Non-thermal dark matter with stable charged particles : a study in some non-supersymmetric scenarios

Avirup Ghosh

Harish-Chandra Research Institute

Based on 1706.06815 (Accepted in JHEP)
in collaboration with T.Mondal and B.Mukhopadhyaya

14th December, 2017

Abstract: A few words

In view of the fact DM particles has yet not left its footprints in direct-detection and LHC experiments

⇒ Two BSM scenarios with a non-thermal Dark Matter(DM) candidate accompanied by a charged long-lived particle have been discussed.

⇒ Discovery prospects of both the scenarios during upcoming runs of LHC has also been anlyzed.

Dark Matter: current status and motivation for non-thermal Dark Matter

- WIMP miracle: DM particles with electroweak scale mass and couplings (in the same order as elctroweak couplings)
  $\Rightarrow <\sigma v> \sim 3 \times 10^{-26} cm^3 s^{-1}$
  $\Rightarrow$ Correct Relic Abundance (~ 0.12)

Dark Matter: current status and motivation for non-thermal Dark Matter

- WIMP miracle: DM particles with electroweak scale mass and couplings (in the same order as elctroweak couplings)
  $\Rightarrow <\sigma v> \sim 3 \times 10^{-26} cm^3 s^{-1}$
  $\Rightarrow$ Correct Relic Abundance (~ 0.12)
- Direct search experiments, try to measure the DM-Nucleon cross-section.

Dark Matter: current status and motivation for non-thermal Dark Matter

- WIMP miracle: DM particles with electroweak scale mass and couplings (in the same order as elctroweak couplings)
  $\Rightarrow <\sigma v> \sim 3 \times 10^{-26} cm^3 s^{-1}$
  $\Rightarrow$ Correct Relic Abundance (~ 0.12)
- Direct search experiments, try to measure the DM-Nucleon cross-section.
- Recent direct search experiments data $\Rightarrow \sigma_{SI} \sim 10^{-46} cm^2$ (For DM mass $\sim$100 GeV)$\Rightarrow$ Still no sign of DM.

Dark Matter: current status and motivation for non-thermal Dark Matter

- WIMP miracle: DM particles with electroweak scale mass and couplings (in the same order as elctroweak couplings)
  $\Rightarrow < \sigma v > \sim 3 \times 10^{-26} cm^3 s^{-1}$
  $\Rightarrow$ Correct Relic Abundance (~ 0.12)
- Direct search experiments, try to measure the DM-Nucleon cross-section.
- Recent direct search experiments data $\Rightarrow \sigma_{SI} \sim 10^{-46} cm^2$ (For DM mass $\sim$100 GeV)$\Rightarrow$ Still no sign of DM.
- DM interaction strength is much smaller with the SM particles
  $\Rightarrow$ DM particles had never been in thermal equillibrium $\Rightarrow \frac{\Gamma_\chi}{H} < 1$.
  $\Rightarrow$ Non-thermal dark matter.(FIMP)

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).
- LLP candidates are charged $\Rightarrow$ For example in MSSM+$\tilde{\nu}_R$, stau **NLSP** and dirac-sneutrino **LSP** ($y_\nu \sim 10^{-13}$).

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).
- LLP candidates are charged $\Rightarrow$ For example in MSSM+$\tilde{\nu}_R$, stau **NLSP** and dirac-sneutrino **LSP** ($y_\nu \sim 10^{-13}$).
- Charged LLP $\Rightarrow$ **BBN** constraint $\rightarrow$ $\tau_{LLP}^{max} \sim 100 sec$

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).
- LLP candidates are charged $\Rightarrow$ For example in MSSM+$\tilde{\nu}_R$, stau **NLSP** and dirac-sneutrino **LSP** ($y_\nu \sim 10^{-13}$).
- Charged LLP $\Rightarrow$ **BBN** constraint $\rightarrow$ $\tau_{LLP}^{max} \sim 100 sec$
- Two non-supersymmetric scenarios have been considered,

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).
- LLP candidates are charged $\Rightarrow$ For example in MSSM$+\tilde{\nu}_R$, stau **NLSP** and dirac-sneutrino **LSP** ($y_\nu \sim 10^{-13}$).
- Charged LLP $\Rightarrow$ **BBN** constraint $\rightarrow$ $\tau_{LLP}^{max} \sim 100 sec$
- Two non-supersymmetric scenarios have been considered, $\Rightarrow$ (A) Type III seesaw model with a sterile neutrino DM.

