Institute for Basic Science

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Stop/sbottom LSP with RPV

Eung Jin Chun

EJC, S. H. Jung, H.M. Lee, S.C. Park, 1408.4508

Outline

- Anomalies at the LHC: R_K, W_R, LeptoQuark.
- RPV & neutrino masses.
- Stop/sbottom LSP: constraints and LQ signatures.

R_K in $b \to sll$: LHCb, 1406.6482

- 2.6σ

$$R_K = \frac{\mathcal{B}(\bar{B} \to \bar{K}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}ee)} \qquad R_K^{LHCb} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

- **Model-independent analysis:** Hiller-Schmaltz, 1408.1627

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu\gamma_5 \ell]\,,$$

$$\mathcal{O}_S = [\bar{s}P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}_P = [\bar{s}P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \qquad \mathcal{O}'\,(P_L \leftrightarrow P_R)$$

$$\mathcal{O}_T = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu} \ell]\,, \quad \mathcal{O}_{T5} = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell]\,.$$

$$0.7 \lesssim {\rm Re}[X^e - X^\mu] \lesssim 1.5\,,$$
$$X^\ell = C_9^{{\rm NP}\ell} + C_9^{\prime\ell} - (C_{10}^{{\rm NP}\ell} + C_{10}^{\prime\ell})\,, \quad \ell = e, \mu\,.$$

A model

- Introduce a scalar leptoquark ϕ :

$$\mathcal{L} = -\lambda_{be}\,\phi\,(\bar{b}P_L\ell_e) - \lambda_{se}\,\phi\,(\bar{s}P_L\ell_e)$$

- Leading to $\mathcal{H}_{\rm eff} = \dfrac{\lambda_{se}\lambda_{be}^*}{2M^2}\,[\bar{s}\gamma^\mu P_R b]\,[\bar{\ell}_e\gamma_\mu P_L\ell_e]$

$$C_{10}^{\prime e} = -C_9^{\prime e} = \frac{\lambda_{se}\lambda_{be}^*}{V_{tb}V_{ts}^*}\frac{\pi}{\alpha_e}\frac{\sqrt{2}}{4M^2G_F} = -\frac{\lambda_{se}\lambda_{be}^*}{2M^2}(24\,\text{TeV})^2$$

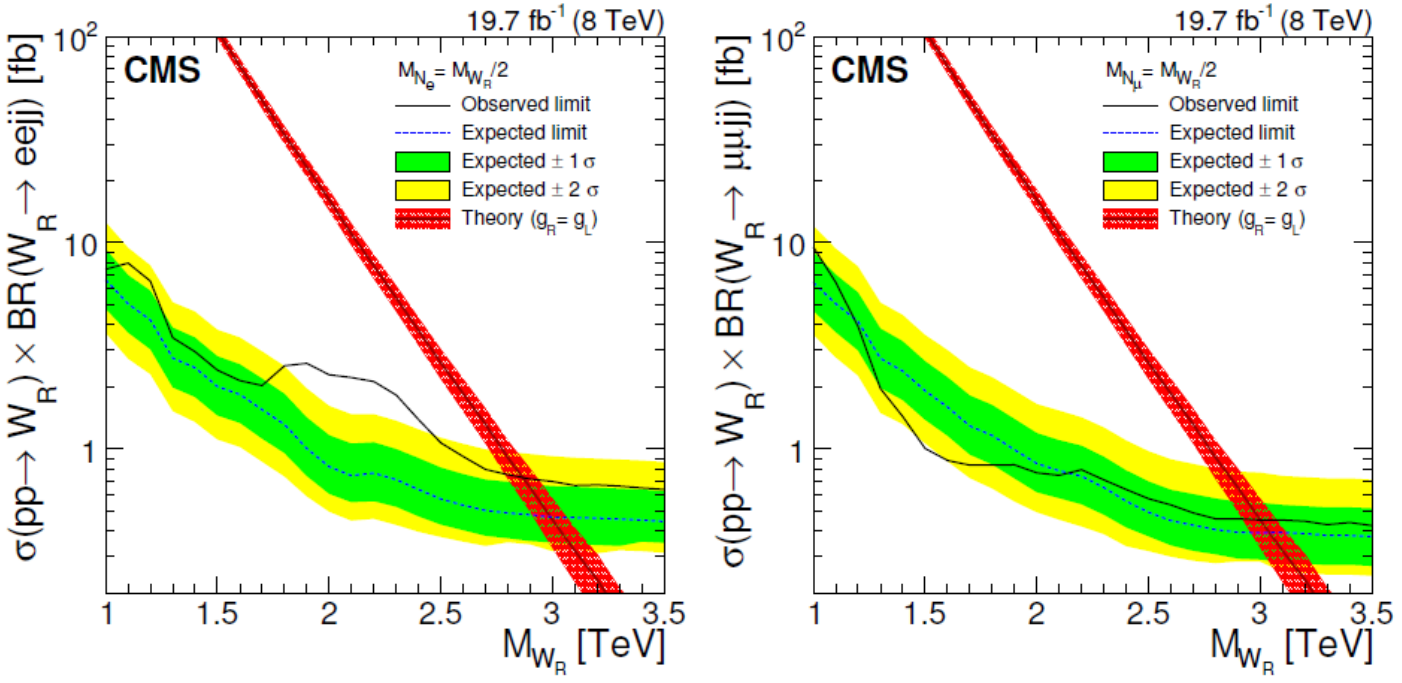
- R_K requires $C_9^{\prime e} = -C_{10}^{\prime e} \simeq 1/2$

$$1\,\text{TeV} \lesssim M \lesssim 48\,\text{TeV}$$
$$2\cdot 10^{-3} \lesssim |\lambda_{se}\lambda_{be}^*| \lesssim 4$$
$$4\cdot 10^{-4} \lesssim |\lambda_{qe}| \lesssim 5$$

