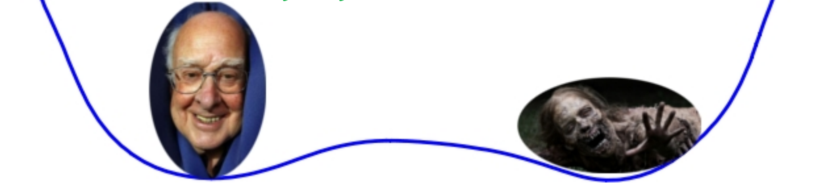
To Higgs or not to Higgs

vacuum stability beyond the Standard Model



Wolfgang Gregor Hollik

DESY Hamburg, Theory Group

Nov 11 2016 | LHC Discussion @ DESY Hamburg

The Standard Model (In)Stability

$$V_{\mathsf{SM}} = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H \right)^2$$

- large field values: $V \sim \lambda (H^\dagger H)^2$
- RGE: $\lambda \to \lambda(Q)$, where $Q \sim H$
- $\lambda \to 0$ around $Q \sim 10^{10}\,\mathrm{GeV}$, new minimum beyond M_{Planck}

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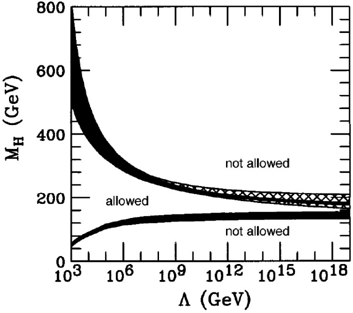
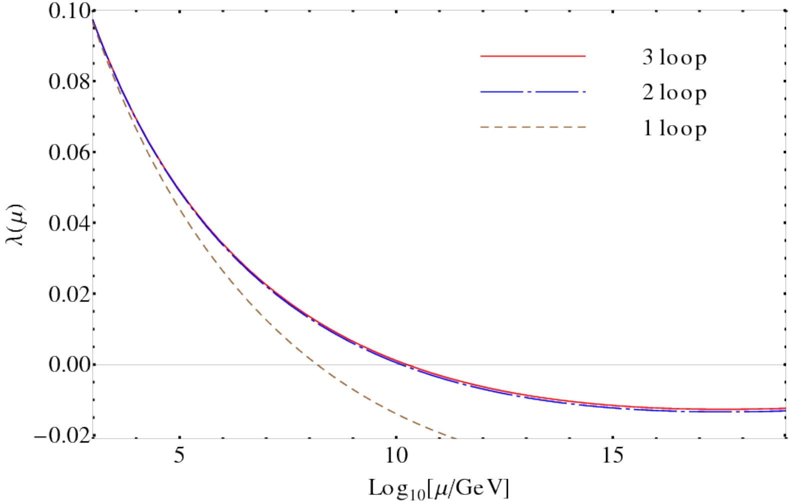


[Hambye, Riesselmann '97]

Precise analysis: up to three loops!



[Zoller 2014]

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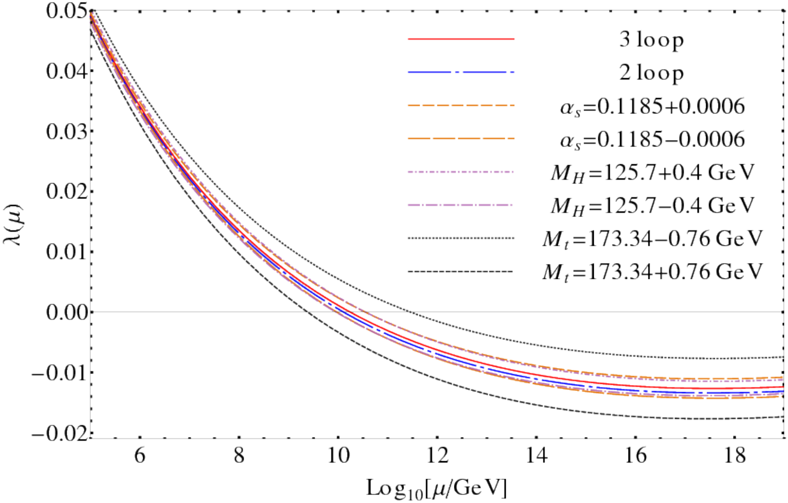

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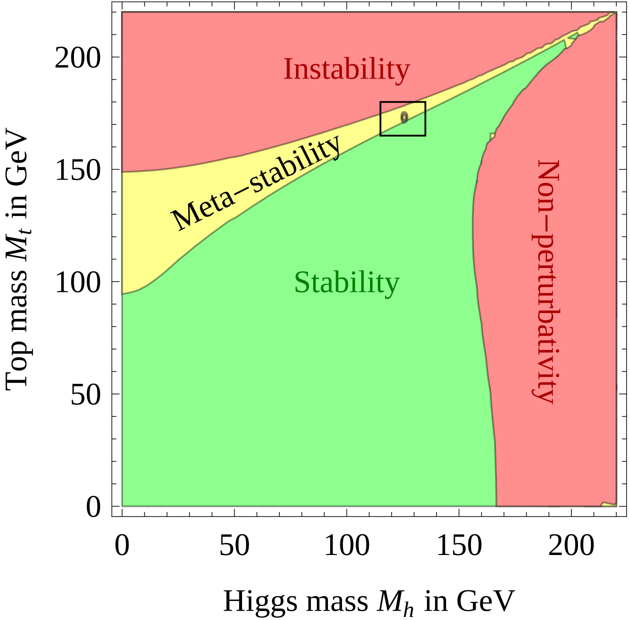
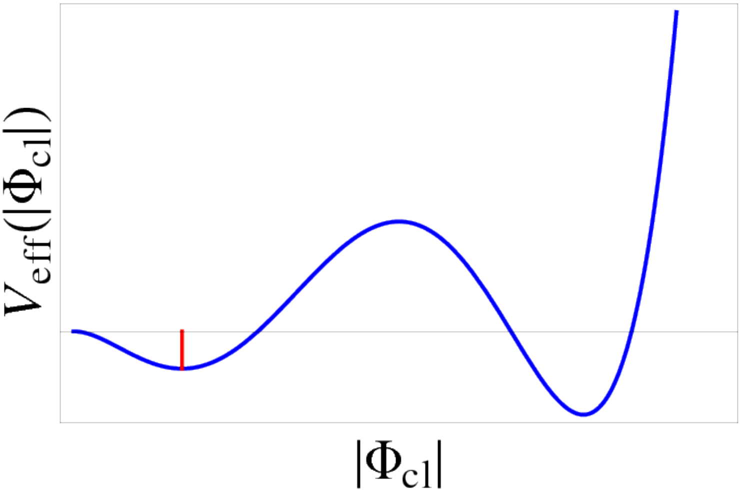


[Degrassi et al. JHEP 1208 (2012) 098]

Stability, instability or metastability?



