# Resonant slepton production and right sneutrino DM in in Left-Right supersymmetry

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- LHC is doing great ! History made with Higgs boson discovery !
- The full exploitation of the LHC is now the highest priority.
- Just the Higgs discovery and nothing else however will open up a lot more questions.
- LHC is still young and perhaps we need to be patient !

# Theoretical setting for seesaw…

- Adding $\nu_R$ to SM makes fermion spectrum left-right symmetric

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \leftrightarrow \begin{pmatrix} u_R \\ d_R \end{pmatrix}; \qquad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$Tr(B-L) = 0 \qquad Tr(B-L)^3 = 0$$

$(B-L)$ **is a gauge symmetry !!**

- Electroweak gauge group expands to the left-right symmetric model

$$\boxed{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$

# Minimal Left-Right Symmetry Model

- Gauge group for the left-right symmetric theory becomes

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Particle multiplets:

$SU(2)_L$ Doublets: $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$; $\psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; $SU(2)_R$ doublets: $Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix}$; $\psi_R \equiv \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

The Higgs sector:

$$\Delta_L \equiv \begin{bmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{bmatrix}$$

$$\phi \equiv \begin{bmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{bmatrix}$$

$$\Delta_R \equiv \begin{bmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{bmatrix}$$

# TeV scale seesaw and left-right symmetry

- New gauge bosons at the TeV scale and heavy Majorana neutrinos would be a clear hint of left-right symmetric theory.

- How can we test these ideas?

Introducing new heavy particles:

Gauge bosons: $W_R^+$, $W_R^-$ and $Z'$

Majorana massive right-handed neutrinos: $N_e$, $N_\mu$, $N_\tau$

## The superpotential

$$W = (Q_L)^T Y_Q^1 \Phi_1 (Q_R) + (Q_L)^T Y_Q^2 \Phi_2 (Q_R) + (L_L)^T Y_L^1 \Phi_1 (L_R) \\ + (L_L)^T Y_L^2 \Phi_2 (L_R) + (L_L)^T Y_L^3 \Delta_{2L} (L_L) + (L_R)^T Y_L^4 \Delta_{1R} (L_R) \\ + S[\lambda_L \mathrm{Tr}(\Delta_{1L} \cdot \Delta_{2L}) + \lambda_R \mathrm{Tr}(\Delta_{1R} \cdot \Delta_{2R}) + \lambda_3 \mathrm{Tr}(\Phi_1^T \tau_2 \Phi_2 \tau_2) \\ + \lambda_4 \mathrm{Tr}(\Phi_1^T \tau_2 \Phi_1 \tau_2) + \lambda_5 \mathrm{Tr}(\Phi_2^T \tau_2 \Phi_2 \tau_2) + \lambda_S S^2 + \xi_F].$$

- Contains Yukawa terms for all fermions, the seesaw couplings between the triplets and the leptons, all gauge invariant trilinear combinations of the Higgses and a tadpole term for the singlet.
- An enhancement to the Higgs mass at tree-level from D-terms due to the larger gauge group ($g_L^2 + g_Y^2 \to g_L^2 + g_R^2$)

# There are lots of Higgses in LR models

- Need for Higgs fields that are singlets under $\mathrm{SU}(2)_L$ and not under $\mathrm{SU}(2)_R$ to break left-right symmetry
- We choose triplets ($\Rightarrow$ seesaw mass term for $\nu_R$) of $\mathrm{SU}(2)_R$ with $B-L=2 \Rightarrow$ anomaly cancellation requires a triplet with $B-L=-2$ and LR symmetry the corresponding triplets of $\mathrm{SU}(2)_L$
- The addition of a singlet is also phenomenologically motivated (breaking of $\mathrm{SU}(2)_R$ and breaking of SUSY are independent)
- Altogether nine CP-even, seven CP-odd, six singly charged and four doubly charged Higgses

