R-Parity Violating Supersymmetry and the 125 GeV Higgs signals

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Outline

- Motivation
- The RPV SUSY framework
- The 125 GeV Higgs signals
- Bilinear RPV
- Trilinear RPV
- Summary

Motivation

- Higgs discovery → Higgs precision measurements

- Patterns of deviations in Higgs signals may shed light on underlying NP where Higgs plays a central role:

  - SUSY, Composite Higgs, SMEFT, Higgs-portal…

- However, non-observation of SUSY particles pushes typical SUSY scale to the multi-TeV range…

Motivation

Heavy SUSY + Decoupling Limit provides natural setting for RPV SUSY:

- 125 GeV Higgs mass obtained from heavy squarks
- RPV bounds relaxed by heavy sleptons/squarks
- RPC effect on Higgs signals is negligible at decoupling limit

- Can generically generate neutrino masses in RPV SUSY

- Experimentally, bounds from traditional SUSY searches do not necessarily apply

The RPV SUSY framework

- Construct additional RPV interactions by replacing $\hat{H}_d \rightarrow \hat{L}$ in $\mathcal{W}_{\text{RPC}}$

Consider only LNV terms

$$\mathcal{W}_{RPV(\not{L})} \supset \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k - \epsilon_i\hat{L}_i\hat{H}_u$$

TRPV (λ_{ijk}, λ'_{ijk}) BRPV (ϵ_i)

$$V_{BRPV} = (M^2_{\tilde{L}H})_i\tilde{L}_iH_d - (B_\epsilon)_i\tilde{L}_iH_u$$

$(B_\epsilon)_3\,,\ \epsilon_3 \neq 0$

- Assume 3rd gen RPV & define RPV "measures": $\delta_B \equiv \dfrac{B_\epsilon}{B_\mu}\,,\quad \delta_\epsilon \equiv \dfrac{\epsilon}{\mu}$

The RPV SUSY framework

- The induced CP-even scalar mass matrix in the $(H_d,\, H_u\,,\, \tilde{\nu}_\tau)^T$ basis:

$$m_E^2 = \begin{pmatrix} s_\beta^2 m_A^2 + m_Z^2 c_\beta^2 + \delta_{11}^{t-\tilde{t}} & -s_\beta c_\beta m_A^2 - m_Z^2 s_\beta c_\beta + \delta_{12}^{t-\tilde{t}} & -\delta_B m_A^2 s_\beta^2 \\ -s_\beta c_\beta m_A^2 - m_Z^2 s_\beta c_\beta + \delta_{12}^{t-\tilde{t}} & c_\beta^2 m_A^2 + m_Z^2 s_\beta^2 + \delta_{22}^{t-\tilde{t}} & \delta_B m_A^2 s_{2\beta}/2 \\ -\delta_B m_A^2 s_\beta^2 & \delta_B m_A^2 s_{2\beta}/2 & m_{\tilde{\nu}_\tau}^2 \end{pmatrix}$$

- We interpret the observed 125 GeV Higgs as the lightest Higgs-sneutrino mixed state h_{RPV}
- Assume the decoupling limit $m_A^2 \gg m_Z^2$
- Assume heavy (multi-TeV) sfermion soft-masses

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- “2X2 RPC block”

The RPV SUSY framework

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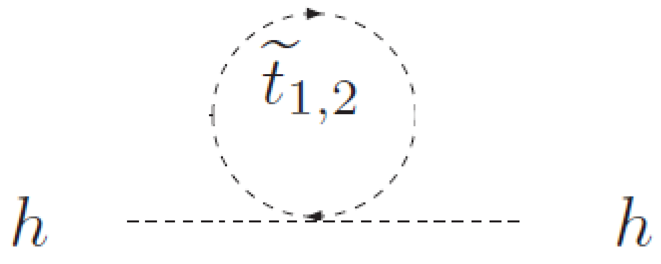
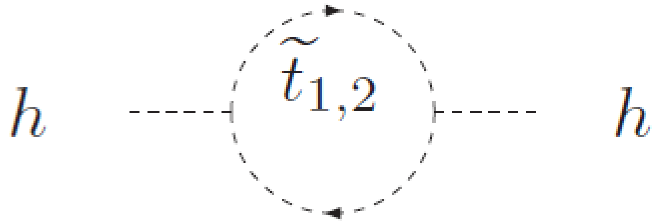
- Top-stop loop corrections necessary to lift Higgs mass ($\delta_{ij}^{t-\tilde{t}}$)





The RPV SUSY framework

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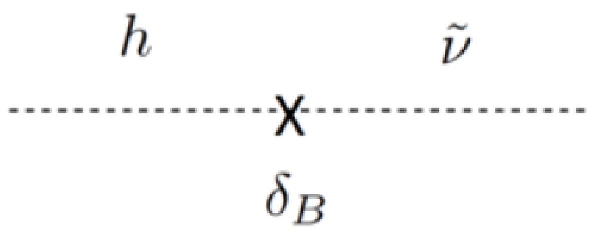
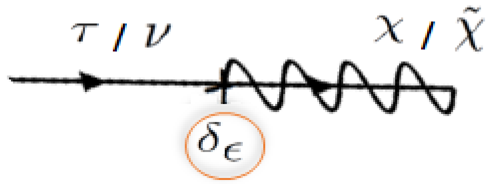
$$m_E^2 = \begin{pmatrix} s_\beta^2 m_A^2 + m_Z^2 c_\beta^2 + \delta_{11}^{t-\tilde{t}} & -s_\beta c_\beta m_A^2 - m_Z^2 s_\beta c_\beta + \delta_{12}^{t-\tilde{t}} & -\delta_B m_A^2 s_\beta^2 \\ -s_\beta c_\beta m_A^2 - m_Z^2 s_\beta c_\beta + \delta_{12}^{t-\tilde{t}} & c_\beta^2 m_A^2 + m_Z^2 s_\beta^2 + \delta_{22}^{t-\tilde{t}} & \delta_B m_A^2 s_{2\beta}/2 \\ -\delta_B m_A^2 s_\beta^2 & \delta_B m_A^2 s_{2\beta}/2 & m_{\tilde{\nu}_\tau}^2 \end{pmatrix}$$

- Top-stop loop corrections necessary to lift Higgs mass ($\delta_{ij}^{t-\tilde{t}}$)
- New BRPV terms generating Higgs-sneutrino mixing (δ_B)



Higgs decays to gauginos

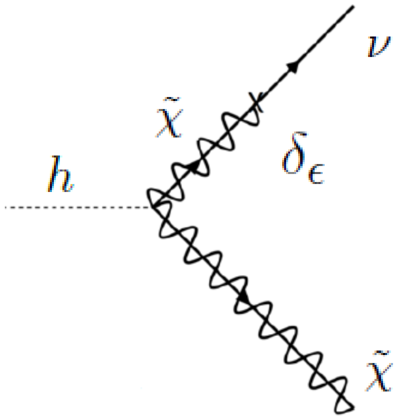


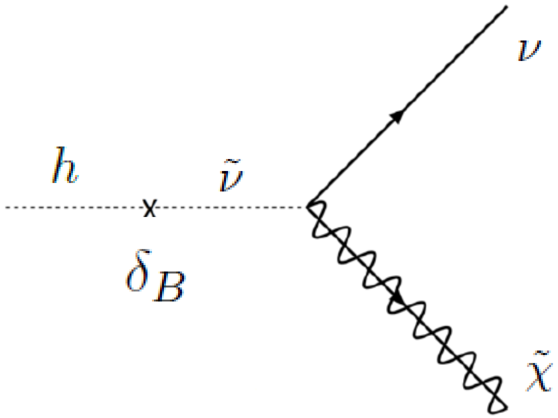
- Similarly $\delta_\epsilon \equiv \frac{\epsilon}{\mu}$ will generate neutrino-neutralino & lepton-chargino mixing in the gaugino sectors:

$h \to \nu_\tau \tilde{\chi}_2^0$

Lightest neutralino

$\nu_\tau \equiv \tilde{\chi}_1^0$

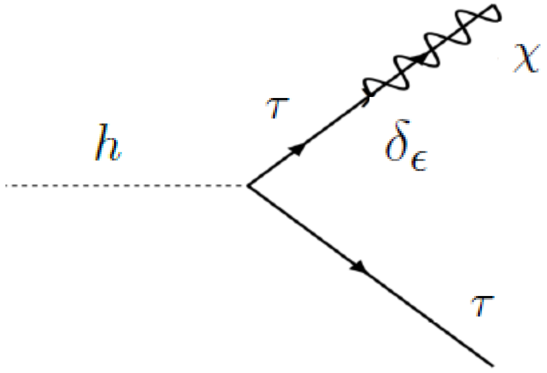


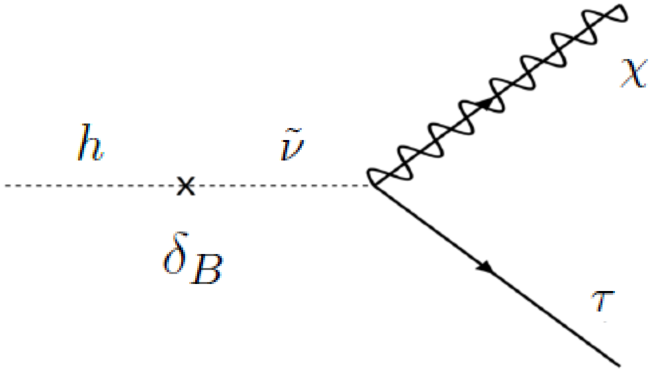


$h \to \tau^\pm \chi_2^\mp$

Lightest chargino

$\tau^+ \equiv \chi_1^+$

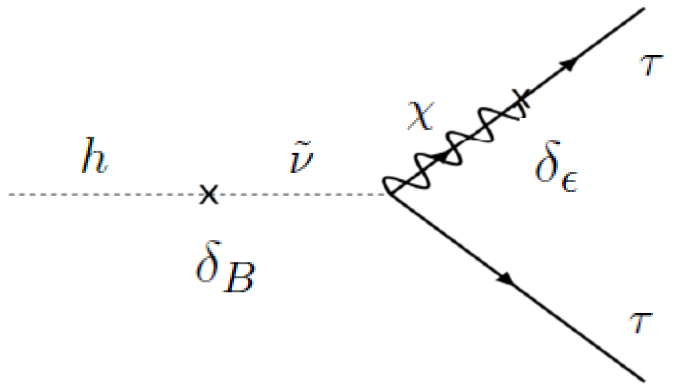




Leptonic Higgs decays

- BRPV effect in Higgs coupling to leptons:

$h \to \tau^+\tau^-$



$\propto \delta_B \delta_\epsilon$

- For 2nd gen BRPV: $\tau \to \mu$ ⇨ BRPV effect in $h \to \mu^+\mu^-$

  (2nd gen BRPV: $\epsilon_2 \neq 0$)

The 125 GeV Higgs signals

- Notation: $$\mu_{if}^{(P)} \equiv \mu_i^{(P)} \cdot \mu_f \cdot \frac{\Gamma_{SM}^h}{\Gamma^h}$$

$$\mu_i^{(P)} = \frac{\sigma(i \to h)}{\sigma(i \to h)_{SM}} \quad , \quad \mu_f = \frac{\Gamma(h \to f)}{\Gamma(h \to f)_{SM}}$$

