Non-thermal dark matter with stable charged particles at LHC

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Dark Matter

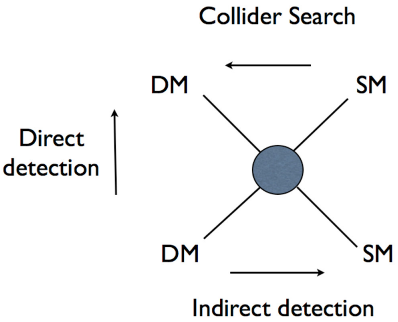
There is overwhelming evidence for the existence of dark matter :

- Galaxy rotation curves
- Bullet Cluster
- Acoustic peaks in the Cosmic Microwave Background (CMB)
- Gravitational lensing etc

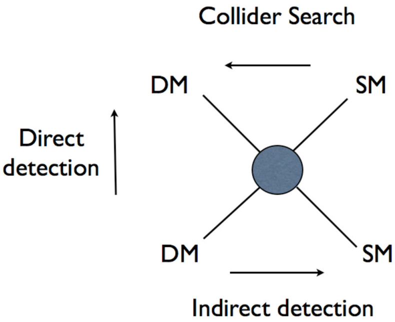
Most popular DM scenario is WIMP scenario

- DM particles with EW-scale mass and EW-couplings
- $\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3\, s^{-1}$
- Thermal freeze out of WIMP with a mass near the weak scale leads to the observed relic abundance of dark matter.
- Eg. Neutralino in SUSY

Search for DM



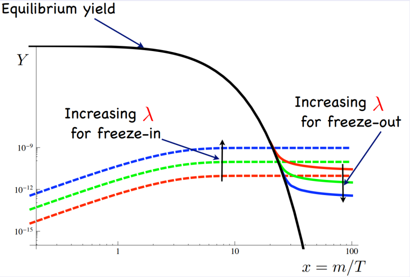
Search for DM



- Few intriguing signatures: 3.5 keV x-ray, GCE, positron excess etc
- Sometimes excesses can be explained with astrophysics e.g. pulsars
- No conclusive signal.
- Limit on SI scattering cross-section for a 100 GeV WIMP is $\sigma_{SI} < 10^{-10}$ pb !
- The scenario started to be constrained by experiments.
- Any other mechanisms for dark matter production ?

Non thermal dark matter

- DM is produced via decay/annihilation of heavier particles.
- Extremely small couplings with other particles (SM or BSM)
- Freeze-in mechanism : relevant for particles that are feebly coupled.
- FIMP : Feebly Interacting Massive Particles. [L. J. Hall et al 0911.1120]
- Dominant production occurs at $T \sim M_\chi$.
- Increase in interaction strength increases DM density ! (Opposite to Freeze-out scenario).



Signature of Freeze-in mechanism

- Since the interaction strength is very small, DD is not possible.
- Direct production at collider is also very hard.
- Cosmological and astrophysical observations (indirect detection) may test this mechanism.
- One experimental signature is Long Lived Particles.
- Next-to-Lightest Odd Particle (NLOP) couples feebly with the DM.
- Decay width of NLOP is small and it can be long lived.
- BBN limits its lifetime to be < 100 sec.
- If the NLOPs are charge we can see long lived charged tracks at collider.

Signature of Freeze-in mechanism

Classic Example of LLPs with freeze-in DM:

- MSSM + RH neutrino superfield model with Dirac neutrino masses.
- $\Rightarrow y_\nu \sim 10^{-13}$ which yields correct relic with $\mathcal{O}(100)$ GeV $\tilde{\nu}_R$ LSP.
- The NLSP is $\tilde{\tau}_1$ which can give LL charged track signature.

In this talk

- Two examples of non-SUSY scenario with freeze in DM and neutrino masses generation.
  - (A) Type-III seesaw with a sterile neutrino DM.
  - (B) Inert Doublet Model with Majorana neutrino DM.
- LLPs are the characteristic signal for both the models.
- It is possible to distinguish between the models at the collider.

Model I : Type III seesaw with a sterile neutrino

Type III seesaw with a sterile neutrino

- Particle content : SM fields + $\Sigma_{jR} + \nu_{sR}$ j=1–3
  - Σ_{jR} : $Y = 0, SU(2)_L$ Triplet RH Weyl spinor .
    $$\Sigma_{jR} = \begin{bmatrix} \Sigma^0_{jR}/\sqrt{2} & \Sigma^+_{jR} \\ \Sigma^-_{jR} & -\Sigma^0_{jR}/\sqrt{2} \end{bmatrix}$$
  - ν_{sR} : SM gauge singlet right-handed Weyl fermion
- DM stability : Imposed $\mathbb{Z}_2$ symmetry under which Σ_{3R} and ν_{sR} odd.
- Linear combination of Σ^0_{3R} and ν_{sR} is the DM.
- Without the sterile neutrino Σ^0_{3R} can be a DM.
- Then mass of DM $\sim$ few TeV (like wino case).
- With sterile neutrino DM is accessible at collider.

