Higgs to Di-photon in SUSY without R-parity (Preliminary results)

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125 GeV Higgs at LHC

125 GeV scalar coupled with non-observation of super-partners has not quite helped the finetunning problem.

- Minimal GMSB and AMSB suffer severe fine-tuning [Drape et.al, Arbey et.al, Babu et.al]
- CMSSM and mSUGRA can marginally accommodate [J. Cao et.al, H. Baer et. al]
- MSSM, nMSSM, NMSSM can predict 125 GeV Higgs but MSSM suffers fine tuning and nMSSM severely suppresses the di-photon signal rate.
- Required large stop mixing may induce CCB minima spoiling the stability of vacuum.

$$h \to \gamma\gamma$$

- First results of excess in this channel did raise a glimmer of hope about new physics.
- With more data CMS results match SM expectations whereas ATLAS still reports about 1.6 times SM expectations.
- There are models galore to explain such an excess.
- SUSY with light stau can “easily” accommodate such enhanced rates but may run into problem with vacuum stability [Carena et al. 2012, Kitahara 2013].
- Metastability of vacuum constrains the enhancement to about 25% with staus 100 GeV. Can this burden be shared by other SUSY contributions?

R-parity violating SUSY

- MSSM and its various variants are not the natural consequence of the supersymmetrization of SM.
- L and B conservation in SM are accidental symmetries which are no longer preserved in most general renormalizable supersymmetrization of SM respecting gauge and lorentz symmetries.
- Simultaneous presence of L and B violation can lead to rapid proton decay.
- This is rescued through imposing an ad-hoc discrete symmetry called R-parity.

$$P_R = (-1)^{2S+3B+L}$$

SUSY with R-parity conservation

- R-paity Conservation makes lightest super-partner (LSP) stable
- In models where LSP is neutral and weakly interacting sparticle production is characterised by large missing transverse momentum due LSP escaping detector.
- Many SUSY searches at hadron colliders rely on this large missing $E_{\mathrm{T}}^{\mathrm{miss}}$ signature or exotic charged tracks.
- LSP may provide for a good dark matter candidate.

SUSY with R-parity violation

- If R-paity is violated, standard search signatures would not be applicable and LHC bounds would be weakened significantly easing the conflict with naturalness.
- LSP no longer provides for a dark matter candidate.
- Proton decay can be easily taken care of by imposing lepton parity or baryon parity.
- R-parity violation provides a good framework for understanding Majorana neutrino masses and mixing.

R-parity Violation: Supersymmetrizing without prejudice

$\left(\hat{L}_i, \hat{H}_d\right)$ carry identical gauge quantum numbers

$\Rightarrow$ gauge int. respect an SU(4) symmetry in $\left(\hat{L}_i, \hat{H}_d\right)$ space

$\Rightarrow$ Yukawa int. break SU(4) symmetry

$\Rightarrow$ several choices before you write Superpotential W:

Choice A: impose L and B conservation $\Rightarrow$ **MSSM**

$$W_{MSSM} = \mu_0 \hat{H}_u \hat{H}_d + h^u_{ij} \hat{Q}_i \hat{H}_u \hat{U}^c_j + h^d_i \hat{H}_d \hat{Q}_i \hat{D}^c_i + h^e_i \hat{H}_d \hat{L}_i \hat{E}^c_i$$

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Choice B: L violation $\Rightarrow \hat{H}_d \longrightarrow \hat{L}_\alpha = (\underbrace{\hat{L}_0}_{\hat{H}_d}, \hat{L}_i)$

$$\boxed{h^d_i \longrightarrow \lambda'_{\alpha jk} = (\underbrace{\lambda'_{0ii}}_{h^d_i}, \lambda'_{ijk})} \qquad \boxed{h^e_i \longrightarrow \lambda_{\alpha\beta k} = (\underbrace{\lambda_{0ii}}_{h^e_i}, \lambda_{ijk})}$$

$$W_{\mathrm{MSSM+LV}} = \mu_\alpha \hat{H}_u \hat{L}_\alpha + h^u_{ik} \hat{Q}_i \hat{H}_u \hat{U}^c_k + \lambda'_{\alpha jk} \hat{L}_\alpha \hat{Q}_j \hat{D}^c_k + \frac{1}{2} \lambda_{\alpha\beta k} \hat{L}_\alpha \hat{L}_\beta \hat{E}^c_k$$

