Phenomenology of Supersymmetric Gauge-Higgs Unification

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Based on work (in progress) with

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as well as on previous work with

John March-Russell and Robert Ziegler (0801.4101 [hep-ph])

Outline

- 5d and heterotic gauge-Higgs unification
- Importance of the Chern-Simons term
- Phenomenology in a simplified setting
- Towards a complete model

Motivation

- **Our main Paradigm: SUSY GUTs**
- **Simplest explicit models:**
  5d or 6d Orbifold GUTs with compactification scale $\sim M_{GUT}$
- **Natural microscopic origin: Heterotic orbifold models**
  Motivation in this context: String-scale/GUT-scale problem; 'solved' by using anisotropic orbifolds
- **Fundamental problem of 'conventional' orbifold GUTs:**
  few extra predictions (beyond those of old-fashioned SUSY-GUT framework)
- **Our main point:**
  There may be simple and testable consequences for SUSY breaking in the Gauge/Higgs sector + natural way to generate $\mu/B\mu$

SUSY Gauge-Higgs Unification

(cf. Burdman/Nomura 2003)

- **5d SU(6) super-Yang-Mills theory on** $S^1/(Z_2 \times Z_2')$
- **Gauge-symmetry broken at boundaries to SM (MSSM field content below compactification scale)**
- **Field content in** $\mathcal{N} = 1$ **language: vector** V **+ chiral adjoint** Φ
- Φ **in 35 of SU(6);** $35 = 24 + 5 + \bar{5} + 1$**;** $5 = 3 + 2$ **and** $\bar{5} = \bar{3} + \bar{2}$
- **Only the** 2 **and** $\bar{2}$ **survive boundary-breaking**
- **Matter in bulk, Yukawas from gauge couplings (details later)**

Soft terms from radion superfield

(cf. Choi/Haba/Jeong/Okumura/Shimizu/Yamaguchi 2004)

- $T = R + iA_5$; **Due to no-scale structure F_T is naturally the dominant source for SUSY-breaking in many concrete models**
- **The 5d action in terms of $\mathcal{N} = 1$ superfields, coupled to radion à la Marti/Pomarol, contains terms**

$$\int d^2\theta \, T \, \mathbf{tr} W^2 \qquad , \qquad \int d^4\theta \, \bar{\varphi}\varphi \, \frac{\mathbf{tr}(\Phi + \bar{\Phi})^2}{T + \bar{T}}$$

(φ is 'chiral compensator'; generically $F_\varphi \neq 0$ after T is stabilized)

- **For $H_1, H_2 \subset \Phi$ one finds:**

$$\int d^4\theta \, \bar{\varphi}\varphi \, \frac{(\bar{H}_1 + H_2)(\bar{H}_2 + H_1)}{T + \bar{T}}$$

- **One immediately reads off:**

$$M_{1/2} = \frac{\bar{F}_T}{2R} \qquad \textbf{and} \qquad \mu = \bar{F}_\varphi - \frac{\bar{F}_T}{2R}$$

- **In addition, for the Higgs mass parameters in**

$$V = m_1^2|H_1|^2 + m_2^2|H_2|^2 + m_3^3(H_2H_1 + \text{h.c.})\,,$$

one finds:

$$m_1^2 = m_2^2 = m_3^2 = |F_\varphi|^2 - \frac{F_\varphi\bar{F}_T + \text{h.c.}}{2R}$$

(note our conventions: $\quad m_{1,2}^2 \equiv |\mu|^2 + m_{H_{1,2}}^2 \quad$ **and** $\quad m_3^2 \equiv B\mu$ **)**

- **This is marginally inconsistent with the EWSB conditions**

$$m_1^2m_2^2 < (m_3^2)^2 \qquad \textbf{and} \qquad 2m_3^2 < m_1^2 + m_2^2\,,$$

which can however be fulfilled after RG running.

Structural Origin of the above
'GHU boundary conditions'

- **Crucial point:** H_1 **and** H_2 **enter the Kähler potential only in the combinations** $(H_1 + \bar{H}_2)$ **and** $(\bar{H}_1 + H_2)$
- **Reason:** Φ **enters the Kähler potential only in combination** $(\Phi + \bar{\Phi})$
- **Reason:** $\Phi = \Sigma + iA_5$**;** **where** A_5 **should cancel in lowest component to avoid non-derivative couplings**

Heterotic String Motivation

- **These 'GHU boundary conditions' are also found in some heterotic orbifold models**

  (cf. Antoniadis/Gava/Narain/Taylor 1994
  Lopes Cardoso/Lüst/Mohaupt 1994
  Brignole/Ibanez/Munoz 1995-1997)

- **In more detail: The Kähler potential for matter fields A, B is**

$$K = Y A\bar{A} + \tilde{Y} B\bar{B} + (ZAB + \mathbf{h.c.})$$

  where $Y, \tilde{Y}, Z$ are functions of the moduli.

- **In some cases one has explicitly**

$$Y = \tilde{Y} = Z = \frac{1}{(T+\bar{T})(U+\bar{U})}$$

  which implies the required structure $(A+\bar{B})(\bar{A}+B)$

- **Specifically, the conditions are:**

  A and B are untwisted matter fields associated with a common complex plane.

  This plane possesses a complex structure modulus, U.

- **Our present understanding of these conditions:**

  The 'common plane' allows for a 6d limit in which A and B are 6d gauge fields.

  The presence of U allows for a 5d limit, such that A and B become part of the chiral adjoint Φ.

  The previous 5d argument explains the special structure of the Kähler potential (even if we are not in this particular 5d limit in moduli space)

- **This would be interesting to understand in more detail...**

Summary so far:

- **Interesting specific class of high-scale boundary conditions related to GHU**
- **Motivation in 5d and some more general heterotic models**
- **Unfortunately: Choi et al. find that no reasonable phenomenology emerges except in some extremely fine-tuned corner of parameter space**
- **Their solution: Include extra SUSY-breaking sources (F-terms of other fields)**
- **Unsatisfactory? . . .**

Our suggestion:

(developing and correcting previous work with March-Russell and Ziegler)

- **Include the effects of the 5d Chern-Simons term and perform a state-of-the-art phenomenological analysis (using SuSpect)**
- **The SUSY extension of the CS-term $A \wedge F \wedge F$ is generically present in 5d SYM theories**
- **In compactifications on an interval its coefficient is fixed by boundary-anomaly-cancellation**
- **when coming from $d > 5$, it is induced at 1-loop**

  (cf. Seiberg 1996 and Intriligator/Morrison/Seiberg 1997)
- **Its effect softens, in particular, the strict relation between gaugino mass and Higgs mass parameters**

- **The SUSY CS-term corrects**

$$\int d^2\theta\, T\, \mathbf{tr} W^2 \qquad , \qquad \int d^4\theta\, \bar{\varphi}\varphi\, \frac{\mathbf{tr}(\Phi+\bar{\Phi})^2}{T+\bar{T}}$$

by

$$\int d^2\theta\, \mathbf{tr}\Phi W^2 \qquad , \qquad \int d^4\theta\, \bar{\varphi}\varphi\, \frac{\mathbf{tr}(\Phi+\bar{\Phi})^3}{(T+\bar{T})^2}$$