Type III seesaw with a sterile neutrino

- Lagrangian :

$$\mathcal{L} = \text{Tr}\left[\bar{\Sigma}_{jR} i \not{D} \Sigma_{jR}\right] - \frac{1}{2}\text{Tr}\left[\bar{\Sigma}_{jR} M_\Sigma \Sigma^c_{jR} + h.c\right]$$
$$-\left(\sqrt{2}\bar{L}_{Lj} Y_\Sigma \Sigma_{\alpha R} \tilde{\Phi} + h.c\right) + \frac{i}{2}\bar{\nu}_{sR} \not{\partial} \nu_{sR} - \frac{1}{2}\left(\bar{\nu}_{sR} M_{\nu_s} \nu^c_{sR} + h.c\right)$$

$$\text{j} = 1,\ 2,\ 3 \text{ and } \alpha = 1,\ 2$$

- At tree level one light neutrino is massless ($\mathbb{Z}_2$ symmetry)
- DM is predominantly sterile ν_{sR} with very small mixture of Σ^0_{3R}.
- DM interacts with the thermal bath via the tiny mixing $\Rightarrow$ Freeze-in.
- Smallness of the mixing can be justified using D=5 interactions:

$$\frac{\alpha_{\Sigma\nu_s}}{\Lambda}\Phi^\dagger \bar{\Sigma}_{3R} \Phi \nu^c_{sR} \quad \frac{\alpha_{\nu_s}}{\Lambda}\Phi^\dagger \Phi \bar{\nu}_{sR} \nu^c_{sR} \quad \frac{\alpha_\Sigma}{\Lambda}\Phi^\dagger \bar{\Sigma}_{3R} \Sigma^c_{3R} \Phi$$

Λ : Scale of new physics

Type III seesaw with a sterile neutrino

The $\mathbb{Z}_2$-odd sector in four component notation:

- Charged Dirac fermion : $\eta_3^- = \Sigma_{3R}^- + \Sigma_{3R}^{+c}$ with mass $M_\Sigma - \frac{\alpha_\Sigma v^2}{2\Lambda}$
- Majorana fermions: $\eta_3^0 = \Sigma_{3R}^0 + \Sigma_{3R}^{0c}$, $N^0 = \nu_{sR}^0 + \nu_{sR}^{0c}$
- D=5 terms $\Rightarrow$ η_3^0 and N^0 mixes.
- The mass matrix $\begin{bmatrix} M_{\nu_s} - \frac{\alpha_{\nu_s} v^2}{\Lambda} & \frac{\alpha_{\Sigma\nu_s} v^2}{\sqrt{2}\Lambda} \\ \frac{\alpha_{\Sigma\nu_s} v^2}{\sqrt{2}\Lambda} & M_\Sigma - \frac{\alpha_\Sigma v^2}{2\Lambda} \end{bmatrix}$,
- Mass eigenstates,

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

$$\tan 2\beta = \frac{(\alpha_{\Sigma\nu_s} v^2)/\sqrt{2}\Lambda}{(M_\Sigma - \alpha_\Sigma v^2/2\Lambda - M_{\nu_s} + \alpha_{\nu_s} v^2/\Lambda)}.$$

- M_{ν_s} : Majorana mass for ν_{sR} & M_Σ : Majorana mass for Σ_{3R}
- Assume $M_{\nu_s} < M_\Sigma$ Then χ is the DM and dominantly sterile.
- All DM interactions $\propto \dfrac{1}{\Lambda}$. Very large $\Lambda \Rightarrow \chi$ is a FIMP

Type III seesaw with a sterile neutrino

- NLOP : Both $\eta_3^\pm$ and ψ. Nearly degenerate.
- χ production in the early Universe :

$$\eta_3^\pm \to \chi\, W^\pm \quad \& \quad \psi \to \chi\, h$$

- The density of χ rises via
  - Freeze-in process when the NLOP were still in thermal equilibrium,
  - Decay of NLOP into χ after freeze-out.
- DM yield during freeze-in

$$Y_\chi = \frac{45}{(4\pi^4)1.66} \frac{g_\Sigma\ M_{Pl}\ \Gamma}{M_\Sigma^2\ h_{eff}\sqrt{g_{eff}}} \int_{x=0}^{x_f} K_1(x) x^3 dx$$

- Yield from post freeze-out decay of NLSP

$$\frac{dY_{NLOP}}{dx} = -\sqrt{\frac{\pi}{45G}} \frac{g_*^{1/2} M_\Sigma}{x^2} \langle \sigma v \rangle (Y_{NLOP}^2 - Y_{NLOP}^{eq2}) - \sqrt{\frac{45}{\pi^3 G}} \frac{x}{2\sqrt{g_{eff}} M_\Sigma^2} \langle \Gamma \rangle Y_{NLOP},$$

$$\frac{dY_\chi}{dx} = \sqrt{\frac{45}{\pi^3 G}} \frac{x}{2\sqrt{g_{eff}} M_\Sigma^2} \langle \Gamma \rangle Y_{NLOP},$$

