LHC phenomenology of a Z_3 Dark matter and neutrino mass model

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Z_3 model: Fields

Ma (2007)

- New fields:

  2 singlet scalars of $Y = 0$: χ_a $(a = 1, 2)$

  1 vector-like, doublet fermion of $Y = -1$: $\Psi = (N, E)$

  1 vector-like, singlet fermion of $Y = 0$: S

  All transform under Z_3 as, e.g.,

$$S \to \omega S, \omega = \exp(i2\pi/3)$$

- SM fields:

  Higgs scalar: $\Phi = (G^+, (\mathrm{v} + h + iG^0)/\sqrt{2})$

  Leptons: $F_L^i = \left(\nu_L^i, \ell_L^i\right)$, ℓ_R^i

Z_3 model: Interactions

- Gauge interactions plus the following ones.
- Mass and Yukawas:

$$\mathcal{L}_{\text{Yuk}} = -m_S \overline{S_L} S_R - m_\Psi \overline{\Psi_L} \Psi_R - y'_{ij} \overline{F^i_L} \Phi \ell^i_R - z'_{ai} \chi^\dagger_a \overline{F^i_L} \Psi_R$$

$$-\frac{1}{2} x'_{aL} \chi_a \overline{S^C_L} S_L - \frac{1}{2} x'_{aR} \chi_a \overline{S^C_R} S_R - z'_L \overline{S_L} \widetilde{\Phi}^\dagger \Psi_R - z'_R \overline{S_R} \widetilde{\Phi}^\dagger \Psi_L + \mathrm{h.c.}$$

- Scalar potential:

$$V = -m^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda_1 \left(\Phi^\dagger \Phi\right)^2 + \left(M^2\right)_{ab} \chi^\dagger_a \chi_b$$

$$+\frac{1}{6}\left(\mu^{abc} \chi_a \chi_b \chi_c + \mathrm{h.c.}\right) + \frac{1}{2} \lambda_2^{ab;cd} \chi^\dagger_a \chi_b \chi^\dagger_c \chi_d + \lambda_3^{ab} \Phi^\dagger \Phi \chi^\dagger_a \chi_b$$

Z_3 model: Parameters

- Simplifications:

$$\lambda_2^{ab;cd} = \lambda_2, \lambda_3^{ab} = \lambda_3, \mu^{abc} = \mu; z'_L = z'_R = z'$$

- Constraints from perturbativity and no SSB of Z_3:

Belanger et al (2012)

$$|\lambda_2| < \frac{4\pi}{3}, |\lambda_3| < 4\pi; \lambda_{1,2} > 0, 2\sqrt{\lambda_1\lambda_2} + \lambda_3 > 0, \frac{\mu^2}{16\lambda_2} > m_{\chi_L}^2$$

- Diagonalization:

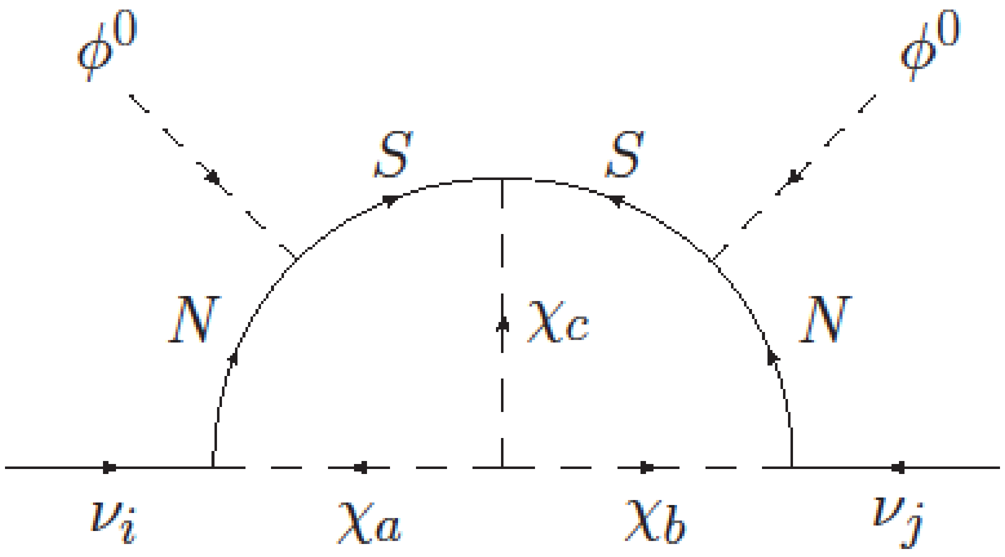
$\chi_{1,2} \Rightarrow \chi_{L,R}$ angle α $N, S \Rightarrow N_{1,2}$ angle β

no mixing between Z_3 and SM particles

In terms of $\chi_{L,R}$ and $N_{1,2}$, input parameters become

$$m_{\chi_{L,R}}, m_{N_{1,2}}, m_E, \alpha, \beta, x_{L,R}^a, z_{ai}, \lambda_{2,3}, \mu$$

Z_3 model: Neutrino masses



- $(m_\nu)^{ij} = (z^T \Lambda z)^{ij}$, 2×3, 2×2,function of masses and couplings
- In the basis where ℓ's are diagonalized, m_ν is diagonalized by U_{PMNS}. $(m_\nu)^{ij}$ being degenerate, one ν is massless, in either NH or IH.

  z is a function of ν masses, U_{PMNS}, Λ, and a new complex parameter.

Z_3 model: Constraints

- $\ell_\alpha \to \ell_\beta \gamma$ from $\chi_{L,R} - E$ loop

  Upper bounds (90% CL):

$$\mathrm{Br}(\mu \to e\gamma) < 5.7\ 10^{-13}$$
$$\mathrm{Br}(\tau \to e\gamma) < 3.3\ 10^{-8}$$
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4\ 10^{-8}$$

  translate, e.g., for $m_{\chi_{L,R}} \sim m_E$, into

$$\left|z_{ae} z_{a\mu}\right| \lesssim 5.1\ 10^{-5} \left(\frac{m_E}{100\ \mathrm{GeV}}\right)^2$$
$$\left|z_{a\tau} z_{ae}\right| \lesssim 3.0\ 10^{-2} \left(\frac{m_E}{100\ \mathrm{GeV}}\right)^2$$
$$\left|z_{a\mu} z_{a\tau}\right| \lesssim 3.4\ 10^{-2} \left(\frac{m_E}{100\ \mathrm{GeV}}\right)^2$$

Liao, Liu (2009)
Ding et al (2014)

Z_3 model: Constraints

- Invisible Higgs decays in case of light DM χ_L or N_1:

  Upper bounds from direct searches $(95\%\ \mathrm{CL})$:

  WBF: 28% (ATLAS), 65% (CMS)

  ZH production: 75% (ATLAS), 83% (CMS)

