A stable vacuum: why we found no SUSY

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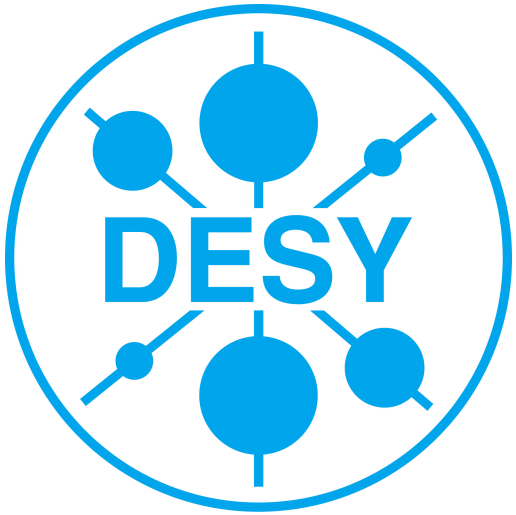
Wolfgang Gregor Hollik



DESY Hamburg, Theory Group

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The Standard Model (In)Stability

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

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

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The MSSM: less simple

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

with (only 3rd generation squarks and Higgses; intro to MSSM omitted)

$$\begin{aligned} V_{\text{soft}} = {} & m_{H_\text{d}}^2 |h_\text{d}|^2 + m_{H_\text{u}}^2 |h_\text{u}|^2 - (B_\mu h_\text{d} \cdot h_\text{u} + \text{h. c. }) \\ & + \tilde{t}_\text{L}^* \tilde{m}_Q^2 \tilde{t}_\text{L} + \tilde{t}_\text{R}^* \tilde{m}_t^2 \tilde{t}_\text{R} + \tilde{b}_\text{L}^* \tilde{m}_Q^2 \tilde{b}_\text{L} + \tilde{b}_\text{R}^* \tilde{m}_b \tilde{b}_\text{R} \\ & + \left(A_\text{t} h_\text{u} \tilde{t}_\text{L}^* \tilde{t}_\text{R} + A_\text{b} h_\text{d} \tilde{b}_\text{L}^* \tilde{b}_\text{R} + \text{h. c. } \right) \end{aligned}$$

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
- SUSY threshold corrections for m_b influence y_b

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An analytic solution?

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An analytic solution?

impossible!

Simplifications apparently possible...

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

with $h_u = \phi$, $h_d = \eta\phi$ ($\phi, \eta \in \mathbb{R}$) and $|\tilde{t}|^2 = \alpha^2\phi^2$, $|\tilde{b}|^2 = \beta^2\phi^2$, such that $m^2, A, \lambda = f(\eta, \alpha, \beta)$

Existing 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.)

$$A_{\mathrm{t}}^2 < 3(m_{H_u}^2 + |\mu|^2 + \tilde{m}_Q^2 + \tilde{m}_t^2)$$

[Frère et al. '83, Gunion et al. '88, Casas et al. '96]

A generalization [WGH '16]

$$\min_{\{\eta,\alpha,\beta\}} \left[4\lambda(\eta,\alpha,\beta)\, m^2(\eta,\alpha,\beta) - (A(\eta,\alpha,\beta))^2\right] > 0$$

Why do we need a reassessment?

Done.

- classification of all dangerous directions [Casas, Lleyda, Muñoz '96]
- tool: VeVacious [Camargo-Molina, O'Leary, Porod, Staub '13]

New.

$m_h = 125\,\mathrm{GeV}$ and no sign of SUSY!

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Let us be more open minded...

- no neglect of field directions (i.e. $\eta, \alpha, \beta \neq 0$)
- especially $|\eta| > 1$ allowed (compared to Casas et al.)
- "new" (=true) $\tan\beta < 1$
- and also $h_d \sim -h_u$ (meaning $\eta < 0$)

Constraints in parameter space: μ, $A_{t,b}$, $\tan\beta$, M_{SUSY}, $X_t = A_t/y_t - \mu\cot\beta$

Cosmological stability

bounce action

$$B \gtrsim 400$$

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

Decay probability (per unit volume)

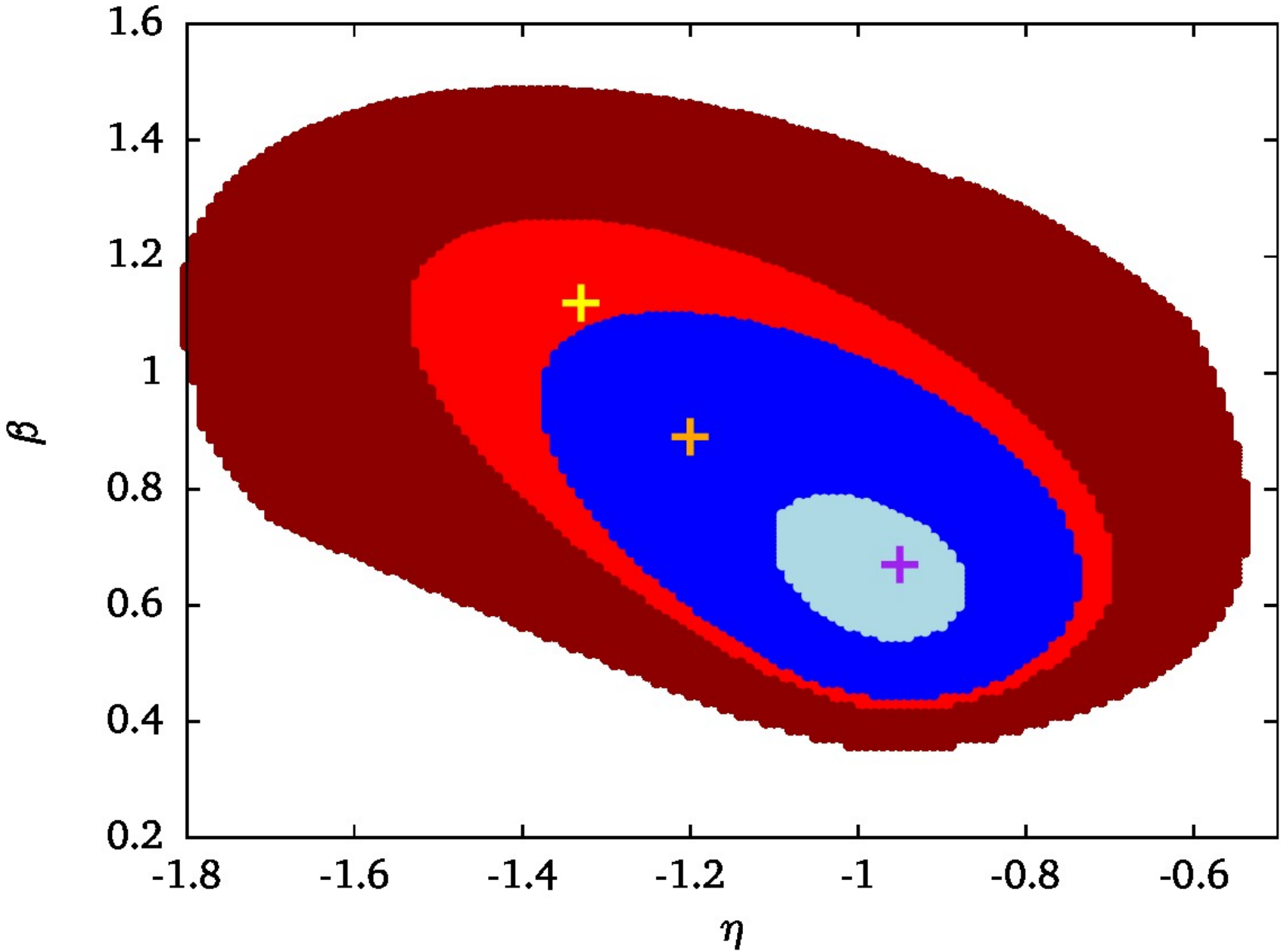
$$\frac{\Gamma}{V} = Ae^{-B/\hbar}$$

[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 $\mu = 500\,\mathrm{GeV}, A_b = A_t = 1500\,\mathrm{GeV}$