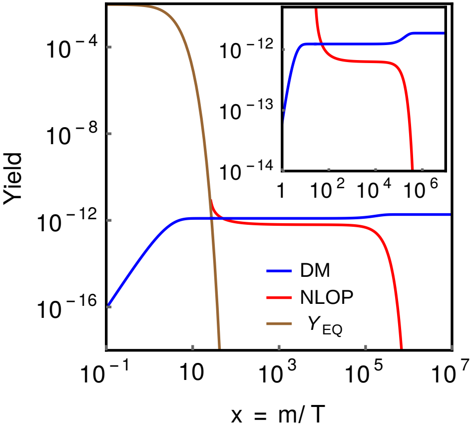
Type III seesaw with a sterile neutrino

- $\Omega_\chi h^2 \simeq 2.8 \times 10^8 \times \left(\frac{M_{\nu_s}}{GeV}\right) Y_\chi(x \to \infty)$
- $\Omega_\chi h^2|_{\text{freeze-in}} \approx \dfrac{1.09 \times 10^{27}\, g_{NLOP}}{g_*^{3/2}} \ \dfrac{M_\chi \Gamma_{NLOP}}{M_{NLOP}^2}$
- $\Omega_\chi h^2|_{\text{freeze-out}} \approx \dfrac{M_\chi}{M_{NLOP}} \Omega_{NLOP} h^2$
- Constraints on Γ_{NLOP} :
  - Upper limit from $\Omega_\chi h^2 < 0.12$
  - Lower limit from $\tau_{NLOP} < 100$ sec.
- This limits the parameter space of the model.

- Q. Is is possible to satisfy these constraints and have a viable parameter space to be searched at the collider ?

Type III seesaw with a sterile neutrino

DM Yield for a given Λ and M_χ and NLOP mass M_Σ



Type III seesaw with a sterile neutrino

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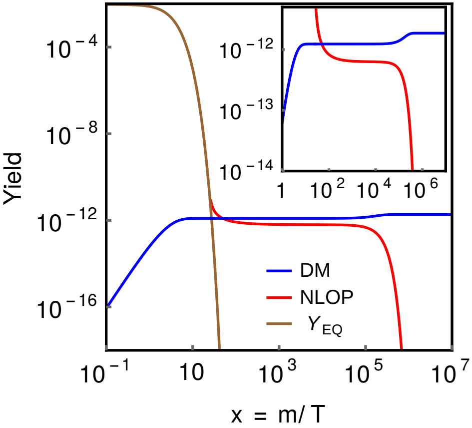

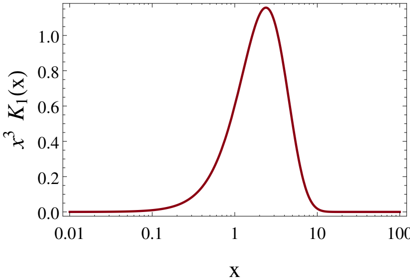

Type III seesaw with a sterile neutrino

The decay width of $\eta_3^\pm$ into χ is given by

$$\Gamma_{\eta_3^\pm \to \chi W^\pm} = \frac{g^2 \sin^2 \beta \sqrt{E_w^2 - M_w^2}}{4\pi M_\Sigma^2} \left(M_\Sigma (M_\Sigma - E_w) - 3 M_{\nu_s} M_\Sigma + \frac{2 M_\Sigma E_w}{M_w^2} (M_\Sigma E_w - M_w^2) \right),$$

where $E_w = \frac{M_\Sigma^2 - M_{\nu_s}^2 + M_w^2}{2 M_\Sigma}$.

- One benchmark: $M_\Sigma = 1$ TeV, $M_{\nu_s} = 500$ GeV and $\Lambda = 10^{15}$ GeV.
- Then lifetime of $\eta_3^\pm$ is 0.167 s.
- Other NLOP ψ has a lifetime of 0.169 s for the decay $\psi \to \chi H$
- $\eta_3^\pm$ or ψ never decays inside the LHC detector for such masses and Λ which is at the origin of the dimension-5 terms.

Type III seesaw with a sterile neutrino

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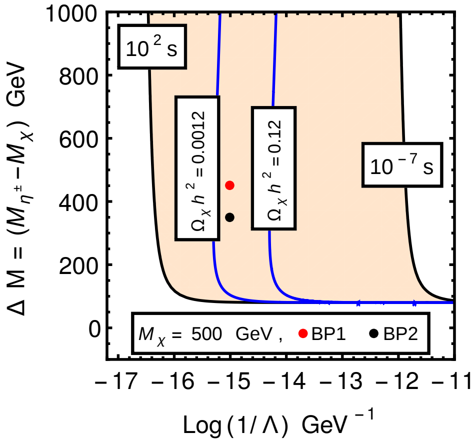
Parameter scan

Type III seesaw with a sterile neutrino



- Increase(decrease) in M_χ moves the blue contours slightly to the right(left).
- BPs are for collider analysis and does not depend on x-axis.

