CP violating asymmetry in stop decay into bottom and chargino

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Outline

1. Motivation

2. CP violating decay rate asymmetry
   - Definitions
   - Contributions
   - Numerical results

3. Conclusions and Outlook
**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 $\eta$ 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
**Definition**

Decay rate asymmetry \( \delta^{CP} \)

\[
\delta^{CP} = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}
\]

- In our case: decay of stop into bottom and chargino
  \[
  \Gamma^+ = \Gamma(\tilde{t}_i \rightarrow b \tilde{\chi}^+_k), \quad \Gamma^- = \Gamma(\tilde{t}_i^* \rightarrow \bar{b} \tilde{\chi}^{+c}_k)
  \]

- In general: \( \Gamma^\pm \propto \sum_s |M^\pm_{\text{tree}}|^2 + 2 \text{Re}\left( \sum_s (M^\pm_{\text{tree}})^\dagger M^\pm_{\text{loop}} \right) \)

- Asymmetry can be approximated to
  (no CP violation at tree level, one loop contributions small)

\[
\delta^{CP} \cong \frac{\Gamma^+ - \Gamma^-}{2 \Gamma_{\text{tree}}} = A^+_{CP} - A^-_{CP} \quad A^\pm_{CP} = \frac{\text{Re}\left( \sum_s (M^\pm_{\text{tree}})^\dagger M^\pm_{\text{loop}} \right)}{\sum_s |M^\pm_{\text{tree}}|^2}
\]
Further calculations (e.g. defining combined coupling matrices $C_{ij}^\pm$) result in *decomposition* into CP invariant ($C_{ij}^{\text{inv}}$) and CP violating part ($C_{ij}^{\text{CP}}$) ($i, j \in \{R, L\}$).

**Decay rate asymmetry $\delta^{CP}$**

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

$$\Delta = (m_{t_i}^2 - m_b^2 - m_{\tilde{\chi}_k^+}^2) \quad C_{CP}^{ij} \propto -2\text{Im}(bg_0g_1g_2)\text{Im}(PaVe)$$

$b$ ... tree level coupling

g_0g_1g_2 ... couplings of vertices
Resulting from

\[ C_{CP}^{ij} \propto -2 \text{Im}(b g_0 g_1 g_2) \text{Im}(PaVe) \]

we observe that decay rate asymmetry \( \delta^{CP} \) 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 \( \tilde{t}_i \rightarrow b \tilde{\chi}_k^+ \) e.g. as well \( \tilde{t}_i \rightarrow \tilde{g} t \) open)
Gluino $\tilde{g}$ couples with strong interaction force (QCD)

Thus, if decay $\tilde{t}_i \rightarrow t \tilde{g}$ 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

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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 ($\Omega_{CDM}$) and $B \rightarrow X_s \gamma$ with MicrOMEGAs.
- Parameters:
  - Coupling $\alpha_s$ 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)
  $M_{\tilde{Q}} = M_{\tilde{u}} = M_{\tilde{d}} = 650 \text{ GeV}$, $M_{\tilde{L}} = M_{\tilde{e}} = 600 \text{ GeV}$

- 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 $\delta^{CP}$ negligible, $\varphi_{\tilde{g}} = 0$ at first)

- Gaugino masses $M_2 = 150 \text{ GeV}$,
  $|M_1| = M_2/2$ (GUT relation)

- Higgsino mass parameter $|\mu| = 830 \text{ GeV}$

- $\tan \beta = 5$

- $M_{A^0} = 1000 \text{ GeV}$
Implications of our scenario:

- Phase $\varphi_{A_{t}}$ 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 $\delta_{CP}$ 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
\( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^+ \) (all contributions)

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

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

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

- High $\delta^{CP}$ needs gluino contributions $\Rightarrow$ $BR$ falls off
- High $BR$ needs NO gluino contributions $\Rightarrow$ $\delta^{CP}$ 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 $\delta^{CP}$
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

\( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^+ \) (all contributions)

\[ \delta_{CP} \] 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 \(\delta^{CP}\)
- The heavier the decaying particle \((m_{\tilde{t}_1} \sim M_{\tilde{Q}})\)
  - the higher \(\delta^{CP}\) gets
  - the lower \(BR(\tilde{t}_1 \to b\tilde{\chi}_1^+)\) becomes
| $|A_t|$ | determines degree of mass splitting of $m_{\tilde{t}_1,2}$

| $|A_t|$ | $\sim 190$: mass splitting low ($m_{\tilde{t}_1} \sim 603 \text{ GeV}, m_{\tilde{t}_2} \sim 641 \text{ GeV}$)

Low mass splitting enhances gluino in selfenergy contribution (propagator $\propto 1/(m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2)$)
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)

$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$

$\delta_{CP} [%]$

$BR [%]$

$m_{\tilde{t}_2} [GeV]$
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 ($\delta_{CP}$ low)
- $m_{LL} > m_{RR}$: $\tilde{t}_1$ RH ($BR$ low), $\tilde{t}_2$ LH ($\delta_{CP}$ high)

Either way, combination of $\delta_{CP}$ and $BR$ keeps low, unless mass splitting of $\tilde{t}_1$ and $\tilde{t}_2$ is low!

Mass splitting cannot be arbitrarily small (otherwise $M_{\tilde{Q}}, M_{\tilde{U}} \in \mathbb{C}$)
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 $\varphi_{A_t}$
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 \text{ fb} @ \tilde{t}_1 = 610 \text{ GeV}, \tilde{t}_2 = 710 \text{ GeV}
Experimental measurability

- Luminosity $\mathcal{L} = 300 \text{[fb]}^{-1}$ 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 $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$ and $\tilde{t}_1^* \rightarrow \bar{b} \tilde{\chi}_1^{+c}$
  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 $W^{\pm} \rightarrow l\nu_l$
- 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 ($\varphi_{A_t}$ and $\varphi_{\tilde{g}}$)

- $\delta^{CP}$ of several percent are obtained, mainly due to gluino contribution in selfenergy loop

- High $\delta^{CP}$ reached with low mass splitting and high mixing of stop particles, chargino should be gaugino-like

- But $\delta^{CP}$ must be always seen in relation to $BR$ (opposing $\delta^{CP}$) and $\sigma_{\text{prod}}$ (stop should be rather light)

- Measurement at LHC possible (2nd phase)
Present results will be published soon . . .

Further scenario: mSUGRA with complex phase $\varphi_A$

Possible further study of production and decay
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- 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 \text{ GeV}, |\mu| = 150 \text{ GeV}
  \Rightarrow \tilde{\chi}_1^+ \text{ (and } \tilde{\chi}_1^0 \text{) becomes higgsino-like}
**Motivation**

CP violating decay rate asymmetry

**Conclusions and Outlook**

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

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