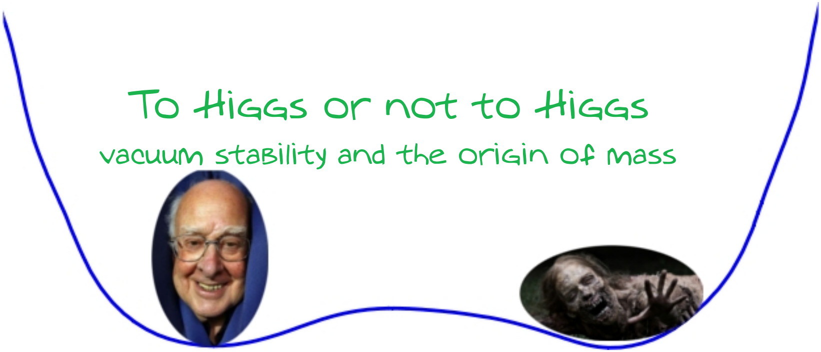
To Higgs or not to Higgs

vacuum stability and the origin of mass

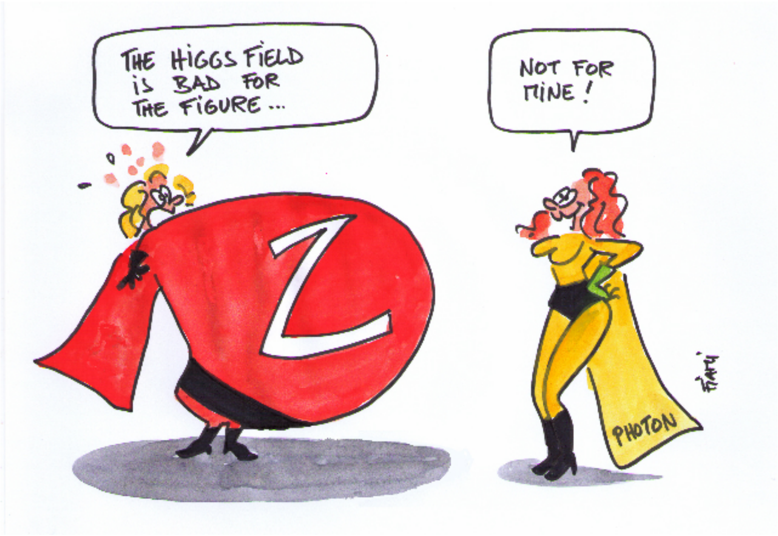


Wolfgang Gregor Hollik

DESY Hamburg Theory Group

Dec 12 2016 | MU Programmtag Mainz

The Higgs mechanism and the origin of mass



[CERN bulletin]

The tale of the Higgs dale

- potential instable at the origin
- ground state (= *vacuum*) breaks symmetry

Massive Gauge Bosons

spontaneously broken $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y$

$$\Phi(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to \begin{pmatrix} 0 \\ v + \frac{1}{\sqrt{2}} h(x) \end{pmatrix}$$

$(D_\mu \phi)^\dagger D^\mu \phi$ $\hookrightarrow$ quadratic terms for gauge fields:

$$\frac{1}{4} v^2 \left(g A^3_\mu - g' B_\mu\right)\left(g A^{3\,\mu} - g' B^\mu\right) + \frac{1}{2} g^2 v^2 A^+_\mu A^{-\,\mu},$$

with $A^\pm_\mu = \frac{1}{\sqrt{2}}(A^1_\mu \pm i A^2_\mu)$.

Masses for W and Z

$$m_W^2 = \frac{v^2 g^2}{2}\,, \quad m_Z^2 = \frac{v^2}{2}\left(g^2 + g'^2\right)\,,$$

weak mixing angle

$$\tan\theta_w = \frac{g'}{g}\,, \quad m_W = \cos\theta_w m_Z\,.$$

Fundamental masses

all fundamental masses $\sim \boldsymbol{v = 246\,\mathrm{GeV}}$ in the Standard Model

Masses for fermions

Yukawa interactions:

$$\mathcal{L}_{\mathsf{Yuk}} = Y\ \bar{\Psi}_{\mathrm{L}} \cdot \Phi \Psi_{\mathrm{R}} + \text{h. c.} \ = Y\ \begin{pmatrix} \bar{\psi}_{\mathrm{L}}^u & \bar{\psi}_{\mathrm{L}}^d \end{pmatrix} \cdot \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \psi_R^d + \text{h. c.}$$

(for up-type fields: $\Phi \to \tilde{\Phi} = i\sigma_2 \Phi^*$ and $\psi_{\mathrm{R}}^d \to \psi_{\mathrm{R}}^u$) $\boldsymbol{m_\psi = \frac{v}{\sqrt{2}} Y}$

Origin of mass = origin of v

In the Standard Model, by construction,

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

leads to $v^2 = \mu^2/\lambda$ (with $\mu^2 > 0$, $\lambda > 0$).

- measuring gauge boson masses + gauge couplings: v^2
- measuring Higgs boson mass: λ

So what?

- only tree level
- no new physics?
- V_{SM} put by hand...
- going beyond tree and SM: minimum may get unstable
  $\hookrightarrow$ "new" minimum: different v = different mass
  may break additional "good" symmetries of the SM

The Standard Model (In)Stability

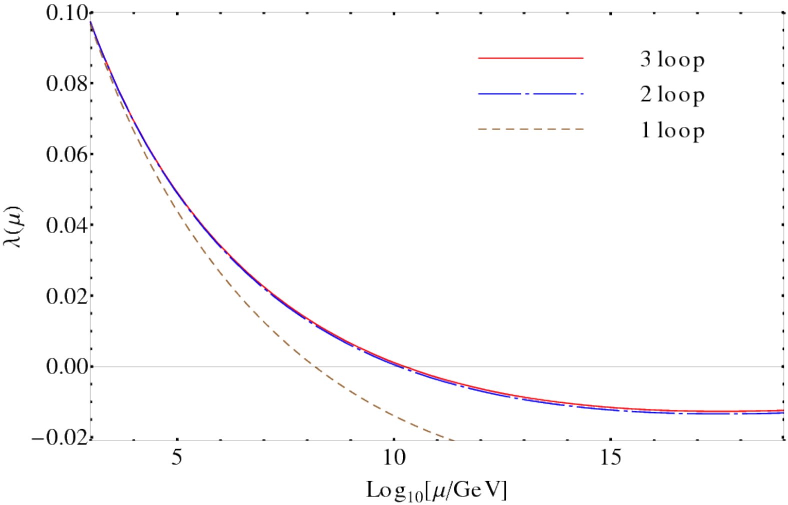
$$V_{\mathsf{SM}} = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