@ 13 TeV

	ATLAS + CMS
$\mu_{Vbb}^{(hV/hW)}$	$1.07^{+0.23}_{-0.22}$
$\mu_{Vbb}^{(hZ)}$	$1.20^{+0.33}_{-0.31}$
$\mu_{FWW}^{(gg)}$	$1.24^{+0.15}_{-0.16}$
$\mu_{FZZ}^{(gg)}$	$1.09^{+0.11}_{-0.11}$
$\mu_{F\gamma\gamma}^{(gg)}$	$1.02^{+0.12}_{-0.11}$
$\mu_{F\tau\tau}^{(gg)}$	$1.06^{+0.40}_{-0.37}$
$\mu_{V\gamma\gamma}^{(VBF)}$	$1.10^{+0.36}_{-0.31}$
$\mu_{V\tau\tau}^{(VBF)}$	$1.15^{+0.36}_{-0.34}$
$\mu_{F\mu\mu}^{(gg)}$	$0.55^{+0.70}_{-0.70}$

Recently measured signal strength in $h \to \mu\mu$

The 125 GeV Higgs signals

- Notation: $$\mu_{if}^{(P)} \equiv \mu_i^{(P)} \cdot \mu_f \cdot \frac{\Gamma^h_{SM}}{\Gamma^h}$$

$$\mu_i^{(P)} = \frac{\sigma(i \to h)}{\sigma(i \to h)_{SM}} \quad , \quad \mu_f = \frac{\Gamma(h \to f)}{\Gamma(h \to f)_{SM}}$$

- In the BRPV scenario:

Production:

$$\mu_F^{(gg)} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} \ ,$$

$$\mu_V^{(hV)} = \mu_V^{(VBF)} = (g_{hVV}^{RPC})^2$$

$$\langle \tilde{\nu}_\tau \rangle = v_{\tilde{\nu}_\tau} = 0$$

no-"vev" basis

Decay:

$$\mu_{bb} = (g_{hbb}^{RPC})^2 \ ,$$

$$\mu_{VV^\star} = (g_{hVV}^{RPC})^2 \ ,$$

$$\mu_{\mu\mu/\tau\tau} = \frac{\Gamma(h \to \mu^+\mu^-/\tau^+\tau^-)}{\Gamma(h \to \mu^+\mu^-/\tau^+\tau^-)_{SM}} \ ,$$

$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}}$$

@ 13 TeV

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$\mu_{Vbb}^{(hV/hW)}$	$1.07^{+0.23}_{-0.22}$
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$\mu_{F\mu\mu}^{(gg)}$	$0.55^{+0.70}_{-0.70}$

BRPV – numerical setup

- To quantify the impact of BRPV on the Higgs signals we perform numerical simulations

- We randomly vary the input parameters within fixed ranges (ranges further refined for optimization purposes)

- Consider light gaugino states of $\mathcal{O}(100\ \mathrm{GeV})$ in cases where $h \to \nu_\tau \tilde{\chi}_2^0$ / $\tau^\pm \chi_2^\mp$

Input parameters

	Range	
δ_ϵ	$[0, 0.5]$	
μ	$[90, 1000]$	[GeV]
M_1	$[100, 2500]$	[GeV]
M_2	$[100, 2500]$	[GeV]
t_β	$[2, 30]$	
δ_B	$[0, 0.5]$	
m_A	$[1000, 10000]$	[GeV]
$m_{\tilde{\nu}_\tau}$	$[200, 800]$	[GeV]
$m_{\tilde{q}}$	$[1000, 8000]$	[GeV]
$\tilde{A}$	$[0, 4000]$	[GeV]
$m_{\tilde{b}_{RR}}$	$[2000, 5000]$	[GeV]
$m_{\tilde{\tau}_{RR}}$	$[1000, 5000]$	[GeV]

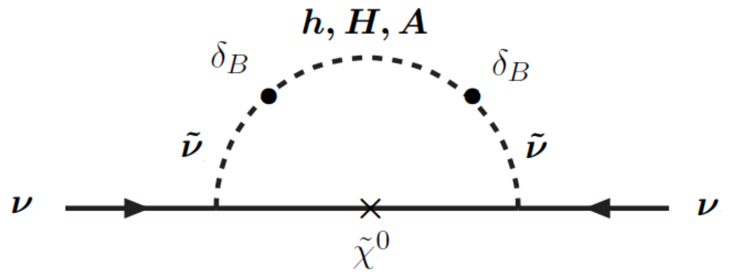
BRPV – “filters”

- Higgs mass: $122\,\mathrm{GeV} < m_h^{calc} < 128\ \mathrm{GeV}$

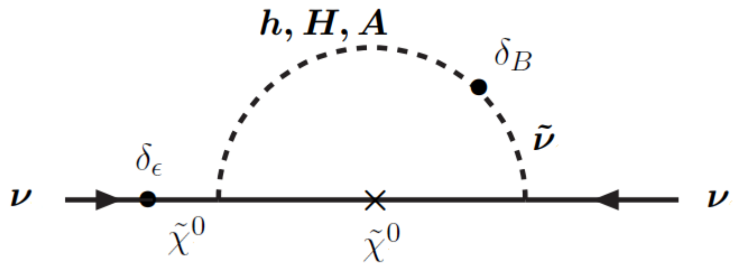
  Allow for $\pm 3\ \mathrm{GeV}$ theoretical uncertainty in m_h^{calc}

- Neutrino mass: $m_{\nu_\mu} < 0.19\ \mathrm{MeV}$ (2nd gen BRPV) or $m_{\nu_\tau} < 18.2\ \mathrm{MeV}$ (3rd gen BRPV)

  Strongest constraints on BRPV parameters arise @ tree-level $m_\nu \propto \delta_\epsilon^2$ & 1-loop



$m_\nu \propto \delta_B^2$

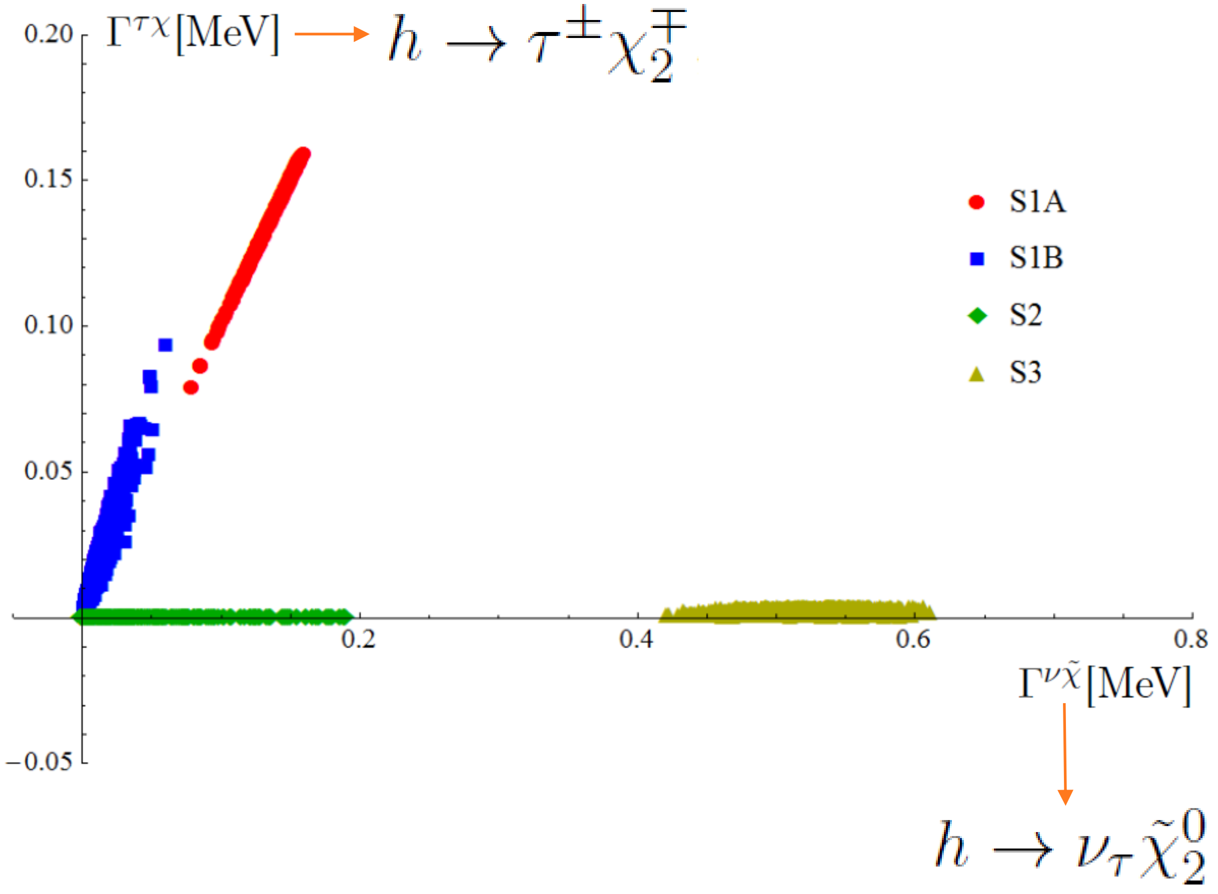


$m_\nu \propto \delta_B \delta_\epsilon$

- Higgs signals: Require them to agree with measurements @ 2σ level

BRPV Higgs decays $h \to \nu_\tau \tilde{\chi}_2^0$ / $\tau^\pm \chi_2^\mp$

- S1A: gaugino-like scenario $M_2 \ll \mu$ & nearly degenerate neutralino-chargino, $m_{\tilde{\chi}_2^0} \simeq m_{\chi_2^\pm} < m_h$
- S1B: higgsino-like scenario $\mu \ll M_2$ & nearly degenerate neutralino-chargino, $m_{\tilde{\chi}_2^0} \simeq m_{\chi_2^\pm} < m_h$
- S2: $m_{\tilde{\chi}_2^0} < m_h < m_{\chi_2^\pm}$ such that only $h \to \nu_\tau \tilde{\chi}_2^0$ is kinematically allowed (broken degeneracy)
- S3: Hierarchy $\mu \sim M_1 \ll M_2$ with $m_{\tilde{\chi}_2^0} < m_{\chi_2^\pm} \lesssim m_h$ (broken degeneracy)

