DMAstroLHC

Non-standard SUSY DM

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LAPTH Annecy-le-Vieux

Is SUSY alive and Well, IFT - Madrid, 28/09/2016

Outline

- Introduction
- RH Sneutrino in MSSM+RHneutrino
- Singlino in nMSSM
- Conclusion

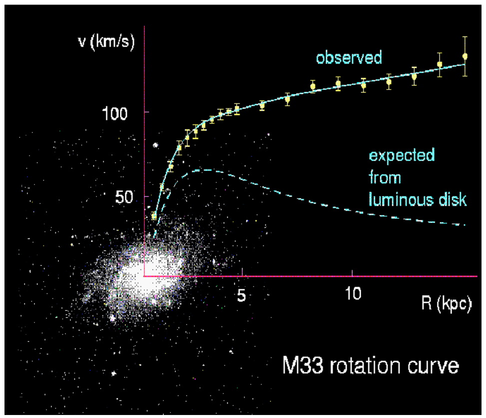
Introduction

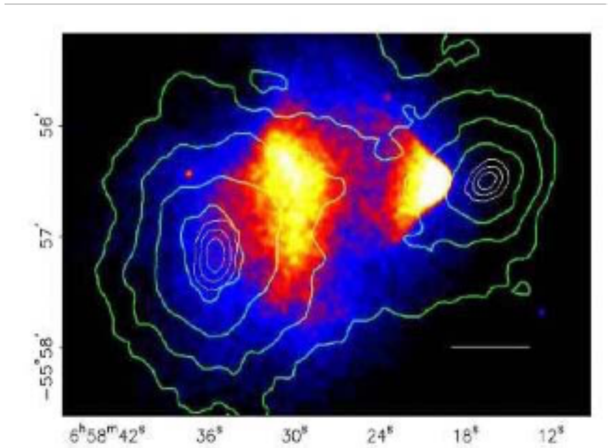
Strong evidence for dark matter from astrophysical and cosmological observations

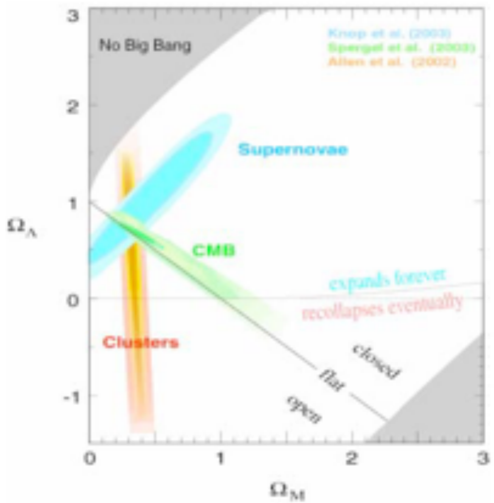
Motivation for new particles beyond standard model