- 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}

Connection to Matter & Universe

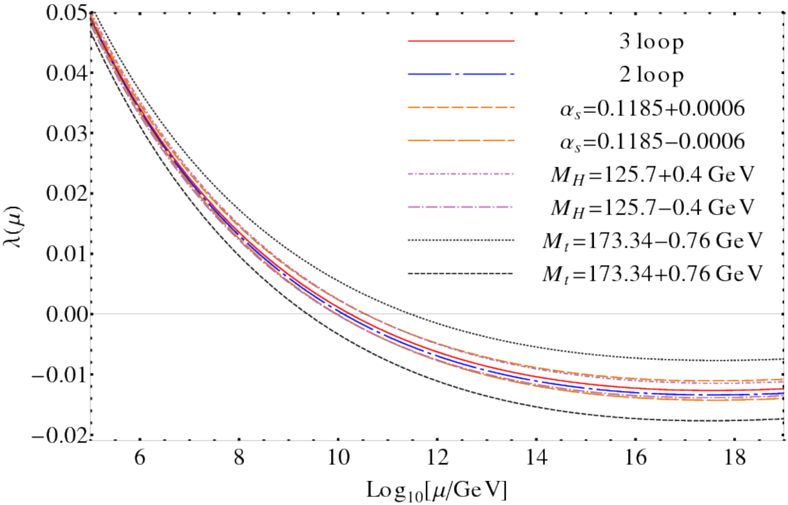
- transplanckian vev: different physics
- particle masses beyond M_{Planck}: link to gravitational physics
- Higgs inflation? [Bezrukov, Rubio, Shaposhnikov '14]
- main sources for uncertainty: m_t and α_S

Precise analysis: up to three loops!

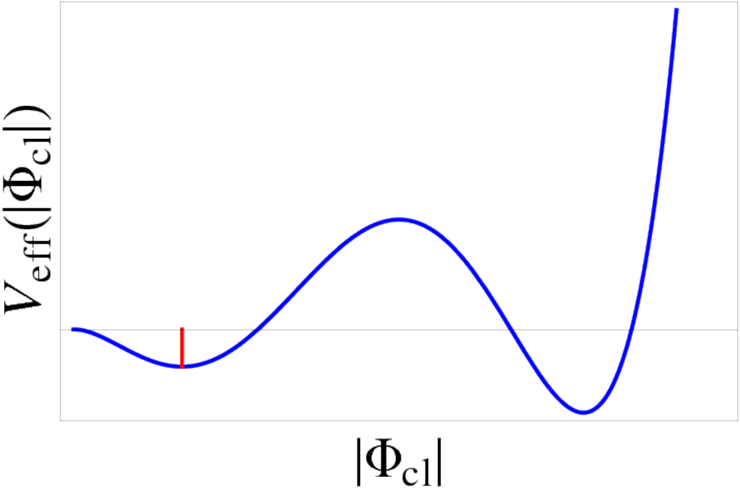


[Zoller 2014]

Precise analysis: up to three loops!

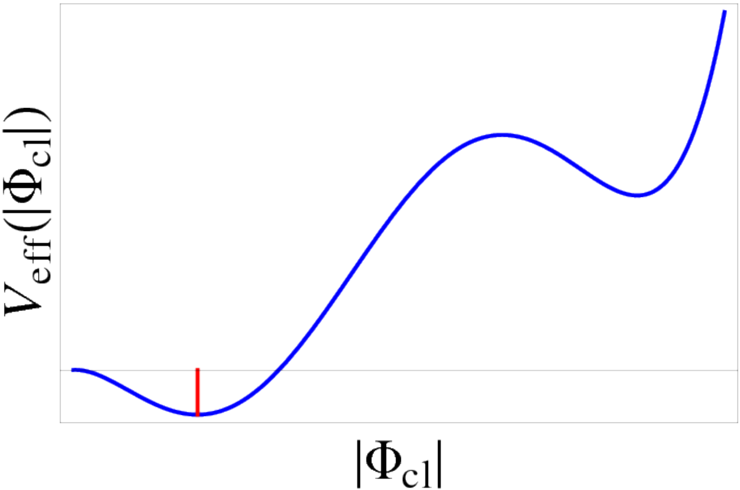


[Zoller 2014]



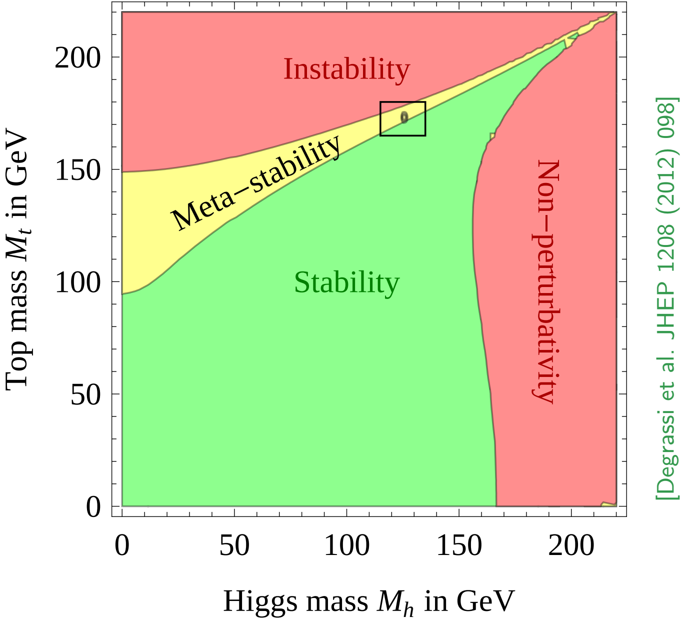
[Courtesy of Max Zoller]

Stability, instability or metastability?



[Courtesy of Max Zoller]

The SM phase diagram



Vacuum stability beyond the Standard Model

- Quantum effects: new particles in the loop
- tree level: multi-scalar potentials
  - Two Higgs Doublet Models (2HDM): no charge breaking
  - 2HDM + Singlet: more involved
- Minimal Supersymmetric Standard Model (MSSM):
  - sfermions: additional electrically and color charged directions
  - NMSSM: additional non-trivial neutral vacua
- severe constraints for any model, can be tested numerically

  [cf. Vevacious]
- generically difficult to get practical limits
  - i.e. noanalytical bounds
  - if so, with many simplifications (see next slides)

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[cf. Vevacious]

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The MSSM tree-level scalar potential, 3rd generation squarks

