A Detailed Analysis of FCNC Decays of the Top Quark

Debjyoti Bardhan

Dept. of Theoretical Physics,
Tata Institute of Fundamental Research,
Mumbai, India

Collaboration: DB, G. Bhattacharyya, D. Ghosh, M. Patra, S. Raychaudhuri

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Introduction to Top Decays

- The top quark decays before hadronisation due to its very large mass
- The decay thus doesn't involve non-perturbative processes such as parton showering
- Dominant decay mode: $\boldsymbol{t} \rightarrow \boldsymbol{b}\,\boldsymbol{W}$ (almost 100% BR)
- Flavour Changing Neutral Current (FCNC) decays – rare decays like $\boldsymbol{t} \rightarrow \boldsymbol{c}\,\boldsymbol{h}$
- Consider the indirect contributions of BSM particles through loop diagrams
- Won't be considering any flavour changing couplings for Higgs

LHC Reach

- CMS Collaboration places a 95% CL using Run-I data

$$\boldsymbol{BR(t \to ch) < 5.6 \times 10^{-3}}$$

$$\boldsymbol{BR(t \to cZ) < 5.0 \times 10^{-4}}$$

- Can reach the exclusion limit (2-sigma) of (at 3000 fb^{-1} of 13 TeV data):

$$\boldsymbol{BR_{3ab^{-1}}(t \to ch) = 1.5 \times 10^{-4}}$$

$$\boldsymbol{BR_{3ab^{-1}}(t \to cZ) = 7.0 \times 10^{-5}}$$

- Optimistic limit : $\boldsymbol{BR_{3ab^{-1}}(t \to ch) \sim 10^{-5}}$

Outline

- Standard Model Process
- Analysis using a toy model
- Process in cMSSM
- Process in RPV SUSY

Calculating Top FCNC Decay

$$\boldsymbol{t(p) \rightarrow c(p+k) + h(-k)}$$

$$\textbf{Scalar}: \boldsymbol{iM = \bar{c}(p+k)\, i\Gamma\, t(p)}$$

- Calculated the process $t \rightarrow c\ h$ with generic couplings in the Feynman gauge. Form factors have been used:

- Contribution to effective vertex of the nth diagram is:

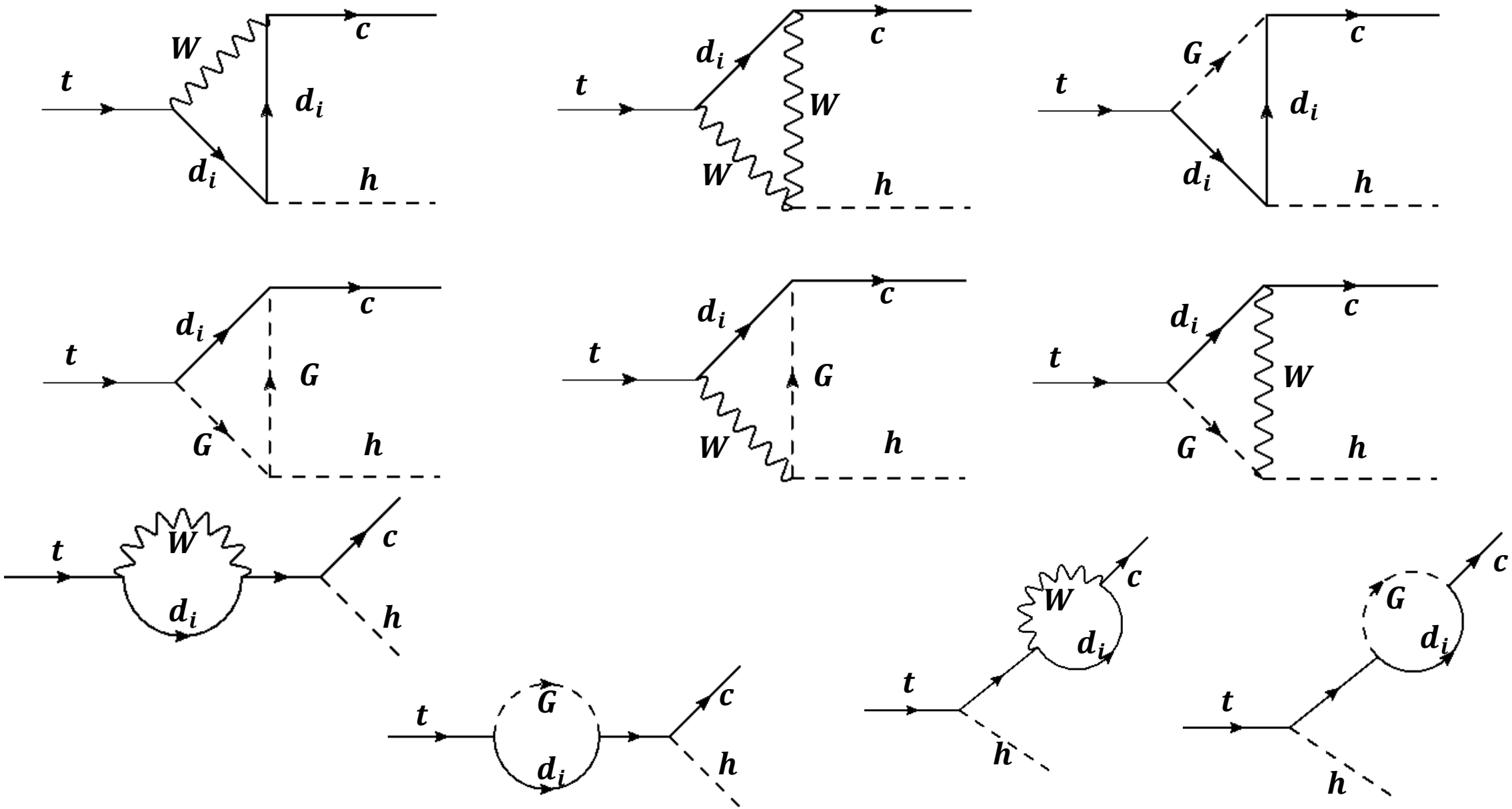
$$\boxed{i\,\Gamma_n = \frac{ig^3}{16\pi^2}\sum_{i=1}^{3}\lambda_i\left(F_{1i}^{(n)}P_L + F_{2i}^{(n)}P_R\right)}$$

$$\Gamma = \sum_n \Gamma_n$$

- GIM suppression comes from the factor:

$$\boldsymbol{\lambda_i = V_{ci}V_{ti}^*}$$

Feynman Diagrams in the SM



Result (in the SM)

In the SM

$$BR(t \to ch) \sim 10^{-15}$$

No way of seeing a SM signal

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Sources of Suppression

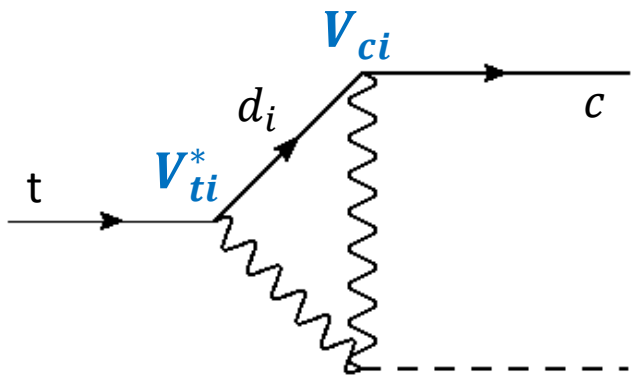
1. GIM Cancellation

2. MFV structure of the quark sector

3. Low value of the coupling constant

GIM Suppression

- First proposed by Glashow, Iliopoulos and Miani to explain the suppression of the FCNC decay amplitudes seen in $\Delta S = 2$ decays