Model II : IDM with majorana neutrino DM

IDM with majorana neutrino DM

- Particle content : SM fields + Φ_2+N_{jR}
- Φ_2 : $SU(2)_L$ doublet with Y=1. $\begin{pmatrix} H^+ \\ H^0 + i\,A^0 \end{pmatrix}$
- N_{jR} : SM gauge singlet fermion.
- DM stability : Φ_2 and $N_{3R} \Rightarrow \mathbb{Z}_2$ odd.
- N_{1R} and N_{2R} mix with the SM particles to generate neutrino masses through Type-I seesaw.
- Φ_2 does not get a vev $\Rightarrow$ Inert doublet.
- The scalar potential

$$\begin{aligned} V &= \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) \\ &\quad + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c\right] + \mu_1\Phi_1^\dagger\Phi_1 + \mu_2\Phi_2^\dagger\Phi_2, \end{aligned}$$

IDM with majorana neutrino DM

- The discrete symmetry prevents mixing between the doublets
$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \mathbf{h} + i\,G^0) \end{bmatrix}, \;\; \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + i\,A^0) \end{bmatrix}$
- mass of the new scalars:

$$M^2_{H^\pm} = \mu_2 + \frac{1}{2}\lambda_3 v^2,$$

$$M^2_{H^0} = \mu_2 + \frac{1}{2}\lambda_L v^2, \qquad M^2_{A^0} = \mu_2 + \frac{1}{2}\lambda_A v^2,$$

where $\lambda_{L/A} = (\lambda_3 + \lambda_4 \pm \lambda_5)$

- It is possible to have $H^\pm$ ligher compared to H^0/A^0.
- Boundedness of the potential

$$\lambda_{1,2} > 0, \;\; \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \;\; \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} > 0.$$

IDM with majorana neutrino DM

- Yukawa sector of the model :

$$\mathcal{L}_Y = y_{\nu j}\bar{N}_{3R}\tilde{\Phi}_2^{\dagger}L_{Lj} + y_{\alpha j}\bar{N}_{\alpha R}\tilde{\Phi}_1^{\dagger}L_{Lj} + \frac{M_j}{2}\bar{N}_{jR}^{c}N_{jR} + h.c,$$

  here $\alpha = 1{,}2$ and $j = 1{,}2{,}3$ whereas $L_L = (\nu_L, l_L)^T$
- 2nd term generates Dirac type mass term for two light neutrinos
- At tree level two light neutrinos are massive (Type-I seesaw).
- The term $y_{\nu j}\bar{N}_{3R}\tilde{\Phi}_2^{\dagger}L_{Lj}$ generates neutrino mass at 1-loop.
- $y_{\nu j}$ can be very small ($\sim 10^{-12}$) since oscillation data requires only two massive enutrinos.
- If N_{3R} is lighter than $H^{\pm}$ then it is the DM (χ).
- All interactions of DM is governed by the $y_{\nu j}$.

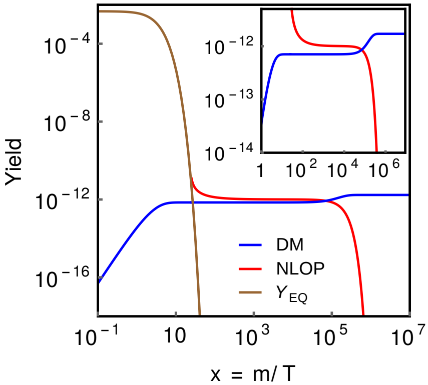
IDM with majorana neutrino DM

- DM is non thermal : Yukawa coupling 10^{-12}.
- DM production in eayly universe :

$$H^{\pm} \to \chi \, \ell^{\pm} \qquad H^0(A) \to \chi \, \nu$$

- As before: $\Omega_\chi h^2 = \Omega_\chi h^2|_{\text{freeze-in}} + \Omega_\chi h^2|_{\text{freeze-out}}$
- Correct relic density and BBN will cosntraint the relevant decay widths.
- $\Gamma_{H^\pm \to \chi l^\pm} = \dfrac{y_{\nu j}^2 M_{H^\pm}}{4\pi} \left(1 - \frac{M_3^2}{M_{H^\pm}^2}\right)^2.$
- These limits can be recast into limit on Yukawa coupling.