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

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





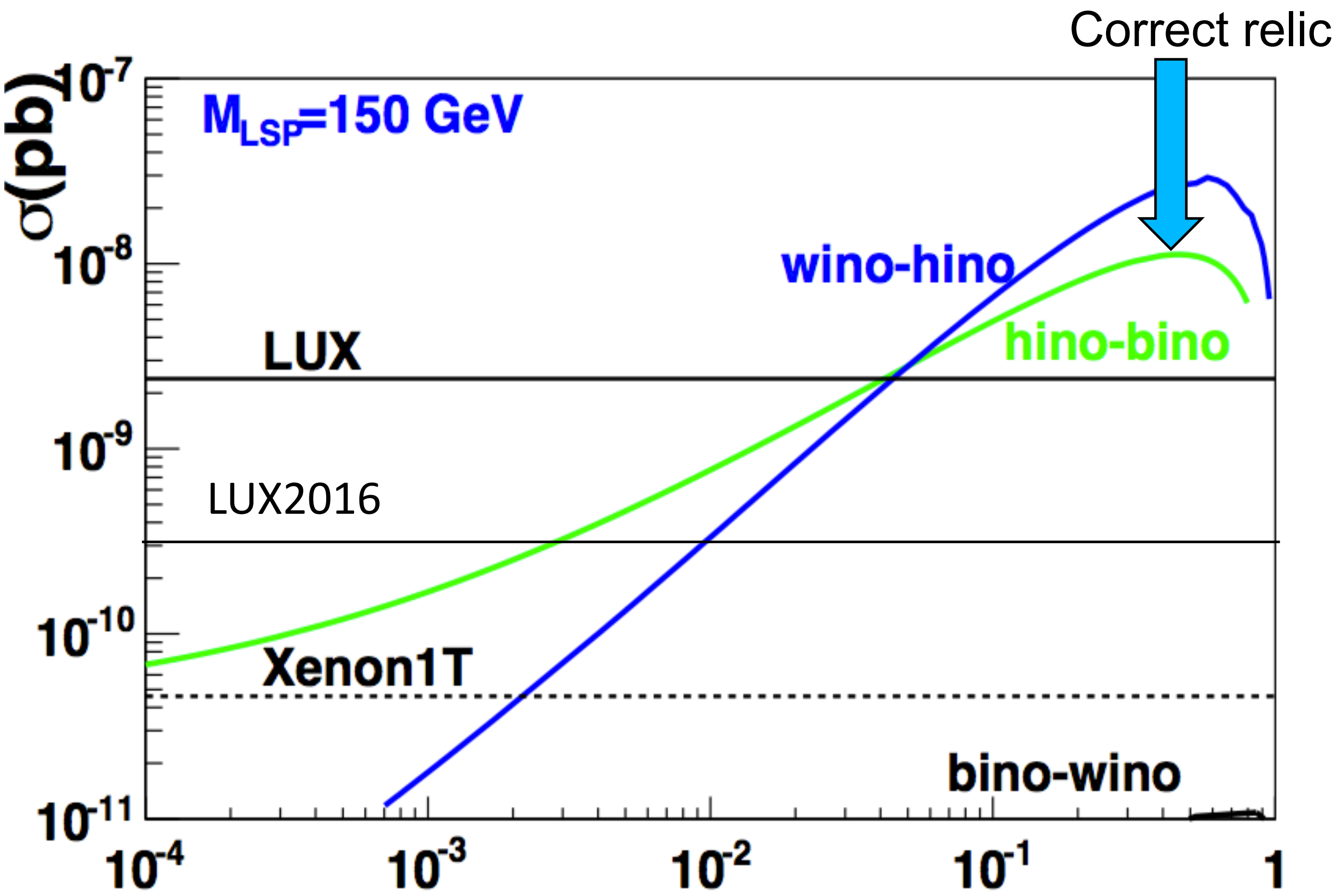


- Supersymmetry one of best motivated extension of SM
- No sign at LHC → does that mean that most popular WIMP model (neutralino) is ruled out?
- Strong constraints from LHC + direct detection especially if below TeV scale
- Properties of neutralino DM : strong dependence on its nature : partner of gauge 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

Direct detection

- Coupling of LSP to Higgs maximal for mixed gaugino/higgsino

$$g_{h\chi\chi} = g(\mathcal{N}_{\chi 2} - t_W \mathcal{N}_{\chi 1})(\mathcal{N}_{\chi 3} \sin\alpha + \mathcal{N}_{\chi 4} \cos\alpha) \cdot$$

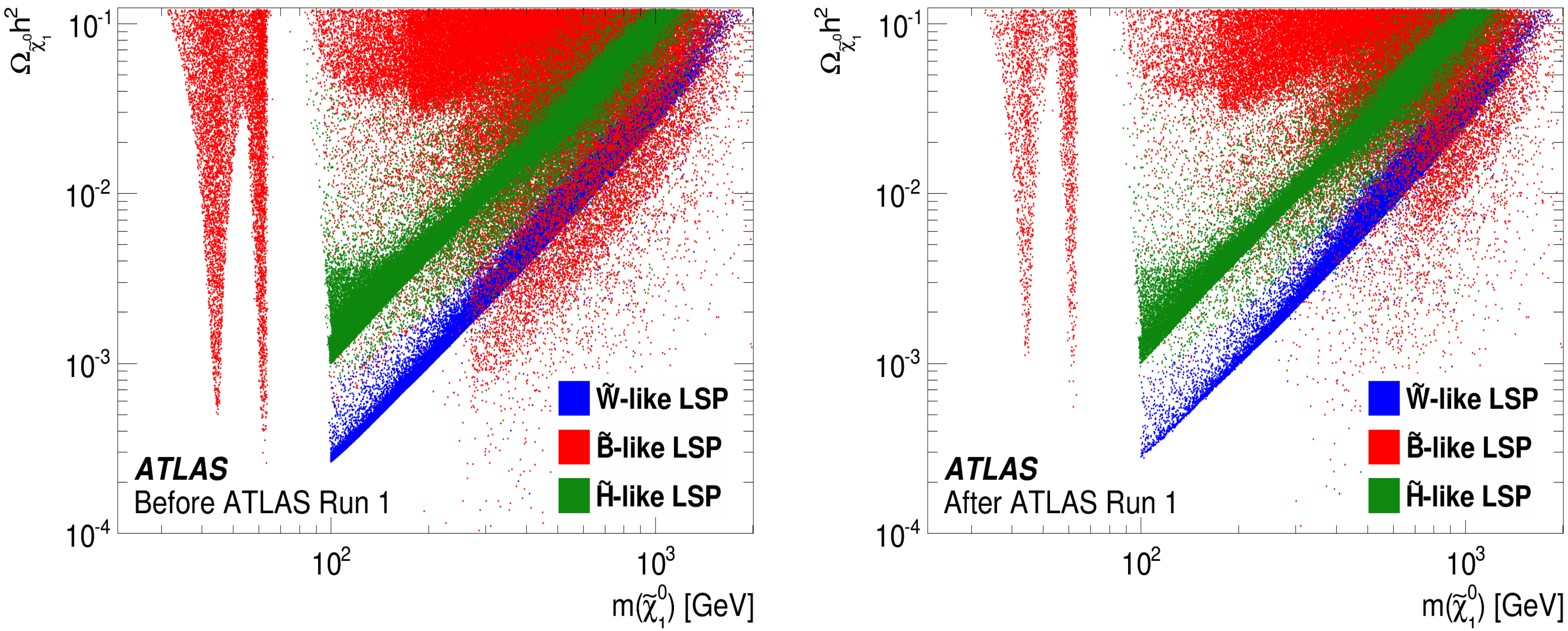


LUX rules out light higgsino/bino compatible with relic density

Bino/wino escape detection

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, long-lived staus) (Arina, Cabrera, 1311.6549, Arina et al, 1503.02960, GB et al, 1505.06243)
- Will rather consider the case where sneutrino not thermalized – feebly interacting

