A new view on charge and color breaking minima in the MSSM

Wolfgang Gregor Hollik

DESY Hamburg, Theory Group

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DISCLAIMER: No $\gamma\gamma$ excess!

MSSM may be ruled out anyway. . .

. . . or not? (cf. Djouadi's talk?)


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FRANKLY, I WAS EXPECTING SOMETHING A BIT MORE SOPHISTICATED...

Brout–Englert–Higgs mechanism

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \quad \rightarrow \quad \mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$$

Consequence: The (in)famous Higgs boson!

- scalar mass sensitive to high scale physics (hierarchy problem)
- Standard Model vacuum metastable (will eventually decay)
  [Degrassi et al. 2012]
- its mass could not be predicted (in the SM)

A viable solution / extension of the SM

- The Minimal Supersymmetric Standard Model (MSSM)
- "predicts" the Higgs mass; defines Higgs potential
- solves the hierarchy problem
- stabilizes the potential

The Minimal Supersymmetric Standard Model: A multi-scalar theory

$$V = V_F + V_D + V_{\text{soft}}$$

with

$$V_F = \sum_i \left| \frac{\partial \mathcal{W}}{\partial \phi_i} \right|^2 ,$$

$$V_D = \frac{1}{2} \sum_a g_a^2 \left(\sum_i \phi_i^\dagger T^a \phi_i \right)^2$$

$$V_{\text{soft}} = \sum_i m_{\phi_i}^2 |\phi_i|^2 + \sum_{ijk} A_{ik}^{(j)} \phi_i^\dagger \phi_j \phi_k$$

$$\leftrightarrow$$

The Standard Model: A single scalar theory

$$V_{\text{SM}} = -\mu^2 H^\dagger H + \frac{\lambda}{4} \left(H^\dagger H \right)^2$$

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

The hazard

- impossible to minimize directly, analytically
- colored directions sensitive to all kinds of SUSY breaking
- spontaneous breaking of color charge: $\langle \tilde{q} \rangle \neq 0$

The true vacuum

- effective potential: average energy density
- global minimum: true ground state of the theory

The third generation MSSM

$$\mathcal{W} = \mu\, H_1 \cdot H_2 + y_t\, H_2 \cdot Q_L \bar{T}_R - y_b\, H_1 \cdot Q_L \bar{B}_R$$

- large couplings to Higgs doublets (y_t and y_b comparably large)
- large stop contribution (X_t, A_t) to light Higgs mass needed
- $\tan\beta$ resummation for m_b influences y_b

Properties of the (effective) scalar potential

- no UFB directions (due to quantum corrections)
- D-terms: (comparably) large contributions ϕ^4
- "dangerous" directions: small quadrilinears + large trilinears

Analytic constraints

- define certain directions in field space: great simplification
- e.g. D-terms absent: $|\tilde{Q}_L| = |\tilde{t}_R| = |h_2|$ (possibly miss sth.)

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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& + \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] \\
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& + \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 \\
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\end{aligned}
$$

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

The tree-level scalar potential

$$V_{\tilde{q},h} = \tilde{t}\ ^* \left(\tilde{m}_L^2 + |y_t h_2|^2\right) \tilde{t}\ \ + \tilde{t}\ ^* \left(\tilde{m}_t^2 + |y_t h_2|^2\right) \tilde{t}$$
$$+\tilde{b}\ ^* \left(\tilde{m}_L^2 + |y_b h_1|^2\right) \tilde{b}\ \ + \tilde{b}\ ^* \left(\tilde{m}_b^2 + |y_b h_1|^2\right) \tilde{b}$$
$$- \left[\tilde{t}\ ^* (\mu^* y_t\ h_1{}^* - A_t h_2)\, \tilde{t}\ \ + \text{h.c.}\right]$$
$$- \left[\tilde{b}\ ^* (\mu^* y_b\ h_2{}^* - A_b h_1)\, \tilde{b}\ \ + \text{h.c.}\right]$$
$$+ |y_t|^2 |\tilde{t}\ \ |^2 |\tilde{t}\ \ |^2 + |y_b|^2 |\tilde{b}\ \ |^2 |\tilde{b}\ \ |^2$$
$$+ \frac{g_1^2}{8} \left(|h_2|^2 - |h_1|^2 + \ \ |\tilde{b}\ \ |^2 \qquad - \ \ |\tilde{t}\ \ |^2 \qquad \right)^2$$
$$+ \frac{g_2^2}{8} \left(|h_2|^2 - |h_1|^2 + |\tilde{b}\ \ |^2 - |\tilde{t}\ \ |^2\right)^2$$

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

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

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& - \left[\tilde{t}^{\;*}\left(\mu^* y_t\, h_1{}^* - A_t h_2\right)\tilde{t} + \text{h.c.}\right] \\
& - \left[\tilde{b}^{\;*}\left(\mu^* y_b\, h_2{}^* - A_b h_1\right)\tilde{b} + \text{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 - |\tilde{t}|^2\right)^2 \\
& + \frac{g_2^2}{8}\left(|h_2|^2 - |h_1|^2 + |\tilde{b}|^2 - |\tilde{t}|^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).
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$|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}|$, $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}|$; $|\tilde{b}| = |h_1| = |\phi_1|$, $|\tilde{t}| = |h_2| = |\phi_2|$

The tree-level scalar potential

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

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

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

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

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

$$+ |y_t|^2|\phi_2|^2|\phi_2|^2$$

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

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

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 $\lambda = 3y_t^2$.

Mathematics for the kindergarden

Minimize the potential

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

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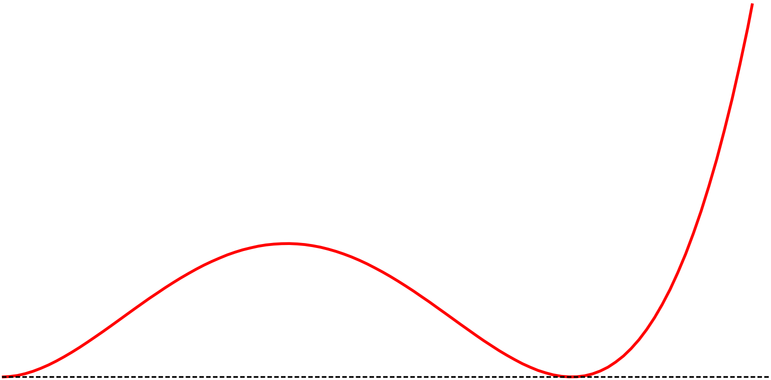
Well-known constraints [Gunion, Haber, Sher '88]

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

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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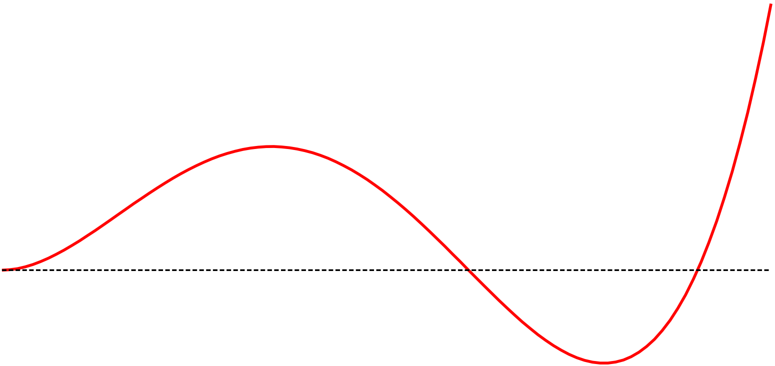
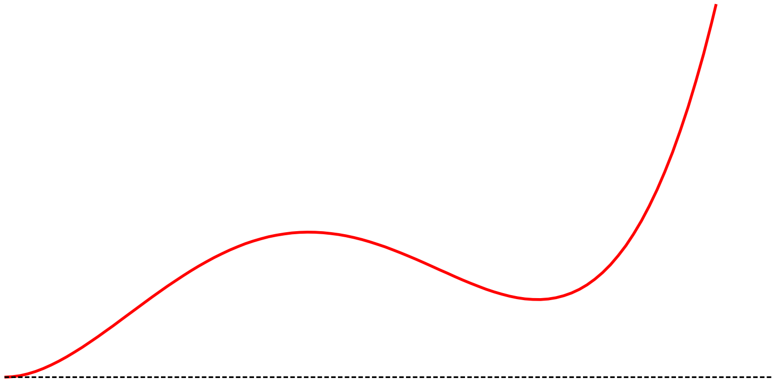


$A^2 < 4\lambda m^2$



Problem already known for a while

- problem noticed [Frere, Jones, Raby '83]
- "A-parameter bounds" [Gunion, Haber, Sher '87]
- classification of all dangerous directions [Casas, Lleyda, Muñoz '96]
- including flavor violation [Casas and Dimopuolos '96]

Stability $\neq$ no Instability $\Rightarrow$ Metastability

Vacuum tunneling [Kusenko, Langacker '96; Blinov, Morissey '13]

The tool

VeVacious [Camargo-Molina, O'Leary, Porod, Staub '13]

- finds all (?) tree-level minima
- minimizes scalar potential in the vicinity at one loop
- calculates bounce action / tunneling times [CosmoTransitions]

1. We have discovered the Higgs!
2. No sign of SUSY so far. . .
3. $\boldsymbol{m_h = 125\,\text{GeV}}$
   (all SUSY literature during LEP era expected it to be $\lesssim 100\,\text{GeV}$)
4. Consequently: large radiative corrections!
5. large stop mixing needed? heavy SUSY spectrum?
   (or hidden in some hardly accessible valley)
6. approach today:
   - less focused on unified models
   - still certain scenarios
   - $\tan\beta$ resummation for bottom quark mass (large $\tan\beta$)
   - low $\tan\beta$ favored (for $M_A \lesssim 800\,\text{GeV}$, direct search $A \to \tau\tau$)

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Semi-analytical bounds/exclusions imortant for fast processing!

My "pMSSM"

- no unification (more than m_0, $m_{1/2}$, A_0, $\tan\beta$ and $\operatorname{sign}\mu$)
- free parameters: (although similar choice as in CMSSM)
  - $\tilde{m}_L^2 = \tilde{m}_t^2 = \tilde{m}_b^2 = M_{\mathsf{SUSY}}^2$
  - μ, $\tan\beta$
  - A_t, A_b (not necessarily equal)
- $m_{h_{1,2}}^2$ determined from ew breaking, B_μ related to M_A
- no RG running needed = parameters taken at the SUSY scale

Why no RG-improvement?

- SUSY scale parameters; limits on this parameters
- destabilization of ew vacuum *around* SUSY scale
- no Planck scale vevs! (maybe there are… in addition)
- in the spirit of the pMSSM as phenomenologically as possible
- only small RG modifications, qualitative features unchanged

Less constraints, more parameters, more fields, more vevs...

Restriction to certain directions too restrictive!

- give up $|\tilde{q}_L| = |\tilde{t}_R| = |h_2|$
- allow for $h_1 \neq 0$ and $\tilde{b} \neq 0$
- "break" $\tilde{q}_L \to \tilde{t}_L + \tilde{b}_L$
- back to full scalar potential!

