FCNC Decays of the Top Quark

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Motivation

- New Physics could be anywhere

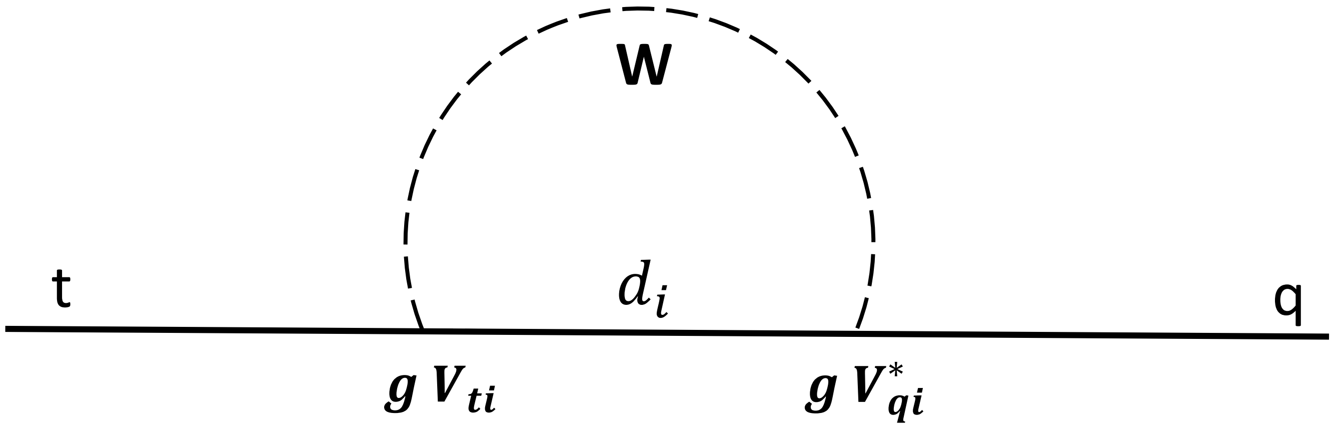
- Could discover particles
    - Resonant production: $p + p \to P \to X + Y$
    - Pair production: $p + p \to P + \bar{P} \to X + Y + \bar{X} + \bar{Y}$
    - Associated production: $p + p \to P + Z$
  - Fine print – Mass of new particle $\sim 2 - 2.5$ TeV

- Look at loop effects for contribution of new particles
  - Fine print – Small effect; can only be seen if SM contribution is small

Thus, Top FCNC Decays…

- Obvious candidate: FCNC processes and GIM suppression
- **Top Decay:** Dominant decay mode: $t \rightarrow b\, W$ (almost 100% BR)
- Flavour Changing Neutral Current (FCNC) decays – rare decays like $\boldsymbol{t \rightarrow c\, h}$
- **Bonus:** No hadronisation!
  - ➢ Large top mass
  - ➢ No non-perturbative processes like parton showering
- **Caveat:** Won’t be considering any flavour changing couplings for Higgs

Top FCNC Decays in the SM



$$\mathcal{M}_{tq} = \sum_{i=1}^{3} \lambda_i\, g^2\, \mathcal{A}(x_i, M_W) \qquad \lambda_i = V_{ti}V_{qi}^*;\;\; x_i = \frac{m_{d_i}^2}{M_W^2} \qquad \sum_{i=1}^{3} \lambda_i = 0$$

$$\mathcal{M}_{tq} = \sum_{i=1}^{3} \lambda_i\, g^2\, \left[\boldsymbol{\mathcal{A}(0, M_W)} + x_i \mathcal{A}'(0, M_W) + x_i^2 \mathcal{A}''(0, M_W) + \;\ldots\right]$$

GIM Mechanism

$$= g^2 \mathcal{A}(0, M_W) \sum_{i=1}^{3} \lambda_i \; + \boldsymbol{g^2 \mathcal{A}'(0, M_W) \sum_{i=1}^{3} \lambda_i x_i} + g^2 \mathcal{A}''(0, M_W) \sum_{i=1}^{3} \lambda_i x_i^2 + \;\ldots$$

0

$$\approx \boldsymbol{g^2 \mathcal{A}'(0, M_W)\, \lambda_b\, x_b} \qquad x_b = \left(\frac{3}{80}\right)^2 \approx 1.4 \times 10^{-3}$$

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

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

Top FCNC Decays in the SM

$$\Gamma \approx \left|g^2 \mathcal{A}'(0, M_W)\, V_{qb}^*\, x_b\right|^2 \approx m_t\, g^4 \left(\frac{1}{16\pi^2}\right)^2 \left|V_{qb}\right|^2 x_b^2$$

Coupling: 0.19

Loop: 4×10^{-5}

CKM: 1.6×10^{-3}

GIM: 2×10^{-6}

GIM Relaxation: Enhancement of $\sim \left[\left(\frac{m_b}{M_\omega}\right)^4\right]^{-1} \approx 10^6$

Non-MFV: Enhancement of $\approx 10^4$

Large Couplings: Enhancement of $\approx 10^2$

10^{12} **enhancement In the decay width**

Calculating Top FCNC Decay

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

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

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

- Contribution to effective vertex of the nth diagram is:

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

$$\Gamma = \sum_n \Gamma_n$$

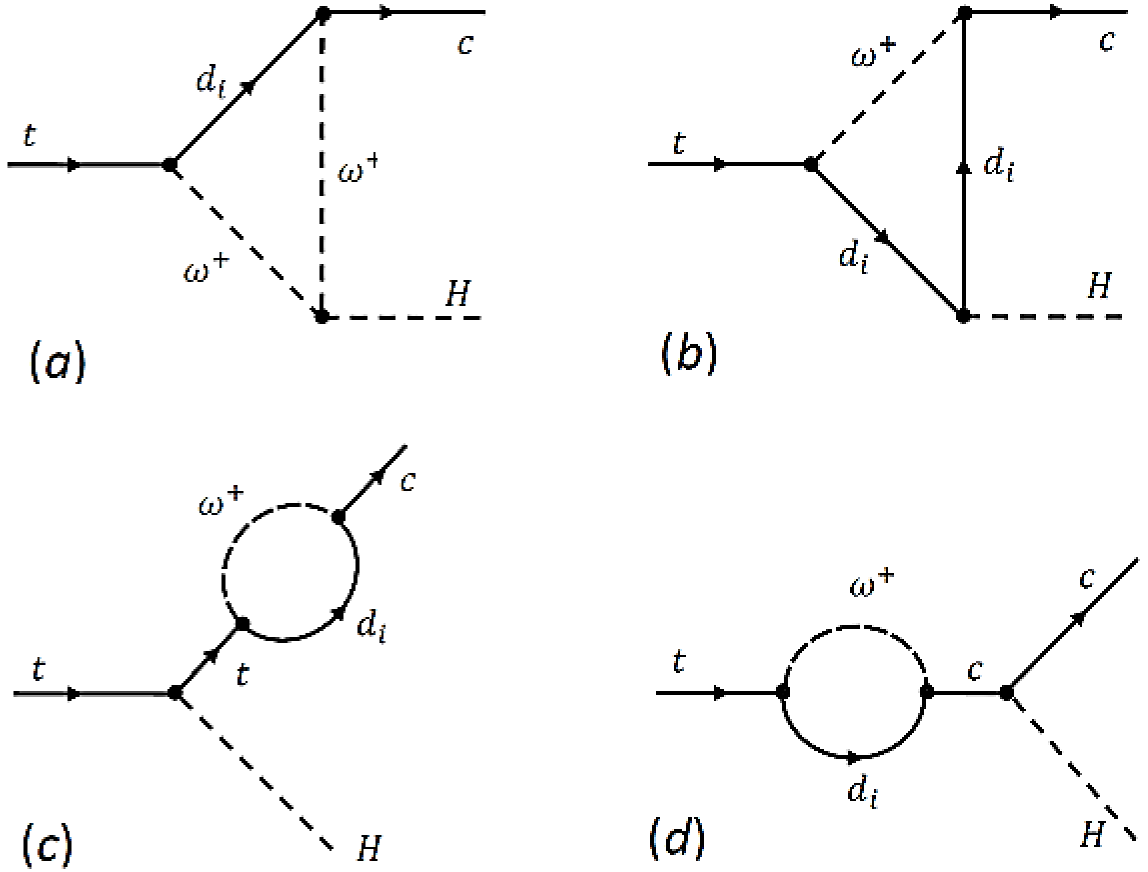
- GIM suppression comes from the factor:

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

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

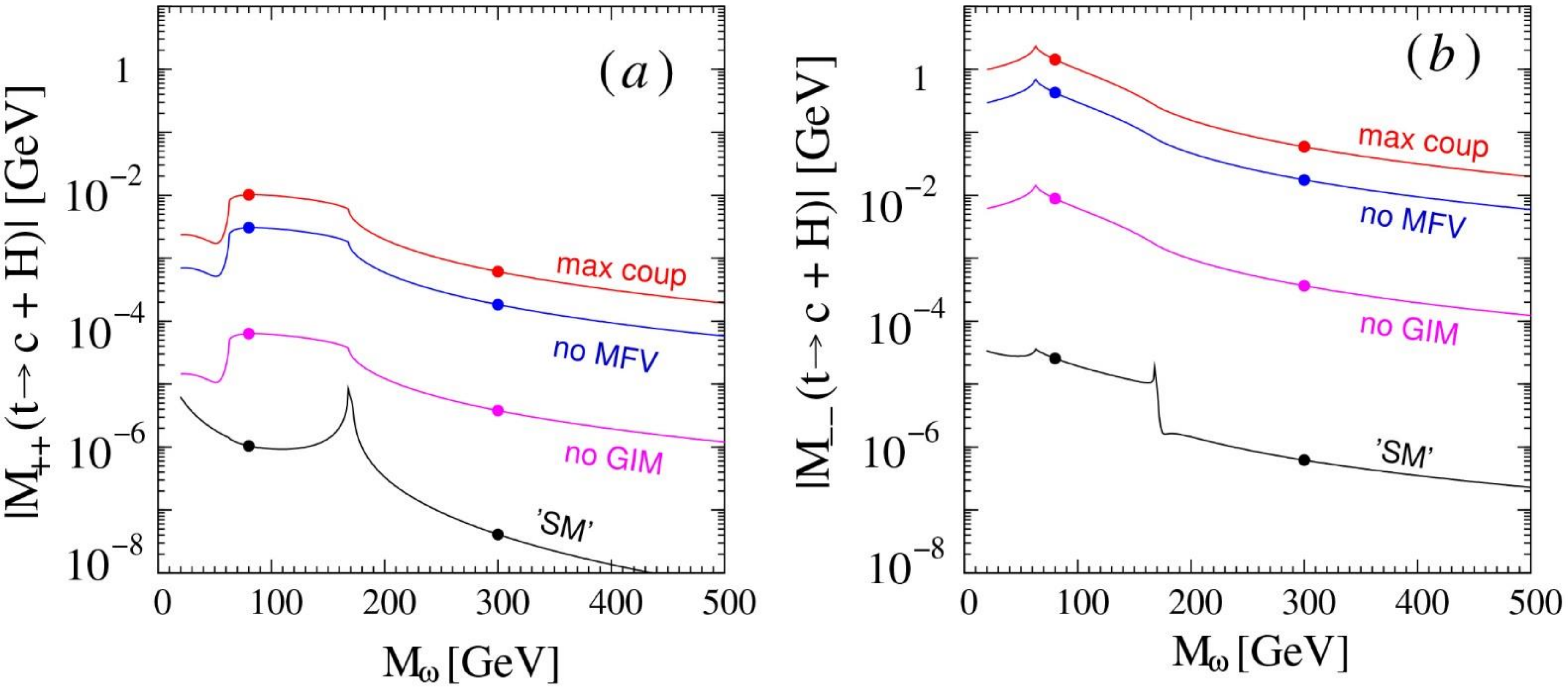
- Used helicity amplitude techniques to calculate the Branching Ratios
- Amplitudes for each helicity combination of top, charm: $A_i(h_c\ , h_t)$
- Only two combinations non-zero: $\boldsymbol{A_i}(+\ ,+);\ \boldsymbol{A_i}(-,-)$