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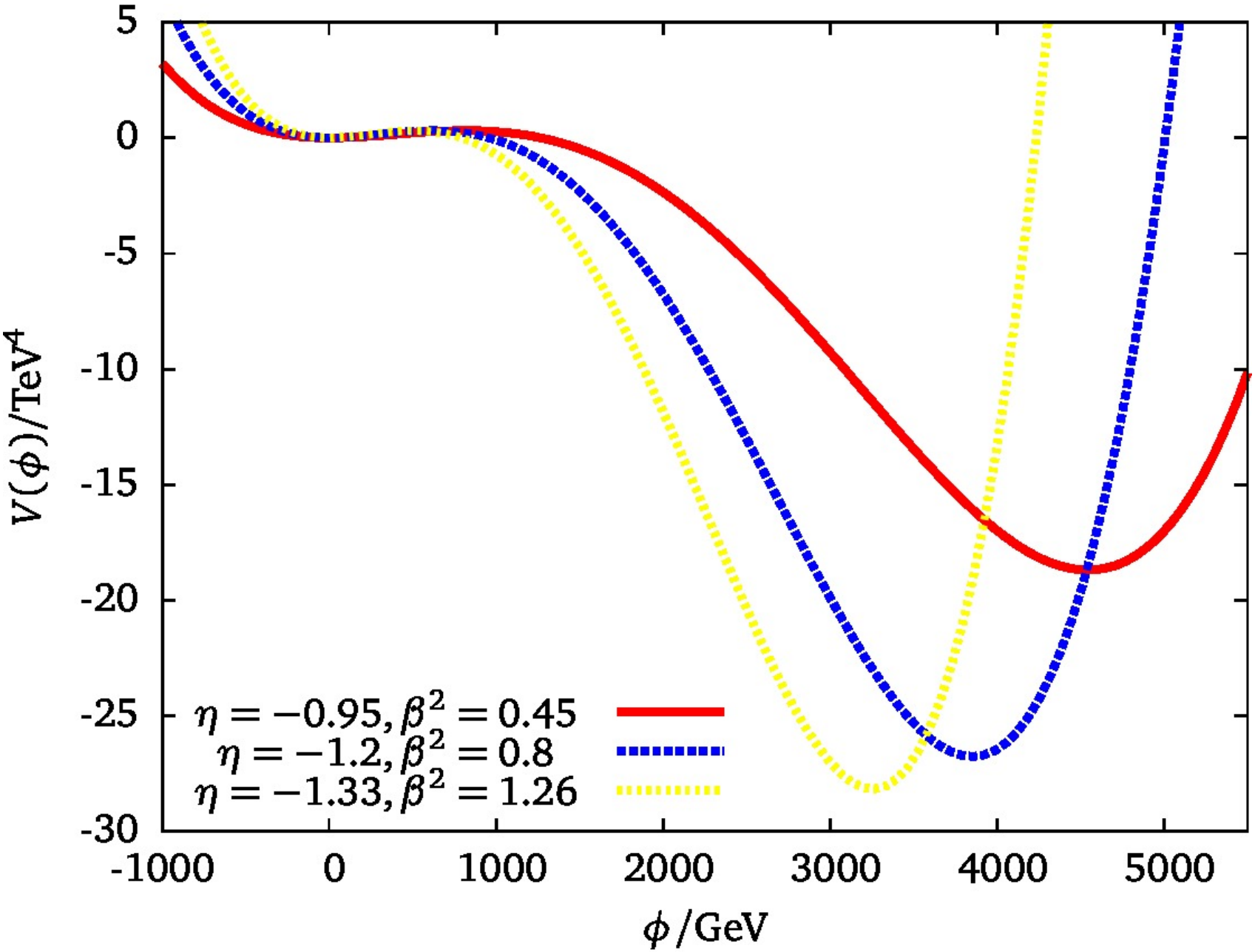
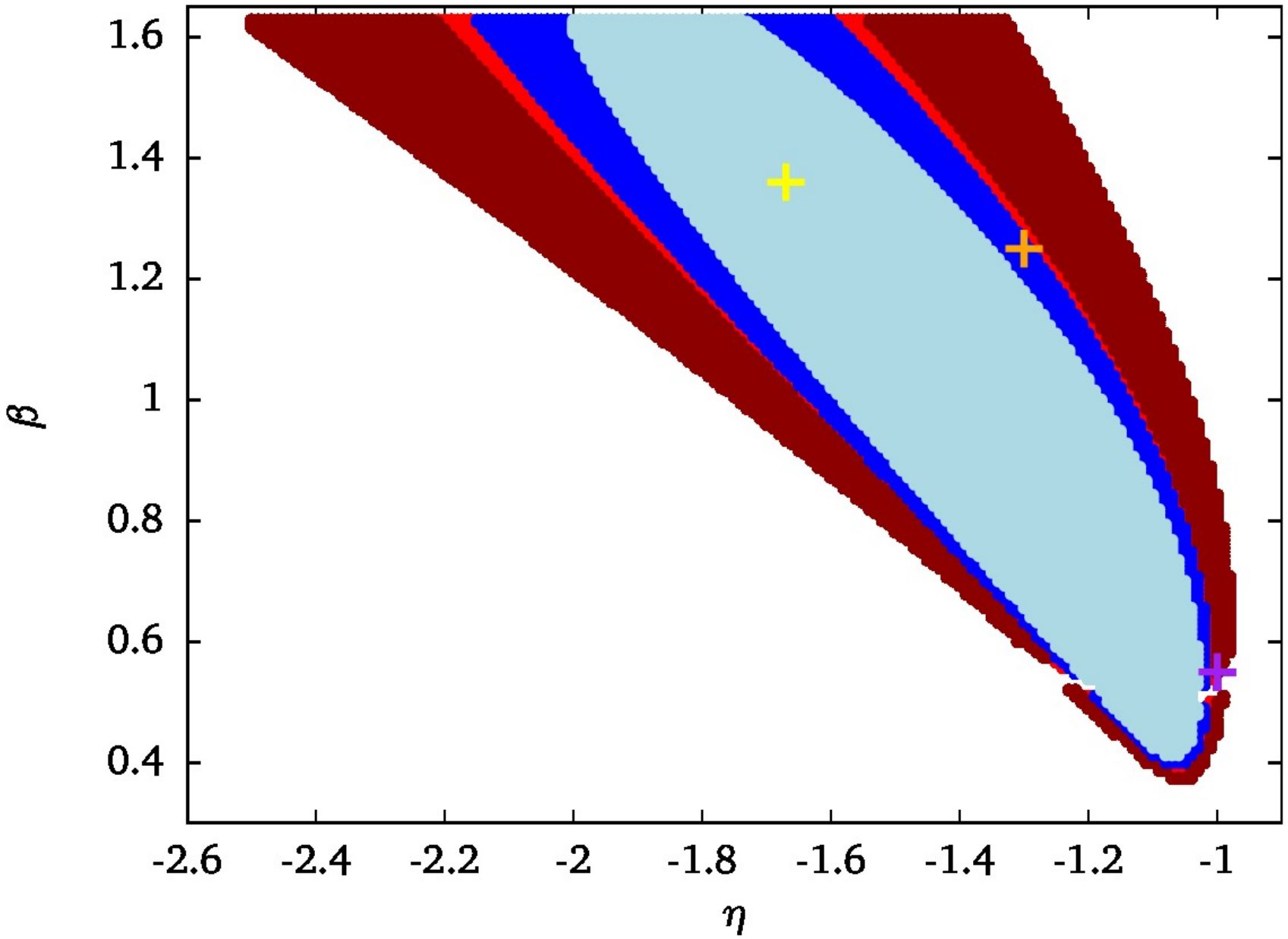