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

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

$|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}|$, $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}|$

$$V_{\tilde{q},h} = \tilde{t}\ ^* \left(\tilde{m}_L^2 + |y_t h_2|^2\right) \tilde{t}\ \ + \tilde{t}\ ^* \left(\tilde{m}_t^2 + |y_t h_2|^2\right) \tilde{t}$$

$$+\tilde{b}\ ^* \left(\tilde{m}_L^2 + |y_b h_1|^2\right) \tilde{b}\ \ + \tilde{b}\ ^* \left(\tilde{m}_b^2 + |y_b h_1|^2\right) \tilde{b}$$

$$- \left[\tilde{t}\ ^* (\mu^* y_t\ h_1{}^* - A_t h_2)\, \tilde{t}\ \ + \text{h.c.}\right]$$

$$-\left[\tilde{b}\ ^* (\mu^* y_b\ h_2{}^* - A_b h_1)\, \tilde{b}\ \ + \text{h.c.}\right]$$

$$+ |y_t|^2 |\tilde{t}\ |^2 |\tilde{t}\ |^2 + |y_b|^2 |\tilde{b}\ |^2 |\tilde{b}\ |^2 + |y_t|^2 |\tilde{b}\ |^2 |\tilde{t}\ |^2 + |y_b|^2 |\tilde{t}\ |^2 |\tilde{b}\ |^2$$

$$+ \frac{g_1^2}{8} \left(|h_2|^2 - |h_1|^2 + \ \ |\tilde{b}\ |^2 \qquad\qquad - \ \ |\tilde{t}\ |^2 \qquad\qquad \right)^2$$

$$+ \frac{g_2^2}{8} \left(|h_2|^2 - |h_1|^2 + |\tilde{b}\ |^2 - |\tilde{t}\ |^2 \right)^2 + \frac{g_2^2}{2} |\tilde{t}\ |^2 |\tilde{b}\ |^2$$

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

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\begin{aligned}
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& + (m_{h_2}^2 + |\mu|^2)|h_2|^2 + (m_{h_1}^2 + |\mu|^2)|h_1|^2 - 2\,\mathrm{Re}(B_\mu\, h_1 h_2).
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$|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}|$, $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}|$; $|\tilde{b}| = |h_1| = |\phi_1|$, $|\tilde{t}| = |h_2| = |\phi_2|$

$$V_{\tilde{q},h} = {\phi_2}^* \left(\tilde{m}_L^2 + |y_t\phi_2|^2\right) \phi_2 + {\phi_2}^* \left(\tilde{m}_t^2 + |y_t\phi_2|^2\right) \phi_2$$
$$+ {\phi_1}^* \left(\tilde{m}_L^2 + |y_b\phi_1|^2\right) \phi_1 + {\phi_1}^* \left(\tilde{m}_b^2 + |y_b\phi_1|^2\right) \phi_1$$
$$- \left[{\phi_2}^* \left(\mu^* y_t \, {\phi_1}^* - A_t\phi_2\right) \phi_2 + \text{h.c.}\right]$$
$$- \left[{\phi_1}^* \left(\mu^* y_b \, {\phi_2}^* - A_b\phi_1\right) \phi_1 + \text{h.c.}\right]$$
$$+ |y_t|^2|\phi_2|^2|\phi_2|^2 + |y_b|^2|\phi_1|^2|\phi_1|^2 + |y_t|^2|\tilde{b}\;\;|^2|\tilde{t}\;\;|^2 + |y_b|^2|\tilde{t}\;\;|^2|\tilde{b}\;\;|^2$$

$$+ \frac{g_2^2}{2}|\tilde{t}\;\;|^2|\tilde{b}\;\;|^2$$

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

$|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}|$, $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}|$; $|\tilde{b}| = |h_1| = |\phi_1|$, $|\tilde{t}| = |h_2| = |\phi_2|$

$$V_{\tilde{q},h} = \phi_2{}^* \left(\tilde{m}_L^2 + |y_t \phi_2|^2\right) \phi_2 + \phi_2{}^* \left(\tilde{m}_t^2 + |y_t \phi_2|^2\right) \phi_2$$

$$- \left[\phi_2{}^* \left(\qquad - A_t \phi_2\right) \phi_2 + \text{h.c.}\right]$$

$$+ |y_t|^2 |\phi_2|^2 |\phi_2|^2 \qquad + |y_t|^2 |\tilde{b}|^2 |\tilde{t}|^2 + |y_b|^2 |\tilde{t}|^2 |\tilde{b}|^2$$

$$+ \frac{g_2^2}{2} |\tilde{t}|^2 |\tilde{b}|^2$$

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

$|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}|$, $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}|$; $|\tilde{b}| = |h_1| = |\phi_1|$, $|\tilde{t}| = |h_2| = |\phi_2|$

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:

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

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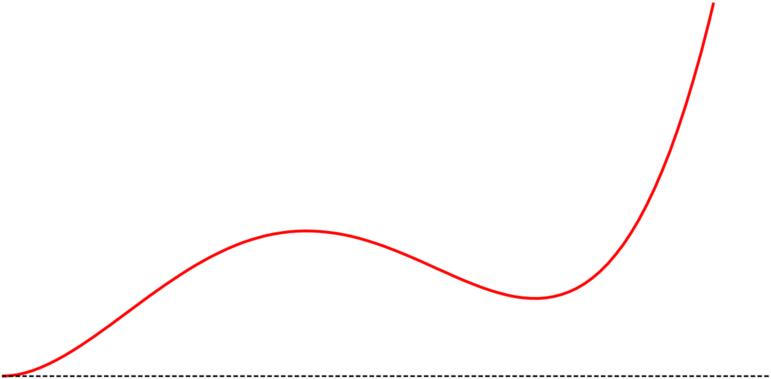
Well-known constraints [Gunion, Haber, Sher '88]

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

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

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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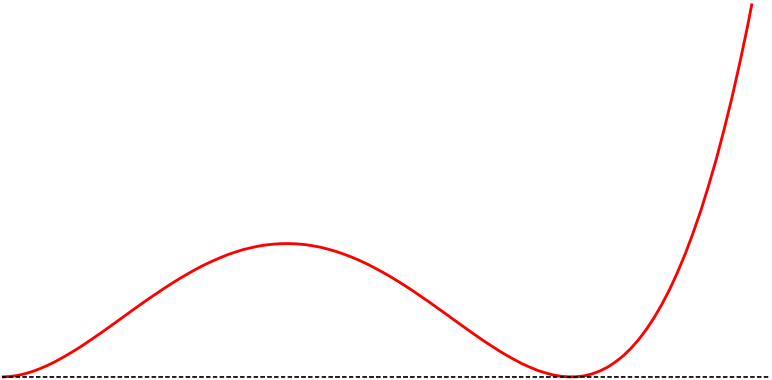

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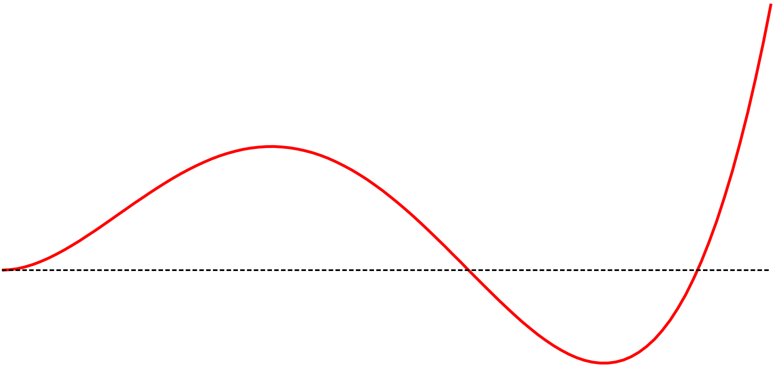


$$h_2 = \phi, \qquad |\tilde{t}| = \alpha|\phi|, \qquad h_1 = \eta\phi, \qquad |\tilde{b}| = \beta|\phi|$$