Choice C: **R-parity violation** $\Rightarrow W_{\mathrm{MSSM+LV}} + \frac{1}{2} \lambda''_{ijk} \hat{U}^c_i \hat{D}^c_j \hat{D}^c_k$

Soft Potential including RPV

$$
\begin{aligned}
V_{\rm soft} = {} & \epsilon_{ab} B_\alpha H_u^a \tilde{L}_\alpha^b + \epsilon_{ab}\left[A_{ij}^U \tilde{Q}_i^a H_u^b \tilde{U}_j^C + A_{ij}^D H_d^a \tilde{Q}_i^b \tilde{D}_j^C + A_{ij}^E H_d^a \tilde{L}_i^b \tilde{E}_j^C\right] + \text{h.c.} \\
& + \epsilon_{ab}\left[A_{ijk}^{\lambda'} \tilde{L}_i^a \tilde{Q}_j^b \tilde{D}_k^C + \frac{1}{2} A_{ijk}^{\lambda} \tilde{L}_i^a \tilde{L}_j^b \tilde{E}_k^C\right] + \frac{1}{2} A_{ijk}^{\lambda''} \tilde{U}_i^C \tilde{D}_j^C \tilde{D}_k^C + \text{h.c.} \\
& + \tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + \tilde{L}^\dagger \tilde{m}_L^2 \tilde{L} + \tilde{E}^\dagger \tilde{m}_E^2 \tilde{E} + \tilde{m}_{H_u}^2 |H_u|^2 \\
& + \frac{M_1}{2} \tilde{B}\tilde{B} + \frac{M_2}{2} \tilde{W}\tilde{W} + \frac{M_3}{2} \tilde{g}\tilde{g} + \text{h.c.}\,,
\end{aligned}
$$

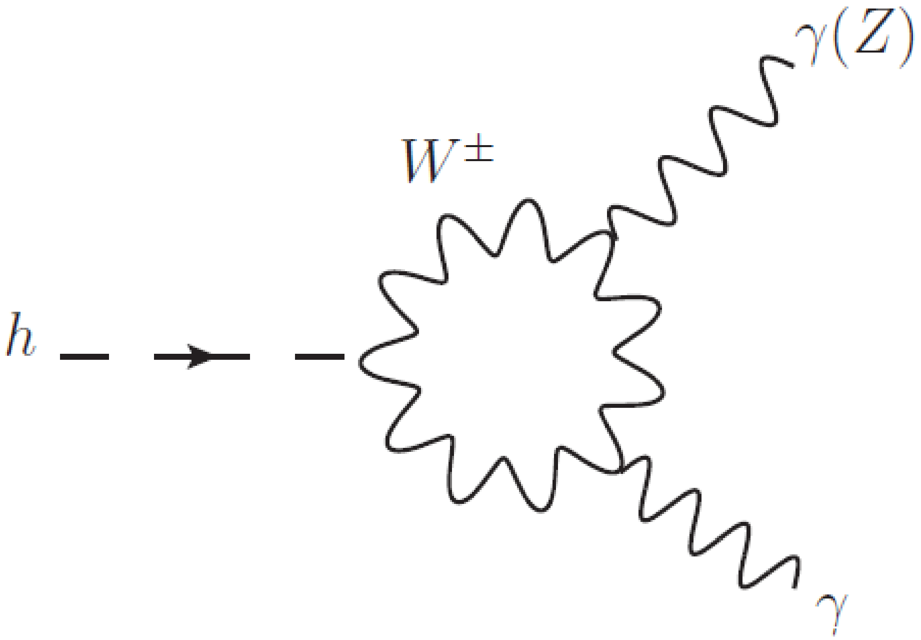
RPV Soft trilinear terms are phenomenologically hardly studied and hence completely unconstrained (see for instance A.Arhrib, Otto. Kong PRD 2013)

