Di-Higgs signatures from R-parity violating SUSY

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PLAN

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  - ⇒ **Neutrino Mass**

- **Constraints.**
  - ⇒ **Indirect Constraints**
  - ⇒ **Direct Constraints**

- **Decays and Branching ratio of $\tilde{\chi}^0 \to \nu h$.**

- **Signal & Backgrounds.**

- **Conclusions.**

Introduction

- SUSY: The best framework to protect EW scale from quadratic divergence caused by Planck scale physics,
- Provides a candidate for dark matter if R-parity conserved,
- Otherwise provides a mechanism of generating tiny neutrino masses,
- Allowing lepton number violation, the R-parity conserving W_0 and violating W_1 parts are following;

$$
\begin{aligned}
W_0 &= \mu H_1 H_2 + h^e_{ij} L_i H_2 E^c_j + h^d_{ij} Q_i H_2 D^c_j + h^u_{ij} Q_i H_1 U^c_j \\
W_1 &= \epsilon_i \mu L_i H_1 + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k \,.
\end{aligned}
$$

Neutrino Mass

- Here we focus on Bilinear term of the superpotential,
- Under BRpV, Neutralinos-neutrino sector forms a 7×7 mass matrix,

$$\left(\begin{array}{c|c} \begin{array}{c}\text{MSSM}\\ \text{neutralino (chargino)}\\ \text{mass matrix}\end{array} & \not{R}_p \text{ terms} \\ \hline \not{R}_p \text{ terms} & \begin{array}{c}\text{neutrino}\\ \text{(charged lepton)}\\ \text{mass matrix}\end{array} \end{array}\right)$$

- After seesaw diagonalization, $\mathcal{M}^D_{ij}$ is rotated away giving rise to "tree-level" neutrino mass matrix

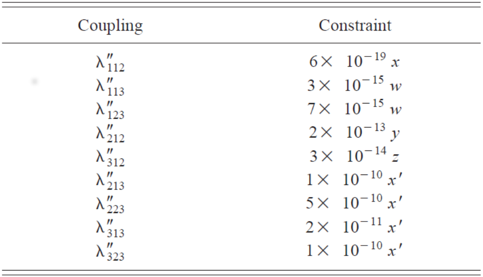
$$\mathcal{M}^\nu_{ij} = -(\mathcal{M}^D {\mathcal{M}^N}^{-1} {\mathcal{M}^D}^T)_{ij} = -\frac{M_Z^2}{F_N}\xi_i\xi_j c_\beta^2$$

- This mechanism provides mass to ν_3 while other two masses are generated radiatively at one-loop

Proton Decay

- RpV induces decay of protons into pions and leptons,
- Requires both L and B number violation,
- Can be avoided by switching off either of them,
- Or impose Baryon parity instead of R-parity on superpotential,
- If both L and B are present, the bounds are on product of L and B couplings

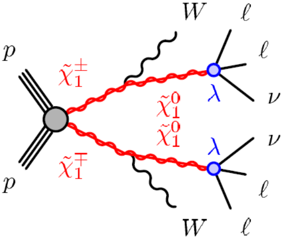
[E.J. Chun, J. S. Lee]

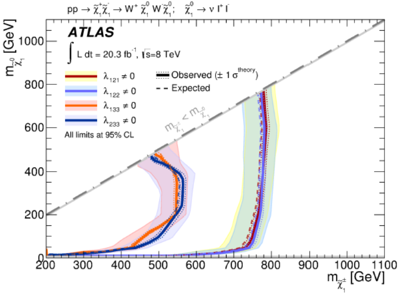


Coupling	Constraint
λ''_{112}	$6\times 10^{-19}\,x$
λ''_{113}	$3\times 10^{-15}\,w$
λ''_{123}	$7\times 10^{-15}\,w$
λ''_{212}	$2\times 10^{-13}\,y$
λ''_{312}	$3\times 10^{-14}\,z$
λ''_{213}	$1\times 10^{-10}\,x'$
λ''_{223}	$5\times 10^{-10}\,x'$
λ''_{313}	$2\times 10^{-11}\,x'$
λ''_{323}	$1\times 10^{-10}\,x'$

LHC Bounds

arxiv:1405.5086





- The LHC bounds can be evaded due to the almost degenerate chargino and neutralino mass
- The bounds also get weaker due the suppression of the direct leptonic decay mode of the neutralino

R-parity violating Higgsino decays

- The LSP, $\tilde{\chi}_1^0$, is not stable,
- We consider the decay of LSP for the following decay processes:

$$\tilde{\chi}_1^0 \to Z\nu_\ell, \qquad \tilde{\chi}_1^0 \to lW, \qquad \tilde{\chi}_1^0 \to h\nu_\ell$$

