CP violating asymmetry in stop decay into bottom and chargino

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Outline

Baryon asymmetry of the universe

- Exists much more baryonic matter than antimatter
- Standard Model (SM) *cannot* explain baryon asymmetry of the universe (BAU)!
- Evidence from acoustic peaks (early universe baryon-photon plasma oscillations) deduced from Cosmic Microwave Background measurements

Baryon-to-photon ratio

$$\eta \equiv \frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

s . . . entropy density (roughly photon density)
$n_b(n_{\bar{b}})$ . . . number densities of baryons (antibaryons)

Baryogenesis

Problem

How does η get this small value from expected initial condition $\eta = 0$?

Criteria of a solution

Three necessary conditions for baryogenesis:
Sakharov requirements

1. Baryon number violation
2. Departure from thermal equilibrium
3. Charge (C) and *Charge-Parity (CP) violation*

SM can meet Sakharov criteria but baryon asymmetry is *too small*!

Possible solution

Electroweak Baryogenesis

- Supersymmetric extensions of SM can contain new sources of CP violation
- Lead to increase and thus possible explanation of baryon asymmetry
- Special case: Minimal Supersymmetric Standard Model (MSSM) introduces new parameters
- If some parameters are chosen *complex*, processes can lead to *new CP violating asymmetries*
- Even if BAU cannot be explained, study of CP violation and values of (possible complex!) parameters is important

Decay rate asymmetry δ^{CP}

Definition

Decay rate asymmetry $\delta^{CP} = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$

- In our case: decay of stop into bottom and chargino
  $\Gamma^+ = \Gamma(\tilde{t}_i \to b\,\tilde{\chi}_k^+)$, $\Gamma^- = \Gamma(\tilde{t}_i^* \to \bar{b}\,\tilde{\chi}_k^{+c})$
- In general: $\Gamma^\pm \propto \sum_s |\mathcal{M}^\pm_{\text{tree}}|^2 + 2\text{Re}\left(\sum_s (\mathcal{M}^\pm_{\text{tree}})^\dagger \mathcal{M}^\pm_{\text{loop}}\right)$
- Asymmetry can be approximated to
  (no CP violation at tree level, one loop contributions small)

$$\delta^{CP} \cong \frac{\Gamma^+ - \Gamma^-}{2\Gamma_{\text{tree}}} = A^{CP}_+ - A^{CP}_- \qquad A^{CP}_\pm = \frac{\text{Re}\left(\sum_s (\mathcal{M}^\pm_{\text{tree}})^\dagger \mathcal{M}^\pm_{\text{loop}}\right)}{\sum_s |\mathcal{M}_{\text{tree}}|^2}$$

Decay rate asymmetry δ^{CP}

Further calculations (e.g. defining combined coupling matrices $C_{\pm}^{ij}$) result in *decomposition* into CP invariant (C_{inv}^{ij}) and CP violating part (C_{CP}^{ij}) ($i, j \in \{R, L\}$)

Decay rate asymmetry δ^{CP}

$$\delta^{CP} = \frac{1}{2\sum_s |\mathcal{M}_{\mathrm{tree}}|^2} \left(2\Delta (C_{\mathrm{CP}}^{RR} + C_{\mathrm{CP}}^{LL}) - 4 m_b m_{\tilde{\chi}_k^+} (C_{\mathrm{CP}}^{RL} + C_{\mathrm{CP}}^{LR}) \right)$$

$$\Delta = (m_{\tilde{t}_i}^2 - m_b^2 - m_{\tilde{\chi}_k^+}^2) \qquad C_{\mathrm{CP}}^{ij} \propto -2\mathrm{Im}(b g_0 g_1 g_2)\mathrm{Im}(\mathrm{PaVe})$$

b ... tree level coupling

$g_0 g_1 g_2$ ... couplings of vertices

Decay rate asymmetry δ^{CP}

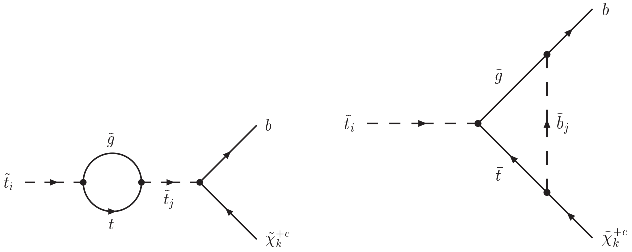
Resulting from

$$C_{\mathrm{CP}}^{ij} \propto -2\,\mathrm{Im}(b g_0 g_1 g_2)\,\mathrm{Im}(\mathrm{PaVe})$$