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

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

- For hierarchical neutrino masses

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

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

$$\sum_{i=1}^{3} m_i < 0.23 \text{ eV at } 95\% \text{ CL;}$$

$$(y_\nu^H \sin\beta)_{\max} \simeq 4.4 \times 10^{-13}$$

(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

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

- 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

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

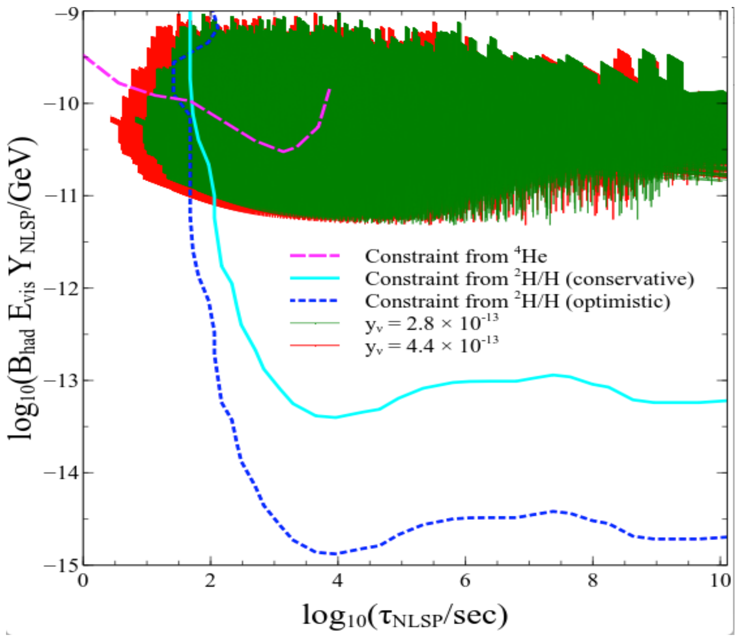
- … and the chain continues with production of heavier elements
- Relationship between expansion rate of Universe (relate to total matter density) and density of p and n (baryonic matter density) determine abundance of light elements

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

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

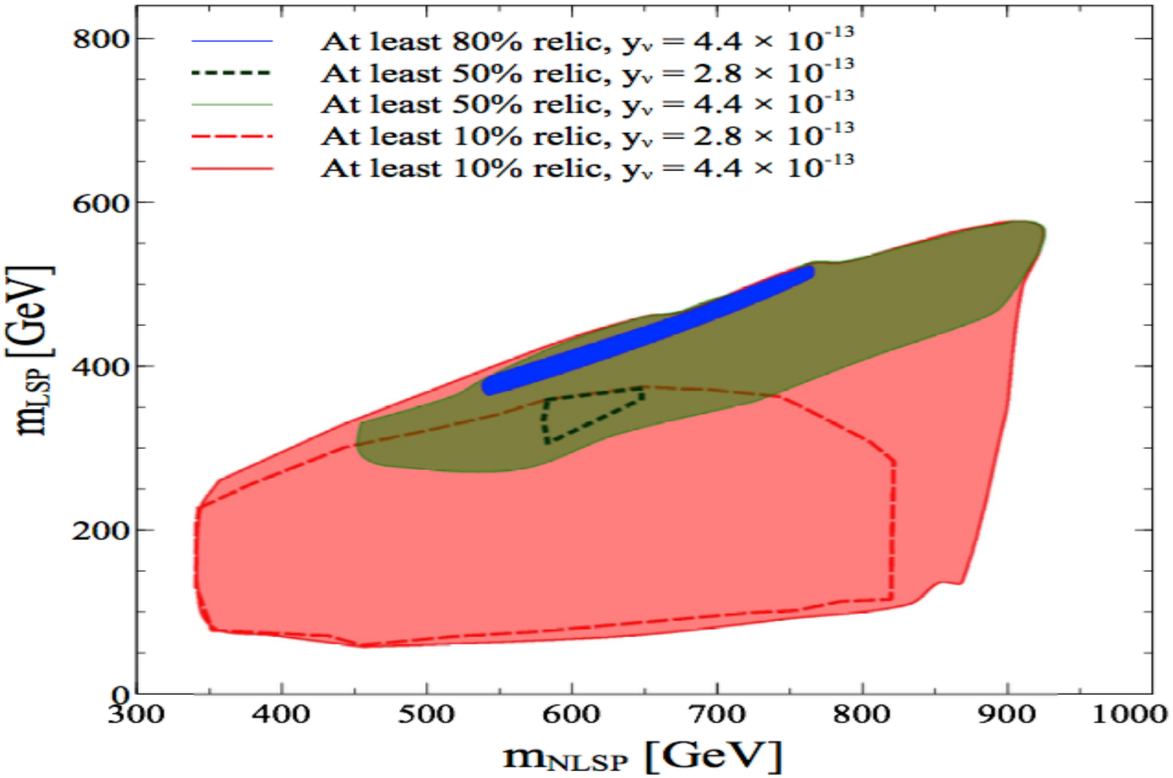
- If particle with lifetime > 0.1s decays can cause non-thermal nuclear reaction during or after BBN – spoiling predictions – in particular if new particle has hadronic decay modes
    - Kawasaki, Kohri, Moroi, PRD71, 083502 (2005)
- Alteration of n/p ratio - for example
    - -> overproduction He^4
- Hadrodissociation of He^4 causes overproduction of D
    - $n+He^4 \rightarrow He^3+D,\ 2D+n,\ D+p+n$

