Rare Top-quark decays to Higgs boson in the MSSM

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Outline

- Introduction
  - Why $t \to q\,h$ is rare in the SM?
  - Branching Ratio for $t \to q\,h$
  - How to search for $t \to q\,h$ at LHC?
  - Supersymmetry (SUSY)
  - MSSM flavour sector
  - Flavour Changing Neutral Currents
- SUSY effects on $t \to q\,h$
  - The calculation
  - Operators
  - Cancellations and Decoupling
  - Enhanced Scenarios
- Other Model effects on $t \to q\,h$
  - R-Parity Violating SUSY
  - Multi-Higgs Doublet Models
- Conclusions

Introduction

Last 20 years three elementary particles discovered: t, h and ν_τ

$$\text{top} - \text{quark}: \quad m_t = 172.5 \text{ GeV} , \quad \text{(Tevatron)}$$

$$\text{Brout} - \text{Englert} - \text{Higgs boson}: \quad m_H = 125 \text{ GeV} , \quad \text{(LHC)}$$

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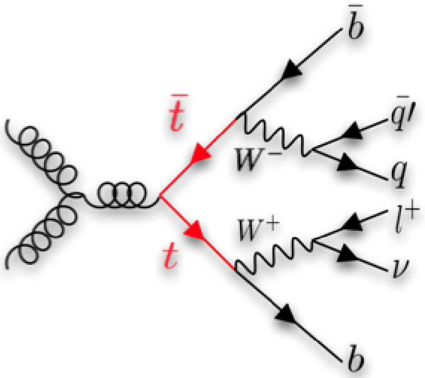
Questions:

- Why m_t is much heavier than all other fermions ?
- EWSB and Vacuum stability in Standard Model (SM) ?
- Can we see top-quark decays to Higgs boson at LHC ?

The top-quark has been produced in large numbers at LHC. More than 2 million $t\bar{t}$-pairs have been produced so far ($\sigma_{t\bar{t}} \approx 200$ pb at $\sqrt{s} = 7$ TeV).



This is an ideal place to study decays of top-quarks!

Lorentz invariance suggests two types of decays

$$t \longrightarrow \Phi \ + \ q \quad \text{or} \quad t \longrightarrow V \ + \ q$$

and in the SM

$$\begin{aligned} V &= W, Z, \gamma, g \\ \Phi &= Higgs - boson \\ q &= light - quark \end{aligned}$$

$t \to bW$ is the dominant (and well measured) decay, $t \to (s,d)W$ less frequent and all others, $t \to q\,\gamma, t \to q\,Z, t \to q\,g, t \to q\,h$, extremely rare!

In this talk I am going to discuss the rare top-decays:

$$t \to q\,h\,, \qquad q = u, c$$

Outline

Why $t \to q\, h$ is rare in the SM?

Quark-scalar field interactions originate in the SM from

$$\mathcal{L}_{\rm SM} \supseteq - Y_u^{ij}\, \epsilon^{ab}\, \overline{Q}^i_{L\,a}\, H^\dagger_b\, u^j_R - Y_d^{ij}\, \overline{Q}^i_L \cdot H\, d^j_R + \text{h.c.}$$

where

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

By performing chiral transformations to quark fields we can simplify this into ($i = 1...3$)

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

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Therefore, Higgs couplings to quarks can be brought to diagonal form. In the SM, at tree level, there is no $t \to q\, h$ transitions.

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The effect of the chiral transformations affect only the current,

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

that couples to W^+-field. These vertices may appear at one-loop Feynman diagrams and induce $t \to q\, h$ transitions.