Non-thermal DM : Intrduction

- Non-thermal DM are produced from decay or collision of heavier particles.
- The non-thermal DM coupling $\sim 10^{-10}$ [L. J. Hall *et al* 0911.1120] $\Rightarrow$ long-lived particle(LLP).
- LLP candidates are charged $\Rightarrow$ For example in MSSM+$\tilde{\nu}_R$, stau **NLSP** and dirac-sneutrino **LSP** ($y_\nu \sim 10^{-13}$).
- Charged LLP $\Rightarrow$ **BBN** constraint $\rightarrow$ $\tau_{LLP}^{max} \sim 100 sec$
- Two non-supersymmetric scenarios have been considered,
  $\Rightarrow$ (A) Type III seesaw model with a sterile neutrino DM.
  $\Rightarrow$ (B) IDM with a Majorana neutrino DM.

Type III seesaw with a sterile neutrino

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma^{+}_{jR}, \Sigma^{0}_{jR}, \Sigma^{-}_{jR}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma_{jR}^{+}, \Sigma_{jR}^{0}, \Sigma_{jR}^{-}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma^{+}_{jR}, \Sigma^{0}_{jR}, \Sigma^{-}_{jR}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM
- $\mathbb{Z}_2$ odd:- Σ_{3R}, ν_{sR}

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma^{+}_{jR}, \Sigma^{0}_{jR}, \Sigma^{-}_{jR}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM
- $\mathbb{Z}_2$ odd:- Σ_{3R}, ν_{sR}
- Neutrino(ν) mass: $\sqrt{2}\overline{L}_{Lj} Y_{\Sigma} \Sigma_{\alpha R} \tilde{\Phi}$, $\alpha = 1, 2$

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma^{+}_{jR}, \Sigma^{0}_{jR}, \Sigma^{-}_{jR}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM
- $\mathbb{Z}_2$ odd:- Σ_{3R}, ν_{sR}
- Neutrino(ν) mass: $\sqrt{2}\bar{L}_{Lj} Y_{\Sigma} \Sigma_{\alpha R} \tilde{\Phi}$, $\alpha = 1, 2$
- dimension-5 interactions:-
  $\frac{\alpha_{\Sigma\nu_s}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Phi \nu^{c}_{sR}$, $\frac{\alpha_{\nu_s}}{\Lambda} \Phi^{\dagger} \Phi \bar{\nu}_{sR} \nu^{c}_{sR}$, $\frac{\alpha_{\Sigma}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Sigma^{c}_{3R} \Phi$
  Λ:- Scale of new physics.

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma^{+}_{jR}, \Sigma^{0}_{jR}, \Sigma^{-}_{jR}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM
- $\mathbb{Z}_2$ odd:- Σ_{3R}, ν_{sR}
- Neutrino(ν) mass: $\sqrt{2}\bar{L}_{Lj} Y_{\Sigma} \Sigma_{\alpha R} \tilde{\Phi}$, $\alpha = 1, 2$
- dimension-5 interactions:-
  $\frac{\alpha_{\Sigma\nu_s}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Phi \nu^{c}_{sR}$, $\frac{\alpha_{\nu_s}}{\Lambda} \Phi^{\dagger} \Phi \bar{\nu}_{sR} \nu^{c}_{sR}$, $\frac{\alpha_{\Sigma}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Sigma^{c}_{3R} \Phi$
  Λ:- Scale of new physics.
- Dirac Fermions:- $\eta^{-}_{3} = \Sigma^{-}_{3R} + \Sigma^{+c}_{3R}$
  Majorana Fermions:- $\eta^{0}_{3} = \Sigma^{0}_{3R} + \Sigma^{0c}_{3R}$, $N^0 = \nu^{0}_{sR} + \nu^{0c}_{sR}$.

Model A: Type III seesaw with a sterile neutrino

- SM fields + Σ_{jR} ($\Rightarrow$ $\Sigma_{jR}^{+}, \Sigma_{jR}^{0}, \Sigma_{jR}^{-}$) + ν_{sR}
  Σ_{jR}:- Y=0, $SU(2)_L$ Triplet Fermion (j=1,2,3)
  ν_{sR}:- SM gauge singlet Fermion
- $\mathbb{Z}_2$ symmetry:- stable DM
- $\mathbb{Z}_2$ odd:- Σ_{3R}, ν_{sR}
- Neutrino(ν) mass: $\sqrt{2}\bar{L}_{Lj} Y_{\Sigma} \Sigma_{\alpha R} \tilde{\Phi}$, $\alpha = 1, 2$
- dimension-5 interactions:-
  $\frac{\alpha_{\Sigma\nu_s}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Phi \nu_{sR}^{c}$, $\frac{\alpha_{\nu_s}}{\Lambda} \Phi^{\dagger} \Phi \bar{\nu}_{sR} \nu_{sR}^{c}$, $\frac{\alpha_{\Sigma}}{\Lambda} \Phi^{\dagger} \bar{\Sigma}_{3R} \Sigma_{3R}^{c} \Phi$
  Λ:- Scale of new physics.
- Dirac Fermions:- $\eta_3^{-} = \Sigma_{3R}^{-} + \Sigma_{3R}^{+c}$
  Majorana Fermions:- $\eta_3^{0} = \Sigma_{3R}^{0} + \Sigma_{3R}^{0c}$, $N^0 = \nu_{sR}^{0} + \nu_{sR}^{0c}$.
- dimension-5 interactions $\Rightarrow$ η_3^0 and N^0 mixes.