Simplify your life

- $h_2 = \phi$
- $|\tilde{t}_L| = |\tilde{t}_R| = |\tilde{t}| = \alpha|\phi|$
- $h_1 = \eta\phi$
- $|\tilde{b}_L| = |\tilde{b}_R| = |\tilde{b}| = \beta|\phi|$
- all fields and parameters real, $\alpha, \beta > 0$, $\eta \in \mathbb{R}$
- $\mathrm{SU}(3)_c$-flatness: $\tilde{t}_L = \tilde{t}_R$ and $\tilde{b}_L = \tilde{b}_R$

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

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

with

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

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

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

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

$$\downarrow$$

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

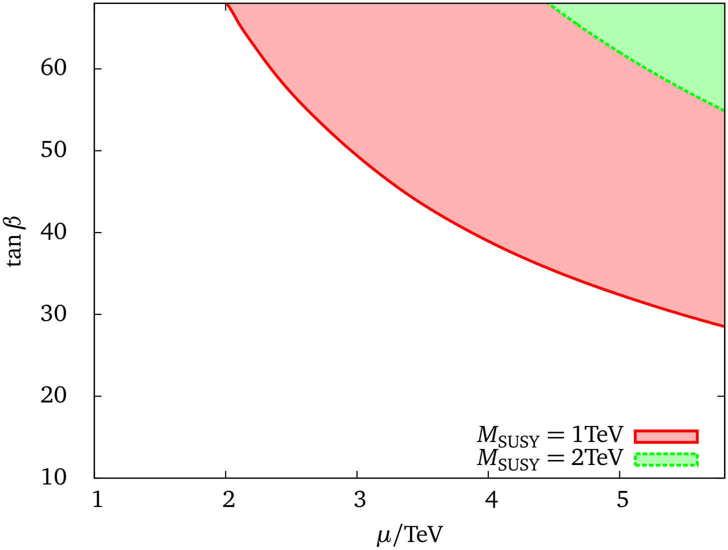
$h_u = \tilde{b}$, $h_d^0 = 0$ [WGH'15]

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

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

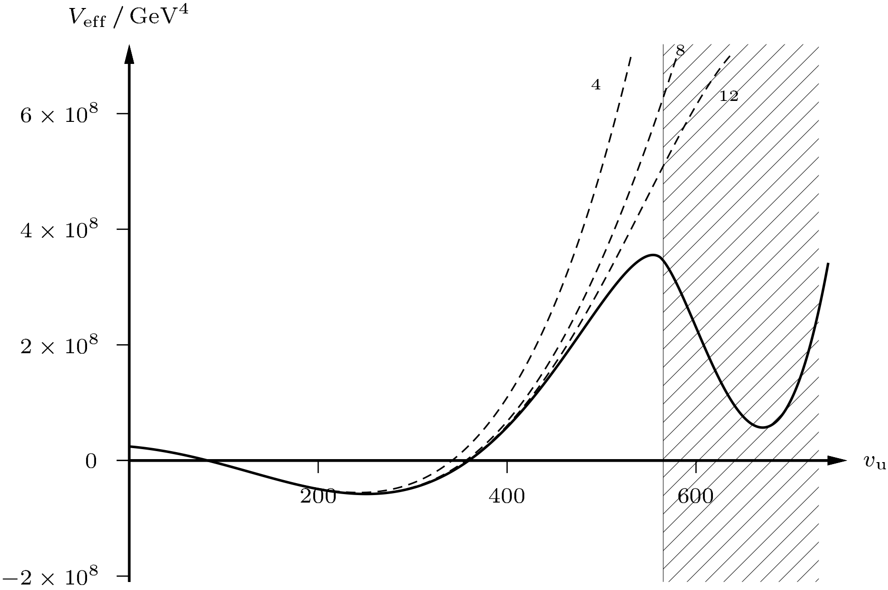
$$m_{11}^2(1+\alpha^2) + m_{22}^2 \pm 2m_{12}^2\sqrt{1+\alpha^2} + \alpha^2(\tilde{m}_Q^2 + \tilde{m}_b^2) > \frac{4\mu^2\alpha^2}{2+3\alpha^2}$$

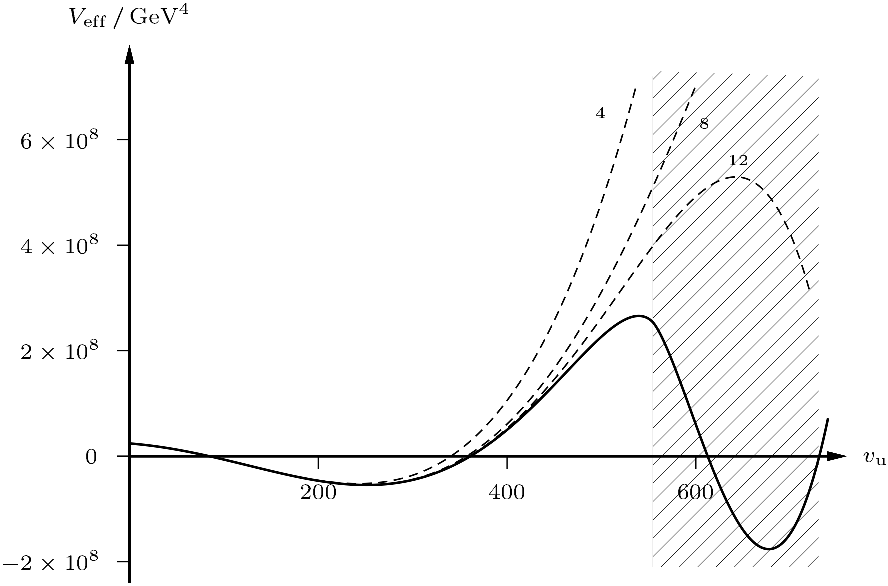
[Bobrowski, Chalons, WGH, Nierste '14]



1-loop

Higgs potential (h_u and h_d), new CC *conserving* min @ 1-loop


V_{eff} / GeV^4
6×10^8
4×10^8
2×10^8
0
-2×10^8
200
400
600
v_u
4
8
12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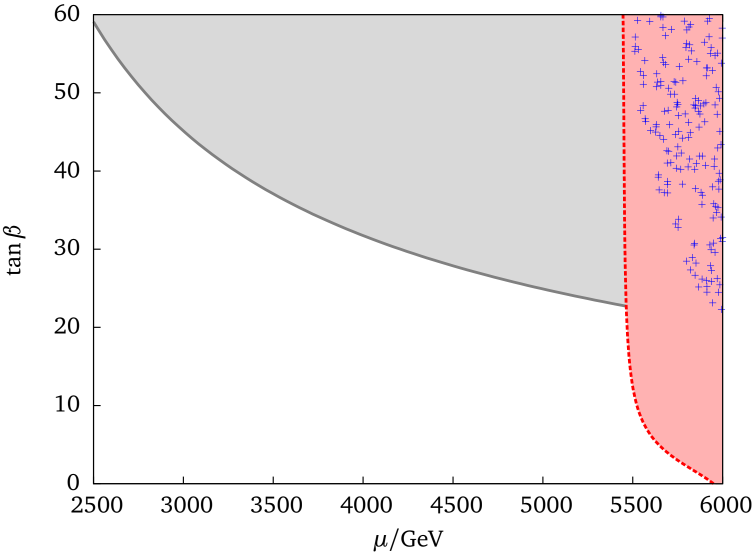
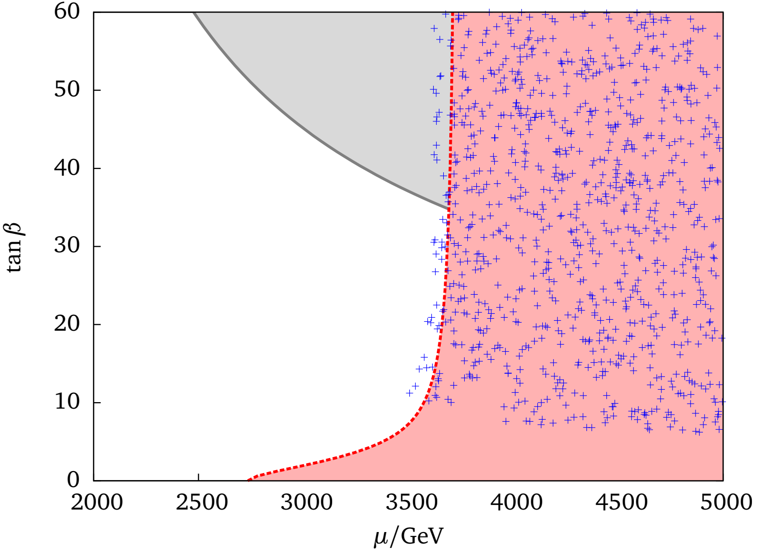
12

[WGH: PLB752 7 (2016)]



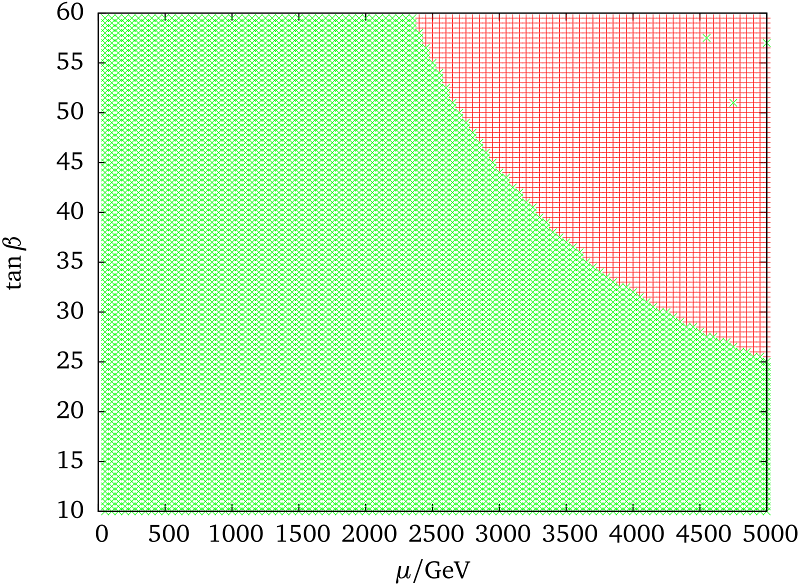
CCB sbottom vev, $h_d = -\sqrt{|h_u|^2 + |\tilde{b}|^2}$

[WGH: PLB752 7 (2016)]

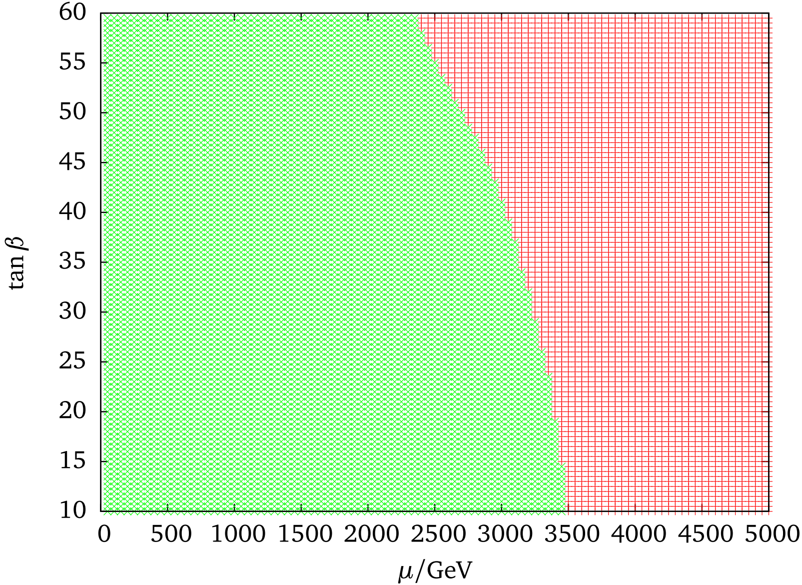


CCB sbottom vev, $h_d = +\sqrt{|h_u|^2 + |\tilde{b}|^2}$

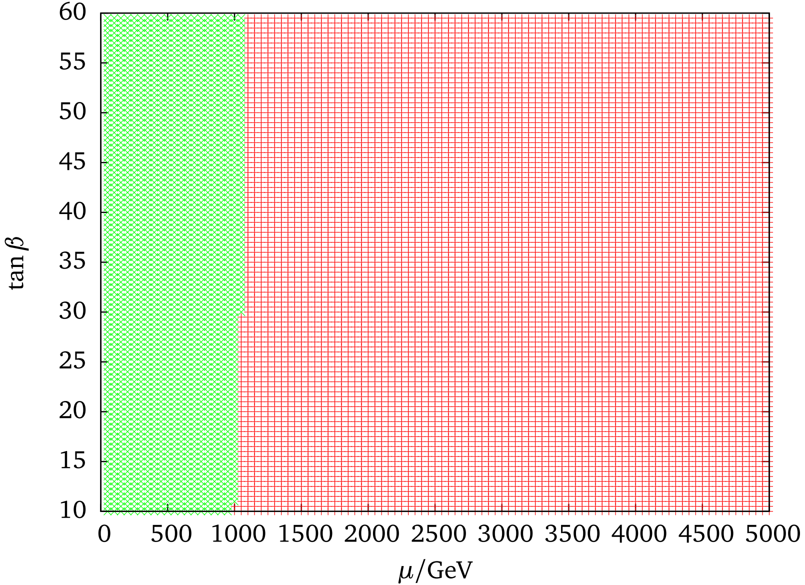
Include more field freedom, extent exclusion bounds.



