A Critical Look at FCNC Decays of the Top Quark

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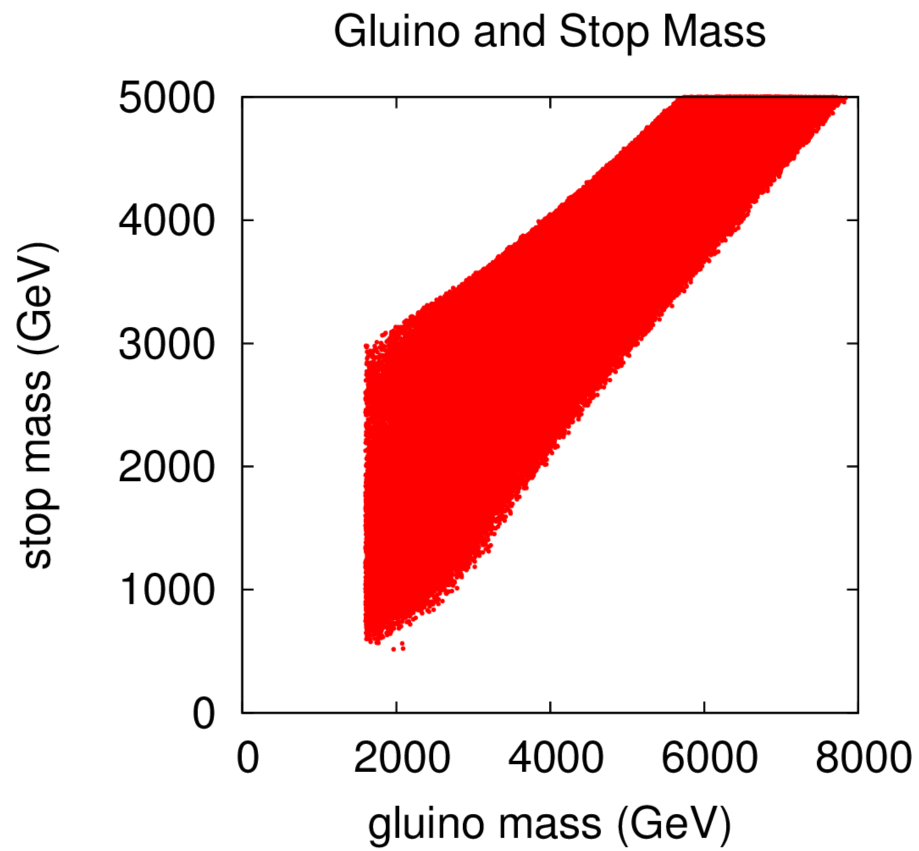
Why FCNCs?

- No SUSY particles from LHC Run-I
- These new particles might be too heavy to produce on-shell – direct searches fail

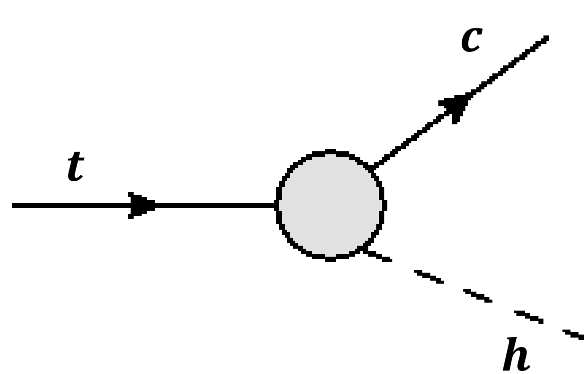
- Consider the indirect effects of these particles through loop contributions
- Find a rare SM process and find enhancements - $t \to ch$

SuSpect v2.3; cMSSM framework



Top Quark Exotic Decays: Introduction

- 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: $\boldsymbol{t \rightarrow b\, W}$
- Interesting to see FCNC decays – rare decays of the top like $t \rightarrow c\, h$
- GIM suppressed processes



Literature on the subject

- Quite a lot of literature available on FCNC decays of the top
- Most of it is quite nebulous; some quote extremely optimistic values
- **SM predictions (BR ($t \rightarrow ch$)):**
  - 10^{-7} Eilam et al. Phys Rec D44 (1991) 1473
  - 10^{-7} Jin Min Yang et al. Phys Rec D49 (1994) 3412
- **MSSM predictions (BR ($t \rightarrow ch$)):**
  - 10^{-5} (by Guasch, hep-ph/9710267)
  - 10^{-3} (by Cordero-Cid et al. hep-ph/0407127)

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

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

- Sensitivity may improve up to $\mathbf{10^{-5}}$ in Run – II

V. Khachatryan et al, PRD (Dec 2014)

Outline

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

Top FCNC Decay in the SM

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

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

- 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:

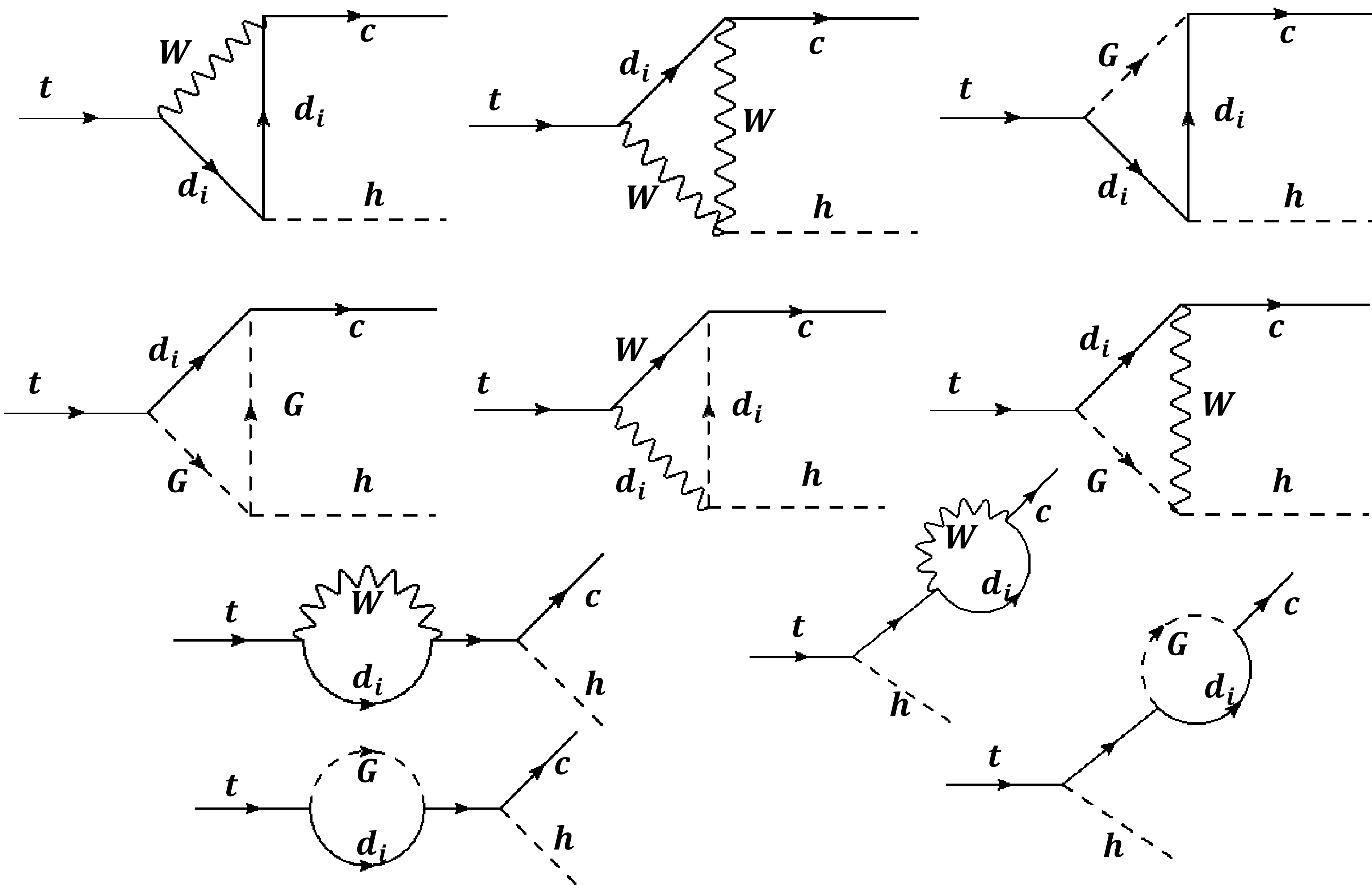
$$i\,\Gamma_n = \frac{i g^3}{16\pi^2} \sum_{i=1}^{3} \lambda_i \left(F_{1i}^{(n)} P_L + F_{2i}^{(n)} P_R \right)$$

$$\Gamma = \sum_n \Gamma_n$$

- GIM suppression comes from the factor:

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

Top Quark FCNC Decay Diagrams (in SM)



Top Quark FCNC Decay Diagrams (in SM)

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

No way of seeing a SM signal

Three Reasons:

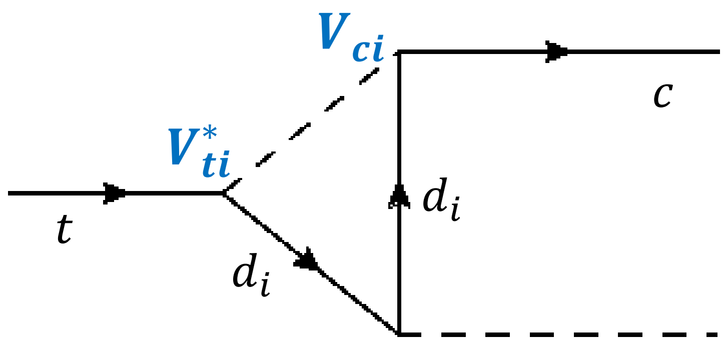
1. GIM Cancellation
2. MFV structure of the quark sector
3. Low value of the coupling constant

Study the relaxation of each of these factors one-by-one

- Use a toy model

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



- The FCNC amplitude is of the form

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

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

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

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

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:

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

0

Unitarity

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

GIM Violation

- 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

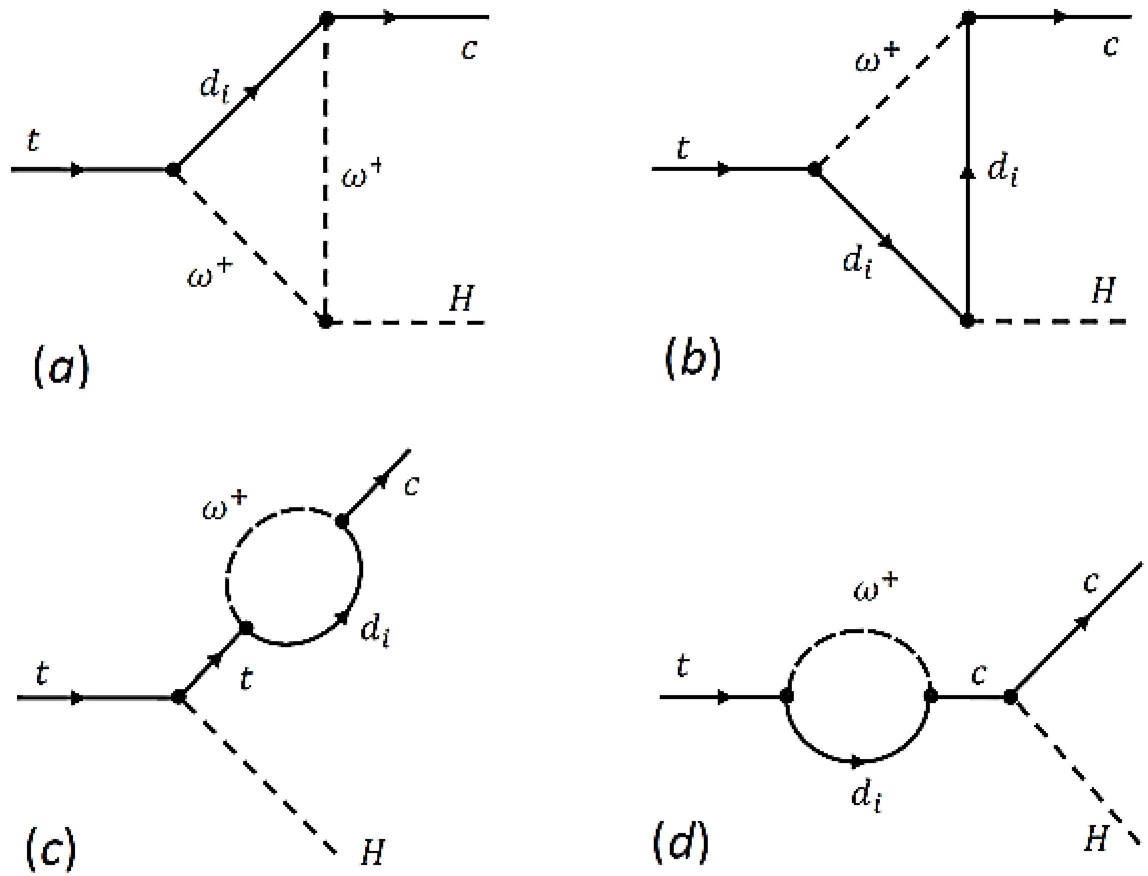
$$CKM \approx \begin{pmatrix} 1 & \lambda & A\lambda^3 \\ -\lambda & 1 & A\,\lambda^2 \\ A\lambda^3 & -A\lambda^2 & 1 \end{pmatrix} \approx \begin{pmatrix} 1 & 0.2 & 0.003 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

