Flavor Signals at SUSY benchmark points

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work in progress with:

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Introduction

SUSY is intensively studied for years, as a promising candidate of the new physics beyond the SM.

Simplest SUSY extension of the SM: MSSM

MSSM provides...

- New particles (superpartners).
- New source of flavor mixing/CP violation.
- Dark matter candidate (stable LSP).

In general, MSSM has too many (> 100) parameters in the SUSY breaking sector.

Simple assumptions on the SUSY breaking sector are required for actual studies.

⇒ Minimal supergravity.
Minimal supergravity model (mSUGRA, CMSSM)

- \( \mu_G: m_0, m_{1/2}, A_0 \)
- \( \mu_W: \) radiative EWSB.
- \( \tan \beta = \langle H_2 \rangle / \langle H_1 \rangle, \sgn(\mu), V_{\text{CKM}}, \) quark/lepton masses.

- EWSB/squark flavor mixing induced by running effect.
  \[
  \delta m_H^2 \sim m_0^2 \text{tr} Y_u Y_u^\dagger \log \frac{\mu_W}{\mu_G}, \quad \delta m_Q^2 \sim m_0^2 Y_u Y_u^\dagger \log \frac{\mu_W}{\mu_G}.
  \]

- Squark flavor mixing also governed by \( V_{\text{CKM}}. \)

- Lepton flavor conserved (no \( \nu_R \)).
Benchmark points

- The parameter space is still huge for detailed study.
- Cosmology excludes much of parameter space.

Benchmark points are proposed for LHC/ILC studies.
- SPS (Snowmass 2001)
- Battaglia et al., LCWS05

Flavor signals @ benchmark points?

(Feng, LCWS05)
Here we take three benchmark points as references.

- Bulk point
- Stau coannihilation
- Focus point

The model is extended to SU(5) SUSY-GUT with $\nu_R$.

$\Rightarrow$ Additional sources of flavor mixing:

- $\nu$ Yukawa couplings / $M_{\nu_R}$ ($\leftarrow \nu$ mixing).
- GUT scale $\Leftrightarrow$ Planck scale running.
“Bulk point”

- LSP = $\chi_1^0$ ($\tilde{B}$-like).
- Annihilate to $\ell \ell$ through $\tilde{\ell}$ exchange.
- $m_0 < m_{1/2} \approx 250$ GeV.
“Stau coannihilation”

- LSP = $\chi^0_1$ ($\tilde{B}$-like).
- $m(\tilde{\tau})$ close to $m(\chi^0_1)$.
- $\tilde{\tau} \chi^0_1 \rightarrow \tau \gamma$ enhanced.
“Focus point”

- LSP $= \chi^0_1$ ($\tilde{h}$-like).
- Annihilate to $W^+ W^-$ through $\chi^{\pm}$ exchange.
- $\mu < M_1 (\approx 0.4 m_{1/2}) \ll m_0$. 

![Graphical representation](image-url)
SU(5) SUSY-GUT $\oplus \nu_R$

An extension of mSUGRA, introducing heavy Majorana $\nu_R$ and Yukawa coupling in $\nu$ sector.

$\mu_P$: $m_0, m_{1/2}, A_0$ (mSUGRA type SUSY breaking).

$\mu_G$: SU(5)$\rightarrow$SU(3)$\times$SU(2)$\times$U(1) by $\langle \Sigma \rangle$.

$\mu_R$: $\nu_R$ integrated out.

$\mu_W$: EWSB. $\tan \beta$, sgn($\mu$), $V_{CKM}, V_{MNS}$, q/\ell/\nu masses.

- Flavor mixing in $\tilde{d}_R \Leftarrow \nu$-Yukawa & GUT interactions.

- LFV in $\tilde{\ell}_L \Leftarrow \nu$-Yukawa.

($\mu \rightarrow e\gamma$ constraint)

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New CP violating phases appear @μ_G.

$$10_i = \left\{ Q_i, \ (V_{\text{CKM}}^\dagger U^c)_i, \ e^{i\phi_i^L} E^c_i \right\},$$

$$\bar{5}_i = \left\{ D^c_i, \ e^{-i\phi_i^L} L_i \right\},$$

- $\phi_i^L \Leftrightarrow$ lepton flavor number; physical in a model with LFV.
- Complex phases induced in $\tilde{d}_R$ mass matrix (Moroi).
Numerical results

Two patterns for the $\nu$-Yukawa/$M_\nu R$ structure studied.

- “Degenerate”: $M_\nu R \propto 1$.

- “Non-degenerate”: $M_\nu R \not\propto 1$, a texture $Y_\nu \propto \begin{pmatrix} * & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$ assumed.

  1-2 mixing ($\mu \rightarrow e \gamma, \varepsilon_K$) smaller compared to the degenerate case.

Fixed parameters:

- $q/l/\nu$ masses, $V_{us}, V_{cb}, V_{MNS}$.
- $m_0, m_{1/2}, A_0, \tan \beta$, for each benchmark point.
  - $\mu$ and $A_0$ are taken as real (to avoid large EDMs).