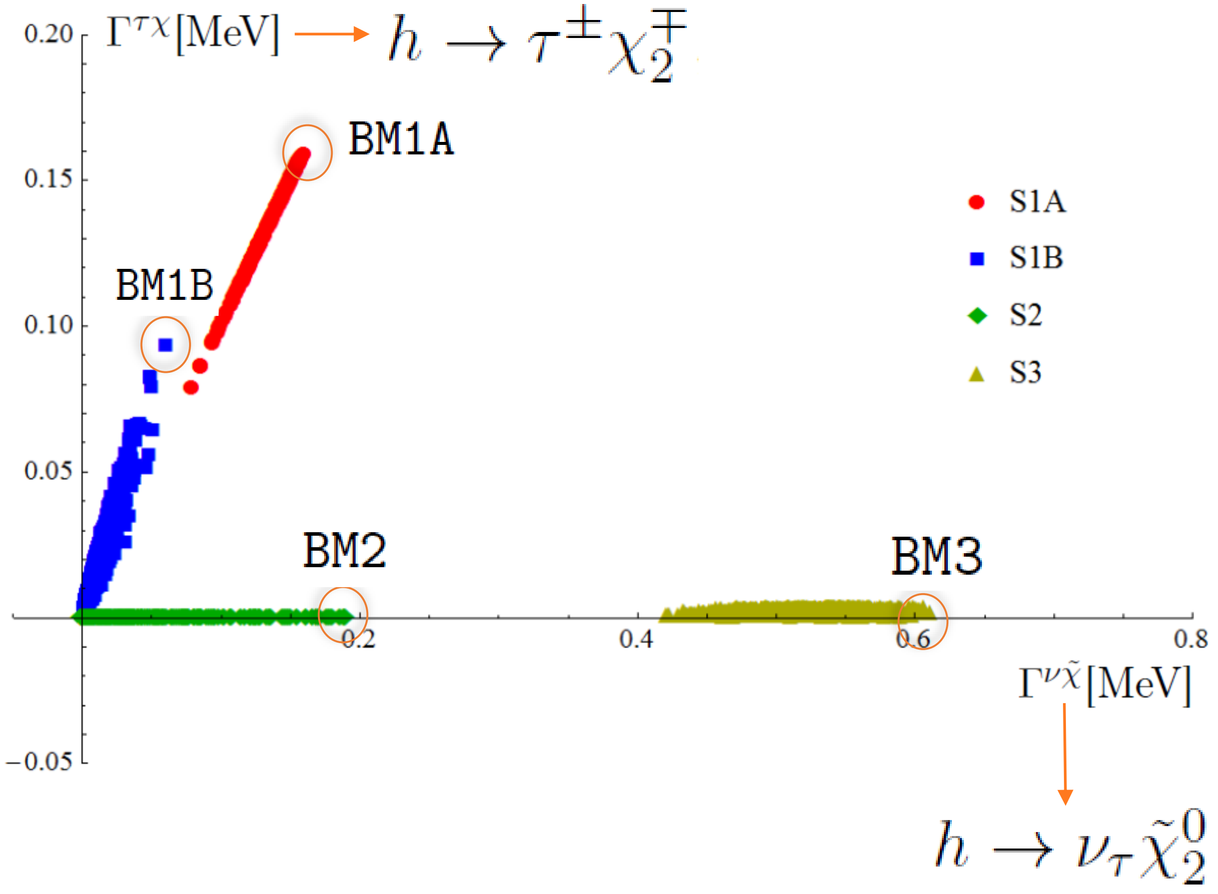


BRPV Higgs decays $h \to \nu_\tau \tilde{\chi}_2^0 \,/\, \tau^\pm \chi_2^\mp$

Benchmarks chosen so as to maximize the BRPV effect

		BM1A	BM1B	BM2	BM3	
$h \to \nu_\tau \tilde{\chi}_2^0$ ←	$\Gamma^{\nu\tilde{\chi}}$	0.159	0.06	0.189	0.61	[MeV]
$h \to \tau^\pm \chi_2^\mp$ ←	$\Gamma^{\tau\chi}$	0.158	0.09	0	0.002	[MeV]

Will affect Higgs signals via Γ^h



BRPV Higgs decays $h \to \nu_\tau \tilde{\chi}_2^0 \,/\, \tau^\pm \chi_2^\mp$

- $\mathcal{O}(25\%)$ deviation in di-photon channels due to light charginos in BM1A
- $\mathcal{O}(20\%)$ deviation in di-tau channels in BM1B
- No significant deviation from SM in BM2
- $h \to \tau^+\tau^-$ & $h \to b\bar{b}$ sensitive to BM3

	BM1A	BM1B	BM2	BM3
$\mu^{(gg)}_{F\gamma\gamma}$	1.24	1.09	0.99	1.01
$\mu^{(gg)}_{FZZ}$	0.92	0.92	0.92	0.92
$\mu^{(gg)}_{FWW}$	0.92	0.92	0.92	0.92
$\mu^{(gg)}_{F\tau\tau}$	0.91	0.77	0.92	0.82
$\mu^{(gg)}_{F\mu\mu}$	0.92	0.97	0.96	0.96
$\mu^{(hV)}_{Vbb}$	0.92	0.98	0.97	0.88
$\mu^{(VBF)}_{V\gamma\gamma}$	1.24	1.10	1.00	0.93
$\mu^{(VBF)}_{V\tau\tau}$	0.92	0.78	0.93	0.75

BRPV Higgs decays $h \to \nu_\tau \tilde{\chi}_2^0 \;/\; \tau^\pm \chi_2^\mp$

- $\mathcal{O}(25\%)$ deviation in di-photon channels due to light charginos in BM1A
- $\mathcal{O}(20\%)$ deviation in di-tau channels in BM1B
- No significant deviation from SM in BM2
- $h \to \tau^+\tau^-$ & $h \to b\bar{b}$ sensitive to BM3
- For the subsequent gaugino decays we find:

$$BR(\chi_2^+ \to \nu W^+),\; BR(\tilde{\chi}_2^0 \to \tau^- W^+) \gtrsim 90\%$$

Extra handle: ($\ell = e, \mu, \tau$)

$$\mu_{\tau\ell+\not{E}_T} \equiv \frac{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)}{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}} \sim 2.5 - 7$$

several times larger than the expected SM signal

	BM1A	BM1B	BM2	BM3
$\mu_{F\gamma\gamma}^{(gg)}$	1.24	1.09	0.99	1.01
$\mu_{FZZ}^{(gg)}$	0.92	0.92	0.92	0.92
$\mu_{FWW}^{(gg)}$	0.92	0.92	0.92	0.92
$\mu_{F\tau\tau}^{(gg)}$	0.91	0.77	0.92	0.82
$\mu_{F\mu\mu}^{(gg)}$	0.92	0.97	0.96	0.96
$\mu_{Vbb}^{(hV)}$	0.92	0.98	0.97	0.88
$\mu_{V\gamma\gamma}^{(VBF)}$	1.24	1.10	1.00	0.93
$\mu_{V\tau\tau}^{(VBF)}$	0.92	0.78	0.93	0.75

Leptonic BRPV Higgs decays $h \to \mu^+\mu^-$ & $h \to \tau^+\tau^-$

- Better sensitivity when $m_{\tilde{\chi}_2^0}, m_{\chi_2^+} > m_h$ (no gaugino channels)

- Leptonic Higgs decays are suppressed by 25% primarily due to lepton-chargino BRPV mixing whereas RPC SUSY effect is negligible at decoupling

- Particularly interesting signals of BRPV since all other channels are SM-like

	2nd gen BRPV: BMμ	3rd gen BRPV: BMτ
$\mu^{(gg)}_{F\gamma\gamma}$	1.00	1.02
$\mu^{(gg)}_{FZZ}$	0.98	1.00
$\mu^{(gg)}_{FWW}$	0.98	1.00
$\mu^{(gg)}_{F\tau\tau}$	0.99	0.73
$\mu^{(gg)}_{F\mu\mu}$	0.75	1.01
$\mu^{(hV)}_{Vbb}$	1.00	1.02
$\mu^{(VBF)}_{V\gamma\gamma}$	1.01	1.02
$\mu^{(VBF)}_{V\tau\tau}$	1.00	0.73

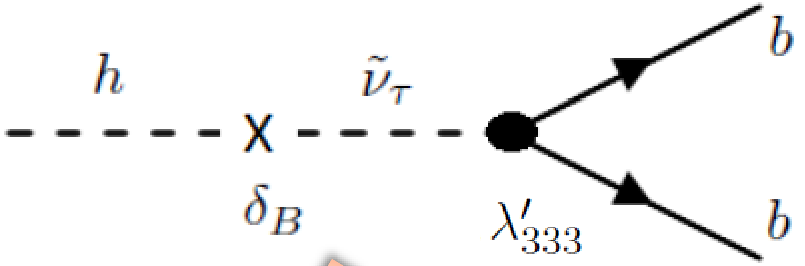
Trilinear RPV

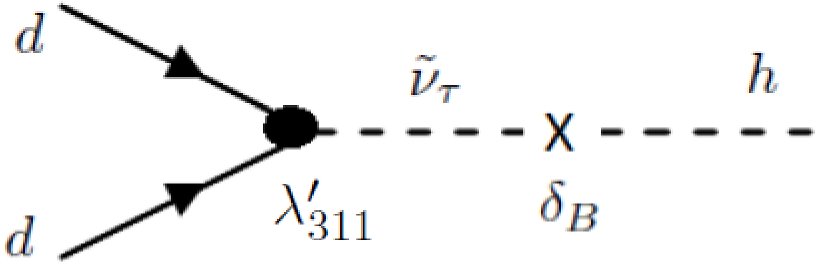
λ'_{333}	λ'_{311}	λ_{233}	λ_{322}
⇓	⇓	⇓	⇓
$\tilde{\nu}_\tau \bar{b} b$	$\tilde{\nu}_\tau \bar{d} d$	$\tilde{\nu}_\mu \tau^+ \tau^-$	$\tilde{\nu}_\tau \mu^+ \mu^-$

Assume one-parameter scheme and $\delta_\epsilon = 0$

TRPV

- $\delta_B \cdot \lambda'$ effects:





λ'_{333} TRPV effect expected in $h \to b\bar{b}$

$$\Lambda_{hb\bar{b}} = g_b^{SM} \left(g_{hb\bar{b}}^{RPC} + \frac{\lambda'_{333} Z_{h3}}{\sqrt{2} g_b^{SM}} \right)$$

$$g_b^{SM} = \frac{m_b}{v}, \; g_{hb\bar{b}}^{RPC} \equiv \frac{Z_{h1}}{c_\beta}$$

Additional Higgs production via $d\bar{d}$ fusion

$$\mu_F^{(gg+dd)} \equiv \frac{\sigma(gg \to h) + \sigma(d\bar{d} \to h)}{\sigma(gg \to h)_{SM}} = \mu_F^{(gg)} + \frac{\sigma(d\bar{d} \to h)}{\sigma(gg \to h)_{SM}}$$

$$\frac{\sigma(d\bar{d} \to h)}{\sigma(gg \to h)_{SM}} \simeq 0.73 \left(\kappa_d^{TRPV} \right)^2 ,$$

$$\kappa_d^{TRPV} \equiv \frac{\lambda'_{311} Z_{h3}}{y_b} .$$

TRPV: $\delta_B \cdot \lambda'$ effects ($\delta_\epsilon = 0$)

Corresponding bounds for 1 TeV RR squark soft mass terms

$\lambda'_{333} \sim 0.5$ $\lambda'_{311} \sim 1$

$\mathrm{BM}\lambda'_{333}$
- Enhanced di-photon rate due to light charginos
- Only mild enhancement in bottom channel (y_b dominated)

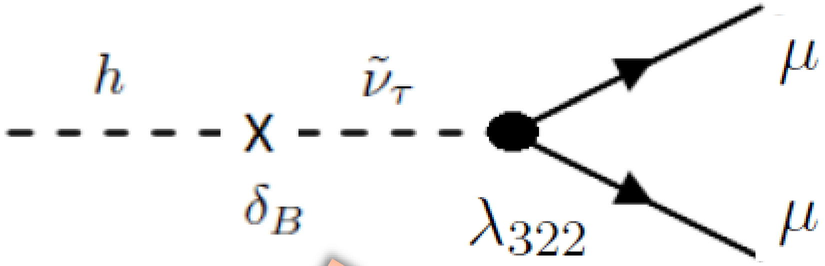
$\mathrm{BM}\lambda'_{311}$
- Overall increase in (previously) gluon-fusion initiated channels from new $d\bar{d} \to h$ production mechanism
- Overall decrease in μ_{Vjj} (suppressed by total width)