- Led to the prediction of the *charm* quark

- Directly related to the unitarity of the CKM matrix

- Unitarity Condition: $$\sum_i \lambda_i = \sum_i V_{ti}^* V_{ci} = 0$$

$$\lambda_i = V_{ti}^* V_{ci}$$

- The FCNC amplitude is of the form

$$\mathcal{A} = C \left[\sum_i \lambda_i \, A(x_i) \right]$$

$$x_i = \left(\frac{m_i}{M_W} \right)^2$$

GIM Suppression

- Taylor expand the amplitude in $x_i's$ since they are small numbers

$$\boldsymbol{A(x_i) = A(0) + x_i A'(0) + \ldots}$$

- Put this back:

$$\left[\sum_i \lambda_i\, A(x_i)\right] = A(0) \overset{0}{\cancel{\sum_i \lambda_i}} + A'(0) \sum_i \lambda_i \boldsymbol{x_i}$$

Unitarity of CKM

- Thus the leading amplitude is proportional to $x_i\ 's$

Avoiding GIM Suppression

- If FC coupling depends on the mass, we can violate GIM

$$\left[\sum_i \lambda_i\, \boldsymbol{m_i} A(x_i)\right] = A(0) \sum_i \lambda_i\, \boldsymbol{m_i} + A'(0) \sum_i \lambda_i \boldsymbol{m_i} x_i$$

MFV structure of the Quark sector

- **MFV hypothesis:** Yukawas are the only source of flavour violation in the SM and in any BSM models

R.S. Chivukula, H. Georgi, Phys. Lett. B 188, 99 (1987)

- Yukawas might have a high energy dynamical origin

Implications:

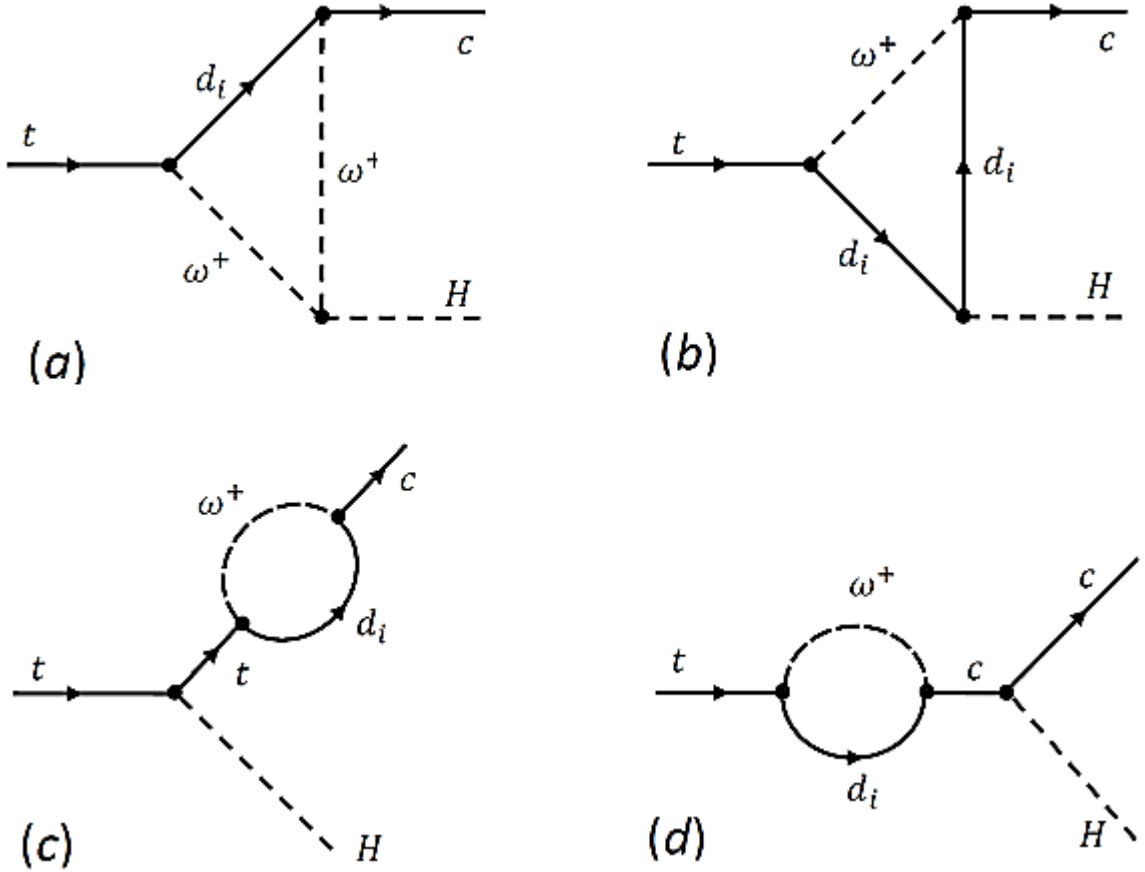
- SM flavour structure is all that there is
- Produces additional suppression for NP flavour transitions
- Inherits the hierarchical nature of the CKM matrix

$$CKM \approx \begin{pmatrix} 1 & \lambda & A\lambda^3 \\ -\lambda & 1 & A\,\lambda^2 \\ A\lambda^3 & -A\lambda^2 & 1 \end{pmatrix} \approx \begin{pmatrix} 1 & 0.2 & 0.003 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

Toy Model

- Introduce a charged scalar – a scalar version of the W- boson

$$\mathcal{L}_{int} = \xi\, \omega^+\omega^-\, h \; + \sum_{i,j=1}^{3} \eta\, V_{ij}\, \bar{u}_i P_L d_j\, \omega^+ + h.c.$$



Toy Model

- Used helicity amplitude techniques to calculate the Branching Ratios
- Amplitudes for each helicity combination of top, charm: $A_i(h_c\ , h_t)$
- Only two combinations non-zero: $\boldsymbol{A_i}(+\ ,+)$; $\boldsymbol{A_i}(-,-)$

"SM Like" amplitudes

$$\mathcal{A} = \sum_i \lambda_i\ A\ (\ m_i, X) \qquad \lambda_i = V_{ti}^*\ V_{ci}$$

Suppression Mechanisms

Break GIM

$$\mathcal{M} = \sum_i \lambda_i \, \mathcal{A}_i \, (m_i, X) \quad \times \left(\frac{m_i}{m_b}\right)^2 \qquad m_i = (m_d, m_s, m_b)$$

GIM Relaxation:

Gives us an enhancement of $\sim \left[\left(\frac{m_b}{M_\omega}\right)^2\right]^{-1} \approx \mathbf{10^2 - 10^4}$ $\qquad M_\omega \sim M_W = 80.4$ GeV

Go beyond MFV

$$V'_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & cos\theta \end{pmatrix} \qquad \text{For } \theta = \frac{\pi}{4}; \;\; \lambda_3 = \left(0, \; -\frac{1}{2}, \frac{1}{2}\right)$$