we observe that decay rate asymmetry δ^{CP} only $\neq 0$ if

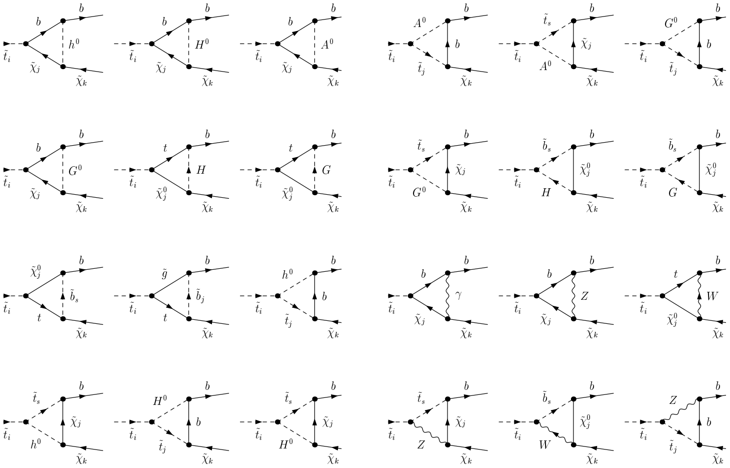
1. Inclusion of at least one loop corrections and
2. Complex couplings (via complex MSSM parameters) and
3. At least a second decay channel kinematically open (i.e. in addition to $\tilde{t}_i \to b\,\tilde{\chi}_k^+$ e.g. as well $\tilde{t}_i \to \tilde{g}\,t$ open)

Most important contributions (expected)
All gluino contributions

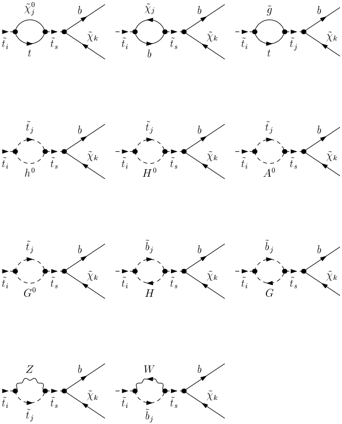


- Gluino $\tilde{g}$ couples with strong interaction force (QCD)
- Thus, if decay $\tilde{t}_i \to t\,\tilde{g}$ becomes possible (i.e. $m_{\tilde{t}_i} \geq m_t + m_{\tilde{g}}$) these contributions should dominate over all others

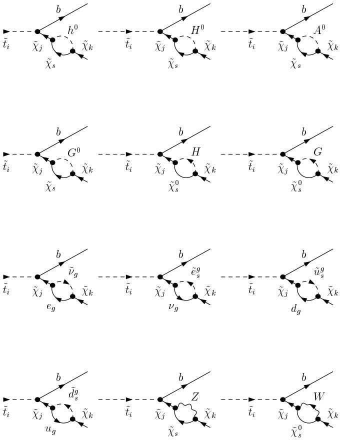
All vertex contributions



All stop-selfenergy contributions



All chargino-selfenergy contributions



Calculation

- All 47 CP violating contributions calculated with FeynArts
- Most important contributions calculated independently for cross check and complex gluino phase
- Checks:
  - Electric dipole moments (EDM) with own code
  - Cold dark matter relic density (Ω_{CDM}) and $B \to X_s\gamma$ with MicrOMEGAs
- Parameters:
  - Coupling α_s taken running in $\overline{DR}$ scheme, renormalized at scale of decaying stop mass $m_{\tilde{t}_i}$ in SPA convention
  - 3rd generation Yukawa couplings h_t, h_b taken running
  - GUT relations for gaugino masses used $\Rightarrow$ gluino mass $m_{\tilde{g}}$ related to M_2