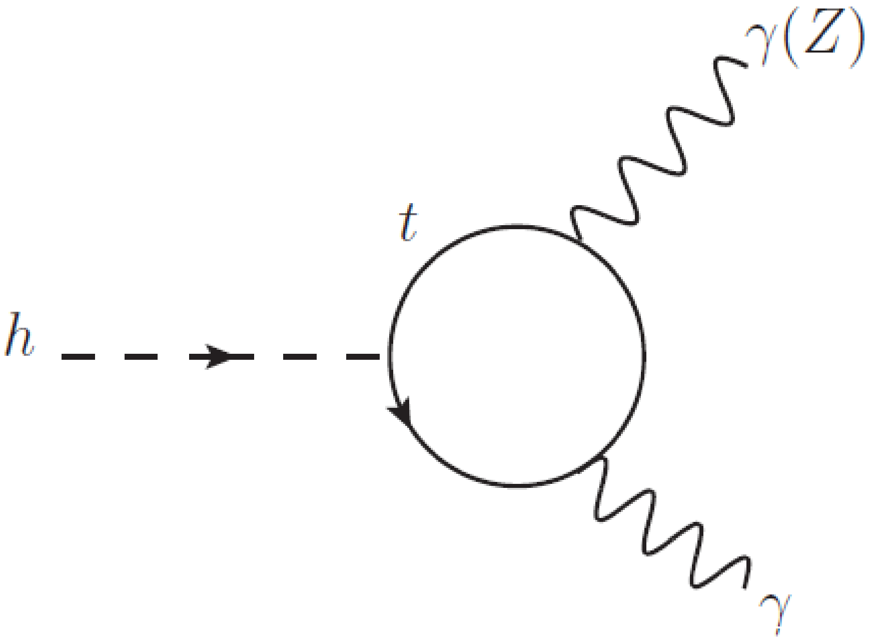
What has $h \to \gamma\gamma$ got to do with R-parity violation?

- It violates neither L, nor B, nor flavor !
- Soft trilinear RPV terms have a special role to play here.
- Since it involves three heavy particles, its phenomenology can be studied through loop induced processes.
- Higgs is first such heavy particle to be discovered and whose decay modes are actually measured.
- $h \to \gamma\gamma$ presents a perfect case study.