- **Being a higher-dimension operator, it is only important if** $\langle\Phi\rangle \neq 0$**.**

- **This is rather generic. The simplest realization in our setting is**

$$\mathbf{SU(6)} \rightarrow \mathbf{U(6)} \qquad \textbf{and} \qquad \langle\Phi\rangle = v\,\mathbb{1}$$

- **Combining the CS-term-coefficient c, the VEV v and the 5d gauge coupling g_5 in the dimensionless parameter c', we now have:**

$$M_{1/2} = \frac{\overline{F}^T}{2R} \frac{1}{1+c'}$$

$$\mu = \bar{F}^{\bar{\varphi}} - \frac{\bar{F}^T}{2R} \frac{1+2c'}{1+c'}$$

$$m_i^2 = |F^\varphi|^2 - \frac{(F^\varphi \overline{F}^T + \text{h.c.})}{2R} \frac{1+2c'}{1+c'} + \frac{|F^T|^2}{(2R)^2} \frac{2c'^2}{(1+c')^2}.$$

- **For a first phenomenological analysis, we neglect all matter soft terms (except for the top-quark) and use $y_t \simeq g_{GUT}$**
- **This corresponds to realizing Q_3 and U_3 as bulk fields with flat profile**
- **All other matter fields are brane fields**
- **Thus, T enters only via the Kähler-coefficients**

$$Y_{Q_3} = Y_{U_3} = \frac{T + \bar{T}}{2R} \, .$$

- **From this, we find**

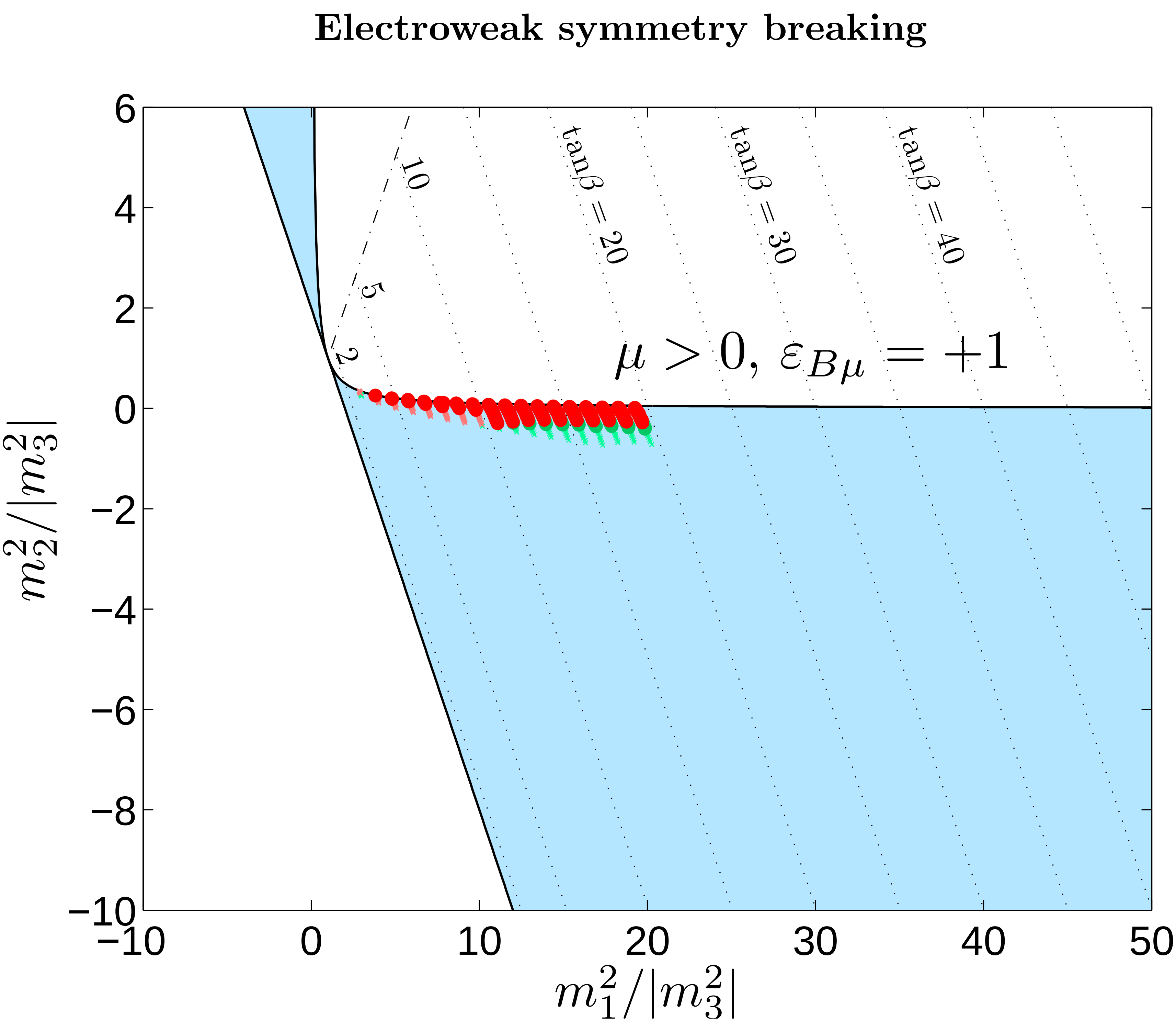
$$m_{Q_3}^2 = m_{U_3}^2 = \left| \frac{F_T}{2R} \right|^2 \qquad \textbf{and} \qquad A_t = \frac{F_T}{2R} \cdot \frac{1}{1 + c'} \, .$$

Challenges in the implementation of GHU boundary conditions:

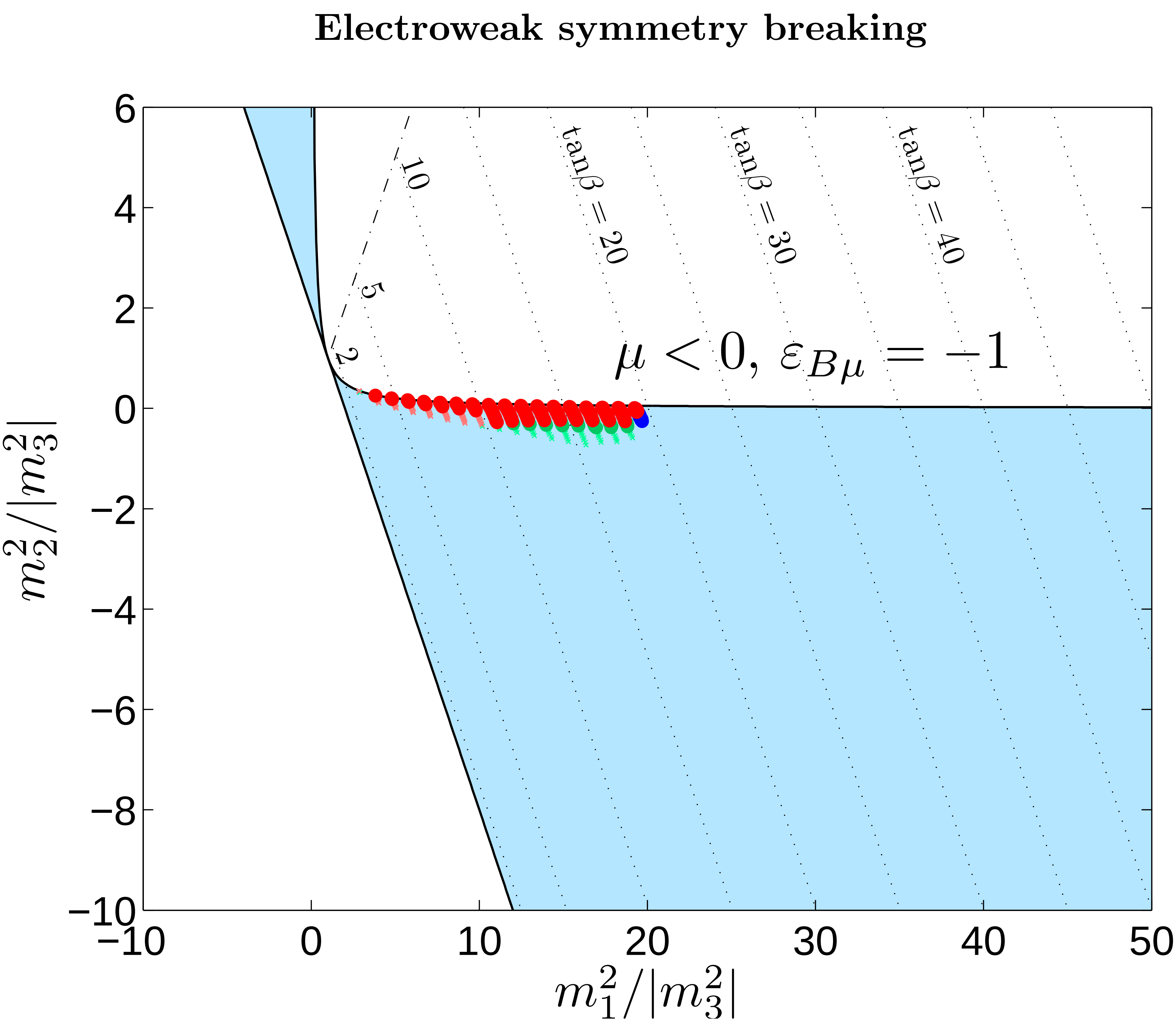
- **Usual procedure: tanβ and M_Z as low-scale input; μ and $B\mu$ are computed from EWSB conditions (iterative running between low and high scale required)**
- **This does not work in GHU since μ, $B\mu$, $M_{1/2}$ and $m^2_{H_{1,2}}$ at the high scale are not independent**

Simple solution:

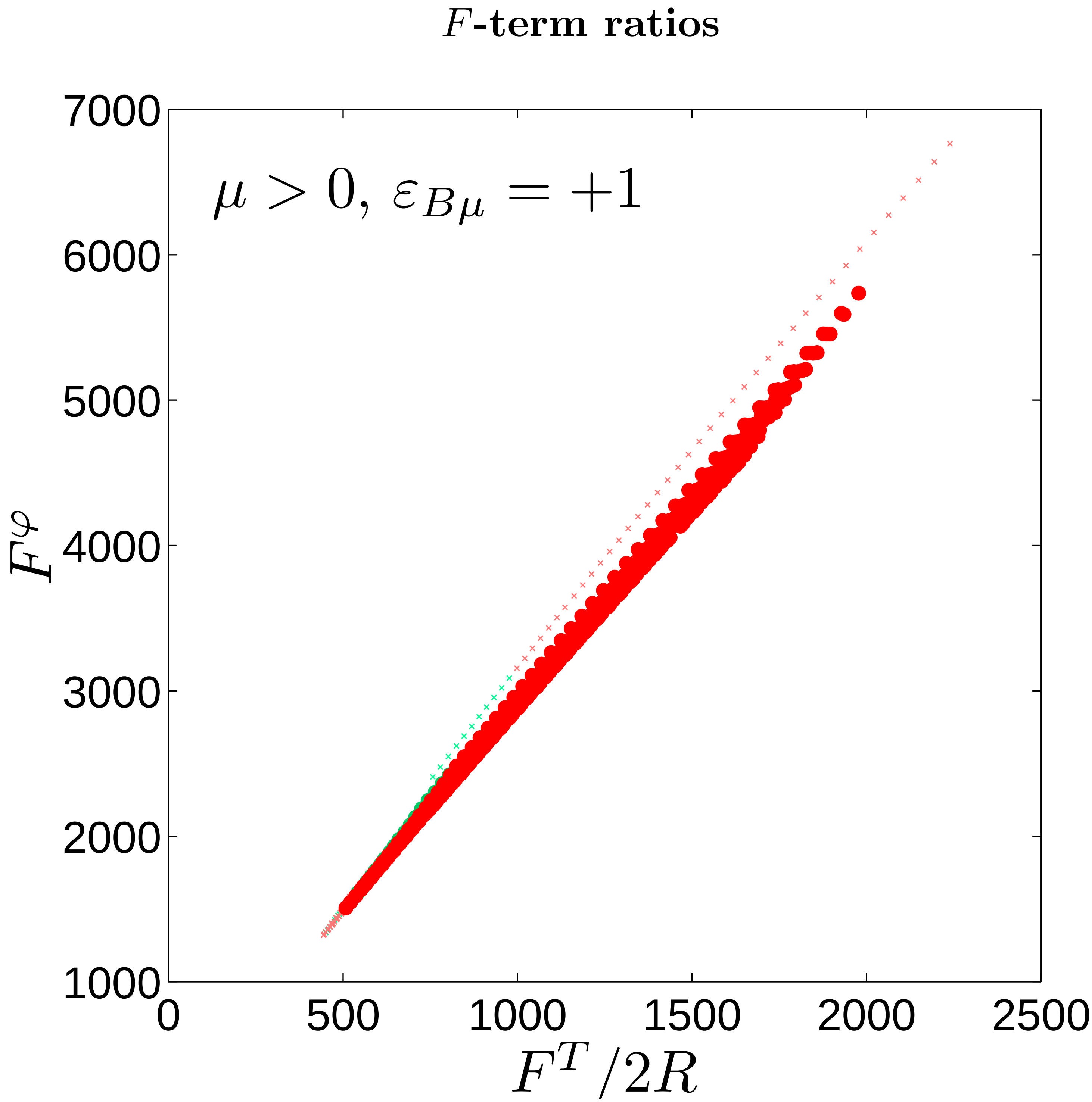
- **Implement $m^2_{H_{1,2}} = B\mu - |\mu|^2$ at the GUT scale in every step of the iteration.**
- **The input parameters are M_Z and tanβ at the low scale as well as $M_{1/2}$ at the high scale.**
- **After convergence, one obtains certain values for μ and $B\mu$.**
- **Finally, $M_{1/2}$, μ and $B\mu$ can be translated into F_T, F_ϕ and c'.**
- **This allows to indirectly scan the space of these fundamental parameters.**