"SM Like" amplitudes

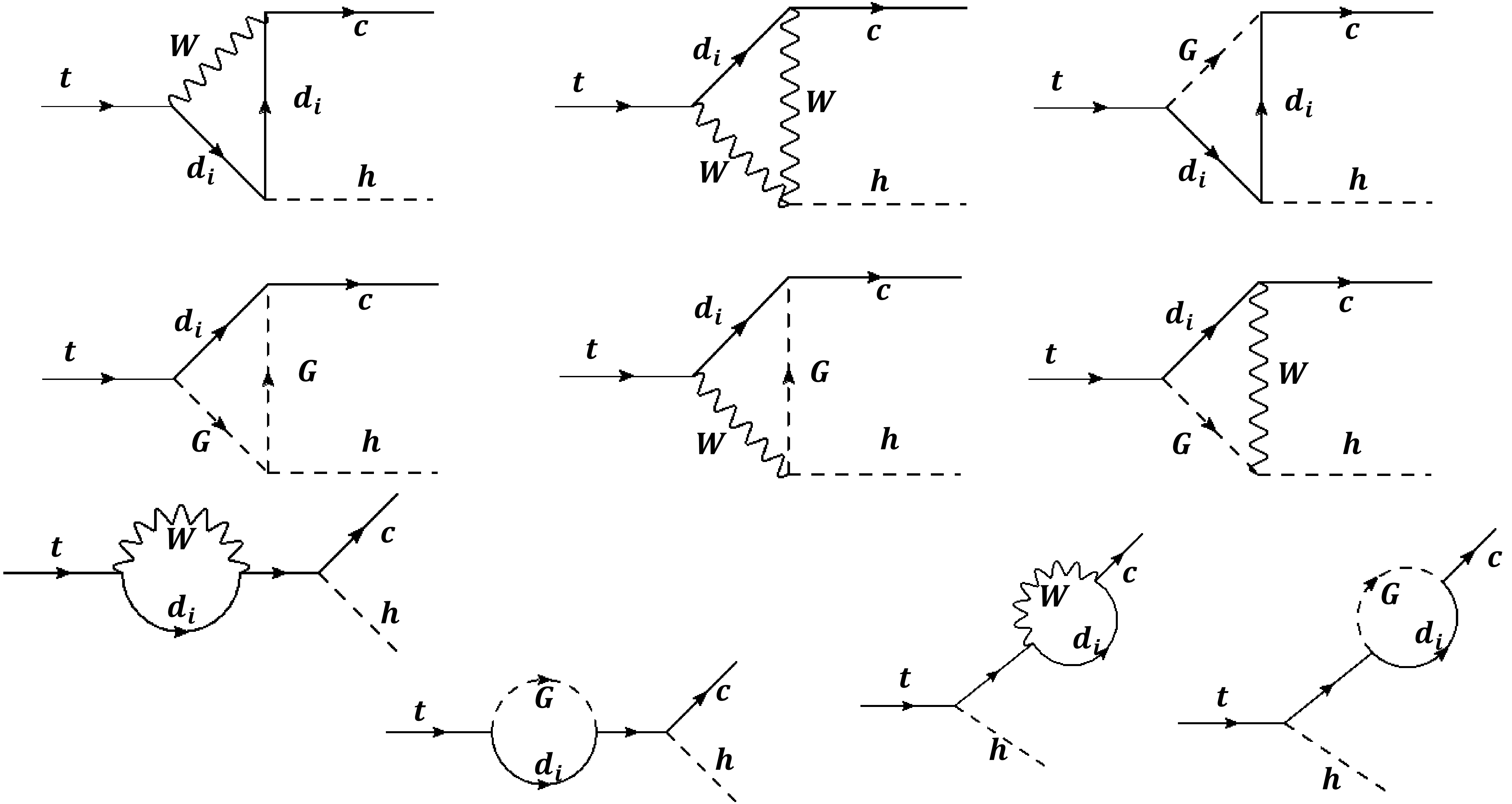
$$\mathcal{A} = \sum_i \lambda_i\, A\,(\,m_i, X)$$

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

Toy Model Amplitudes for $t \to ch$



Feynman Diagrams in the SM



Result (in the SM)

No way of seeing a SM signal

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

Observed Top FCNC would definitely be New Physics

LHC Reach

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

$$\boldsymbol{BR(t \to ch) < 4 \times 10^{-3}}$$ $$\boldsymbol{BR(t \to cZ) < 5.0 \times 10^{-4}}$$

Talk by **Sandeep Bhowmik**

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

$$\boldsymbol{BR_{3ab^{-1}}(t \to cZ) = 7.0 \times 10^{-5}}$$ $$\boldsymbol{BR_{3ab^{-1}}(t \to ch) = 1.5 \times 10^{-4}}$$

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

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 $\Rightarrow$ 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 $B \to D^*\tau\nu$