• Key elements : B_{had}, E_{vis} (net energy carried away by hadrons), Y_{NLSP} : yield



Allowed region

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



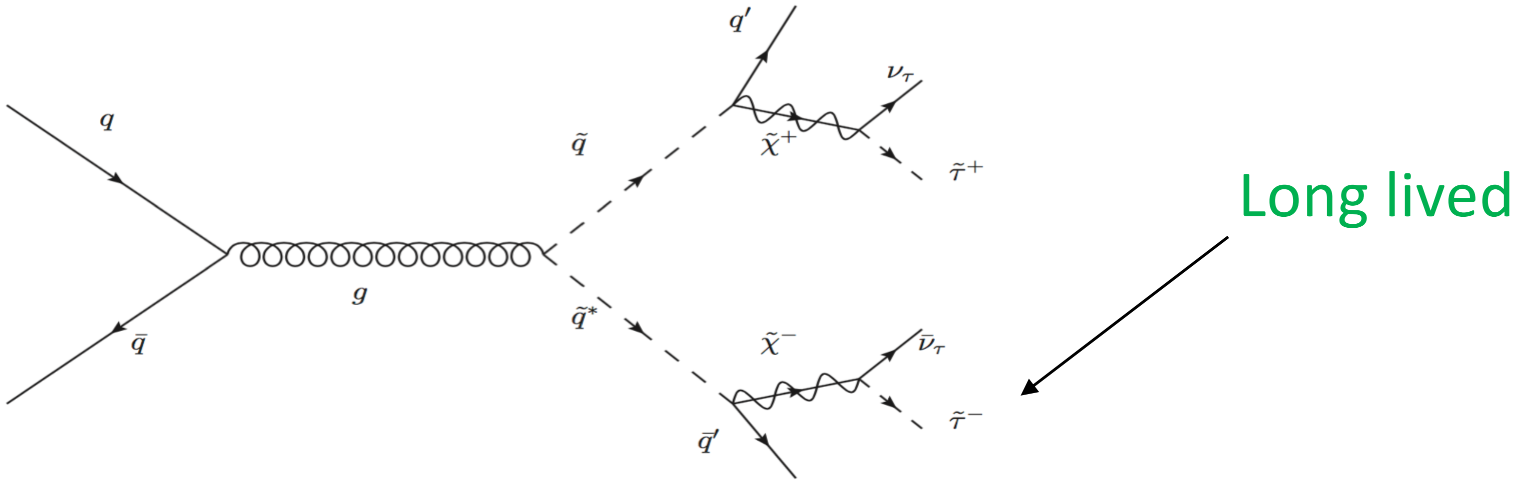
Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

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)

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

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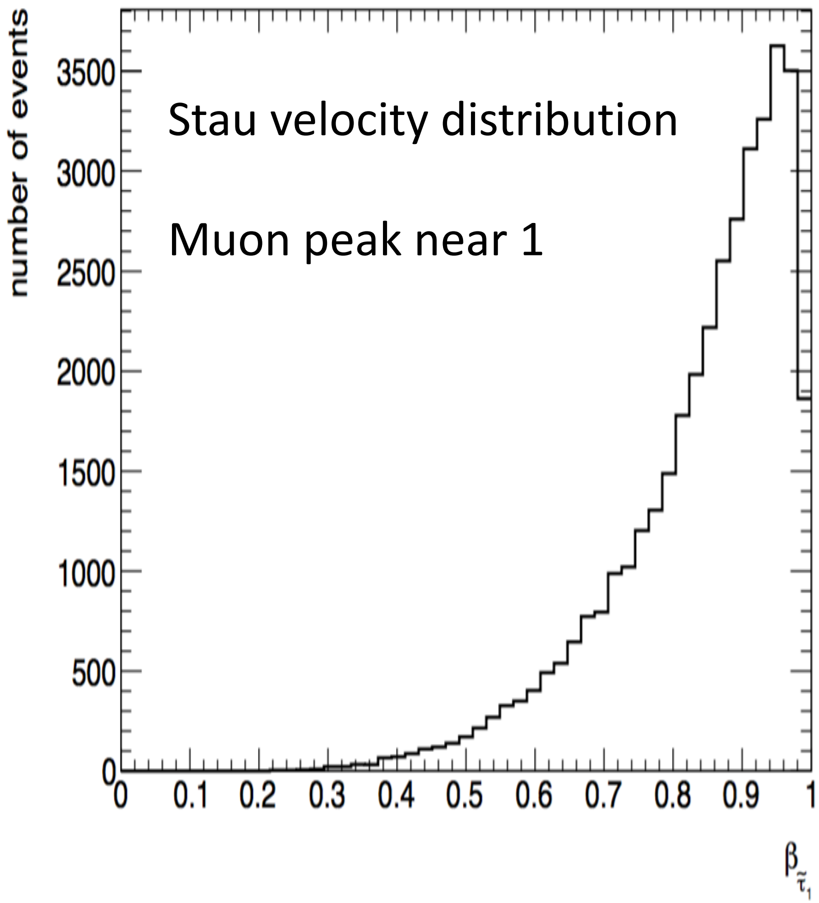