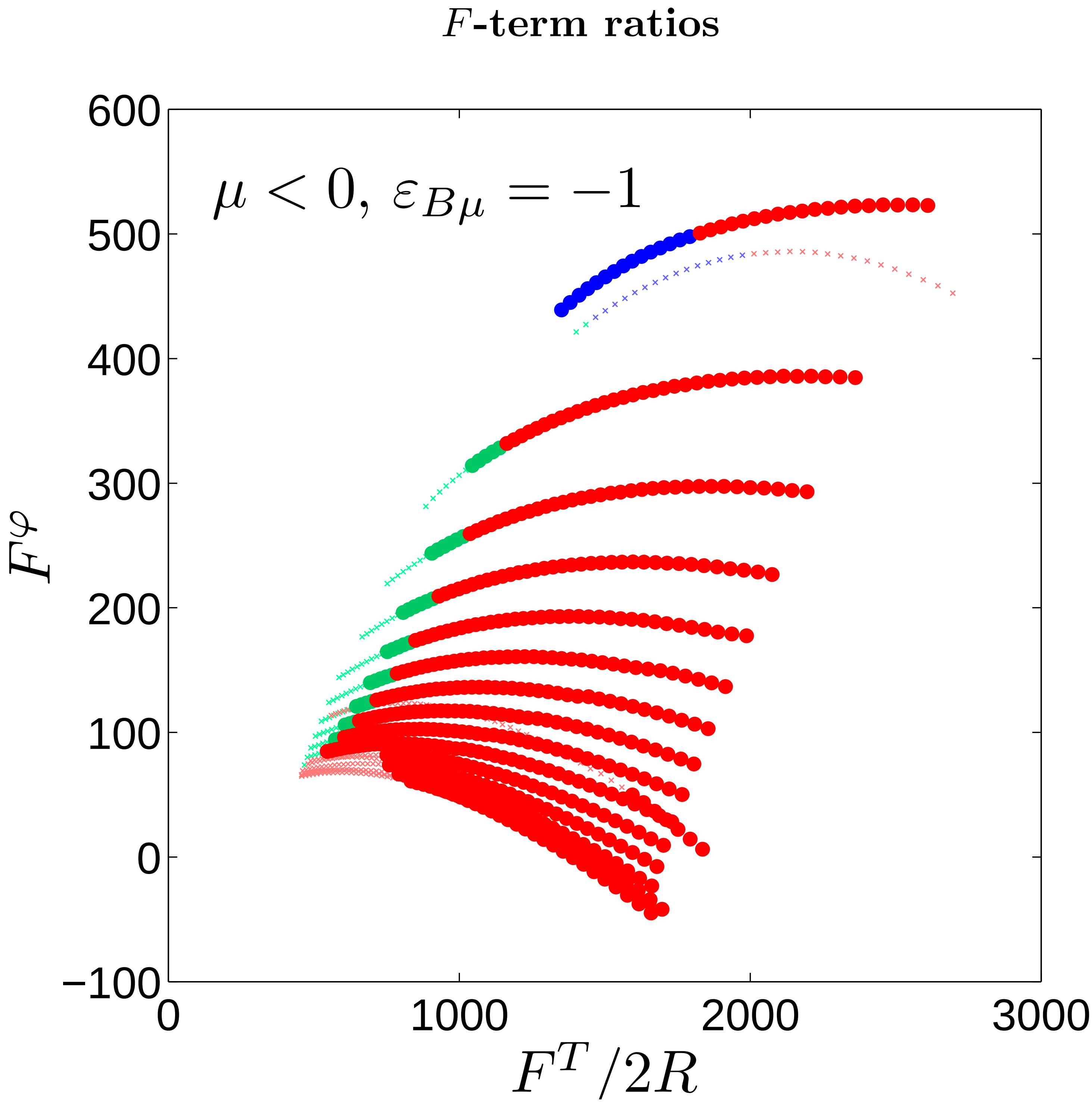


Electroweak symmetry breaking
$\mu > 0,\ \varepsilon_{B\mu} = +1$
$\tan\beta = 20$
$\tan\beta = 30$
$\tan\beta = 40$
10
5
2
$m_2^2/|m_3^2|$
$m_1^2/|m_3^2|$
6
4
2
0
−2
−4
−6
−8
−10
−10
0
10
20
30
40
50