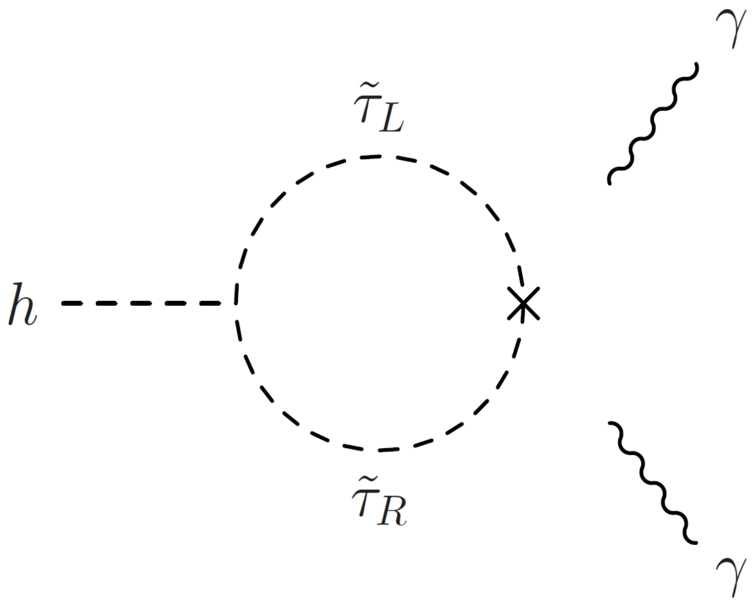
$h \to \gamma\gamma$ in SM

W boson loop far dominates the top loop and the two interfere destructively

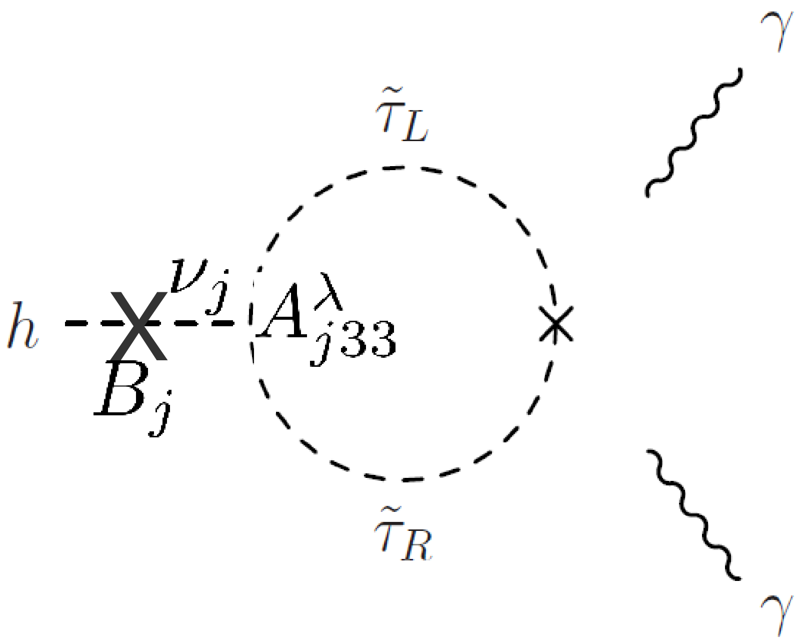




$h \to \gamma\gamma$ Supersymmetry with and without R-parity



With R-parity conservation



With R-parity violation

Enhancement over SM

$$R_{\gamma\gamma} = \left| 1 + \frac{g_{hss}}{2} \frac{v}{m_S^2} \frac{A_0(\tau_S)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \right|^2$$

$$\mathcal{L} = \mathbf{g}^{-}_{abm} \Phi^{\dagger}(\phi^{-}_{a}) \Phi(\phi^{-}_{b}) \Phi(\phi^{0}_{m})$$

MSSM mu-term + RPV superpotential

$$
\begin{aligned}
g^{-}_{abm} = {} & \frac{1}{\sqrt{2}}(\mu_0^* \delta_{pq} y_{e_q} + \mu_i^* \lambda_{ipq}) \mathcal{D}^{l*}_{(q+5)a} \mathcal{D}^{l}_{(p+2)b} (\mathcal{D}^{s}_{1m} + i \mathcal{D}^{s}_{6m}) \\
& \frac{1}{\sqrt{2}}(\mu_0 \delta_{pq} y_{e_q} + \mu_i \lambda^*_{ipq}) \mathcal{D}^{l*}_{(p+2)a} \mathcal{D}^{l}_{(q+5)b} (\mathcal{D}^{s}_{1m} - i \mathcal{D}^{s}_{6m}) \\
& \frac{1}{\sqrt{2}}(\mu_0^* \delta_{pq} y_{e_q} + \mu_i^* \lambda_{ipq}) \mathcal{D}^{l*}_{(q+5)a} \mathcal{D}^{l}_{1b} (\mathcal{D}^{s}_{(p+2)m} + i \mathcal{D}^{s}_{(p+7)m}) \\
& \frac{1}{\sqrt{2}}(\mu_0 \delta_{pq} y_{e_q} + \mu_i \lambda^*_{ipq}) \mathcal{D}^{l*}_{1a} \mathcal{D}^{l}_{(q+5)b} (\mathcal{D}^{s}_{(p+2)m} - i \mathcal{D}^{s}_{(p+7)m})
\end{aligned}
$$

