Sneutrino dark matter

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Introduction

Strong evidence for dark matter from astrophysical and cosmological observations

Motivation for new particles beyond standard model

Implication of precise determination of amount of CDM on DM particle properties

\[ \Omega_{\text{cdm}} h^2 = 0.1196 \pm 0.0031 \]
A wide variety of DM candidates

WIMPs
FIMPs
SIMPs
Asymmetric

L. Roszkowski
• Supersymmetry one of best motivated extension of SM
• No sign at LHC → does that mean that most popular WIMP model (neutralino) is ruled out?
• Strong constraints from LHC + direct detection especially if below TeV scale
• Properties of neutralino DM: strong dependence on its nature: partner of gauge boson (B, W) or Higgs
  • SU(2) number: efficient annihilation into WW→ relic density prefers TeV scale (higgsino) or 2 TeV (wino)
  • U(1) only: bino need light sfermions – LHC disfavoured
  • Mixed: satisfies relic density for any scale – mixed bino-higgsino strongly constrained from direct detection (bino-wino allowed)
Still large area of parameter space to be explored by LHC and (in)direct searches

What about other supersymmetry candidates?
Sneutrino DM

- Another neutral particle in SUSY: the sneutrino
- Partner of LH neutrino NOT a good DM candidate
  - Very large contribution to direct detection - through Z exchange (Falk, Olive, Srednicki, PLB354 (1995) 99) + efficient annihilation
- Neutrino have masses – RH neutrino + supersymmetric partner well-motivated – if LSP then can be dark matter
- Thermalized?
  - New interactions – Gauge: MSSM+U(1) (GB et al JCAP 1112:014) or scalar eg NMSSM (Cerdeno, Seto, JCAP0908:032)
  - Both cases are viable with respect to LHC constraints and feature new signatures – leptons (same-sign, monoleptons) (Arina, Cabrera, 1311.6549, Arina et al, 1503.02960, GB et al, 1505.06243)
Sneutrino DM

- Or not thermalized –
  - abundance from decay of other particles ‘next to lightest dark’ particle which has long lifetime,
  - NLSP freeze-out as usual then decays to feebly interacting sneutrino
MSSM+RH neutrino

- The framework: MSSM + three generations ($\nu_R + \text{sneutrino}_R$).
- Assume pure Dirac neutrino masses.
- Superpotential
  \[ W = y_\nu \hat{H}_u \cdot \hat{L} \hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L} \hat{\nu}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u \]
- Couplings of sneutrino proportional to neutrino mass.
- Lower bound on neutrino mass from fits to solar, atmospheric, accelerator neutrino data
  \[ |\Delta m^2| = 2.43 \pm 0.06 \times 10^{-3} \text{eV}^2 \rightarrow m^H_\nu > 0.049 \text{eV} \]
- For hierarchical neutrino masses
  \[ (y^H_\nu \sin \beta)_{\text{min}} \simeq 2.8 \times 10^{-13} \]
- Upper limit on Yukawa couplings from cosmological bound – Planck temperature and polarisation data, lensing, supernovae, BAO
  \[ \sum_{i=1}^{3} m_i < 0.23 \text{ eV at 95\% CL} \]
  \[ (y^H_\nu \sin \beta)_{\text{max}} \simeq 4.4 \times 10^{-13} \]
  (for quasi-degenerate neutrinos)
MSSM+RH neutrino

- Sneutrino mass same order as other sfermions – can be LSP

\[ -\mathcal{L}_{\text{soft}} \supset M_{\tilde{\nu}_R}^2 |\tilde{\nu}_R|^2 + (y_{\nu} A_{\nu} H_u \tilde{L} \tilde{\nu}_R^c + h.c.) \]

- Sneutrino mixing is very small – can be neglected

\[ \tan 2\tilde{\Theta} = \frac{2y_{\nu} v \sin \beta |\cot \beta \mu - A_{\nu}|}{m_{\tilde{\nu}_L}^2 - m_{\tilde{\nu}_R}^2} \]

- Assume mass of RH sneutrino is free parameter (even in sneu-CMSSM)

