Light LSP in PMSSM/NMSSM

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New directions for SUSY searches with the Run-3 data, 15-16 November 2021.

- Introduction.

- Low mass ($m_{LSP} < m_{h_{SM}}$) DM in SUSY.

1 $\tilde{\chi}_1^0$ LSP: pMSSM, NMSSM

2 $\tilde{\nu}_R$: cMSSM,pMSSM,NMSSM (work by others)

- If time is left I want to share some thoughts on Heavy Higgs with emphasis on electro weakino final state.

Most of us grew up in the period where SUSY was the 'standard BSM' and the Lightest Supersymmetric Particle (LSP) was the most attractive, Weakly Interacting Massive Particle as the candidate for the DM.

This audience does not require to be reminded of the reasons why we found SUSY attractive.

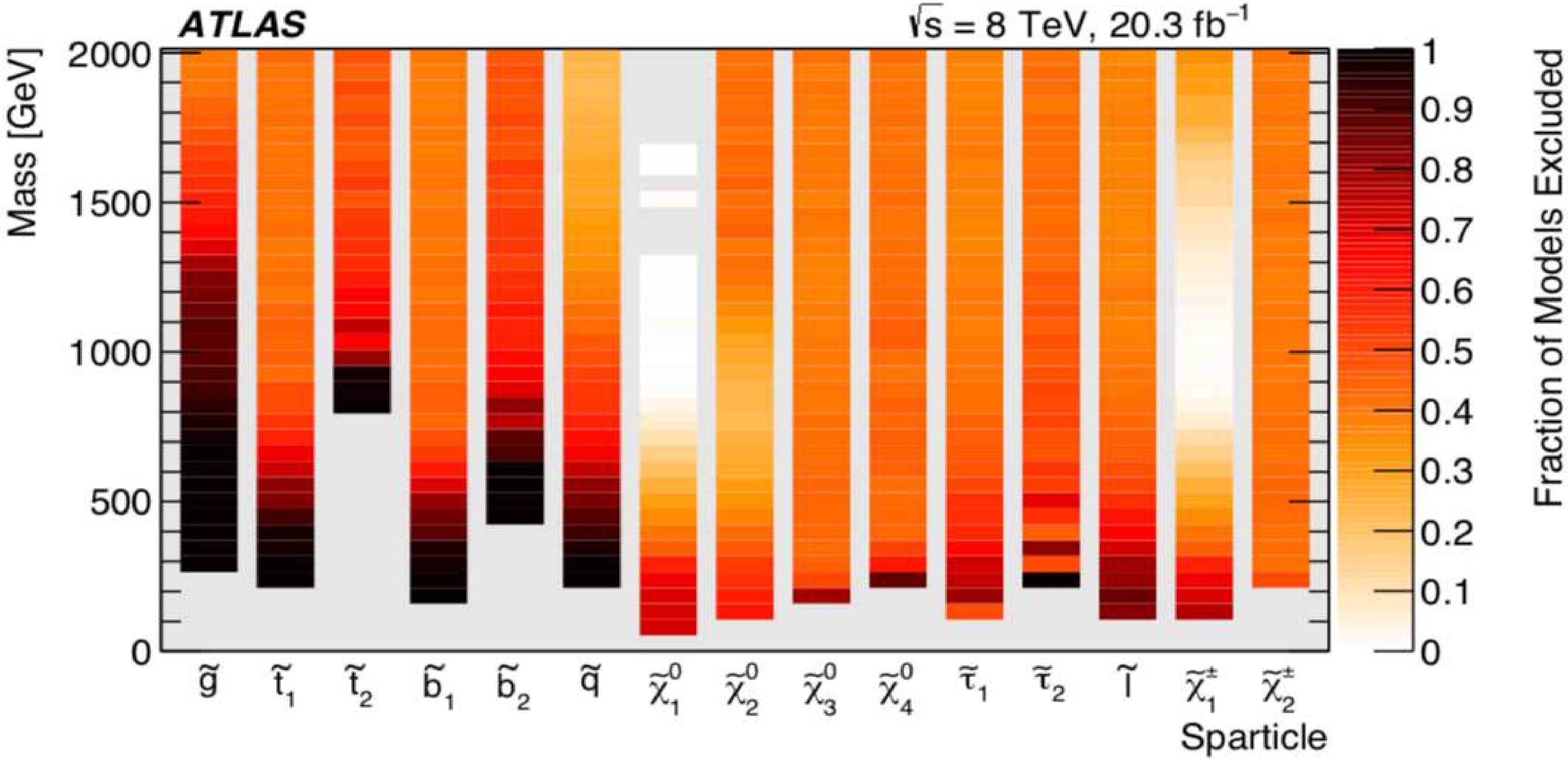
But LHC results have put the idea of 'natural' SUSY under stress and the XENON-1T results have put the WIMP paradigm under stress.