  Bounds from fitting to visible decays $(95\%\ \mathrm{CL})$: 25% (ATLAS) $\surd$

  $\Rightarrow$

  χ_L as DM: $\lambda_{h\chi_L} \lesssim 0.01$

  N_1 as DM: $\sin\beta \lesssim 0.09$ for $m_{N_2} \sim \mathrm{v}$

Z_3 model: Constraints

- Invisible Z decays in case of light DM χ_L or N_1: less stringent

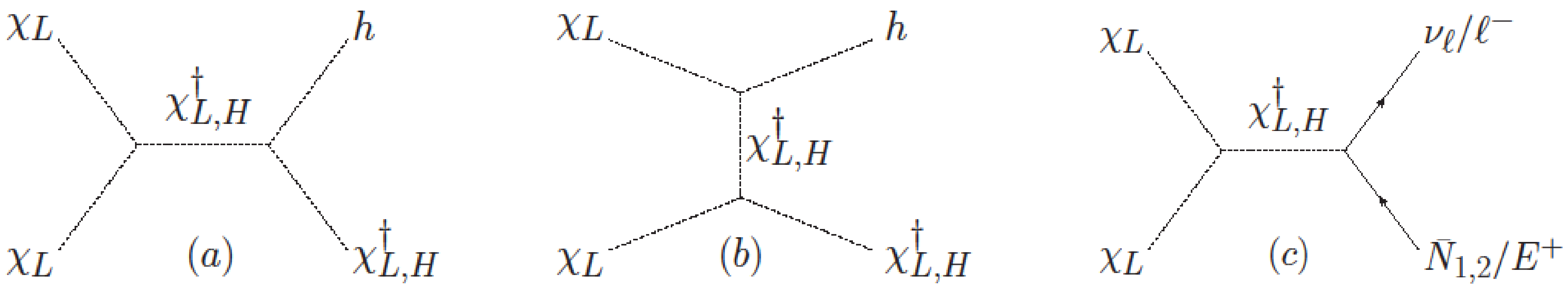
- Constraint from ρ or ΔT parameter due to fermion mass splitting:

  For small β, $|m_E - m_{N_2}| \lesssim \text{few GeV}$ Bhattacharya et al (2015)

DM

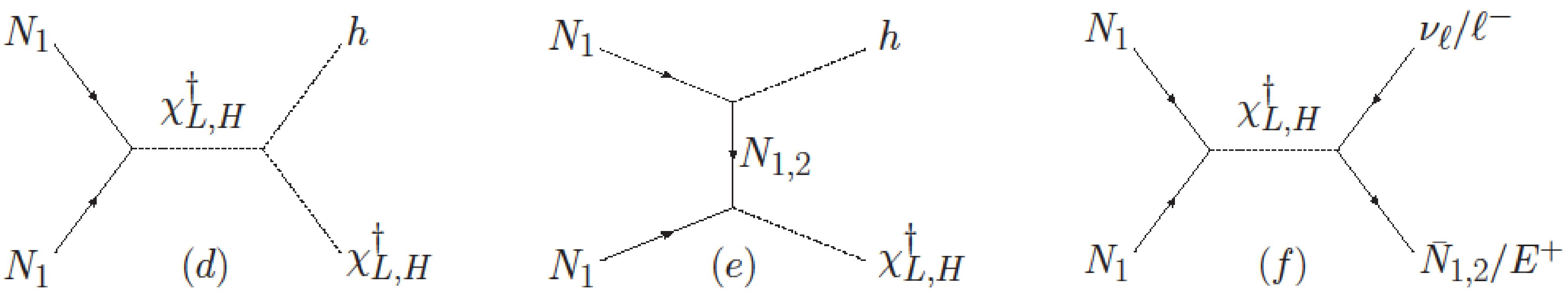
- Due to Z_3 both annihilation and semi-annihilation are possible – possible decoupling of constraints between relic and direct detection.
- Both χ_L and N_1 can be a candidate.

- Semi-annihilation of χ_L as DM:



DM

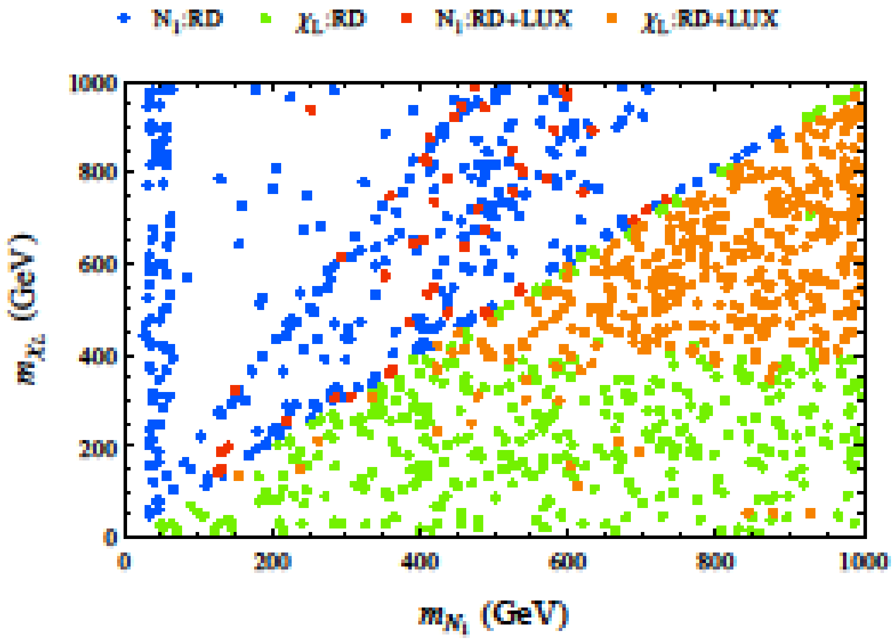
- Semi-annihilation of N_1 as DM:



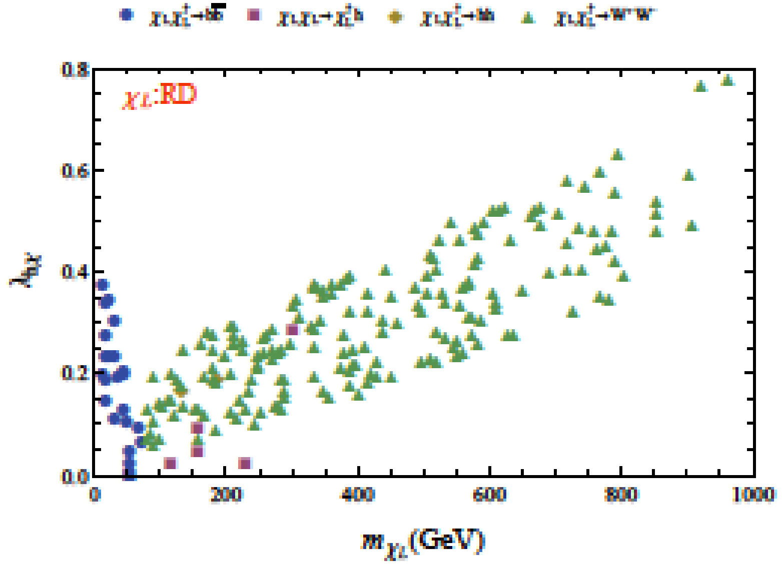
- Scan multi-parameter space with constraints from Planck alone or from both Planck and LUX. Projecting the allowed regions onto a two-parameter plane yields the following figs.