- Note that natural for sneutrinoR to be lightest particle as its mass does not evolve much with energy contrary to other sfermions.
• Sneutrino not thermalized in early universe – its interactions are too weak
• One possibility for DM is production through decays of sparticles
• Consider the case where stau is the NLSP (here assume CMSSM relations, for general MSSM Heisig et al 1310.2825) – neutralino NLSP no distinctive LHC signature
• Lifetime of stau (2 or 3-body decay) depends on mixing in sneutrino/stau sectors =- from a few seconds to $10^{11}$s.

$$
\Gamma_{\tilde{\tau}_1 \rightarrow \nu_R W} = \frac{g^2 \bar{\Theta}^2}{32 \pi} |U_{L1}|^2 \frac{m_{\tilde{\tau}_1}^3}{m_W^2} \left[ 1 - \frac{2(m_{\tilde{\nu}_R}^2 + m_W^2)}{m_{\tilde{\tau}_1}^2} + \frac{(m_{\tilde{\nu}_R}^2 - m_W^2)^2}{m_{\tilde{\tau}_1}^2} \right]^{3/2}
$$

• Decay of NLSP (MSSM-LSP) after freeze-out
• Relic density obtained from that of the NLSP – can be charged

$$
\Omega_{\tilde{\nu}_R}^{FO} = \frac{m_{\tilde{\nu}_R}}{m_{\text{MSSM-LSP}}} \Omega_{\text{MSSM-LSP}}
$$
Model parameters and constraints

- CMSSM + RH neutrino
- Scan range
  \[ m_0 < 2500 \text{ GeV} ; \quad m_{1/2} < 2500 \text{ GeV} ; \quad |A_0| < 3000 \text{ GeV} \]
  - and at electroweak scale\[ 0 < m_{\tilde{\nu}_R} < m_{\tilde{\tau}_1} ; \quad 5 < \tan \beta < 40 \]
- \( M_{\text{gluino}} > 1.8 \text{ TeV} \)
- Collider constraints – Higgs mass and couplings;
- Flavour constraints \( b-s\gamma, B_s-\mu\mu, B-\tau\nu \);
- Susy searches (mostly not valid because stau is collider stable and charged);
- Charged stable stau \( m>340 \text{ GeV} \) (from CMS Run 1 search)
- Constraints from BBN: lifetime of stau can be long enough for decay around or after BBN → impact on abundance of light elements
**Big Bang Nucleosynthesis**

- BBN (T~MeV-10keV, t~0.1-10^4s) allow to predict abundances of light elements \(D, He^3, He^4, ^7Li\).
- Depends on photon to baryon ratio
- In early Universe, energy density dominated by radiation
- At high T, weak interaction rates were in thermal equilibrium and n/p~1
  \[n + e^+ \rightarrow p + \nu \]
  \[n + \nu \rightarrow p + e^-\]
- At lower T: weak interactions fall out of equilibrium
- Freeze-out when interaction rate \(\Gamma_{\text{weak}} < H\), species decouple
- When T approaches freeze-out (around 0.8MeV)
  \[n/p \approx \exp^{-\Delta m/T} \approx 1/6\]
• Nucleosynthesis begins with formation of Deuterium
• Number of photons >> number of nucleons the reverse process occurs much faster, deuterium production is delayed, starts only at $T \approx 0.1$ MeV
\[ p + n \rightarrow D + \gamma \]
• … and the chain continues with production of heavier elements
• Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements
\[ Y \approx \frac{2n/p}{1 + n/p} \approx 0.25 \]
• Main product of BBN $^4$He
• Other elements produced in lesser amounts D, $^3$He, $^7$Li
• If particle with lifetime > 0.1s decays can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
  • Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)
• Alteration of n/p ratio - for example $\pi^- + p \rightarrow \pi^0 + n$
  • -> overproduction He$^4$
• Hadrodissociation of He$^4$ causes overproduction of D
  • n+He$^4$ $\rightarrow$ He$^3$+D, 2D+n, D+p+n
• Key elements:
  • Bhad: hadronic BR of stau (nuR+W)
  • Evis: net energy carried away by hadrons
  • Ystau: yield
• After all constraints – room for sneutrino DM (even in CMSSM)
• Can constitute dominant dark matter component
LHC signatures