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

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

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

with

$$\begin{aligned} M^2 = & \; m_{h_2}^2 + \eta^2 m_{h_1}^2 + (1+\eta^2)\mu^2 - 2B_\mu\eta \\ & + (\alpha^2+\beta^2)\tilde{m}_L^2 + \alpha^2\tilde{m}_t^2 + \beta^2\tilde{m}_b^2\,, \end{aligned}$$

$$\mathcal{A} = \; 2\alpha^2\eta\mu y_t - 2\alpha^2 A_t + 2\beta^2\mu y_b - 2\eta\beta^2 A_b\,,$$

$$\begin{aligned} \lambda = & \; \frac{g_1^2+g_2^2}{8}(1-\eta^2+\beta^2-\alpha^2)^2 \\ & + (2+\alpha^2)\alpha^2 y_t^2 + (2\eta^2+\beta^2)\beta^2 y_b^2\,. \end{aligned}$$

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

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

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

$$\downarrow$$

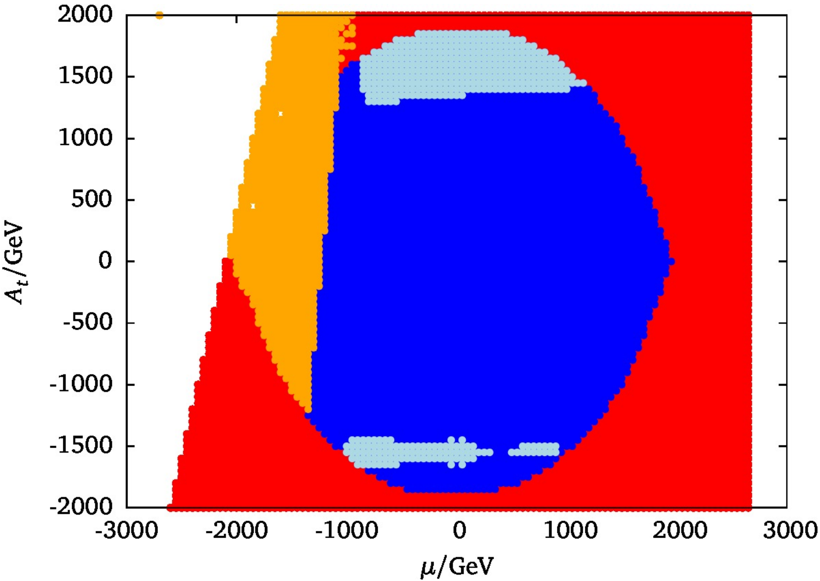
$$4\lambda(\eta,\alpha,\beta)M^2(\eta,\alpha,\beta) > (\mathcal{A}(\eta,\alpha,\beta))^2$$

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

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

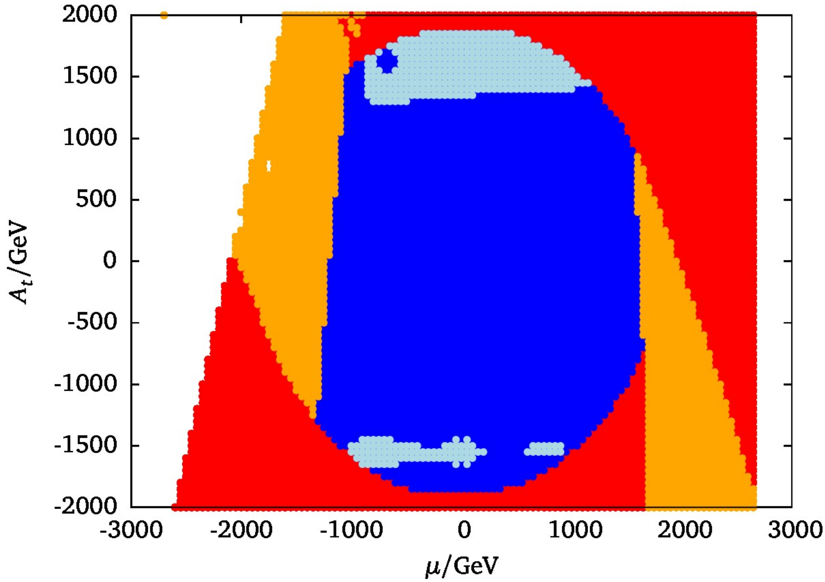
$|h_d|^2 = |h_u|^2 + |\tilde{b}|^2$, $\tilde{b} = \alpha h_u$ [WGH'15]

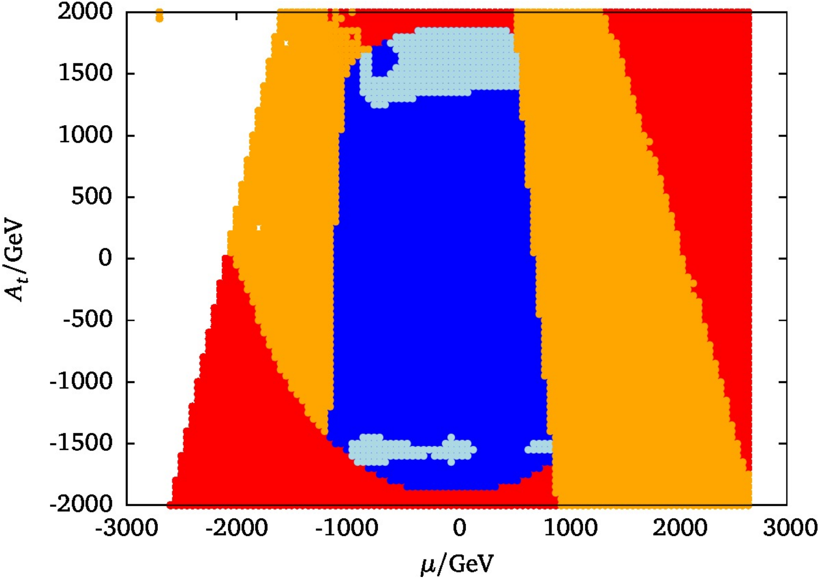
$$m_{11}^2(1+\alpha^2) + m_{22}^2 \pm 2m_{12}^2\sqrt{1+\alpha^2} + \alpha^2(\tilde{m}_Q^2 + \tilde{m}_b^2) > \frac{4\mu^2\alpha^2}{2+3\alpha^2}$$

