

Measuring flavor mixing with minimal flavor violation at the LHC

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ABSTRACT: The mixing between third and second (or first) generation squarks is very small in supersymmetric models with minimal flavor violation such as gauge-, anomaly- or gaugino-mediation. An opportunity to measure this mixing will arise if the lightest stop is close enough in mass to the lightest neutralino, so that the decays into third generation quarks are kinematically forbidden. We analyze under which circumstances it might become possible to measure at the Large Hadron Collider (LHC) the rate of the flavor changing stop decays.

KEYWORDS: Supersymmetry Phenomenology, Supersymmetric Standard Model, Beyond Standard Model, Rare Decays.

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1. Introduction

Significant progress has been achieved in recent years in flavor precision measurements. All measurements are, however, consistent with the Standard Model picture, whereby the only source of violation of the global $SU(3)^5$ symmetry of the gauge interactions are the quark and lepton Yukawa interactions. Such a situation is not expected if there is new physics at the TeV scale with generic flavor structure (for a review, see ref. [1]). This so-called “New Physics Flavor Puzzle” is, however, solved if the new physics is subject to the principle of Minimal Flavor Violation (MFV) [2]. This principle states that the Yukawa interactions remain the only source of the $SU(3)^5$ breaking even in the presence of new physics. Known examples of models in this class are supersymmetric models with gauge-, anomaly-, or gaugino-mediation of supersymmetry breaking. More concretely, MFV in the quark sector implies that the only spurions that break the global flavor symmetry

$$G_q = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \tag{1.1}$$

are the up- and down-Yukawa matrices, with the following transformation properties under G_q :

$$Y_u(3, \bar{3}, 1), \quad Y_d(3, 1, \bar{3}). \tag{1.2}$$

One of the most powerful predictions of MFV for new physics models is that flavor mixing is always proportional to the off-diagonal CKM elements. Since the elements that connect the third generation to the two lighter ones, V_{ub}, V_{cb}, V_{td} and V_{ts} , have magnitudes

in the range $0.004 - 0.04$, the third generation is almost decoupled from the first two [3]. In the context of supersymmetry, this aspect of MFV has the following consequences: The third generation squarks, $\tilde{t}_L, \tilde{b}_L, \tilde{t}_R$ and \tilde{b}_R , decay predominantly into the third generation quarks, t and b ; The branching ratios into the lighter generations are $\lesssim |V_{ts}|^2 \sim 2 \times 10^{-3}$. If MFV is strongly violated, it may be possible to experimentally exclude it by observing decays into the lighter generations with branching ratios that are significantly larger than that. (For indirect tests, see, e.g., [4].) If, however, MFV applies, it will be a much more challenging task to establish it. One would like to measure the sub-dominant branching ratios and show that they indeed have the size predicted by the CKM suppression. But tagging flavor with such an accuracy is probably beyond the capabilities of the ATLAS and CMS experiments.

Here we point out that, under certain circumstances, measuring the decay *rate* (rather than the *branching ratio*) of a third generation squark into non-third generation quarks might become possible. What is required is an approximate degeneracy between the lightest stop and the lightest neutralino. Then, if the higgsino/gaugino decomposition of the neutralino, and the left/right decomposition of the stop are known, one can factor out the flavor suppression in the decay, and ask whether it fits the CKM dependence predicted by MFV, or not.

Our main emphasis in measuring intergenerational squark mixing will be on flavor changing neutral current (FCNC) decays. Charged current processes have always a tree level component inherited from the Standard Model, irrespective of the flavor structure of the supersymmetry breaking.

The plan of the paper is as follows: In section 2 we give the ingredients for the stop to have a picosecond lifetime dominated by FCNC decays. The magnitude of the relevant stop couplings in MFV are worked out in section 3. Prospects for the LHC making stop decay length measurements are analyzed in section 4. We discuss the backgrounds from stop four-body decays in section 5. We further comment in section 6 on a variant of our scenario with a light chargino, where the stop decays predominantly through charged current interactions. In section 7 we analyze models with quark-squark alignment, which provide an alternative solution to the flavor puzzle without MFV, and argue that they can differ significantly in their predictions for the relevant flavor changing couplings from MFV models. We conclude in section 8.

2. The $\tilde{t} \rightarrow c\chi^0$ decay rate

Consider a situation where the light stop is the next-to-lightest supersymmetric particle (NLSP) and that, furthermore, its decays into final third generation quarks are kinematically forbidden:

$$m_{\tilde{t}_1} - m_{\chi_1^0} \leq m_b. \quad (2.1)$$

(From here on, we consider only the lightest stop and the lightest neutralino, and omit the sub-index 1.) Then, with MFV, the leading decay mode into second generation quarks is:

$$\tilde{t} \rightarrow \chi^0 + c. \quad (2.2)$$

The question of interest to us is whether such fortunate circumstances can be exploited to measure the decay rate, with the goal of examining whether it is suppressed (or not) as predicted by MFV.