# The desired vacuum structure would be a neutral one...

$$
\begin{aligned}
\Phi_1 &= \begin{pmatrix} \varphi_1^0 & \varphi_1^+ \\ \varphi_1^- & \varphi_1^{\prime 0} \end{pmatrix} \rightarrow \begin{pmatrix} v_d/\sqrt{2} & 0 \\ 0 & 0 \end{pmatrix} \\
\Phi_2 &= \begin{pmatrix} \varphi_2^{\prime 0} & \varphi_2^+ \\ \varphi_2^- & \varphi_2^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 \\ 0 & v_u/\sqrt{2} \end{pmatrix} \\
\Delta_{1R} &= \begin{pmatrix} \delta_{1R}^-/\sqrt{2} & \delta_{1R}^0 \\ \delta_{1R}^{--} & -\delta_{1R}^-/\sqrt{2} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & v_{1R}/\sqrt{2} \\ 0 & 0 \end{pmatrix} \\
\Delta_{2R} &= \begin{pmatrix} \delta_{2R}^+/\sqrt{2} & \delta_{2R}^{++} \\ \delta_{2R}^0 & -\delta_{2R}^+/\sqrt{2} \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 \\ v_{2R}/\sqrt{2} & 0 \end{pmatrix} \\
S &\rightarrow v_S/\sqrt{2}, \quad \langle \Delta_{1L} \rangle = \langle \Delta_{2L} \rangle = 0.
\end{aligned}
$$

# . . . but it is often unstable

The determinant of the doubly charged Higgs mass matrix is negative if the triplet has a VEV $\Rightarrow$ not a problem for $\Delta_L$ (can be inert), but a definite problem for $\Delta_R$

There are several proposed solutions:

- Spontaneous R-parity violation ($\tilde{\nu}_R$ VEVs) [Kuchimanchi, Mohapatra, hep-ph/9306290]
- Nonrenormalizable operators [Mohapatra, Rasin, hep-ph/9511391, Aulakh et. al., hep-ph/9707256]
- Adding triplets with $B - L = 0$ [Aulakh et. al., hep-ph/9703434, hep-ph/9712551]
- Radiative corrections [Babu, Mohapatra, 0807.0481]

We choose the last option in our work.

Coleman-Weinberg effective potential terms, generated by right-chiral leptons coupling to the $\Delta^c$ field:

$$V_{\text{eff}}^{\text{1-loop}} = \frac{1}{16\pi^2}\sum_i (-1)^{2s}(2s+1)M_i^4\left[\ln\left(\frac{M_i^2}{\mu^2}\right) - \frac{3}{2}\right].$$

Basso et. al. [1503.08211] considered the full one-loop corrections and also the gauge and Higgs sectors can give a significant contribution

When these corrections are made large and the (s)lepton-triplet coupling is moderate, the mass of the doubly charged Higgs can be beyond 300 GeV with light sleptons

## Right-handed gauge bosons can decay hadronically or leptonically

Currently the strongest constraint from dijet searches $m(W_R) > 2.7$ TeV, but only SM+$N_R$ decay modes assumed

We take two benchmarks with $W_R$ around 2.7 TeV and two benchmarks with 3.5 TeV

Constraints for $Z'$ mass always satisfied if $W_R$ OK

The projected LHC sensitivity for $100\,\mathrm{fb}^{-1}$ of luminosity shows a reach for a potential $3\sigma$ discovery that extends up to $950\,\mathrm{GeV}$ [arXiv:1612.09224] when the doubly-charged Higgs boson exclusively decays into electrons or muons

In the interaction basis $(\tilde{L}_L^i, \tilde{L}_R^i)$, the squared-mass matrix for the sleptons

$$\mathcal{M}_L^2 = \begin{pmatrix} m_{\tilde{L}_L}^2 + m_\ell^2 + D_{11} & (T_L^3)_{ij} v \cos\beta + \mu_{\text{eff}} m_\ell \tan\beta \\ (T_L^3)_{ij} v \cos\beta + \mu_{\text{eff}} m_\ell \tan\beta & m_{\tilde{L}_R}^2 + m_\ell^2 + D_{22} \end{pmatrix},$$

$$\mathcal{M}_{\tilde{\nu}}^2 = \begin{pmatrix} M^2_{\tilde{\nu}_L\tilde{\nu}_L} & M^2_{\tilde{\nu}_L\tilde{\nu}_R} \\ M^2_{\tilde{\nu}_R\tilde{\nu}_L} & M^2_{\tilde{\nu}_R\tilde{\nu}_R} \end{pmatrix}.$$