Need to be updated

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

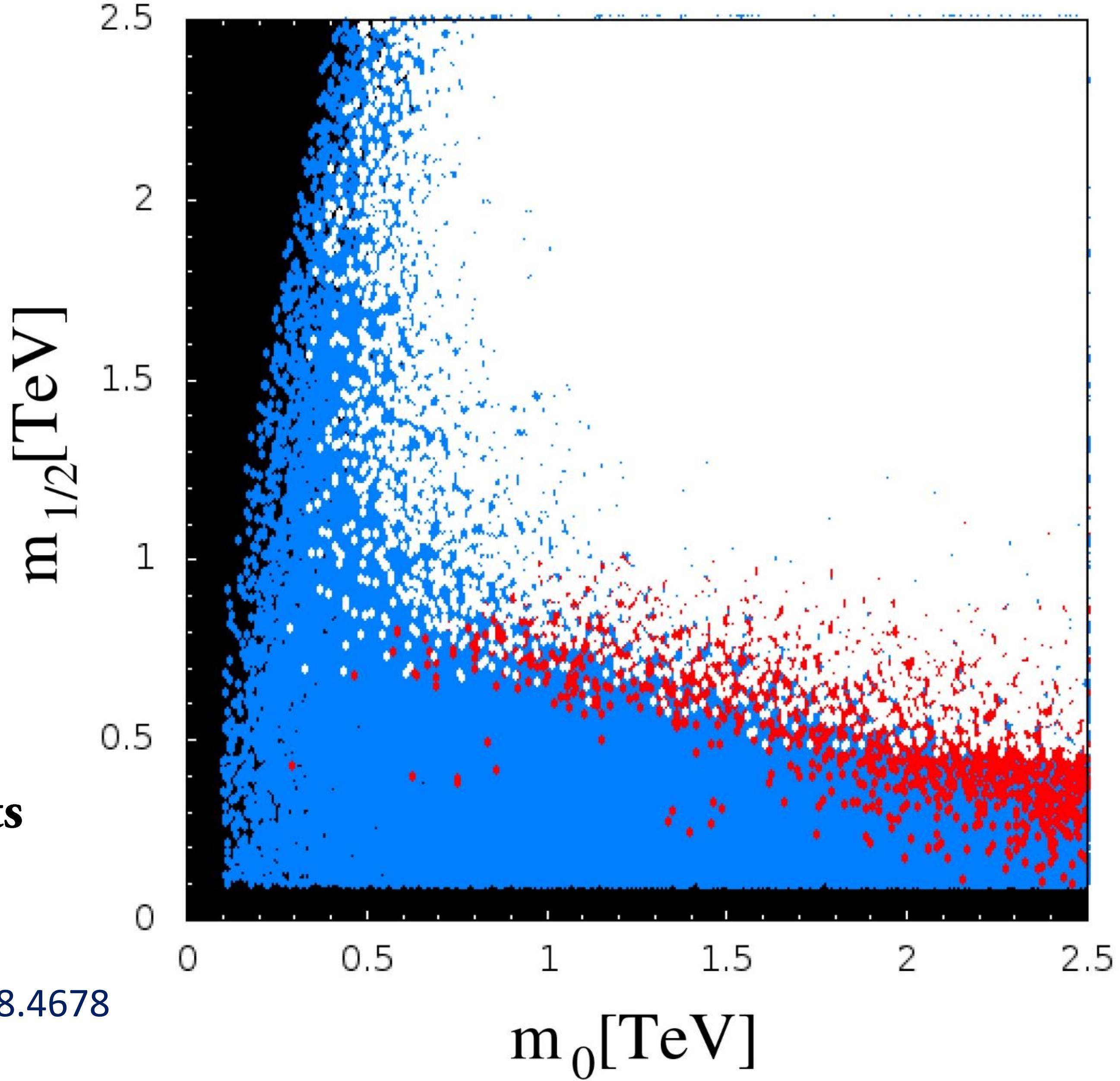
Blue – ruled out by mass constraints

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

Red – ruled out by Flavour Physics constraints

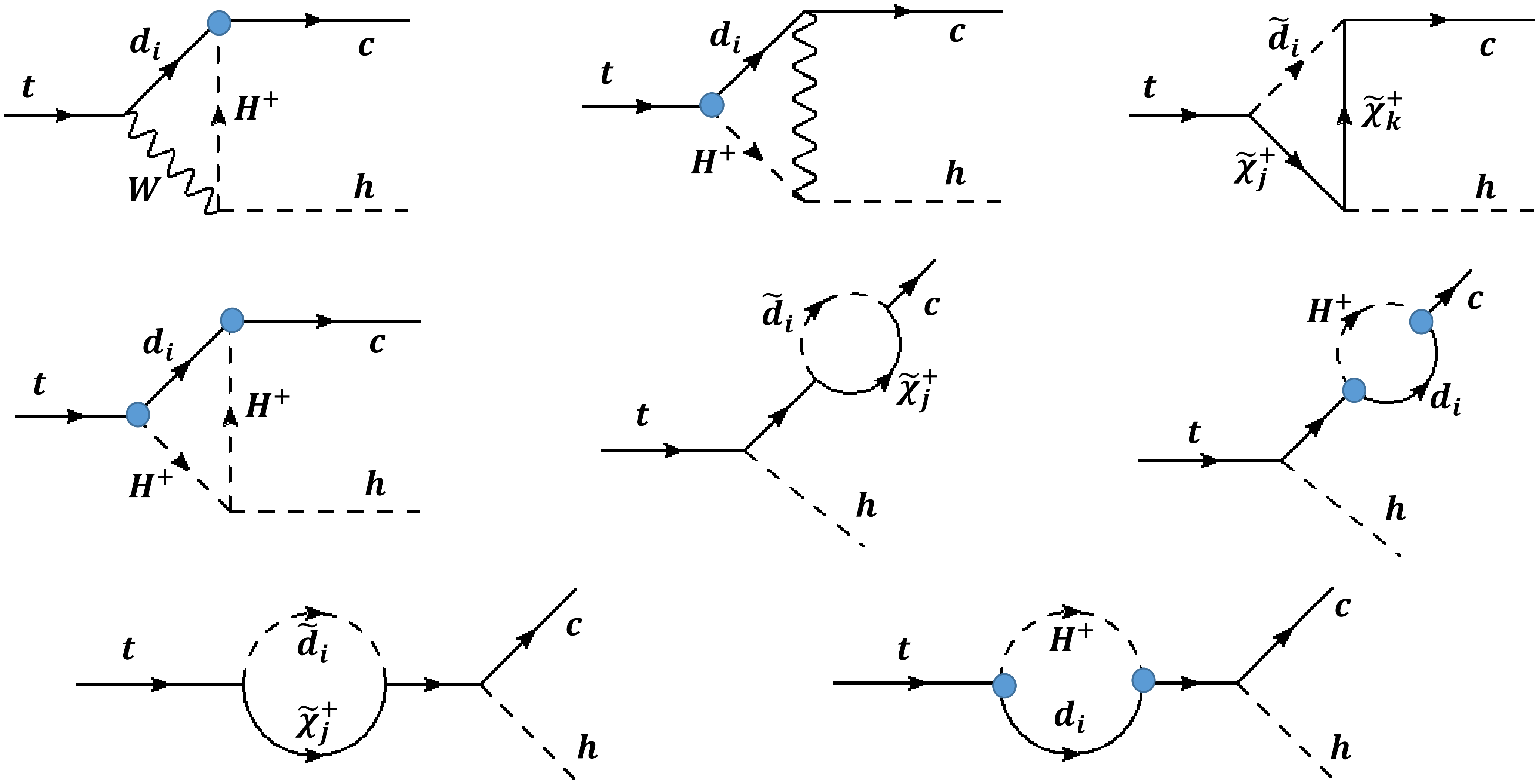
- b-quark physics; FCNC processes
- $B \to K^*\gamma$ and $B \to \mu^+\mu^-$ are almost SM-like