Experimental constraints on masses of various sparticles from the LHC

These translate into constraints on SUSY parameters.

Many are constrained to have very high values.

One that is still allowed to be 'light' is the lightest neutralino $\tilde{\chi}_1^0$



SMS analyses transferred to PMSSM models. A small mass $\tilde{\chi}_1^0$ still allowed in PMSSM!

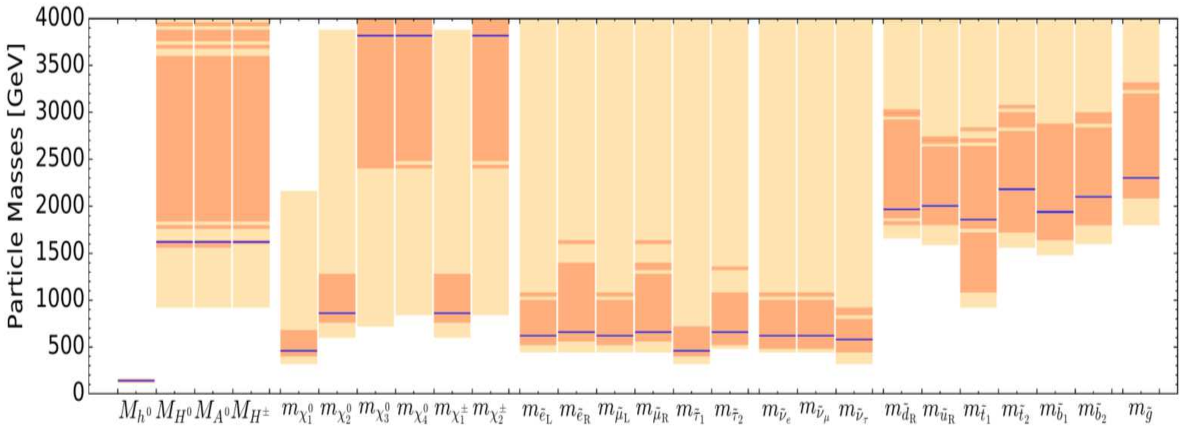
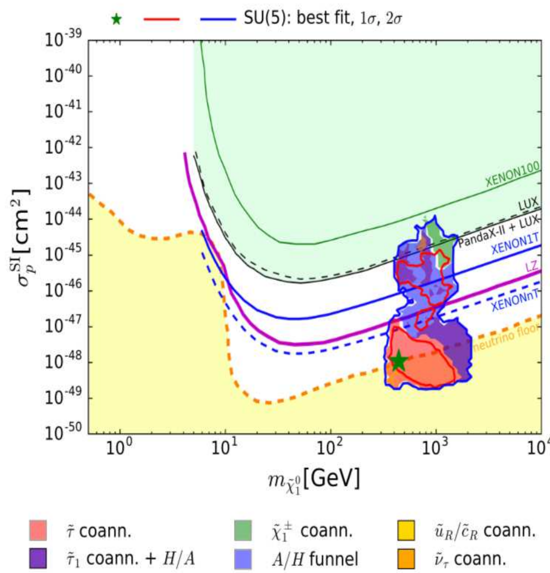


Fig. 12 The one-dimensional 68 and 95% CL ranges of masses we obtain for the current fit in the supersymmetric SU(5) model, shown in dark and light orange, respectively. The best-fit point is represented by blue lines



However, their best fit point LSP had a mass a few hundred GeV! (Bagnaschi et al, arXiv: 1610.10084)

In general LHC constraints on the Electro Weakinos are the weakest.

