Constructive Interference in the $B \rightarrow \tau \nu$ Amplitude in the MSSM with negative $\mu$

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Outline

- Motivation: $B \rightarrow \tau \nu$ in SM vs. Experiment
- $B \rightarrow \tau \nu$ in the MSSM
  - What large and negative $\mu$ can do for us
- Constraints/Consequences for other processes
- Vacuum stability
- Summary
SM vs Experiment

- SM has been verified experimentally to an astounding precision
- However, there are some small(?) deviations
  - $t\bar{t}$ asymmetry
  - ...
  - $BR(B \to \tau\nu)$

<table>
<thead>
<tr>
<th>SM (UTfit)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(0.81 \pm 0.12) \times 10^{-4}$</td>
<td>$(1.68 \pm 0.31) \times 10^{-4}$</td>
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</table>

⇒ This is $(2 - 3)\sigma$ discrepancy

- Is this new physics? If so, what could cause this?
$B \to \tau\nu$: New physics?

- How well is SM value known?

$$\mathcal{BR}(B \to \tau\nu)_{SM} = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_T^2 f_B^2 m_B \left(1 - \frac{m_T^2}{m_B^2}\right)^2$$

$\Rightarrow$ Largest error from $f_B$ and $V_{ub}$:

$$\mathcal{BR}(B \to \tau\nu)_{SM} \sim (0.73 - 0.83) \times 10^{-4}$$

- Still no agreement with experiment ($\sim 1.6 \times 10^{-4}$).

Working assumption

Assume this is due to new physics.
$B \to \tau \nu$ in general Two Higgs Doublet models

- The charged Higgs $H^\pm$ can mediate (almost) the same interactions like the $W^\pm$
  \[ \mathcal{L} \sim \bar{\Psi}_L \gamma^\mu W^\mu \Psi_L + \bar{\Psi}_L \cdot \phi_H \psi_R \]

- Leptonic B decays get another contribution (compared to SM)

\[ \frac{\mathcal{BR}(B \to \tau \nu)_{2HDM}}{\mathcal{BR}(B \to \tau \nu)_{SM}} = \left| 1 + \frac{m_B^2}{m_b m_\tau} C^{\tau}_{NP} \right|^2 \]

$\Rightarrow$ Looks promising.
A closely related decay is \( B \to D\tau \nu \):

\[
\begin{align*}
\mathcal{B}(B \to D\tau \nu) &= (0.28 \pm 0.02) \times \left[ 1 + 1.38(3) \text{Re} C_{\tau NP}^\tau + 0.88(2) |C_{\tau NP}^\tau|^2 \right] \\
\mathcal{B}(B \to D\tau \nu) &= \mathcal{B}(B \to D\tau \nu) / \mathcal{B}(B \to D\nu) \\
&\Rightarrow \text{How does this compare to } \mathcal{B}(B \to \tau \nu) \text{ in MSSM with large negative } \mu \text{?}
\end{align*}
\]
Fit for $C_{NP}$

- Allowed region with 1σ and 2σ contours in the complex $C_{NP}$ plane:

⇒ Best fit for real $C_{NP} \sim +0.1$. From now on, assume that $C_{NP}$ is real.
In the MSSM

\[ C_{NP} = - \frac{m_b m_\tau}{m_{H^+}^2} \tan^2 \beta \]

- In a specific model we can compute \( C_{NP} \)
- This is negative!
- No overlap in preferred regions.
- Can we change the sign?
\( C_{NP} \) in the MSSM

- \( C_{NP} \) gets loop correction from the bottom mass \( m_b \)

\[
C_{NP}^\tau = - \frac{m_b m_\tau}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}
\]

- The loop correction is

\[
\epsilon_0 \sim \frac{b_R \tilde{b}_R}{m_2 \tilde{b}_1} \frac{g}{H_u}
\]

\[ b_L \]

\[ \tilde{b}_L \]

---

**Measure of \( U(1)_{PQ} \) violation in the MSSM**

\[
\epsilon_0 = \frac{2 \alpha_s}{3 \pi} M_3 \mu I(m_{b_1}^2, m_{b_2}^2, M_3^2)
\]

\[ \Rightarrow C_{NP} \text{ is positive, if } \mu \text{ is negative and } \tan \beta \text{ large: } 1 + \epsilon_0 \tan \beta < 0. \]
Fit for $C_{NP}$

- “Usually” $|\epsilon_0| \lesssim 1 - 2\%$, but assume we had $\epsilon_0 = -3\%$:

$$C_{NP}^\tau = -\frac{m_b m_\tau}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}$$

$\Rightarrow$ Large $\tan \beta$ and $m_{H^+}$

- Can be $|\epsilon_0|$ this big?
- How will this manifest in other measurements?
“Usually” $|\epsilon_0| \lesssim 1 - 2\%$, but assume we had $\epsilon_0 = -3\%$:

- Can be $|\epsilon_0|$ this big?
- How will this manifest in other measurements?