only h_u, and $\tilde{b}$; $A_b = 0$

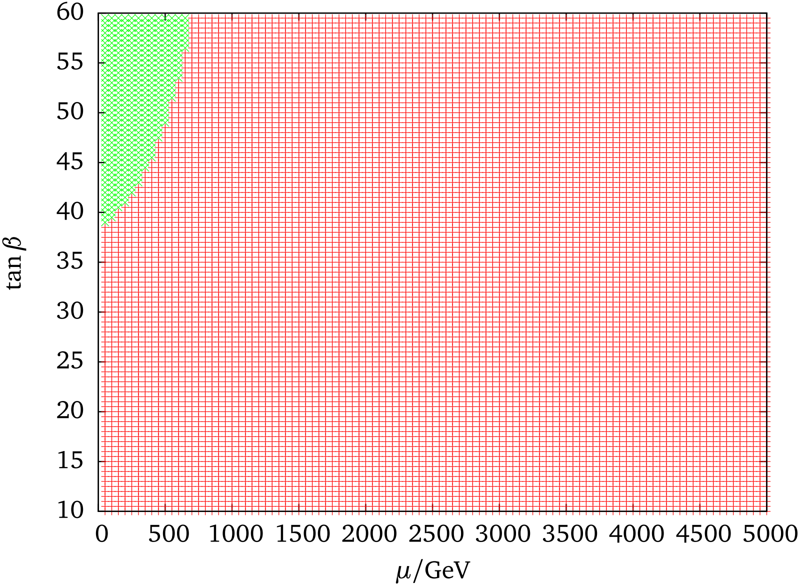


only h_u, h_d, and $\tilde{b}$; $A_b = 0$



only h_u, h_d, $\tilde{t}$, and $\tilde{b}$; $A_b = 0$

More fields, more freedom, stronger (!) bounds MSUSY =1 TeV



only h_u, h_d, $\tilde{t}$, and $\tilde{b}$; $A_b = A_t = -1500\,\mathrm{GeV}$

"A-parameter" bounds

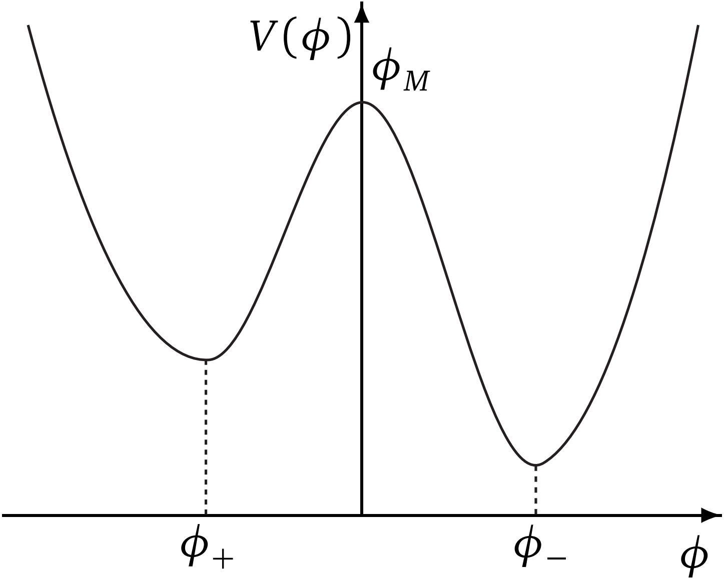
$$4\lambda(\eta,\alpha,\beta)M^2(\eta,\alpha,\beta) > \left(\mathcal{A}(\eta,\alpha,\beta)\right)^2$$

- no unique solution (many combinations possible)
- no clear analytic bound (no robust exclusion)
- numerical exclusions possible
- may run into deep minimum at $\eta, \alpha, \beta \gg 1$
- find pathologic configurations

Global minimum (true vacuum) vs. local minima and saddle points

How much excluded is an excluded point?

Tunneling = Tunneling?


$V(\phi)$
ϕ_M
ϕ_+
ϕ_-
ϕ

Decay probability (per unit volume)

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

[Coleman '77]

Some approximation...

$$B = \frac{2\pi^2}{3} \frac{\left[(\Delta\phi_+)^2 - (\Delta\phi_-)^2\right]^2}{\Delta V_+}$$

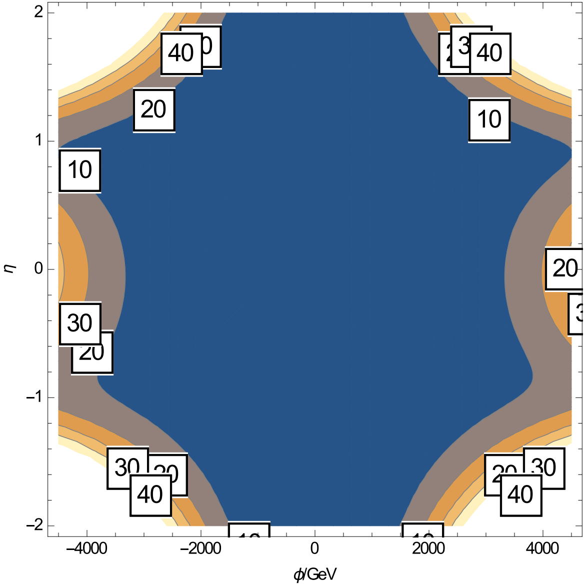
[Duncan, Jensen '92]

Metastability bound

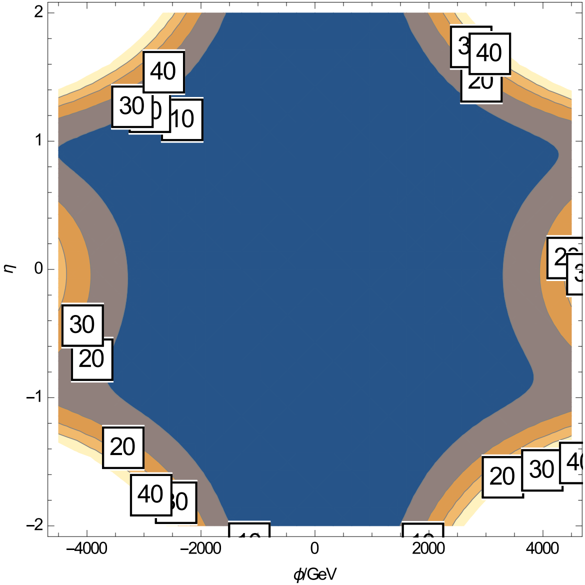
$$B \gtrsim 400$$

- value of B depends on path
- different conclusions for different η, α, β

Tomography of the scalar potential—sbottom direction

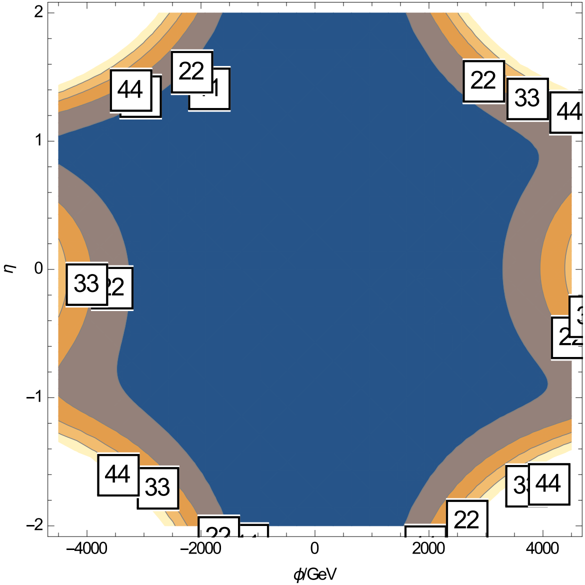


$\tilde{b} = 0 h_u,\ h_d = \eta h_u$



$$\tilde{b} = 0.1 h_u,\ h_d = \eta h_u$$

Tomography of the scalar potential—sbottom direction



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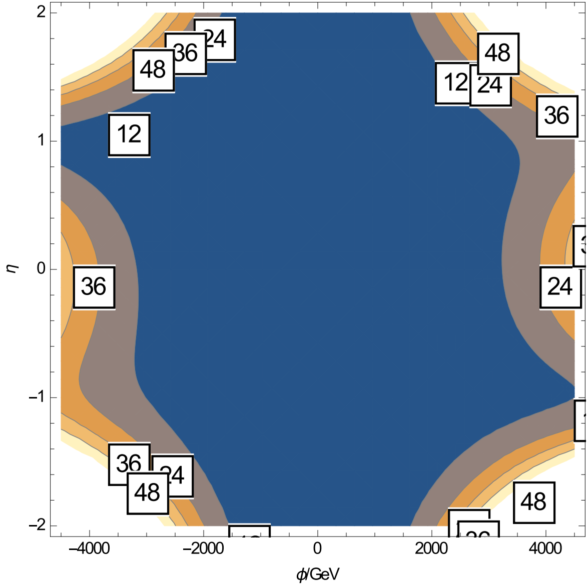
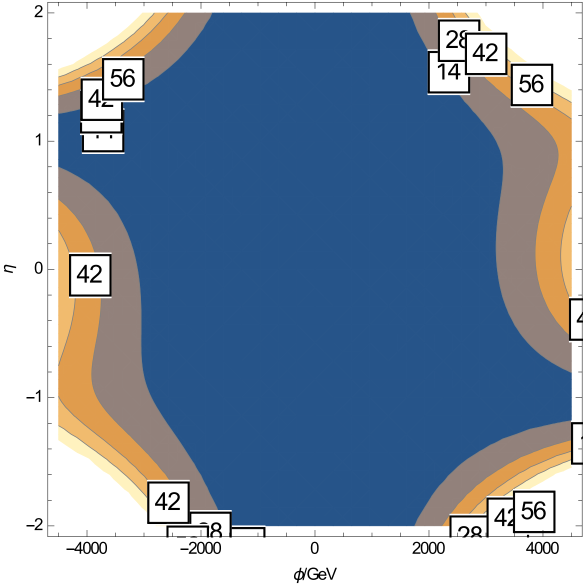