Run-II data 35fb^{-1} .

Higgsino upto 390 GeV ruled out. G. Pozzo et al. Phys. Lett. B, 789:582–591, 2019. arXiv: 1807.01476 : Pure Wino upto 650 GeV ruled out (CMS data).

Critically evaluate the case of a light LSP (in general light EW sector).

That is the subject of my talk: A light LSP $(2m_{\tilde{\chi}_1^0} < m_{h125})$

(one comment on Heavy SUSY Higgs decaying into Electroweakinos!)

The small mass of the observed Higgs 'smells' of SUSY

But its mass close to the upper limit of 132 GeV in MSSM implies larger values of M_S!

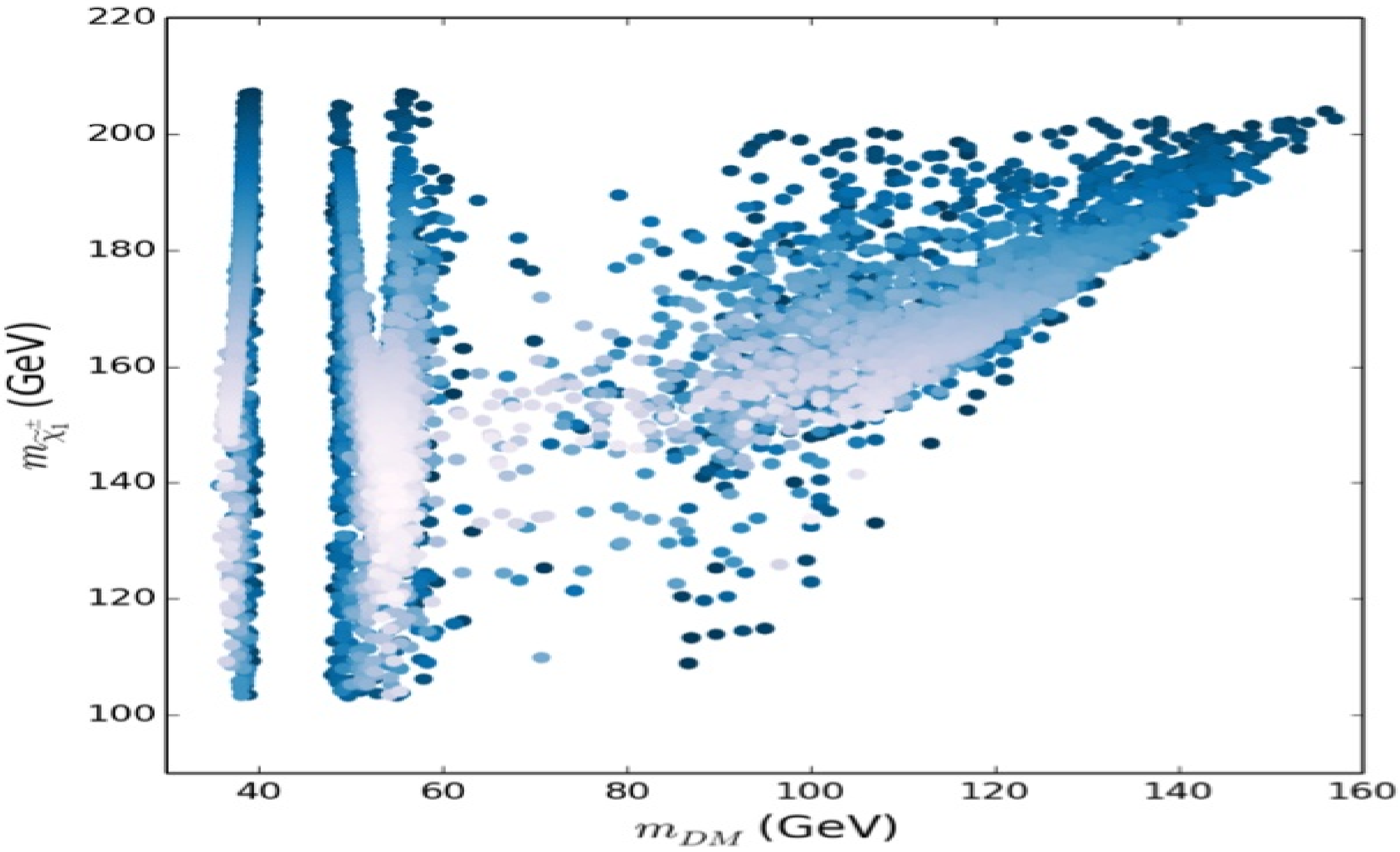
For many people this indicates 'unnaturalness' ! For example Dine: "Naturalness Under Stress"......