[Courtesy of Max Zoller]

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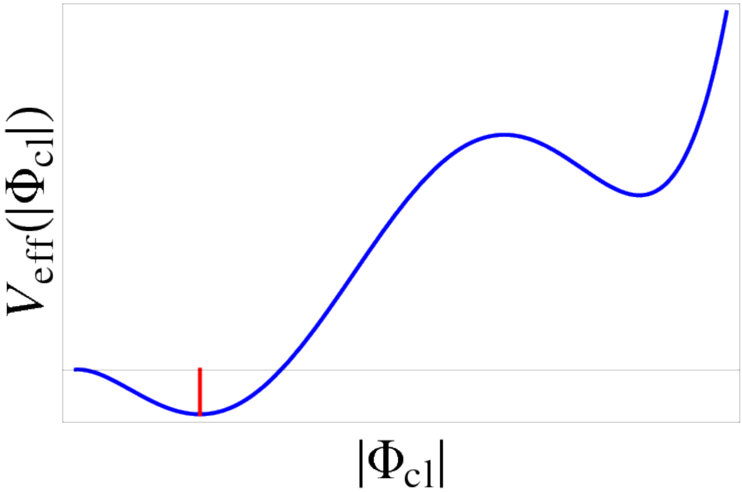

[Courtesy of Max Zoller]

Metastability of the Standard Model

- $m_h = 125\,\mathrm{GeV}$: metastable electroweak vacuum
- metastability: decay time of false vacuum large
- instability scale around $10^{10\ldots12}\,\mathrm{GeV}$
- SM sufficiently stable
- neutrino masses missing

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Task: Do not introduce further instabilities!
(generically difficult)

A multi-scalar theory

- 2 Higgs doublets
- 2×6 scalar quarks, $6 + 3$ scalar leptons
- 12 colored and 18 + 2 charged directions
- charged Higgs directions "safe" [Casas et al. 1996]
- SM Higgs potential: $\mathrm{SO}(4)$ symmetry

- large couplings to Higgs doublets (y_t and y_b comparably large)
- large stop contribution (X_t, A_t) to light Higgs mass needed
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$$m_{h^0}^2 \simeq m_Z^2 + \frac{3m_t^2}{2\pi^2 v^2}\left[\ln\left(\frac{M_S^2}{m_t}^2\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{6M_S^2}\right)\right]$$

The tree-level scalar potential

$$
\begin{aligned}
V_{\tilde{q},h} = & \,\tilde{t}_L{}^* \left(\tilde{m}_L^2 + |y_t h_2|^2\right) \tilde{t}_L + \tilde{t}_R{}^* \left(\tilde{m}_t^2 + |y_t h_2|^2\right) \tilde{t}_R \\
& + \tilde{b}_L{}^* \left(\tilde{m}_L^2 + |y_b h_1|^2\right) \tilde{b}_L + \tilde{b}_R{}^* \left(\tilde{m}_b^2 + |y_b h_1|^2\right) \tilde{b}_R \\
& - \left[\tilde{t}_L{}^* \left(\mu^* y_t \, h_1{}^* - A_t h_2\right) \tilde{t}_R + \text{h.c.}\right] \\
& - \left[\tilde{b}_L{}^* \left(\mu^* y_b \, h_2{}^* - A_b h_1\right) \tilde{b}_R + \text{h.c.}\right] \\
& + |y_t|^2 |\tilde{t}_L|^2 |\tilde{t}_R|^2 + |y_b|^2 |\tilde{b}_L|^2 |\tilde{b}_R|^2 \\
& + \frac{g_1^2}{8} \left(|h_2|^2 - |h_1|^2 + \frac{1}{3}|\tilde{b}_L|^2 + \frac{2}{3}|\tilde{b}_R|^2 + \frac{1}{3}|\tilde{t}_L|^2 - \frac{4}{3}|\tilde{t}_R|^2\right)^2 \\
& + \frac{g_2^2}{8} \left(|h_2|^2 - |h_1|^2 + |\tilde{b}_L|^2 - |\tilde{t}_L|^2\right)^2 \\
& + \frac{g_3^2}{8} \left(|\tilde{t}_L|^2 - |\tilde{t}_R|^2 + |\tilde{b}_L|^2 - |\tilde{b}_R|^2\right)^2 \\
& + (m_{h_2}^2 + |\mu|^2)|h_2|^2 + (m_{h_1}^2 + |\mu|^2)|h_1|^2 - 2\,\text{Re}(B_\mu \, h_1 h_2).
\end{aligned}
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& - \left[\tilde{b}\ ^*(\mu^* y_b\ h_2{}^* - A_b h_1)\,\tilde{b}\ \ + \mathrm{h.c.}\right] \\
& + |y_t|^2|\tilde{t}\ \ |^2|\tilde{t}\ \ |^2 + |y_b|^2|\tilde{b}\ \ |^2|\tilde{b}\ \ |^2 \\
& + \frac{g_1^2}{8}\left(|h_2|^2 - |h_1|^2 + \ \ |\tilde{b}\ \ |^2 \qquad - \ \ |\tilde{t}\ \ |^2 \qquad \right)^2 \\
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$$V_{\tilde{q},h} = {\phi_2}^* \left(\tilde{m}_L^2 + |y_t\phi_2|^2\right)\phi_2 + {\phi_2}^* \left(\tilde{m}_t^2 + |y_t\phi_2|^2\right)\phi_2$$
$$+{\phi_1}^* \left(\tilde{m}_L^2 + |y_b\phi_1|^2\right)\phi_1 + {\phi_1}^* \left(\tilde{m}_b^2 + |y_b\phi_1|^2\right)\phi_1$$
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$$-\left[{\phi_1}^* \left(\mu^* y_b\, {\phi_2}^* - A_b\phi_1\right)\phi_1 + \mathrm{h.c.}\right]$$
$$+|y_t|^2|\phi_2|^2|\phi_2|^2 + |y_b|^2|\phi_1|^2|\phi_1|^2$$

$$+(m_{h_2}^2 + |\mu|^2)|\phi_2|^2 + (m_{h_1}^2 + |\mu|^2)|\phi_1|^2 - 2\,\mathrm{Re}(B_\mu\, \phi_1\phi_2).$$

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$$+ (m_{h_2}^2 + |\mu|^2)|\phi_2|^2 \qquad .$$

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Minimize the potential

$$V(\phi) = m^2\phi^2 - A\phi^3 + \lambda\phi^4,$$

with $m^2 = m_{h_2}^2 + |\mu|^2 + \tilde{m}_L^2 + \tilde{m}_t^2$, $A = -A_t$ and $\lambda = 3y_t^2$.