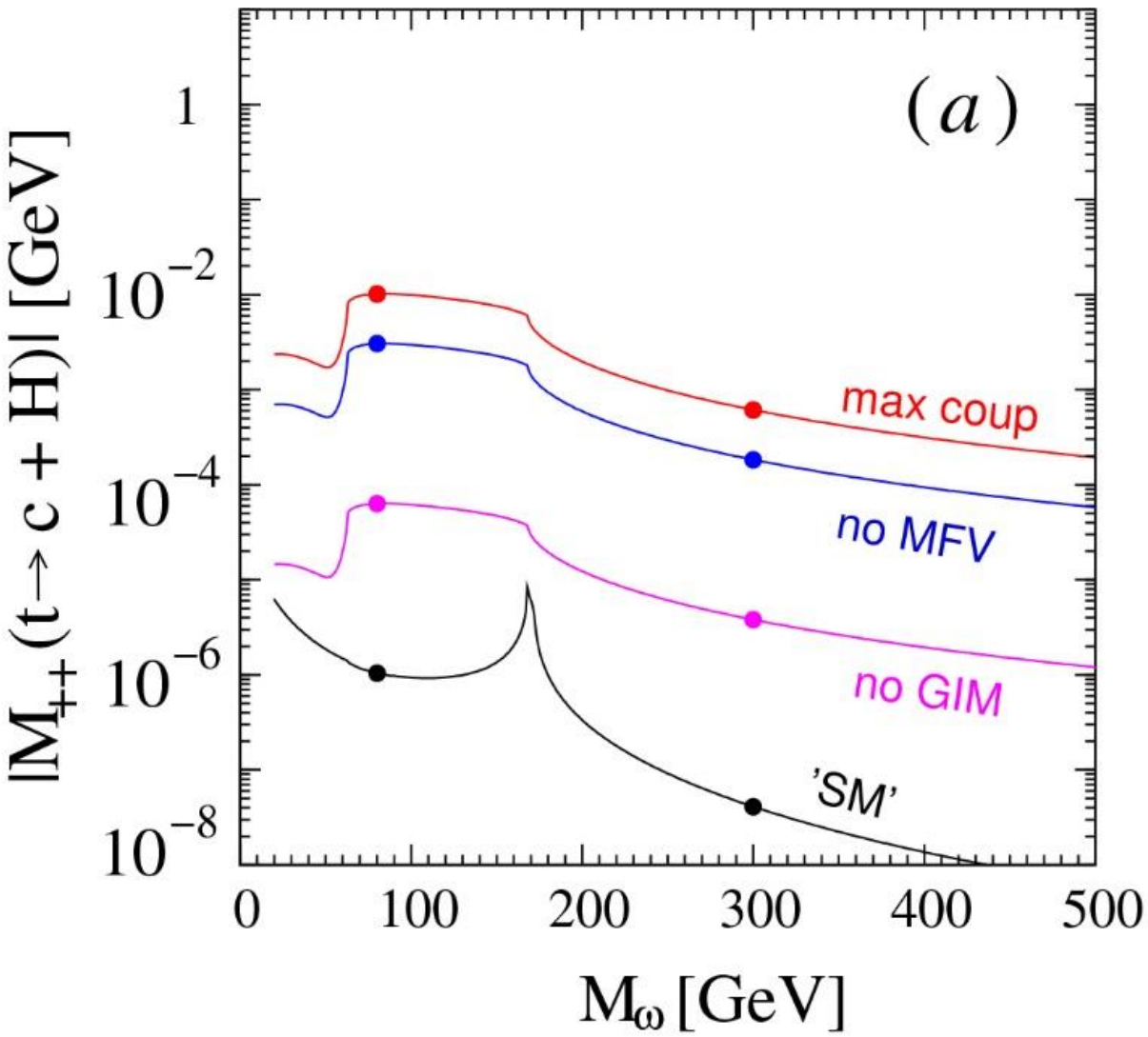
Departure from MFV:

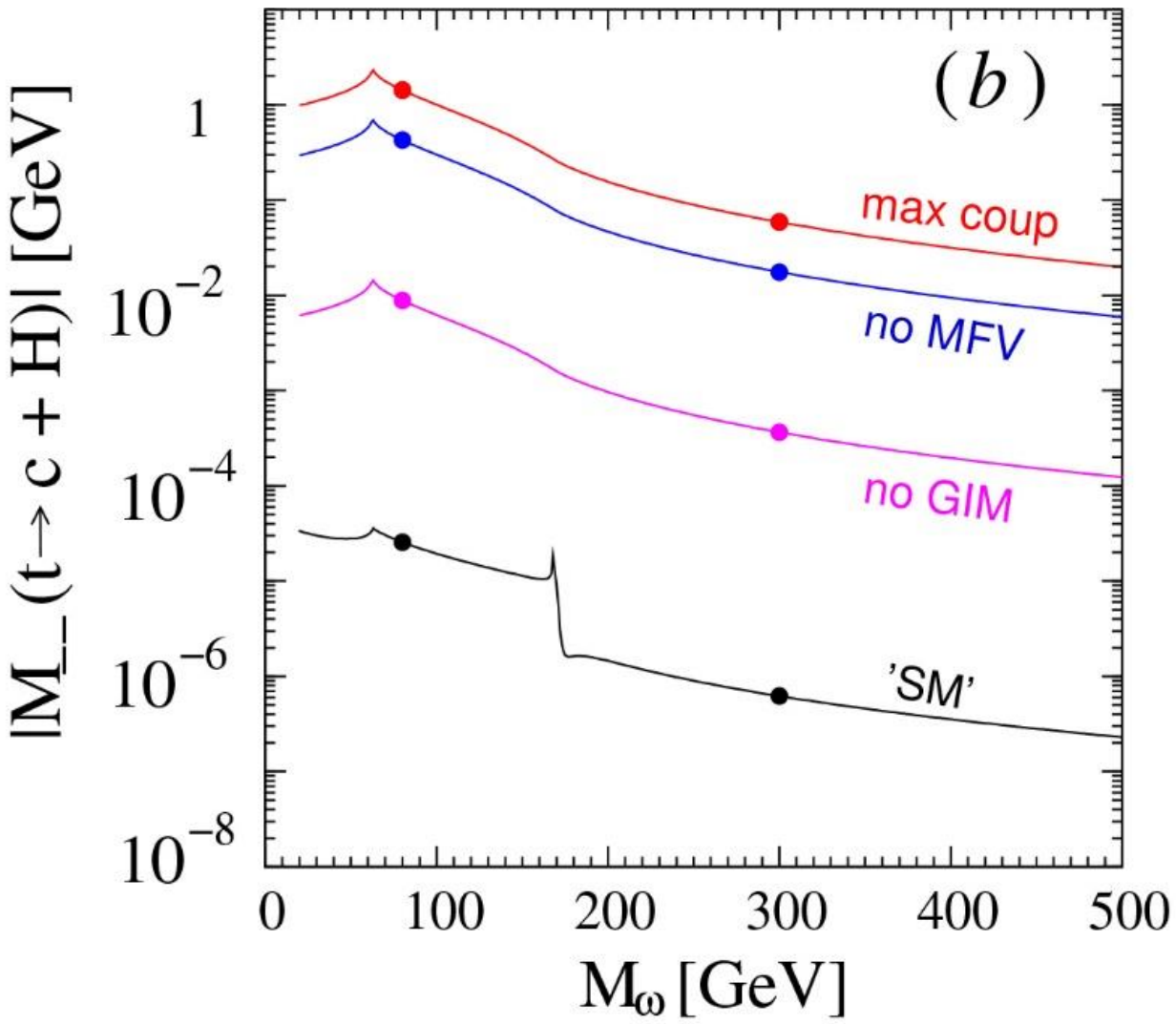
Gives us an enhancement of **1 order** of magnitude