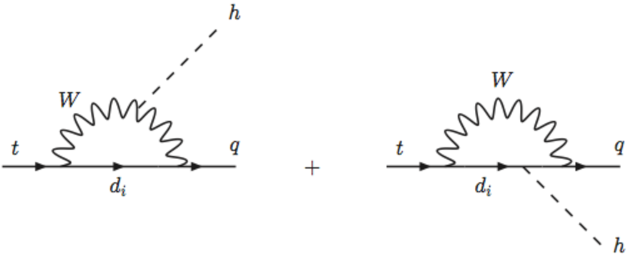

Figure: Feynman diagrams for SM contributions to $t \to q\, h$-amplitude

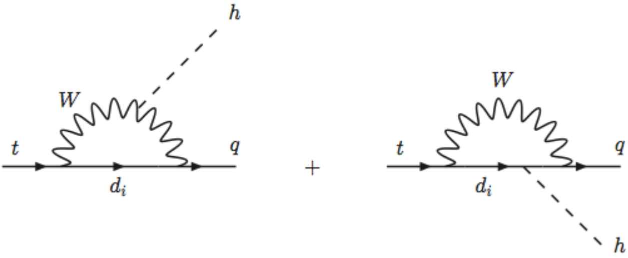

Figure: Feynman diagrams for SM contributions to $t \to q\, h$-amplitude

In summary, there are three reasons for $t \to q\, h$ suppression:

- no tree level coupling
- unitarity of V_{CKM}
- down-quarks circulating in the loop - small mass differences

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Branching Ratio for $t \to q\, h$

The relevant Lagrangian is

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

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

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

$$\approx \frac{1}{4} \left(|C_L^{(h)}|^2 + |C_R^{(h)}|^2 \right)$$

Therefore in the Standard Model :

$$\mathcal{B}(t \to u\, h)_{\rm SM} \approx 4 \times 10^{-17}$$

$$\mathcal{B}(t \to c\, h)_{\rm SM} \approx 4 \times 10^{-14}$$

A signal for $t \to q\, h$ at LHC will mean New Physics Beyond the SM!

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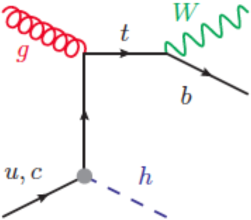
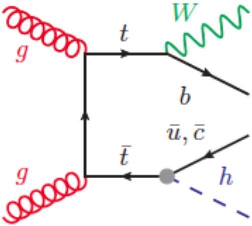
  "A New evaluation of the $t \to cH$ decay width in the standard model,"
  Phys.Lett. **B435** (1998) 401–406, `arXiv:hep-ph/9805498 [hep-ph]`.

Outline

How to search for $t \to q\, h$ at Hadron Colliders?





[1]

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

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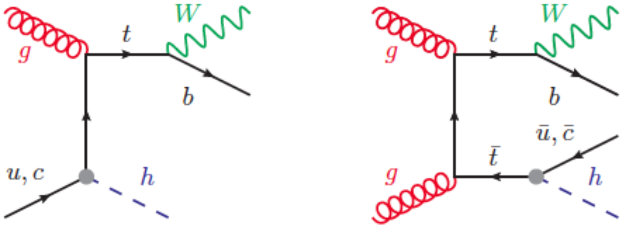

[1]

Currently LHC sets an upper bound:

$\mathcal{B}(t \to q\,h) \leq 0.79\%$ (ATLAS) , $\mathcal{B}(t \to q\,h) \leq 0.56\%$ (CMS) .

This means that: $|C_L|, |C_R| \lesssim 0.1$.

LHC future reach (3000 fb^{-1}, 14 TeV): $\mathcal{B}(t \to q\,h) \leq 2 \times 10^{-4}$.

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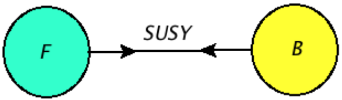
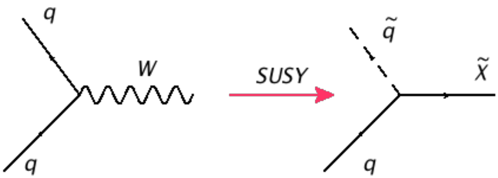
Supersymmetry is a theory that relates fermions and bosons in a non-trivial way.



'non-trivial' $\longrightarrow$ new interactions among particles. For example,



SUSY discovered almost 40 years ago after the pioneering work by Wess and Zumino, and independently by Volkov and Akulov.