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Answer:

$$\phi_0 = 0, \qquad \phi_\pm = \frac{3A \pm \sqrt{9A^2 32\lambda\, m^2}}{8\lambda}.$$

Condition to be safe from non-standard (i.e. non-trivial) minima:

$$V(\phi_\pm) > 0 \quad \hookrightarrow \quad m^2 > \frac{A^2}{4\lambda}$$

Mathematics for the kindergarden

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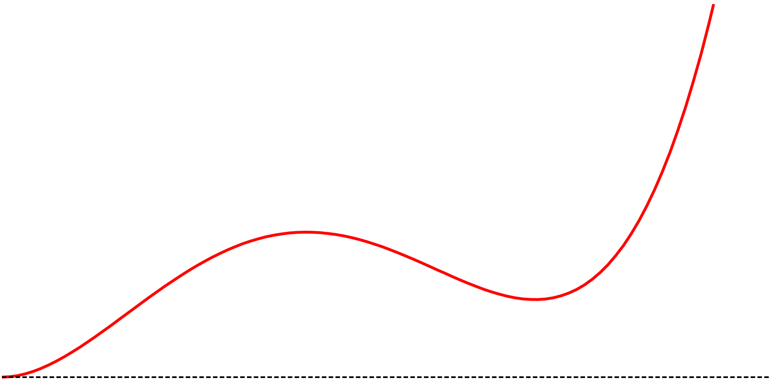
Well-known constraints [Gunion, Haber, Sher '88]

$$|A_t|^2 < 3y_t^2\left(m_{h_2}^2 + |\mu|^2 + \tilde{m}_L^2 + \tilde{m}_t^2\right)$$
$$|A_b|^2 < 3y_b^2\left(m_{h_1}^2 + |\mu|^2 + \tilde{m}_L^2 + \tilde{m}_b^2\right)$$

for the limiting cases $|\tilde{t}_L| = |\tilde{t}_R| = |h_2|$ and $|\tilde{b}_L| = |\tilde{b}_R| = |h_1|$!

$A^2 < 4\lambda m^2$



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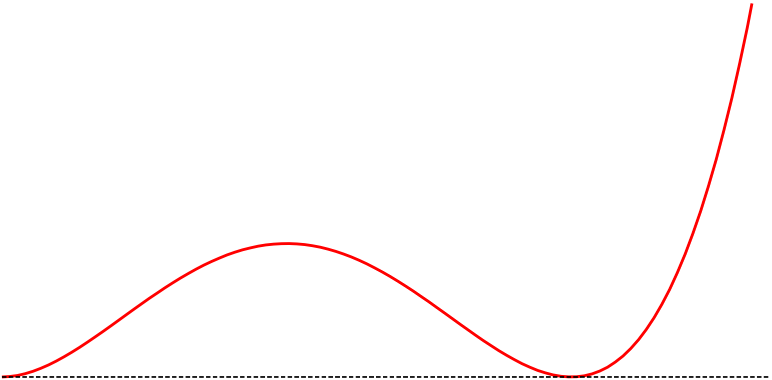

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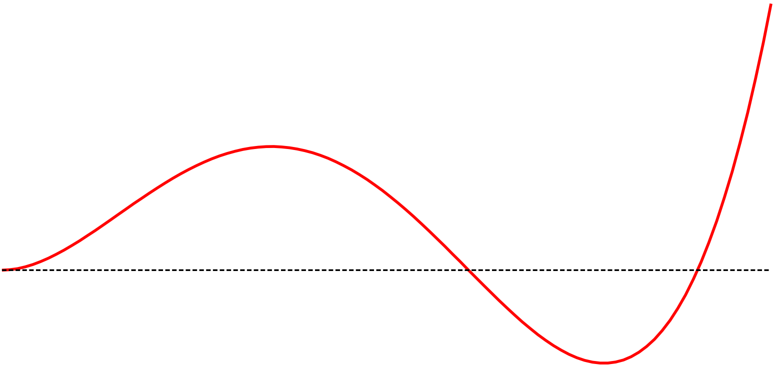

$$h_2 = \phi, \qquad |\tilde{t}| = \alpha|\phi|, \qquad h_1 = \eta\phi, \qquad |\tilde{b}| = \beta|\phi|$$

$$\begin{aligned} V_\phi =& \Big(m_{h_2}^2 + \eta^2 m_{h_1}^2 + (1+\eta^2)\mu^2 - 2B_\mu \eta \\ & \qquad + (\alpha^2+\beta^2)\tilde{m}_L^2 + \alpha^2 \tilde{m}_t^2 + \beta^2 \tilde{m}_b^2\Big)\phi^2 \\ & - 2\left(\alpha^2(\mu y_t \eta - A_t) + \beta^2(\mu y_t - \eta A_b)\right)\phi^3 + (\alpha^2 y_t^2 + \beta^4 y_b^2)\phi^4 \\ & + \left(\frac{g_1^2+g_2^2}{8}(1-\eta^2+\beta^2-\alpha^2)^2 + 2\alpha^2 y_t^2 + 2\beta^2 y_b^2\right)\phi^4 \\ \equiv & \boldsymbol{M^2(\eta,\alpha,\beta)\phi^2 - \mathcal{A}(\eta,\alpha,\beta)\phi^3 + \lambda(\eta,\alpha,\beta)\phi^4}, \end{aligned}$$

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with

$$\begin{aligned} M^2 =& \; m_{h_2}^2 + \eta^2 m_{h_1}^2 + (1+\eta^2)\mu^2 - 2B_\mu\eta \\ &+ (\alpha^2+\beta^2)\tilde{m}_L^2 + \alpha^2\tilde{m}_t^2 + \beta^2\tilde{m}_b^2\,, \\ \mathcal{A} =& \; 2\alpha^2\eta\mu y_t - 2\alpha^2 A_t + 2\beta^2\mu y_b - 2\eta\beta^2 A_b\,, \\ \lambda =& \; \frac{g_1^2+g_2^2}{8}(1-\eta^2+\beta^2-\alpha^2)^2 \\ &+ (2+\alpha^2)\alpha^2 y_t^2 + (2\eta^2+\beta^2)\beta^2 y_b^2\,. \end{aligned}$$