Maximize coupling

Increase Coupling Constant **Factor of 3 - 5**

Toy Model Amplitudes for $t \to ch$





Top Rare Decays in the cMSSM

Introduction to cMSSM

- The simplest version of the MSSM
- cMSSM contains 5 free parameters – m_0, $m_{1/2}$, A_0, $\tan\beta$, $sgn(\mu)$
- GIM would be broken by the charged Higgs
- MFV structure retained
- Couplings similar to those of the SM particles, scaled by factors like $\tan\beta$

Top Rare Decays in the cMSSM

Parameter Space - Constraints

- **Theory Constraints**
  - Issues like vacuum stability, proper LSP etc.
- **Higgs Mass constraint**
  - light Higgs mass taken between 124 to 127 GeV (2σ interval)
  - Constraints m_0 values ⇒ charged Higgs mass is large
- **Direct mass constraints**
  - Latest results by ATLAS
  - $m_{\tilde{g}} \geq 1.7\ TeV\ ; m_{\tilde{q}} \geq 1000\ GeV; m_{\tilde{t}}(b\chi^{+}) > 380\ GeV$
- **Flavour Physics constraints**
  - FCNC processes involving *b*-quark are also GIM-violating
  - $B \to K^{*}\gamma$ and $B_s \to \mu^{+}\mu^{-}$ are measured very close to SM
  - Although, we don't take the anomalies like R_D, R_{D^*} and $B \to D^{*}\tau\nu$

LHCb: 1211.2674;
Belle: 1208.4678

Top Rare Decays in the cMSSM

Parameter Space - Constraints

Black – ruled out by 'theory constraints':

- Shape of the EW potential
- LSP is DM candidate – not coloured or charged

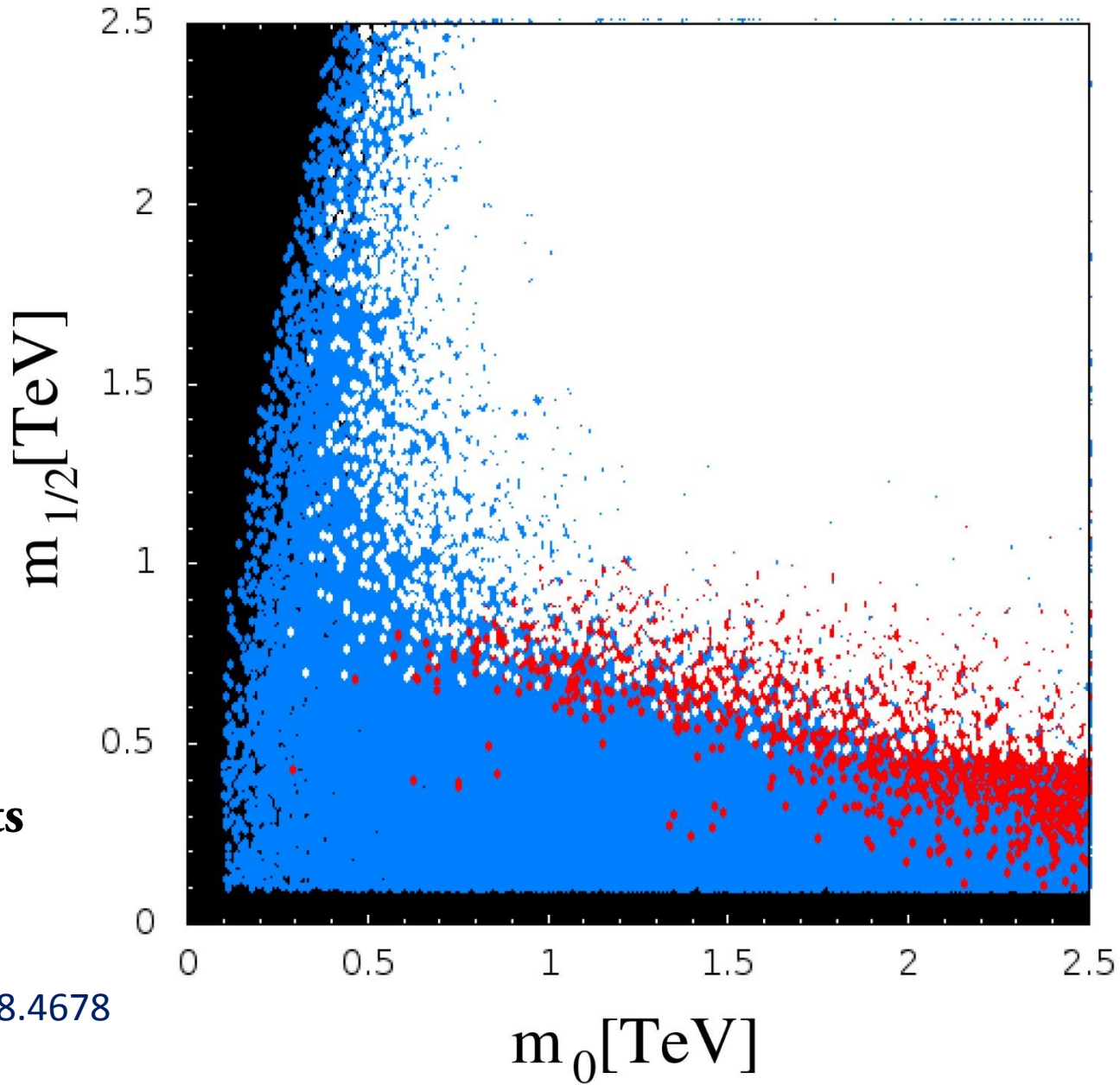
Blue – ruled out by mass constraints

- Higgs mass: $124 \leq m_H \leq 127$
- Direct searches bounds for sparticle masses