- We assume $\mu < M_1, M_2$ leading to the Higgsino LSP,

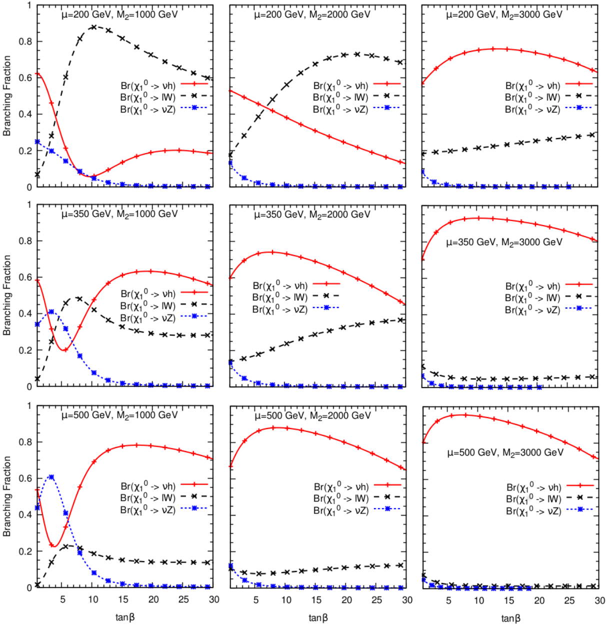
  ⇒ The lightest states $\tilde{\chi}_{1,2}^0$ and $\tilde{\chi}_1^\pm$ are Higgsino-like;

  ⇒ With $M_1 < M_2$, $\tilde{\chi}_3^0$ is bino-like while $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_4^0$ are wino-like;

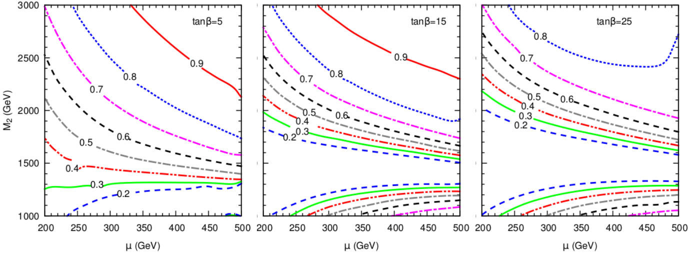
  ⇒ For $M_2 < M_1$, $\tilde{\chi}_4^0$ is bino-like while $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_3^0$ are wino-like.

- We fix $M_1 = 1.0$ TeV, $\tan\beta = 10$ and vary both μ and M_2,
- Masses of inos are determined from M_1, M_2 and μ.

Branching ratios of $\tilde{\chi}_0$ decays



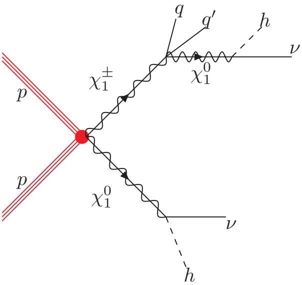
Branching ratios of $\tilde{\chi}_0 \to \nu h$ decays in $\mu - M_2$ plane



- Spectrum and decay rates are obtained by using `SARAH` and `SPheno`,
- Decays $\tilde{\chi}_0 \to \nu h$ is significant in large part of parameter space,
- BR is larger at small $\tan\beta$ and large μ.

Di-Higgs Signal at the LHC

1. Neutralino pair production: $pp \to \tilde{\chi}_1^0 \tilde{\chi}_i^0$,
2. Chargino pair production : $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$,
3. Associated neutralino and chargino production : $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_i^0$,



- The RpV decays of $\tilde{\chi}_1^\pm$ $(\ell h, \nu W, \ell Z)$ are suppressed due to tiny RpV couplings.
- $\tilde{\chi}_1^\pm$ mainly decays via RPC couplings i.e., $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{\pm *}$ almost 90% of time
  $\Rightarrow$ Ends up with a pair of LSP's decaying to $\tilde{\chi}_1^0 \to \nu h$ via RpV interactions.
- Leads to di-Higgs $+\not{E}_T$ final state.

Di-Higgs decays

Channel	BR(%)
bbbb	36
bbWW	24.7
$bb\tau\tau$	7.3
$WWWW$	4.3
$bb\gamma\gamma$	0.27
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015
$\gamma\gamma\gamma\gamma$	0.00052

Table : Branching ratios for different di-Higgs channels.

- Among all channels, we consider $\gamma\gamma b\bar{b}$ decays of di-Higgs in this work,
- Thus the final signal at LHC is $\gamma\gamma b\bar{b}\not{E}_{\mathrm{T}} + \mathrm{X}$.