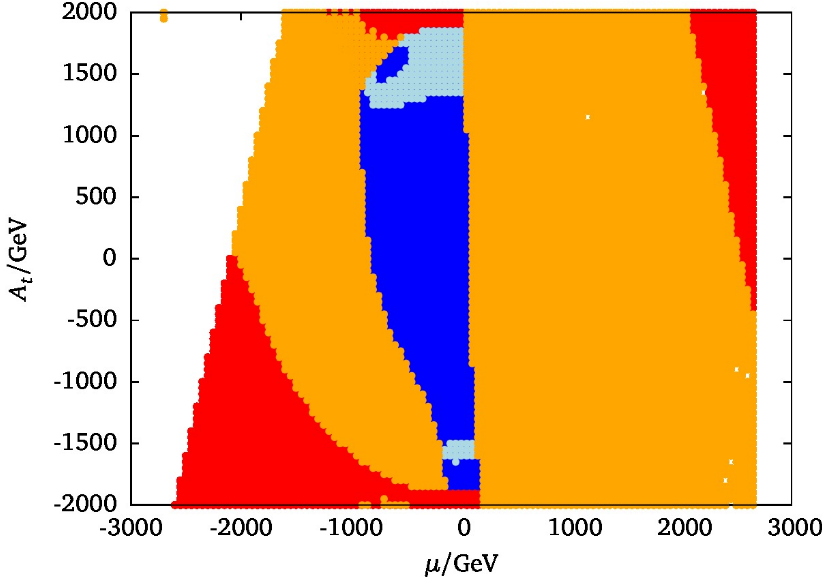


2000
1500
1000
500
0
-500
-1000
-1500
-2000
A_t/GeV
-3000
-2000
-1000
0
1000
2000
3000
μ/GeV

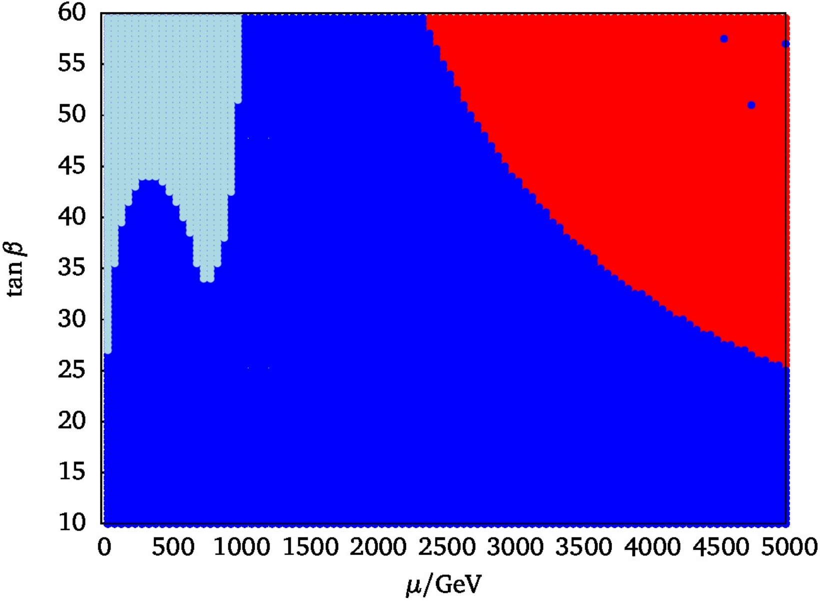
Closing in on the parameter space $A_b = 500\,\mathrm{GeV}$



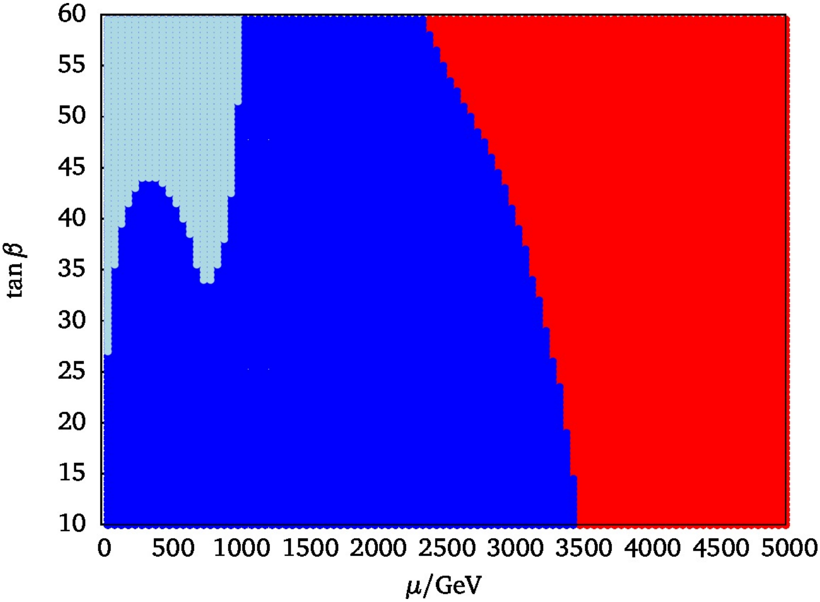

2000
1500
1000
500
0
-500
-1000
-1500
-2000
A_t/GeV
-3000
-2000
-1000
0
1000
2000
3000
μ/GeV


2000
1500
1000
500
0
-500
-1000
-1500
-2000
A_t/GeV
-3000
-2000
-1000
0
1000
2000
3000
μ/GeV

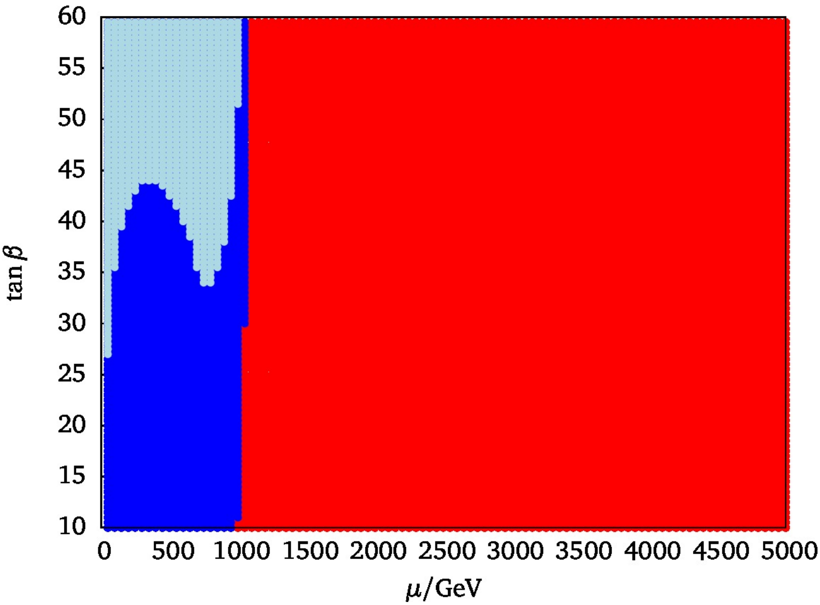
The issue of including field directions $\tilde{t} = 0, h_d = 0, A_b = 0$



