Rare top-quark decays to Higgs boson in the MSSM [1]

C. Soutzios

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University of Ioannina, Greece

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[1] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, K. Tamvakis, "Rare Top-quark Decays to Higgs boson in MSSM" JHEP 1411 **137** (2014)

Overview

Introduction

The top-quark has been produced in large numbers at LHC. More than two million $t\bar{t}$-pairs have been produced so far ($\sigma_{t\bar{t}} \approx 200$pb at $\sqrt{s} = 7$ TeV). Therefore LHC is an ideal place to study top-quark decays.

Lorentz invariance suggests two types of decays,

$$t \to \Phi + q \quad \text{and} \quad t \to V + q$$

where

$$V = W, Z, \gamma, g$$
$$\Phi = Higgs - boson$$
$$q = light \;\; quark$$

The decay $t \to bW$ is dominant and well measured, but the other decays $t \to q\,\gamma, t \to q\,Z, t \to q\,g, t \to q\,h$ are very rare.

$t \to qh$ in the SM

In the SM the quark-scalar interactions originate from the Lagrangian:

$$\mathcal{L}_{SM} \supseteq -Y_u^{ij} \epsilon^{ab} \bar{Q}_{La}^i H_b^\dagger u_R^j - Y_d^{ij} \bar{Q}_L^i H d_R^j + h.c.$$

where

$$\begin{aligned}
Y_u,\ Y_d &= \text{general complex } 3 \times 3 \text{ matrices} \\
u_R^i &= \big(u_R, c_R, t_R\big), \quad SU(2) - singlets, \\
d_R^i &= \big(d_R, s_R, b_R\big), \quad SU(2) - singlets, \\
Q_L^i &= \big(u_L, d_L\big)^T, \big(c_L, s_L\big)^T, \big(t_L, b_L\big)^T, \quad SU(2) - doublets, \\
H &= \mathcal{U} \frac{1}{\sqrt{2}} \big(0, v + h\big)^T, \quad SU(2) - doublet,
\end{aligned}$$

$t \to qh$ in the SM

By performing chiral transformations to quark fields the interaction terms take the form:

$$\mathcal{L}_{SM} \supseteq -m_u^i \,\bar{u}_L^i \, u_R^i \left(1 + \frac{h}{v}\right) + m_d^i \,\bar{d}_L^i \, d_R^i \left(1 + \frac{h}{v}\right) + h.c.$$

It is important that the Higgs boson couples to quarks in a diagonal form.
In the SM there are not $t \to qh$ transitions at tree level!
The chiral transformations affect only the current:

$$J^{\mu +} = \frac{1}{\sqrt{2}} \,\bar{u}_L^i \, \gamma^\mu \left(V_{CKM}\right)^{ij} d_L^j$$

which couples to W_μ^+-field.
The $t \to qh$ transitions are induced only by loop Feynman diagrams that contain these vertices.

$t \to qh$ in the SM

Why $t \to qh$ is rare in the SM?
There are three reasons for $t \to qh$ suppression in the SM:

- no tree level coupling
- unitarity of V_{CKM}
- down type quarks enter in the loop

Branching ratio for $t \to qh$ in the SM.

$$\mathcal{B}(t \to uh)_{SM} \approx 4 \times 10^{-17}, \qquad \mathcal{B}(t \to ch)_{SM} \approx 4 \times 10^{-14}$$

G. Eilam, J.Hewett, and A.Soni, *Phys.Rev.* **D44** (1991) 1473-1484

B. Mele, S.Petrarca, and A.Soddu, *Phys.Lett.* **B435** (1998) 401-406.

LHC bounds on $t \to qh$

The relevant Lagrangian is:

$$\mathcal{L} \supseteq -C_L^{(h)}\, \bar{q}_R\, t_L\, h - C_R^{(h)}\, \bar{q}_L\, t_R\, h + h.c.$$

$$\mathcal{B}(t \to qh) = \frac{1}{1.39\,GeV} \frac{m_t}{32\pi}\left(|C_L^{(h)}|^2 + |C_R^{(h)}|^2\right)\left(1 - \frac{m_h^2}{m_t^2}\right)^2 \approx \frac{1}{4}\left(|C_L^{(h)}|^2 + |C_R^{(h)}|^2\right)$$

Currently LHC sets an upper bound:

$$\mathcal{B}(t \to qh) \leq 0.79\% \;\; (ATLAS), \quad \mathcal{B}(t \to qh) \leq 0.56\% \;\; (CMS).$$

This corresponds to an upper bound on C_L and C_R: $|C_L|, |C_R| \lesssim 0.1$
LHC future reach $(3000 fb^{-1}, 14\,TeV)$: $\mathcal{B}(t \to qh) \leq 2 \times 10^{-4}$
This means that: $|C_L|, |C_R| \lesssim 0.01$
A signal for $t \to qh$ at LHC will mean New Physics Beyond the SM!