W_R anomaly: CMS, 1407.3683

- 2.8 σ

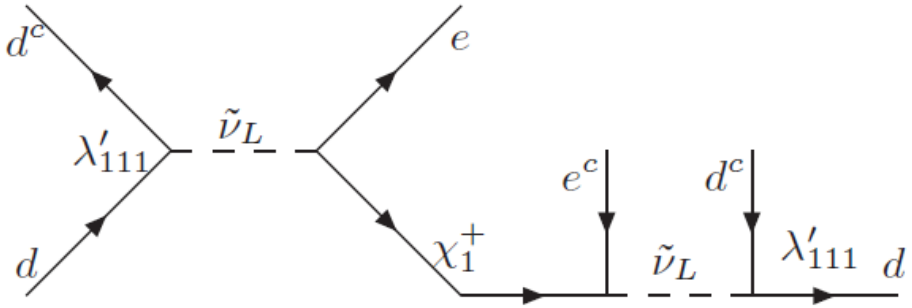
$$W_R \to \ell_1 N_\ell \to \ell_1 \ell_2 W_R^* \to \ell_1 \ell_2 q\bar{q}.$$



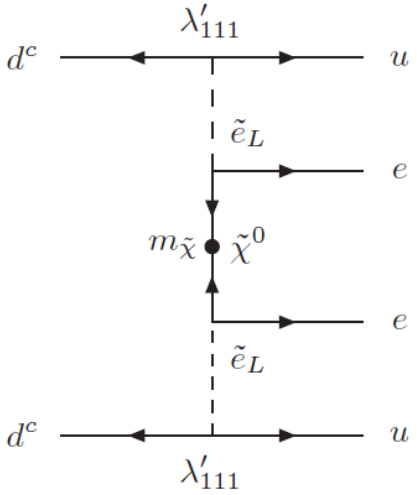
- An eejj resonance around 2 TeV.

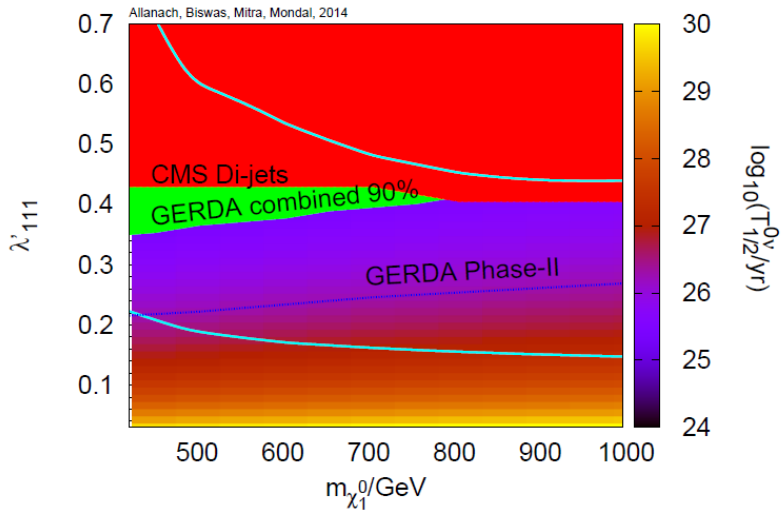
Allanach, et.al., 1408.5439

- Single production of a sneutrino and decay via LQD_{111} :



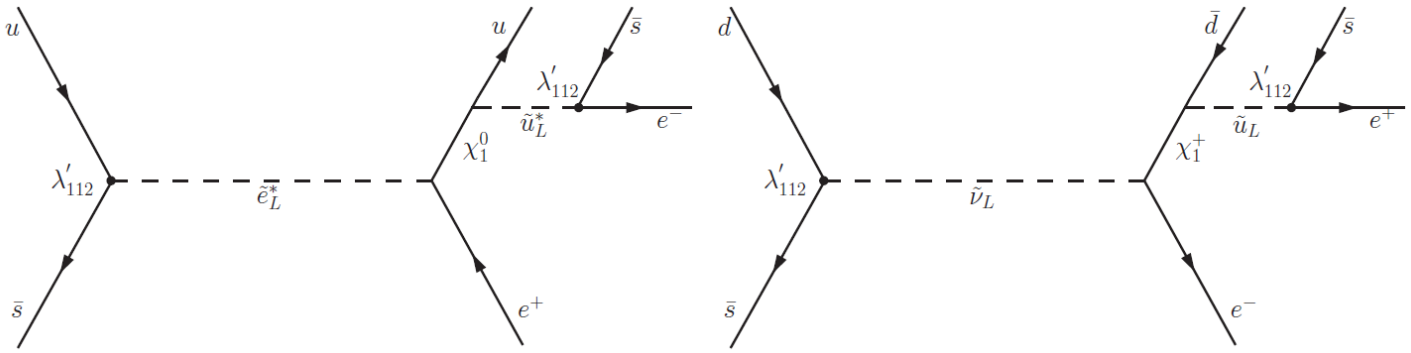
- Connection to $0\nu\beta\beta$:



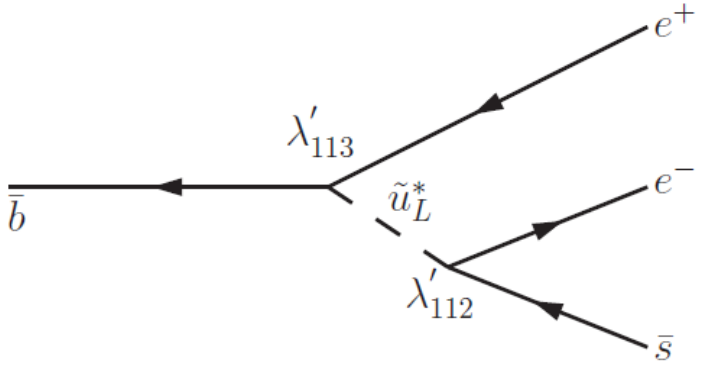


Biswas, et.al., 1409.0882

- A slepton for eejj from LQD_{112}:



- R_K combined with LQD_{113}:

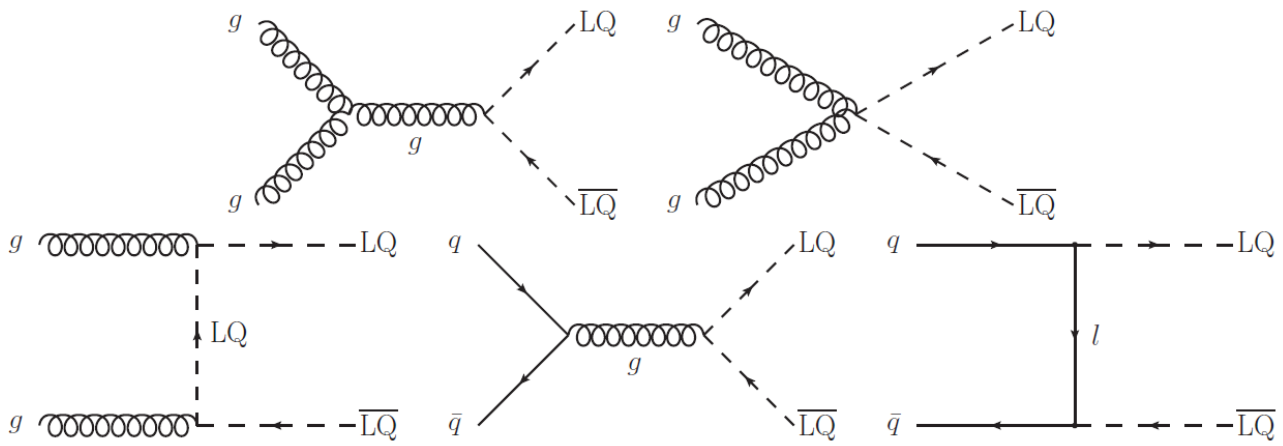


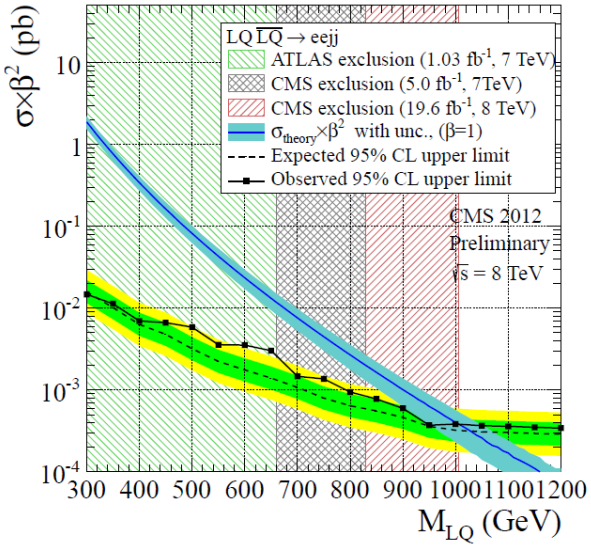
$$\frac{0.7}{(21\ \text{TeV})^2} \lesssim \text{Re}\left[\frac{\lambda'_{112}\lambda'^*_{113}}{m^2_{\tilde{u}_L}}\right] \lesssim \frac{1.5}{(21\ \text{TeV})^2}$$

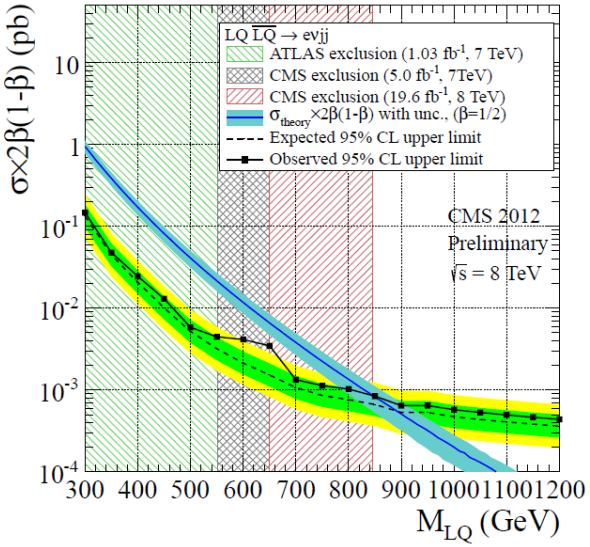
$$C'^{e}_{10} = -C'^{e}_{9} \simeq -\frac{\lambda'_{112}\lambda'^*_{113}}{2m^2_{\tilde{u}_L}}(21\ \text{TeV})^2$$