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-

$$\chi = \cos\beta\ N^0 - \sin\beta\ \eta_3^0\ ,\ \ \psi = \sin\beta\ N^0 + \cos\beta\ \eta_3^0 .$$

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-

$$\chi = \cos\beta \; N^0 - \sin\beta \; \eta_3^0 \, , \;\; \psi = \sin\beta \; N^0 + \cos\beta \; \eta_3^0 .$$

- The mixing angle:- $\tan 2\beta = \dfrac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}$

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-
$$\chi = \cos\beta\ N^0 - \sin\beta\ \eta_3^0\ ,\ \ \psi = \sin\beta\ N^0 + \cos\beta\ \eta_3^0 .$$
- The mixing angle:- $\tan 2\beta = \dfrac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}$
- $M_\Sigma \ \Rightarrow$ Majorana mass for Σ_{3R}
  $M_{\nu_s} \ \Rightarrow$ Majorana mass for ν_{sR}.

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-
$$\chi = \cos\beta\ N^0 - \sin\beta\ \eta_3^0\ ,\ \ \psi = \sin\beta\ N^0 + \cos\beta\ \eta_3^0 .$$
- The mixing angle:- $\tan 2\beta = \dfrac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}$
- $M_\Sigma \ \Rightarrow$ Majorana mass for Σ_{3R}
  $M_{\nu_s} \ \Rightarrow$ Majorana mass for ν_{sR}.
- Assume, $M_\Sigma \ > \ M_{\nu_s} \ \Rightarrow \chi$ is lightest $\mathbb{Z}_2$ odd particle
  $\Rightarrow$ Dark Matter.

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-
$$\chi = \cos\beta\ N^0 - \sin\beta\ \eta_3^0\ ,\ \ \psi = \sin\beta\ N^0 + \cos\beta\ \eta_3^0 .$$
- The mixing angle:- $\tan 2\beta = \dfrac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}$
- $M_\Sigma \Rightarrow$ Majorana mass for Σ_{3R}
  $M_{\nu_s} \Rightarrow$ Majorana mass for ν_{sR}.
- Assume, $M_\Sigma > M_{\nu_s} \Rightarrow \chi$ is lightest $\mathbb{Z}_2$ odd particle
  $\Rightarrow$ Dark Matter.
- All χ interactions $\propto \frac{1}{\Lambda}$

Model A: Type III seesaw with a sterile neutrino

- Majorana mass eigenstates:-
$$\chi = \cos\beta\ N^0 - \sin\beta\ \eta_3^0\ ,\ \ \psi = \sin\beta\ N^0 + \cos\beta\ \eta_3^0 .$$
- The mixing angle:- $\tan 2\beta = \dfrac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}$
- $M_\Sigma \ \Rightarrow$ Majorana mass for Σ_{3R}
  $M_{\nu_s} \ \Rightarrow$ Majorana mass for ν_{sR}.
- Assume, $M_\Sigma > M_{\nu_s} \Rightarrow \chi$ is lightest $\mathbb{Z}_2$ odd particle
  $\Rightarrow$ Dark Matter.
- All χ interactions $\propto \frac{1}{\Lambda}$
- Large $\Lambda \Rightarrow \chi$ is non-thermal DM.

Model A: Type III seesaw with a sterile neutrino

- χ production in early universe:- $\eta_3^{\pm} \rightarrow \chi\, W^{\pm}$ and $\psi \rightarrow \chi\, h$ (No Z_μ coupling) $\Rightarrow$ From decay of next-to-lightest odd particles (NLOP).

