Collider Signatures of Minimal Flavor Mixing from Stop Decay Length Measurements†

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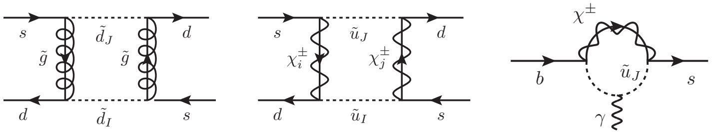
† Based on Gudrun Hiller, Jong Soo Kim, HS, `arXiv:0910.2124(hep-ph)`

MSSM and flavor

- The MSSM implementation of susy breaking does not predict a viable flavor structure.
- Bounds from meson mixing, rare decays:



  If realized at the TeV–scale, the MSSM must have a suitable flavor structure to suppress the corrections.
- A generic framework consistent with current data is mininmal flavor violation (MFV).

Minimal flavor violation (MFV)

Definition: A model is MFV if the dynamics of flavor violation is completely determined by the structure of the SM Yukawa couplings. (D'Ambrosio, Giudice, Isidori and Strumia, 2002)

MSSM soft squark couplings in MFV:

$$
\begin{aligned}
\mathrm{M}^2_{\tilde{Q}} &= \tilde{m}^2(a_1 \mathbb{1} + b_1 \mathrm{Y}_u \mathrm{Y}_u^\dagger + b_2 \mathrm{Y}_d \mathrm{Y}_d^\dagger + \ldots) \\
\mathrm{M}^2_{\tilde{U}} &= \tilde{m}^2(a_2 \mathbb{1} + b_5 \mathrm{Y}_u^\dagger \mathrm{Y}_u + c_1 \mathrm{Y}_u^\dagger \mathrm{Y}_d \mathrm{Y}_d^\dagger \mathrm{Y}_u + \ldots) \\
\mathrm{A}_u &= A\,(a_4 \mathbb{1} + b_7 \mathrm{Y}_d \mathrm{Y}_d^\dagger + \ldots)\mathrm{Y}_u
\end{aligned}
$$

MFV: AMSB, models with flavor–diagonal masses at a high scale (mSUGRA), ...

not MFV: Models of alignment with horizontal symmetries (Nir and Seiberg, 1993; Leurer, Nir and Seiberg, 1994), ...

Consequences of MFV mixing

The 3rd generation of squarks decouples due to the smallness of the $(1,3)$ and $(2,3)$ elements of V_{CKM}.

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

- If the squarks of the 3rd generation are sufficiently heavy, they decay almost exclusively in their own generation.
- If these decays are forbidden kinematically, their decay is suppressed by the very small flavor mixing couplings.
  $\rightarrow$ long lifetimes

Can the lifetimes of the 3rd generation be large enough to be measured at the LHC?

- If so: establish MFV
- Extract the flavor mixing couplings

Most promising candidates: light stops

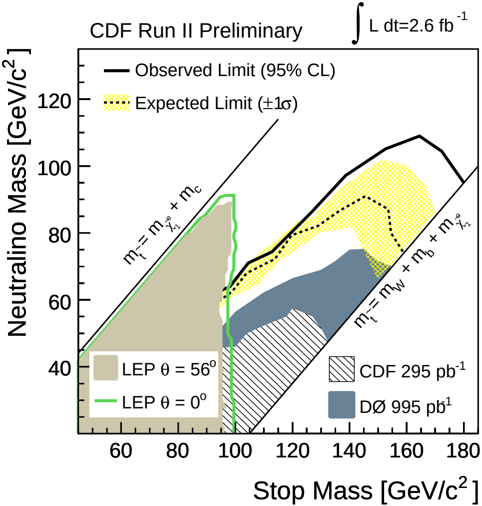
Why can they be light?

- Large mass splittings between $\tilde{t}_1$ and $\tilde{t}_2$ are supported by large *L*-*R* mixing mass terms ($\propto \mathrm{Y}_t$).
- In RGE–running, the β-functions of the soft stop bilinear terms are suppressed by Y_t couplings.
- Not ruled out by the experiments.