	$\mathrm{BM}\lambda'_{333}$	$\mathrm{BM}\lambda'_{311}$
$\mu^{(gg)}_{F\gamma\gamma}$	1.26	1.11
$\mu^{(gg)}_{FZZ}$	0.92	1.09
$\mu^{(gg)}_{FWW}$	0.92	1.09
$\mu^{(gg)}_{F\tau\tau}$	0.93	1.51
$\mu^{(gg)}_{F\mu\mu}$	0.93	1.51
$\mu^{(hV)}_{Vbb}$	1.04	0.71
$\mu^{(VBF)}_{V\gamma\gamma}$	1.27	0.48
$\mu^{(VBF)}_{V\tau\tau}$	0.94	0.65

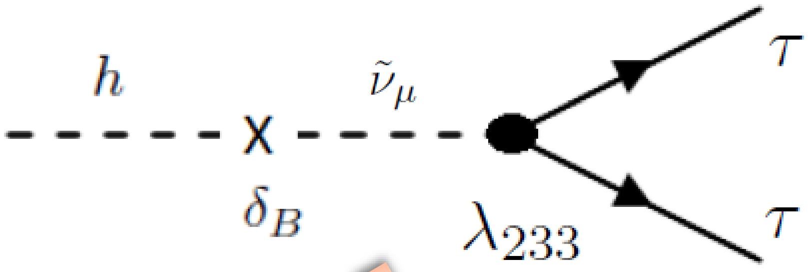
TRPV

- $\delta_B \cdot \lambda$ effects:

3rd gen BRPV



2nd gen BRPV



λ_{322} TRPV effect expected in $h \to \mu^+\mu^-$

$$\Lambda_{h\mu\mu} = g_\mu^{SM}\left(g_{h\mu\mu}^{RPC} + \frac{\lambda_{322} Z_{h3}}{\sqrt{2} g_\mu^{SM}}\right)$$

λ_{233} TRPV effect expected in $h \to \tau^+\tau^-$

$$\Lambda_{h\tau\tau} = g_\tau^{SM}\left(g_{h\tau\tau}^{RPC} + \frac{\lambda_{233} Z_{h3}}{\sqrt{2} g_\tau^{SM}}\right)$$

(where $g_l^{SM} = \frac{m_l}{v}$, $g_{hll}^{RPC} = \frac{Z_{h1}}{c_\beta}$)

TRPV: $\delta_B \cdot \lambda$ effects ($\delta_\epsilon = 0$)

Corresponding bounds for 1 TeV RR slepton soft mass terms

2nd gen BRPV $\lambda_{233} = 0.7$

3rd gen BRPV $\lambda_{322} = 0.7$

$\mathrm{BM}\lambda_{233}$
- Enhanced TRPV di-tau rate
- Rest of Higgs signals mildly suppressed due to enlarged Γ^h

$\mathrm{BM}\lambda_{322}$
- Di-muon channel nearly doubled while the rest are SM-like

In RPC (Decoupling) $\mu_{F\tau\tau,V\tau\tau}(\lambda_{233} = 0) \sim 1$, $\mu^{(gg)}_{F\mu\mu}(\lambda_{322} = 0) \sim 1$

	$\mathrm{BM}\lambda_{233}$	$\mathrm{BM}\lambda_{322}$
$\mu^{(gg)}_{F\gamma\gamma}$	0.94	1.04
$\mu^{(gg)}_{FZZ}$	0.92	0.99
$\mu^{(gg)}_{FWW}$	0.92	0.99
$\mu^{(gg)}_{F\tau\tau}$	1.85	0.99
$\mu^{(gg)}_{F\mu\mu}$	0.94	1.96
$\mu^{(hV)}_{Vbb}$	0.94	1.00
$\mu^{(VBF)}_{V\gamma\gamma}$	0.95	1.05
$\mu^{(VBF)}_{V\tau\tau}$	1.86	1.00

Summary

- We've studied the impact of RPV on the Higgs signals, under:
  - Multi-TeV sfermion soft masses
  - Decoupling limit in the Higgs sector (RPC ~ SM in Higgs signals)
  - Single-flavor (mostly 3rd gen) BRPV generating Higgs-sneutrino, neutrino-neutralino & lepton-chargino mixings

BRPV

- New Higgs decays to lepton-gaugino pairs $h \to \nu_\tau \tilde{\chi}_2^0$,$\tau^\pm \chi_2^\mp$ accompanied by enhanced $h \to \gamma\gamma$ signal
- leading to $h \to \tau^\pm \ell^\mp + \not{E}_T \;\; (\ell = e, \mu, \tau)$, with rates much larger than SM
- Notable deviations of $\mathcal{O}(20{-}30\%)$ in conventional Higgs channels: $h \to \mu^+\mu^-, \tau^+\tau^-$

(no such effect in the RPC decoupling SUSY)

TRPV

- Gluon-fusion Higgs production mode roughly doubled by $d\bar{d} \to h$
- Large deviations of up to $\mathcal{O}(100\%)$ are expected in $h \to \mu^+\mu^-, \tau^+\tau^-$

Summary

- Expected RPV effects on the Higgs signals:

	Production mode		
Decay Mode	$gg \to h$	hV	VBF
$h \to \gamma\gamma$	$\mu^{(gg)}_{F\gamma\gamma} \sim 1.26,\ \mathtt{BM}\lambda'_{333}$	-	$\mu^{(VBF)}_{V\gamma\gamma} \sim 0.48,\ \mathtt{BM}\lambda'_{311}$
$h \to ZZ^\star$	SM-like	-	-
$h \to WW^\star$	SM-like	-	-
$h \to b\bar{b}$	-	$\mu^{(hV)}_{Vbb} \sim 0.71,\ \mathtt{BM}\lambda'_{311}$	-
$h \to \tau^+\tau^-$	$\mu^{(gg)}_{F\tau\tau} \sim \begin{cases} 0.73, & \mathtt{BM}\tau \\ 1.85, & \mathtt{BM}\lambda_{233} \end{cases}$	-	$\mu^{(VBF)}_{V\tau\tau} \sim \begin{cases} 0.65, & \mathtt{BM}\lambda'_{311} \\ 1.85, & \mathtt{BM}\lambda_{233} \end{cases}$
$h \to \mu^+\mu^-$	$\mu^{(gg)}_{F\mu\mu} \sim \begin{cases} 0.75, & \mathtt{BM}\mu \\ 1.96, & \mathtt{BM}\lambda_{322} \end{cases}$	-	-

\+ $\mu_{\tau\ell + \not{E}_T} \equiv \dfrac{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)}{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}} \sim 2.5 - 7$, BM1A - BM3

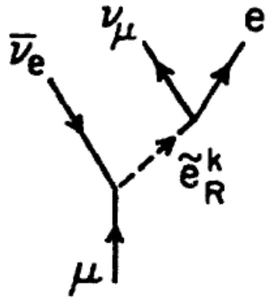
Backup Slides

- TRPV bounds arise e.g. from universality tests in rare lepton decays:

$\lambda_{233}\ ,\ \lambda_{322}$

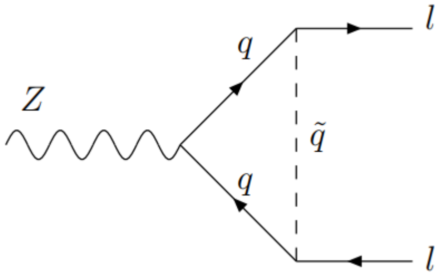
$$R_\tau = \Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$$

$$R_{\tau\mu} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$$



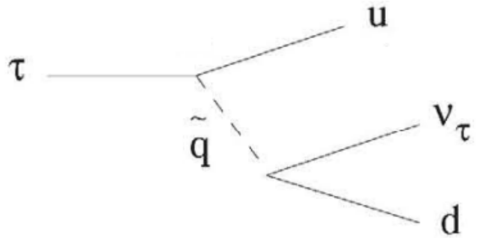
λ'_{333}

$$R_l = \Gamma(Z \to \text{had})/\Gamma(Z \to l\bar{l})$$



λ'_{311}

$$R_{\tau\pi} = \Gamma(\tau \to \pi\nu_\tau)/\Gamma(\pi \to \mu\nu_\mu)$$



Backup Slides

- Minima conditions:

$$1)\quad m_{H_d}^2 v_d - v_u B_\mu + \frac{1}{8}\left(g_1^2 + g_2^2\right) v_d \left(-v_u^2 + v_d^2\right) + |\mu|^2 v_d = 0$$

$$2)\quad -\frac{1}{8}\left(g_1^2 + g_2^2\right) v_u \left(-v_u^2 + v_d^2\right) + \frac{1}{2}\left(-2 v_d B_\mu + 2 v_u \left(m_{H_u}^2 + |\mu|^2 + |\epsilon_3|^2\right)\right) = 0$$

$$3)\quad \left(m_{LH}^2\right)_3 + \left(B_\epsilon\right)_3 \tan\beta - \epsilon_3 \mu = 0$$

Backup Slides

- CP-even scalar mass matrix – aspects and features
- Diagonlized by unitary matrix:

$$Z^E = \begin{pmatrix} Z_{h1} & Z_{H1} & Z_{\tilde{\nu}1} \\ Z_{h2} & Z_{H2} & Z_{\tilde{\nu}2} \\ Z_{h3} & Z_{H3} & Z_{\tilde{\nu}3} \end{pmatrix}$$

$$\begin{aligned} H_d &= Z_{h1} h_{RPV} + Z_{H1} H_{RPV} + Z_{\tilde{\nu}1} \tilde{\nu}_{RPV} \\ H_u &= Z_{h2} h_{RPV} + Z_{H2} H_{RPV} + Z_{\tilde{\nu}2} \tilde{\nu}_{RPV} \\ \tilde{\nu}_{RPC} &= Z_{h3} h_{RPV} + Z_{H3} H_{RPV} + Z_{\tilde{\nu}3} \tilde{\nu}_{RPV} \end{aligned}$$

- Lightest state identified as Higgs
- BRPV communicated via sneutrino component $Z_{h3} = Z_{h3}(\delta_B)$
- Z_{h1} and Z_{h2} at leading order are the same as RPC-elements