$\tilde{b} = 0.3h_u,\ h_d = \eta h_u$



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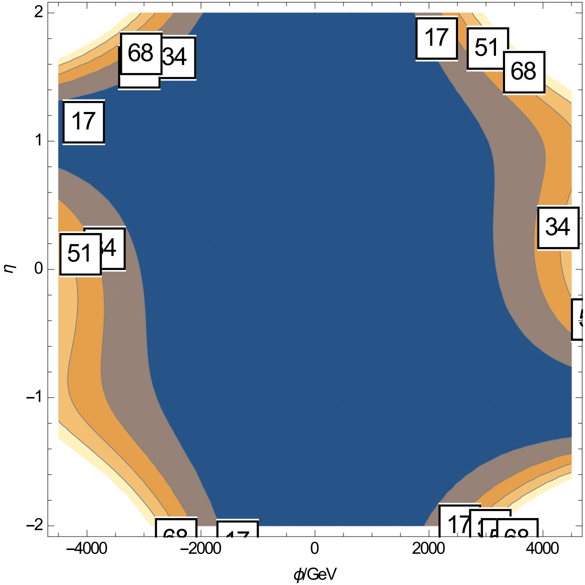
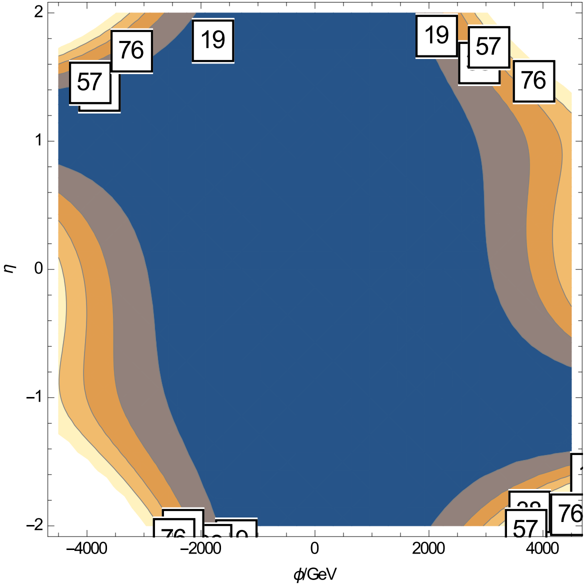
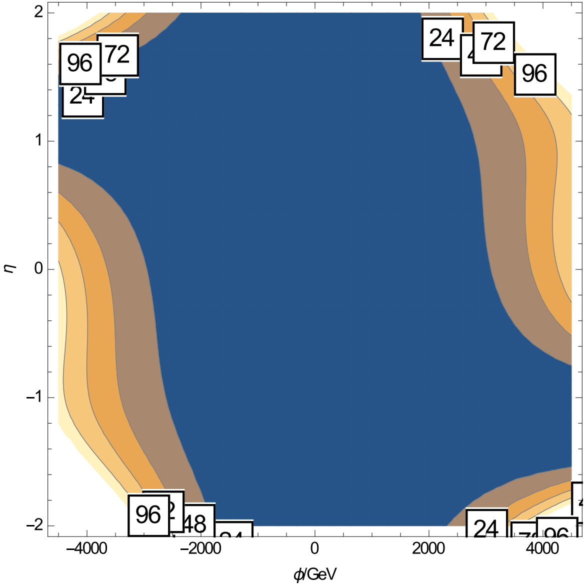


$\tilde{b} = 0.5 h_u,\ h_d = \eta h_u$

Tomography of the scalar potential—sbottom direction



$$\tilde{b} = 0.6 h_u,\ h_d = \eta h_u$$



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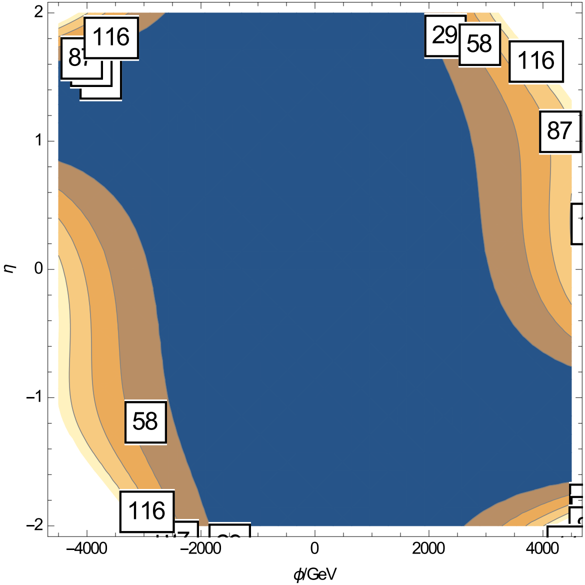

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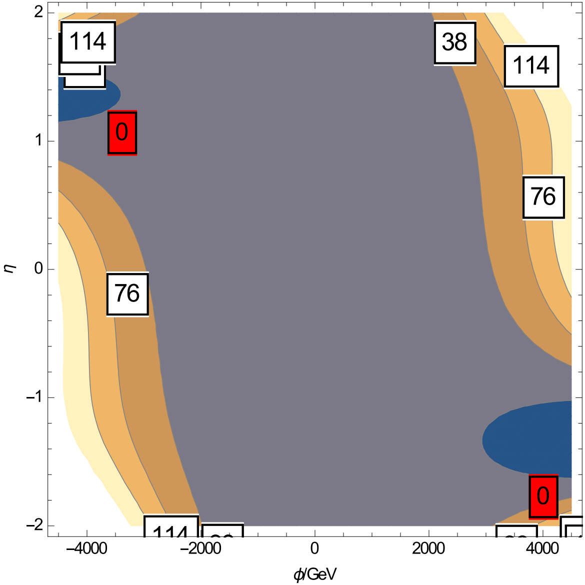

$\tilde{b} = 0.9h_u,\ h_d = \eta h_u$

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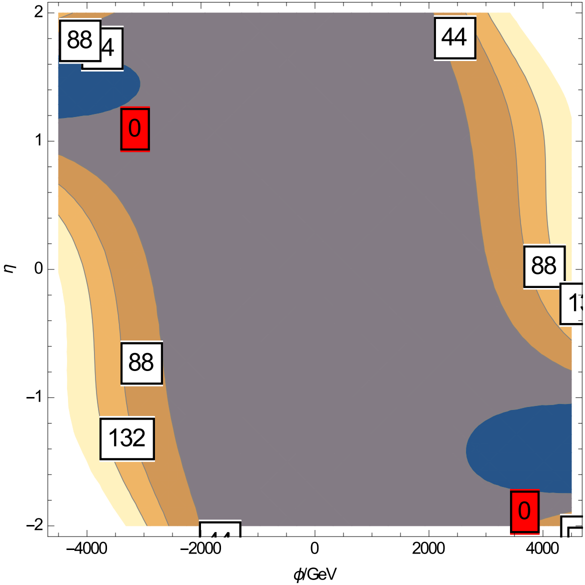

$$\tilde{b} = 1.0 h_u,\ h_d = \eta h_u$$

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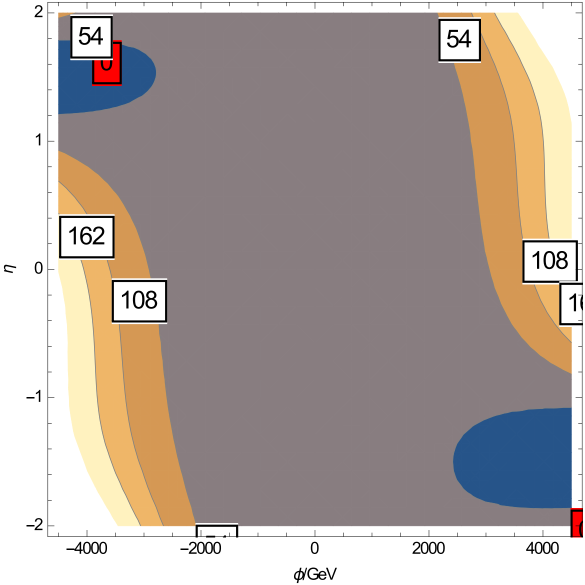

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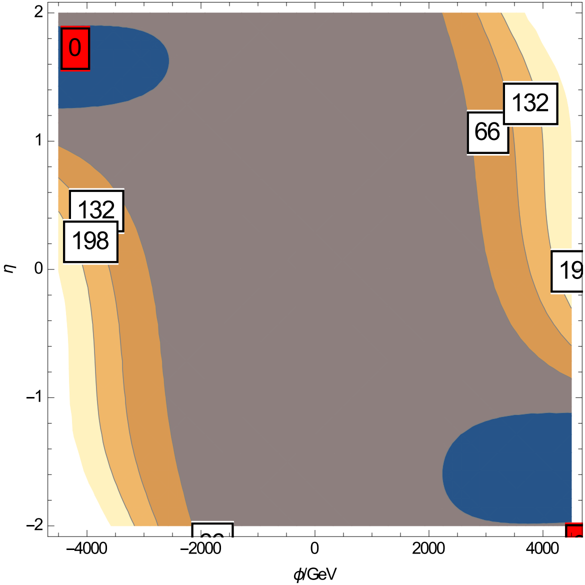

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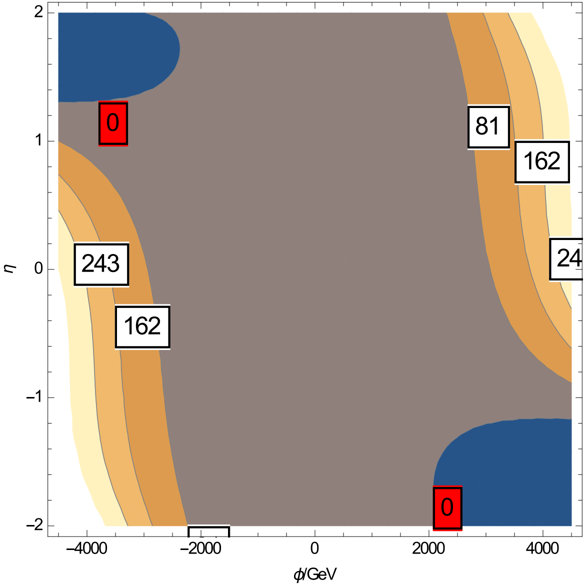

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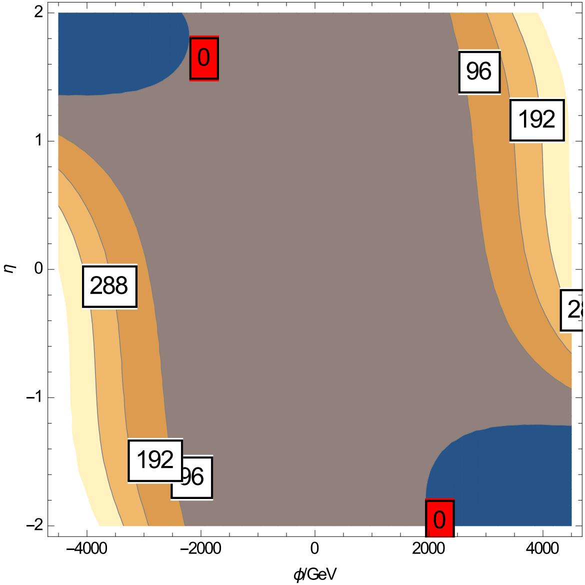

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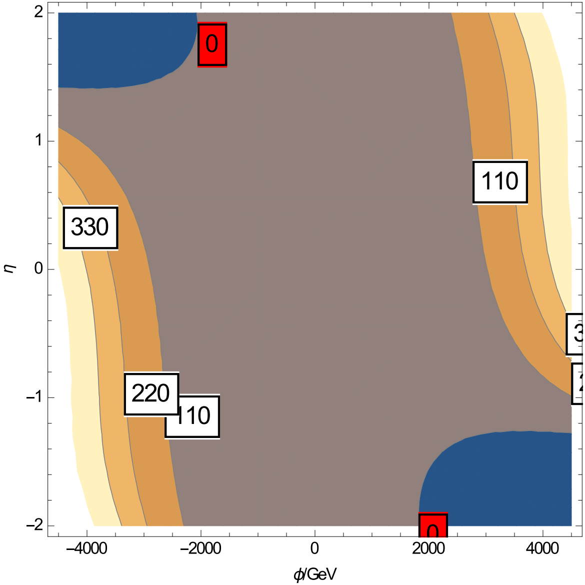

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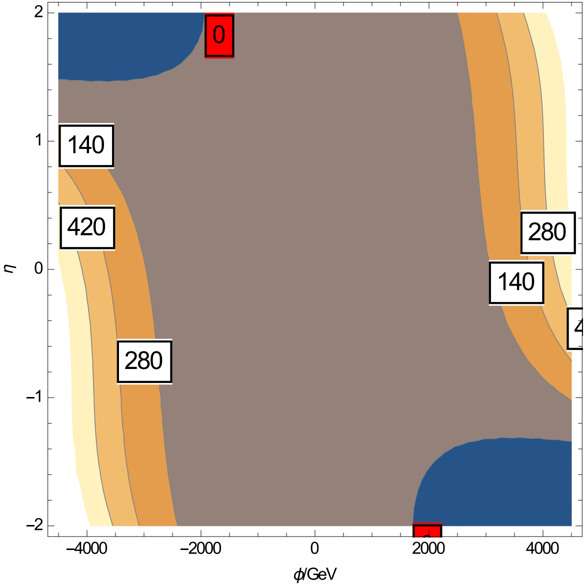