Cut	Benchmark	
$\Delta R(\mu\mu) > 0.4$	357 GeV	1
$\beta < 0.95$	400 GeV	1
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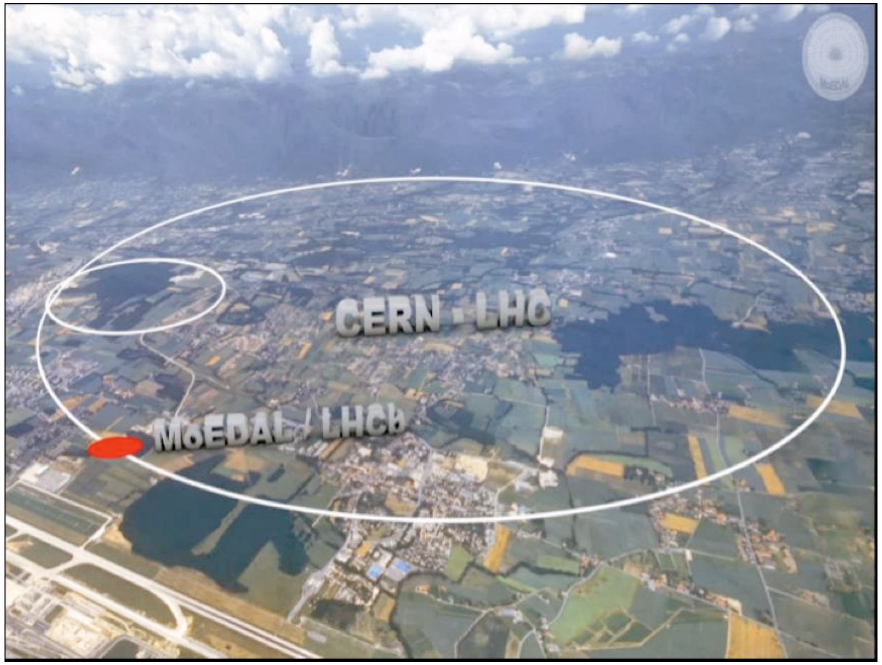
Banerjee, GB, Mukhopadyhyay, Serpico, 1603.08834

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 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

Banerjee, et al, 1603.08834

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

Singlino in nMSSM

Motivation for singlet extensions of MSSM : μ problem + Higgs mass

Most studied : NMSSM with Z_3 symmetry

Discrete symmetry broken in early universe and domain walls are produced -- Can be cosmologically dangerous unless disappear before nucleosynthesis

A solution to domain wall and stability : impose discrete R-symmetry (all fields flip sign) on full theory including non-renormalizable terms.

Tadpole terms generated at higher loop order $\delta W = \xi_F S\,, \quad \delta V = \xi_S (S + S^*)$

$\xi_F \lesssim M^2_{\rm susy}$ and $\xi_S \lesssim M^3_{\rm susy}$

nMSSM : the new minimal supersymmetric standard model with global discrete R-symmetry and without cubic self interactions

Panagiotakopoulos, Tamvakis, PLB469 (1999) 145.

Abel et al, NPB392 (1993) 83

The model : nMSSM

Field content : MSSM + Singlet superfield

Superpotential

$$W_{\rm nMSSM} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \xi_F\widehat{S} + h_u\widehat{Q}\widehat{U}^c\widehat{H}_u + h_d\widehat{Q}\widehat{D}^c\widehat{H}_d + h_e\widehat{L}\widehat{E}^c\widehat{H}_d$$

Soft susy breaking potential

$$\begin{aligned} V_{\rm nMSSM} = & \; m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + (\lambda A_\lambda H_u H_d S + \xi_S S + \text{h.c.}) \\ & + m_Q^2|Q^2| + m_U^2|U_R^2| + m_D^2|D_R^2| + m_L^2|L^2| + m_E^2|E_R^2| \\ & + (h_u A_u Q H_u U_R^c - h_d A_d Q H_d D_R^c - h_e A_e L H_d E_R^c + \text{h.c.}) \\ & + M_1 \widetilde{B}\,\widetilde{B} + M_2 \widetilde{W}\,\widetilde{W} + M_3 \widetilde{g}\,\widetilde{g}\,. \end{aligned}$$

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The model : nMSSM

Field content : MSSM + Singlet superfield

Superpotential

NMSSM
κS³

$$W_{\text{nMSSM}} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \xi_F\widehat{S} + h_u\widehat{Q}\widehat{U}^c\widehat{H}_u + h_d\widehat{Q}\widehat{D}^c\widehat{H}_d + h_e\widehat{L}\widehat{E}^c\widehat{H}_d$$

