Rare Top-quark decays to Higgs boson in the MSSM

Athanasios Dedes

Department of Physics
University of Ioannina, Greece

SUSY 2014
July 21-26, Univ. of Manchester, UK

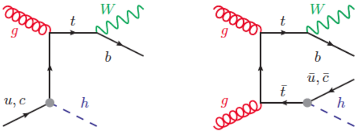
Outline

Introduction

- Last 20 years two elementary(?) particles discovered: t and h
- Interesting to search for rare top decays

$$t \to u\,h\,, \quad \text{or} \quad t \to c\,h$$

- In SM : $\mathcal{B}(t \to u\,(c)\,h)_{\rm SM} \approx 4 \times 10^{-17(14)}$ because of GIM
- In MSSM : no GIM in sflavour $\Rightarrow$ large ratios are expected
- LHC bound : $\mathcal{B}(t \to u\,h) \leq 0.56\%$ * †
- LHC projective reach (3000 fb^{-1}, 14 TeV) : $\gtrsim 2 \times 10^{-4}$ ‡



*CMS Collaboration, CMS-PAS-HIG-13-034.

†A. Greljo, J. F. Kamenik, and J. Kopp, arXiv:1404.1278 [hep-ph].

‡**Top Quark Working Group**, "Snowmass 2013," arXiv:1311.2028.

Lagrangian and Branching Ratio for $t \to u\, h$

The relevant Lagrangian is

$$-\mathcal{L} \supset C_L^{(h)} \bar{u}_R\, t_L\, h + C_R^{(h)}\, \bar{u}_L\, t_R\, h + \mathrm{H.c}\,,$$

Therefore, for $m_{u(c)} = 0$ and $\Gamma(t \to bW) = 1.39$ GeV

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

The current LHC bound provides us with a "tree level" bound:
$|C_L|, |C_R| \lesssim 0.1$

Bibliography (SM)

G. Eilam, J. Hewett, and A. Soni,
"Rare decays of the top quark in the standard and two Higgs doublet models,"
Phys.Rev. **D44** (1991) 1473–1484; Erratum-ibid. D59 (1999) 039901

B. Mele, S. Petrarca, and A. Soddu,
"A New evaluation of the $t \to cH$ decay width in the standard model,"
Phys.Lett. **B435** (1998) 401–406, arXiv:hep-ph/9805498 [hep-ph].

Bibliography (MSSM)

- J. Guasch and J. Sola,
  "FCNC top quark decays: A Door to SUSY physics in high luminosity colliders?,"
  Nucl.Phys. **B562** (1999) 3–28, arXiv:hep-ph/9906268 [hep-ph].

- J. Cao, G. Eilam, M. Frank, K. Hikasa, G. Liu, *et al.*,
  "SUSY-induced FCNC top-quark processes at the large hadron collider,"
  Phys.Rev. **D75** (2007) 075021, arXiv:hep-ph/0702264 [hep-ph].

- J. Cao, C. Han, L. Wu, J. M. Yang, and M. Zhang,
  "SUSY induced top quark FCNC decay $t \to ch$ after Run I of LHC,"
  arXiv:1404.1241 [hep-ph].

What is new in this work?

A. D., M. Paraskevas, J. Rosiek, K. Suxho, K. Tamvakis,
Rare Top-quark Decays to Higgs boson in the MSSM revisited
to appear soon

1. Includes NLO QCD Effects from SUSY-loops on chromomagnetic operator + running
2. Detailed analysis of cancellations
3. Effects from non-holomorphic SUSY breaking terms
4. Complete up-to-date constraints, $\Delta M_D, b \to s\gamma$, ... e.t.c
5. All MSSM contributions are included into SUSY_FLAVOR[§]

[§] A. Crivellin, J. Rosiek, P. H. Chankowski, A. D., S. Jaeger and P. Tanedo, [arXiv:1203.5023 [hep-ph]].