MSSM framework

We are working in the R-parity conserving MSSM.
In MSSM are fulfilled some conditions that allow an enhancement of $\mathcal{B}(t \to qh)$.

- Although the GIM mechanism is still operative in the quark-interactions, it is not, in general, in the squark interactions.
- Coloured scalars, the squarks, enter in loops with potentially large mass differences.

Depending on MSSM input parameters, there is a maximum prediction $\mathcal{B}(t \to ch) \approx 4 \times 10^{-4}$, while an analysis taking into account constraints from rare B-meson decays, concluded a maximum branching fraction of up to $\mathcal{B}(t \to ch) \approx 6 \times 10^{-5}$.

J. Guasch and J. Sola, Nucl.Phys. **B562** (1999) 3-28.

J. Cao, G. Eilam, M. Frank, K. Hikasa, G. Liu, et al., Phys.Rev. **D75** (2007) 075021.

MSSM flavour sector

The relevant Lagrangian in the MSSM framework has the form:

$$
\begin{aligned}
\mathcal{L}_{\mathrm{MSSM}} \supset & -\widetilde{Q}_L^\dagger m_{Q_L}^2 \widetilde{Q}_L - \widetilde{U}_R^\dagger m_{U_R}^2 \widetilde{U}_R - \widetilde{D}_R^\dagger m_{D_R}^2 \widetilde{D}_R \\
& + \left(H_2\, \widetilde{Q}_L\, A_U\, \widetilde{U}_R + H_1\, \widetilde{Q}_L\, A_D\, \widetilde{D}_R + \mathrm{H.c} \right) \\
& + \left(H_1^\dagger\, \widetilde{Q}_L\, A'_U\, \widetilde{U}_R + H_2^\dagger\, \widetilde{Q}_L\, A'_D\, \widetilde{D}_R + \mathrm{H.c} \right) ,
\end{aligned}
$$

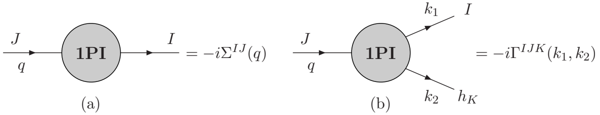
$m_{Q_L}^2, m_{U_R}^2, m_{D_R}^2$: soft SUSY breaking mass matrices
A_U, A_D : soft SUSY breaking trilinear matrices [2]
A'_U, A'_D : non-holomorphic soft SUSY breaking trilinear matrices[3] [4]

[2] M.Misiak, S.Pokorski and J.Rosiek [hep-ph/9703442]

[3] L.J.Hall and L.Randall, Phys. Rev. Lett. **65**, 2939 (1990)

[4] F.Borzumati, G.R. Farrar, N.Polonsky and S.D.Thomas, Nucl.Phys.B **555**, 53 (1999)

The Calculation



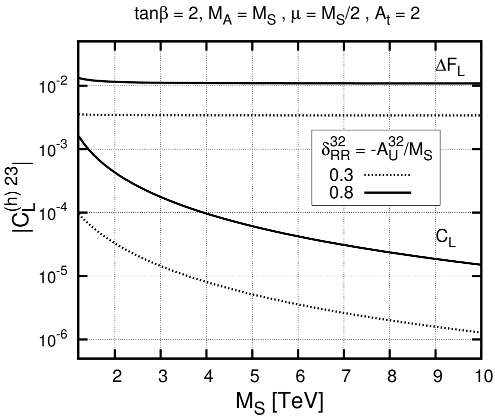
In the limit $m_I = m_u(m_c) \to 0$, the Wilson coefficients can be written simply as ($I = 1, 2,\ J = 3$):

$$C_L^{(h)\,IJ} \;=\; \Delta F_L^{(h)\,IJ} \;-\; \frac{1}{v}\left(\frac{\cos\alpha}{\sin\beta}\right)\Sigma_{mL}^{IJ}(0)\,,$$

$$C_{L,R}^{(h)} \;\approx\; \frac{\alpha_s}{4\pi}\left(\frac{m_{\tilde{g}}}{M_S}\right) f(\delta_{LR}^{32}\ldots), \quad \text{where}\;\; \delta_X^{JI} = \frac{(m_X^2)^{JI}}{\sqrt{(m_X^2)^{II}\,(m_X^2)^{JJ}}}.$$

All particle corrections have been taken into account.
However, the gluino diagram is the dominant.