Soft susy breaking potential

NMSSM:
κA$_\kappa$S³

$$\begin{aligned} V_{\text{nMSSM}} = & \; m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + (\lambda A_\lambda H_u H_d S + \xi_S S + \text{h.c.}) \\ & + m_Q^2|Q^2| + m_U^2|U_R^2| + m_D^2|D_R^2| + m_L^2|L^2| + m_E^2|E_R^2| \\ & + (h_u A_u Q H_u U_R^c - h_d A_d Q H_d D_R^c - h_e A_e L H_d E_R^c + \text{h.c.}) \\ & + M_1 \widetilde{B}\,\widetilde{B} + M_2 \widetilde{W}\,\widetilde{W} + M_3 \widetilde{g}\,\widetilde{g}\,. \end{aligned}$$

Particles : 3 CP even neutral + 2CP odd + charged Higgs

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Neutralino sector

Neutralino mass $\psi^0 = (-i\lambda_1, -i\lambda_2^3, \psi_d^0, \psi_u^0, \psi_S)$

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 0 \end{pmatrix}$$

Singlino mass (lower bound on μ from chargino + upper bound on λ from perturbativity) → upper bound on singlino mass ~ 75GeV

$$m_{\widetilde{S}} \simeq \frac{\mu \lambda^2 v^2}{\mu^2 + \lambda^2 v^2} \sin 2\beta \ .$$

Light singlino – different DM phenomenology than MSSM

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Scan and constraints

Semi-universal nMSSM

$$m_0,\ M_{1/2},\ A_0,\ \mu,\ \tan\beta,\ \lambda,\ \xi_F,\ \xi_S,\ A_\lambda$$

Scan method : MCMC in NMSSMTools tuned for LHC run2

Basic constraints (from NMSSMTools)

- Theory (no Landau pole below GUT, no unphys min of potential)
- Invisible Z< 0.5MeV
- B physics (bsg, bsm,btaunu….)
- LEP+Tevatron (sparticles and Higgs)
- At least one Higgs 125.1+/-3 GeV
- Chi2 fit to Higgs couplings

Upper bound on relic density < 0.131

Upper bound on direct detection from LUX (rescaled)

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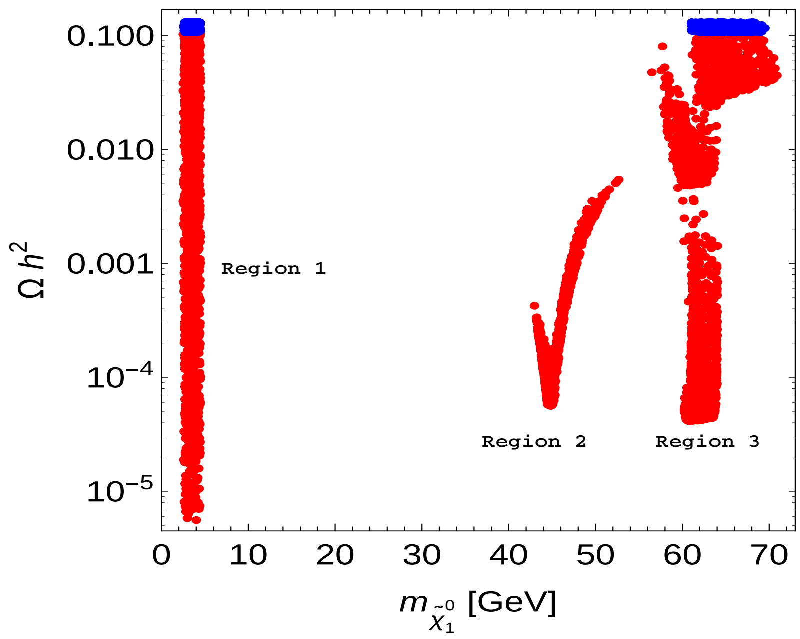
Results