Outline

MSSM flavour sector

$$\begin{aligned}\mathcal{L}_{\rm MSSM} \;\supset\; & -\widetilde{Q}_L^\dagger m^2_{Q_L}\widetilde{Q}_L - \widetilde{U}_R^\dagger m^2_{U_R}\widetilde{U}_R - \widetilde{D}_R^\dagger m^2_{D_R}\widetilde{D}_R \\ & + \left(H_2\,\widetilde{Q}_L\,A_u\,\widetilde{U}_R + H_1\,\widetilde{Q}_L\,A_d\,\widetilde{D}_R + \mathrm{H.c}\right) \\ & + \left(H_1^\dagger\,\widetilde{Q}_L\,A'_u\,\widetilde{U}_R + H_2^\dagger\,\widetilde{Q}_L\,A'_d\,\widetilde{D}_R + \mathrm{H.c}\right),\end{aligned}$$

$m^2_{Q_L}$, $m^2_{U_R}$, $m^2_{D_R}$: soft SUSY breaking mass matrices

A_u and A_d : soft SUSY breaking trilinear (mass) matrices [¶]

A'_u, A'_d : non-holomorphic soft SUSY breaking trilinear (mass matrices) [‖] [**]

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

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

[**] F. Borzumati, G. R. Farrar, N. Polonsky and S. D. Thomas, Nucl. Phys. B **555**, 53 (1999) [hep-ph/9902443].

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+ & \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) ,
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Outline

QCD Mixed Operators

$$O^{(h)} = \left(H^\dagger H\right) \overline{Q}^I_L \, u^J_R \, \widetilde{H} \; + \; \mathrm{H.c}\,.$$

$$O^{(g)} = g_s \, \overline{Q}^I_L \, \sigma^{\mu\nu} \, \lambda^A \, u^J_R \, \widetilde{H} \, G^A_{\mu\nu} \; + \; \mathrm{H.c}$$

Strategy

1. Full calculation of the relevant one-Particle-Irreducible (1PI) Feynman diagrams $C^{(h)}_{L,R}$ at scale M_S, where M_S is the lightest coloured sparticle (usually gluino) mass.
2. Full calculation of the SUSY induced Wilson coefficient $C^{(g)}_{L,R}$ associated with the dipole operator $O^{(g)}$ that mix with strong (QCD) quantum corrections.
3. Use RGEs [††] to run all operators down to m_t^{pole}
4. Calculate $\mathcal{B}(t \to u\, h)$

[††] C. Zhang and F. Maltoni, arXiv:1305.7386

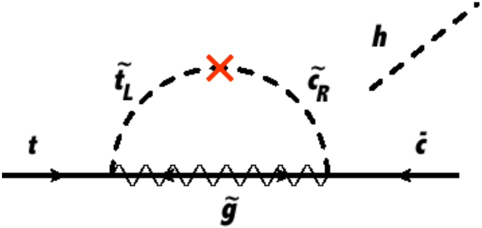
Outline

The calculation

Assuming $m_{u,c} \to 0$ the Wilson coefficient is e.g.,

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

no $\tan\beta$ enhancement

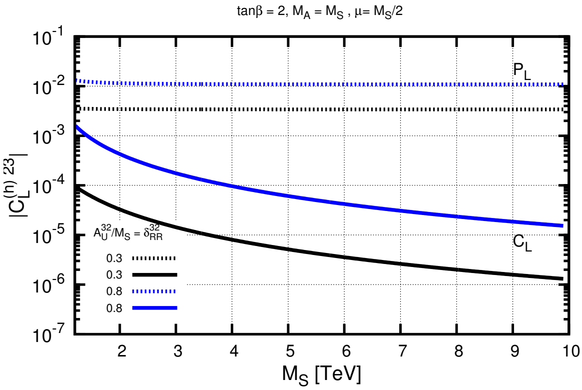


$$C_L^{(h)} \sim \left(\frac{\alpha_s}{4\pi}\right)\left(\frac{m_{\tilde{g}}}{M_S}\right) f(\delta_{LR}^{23}, \ldots)$$