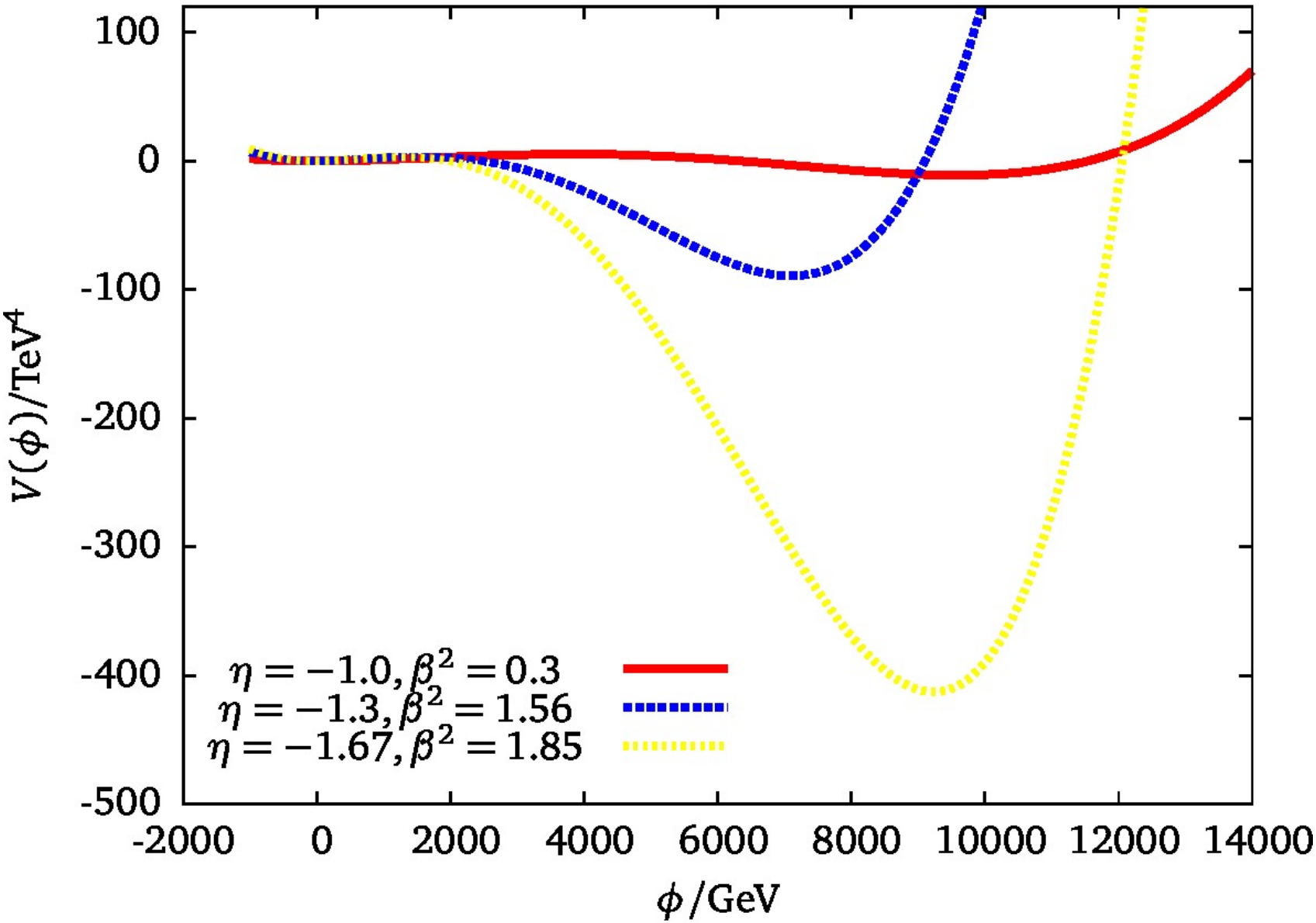
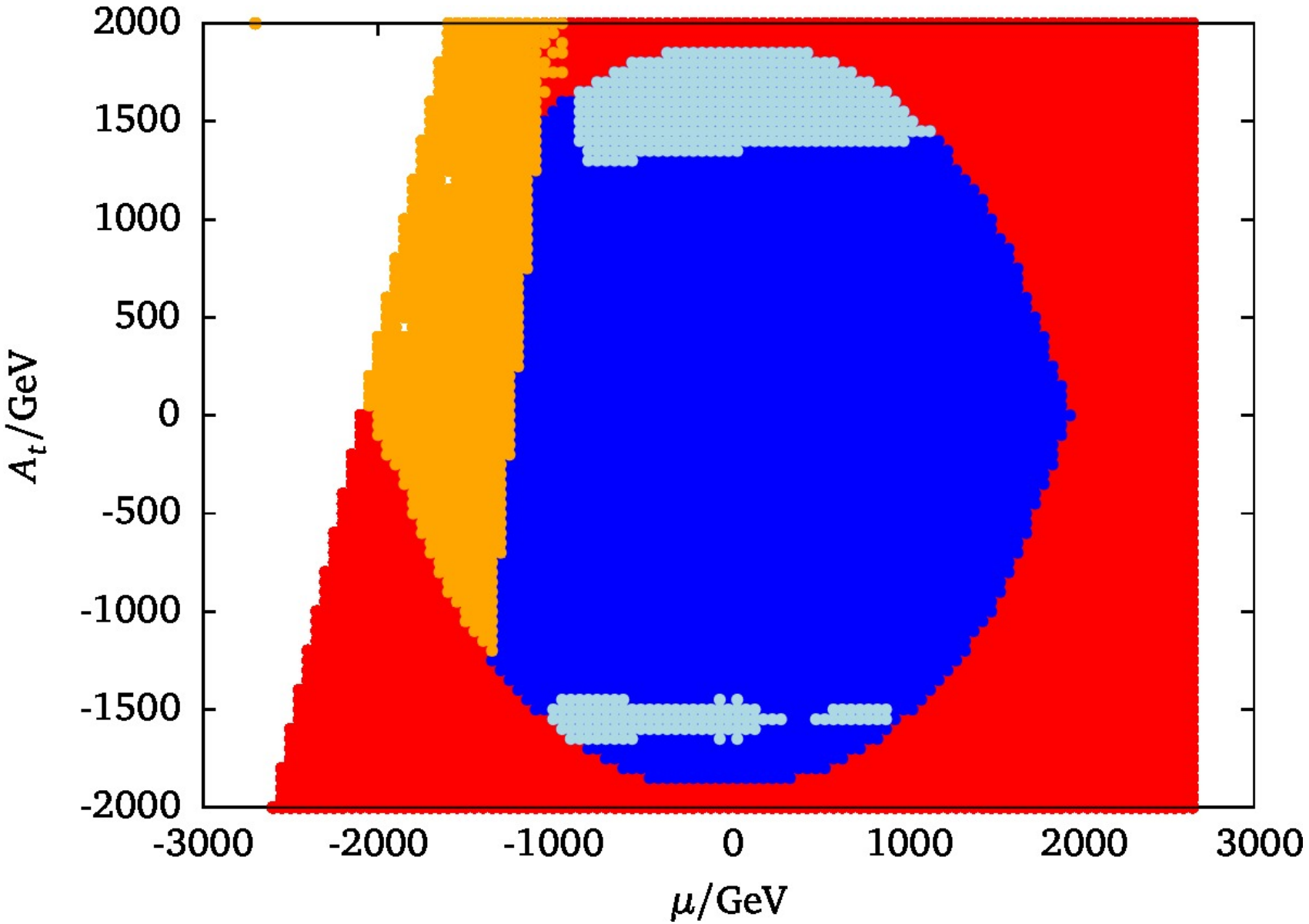
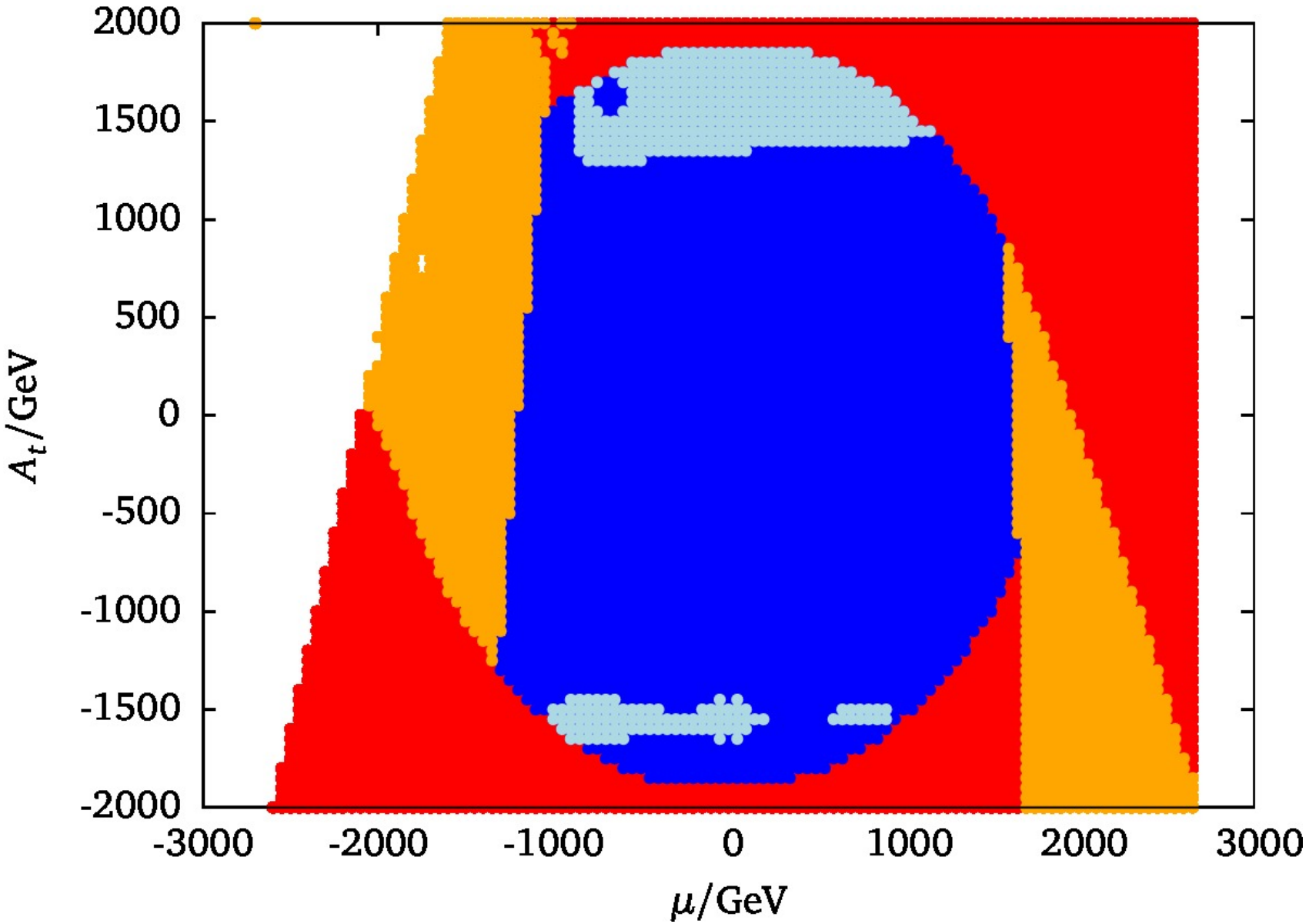