MSSM A term + Soft RPV terms

$$\mathbf{g}^{-}_{abm} =$$

$$-\frac{1}{\sqrt{2}}A^{E}_{pq}\mathcal{D}^{l*}_{(q+5)a}\mathcal{D}^{l}_{(p+2)b}(\mathcal{D}^{s}_{2m}+i\mathcal{D}^{s}_{7m}) \quad -\frac{1}{\sqrt{2}}A^{E*}_{pq}\mathcal{D}^{l*}_{(p+2)a}\mathcal{D}^{l}_{(q+5)b}(\mathcal{D}^{s}_{2m}-i\mathcal{D}^{s}_{7m})$$

$$+\frac{1}{\sqrt{2}}A^{E}_{pq}\mathcal{D}^{l*}_{(q+5)a}\mathcal{D}^{l}_{2b}(\mathcal{D}^{s}_{(p+2)m}+i\mathcal{D}^{s}_{(p+7)m}) \quad +\frac{1}{\sqrt{2}}A^{E*}_{pq}\mathcal{D}^{l*}_{2a}\mathcal{D}^{l}_{(q+5)b}(\mathcal{D}^{s}_{(p+2)m}-i\mathcal{D}^{s}_{(p+7)m})$$

$$-\frac{1}{\sqrt{2}}A^{\lambda}_{jpq}\mathcal{D}^{l*}_{(q+5)a}\mathcal{D}^{l}_{(p+2)b}(\mathcal{D}^{s}_{(j+2)m}+i\mathcal{D}^{s}_{(j+7)m} \quad -\frac{1}{\sqrt{2}}A^{\lambda*}_{jpq}\mathcal{D}^{l*}_{(p+2)a}\mathcal{D}^{l}_{(q+5)b}(\mathcal{D}^{s}_{(j+2)m}-i\mathcal{D}^{s}_{(j+7)m}).$$

Here $\mathcal{D}^{l}$ and $\mathcal{D}^{s}$ are 8X8 and 10X10 matrices that diagonalize all the colorless charged and neutral scalars (including Higgs) mass matrices.

soft RPV A-term contributions in the perturbative approximation

$$\boldsymbol{g}^{-}_{abm} = -\sqrt{2}A^{\lambda}_{jpq}\mathcal{D}^{l}_{(q+5)a}\mathcal{D}^{l}_{(p+2)b}\left(\mathcal{D}^{s}_{(j+2)m}\right)$$

$$g_{331} = \sqrt{2}A^{\lambda}_{j33}\left(\frac{\widetilde{M}^{2}_{RL_{33}}\widetilde{M}^{2}_{LL_{33}}}{M_s^4}\right)\frac{B_j(\tan\beta\sin\alpha - \cos\alpha)}{M_s^2}$$

$$g_{332} = \sqrt{2}A^{\lambda}_{j33}\left(\frac{\widetilde{M}^{2}_{RL_{33}}\widetilde{M}^{2}_{LL_{33}}}{M_s^4}\right)\frac{B_j(\tan\beta\cos\alpha + \sin\alpha)}{M_s^2}$$