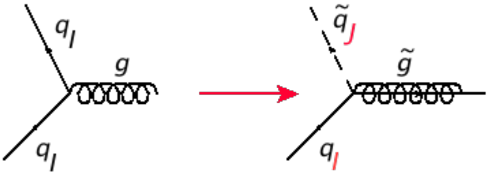
In 80's, it was realised that a minimal version of the SM, called MSSM, can be constructed.

The MSSM is capable to provide:

- the "technical" aspect of the hierarchy problem
- the dark matter problem
- unification of couplings
- electroweak symmetry breaking

In MSSM, the top-Yukawa coupling (Y_u^{33}) *must* be large for electroweak symmetry breaking !

MSSM: flavour changing interactions appear at tree level e.g.,



Outline

MSSM flavour sector

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

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

A_u and A_d : soft SUSY breaking trilinear (mass) matrices [2]

A_u', A_d' : non-holomorphic soft SUSY breaking trilinear (mass 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) [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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MSSM FCNCs

In MSSM we have 105 parameters and not so many nice SUSY breaking scenarios! The experiment however makes suggestions.

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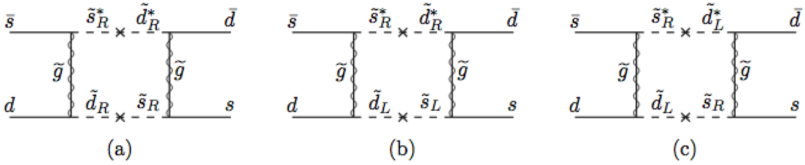


$$\frac{|\mathrm{Re}[m^2_{\tilde{s}^*_R \tilde{d}_R} m^2_{\tilde{s}^*_L \tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

SUSY Flavor problem

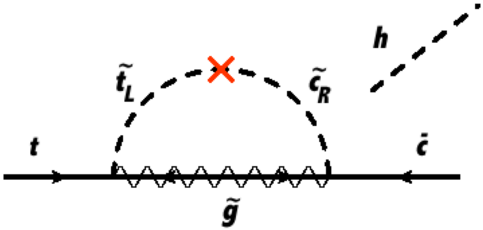
Avoiding the SUSY flavour problem...

- Universality : squark and slepton masses are proportional to the identity matrix and the trilinear couplings proportional to the Yukawa ones at some high scale. Need RGEs to run down
- Hierarchy : first and second generation masses much heavier than the third
- Alignment : Flavour Symmetries to avoid large FCNCs

SUSY flavour expansion (mass insertions), e.g.,

$$\delta_{RR}^{23} = \frac{(m^2_{U_R})^{23}}{\sqrt{(m^2_{U_R})^{22}\,(m^2_{U_R})^{33}}}\,, \qquad \delta'^{23}_{LR} = \frac{(A'_u)^{23}}{\sqrt{(m^2_{U_R})^{22}\,(m^2_{U_R})^{33}}}\,,$$

A typical but dominant MSSM contribution to $t \to c\, h$



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  Phys.Rev. **D75** (2007) 075021, arXiv:hep-ph/0702264 [hep-ph].

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  "SUSY induced top quark FCNC decay $t \to ch$ after Run I of LHC,"
  arXiv:1404.1241 [hep-ph].

What is new in our work?

A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, K. Tamvakis, "Rare Top-quark Decays to Higgs boson in MSSM," arXiv:1409.6546 [hep-ph], JHEP to appear

1. Includes NLO QCD Effects from SUSY-loops on chromomagnetic operator + RGE 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[5]

http://www.fuw.edu.pl/susy_flavor

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

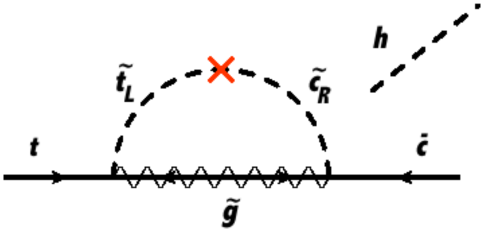
Outline

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

QCD Mixed Operators

$$O^{(h)} = \left(H^\dagger H\right) \overline{Q}_L^I u_R^J \widetilde{H} + \mathrm{H.c}\,.$$

$$O^{(g)} = g_s \overline{Q}_L^I \sigma^{\mu\nu} \lambda^A u_R^J \widetilde{H} G_{\mu\nu}^A + \mathrm{H.c}$$