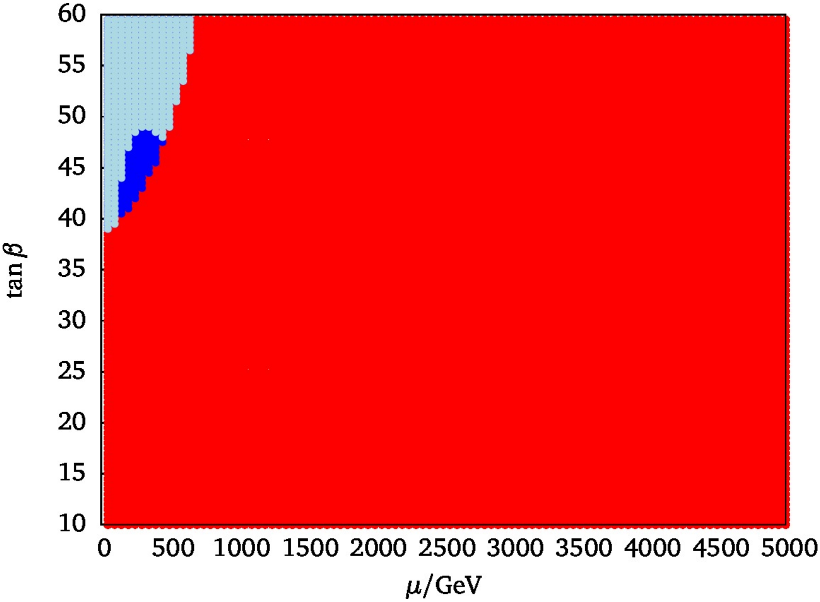
The issue of including field directions $\tilde{t} = 0, A_b = 0$



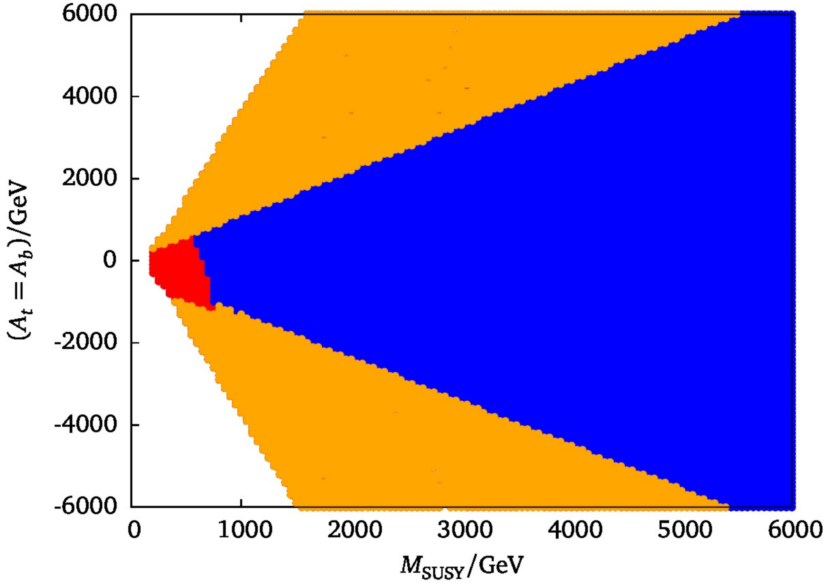
The issue of including field directions $A_b = 0$



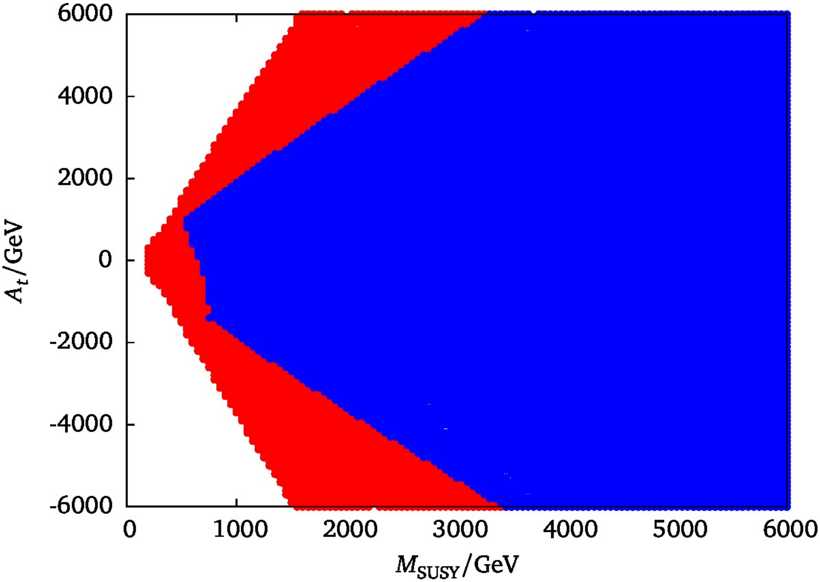
The issue of including field directions $A_b = A_t$



Resort comes close (increasing MSUSY)