Distinct regions for singlino mass



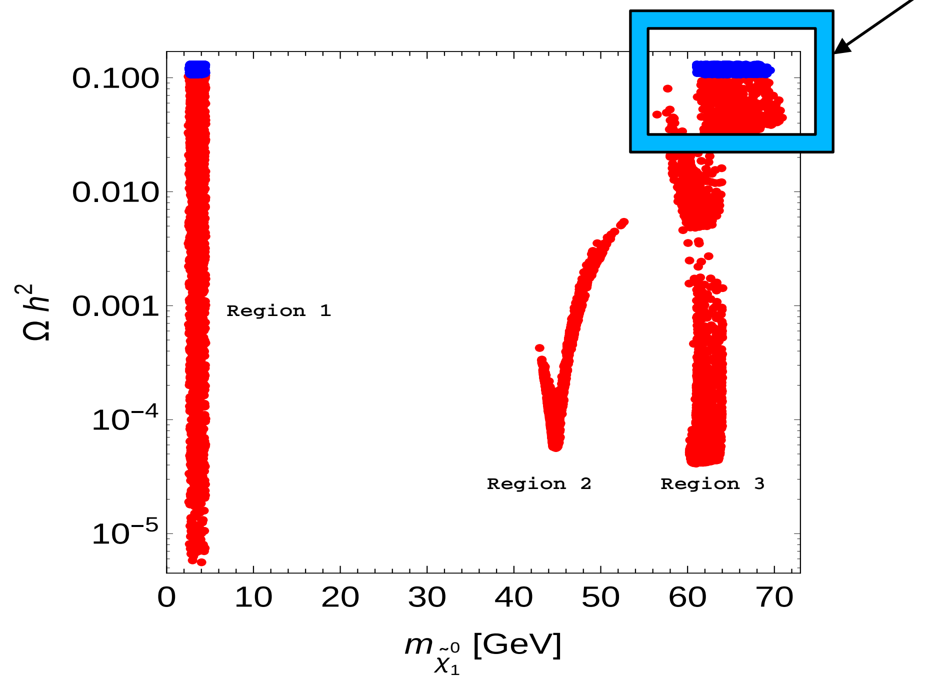
All have small μ

Subregions corresponding to different $m_0, m_{1/2}$ ….

Results

Distinct regions for singlino mass

This region always has light gluinos, ruled out by LHC Run 1



All have small μ

Subregions corresponding to different $m_0, m_{1/2}$ ….

Light singlino

Region	1A		1B	
$\tan\beta$	6.6	10	6	8
λ	0.33	0.53	0.49	0.52
μ	240	400	350	430
m_0	0	1080	4040	4800
$M_{1/2}$	630	1200	280	440
A_0	-1700	50	6700	7900
A_λ	1400	6000	7000	7900
ξ_F	10	100	$-1.5\cdot10^4$	$-1.4\cdot10^4$
ξ_S	$-6\cdot10^4$	$2\cdot10^4$	$-1.9\cdot10^7$	$-1.6\cdot10^7$
M_1	270	520	110	190
M_2	500	950	200	340
$m_{\tilde{q}}$	1300	2400	> 3000	
$m_{\tilde{t}_1}$	350	1300	1050	1900
$m_{\tilde{l}}$	180	1100	> 3000	
$m_{\tilde{g}}$	1450	2600	780	1250

Impact of LHC – Run1

SmodelS : Tool to decompose a given SUSY scenario into simplified models topologies and compare those with exclusions of ATLAS and CMS (assumptions on sparticle decays can be much different than those used for SMS searches)

Kraml, Kulkarni, Laa, Lessa et al, 1312.4175

Input SLHA file, spectrum + decay + production cross sections,

nllfast for production of coloured sparticles

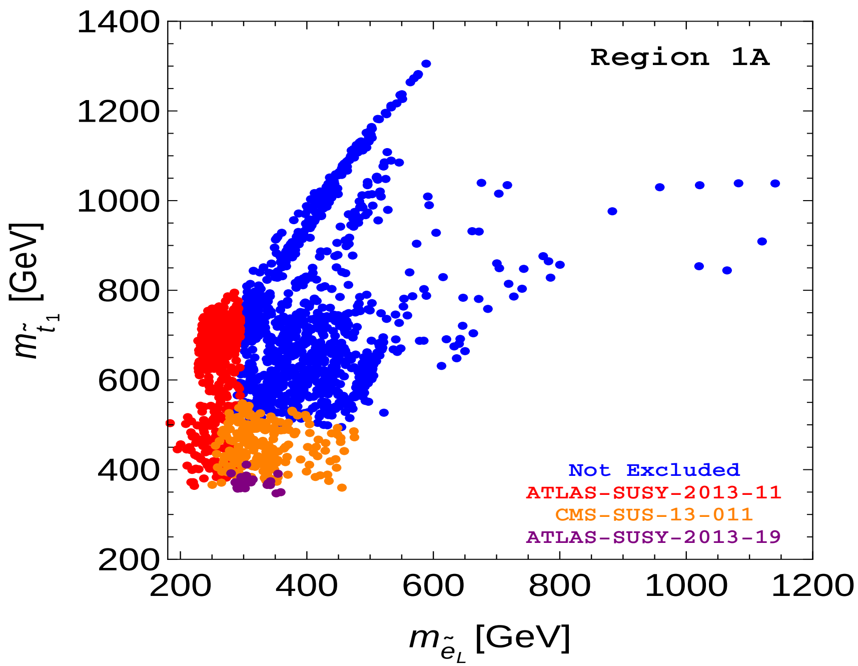
MadAnalysis5 Public data base : more general approach to recast limits set by ATLAS and CMS in a generic model, a selection of experimental searches implemented and validated

Useful to constrain gluinos up to 1.1TeV which decay through heavier neutralinos and charginos

Region 1 : light singlino

Singlino and a_1 mass are linked (consequence of relic density constraint) $|m_{a1} - 2m_\chi| <\sim 1.5$ GeV

Singlino light and weakly coupled → most decay of sparticles go preferably through heavier neutralinos (still constrain gluino up to 1.1TeV)



SmodelS

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Prospects for LHC Run2

Extend the reach in stop

best channels: $b\chi^+$, tZ+MET, th+MET (from χ_2, χ_3)

Or gluinos or sleptons (need factor two improvement to nearly cover region 1A)

or EW-ino (channel χ_2->$Z\chi_1$ and χ+->$W\chi_1$ are open)