Model A: Type III seesaw with a sterile neutrino

- χ production in early universe:- $\eta_3^{\pm} \rightarrow \chi W^{\pm}$ and $\psi \rightarrow \chi h$ (No Z_μ coupling) $\Rightarrow$ From decay of next-to-lightest odd particles (NLOP).
- χ relic density, $\Omega_\chi h^2 = \Omega_\chi h^2|_{freze-in} + \Omega_\chi h^2|_{freze-out}$

Model A: Type III seesaw with a sterile neutrino

- χ production in early universe:- $\eta_3^{\pm} \rightarrow \chi\, W^{\pm}$ and $\psi \rightarrow \chi\, h$ (No Z_μ coupling) $\Rightarrow$ From decay of next-to-lightest odd particles (NLOP).
- χ relic density, $\Omega_\chi h^2 = \Omega_\chi h^2|_{freze-in} + \Omega_\chi h^2|_{freze-out}$
- $\Omega_\chi h^2|_{freze-in} \approx \frac{1.09\times 10^{27}\, g_{NLOP}}{g_*^{3/2}} \frac{M_\chi\, \Gamma_{NLOP}}{M^2_{NLOP}}$

  $\Omega_\chi h^2|_{freze-out} = \frac{M_\chi}{M_{NLOP}}\, \Omega_{NLOP} h^2$

Model A: Type III seesaw with a sterile neutrino

- χ production in early universe:- $\eta_3^\pm \rightarrow \chi\, W^\pm$ and $\psi \rightarrow \chi\, h$ (No Z_μ coupling) $\Rightarrow$ From decay of next-to-lightest odd particles (NLOP).
- χ relic density, $\Omega_\chi h^2 = \Omega_\chi h^2|_{freze-in} + \Omega_\chi h^2|_{freze-out}$
- $\Omega_\chi h^2|_{freze-in} \approx \frac{1.09\times 10^{27}\, g_{NLOP}}{g_*^{3/2}} \frac{M_\chi\, \Gamma_{NLOP}}{M_{NLOP}^2}$

  $\Omega_\chi h^2|_{freze-out} = \frac{M_\chi}{M_{NLOP}}\, \Omega_{NLOP} h^2$
- Constraints on Γ_{NLOP}

  $\Rightarrow$ Upper limit from $\Omega_\chi h^2 \lesssim 0.12$

  $\Rightarrow$ Lower limit from $\tau_{NLOP} \lesssim 100 sec$

Model A: Type III seesaw with a sterile neutrino

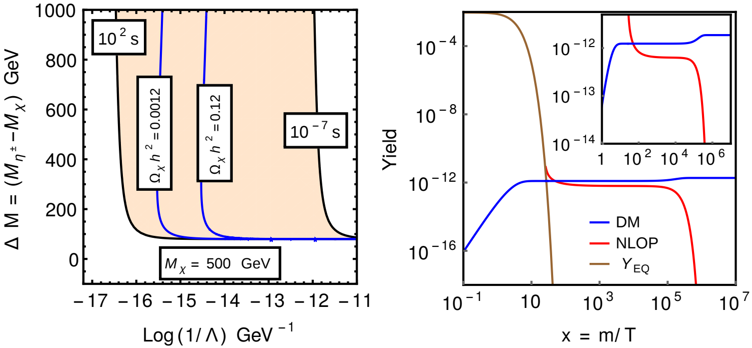

Figure : Region of parameter space allowed by DM relic density and BBN constraints (left). DM and NLOP yield as a function of x=$\frac{M_\Sigma}{T}$(right). Plot is for $M_\chi = 500$ GeV.

Model A: Type III seesaw with a sterile neutrino

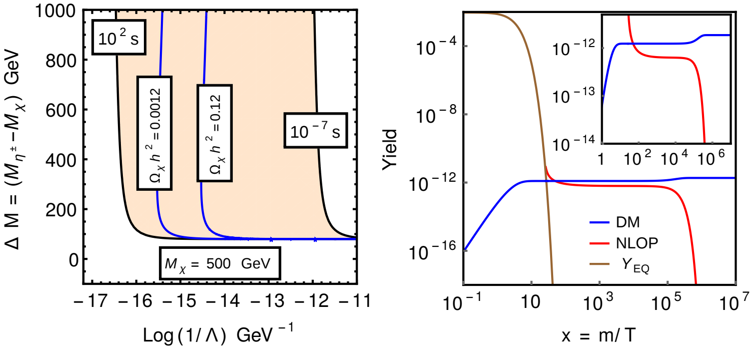

Figure : Region of parameter space allowed by DM relic density and BBN constraints (left). DM and NLOP yield as a function of x=$\frac{M_\Sigma}{T}$(right). Plot is for $M_\chi = 500$ GeV.

- $\Lambda \sim 14.5\,\text{GeV}$, $\Delta M \sim 300\,\text{GeV} \Rightarrow$ Correct Relic density and collider scale stable **NLOP** $(\eta^\pm,\psi)$.