More

Toy Model

- Introduce a scalar – something like 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

"SM Like" amplitudes

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

Break GIM

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

Go beyond MFV

$$V'_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & cos\theta \end{pmatrix}$$

For $\theta = \frac{\pi}{4}$; $\lambda = \left(0, \; -\frac{1}{2}, \frac{1}{2}\right)$

Maximize coupling $\quad g \to 1$

Toy Model

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

GIM Relaxation:

- Gives us an enhancement of $\sim \left[\left(\frac{m_b}{M_\omega}\right)^2\right]^{-1} \approx 10^2 \; - 10^4$

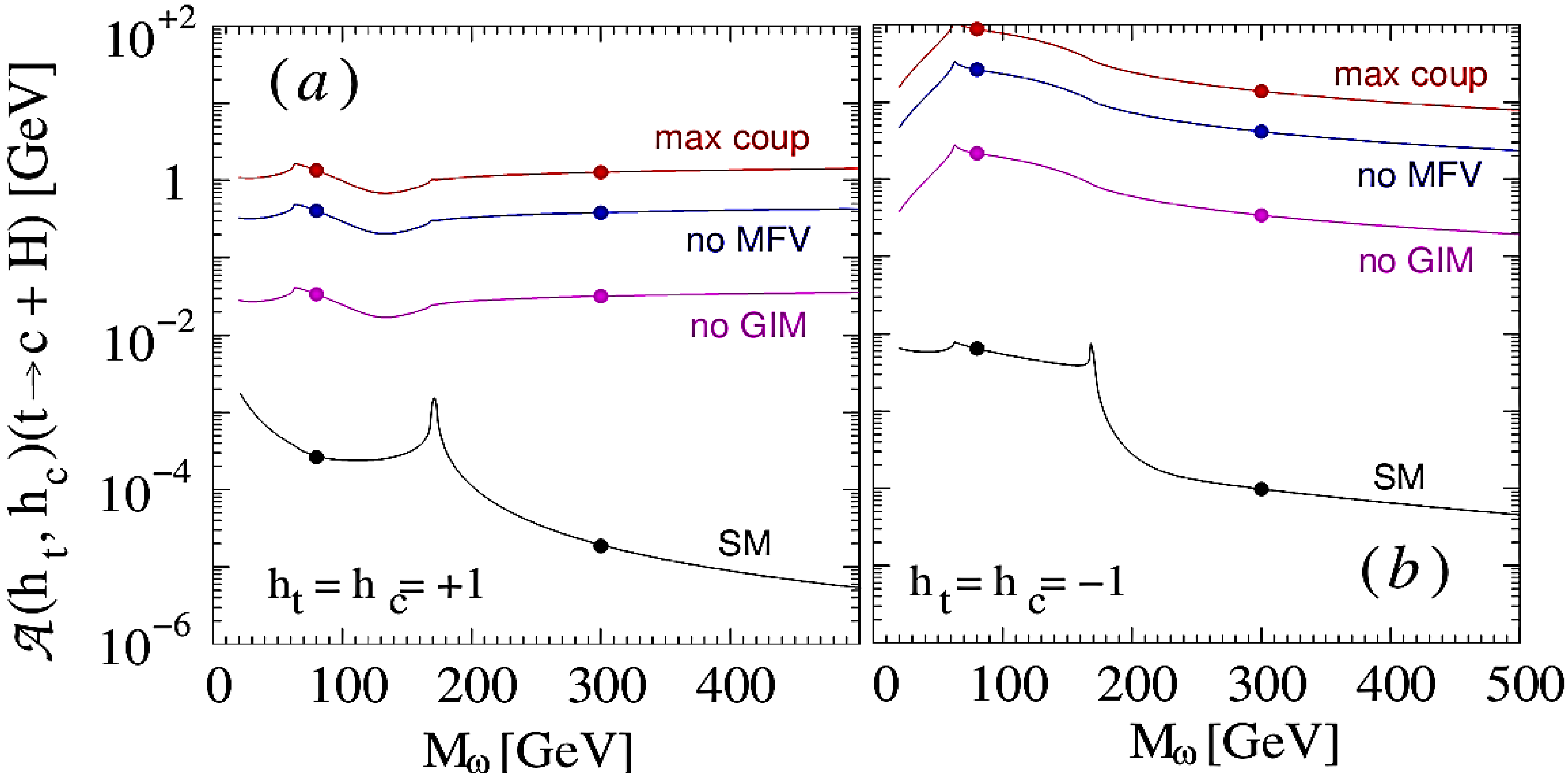
Departure from MFV:

- Gives us an enhancement of 1 to 2 orders of magnitude

Maximal couplings:

- Factor of 3 - 5

Toy Model

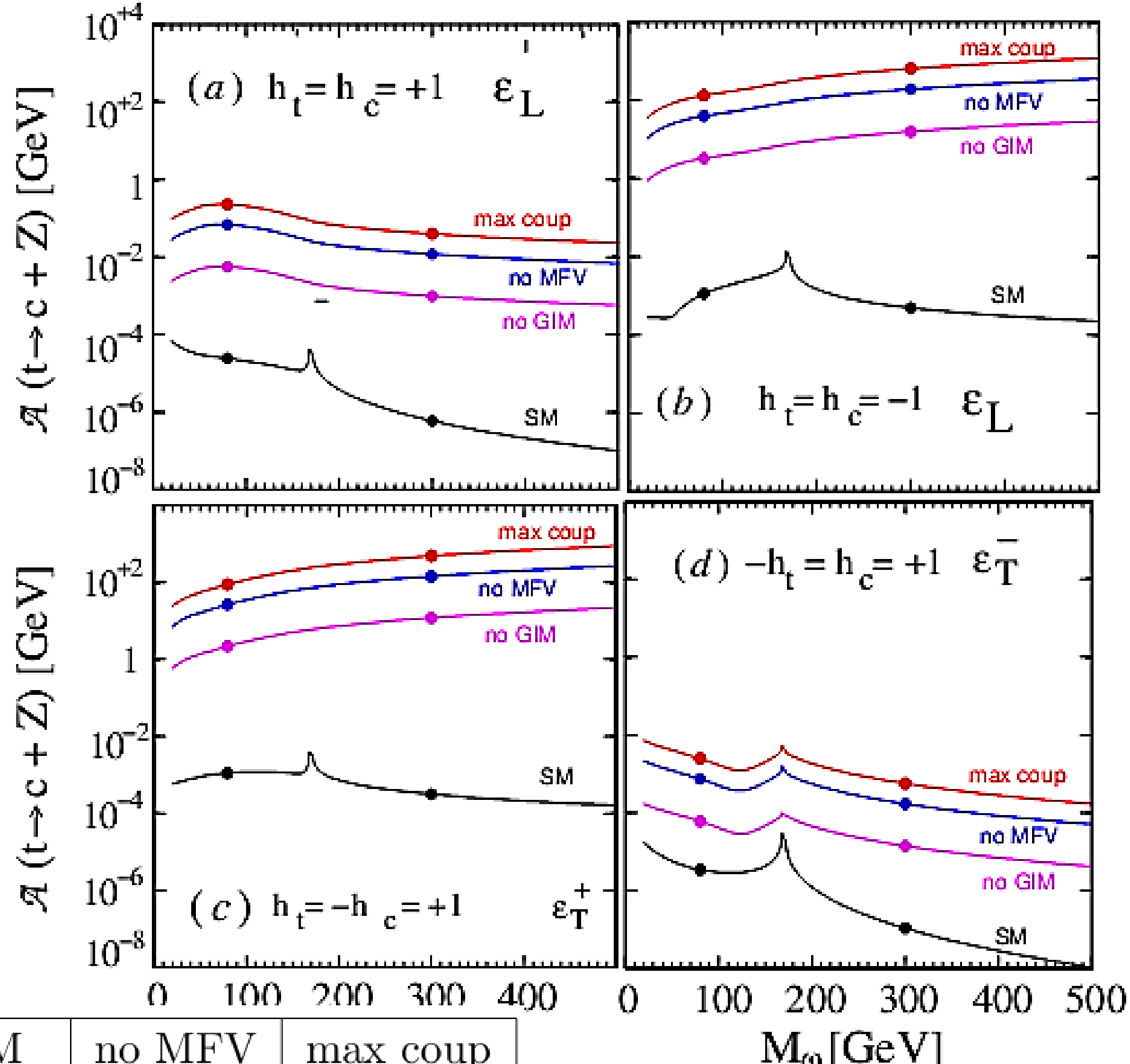


Branching Ratio

M_ω	SM	no GIM	no MFV	max coup
80 GeV	8.8×10^{-10}	9.9×10^{-5}	1.5×10^{-2}	1.6×10^{-1}
300 GeV	2.1×10^{-13}	2.5×10^{-6}	3.6×10^{-4}	4.1×10^{-3}

Toy Model — for $t \to c\,Z$

- Similar results – 4 combinations survive out of 12



M_ω	SM	no GIM	no MFV	max coup
80 GeV	7.4×10^{-10}	7.3×10^{-3}	0.52	0.92
300 GeV	1.7×10^{-10}	1.6×10^{-1}	0.97	0.99

The 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 $\tan\beta$

cMSSM

- Theory Constraints
  - Issues like vacuum stability, proper LSP etc.

- Higgs Mass constraint
  - light Higgs mass taken between 124 to 127 (2σ interval)
  - Constraints m_0 values ⇒ charged Higgs mass is large

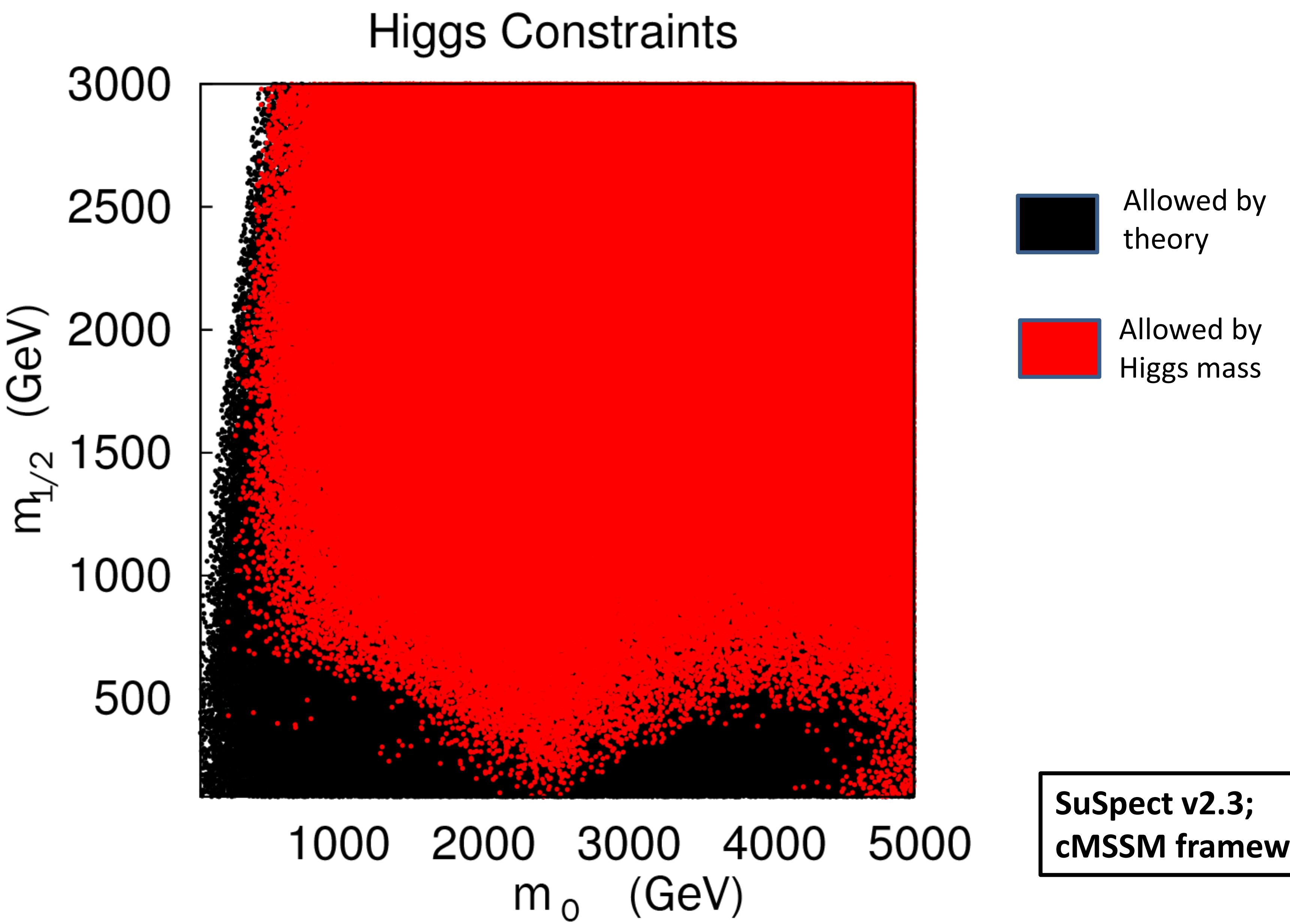
- Direct mass constraints
  - Latest results by ATLAS