1.6
1.4
1.2
1
0.8
0.6
0.4
β
-2.6
-2.4
-2.2
-2
-1.8
-1.6
-1.4
-1.2
-1
η


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


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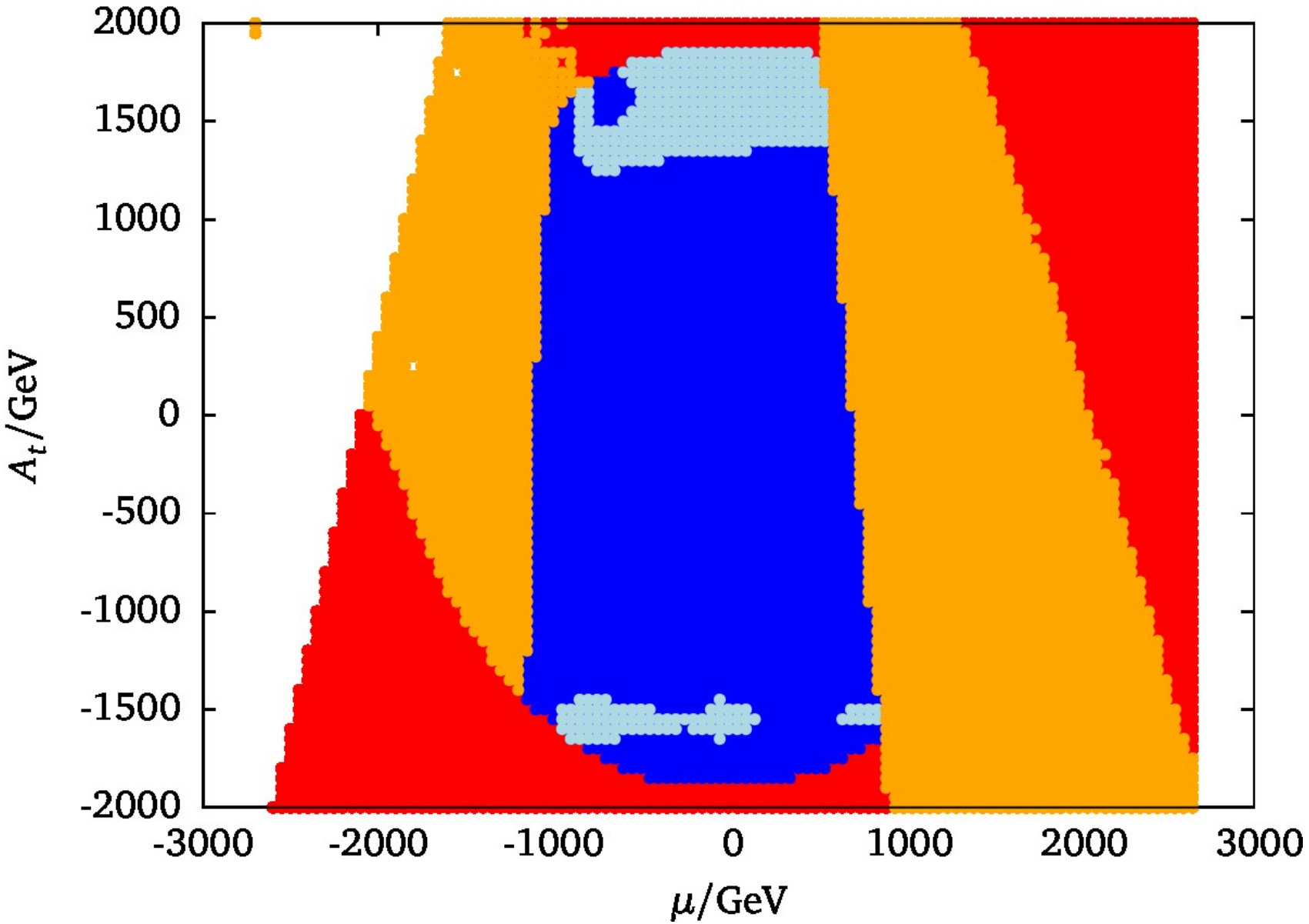
A_t/GeV
-3000
-2000
-1000
0
1000
2000
3000
μ/GeV


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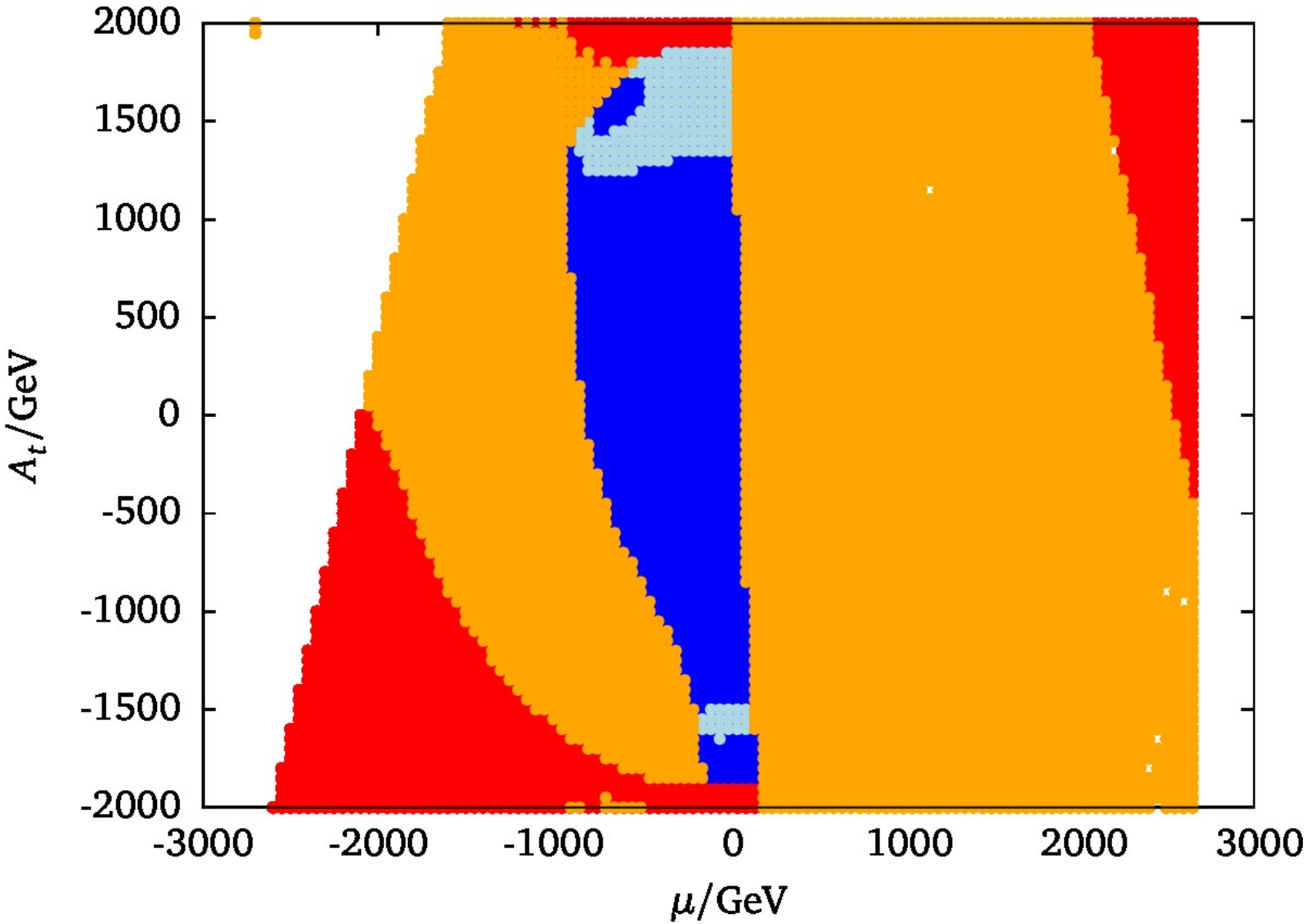
-2000
A_t/GeV
-3000
-2000
-1000
0
1000
2000
3000
μ/GeV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A_t/GeV
-3000
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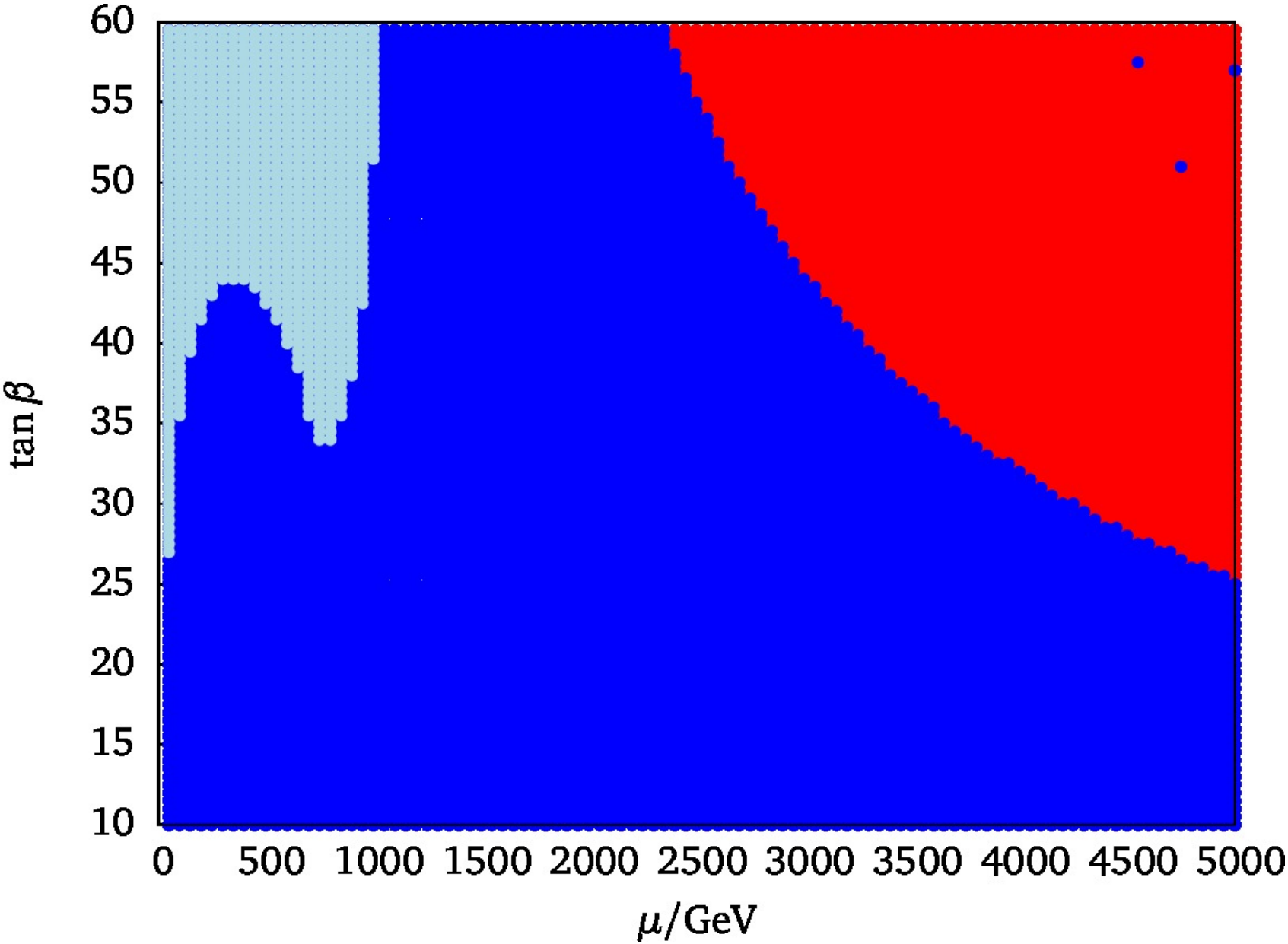
0
1000
2000
3000
μ/GeV