Red – ruled out by Flavour Physics constraints

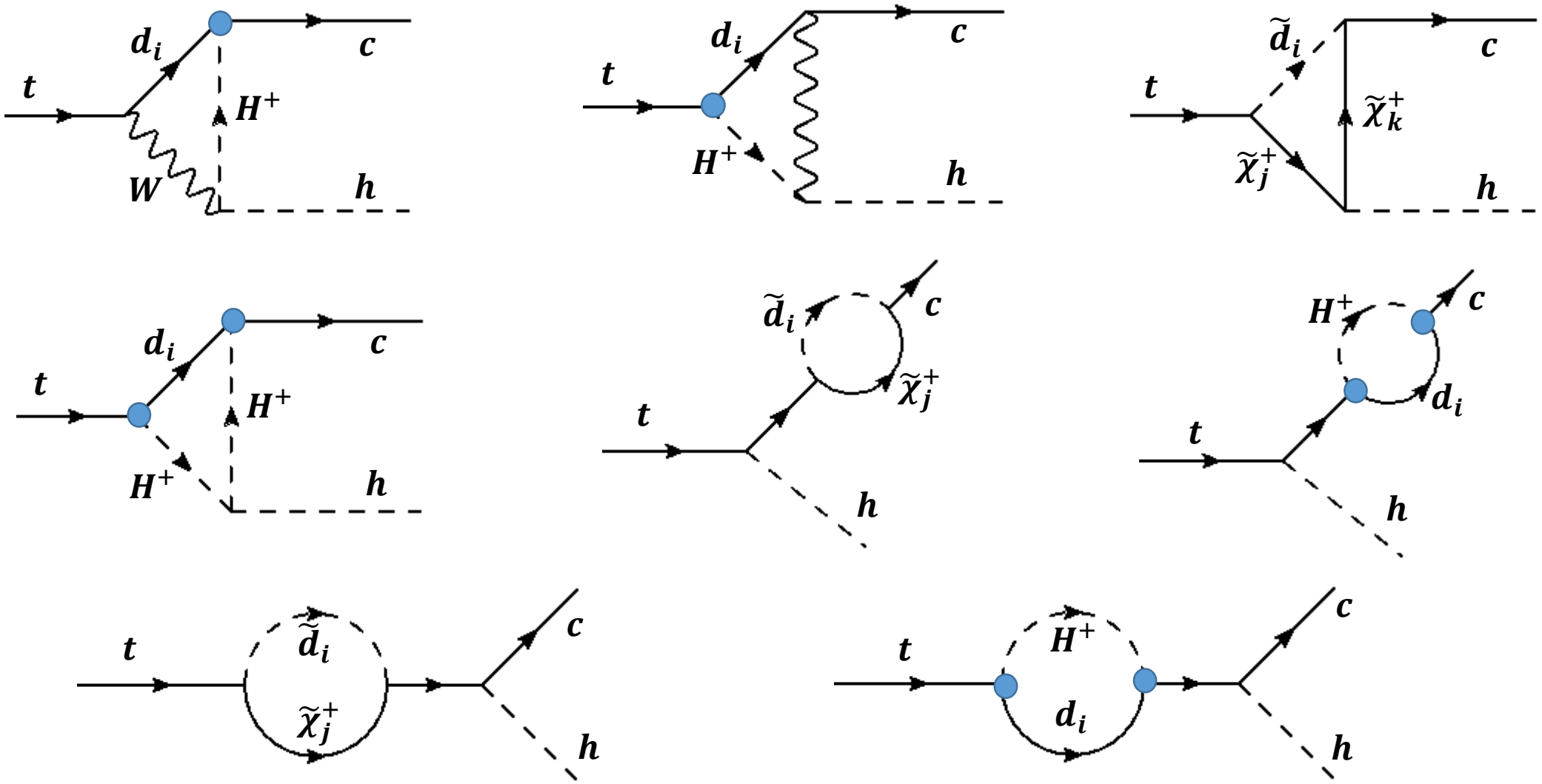
- b-quark physics; FCNC processes
- $B \to K^*\gamma$ and $B \to \mu^+\mu^-$ are almost SM-like

LHCb: 1211.2674; Belle: 1208.4678



SUSY Contributions

- Additional diagrams with (a) charged Higgs bosons (b) charginos (c) d-squarks



Top Rare Decays in the cMSSM

Blue – Mass forbidden:

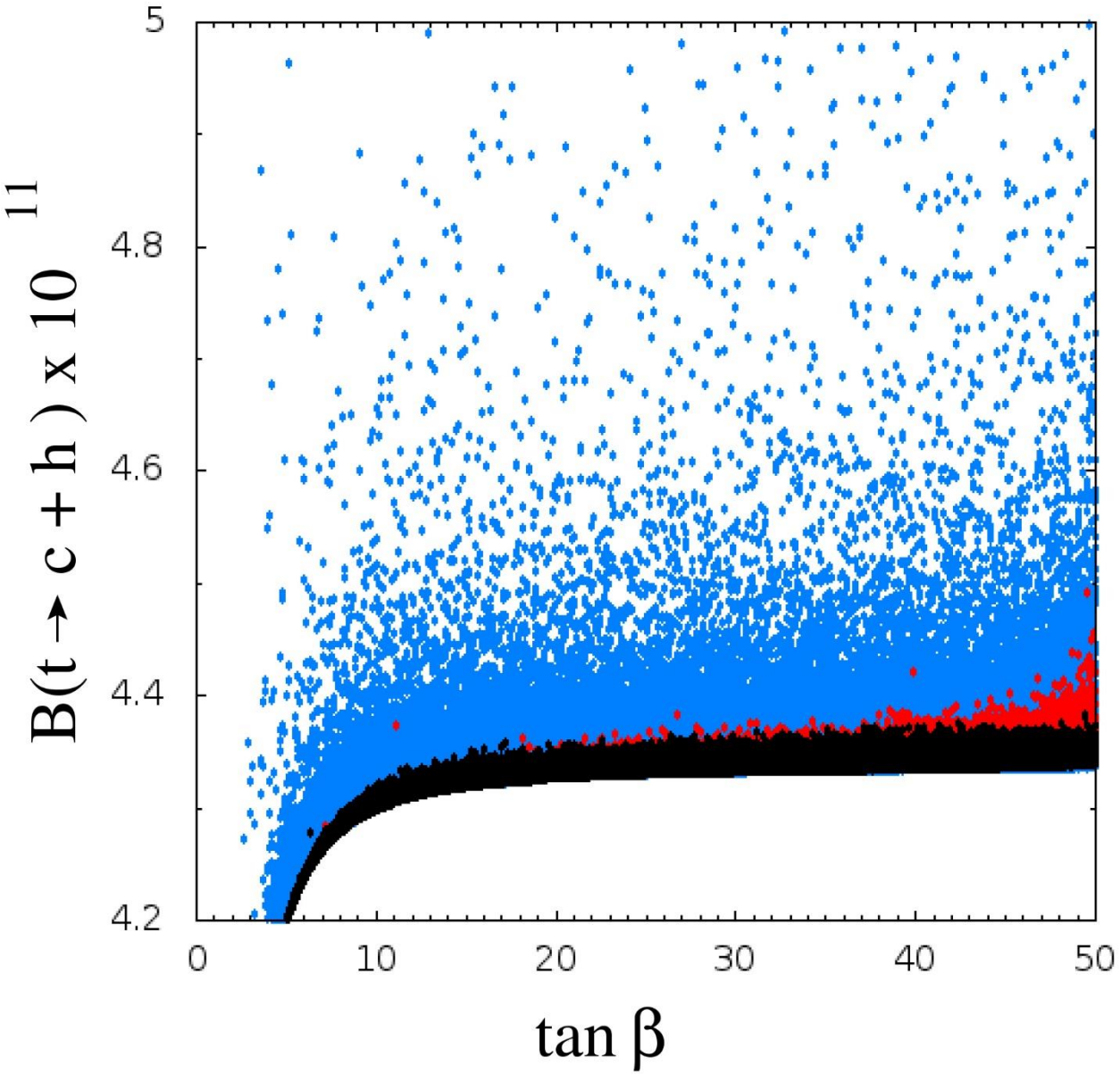
- Higgs and sparticle mass disallowed

Red – Flavour forbidden:

- Ruled out by flavour data

Black – Allowed points:

- Gives us a *tiny* branching ratio



R-parity Violating SUSY

- R-parity is a $\mathbb{Z}_2$ symmetry which differentiates between SM and SUSY particles

$$\boldsymbol{R = (-1)^{2s+3B+L}}$$

- SUSY particles are odd and SM particles are even under R-parity: R-parity conservation gives a viable dark matter candidate, the LSP

