Left-right supersymmetry and signals at the LHC

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Outline:

- Motivation
- Left-right symmetric extensions (LR) of the Standard Model
- LR models with supersymmetry (LRSUSY)
- Dark matter in LRSUSY models
- Signals of LRSUSY at the LHC

Motivation

Electromagnetic and strong interactions conserve parity.
Maybe parity is conserved at high energies also by weak interactions and broken dynamically Pati, Salam (1974); Mohapatra, Pati (1975); Senjanovic, Mohapatra (1975)

If weak interactions were parity conserving at a high scale, every left-handed particle would need a right-handed counterpart

➡ right-handed neutrinos needed

After neutrinos were deemed massive, neutrino mass has also become a motivation.

Smallest gauge group where left-right symmetry can be implemented is
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ Davidson (1979), Mohapatra, Marshak (1980)

Gauge symmetry could originate from SO(10) or E_6 unified model

Add supersymmetry to the left-right model

$R_{parity}=(-1)^{3(B-L)+2s}$ is an exact symmetry as B-L is a gauge symmetry;

if $SU(2)_R \times U(1)_{B-L}$ is broken by $L=\pm 2$ triplet, R_{parity} remains unbroken also after symmetry breaking Mohapatra, PRD (1986); Font, Ibanez, Quevedo, PLB (1989); Martin PRD (1992)

$\Rightarrow$ LSP is a dark matter candidate

$\Rightarrow$ proton remains stable

There is no SUSY CP problem because of parity invariance

Kuchimanchi, PRL (1996), Mohapatra, Rasin, PRL (1996)

Also strong CP problem may be solved

Beg, Tsao (1978); Mohapatra, Rasin, (1996); Babu, Dutta, Mohapatra (2002)

Left-right symmetric extensions of the Standard Model; $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$

Fermions:

$$(Q_L)^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} = \left(\mathbf{3}, \mathbf{2}, \mathbf{1}, \tfrac{1}{3}\right),\ (Q_R)^i = \begin{pmatrix} u_R^i \\ d_R^i \end{pmatrix} = \left(\mathbf{3}, \mathbf{1}, \mathbf{2}, \tfrac{1}{3}\right),$$

$$(L_L)^i = \begin{pmatrix} \nu_L^i \\ \ell_L^i \end{pmatrix} = (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1\ ),\ (L_R)^i = \begin{pmatrix} \nu_R^i \\ \ell_R^i \end{pmatrix} = (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1\ )$$

with L,R the left- and right-chiral components, $P_{L,R} = (1 \pm \gamma_5)$

$$\boxed{Q = I_{3L} + I_{3R} + \frac{B-L}{2}}$$

Higgs sector: need to break $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(2)_L \times U(1)_Y$

Break $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ by a triplet:

$$\Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} = (\mathbf{1}, \mathbf{1}, \mathbf{3}, 2); \ \langle \Delta_R^0 \rangle = v_R$$

For simplicity, assume that Δ_L is decoupled Chang, Mohapatra, Parida, PRL (1984)
Inert Δ_L is also motivated by electroweak ρparameter.

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ by a bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} = (\mathbf{1}, \mathbf{2}, \mathbf{2}, 0); \ \langle \Phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix}$$

$v_R \gg \kappa \gg \kappa'; \ \kappa^2 + \kappa'^2 = v_{SM}^2$

$K^0 - \overline{K^0}$ mixing constraints $\propto \kappa\kappa' e^{i\alpha}$
Beall, Bander, Soni (1982)

Fermion masses can be found from:

$$\mathcal{L}_Y = h^a_{q,ij}\bar{Q}_{L,i}\Phi_a Q_{R,j} + \tilde{h}^a_{q,ij}\bar{Q}_{L,i}\tilde{\Phi}_a Q_{R,j} + h^a_{\ell,ij}\bar{L}_{L,i}\Phi_a L_{R,j} + \tilde{h}^a_{\ell,ij}\bar{L}_{L,i}\tilde{\Phi}_a L_{R,j}$$
$$+ f_{ij} L^T_{R,i} C i\tau_2 \Delta_R L_{R,j} + h.c.$$

with $\tilde{\Phi} = i\sigma_2 \Phi^* \sigma_2$

Quark masses:

$$M_u = h_u \kappa + \tilde{h}_u\, e^{-i\alpha}\kappa'; M_d = h_d e^{i\alpha}\kappa' + \tilde{h}_d\, \kappa$$