In the scalar case, the mass matrix entries are

$$M^2_{\tilde{\nu}_L\tilde{\nu}_L} = m^2_{\tilde{L}_L} + D_{11}\,,$$
$$M^2_{\tilde{\nu}_L\tilde{\nu}_R} = M^2_{\tilde{\nu}_R\tilde{\nu}_L} = (T_L^2 v - Y_L^2 Y_L^4 v_{1R}) \sin\beta + Y_L^2 \mu_{\text{eff}} \frac{v\cos\beta}{\sqrt{2}}\,,$$
$$M^2_{\tilde{\nu}_R\tilde{\nu}_R} = m^2_{\tilde{L}_R} + D_{22} + 2(Y_L^4)^2 v_{1R}^2 - \sqrt{2} T_L^4 v_{1R} + Y_L^4 \lambda_R v_S v_{2R},$$

The pseudoscalar mass matrix

$$M^2_{\tilde{\nu}_{IL}\tilde{\nu}_{IR}} = M^2_{\tilde{\nu}_{IR}\tilde{\nu}_{IL}} = (T_L^2 v + Y_L^2 Y_L^4 v_{1R}) \sin\beta + Y_L^2 \mu_{\text{eff}} \frac{v\cos\beta}{\sqrt{2}}$$
$$M^2_{\tilde{\nu}_{IR}\tilde{\nu}_{IR}} = m^2_{\tilde{L}_R} + D_{22} + 2(Y_L^4)^2 v_{1R}^2 + \sqrt{2} T_L^4 v_{1R} - Y_L^4 \lambda_R v_S v_{2R}$$

$$D_{11} = -\frac{g_L^2}{8} v^2 \cos 2\beta + g_{B-L}^2 (v_{1R}^2 - v_{2R}^2) \quad \text{and}$$
$$D_{22} = \frac{g_R^2}{8}\left[2(v_{1R}^2 - v_{2R}^2) - v^2\cos 2\beta\right] - g_{B-L}^2 (v_{1R}^2 - v_{2R}^2).$$

The D-term contribution to the scalar potential

$$
\begin{aligned}
V_D = \sum_i \Bigg[ & \frac{g_L^2}{8} \left| \mathrm{Tr}(2\Delta_{1L}^\dagger \tau_i \Delta_{1L} + 2\Delta_{2L}^\dagger \tau_i \Delta_{2L} + \Phi_a \tau_i^T \Phi_b^\dagger) + \tilde{L}_L^\dagger \tau_i \tilde{L}_L \right|^2 \\
& + \frac{g_R^2}{8} \left| \mathrm{Tr}(2\Delta_{1R}^\dagger \tau_i \Delta_{1R} + 2\Delta_{2R}^\dagger \tau_i \Delta_{2R} + \Phi_a^\dagger \tau_i^T \Phi_b) + \tilde{L}_R^\dagger \tau_i \tilde{L}_R \right|^2 \Bigg] \\
& + \frac{g_{B-L}^2}{2} \left[ \mathrm{Tr}(-\Delta_{1L}^\dagger \Delta_{1L} + \Delta_{2L}^\dagger \Delta_{2L} - \Delta_{1R}^\dagger \Delta_{1R} + \Delta_{2R}^\dagger \Delta_{2R}) - \tilde{L}_L^\dagger \tilde{L}_L + \tilde{L}_R^\dagger \tilde{L}_R \right]^2 ,
\end{aligned}
$$

gives the coupling of the neutrino with the Higgs

$$\lambda_{h\tilde{\nu}_{RI}\tilde{\nu}_{RI}} = \frac{1}{4} g_R^2 v \sin(\alpha + \beta) \simeq -\frac{1}{4} g_R^2 v \cos 2\beta,$$

