Light Stop Decay in the MSSM with Minimal Flavour Violation

in collaboration with M. Mühlleitner,
JHEP 1104:095,2011

Eva Popenda | 5.10.2011

INSTITUTE FOR THEORETICAL PHYSICS

Outline

Introduction

- Precision measurements in flavour physics:

  - In agreement with predictions of Standard Model (SM)

  - Observed flavour violation can be described by Cabibbo-Kobayashi-Maskawa (CKM) mechanism of SM

  ➡ New Physics cannot contain much more flavour violation than SM

- Minimal supersymmetric extension of SM (MSSM):

  In general many new flavour violating sources

  = “New Physics Flavour Problem”

- Minimal Flavour Violation (MFV):

  Provides solution, agrees with precision measurements

  - All flavour changing transitions are governed by the CKM matrix

  - No flavour changing, neutral currents (FCNC) at tree level at $\mu = \mu_{MFV}$

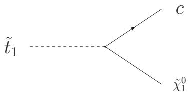
- Supergravity models

  Flavour independent scalar mass terms at high scale M_P:
  MFV arises naturally

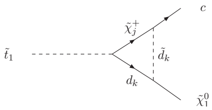
FCNC decay $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$

Name	Spin 0	Spin 1/2	Mass eigenstates
Higgsino	$H_d^0,\ H_u^0$	$\tilde{H}_d^0,\ \tilde{H}_u^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$
Wino	W^0	$\tilde{W}^0$	
Bino	B^0	$\tilde{B}^0$	
Stop	$\tilde{t}_L,\ \tilde{t}_R$	$t_L,\ t_R$	$\tilde{t}_1\ \tilde{t}_2$

- Light stop $\tilde{t}_1$ arises naturally
- In MFV no tree level coupling $\tilde{t}_1 - c - \tilde{\chi}_1^0$ at μ_{MFV}
  $\Rightarrow$ Decay mediated via one-loop diagrams with charged particles in loops



= 0 $\Rightarrow$



FCNC decay $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$

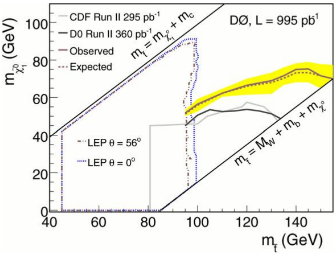
Name	Spin 0	Spin 1/2	Mass eigenstates
Higgsino	$H_d^0, \ H_u^0$	$\tilde{H}_d^0, \ \tilde{H}_u^0$	$\tilde{\chi}_1^0 \ \tilde{\chi}_2^0 \ \tilde{\chi}_3^0 \ \tilde{\chi}_4^0$
Wino	W^0	$\tilde{W}^0$	
Bino	B^0	$\tilde{B}^0$	
Stop	$\tilde{t}_L, \ \tilde{t}_R$	$t_L, \ t_R$	$\tilde{t}_1 \ \tilde{t}_2$

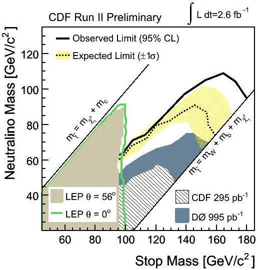
- Light stop $\tilde{t}_1$ arises naturally
- In MFV no tree level coupling $\tilde{t}_1 - c - \tilde{\chi}_1^0$ at μ_{MFV}
  $\Rightarrow$ Decay mediated via one-loop diagrams with charged particles in loops
- Suppressed by small CKM matrix elements: $|V_{cb}| = 0.04$
- For scenarios with light $\tilde{t}_1$ with $\quad m_c + m_{\tilde{\chi}_1^0} < m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}$

  $\Rightarrow$ Dominant decay mode: $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$

Phenomenology

- Exclusion limits from Tevatron assume $BR(\tilde{t}_1 \to c + \tilde{\chi}_1^0) = 1$
  - Analysis of 2 c-jets and large MET final state

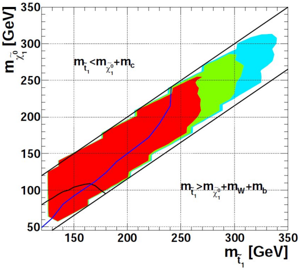




Phenomenology

- Exclusion limits from Tevatron assume $BR(\tilde{t}_1 \to c + \tilde{\chi}_1^0) = 1$
  - Analysis of 2 c-jets and large MET final state
- Light stop searches in this scenario
  - Light stops can be discovered at LHC [Bornhauser, Drees, Grab & Kim '10]
    $pp \to \tilde{t}_1 \tilde{t}_1^* b\bar{b}$, $\tilde{t}_1 \to c + \tilde{\chi}_1^0$
    Signature: Large MET + 2 b-flavoured jets