Backup Slides

- CP-odd scalar mass matrix

$$m_O^2 = \begin{pmatrix} s_\beta^2 m_A^2 & m_A^2 s_\beta c_\beta & -\delta_B m_A^2 s_\beta^2 \\ m_A^2 s_\beta c_\beta & c_\beta^2 m_A^2 & -\delta_B m_A^2 s_\beta c_\beta \\ -\delta_B m_A^2 s_\beta^2 & -\delta_B m_A^2 s_\beta c_\beta & m_{\tilde{\nu}_\tau}^2 \end{pmatrix}$$

where we used the RPC relation $m_A^2 \equiv \csc\beta \sec\beta \, B_\mu$

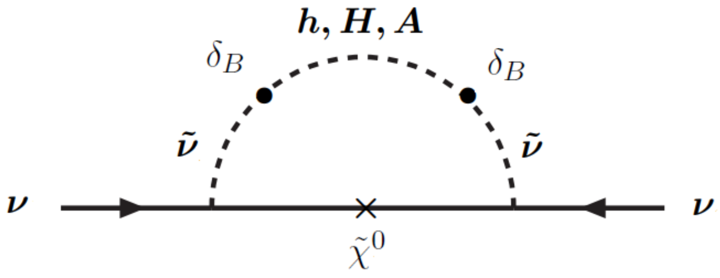
- Massless state corresponds to the GB

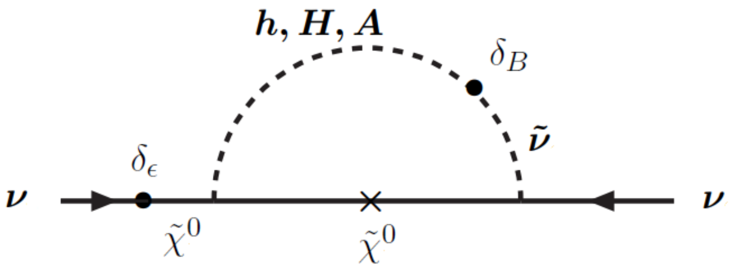
The RPV SUSY framework

- The neutralino sector in the $(\nu_\tau, \tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$ basis

$$m_N = \begin{pmatrix} (m_{\nu_\tau})^{\delta_B\delta_B}_{loop} + (m_{\nu_\tau})^{\delta_B\delta_\epsilon}_{loop} & 0 & 0 & 0 & \delta_\epsilon\mu \\ 0 & M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ 0 & -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ \delta_\epsilon\mu & m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

- BRPV loop contributions to neutrino mass:



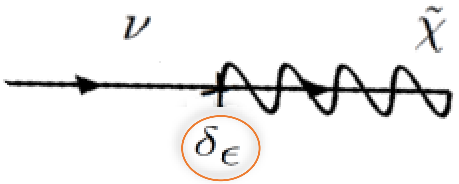


The RPV SUSY framework

- The neutralino sector in the $(\nu_\tau, \tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$ basis

$$m_N = \begin{pmatrix} (m_{\nu_\tau})^{\delta_B \delta_B}_{loop} + (m_{\nu_\tau})^{\delta_B \delta_\epsilon}_{loop} & 0 & 0 & 0 & \delta_\epsilon \mu \\ 0 & M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ 0 & -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ \delta_\epsilon \mu & m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

- New BRPV terms generating neutrino-neutralino mixing:

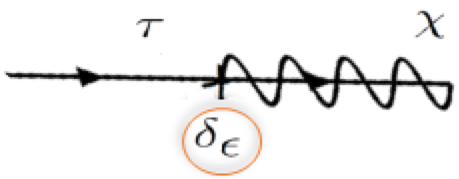


The RPV SUSY framework

- The chargino sector in the $(\tau_L, \tilde{W}^-, \tilde{H}_d^-), (\tau_R, \tilde{W}^+, \tilde{H}_u^+)$ basis

$$m_c = \begin{pmatrix} m_\tau & 0 & -\delta_\epsilon \mu \\ 0 & M_2 & \sqrt{2} m_W s_\beta \\ 0 & \sqrt{2} m_W c_\beta & \mu \end{pmatrix}$$

- New BRPV term generating tau-chargino mixing:



- For 2nd gen BRPV will generate muon-chargino mixing

$\tau \to \mu$

Backup Slides

- Charged Higgs – Slepton sector in the basis $(H_d^-, H_u^+, \tilde{\tau}_L, \tilde{\tau}_R)$

$$m_{\tilde{\tau}}^2 = \begin{pmatrix} m_W^2 s_\beta^2 + m_A^2 s_\beta^2 & m_W^2 s_\beta c_\beta + \frac{1}{2} m_A^2 s_{2\beta} & -\delta_B s_\beta^2 m_A^2 & -\delta_\epsilon \mu m_\tau t_\beta \\ m_W^2 s_\beta c_\beta + \frac{1}{2} m_A^2 s_{2\beta} & m_W^2 c_\beta^2 + m_A^2 c_\beta^2 & -\frac{1}{2}\delta_B m_A^2 s_{2\beta} & -\delta_\epsilon \mu m_\tau \\ -\delta_B s_\beta^2 m_A^2 & -\frac{1}{2}\delta_B m_A^2 s_{2\beta} & m_\tau^2 + m_{\tilde{\nu}_\tau}^2 - m_W^2 (c_\beta^2 - s_\beta^2) & (A_\tau - \mu t_\beta) m_\tau \\ -\delta_\epsilon \mu m_\tau t_\beta & -\delta_\epsilon \mu m_\tau & (A_\tau - \mu t_\beta) m_\tau & m_\tau^2 + m_{\tilde{\tau}_{RR}}^2 - \frac{1}{4} g_1^2 v (c_\beta^2 - s_\beta^2) \end{pmatrix}$$

- New BRPV Charged Higgs – Slepton mixing terms
- Relative effect of D-terms is larger than in squark sector

BRPV – numerical setup (details)

- Assume common left-handed soft squark mass $m_{\tilde{q}}\tilde{q}_L^\star \tilde{q}_L$
- In stop sector we have $m_{\tilde{t}_{RR}} = m_{\tilde{q}}$ as used for $\delta_{ij}^{t-\tilde{t}}$
- Adopt MFV in sfermion trilinears $A_f = y_f \cdot \tilde{A}$, for $f = t, b, \tau$
- Consider light gaugino states of $\mathcal{O}(100 \text{ GeV})$

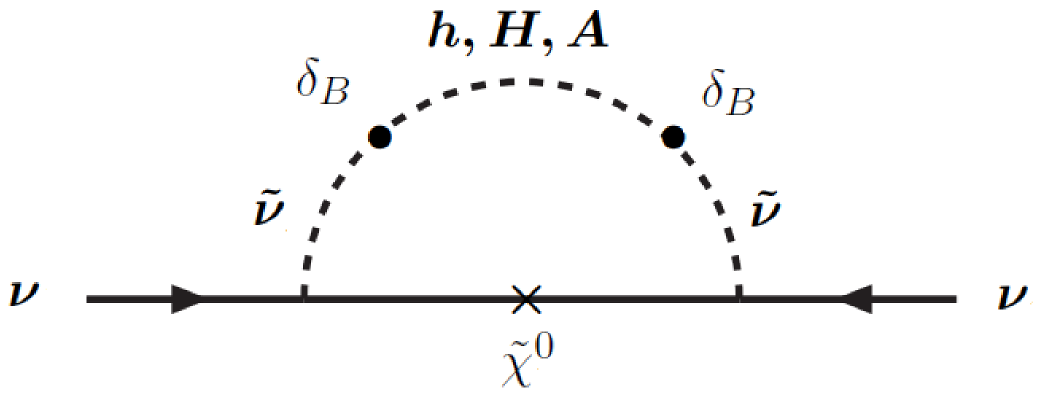
in cases where $h \to \nu_\tau \tilde{\chi}_2^0$ / $\tau^\pm \chi_2^\mp$

Input parameters

	Range	
δ_ϵ	$[0, 0.5]$	
μ	$[90, 1000]$	[GeV]
M_1	$[100, 2500]$	[GeV]
M_2	$[100, 2500]$	[GeV]
t_β	$[2, 30]$	
δ_B	$[0, 0.5]$	
m_A	$[1000, 10000]$	[GeV]
$m_{\tilde{\nu}_\tau}$	$[200, 800]$	[GeV]
$m_{\tilde{q}}$	$[1000, 8000]$	[GeV]
$\tilde{A}$	$[0, 4000]$	[GeV]
$m_{\tilde{b}_{RR}}$	$[2000, 5000]$	[GeV]
$m_{\tilde{\tau}_{RR}}$	$[1000, 5000]$	[GeV]

Neutrino mass - BRPV

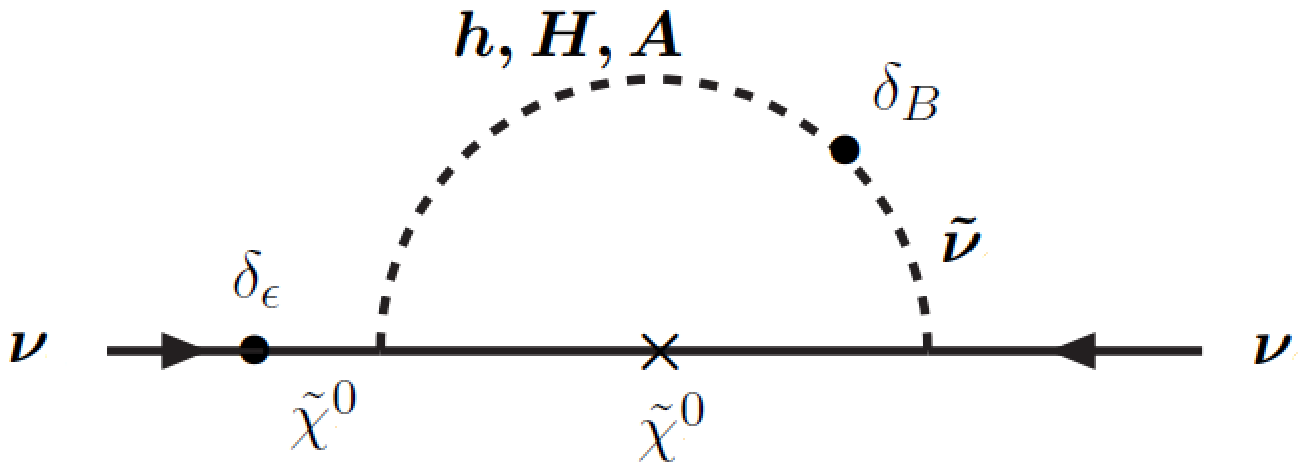
- $(m_{\nu_\tau})^{\delta_B \delta_B}_{loop}$



$$(m_{\nu_\tau})^{\delta_B \delta_B}_{loop} = \sum_{\alpha=1}^{4} \frac{\left(\frac{\delta_B m_A^2 s_{2\beta}}{2}\right)^2}{4c_\beta^2} \left(g_2 U^{RPC}_{\alpha 2} - g_1 U^{RPC}_{\alpha 1}\right)^2 m_{\tilde{\chi}_\alpha}$$
$$\times \Big[I_4\left(m_h, m_{\tilde{\nu}_\tau}, m_{\tilde{\nu}_\tau}, m_{\tilde{\chi}_\alpha}\right)\left(1 - \left(c_\beta Z_{h1} + s_\beta Z_{h2}\right)^2\right)$$
$$+ I_4\left(m_H, m_{\tilde{\nu}_\tau}, m_{\tilde{\nu}_\tau}, m_{\tilde{\chi}_\alpha}\right)\left(c_\beta Z_{h1} + s_\beta Z_{h2}\right)^2 - I_4\left(m_A, m_{\tilde{\nu}_\tau}, m_{\tilde{\nu}_\tau}, m_{\tilde{\chi}_\alpha}\right)\Big]$$