In the MSSM, the production of weakly interacting superpartners is limited

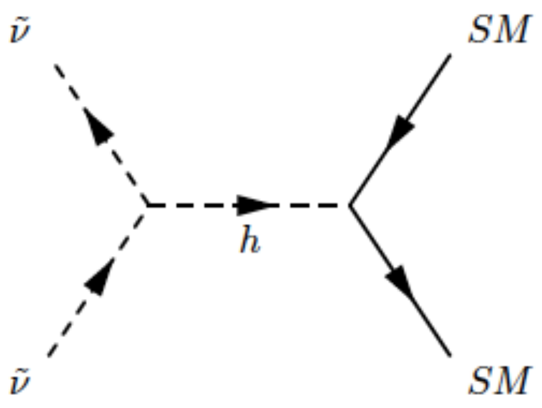
Current search limits for sleptons and electroweakinos are weaker where searches additionally rely on a very high LHC luminosity to be sensitive to superparticles lying in the 1TeV mass regime.

This is one of the most crucial differences for the LRSUSY case, RH scalar production cross sections being enhanced thanks to the gauging of the RH sector.

On top of that a RH sneutrino can be a good DM candidate.

**The corresponding rates are enhanced if resonant configurations are reached, so that the LHC is possibly sensitive to high mass scales**

**Most analyses have been performed in the case where the sneutrino is a gauge singlet**




The coupling governing DM annihilation is a gauge coupling

The sneutrino annihilates mostly via the SM-like Higgs

- In the alignment limit the relevant coupling is determined by gauge interactions: $\lambda_{h\tilde{\nu}\tilde{\nu}} = -\frac{1}{4} g_R^2 v \cos 2\beta$
- Hence the annihilation cross section depends only on the sneutrino mass (and mildly on $\tan\beta$)

The correct relic density is obtained with a sneutrino with a mass in the range $250 \ldots 290$ GeV

# We consider four benchmark points

BP1: sneutrino LSP, light $W_R$, BP2: sneutrino LSP, heavy $W_R$, BP3: neutralino LSP, light $W_R$, BP4: neutralino LSP, heavy $W_R$

| Particle | BP1 | BP2 | BP3 | BP4 |
|---|---|---|---|---|
| $h$ | 125.2 | 125.5 | 124.8 | 125.3 |
| $H_2$ | 551.1 | 748.5 | 492.4 | 657.9 |
| $A_1$ | 551.1 | 748.5 | 492.4 | 657.9 |
| $H_1^\pm$ | 563.7 | 757.7 | 506.0 | 668.1 |
| $H_1^{\pm\pm}$ | 339.1 | 494.6 | 431.7 | 509.8 |
| $W_R^\pm$ | 2668 | 3510 | 2668 | 3510 |
| $Z'$ | 4476 | 5889 | 4476 | 5889 |
| $\tilde{\nu}_\tau$ | 266.5 | 271.6 | 354.0 | 299.7 |
| $\tilde{\nu}_e$ | 813.8 | 663.6 | 632.2 | 896.3 |
| $\tilde{\ell}_e$ | 931.7 | 813.8 | 773.3 | 1011 |
| $\tilde{\chi}_1^0$ | 731.1 | 609.8 | 61.9 | 62.4 |
| $\tilde{\chi}_2^0$ | 750.6 | 711.3 | 486.6 | 447.2 |
| $\tilde{\chi}_1^\pm$ | 744.0 | 703.7 | 487.5 | 447.8 |