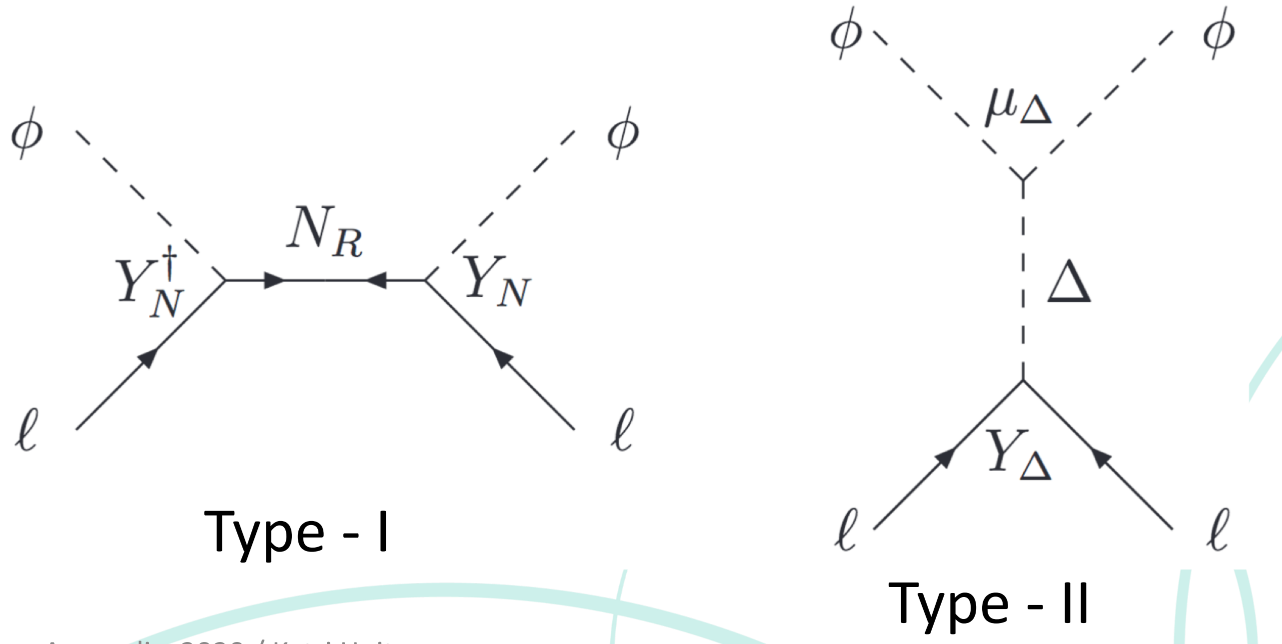
Charged lepton masses $M_\ell = h_\ell e^{i\alpha}\kappa' + \tilde{h}_\ell\, \kappa$

Neutrino masses $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$; $m_D = h_\nu \kappa + \tilde{h}_\nu\, e^{-i\alpha}\kappa'$; $M_N = f v_R$

Type-I seesaw, no neutrino Majorana mass: $m_\nu = -m_D M_N^{-1}\, m_D^T$

Note: if Δ_L included, one gets also Majorana mass for the light neutrinos, and thus type-II seesaw

Gell-Mann, Ramond, Slansky (1979); Yanagida (1979); Mohapatra, Senjanovic (1980); Schechter, Valle (1980)



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

New gauge bosons connected to enlarged gauge group W_R, W, Z_R, Z, γ

$$m_W^2 = \frac{g_L^2}{2}(\kappa^2 + \kappa'^2); \qquad m_{W_R}^2 = g_R^2 v_R^2$$

$$m_Z^2 = \frac{g_L^2}{2\ \cos^2\theta_W}(\kappa^2 + \kappa'^2); \qquad m_{Z_R}^2 = 2(g_R^2 + g_{BL}^2)v_R^2$$

Theoretically $\frac{g_R}{g_L} \gtrsim 0.55$ Bhupal Dev, Mohapatra, Zhang, JHEP 05 (2016)

$W - W_R$ mixing $\approx \frac{g_L}{g_R}\frac{\kappa\kappa\prime}{v_R^2}$

PDG mass limits:

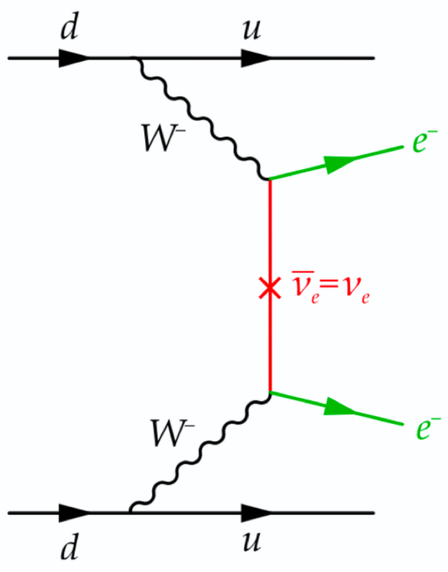
$m_{W_R} > 5.2$ TeV assuming $m_{N_R} \ll m_{W_R}$