[Gunion, Haber, Sher '88; Casas, Lleyda, Muñoz '96]

The same but different ("A-parameter bounds")

$$\mathcal{A}^2 < 4\lambda M^2$$

$$\downarrow$$

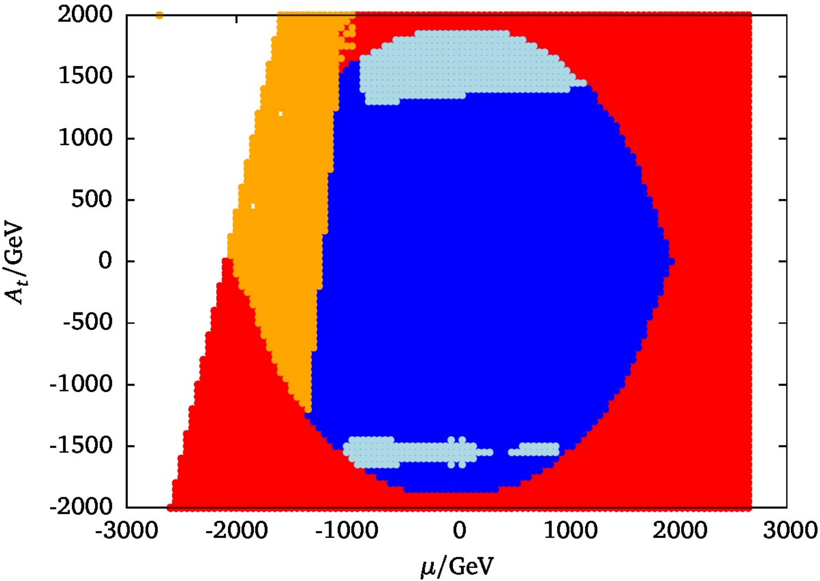
$$4 \min_{\{\eta,\alpha,\beta\}} \lambda(\eta,\alpha,\beta) M^2(\eta,\alpha,\beta) > \max_{\{\eta,\alpha,\beta\}} \left(\mathcal{A}(\eta,\alpha,\beta)\right)^2$$

$h_u = \tilde{b}$, $h_d^0 = 0$ [WGH'15]

$$m_{H_u}^2 + \mu^2 + \tilde{m}_Q^2 + \tilde{m}_b^2 > \frac{(\mu y_b)^2}{y_b^2 + (g_1^2 + g_2^2)/2}$$

$|h_d|^2 = |h_u|^2 + |\tilde{b}|^2$, $\tilde{b} = \alpha h_u$ [WGH'15]