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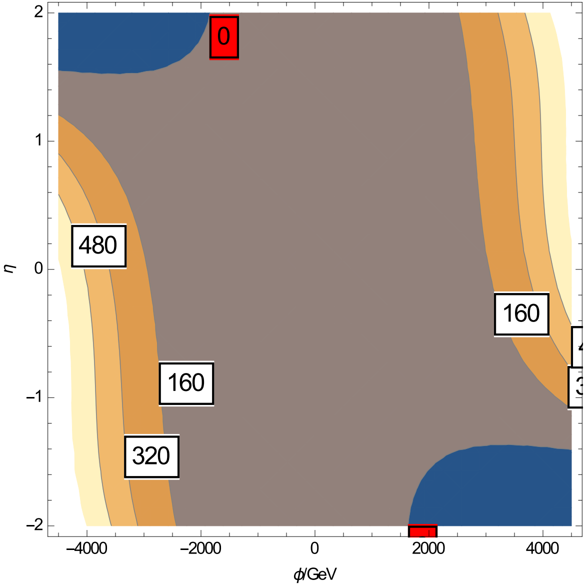

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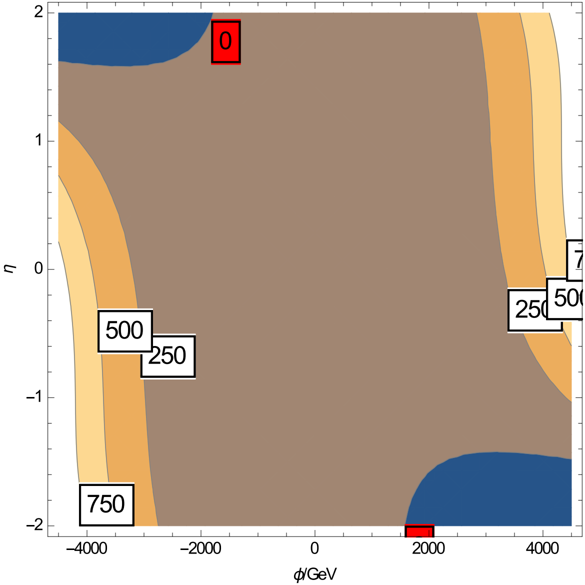

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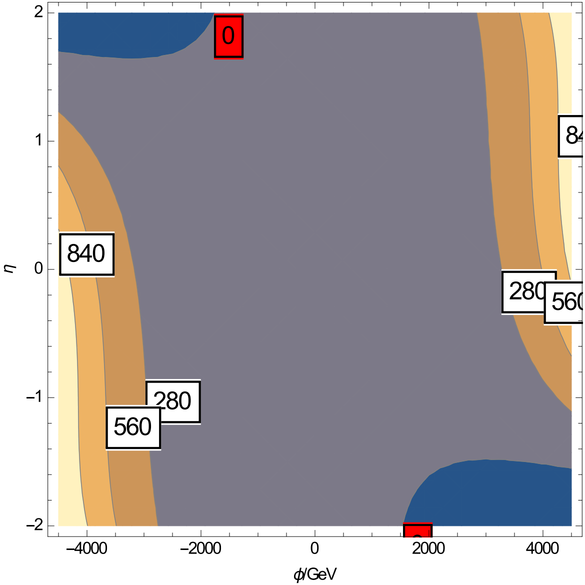

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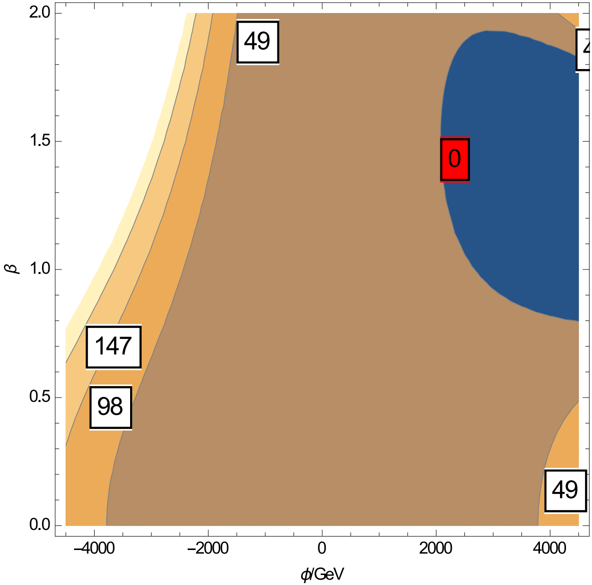
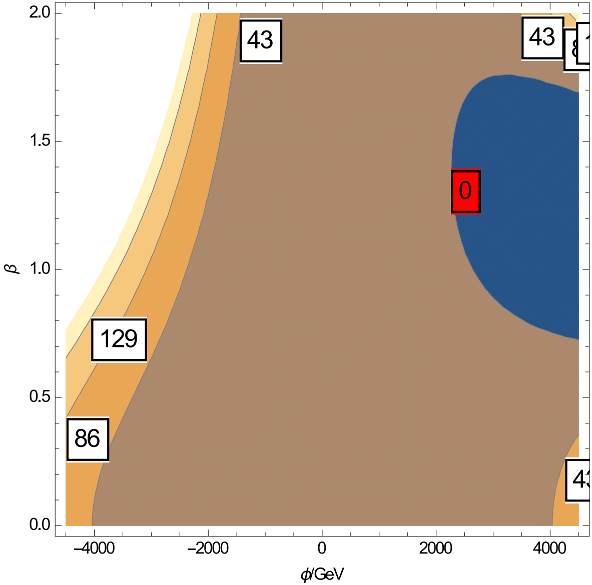
Tomography of the scalar potential—h_d direction



$$\tilde{h}_d = -1.5 h_u,\ \tilde{b} = \beta h_u$$

Tomography of the scalar potential—h_d direction



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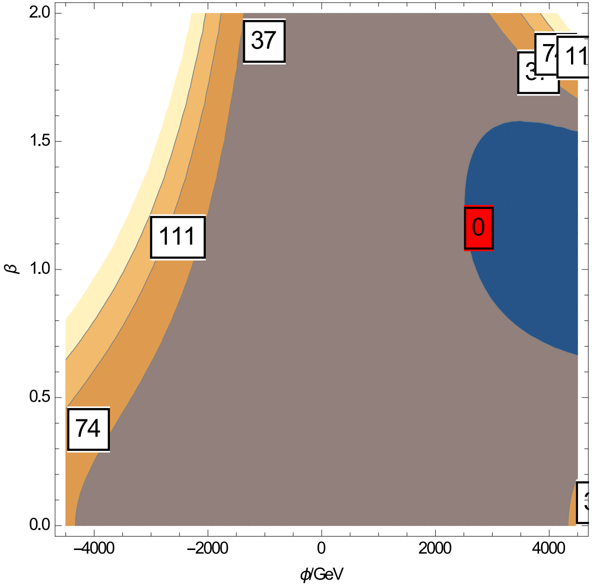

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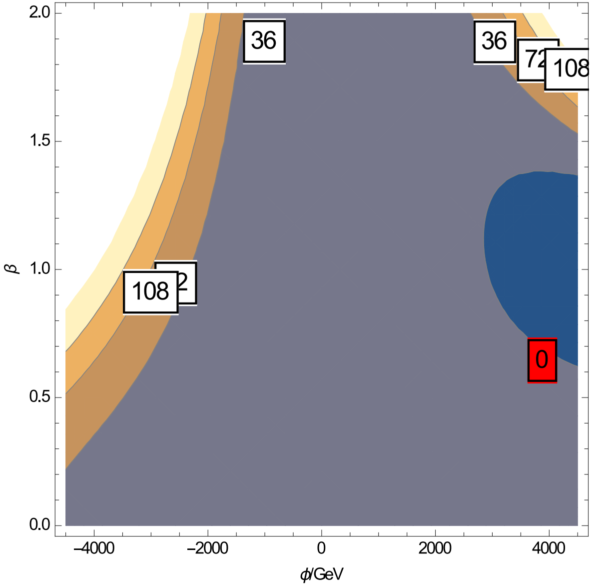

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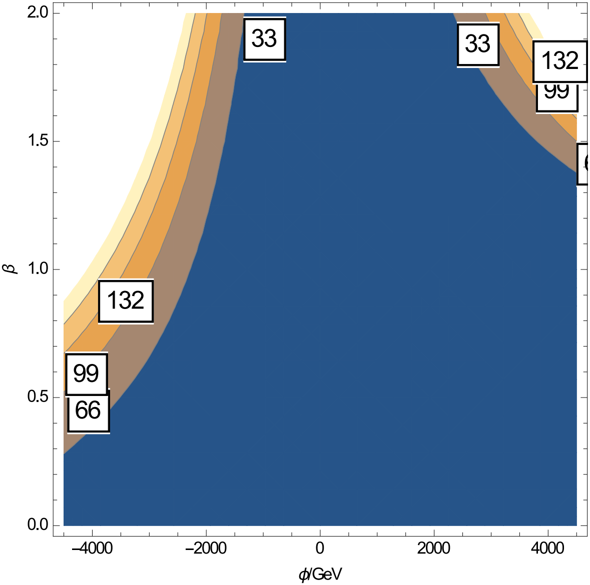

$$\tilde{h}_d = -1.1 h_u,\ \tilde{b} = \beta h_u$$

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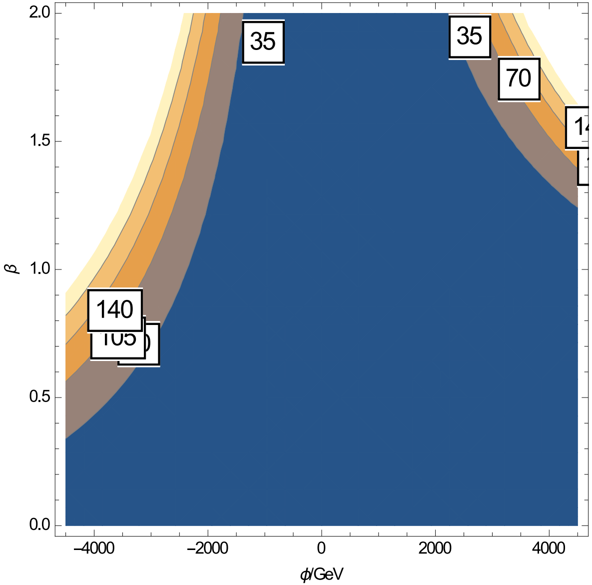

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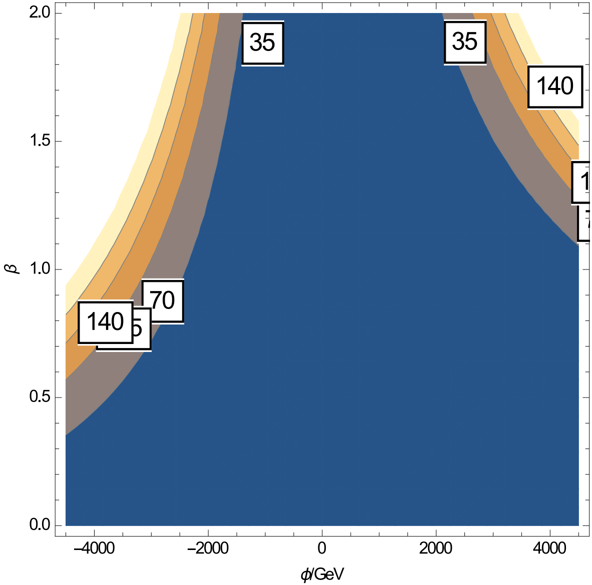

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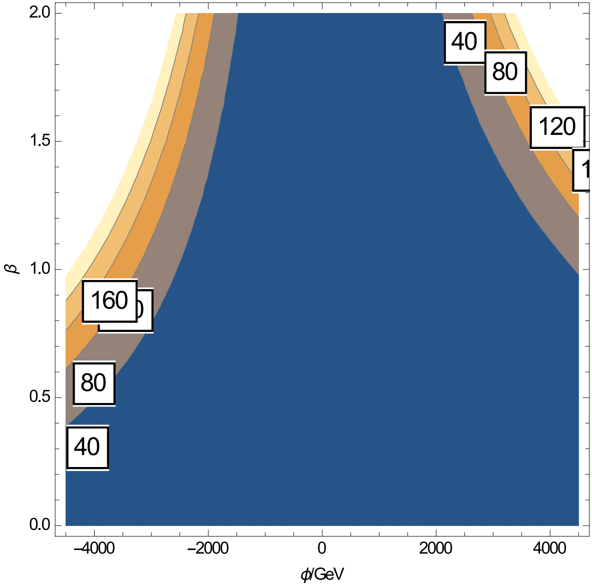