Note that $m_{Z_R} > m_{W_R}$

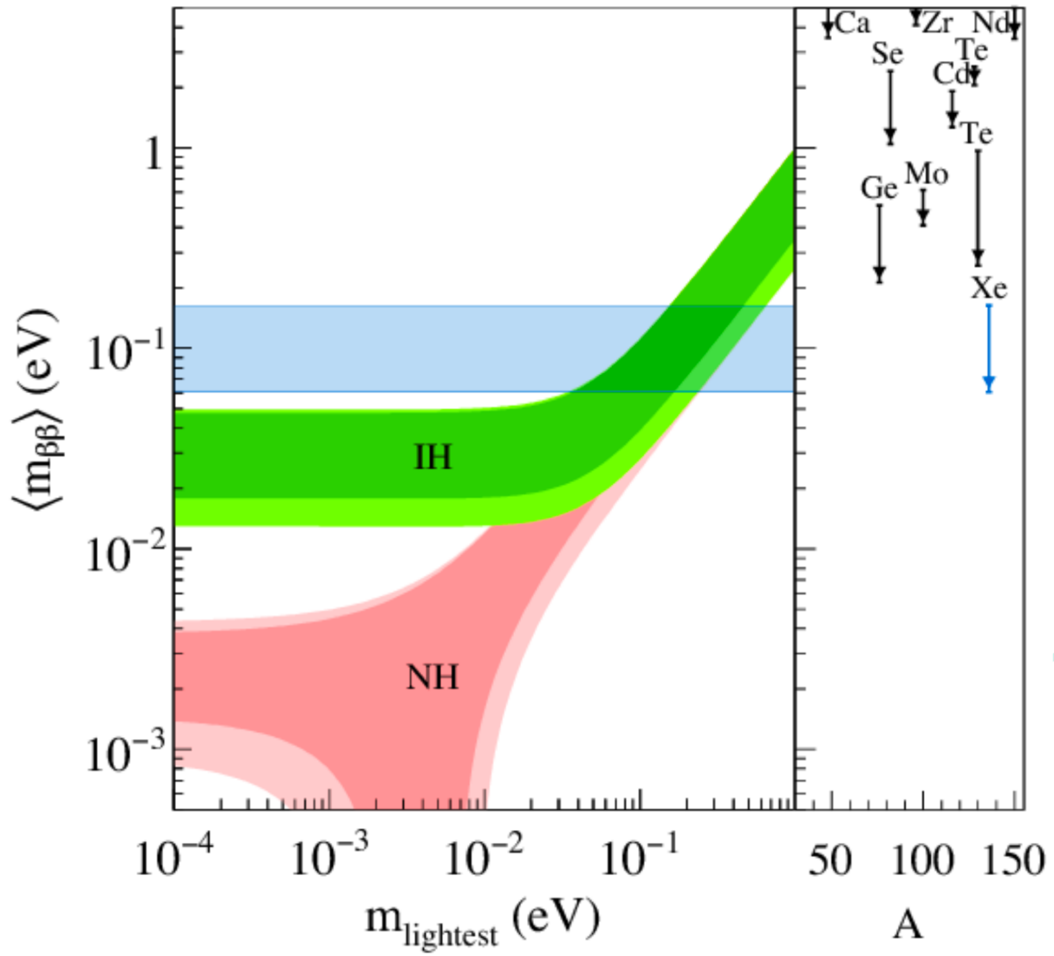
Tests of left-right model

Lepton number violating processes:

Neutrinoless double beta decay, $0\nu\beta\beta$



J. Engel et al, Rept.Prog.Phys (2017)

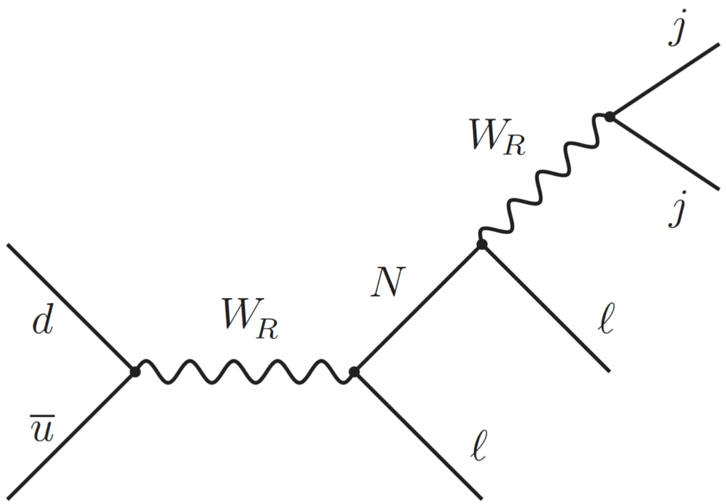


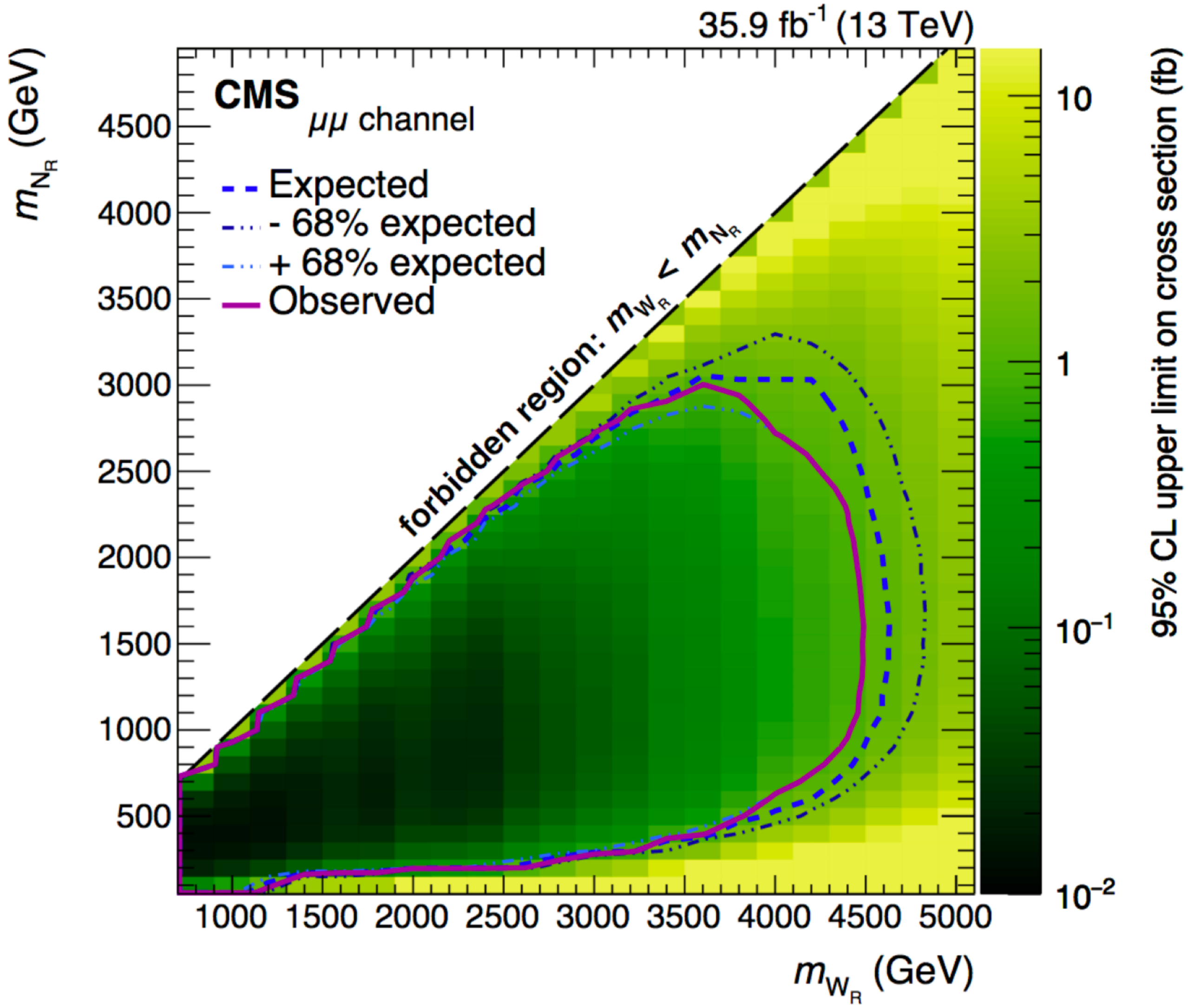
Lepton flavour violation in meson decays, $\tau \to \mu, e\gamma, \mu \to e\gamma, \mu \leftrightarrow e$ –conversion,…