Backgrounds

QCD background processes for the $\gamma\gamma b\bar{b}$ channel are

- $b\bar{b}\gamma\gamma$,
- $b\bar{b}h(\rightarrow \gamma\gamma)$,
- $t\bar{t}h(\rightarrow \gamma\gamma)$,
- $\gamma\gamma h(\rightarrow b\bar{b})$

Multijet QCD backgrounds resulting from jets faking either as b-jets or photons

- $jj\gamma\gamma$ with two fake b jets;
- $b\bar{b}j\gamma$ with j faking photon;
- $b\bar{b}jj$ with two fake photons;
- $jjj\gamma$ with two fake b jets and one fake photon;
- $jjjj$ with two fake b-jets and two photons;
- $jjh(\rightarrow \gamma\gamma)$ with either two fake b jets or two fake photons;
- $j\gamma h(\rightarrow \gamma\gamma)$ with one fake photon.

Cut1: Acceptance cuts

ϵ_γ	ϵ_b	$P_{c\to b}$	$P_{\tau\to b}$	$P_{j\to b}$	$P_{j\to\gamma}$
90%	70%	$1/8$	1/26	$1/440$	$1/1000$

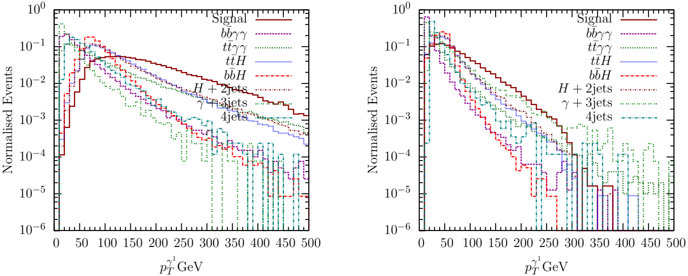
1. Accept events with two photons, 2 b-jets and missing energy,
2. Photons must have transverse momentum $p_T^\gamma > 10$ GeV and rapidity $|\eta^\ell| < 2.5$,
3. All b-jets must have following p_T and η requirements:

$$p_T^b > 20 \text{ GeV}, |\eta^b| < 2.5$$

4. All pairs of jets, photons and photon plus jets should be well separated with each other by:

$$\Delta R_{jj,jb,bb,\gamma j,\gamma b,\gamma\gamma} \geq 0.4 \quad \text{where} \quad \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

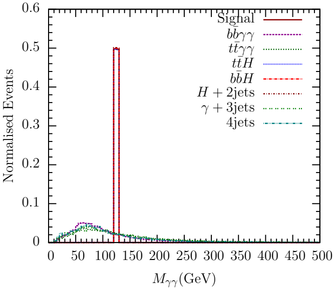
Cut2: p_T distribution of photons



- To get rid of soft photons coming from the decay of mesons or radiations, we further put the following p_T cuts on the two photons:

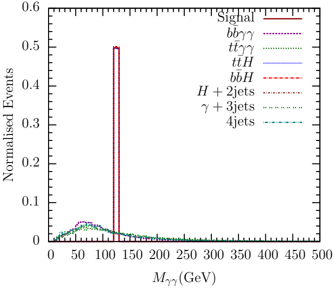
$$p_T^{\gamma_1} > 30\text{GeV} \quad \text{and} \quad p_T^{\gamma_2} > 20\text{GeV}.$$

Cut3: Invariant mass distribution of $\gamma\gamma$ and $b\bar{b}$ pair



- Look for diphoton invariant mass distribution,
- The mass resolution is very high in this mode,
- Backgrounds containing Higgs also peaks at m_H

Cut3: Invariant mass distribution of $\gamma\gamma$ and $b\bar{b}$ pair



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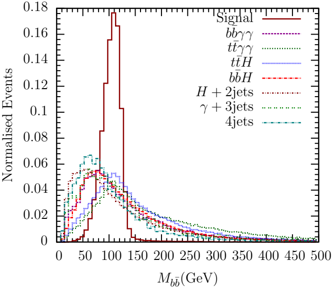
- Study $b\bar{b}$ pair invariant mass distribution,
- The mass resolution is poor in this mode,
- Needs a large window at around m_H



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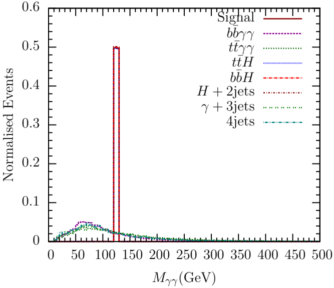