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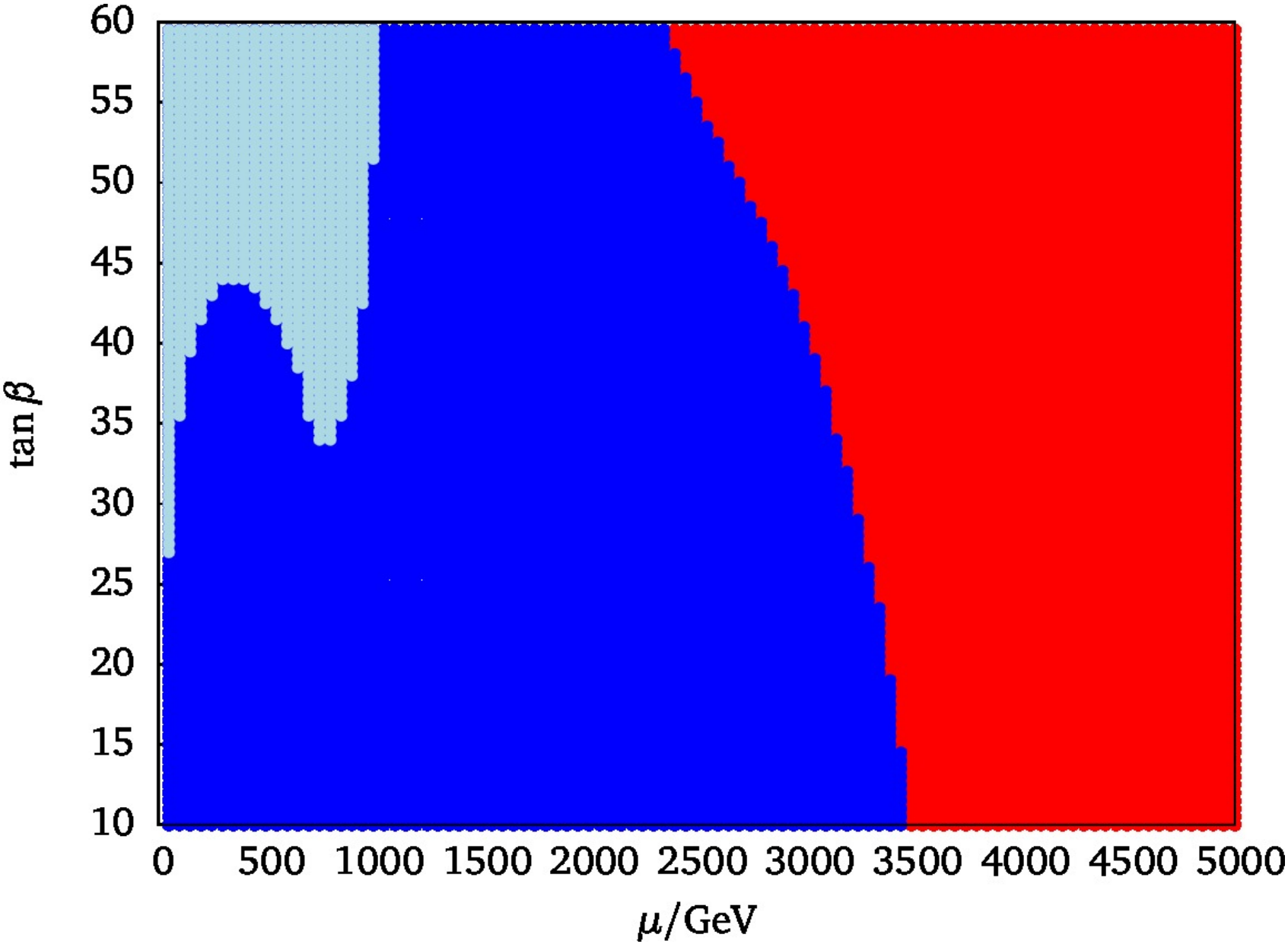
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
μ/GeV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tan β
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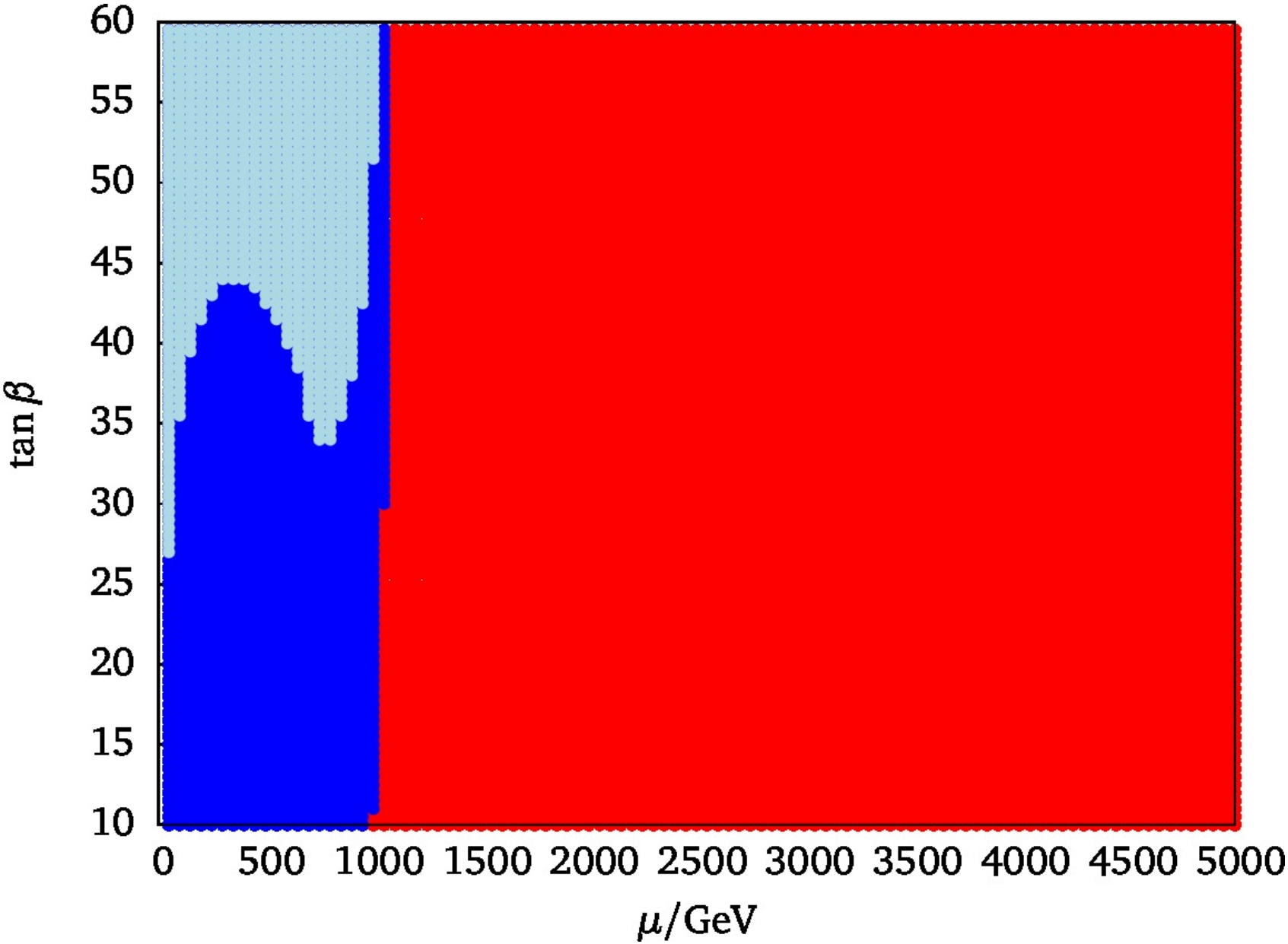
4500
5000
μ/GeV