$$m_{11}^2(1+\alpha^2) + m_{22}^2 \pm 2m_{12}^2\sqrt{1+\alpha^2} + \alpha^2(\tilde{m}_Q^2 + \tilde{m}_b^2) > \frac{4\mu^2\alpha^2}{2+3\alpha^2}$$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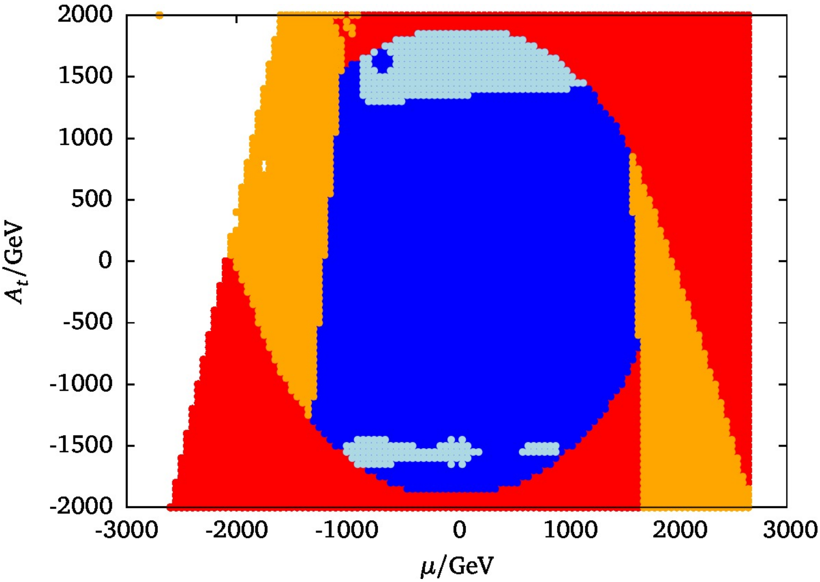
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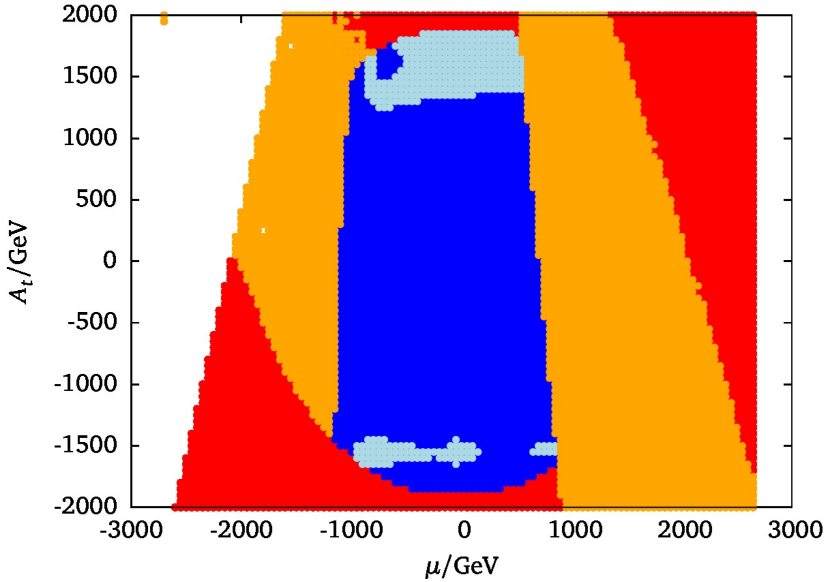
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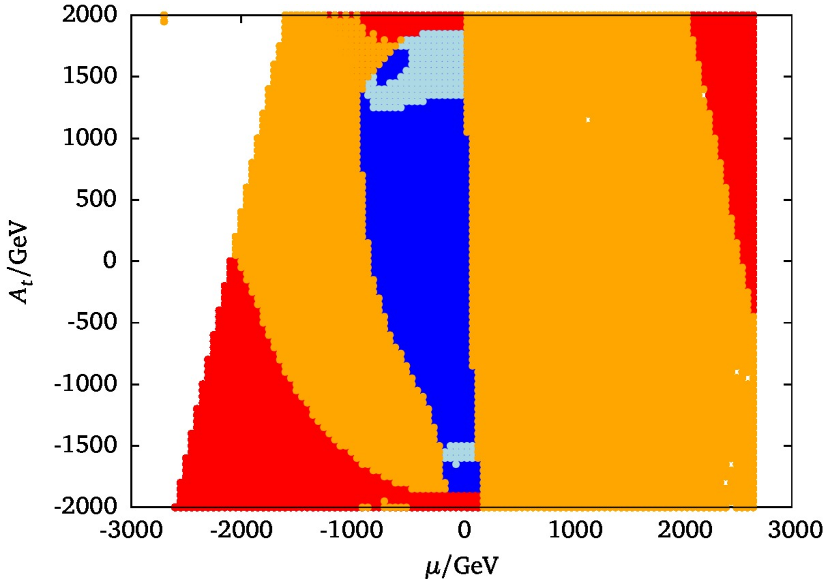
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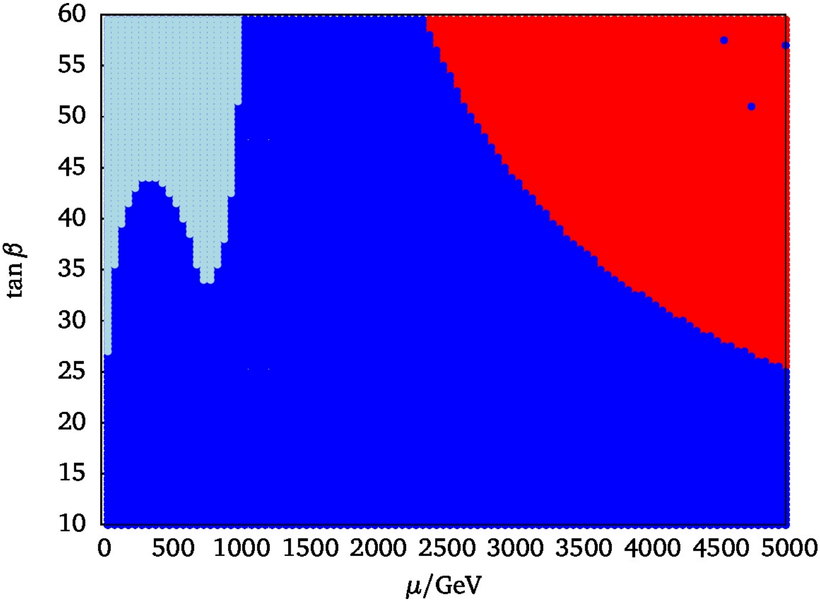
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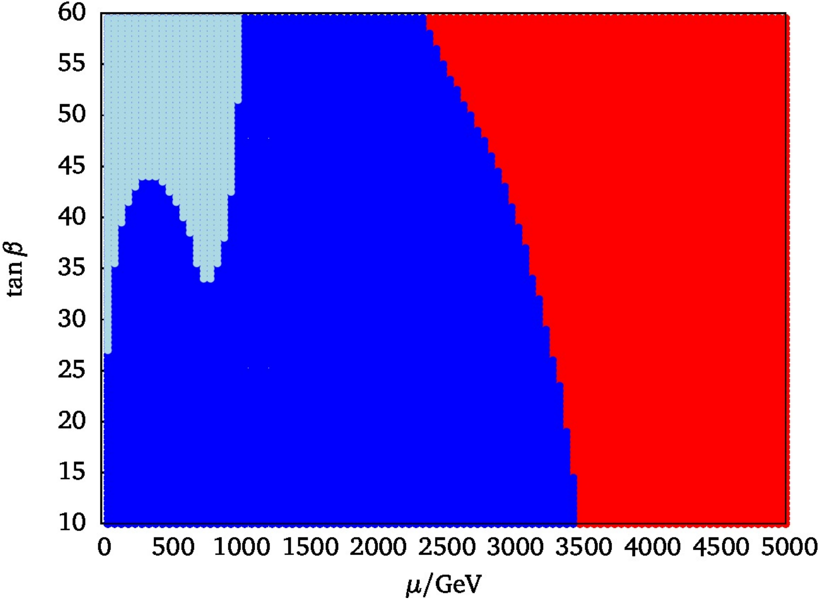
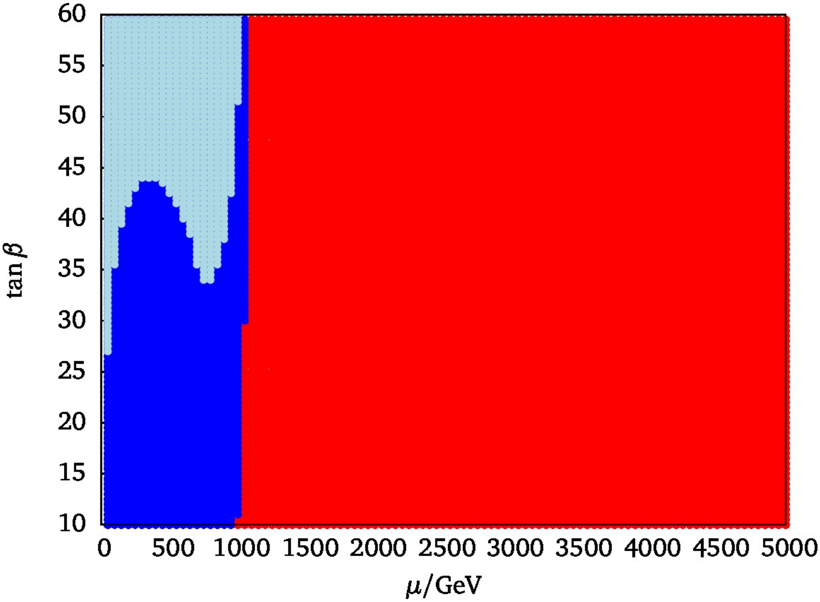
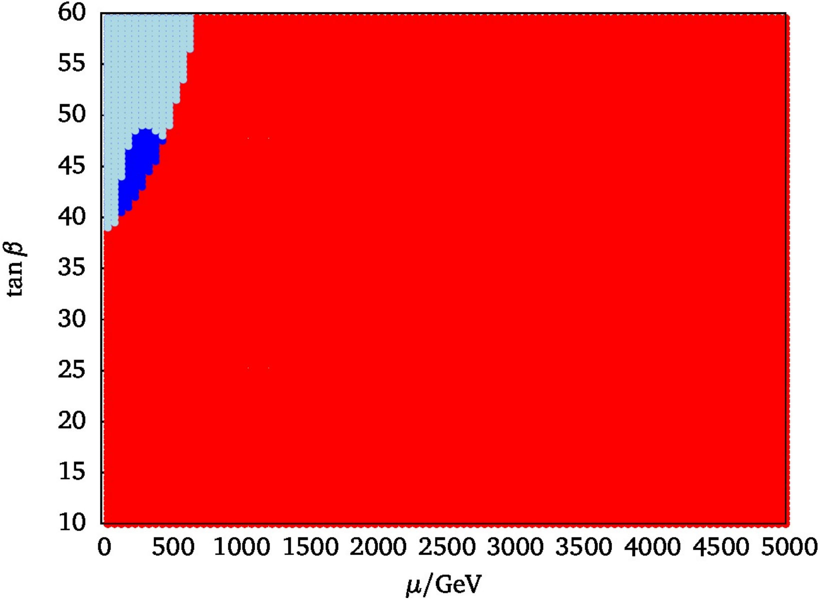
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
μ/GeV