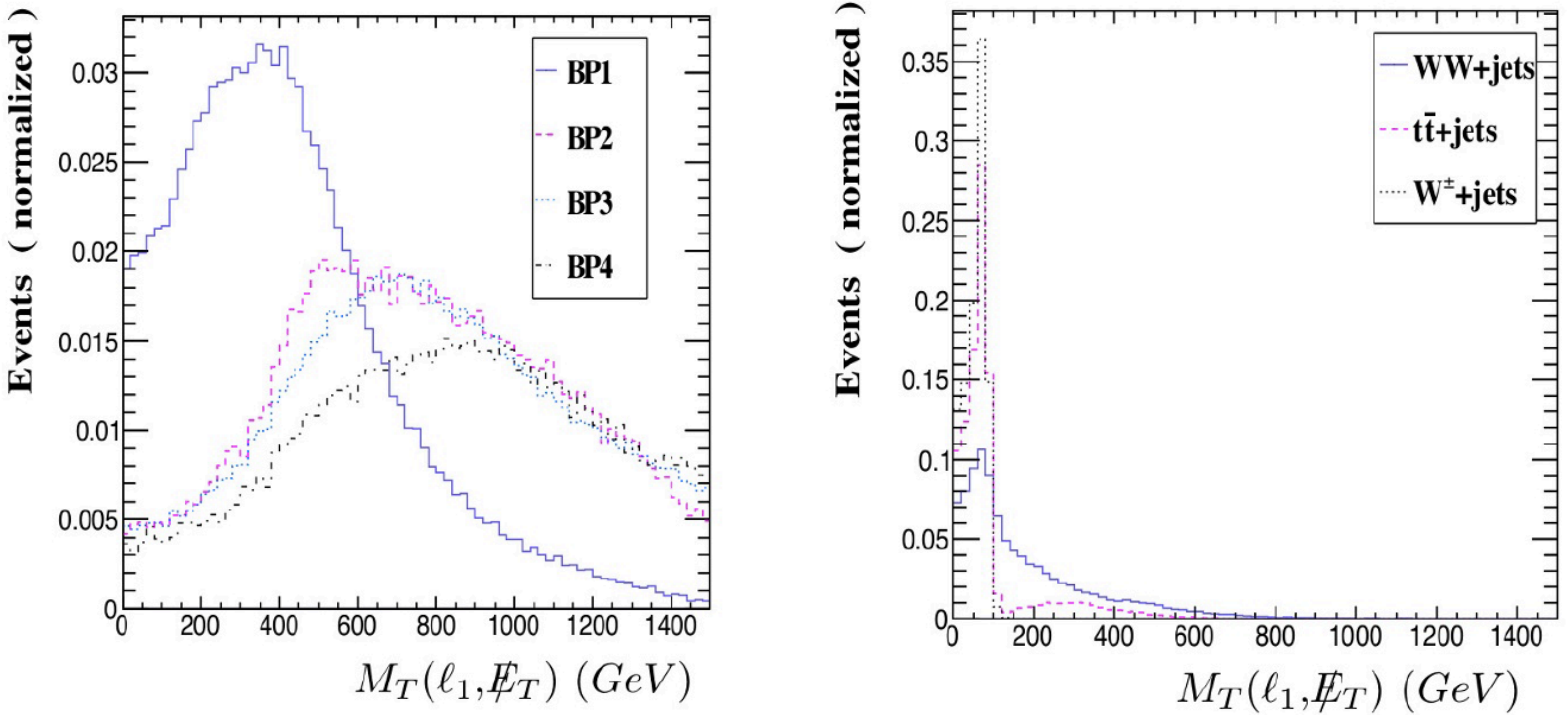
- moderate $\tan\beta \sim 7$
- $\tan\beta_R = v_{2R}/v_{1R}$ close to 1.05
- $\sigma(pp \to W_R) \times BR(W_R \to \text{sleptons}) \simeq 5/1$ fb for 2.7/3.5 TeV $W_R$ before cuts
- BP's give relic density $\sim 0.12$ and satisfy direct detection bounds

| | BP1 | BP2 | BP3 | BP4 |
|---|---|---|---|---|
| $\sigma(pp \to W_R)$ (fb) | 245 | 38 | 245 | 38 |
| $\mathrm{BR}(W_R \to \tilde{\nu}_{I\tau}\tilde{\ell}_\tau)$ | 0.52% | 0.52% | 0.38% | 0.61% |
| $\mathrm{BR}(W_R \to \tilde{\nu}_{Ie}\tilde{\ell}_e)$ | 0.64% | 1.06% | 0.80% | 0.82% |
| $\mathrm{BR}(W_R \to \tilde{\nu}_{I\mu}\tilde{\ell}_\mu)$ | 0.60% | 0.98% | 0.57% | 0.74% |
| $\mathrm{BR}(W_R \to \tilde{\nu}_{Re}\tilde{\ell}_e)$ | 0.21% | 0.60% | 0.42% | 0.47% |
| $\mathrm{BR}(W_R \to \tilde{\nu}_{R\mu}\tilde{\ell}_\mu)$ | 0.24% | 0.47% | 0.19% | 0.36% |
| $\sigma \times \sum \mathrm{BR}(W_R \to \tilde{\nu}\tilde{\ell})$ (fb) | 5.4 | 1.4 | 5.8 | 1.1 |