60
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tan β
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2500
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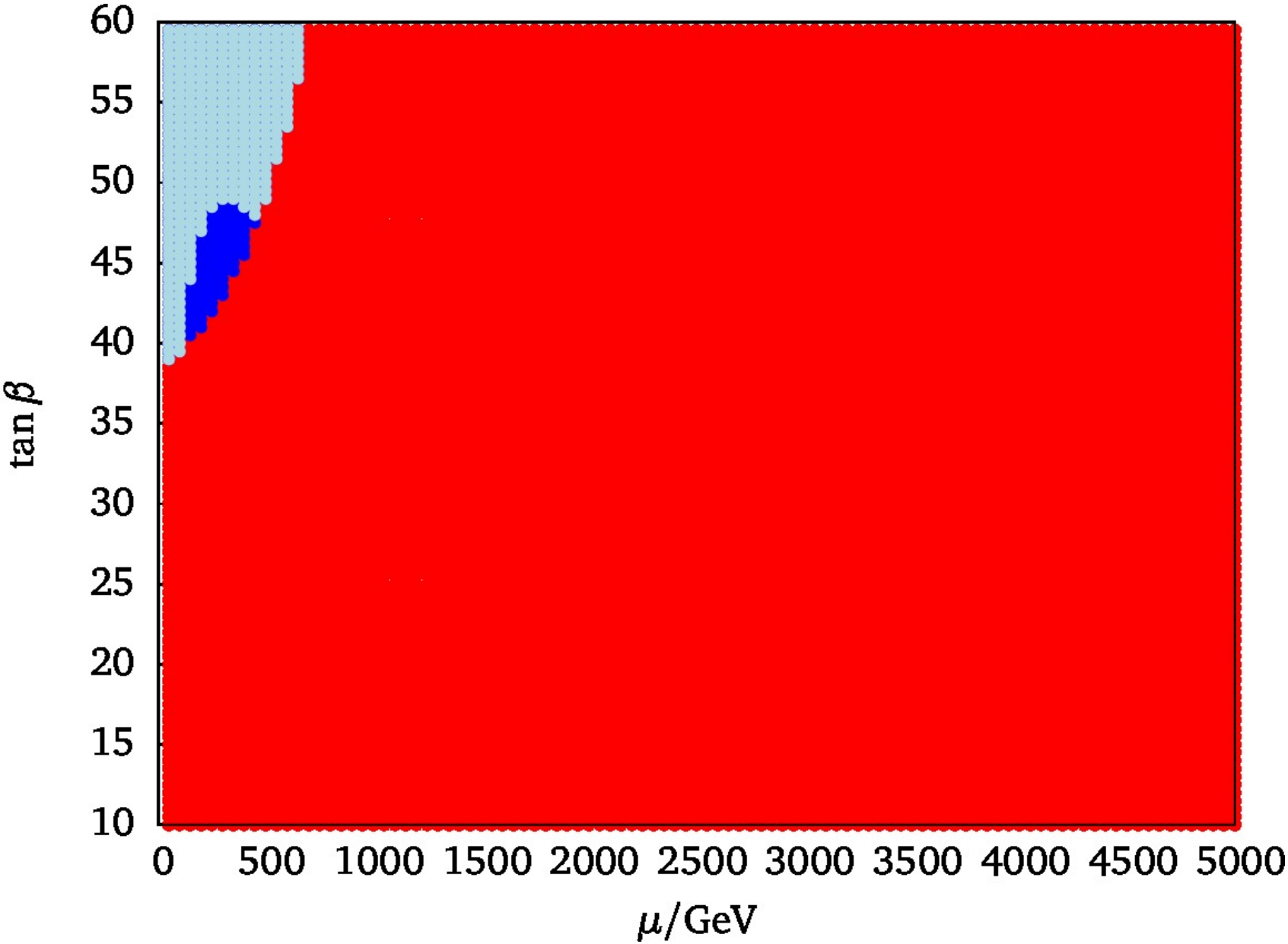
3500
4000
4500
5000
μ/GeV