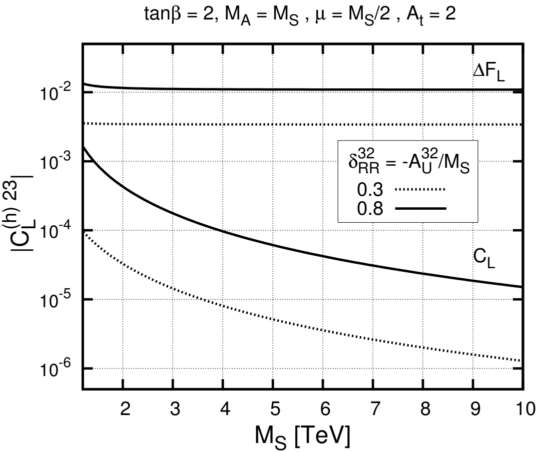
Strategy

1. Full calculation of the relevant one-Particle-Irreducible (1PI) Feynman diagrams $C_{L,R}^{(h)}$ at scale M_S, where M_S is the lightest coloured sparticle (usually gluino) mass.
2. Full calculation of the SUSY induced Wilson coefficient $C_{L,R}^{(g)}$ associated with the dipole operator $O^{(g)}$ that mix with strong (QCD) quantum corrections.
3. Use RGEs [6] to run all operators down to m_t^{pole}
4. Calculate $\mathcal{B}(t \to q\, h)$

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

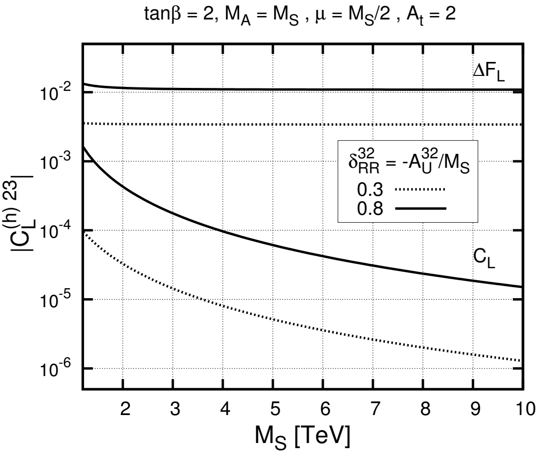
Outline

Cancellations and Decoupling



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

Cancellations and Decoupling



- Degenerate squark mass spectrum (in flavour space)
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The decoupling works

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

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:

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

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

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

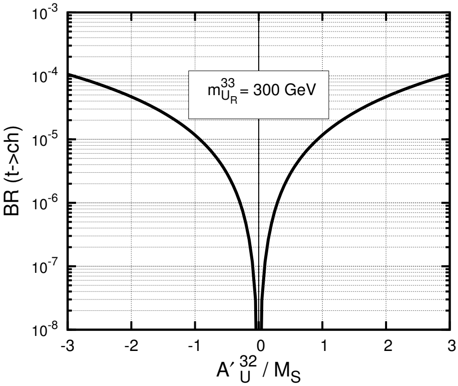
$$\sim\sum_{A=1}^{3}\sum_{B=1}^{3}\ \delta_{LR}^{JA}\,\delta_{RL}^{AB}\,\delta_{LR}^{BI}\left(\frac{\cos\alpha}{\sin\beta}\right)\mathcal{O}\left(\frac{M_S}{m_t}\right)$$