Let us denote the $\tilde{t} - c - \chi^0$ coupling by Y . More specifically, $Y = \sqrt{|y_L|^2 + |y_R|^2}$, where the FCNC couplings y_L, y_R parameterize

$$\mathcal{L}_{\tilde{c}\tilde{\chi}^0} = \bar{c}(y_L P_L + y_R P_R)\chi^0 \tilde{t} + \text{h.c.}, \quad (2.3)$$

with the chiral projectors $P_{L/R} = (1 \mp \gamma_5)/2$. We further define $M \equiv m_{\tilde{t}}$, $m \equiv m_{\chi^0}$ and $\Delta m \equiv M - m$. We approximate in kinematical factors $m_c \approx 0$ and, as explained above, consider the case $\Delta m \ll M$. The $\tilde{t} \rightarrow c\chi^0$ decay rate is then given by

$$\Gamma = \frac{MY^2}{16\pi} \left(1 - \frac{m^2}{M^2}\right)^2 \approx \frac{MY^2}{4\pi} \left(\frac{\Delta m}{M}\right)^2. \quad (2.4)$$

To get a rough idea of the flavor suppression in Y required for a long living stop, we rewrite eq. (2.4) as follows:

$$\tau_{\tilde{t}} \sim \text{ps} \left(\frac{M}{100 \text{ GeV}}\right) \left(\frac{0.03}{\Delta m/M}\right)^2 \left(\frac{10^{-5}}{Y}\right)^2. \quad (2.5)$$

With such a large lifetime, $\tau_{\tilde{t}} \gg 1/\Lambda_{QCD} \sim 10^{-24}$ s, the light stop hadronizes before decay.

Our scenario contains phase space suppression by construction to avoid stop decays to t or b quarks. We assume $\Delta m/M = \mathcal{O}(0.03)$ unless otherwise stated. Within the MFV framework, the value of Y is driven by the quark Yukawa couplings, and depends on the $\tilde{t}_L - \tilde{t}_R$ decomposition of the \tilde{t} and the $\tilde{H}^0 - \tilde{w}^0 - \tilde{B}$ decomposition of the χ^0 . We work out the size of Y within MFV in the next section.

3. Third generation flavor mixing with MFV

Following the MFV rules, we can write the relevant supersymmetry breaking squark mass terms up to higher powers of the quark Yukawa couplings [2]:

$$\begin{aligned} \tilde{m}_{Q_L}^2 &= \tilde{m}^2(a_1 \mathbf{1} + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger), \\ \tilde{m}_{U_R}^2 &= \tilde{m}^2(a_2 \mathbf{1} + b_5 Y_u^\dagger Y_u + c_1 Y_u^\dagger Y_d Y_d^\dagger Y_u), \\ A_u &= A(a_4 \mathbf{1} + b_7 Y_d Y_d^\dagger) Y_u. \end{aligned} \quad (3.1)$$

We use here the notation of ref. [2]. We omit their $b_{3,4}$ terms that are not important for our purposes, and add the c_1 term that, albeit small, can be important in our context. Since we are interested in the $\tilde{t}_{L,R}$ couplings, it is convenient to work in the up mass basis, that is,

$$Y_u = \lambda_u, \quad Y_d = V \lambda_d, \quad (3.2)$$

where V denotes the CKM matrix and λ_q are the generation diagonal Yukawa matrices. We are particularly interested in the 2 – 3 elements of the up squark mass matrices:

$$\begin{aligned}
 (\tilde{m}_{Q_L}^2)_{23} &= \tilde{m}^2 b_2 \lambda_b^2 V_{cb} V_{tb}^*, \\
 (\tilde{m}_{U_R}^2)_{23} &= \tilde{m}^2 c_1 \lambda_c \lambda_t \lambda_b^2 V_{cb} V_{tb}^*, \\
 (A_u)_{23} &= A b_\tau \lambda_t \lambda_b^2 V_{cb} V_{tb}^*, \\
 (A_u)_{32} &= A b_\tau \lambda_c \lambda_b^2 V_{cb}^* V_{tb}.
 \end{aligned}
 \tag{3.3}$$

Stop-scharm mixing in MFV thus requires at least two powers of the bottom Yukawa and is CKM suppressed by V_{cb} .

We separate the small flavor mixing effects, which we treat as mass insertions, from possible large mixings, unsuppressed by flavor. In particular, we take the decomposition of the light stop mass eigenstate as follows:

$$\tilde{t}(\equiv \tilde{t}_1) = \cos \theta_{\tilde{t}} \tilde{t}_R + \sin \theta_{\tilde{t}} \tilde{t}_L,
 \tag{3.4}$$

and explore the full range for $|\sin \theta_{\tilde{t}}|$ (between 0 and 1).