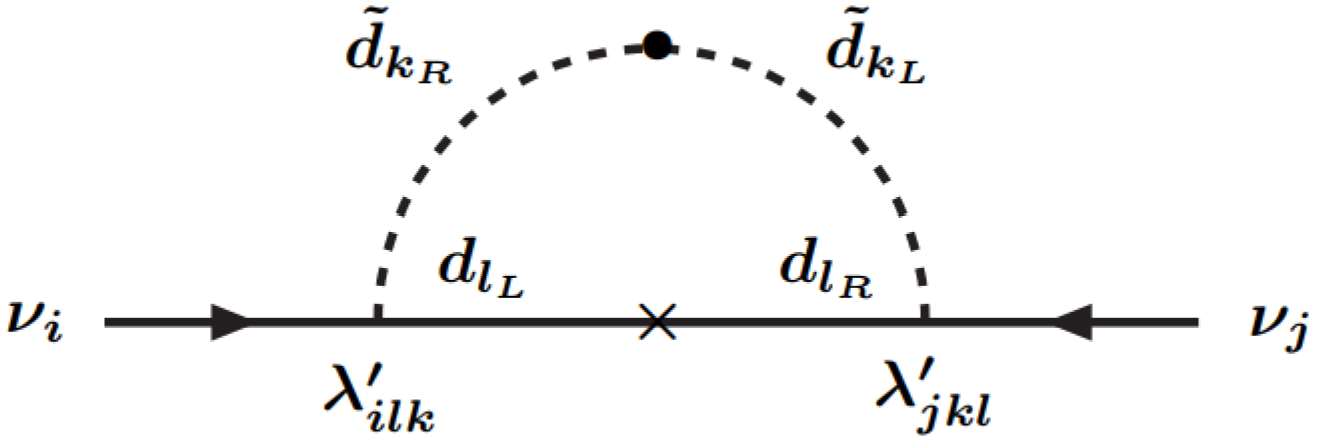
Neutrino mass - BRPV

- $(m_{\nu_\tau})^{\delta_B \delta_\epsilon}_{loop}$



Neutrino mass - TRPV

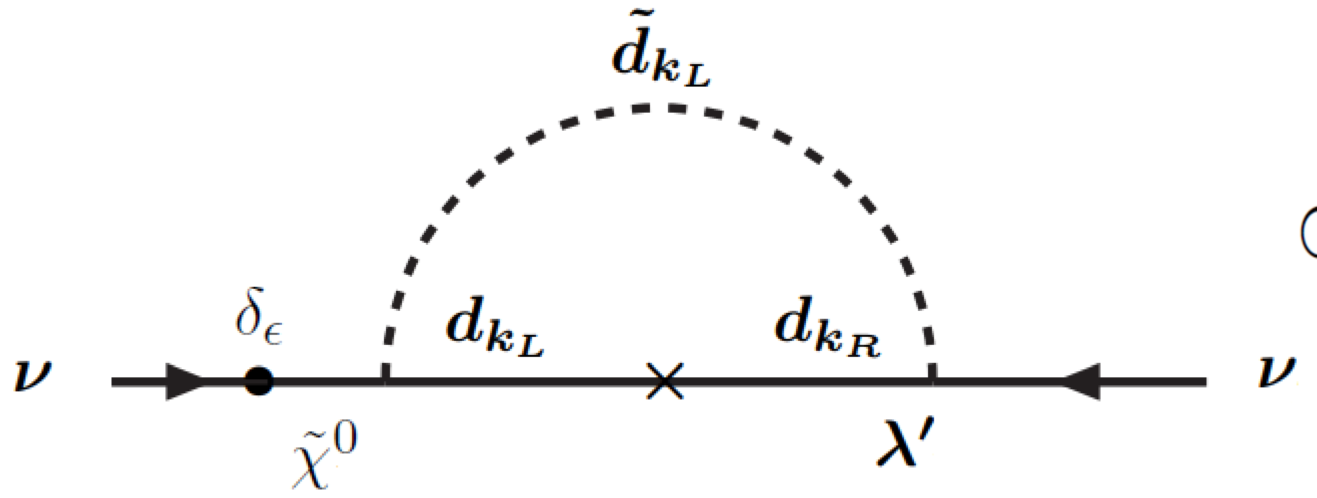
- $(m_{\nu_\tau})^{\lambda'_{3ii}\lambda'_{3ii}}_{loop} \sim \frac{3}{8\pi^2}(\lambda'_{3ii})^2\frac{m^2_{q_i}}{\bar{m}_{\tilde{q}_i}}$,



- Similarly for $(m_{\nu_k})^{\lambda_{kii}\lambda_{kii}}_{loop} \sim \frac{1}{8\pi^2}(\lambda_{kii})^2\frac{m^2_{\ell_i}}{\bar{m}_{\tilde{\ell}_i}}$
- The largest effect arises from λ'_{333} since it is $\propto m_b$

Neutrino mass - TRPV

- Additional 1-loop TRPV contribution:



$$\propto \delta_\epsilon \cdot \lambda'$$

- Can be discarded by virtue of $\delta_\epsilon \to 0$

BRPV - Input parameters

	BM1A	BM1B	BM2	BM3	
δ_ϵ	0.04	0.27	0.10	0.22	
μ	626.54	92.90	220.38	120.05	[GeV]
M_1	523.19	2030.48	104.94	130.56	[GeV]
M_2	103.83	1028.05	991.55	999.39	[GeV]
t_β	2.14	2.73	2.81	3.15	
δ_B	0.05	0.11	0.17	0.10	
m_A	4467.78	2558.96	2710.2	3162.6	[GeV]
$m_{\tilde{\nu}_\tau}$	291.65	317.38	506.78	358.69	[GeV]
$m_{\tilde{q}}$	6071.69	2860.5	4628.27	1094.07	[GeV]
$\tilde{A}$	1537.44	2842.51	66.19	3180.91	[GeV]
$m_{\tilde{b}_{RR}}$	4814.49	4996.39	4245.07	4721.63	[GeV]
$m_{\tilde{\tau}_{RR}}$	1509.25	1303.96	1122.68	2670.45	[GeV]

BRPV - Input parameters

	BMμ	BMτ	
δ_ϵ	0.47	0.49	
μ	642.71	631.61	[GeV]
M_1	1426.05	1651.6	[GeV]
M_2	682.82	687.75	[GeV]
t_β	6.31	6.76	
δ_B	0.05	0.05	
m_A	8981.82	8530.08	[GeV]
$m_{\tilde{\nu}_l}$	543.82	535.47	[GeV]
$m_{\tilde{q}}$	2210.72	2415.51	[GeV]
$\tilde{A}$	520.38	247.83	[GeV]
$m_{\tilde{b}_{RR}}$	4720.75	4594.09	[GeV]
$m_{\tilde{l}_{RR}}$	4249.44	4145.23	[GeV]

TRPV - Input parameters

	$\mathtt{BM}\lambda'_{333}$	$\mathtt{BM}\lambda'_{311}$	
δ_ϵ	0	0	
μ	202.46	556.34	[GeV]
M_1	759.74	1747.98	[GeV]
M_2	251.55	1589.49	[GeV]
t_β	2.77	16.59	
δ_B	0.11	0.45	
m_A	2150.46	1508.96	[GeV]
$m_{\tilde{\nu}_\tau}$	768	723.75	[GeV]
$m_{\tilde{q}}$	3461.04	2008.27	[GeV]
$\tilde{A}$	953.94	2.89	[GeV]
$m_{\tilde{b}_{RR}}$	2764.42	2421.53	[GeV]
$m_{\tilde{\tau}_{RR}}$	2357.42	3693.50	[GeV]

TRPV - Input parameters

	BMλ_{233}	BMλ_{322}	
δ_ϵ	0	0	
μ	958.82	270.48	[GeV]
M_1	593.21	290.19	[GeV]
M_2	1355.12	1222.63	[GeV]
t_β	4.35	2.72	
δ_B	0.03	0.02	
m_A	2141.48	5007.63	[GeV]
$m_{\tilde{\nu}_l}$	218.16	718.52	[GeV]
$m_{\tilde{q}}$	2591.04	2782.38	[GeV]
$\tilde{A}$	95.18	1772.84	[GeV]
$m_{\tilde{b}_{RR}}$	4703.45	2381.95	[GeV]
$m_{\tilde{l}_{RR}}$	3133.34	2371.34	[GeV]

$h \to \nu_\tau \tilde{\chi}_2^0$ / $\tau^\pm \chi_2^\mp$ BRPV signatures

BM1A, BM1B, BM2 and BM3

- Consider the subsequent gaugino decays: $\chi_2^+ \to \nu W^+, \ \tau^+ Z$ and $\tilde{\chi}_2^0 \to \tau^- W^+, \nu Z$
- We find $BR(\chi_2^+ \to \nu W^+), \ BR(\tilde{\chi}_2^0 \to \tau^- W^+) \gtrsim 90\%$
- These gaugino 2-body BRPV decays are prompt, within the detector
- Taking into account the W-boson decays:

$$h \to \tau^\pm \chi_2^\mp \to \tau^\pm \ell^\mp + \not{E}_T \quad , \quad h \to \nu_\tau \tilde{\chi}_2^0 \to \tau^\pm \ell^\mp + \not{E}_T \quad , \quad \ell = e, \mu, \tau$$

- Define the following decay signal:

$$\mu_{\tau\ell + \not{E}_T} \equiv \frac{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)}{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}}$$

$$\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)_{SM} = \Gamma(h \to W W^\star \to \tau^\pm \ell^\mp + \not{E}_T)_{SM} \sim 0.01 \text{ MeV}$$

$$\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T) = \Gamma(h \to W W^\star \to \tau^\pm \ell^\mp + \not{E}_T) + \Gamma(h \to \tau^\pm \chi_2^\mp \to \tau^\pm \ell^\mp + \not{E}_T) + \Gamma(h \to \nu_\tau \tilde{\chi}_2^0 \to \tau^\pm \ell^\mp + \not{E}_T)$$

$h \to \nu_\tau \tilde{\chi}_2^0 \,/\, \tau^\pm \chi_2^\mp$ BRPV signatures

BM1A, BM1B, BM2 and BM3

- In particular

$$\Gamma(h \to WW^\star \to \tau^\pm \ell^\mp + \not{E}_T) = \left(g_{hVV}^{RPC}\right)^2 \Gamma(h \to WW^\star \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}$$

such that
$$\mu_{\tau\ell+\not{E}_T} = \left(g_{hVV}^{RPC}\right)^2 + \frac{\Gamma(h \to \tau^\pm \chi_2^\mp \to \tau^\pm \ell^\mp + \not{E}_T) + \Gamma(h \to \nu_\tau \tilde{\chi}_2^0 \to \tau^\pm \ell^\mp + \not{E}_T)}{\Gamma(h \to WW^\star \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}}$$

- Note that in these benchmark models:

$$\begin{cases} \mu_{FWW}^{(gg)} \sim \left(g_{hVV}^{RPC}\right)^2 \sim 0.92 \\ \Gamma(h \to \tau^\pm \chi_2^\mp) + \Gamma(h \to \nu_\tau \tilde{\chi}_2^0) \sim 0.3, 0.15, 0.2, 0.6 \text{ MeV} \end{cases}$$