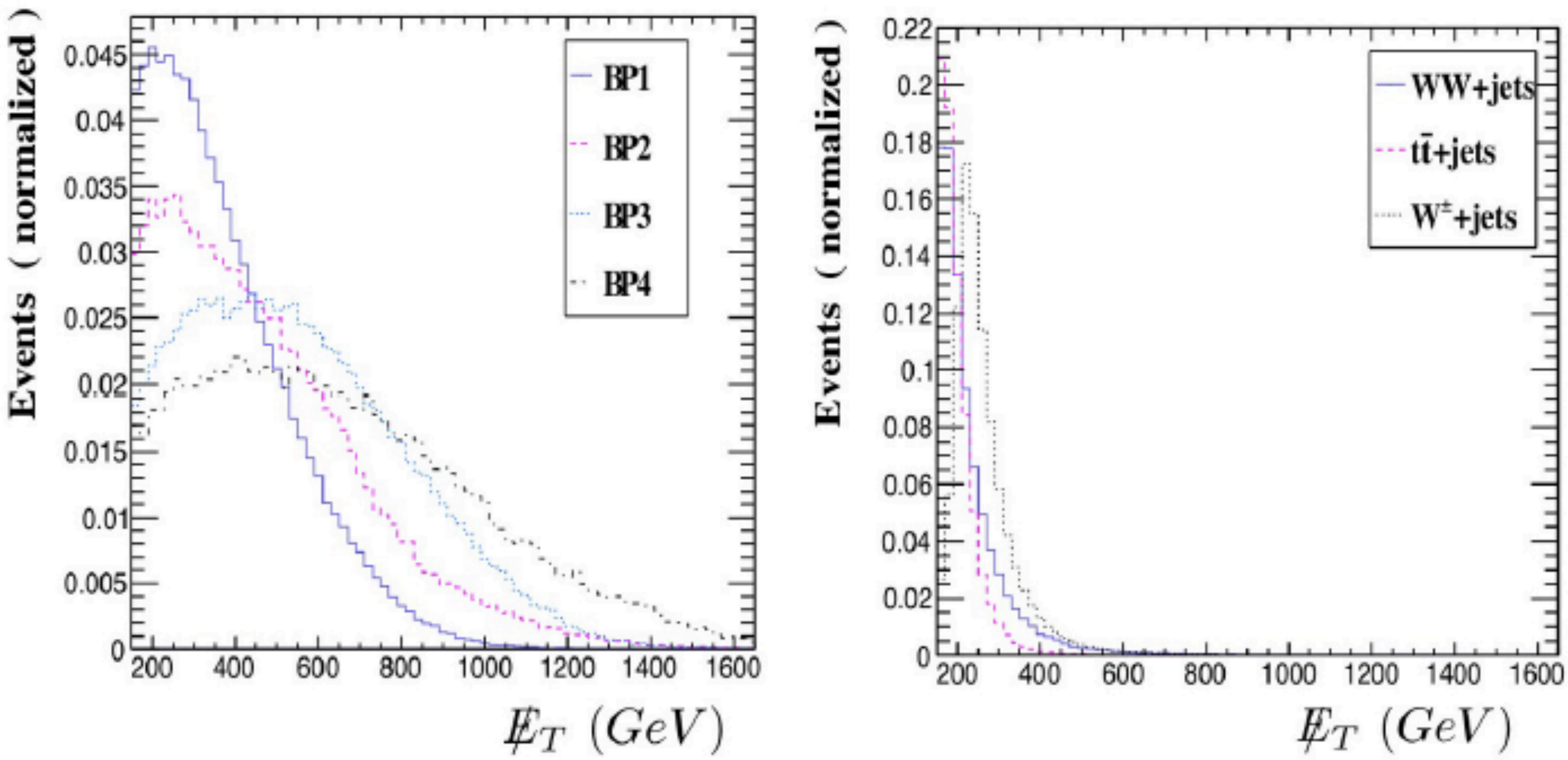
$$pp \to \sum \tilde{\nu}\, \tilde{\ell}$$