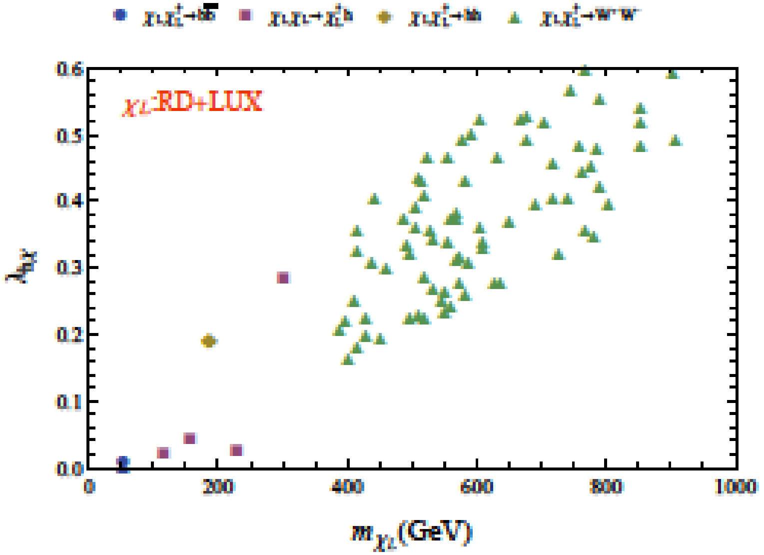
DM

Either χ_L (lower-right) or N_1(upper-left) as DM with relic alone or both relic and LUX

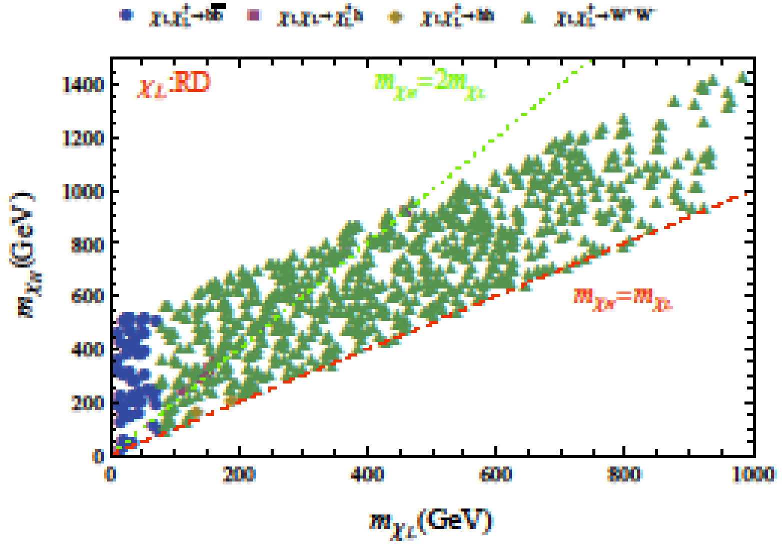


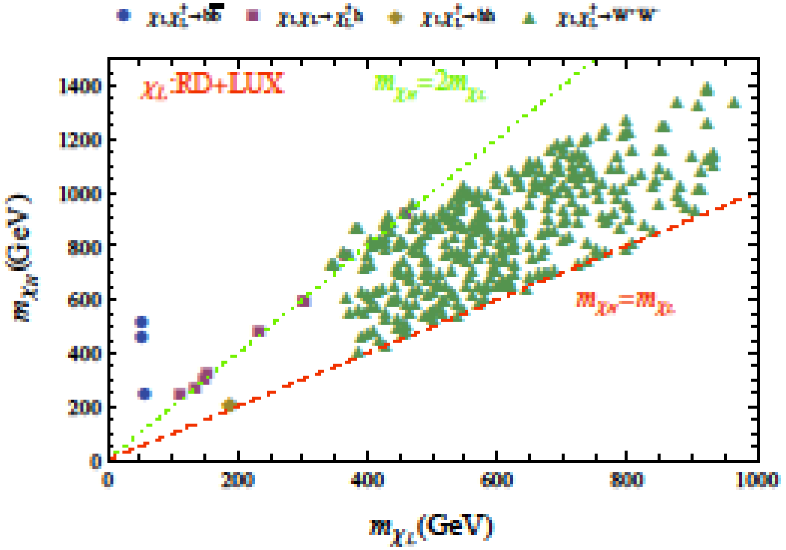
χ_L as DM





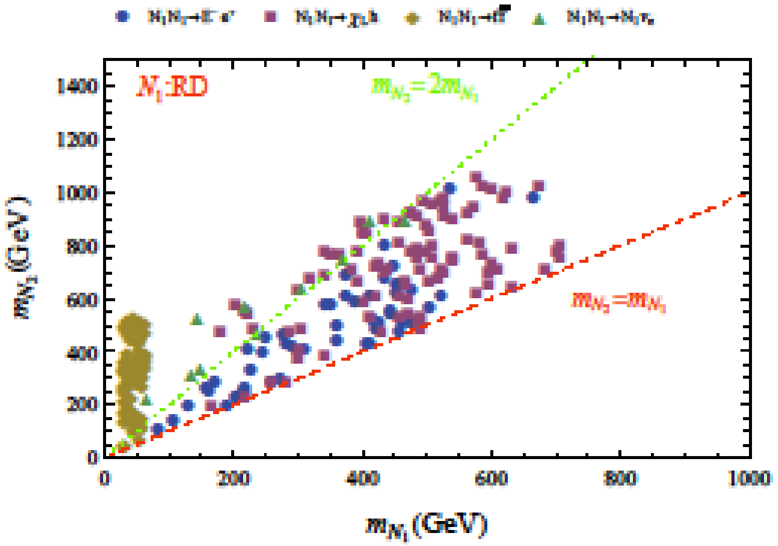
$\lambda_{h\chi_L}$ vs m_{χ_L} w/o LUX for various (semi-)annihilations

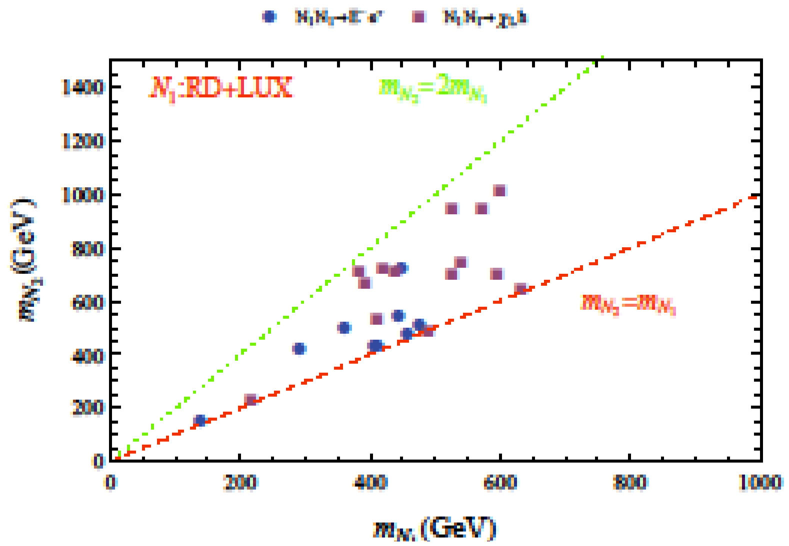




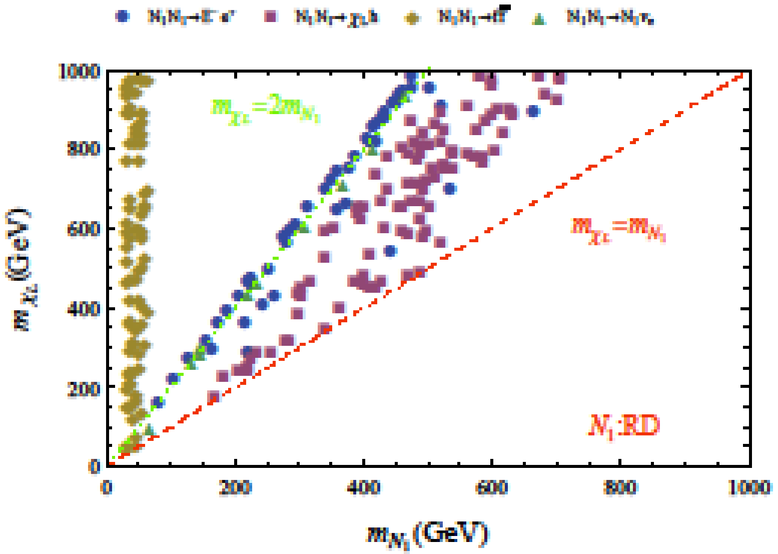
m_{χ_H} vs m_{χ_L} w/o LUX for various (semi-)annihilations

