DMAstroLHC

Sneutrino dark matter

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LAPTH Annecy-le-Vieux

Multi-component dark matter, Warsaw, 03/06/2016

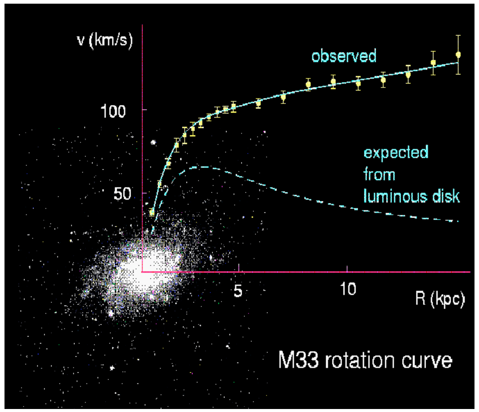
Introduction

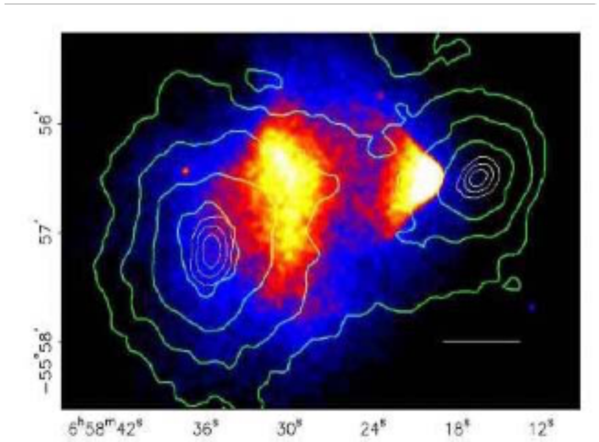
Strong evidence for dark matter from astrophysical and cosmological observations

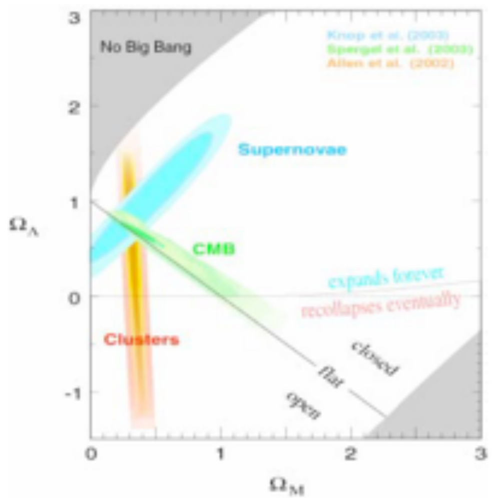
Motivation for new particles beyond standard model