    ATLAS SUSY Searches Summary, July 2015
  - $m_{\tilde{g}} > 1.6\ TeV$; $m_{\tilde{q}} > 800\ GeV$; $m_{\tilde{t}}(b\chi^+) > 460\ GeV$

- 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
  - Values taken at a 2 σ level

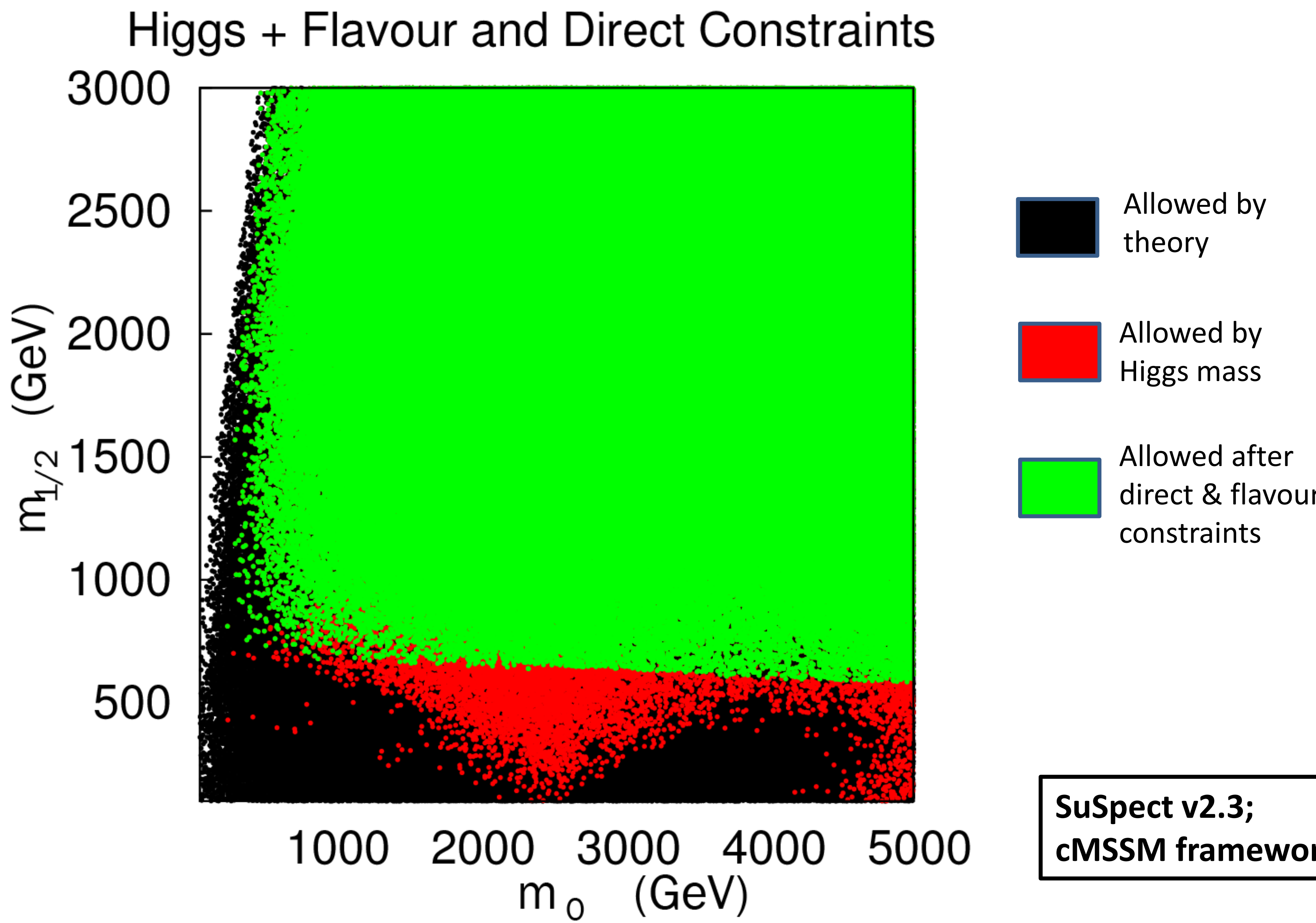
    LHCb: 1211.2674; Belle: 1208.4678
  - Constraints on GIM-violation effects : $M(H^+)$, tan β