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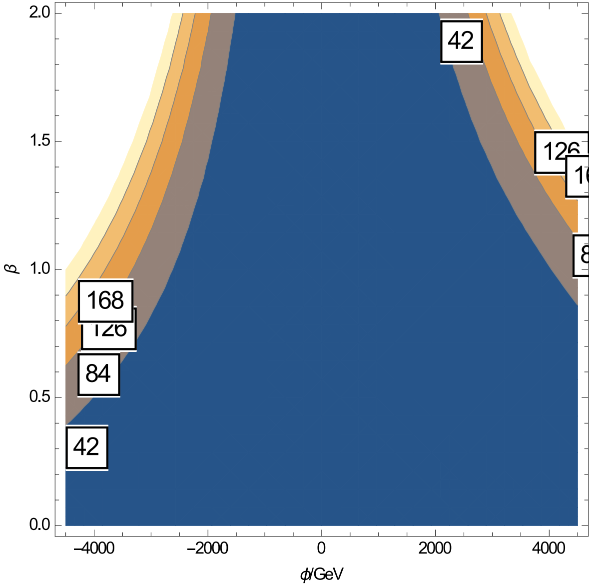

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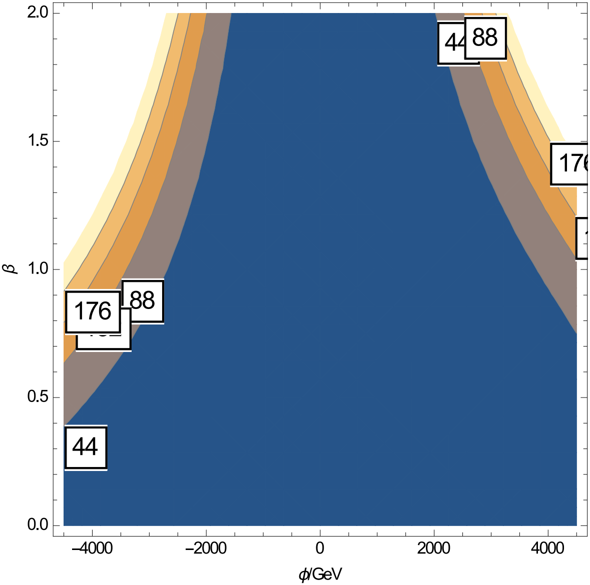

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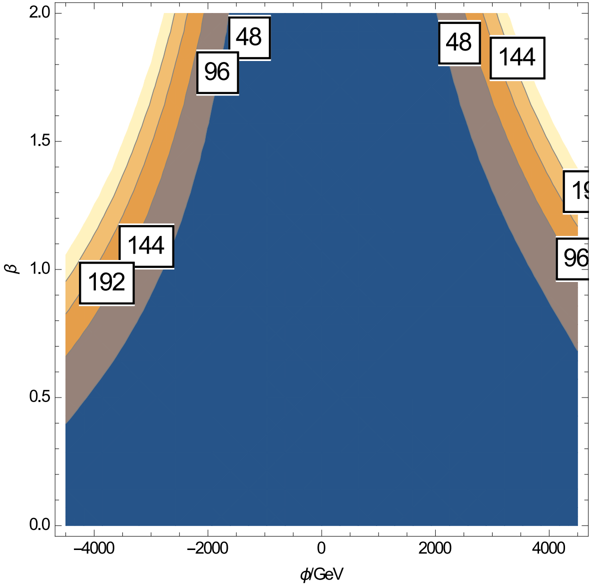
Tomography of the scalar potential—h_d direction



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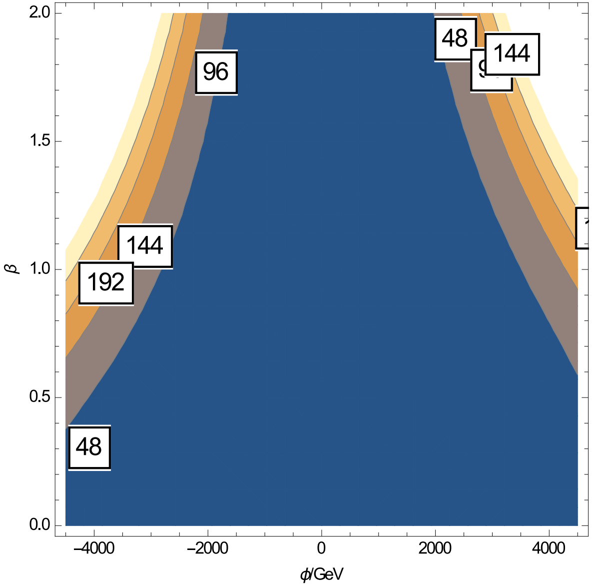

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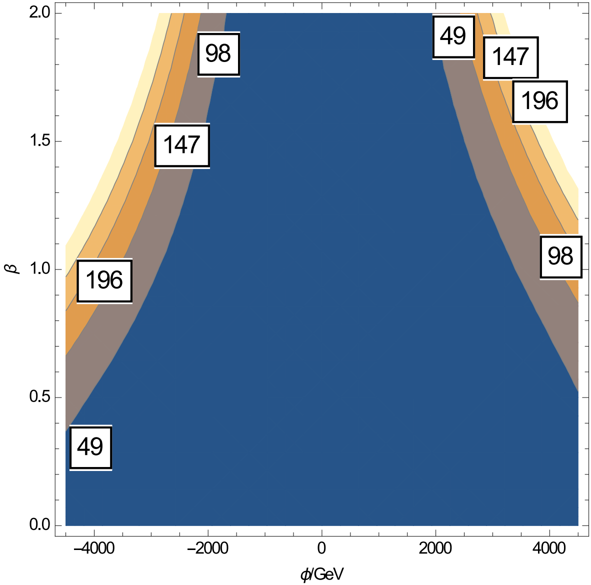

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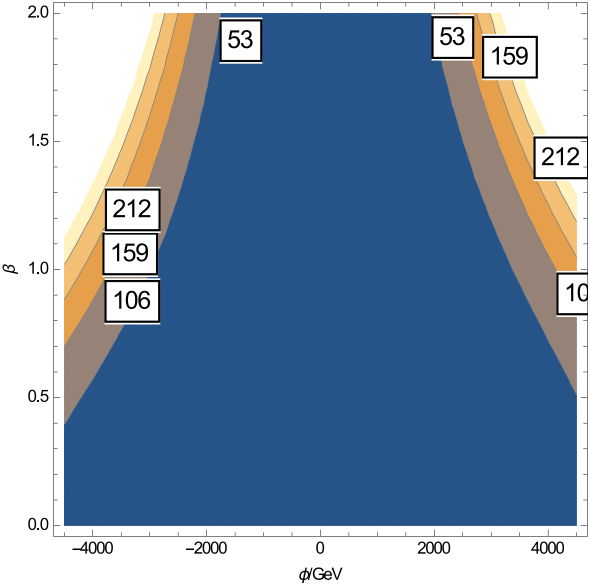

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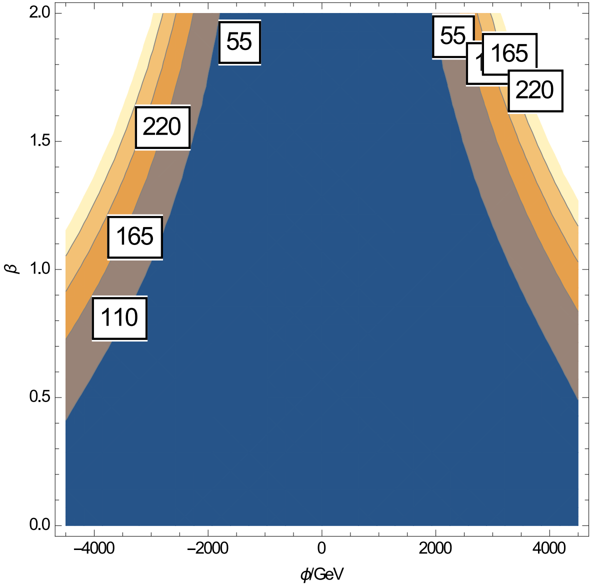

$$\tilde{h}_d = -0.1 h_u,\ \tilde{b} = \beta h_u$$

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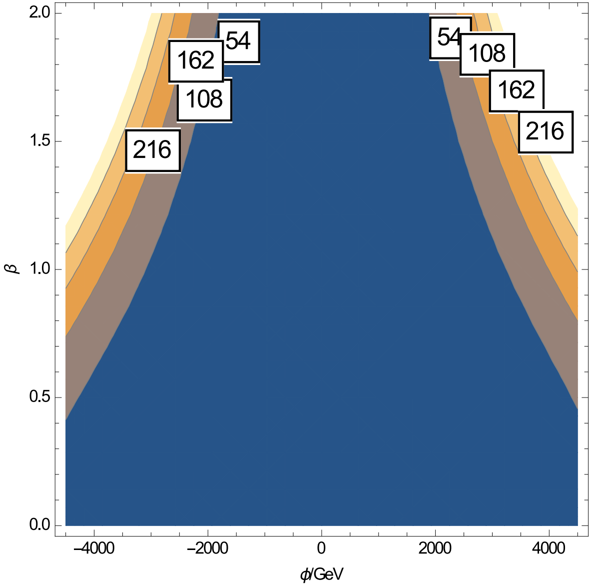

$$\tilde{h}_d = 0h_u,\ \tilde{b} = \beta h_u$$

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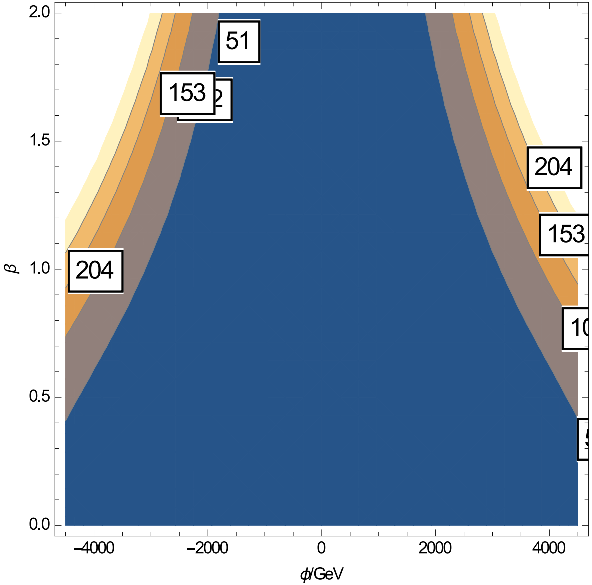

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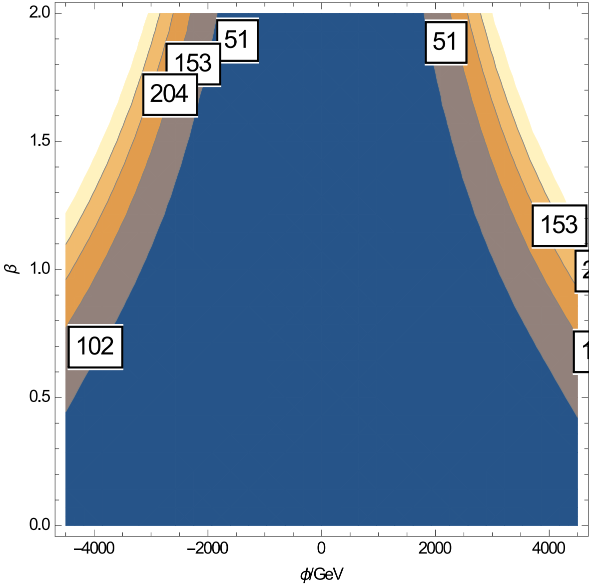