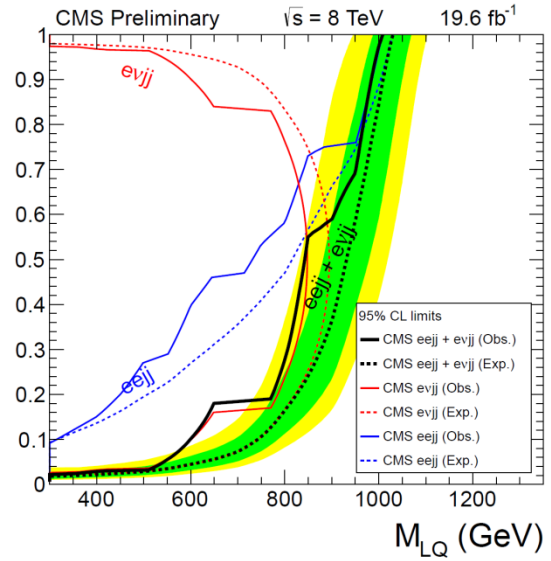
LQ excesses: CMS EXO-PAS-12-041

- 2.6σ

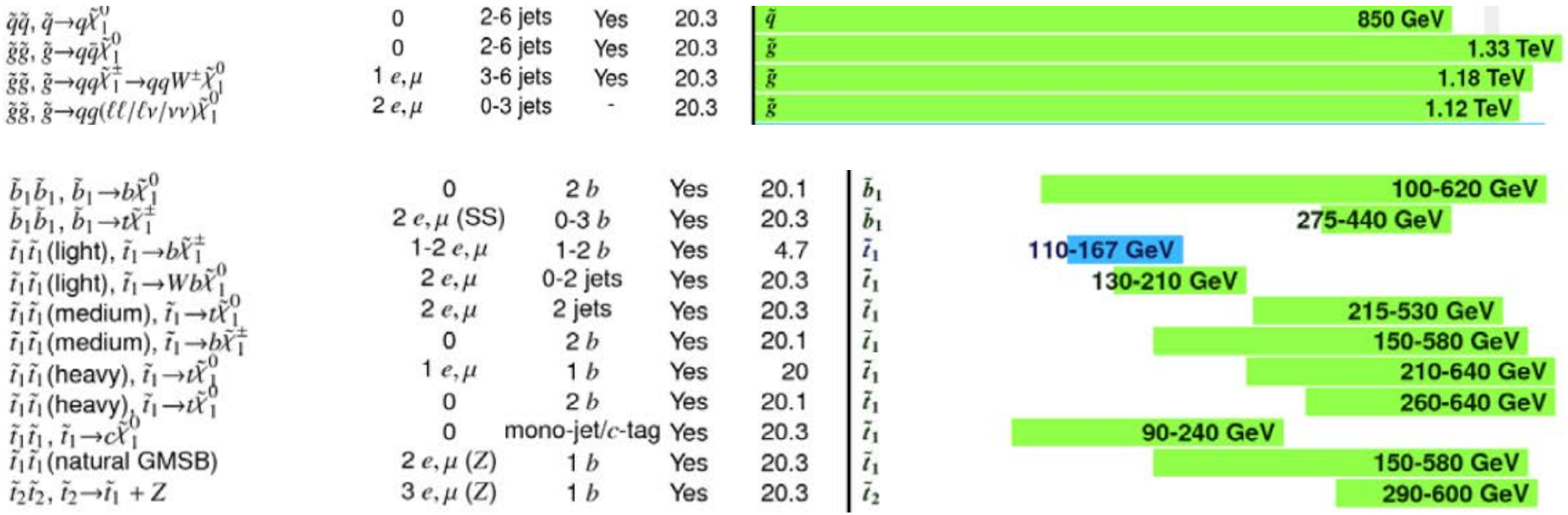


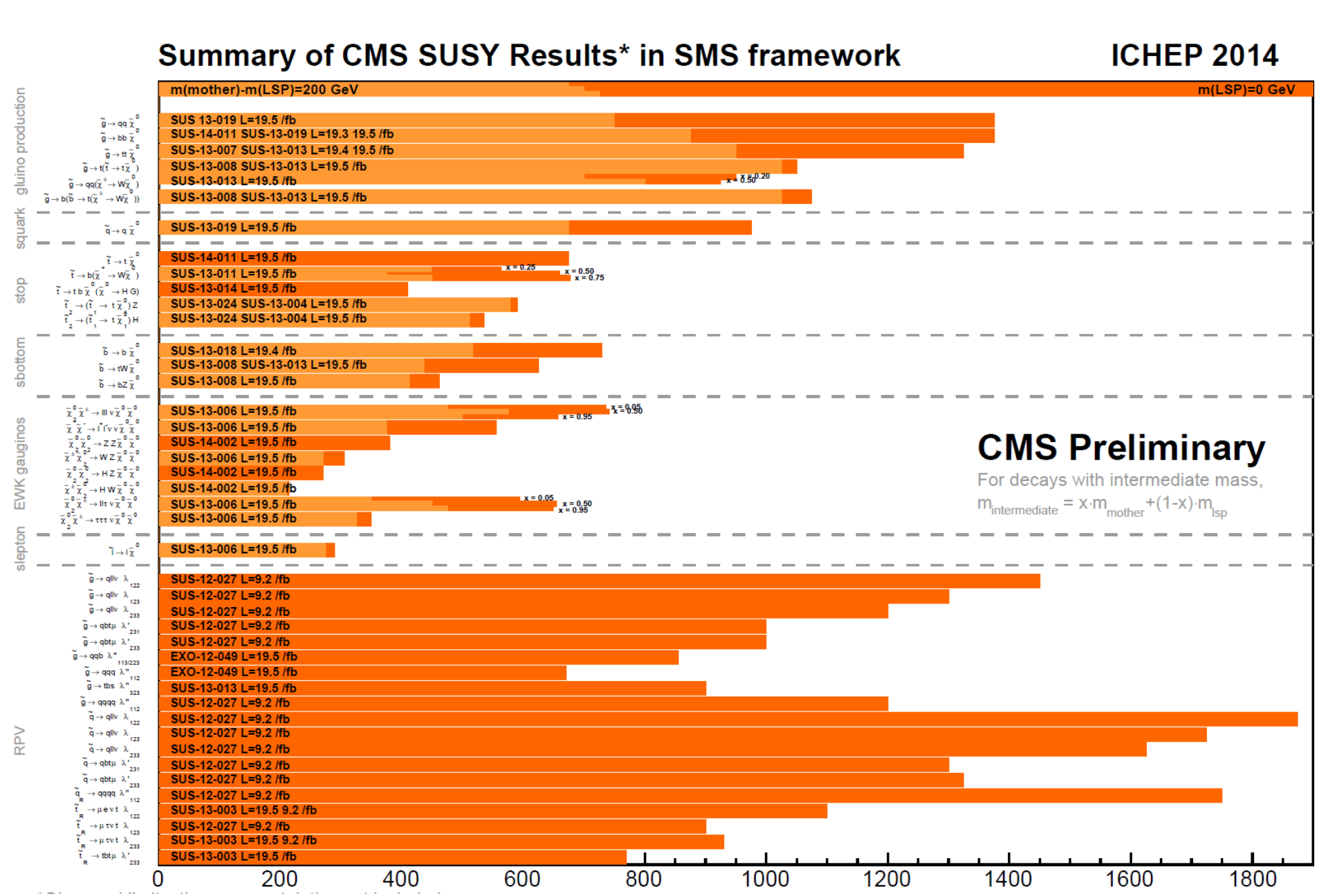






SUSY hospitalized …




Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-13-019 L=19.5 /fb
SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-13-006 L=19.5 /fb
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SUS-14-002 L=19.5 /fb
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SUS-13-006 L=19.5 /fb
SUS-12-027 L=9.2 /fb
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SUS-12-027 L=9.2 /fb
EXO-12-049 L=19.5 /fb
EXO-12-049 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-12-027 L=9.2 /fb
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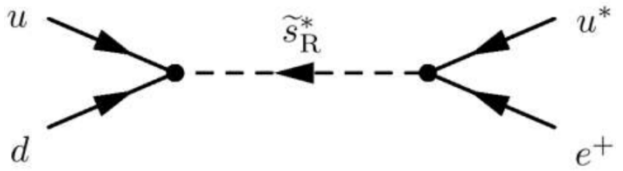
SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother +(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800

RPV SUSY

- Gauge invariance allows L & B violation:

$$W_{\rm RPV} = \epsilon_i \mu L H_u + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k$$

- Proton stability: $|\lambda'\lambda''| < 10^{-22}$



- B parity allowing L violation:

$$W_{\rm RPV} = \epsilon_i \mu L H_u + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k$$

$$V_{\rm soft,LH} = B_i L_i H_u + m^2_{L_i H_d} L_i H^\dagger_d + h.c.$$

$$\Rightarrow \langle \tilde{\nu}_i \rangle \equiv a_i \langle H_d \rangle \qquad a_i = (B_i t_\beta + m^2_{L_i H_d})/m^2_{\tilde{\nu}_i}$$

Bilinear RPV (LH)

- Neutrino–neutralino, charged-lepton–chargino mixing:

$$\begin{pmatrix}\nu_i\\ \chi_j^0\end{pmatrix}\longrightarrow\begin{pmatrix}\nu_i-\theta_{ik}^N\chi_k^0\\ \chi_j^0+\theta_{lj}^N\nu_l\end{pmatrix}\qquad \begin{pmatrix}e_i\\ \chi_j^-\end{pmatrix}\to\begin{pmatrix}e_i-\theta_{ik}^L\chi_k^-\\ \chi_j^-+\theta_{lj}^L e_l\end{pmatrix}\quad;\quad \begin{pmatrix}e_i^c\\ \chi_j^+\end{pmatrix}\to\begin{pmatrix}e_i^c-\theta_{ik}^R\chi_k^+\\ \chi_j^++\theta_{lj}^R e_l^c\end{pmatrix}$$

$$(\tilde B,\tilde W_3,\tilde H_d^0,\tilde H_u^0)\qquad (\tilde W^-,\tilde H^-)\qquad (\tilde W^+,\tilde H^+)$$

$$\theta_{ij}^N = \xi_i c_j^N c_\beta - \epsilon_i\delta_{j3}$$

$$(c_j^N) = \frac{M_Z}{F_N}\left(\frac{s_W M_2}{c_W^2 M_1+s_W^2 M_2},-\frac{c_W M_1}{c_W^2 M_1+s_W^2 M_2},-s_\beta\frac{M_Z}{\mu},c_\beta\frac{M_Z}{\mu}\right)$$

$$\theta_{ij}^L = \xi_i c_j^L c_\beta - \epsilon_i\delta_{j2}\ ,\quad \theta_{ij}^R = \frac{m_i^e}{F_C}\xi_i c_j^R c_\beta$$

$$(c_j^L) = -\frac{M_W}{F_C}\left(\sqrt{2},2s_\beta\frac{M_W}{\mu}\right)\ ,$$

$$(c_j^R) = -\frac{M_W}{F_C}\left(\sqrt{2}\left(1-\frac{M_2}{\mu}t_\beta\right),\frac{M_2^2 c_\beta^{-1}}{\mu M_W}+2\frac{M_W}{\mu}c_\beta\right)$$

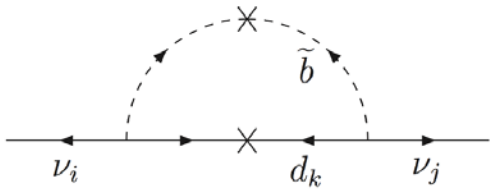
$$\xi_i \equiv a_i - \epsilon_i$$

$$F_N = M_1M_2/(c_W^2M_1+s_W^2M_2)+M_Z^2 s_{2\beta}/\mu$$

$$F_C = M_2+M_W^2 s_{2\beta}/\mu$$

Neutrino masses from RPV

- Tree (LH) + loop (LQD, LLE):



$$m^{\rm tree}_{\nu,ij} = \frac{M_Z^2}{F_N}\xi_i\xi_j c_\beta^2\,,$$

$$m^{\rm loop}_{\nu,ij} = \sum_{k=1}^{3}\frac{3}{16\pi^2}(\lambda'_{ik3}\lambda'_{j3k}+\lambda'_{i3k}\lambda'_{jk3})\frac{m_{d_k}m_b X_b}{m^2_{\tilde{b}_2}-m^2_{\tilde{b}_1}}\ln\frac{m^2_{\tilde{b}_2}}{m^2_{\tilde{b}_1}},$$

- Neutrino mass ~ 0.1 eV requires

$$|\xi_i c_\beta| \approx 10^{-6}\,,$$

$$|\lambda'_{ik3}\lambda'_{i3k}|^{1/2} \approx 3.4\times10^{-3}\sqrt{\frac{m_d}{m_{d_k}}},$$