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

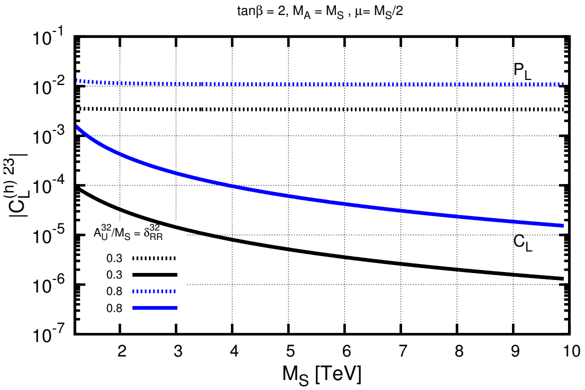
Outline

Cancellations and Decoupling



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

Cancellations and Decoupling



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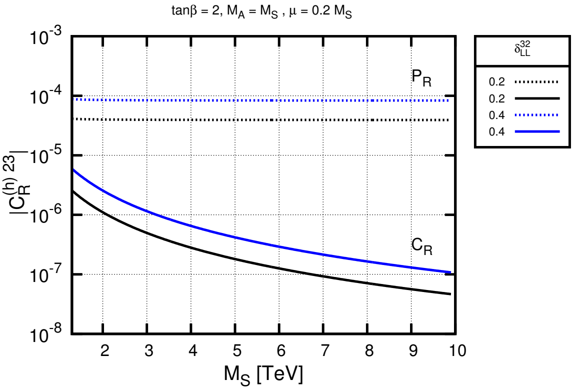
The decoupling works

Cancellations and Decoupling (cont'd)



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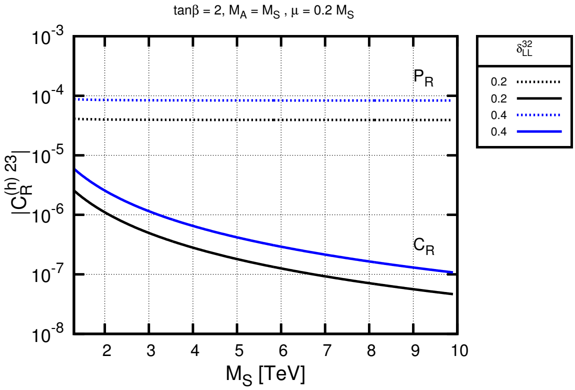


- Degenerate squark mass spectrum (in flavour space)
- Uniform mass scaling, $(m_{\tilde{g}} = M_A = M_S)$

The decoupling works (despite claims in `arXiv:1404.1241`)

Remnants for $\mathcal{B}(t \to u\, h)$

The remaining corrections are proportional to $\frac{m_t^2}{M_S^2}$ or smaller.

Expansion of the 1-loop gluino contributions give for $C_L^{(h)}$ terms:

$$\sim\ A_U'^{JI}\, \frac{\cos(\alpha-\beta)}{\sin\beta}\ \ \mathcal{O}\left(\frac{1}{M_S}\right) \qquad \sim\ \hat{\delta}^{JI}_{RR}\left(\frac{\cos\alpha}{\sin\beta}\right)\mathcal{O}\left(\frac{m_t^2}{M_S^2}\right)$$

$$\sim\ \mu^*\, \hat{\delta}^{JI}_{RR}\, \frac{\cos(\alpha-\beta)}{\sin\beta}\ \mathcal{O}\left(\frac{1}{M_S}\right) \qquad \sim\ \sum_{A=1}^{3} \hat{\delta}^{JA}_{RL}\hat{\delta}^{AI}_{LR}\ \left(\frac{\cos\alpha}{\sin\beta}\right)\mathcal{O}(1)$$

$$\sim\ \hat{\delta}^{JI}_{LR}\ \left(\frac{\cos\alpha}{\sin\beta}\right)\ \mathcal{O}\left(\frac{m_t}{M_S}\right)$$

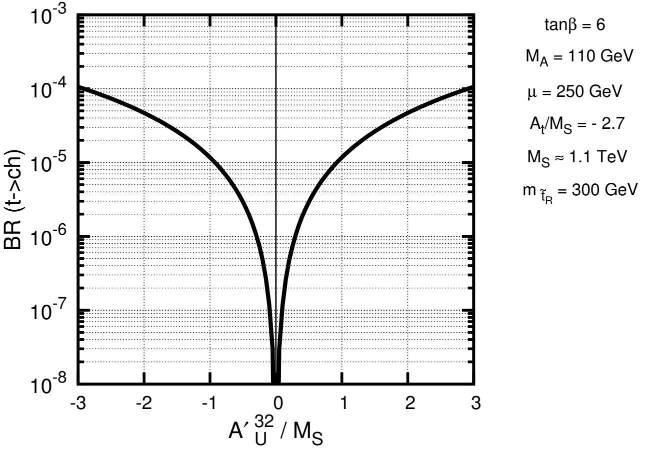
$$\sim \sum_{A=1}^{3}\sum_{B=1}^{3}\ \hat{\delta}^{JA}_{LR}\,\hat{\delta}^{AB}_{RL}\,\hat{\delta}^{BI}_{LR}\left(\frac{\cos\alpha}{\sin\beta}\right)\mathcal{O}\left(\frac{M_S}{m_t}\right)$$