IDM with majorana neutrino DM

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:-$Y = 1, SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:-$Y = 1$,$SU(2)_L$ Doublet (H^+,$H^0 + iA^0$)
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:-$Y = 1$,$SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.
- $\mathbb{Z}_2$ odd Φ_2 $\Rightarrow$ no VEV
  $\Rightarrow$ $V(\Phi_1, \Phi_2) \supset$
  $\{\mu_2\, \Phi_2^\dagger \Phi_2,\ \lambda_2\, (\Phi_2^\dagger\, \Phi_2)^2,\ \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2),\ \lambda_4\, (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2),$
  $\frac{\lambda_5}{2}\, (\Phi_1^\dagger \Phi_2)^2\}$

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:- $Y = 1, SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.
- $\mathbb{Z}_2$ odd Φ_2 $\Rightarrow$ no VEV
  $\Rightarrow$ $V(\Phi_1, \Phi_2) \supset$
  $\{\mu_2\, \Phi_2^\dagger \Phi_2,\ \lambda_2\, (\Phi_2^\dagger\, \Phi_2)^2,\ \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2),\ \lambda_4\, (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2),$
  $\frac{\lambda_5}{2}\, (\Phi_1^\dagger \Phi_2)^2\}$
- N_{1R}, N_{2R} are $\mathbb{Z}_2$ even $\Rightarrow$ Neutrino mass (Type I Seesaw)

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:- $Y = 1, SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.
- $\mathbb{Z}_2$ odd Φ_2 $\Rightarrow$ no VEV
  $\Rightarrow$ $V(\Phi_1, \Phi_2) \supset$
  $\{\mu_2\, \Phi_2^\dagger \Phi_2,\ \lambda_2\, (\Phi_2^\dagger\, \Phi_2)^2,\ \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2),\ \lambda_4\, (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2),$
  $\frac{\lambda_5}{2}\, (\Phi_1^\dagger \Phi_2)^2\}$
- N_{1R}, N_{2R} are $\mathbb{Z}_2$ even $\Rightarrow$ Neutrino mass (Type I Seesaw)
- N_{3R} interactions :- $y_{\nu j} \bar{N}_{3R} \tilde{\Phi}_2^\dagger L_{Lj}$

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:- $Y = 1$, $SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.
- $\mathbb{Z}_2$ odd Φ_2 $\Rightarrow$ no VEV
  $\Rightarrow$ $V(\Phi_1, \Phi_2) \supset$
  $\{\mu_2\, \Phi_2^\dagger \Phi_2,\ \lambda_2\, (\Phi_2^\dagger\, \Phi_2)^2,\ \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2),\ \lambda_4\, (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2),$
  $\frac{\lambda_5}{2}\, (\Phi_1^\dagger \Phi_2)^2\}$
- N_{1R}, N_{2R} are $\mathbb{Z}_2$ even $\Rightarrow$ Neutrino mass (Type I Seesaw)
- N_{3R} interactions :- $y_{\nu j} \bar{N}_{3R} \tilde{\Phi}_2^\dagger L_{Lj}$
- Proper choice of μ_2, λ_3, λ_4, λ_5 and M_3(Majorana mass for N_{3R})
  $\Rightarrow$ $M_{A^0}^2 \simeq M_{H^0}^2 > M_{H^\pm}^2 > M_3$

Model B: IDM with a Majorana neutrino DM

- SM fields + Φ_2 + N_{jR}
  Φ_2:- $Y = 1, SU(2)_L$ Doublet $(H^+, H^0 + iA^0)$
  N_{jR}:-SM gauge singlet
- $\mathbb{Z}_2$ symmetry $\Rightarrow$ stable DM $\Rightarrow$ Φ_2 and N_{3R} odd.
- $\mathbb{Z}_2$ odd Φ_2 $\Rightarrow$ no VEV
  $\Rightarrow V(\Phi_1, \Phi_2) \supset$
  $\{\mu_2\, \Phi_2^\dagger \Phi_2,\ \lambda_2\, (\Phi_2^\dagger\, \Phi_2)^2,\ \lambda_3\, (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2),\ \lambda_4\, (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2),$
  $\frac{\lambda_5}{2}\, (\Phi_1^\dagger \Phi_2)^2\}$
- N_{1R}, N_{2R} are $\mathbb{Z}_2$ even $\Rightarrow$ Neutrino mass (Type I Seesaw)
- N_{3R} interactions :- $y_{\nu j} \bar{N}_{3R} \tilde{\Phi}_2^\dagger L_{Lj}$
- Proper choice of μ_2, λ_3, λ_4, λ_5 and M_3(Majorana mass for N_{3R})
  $\Rightarrow M^2_{A^0} \simeq M^2_{H^0} > M^2_{H^\pm} > M_3$
- N_{3R} is only $\mathbb{Z}_2$ odd fermion $\Rightarrow$ $\chi\ (= N_{3R} + N^c_{3R})$ is DM.
  $\Rightarrow M_\chi = M_3$

Model B: IDM with a Majorana neutrino DM

- All χ interactions $\propto$ $y_{\nu j}$

Model B: IDM with a Majorana neutrino DM

- All χ interactions $\propto\ y_{\nu j}$
- Small $y_{\nu j}\ \Rightarrow\ \chi$ is non-thermal DM candidate.