Stop/sbottom vertices from LH

$$
\begin{aligned}
-\mathcal{L} &= \tilde{t}_L \bar{t} \left(\kappa^t_{L\nu_i} P_L + \kappa^t_{R\nu_i} P_R\right) \nu_i + \tilde{t}_R \bar{t} \left(\rho^t_{L\nu_i} P_L + \rho^t_{R\nu_i} P_R\right) \nu_i + h.c. \\
&+ \tilde{t}_L \bar{b} \left(\kappa^t_{Le_i} P_L + \kappa^t_{Re_i} P_R\right) e_i + \tilde{t}_R \bar{b} \left(\rho^t_{Le_i} P_L + \rho^t_{Re_i} P_R\right) e_i + h.c., \\
-\mathcal{L} &= \tilde{b}_L \bar{b} \left(\kappa^b_{L\nu_i} P_L + \kappa^b_{R\nu_i} P_R\right) \nu_i + \tilde{b}_R \bar{b} \left(\rho^b_{L\nu_i} P_L + \rho^b_{R\nu_i} P_R\right) \nu_i + h.c. \\
&+ \tilde{b}_L \bar{t} \left(\kappa^b_{Le_i} P_L + \kappa^b_{Re_i} P_R\right) e_i + \tilde{b}_R \bar{t} \left(\rho^b_{Le_i} P_L + \rho^b_{Re_i} P_R\right) e_i + h.c.,
\end{aligned}
$$

$$
\begin{aligned}
&\kappa^t_{L\nu_i} = y_t c_4^N \xi_i c_\beta\,, && \kappa^t_{R\nu_i} = (\frac{\sqrt{2}}{6} g' c_1^N + \frac{1}{\sqrt{2}} g c_2^N) \xi_i c_\beta, \\
&\rho^t_{L\nu_i} = \frac{2\sqrt{2}}{3} g' c_1^N \xi_i c_\beta\,, && \rho^t_{R\nu_i} = y_t c_4^N \xi_i c_\beta, \\
&\kappa^t_{Le_i} = -y_b c_2^L \xi_i c_\beta + y_b \epsilon_i\,, && \kappa^t_{Re_i} = g \frac{m_i^e}{F_C} c_1^R \xi_i c_\beta, \\
&\rho^t_{Le_i} = 0\,, && \rho^t_{Re_i} = -y_t \frac{m_i^e}{F_C} c_2^R \xi_i c_\beta.
\end{aligned}
$$

$$
\begin{aligned}
&\kappa^b_{L\nu_i} = y_b c_3^N \xi_i c_\beta - y_b \epsilon_i\,, && \kappa^b_{R\nu_i} = (\frac{\sqrt{2}}{6} g' c_1^N - \frac{1}{\sqrt{2}} g c_2^N) \xi_i c_\beta, \\
&\rho^b_{L\nu_i} = -\frac{\sqrt{2}}{3} g' c_1^N \xi_i c_\beta\,, && \rho^b_{R\nu_i} = y_b c_3^N \xi_i c_\beta - y_b \epsilon_i, \\
&\kappa^b_{Le_i} = -y_t \frac{m_i^e}{F_C} c_2^R \xi_i c_\beta\,, && \kappa^b_{Re_i} = g \frac{m_i^e}{F_C} c_1^R \xi_i c_\beta, \\
&\rho^b_{Le_i} = 0\,, && \rho^b_{Re_i} = -y_b c_2^L \xi_i c_\beta + y_b \epsilon_i.
\end{aligned}
$$

Stop/sbottom vertices from LQD

$$
\begin{aligned}
-\mathcal{L} &= \lambda'_{i33}\left(\tilde{b}_L\bar{b}P_L\nu_i + \tilde{b}_R\bar{b}P_R\nu_i - \tilde{t}_L\bar{b}P_Le_i - \tilde{b}_R\bar{t}P_Re_i\right) + h.c. \\
&+ \lambda'_{ij3}\left(\tilde{b}_R\bar{d}_jP_R\nu_i - \tilde{b}_R\bar{u}_jP_Re_i\right) + h.c. \\
&+ \lambda'_{i3k}\left(\tilde{b}_L\bar{d}_kP_L\nu_i - \tilde{t}_L\bar{d}_kP_Le_i\right) + h.c..
\end{aligned}
$$

Sbottom/stop decays from LH

$$\tilde{b}_1 \to e_i t, \nu_i b$$

$$\tilde{t}_1 \to e_i b, \nu_i t.$$

$$\begin{aligned} \tilde{q}_L &= \cos\theta_{\tilde{q}}\,\tilde{q}_1 - \sin\theta_{\tilde{q}}\,\tilde{q}_2, \\ \tilde{q}_R &= \sin\theta_{\tilde{q}}\,\tilde{q}_1 + \cos\theta_{\tilde{q}}\,\tilde{q}_2, \end{aligned}$$

$$\beta_{\tilde{b}} \equiv \mathrm{BR}(\tilde{b}_1 \to e_i t)$$

$$\beta_{\tilde{t}} \equiv \mathrm{BR}(\tilde{t}_1 \to e_i b)$$

$$\beta_{\tilde{b}} \approx \frac{\sin^2\theta_{\tilde{b}}|y_b\epsilon_i|^2}{\left[\cos^2\theta_{\tilde{b}}|\frac{\sqrt{2}}{6}g'c_1^N - \frac{1}{\sqrt{2}}gc_2^N|^2 + \sin^2\theta_{\tilde{b}}|\frac{\sqrt{2}}{3}g'c_1^N|^2\right]|\xi_i c_\beta|^2 + (1+\sin^2\theta_{\tilde{b}})|y_b\epsilon_i|^2},$$

$$\beta_{\tilde{t}} \approx \frac{\cos^2\theta_{\tilde{t}}|y_b\epsilon_i|^2}{\left[\cos^2\theta_{\tilde{t}}|\frac{\sqrt{2}}{6}g'c_1^N + \frac{1}{\sqrt{2}}gc_2^N|^2 + \sin^2\theta_{\tilde{t}}|\frac{2\sqrt{2}}{3}g'c_1^N|^2\right]|\xi_i c_\beta|^2 + \cos^2\theta_{\tilde{t}}|y_b\epsilon_i|^2}.$$