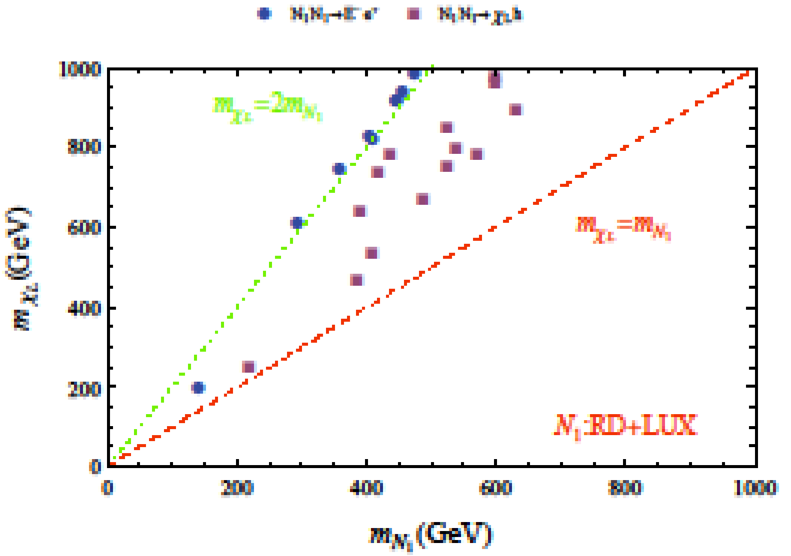
N_1 as DM





m_{N_2} vs m_{N_1} w/o LUX for various (semi-) annihilations



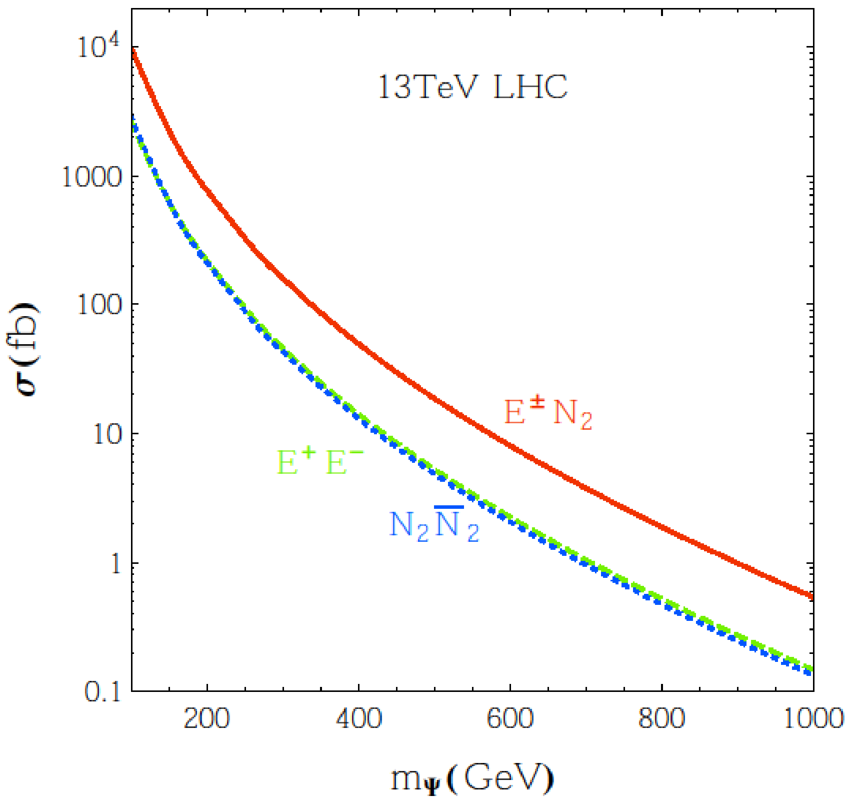


m_{χ_L} vs m_{N_1} w/o LUX for various (semi-) annihilations

σ_{tot} at LHC

s-channel Drell-Yan dominant; e.g., for $\beta = 0$,

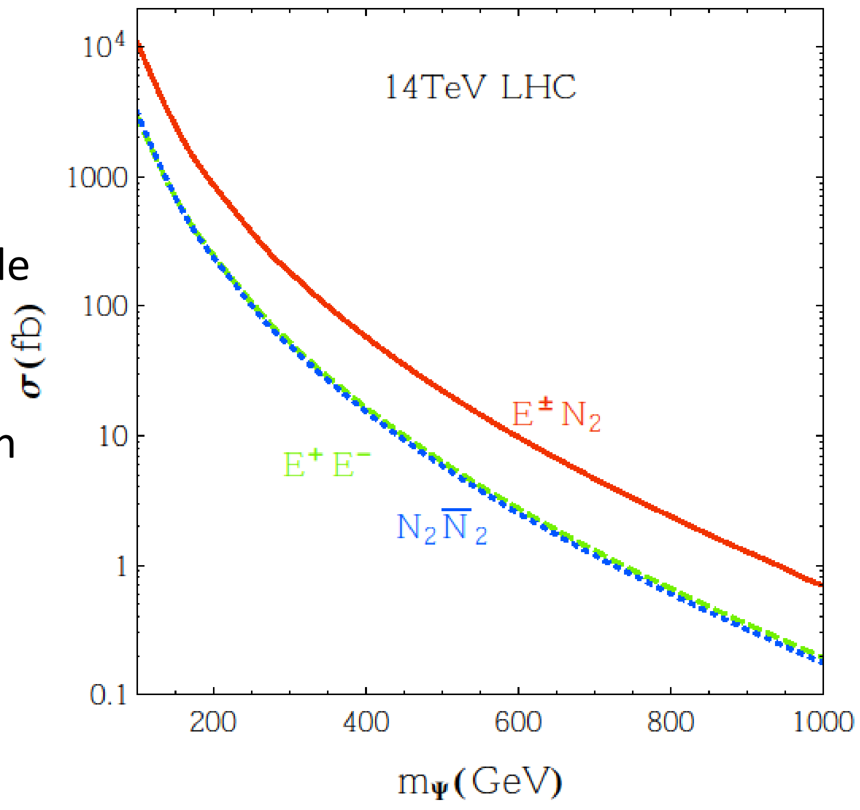
$$pp \to E^{\pm}N, E^{+}E^{-}, N\bar{N} + X$$



typical of EW processes

N_1 and $\chi_{L/H}$ produced via cascade
Decays of $N_2, E^{\pm}$ for $\beta \neq 0$

promising to detect multi-lepton signals



New particles decays

Decays proceed via 3 types of interactions:

(1) Gauge interactions ,e,g, $E^- \to W^- N_1$

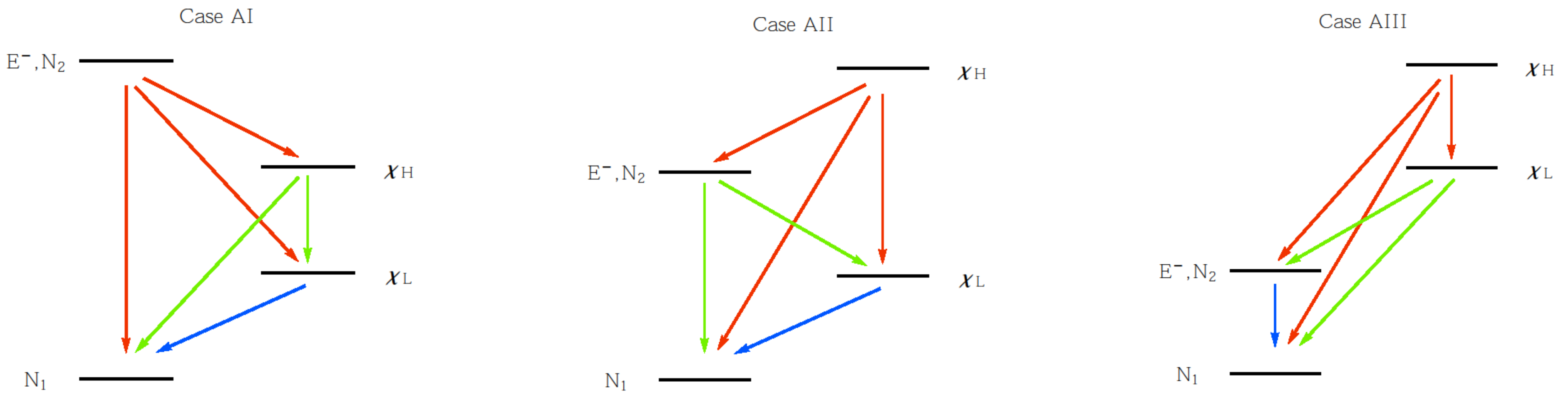
(2) Yukawa couplings, e.g. , $E^- \to \chi_L \ell^-$

(3) Scalar self-interactions, e.g., $\chi_H \to \chi_L h$

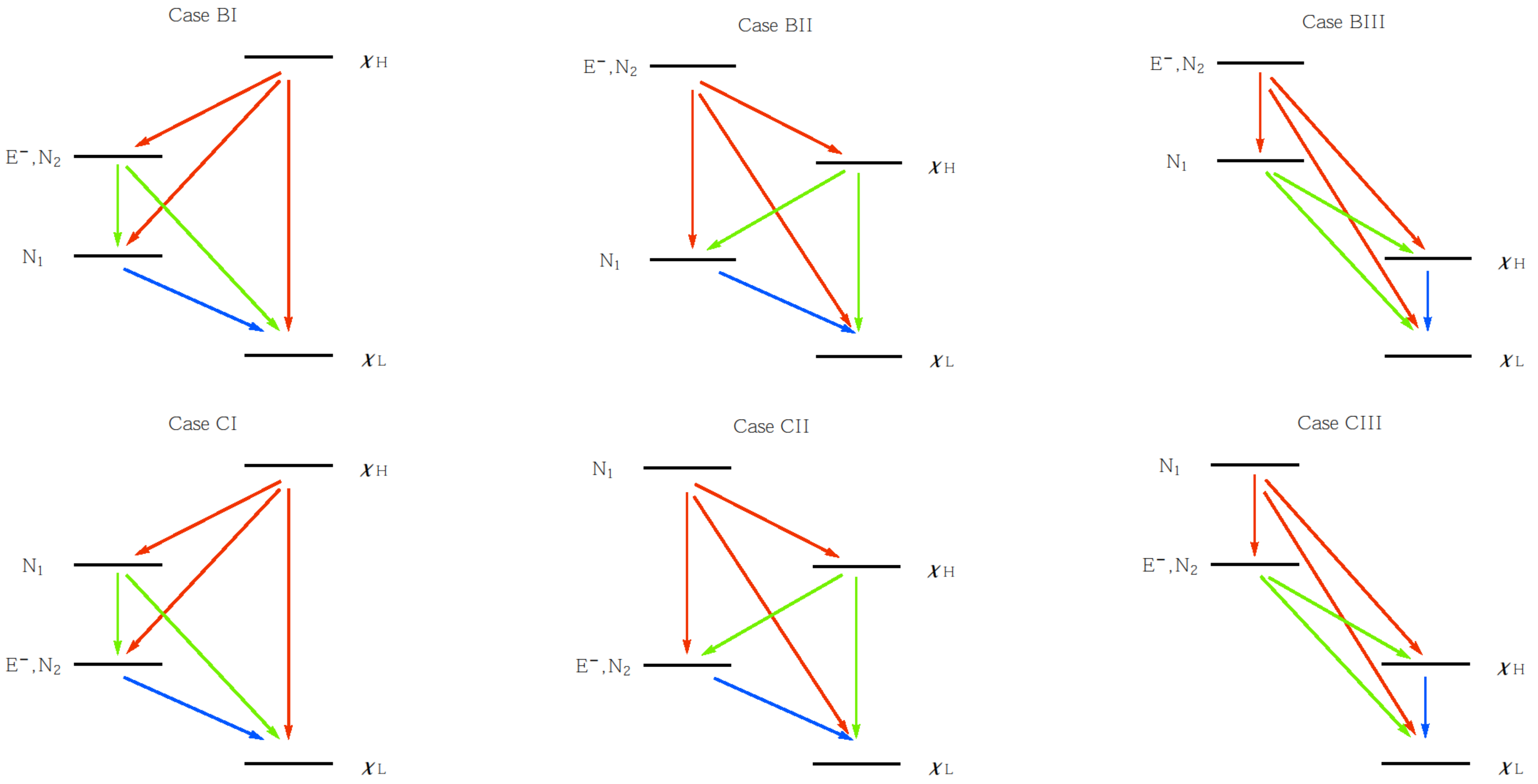
Decay properties to be illustrated at the point:

$$\sin\alpha = 0.1, \sin\beta = 0.01, \lambda_2 = \lambda_3 = 0.1,$$
$$z_{ai} = 0.01, x_{aL} = x_{aR} = 1, \mu = 10 \text{ GeV}$$