Statistical signal significance, $\sqrt{s} = 14$ TeV, 100 $fb^{-}1$



Phenomenology

- Exclusion limits from Tevatron assume $BR(\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0) = 1$
  - Analysis of 2 c-jets and large MET final state
- Light stop searches in this scenario
  - Light stops can be discovered at LHC *[Bornhauser, Drees, Grab & Kim '10]*
    $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* b\bar{b}$, $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$
    Signature: Large MET + 2 b-flavoured jets
  - Stop decay length measurements: *[Hiller & Nir '08]*
    CKM suppression in MFV $\rightarrow$ large $\tilde{t}_1$ lifetimes
    Test minimal flavour violation by observing secondary vertices
- Existing work *[Hikasa & Kobayashi '87]*
  Approximate calculation:
  - Calculation with no FCNC at high scale M_P
  - Taking into account only leading log $\Rightarrow \ln(M_P^2/M_W^2)$
- In this work:
  - Complete one-loop calculation of $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ in MFV
  - Full renormalization program, including finite non-logarithmic terms

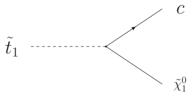
  $\Rightarrow$ Study importance of neglected non-logarithmic pieces in previous work

Resummation

- Assumption of MFV not invariant under RGE's *[D'Ambrosio, Giudice, Isidori, Strumia '02]*

  - Weak interactions affect squark and quark mass matrices differently
  - Squark and quark mass matrices cannot be diagonalized simultaneously
  - Top superpartner receives admixture from charm superpartner

  $\Rightarrow$ FCNC coupling between $\tilde{t}_1 - c - \tilde{\chi}_1^0$ at tree level



$\neq 0$ at any $\mu \neq \mu_{MFV}$

- Solving renormalization group equations (RGE) for scalar soft SUSY breaking squark masses: Resummation of large logarithm
- Exact one-loop result = First order in expansion in powers of α

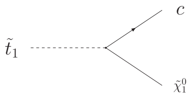
$$\underline{\alpha\ (A_1 \log} + A_0) + \underline{\alpha^2\ (B_2 \log^2} + \underline{B_1 \log} + B_0) + \underline{\alpha^3\ (C_3 \log^3} + \ldots) + \ldots$$

- Comparison of exact one-loop result and tree level FV decay:

  $\Rightarrow$ Estimate importance of resummation of large logarithms

Calculation: Tree level

In MFV the decay is forbidden at $\mu = \mu_{MFV}$:



= 0

What does that mean for corresponding expressions?

Flavour mixing in the SM:

$$\overline{q_L}\ m\ q_R \qquad \text{with} \qquad q_L = U^{qL} q^{(m)} \quad q_R = U^{qR} q^{(m)} \qquad q = u, d$$

- Unitary Matrices $U^{qL\dagger} U^{qL} = 1_{3x3}$
- $U^{qL,R}$ diagonalize mass matrix m: $U^{uL}\ m\ U^{uR} = m_{\text{Diag}}$
- CKM-Matrix $V^{CKM} = U^{uL\dagger} U^{dR}$
- No further flavour transitions possible in SM

Calculation: Tree level

Karlsruhe Institute of Technology

Flavour- & RL-mixing in MSSM:

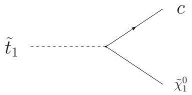
$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{c}_1 \\ \tilde{t}_1 \\ \tilde{u}_2 \\ \tilde{c}_2 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \text{Squark-} \\ \text{mixing-} \\ \text{matrix} : \widetilde{W} \\ (6 \times 6) \end{pmatrix} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

- Unitary matrix $\widetilde{W}^\dagger \widetilde{W} = 1_{6x6}$
- Diagonalizes mass matrix: $\widetilde{W}^\dagger M^{\tilde{q}} \widetilde{W} = M^{\tilde{q}}_{\text{Diag}}$
- In general: Many, new flavour violating sources

Factorization in MFV:

$$\widetilde{W} = \begin{pmatrix} U^{uL} & 0 \\ 0 & U^{uR} \end{pmatrix} \begin{pmatrix} \cos\theta_{\tilde{u}_i} & \sin\theta_{\tilde{u}_i} \\ -\sin\theta_{\tilde{u}_i} & \cos\theta_{\tilde{u}_i} \end{pmatrix} = U \cdot \underbrace{W}_{\text{flavour diagonal}}$$

➡ Process vanishes at tree level:



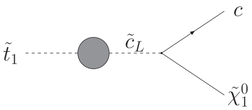
$\sim W_{ct} = 0$

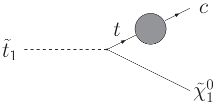
One-loop: Feynman diagrams & Divergencies

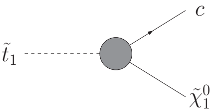
Karlsruhe Institute of Technology

At one-loop level 3 types of diagrams contribute:

Squark self-energies | **Quark self-energies** | **Vertex diagrams**



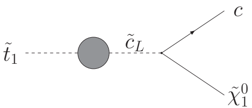
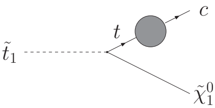
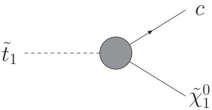




Divergencies + Divergencies + Divergencies $\neq 0$

Field renormalization

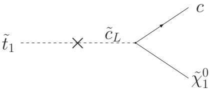
At one-loop level 3 types of diagrams contribute:

Squark self-energies		Quark self-energies		Vertex diagrams	
					
Divergencies	+	Divergencies	+	Divergencies	$\neq 0$

1. Field renormalization

Squarks

$$\tilde{q}_s^0 = (\delta_{st} + \tfrac{1}{2}\delta\widetilde{Z}_{st})\tilde{q}_t$$

\+ 

$= \hat{\Sigma}_{\tilde{t}_1 \tilde{c}_L}(m^2_{\tilde{t}_1})$

On-shell scheme

Propagator in higher orders:

$$\frac{i}{k^2 - m^2} \longrightarrow \frac{i}{k^2 - m^2 + \hat{\Sigma}}$$

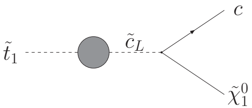
- On-shell renormalization condition:
  m keeps meaning of physical mass

$$\hat{\Sigma}(m^2) = 0$$

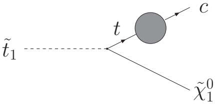
Field renormalization

At one-loop level 3 types of diagrams contribute:

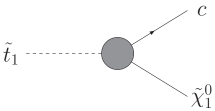
Squark self-energies



Quark self-energies



Vertex diagrams



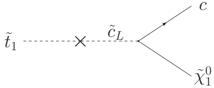
Divergencies + Divergencies + Divergencies $\neq 0$

1. Field renormalization

Squarks

$$\tilde{q}_s^0 = (\delta_{st} + \tfrac{1}{2}\delta\widetilde{Z}_{st})\tilde{q}_t$$

\+

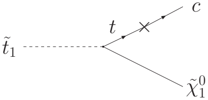


= 0

Quarks

$$q_i^0 = (\delta_{ik} + \tfrac{1}{2}\delta Z_{ik})q_k$$

\+



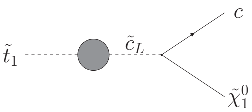
= 0

Divergencies

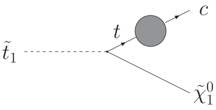
Vertex Counterterm

At one-loop level 3 types of diagrams contribute:

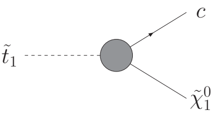
Squark self-energies



Quark self-energies



Vertex diagrams



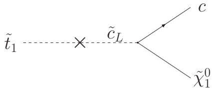
Divergencies + Divergencies + Divergencies $\neq 0$

1. Field renormalization

Squarks

$$\tilde{q}^0_s = (\delta_{st} + \tfrac{1}{2}\delta\widetilde{Z}_{st})\tilde{q}_t$$

\+

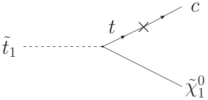


= 0

Quarks

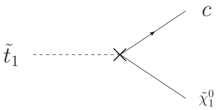
$$q^0_i = (\delta_{ik} + \tfrac{1}{2}\delta Z_{ik})q_k$$

\+



= 0

Vertex Counterterm



$$\left(\tfrac{1}{2}\delta Z^{L\dagger}_{ct} + \delta U^{U_L}_{ct}\right)\cos\theta_{\tilde{t}} + \tfrac{1}{2}\delta\tilde{Z}_{\tilde{c}_L\tilde{t}_1} + \delta\widetilde{W}^{\dagger}_{\tilde{c}_L\tilde{t}_1}$$

Mixing matrices

- Renormalization of quark $U^{qL,R}$ and squark mixing matrices $\widetilde{W}$ necessary

$$U_{ij}^{(0)} = (\delta_{ik} + \delta U_{ik}) U_{kj} \qquad \widetilde{W}_{su}^{(0)} = (\delta_{st} + \delta \widetilde{W}_{st}) \widetilde{W}_{tu}$$

MFV imposed on $U, \widetilde{W}$ at scale μ_{MFV}
$U, \widetilde{W}$ unitary $\Rightarrow$ Antihermitian counterterms:

$$\delta U_{ik} = \frac{1}{4}(\delta Z_{ik} - \delta Z_{ki}^{*}) \qquad \delta \widetilde{W}_{st} = \frac{1}{4}(\delta \widetilde{Z}_{st} - \delta \widetilde{Z}_{ts}^{*})$$

[Denner & Sack '90]

- Finite part of counterterm depends on renormalization scheme:

Minimal Subtraction $\Rightarrow$ gauge independent

[Degrassi, Gambino, Slavich '06]

$$\delta U_{ik} = \frac{1}{4}(\delta Z_{ik}^{Div} - \delta Z_{ki}^{*\,Div})_{|p^2=0} \qquad \delta \widetilde{W}_{st} = \frac{1}{4}(\delta \widetilde{Z}_{st}^{Div} - \delta \widetilde{Z}_{ts}^{*\,Div})$$

$\Rightarrow$ Result depends on MFV scale μ_{MFV}

Results: Formulas & Scenarios

$$\Gamma(\tilde{t}_1 \to c\tilde{\chi}_1^0) = \frac{g^2}{16\pi^2} \frac{(m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0})^2}{m_{\tilde{t}_1}^3} |F_R|^2$$

- Complete one-loop calculation:

$$F_R \approx \ldots V_{cb} V_{tb}^* \ldots \log \frac{\mu_{MFV}^2}{m_{loop}^2} + \text{'finites'}$$

- Calculation by Hikasa/Kobayashi:

$$F_R^{H/K} \approx \ldots V_{cb} V_{tb}^* \ldots \log \frac{M_P^2}{m_W^2}$$

- For numerical analysis: mSUGRA framework
  - Flavour independent parameters at GUT scale $M_{GUT} = 10^{16}\text{GeV} = \mu_{MFV}$:
  - Scenarios with very light stop: $\tilde{\chi}_1^0$ LSP and $\tilde{t}_1$ NLSP

[SPheno, Porod '03]
[SOFTSUSY, Allanach '02]

$\Rightarrow$ possible decay modes

$\tilde{t}_1 \to c + \tilde{\chi}_1^0$	dominating $V_{cb} \approx 0.04$
$\tilde{t}_1 \to u + \tilde{\chi}_1^0$	suppressed by $V_{ub} \approx 0.003$
$\tilde{t}_1 \to \tilde{\chi}_1^0\, b\, f \bar{f}$	suppressed due to phase space

Results: Widths

Comparison of exact one-loop formula to approximation by H/K

$$m_{\tilde{t}_1} = 130 \text{ GeV} \quad m_{\tilde{\chi}_1^0} = 92 \text{ GeV} \quad m_{\tilde{\chi}_1^+} = 175 \text{ GeV}$$

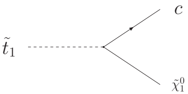
$\Gamma^{\text{1-loop}}$[GeV]	$\Gamma^{\text{H/K}}$[GeV]
$5.862\,10^{-9}$	$6.446\,10^{-9}$

[SUSY-HIT, Djouadi, Mühlleitner, Spira '07]

- Exact and approximate decay width differ by $\mathcal{O}(10)\%$
- Finite terms extracted one-loop formula contribute with $\sim 3-5\%$ to F_R
- Finite terms account for difference of form factors
  $\Rightarrow$ 10% effect in decay widths
- Difference in branching ratios negligible

Results: Resummation effects

Renormalization group approach: Includes resummation of large logarithms

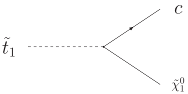


$$\sim \widetilde{W}_{\tilde{t}_1 \tilde{c}_1} = 0 \quad \text{at} \quad \mu_{MFV} = 10^{16}\text{GeV}$$

MFV assumption is not RGE invariant and holds only at scale $\mu_{MFV} = 10^{16}$GeV

Flavour off-diag matrix element = Result of RG evolution down to EWSB scale

$\Rightarrow$ tree level FCNC decay at EWSB scale



$$\sim \widetilde{W}_{\tilde{u}_1 \tilde{c}_L} \neq 0 \qquad F_R^{FV} = -\sqrt{2}\left[\frac{Z_{11}}{6}\tan\theta_W + \frac{Z_{12}}{2}\right]\widetilde{W}_{\tilde{u}_1 \tilde{c}_L}$$

Comparison of one-loop MFV to FV tree level result:

$\Gamma^{\text{1-loop}}$ [GeV]	Γ^{FV} [GeV]
$5.862 \cdot 10^{-9}$	$3.006 \cdot 10^{-10}$

Results: Branching ratios

$\tilde{t}_1 \to \tilde{\chi}^0_1 u$: Resummed flavour off-diag matrix element $\widetilde{W}_{\tilde{u}_1 \tilde{u}_L}$

$\tilde{t}_1 \to \tilde{\chi}^0_1 b\, f\bar{f}'$: Calculation including tree level FV couplings not available

$\Rightarrow$ Additional contributions expectetd to be small due to CKM suppression

branching ratio	BR($\tilde{t}_1 \to \tilde{\chi}^0_1 c$)	BR($\tilde{t}_1 \to \tilde{\chi}^0_1 u$)	BR($\tilde{t}_1 \to \tilde{\chi}^0_1 bf\bar{f}'$)
Exact 1-loop	0.9443	0.0053	0.0504
Resummed TL	0.4884	0.0032	0.5084