Similarly, we consider an arbitrary decomposition of the light neutralino,

$$\chi^0(\equiv \chi_1^0) = V_{1B} \tilde{B} + V_{1w} \tilde{w}^0 + V_{1u} \tilde{H}_u^0 + V_{1d} \tilde{H}_d^0.
 \tag{3.5}$$

From tree-level, single squark mass insertions to the $\tilde{c} \tilde{B} c$, $\tilde{c} \tilde{w}^0 c$ and $\tilde{c} \tilde{H}_u^0 c$ vertex (for supersymmetric Feynman rules see, e.g., [5]) one finds:

- The $\tilde{t}_R - c_R - \tilde{B}$ coupling is induced by $(\tilde{m}_{U_R}^2)_{23}$. The $\tilde{t}_R - c_R - \tilde{w}^0$ coupling vanishes.
- The $\tilde{t}_R - c_L - (\tilde{w}^0, \tilde{B})$ coupling is induced by $(A_u)_{23}$.
- The $\tilde{t}_R - c_R - \tilde{H}_u^0$ coupling is induced by a combination of $(A_u)_{23}$ and λ_c .
- The $\tilde{t}_R - c_L - \tilde{H}_u^0$ coupling is induced by a combination of $(\tilde{m}_{U_R}^2)_{23}$ and λ_c .
- The $\tilde{t}_L - c_L - (\tilde{w}^0, \tilde{B})$ coupling is determined by $(\tilde{m}_{Q_L}^2)_{23}$.
- The $\tilde{t}_L - c_R - \tilde{B}$ coupling is induced by $(A_u)_{32}$. The $\tilde{t}_L - c_R - \tilde{w}^0$ coupling vanishes.
- The $\tilde{t}_L - c_L - \tilde{H}_u^0$ coupling is induced by a combination of λ_c and $(A_u)_{32}$.
- The $\tilde{t}_L - c_R - \tilde{H}_u^0$ coupling is induced by a combination of λ_c and $(\tilde{m}_{Q_L}^2)_{23}$.

The situation is summarized in table 1, where the gauge and flavor factors and the numerical size of Y modulo the MFV coefficients b_i defined in eq. (3.3) are given for the various cases. We use $|V_{cb} V_{tb}^*| \sim 0.04$, $\lambda_t \sim 1$, $\lambda_b^2 \sim 10^{-3} \tan^2 \beta$, and $\lambda_c \sim 10^{-2}$ and denote by $I_3 = 1/2$ and $Y_Q = 1/6$ the weak isospin and hypercharge of the charm (s)quark doublets.

The leading couplings to the left-handed stop are induced by $(\tilde{m}_{Q_L}^2)_{23}$, whereas the ones to the right-handed stop component by $(A_u)_{23}$. (The c_1 term gives only a subleading contribution.) The higgsino-stop couplings receive an additional suppression from the

	\tilde{t}_L	\tilde{t}_R
\tilde{H}_u^0	$\lambda_c \lambda_b^2 V_{cb} V_{tb}^* \sim 4 \times 10^{-7} t_\beta^2$	$\lambda_c \lambda_t \lambda_b^2 V_{cb} V_{tb}^* \frac{Av_u}{\tilde{m}^2} \sim 4 \times 10^{-7} t_\beta^2 a_u$
\tilde{B}	$\sqrt{2} g' Y_Q \lambda_b^2 V_{cb} V_{tb}^* \sim 3 \times 10^{-6} t_\beta^2$	$\sqrt{2} g' Y_Q \lambda_t \lambda_b^2 V_{cb} V_{tb}^* \frac{Av_u}{\tilde{m}^2} \sim 3 \times 10^{-6} t_\beta^2 a_u$
\tilde{w}^0	$\sqrt{2} g I_3 \lambda_b^2 V_{cb} V_{tb}^* \sim 2 \times 10^{-5} t_\beta^2$	$\sqrt{2} g I_3 \lambda_t \lambda_b^2 V_{cb} V_{tb}^* \frac{Av_u}{\tilde{m}^2} \sim 2 \times 10^{-5} t_\beta^2 a_u$

Table 1: Flavor structure and numerical size of the $\tilde{t}c\chi^0$ coupling Y modulo the b_i coefficients. For details see text. Here $t_\beta \equiv \tan \beta$ and $a_u \equiv Av_u/\tilde{m}^2$.

charm Yukawa. The (hyper)charge assignments and the gauge coupling suppress the stop-bino with respect to the stop-wino interaction.

Depending on the value of the soft parameters A and the overall squark mass scale \tilde{m} , the neutralino coupling to the \tilde{t}_R varies and can differ from the one to the \tilde{t}_L . In case that $Av_u/\tilde{m}^2 \sim 1$, the couplings to \tilde{t}_L and \tilde{t}_R are of the same size and, moreover, the light stop mass eigenstate has comparable components of the two: $\theta_{\tilde{t}} \sim m_t(A - \mu/\tan \beta)/\tilde{m}^2$. Such large $\tilde{t}_L - \tilde{t}_R$ mixing is required in scenarios with a light stop mass as low as $\mathcal{O}(100)$ GeV to lift the lightest Higgs mass above the experimental limit, see, for instance, [6]. In case that $Av_u/\tilde{m}^2 \ll 1$, the couplings of \tilde{t}_R are correspondingly smaller than those of \tilde{t}_L and, furthermore, the light stop could be dominantly \tilde{t}_R .