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

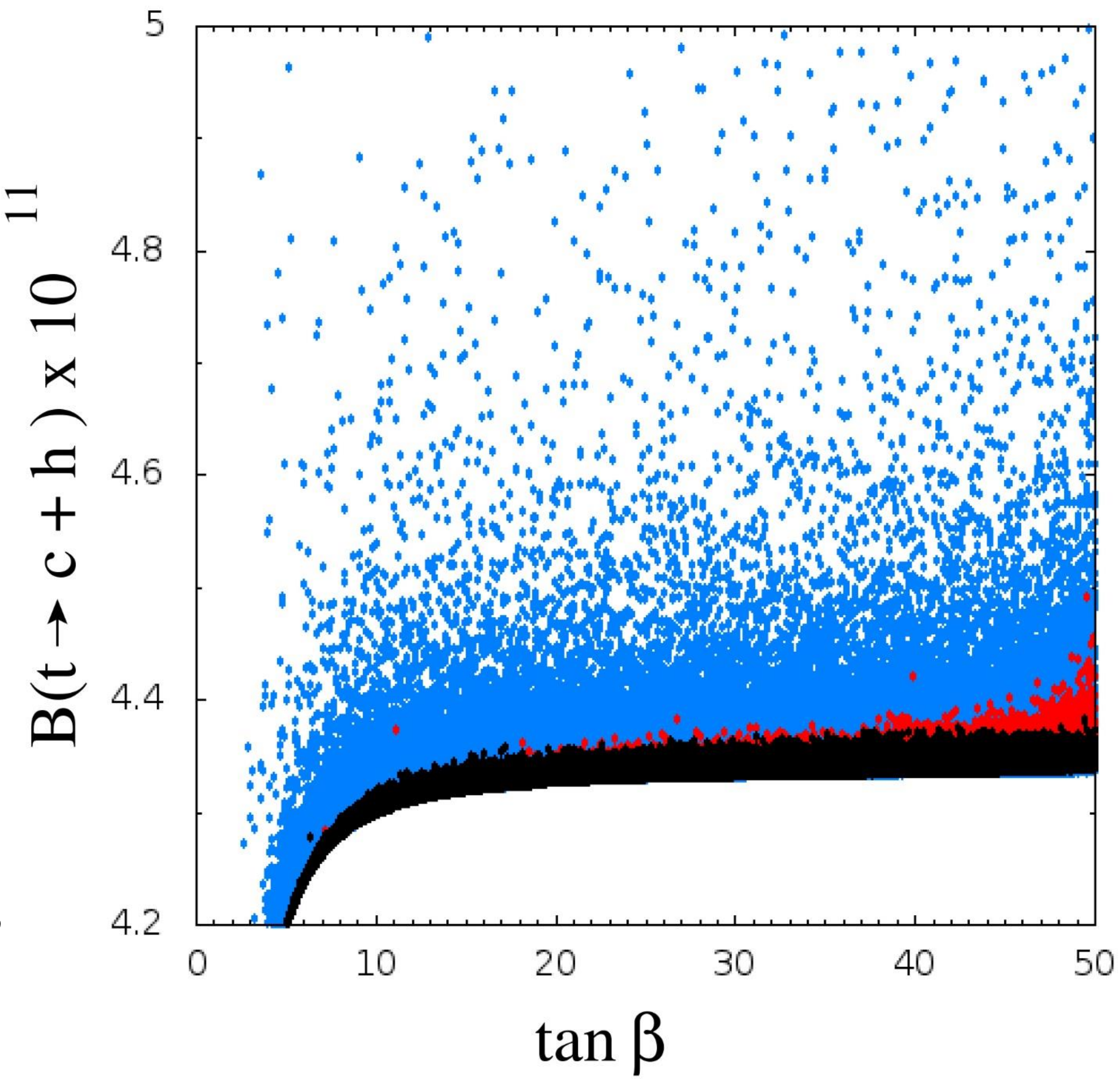
Black – Allowed points:

- Gives us a *tiny* branching ratio

$$BR \sim 4.5 \times 10^{-11}$$

Reasons

- Higgs mass constraint = Heavy charged Higgs
- Within MFV paradigm: $\frac{m_t}{M_W} \cot\beta + \frac{m_b}{M_W} \tan\beta$



R-parity Violating SUSY

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

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

- R-parity violating SUSY superpotential -

$$W_{RPV} = \mu_i \hat{H}_u \hat{L}_i + \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k + \frac{1}{2}\lambda''_{ijk}\hat{U}^c_i\hat{D}^c_j\hat{D}^c_k$$

LQD **UDD**

- No Unitary Requirements – **No GIM Cancellation**
- No Specific 'CKM' structure – **No MFV Structure**
- Size of couplings – **Can be Large**

R-parity Violating SUSY

- RPV couplings needn't be small
- Update old limits and incorporate new squark/slepton masses

	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
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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