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

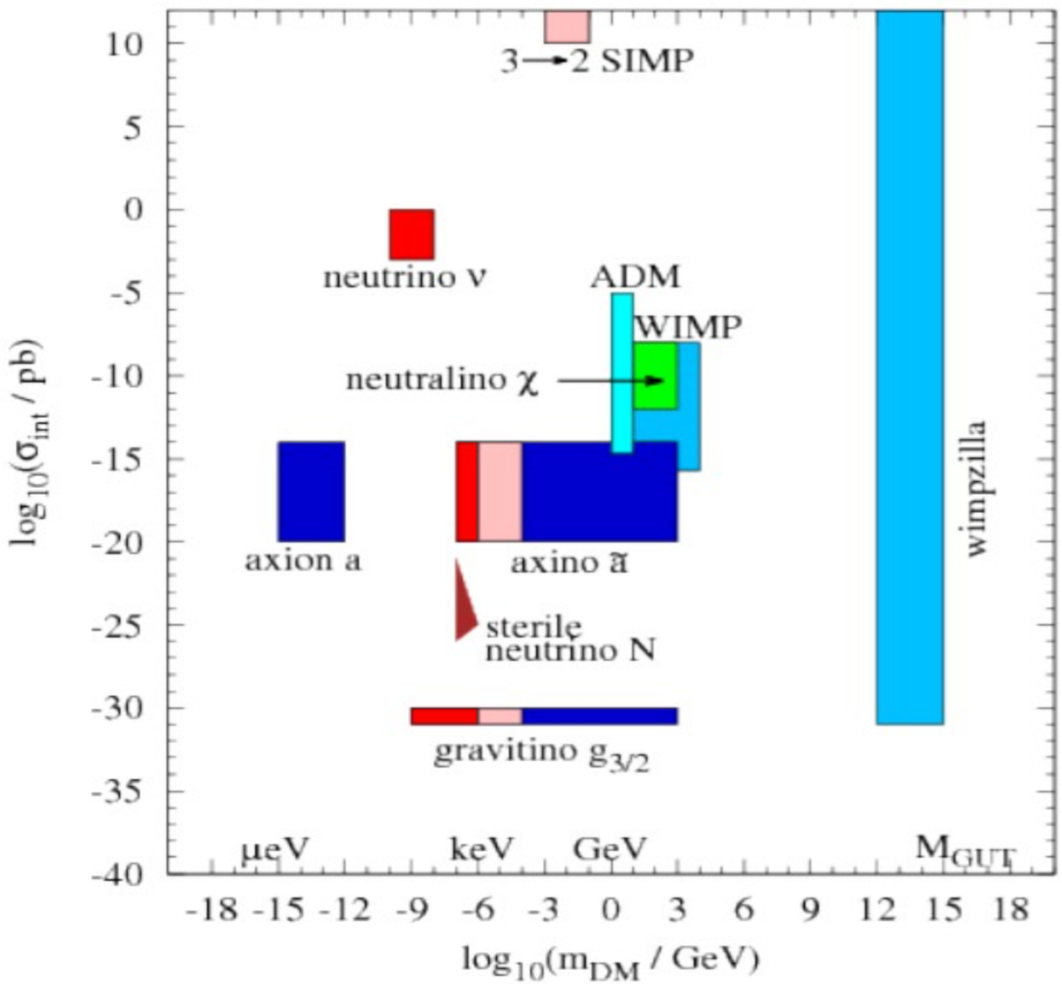
$\Omega_{cdm}\, h^2 = 0.1196 +/- 0.0031$