There can be further, model-dependent suppression of the $\tilde{t}c\chi^0$ coupling Y if b_i and/or c_i , the coefficients of the flavor changing squark mass-squared terms, are small. For a generic MFV model, $b_i, c_i \lesssim 1$. In models where, at the scale of supersymmetry breaking mediation the soft terms are universal ($b_i = c_i = 0$), they are nevertheless generated at lower scales by renormalization group evolution (RGE). The b_i coefficients are generated at one loop, while c_1 is generated at two loops (see, for example, ref. [7]). It thus makes sense to consider as lower bounds $b_i \gtrsim (1/16\pi^2) \times \log s$ and $c_1 \gtrsim (1/16\pi^2)^2 \times \log s$. We term $b_i, c_1 \sim 1$ as “weak MFV” and $b_i \sim 10^{-2}$, $c_1 \sim 10^{-4}$ as “strong MFV”. Weak MFV can be realized with, for example, Yukawa deflected gauge mediation [8, 9], while strong MFV can be realized with, for example, standard low energy gauge mediation [10]. An experimental determination of the b_i, c_i is possible from the stop FCNC coupling Y once MFV has been established and the stop and neutralino decomposition and $\tan \beta$ are known.

To summarize, the range of Y covered in MFV models is given as

$$10^{-10} \lesssim Y \lesssim 10^{-4} \quad (\text{strong MFV}), \quad 10^{-8} \lesssim Y \lesssim 10^{-2} \quad (\text{weak MFV}). \quad (3.6)$$

The upper bounds are reached with large $\tan \beta \sim 30$ whereas for the lower bounds we assumed $\tilde{t}_L - \tilde{t}_R$ mixing above the percent level.

4. Measuring flavor changing decay rates at the LHC

If the flavor structure of the squark mass matrices is minimally flavor violating, and if the decays of the lightest stop into third generation quarks are kinematically forbidden, the stop will be surprisingly long-lived. In particular, its lifetime may be long enough that its decay may give a signature of a secondary vertex at the ATLAS and CMS experiments.

	weak MFV	strong MFV
\tilde{H}_u^0	1×10^{-7}	1×10^{-9}
\tilde{B}	9×10^{-7}	9×10^{-9}
\tilde{w}^0	5×10^{-6}	5×10^{-8}

Table 2: The numerical size of $Y(\Delta m/M)$ with Y taken from table 1, $\Delta m/M \sim 0.03$, $\tan \beta \sim 3$, $Av_u/\tilde{m}^2 \sim 1$ and $b_i \sim 1$ (weak MFV) and $b_i \sim 10^{-2}$ (strong MFV).

The precise minimal decay length that will allow a measurement of the lifetime depends on various details of the detector (see, for example, the discussion in [11]) and on the typical boost of the stop squarks. We assume here that $\beta\gamma$ is of order one, and take the minimal lifetime to be measured via secondary vertex as 0.3 ps, corresponding to a decay length of 0.1 mm. From eq. (2.5) we learn that the lifetime will be long enough for a measurement if

$$Y(\Delta m/M) \lesssim 5 \times 10^{-7}. \tag{4.1}$$

When we estimate the lifetime of the light stop, we have to take into account the decomposition of the stop and of the neutralino, and the flavor suppression factors of table 1. In addition, within our scenario, the phase space factor provides further suppression, $\Delta m/M \sim 0.03$, and there can be weak or strong MFV suppression in the b_i, c_i coefficients, which have been discussed in section 3.

We remark that there are also charged current contributions to $\tilde{t} \rightarrow c\chi^0$ decays induced at one loop [12]. MFV enforces that their flavor structure is the same as that of the corresponding Y . The dominant, logarithmic part of the loops stems from the soft mass counter term and induces the same decay amplitude as the pure RGE contribution [12]. It is hence included in Y with the b_i taken at the low scale. The remaining, non-logarithmic corrections from the loops to the relation between Y and the decay rate eq. (2.4) are subleading and can be neglected for this study.

Our estimate of $Y(\Delta m/M)$ for both MFV cases are given in table 2. Here, we assume $Av_u/\tilde{m}^2 \sim 1$, hence the couplings to \tilde{t}_L and \tilde{t}_R are of the same size and not given separately. Comparing this table with eq. (4.1), we conclude that it will be possible to measure the lifetime of the light stop for a rather large part of the parameter space. In particular, within our scenario and working assumptions, a measurement will be possible for low values of $\tan \beta \sim 3$ in the weak MFV scenario if the light neutralino is predominantly the higgsino or bino ($|V_{1w}| \lesssim 0.1$) or, for any decomposition of the neutralino, if $Av_u/\tilde{m}^2 \lesssim 0.1$ (and correspondingly $\sin \theta_{\tilde{t}} \lesssim 0.1$). As concerns strong MFV, we find that the stop lifetime is longer than 30 ps in the entire parameter space.

Keeping the masses fixed, the $\tan \beta$ dependence of our findings is dominated by the two powers of the bottom Yukawa in Y , see table 1. The $\tilde{t} \rightarrow c\chi^0$ decay rate hence exhibits a steep $\tan \beta$ dependence, $\Gamma \propto \tan^4 \beta$, and the region in parameter space with visible secondary vertex gets constrained towards larger values of $\tan \beta$. For example, for $\tan \beta \sim 10$, eq. (4.1) requires in the weak MFV scenario the stop to be right-handed with an \tilde{t}_L admixture of at most a few percent. In scenarios with strong MFV suppression the

lifetime can still be measured in the whole region given a higgsino-type neutralino or a mostly bino gaugino ($|V_{1w}| \lesssim 0.9$) or simply $\sin \theta_{\tilde{t}} \lesssim 0.9$.