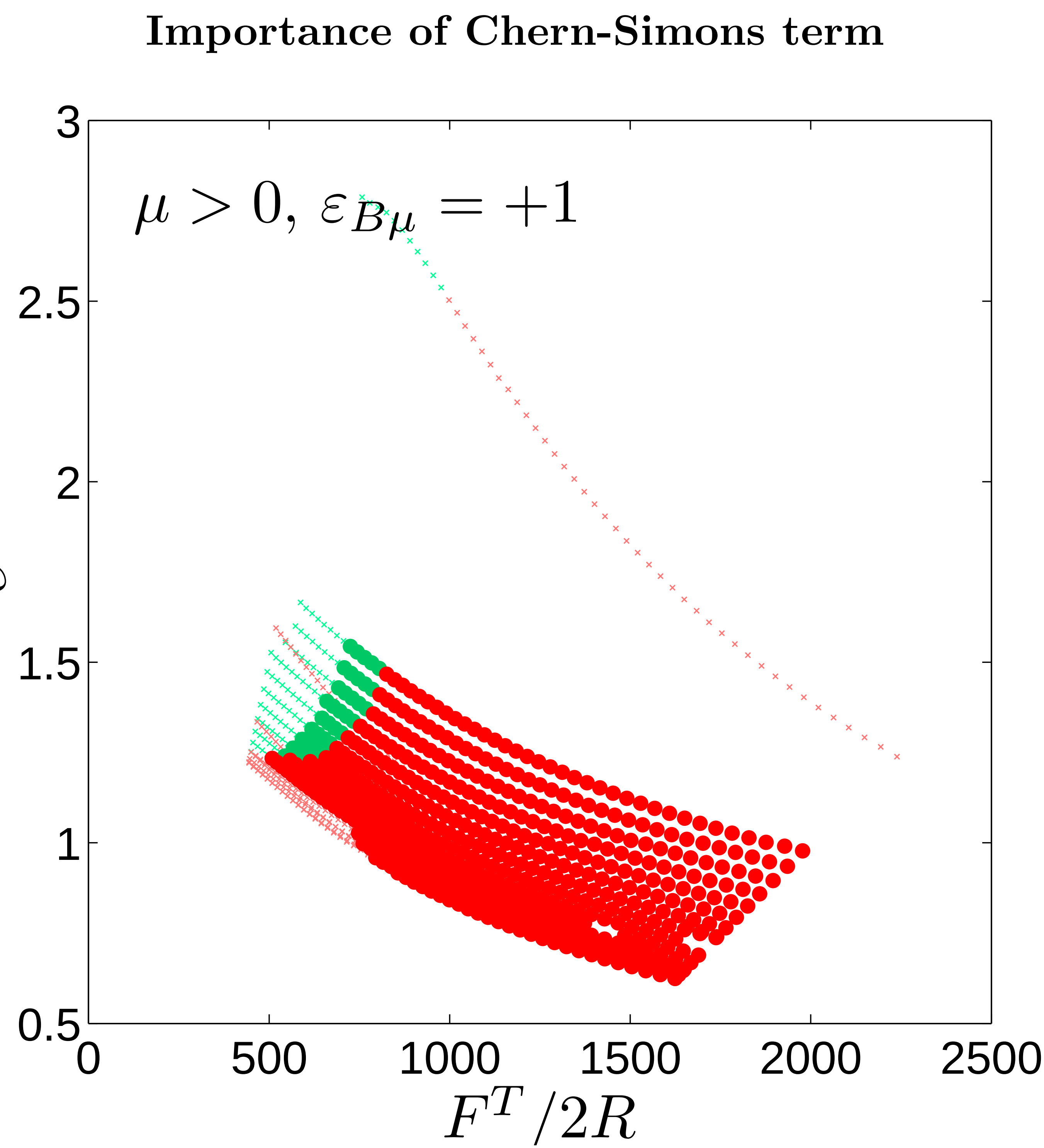


Electroweak symmetry breaking
$\mu < 0,\ \varepsilon_{B\mu} = -1$
$\tan\beta = 20$
$\tan\beta = 30$
$\tan\beta = 40$
10
5
2
$m_1^2/|m_3^2|$
$m_2^2/|m_3^2|$
6
4
2
0
−2
−4
−6
−8
−10
−10
0
10
20
30
40
50

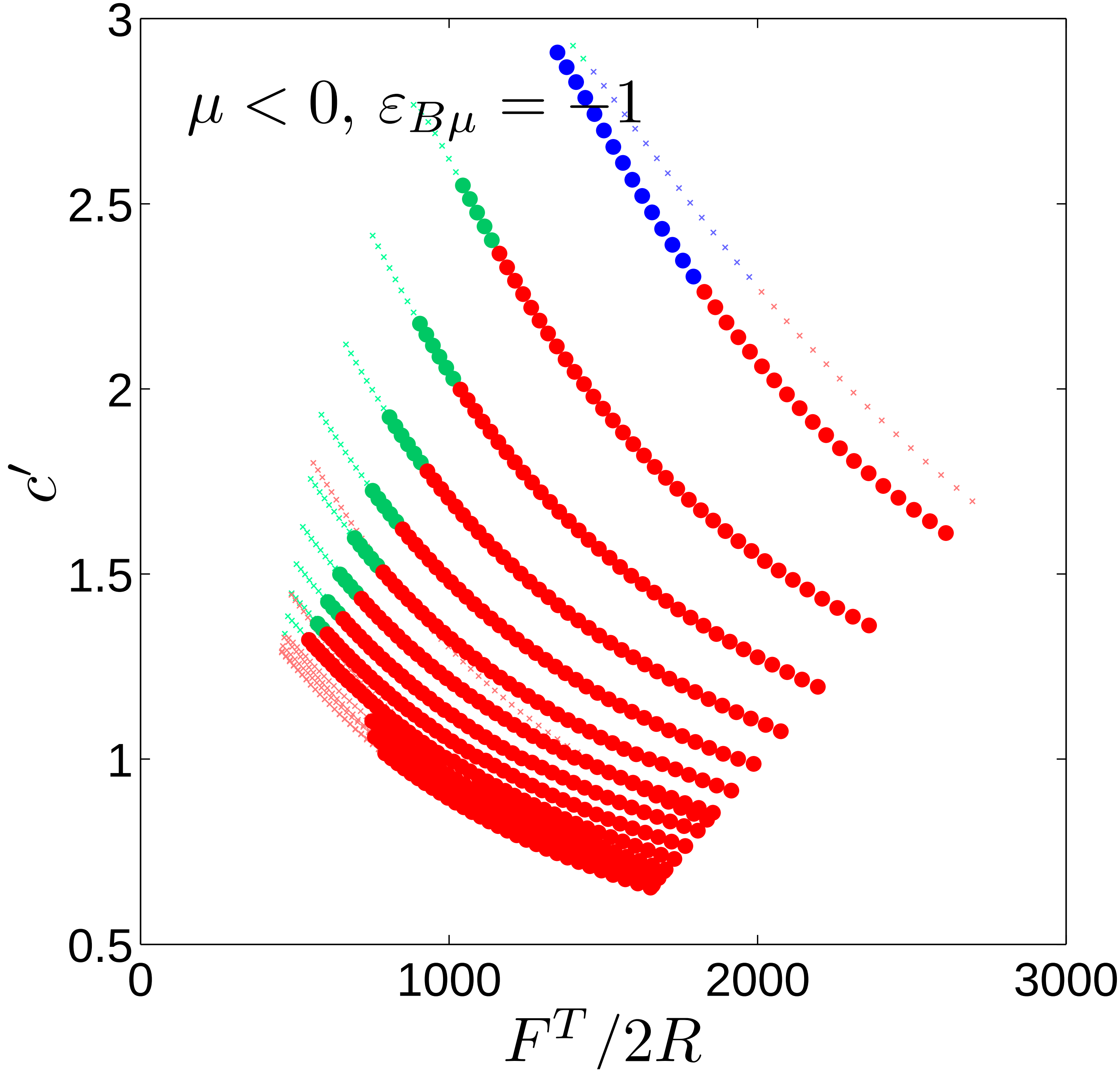

F-term ratios
$\mu > 0$, $\varepsilon_{B\mu} = +1$
F^{φ}
$F^T/2R$
7000
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500