Sbottom/stop decays from LQD

- $\mathrm{LQD}_{\mathrm{i33}}$: $\tilde{b}_1 \to e_i t, \nu_i b \qquad \tilde{t}_1 \to e_i b$

$$\beta_{\tilde{b}} \equiv \mathrm{BR}(\tilde{b}_1 \to e_i t) = \frac{\sin^2\theta_{\tilde{b}}}{1+\sin^2\theta_{\tilde{b}}},$$

$$\beta_{\tilde{t}} \equiv \mathrm{BR}(\tilde{t}_1 \to e_i b) = 1\,.$$

- $\mathrm{LQD}_{\mathrm{ij3+i3j}}$: $\tilde{b}_1 \to e_i u_j, \nu_i d_j$ or $\tilde{t}_1 \to e_i d_j$.

$$\beta_{\tilde{b}} \equiv \mathrm{BR}(\tilde{b}_1 \to e_i u_j) = \frac{\sin^2\theta_{\tilde{b}}|\lambda'_{ij3}|^2}{\cos^2\theta_{\tilde{b}}|\lambda'_{i3j}|^2 + 2\sin^2\theta_{\tilde{b}}|\lambda'_{ij3}|^2},$$

$$\beta_{\tilde{t}} \equiv \mathrm{BR}(\tilde{t}_1 \to e_i d_j) = 1\,.$$

LHC constraints for LH_1/LQD_{133}

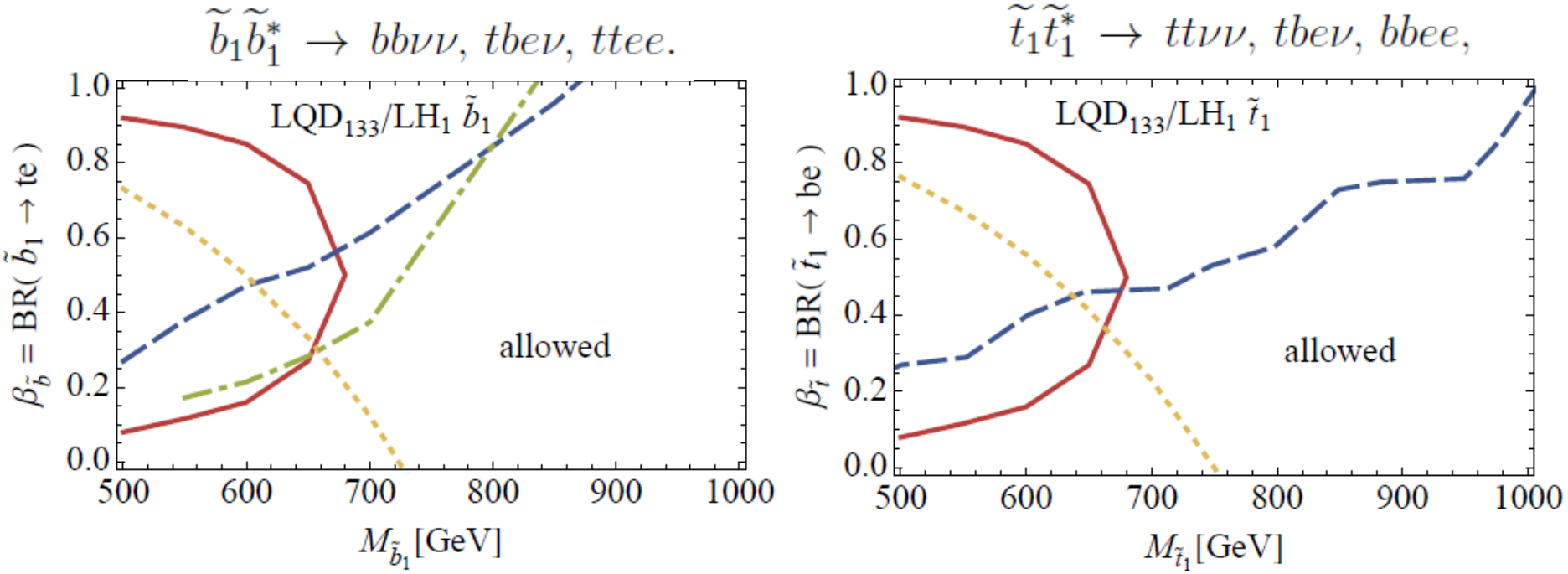
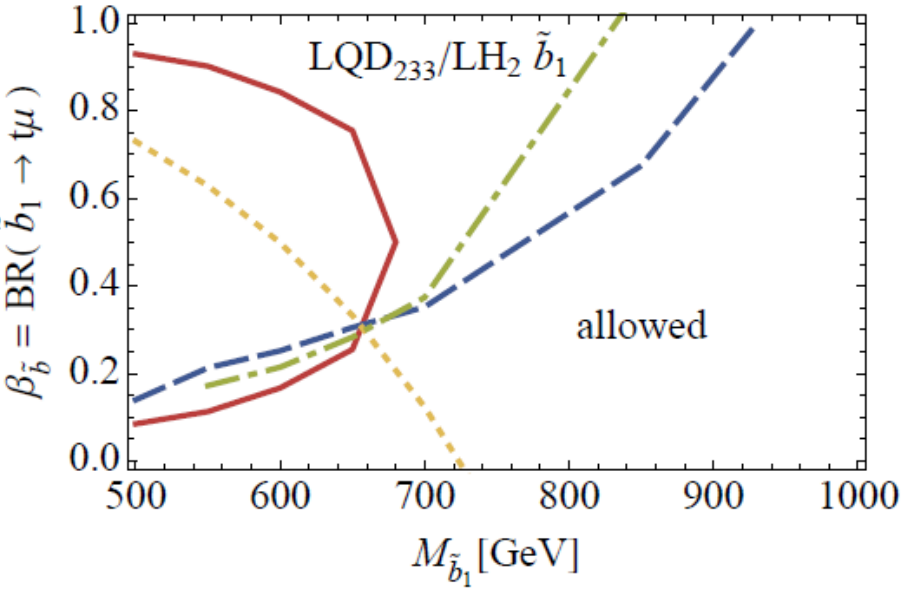
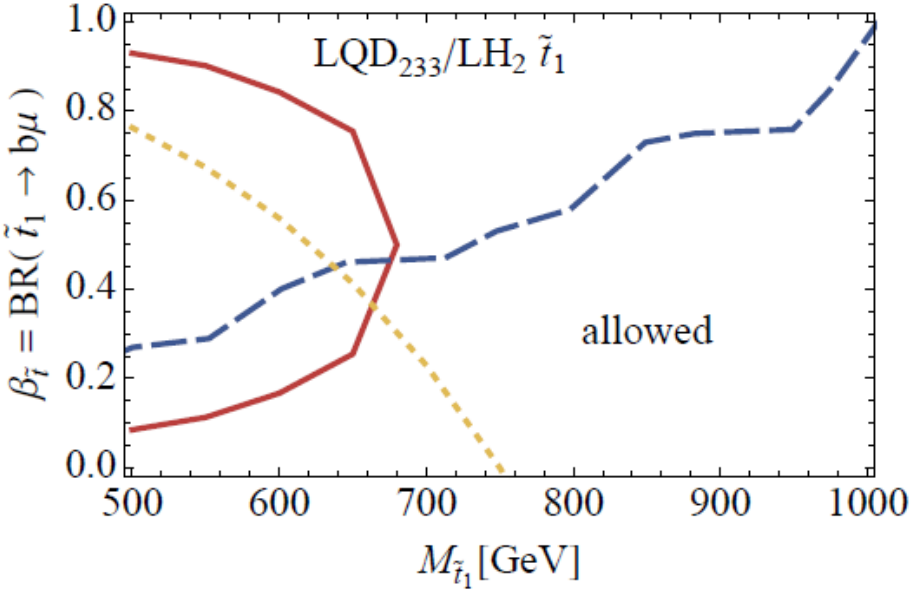