A wide variety of DM candidates



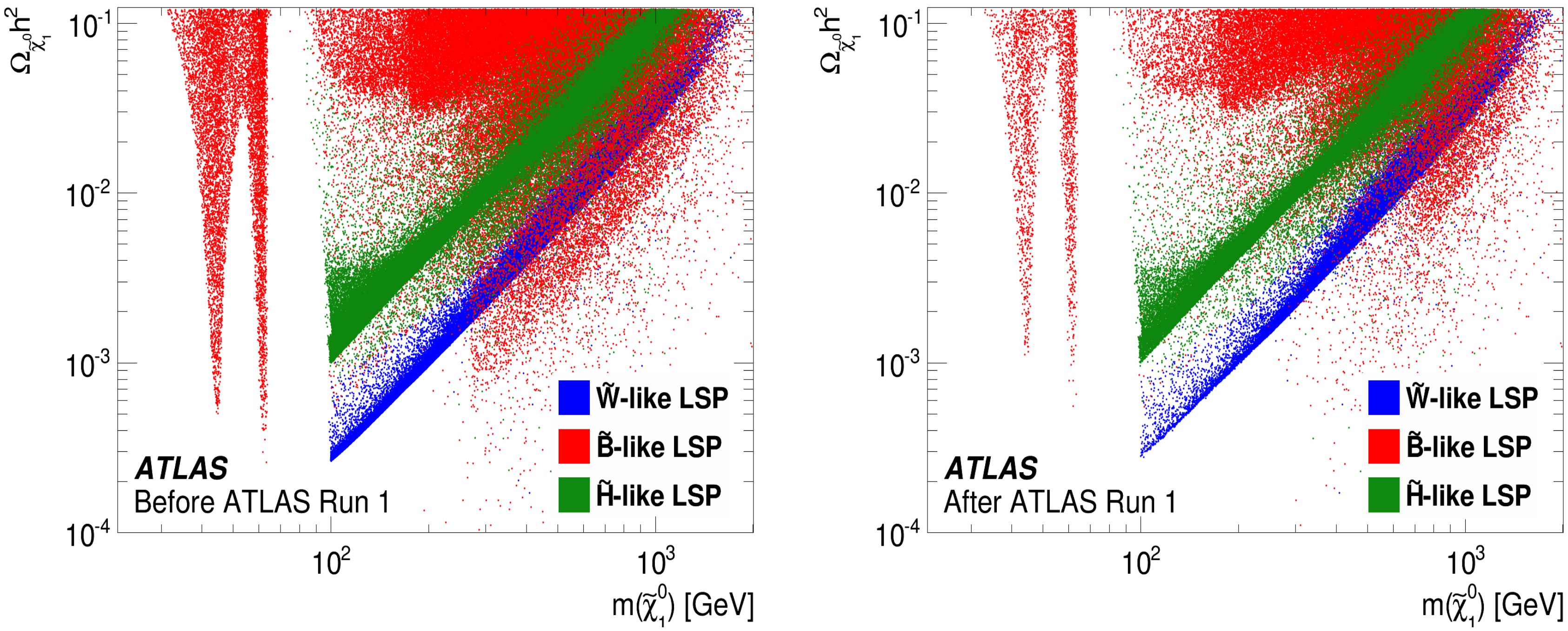
L.Roszkowski

- WIMPs
- FIMPs
- SIMPs
- Asymmetric

- 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 2TeV (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)

What's left after LHC

ATLAS 1508.06608



(a) Before ATLAS Run 1 (b) After ATLAS Run 1

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?
  - Non-negligible L-R mixing - Arkani-Hamed et al PRD61 (2001), Borzumati, Namura PRD64 (2002) 053002
  - 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 (ν_R + sneutrinoR).
- Assume pure Dirac neutrino masses
- Superpotential $W = y_\nu \hat{H}_u \cdot \hat{L} \hat{\nu}_R^c - y_e \hat{H}_d \cdot \hat{L} \hat{\ell}_R^c + \mu_H \hat{H}_d \cdot \hat{H}_u$
- Couplings of sneutrino proportional to neutrino mass
- Lower bound on neutrino mass from fits to solar, atmospheric, accelerator neutrino data

$$|\Delta m^2| = 2.43 \pm 0.06 \times 10^{-3}\text{eV}^2 \quad \rightarrow m_\nu^H > 0.049\text{eV}$$

- For hierarchical neutrino masses

$$(y_\nu^H \sin\beta)_{\text{min}} \simeq 2.8 \times 10^{-13}$$

- Upper limit on Yukawa couplings from cosmological bound – Planck temperature and polarisation data, lensing, supernovae, BAO

$$\sum_{i=1}^{3} m_{\rm i} < 0.23 \text{ eV at } 95\% \text{ CL;} \qquad (y_\nu^H \sin\beta)_{\text{max}} \simeq 4.4 \times 10^{-13}$$

(for quasi-degenerate neutrinos)

MSSM+RH neutrino

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

$$-\mathcal{L}_{soft} \supset M^2_{\tilde{\nu}_R}|\tilde{\nu}_R|^2 + (y_\nu A_\nu H_u \tilde{L}\,\tilde{\nu}^c_R + h.c.)$$

- Sneutrino mixing is very small – can be neglected

$$\tan 2\tilde{\Theta} = \frac{2y_\nu v \sin\beta|\cot\beta\mu - A_\nu|}{m^2_{\tilde{\nu}_L} - m^2_{\tilde{\nu}_R}}$$

- 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.

$$\Gamma_{\tilde{\tau}_1 \to \tilde{\nu}_R W} = \frac{g^2 \tilde{\Theta}^2}{32\pi} |U_{L1}^{(\tilde{\tau}_1)}|^2 \frac{m_{\tilde{\tau}_1}^3}{m_W^2} \left[1 - \frac{2(m_{\tilde{\nu}_R}^2 + m_W^2)}{m_{\tilde{\tau}_1}^2} + \frac{(m_{\tilde{\nu}_R}^2 - m_W^2)^2}{m_{\tilde{\tau}_1}^4} \right]^{3/2}$$