cMSSM



SuSpect v2.3; cMSSM framework

cMSSM

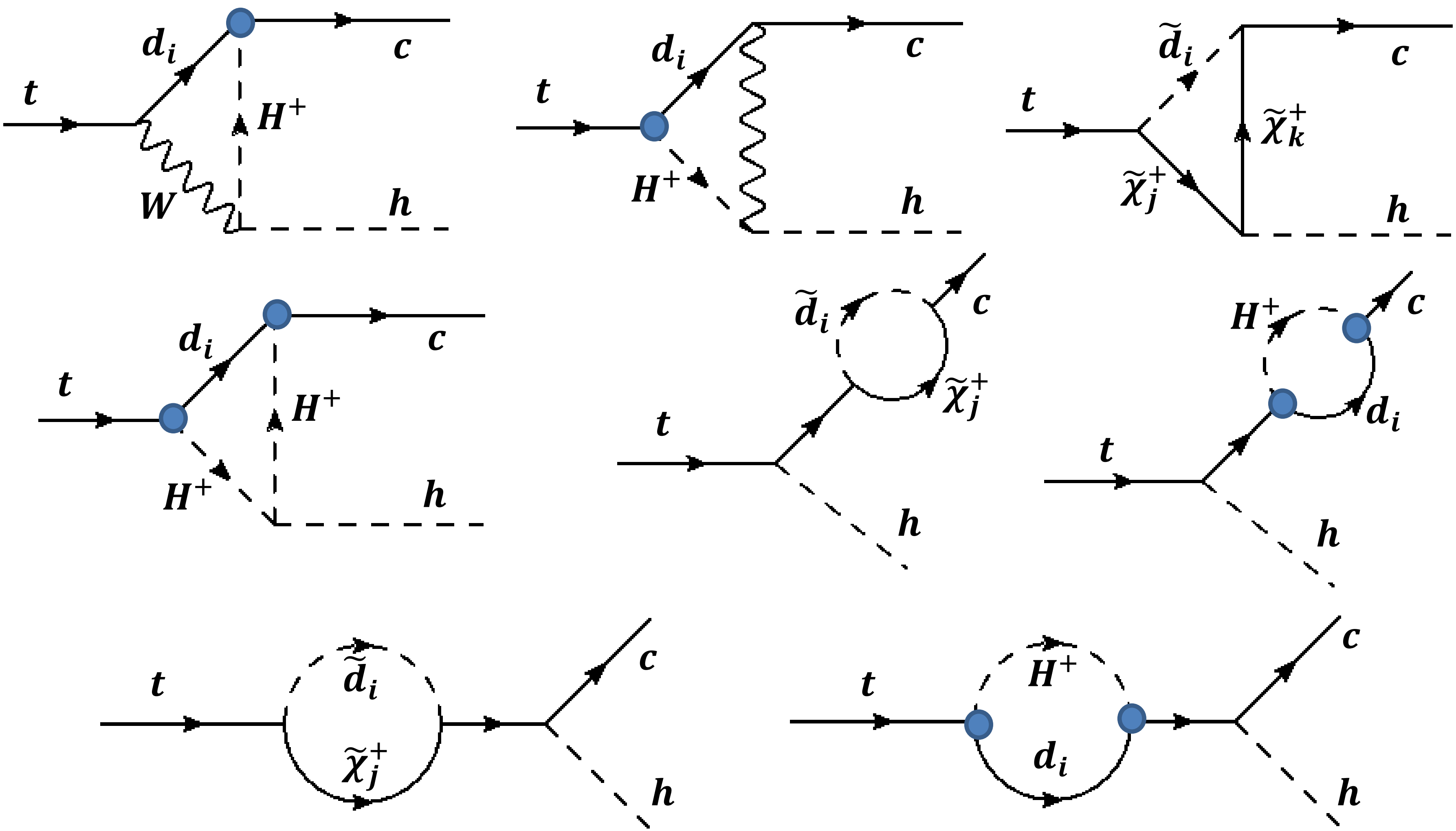


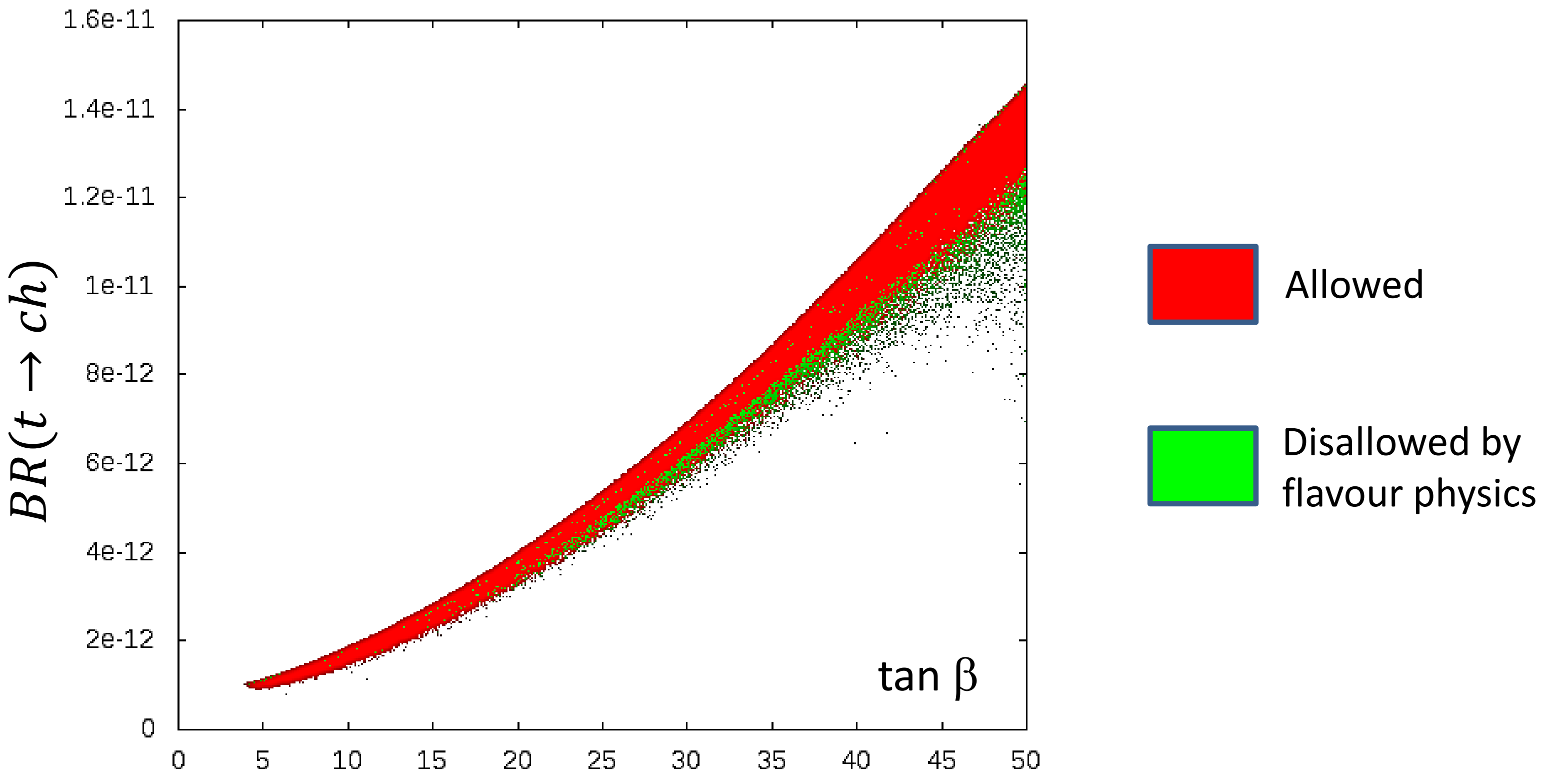
SuSpect v2.3; cMSSM framework

SUSY Contributions

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

  (c) d-squarks





- GIM would be broken by the charged Higgs, but not by other sparticles
- The charged Higgs sector is MFV
- Suppression due to large SUSY particle masses in cMSSM