- R-parity violating SUSY superpotential -

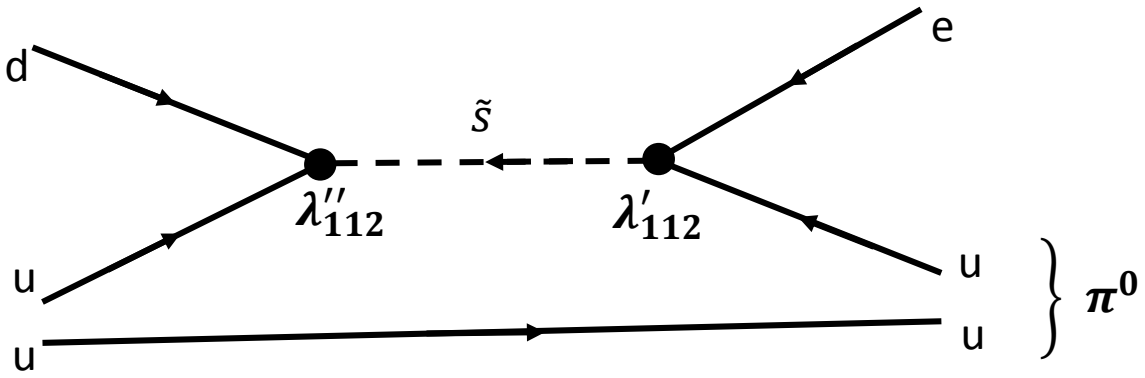
$$\boldsymbol{W_{RPV} = \mu_i \widehat{H}_u \widehat{L}_i + \frac{1}{2}\lambda_{ijk}\widehat{L}_i\widehat{L}_j\widehat{E}_k^c + \lambda'_{ijk}\widehat{L}_i\widehat{Q}_j\widehat{D}_k^c + \frac{1}{2}\lambda''_{ijk}\widehat{U}_i^c\widehat{D}_j^c\widehat{D}_k^c}$$

- LQD - Lagrangian

$$\boldsymbol{\mathcal{L}_{LQD} = -\lambda'_{ijk}\left(\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iR}d_{jL} - (\nu_L \to l_L, d_L \to u_L)\right) + h.c.}$$

RPV-SUSY Couplings

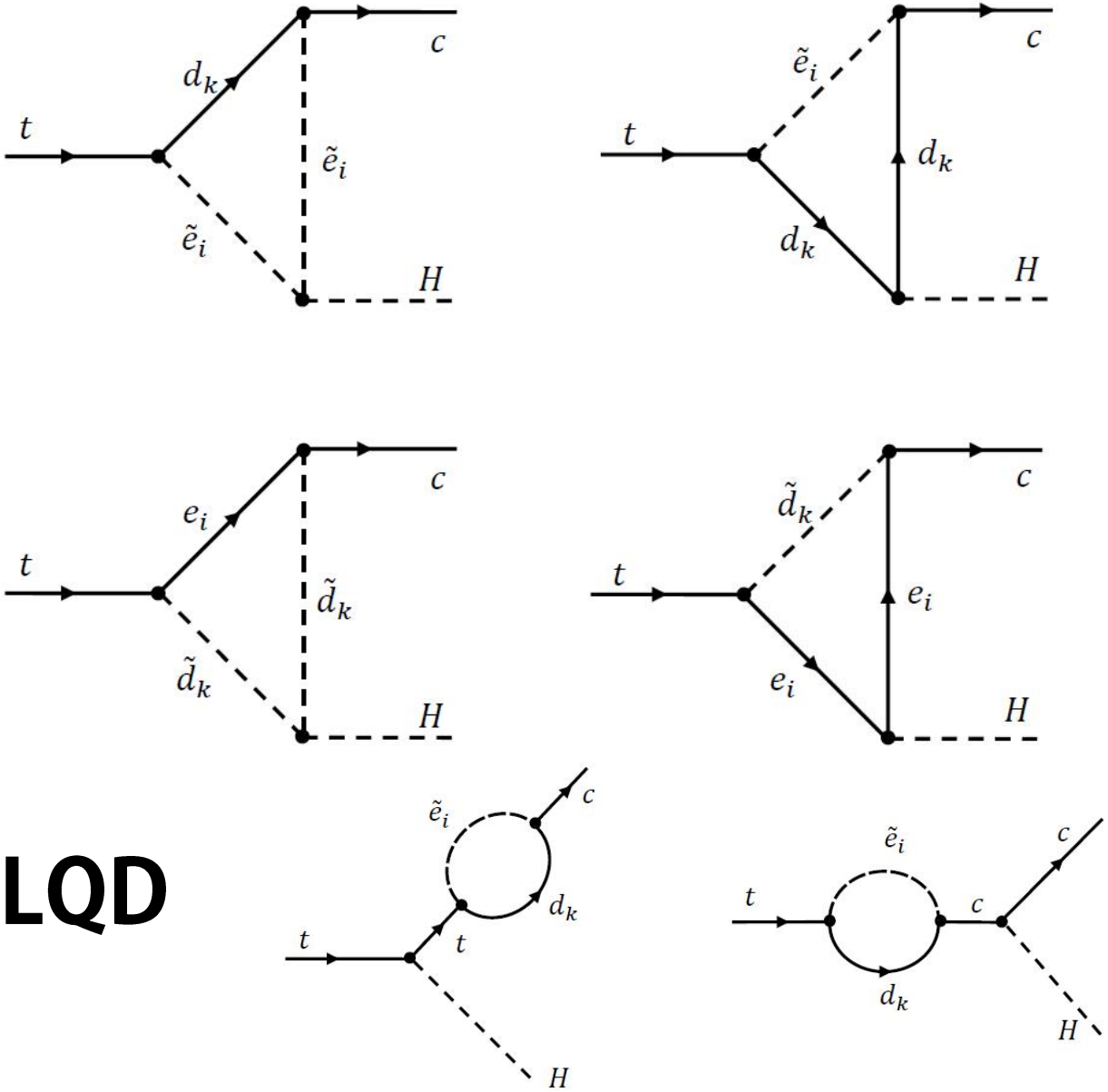
- Having both λ' and λ'' terms leads to proton decay – severely constrained (10^{33} yrs)



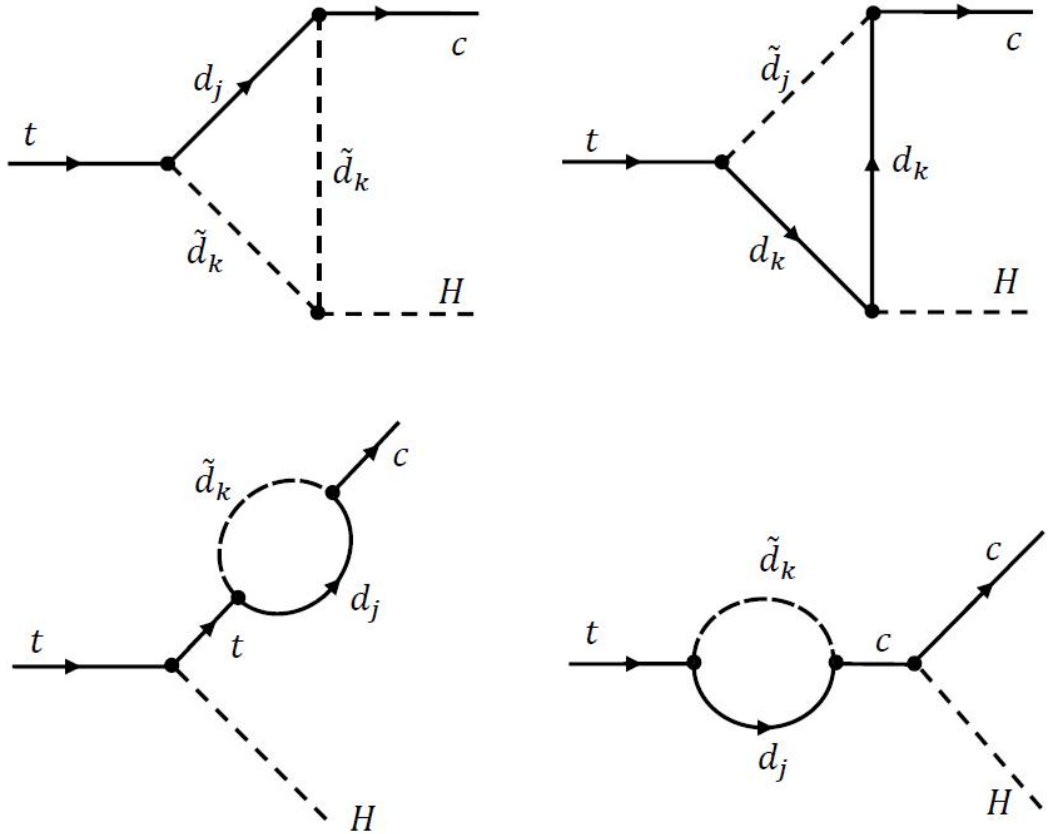
- Have either λ' or λ'', but not both – either L- violating or B- violating