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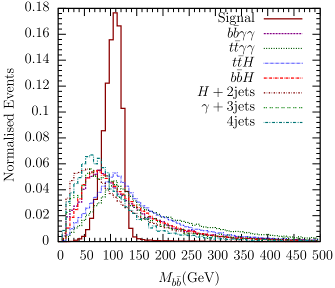
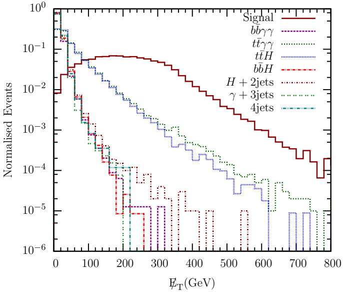


CUT3 : $|M_{\gamma\gamma} - M_h| < 2.5$ GeV, $|M_{b\bar{b}} - M_h| < 15$ GeV

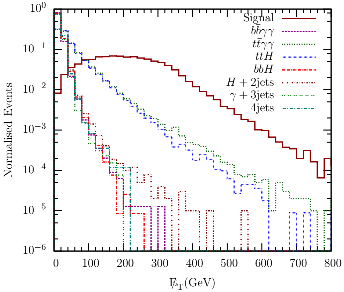
Cut4: Missing transverse energy distribution



- Look for $\not{E}_T$ distribution,
- The $\not{E}_T$ distribution for signal peaks at large value,
- We impose following cut:

$$\not{E}_T > 100 \text{ GeV},$$

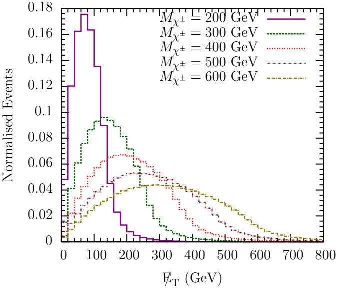
Cut4: Missing transverse energy distribution



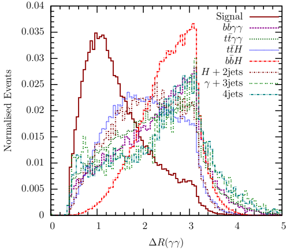
- Look for $\not\!\!E_T$ distribution,
- The $\not\!\!E_T$ distribution for signal peaks at large value,
- We impose following cut:

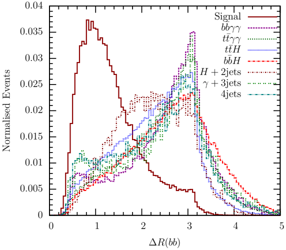
$$\not\!\!E_T > 100 \text{ GeV},$$

- We also study for $\not\!\!E_T$ distribution for various χ^+ masses,
- Peaks shift to higher values for large χ^+ masses,
- Need to optimize $\not\!\!E_T$ cut for different masses,

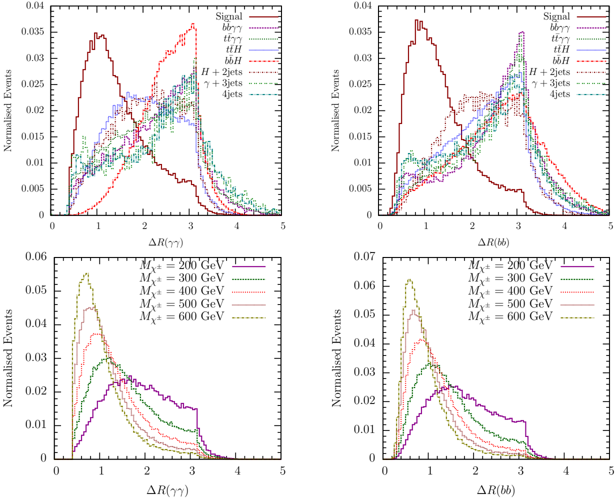


Cut5: ΔR separation of $\gamma\gamma$ and $b\bar{b}$ pair

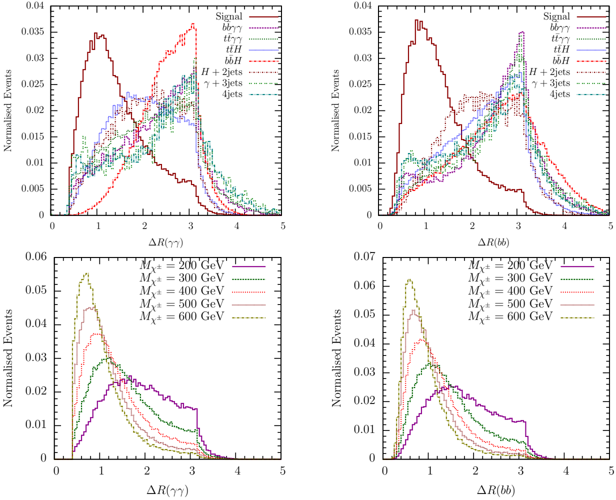




Cut5: ΔR separation of $\gamma\gamma$ and $b\bar{b}$ pair



Cut5: ΔR separation of $\gamma\gamma$ and $b\bar{b}$ pair



- We impose following cut on the ΔR:

$$\Delta R_{b\bar{b}} < 2.0, \qquad \Delta R_{\gamma\gamma} < 2.0.$$

Cut-flow of the signal and backgrounds

μ (GeV)	Cut 1 (fb)	Cut 2 (fb)	Cut 3 (fb)	Cut 4 (fb)	Cut 5 (fb)
300	9.6×10^{-2}	9.0×10^{-2}	5.3×10^{-2}	3.8×10^{-2}	1.9×10^{-2}
400	3.5×10^{-2}	3.3×10^{-2}	2.0×10^{-2}	1.6×10^{-2}	1.1×10^{-2}
500	1.5×10^{-2}	1.4×10^{-2}	8.5×10^{-3}	7.6×10^{-3}	5.9×10^{-3}
600	7.1×10^{-3}	6.6×10^{-3}	4.0×10^{-3}	3.7×10^{-3}	3.2×10^{-3}

Table : Effects of the cut flow on the signal events.

	Cut 1 (fb)	Cut 2 (fb)	Cut 3 (fb)	Cut 4 (fb)	Cut 5 (fb)
$b\bar{b}\gamma\gamma$	4.3×10^{1}	1.3×10^{1}	4.5×10^{-2}	2.1×10^{-4}	1.0×10^{-4}
$Hb\bar{b}$	9.5×10^{-3}	9.0×10^{-3}	1.5×10^{-3}	1.0×10^{-6}	4.8×10^{-7}
Hjj	2.9×10^{-5}	2.8×10^{-5}	5.5×10^{-6}	1.1×10^{-8}	1.0×10^{-8}
$t\bar{t}\gamma\gamma$	1.2×10^{0}	6.1×10^{-1}	2.2×10^{-3}	2.5×10^{-4}	4.7×10^{-5}
$t\bar{t}H$	1.1×10^{-1}	1.0×10^{-1}	2.0×10^{-2}	1.9×10^{-3}	5.0×10^{-4}
$b\bar{b}jj$	4.2×10^{1}	3.5×10^{1}	1.5×10^{-1}	1.6×10^{-3}	4.0×10^{-4}
$jj\gamma\gamma$	9.3×10^{-2}	2.6×10^{-2}	8.9×10^{-5}	–	–
$jjjj$	1.8×10^{-2}	1.5×10^{-2}	5.6×10^{-5}	–	–
Σ (bckg.)					1.1×10^{-3}

Table : Effects of the cut flow on the background events.

Reach in parameter space

μ (GeV)	Sig. (1 ab^{-1})	Sig. (2 ab^{-1})	Sig. (3 ab^{-1})
300	10.3	14.6	17.2
400	6.6	9.3	11.3
500	4.1	5.7	7.1
600	2.4	4.2	5.7

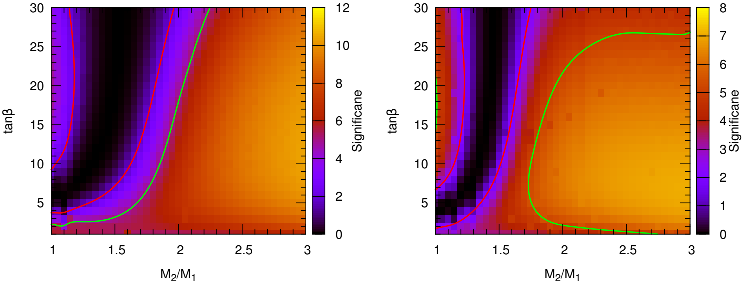


Figure : $\mu = 300$ GeV, $\mathcal{L} = 1ab^{-1}$ (left) and 500 GeV, $\mathcal{L} = 3ab^{-1}$ (right).

Conclusions

- The LHC has discovered a 125 GeV Higgs-like resonance,
- Measurement of its properties are in good agreement with the SM,
- Di-Higgs cross section is next important measurement in this step,
- Di-Higgs can also be used as a tool to study new physics with enhanced cross section/event kinematics,
- Resonant $b\gamma\gamma \not{E}_{\mathrm{T}}$ can be a clean signature to probe BSM physics like RpV SUSY.