Model B: IDM with a Majorana neutrino DM

- All χ interactions $\propto y_{\nu j}$
- Small $y_{\nu j} \Rightarrow \chi$ is non-thermal DM candidate.
- χ production in early universe $\Rightarrow H^{\pm} \rightarrow \chi\, l^{\pm}$, $H^0(A^0) \rightarrow \chi\, \nu$
  $\Rightarrow$ from decay of NLOPs ($H^{\pm}$, H^0 , A^0)

Model B: IDM with a Majorana neutrino DM

- All χ interactions $\propto \; y_{\nu j}$
- Small $y_{\nu j} \;\Rightarrow\; \chi$ is non-thermal DM candidate.
- χ production in early universe $\Rightarrow\; H^{\pm} \;\rightarrow\; \chi\, l^{\pm},\; H^0(A^0) \;\rightarrow\; \chi\,\nu$
  $\Rightarrow$ from decay of NLOPs ($H^{\pm}$, H^0 , A^0)
- Relic density, $\Omega_\chi h^2 \;=\; \Omega_\chi h^2|_{freze-in} \;+\; \Omega_\chi h^2|_{freze-out}$

Model B: IDM with a Majorana neutrino DM

- All χ interactions $\propto \; y_{\nu j}$
- Small $y_{\nu j} \;\Rightarrow\; \chi$ is non-thermal DM candidate.
- χ production in early universe $\Rightarrow \; H^{\pm} \;\to\; \chi \, l^{\pm}, \; H^0(A^0) \;\to\; \chi \, \nu$
  $\Rightarrow$ from decay of NLOPs ($H^{\pm}$, H^0 , A^0)
- Relic density, $\Omega_{\chi} h^2 \;=\; \Omega_{\chi} h^2|_{freze-in} \;+\; \Omega_{\chi} h^2|_{freze-out}$
- Relic density and BBN data constraints Γ_{NLOP}.

Model B: IDM with a Majorana neutrino DM

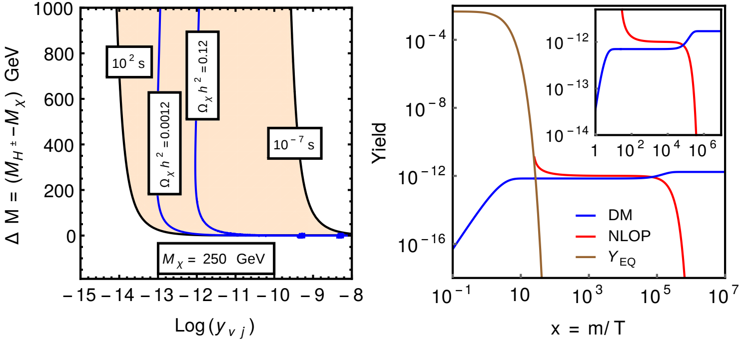

Figure : Region of parameter space allowed by DM relic density and BBN constraints (left) and DM and NLOP yield as a function of x$=\frac{M_{H\pm}}{T}$. Plot is for $M_\chi = 250$ GeV.

Model B: IDM with a Majorana neutrino DM

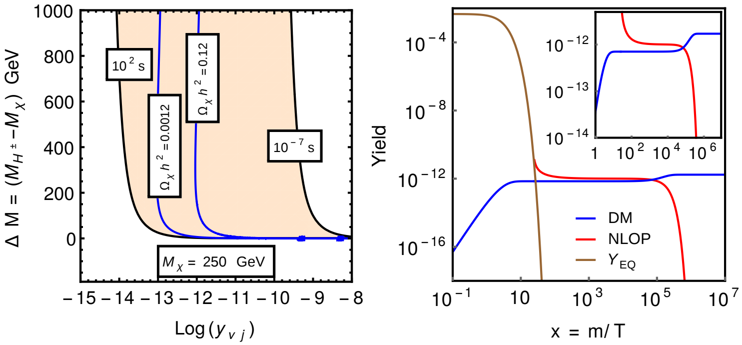

Figure : Region of parameter space allowed by DM relic density and BBN constraints (left) and DM and NLOP yield as a function of x$=\frac{M_{H^\pm}}{T}$. Plot is for $M_\chi = 250$ GeV.

- $y_{\nu j} \sim 10^{-12}$, $M_{H^\pm} \sim 500$ GeV and $M_\chi \sim 250$ GeV $\Rightarrow \tau_{NLOP} \sim 0.0297\ s \Rightarrow H^\pm$ will decay outside detectors.