Preliminary results

Parameter specifications that yield higgs of 125 GeV

$$\mu = 1000\ GeV$$

$$\tilde{m}_Q^2 = \tilde{m}_U^2 = \tilde{m}_D^2 = 1500\ GeV$$

$$\tilde{m}_L^2 = \tilde{m}_E^2 = 50 - 500\ GeV$$

$$A_t/\mu = 2.5$$

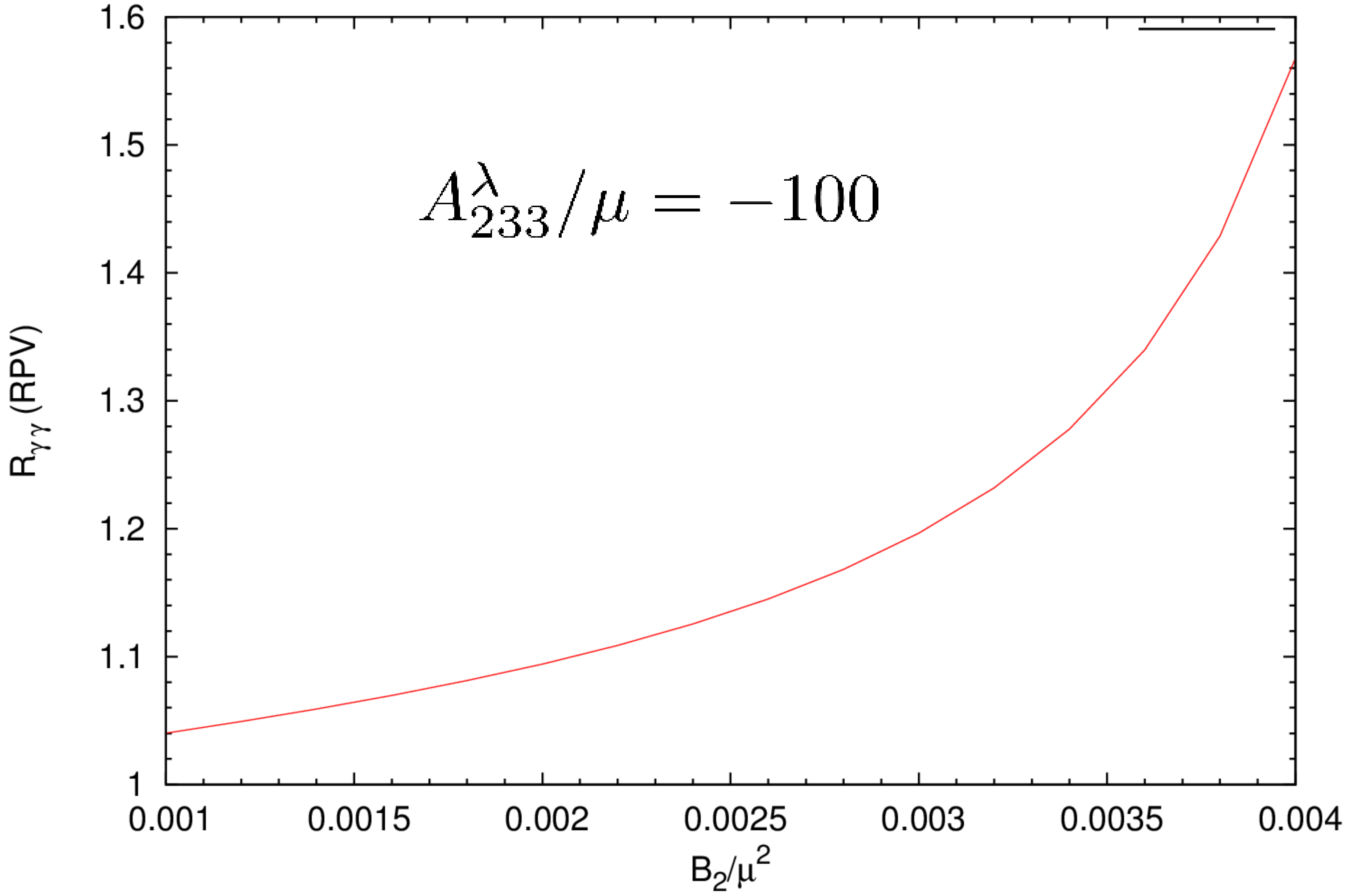
$$-250 \leq \frac{A_{j33}^{\lambda}}{\mu} \leq 250$$