A typical scenario

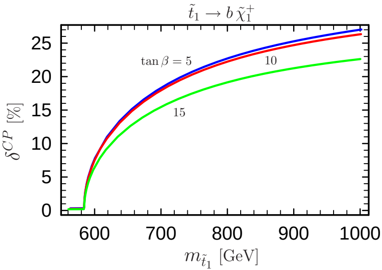
- Parameters:
  - SUSY breaking mass parameters (all generations) $M_{\tilde{Q}} = M_{\tilde{u}} = M_{\tilde{d}} = 650$ GeV, $M_{\tilde{L}} = M_{\tilde{e}} = 600$ GeV
  - Trilinear breaking parameters $|A_t| = |A_b| = |A_\tau| = 190$ (1st and 2nd generation set to zero)
  - Complex phases $\varphi_{A_t} = \varphi_{A_b} = \varphi_{A_\tau} = \pi/4$ ($\varphi_\mu = 0$ due to EDM problems, $\varphi_{M_1} = 0$ effect on δ^{CP} negligible, $\varphi_{\tilde{g}} = 0$ at first)
  - Gaugino masses $M_2 = 150$ GeV, $|M_1| = M_2/2$ (GUT relation)
  - Higgsino mass parameter $|\mu| = 830$ GeV
  - $\tan\beta = 5$
  - $M_{A^0} = 1000$ GeV

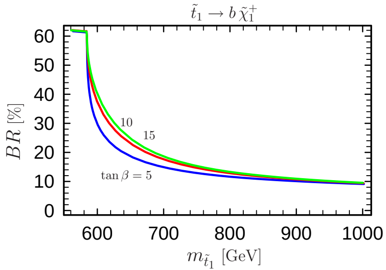
A typical scenario

- Implications of our scenario:
  - Phase φ_{A_t} is at first only source of CP violation (gluino phase $\varphi_{\tilde{g}}$ set to zero in the beginning)
  - Chargino $\tilde{\chi}_1^+$ of our decay $\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ is gaugino-like (due to $M_2 \ll |\mu|$)
  - Higgsino-like chargino ($M_2 \gg |\mu|$) only possible if GUT relation is relaxed and gluino mass becomes free parameter (otherwise gluino gets too heavy and main contribution to δ^{CP} via $\tilde{t}_1 \to \tilde{g}\,t$ not possible)
  - Stops $\tilde{t}_1$ and $\tilde{t}_2$ have low mass splitting and high mixing $\Rightarrow$ stops quite similar $\Rightarrow$ $\tilde{t}_2$ decay not of interest

Numerical results

$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (all contributions)

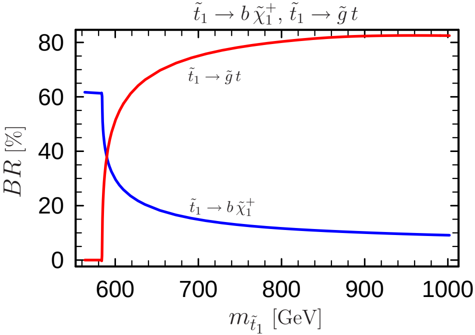




- Convenience: output parameter $m_{\tilde{t}_1}$ shown, but actually input parameter $M_{\tilde{Q}}$ varied
- Decay channel $\tilde{t}_1 \to t\,\tilde{g}$ opens up at $m_{\tilde{t}_1} \sim 582$ GeV
- Dominance of both gluino contributions over all others
- However if $\tilde{t}_1 \to t\,\tilde{g}$ opens up, $BR(\tilde{t}_1 \to b\,\tilde{\chi}_1^+)$ drops quickly!

Numerical results

Comparison $BR(\tilde{t}_1 \to b\,\tilde{\chi}_1^+)$ vs $BR(\tilde{t}_1 \to \tilde{g}\,t)$

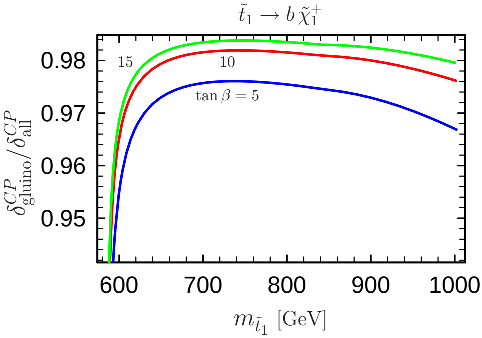


Permanent conflict between δ^{CP} and $BR(\tilde{t}_1 \to b\,\tilde{\chi}_1^+)$!