IDM with majorana neutrino DM



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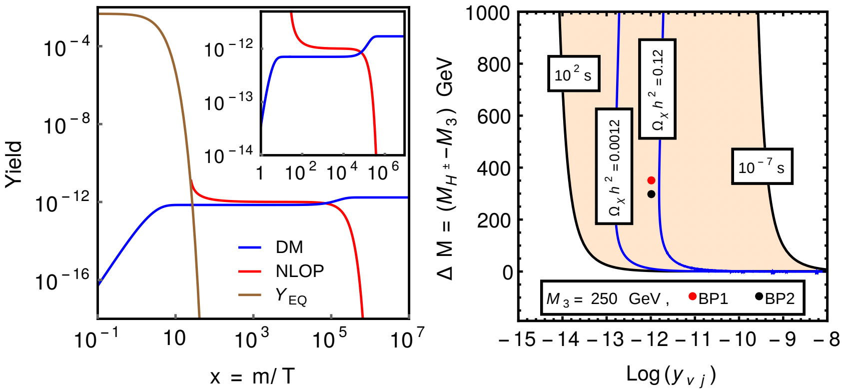


- $y_{\nu j} \sim 10^{-12}, M_{H^\pm} \sim 500 GeV, M_\chi \sim 250 GeV \Rightarrow \tau_{H^\pm} \sim 0.0297 sec.$
- NLOP decays outside the detector.

Collider Phenomenology

Collider signals

Type III seesaw + ν_s

- Opposite sign charged tracks:
  $p\,p \to Z^* \to \eta_3^+ \eta_3^-$
- Single charged track + $\not{E}_T$:
  $p\,p \to W^* \to \eta_3^+ \psi$

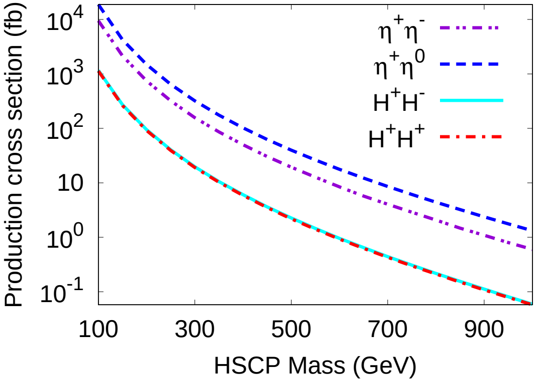
IDM + ν_s

- Opposite sign charged tracks:
  $p\,p \to Z^* \to H^+ H^-$
  $p\,p \to W^* \to H^+ H^0(A^0) \to H^+ H^- X$
- Same sign charged tracks:
  $p\,p \to W^* \to H^+ H^0(A^0) \to H^+ H^+ X$

It is possible to differentiate between the models based on collider signature.

Backgrounds to the signals : Muons only, since the signal is a charged track all the way to the muon chamber.

Production cross-section



Signal characteristic

- The LLP behaves like a muon.
- But they are substantially heavy (500 GeV or more) and the charged tracks behave just like a slow muon.
- Velocity $\beta = p/E$ is considerably lower than unity, which is not the case for muons.
- Also they have very high transverse momentum.

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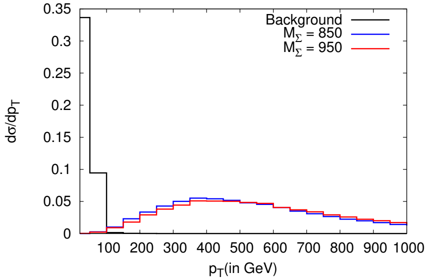
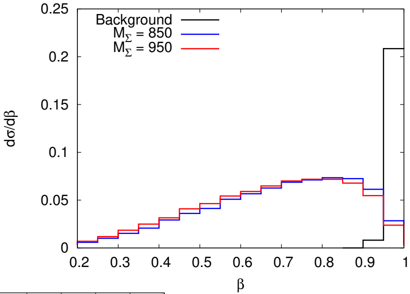
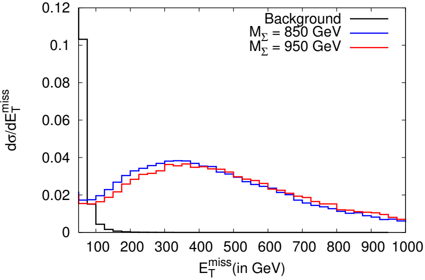
Parameter	β	p_T	$\lvert y(\mu_{1,2})\rvert$	$\Delta R(\mu_1, \mu_2)$
Cut values	(A)[0.2, 0.95] (B)[0.2, 0.80]	> 70 GeV > 70 GeV	< 2.5 < 2.5	> 0.4 > 0.4

- Cutset A : Same as ATLAS specification 1411.6795.
- Cutset B : Experiment with stronger β cut. Ref: CMS-1305.0491.
- Cutset B is very effective for single track + $\not{E}_T$ signal.

Collider analysis : Type III seesaw + ν_s







Collider analysis : Type III seesaw + ν_s

We focus on the following channels

- Opposite-sign charge tracks: $p\,p \to Z^* \to \eta_3^{\pm}\,\eta_3^{\mp}$.
- Single charge track + $\not{E}_T$: $p\,p \to W^{\pm *} \to \eta_3^{\pm}\,\psi$.