CMS, JHEP 05 (2018), arXiv: 1803.11116

$$W_R \to \mathrm{N}_R \ell \to \ell\ell jj$$

N_R Majorana ➡ similar amounts of same sign and opposite sign dileptons
Keung, Senjanovic, PRL 50 (1983) 1427





Discovery of W_R and N_R would be a clear signal of left-right symmetry

Supersymmetric left-right symmetric model (LRSUSY)

The Higgses in LRSUSY

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

$$\Phi_1 = \begin{pmatrix} \Phi_{11}^{+} & \Phi_{11}^{0} \\ \Phi_{12}^{0} & \Phi_{12}^{-} \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0)\,, \qquad \Phi_2 = \begin{pmatrix} \Phi_{21}^{+} & \Phi_{21}^{0} \\ \Phi_{22}^{0} & \Phi_{22}^{-} \end{pmatrix} \sim (\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0)\,,$$

$$\Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_L^{-} & \Delta_L^{0} \\ \Delta_L^{--} & -\frac{1}{\sqrt{2}}\Delta_L^{-} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}, -2), \qquad \delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_L^{+} & \delta_L^{++} \\ \delta_L^{0} & -\frac{1}{\sqrt{2}}\delta_L^{+} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, \mathbf{1}, 2)$$

$$\Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_R^{-} & \Delta_R^{0} \\ \Delta_R^{--} & -\frac{1}{\sqrt{2}}\Delta_R^{-} \end{pmatrix} \sim (\mathbf{1}, \mathbf{1}, \mathbf{3}, -2), \qquad \delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_R^{+} & \delta_R^{++} \\ \delta_R^{0} & -\frac{1}{\sqrt{2}}\delta_R^{+} \end{pmatrix} \sim (\mathbf{1}, \mathbf{1}, \mathbf{3}, 2)$$

$$S \sim (\mathbf{1}, \mathbf{1}, \mathbf{1}, 0)\,,$$

with VEVs

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 & 0 \\ \frac{v_1}{\sqrt{2}} & 0 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 & \frac{v_2}{\sqrt{2}} \\ 0 & 0 \end{pmatrix}, \quad \langle \Delta_R \rangle = \begin{pmatrix} 0 & \frac{v_R}{\sqrt{2}} \\ 0 & 0 \end{pmatrix}, \quad \langle \delta_R \rangle = \begin{pmatrix} 0 & 0 \\ \frac{v_R'}{\sqrt{2}} & 0 \end{pmatrix}$$

$$\langle S \rangle = \frac{v_S}{\sqrt{2}}\,.$$

Superpotential:

$$
\begin{aligned}
W = \quad & Q_L^T \boldsymbol{Y}_Q^{(i)} \Phi_i Q_R + L_L^T \boldsymbol{Y}_L^{(i)} \Phi_i L_R + L_L^T \boldsymbol{h}_{LL} \delta_L L_L + L_R^T \boldsymbol{h}_{RR} \Delta_R L_R + \lambda_L S \,\mathrm{Tr}\,[\Delta_L \delta_L] \\
& + \lambda_R S \,\mathrm{Tr}\,[\Delta_R \delta_R] + \lambda_3 S \,\mathrm{Tr}\left[\tau_2 \Phi_1^T \tau_2 \Phi_2\right] + \lambda_4 S \,\mathrm{Tr}\left[\tau_2 \Phi_1^T \tau_2 \Phi_1\right] \\
& + \lambda_5 S \,\mathrm{Tr}\left[\tau_2 \Phi_2^T \tau_2 \Phi_2\right] + \lambda_S S^3 + \xi_F S
\end{aligned}
$$

Problems with scalar potential:
to preserve electric charge and R-parity conservation in the vacuum, add

- non-renormalizable terms Mohapatra, Rasin, PRL 76 (1996), PRD 54 (1996)
- additional B-L triplets Aulakh, Melfo, Rasin, Senjanovic, PRD 58 (1998)
- include radiative corrections → scale < 15 TeV → hopes to find at the LHC
  Kuchimanchi, Mohapatra, PRD 48 (1993); Babu, Mohapatra, PLB 668 (2008);
  Basso, Fuks, Krauss, Porod, JHEP 07 (2015)

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Constraints on spectrum

Spectrum largely determined by $\langle \Delta_R^0 \rangle \sim v_R \in [10, 15]$ TeV