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

$$\Omega_{\tilde{\nu}_R}^{\rm FO} = \frac{m_{\tilde{\nu}_R}}{m_{\rm MSSM\text{-}LSP}} \Omega_{\rm MSSM\text{-}LSP}$$

Model parameters and constraints

- CMSSM + RH neutrino
- Scan range

$$m_0 < 2500\,\mathrm{GeV}\ ; \quad m_{1/2} < 2500\,\mathrm{GeV}\ ; \quad |A_0| < 3000\,\mathrm{GeV}$$

  - and at elevtroweak scale

$$0 < m_{\tilde{\nu}_R} < m_{\tilde{\tau}_1}\ ; \quad 5 < \tan\beta < 40$$

- M_gluino > 1.8TeV
- Collider constraints – Higgs mass and couplings;
- Flavour constraints b-sγ, Bs-μμ,B-τυ;
- Susy searches (mostly not valid because stau is collider stable and charged);
- Charged stable stau m>340 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 Γ_{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~0.1MeV

$$p+n \rightarrow D+\gamma$$

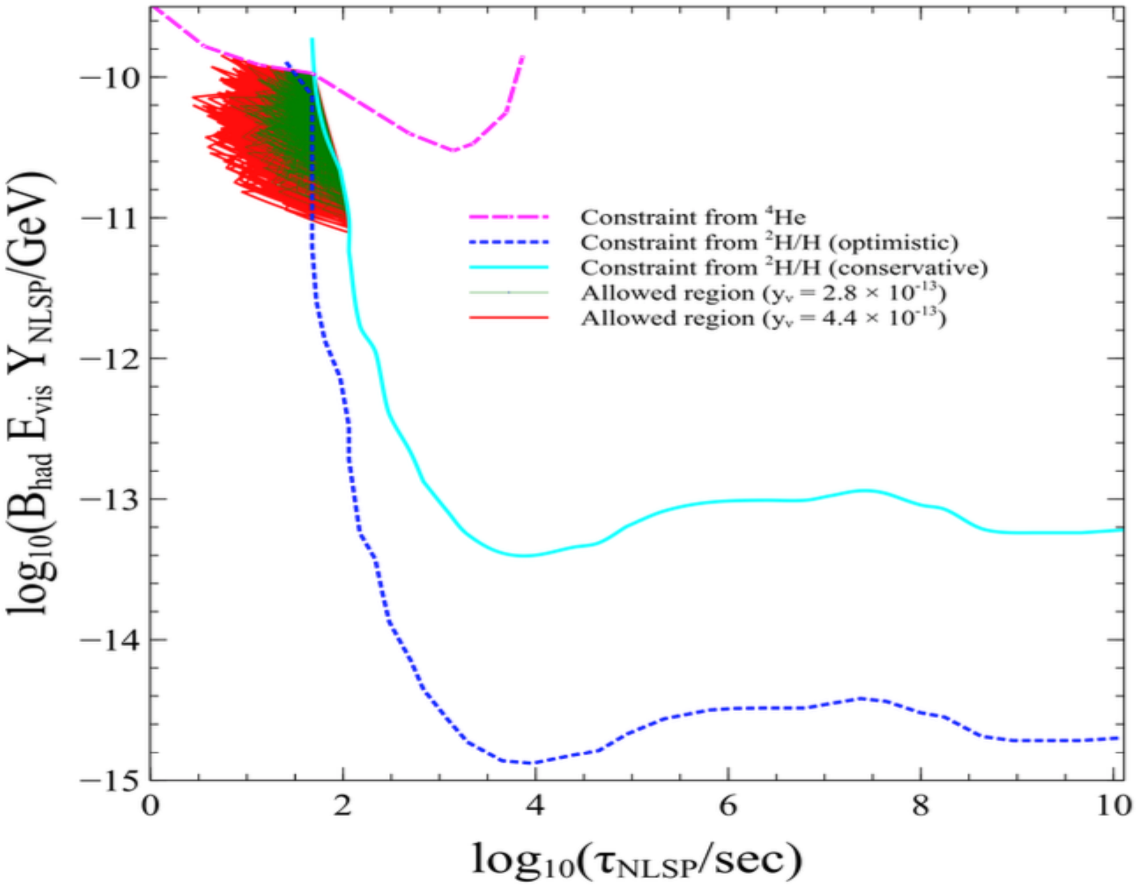
- … and the chain continues with production of heavier elements
- Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements

$$Y \approx \frac{2n/p}{1+n/p} \approx 0.25$$

- Main product of BBN ^{4}He
- Other elements produced in lesser amounts D, ^{3}He, ^{7}Li