Guide to search for enhanced effects in $\mathcal{B}(t \to u\, h)$

Outline

Enhanced Scenarios

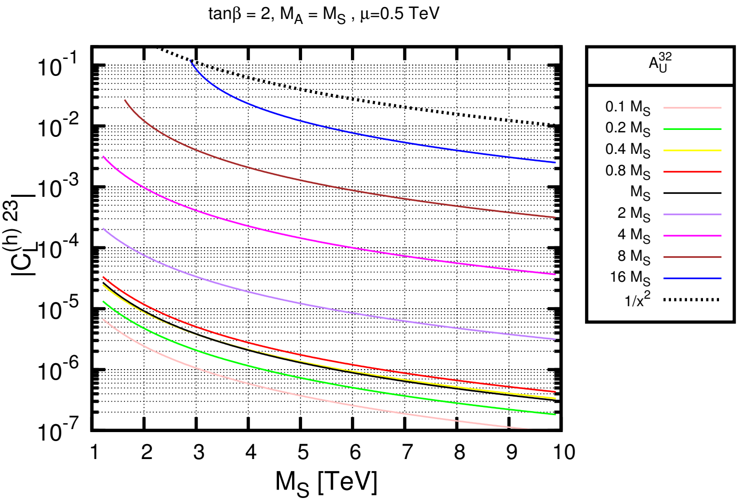
1. Observed Higgs is H and non-holomorphic coupling $\mathbf{A'^{32}_U}$



* challenged by LHC charged Higgs searches (ATLAS-CONF-2013-090) *

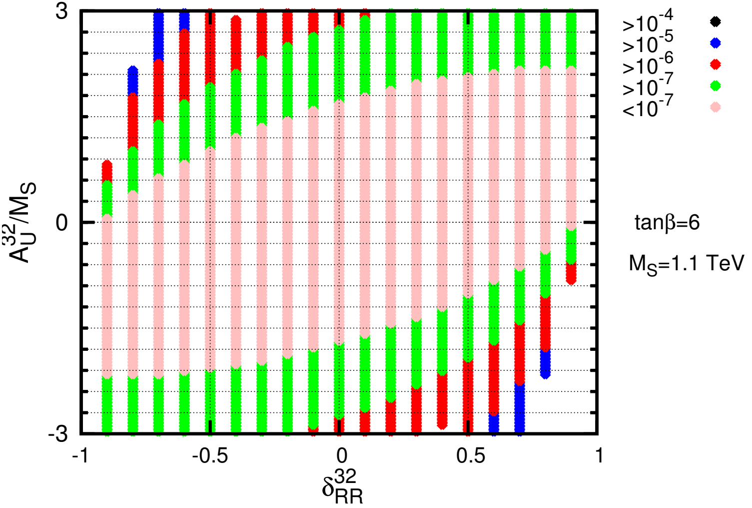
Enhanced Scenarios

2. Enhancement through $\delta^{32}_{LR} \propto \mathbf{A^{32}_U/M_S > 1}$



Enhanced Scenarios

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



Conclusions

- We have studied rare and flavour changing top decays to Higgs boson in MSSM
- The relevant flavour changing squark mass insertions are mostly unconstrained
- However, large cancellations between diagrams do take place, and effects are proportional to m_t^2/M_S^2 at best
- Classified all dominant contributions
- $\mathcal{B}(t \to c\, h)$ may become visible at LHC if the Higgs boson we see is the heavy Higgs (H) and the non-holomorphic term, $A_U'^{32}$, is of order M_S
- For all other points with $\delta_{LR}^{32} \gtrsim O(1)$ or $\delta_{RR}^{32} \sim O(1)$ we obtain $\mathcal{B}(t \to c\, h) \lesssim 10^{-4}$ consistent with constraints

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Thank you!