cMSSM doesn't do it

R-Parity Violating SUSY

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

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

- R-parity conservation gives a viable dark matter candidate, the LSP

- R-parity violating SUSY superpotential -

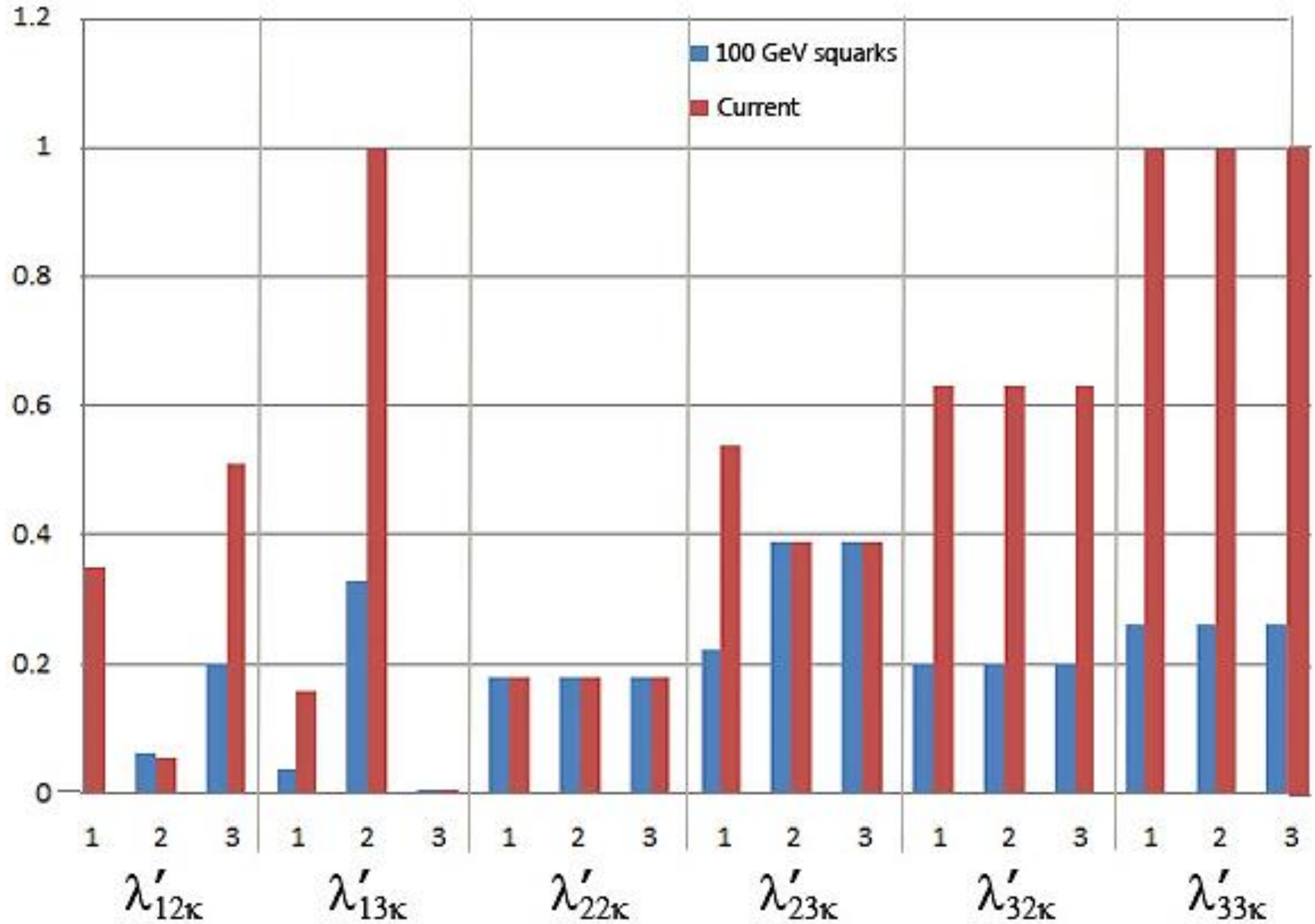
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \boldsymbol{\lambda'_{ijk} L_i Q_j D_k^c} + \frac{1}{2}\lambda''_{ijk}\, U_i^c D_j^c D_k^c$$

- LQD - Lagrangian

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

RPV SUSY Couplings

- Direct squark mass bounds: heavy squarks → weaker constraints



Dreiner. hep-ph/9707435

Eilam et al. hep-ph/0102037

More

RPV SUSY Couplings

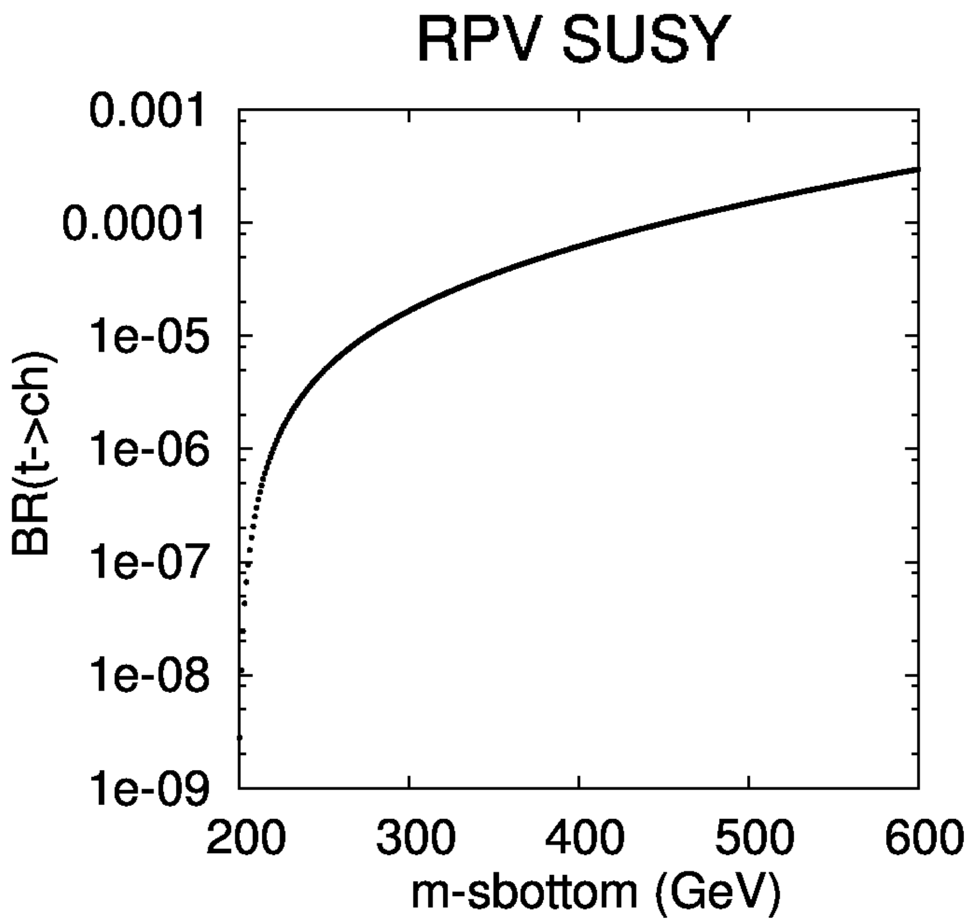
- The couplings occur as: $\lambda'_{i2k}\lambda'_{i3k}$ and $\lambda''_{2jk}\lambda''_{3jk}$ combinations
- Most important couplings: $\lambda'_{323}\lambda'_{333}$
- $\lambda'_{323} = 0.66\,;\ \lambda'_{333} = 1.0$