Varied parameters:

- $|V_{ub}|, \phi_3, \phi_i^L, \mu_R$.
  - $M_\nu R$ scales as $\det M_\nu R = \mu_R^3$.
  - $Y_\nu$ chosen to reproduce $\nu$ masses and $V_{MNS}$.
“Bulk point”: $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$

- $m(\tilde{\ell}) \sim 200$ GeV  
  $\Rightarrow$ LFV enhanced.
- $\mu_R \gtrsim 10^{13}$ GeV excluded for degenerate case.
- $\mu_R \gtrsim 10^{14}$ GeV excluded for non-degenerate case.

SUSY contributions to quark flavor observables are strongly constrained.
Time-dependent CP asymmetries

\[ S(B \rightarrow \phi K_S) \]

- mSUGRA
- SU(5) \( v_R \), degenerate
- SU(5) \( v_R \), non-degenerate

\[ S(B \rightarrow K_{CP} \gamma) \]

- mSUGRA
- SU(5) \( v_R \), degenerate
- SU(5) \( v_R \), non-degenerate

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$\Delta m_{B_s}$, $\varepsilon K$

![Graph 1: $\Delta m_{B_s}$ vs $\mu_R$](image1)

- mSUGRA
- SU(5) $v_R$, degenerate
- SU(5) $v_R$, non-degenerate

![Graph 2: $\varepsilon_K/(\varepsilon_K)_{SM}$ vs $\mu_R$](image2)

- mSUGRA
- SU(5) $v_R$, degenerate
- SU(5) $v_R$, non-degenerate
“Stau co-annihilation”: $\mu \rightarrow e \gamma$, $\tau \rightarrow \mu \gamma$

- Large $\tilde{\tau}_L-\tilde{\tau}_R$ mixing required for $m(\tilde{\tau}_1) \sim m(\chi^0_1)$.
  $\Rightarrow$ $\mu \rightarrow e \gamma$, $\tau \rightarrow \mu \gamma$ more enhanced than “bulk”.
- $m(\tilde{\ell}) \sim 300$ GeV.
- $\mu_R \gtrsim 10^{13}$ GeV excluded for both cases.

SUSY contributions to quark flavor observables are constrained.
Time-dependent CP asymmetries

"Stau co-annihilation"

$m \leq 0.70$

$\mu_R$ [GeV]

$m_{\text{SUGRA}}$

SU(5) $v_{R^*}$ degenerate

SU(5) $v_{R^*}$ non-degenerate

$m \leq 0.70$

$\mu_R$ [GeV]

$m_{\text{SUGRA}}$

SU(5) $v_{R^*}$ degenerate

SU(5) $v_{R^*}$ non-degenerate
$\Delta m_{B_{s}}, \varepsilon K$

"Stau co-annihilation"

- mSUGRA
- SU(5) $\nu_{R}$, degenerate
- SU(5) $\nu_{R}$, non-degenerate

$\Delta m(B_{s})$ [ps$^{-1}$]

$\varepsilon_{K}/(\varepsilon_{K})_{SM}$

$\mu_{R}$ [GeV]
“Focus point”

\[
\begin{align*}
\tan \beta &= 10 \\
m_{1/2}(\mu_G) &= 284 \text{ GeV} \\
A_0 &= 0 \\
\text{degenerate}
\end{align*}
\]

- \( m_0 \uparrow \) for \( \mu_R \uparrow \) in order to obtain \( \mu \sim 100 \text{ GeV} \) (required for \( \tilde{h} \)-like LSP).

\[ m(\tilde{q}, \tilde{\ell}) > 3 \text{ TeV}, \text{ decouples.} \]
"Focus point": $\mu \rightarrow e \gamma$, $\tau \rightarrow \mu \gamma$

- Degenerate, $\mu_R = 2 \times 10^{12}\text{GeV}$
- Degenerate, $\mu_R = 2 \times 10^{13}\text{GeV}$
- Non-degenerate, $\mu_R = 2 \times 10^{12}\text{GeV}$
- Non-degenerate, $\mu_R = 2 \times 10^{13}\text{GeV}$
Time-dependent CP asymmetries

"Focus point"
$\Delta m_{B_s}$, $\varepsilon_K$

"Focus point"

- mSUGRA
- SU(5) $\nu_R^\prime$, degenerate
- SU(5) $\nu_R^\prime$, non-degenerate

$\Delta m(B_s)$ [ps$^{-1}$]

$\varepsilon_K / (\varepsilon_K)_{SM}$

$\mu_R$ [GeV]
Summary

Flavor observables studied in SU(5) SUSY-GUT $\oplus \nu_R$ for “benchmark points”.

<table>
<thead>
<tr>
<th></th>
<th>$\mu \rightarrow e\gamma$</th>
<th>$\tau \rightarrow \mu\gamma$</th>
<th>$\varepsilon_K$</th>
<th>$B$ obs.</th>
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</thead>
<tbody>
<tr>
<td>“Bulk point”</td>
<td>D large</td>
<td>$\sim 10^{-9}$</td>
<td>$\sim 5%$</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>ND large</td>
<td>$\sim 10^{-8}$</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>“Stau-coannihilation”</td>
<td>D large</td>
<td>$\sim 10^{-9}$</td>
<td>$\sim 5%$</td>
<td>small</td>
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(D=Degenerate, ND=Non-degenerate)