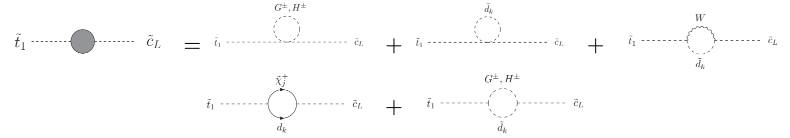
- Decay width of 4 body decay unchanged in both cases
- Branching ratio of $\tilde{t}_1 \to \tilde{\chi}^0_1 u$ always suppressed by 2 orders of magnitude
- Resummation effects reduce $\Gamma(\tilde{t}_1 \to \tilde{\chi}^0_1 c)$ by factor ~ 20
  $\Rightarrow$ Decrease of branching ratio by factor $1/2$
  $\Rightarrow$ No longer in agreement with BR=1, as used in all analyses

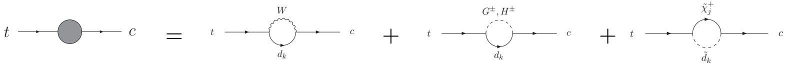
$\Rightarrow$ Resummation effects important for large scale $\mu_{MFV} = M_{GUT}$

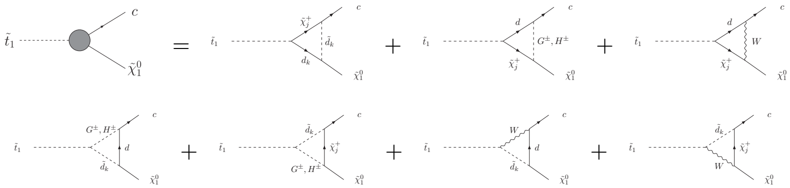
Summary & Outlook

- Complete one-loop calculation of $\tilde{t}_1 \to c + \tilde{\chi}_1^0$ in MFV, including finite terms, which do not depend on $\log \mu_{MFV}$
- Full renormalization program, including gauge-independent renormalization of mixing matrices
- Comparison to existing approximative formula by Hikasa/Kobayashi: Difference in partial width $\mathcal{O}(10)\%$ because of finite terms
- Comparison to tree level decay with FV coupling due to RGE evolution
  $\to$ Resummation effects important for large μ_{MFV}
  $\to$ Big impact on branching ratio
- Next step: Improve predictions for light stop decay width by calculating one-loop corrections to FV tree level decay

Feynman diagrams







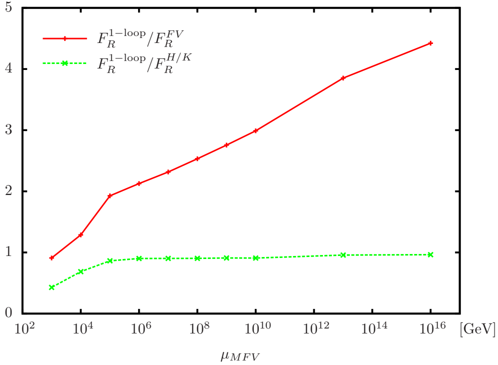
Results: Analysis for different μ_{MFV}

With decreasing μ_{MFV} :

- One-loop MFV result approaches resummed FV tree level result
- One-loop MFV result better than approximate formula by Hikasa/Kobayashi

For numerical analysis:

Scenarios with different μ_{MFV} but the same mass spectrum
$\Rightarrow$ achieved by adjusting input parameters at high scale

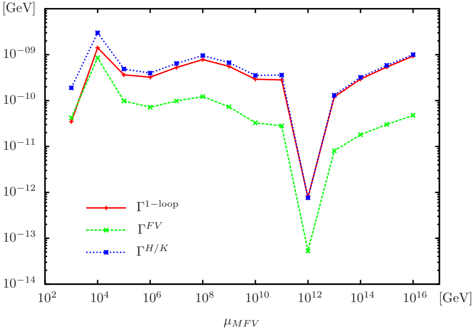


Results: Analysis for different μ_{MFV}

Size of decay width: Does not only depend on size of log

Coefficient of logarithmic term:

$$\frac{\cos\theta_{\tilde{t}}}{m^2_{\tilde{t}_1} - m^2_{\tilde{c}_L}} \left(m^2_{\tilde{c}_L} - \mu^2 + A_b^2 + M^2_{\tilde{b}_R} + c^2_\beta (M^2_W (t^2_\beta - 1) + M^2_A t^2_\beta) + m_t A_b \tan\theta_{\tilde{t}} \right)$$



Small stop decay widths → Long stop lifetimes → Secondary vertex *[Hiller & Nir '08]*

- Observing secondary vertex: Strong support to MFV principle
- Measuring lifetime: Information on size of flavour changing coupling