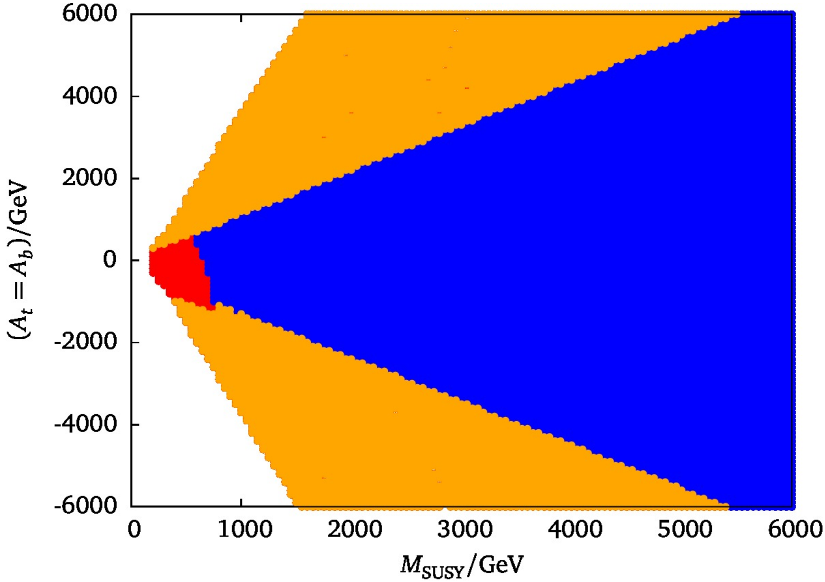

60
55
50
45
40
35
30
25
20
15
10
tan β
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
μ/GeV

The issue of including field directions $A_b = 0$

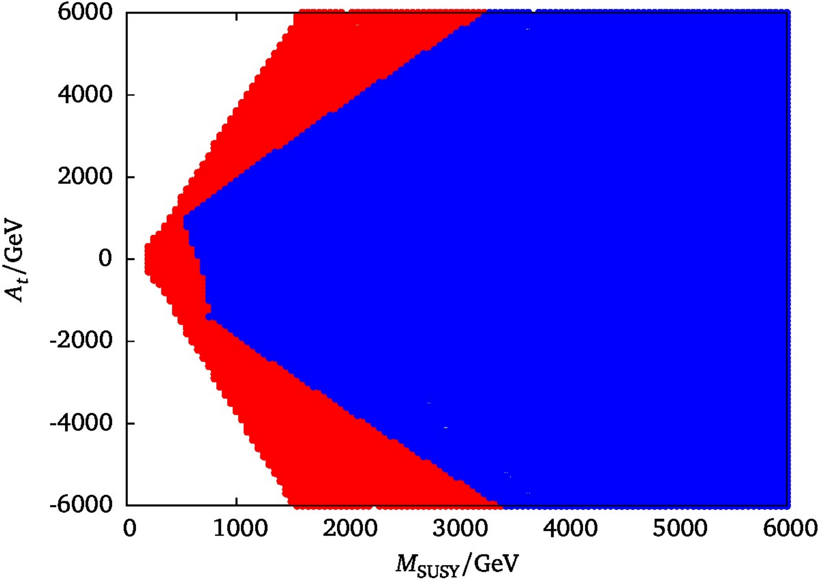



60
55
50
45
40
35
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
$\tan\beta$
μ/GeV

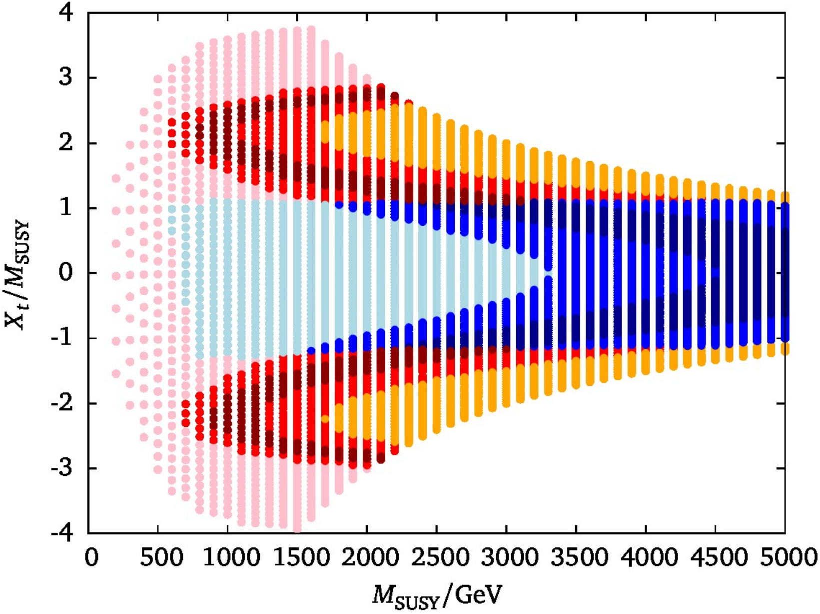
Resort comes close (increasing MSUSY)