Light stops have been searched for already at colliders assuming that the dominant decay mode is $\tilde{t} \rightarrow c\chi^0$, that is, in missing energy plus jet signatures [13, 14]. A discovery in this channel will determine the mass, but not the stop flavor couplings, which can be extracted from analyzing the stop decay length.

5. $m_{\tilde{t}} - m_{\chi^0} > m_b$ and four body decays

Identifying a secondary vertex from a charm jet with energy of the order $\Delta m \leq m_b$ times a boost factor, see eq. (2.1), is experimentally challenging. Therefore, and also to understand the general situation in supersymmetric models, we would like to investigate the possibility of relaxing the constraint on the stop-neutralino splitting. In other words, we still consider a scenario where the light stop is the NLSP, but with larger mass splitting, $m_{\tilde{t}} - m_{\chi^0} > m_b$.

Our proposal to measure MFV couplings is based on the dominance of $\tilde{t} \rightarrow c\chi^0$ decays and as long as this is true, Δm could be larger. Since the light stop is the NLSP, decays such as $\tilde{t} \rightarrow b\chi^+$ are forbidden. The four body decays $\tilde{t} \rightarrow b\chi^0 l\nu$ [12] are, however, kinematically open. Several diagrams contribute at tree level $\sim V_{tb}^*$, with the potentially dangerous ones containing charginos and the W -boson or sleptons [15].

We give here a rough estimate of these contributions to the four body decay rate. The matrix elements squared of the leading diagrams of $\tilde{t} \rightarrow b\chi^0 l\nu$ decays go with the third power of light fermion (b, l, ν) momenta. Furthermore, from phase space we get four powers of light momenta. This suggests that $\Gamma_{4\text{-body}} \sim \delta m^7 / (m_W^4 m_{\chi^+}^2)$ or $\delta m^7 / (m_{\tilde{t}}^4 m_{\chi^+}^2)$ where we assumed $m_{\tilde{t},\chi^0} \ll m_{\chi^+, \tilde{t}}$ and $\delta m = \Delta m - m_b$ is the available kinetic energy. We obtain for the (leading) W -contribution:

$$\frac{\Gamma(\tilde{t} \rightarrow b\chi^0 l\nu)}{\Gamma(\tilde{t} \rightarrow c\chi^0)} \approx \frac{g^6 |V_{tb}|^2}{2} \frac{(\Delta m - m_b)^7}{[Y(\Delta m/M)]^2 M m_W^4 m_{\chi^+}^2}. \quad (5.1)$$

Despite the substantial mass and phase space suppression of this ratio, numerically it turns out that, for m_{χ^+} below 500 GeV, Δm can only be lifted by a few GeV above the bottom mass without invalidating our assumptions. This is caused by the smallness of the coupling Y in the denominator, for which we require to yield a macroscopic decay length, i.e., eq. (4.1).

The situation is schematically depicted in figure 1. We distinguish various interesting regions in the $Y - \Delta m/M$ plane, shown for fixed $m_{\tilde{t}} = 100$ GeV and $m_{\chi^+} = 500$ GeV:

- (i) Below the single curved (blue) line, the stop lifetime is long enough for a secondary vertex to appear, that is, eq. (4.1) is fulfilled.
- (ii) Above and to the left of the triple lines, the $\tilde{t} \rightarrow c\chi^0$ decay dominates. More precisely, the ratio of eq. (5.1) is smaller than 5,1,1/5, for the lower, middle and upper line, with the spread modeling the uncertainty of our estimate for the $\tilde{t} \rightarrow b\chi^0 l\nu$ decay rate.

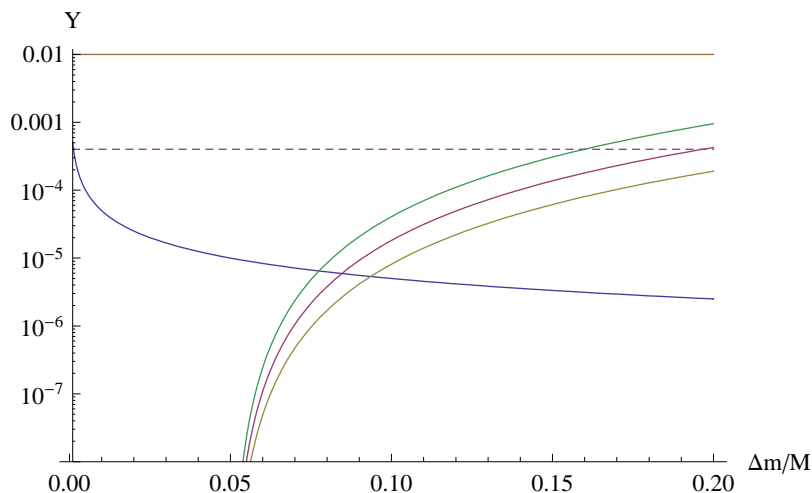


Figure 1: Interesting regions in the $Y - \Delta m/M$ plane: (i) The single curved line separates the regions where a secondary vertex appears (below) or does not appear (above); (ii) The triplet of curved lines distinguishes the region where the stop two-body decay dominates (left and above) from the region where the four-body decays dominate (below and right); (iii) The horizontal dashed line marks the lower bound on the region accessible to models with alignment; (iv) The horizontal solid line marks the lower bound if the up squark flavor parameters are anarchical. The plot is shown for fixed $m_{\tilde{t}} = 100$ GeV and $m_{\chi^+} = 500$ GeV. For details see text.