Collider signal

- **Model A** :-
  $p\ p \rightarrow \eta_3^{\pm}\ \eta_3^{\mp}$ (Opposite-sign tracks) $\Rightarrow$ Z-mediation
  $p\ p \rightarrow \eta_3^{\pm}\ \psi$ (Single track + $\not{E}_T$) $\Rightarrow$ $W^{\pm}$-mediation

Collider signal

- **Model A** :-
  $p\,p \;\rightarrow\; \eta_3^{\pm}\,\eta_3^{\mp}$ (Opposite-sign tracks) $\Rightarrow$ Z-mediation
  $p\,p \;\rightarrow\; \eta_3^{\pm}\,\psi$ (Single track $+\,\not{E}_T$) $\Rightarrow$ $W^{\pm}$-mediation
- **Model B** :-
  $p\,p \;\rightarrow\; H^{\pm}\,H^{\mp}$ Z-mediation

  $p\,p \;\rightarrow\; H^{\pm}H^{0}(A^{0}) \;\rightarrow\; H^{\pm}\,H^{\mp}$ X $\rightarrow$ W-mediation $\rightarrow$ Opposite-sign tracks

  $p\,p \;\rightarrow\; H^{\pm}H^{0}(A^{0}) \;\rightarrow\; H^{\pm}\,H^{\pm}$ X $\rightarrow$ W-mediation $\rightarrow$ Same-sign tracks

  where X $= l^{+}\,\nu,\; l^{-}\,\bar{\nu}$, jj

Collider signal

- **Model A** :-
  $p\ p\ \rightarrow\ \eta_3^{\pm}\ \eta_3^{\mp}$ (Opposite-sign tracks) $\Rightarrow$ Z-mediation
  $p\ p\ \rightarrow\ \eta_3^{\pm}\ \psi$ (Single track + $\not{E}_T$) $\Rightarrow$ $W^{\pm}$-mediation
- **Model B** :-
  $p\ p\ \rightarrow\ H^{\pm}\ H^{\mp}$ Z-mediation
  $p\ p\ \rightarrow\ H^{\pm} H^{0}(A^{0})\ \rightarrow\ H^{\pm}\ H^{\mp}$ X $\rightarrow$ W-mediation $\rightarrow$ Opposite-sign tracks
  $p\ p\ \rightarrow\ H^{\pm} H^{0}(A^{0})\ \rightarrow\ H^{\pm}\ H^{\pm}$ X $\rightarrow$ W-mediation $\rightarrow$ Same-sign tracks
  where X = $l^{+}\,\nu$, $l^{-}\,\bar{\nu}$, jj
- **Background** :-
  Opposite sign :- Drell-yan, $t\ \bar{t}$ and di-boson.
  Single track :- $t\ \bar{t}$, di-boson.
  Same sign :- $t\ \bar{t}$, $t\ \bar{t}\ W^{\pm}$ and di-boson.
  $\rightarrow$ Cosmic-ray muon in each case.

Collider Analysis

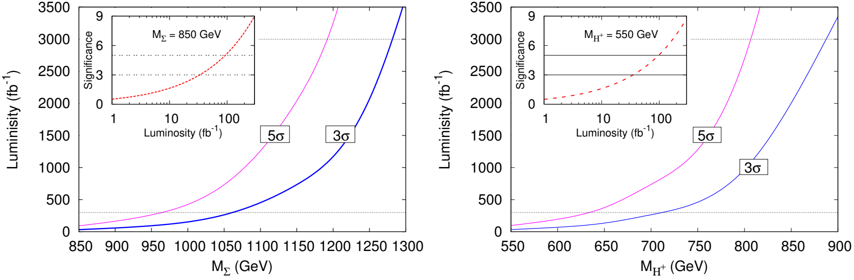

Figure : Integrate luminosity vs NLOP mass reach for Opposite-sign charged tracks of the Model A(left) and Model B(right) in 14 TeV run of LHC. Inset shows the significance vs luminosity for fixed BP in each case.

- Proper choice of kinematic cuts (JHEP 01 (2015) 068, 1411.6795) $+ \int \mathcal{L}\, dt\ 300\ fb^{-1} \Rightarrow$
  Model A:- $M_\Sigma =$ 970(1060)GeV at $5\sigma(3\sigma)$ statistical significance.
  Model B:- $M_{H^\pm} =$ 630(710)GeV at $5\sigma(3\sigma)$ statistical significance.

Summary

- Stability of DM is usually achieved by imposition of some symmetry. In general DM candidate is lightest particle charged under that symmetry.