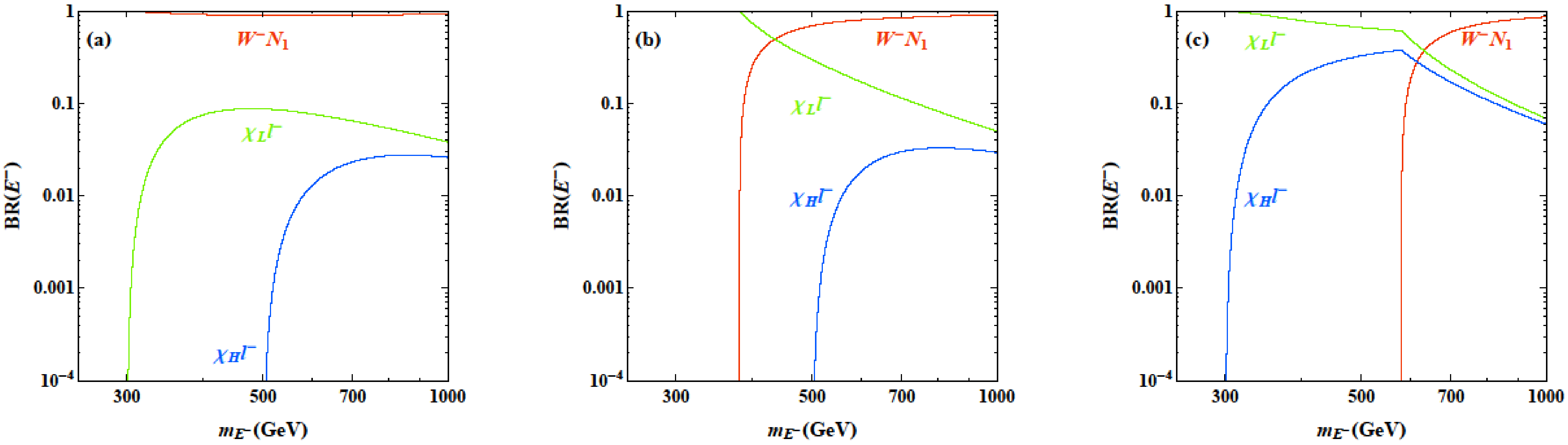
Cascade decay patterns with N_1 as DM



Cascade decay patterns with χ_L as DM



Decay properties: E^-

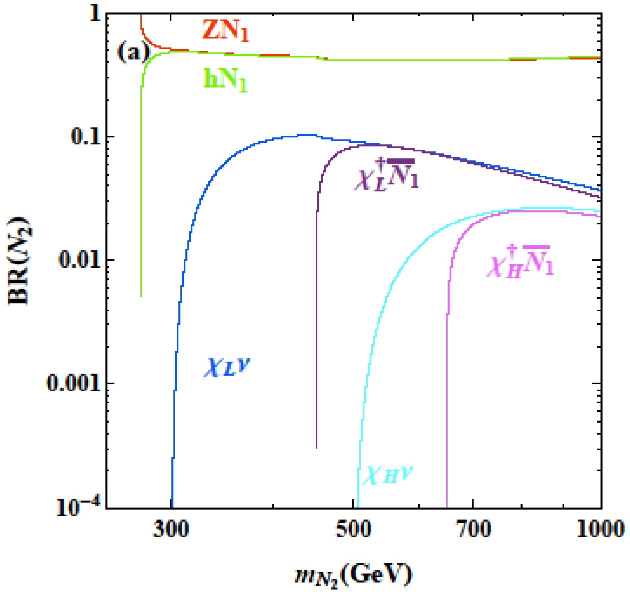


$m_{N_1} = 150$ GeV
$m_{\chi_L} = 300$ GeV
$m_{\chi_H} = 500$ GeV
$E^- \to W^- N_1$

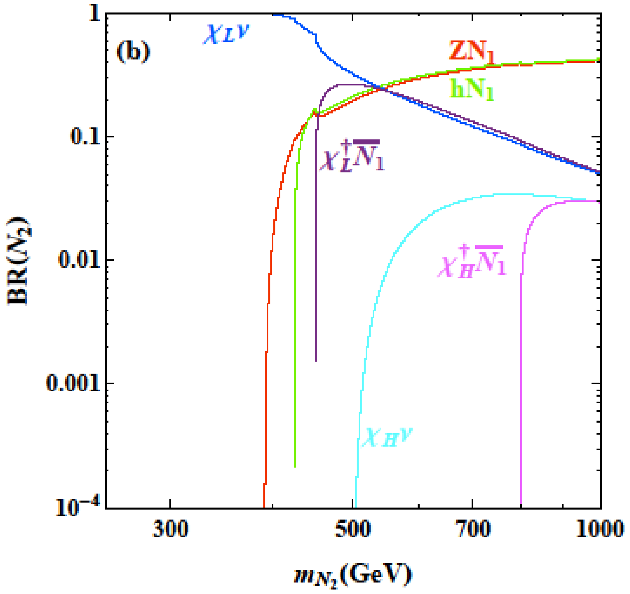
$m_{N_1} = 300$ GeV
$m_{\chi_L} = 150$ GeV
$m_{\chi_H} = 500$ GeV
$E^- \to \ell^- \chi_L$
$E^- \to W^- N_1$

$m_{N_1} = 500$ GeV
$m_{\chi_L} = 150$ GeV
$m_{\chi_H} = 300$ GeV
$E^- \to \ell^- \chi_L$
$E^- \to W^- N_1$
$E^- \to \ell^- \chi_H$

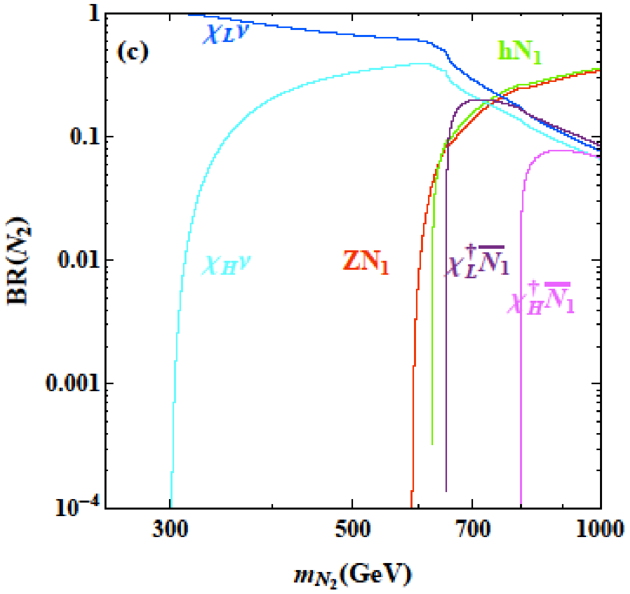
Decay properties: N_2



$m_{N_1} = 150$ GeV
$m_{\chi_L} = 300$ GeV
$m_{\chi_H} = 500$ GeV
$N_2 \to N_1 Z, N_1 h$



$m_{N_1} = 300$ GeV
$m_{\chi_L} = 150$ GeV
$m_{\chi_H} = 500$ GeV
$N_2 \to \chi_L \nu$
$N_2 \to N_1 Z, N_1 h$



$m_{N_1} = 500$ GeV
$m_{\chi_L} = 150$ GeV
$m_{\chi_H} = 300$ GeV
$N_2 \to \chi_L \nu$
$N_2 \to N_1 Z, N_1 h$

LHC signatures

- Governed by Z_3 fermion doublet production and cascade decays.

- Most interesting signatures for neutrino mass models involve multi-leptons, now w/o h.

  $\Longrightarrow$ Classification of signatures accordingly.