- (iii) Above the horizontal dashed line at $Y = \lambda_c V_{cb} = 4 \times 10^{-4}$ is the region accessible to alignment models (see section 7 for details).
- (iv) Above the horizontal solid line at $Y = 0.01 = \lambda_c$ is the region accessible with 'squark flavor anarchy', i.e. no special structure in the relevant soft supersymmetry breaking terms (see section 7).

Our stop search strategy works in the lower left corner of the $Y - \Delta m/M$ plane.

With the requisite replacements, it follows also from eq. (5.1) that the CKM suppressed modes $\tilde{t} \rightarrow s\chi^0 l\nu$, which are not excluded by the mass constraint eq. (2.1), are not competitive with $\tilde{t} \rightarrow c\chi^0$ decays for Δm below $\mathcal{O}(5 - 10)$ GeV.

6. A light chargino

It is interesting to consider the case where the light stop \tilde{t} is the NNLSP, with the lighter chargino χ^+ being the NLSP:

$$m_{\tilde{t}} > m_{\chi^+} > m_{\chi^0}, \quad (6.1)$$

which we assume in addition to the condition (2.1). Then, besides the decay mode (2.2), the stop can decay through

$$\tilde{t} \rightarrow \chi^+ + s. \quad (6.2)$$

We consider an arbitrary decomposition of the light chargino,

$$\chi^+ (\equiv \chi_1^+) = \cos \theta_+ \tilde{w}^+ + \sin \theta_+ \tilde{H}^+, \quad (6.3)$$

	\tilde{t}_L	\tilde{t}_R
\tilde{H}^+	$\sin \beta \lambda_s V_{ts}^* \sim 2 \times 10^{-5} t_\beta$	$\cos \beta \lambda_t V_{ts}^* \sim 4 \times 10^{-2} / t_\beta$
\tilde{w}^+	$g V_{ts}^* \sim 3 \times 10^{-2}$	0

Table 3: Flavor structure and numerical size of the supersymmetric contributions to the $\tilde{t}s\chi^+$ coupling. Here $t_\beta \equiv \tan \beta$.

where $\tilde{H}^+ = \sin \beta \tilde{H}_d^{*+} + \cos \beta \tilde{H}_u^+$.

A crucial point here is that, unlike the case of a final neutralino, we now have flavor changing couplings even in the supersymmetric limit. This is in correspondence to the fact that, within the Standard Model, there are flavor changing charged current interactions but (at tree level) no flavor changing neutral current interactions. We have the following relevant couplings:

- The $\tilde{t}_L - s_L - \tilde{w}^+$ coupling is related via supersymmetry to the SM $t_L - s_L - W^+$ coupling.
- The $\tilde{t}_L - s_R - \tilde{H}^+$ coupling comes from the down Yukawa coupling and quark mixing.
- The $\tilde{t}_R - s_R - \tilde{w}^+$ coupling vanishes.
- The $\tilde{t}_R - s_L - \tilde{H}^+$ coupling is given by the up Yukawa coupling and quark flavor mixing.

The situation is summarized in table 3. In addition to the previously used parameters, we use $|V_{ts}| \sim 0.04$ and $\lambda_s \sim 5 \times 10^{-4} \tan \beta$.

We learn that the flavor suppression of the chargino modes is not strong enough to induce a secondary vertex. Even assuming a pure gaugino and a \tilde{t}_L admixture as small as $\text{few} \times 10^{-4}$ with $\Delta m/M \sim 0.03$ violates the condition eq. (4.1). It will therefore be difficult to establish the CKM suppression of the stop decays into lighter generations if the chargino is lighter than the stop.

It is amusing to note that if the stop-chargino degeneracy is strong enough that even the decays to final states with strangeness are kinematically forbidden, then the decay rate is further suppressed by the smaller phase space $\Delta m/M \sim 10^{-3}$, by the smaller CKM element, $|V_{td}| \sim 0.2|V_{ts}|$, and, where relevant, by a smaller Yukawa coupling, $\lambda_d \sim 0.05\lambda_s$. Still, in most of the parameter space, the decay length will be too short to be measurable.

In any case, we should emphasize that the CKM suppression of the charged current $\tilde{t}s\chi^+$ coupling as shown in table 3 is generic in supersymmetry. It is a consequence of supersymmetry, and is not related to the question of whether the mediation of supersymmetry breaking is MFV or not. However, beyond MFV, squark loops can alter charged current couplings significantly from their tree level values, which can be used to signal the breakdown of MFV, see [16] for an LHC example.