Basso, Fuks, Krauss, Porod, JHEP 07 (2015)

Scalar potential terms include Frank, Fuks, KH, Mondal, Rai, Waltari, PRD 101 (2020)

$$| \, \xi_F + \lambda_L \mathrm{Tr}[\Delta_L \delta_L] + \lambda_R \mathrm{Tr}[\Delta_R \delta_R] + \lambda_3 \mathrm{Tr}[\tau_2 \Phi_1^T \tau_2 \Phi_2] + \lambda_4 \mathrm{Tr}[\tau_2 \Phi_1^T \tau_2 \Phi_1]$$
$$+ \lambda_5 \mathrm{Tr}[\tau_2 \Phi_2^T \tau_2 \Phi_2] + 3\lambda_S S^2 \, |^2$$

Thus, large v_R lifts the energy of the ground state. If sign(λ_R)= - sign (λ_S), can still find a parameter region, where $m_{\text{gauge bosons}}$ is not within reach of LHC or HE-LHC

W_R decays to superpartners around 20% → $m_{W_R} \geq 3.3$ TeV → $m_{Z_R} \geq 5.6$ TeV

…Constraints on spectrum

Impose m_h=125.1$\pm$0.3 GeV

tan $\beta \geq 5$, stop masses ≈a couple of TeV and stop mixings

Mass of the doubly charged Higgses generated at loop-level Babu, Mohapatra, PLB 668 (2008)

$m_{H^{\pm\pm}} > 350$ GeV

$m_{H^{\pm\pm}}$ not much above 1 TeV

fix $BR(H^{\pm\pm} \rightarrow \tau^{\pm}\tau^{\pm})$=92%, $BR(H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}/e^{\pm}e^{\pm})$=4%, $m_{H^{\pm\pm}} > 350$ GeV

$(m_N)_{\mathrm{ij}} = (h_{RR})_{\mathrm{ij}}\, v_R$ → m_{N_τ} ≈750 GeV, $m_{N_e} \approx m_{N_\mu} \approx$ 150 GeV

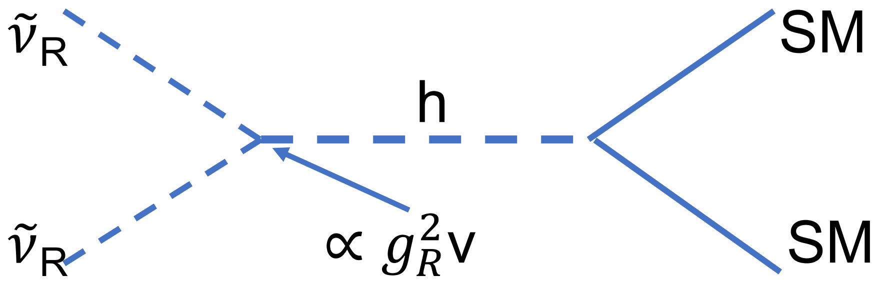
$m_{H_2^0} \approx m_{A_1^0} \approx m_{H_1^\pm}$ constrained by $B_s \rightarrow \mu\mu$, which favors moderate tan β

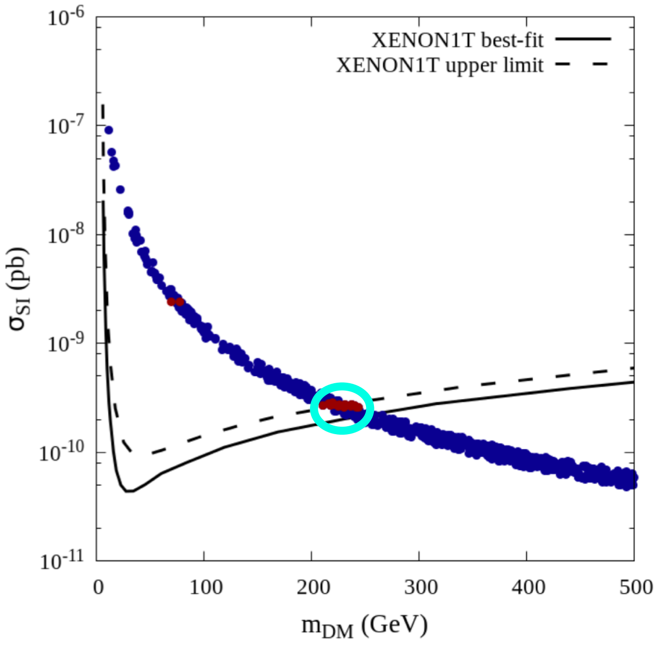
Other Higgs masses several TeV ($\approx v_R$ or v_S).