- Our process: require couplings of the form: $\lambda'_{i2k}\lambda'_{i3k}$ (LQD) or $\lambda''_{2jk}\lambda''_{3jk}$ (UDD)

RPV SUSY Contributions



LQD



UDD

RPV SUSY Results

Current Bounds (with 20 fb^{-1})

- $B(t \to cH) < 5.6 \times 10^{-3}$

  CMS PAS-Hig-13-034

- $B(t \to cZ) < 5.0 \times 10^{-4}$

  PRL 112 (2014) 171802

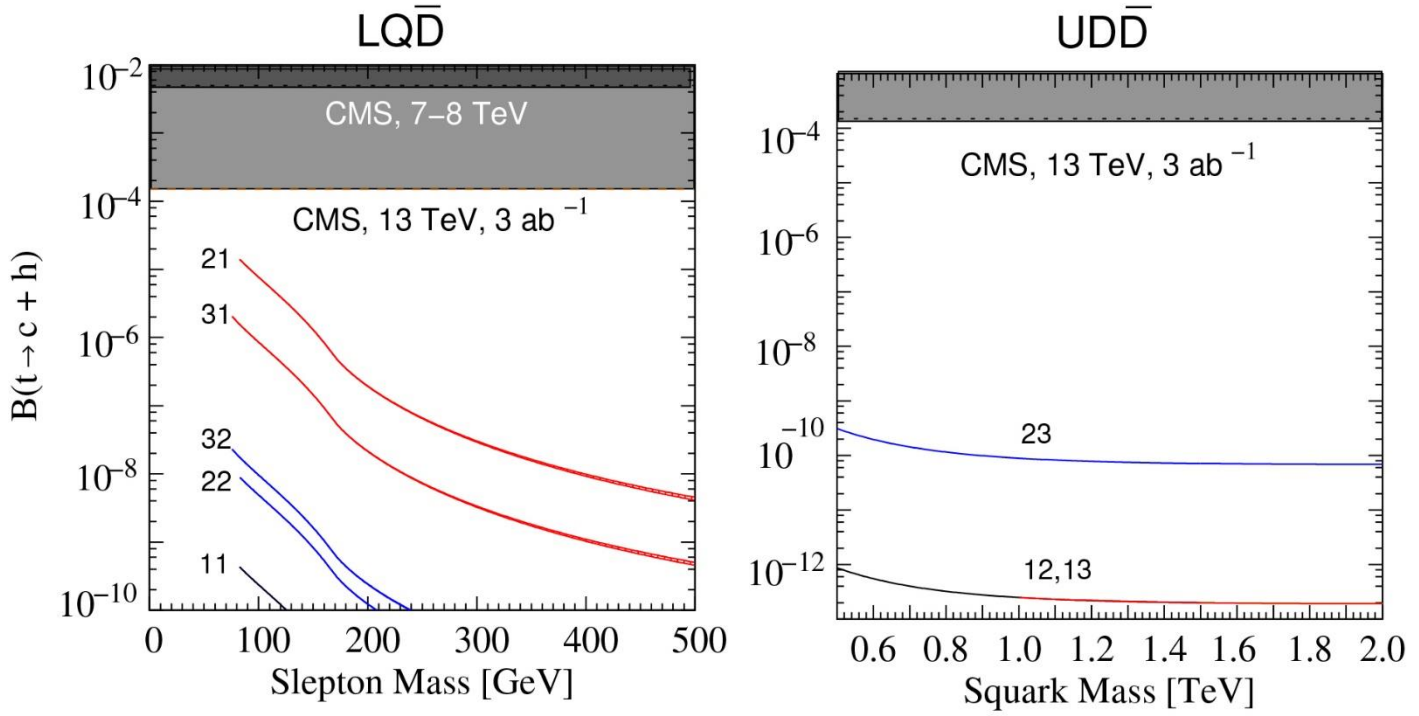
Projections (with 3000 fb^{-1})