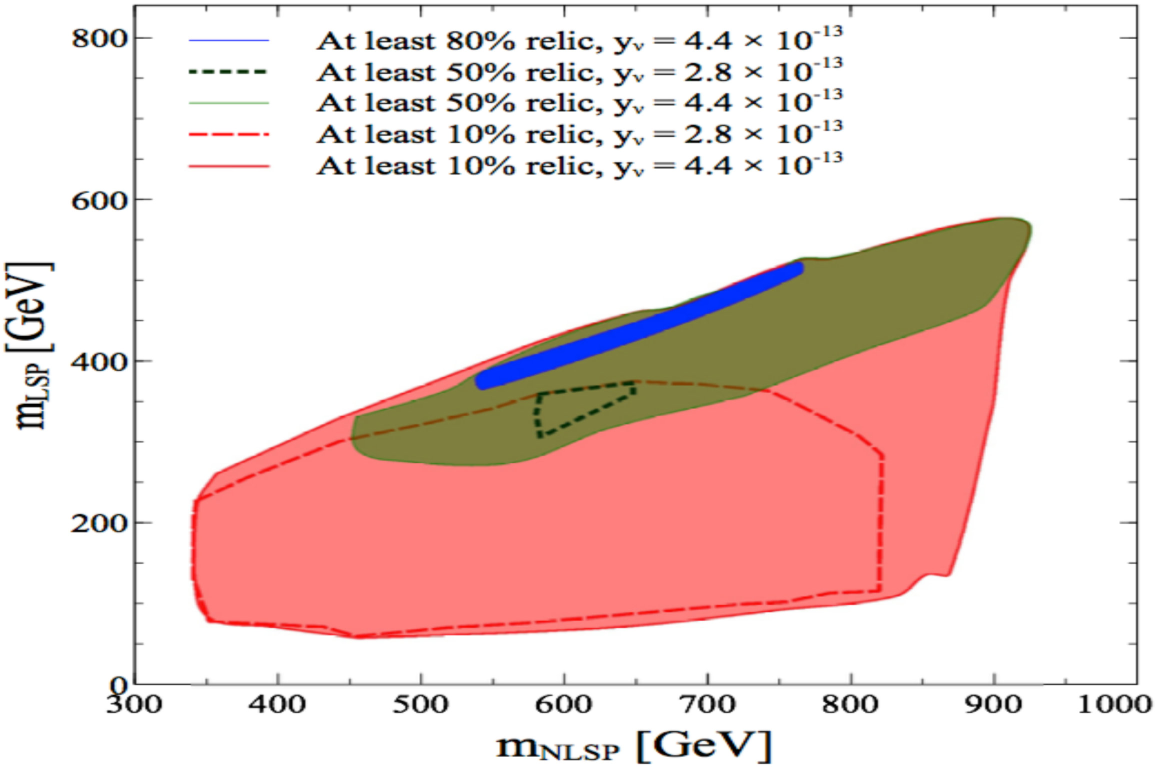
- If particle with lifetime > 0.1s decays can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
    - Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)
- Alteration of n/p ratio - for example . $\pi^- + p \rightarrow \pi^0 + n$
  - -> overproduction He^4
- Hadrodissociation of He^4 causes overproduction of D
  - $n+He^4$ -> 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



Allowed region

- After all constraints – room for sneutrinoR DM (even in CMSSM)
- Can constitute dominant dark matter component