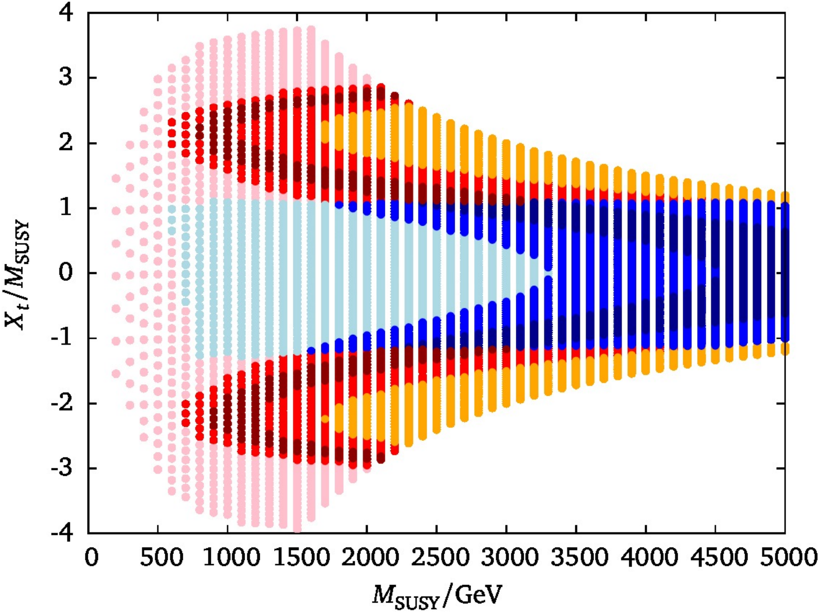


Resort comes close (increasing MSUSY) $A_b = 0$



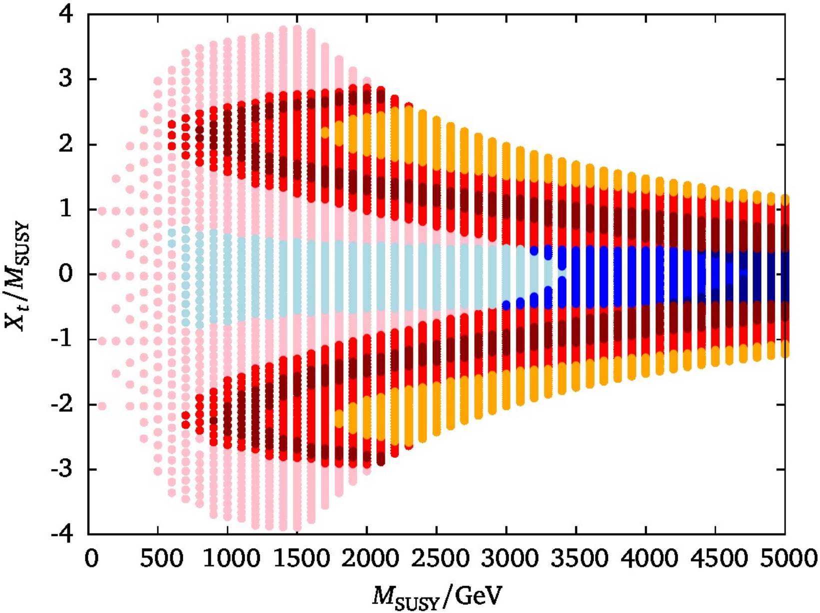
Parameter choice crucial

$\mu = 350\,\mathrm{GeV}$



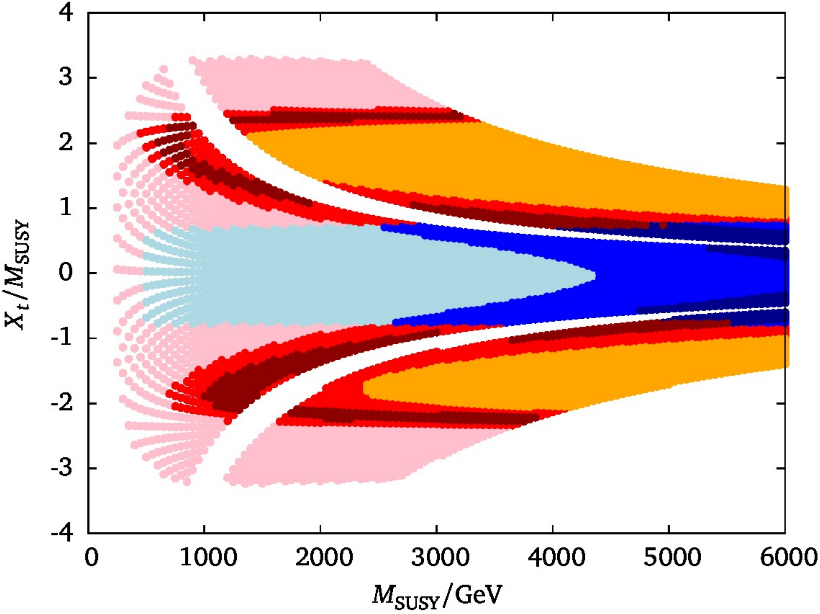
Parameter choice crucial

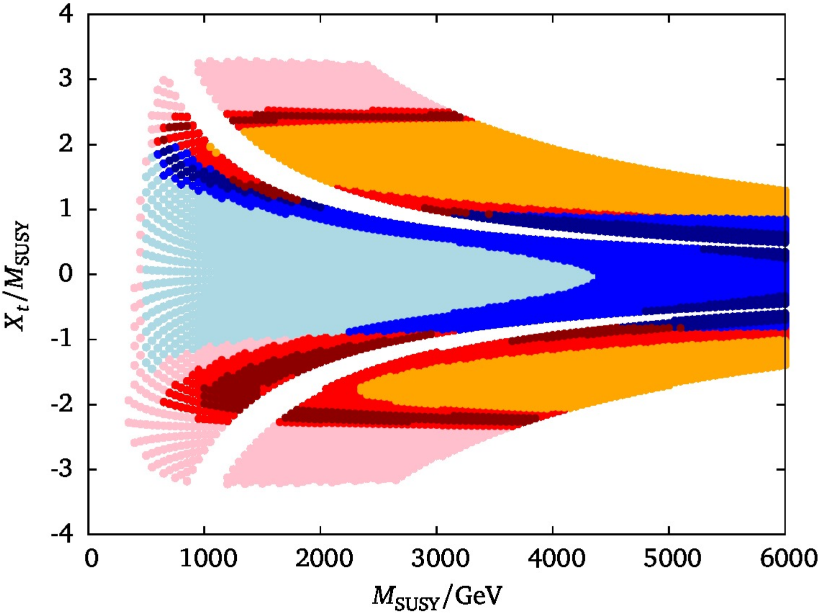
$\mu = M_{\mathrm{MSUSY}}$



Parameter choice crucial

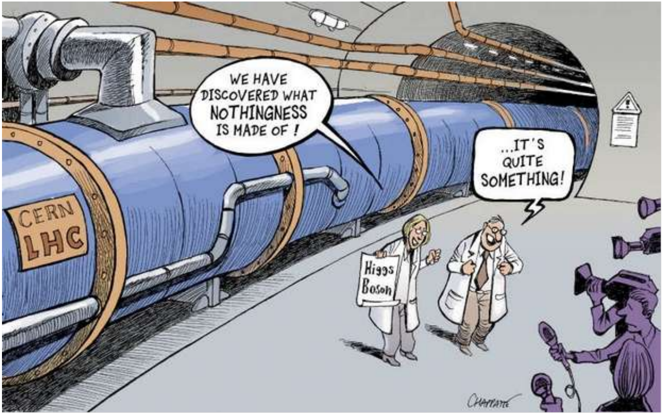
$\mu = 500\,\mathrm{GeV}$




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

Short summary

- Vacuum stability and the origin of mass:
  $v = 246\,\mathrm{GeV}$ vs. $v > M_{\mathrm{Planck}}$ or $\tilde{v} \approx M_{\mathrm{SUSY}}$
- constraints on model parameters from theoretical consistency: global minimum has to be electroweak minimum
- "heavy" light Higgs @ $125\,\mathrm{GeV}$: large SUSY corrections
  - e.g. MSSM: large $A_{t,b}$ and μ induce squark vevs



Backup

Slides

Cosmological stability

bounce action

$$B \gtrsim 400$$

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

Decay probability (per unit volume)