Non MSSM signatures a_1 (5-10GeV) and h_1 (30-75 GeV)

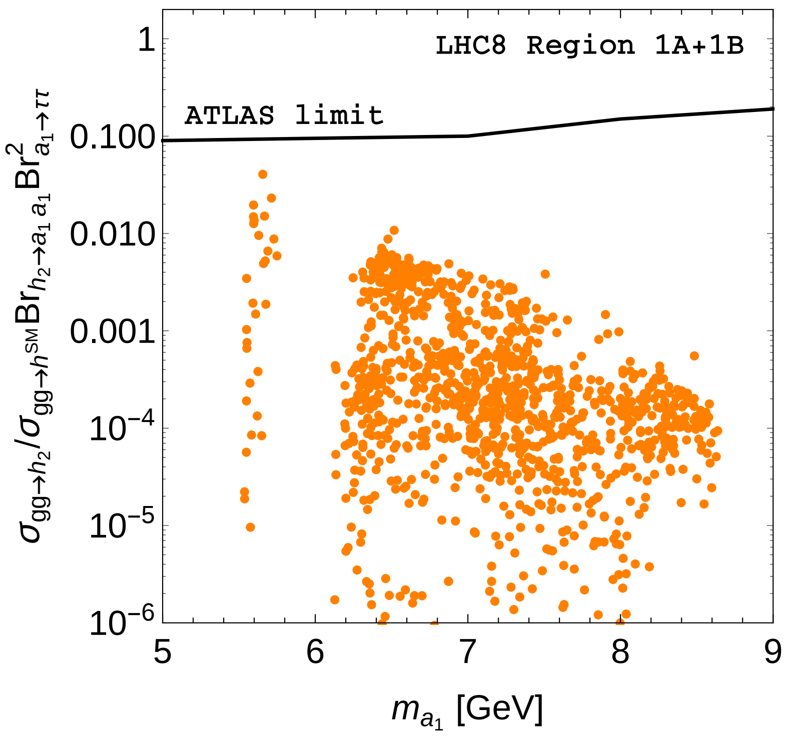
h_2->h_1h_1 -> 4b (or $2\tau 2b$)

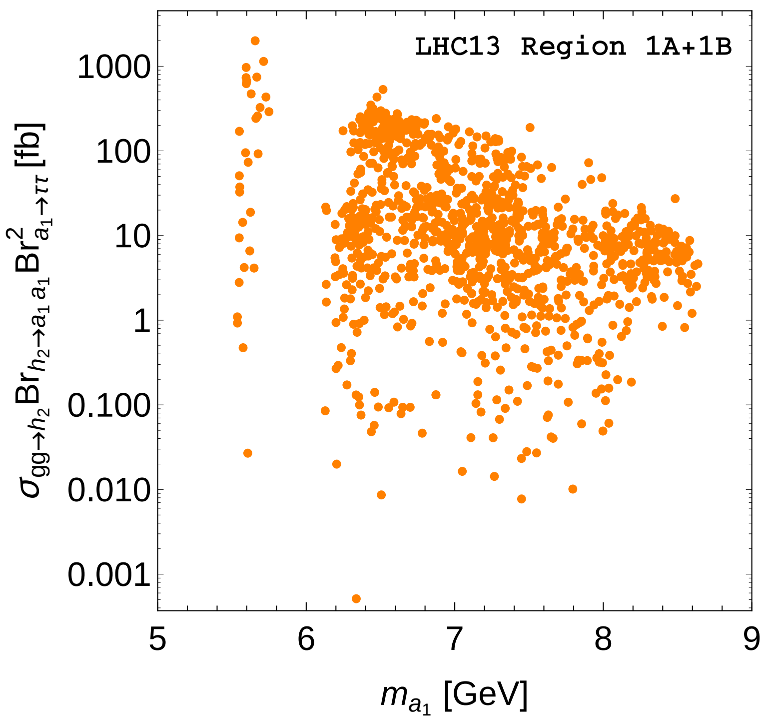
or h_2->a_1a_1

Masses	$m_{h_1} = 37.0$ $m_{a_1} = 6.8$
$\sigma^{13\text{ TeV}}$ [pb]	$\sigma(gg \to h_2) = 41.5$ $\sigma(gg \to h_1) = 13.0$ $\sigma(gg \to a_1) = 242.8$
$\text{Br}(h_2)$	$\text{Br}(h_2 \to a_1 a_1)$=8%
$\text{Br}(h_1)$	$\text{Br}(h_1 \to b\bar{b})$=85% $\text{Br}(h_1 \to \tau\tau)$ =7% $\text{Br}(h_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$=7%
$\text{Br}(a_1)$	$\text{Br}(a_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$=73% $\text{Br}(a_1 \to \tau\tau)$=25%

Prospects for LHC Run2

$h_2 \to a_1 a_1 \to 4\tau$ (or $2\tau 2\mu$)





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CONCLUSION

Neutralino in MSSM is somewhat under pressure as a dominant DM candidate

Sneutrino viable very weakly interacting DM candidate in supersymmetry although BBN constraints are important

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

In general non-standard candidates can have quite different specific signatures

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,