Dark matter in LRSUSY

LRSUSY specific options: sneutrino and higgsino

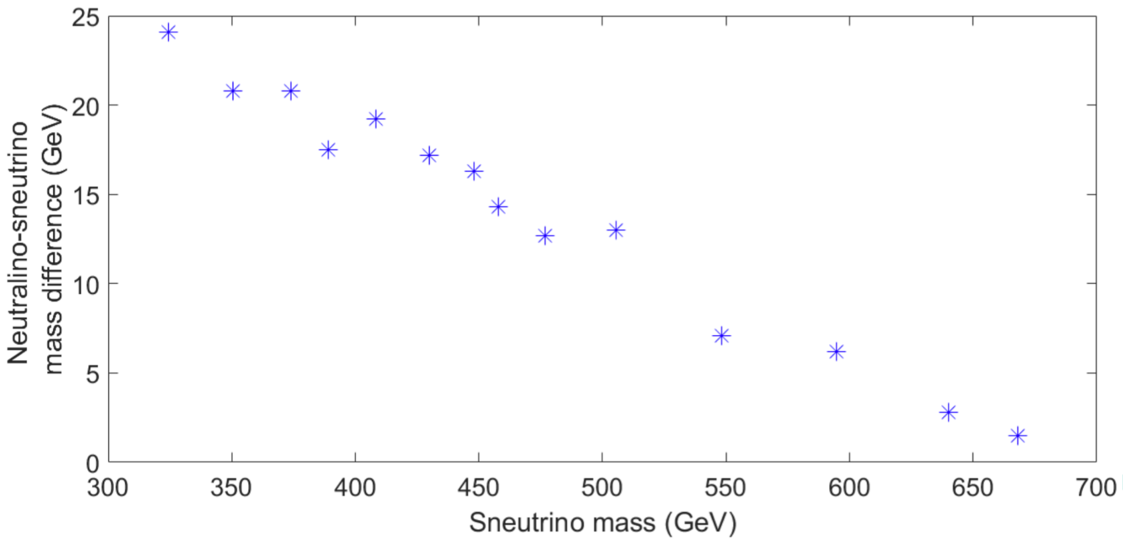
1) $\tilde{\nu}_R$ can produce DM





Right-sneutrino mass is the only free parameter
→ relic density determines $m_{\tilde{\nu}_R} \approx 250 - 300$ GeV

Frank, Fuks, KH, Rai, Waltari (2017);
Chatterjee, Frank, Fuks, KH, Mondal, Rai, Waltari (2019)



$\tilde{\nu}_R$ LSP with coannihilations with neutralinos

$m_{\tilde{\nu}_R} \approx 700$ GeV possible

2) SUSY partners of gauge bosons or Higgses can be the dark matter

Chatterjee, Frank, Fuks, KH, Mondal, Rai, Waltari (2019)

Bidoublet higgsinos form a nearly degenerate set of four neutralinos and two charginos

➡ Coannihilations cannot be avoided, when the lightest higgsino is the LSP

The Planck-value for relic density is achieved with 750 GeV LSP higgsino (could be slightly decreased with further coannihilations, with e.g. sneutrino)

Note that in this case the spectrum is rather heavy and compressed

➡ difficult to detect

Dominantly bino-like neutralino with mass $m_h/2$.

”Bino” refers to B-L –gaugino.

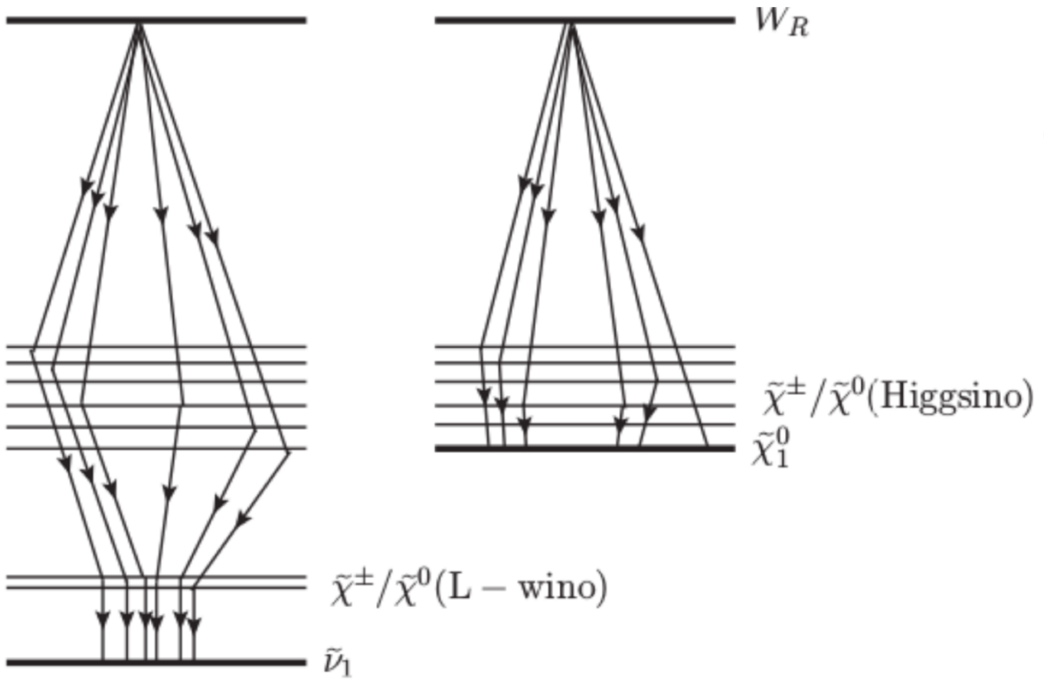
Collider signals at the LHC

Particles light enough to be accessed experimentally? Consider W_R and $H^{\pm\pm}$
Also A_1, H_2, $H_1^{\pm}$ could be within LHC reach: almost degenerate with mass $\gtrsim$ 700 GeV

1) Robust signal of LR symmetry is W_R together with N_R
   Assume two different cases: dark matter from right sneutrino or higgsino