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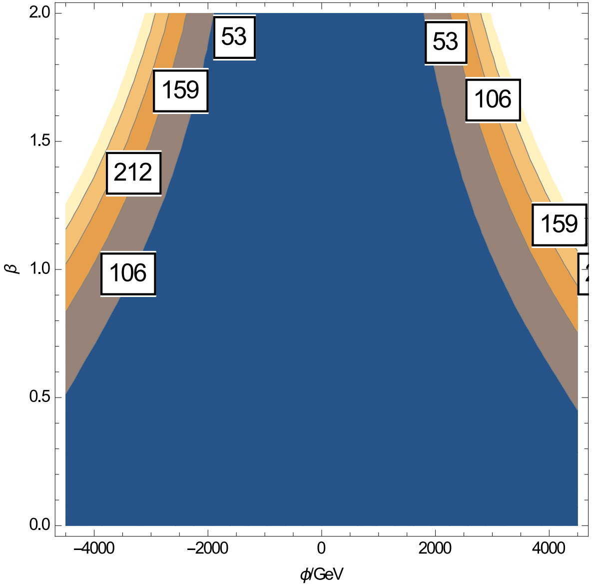

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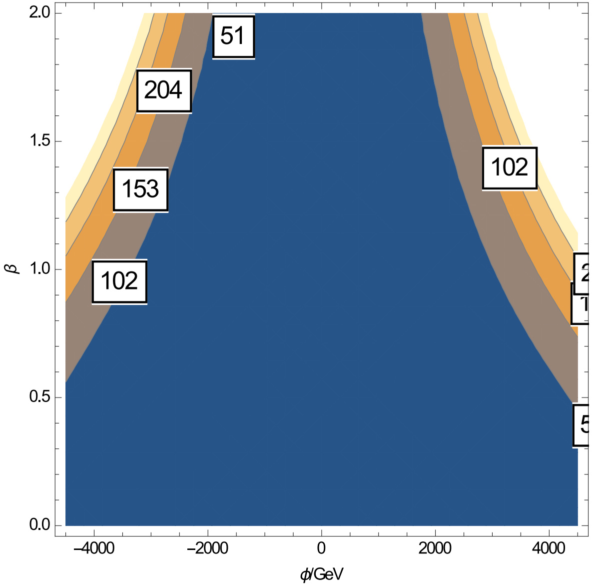

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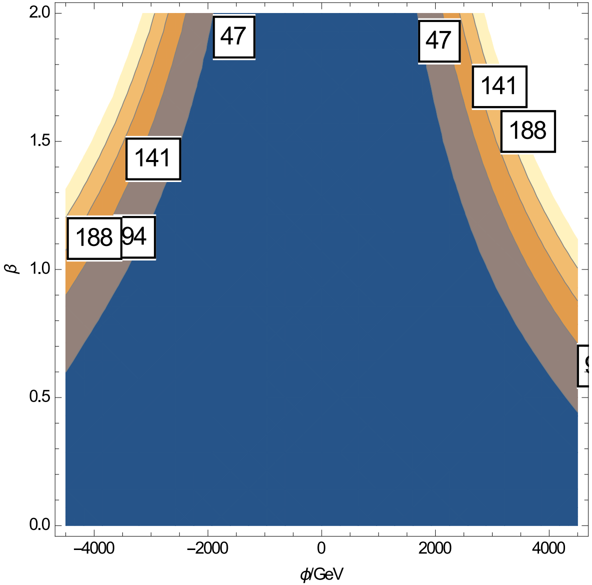

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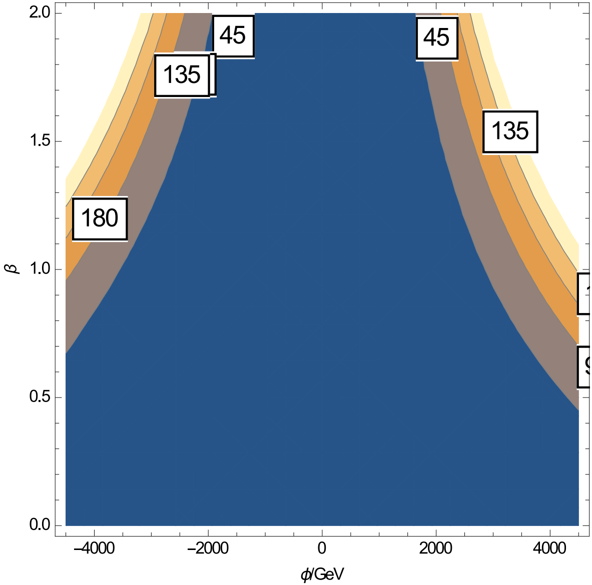

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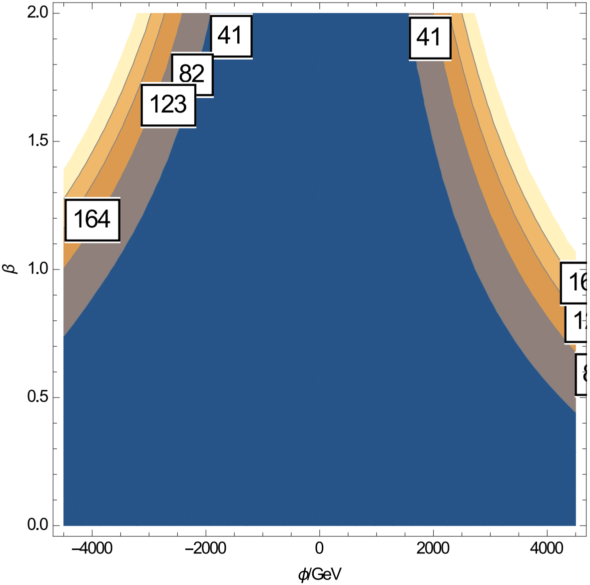

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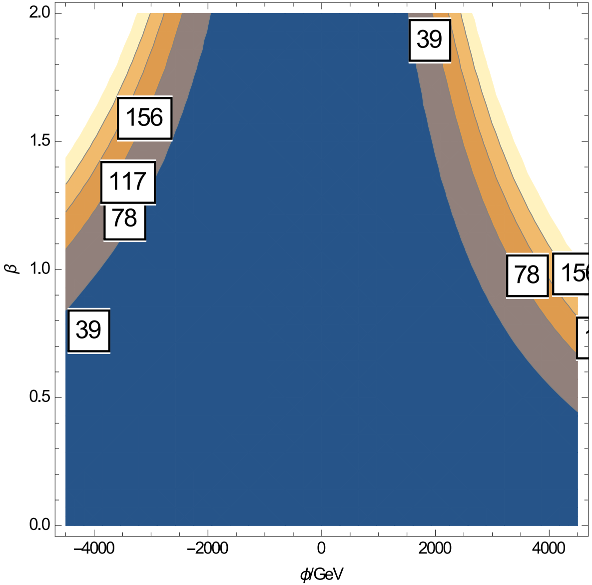

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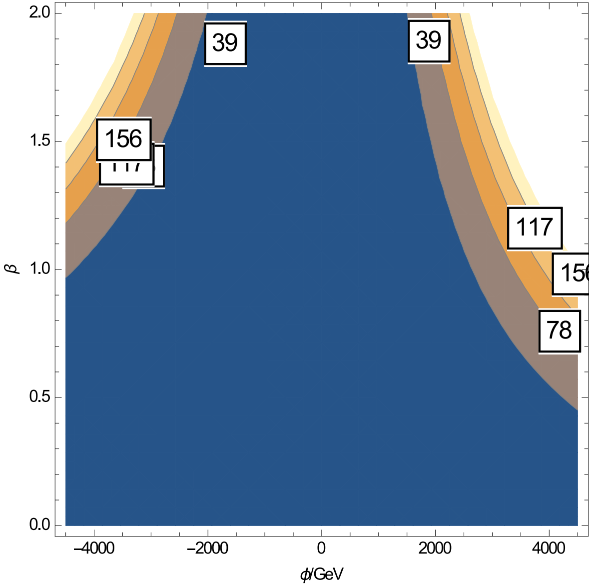

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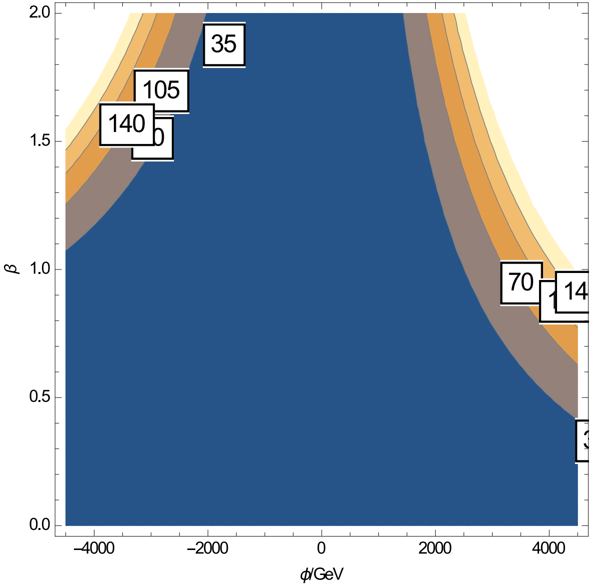
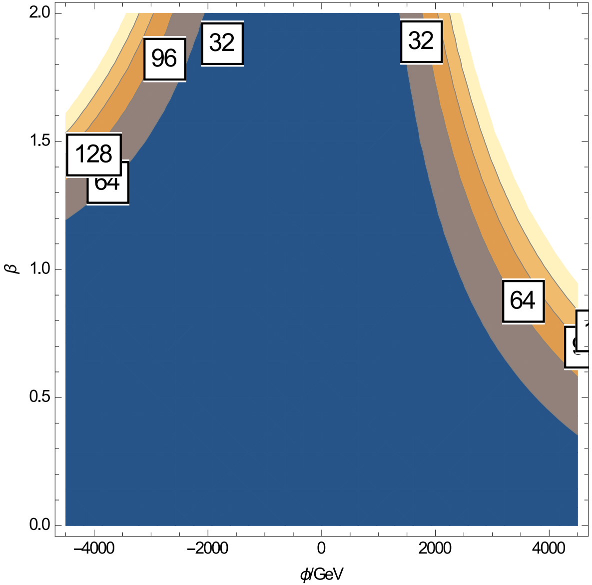


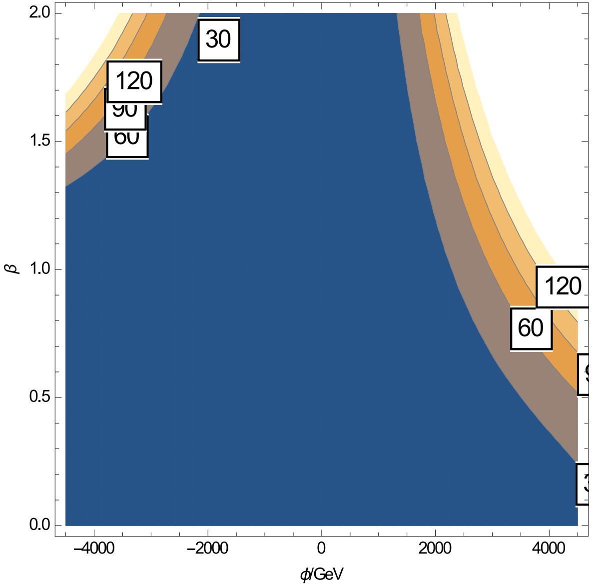
$$\tilde{h}_d = 1.0 h_u,\ \tilde{b} = \beta h_u$$