- High δ^{CP} needs gluino contributions $\Rightarrow$ *BR* falls off
- High *BR* needs NO gluino contributions $\Rightarrow$ δ^{CP} keeps low
- Solution is to compromise ...

Numerical results

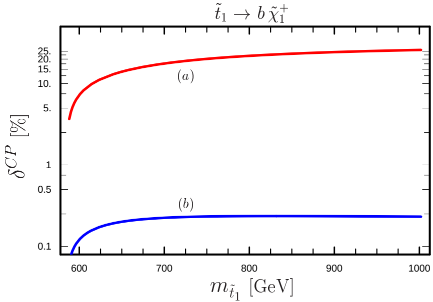
Gluino vs all other contributions



- After threshold at $m_{\tilde{t}_1} \sim 582$ GeV gluino contributions account for $\sim 98\,\%$ of all contributions to δ^{CP}

Numerical results

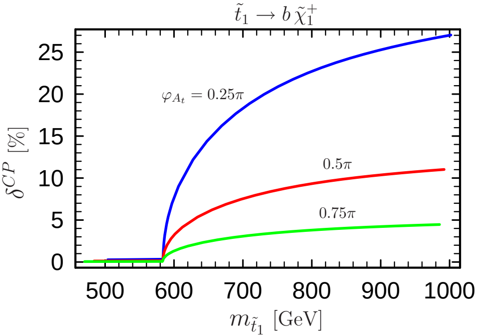
Comparison of gluino contributions



- (a) Gluino in selfenergy loop,
  (b) Gluino in vertex correction
- Contrary to expectation only *one* gluino contribution dominates!
- Major reason lies in $Im(C_2)$ embedded in form factor of vertex correction, however no simple explanation possible

Numerical results

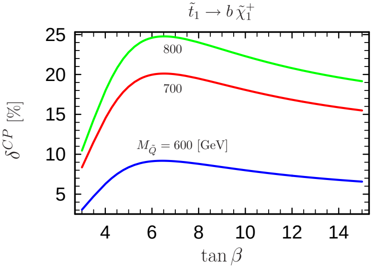
$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (all contributions)

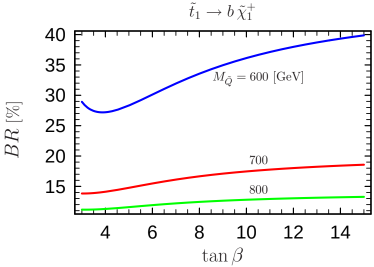


- φ_{A_t} is the only complex phase and thus only source of CP violation
- Maximum at $\varphi_{A_t} = \pi/4$

Numerical results

$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (all contributions)

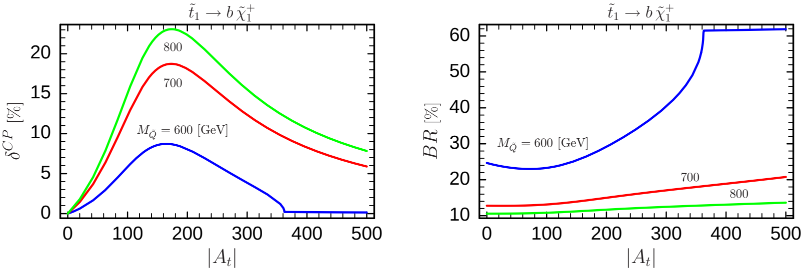




- $\tan\beta$ low for high δ^{CP}
- The heavier the decaying particle ($m_{\tilde{t}_1} \sim M_{\tilde{Q}}$)
  - the higher δ^{CP} gets
  - the lower $BR(\tilde{t}_1 \to b\,\tilde{\chi}_1^+)$ becomes

Numerical results

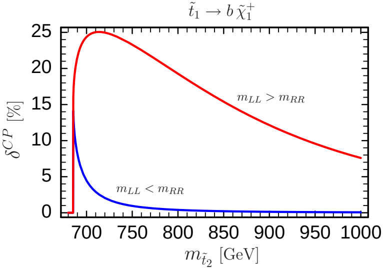
$\tilde{t}_1 \longrightarrow b\,\tilde{\chi}_1^+$ (all contributions)