Results: Branching ratios, exact formula

$$
\begin{array}{lllll}
(1) & m_{\tilde{t}_1} = 104\ \text{GeV} & m_{\tilde{\chi}_1^0} = 92\ \text{GeV} & m_{\tilde{\chi}_1^+} = 175\ \text{GeV} & \\
M_0 = 200\ \text{GeV} & M_{1/2} = 230\ \text{GeV} & A_0 = -920\ \text{GeV} & \tan\beta = 10 & \text{sign}(\mu) = +
\end{array}
$$

$$
\begin{array}{lllll}
(2) & m_{\tilde{t}_1} = 130\ \text{GeV} & m_{\tilde{\chi}_1^0} = 92\ \text{GeV} & m_{\tilde{\chi}_1^+} = 175\ \text{GeV} & \\
M_0 = 200\ \text{GeV} & M_{1/2} = 230\ \text{GeV} & A_0 = -895\ \text{GeV} & \tan\beta = 10 & \text{sign}(\mu) = +
\end{array}
$$

branching ratio	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 c$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 u$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 b f \bar{f}'$)
Scenario(1)	0.9944	0.0056	$4.587 \cdot 10^{-5}$
Scenario(2)	0.9443	0.0053	0.0504

- FCNC decay dominating in both scenarios
- Decay into up-quark suppressed by 2 orders of magnitude
- 4-body decay is less important in (1), due to reduced phase space
- Effect on BR of interest only at the percent level

Results: Branching ratios, exact formula vs. H/K

$$\begin{array}{llll} (1) & m_{\tilde{t}_1} = 104\text{ GeV} & m_{\tilde{\chi}_1^0} = 92\text{ GeV} & m_{\tilde{\chi}_1^+} = 175\text{ GeV} \\ (2) & m_{\tilde{t}_1} = 130\text{ GeV} & m_{\tilde{\chi}_1^0} = 92\text{ GeV} & m_{\tilde{\chi}_1^+} = 175\text{ GeV}\,. \end{array}$$

Exact 1-loop result:

branching ratio	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 c)$	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 u)$	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 b f \bar{f}')$
Scenario(1)	0.9944	0.0056	$4.587 \cdot 10^{-5}$
Scenario(2)	0.9443	0.0053	0.0504

Approximation by H/K:

branching ratio	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 c)$	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 u)$	$BR(\tilde{t}_1 \to \tilde{\chi}_1^0 b f \bar{f}')$
Scenario(1)	0.9944	0.0056	$4. \cdot 10^{-5}$
Scenario(2)	0.9486	0.0053	0.0460

Results: Branching ratios, 1-loop vs. FV TL

$$\begin{aligned} &(1) \quad m_{\tilde{t}_1} = 104 \text{ GeV} \quad m_{\tilde{\chi}_1^0} = 92 \text{ GeV} \quad m_{\tilde{\chi}_1^+} = 175 \text{ GeV} \\ &(2) \quad m_{\tilde{t}_1} = 130 \text{ GeV} \quad m_{\tilde{\chi}_1^0} = 92 \text{ GeV} \quad m_{\tilde{\chi}_1^+} = 175 \text{ GeV} . \end{aligned}$$

Exact 1-loop result:

branching ratio	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 c$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 u$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 b f \bar{f}'$)
Scenario(1)	0.9944	0.0056	$4.587 \cdot 10^{-5}$
Scenario(2)	0.9443	0.0053	0.0504

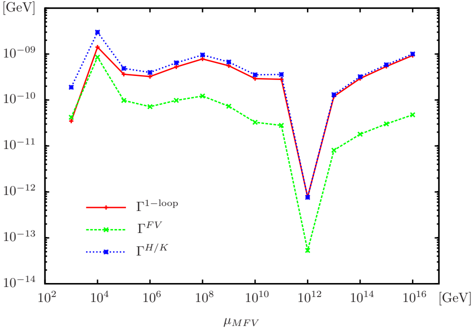
Resummed FV TL:

branching ratio	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 c$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 u$)	BR($\tilde{t}_1 \to \tilde{\chi}_1^0 b f \bar{f}'$)
Scenario(1)	0.9925	0.0066	$8.956 \cdot 10^{-4}$
Scenario(2)	0.4884	0.0032	0.5084

Results: Analysis for different μ_{MFV}

With decreasing μ_{MFV} :
- One-loop MFV result approaches resummed FV tree level result
- One-loop MFV result better than approximate formula by Hikasa/Kobayashi

For numerical analysis:
Scenarios with different μ_{MFV} but the same mass spectrum



$$\mathcal{A} = -\mu^2 + A_b^2 + M_{\tilde{b}_R}^2 + c_\beta^2 (M_W^2 (t_\beta^2 - 1) + M_A^2 t_\beta^2) + m_t A_b \tan\theta_t$$