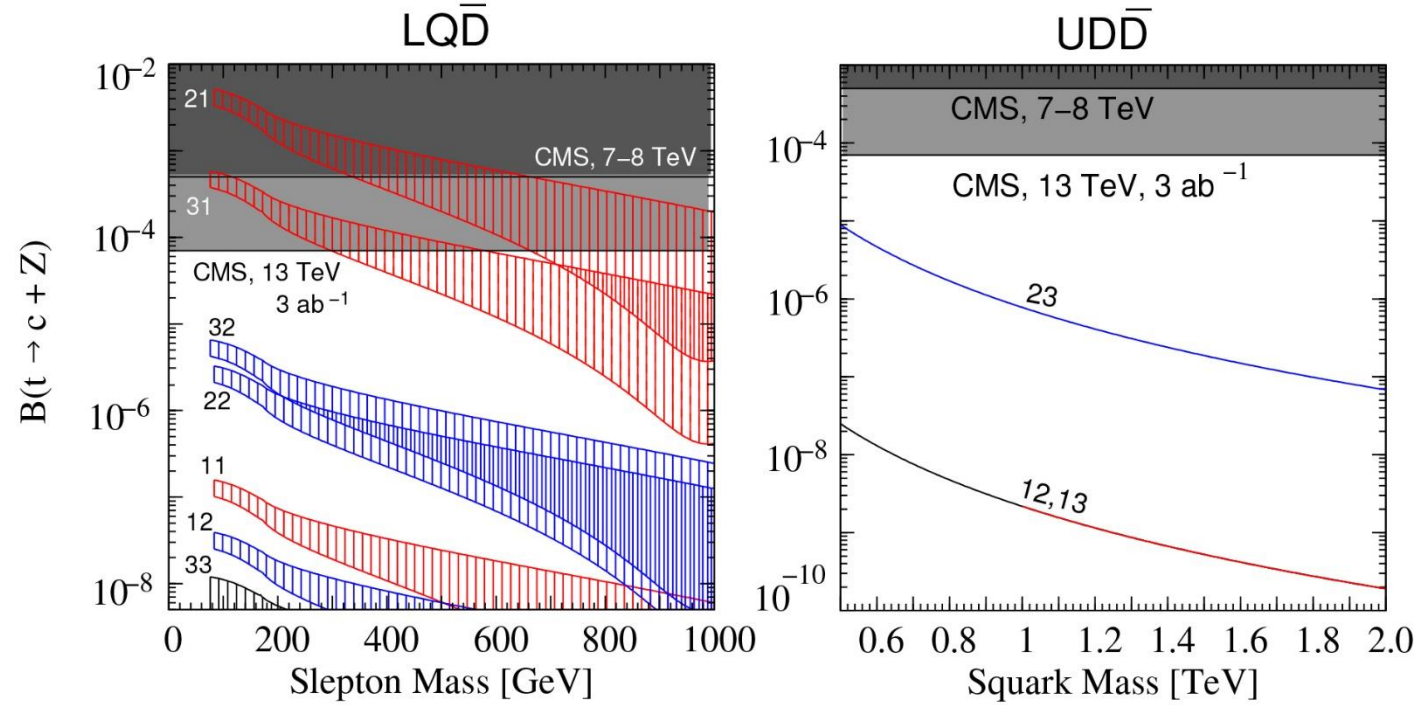
- $B(t \to cH) < 1.5 \times 10^{-4}$

  ATL-PHYS-PUB-2013-012

- $B(t \to cZ) < 7.0 \times 10^{-5}$

  hep-ex/1311.2028





Conclusion and Summary

- Studied the different suppression mechanisms and possible enhancement factors for $t \to ch$ using a toy model

- Collider reach $\mathrm{BR} \sim 10^{-5}$

- Impossible to probe in SM or cMSSM framework

- Might be observable in RPV-SUSY scenarios the near future

Conclusion and Summary

- Studied the different suppression mechanisms and possible enhancement factors for $t \to ch$ using a toy model

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Thank You!

BACKUP SLIDES

MFV structure of the Quark sector

- Total SM fermion flavour structure

$$G_f = \boldsymbol{SU(3)_q} \otimes \boldsymbol{SU(3)_U} \otimes \boldsymbol{SU(3)_D} \quad \otimes SU(3)_l \otimes SU(3)_E$$

- Introduce spurions like Yukawa fields to break G_f^Q

$$Y_u \sim (3, \bar{3}, 1); \qquad Y_d \sim (3, 1, \bar{3})$$

$$\mathcal{L} = \bar{Q} Y_d D \phi + \bar{Q} Y_u U \tilde{\phi} + h.c.$$ ← Invariant under G_f

- Source of Yukawa fields – some high energy dynamics

- Dim-5 terms in EFT

Passarino Veltman Integrals

- Algorithm provided by Passarino and Veltman

G.Passarino and M.J.G. Veltman, Nucl. Phys. B 160, 151 (1979)

$$B_0(m_1, m_2; M) = \int \frac{d^4k}{\pi^2} \frac{1}{(k^2 + m_1^2)((k+p)^2 + m_2^2)}$$

$$p_\mu B_1(m_1, m_2; M) = \int \frac{d^4k}{\pi^2} \frac{k_\mu}{(k^2 + m_1^2)((k+p)^2 + m_2^2)}$$

$$p^2 = -M^2$$

$$C_0(m_1, m_2, m_3; M_1, M_2, M_3) = \int \frac{d^4k}{\pi^2} \frac{1}{(k^2 + m_1^2)((k+p_2)^2 + m_2^2)((k+p_2+p_3)^2 + m_3^2)}$$

$$C_{11} p_{2\mu} + C_{12} p_{3\mu} = \int \frac{d^4k}{\pi^2} \frac{k_\mu}{(k^2 + m_1^2)((k+p_2)^2 + m_2^2)((k+p_2+p_3)^2 + m_3^2)}$$

$$p_i^2 = -M_i^2$$

RPV Couplings

	Strongest Constraint arises from	Scales as mass of	Scaling Exponent	Upper bound (100 GeV)	Sfermion mass (GeV)	Current upper bound
λ'_{121}	CC Universality [67]	$\tilde{q}_L$	1	0.035	1350 [52]	0.385
λ'_{122}	ν_e mass bound [53]	$\tilde{d}_R$	$^1/_2$	0.004	1100 [25]	0.013
λ'_{123}	CC Universality [46]	$\tilde{b}_1$	$^1/_2$	0.02	620 [54]	0.05
λ'_{131}	Atomic parity violation [67]	$\tilde{t}_L$	1	0.019	300 [55]	0.057
λ'_{132}	FB asymmetry (e^+e^-) [67] [45]	$\tilde{t}_L$	1	0.28	300 [55]	0.84
λ'_{133}	ν_e mass bound [53]	$\tilde{b}_1$	$^1/_2$	0.0002	620 [54]	0.0005
λ'_{221}	Bounds on $R_{\mu e}$ [56]	$\tilde{d}_R$	1	0.18	1100 [25]	1.98
λ'_{222}	ν_μ mass bound [53]	$\tilde{d}_R$	$^1/_2$	0.015	1100 [25]	0.05
λ'_{223}	D_s meson decay [56]	$\tilde{b}_1$	1	0.18	620 [54]	1.1
λ'_{231}	ν_μ DIS [45,46]	$\tilde{\nu}_\tau$	1	0.22	1700 [57]	2.00
λ'_{232}	Bounds on $R_\mu(Z)$ [58,59]	$\tilde{s}$	1	0.39	1000 [25]	2.00
		$\tilde{\mu}$	-1		100 [25]	
λ'_{233}	ν_μ mass bound [53]	$\tilde{d}_R$	$^1/_2$	0.001	1100 [25]	0.003
λ'_{321}	D_s decays [45]	$\tilde{d}_R$	1	0.52	1100 [25]	0.66
λ'_{322}	ν_τ mass bound [53]	$\tilde{d}_R$	$^1/_2$	0.02	1100 [25]	0.07
λ'_{323}	D_s decay [45]	$\tilde{b}_1$	1	0.52	620 [54]	2.00
λ'_{331}	Bounds on $R_\tau(Z)$ [58]	$\tilde{d}$	1,	0.22	1000 [25]	2.00
λ'_{332}		$\tilde{\tau}$	-1	0.22	100 [25]	2.00
λ'_{333}	ν_τ mass bound [53]	$\tilde{b}_1$	$^1/_2$	0.001	620 [54]	0.003

$\lambda'_{121}\lambda'_{131}$	$\lambda'_{122}\lambda'_{132}$	$\lambda'_{123}\lambda'_{133}$	$\lambda'_{221}\lambda'_{231}$	$\lambda'_{222}\lambda'_{232}$	$\lambda'_{223}\lambda'_{233}$
0.0219	0.0109	2.5×10^{-5}	3.96	0.1	0.0033
$\tilde{e}_L$, $\tilde{d}_R$	$\tilde{e}_L$, $\tilde{s}_R$	$\tilde{e}_L$, $\tilde{b}_R$	$\tilde{\mu}_L$, $\tilde{d}_R$	$\tilde{\mu}_L$, $\tilde{s}_R$	$\tilde{\mu}_L$, $\tilde{b}_R$

$\lambda'_{321}\lambda'_{331}$	$\lambda'_{322}\lambda'_{332}$	$\lambda'_{323}\lambda'_{333}$	$\lambda''_{212}\lambda''_{312}$	$\lambda''_{213}\lambda''_{313}$	$\lambda''_{223}\lambda''_{323}$
1.32	0.14	0.006	0.124	0.124	2.3436
$\tilde{\tau}_L$, $\tilde{d}_R$	$\tilde{\tau}_L$, $\tilde{s}_R$	$\tilde{\tau}_L$, $\tilde{b}_R$	$\tilde{s}_R$	$\tilde{b}_R$	$\tilde{b}_R$