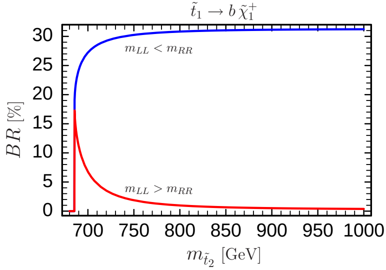


- $|A_t|$ determines degree of mass splitting of $m_{\tilde{t}_{1,2}}$
- $|A_t| \sim 190$: mass splitting low ($m_{\tilde{t}_1} \sim 603$ GeV, $m_{\tilde{t}_2} \sim 641$ GeV)
- Low mass splitting enhances gluino in selfenergy contribution (propagator $\propto 1/(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2})$)

Numerical results

Effect on mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$

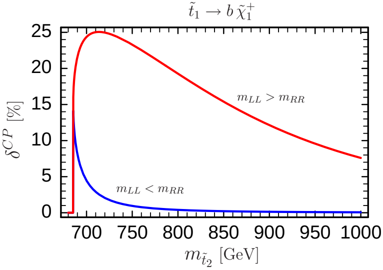


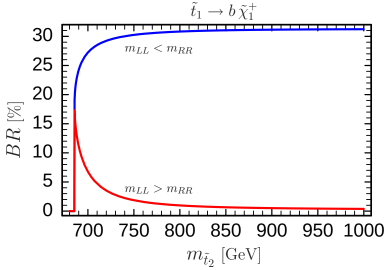


- $m_{\tilde{t}_1} = 650$ GeV, $m_{\tilde{t}_2}$ variable (actually parameter $M_{\tilde{Q}}, M_{\tilde{U}}$ varied)
- Exist two solutions for $M_{\tilde{Q},\tilde{U}}(m_{\tilde{t}_2})$: $m_{LL} < m_{RR}$ and $m_{LL} > m_{RR}$ (diagonal elements of stop mass matrix)
- Gaugino-like chargino couples with left-handed (LH) stop ($\tilde{t}_1$ external, $\tilde{t}_2$ internal particle)

Numerical results

Effect on mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$

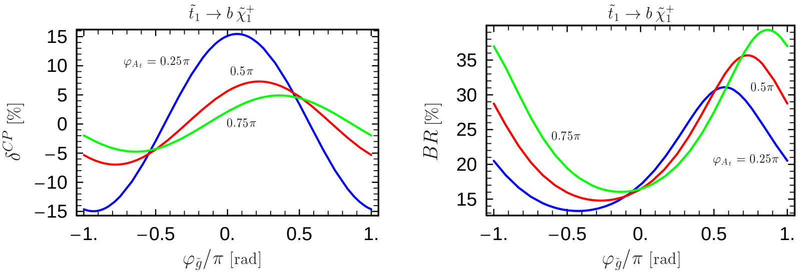




- $m_{LL} < m_{RR}$: $\tilde{t}_1$ LH (BR high), $\tilde{t}_2$ RH (δ^{CP} low)
- $m_{LL} > m_{RR}$: $\tilde{t}_1$ RH (BR low), $\tilde{t}_2$ LH (δ^{CP} high)
- Either way, combination of δ_{CP} and BR keeps low, unless mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$ is low!
- Mass splitting cannot be arbitrarily small (otherwise $M_{\tilde{Q}}, M_{\tilde{U}} \in \mathbb{C}$)

Numerical results

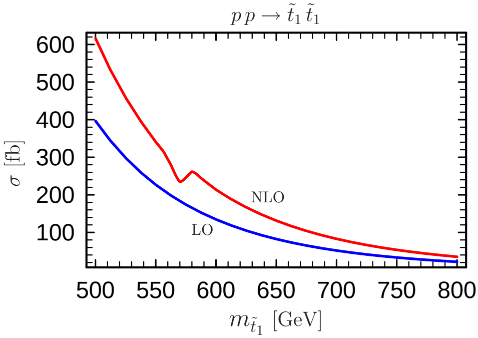
Gluino phase $\varphi_{\tilde{g}}$ (only gluino contributions)



- Now gluino phase $\varphi_{\tilde{g}}$ as 2nd source of CP violation
- Strong dependence on $\varphi_{\tilde{g}}$ as expected
- Periodic behavior of $\varphi_{\tilde{g}}$ as a function of φ_{A_t}