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

Outline

Enhanced Scenarios

1. Observed Higgs[7] is H and non-holomorphic coupling $\mathbf{A'^{32}_U}$

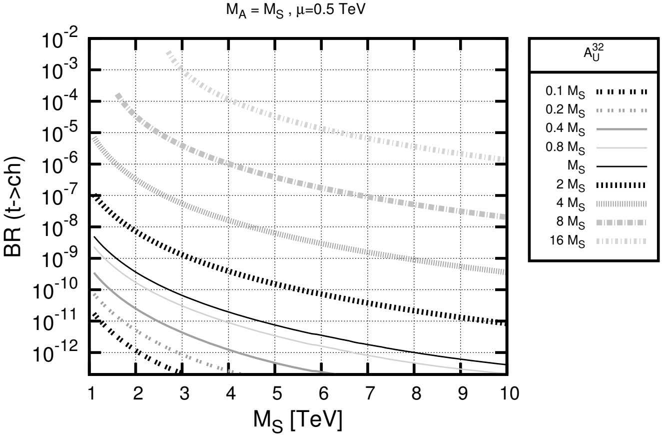


* challenged by LHC charged Higgs searches (ATLAS-CONF-2013-090) *

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

Enhanced Scenarios

2. Enhancement through $\delta^{32}_{LR} \propto \mathbf{A^{32}_{U}/M_{S} > 1}$



For $A_U^{32} \gtrsim 8 M_S$ the $\mathcal{B}(t \to c\, h) \gtrsim 10^{-4}$ becomes observable at LHC. However...

it is excluded because of Charged and Color Breaking Minima (CCB) constraints:[8]

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

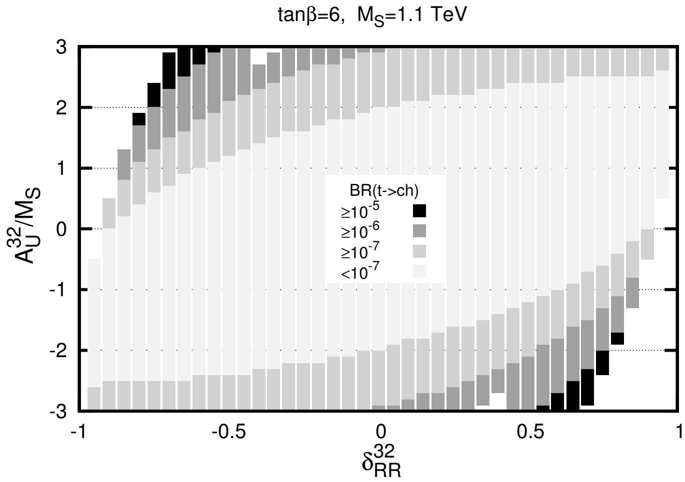
As a result:

$$\mathcal{B}(t \to c\,h) \;\lesssim\; 10^{-7}\;.$$

[8] J. M. Frere, D. R. T. Jones and S. Raby, Nucl. Phys. B **222**, 11 (1983); C. Kounnas, A. B. Lahanas, D. V. Nanopoulos and M. Quiros, Nucl. Phys. B **236**, 438 (1984); J. A. Casas and S. Dimopoulos, Phys. Lett. B **387**, 107 (1996) [hep-ph/9606237].

Enhanced Scenarios

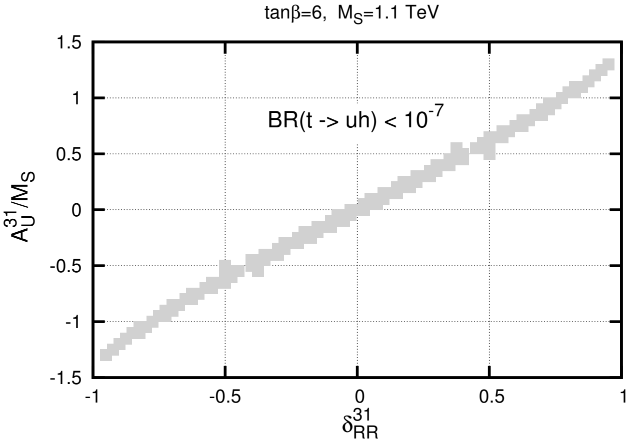
3. Combination of couplings, δ^{32}_{LR}, δ^{32}_{RR}



Nowhere $\mathcal{B}(t \to c\,h)$ bigger than 10^{-4} !