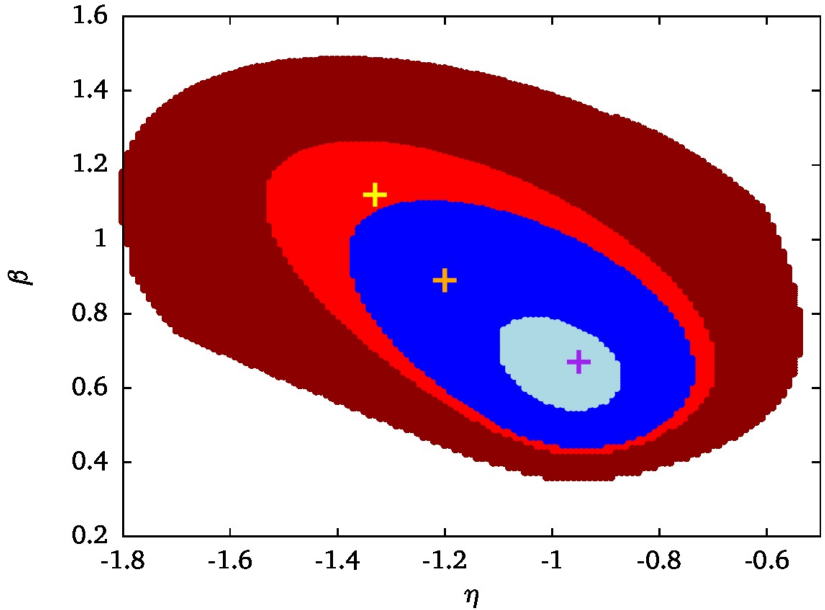
$$\frac{\Gamma}{V} = A e^{-B/\hbar}$$

[Coleman '77]

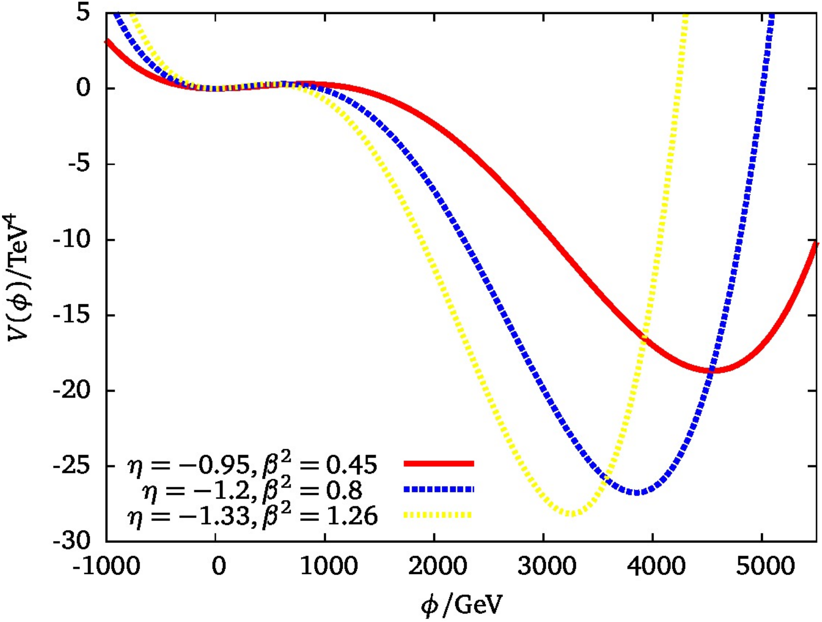
Death and doom

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

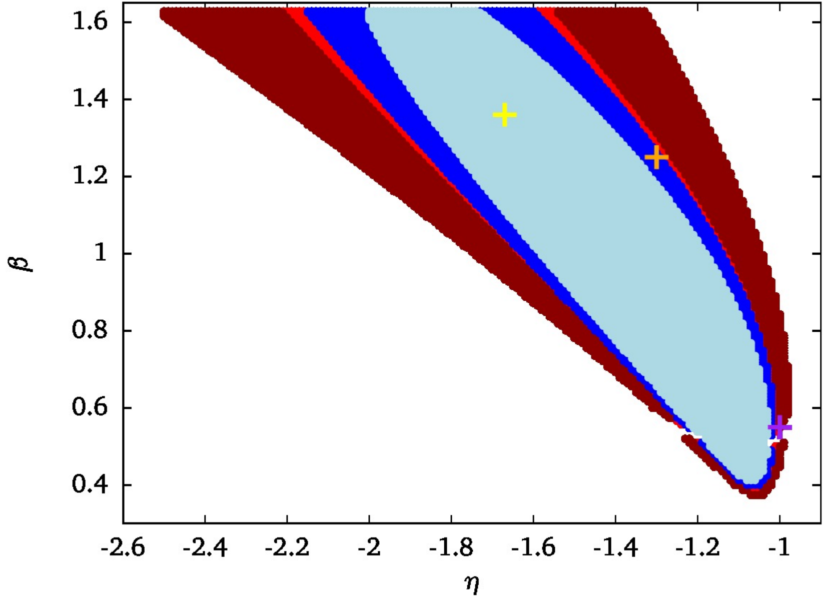
Contours of the Bounce $\mu = 500\,\mathrm{GeV}, A_b = A_t = 1500\,\mathrm{GeV}$

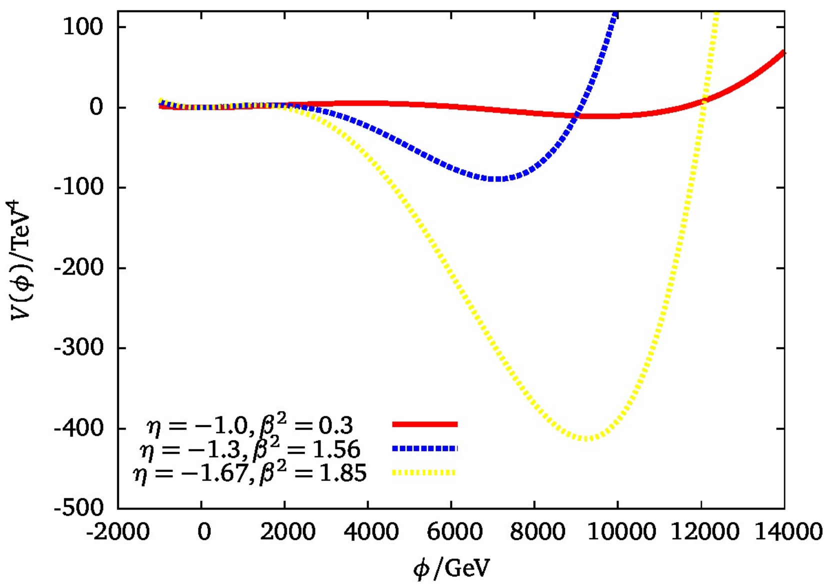


Contours of the Bounce $\mu = 500\,\mathrm{GeV}, A_b = A_t = 1500\,\mathrm{GeV}$



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





100
0
-100
-200
-300
-400
-500
-2000
0
2000
4000
6000
8000
10000
12000
14000
$V(\phi)/\mathrm{TeV}^4$
ϕ/GeV
$\eta = -1.0, \beta^2 = 0.3$
$\eta = -1.3, \beta^2 = 1.56$
$\eta = -1.67, \beta^2 = 1.85$