Tomography of the scalar potential—h_d direction



$\tilde{h}_d = 1.1h_u,\ \tilde{b} = \beta h_u$

Tomography of the scalar potential—h_d direction



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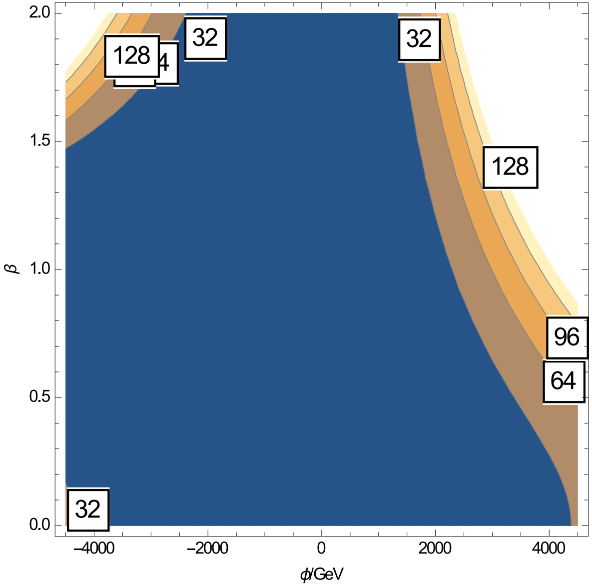

$\tilde{h}_d = 1.3 h_u,\ \tilde{b} = \beta h_u$

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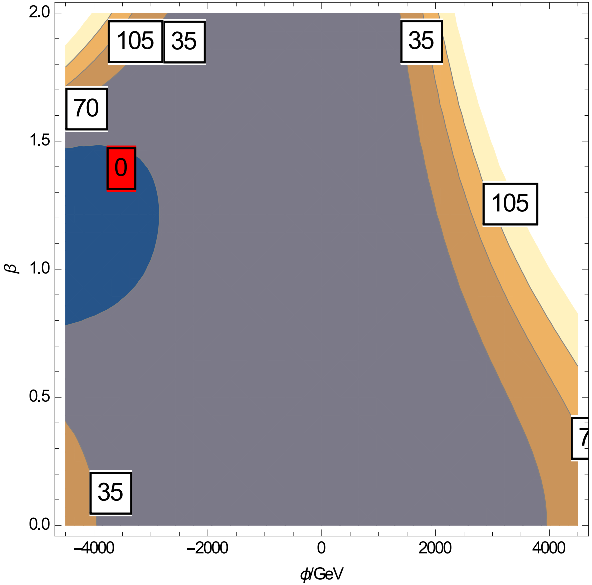

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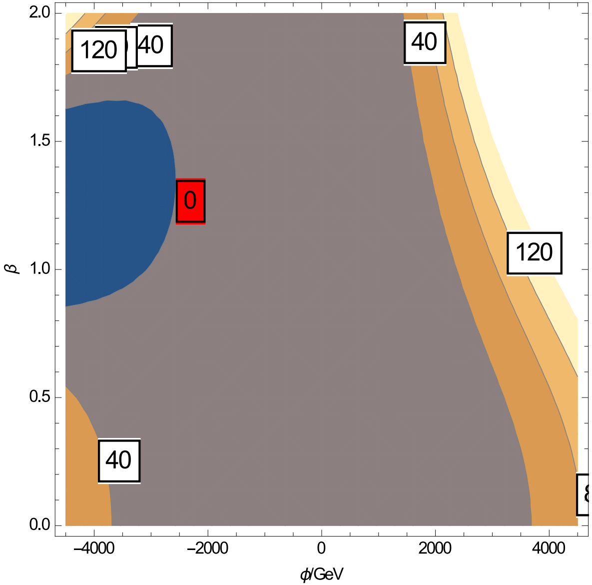
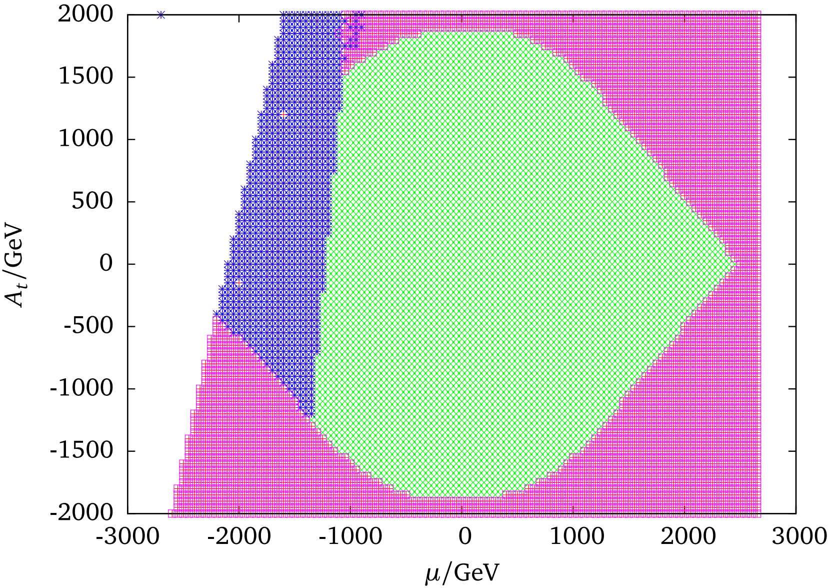
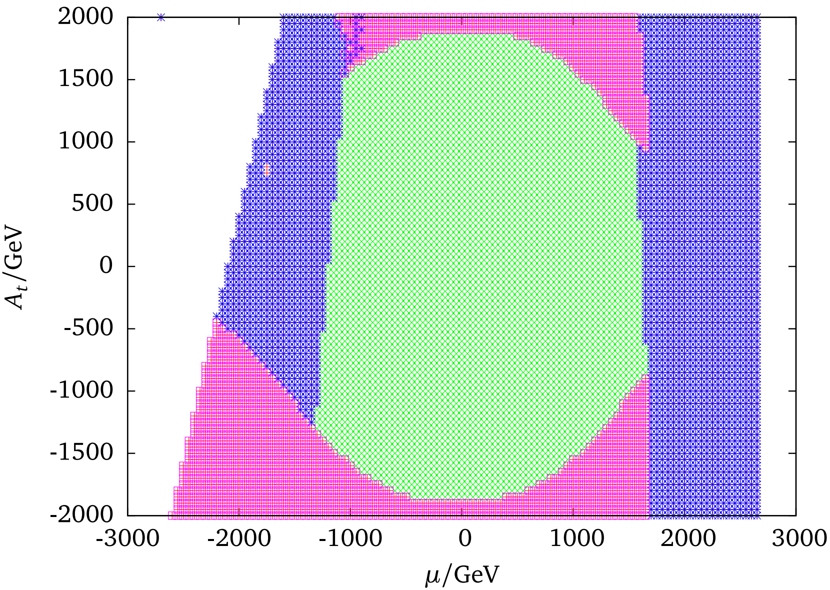


$$\tilde{h}_d = 1.5h_u,\ \tilde{b} = \beta h_u$$

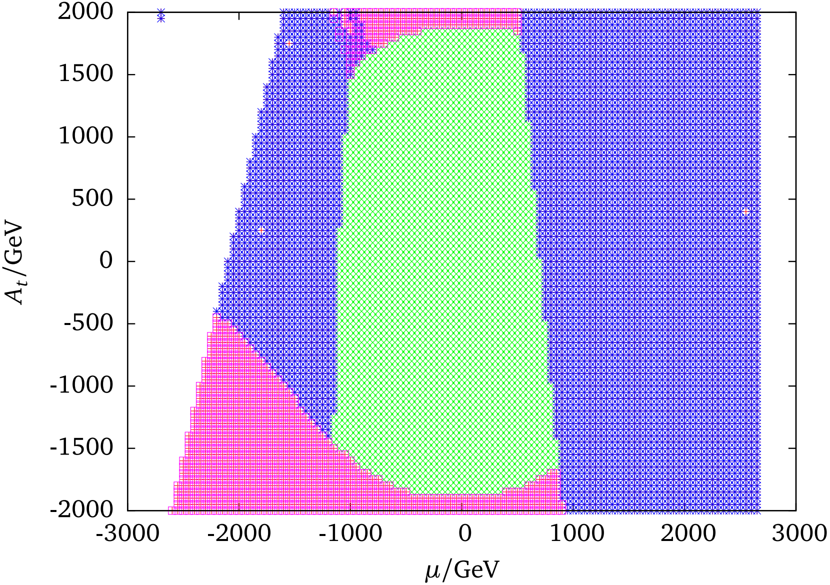
- no pocket-calculator formula :-(
- numerical/graphical exclusion limits in μ-$\tan\beta$-A_t-A_b



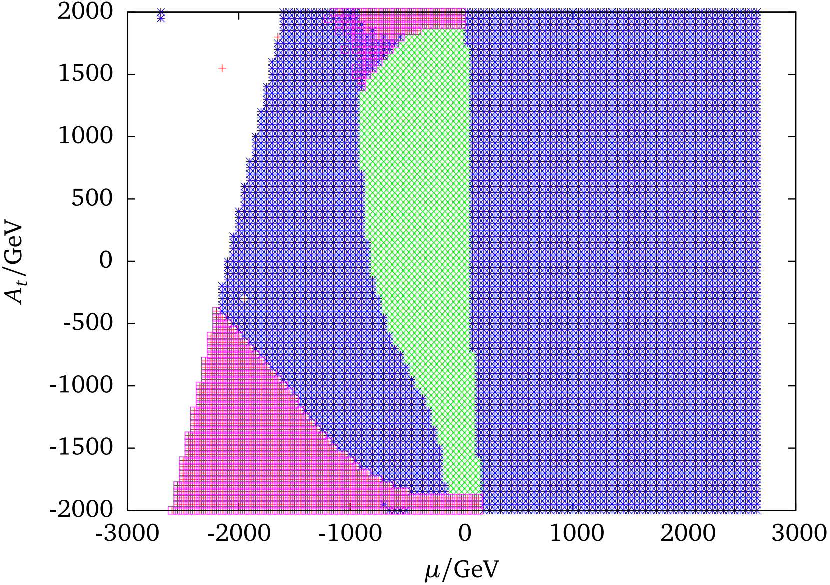
$A_b = 0\,\mathrm{GeV}$



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



$A_b = 1000\,\mathrm{GeV}$



$A_b = 1500\,\mathrm{GeV}$

- charge and color breaking constraints complementary to direct searches
- check for theoretical consistency
- a closer view reveals very strong constraints

Simple analytic formulae — by far not the strongest bounds

- $|\tilde{t}_L| = |\tilde{t}_R| = |h_u|$

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

[Gunion, Haber, Sher '88]

- $|\tilde{b}_L| = |\tilde{b}_R| = |h_u|$

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

[WGH '15]

Actually more involved!

- charge and color breaking constraints complementary to direct searches
- check for theoretical consistency
- a closer view reveals very strong constraints

Simple analytic formulae — by far not the strongest bounds

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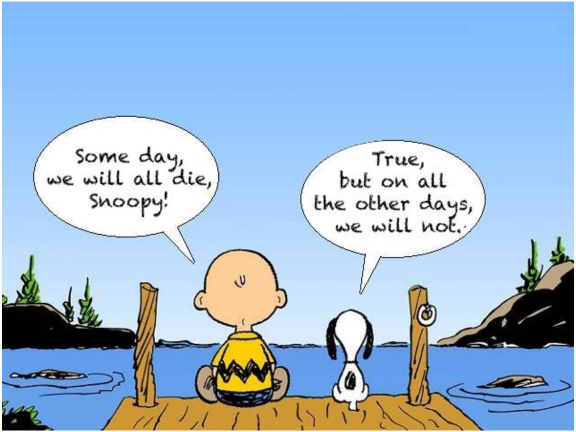
[WGH '15]

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



All the details: `arXiv:1606.0xxxx`

Backup

Slides

Yukawa coupling not directly proportional to mass (same for y_t)

$$y_b = \frac{m_b}{v_d(1+\Delta_b)}$$

[Hall, Rattazzi, Sarid '94; Carena, Garcia, Nierste, Wagner '99]

$$\Delta_b^{\text{gluino}} = \frac{2\alpha_s}{3\pi}\mu M_{\tilde{G}} \tan\beta C_0(\tilde{m}_{\tilde{b}_1}, \tilde{m}_{\tilde{b}_2}, M_{\tilde{G}}),$$
$$\Delta_b^{\text{higgsino}} = \frac{Y_t^2}{16\pi^2}\mu A_t \tan\beta C_0(\tilde{m}_{\tilde{t}_1}, \tilde{m}_{\tilde{t}_2}, \mu).$$