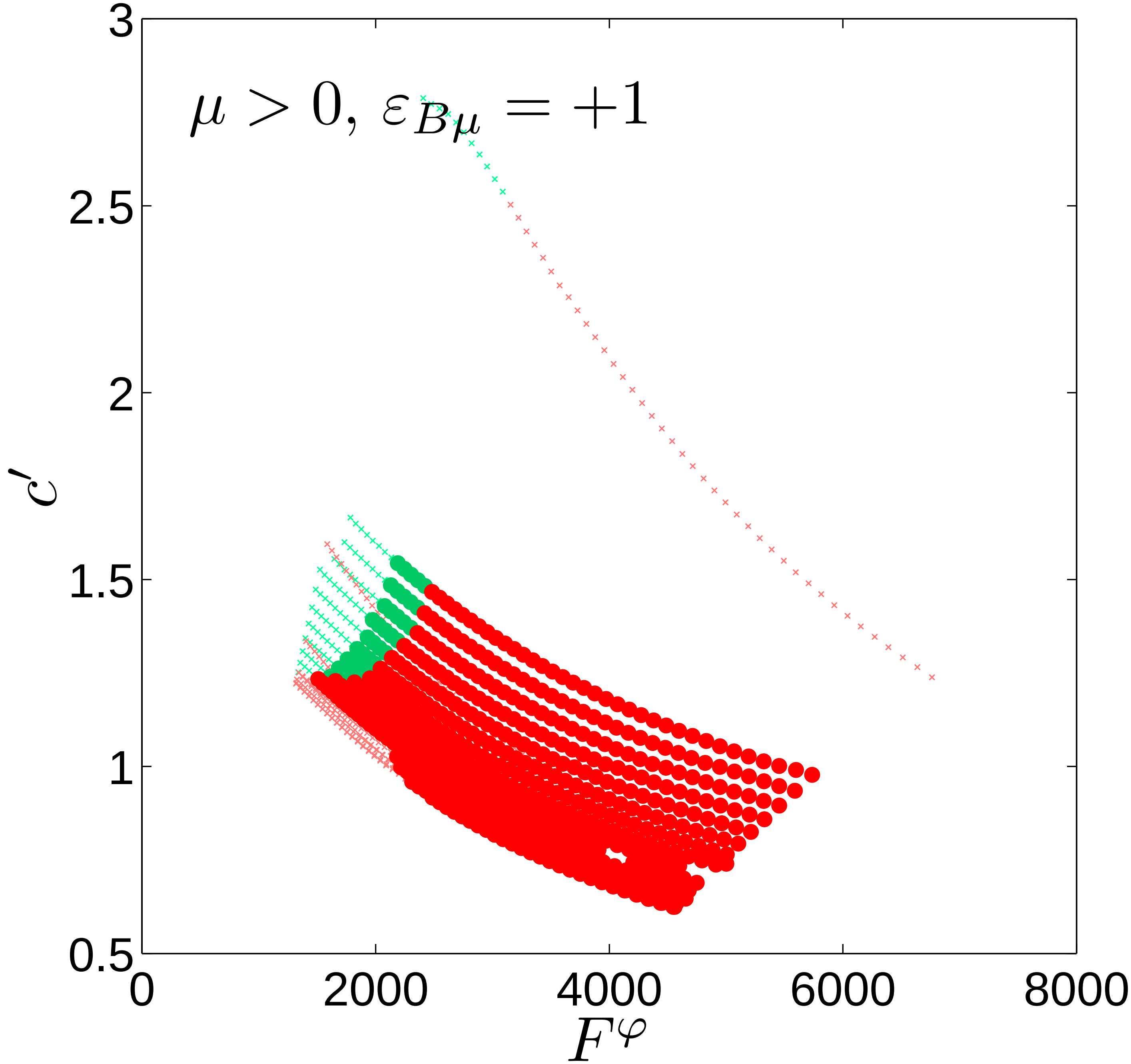
F-term ratios
$\mu < 0$, $\varepsilon_{B\mu} = -1$
600
500
400
300
200
100
0
−100
0
1000
2000
3000
F^{φ}
$F^T/2R$


Importance of Chern-Simons term
$\mu > 0,\ \varepsilon_{B\mu} = +1$
c'
$F^T/2R$
3
2.5
2
1.5
1
0.5
0
500
1000
1500
2000
2500