$$\begin{array}{lll} (i) & \geq 1\ell + nj + \not{E}_T & \text{with} \quad n \leq 3\,, \\ (ii) & \geq 2\ell + nj + \not{E}_T & \text{with} \quad n \leq 3\,, \end{array}$$

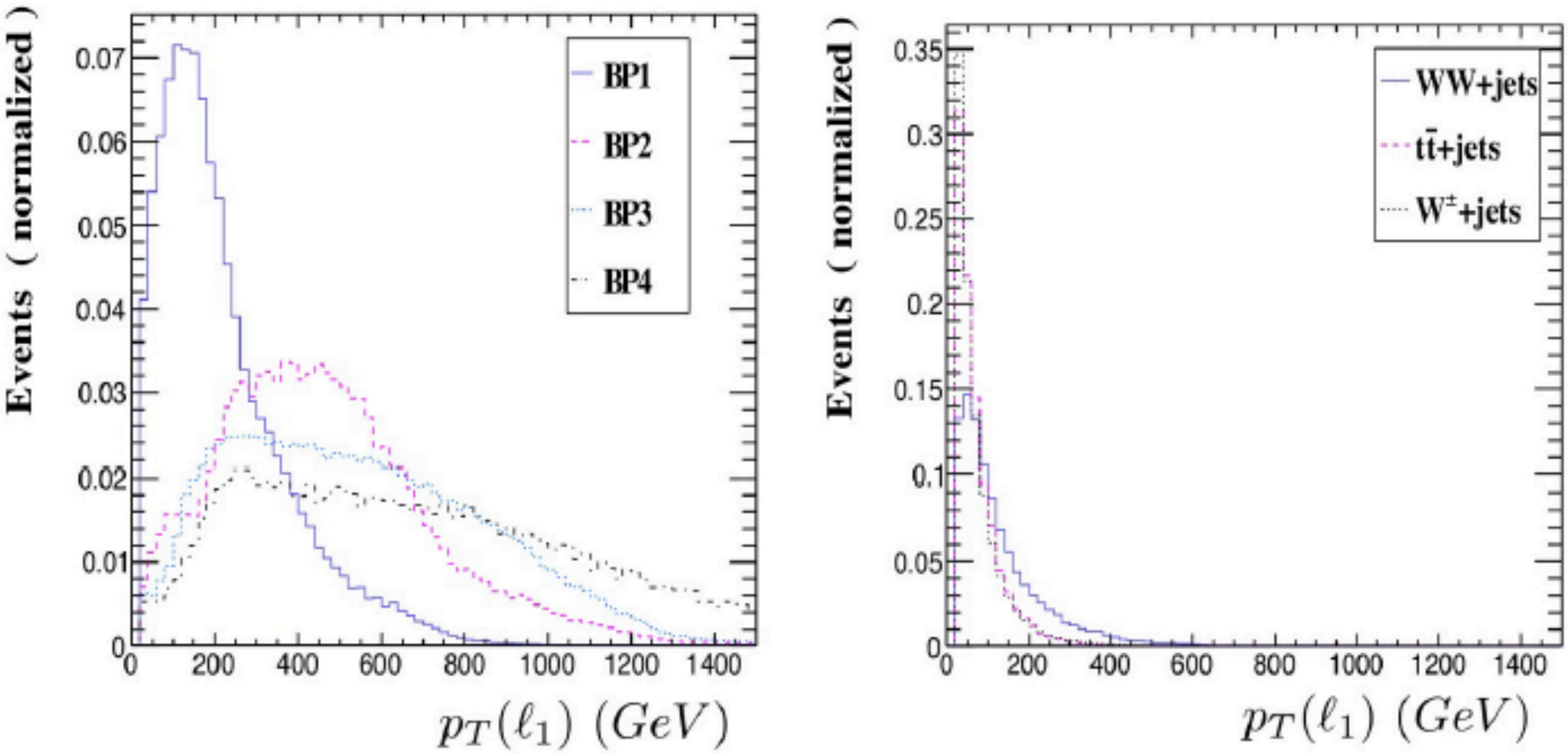
**We make use of resonant slepton and sneutrino production to show how robust and clean these signals can be and how they can provide handles for pushing the LHC reach for the weakly-interacting sector beyond 1TeV.**