Reference point: $\epsilon_0 = -3\%$

$$\tan \beta = 50, \ m_{H^+} = 650 \ \text{GeV}$$
Other observables strongly affected by large, negative $\mu$

- Penguin decay $b \rightarrow s\gamma$
- Anomalous magnetic moment of the muon $a_\mu = \frac{g_\mu - 2}{2}$
- Rare decay $B_s \rightarrow \mu\mu$

Mass constraints from direct searches.
Penguin decay $b \to s\gamma$

**Experimental value**

$$\mathcal{B}\mathcal{R}(b \to s\gamma)_{\text{exp}} = (355 \pm 24) \times 10^{-6}$$

- Receives contributions from charginos and charged Higgses

$$\mathcal{B}\mathcal{R}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \frac{\tan \beta}{1 + \epsilon \tan \beta} (\ldots)$$

$$\mathcal{B}\mathcal{R}(b \to s\gamma)|_{H^\pm} \propto h_t \frac{m_b}{\sqrt{v(1 + \epsilon \tan \beta)}} (\ldots) - \mu M_3 \frac{m_b \tan \beta}{\sqrt{v(1 + \epsilon \tan \beta)}} (\ldots)$$

$\Rightarrow$ Need $A_t > 0$ to cancel competing contributions.
Anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$

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<td>$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (23.9 \pm 9.9) \times 10^{-10}$</td>
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⇒ Discrepancy between the SM and the experimental value of the myon gyromagnetic moment

- How do SUSY partners contribute?
  → For large $\tan \beta$ and $\mu$

$$
\Delta a_\mu^{\text{SUSY}} \propto \frac{m_\mu^2}{M_{SUSY}^2} \tan \beta \ \text{sign}(\mu M_{1,2})
$$

⇒ Need $M_{1,2} < 0$ to get the needed positive contribution.

[Anomaly mediation: $M_i \propto \alpha_i b_i$, with $b_i = (3, -1, -33/5)$]
Rare decay $B_s \rightarrow \mu\mu$

**Experimental value**

$$\mathcal{B}(B_s \rightarrow \mu^+\mu^-)_{\text{exp}} \leq 1.1 \times 10^{-8}$$

- Strongly enhanced for large $\tan \beta$:

$$\sim 13.2 \times 10^{-8} \frac{(16\pi^2\epsilon_Y)^2}{(1 + \epsilon_3 \tan \beta)^2(1 + \epsilon_0 \tan \beta)^2} \left[ \frac{\tan \beta}{50} \right]^6 \left[ \frac{645 \text{ GeV}}{M_A} \right]^4,$$

Weak contribution: $\epsilon_Y \sim \frac{1}{16\pi^2} A_t \mu l(m_{t_1}^2, m_{t_2}^2, \mu^2)$, and $\epsilon_3 = \epsilon_0 + y_t^2 \epsilon_Y$.

⇒ Strongly constraint.
Scanning the parameter space

Let’s see if this idea works.

This is how we proceed

1. Set $\tan \beta = 50$ and choose random soft masses and trilinear terms $m_L = m_R, A_t = A_b, M_3 \in [0, 5]$ Tev.
2. Solve $\epsilon_0 = -3\%$ for $|\mu|$. (Demand $|\mu| \leq 5$ TeV.) Fix $m_{H^\pm} = 600$ GeV and $M_3 = -2M_2 = -6M_1$.
3. Calculate mass spectrum. (Discard if masses are tachyonic or excluded, except by new LHC bounds.)
4. Calculate the other observables
5. Check.

Is there a region in parameter space that fulfills all this? Yes!
Results: $B \to \mu\mu$ vs. $b \to s\gamma$

- Applying all constraints (except LHC mass bounds)

- These two observables restrict the parameters severely.
- BUT: Still a lot of points survive, favoring $\mu$ not too large.
Results: \( m_{\tilde{b}} \) vs. \( M_3 \)

- First two generations can be made heavy easily.
  → Look at sbottoms only, stops are similar (with less splitting).

\[ \begin{array}{cc}
1000 & 2000 \\
3000 & 4000 \\
5000 &
\end{array} \]

\[ \begin{array}{cc}
m_{\tilde{b}} & 2000 \\
1500 & 1000 \\
500 & 1000 \\
1500 & 2000 \\
5000 &
\end{array} \]

A lot of points survive bounds from direct LHC search

- Gluino is heavy: \( \sim \) few TeV.
- Lighter of the sbottoms (and also stops): few 100 GeV to \( \sim \) 1.5 TeV.
Vacuum stability: Can be a problem for large $|\mu|$.

- Problem: SM-vacuum might not be a global minimum.

- SM-vacuum is a stable, global minimum if

$$A^2 + 3|\mu|^2 \lesssim 3(\tilde{m}_1^2 + \tilde{m}_2^2)$$

- [Kusenko, Langacker, Segre '96]: Vacuum must not be stable, as long as it is metastable:

$$A^2 + 3|\mu|^2 \lesssim 2.5 \times 3(\tilde{m}_1^2 + \tilde{m}_2^2)$$
Vacuum stability: Check our points

Check if our parameters describe stable minima:

\[ A_q^2 + 3 \mu^2 \lesssim 2.5 \times 3(\tilde{m}_{q_1} + \tilde{m}_{q_2}) \]

\( \Rightarrow \) No stable vacua, but a lot of metastable vacua.
Mass spectrum II: $m_{\tilde{b}}$ vs. $M_3$

- Look at sbottom spectrum for these metastable parameters

- No big change from before:
  - There are possible parameter points with:
    - $\sim$ few TeV gluino mass and $\sim$ few 100 GeV - 1.5 TeV lighter sbottom mass.
Conclusion

- MSSM can give *positive* correction to $B \rightarrow \tau \nu$ amplitude, if
  - $\mu$ is negative and large ($\sim$ few TeV)
  - $\tan \beta$ is large
- Also need:
  - $A_t > 0$ for $b \rightarrow s \gamma$.
  - $M_{1,2} < 0$ for $g_\mu - 2$.
- After constraints:
  - Get heavy gluino ($\sim$ few TeV) and lighter sbottoms/stops ($\sim$ TeV)
  - Vacuum stability is a concern, but there are metastable parameter points.

**MSSM with large, negative $\mu$ & large $\tan \beta$ ($1 + \epsilon_0 \tan \beta < 0$)**

Viable and interesting corner of parameter space.
Carlos’ conclusion

“We are all going to die ...”
Carlos’ conclusion

”We are all going to die ... ... but not anytime soon!”
Thanks for your attention