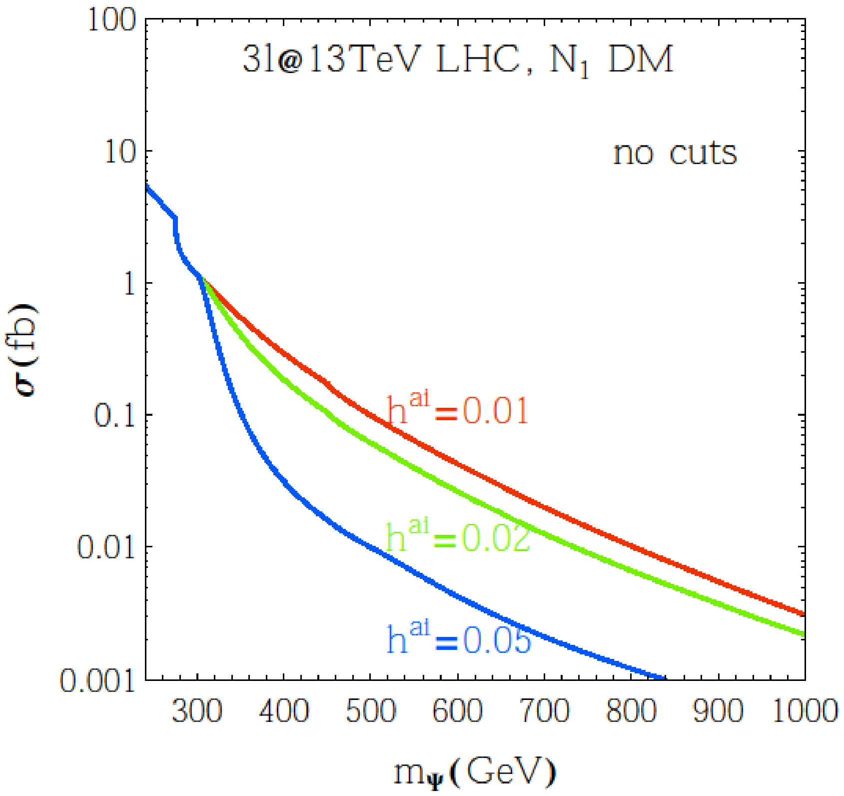
- Some signatures look similar to those in SUSY or seesaws. Current constraints based on simplified assumptions on Br and mass splittings should be taken with care.

LHC signatures: N_1 as DM

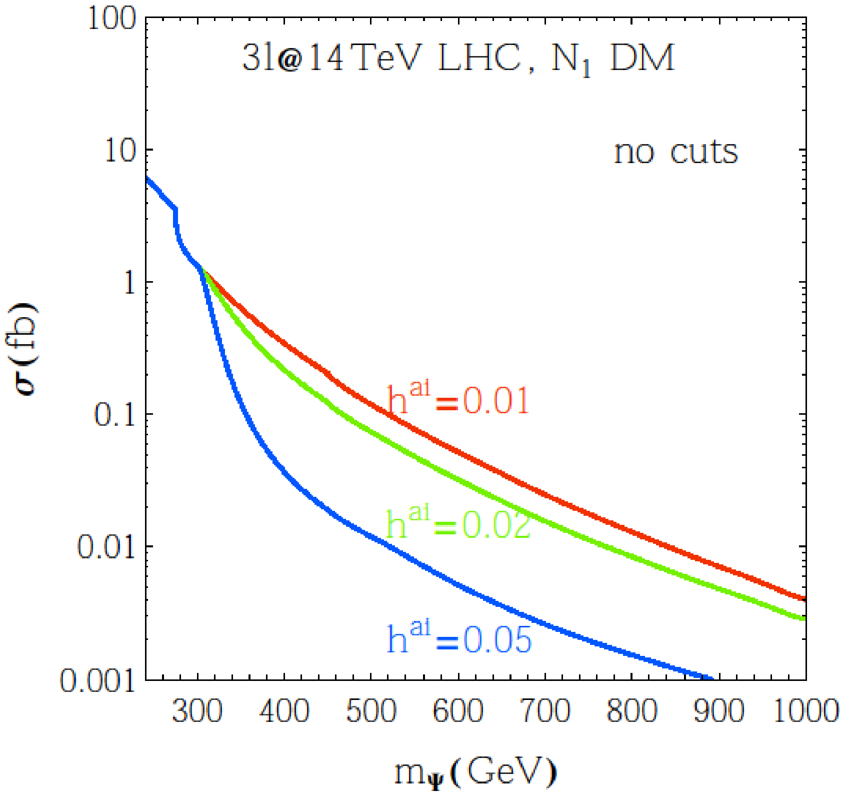
- $0\ell\ 2h$ $pp \to N_2\bar{N}_2 \to hN_1 + h\bar{N}_1,\ h \to b\bar{b}/\gamma\gamma$
- $1\ell\ 1h$ $pp \to E^{\pm}N_2 \to W^{\pm}N_1 + hN_1,\ h \to b\bar{b}/\gamma\gamma$
- 2ℓ without reconstr Z $pp \to E^{+}E^{-} \to W^{+}\bar{N}_1 + W^{-}N_1$
- $2\ell\ 2j$ with reconstr $2Z$ $pp \to N_2\bar{N}_2 \to ZN_1 + Z\bar{N}_1, Z \to 2\ell, Z \to 2j$
- $2\ell\ 1h$ with reconstr Z $pp \to N_2\bar{N}_2 \to ZN_1h\bar{N}_1,\ h \to b\bar{b}/\gamma\gamma$
- 3ℓ with reconstr Z $pp \to E^{+}N_2 \to W^{+}N_1 + ZN_1$
- 4ℓ with reconstr $2Z$ $pp \to N_2\bar{N}_2 \to ZN_1 + Z\bar{N}_1, Z \to 2\ell, Z \to 2\ell$

- Currently most stringent constraint from 3ℓ.
- Some others ($4b$ from $2h$, $2\ell 2b$ from hZ, $2\ell 2j$ from ZZ) will be better for a higher mass.
- Full simulation and recasting desirable.

3ℓ with reconstr Z $\quad pp \to E^+N_2 \to W^+N_1 + ZN_1$



$\sin\beta = 0.01$
$m_{N_1} = 150$ GeV
$m_{\chi_L} = 300$ GeV
$m_{\chi_H} = 500$ GeV



σ comparable to 2ℓ but much cleaner; most stringent constraints possible for $m_\Psi < 250$ GeV
ATLAS, with simplifications: $m_{N_2} > 370$ GeV; combining 2ℓ and 3ℓ: 425 GeV
Recasting in arXiv:1410.5730 for higgsino-bino system in MSSM:
ATLAS search only sensitive to $m_{N_2} < 270$ GeV, $m_{N_1} < 75$ GeV