Enhanced Scenarios

4. Combination of couplings, $\delta^{31}_{\mathbf{LR}}$, $\delta^{31}_{\mathbf{RR}}$



nEDM constraint very important here even for real A_U^{31}

Summary for MSSM predicted $\mathcal{B}(t \to q\, h)$: *too small to be observed at LHC, usually in the ballpark of less than* 10^{-7}.

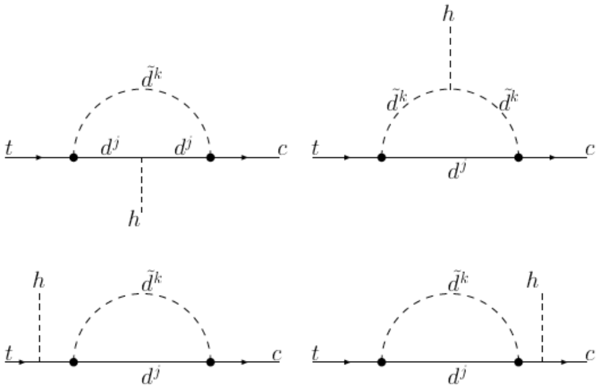
This is still, however, seven orders of magnitude bigger than the SM prediction.

Is there a planned machine that is able to reach this level? FCC, ILC, VLHC...?

... maybe a clever idea about the 'signature' needed...

Outline

R-Parity Violating SUSY



New interactions (B- and L-violating) but not enough to enhance $\mathcal{B}(t \to q\, h)$ above 10^{-5}.[9]

[9] G. Eilam, A. Gemintern, T. Han, J. M. Yang and X. Zhang, Phys. Lett. B **510**, 227 (2001) hep-ph/0102037.

Outline

General 2HDM

$$\mathcal{L}_{\rm SM} \supseteq - Y_u^{ij}\, \overline{Q}_L^i \cdot (H_u)\, u_R^j - Y_d^{ij}\, \overline{Q}_L^i \cdot (H_d)\, d_R^j$$

$$- G_u^{ij}\, \epsilon^{ab}\, \overline{Q}_{L\,a}^i\, (H_d)_b^\dagger\, u_R^j - G_d^{ij}\, \epsilon^{ab}\, \overline{Q}_{L\,a}^i\, (H_u)_b^\dagger\, d_R^j + \text{h.c.}$$

There are not enough chiral transformations to make $G_{u,d}^{ij}$ diagonal. Tree level flavour changing *tqh* couplings will appear.[10]

[10] For a nice review see, J. A. Aguilar-Saavedra, Acta Phys. Polon. B **35**, 2695 (2004) [hep-ph/0409342].

Multi-Higgs Doublet Models

If there are 3 fermion generations, why not 3 Higgs-Doublet generations?

In this case[11], a particular ansatz for tree level Yukawa couplings suggests that:

$$C_{L,R} = \frac{\sqrt{m_q m_t}}{m_W} \approx 0.09$$

which almost saturates the current LHC bound!

However, many couplings are highly constrained by low-energy meson experiments ($D\bar{D}$-mixing for example) to be small. It seems strange that only tqh aren't...

[11] T. P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987).

Conclusions

1. $\mathcal{B}(t \to q\,h)$ is unobservably small in the SM
2. $\mathcal{B}(t \to q\,h) \lesssim 10^{-6}$ in general MSSM due to cancellations, CCBs and other constraints. Effects scale proportional to m_t^2/M_S^2 at best.

   Therefore if LHC sees $t \to q\,h$ this is physics beyond or other than MSSM
3. Multi-Higgs doublet models are candidates for large $\mathcal{B}(t \to q\,h) \approx 10^{-3}$, observable at LHC

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Thank you!