	\tilde{t}_L	\tilde{t}_R
\tilde{H}_u^0	$\max(\frac{\lambda_c^2}{V_{cb}} \frac{Av_u}{\tilde{m}^2}, \lambda_c V_{cb}) \sim \max(2 \times 10^{-3} a_u, 4 \times 10^{-4})$	$\frac{\lambda_c^2}{\lambda_t V_{cb}} \sim 2 \times 10^{-3}$
\tilde{B}	$\sqrt{2} g' \max(Y_U \frac{\lambda_c}{V_{cb}} \frac{Av_u}{\tilde{m}^2}, Y_Q V_{cb}) \sim \max(0.08 a_u, 3 \times 10^{-3})$	$\sqrt{2} g' Y_U \frac{\lambda_c}{\lambda_t V_{cb}} \sim 0.08$
\tilde{w}^0	$\sqrt{2} g I_3 V_{cb} \sim 0.02$	$\sqrt{2} g I_3 \lambda_t V_{cb} \frac{Av_u}{\tilde{m}^2} \sim 0.02 a_u$

Table 4: Flavor structure and numerical size of the $\tilde{t}\chi^0$ coupling Y in naive alignment models. Here $a_u \equiv Av_u/\tilde{m}^2$.

7. Third generation flavor mixing without MFV

The significance of testing the MFV hypothesis can be appreciated by investigating models without MFV. One should ask, first, whether there are natural and viable models of supersymmetry breaking that do not implement the MFV principle and, second, whether their predictions for the flavor changing couplings are significantly different from those of MFV models.

In the case of ‘anarchical’ soft supersymmetry breaking parameters, there is no CKM suppression and the flavor changing $\tilde{t}\chi^0$ vertex is generically $Y \sim \sqrt{2}gI_3, \sqrt{2}g'Y_Q, \lambda_c$ for the wino, bino and higgsino, respectively. However, applying experimental constraints from FCNCs excludes such generic models. A better framework would be one with a natural mechanism to suppress flavor changing couplings. An example of such a framework is that of alignment [17, 18].

Models of alignment are based on an Abelian horizontal symmetry that is broken by small parameters [19]. In the simplest version there is a single $U(1)_H$ which is broken by a single spurion ϵ of charge $H = -1$. Then, the charges of the various superfields are determined by the measured quark parameters:

$$|V_{ij}| \sim \epsilon^{H(Q_{Li})-H(Q_{Lj})} \quad (j > i), \quad \lambda_{u_i} \sim \epsilon^{H(Q_{Li})+H(\bar{U}_{Ri})}. \quad (7.1)$$

The same charges determine also the parametric suppression of the soft supersymmetry breaking parameters, leading to the following order of magnitude relations:

$$\begin{aligned} (\tilde{m}_{Q_L}^2)_{23} &\sim \tilde{m}^2 V_{cb}, \\ (\tilde{m}_{U_R}^2)_{23} &\sim \tilde{m}^2 \lambda_c / (\lambda_t V_{cb}), \\ (A_u)_{23} &\sim A \lambda_t V_{cb}, \\ (A_u)_{32} &\sim A \lambda_c / V_{cb}. \end{aligned} \quad (7.2)$$

We now use the procedure described in section 3, inserting, however, the order of magnitude estimates of eq. (7.2) instead of those of eq. (3.3). This leads to the suppression factors presented in table 4. We denote by $Y_U = 2/3$ the hypercharge of the (s)charm singlet, other parameters are as in section 3.

For $\tan\beta \sim 3$ and $a_u \sim 1$, the alignment couplings are larger by two to three orders of magnitude than the (weak) MFV ones given in table 1 for $b_i \sim 1$. In the very large $\tan\beta$ limit, where the λ_b^2 suppression of the MFV flavor changing couplings is ineffective, the

two models can give comparable couplings. In general, for $a_u \gtrsim 0.01$, alignment models span the following range:

$$10^{-4} \lesssim Y \lesssim 10^{-1} \quad (\text{Alignment}), \tag{7.3}$$

to be compared with the MFV range in eq. (3.6). The most important difference here is that in alignment models the resulting stop lifetime is short, $\tau_t^{\text{alignment}} \sim (10^{-20} - 10^{-15})$ s, and hence, alignment models are not expected to give a secondary vertex signal.

8. Conclusions

The question of whether the mechanism that mediates supersymmetry breaking is MFV is important and provides a window to scales well beyond the direct reach of the LHC. While it may be easy to exclude MFV if it is violated in a strong way, it will be a much more challenging task to experimentally establish MFV in case that it holds. One model-independent prediction of MFV is a high degeneracy between the first two squark generations, below a GeV [20]. Its measurement at the LHC will, like the CKM and Yukawa suppression of the flavor mixing, be most likely impossible.

We point out that, under a certain set of circumstances, measuring the mixing within MFV models might be possible after all. This set of conditions requires that the stop is the NLSP, and that its splitting from the neutralino-LSP is not much bigger than the mass of the bottom quark. Then the light stop decays predominantly into second (or first) generation quarks. Furthermore, the CKM suppression, the Yukawa suppression, and the phase-space suppression combine to make the lifetime of the stop unusually long. In fact, it is long enough that the decay might occur with a secondary vertex. This is the crucial ingredient that may provide ATLAS and CMS with a way to measure the lifetime, and by that provide information on the size of the flavor changing couplings related to the breaking of supersymmetry.

The flavor suppression that is required to provide (in combination with the accidental stop-neutralino degeneracy) a stop lifetime that is long enough to generate a secondary vertex is quite unique to MFV models. Observing such a secondary vertex, even without a precise determination of the lifetime, would lend strong support to the MFV principle.