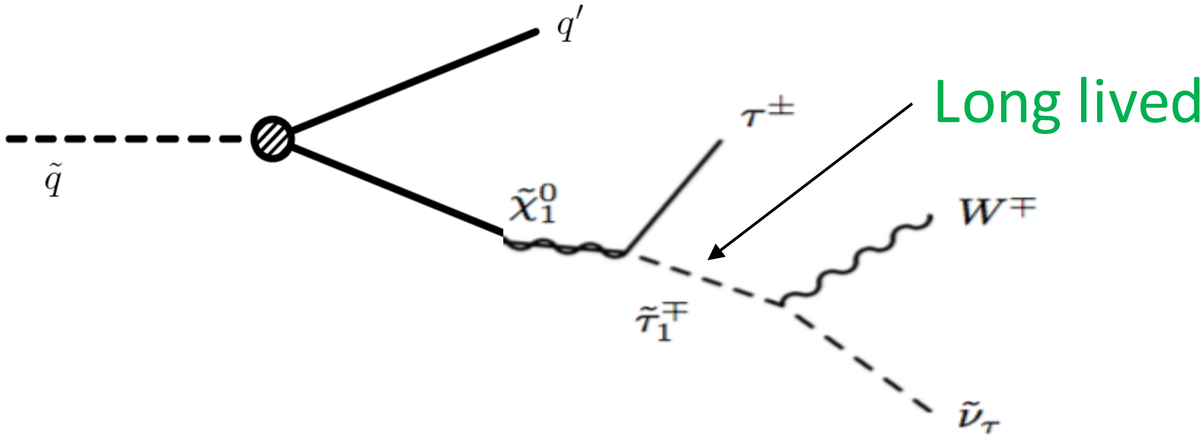
Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

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→ 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, Mukhopadyhyay, 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)

- $p_T^{\mu_{1,2}} > 200$ GeV, $|y(\mu_{1,2})| < 2.4$,
- $p_T^{j_{1,2}} > 200$ GeV, $|\eta(j_{1,2})| < 5.0$,
- $\sum |p_T^{vis.}| > 1000$ GeV,
- $\Delta R(\mu_1, \mu_2) > 0.2$,
- $\Delta R(j, j) > 0.4$,
- $\Delta R(\mu, j) > 0.4$,
- $M_{\mu_1,\mu_2} > 1000$ GeV,

Charged tracks from cascades (2)

Benchmark point	$\mathcal{L}$ for 5σ [fb^{-1}]	N_S	N_B	N_S/N_B
357 GeV	9.1	25	0.35	72
400 GeV	2.5	25	0.09	265
442 GeV	68.5	27	2.7	10
600 GeV	1100	48	43	1.1

- Fairly easy to discover if mass stau < 400 GeV
- Luminosity 1ab^{-1} can probe mass ~580GeV
- Dependence on mass of squarks

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

$\mathcal{L} = 3000 \text{ fb}^{-1}$

Cut	Benchmark	N_S	N_B	N_S/N_B	$\mathcal{S}$
$\Delta R(\mu\mu) > 0.4$	357 GeV	1543		0.44	21.8
$\beta < 0.95$	400 GeV	1014	3481	0.29	15.1
$p_T^{\mu_{1,2}} > 70\text{GeV}$	442 GeV	715		0.21	11.0
$\lvert y(\mu_{1,2})\rvert < 2.5$	600 GeV	211		0.06	3.5

Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

Pair production

- No model dependence – only mass of stau
- Smaller cross section (EW only)
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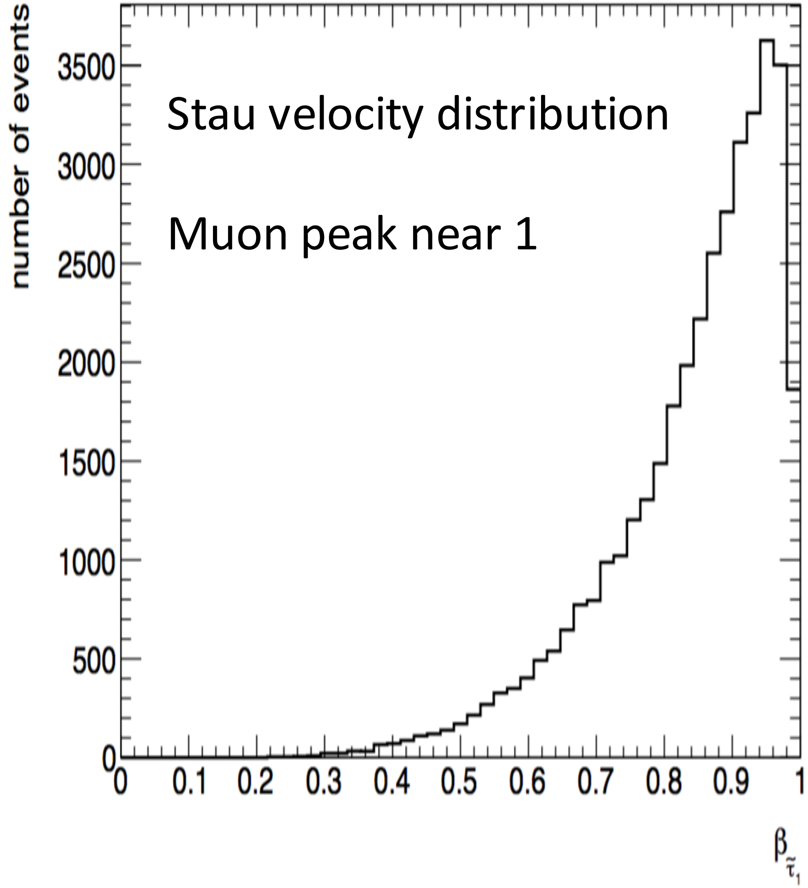
- Best cuts – close to current ATL
- Lower reach than previous chan

Cut	Benchmark	
$\Delta R(\mu\mu) > 0.4$	357 GeV	1
$\beta < 0.95$	400 GeV	1
$p_T^{\mu_{1,2}} > 70\text{GeV}$	442 GeV	
$\lvert y(\mu_{1,2})\rvert < 2.5$	600 GeV	



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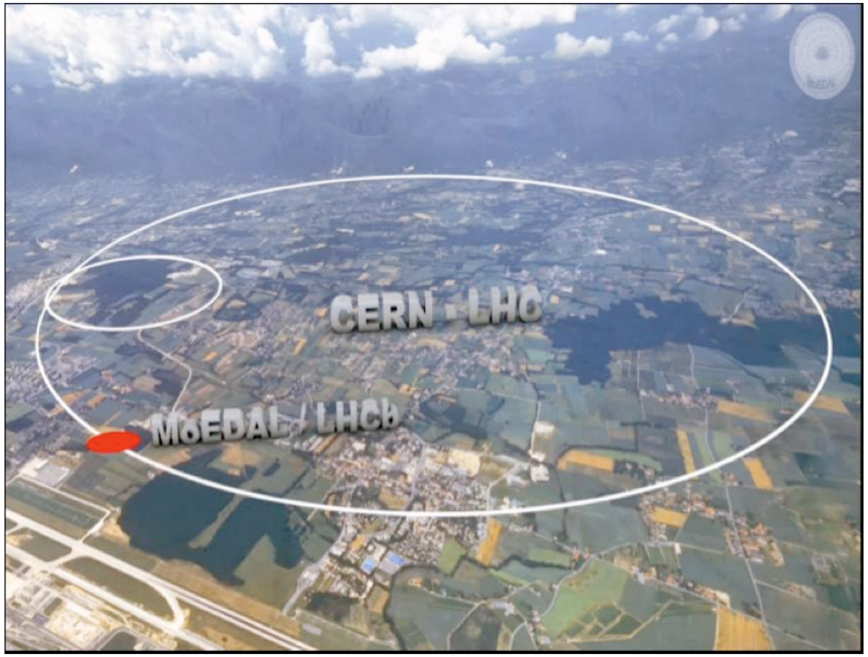
MoEDAL detector



- 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 β<0.2

B. Acharya et al, 1405.7662

Benchmark point	Cascade	Pair
357 GeV	45	2.5
400 GeV	296	1.5
442 GeV	24	1.1
600 GeV	6	0.5

Number of $\tilde{\tau}_1$'s with $\beta \leq 0.2$ with $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$

Banerjee, et al, 1603.08834

CONCLUSION

Sneutrino viable very weakly interacting DM candidate in supersymmetry

BBN constraints are important

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