$M_T^2 = 2(E_T^\ell \not{E}_T - \vec{p}_T^{\,\ell} \cdot \vec{\not{p}}_T)$ (assuming massless lepton)
Note: All samples normalized to unity, in the region $M_T > 250$ GeV total background larger by a factor 5 (BP3) to 30 (BP4)



Events (normalized)
BP1
BP2
BP3
BP4
$\not{E}_T$ (GeV)
Events (normalized)
WW+jets
$t\bar{t}$+jets
$W^{\pm}$+jets
$\not{E}_T$ (GeV)




Cuts: MET$\geq$ 250 GeV, $p_T(\ell_1) \geq 100$ GeV cut the background by a factor 3, while signal largely survives $\Rightarrow$ BP1 and BP3 can reach discovery level ($5\sigma$), BP2 and BP4 smaller deviations

# Cutflow of benchmarks

| | BP1 | BP2 | BP3 | BP4 | diboson | $t\bar{t}$ | $\ell\nu + j$ |
|---|---|---|---|---|---|---|---|
| Preselection | 216 | 83 | 299 | 45 | 2065 | 7192 | $5.94 \times 10^5$ |
| $M_T(\ell_1, \not{E}_T) > 250$ GeV | 153 | 77 | 279 | 42 | 521 | 708 | 142 |
| $p_T(\ell_1) > 100$ GeV | 134 | 75 | 274 | 42 | 440 | 559 | 124 |
| $\not{E}_T > 250$ GeV | 113 | 67 | 258 | 40 | 229 | 149 | 69 |
| integrated luminosity $100\,\mathrm{fb}^{-1}$. | $5\sigma$ | $3\sigma$ | $11\sigma$ | $1.86\sigma$ | | | |

| | BP1 | BP2 | BP3 | BP4 | diboson | top-antitop |
|---|---|---|---|---|---|---|
| $n_\ell \geq 2$; $p_T(\ell_1) > 200$ GeV | 55 | 21 | 77 | 14 | 94 | 50 |
| $p_T(\ell_2) > 40$ GeV | 50 | 18 | 66 | 13 | 72 | 38 |
| $M_T(\ell_2, \not{E}_T) > 50$ GeV | 46 | 17 | 63 | 13 | 41 | 21 |

integrated luminosity $100\,\mathrm{fb}^{-1}$. $2.3\sigma$

- Difference between sneutrino and neutralino DM: sneutrino DM produces more events with three or four leptons ($> 20\%$ of the number of dilepton events), for neutralino DM $\sim 10\%$ of dilepton events $\Rightarrow$ needs a lot of data
- Heavier $W_R$ actually easier to distinguish from the background: harder leptons, more missing transverse momentum, but smaller production cross section and hence more data needed
- Further cuts can improve the significance a bit, but cut the signal a lot, too, if the mass gap between $W_R$ and the LSP is not large (happens with BP1)

# Conclusions

- A right-handed sneutrino is a viable dark matter candidate in LRSUSY
- The annihilation proceeds via gauge couplings, which allows us to predict the sneutrino mass
- Discovery possible with 100 $\mathrm{fb}^{-1}$ for $m(W_R) = 2.7$ TeV for both sneutrino and neutralino DM, for $m(W_R) = 3.5$ TeV the significances 2–3$\sigma$ (discovery needs $\mathcal{O}(500)$ $\mathrm{fb}^{-1}$)
- With LHC Run II we might discover LRSUSY quite early

The LHC is expected in general to be more sensitive to LRSUSY realizations with a sneutrino LSP than for MSSM setups with a RH neutrino