- Thus

$$\Gamma(h \to \tau^\pm \chi_2^\mp \to \tau^\pm \ell^\mp + \not{E}_T) + \Gamma(h \to \nu_\tau \tilde{\chi}_2^0 \to \tau^\pm \ell^\mp + \not{E}_T) \sim 0.015 - 0.06 \text{ MeV}$$

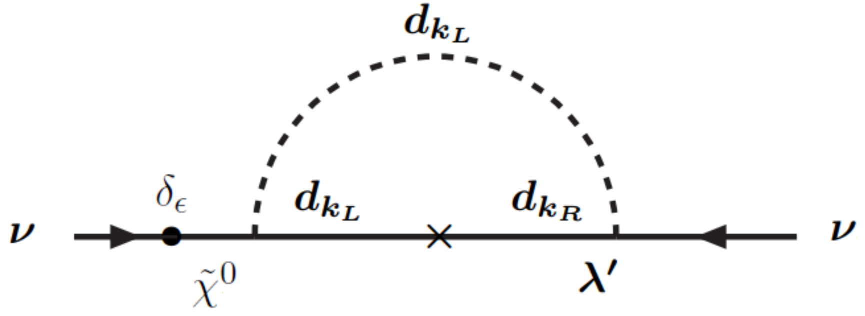
$$\Rightarrow \quad \mu_{\tau\ell+\not{E}_T} \equiv \frac{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)}{\Gamma(h \to \tau^\pm \ell^\mp + \not{E}_T)_{SM}} \sim 2.5 - 7$$

TRPV effects with $\delta_\epsilon \neq 0$

- Sbottom mixing altered by new F-term $\propto \; v\mu s_\beta \cdot (\delta_\epsilon \cdot \lambda'_{333})$ affecting sbottom exchange @ 1-loop in ggh & $\gamma\gamma h$ couplings as well as the predicted Higgs mass:

$$(\Delta m_h^2)_{\tilde{f}} \approx -\frac{N_c^{\tilde{f}}}{\sqrt{2}G_F}\frac{y_f}{96\pi^2}\frac{\mu^4}{m_{\tilde{f}}^2}$$

- Additional 1-loop TRPV contribution to neutrino mass



$\propto \delta_\epsilon \cdot \lambda'$

$\mathtt{BM}\lambda'_{311}$

TRPV effects with $\lambda'_{311} \neq 0$

- TRPV effect is manifest by enhanced Higgs production via $d\bar{d}$-fusion

$$\frac{\sigma(d\bar{d} \to h)}{\sigma(gg \to h)_{SM}} \simeq \frac{\left(\kappa_d^{TRPV}\right)^2 \cdot \sigma(d\bar{d} \to h)_{\kappa_d^{TRPV}=1} \cdot K_d}{\sigma(gg \to h)_{SM}^{N3LO}} \simeq 0.73 \left(\kappa_d^{TRPV}\right)^2$$

where

$\kappa_d^{TRPV} \equiv \frac{\lambda'_{311} Z_{h3}}{y_b}$, $y_b = \sqrt{2} m_b / v$

$\sigma(d\bar{d} \to h)_{\kappa_d^{TRPV}=1} \simeq 23.8$ [pb]

$\sigma(gg \to h)_{SM}^{N3LO} \simeq 48.6$ [pb] — N3LO QCD prediction for ggh @ 13 TeV

$K_d \simeq 1.5$ — Estimated K-factor for sub-process $d\bar{d} \to h$ with $\kappa_d^{TRPV} = 1$

- In $\mathtt{BM}\lambda'_{311}$ we find $\kappa_d^{TRPV} \sim 1.34$ → $\mu_F^{(gg+dd)} \simeq 2.3$

TRPV effects with $\lambda'_{311} \neq 0$

- $\mathtt{BM}\lambda'_{311}$: enhanced coupling to d-quarks also contributes to hV production via a t-channel d-quark exchange diagram $d\bar{d} \to hV$

$$\mu_V^{(hV+dd)} \equiv \frac{\sigma(q\bar{q} \to V \to hV) + \sigma(d\bar{d} \to hV)}{\sigma(q\bar{q} \to V \to hV)_{SM}} = \mu_V^{(hV)} + \frac{\sigma(d\bar{d} \to hV)}{\sigma(q\bar{q} \to V \to hV)_{SM}} \ ,$$

$$\mu_V^{(hV)} = (g_{hVV}^{RPC})^2$$

$$\sigma(d\bar{d} \to hV) = (\kappa_d^{TRPV})^2 \cdot \sigma(d\bar{d} \to hV)_{\kappa_d^{TRPV}=1} \ ,$$

$$\Rightarrow \frac{\sigma(d\bar{d} \to hV)_{\kappa_d^{TRPV}=1}}{\sigma(q\bar{q} \to V \to hV)_{SM}} \sim 0.05 \Rightarrow$$

$$\mu_V^{(hV+dd)} \simeq (g_{hVV}^{RPC})^2 + 0.05 \cdot (\kappa_d^{TRPV})^2$$

$$\mu_{Vbb}^{(hV)} \to \mu_{Vbb}^{(hV+dd)}$$

TRPV with $\lambda_{322} \in [0, 0.7]$

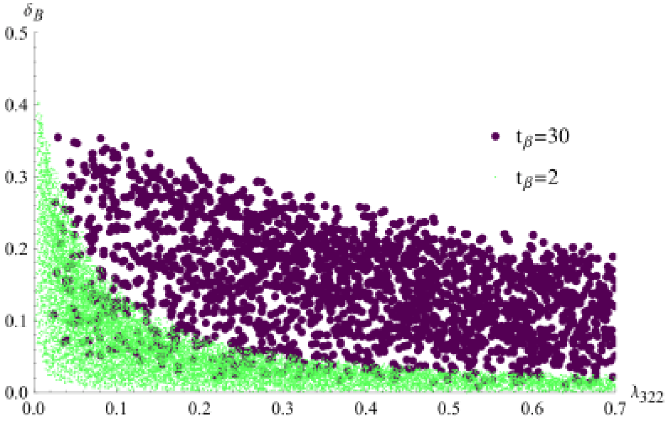
- Consider $h \to \mu^+\mu^-$ with fixed $m_A = 2$ TeV and $\begin{cases} t_\beta = 2 \\ t_\beta = 30 \end{cases}$
- Define "distance" from RPC:

$$\Delta\mu_{F\mu\mu} \equiv \frac{|\mu_{F\mu\mu}^{TRPV} - \mu_{F\mu\mu}^{RPC}|}{\mu_{F\mu\mu}^{RPC}}$$

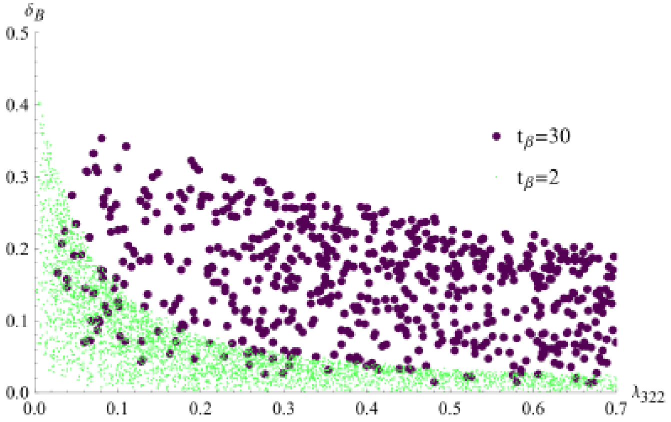
where $\mu_{F\mu\mu}^{TRPV} \equiv \mu_{F\mu\mu}^{(gg)}(\lambda_{322}, \delta_B)$ and $\mu_{F\mu\mu}^{RPC} = \mu_{F\mu\mu}^{(gg)}(\lambda_{322} = 0, \delta_B = 0)$

- Set $\delta_\epsilon = 0$ and apply $\Delta\mu_{F\mu\mu} > 0.5, 0.8, 0.95$
- Recall $\mu_{F\mu\mu}^{RPC} \simeq \mu_{F\mu\mu}^{SM} \simeq 1$ at decoupling

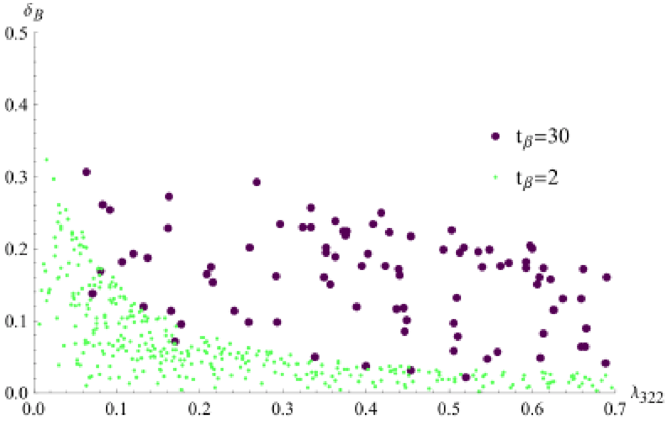
TRPV with $\lambda_{322} \in [0, 0.7]$



(a) $\Delta\mu_{F\mu\mu} > 0.5$



(b) $\Delta\mu_{F\mu\mu} > 0.8$



(c) $\Delta\mu_{F\mu\mu} > 0.95$

- $\texttt{BM}\lambda_{322}$ not unique
- Sizable RPV effect also with $\lambda_{322} \sim \mathcal{O}(0.1)$

Higgs coupling to Vector bosons

- Coupling:

$$\Lambda_{hVV} = g_V^{SM} g_{hVV}^{RPC} ,$$

$$g_Z^{SM} = \frac{1}{2} v \left(g_1 s_W + g_2 c_W\right)^2, \; g_W^{SM} = \frac{1}{2} v g_2^2, \; g_{hVV}^{RPC} = c_\beta Z_{h1} + s_\beta Z_{h2}$$

- Decay:

$$\Gamma\left(h \to VV^\star\right) = \left(g_{hVV}^{RPC}\right)^2 \Gamma_{SM}\left(h \to VV^\star\right)$$

- Production:

$$\sigma\left(q\bar{q} \to V \to hV\right) = \left(g_{hVV}^{RPC}\right)^2 \sigma_{SM}\left(q\bar{q} \to V \to hV\right) ,$$

$$\sigma\left(qq \to hqq\right) = \left(g_{hVV}^{RPC}\right)^2 \sigma_{SM}\left(qq \to hqq\right) .$$

Higgs coupling to quarks/ RPC leptons

- quarks:

$$\Lambda_{hq\bar{q}} = g_q^{SM} g_{hq\bar{q}}^{RPC} \ , \quad g_q^{SM} = \frac{m_q}{v} \text{ and } g_{hu\bar{u}}^{RPC} = \frac{Z_{h2}}{s_\beta}, \ g_{hd\bar{d}}^{RPC} = \frac{Z_{h1}}{c_\beta}$$

- RPC leptons:

$$\Lambda_{hll} = g_l^{SM} g_{hll}^{RPC} \ , \quad g_l^{SM} = \frac{m_l}{v} \text{ and } g_{hll}^{RPC} = \frac{Z_{h1}}{c_\beta}.$$