Result :

$m_{\tilde{q}} = 1\ \mathrm{TeV}\,; m_{\tilde{b}} \sim 300\ GeV$

$m_{\tilde{l}} \sim 300\ GeV$

$\boldsymbol{BR\ (t \to ch) \sim 10^{-5}}$



SUMMARY

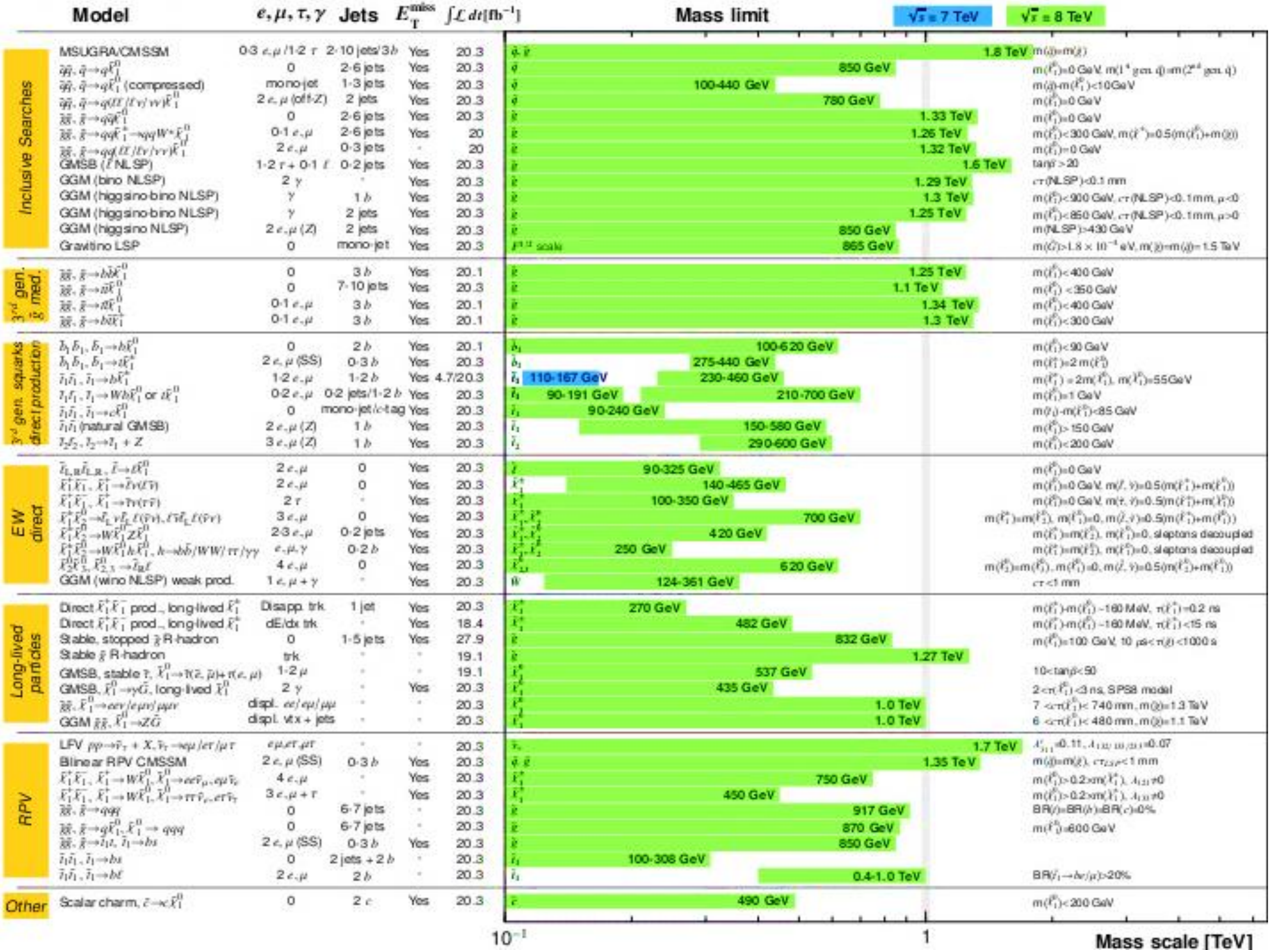
- Indirect searches might be the way to go in case SUSY particles are too heavy for direct detection $-\ t\ \rightarrow ch$
- Heavy suppression of BR in SM coming from GIM mechanism, MFV structure and small couplings
- Have to evade all three to get observable signal
- cMSSM doesn’t do it; RPV-SUSY might be able to

Thank You

BACKUP SLIDES

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015



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

Back

RPV Couplings & Scaling

Coupling	Old Value	Dependence	Mass(GeV)	New Value
λ'_{121}	0.035	$m_{\tilde{d}}/100\ GeV$	1000	0.35
λ'_{122}	0.06	$\sqrt{m_{\tilde{\tau}}/100\ GeV}$	85	0.05
λ'_{123}	0.2	$\sqrt{m_{\tilde{b}}/100\ GeV}$	650	0.51
λ'_{131}	0.035	$m_{\tilde{t}}/100\ GeV$	450	0.16
λ'_{132}	0.28	$m_{\tilde{t}}/100\ GeV$	450	1.0
λ'_{133}	0.002	$\sqrt{m_{\tilde{b}}/100\ GeV}$	650	0.005
$\lambda'_{221}, \lambda'_{222}, \lambda'_{223}$	0.18	$m_{\tilde{d}}/100\ GeV$	1000	1.0
λ'_{231}	0.22	$\sqrt{m_{\tilde{b}}/100\ GeV}$	650	0.54
λ'_{232}	0.39	Z Decay	-	0.39
λ'_{233}	0.39	Neutrino mass	-	0.39
$\lambda'_{321}, \lambda'_{322}, \lambda'_{323}$	0.2	$\sqrt{m_{\tilde{d}}/100\ GeV}$	1000	0.63
$\lambda'_{331}, \lambda'_{332}, \lambda'_{333}$	0.45	$m_{\tilde{t}}/100\ GeV$	450	1.0
λ''_{2jk}				1.0
λ''_{3jk}	0.2	$m_{\tilde{t}}/280\ GeV$	450	0.32