Light stops and MFV are features, for instance, of models with hypercharged anomaly mediation [21]. Here the light stop is mostly left-handed and the neutralino LSP is mostly wino, such that a stop lifetime measurement would work up to moderate values of $\tan \beta$. Note also that our generic requirement of a small mass gap between the lightest stop and the lightest neutralino supports efficient coannihilation in the neutralino relic density calculation [22, 23].

We conclude that a flavor program in ATLAS and CMS can be of unique capability in addressing the flavor puzzles [16, 24, 25].

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References

- [1] Y. Nir, *Probing new physics with flavor physics (and probing flavor physics with new physics)*, [arXiv:0708.1872](#).
- [2] G. D'Ambrosio, G.F. Giudice, G. Isidori and A. Strumia, *Minimal flavour violation: an effective field theory approach*, *Nucl. Phys. B* **645** (2002) 155 [[hep-ph/0207036](#)].
- [3] Y. Grossman, Y. Nir, J. Thaler, T. Volansky and J. Zupan, *Probing minimal flavor violation at the LHC*, *Phys. Rev. D* **76** (2007) 096006 [[arXiv:0706.1845](#)].
- [4] G. Hiller, *Phenomenology of new physics*, [hep-ph/0308180](#).
- [5] J. Rosiek, *Complete set of Feynman rules for the MSSM – ERRATUM*, [hep-ph/9511250](#).
- [6] R. Essig, *Implications of the LEP Higgs bounds for the MSSM stop sector*, *Phys. Rev. D* **75** (2007) 095005 [[hep-ph/0702104](#)].
- [7] S.P. Martin and M.T. Vaughn, *Two loop renormalization group equations for soft supersymmetry breaking couplings*, *Phys. Rev. D* **50** (1994) 2282 [[hep-ph/9311340](#)].
- [8] Z. Chacko and E. Ponton, *Yukawa deflected gauge mediation*, *Phys. Rev. D* **66** (2002) 095004 [[hep-ph/0112190](#)].
- [9] Z. Chacko, E. Katz and E. Perazzi, *Yukawa deflected gauge mediation in four dimensions*, *Phys. Rev. D* **66** (2002) 095012 [[hep-ph/0203080](#)].
- [10] M. Dine, A.E. Nelson, Y. Nir and Y. Shirman, *New tools for low-energy dynamical supersymmetry breaking*, *Phys. Rev. D* **53** (1996) 2658 [[hep-ph/9507378](#)].
- [11] F. Ragusa and L. Rolandi, *Tracking at LHC*, *New J. Phys.* **9** (2007) 336.
- [12] K.-i. Hikasa and M. Kobayashi, *Light scalar top at e^+e^- colliders*, *Phys. Rev. D* **36** (1987) 724.
- [13] D0 collaboration, V.M. Abazov et al., *Search for the pair production of scalar top quarks in the acoplanar charm jet topology in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ -TeV*, *Phys. Lett. B* **645** (2007) 119 [[hep-ex/0611003](#)].
- [14] A brief overview about squark searches at the Tevatron and the LHC can be found in D0 - RUN II collaboration, A. Sopczak, *New physics searches at the Tevatron and the LHC*, [hep-ph/0605236](#).
- [15] C. Boehm, A. Djouadi and Y. Mambrini, *Decays of the lightest top squark*, *Phys. Rev. D* **61** (2000) 095006 [[hep-ph/9907428](#)].
- [16] S. Dittmaier, G. Hiller, T. Plehn and M. Spannowsky, *Charged-Higgs collider signals with or without flavor*, [arXiv:0708.0940](#).
- [17] Y. Nir and N. Seiberg, *Should squarks be degenerate?*, *Phys. Lett. B* **309** (1993) 337 [[hep-ph/9304307](#)].
- [18] M. Leurer, Y. Nir and N. Seiberg, *Mass matrix models: the sequel*, *Nucl. Phys. B* **420** (1994) 468 [[hep-ph/9310320](#)].

- [19] C.D. Froggatt and H.B. Nielsen, *Hierarchy of quark masses, Cabibbo angles and CP-violation*, *Nucl. Phys. B* **147** (1979) 277.
- [20] G. Hiller and M. Schmaltz, *Solving the strong CP problem with supersymmetry*, *Phys. Lett. B* **514** (2001) 263 [[hep-ph/0105254](#)].
- [21] R. Dermisek, H. Verlinde and L.-T. Wang, *Hypercharged Anomaly Mediation*, [arXiv:0711.3211](#).
- [22] C. Boehm, A. Djouadi and M. Drees, *Light scalar top quarks and supersymmetric dark matter*, *Phys. Rev. D* **62** (2000) 035012 [[hep-ph/9911496](#)].
- [23] C. Balázs, M.S. Carena and C.E.M. Wagner, *Dark matter, light stops and electroweak baryogenesis*, *Phys. Rev. D* **70** (2004) 015007 [[hep-ph/0403224](#)].
- [24] J.L. Feng, C.G. Lester, Y. Nir and Y. Shadmi, *The standard model and supersymmetric flavor puzzles at the Large Hadron Collider*, [arXiv:0712.0674](#).
- [25] Y. Nomura, M. Papucci and D. Stolarski, *Flavorful supersymmetry*, [arXiv:0712.2074](#).