Numerical results

Total cross section of stop1 pair production at LHC



- Plot generated with Prospino
- $\sqrt{s} = 14$ TeV
- $\tilde{t}_{1,2}$ mass splitting 100 GeV
- $\sigma = 200$ fb @ $\tilde{t}_1 = 610$ GeV, $\tilde{t}_2 = 710$ GeV

Experimental measurability

- Luminosity $\mathcal{L} = 300\,[\mathrm{fb}]^{-1}$ at LHC in 5 years (design luminosity)
- Rough estimate: number of CP violating events $N = \mathcal{L} \times \sigma \times \delta^{CP} \times BR = 300 \times 200 \times 0.1 \times 0.2 = 1200$
- Measurement of particles of $\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ and $\tilde{t}_1^* \to \bar{b}\,\tilde{\chi}_1^{+c}$ decay only possible *after* good understanding of particle properties of MSSM
- Possible signature: Subsequent decay of $\tilde{\chi}_1^\pm$ into $\tilde{\chi}_1^0$ and $W^\pm \to l\nu_l$
- Measurement at LHC possible, but Super-LHC and CLIC better for detection of this effect

Conclusions

- In MSSM with complex parameters, loop corrections to $\tilde{t}_i \rightarrow b\,\tilde{\chi}_k^+$ decay can lead to CP violating decay rate asymmetry $\delta^{CP} = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$
- Studied this asymmetry at full one-loop level, analyzing dependence on parameters and phases (φ_{A_t} and $\varphi_{\tilde{g}}$)
- δ^{CP} of several percent are obtained, mainly due to gluino contribution in selfenergy loop
- High δ^{CP} reached with low mass splitting and high mixing of stop particles, chargino should be gaugino-like
- But δ^{CP} must be always seen in relation to *BR* (opposing δ^{CP}) and σ_{prod} (stop should be rather light)
- Measurement at LHC possible (2nd phase)

Outlook

- Present results will be published soon ...
- Further scenario: mSUGRA with complex phase φ_A
- Possible further study of *production* and decay

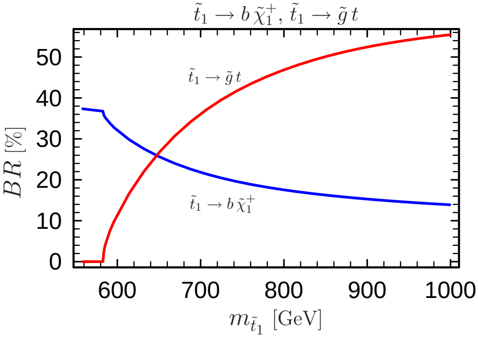
Acknowledgments

Many thanks to . . .

- My supervisors Dr. Majerotto and Dr. Eberl
- All my colleagues at my institute
- YOU for listening!

Numerical results

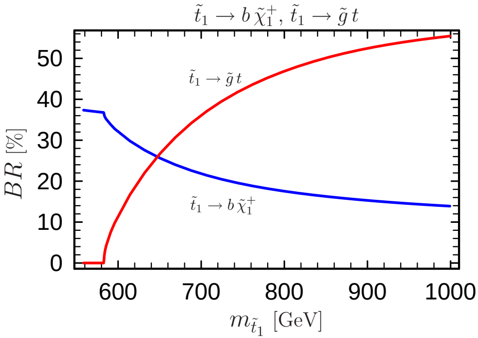
Comparison with higgsino-like chargino



- Relaxing GUT relations for gaugino masses
  $\Rightarrow$ $m_{\tilde{g}}$ becomes free parameter
- Exchanging values of M_2 and $|\mu|$
  $\Rightarrow$ $M_2 = 830$ GeV, $|\mu| = 150$ GeV
  $\Rightarrow$ $\tilde{\chi}_1^+$ (and $\tilde{\chi}_1^0$) becomes higgsino-like

Numerical results

Comparison with higgsino-like chargino



- Yukawa coupling in $\tilde{t}_i\, b\, \tilde{\chi}_k^+$ coupling becomes important
- Since (s)top Yukawa coupling stronger than gauge coupling
  - Faster decay rates for stop
  - Especially decay into neutralino enhanced