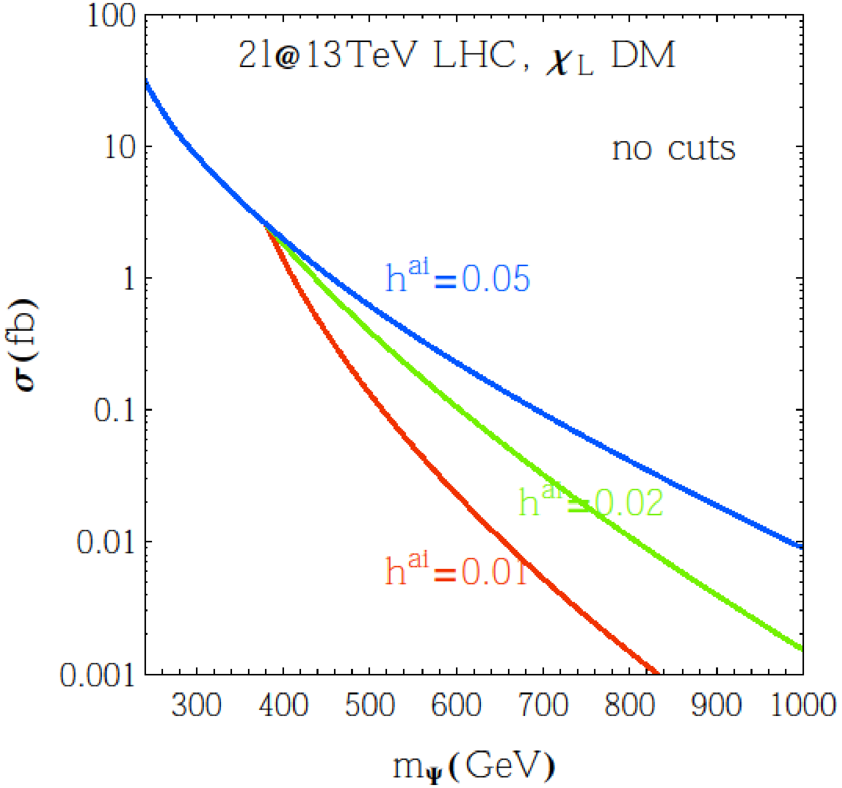
LHC signatures: χ_L as DM

$N_2 \to \chi_L \nu$ results in various mono-X signatures

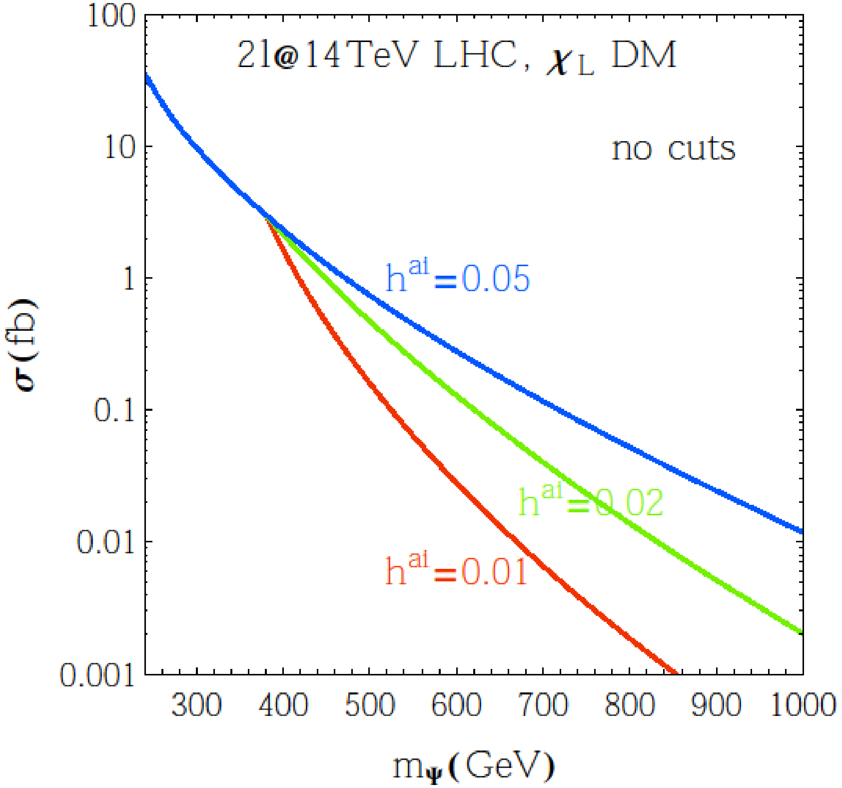
- mono-j $\quad pp \to N_2 \bar{N}_2 + j \to \chi_L \nu \chi_L{}^\dagger \nu + j$
- mono-h $\quad pp \to N_2 \bar{N}_2 \to \chi_H \nu\, \chi_L^\dagger \nu, \chi_L \nu \chi_H^\dagger \nu,\ \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}, h \to b\bar{b}/\gamma\gamma$
- $0\ell\ 2h$ $\quad pp \to N_2 \bar{N}_2 \to \chi_H \nu + \chi_H^\dagger\ \nu,\ \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}, h \to b\bar{b}/\gamma\gamma$
- mono-ℓ $\quad pp \to E^\pm N_2 \to \ell^\pm \chi_L^{(\dagger)} + \chi_L \nu$
- $1\ell\ 1h$ $\quad pp \to E^\pm N_2 \to \ell^\pm \chi_L^{(\dagger)} + \chi_H \nu, \ell^\pm \chi_H^{(\dagger)} + \chi_L \nu, \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}$
- $1\ell\ 2h$ $\quad pp \to E^\pm N_2 \to \ell^\pm \chi_H^{(\dagger)} + \chi_H \nu, \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}$
- 2ℓ without reconstr Z $\quad pp \to E^+ E^- \to \ell^+ \chi_L^\dagger + \ell^- \chi_L$
- $2\ell\ 1h$ without reconstr Z $\quad pp \to E^+ E^- \to \ell^+ \chi_{H,L}^\dagger + \ell^- \chi_{L,H}, \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}$
- $2\ell\ 2h$ without reconstr Z $\quad pp \to E^+ E^- \to \ell^+ \chi_H^\dagger + \ell^- \chi_H, \chi_H^{(\dagger)} \to h \chi_L^{(\dagger)}$
- 3ℓ without reconstr Z $\quad pp \to E^\pm N_2 \to \ell^\pm \chi_{L,H}^{(\dagger)} + \chi_{H,L} \nu, \chi_H^{(\dagger)} \to \ell^+ \ell^- \chi_L^{(\dagger)}$
- 4ℓ without reconstr Z $\quad pp \to N_2 \bar{N}_2 \to \chi_H \nu + \chi_H^\dagger\ \nu,\ \chi_H^{(\dagger)} \to \ell^+ \ell^- \chi_L^{(\dagger)}$

  $\to E^+ E^- \to \ell^+ \chi_{H,L}^\dagger + \ell^- \chi_{L,H},\ \chi_H^{(\dagger)} \to \ell^+ \ell^- \chi_L^{(\dagger)}$

2ℓ without reconstr Z $\quad pp \to E^+E^- \to \ell^+\chi_L^\dagger + \ell^-\chi_L$



$\sin\beta = 0.01$
$m_{\chi_L} = 150$ GeV
$m_{N_1} = 300$ GeV
$m_{\chi_H} = 200$ GeV



2ℓ more energetic than for N_1DM case if $m_\Psi - m_{\chi_L}$ large enough; thus more stringent constraints possible
ATLAS, with simplifications: excluded $160 \text{ GeV} < m_\Psi < 310 \text{ GeV}$ assuming $m_{\chi_L} = 100$ GeV

Summary

- Exact Z_3 symmetry generates desired neutrino parameters at two-loop level, while providing stable DM particles of either scalar or Dirac fermion.

- DM particles pass constraints from relic density and direct detection. Z_3 decouples the two to some extent.

- Z_3 has rich and interesting phenomenology at LHC. New particles are produced at the typical electroweak level.

- 3-lepton channel is most promising for both scalar and Dirac fermion DM. Various mono-*X* signals occur for scalar DM.

  Require full simulation and recasting.