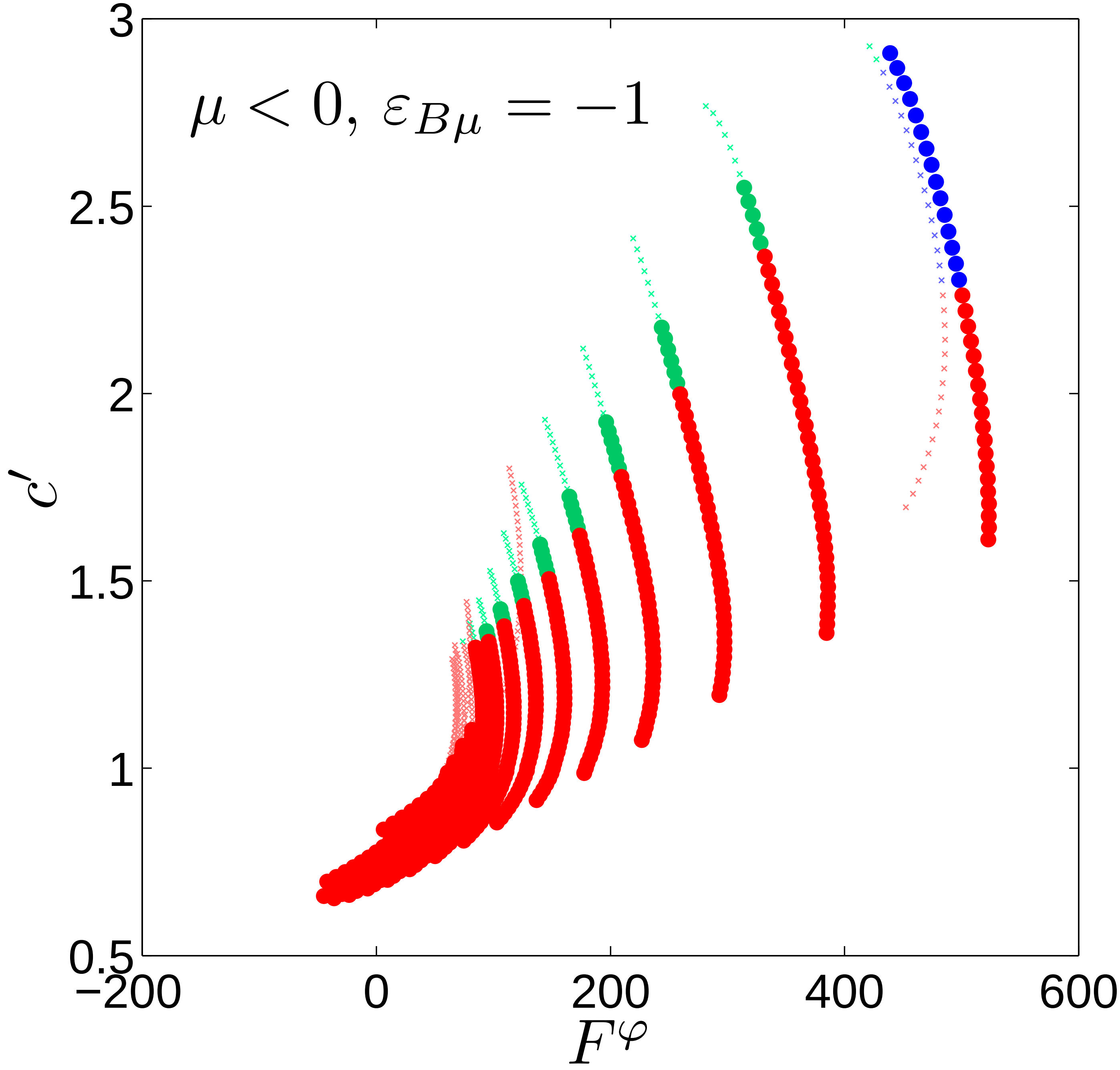
Importance of Chern-Simons term

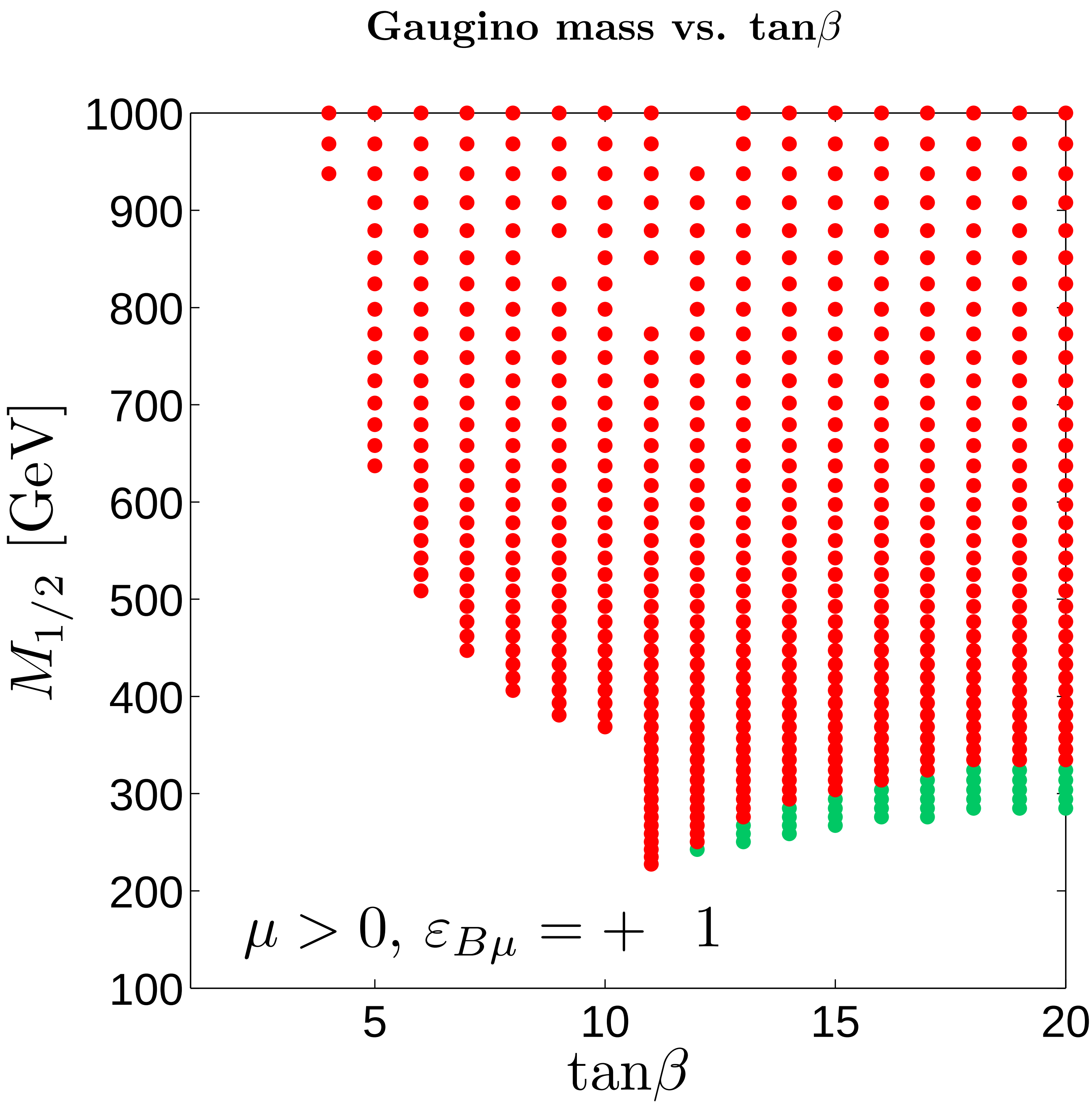


Importance of Chern-Simons term

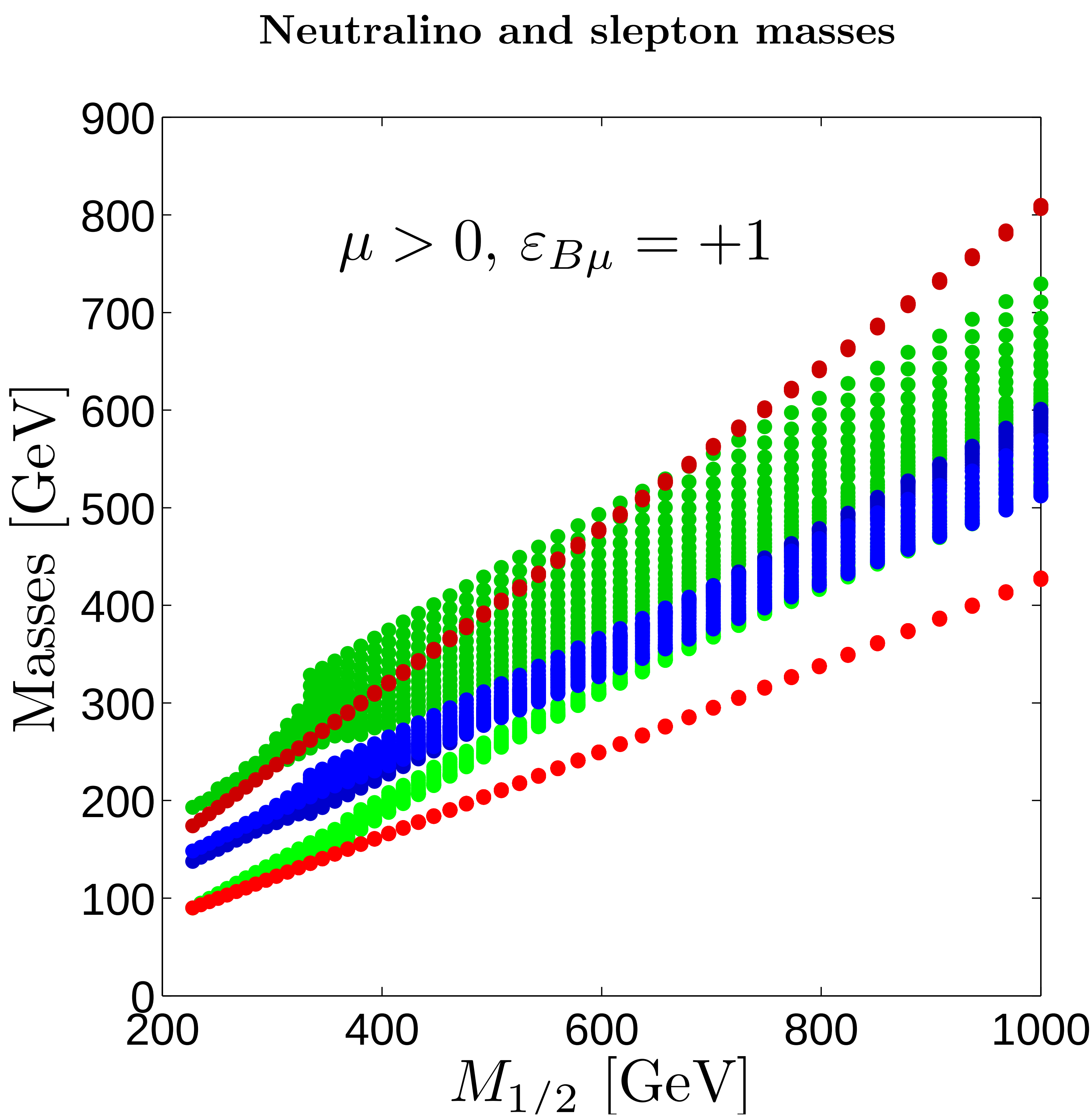


Importance of Chern-Simons term

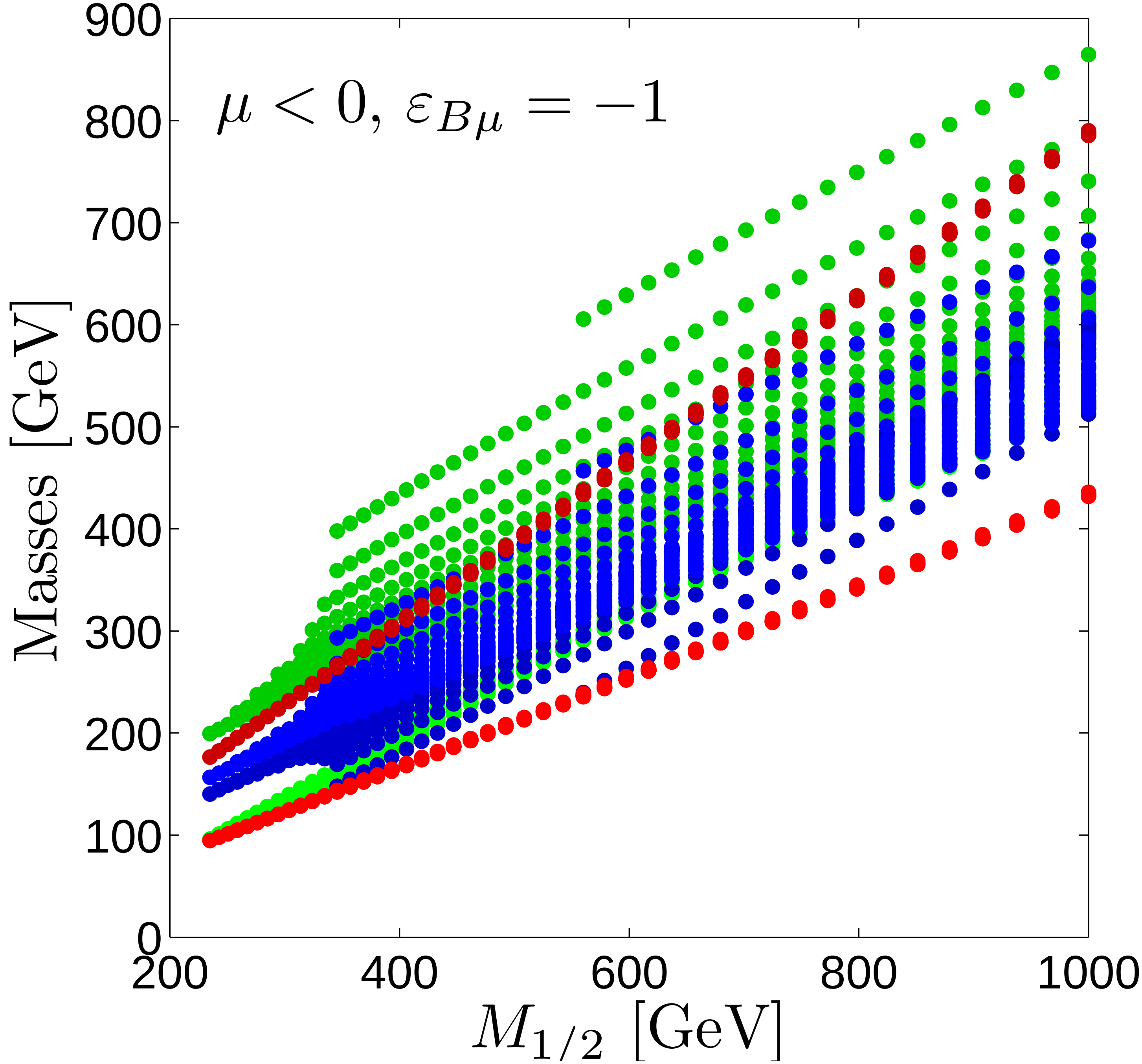




Gaugino mass vs. tanβ
$M_{1/2}$ [GeV]
1000
900
800
700
600
500
400
300
200
100
5
10
15
20
tanβ
$\mu > 0,\ \varepsilon_{B\mu} = +\ 1$


Neutralino and slepton masses
$\mu > 0,\ \varepsilon_{B\mu} = +1$
Masses [GeV]
$M_{1/2}$ [GeV]
0
100
200
300
400
500
600
700
800
900
200
400
600
800
1000

Neutralino and slepton masses



Realistic sfermion soft terms

- **Neglecting the bottom Yukawa is not justified; $y_t \simeq g_{GUT}$ is not valid with sufficient precision**
- **To address this, we need to go into the details of the Burdman-Nomura model:**

  Quarks come from bulk hypermultiplets in the 20 and 15 of SU(6)

  Yukawas come from gauge couplings and have the structure

$$Q_{20}U_{20}H_u + Q_{15}D_{15}H_d \,,$$

  with two independent doublets.

  This problem is solved by mixing Q_{20} with Q_{15} via a brane field, such that only one (mixed) doublet remains massless.

- **Resulting Kähler-coefficients for 3rd generation quark fields: (taking into account bulk-profiles, which is now unavoidable)**