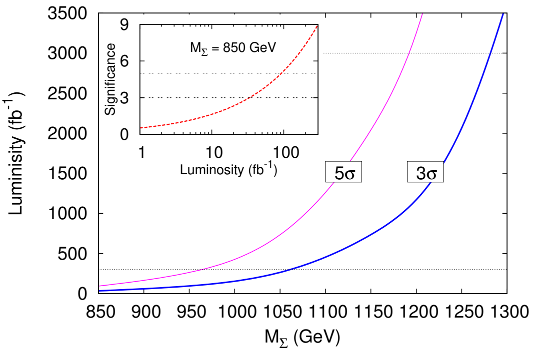
Background

- Opposite-sign muons : Drell-Yan production of $\mu^{\pm}$, $\tau^{\pm}$ and $t\,\bar{t}$.
- For single charged track + $\not{E}_T$ $W^{\pm}$ and $t\bar{t}$ are the dominant.
- For both the cases dibosons (WW, WZ and ZZ) are sub-dominant.

Cosmic muons : Another source of background

- Must be taken into accout for realistic analysis.
- For OS case : $\sim 60\%$ of total background. Ref: CMS, 1305.0491
- For single track this BG is very small. $\sim 0.5\%$ if the number of events is one order of magnitude higher than the OS case.

Collider analysis : Type III seesaw + ν_s



Signal	Benchmark point	$\int \mathcal{L}dt$ for 5σ	N_S	N_B
Opposite Sign Charged Track	BP1(M_Σ =850 GeV)	92.95	92	248
	BP2(M_Σ =950 GeV)	263.23	146	702
Single Charged Track + $\not{E}_T$	BP1	(A)340.40 (B) 24.81	841 46	27436 40
	BP2	(A)1076.19 (B) 56.60	1485 62	86741 91

Collider analysis : IDM + ν_s

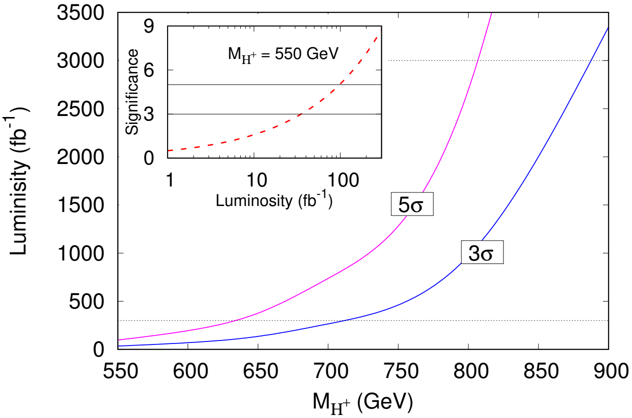
We have explored the following signals in this scenario :

- Opposite-sign charge tracks ($H^{\pm}H^{\mp}$)
- Same-sign charge tracks ($H^{\pm}H^{\pm}$)

Background

- OS scenario : same as before
- SS scenario : $t\bar{t}$, $t\bar{t}W$ and diboson final states.
- Cosmic ray muon BG is assumed to be same as OS case to be conservative.
- SM BG is almost zero after cuts in SS case.

Collider analysis : IDM + ν_s



Conclusion

- FIMP : A new paradigm for DM.
- Heavy stable charged tracks are very interesting and unusual signature of FIMP DM.
- Several studies on MSSM with stau NLSP and RH sneutrino as LSP.
- We studied two possible non-supersymmetric scenarios with FIMP DM and neutrino mass generation.
- The feelble interaction originates via d=5 operator or via tiny Yukawa coupling.
- The models can be distinguished at collider : SS and OS charged track.
- Also there is a loose correlation between life time of the LLP and the DM mass.

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Thank You

Back Up Slides

IDM with majorana neutrino DM

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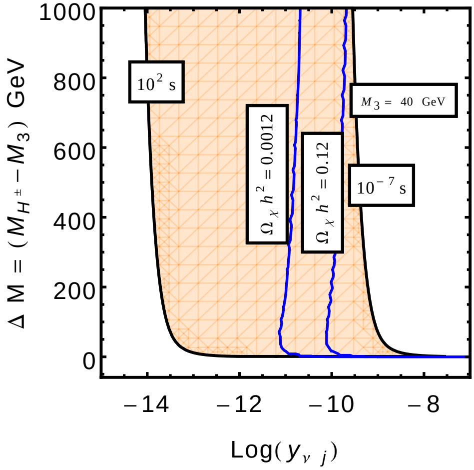

- It is possible to look for dislaced vertex or disappearing charged tracks.
- If DM mass is small we need couplings $\sim 10^{-9}$ or less.
- Then if the NLOP is heavy we can have its decay inside the detector.

Signal characteristic and analysis strategy

- Velocity β is one of the most important variable in our analysis.
- We need the velocity distribution of muons to estimate the backgrounds.
- For muons the mean velocity $\bar{\beta} = 0.999c$ and standard deviation $\sigma_\beta = 0.024c$.
- This is known from a combined measurement of the calorimeter and muon chamber. ATLAS - 1411.6795.
- For the background analysis we generated a Gaussian random number with these parameters and then impose the cuts on the smeared β accordingly.
- For signal smearing we used $\bar{\beta} = p/E$ and the same σ_β.