Why are they interesting?

- $\tilde{t}_1$ can be lighter than the top; flavor conserving neutral current decays could be forbidden kinematically.
- Abundant production at *pp* colliders.

Experimental mass bounds: searches for $\tilde{t}_1 \to \tilde{\chi}_1^0 c$



(CDF note 9834, 2009)

Tree–level FCNC stop decay

Assume $\tilde{t}_1$ cannot decay in the same generation:

- Decay to $t\tilde{\chi}_1^0$ forbidden kinematically: $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < m_t$
- Decay to $b\chi_1^+$ also forbidden: $m_{\tilde{t}_1} < m_{\chi_1^+}$
- Four body final state $b\tilde{\chi}_1^0\bar{\ell}\nu$ suppressed: $\Delta m = \mathcal{O}(\text{few } 5\,\mathrm{GeV})$

2–Body Decay rate for small mass splitting Δm:

$$\Gamma \approx \frac{m_{\tilde{t}_1} Z^2}{16\pi} \left(\frac{\Delta m}{m_{\tilde{t}_1}}\right)^2$$

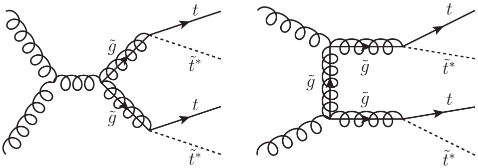
MFV prediction: $Z \propto \lambda_b^2 V_{cb} V_{tb}^* \sim 3 \cdot 10^{-5} \tan^2\beta$ ← small!

$$\frac{1}{\Gamma} = \mathcal{O}(\mathrm{ps}) \text{ in MFV for } m_{\tilde{t}_1} = \mathcal{O}(100\,\mathrm{GeV}), \Delta m = \mathcal{O}(5\,\mathrm{GeV})$$

A picosecond lifetime is possible in MFV.

LHC stop production

Favor same sign (ss) stop pair production: $pp \to \tilde{g}\tilde{g} \to \tilde{t}_1^* \tilde{t}_1^* tt$



$+$ $q\bar{q}$–graphs, u–channels

- Employ the gluino's Majorana nature to reduce the SM background (Kraml and Raklev, 2005)
- Cross section:

$$\sigma_{LO}(pp \to \tilde{g}\tilde{g} \to \tilde{t}_1^* \tilde{t}_1^* tt + \text{c.c.}) = 5\,\text{pb}$$

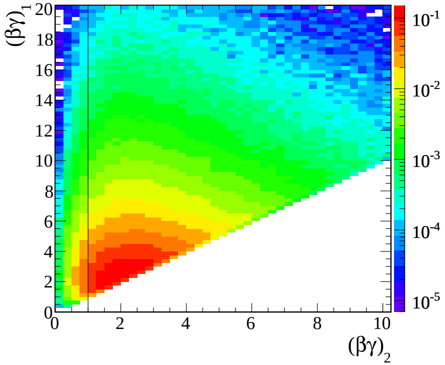
for $\sqrt{s} = 14\,\text{TeV}$, $m_{\tilde{g}} = 500\,\text{GeV}$, $m_{\tilde{t}_1} = 100\,\text{GeV}$

- **Signal:** 2 ss leptons + 4 jets (2 b-tagged, 2 soft) + $\not{E}_T$ (leptonically decaying tops)

Stop parton level events

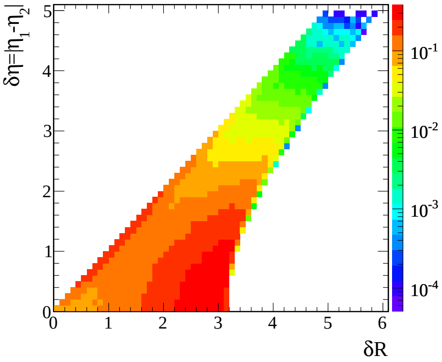
- $m_{\tilde{g}} = 500\,\mathrm{GeV}$, $m_{\tilde{t}_1} = 100\,\mathrm{GeV}$
- LO stop production ($\tilde{t}_1^* \tilde{t}_1^* tt + \mathrm{c.c.}$) with Madgraph/Madevent

Are the stops boosted sufficiently?