FIG. 2: 95%C.L. Exclusion plots for the sbottom LSP (**left**) and the stop LSP (**right**) from CMS leptoquark searches in $eejj$ (blue-dashed) and $e\nu jj$ (red-solid) channels. Also shown are CMS RPC sbottom and stop searches (yellow-dotted) in $b\bar{b}$+MET and $t\bar{t}$+MET channels. For sbottoms, CMS multilepton ($\geq 3\ell$) RPV search constrains additionally (green-dot-dashed). The region left to each line is excluded. The bounds are equally applicable to LH_1 and LQD_{133} models.

LHC constraints for LH_2/LQD_{233}





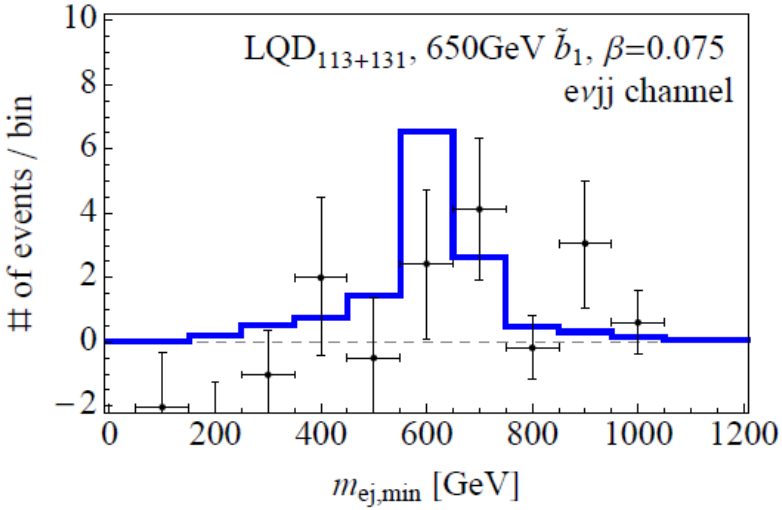
Sbottom RPV for the leptoquark excess

- $\mathrm{LQD}_{113+131}$: $\tilde{b}_1\tilde{b}_1^* \to dd\nu\nu,\ due\nu,\ uuee,$

$$\mathrm{BR}=(1-\beta)^2,\ 2\beta(1-\beta)\ \text{and}\ \beta^2,$$

$$\beta_{\tilde{b}} \equiv \mathrm{BR}(\tilde{b}_1 \to e_i u_j) = \frac{\sin^2\theta_{\tilde{b}}|\lambda'_{ij3}|^2}{\cos^2\theta_{\tilde{b}}|\lambda'_{i3j}|^2 + 2\sin^2\theta_{\tilde{b}}|\lambda'_{ij3}|^2} = 0.075$$

$$\lambda'_{113} = \lambda'_{131}$$
$$\sin^2\theta_{\tilde{b}} = 0.081$$



- Neutrino mass explanation:

$$\lambda'_{113} \sim \lambda'_{131} \sim 10^{-3}$$
$$\lambda'_{i33} \sim 10^{-4} \qquad \xi_i c_\beta \sim 10^{-6}$$

Conclusion

- A few (non-significant) anomlies at LHC so far.
- CMS leptoquark excesses interpreted by a sbottom LSP decaying through a certain LQD couplings.
- Employing the current RPC & RPV SUSY search results at LHC, constrained the scenario of the stop/sbottom LSP with RPV relevant for the neutrino mass generation.