Specific ionization rate $\frac{dE}{dx}$ is high for LLPs.

Refs:

CMS collaboration, S. Chatrchyan et al., Searches for long-lived charged particles in pp collisions at s=7 and 8 TeV, JHEP 07 (2013) 122, [1305.0491].

ATLAS collaboration, G. Aad et al., Searches for heavy long-lived charged particles with the ATLAS detector in proton-proton collisions at [1411.6795].

$\eta_3^\pm$ mixing with a heavy charged VL fermion

- Charged component oa the multiples is usually heavy due to radiative correction (~ 136 MeV). Ref: Cirelli et.al. Nucl. Phys. B 753 (2006) 178
- Introduce vector-like SU(2) singlet singly charged weyl fermions $\lambda_{L,R}$ ($\mathbb{Z}_2$-odd) and a triplet scalar Δ($\mathbb{Z}_2$-odd) with $Y = 2$.
- Then we have

$$\mathcal{L} = -M_\lambda \bar{\lambda}\lambda - (Y_\lambda \, \mathrm{Tr}\left[\bar{\Sigma}^c_{3R} \, \Delta \, \lambda_R + \bar{\Sigma}_{3R} \, \Delta \, \lambda^c_R\right] + h.c),$$

$\lambda = \lambda_L + \lambda_R$ and Δ is defined as

$$\Delta = \begin{bmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2}. \end{bmatrix}$$

- Once the triplet scalar acquires a vev v_Δ the Yukawa term of the above Lagrangian will generate a mixing between $\lambda_{L,R}$ and $\eta_3^\pm$.
- Charged fermion mass matrix

$$\mathcal{M}^\pm = \begin{bmatrix} M_\Sigma - \frac{\alpha_\Sigma v^2}{2\Lambda} & v_\Delta Y_\lambda \\ v_\Delta Y_\lambda^\dagger & M_\lambda \end{bmatrix},$$

$\eta_3^\pm$ mixing with a heavy charged VL fermion

- The eigenvalues of the mass matrix

$$\frac{1}{2}\left[M_\Sigma + M_\lambda \pm \sqrt{(M_\Sigma - M_\lambda)^2 + 4v_\Delta^2\ Y_\lambda^2}\right].$$

- If $M_\lambda > M_\Sigma$ then the lightest state will be triplet dominant with a mass slightly smaller than M_Σ which for all practical purposes, can be identified as $\eta_3^\pm$.

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

Decaywidths : LSP from Sfermions

$$\Gamma\left(\tilde{H}_u^0 \to \tilde{\nu}_R \nu_L\right) = \frac{1}{32\pi M_{\tilde{H}_u^0}} \beta_f(M_{\tilde{H}_u^0}, M_{\nu_L})(M_{\tilde{H}_u^0}^2 + M_{\nu_L}^2 - M_{\tilde{\nu}_R}^2)|\mathcal{A}\left(\tilde{H}_u^0 \to \tilde{\nu}_R \nu_L\right)|^2, \tag{A.1a}$$

$$\Gamma\left(\tilde{H}_u^+ \to \tilde{\nu}_R l^+\right) = \frac{1}{32\pi M_{\tilde{H}_u^+}} \beta_f(M_{\tilde{H}^+}, M_l)(M_{\tilde{H}_u^+}^2 + M_l^2 - M_{\tilde{\nu}_R}^2)|\mathcal{A}\left(\tilde{H}_u^+ \to \tilde{\nu}_R l^+\right)|^2, \tag{A.1b}$$

$$\Gamma\left(\tilde{\nu}_L \to \tilde{\nu}_R h\right) = \frac{1}{32\pi M_{\tilde{\nu}_L}} \beta_f(M_{\tilde{\nu}_L}, M_h)|\mathcal{A}\left(\tilde{\nu}_L \to \tilde{\nu}_R h\right)|^2, \tag{A.1c}$$

$$\Gamma\left(\tilde{\nu}_L \to \tilde{\nu}_R Z\right) = \frac{1}{32\pi M_{\tilde{\nu}_L}} \frac{M_{\tilde{\nu}_L}^4}{M_Z^2} \beta_f^3(M_{\tilde{\nu}_L}, M_Z)|\mathcal{A}\left(\tilde{\nu}_L \to \tilde{\nu}_R Z\right)|^2, \tag{A.1d}$$

$$\Gamma\left(\tilde{l}_L \to \tilde{\nu}_R W^-\right) = \frac{1}{32\pi M_{\tilde{l}_L}} \frac{M_{\tilde{l}_L}^4}{M_W^2} \beta_f^3(M_{\tilde{l}_L}, M_W)|\mathcal{A}\left(\tilde{l}_L \to \tilde{\nu}_R W^-\right)|^2, \tag{A.1e}$$