Cancellations and Decoupling



- Degenerate squark mass spectrum (in flavour space)
- Uniform mass scaling, $(m_{\tilde{g}} = M_A = M_S)$

The decoupling works. There are not non-decoupling effects!

Remnants for $\mathcal{B}(t \to qh)$

The remaining corrections are proportional to m_t^2/M_S^2 or smaller. Expansion of the 1-loop gluino contributions gives for C_L^h:

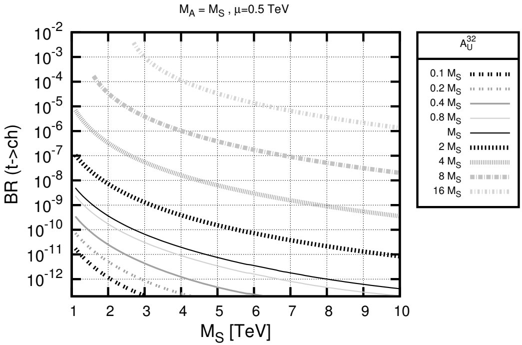
$$
\begin{aligned}
&\sim \quad A_U^{\prime JI} \frac{\cos(\alpha-\beta)}{\sin\beta} \times \mathcal{O}\left(\frac{1}{M_S}\right) &&\sim \delta_{RR}^{JI}\left(\frac{\cos\alpha}{\sin\beta}\right) \times \mathcal{O}\left(\frac{m_t^2}{M_S^2}\right) \\
&\sim \quad \mu^\star \delta_{RR}^{JI} \frac{\cos(\alpha-\beta)}{\sin\beta} \times \mathcal{O}\left(\frac{1}{M_S}\right) &&\sim \sum_{A=1}^{3} \delta_{RL}^{JA}\delta_{LR}^{AI}\left(\frac{\cos\alpha}{\sin\beta}\right) \times \mathcal{O}(1) \\
&\sim \quad \delta_{LR}^{JI}\left(\frac{\cos\alpha}{\sin\beta}\right) \times \mathcal{O}\left(\frac{m_t}{M_S}\right) &&\sim \delta_{LR}^{JJ}\delta_{RR}^{JI}\left(\frac{\cos\alpha}{\sin\beta}\right) \times \mathcal{O}\left(\frac{m_t}{M_S}\right) \\
&\sim \quad \sum_{A,B=1}^{3} \delta_{LR}^{JA}\,\delta_{RL}^{AB}\,\delta_{LR}^{BI}\left(\frac{\cos\alpha}{\sin\beta}\right) \times \mathcal{O}\left(\frac{M_S}{m_t}\right) ,
\end{aligned}
$$

where we have expressed our results in terms of the more useful 3×3 block matrices δ. These are defined through,

$$
\hat{\Delta} \equiv \begin{pmatrix} \delta_{LL} & \delta_{LR} \\ \delta_{RL} & \delta_{RR} \end{pmatrix} \; : \; \delta_{LR} = (\delta_{RL})^\dagger \; , \; \delta_{LL}^{AA} = \delta_{RR}^{AA} = 0 \; , \quad (A = 1, ..3) \; .
$$

Enhanced Scenarios

Enhancement through $\delta_{LR}^{32} \sim A_U^{32}/M_S > 1$



Degenerate spectrum, uniform scaling $m_{\tilde{g}} = M_A = M_S$, $2 \leq \tan(\beta) \leq 4$.
How realistic are these plots?
For $A_U^{32} > 8M_S \Longrightarrow \mathcal{B}(t \to ch) \geq 10^{-4}$ becomes observable at the LHC.
However...