LQD

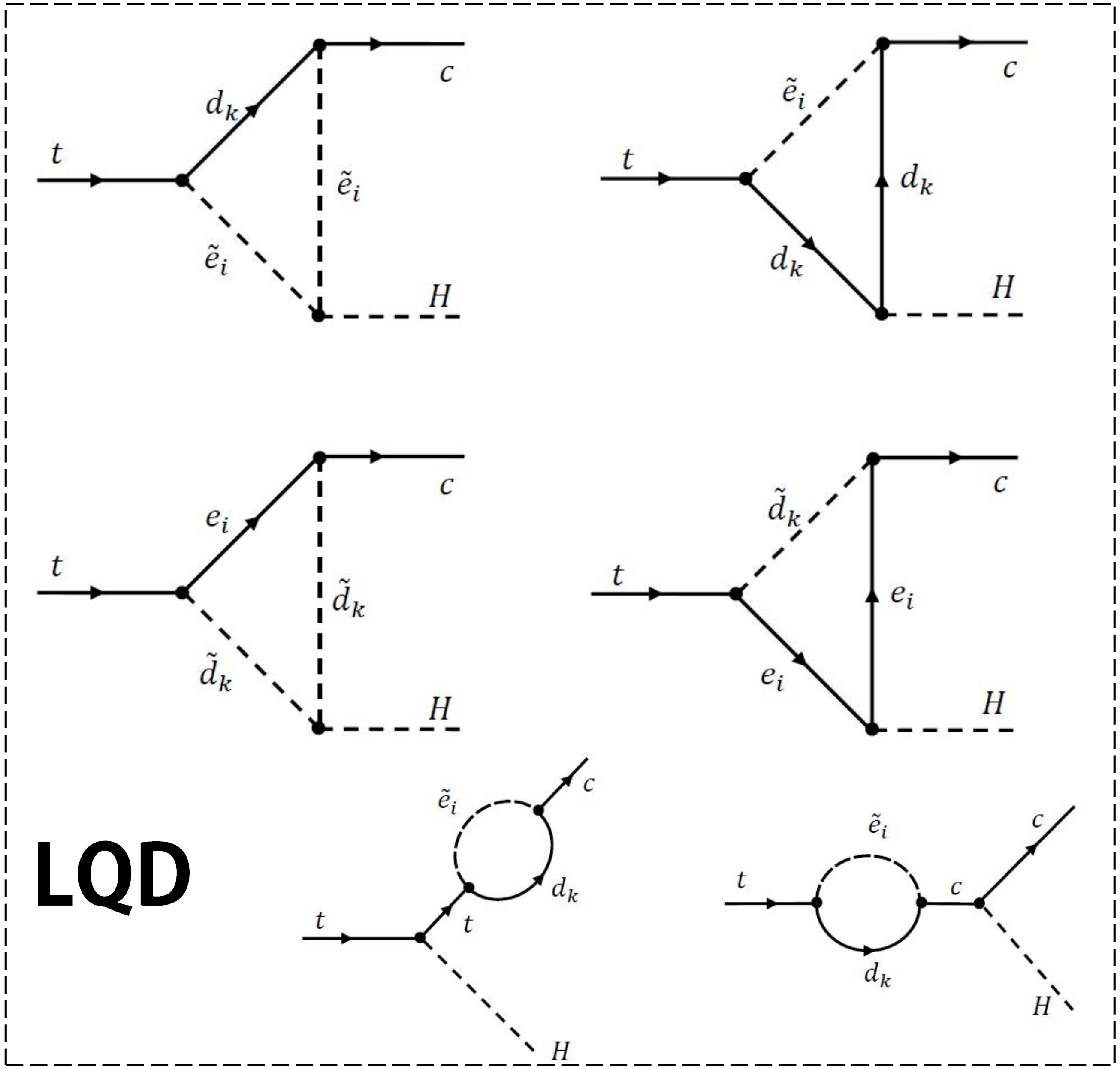
R-parity Violating SUSY

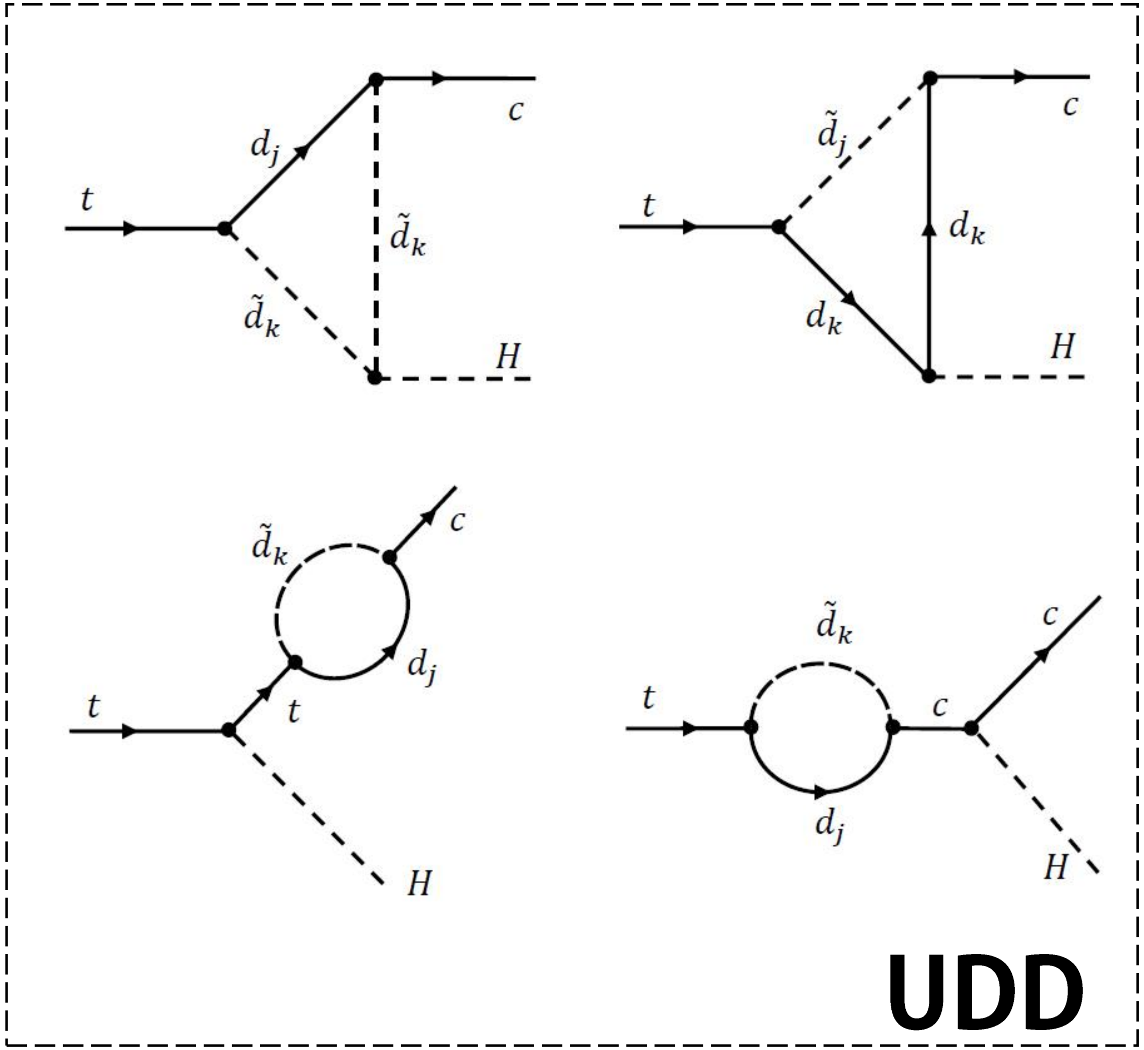
UDD

	Strongest Constraint arises from	Scales as mass of	Scaling Exponent	Upper bound (100 GeV)	Sfermion mass (GeV)	Current upper bound
λ''_{212} λ''_{213} λ''_{223}	Perturbativity [60]	–	–	1.24	–	➡ 1.24