60
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35
30
25
20
15
10
tan β
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500
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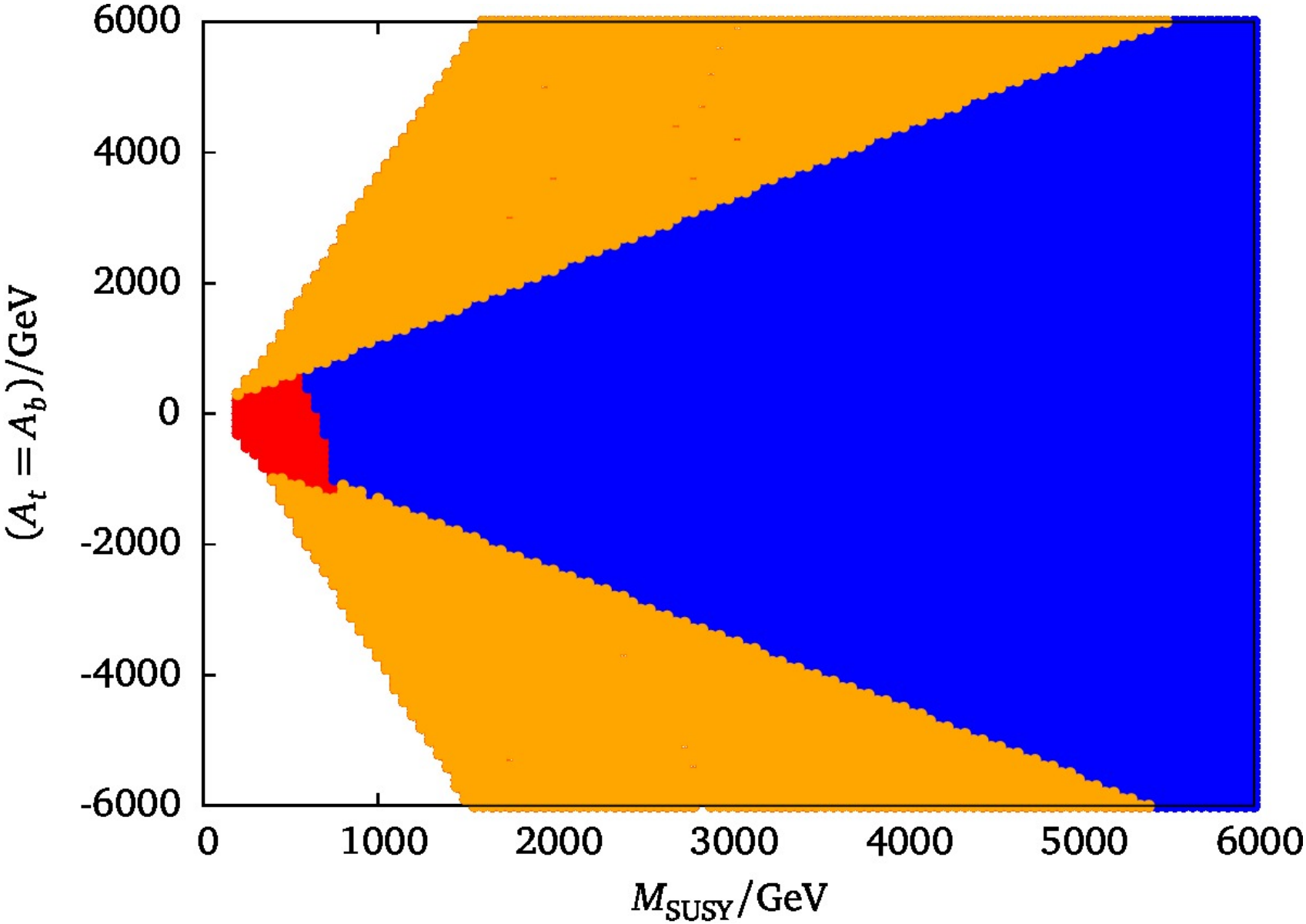
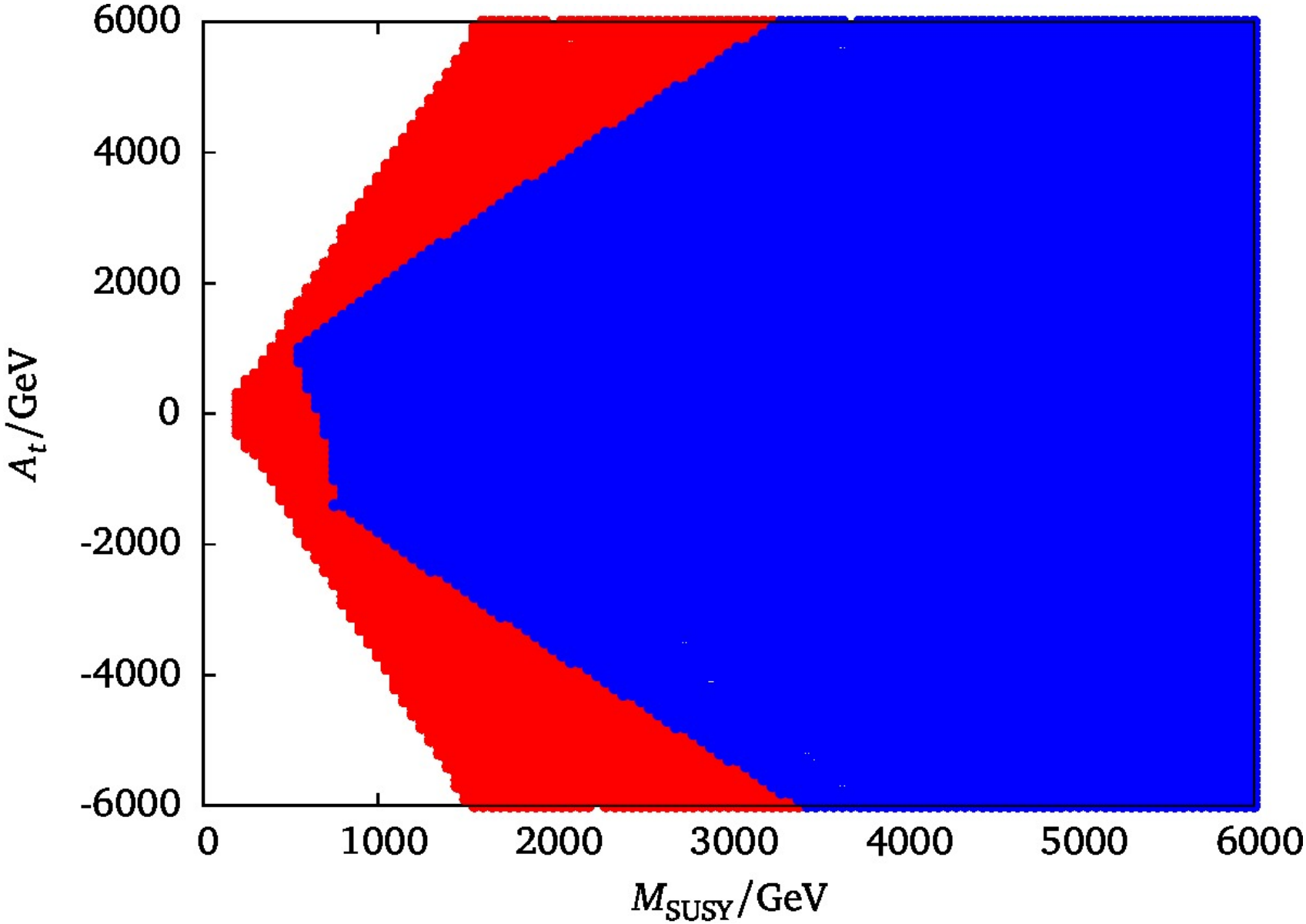
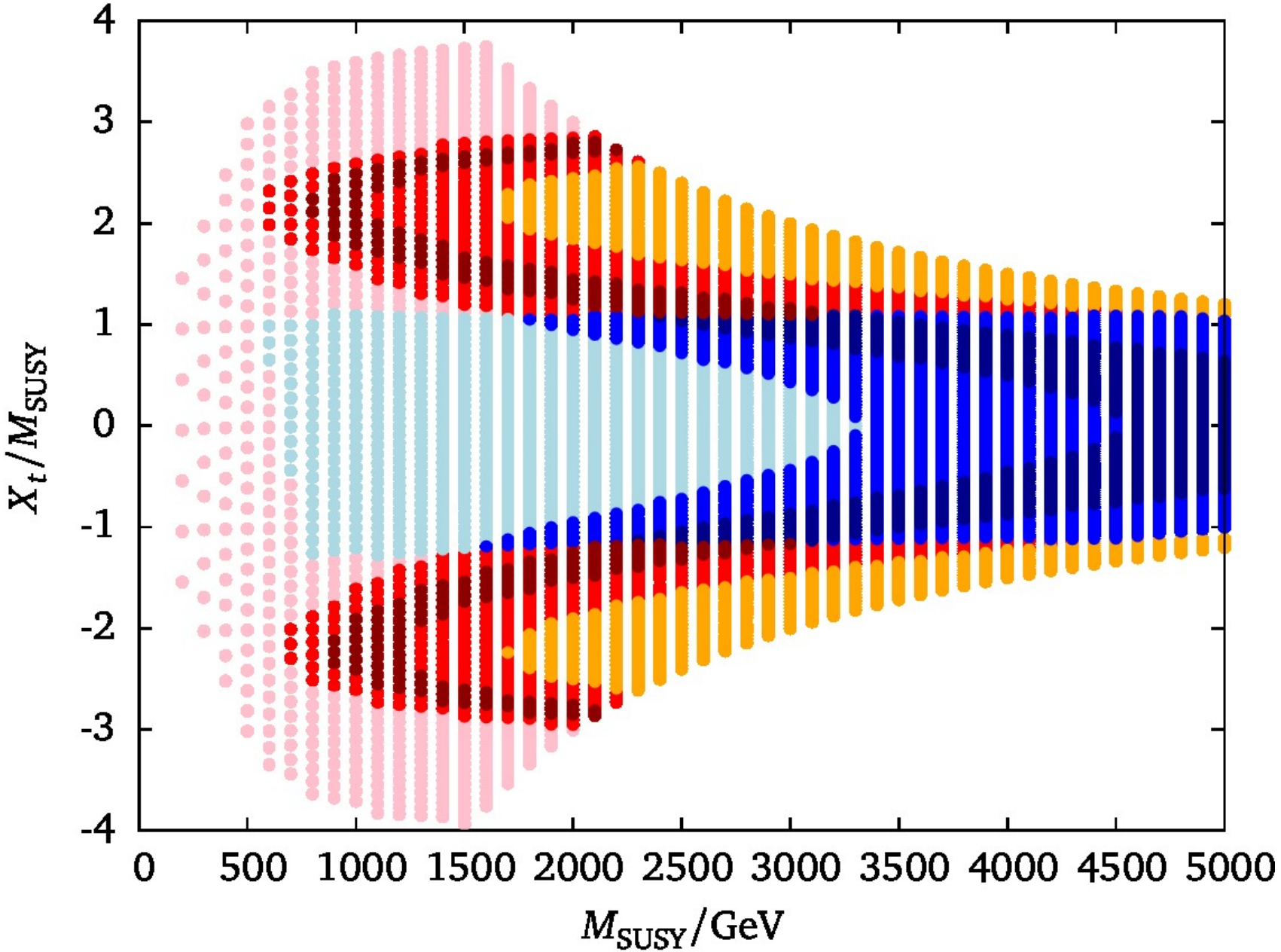
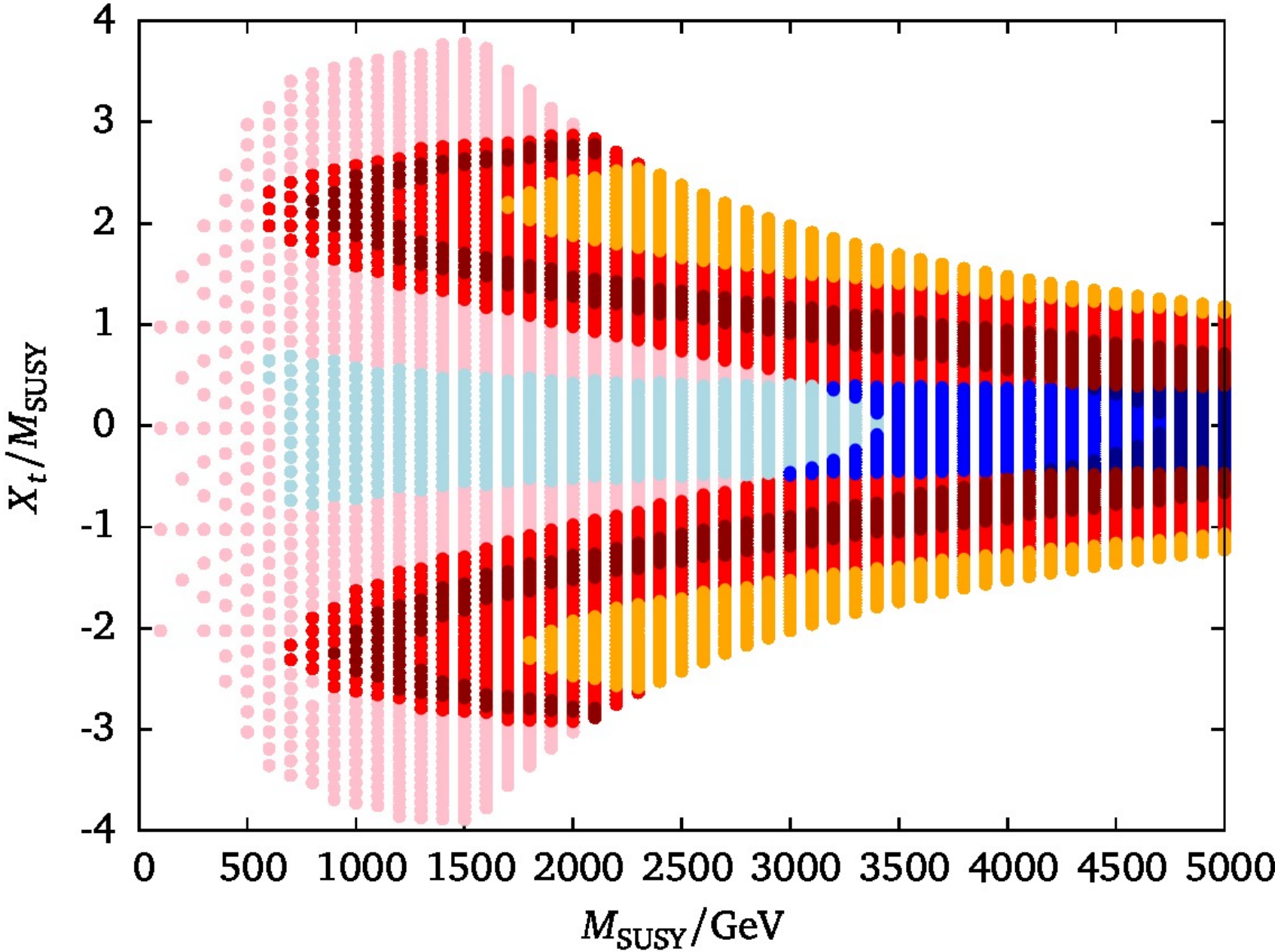
2000
2500
3000
3500
4000
4500
5000
μ/GeV