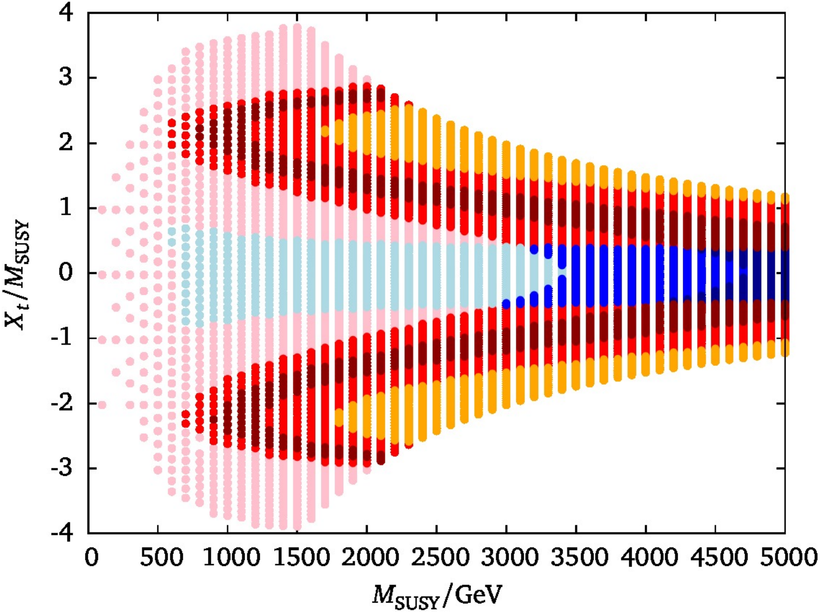


Resort comes close (increasing MSUSY) $A_b = 0$



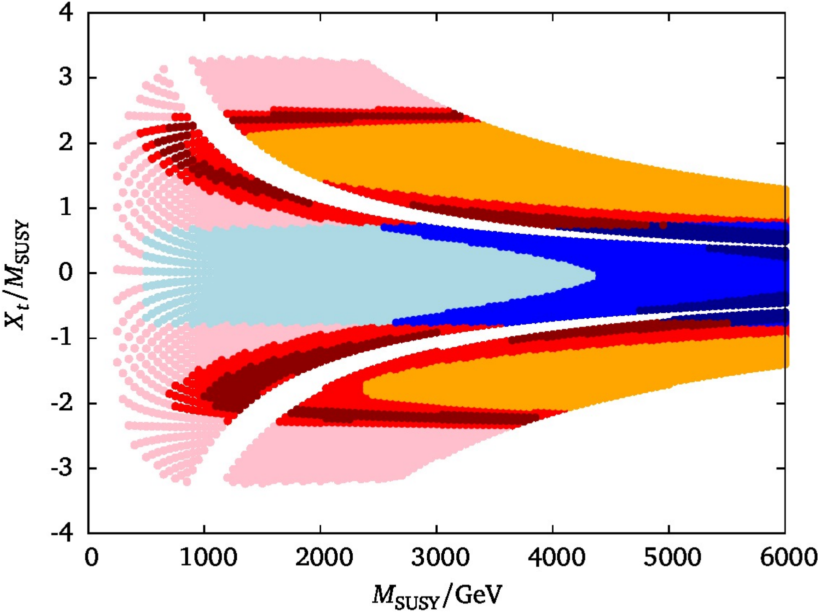
Parameter choice crucial $\mu = 350\,\mathrm{GeV}$

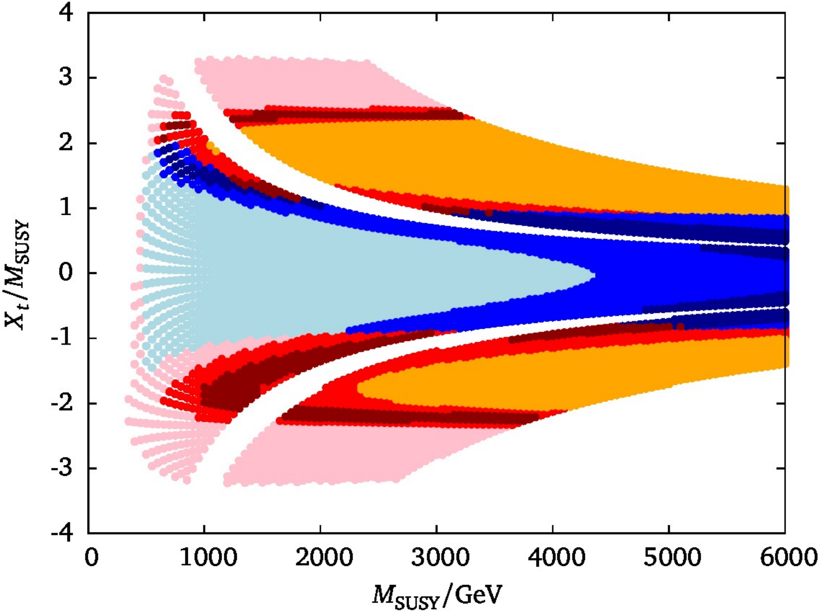




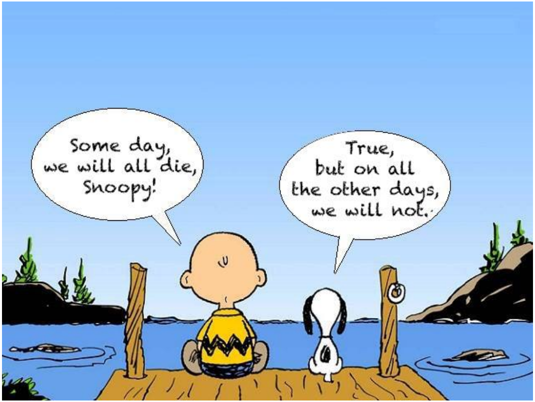
X_t/M_{SUSY}
4
3
2
1
0
-1
-2
-3
-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
$M_{\mathrm{SUSY}}/\mathrm{GeV}$

$\mu = 500\,\mathrm{GeV}$




4
3
2
1
0
-1
-2
-3
-4
X_t/M_{SUSY}
0
1000
2000
3000
4000
5000
6000
$M_{\mathrm{SUSY}}/\mathrm{GeV}$