$$\Gamma\left(\tilde{B}^0 \to \tilde{\nu}_R \nu_L\right) = \frac{1}{32\pi M_{\tilde{B}^0}} \beta_f(M_{\tilde{B}^0}, M_{\nu_L})(M_{\tilde{B}^0}^2 + M_{\nu_L}^2 - M_{\tilde{\nu}_R}^2)|\mathcal{A}\left(\tilde{B}^0 \to \tilde{\nu}_R \nu_L\right)|^2, \tag{A.1f}$$

$$\Gamma\left(\tilde{W}^0 \to \tilde{\nu}_R \nu_L\right) = \frac{1}{32\pi M_{\tilde{W}^0}} \beta_f(M_{\tilde{W}^0}, M_{\nu_L})(M_{\tilde{W}^0}^2 + M_{\nu_L}^2 - M_{\tilde{\nu}_R}^2)|\mathcal{A}\left(\tilde{W}^0 \to \tilde{\nu}_R \nu_L\right)|^2, \tag{A.1g}$$

$$\Gamma\left(\tilde{W}^+ \to \tilde{\nu}_R l^+\right) = \frac{1}{32\pi M_{\tilde{W}^+}} \beta_f(M_{\tilde{W}^+}, M_l)(M_{\tilde{W}^+}^2 + M_l^2 - M_{\tilde{\nu}_R}^2)|\mathcal{A}\left(\tilde{W}^+ \to \tilde{\nu}_R l^+\right)|^2. \tag{A.1h}$$

Amplitudess : LSP from Gauginos

1. $\mathcal{A}\left(\tilde{B}^0 \to \tilde{\nu}^i_R \nu^I_L\right) = \frac{i}{2} g_1 P_L \sum_{k=1}^{3} U^*_{0\,Ik} Z_{\tilde{\nu}\,ik}$

2. $\mathcal{A}\left(\tilde{W}^0 \to \tilde{\nu}^i_R \nu^I_L\right) = -\frac{i}{2} g_2 P_L \sum_{k=1}^{3} U^*_{0\,Ik} Z_{\tilde{\nu}\,ik}$

3. $\mathcal{A}\left(\tilde{H}^0_u \to \tilde{\nu}^i_R \nu^I_L\right) = -\frac{i}{\sqrt{2}} P_L \left(\sum_{k,l=1}^{3} Z^*_{\tilde{\nu}\,ik} Y_{\nu\,lk} U_{V\,I(3+l)} + \sum_{k,l=1}^{3} Z^*_{\tilde{\nu}\,i(3+l)} Y_{\nu\,lk} U_{V\,Ik} \right)$

4. $\mathcal{A}\left(\tilde{W}^- \to \tilde{\nu}^i_R l^{-\,I}\right) = -\frac{i}{2} g_2 P_L Z^*_{\tilde{\nu}\,iI}$

5. $\mathcal{A}\left(\tilde{H}^+_u \to \tilde{\nu}^i_R l^{-\,I}\right) = \frac{i}{2} P_L \sum_{k=1}^{3} Z^*_{\tilde{\nu}\,i(3+k)} Y_{\nu\,kI}$

Amplitudess : LSP from sleptons and sneutrinos

1. $\mathcal{A}\left(\tilde{e}_L^j \to \tilde{\nu}_R^i W^\mu\right) = \frac{i}{2}\, g_2\, Z^*_{\tilde{\nu}\, ij}\, \left(p_{\tilde{\nu}^i} - p_{\tilde{e}_L} \right)^\mu$

2. $\mathcal{A}\left(\tilde{\nu}_H^j \to \tilde{\nu}_R^i Z^\mu\right) = \frac{1}{2}\, (g_2 \cos\theta_w + g_1 \sin\theta_w)\, \left(p_{\tilde{\nu}_H} - p_{\tilde{\nu}^i} \right)^\mu \sum_{k=1}^{3} Z^{*\,H}_{\tilde{\nu}\, jk}\, Z^*_{\tilde{\nu}\, ik}$

$$\begin{aligned}
\mathcal{A}\left(\tilde{\nu}_H^j \to \tilde{\nu}_R^i h\right) = \frac{i}{2\sqrt{2}} \Bigg(& \mu \sum_{p,k=1}^{3} \left[Z^{*\,H}_{\tilde{\nu}\, jk}\, Z^*_{\tilde{\nu}\, i(3+p)} + Z^{*\,H}_{\tilde{\nu}\, j(3+p)}\, Z^*_{\tilde{\nu}\, ik} \right] Y^*_{\nu\, pk} \\
& + \mu^* \sum_{p,k=1}^{3} \left[Z^{*\,H}_{\tilde{\nu}\, jk}\, Z^*_{\tilde{\nu}\, i(3+p)} + Z^{*\,H}_{\tilde{\nu}\, j(3+p)}\, Z^*_{\tilde{\nu}\, ik} \right] Y_{\nu\, pk} \Bigg) \\
& - 2(g_1^2 + g_1^2)\, v_d \sum_{k=1}^{3} Z^{*\,H}_{\tilde{\nu}\, jk}\, Z^*_{\tilde{\nu}\, ik}
\end{aligned}$$