$$Y_U = \frac{1}{2|M_u|}\left(1 - e^{-\pi(T+\overline{T})|M_u|}\right) \quad , \quad Y_D = \frac{1}{2|M_d|}\left(1 - e^{-\pi(T+\overline{T})|M_d|}\right)$$

$$Y_Q = \frac{1}{2|M_u|}\left(1 - e^{-\pi(T+\overline{T})|M_u|}\right)\sin^2(\phi_Q) + \frac{1}{2|M_d|}\left(1 - e^{-\pi(T+\overline{T})|M_d|}\right)\cos^2(\phi_Q)$$

- **The mixing angle and the two bulk masses determine the Yukawa couplings; one extra parameter is thus introduced**

- **The numerical analysis is in progress. While the details of the spectrum will be affected, we expect that the large, phenomenologically viable regions remain intact.**

Summary

- **Gauge-Higgs unification is generic in heterotic orbifold models**
- **An effective 5d setting, motivated by the string-scale/GUT-scale problem allows for predictions for soft masses and μ term**
- **The 5d Chern-Simons term (which is generically present) together with a VEV of the chiral adjoint makes this setting phenomenologically viable**
- **Phenomenology resembles 'Higgs-exempt no-scale models'**
- **Preliminary: A realistic phenomenology results rather naturally**
- **Preliminary: Small mass differences between neutralino and sleptons appear to be generic**