- constraints on model parameters from theoretical consistency: global minimum has to be electroweak minimum
- "heavy" Higgs @ $125\,\mathrm{GeV}$: large SUSY corrections
  - large $A_{t,b}$ and μ induce squark vevs
  - quest for $m_h^0 = 125\,\mathrm{GeV}$ generically wants heavy SUSY



Backup

Slides

Cosmological stability

bounce action

$$B \gtrsim 400$$

$\hookrightarrow$ life-time longer than age of the universe

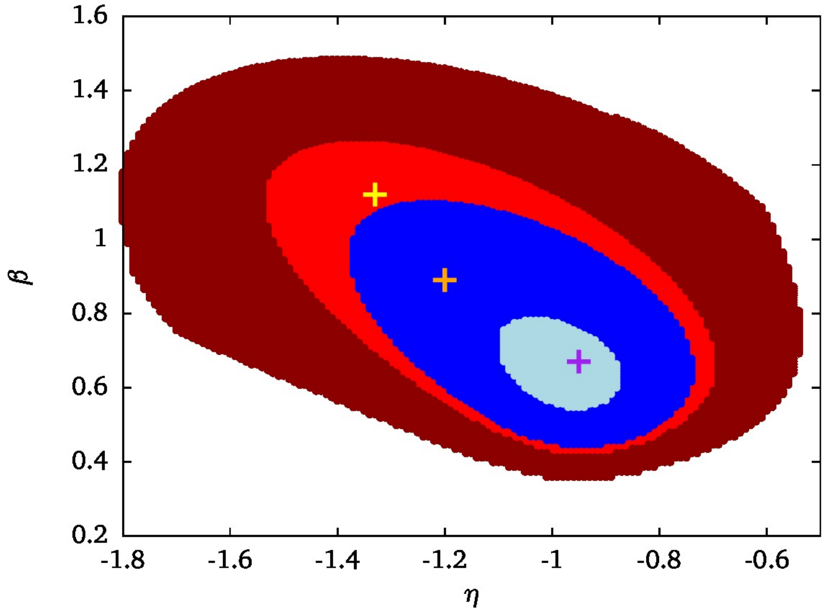
Decay probability (per unit volume)

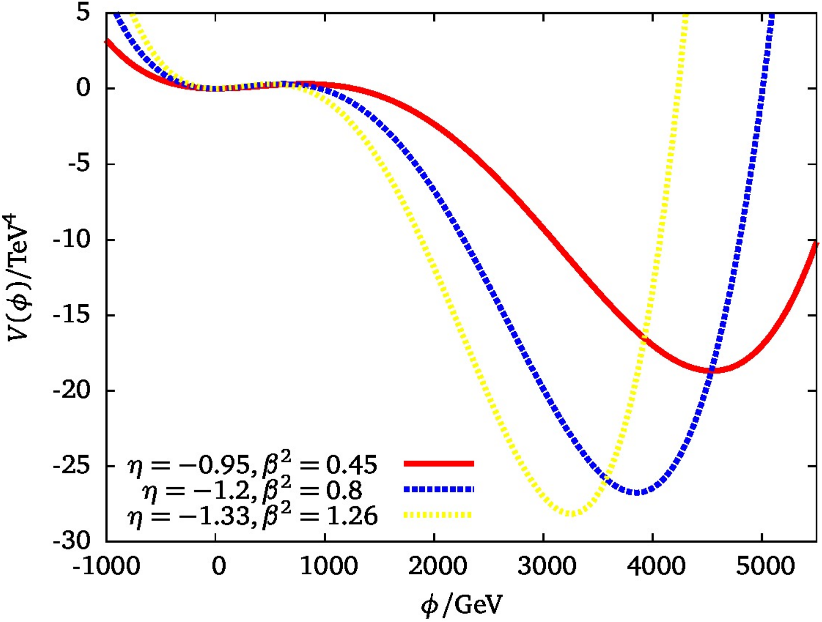
$$\frac{\Gamma}{V} = A e^{-B/\hbar}$$

[Coleman '77]

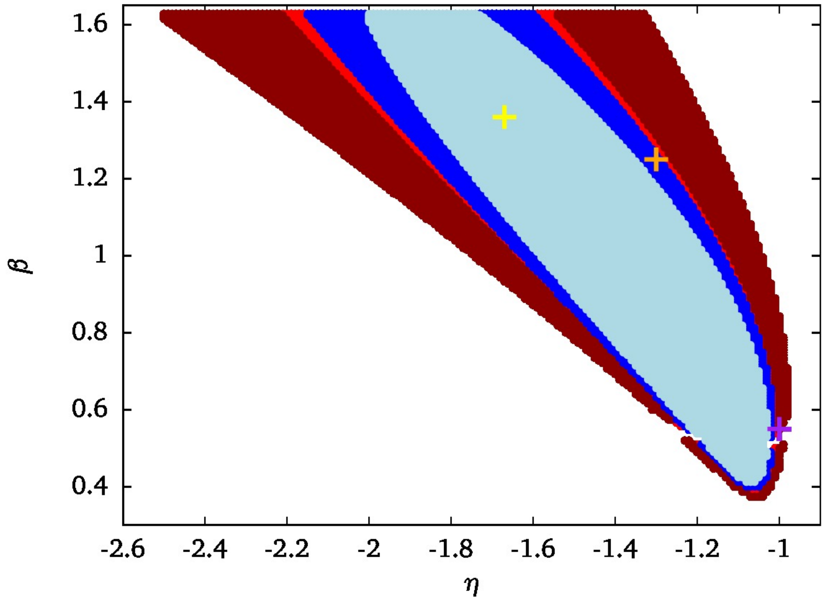
Death and doom

- value of B crucially depends on field space path
- very different conclusions for different η, α, β
- *independent* of SUSY parameter choice


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
β
-1.8
-1.6
-1.4
-1.2
-1
-0.8
-0.6
η



5
0
-5
-10
-15
-20
-25
-30
-1000
0
1000
2000
3000
4000
5000
$V(\phi)/\mathrm{TeV}^4$
ϕ/GeV
$\eta = -0.95, \beta^2 = 0.45$
$\eta = -1.2, \beta^2 = 0.8$
$\eta = -1.33, \beta^2 = 1.26$


1.6
1.4
1.2
1
0.8
0.6
0.4
β
-2.6
-2.4
-2.2
-2
-1.8
-1.6
-1.4
-1.2
-1
η

Contours of the Bounce $\mu = A_b = A_t = 500\,\text{GeV}$