• Characteristic signature: stable charged particle NOT MET
• Staus live from sec to min: decay outside detector
• Searches
  • Cascades: coloured sparticles decay into jets + SUSY $\rightarrow$ N jets + stau
  • Pair production of two stable staus
  • Passive search for stable particles
• Stable stau behaves like « slow » muons $\beta = p/E < 1$
  • Use ionisation properties and time of flight measurement to distinguish from muon
  • kinematic distribution

Banerjee, GB, Mukhopadyhay, Serpico, 1603.08834
Charged tracks from cascades

- Dominant contribution from squark pairs (heavy gluinos)
- Signal computed with Spheno+ Madgraph5aMC@NLO + Pythia+Delphes3+prospino k-factors
- Background: tt,µµ+jets, WW,WZ strongly suppressed with cuts
- Use approach suggested in Gupta et al PRD75075007 (2007)

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834
Charged tracks from cascades (2)

- Luminosity required for 5sigma
- Fairly easy to discover if mass stau < 400 GeV
- Luminosity 1ab\(^{-1}\) can probe mass \(~580\text{GeV}\)
- Dependence on mass of squarks

<table>
<thead>
<tr>
<th>Benchmark point</th>
<th>(\mathcal{L}) for 5(\sigma) [fb(^{-1})]</th>
<th>(N_S)</th>
<th>(N_B)</th>
<th>(N_S/N_B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>357 GeV</td>
<td>9.1</td>
<td>25</td>
<td>0.35</td>
<td>72</td>
</tr>
<tr>
<td>400 GeV</td>
<td>2.5</td>
<td>25</td>
<td>0.09</td>
<td>265</td>
</tr>
<tr>
<td>442 GeV</td>
<td>68.5</td>
<td>27</td>
<td>2.7</td>
<td>10</td>
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<tr>
<td>600 GeV</td>
<td>1100</td>
<td>48</td>
<td>43</td>
<td>1.1</td>
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Pair production

- No model dependence – only mass of stau
- Smaller cross section (EW only)
- Background: muon pairs
- Best cuts – close to current ATLAS analysis - JHEP1501 (2015) 068
- Lower reach than previous channel

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<th>Cut</th>
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<tr>
<td>$\Delta R(\mu\mu) &gt; 0.4$</td>
<td>357 GeV</td>
<td>1543</td>
<td></td>
<td>0.44</td>
<td>21.8</td>
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<tr>
<td>$\beta &lt; 0.95$</td>
<td>400 GeV</td>
<td>1014</td>
<td>3481</td>
<td>0.29</td>
<td>15.1</td>
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<tr>
<td>$p_T^{\mu_1,2} &gt; 70\text{GeV}$</td>
<td>442 GeV</td>
<td>715</td>
<td>0.21</td>
<td>11.0</td>
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<tr>
<td>$</td>
<td>y(\mu_{1,2})</td>
<td>&lt; 2.5$</td>
<td>600 GeV</td>
<td>211</td>
<td>0.06</td>
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$\mathcal{L} = 3000 \text{ fb}^{-1}$

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834
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Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834
MoEDAL detector

- Passive detector
- Array of nuclear track detector stacks
- Surrounds intersection region point 8
- Sensitive to highly ionising particles
- Does not require trigger, one detected event is enough
- Major condition: ionizing particle has velocity $\beta < 0.2$

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<td>24</td>
<td>1.1</td>
</tr>
<tr>
<td>600 GeV</td>
<td>6</td>
<td>0.5</td>
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Number of $\tilde{\tau}_1$'s with $\beta \leq 0.2$ with $\mathcal{L} = 3000$ fb$^{-1}$
CONCLUSION

Sneutrino viable very weakly interacting DM candidate in supersymmetry

LHC has unique potential to probe a whole class of DM models that predict heavy stable charged particles

BBN constraints are important

Class of model with few signatures in astroparticle searches
Charged tracks from cascades (2)

- $p_T^{\mu_1,2} > 200 \text{ GeV, } |y(\mu_1,2)| < 2.4,$
- $p_T^{j_1,2} > 200 \text{ GeV, } |\eta(j_1,2)| < 5.0,$
- $\sum |p_T^{\text{vis.}}| > 1000 \text{ GeV},$
- $\Delta R(\mu_1,\mu_2) > 0.2,$
- $\Delta R(j,j) > 0.4,$
- $\Delta R(\mu,j) > 0.4,$
- $M_{\mu_1,\mu_2} > 1000 \text{ GeV},$