λ''_{312}	$n-\bar{n}$ oscillation [61, 62]	$\tilde{d}_R$	2	10^{-3}	1100 [25]	0.1
λ''_{313}		$\tilde{g}$	$1/2$		1000 [29]	0.1
λ''_{323}	Bounds on $R_b(Z)$ [63]	$\tilde{b}$	1	1.89	500 [54]	➡ 1.89
		$\tilde{\tau}$	-1	1.89	80 [25]	

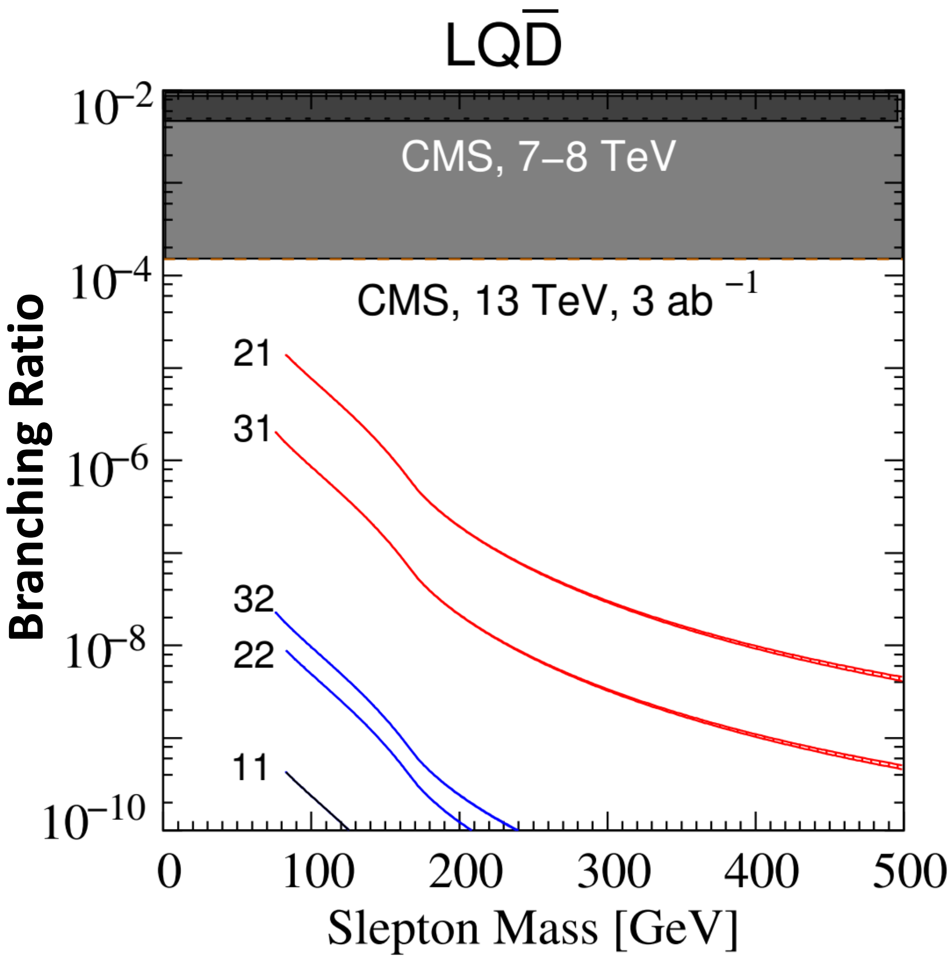
- Only some of the couplings are small – a few can be quite large