$$A_\tau = 500\ GeV$$

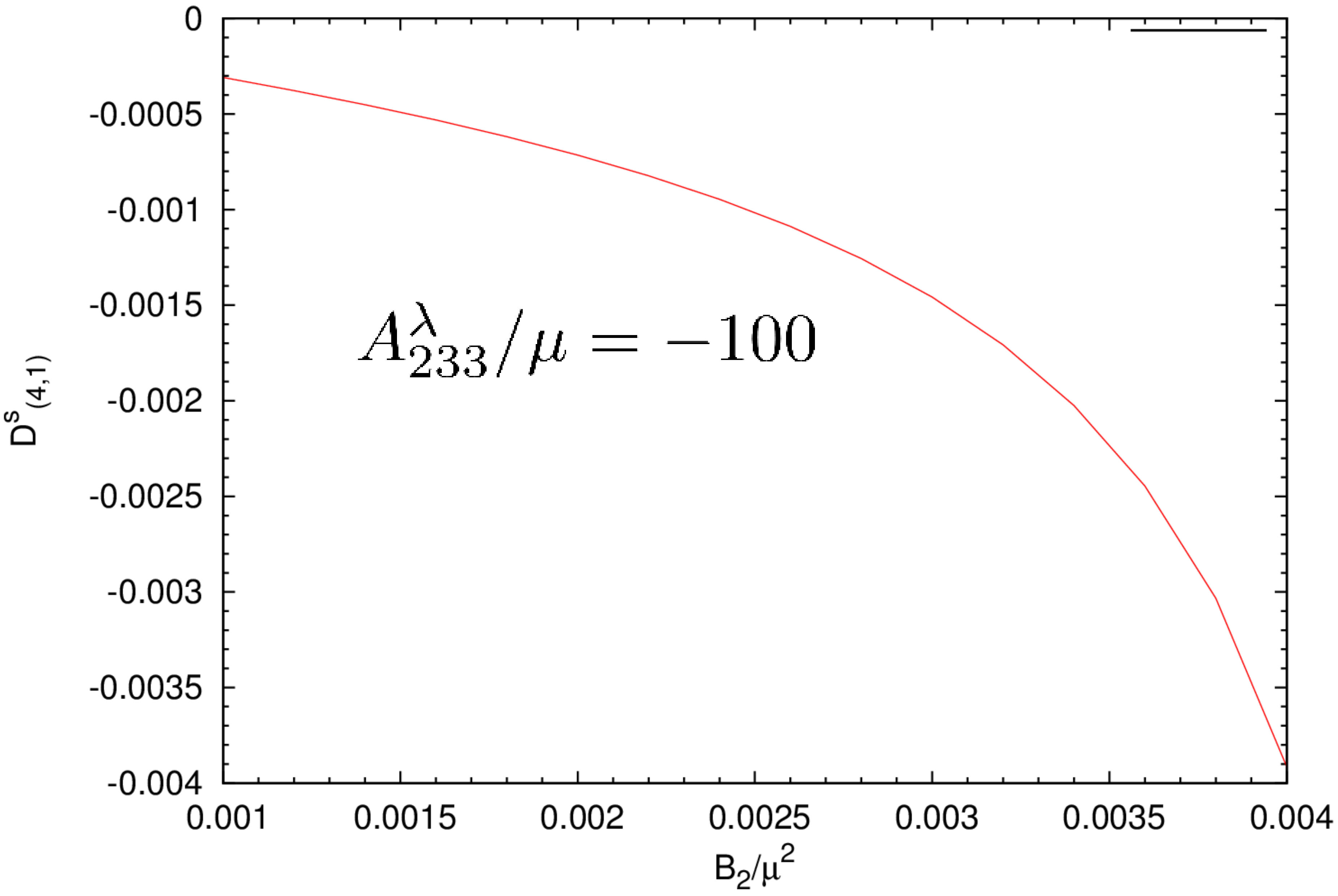
$$\tilde{m}_{h_d}^2 = 150 - 500\ GeV$$

$$1 \leq B_j/\mu^2 < 4$$

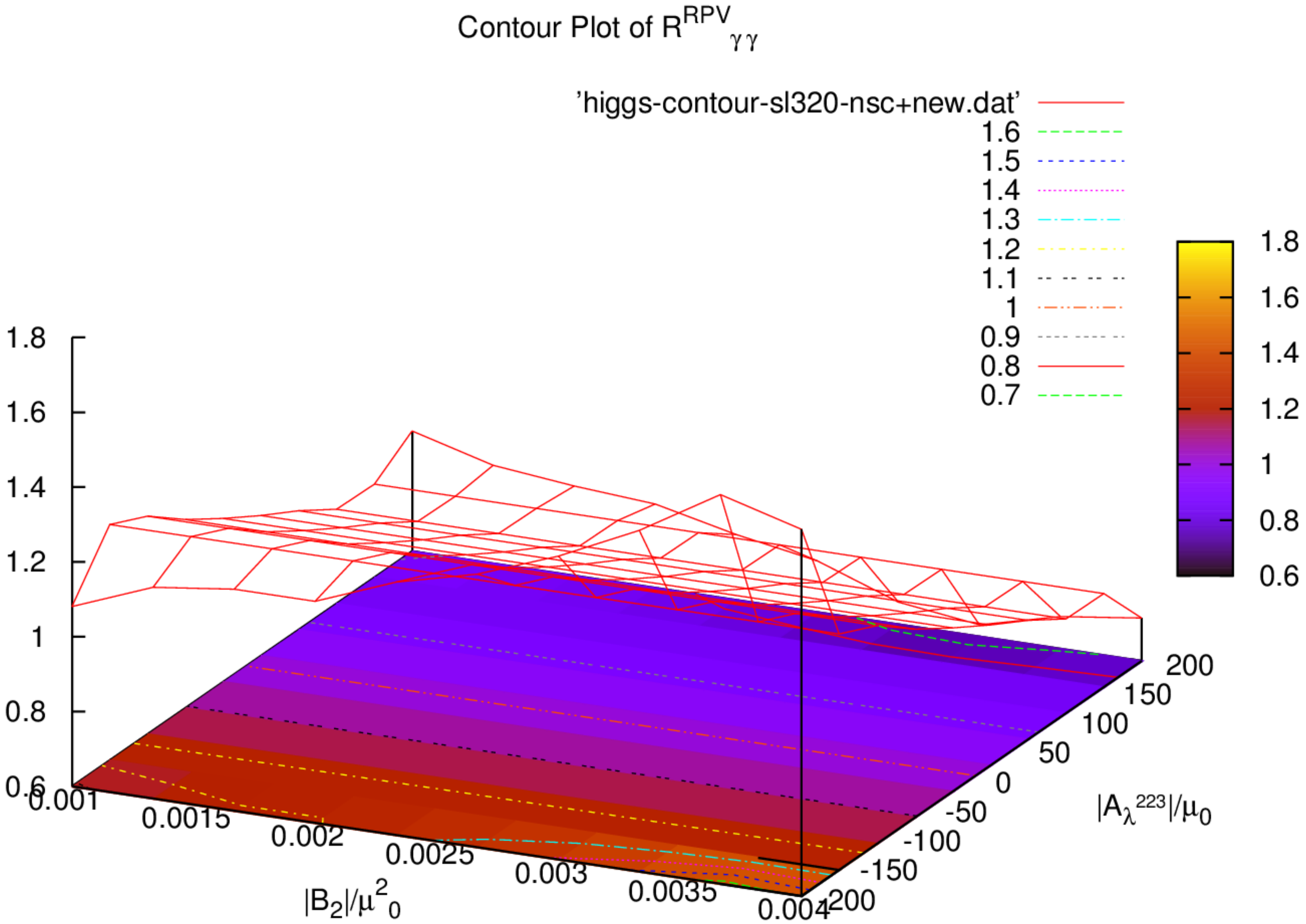
$R_{\gamma\gamma}^{RPV}$ vs. B_2/μ^2



$\mathcal{D}^s_{41}$ vs. B_2/μ^2



Contour plot of $R_{\gamma\gamma}^{RPV}$ the plane of $B_2 A_{233}^{\lambda}$



Summary

- In the absence of theory of flavor the only alternative is to confront various RPV couplings to the constraints from various observables.
- For the soft-trilinear R violating parameters, higgs to di-photon rate offers a unique chance to constrain so far completely unconstrained parameters.
- Interplay of RPV contributions in general is very complicated, however, negative soft trilinear couplings can provide dominating contributions.

Thank You