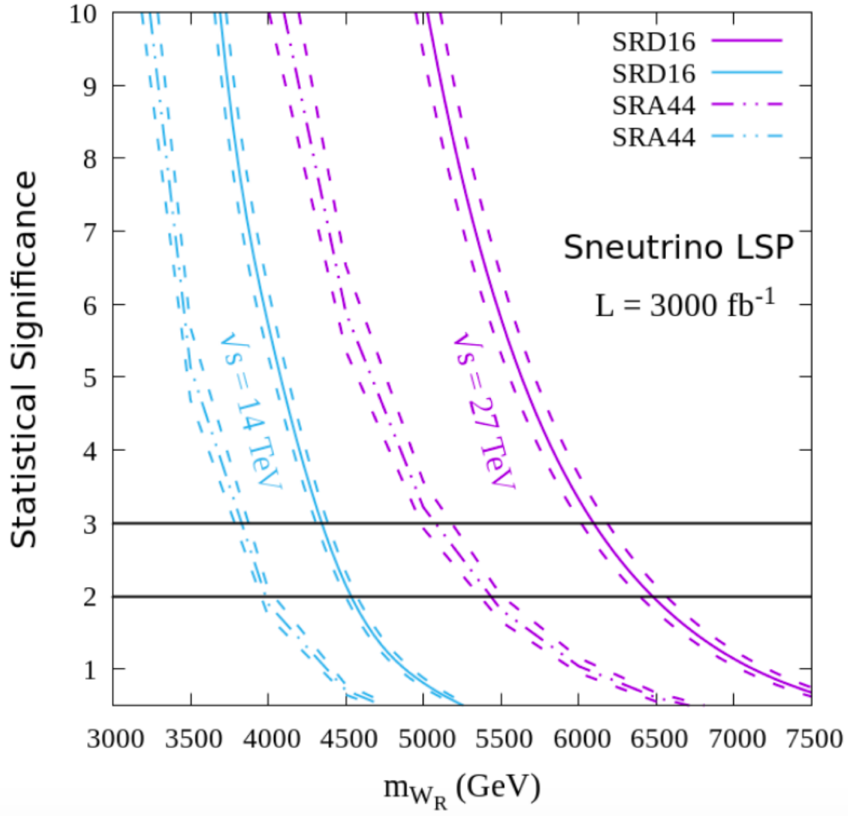
W_R production;
decay to neutralinos, charginos
$BR(W_R \to jj) \approx 50\,\%$, $BR(W_R \to N\ell) \approx 16\,\%$,
$BR(W_R \to \tilde{\chi}\tilde{\chi}) \approx 22\,\%$,
→ Leptons and missing energy
→ Electroweakino searches are relevant

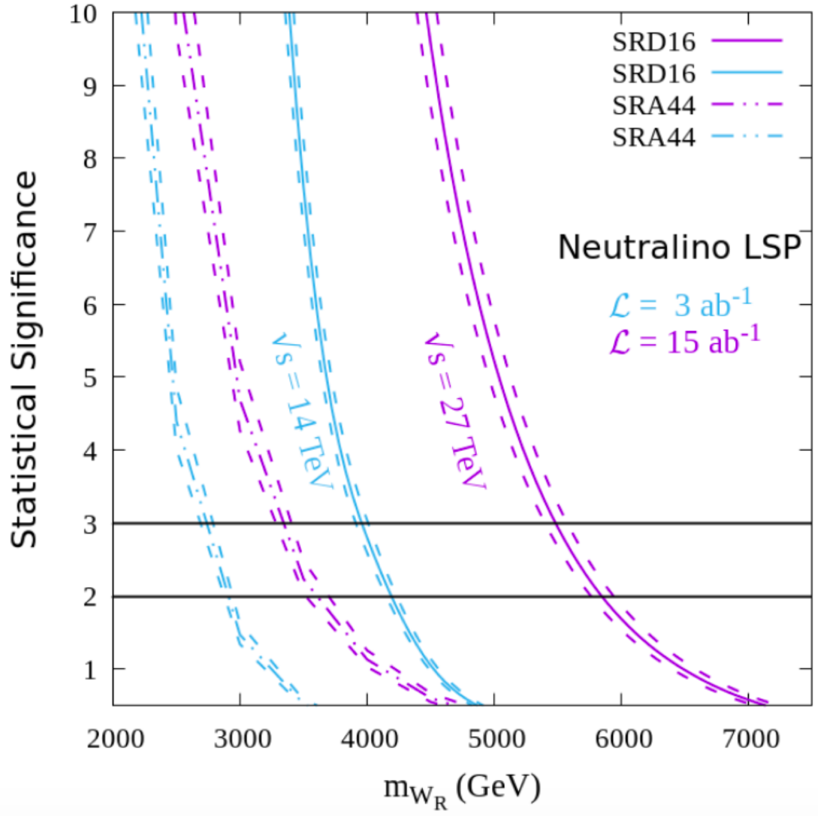
Frank, Fuks, KH, Rai, Waltari in
CERN Yellow Rep. Monogr. 7 (2019)



Signal Regions	Requirements
SRA44	$N_\ell = 3$, $N_{\rm OSSF} \geq 1$, $N_\tau = 0$, $M_T > 160$ GeV, $\not{E}_T \geq 200$ GeV, $M_{\ell\ell} \geq 105$ GeV
SRD16	$N_\ell = 2$, $N_{\rm OS} = 1$, $N_{\rm SF} = 0$, $N_\tau = 1$, $M_{T2} > 100$ GeV, $\not{E}_T \geq 200$ GeV

CMS, JHEP 03 (2018), 166





Frank, Fuks, KH, Rai, Waltari in CERN Yellow Rep. Monogr. 7 (2019)

The most difficult scenario

Frank, Fuks, KH, Mondal, Rai, Waltari, PRD 101 (2020) no.11, 115014

If W_R too heavy to be detected, the $H^{\pm\pm}$ may be the best (only) possibility for experimental detection (SR1: 4 τ_h, require 3 reconstructed τ_h, SR2: $2\tau_h$ 2ℓ)

We studied detection of $H^{\pm\pm}$ at HE-LHC (27 TeV, 15 ab^{-1}) in a class of left-right supersymmetric scenarios favored by dark matter, with a relic density as measured by the Planck collaboration originating from the co-annihilations of multiple higgsino states of about 700 GeV