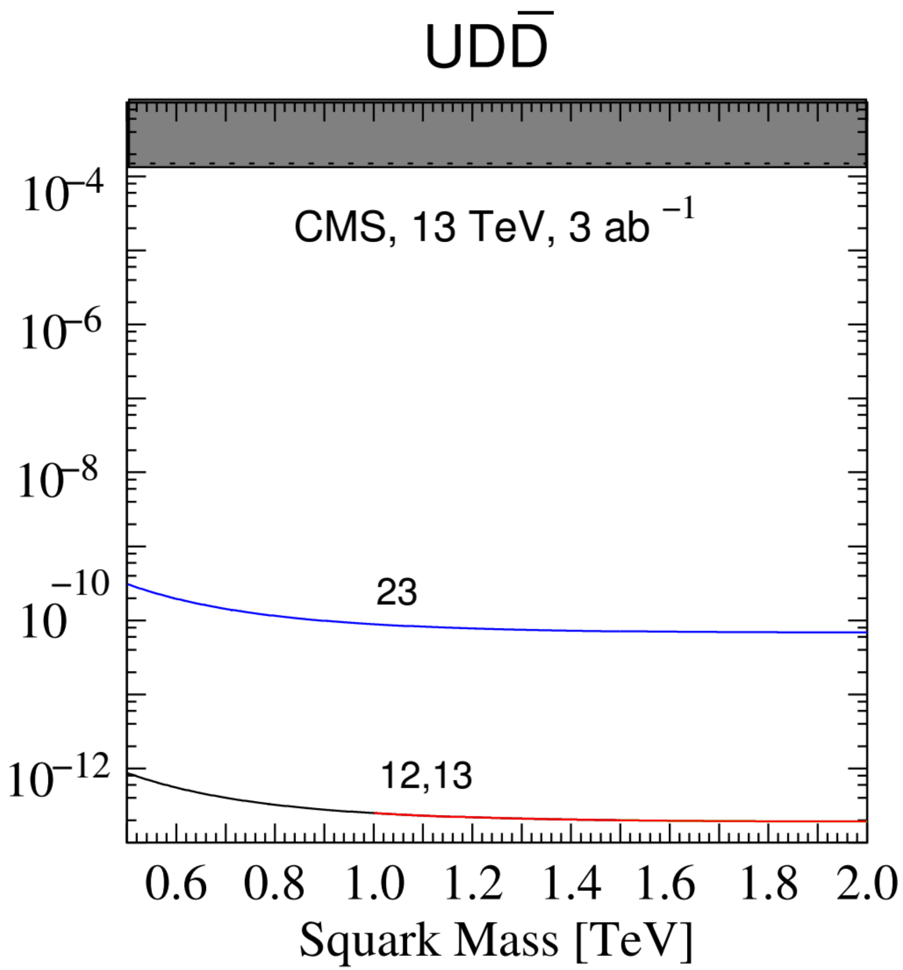
RPV SUSY Contributions





RPV SUSY Results - $t \to c\,H$





Bounds (@ 20 fb^{-1})

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

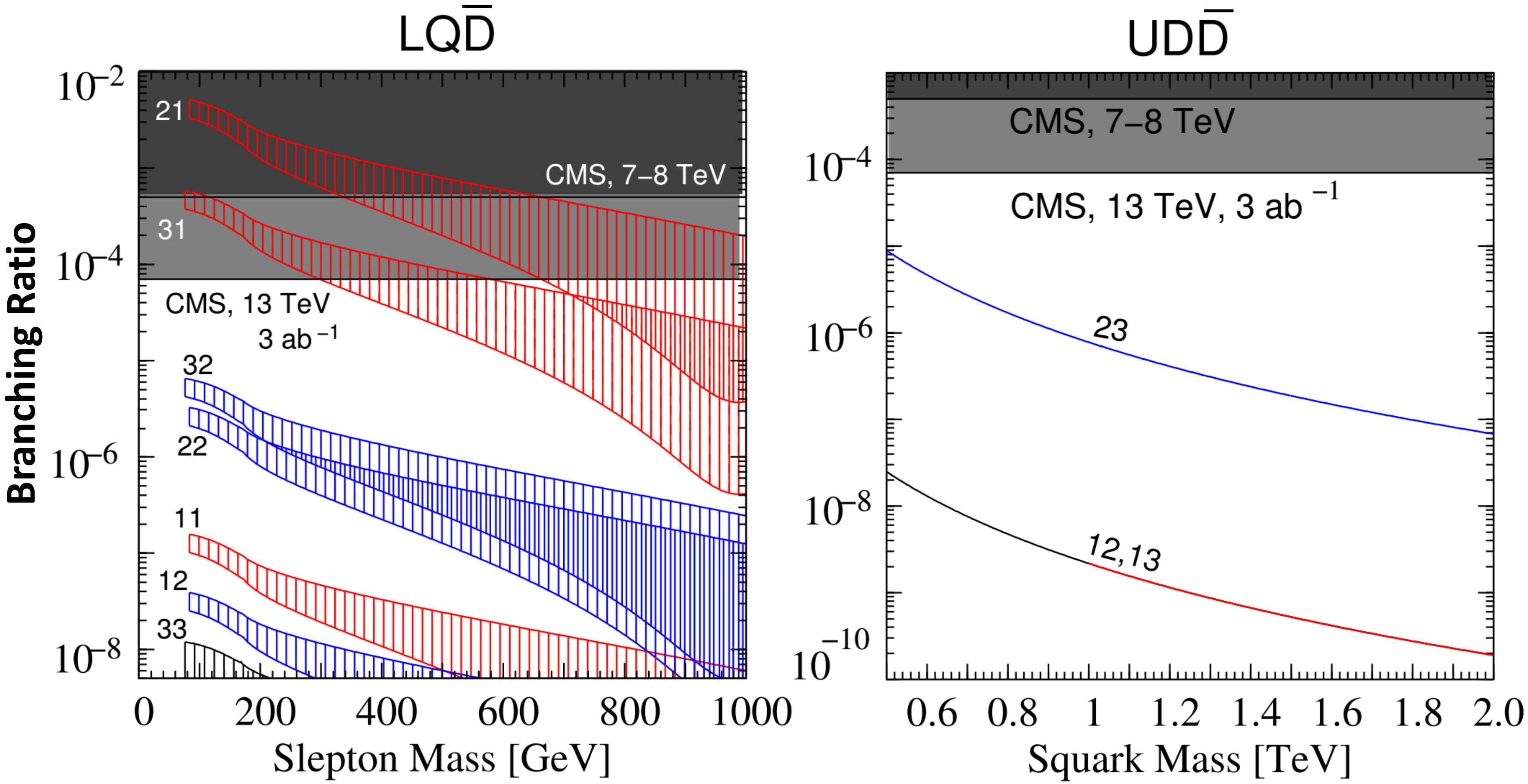
Projections (@ 3000 fb^{-1})

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

ATL-PHYS-PUB-2013-012

- Top decay to Higgs and charm would still be inaccessible in RPV-SUSY at the LHC
- Detection could indicate tree-level FCNC in Higgs couplings

RPV SUSY Results - $t \rightarrow c\,Z$



Bounds (@ 20 fb^{-1})

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

Projections (@ 3000 fb^{-1})

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

hep-ex/1311.2028

- Range of parameters for which top to charm and Z-boson would be visible
- Detection would be signal for RPV-SUSY – but not uniquely

Conclusion and Summary

- Top FCNC’s as a probe of New Physics, especially one that is heavy
- SM branching ratio is way too small – sources of suppression
- Situation doesn’t improve in cMSSM
- Might be observable in RPV-SUSY scenarios the future

Conclusion and Summary

- Top FCNC's as a probe of New Physics, especially one that is heavy
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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

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

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

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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
$\tilde{\tau}_L$, $\tilde{d}_R$	$\tilde{\tau}_L$, $\tilde{s}_R$	$\tilde{\tau}_L$, $\tilde{b}_R$	$\tilde{s}_R$	$\tilde{b}_R$	$\tilde{b}_R$