Light Stop Searches at the LHC in Events with two bJets and Missing Energy

[Bornhauser, Drees, Grab, Kim '10]

Production of $\tilde{t}_1 \tilde{t}_1^* b\bar{b}$ including pure QCD as well as mixed electroweakQCD contributions

$pp \to \tilde{t}_1 \tilde{t}_1^* b\bar{b}$
$\tilde{t}_1 \to c + \tilde{\chi}_1^0$

Small $\tilde{t}_1 - \tilde{\chi}_1^0$ mass splitting
$\Rightarrow$ cjets too soft to be useful

Signature:
large missing energy +
2 b-flavoured jets

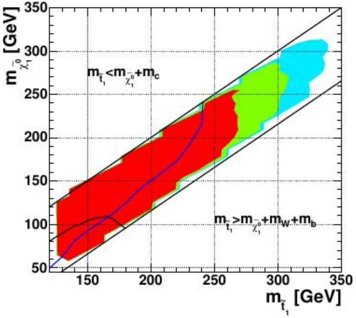


FIG. 10: Statistical signal significance at the LHC with $\sqrt{s} = 14$ TeV as a function of the stop and neutralino mass. The red, green and turquoise region corresponds to an excess of at least 5σ, 3σ and 2σ, respectively, for an integrated luminosity of 100 fb^{-1}. The chargino mass is fixed by Eq. (4). The parameter space *below* the black curve is excluded by Tevatron searches [27], while in the region *above* the blue curve, the stop pair plus single jet ("monojet") signal has significance ≥ 5 [30]. The parameter region where $\tilde{t}_1$ decays into a charm and a neutralino are expected to dominate is given by the condition $m_{\tilde{\chi}_1^0} + m_c < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_W + m_b$.

Measuring Flavor Mixing with Minimal Flavor Violation at the LHC

[G. Hiller & Y. Nir, arXiv:0802.0916]

Challenging task: Experimentally establishing MFV, in case it holds
Under certain circumstances measuring mixing with MFV models might be possible

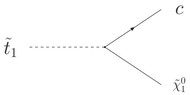
- Stop NLSP, $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \lesssim m_b \qquad \Rightarrow \tilde{t}_1 \to c + \tilde{\chi}_1^0$ dominating
- CKM suppression $\to$ stop lifetime unusually long
  $\to$ secondary vertex

1) Flavour suppression need for secondary vertex = unique to MFV models
Observing secondary vertex $\to$ strong support to MFV principle

2) Measuring lifetime $\to$ information on size of flavour changing coupling
(after higgsino/gaugino decomposition of neutralino
+ left/right decomposition of stop known)

Calculation: Tree level I

In MFV framework the decay is forbidden at tree level:



= 0

What does that mean for our terms?

Flavour mixing in the SM:

$$\overline{\Psi^q_{Li}} m_{ij} \Psi^q_{Rj} \qquad \text{with} \qquad \Psi^q_{Li} = U^{qL}_{ik} q^{(m)}_k \quad \Psi^q_{Rj} = U^{qR}_{jm} q^{(m)}_m \qquad q = u, d$$

- Unitary matrices $U^{qL\dagger} U^{qL} = 1$
- $U^{qL,R}$ diagonalise mass matrix m_{ij}: $U^{uL}_{ki} m_{ij} U^{uR}_{jm} = m_k \delta_{km}$
- CKM matrix $V^{CKM} = U^{uL\dagger} U^{dR}$
- no further flavour transitions possible

Calculation: Tree level II

Flavour & LR mixing in the MSSM:

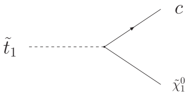
$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{c}_1 \\ \tilde{t}_1 \\ \tilde{u}_2 \\ \tilde{c}_2 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \text{squark} \\ \text{mixing} \\ \text{matrix}: \widetilde{W} \\ (6 \times 6) \end{pmatrix} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

- Unitary matrix $\widetilde{W}^\dagger \widetilde{W} = 1$
- Diagonalises mass matrix: $\widetilde{W}^\dagger M^{\tilde{q}} \widetilde{W} = M^{\tilde{q}}_{\text{Diag}}$
- In general: Lots of new flavour violating sources

Mixing matrix factorises in MFV:

$$\widetilde{W} = \begin{pmatrix} U^{uL} & 0 \\ 0 & U^{uR} \end{pmatrix} \begin{pmatrix} \cos\theta_{\tilde{u}_i} & -\sin\theta_{\tilde{u}_i} \\ \sin\theta_{\tilde{u}_i} & \cos\theta_{\tilde{u}_i} \end{pmatrix} = U \cdot \underbrace{W}_{\text{flavour diagonal}}$$

➡ Process vanishes at tree level:



$\sim W_{ct} = 0$

Calculation: Tree level III

Mixing matrix factorises in MFV:

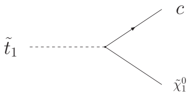
$$\widetilde{W} = \begin{pmatrix} U^{uL} & 0 \\ 0 & U^{uR} \end{pmatrix} \begin{pmatrix} \cos\theta_{\tilde{u}_i} & -\sin\theta_{\tilde{u}_i} \\ \sin\theta_{\tilde{u}_i} & \cos\theta_{\tilde{u}_i} \end{pmatrix} = U \cdot \underbrace{W}_{\text{flavour diagonal}}$$

- MFV hypothesis not renormalization group invariant

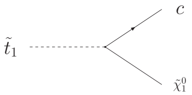
[G.D'Ambrosio et al., arXiv:0207036]

At weak scale:
- Scalar mass terms obtained by solving RGE's
- Weak interactions affect squark and quark mass matrices differently
- Squark and quark mass matrices cannot be diagonalized simultaneously

$\Rightarrow$ stop state receives admixture from scharm



$\sim W_{ct} = 0$ at $\mu = \mu_{MFV}$



$\sim W_{ct} \neq 0$ at $\mu \neq \mu_{MFV}$

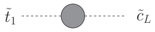
Renormierung: 1. Squarkfelder

Einführen der Renormierungskonstanten:

$$\tilde{q}_j^0 = \widetilde{Z}_{jk}\tilde{q}_k \qquad j,k = 1,2\ldots 6$$

$$\widetilde{Z}_{jk} = \delta_{jk} + \tfrac{1}{2}\delta\widetilde{Z}_{jk}$$

Einsetzen in die Lagrangedichte führt auf renormierte Selbstenergie:



$$= i\,\hat{\Sigma}_{\tilde{t}_1\tilde{c}_1}(q^2) = i\,\Sigma_{\tilde{t}_1\tilde{c}_1}(q^2) \quad + \quad \frac{q^2}{2}\left(\delta\widetilde{Z}_{\tilde{t}_1\tilde{c}_1} + \delta\widetilde{Z}^*_{\tilde{c}_1\tilde{t}_1}\right) \quad - \quad \frac{1}{2}\left(m^2_{\tilde{c}_1}\,\delta\widetilde{Z}_{\tilde{t}_1\tilde{c}_1} + m^2_{\tilde{t}_1}\,\delta\widetilde{Z}^*_{\tilde{c}_1\tilde{t}_1}\right)$$

$\Rightarrow$ Teilchenpropagator in höherer Ordnung: $\frac{i}{k^2-m^2+\hat{\Sigma}(k^2)}$

- On-shell Renormierungsbedingung
  m soll Bedeutung der physikalischen Masse behalten:

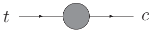
$$\hat{\Sigma}_{\tilde{t}_1\tilde{c}_1}(m^2_{\tilde{t}_1}) = 0 \qquad \Rightarrow \delta\widetilde{Z}_{\tilde{t}_1\tilde{c}_1} = \frac{2}{m^2_{\tilde{c}_1} - m^2_{\tilde{t}_1}}\Sigma_{\tilde{t}_1\tilde{c}_1}(m^2_{\tilde{t}_1})$$

Renormierung: 2. Quarkfelder

Einführen der Renormierungskonstanten:

$$q^0_{\{L,R\},i} = Z^{\{L,R\}}_{ik} q_{\{L,R\},k} \qquad Z^{\{L,R\}}_{ik} = \delta_{ik} + \frac{1}{2}\delta Z^{\{L,R\}}_{ik}$$

Einsetzen in die Lagrangedichte führt auf renormierte Selbstenergie:



$$\begin{aligned} &= \hat{\Sigma}^{tc}(p^2) \\ &= i\,[\underbrace{\not{p}\,\hat{\Sigma}^{tc}_L P_L + \not{p}\,\hat{\Sigma}^{tc}_R P_R}_{\text{für } m_c=0,\,\to 0} + P_L\,\hat{\Sigma}^{tc}_S + P_R\,\hat{\Sigma}^{*,ct}_S] \end{aligned}$$

$$\begin{aligned} \hat{\Sigma}^{tc}_S(p^2) &= \Sigma^{tc}_S(p^2) - \frac{m_t}{2}\delta Z^{*,R}_{tc} \\ \hat{\Sigma}^{*,ct}_S(p^2) &= \Sigma^{*,ct}_S(p^2) - \frac{m_t}{2}\delta Z^{*,L}_{tc} \end{aligned}$$

- On-shell Renormierungsbedingung: $\bar{u}(p)\hat{\Sigma}^{tc}(p^2)|_{(p^2=m_c^2=0)} = 0$

$$\Rightarrow \delta Z^{*,L}_{tc} = \frac{2}{m_t}\Sigma^{*,ct}_S(0) \qquad \delta Z^{*,R}_{tc} = \frac{2}{m_t}\Sigma^{tc}_S(0) = 0$$