Constraints from Charge and Colour Breaking (CCB) minima

...such a large A_U in connection with low stop mass square can possibly trigger unwanted Charge and Colour Breaking minima (CCB).[5]

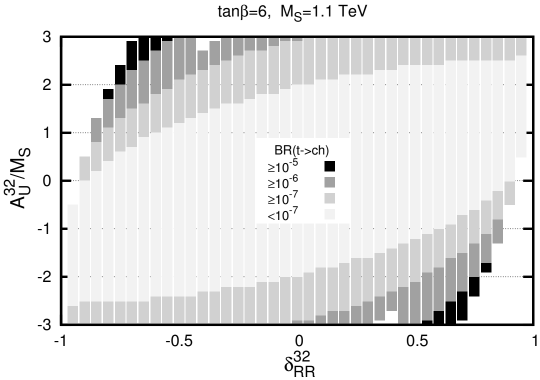
$$|A_U^{32}|^2 \;\lesssim\; Y_t^2\,(m_{H_2}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{c}_R}^2 + \mu^2)$$

For a common squark and Higgs mass scale M_S this constraint results in $|A_U^{32}| \leq \sqrt{3} M_S$.
We deduce that $\mathcal{B}(t \to ch) \leq 10^{-7}$.

This rate is out of near future LHC expected sensitivity.

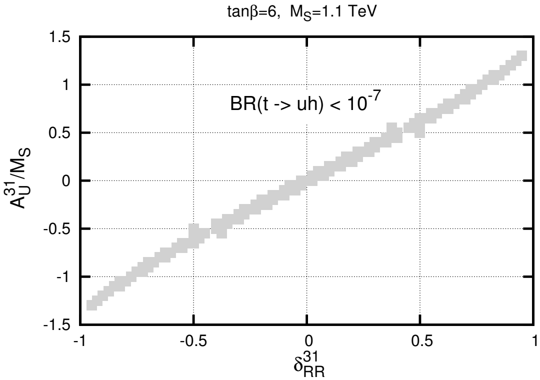
[5] J. A. Casas and S. Dimopoulos, Phys. Lett. B 387, 107 (1996) [hep-ph/9606237].

Combination of couplings δ^{32}_{LR}, δ^{32}_{RR}



We assume $m_{\tilde{g}} = M_A = \mu = M_S$ and $A_t/M_S = 2$.

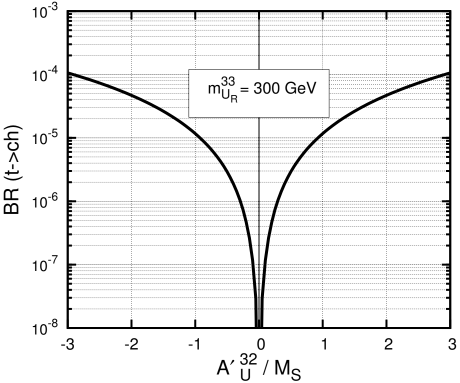
Combination of couplings δ^{31}_{LR}, δ^{31}_{RR}



neutron-EDM constraint very important here even for real A^{31}_U.

Enhanced Scenarios

The light M_A scenario and non-holomorphic coupling A'^{32}_U [6]



$M_A = 110 GeV,\ tan(\beta) = 6,\ \mu = 250 GeV,\ M_S = 1.1 TeV,\ A_t/M_S = 2.7$

Uniform scaling, light $M_A \sim M_Z$, observed Higgs is H.

However this scenario is disfavoured by LHC data.

[6] M. Drees, Phys. Rev. **D 86**, 115018 (2012) [arXiv:1210.6507 [hep-ph]].

Conclusions

- $\mathcal{B}(t \to qh)$ is unobservably small in the SM.
- $\mathcal{B}(t \to qh) \lesssim 10^{-6}$ in general MSSM due to cancellations, CCB and other constraints.
- Effects are proportional to m_t^2/M_S^2 at best.
- We consider the effects of NLO-QCD corrections due to the SUSY loop induced chromomagnetic dipole operator and the running of operators from the SUSY scale M_S to the top quark scale.
- An analytical, detailed presentation of the cancellations and decoupling, using a common scheme for both universal and hierarchical squark mass structures, has been performed.
- We investigate the effect on $\mathcal{B}(t \to qh)$ from non-holomorphic SUSY breaking terms A'_U.
- Finally, we have encoded all our calculations into a publicly available code where a variety of up-to-date experimental constraints has been included.[7]

[7] http://www.fuw.edu.pl/susy_flavor

Thank you!