Resort comes close (increasing MSUSY)




6000
4000
2000
0
-2000
-4000
-6000
A_t/GeV
0
1000
2000
3000
4000
5000
6000
M_{SUSY}/GeV


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


4
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-2
-3
-4
X_t/M_{SUSY}
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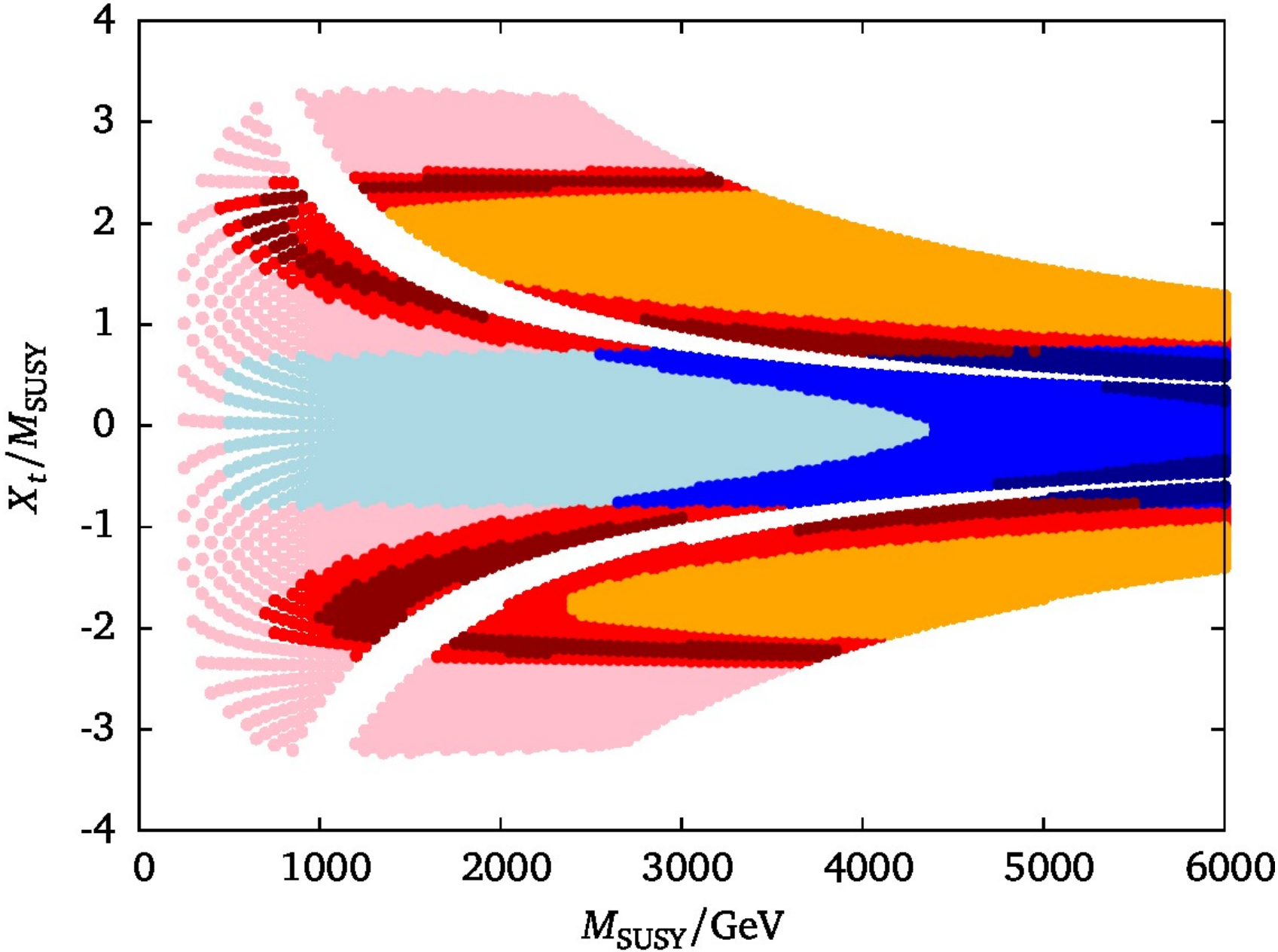
4500
5000
$M_{\mathrm{SUSY}}/\mathrm{GeV}$


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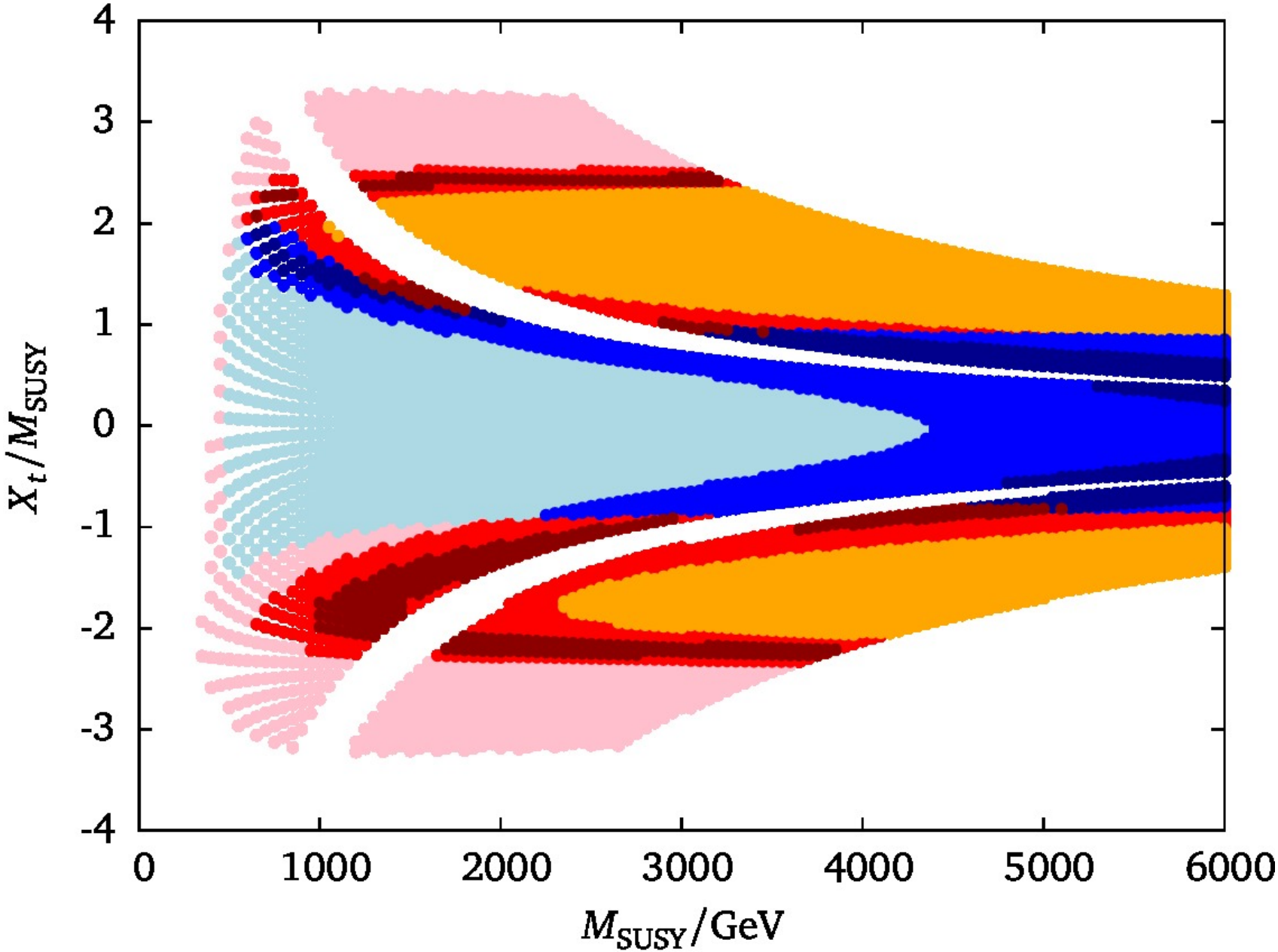
0
-1
-2
-3
-4
X_t/M_{SUSY}
0
1000
2000
3000
4000
5000
6000
$M_{\mathrm{SUSY}}/\mathrm{GeV}$


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

- "heavy" Higgs @ $125\,\mathrm{GeV}$: large SUSY corrections
  - large $A_{t,b}$ and μ induce squark vevs
- investigate larger field space: more room for instabilities
  - allow e.g. $h_d < -h_u$ for true vacuum
- metastability bounds (small tunneling rates) turn to true instability bounds (fast decay)