stop mass seems to be much larger.
Smaller departure from the SM Higgs rates.

Open questions (2)

In UV extensions of the MSSM including triplet $Y = \pm 1$ (and a mixture of gauge mediation and gravity mediation), it is possible to reproduce the LSS at low energy. It alleviates the hierarchy problem and enhances the diphoton decay channel (there are extra gauginos)[Delgado,GN,Quiros, arXiv:1201.5164, arXiv:1207.6596]

Can it qualitatively modify the tension between the LSS and LHC data?


Best-fit Higgs mass m_H :
126.0 ± 0.4 (stat) ± 0.4 (syst) GeV
ATLAS Preliminary
W,Z H → bb
H → ττ
H → WW → lνlν
H → γγ
H → ZZ → 4l
Combined
μ = 1.3 ± 0.3
-1
0
+1
M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV
CMS Preliminary
H → bb (VH tag)
H → bb (ttH tag)
H → ττ (VBF tag)
H → ττ (VH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ZZ
-2
0
2
4

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

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

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

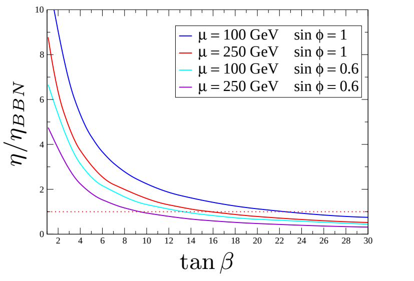
- BAU: fixing $\langle h \rangle_{T_n}/T_n = 1$ [Carena et al.,01]

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

$\Downarrow$

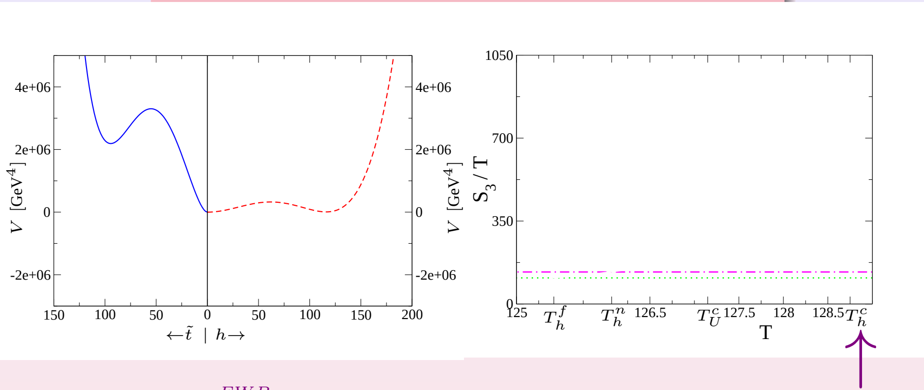
Good choice: $\tan\beta \leq 15$

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

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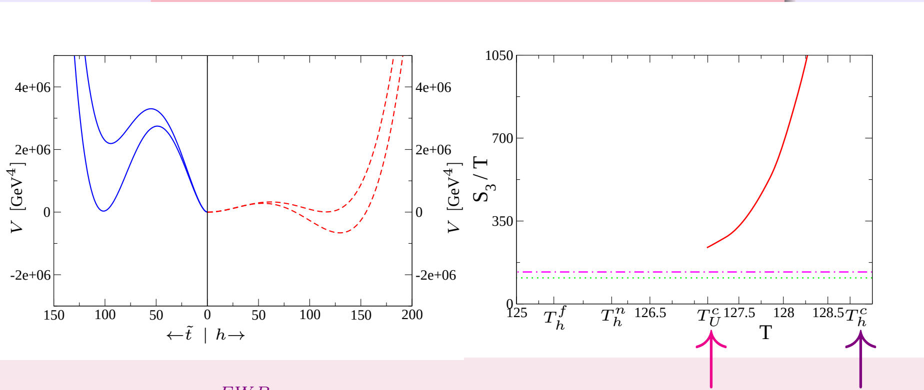

- At $T = T_c^{EWB} = 128.7$ GeV: $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite
- At $T = T_c^{CB} = 127.1$ GeV: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite

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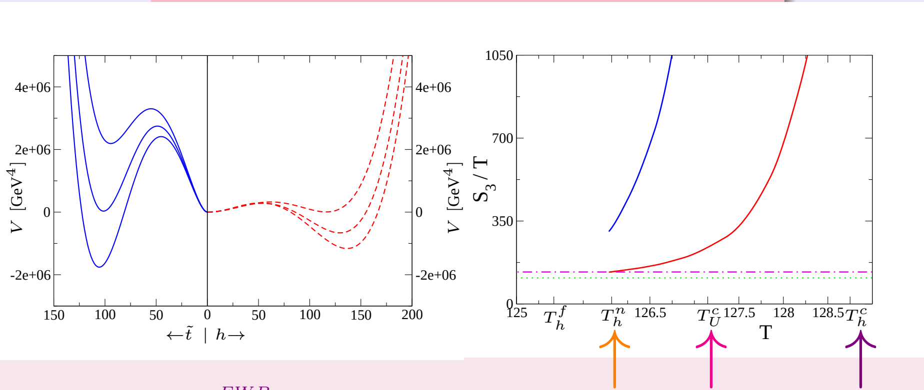
Nucl: $S_3/T \approx 135$ End: $S_3(T_f)/T_f \approx 110$



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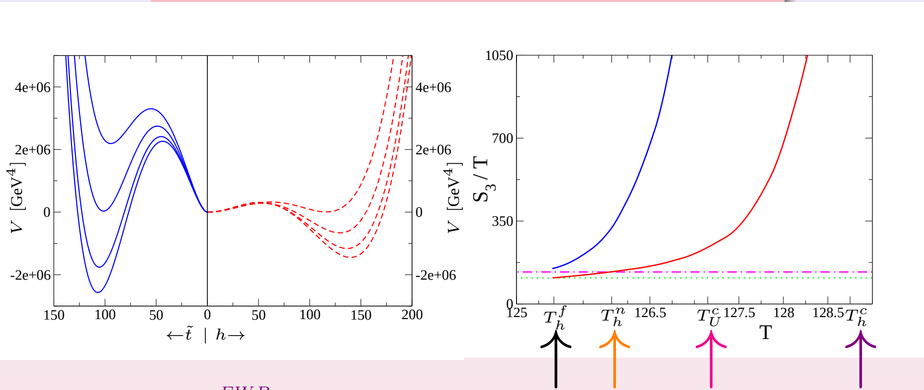
- At $T = T_c^{CB} = 127.1\,\text{GeV}$: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite
- At $T = T_n = 126.0\,\text{GeV}$: $S_{SP\to EWB} = 135$ and $S_{SP\to CB}$ too large
-

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

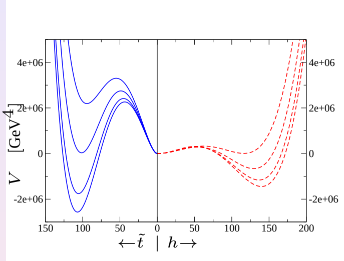
Nucl: $S_3/T \approx 135$ End: $S_3(T_f)/T_f \approx 110$

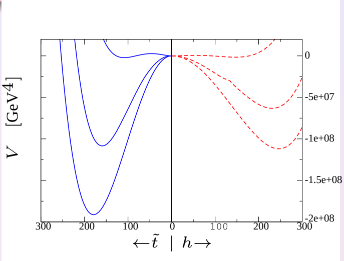


- At $T = T_c^{EWB} = 128.7\,\text{GeV}$: $S_{SP\to EWB}$ and $S_{SP\to CB}$ are infinite
- At $T = T_c^{CB} = 127.1\,\text{GeV}$: $S_{SP\to CB}$ too large and $S_{SP\to CB}$ infinite
- At $T = T_n = 126.0\,\text{GeV}$: $S_{SP\to EWB} = 135$ and $S_{SP\to CB}$ too large
- At $T = T_f = 125.4\,\text{GeV}$: $S_{SP\to EWB} = 110$ and $S_{SP\to CB} > 135$

Metastability

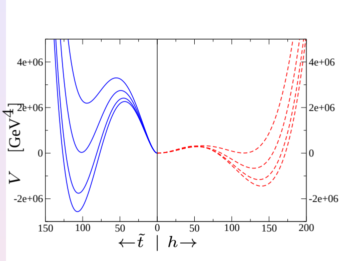
Is the transition EWB→CB possible ?

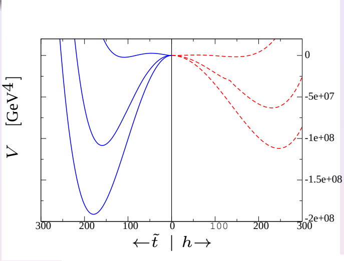




Metastability

Is the transition EWB→CB possible ? NO





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

IT DOESN'T DECAY !