Summary

- Stability of DM is usually achieved by imposition of some symmetry. In general DM candidate is lightest particle charged under that symmetry.
- Production of any of the particles charged under this *extra* symmetry ultimately leads to the production of DM.

Summary

- Stability of DM is usually achieved by imposition of some symmetry. In general DM candidate is lightest particle charged under that symmetry.
- Production of any of the particles charged under this *extra* symmetry ultimately leads to the production of DM.
- The DM particle leaves its signature within the collider-detectors as large missing transverse momentum ($\vec{\not{p}}_T$)or transverse energy($\not{E}_T$) along with jets(or photons).

Summary

- Stability of DM is usually achieved by imposition of some symmetry. In general DM candidate is lightest particle charged under that symmetry.
- Production of any of the particles charged under this *extra* symmetry ultimately leads to the production of DM.
- The DM particle leaves its signature within the collider-detectors as large missing transverse momentum ($\vec{\not{p}}_T$)or transverse energy($\not{E}_T$) along with jets(or photons).
- Heavy stable charged tracks are very interesting and unusual signature of DM.


Thank You

Back-up slides

Backup

- Type III seesaw model + $SU(2)_L$ singlet singly charged Weyl fermion $\lambda_{L,R}$ + $SU(2)_L$ triplet scalar Δ.
- Interactions :- $-M_\lambda \bar{\lambda} \lambda - Y_\lambda \mathrm{Tr}(\bar{\Sigma}^c_{3R} \Delta \lambda_R + \bar{\Sigma}_{3R} \Delta \lambda^c_R) + h.c$
- $\eta_3^\pm$ and λ mixes among themselves $\Rightarrow$ For $M_\lambda > M_\Sigma$ the lower mass eigenstate is $\eta_3^\pm$ dominated.

M_Σ (GeV) $\approx M_\psi$	M_λ (GeV)	Y_λ	Eigenvalues	
			Light(GeV) $\approx M_{\eta_3^\pm}$	Heavy (GeV)
850	2000	5	849.65	2000.35
	2500	5	849.76	2500.24
950	2000	5	949.62	2000.38
	2500	5	949.74	2500.26

Table : Eigenvalues of the nearly degenerate charged and neutral fermions for few benchmark points after mixing between the triplet fermion and vector-like heavy charged fermion. Scalar triplet vev is $v_\Delta = 4$ GeV.

Backup

- The chosen benchmarks for model A:-

Parameters	M_Σ (GeV)	M_{ν_s} (GeV)	Λ (GeV)
BP1	850	500	10^{15}
BP2	950	500	10^{15}

Table : Benchmark points for studying the discovery prospects of stable charged tracks of $\eta_3^\pm$ and ψ for Type III seesaw model at 14 TeV run of LHC.

- The chosen benchmarks for model B:-

Parameters	$M_{H^\pm}$(GeV)	M_{H^0}(GeV)	M_{A^0}(GeV)	M_3 (GeV)	$y_{\nu j}$
BP1	550	555	555	250	10^{-12}
BP2	600	605	605	250	10^{-12}

Table : Benchmark points for studying the discovery prospects of stable charged tracks of $H^\pm$ for IDM at 14 TeV run of LHC. We have consideredλ_2=0.5 and λ_L=0.04.

Backup

- Chosen kinematical cuts:-

Parameter	β	p_T	$\lvert y(\mu_{1,2})\rvert$	$\Delta R(\mu_1, \mu_2)$
Cut values	(A)[0.2, 0.95]	> 70 GeV	< 2.5	> 0.4
	(B)[0.2, 0.80]	> 70 GeV	< 2.5	> 0.4

Table : Basic selection cuts applied to analyze signals of heavy stable charged track.

- Results for Model A:-

Signal	Benchmark point	$\int \mathcal{L}dt$ for 5σ	N_S	N_B	N_S/N_B
Opposite Sign	BP1	92.95	92	248	0.37
	BP2	263.23	146	702	0.21
Single Track $+ \not{E}_T$	BP1	(A)340.40	841	27436	0.030
		(B) 24.81	46	40	1.150
	BP2	(A)1076.19	1485	86741	0.017
		(B) 56.60	62	91	0.681

Table : Integrated luminosity (fb^{-1})required to attain 5σ statistical

Backup

- Results for Model B :-

Signal	Benchmark point	$\int \mathcal{L}dt$ for 5σ	N_S	N_B	N_S/N_B
Opposite Sign	BP1	97.81	94	261	0.36
	BP2	195.16	127	520	0.24
Same Sign	BP1	71.62	67	115	0.58
	BP2	137.45	88	220	0.40

Table : Integrated luminosity(fb^{-1}) required to attain 5σ statistical significance for $H^{\pm} H^{\mp}$ signal for the considered benchmark points during 14 TeV run of LHC.