- Decay:

$$\Gamma\left(h \to q\bar{q}\right) = \left(g_{hq\bar{q}}^{RPC}\right)^2 \Gamma_{SM}\left(h \to q\bar{q}\right)$$

$$\Gamma_{SM}\left(h \to q\bar{q}\right) = N_C \frac{G_F m_q^2}{4\sqrt{2}\pi} m_h \left(1 - \frac{4m_q^2}{m_h^2}\right)^{\frac{3}{2}} \ , \ m_q = \overline{m}_q\left(m_h\right)$$

For RPC leptons:

$q \to l$

$N_C = 1$

Higgs coupling to squarks and sleptons

- sbottom:

$$\Lambda_{h\tilde{b}_i\tilde{b}_j} = \frac{g_2}{m_W} g^{RPC}_{h\tilde{b}_i\tilde{b}_j}$$

(In TRPV can have F-term $\propto y_b \lambda'_{333} Z_{h3}$ indirectly affecting hgg and $h\gamma\gamma$)

- Stop:

$$\Lambda_{h\tilde{t}_i\tilde{t}_j} = \frac{g_2}{m_W}\left(g^{RPC}_{h\tilde{t}_i\tilde{t}_j} - \frac{m_t}{s_\beta} Z^U_{i1} Z^U_{j2} \mu \delta_\epsilon Z_{h3} \right)$$

$\delta_\epsilon \times \delta_B$ effect in gluon-fusion & diphoton

- Sleptons:

$$\Lambda_{h\tilde{\tau}_i\tilde{\tau}_i} = \frac{g_2}{m_W}\Big[g^{RPC}_{h\tilde{\tau}_i\tilde{\tau}_i} - v^2 c_\beta \frac{g_2^2}{4} Z^+_{i1} Z^+_{i3} Z_{h3} + \frac{m_\tau}{c_\beta} A_\tau Z^+_{i1} Z^+_{i4} Z_{h3} + \frac{m_\tau^2}{c_\beta} Z^+_{i1} Z^+_{i3} Z_{h3} +$$

$$+ \delta_\epsilon \mu \frac{m_\tau}{c_\beta} Z^+_{i1} Z^+_{i4} Z_{h2} - v^2 s_\beta \frac{g_2^2}{4} Z_{h3} Z^+_{i3} Z^+_{i2} + \mu \frac{m_\tau}{c_\beta} Z^+_{i4} Z_{h3} Z^+_{i2} + \delta_\epsilon \mu \frac{m_\tau}{c_\beta} Z^+_{i4} Z_{h1} Z^+_{i2} \Big]$$

Higgs coupling to gauginos

- Couplings:

$$\Lambda_{h\tilde{\chi}_i^0\tilde{\chi}_j^0/h\chi_i^+\chi_j^-} = \Lambda_{Lij}^{N/C} L + \Lambda_{Rij}^{N/C} R \; ,$$

- Decays:

$$\Gamma\left(h \to \tilde{\chi}_i^0\tilde{\chi}_j^0/\chi_i^+\chi_j^-\right) = \left[\left(\left|\Lambda_{Lij}^{N/C}\right|^2 + \left|\Lambda_{Rij}^{N/C}\right|^2\right)\left(m_h^2 - m_{\tilde{\chi}_i^0/\chi_i^+}^2 - m_{\tilde{\chi}_j^0/\chi_j^+}^2\right) - 4\,\mathrm{Re}\left\{\Lambda_{Lij}^{N/C}\Lambda_{Rij}^{N/C}\right\} m_{\tilde{\chi}_i^0/\chi_i^+} m_{\tilde{\chi}_j^0/\chi_j^+}\right] \times \frac{\lambda^{\frac{1}{2}}\left(m_h^2, m_{\tilde{\chi}_i^0/\chi_i^+}^2, m_{\tilde{\chi}_j^0/\chi_j^+}^2\right)}{16\pi m_h^3}$$

1-loop diphoton decay

- SM:

$$\Gamma_{SM}(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \left| \sum_f N_C Q_f^2 A_{\frac{1}{2}}(\tau_f) + A_1(\tau_W) \right|^2$$

- BRPV:

$$\begin{aligned}\Gamma(h \to \gamma\gamma) = & \\ \frac{G_F \alpha^2 m_h^3}{128\sqrt{2}\pi^3} \times & \left| \sum_{q=t,b} N_C Q_f^2 g_{hq\bar{q}}^{RPC} A_{\frac{1}{2}}(\tau_q) + g_{hVV}^{RPC} A_1(\tau_W) \right. \\ & + \sum_{i=1}^{3} \frac{2m_W}{m_{\chi_i^\pm}} \frac{\Lambda_{ii}^C}{e} A_{\frac{1}{2}}\left(\tau_{\chi_i^\pm}\right) \\ & + \frac{v}{2} \sum_{i=1}^{2} \left[\frac{\Lambda_{h\tilde{b}_i\tilde{b}_i}}{m_{\tilde{b}_i}^2} N_C Q_{\tilde{b}}^2 A_0\left(\tau_{\tilde{b}_i}\right) + \frac{\Lambda_{h\tilde{t}_i\tilde{t}_i}}{m_{\tilde{t}_i}^2} N_C Q_{\tilde{t}}^2 A_0\left(\tau_{\tilde{t}_i}\right) \right] \\ & \left. + \frac{v}{2} \sum_{i=2}^{4} \frac{\Lambda_{h\tilde{\tau}_i\tilde{\tau}_i}}{m_{\tilde{\tau}_i}^2} A_0\left(\tau_{\tilde{\tau}_i}\right) \right|^2\end{aligned}$$

1-loop Higgs decay to gluons

- SM:

$$\Gamma_{SM}\left(h\to gg\right)=K_{SM}^{QCD}\frac{G_F\alpha_s^2m_h^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4}\sum_{q=t,b}A_{\frac{1}{2}}\left(\tau_q\right)\right|^2$$

- BRPV:

$$\Gamma\left(h\to gg\right)=K^{QCD}\frac{G_F\alpha_s^2m_h^3}{36\sqrt{2}\pi^3}\times\left|\frac{3}{4}\sum_{q=t,b}g_{hq\bar{q}}^{RPC}A_{\frac{1}{2}}\left(\tau_q\right)\right.$$
$$\left.+\frac{3v}{8}\sum_{i=1}^{2}\left[\frac{\Lambda_{h\tilde{b}_i\tilde{b}_i}}{m_{\tilde{b}_i}^2}A_0\left(\tau_{\tilde{b}_i}\right)+\frac{\Lambda_{h\tilde{t}_i\tilde{t}_i}}{m_{\tilde{t}_i}^2}A_0\left(\tau_{\tilde{t}_i}\right)\right]\right|^2$$

BRPV SUSY Spectrum

	BM1A	BM1B	BM2	BM3
$(\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)$	$(94.2, 510.4, 628.3, 650.7)$	$(90.1, 97.6, 1034.6, 2031.4)$	$(93.5, 223.7, 227.6, 999.2)$	$(86.0, 125.9, 163.6, 1006.2)$
$(\chi_2^\pm, \chi_3^\pm)$	$(94.3, 638.7)$	$(91.9, 1034.6)$	$(215.9, 999.2)$	$(118.6, 1006.3)$
$(\tilde{\nu}_\tau^E, H)$	$(200.2, 4473.6)$	$(162.8, 2574.3)$	$(229.8, 2748.4)$	$(163.2, 3179.2)$
$(\tilde{\nu}_\tau^O, A)$	$(200.1, 4472.8)$	$(162.4, 2573.4)$	$(229.5, 2747.6)$	$(163.0, 3178.7)$
$(\tilde{\tau}_2, \tilde{\tau}_3, \tilde{\tau}_4)$	$(210.2, 1509.2, 4473.5)$	$(176.8, 1303.9, 2574.6)$	$(240.1, 1122.6, 2748.7)$	$(178.3, 2670.4, 3179.7)$
$(\tilde{t}_1, \tilde{t}_2)$	$(6056.3, 6091.8)$	$(2779.5, 2949.3)$	$(4631.2, 4631.7)$	$(826.2, 1330.9)$
$(\tilde{b}_1, \tilde{b}_2)$	$(4814.4, 6071.6)$	$(2860.5, 4996.4)$	$(4245.0, 4628.2)$	$(1094.0, 4721.6)$

BRPV SUSY Spectrum

	BMμ	BMτ
$(\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)$	$(632.2, 713.1, 761.7, 1428.1)$	$(633.1, 707.0, 760.1, 1653.1)$
$(\chi_2^{\pm}, \chi_3^{\pm})$	$(633.2, 764.0)$	$(634.1, 762.0)$
$(\tilde{\nu}_l^E, H)$	$(181.3, 8996.4)$	$(174.8, 8545.1)$
$(\tilde{\nu}_l^O, A)$	$(181.3, 8996.4)$	$(174.8, 8545.0)$
$(\tilde{l}_2, \tilde{l}_3, \tilde{l}_4)$	$(197.4, 4249.4, 8996.7)$	$(191.5, 4145.2, 8545.4)$
$(\tilde{t}_1, \tilde{t}_2)$	$(2201.0, 2233.7)$	$(2416.1, 2427.2)$
$(\tilde{b}_1, \tilde{b}_2)$	$(2210.7, 4720.7)$	$(2415.5, 4594.0)$

TRPV SUSY Spectrum

	$\mathtt{BM}\lambda'_{333}$	$\mathtt{BM}\lambda'_{311}$
$(\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)$	$(150.2, 205.4, 303.5, 762.9)$	$(552.0, 558.0, 1594.1, 1749.2)$
$(\chi_2^{\pm}, \chi_3^{\pm})$	$(153.1, 305.9)$	$(554.2, 1594.2)$
$(\tilde{\nu}_\tau^E, H)$	$(725.7, 2166.1)$	$(203.2, 1661.2)$
$(\tilde{\nu}_\tau^O, A)$	$(725.7, 2165.0)$	$(203.1, 1661.1)$
$(\tilde{\tau}_2, \tilde{\tau}_3, \tilde{\tau}_4)$	$(729.1, 2166.5, 2357.4)$	$(218.2, 1663.0, 3693.5)$
$(\tilde{t}_1, \tilde{t}_2)$	$(3443.2, 3487.3)$	$(2014.4, 2017.0)$
$(\tilde{b}_1, \tilde{b}_2)$	$(2764.4, 3461.0)$	$(2008.1, 2421.6)$

TRPV SUSY Spectrum

	BMλ_{233}	BMλ_{322}
$(\chi_2^0, \chi_3^0, \chi_4^0, \chi_5^0)$	$(589.7, 951.3, 959.9, 1367.1)$	$(236.3, 271.8, 319.4, 1228.8)$
$(\chi_2^\pm, \chi_3^\pm)$	$(948.3, 1367.1)$	$(265.7, 1228.8)$
$(\tilde{\nu}_l^E, H)$	$(207.5, 2143.0)$	$(709.3, 5009.4)$
$(\tilde{\nu}_l^O, A)$	$(207.5, 2142.5)$	$(709.3, 5008.9)$
$(\tilde{l}_2, \tilde{l}_3, \tilde{l}_4)$	$(220.9, 2144.0, 3133.3)$	$(712.7, 2371.3, 5009.5)$
$(\tilde{t}_1, \tilde{t}_2)$	$(2592.6, 2600.9)$	$(2735.2, 2839.2)$
$(\tilde{b}_1, \tilde{b}_2)$	$(2591.0, 4703.4)$	$(2381.9, 2782.3)$