The only available decay mode is to leptons.
As previously BR($H^{\pm\pm} \to \tau^{\pm}\,\tau^{\pm}$)=92%, BR($H^{\pm\pm} \to \mu^{\pm}\,\mu^{\pm}$)= BR($H^{\pm\pm} \to e^{\pm}\,e^{\pm}$)=4%

Here $H^{\pm\pm}$ is Drell-Yan pair produced

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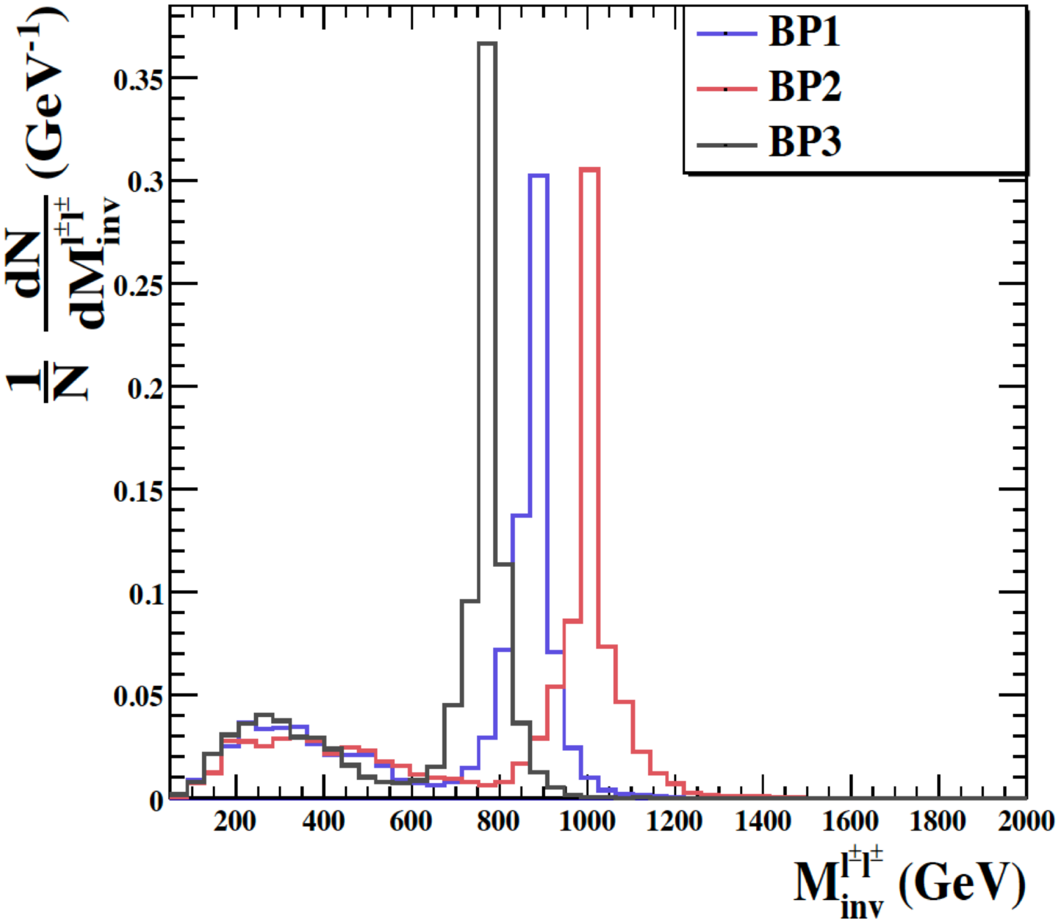
We expect the detection of $H^{\pm\pm}$ at the HE-LHC up to around 1 TeV

	BP1	BP2	BP3
m_{W_R}	6550.5	7486.2	7486.2
$m_{Z'}$	10993.2	12563.6	12563.6
$m_{H_1^{\pm\pm}}$	875.0	1016.4	780.9
$m_{\tilde{\chi}_1^0}$	878.4	803.7	770.1
$m_{\tilde{\chi}_2^0}$	889.7	812.1	777.7
$m_{\tilde{\chi}_3^0}$	893.0	815.3	780.7
$m_{\tilde{\chi}_4^0}$	895.6	817.6	782.9
$m_{\tilde{\chi}_5^0}$	1032.2	1043.5	1048.0
$m_{\tilde{\chi}_1^\pm}$	886.4	809.3	775.1
$m_{\tilde{\chi}_2^\pm}$	893.5	815.7	781.2
$m_{\tilde{\chi}_1^{\pm\pm}}$	7413.2	8412.9	5619.2
$\mathrm{BR}(H_1^{\pm\pm} \to \tau^\pm\tau^\pm)$	0.92	0.92	0.92
$\mathrm{BR}(H_1^{\pm\pm} \to \ell^\pm\ell^\pm)$	0.08	0.08	0.08



$pp \to H^{\pm\pm}H^{\mp\mp} \to \tau^\pm\,\tau^\pm\ell^\mp\,\ell^\mp$

Conclusions

- ✓ LRSUSY is a natural model for supersymmetric dark matter due to B-L –symmetry
- ✓ Excellent viable possibilities for supersymmetric dark matter, different from MSSM options
- ✓ Signals:
    - Detection of W_R together with N_R ➡ LR
    - Supersymmetric channel ➡ LRSUSY
    - Discovery of $H^{\pm\pm}$ ➡ seesaw, type I and type II
    - If W_R is too heavy to be detected, detection of $H^{\pm\pm}$ is still possible
- ✓ With no discovery at 27 TeV, it is almost certain that something more than the minimal model would be needed

Thank You.