(On a lighter note: who are we to tell 'Nature' what is 'natural!')

More seriously, Tata et al suggested a new measure of 'naturalness' Δ_{EW} which can be small even if the Δ_{BG} is large.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri: a light LSP is 'natural' in this sense in the PMSSM.

1612.06333v1: M. van Beekveld, W. Beenakker, Caron, Peeters and Austri. light to dark, Δ varies from 4 to 10.



LSP: Two candidates: the sneutrino $\tilde{\nu}_L$ and the neutralino $\tilde{\chi}_1^0$.

$\tilde{\nu}_L$ has full strength gauge couplings to SM matter. A light $\tilde{\nu}_L$ can not be a good DM candidate and also ruled out by Direct Detection(DD) experiments.

The weakest LHC constraints from non observation are on the mass of the $\tilde{\chi}_1^0$.

Focus on $\tilde{\chi}_1^0$.

Not discussing light gravitino here.

"Status of low mass LSP in SUSY"

Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020), [arXiv:2010.11674 [hep-ph]] and references therein

Question to ask:

How light can a SUSY LSP candidate be and still be a viable DM candidate?

What is meant by that?

- It should not over close the Universe.(If we assume standard cosmology and hence thermal relic) (Will make some comments about non thermal case as well in the end)
- Should be allowed the Direct/Indirect detection constraints.

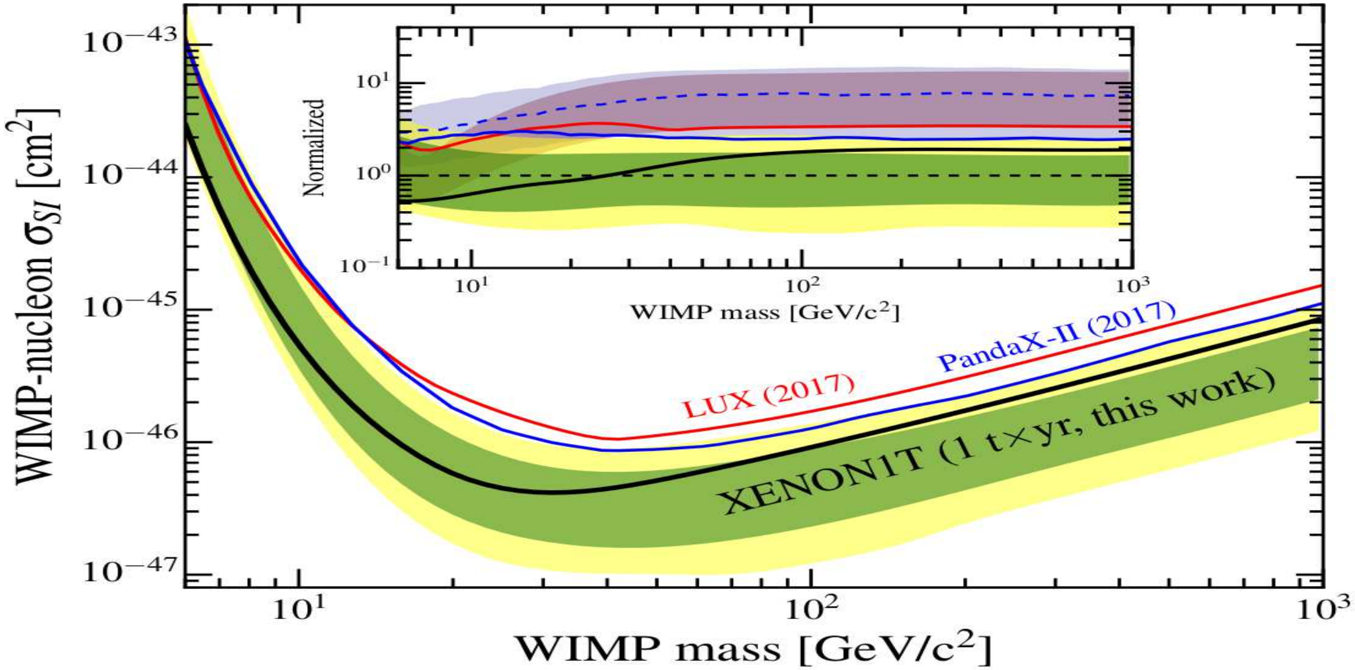
Planck measurements and the anisotropies tell us