$((\beta\gamma)_1 \geq (\beta\gamma)_2\ \forall$ events)

Are they separated spatially?



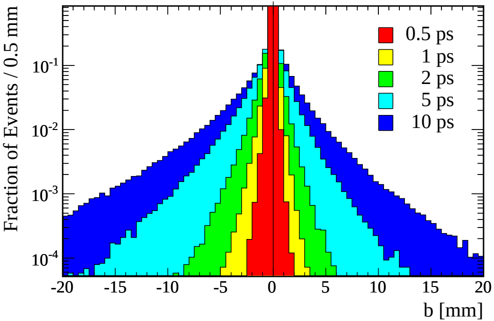
$((\beta\gamma)_i \geq 1\ \forall$ events; $\delta R = \sqrt{\delta\eta^2 + \delta\phi^2}$)

Stop decays: lifetime and impact parameters

Simulation:

- $pp \to \tilde{t}_1 \tilde{t}_1 \bar{t} \bar{t}$
  $(\tilde{t}_1 \to \tilde{\chi}_1^0 c)$
- $m_{\tilde{g}} = 500\,\mathrm{GeV}$,
  $m_{\tilde{t}_1} = 100\,\mathrm{GeV}$

Charm transverse impact parameter b



$b_i > 0$ (< 0) $\hat{=}$ eventwise larger (smaller) charm p_T

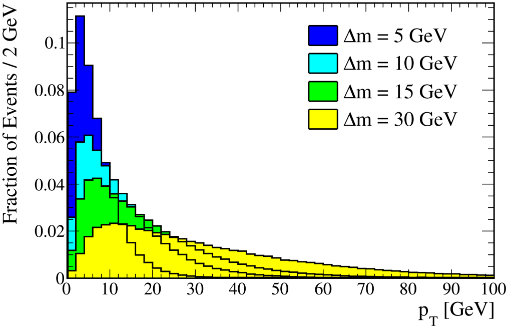
- Negligible Δm–dependence for fixed proper lifetime if $\Delta m \gg m_c$.
- **On average:**

$$< b > \simeq 180\,\mu\mathrm{m} \cdot \left(\frac{\tau}{\mathrm{ps}} \right)$$

How many events survive?

- Most severe reduction due to $\mathcal{B}(t \to \ell X) = 2/9$
- and p_T–cuts on soft $\tilde{t}_1$–decay products (charms)
- Up to ~ 100 events for $10\,\mathrm{fb}^{-1}$.

Charm–p_T from $pp \to \tilde{t}_1\tilde{t}_1\bar{t}\bar{t}$ ($\tilde{t}_1 \to \tilde{\chi}_1^0 c$)



p_T^{min} in GeV	30	35	40	50
$\Delta m = 5$ GeV	0.4%	0.2%	0.08%	0.02%
$\Delta m = 10$ GeV	7%	4%	2%	1%
$\Delta m = 15$ GeV	18%	13%	9%	4%
$\Delta m = 30$ GeV	45%	38%	32%	22%

Tension: For increasing Δm, the charms are less soft; but, the contamination from $\tilde{t}_1 \to b\tilde{\chi}_1^0\nu_\ell\bar{\ell}$ increases.

Summary

- The TeV–scale MSSM needs a flavor structure to satisfy current experimental bounds.
- If flavor is broken in a minimal way, the stop mixing with other up–type squarks is very small.
- An observation of macroscopic stop decay lengths would strongly support the framework of minimal flavor breaking.

Outlook: $\tilde{\chi}_1^0$ needs not to be the LSP.
What if $\tilde{\chi}_1^0$ decays into a $\mathcal{O}$(keV) gravitino and a photon?

References

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