$$\Omega_{DM}h^2 = 0.120 \pm 0.001$$

Major part of the discussion will talk about usual thermal relic.

I] There are some reported low mass LSP Direct Detection, but looks like that it is either due to experimental fluctuations OR not DM.
II] For Indirect detection: Lack of clarity due to uncertainties with astrophysics.

III] The current status of the best limits from Direct Detection, it is straining the WIMP paradigm!



The relic density calculations and also the DM detection cross-sections in a model will depend on the couplings of the DM with the SM particles!

In pMSSM the $\tilde{\chi}_1^0$ is a mixture of Higgsino and Gauginos .

For NMSSM it is a mixture of higgsinos and gauginos as well as a singlino. The scalars are also doublet-singlet mixtures.

For case of $\tilde{\nu}_R$ LSP additional Yukawa couplings may come into play.

The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with all the SM and (N)MSSM particles.

A Wino like or Higgsino like $\tilde{\chi}_1^0$ will have to be heavy to explain the observed relic. How a model can produce a wino like LSP is a different question.

A bino-like $\tilde{\chi}_1^0$ means too high a relic density unless additional annihilation possibilities exist because of smaller couplings!

t-channel light slepton OR a resonant annihilation via Higgs/A/Z. The Z exchange requires a nontrivial Higgsino fraction too in the neutralino! The so called 'well tempered neutralino'.

Note: Early days: In cMSSM the LEP constraint on $m_{\tilde{\chi}_1^\pm}$ and universal gaugino mass would rule out light $\tilde{\chi}_1^0$. So a light $\tilde{\chi}_1^0$ necessarily means non universal gaugino masses. This is what we advocated in 2000!

Till the DM detection experiments came in full swing the collider bounds dominated the story.

How low a mass can a viable DM candidate have in SUSY consistent with all the current exclusions? Can the future colliders probe these 'light' LSP's? Ie. can we rule out this region from collider experiments?Using phenomenology of the heavier electro weakinos.

Can models and observed relic density support a light SUSY DM particle if reported in either Direct or Indirect detection experiment? If yes what can the LHC (current,HL/LHC and HE/LHC) say about it?

Will discuss:

i) PMSSM : The weakest LHC constraints from nonobservation are on the mass of the $\tilde{\chi}_1^0$. The important parameters are μ, M_1, M_2 and $\tan\beta$. Radiative corrections bring in dependence on A_t, m_t. and even M_3. We will discuss this in the context of standard and nonstandard cosmology.

ii) NMSSM (Additional singlet higgs superfield) : In addition to above additional parameters related to this extra field. Additional light (pseudo)scalars. $\kappa, \lambda, A_\kappa, A_\lambda$.

iii) PMSSM + $\tilde{\nu}_R$

iv) NMSSM + $\tilde{\nu}_R$

Till the DM detection expts. came in full swing the collider bounds dominated the story.

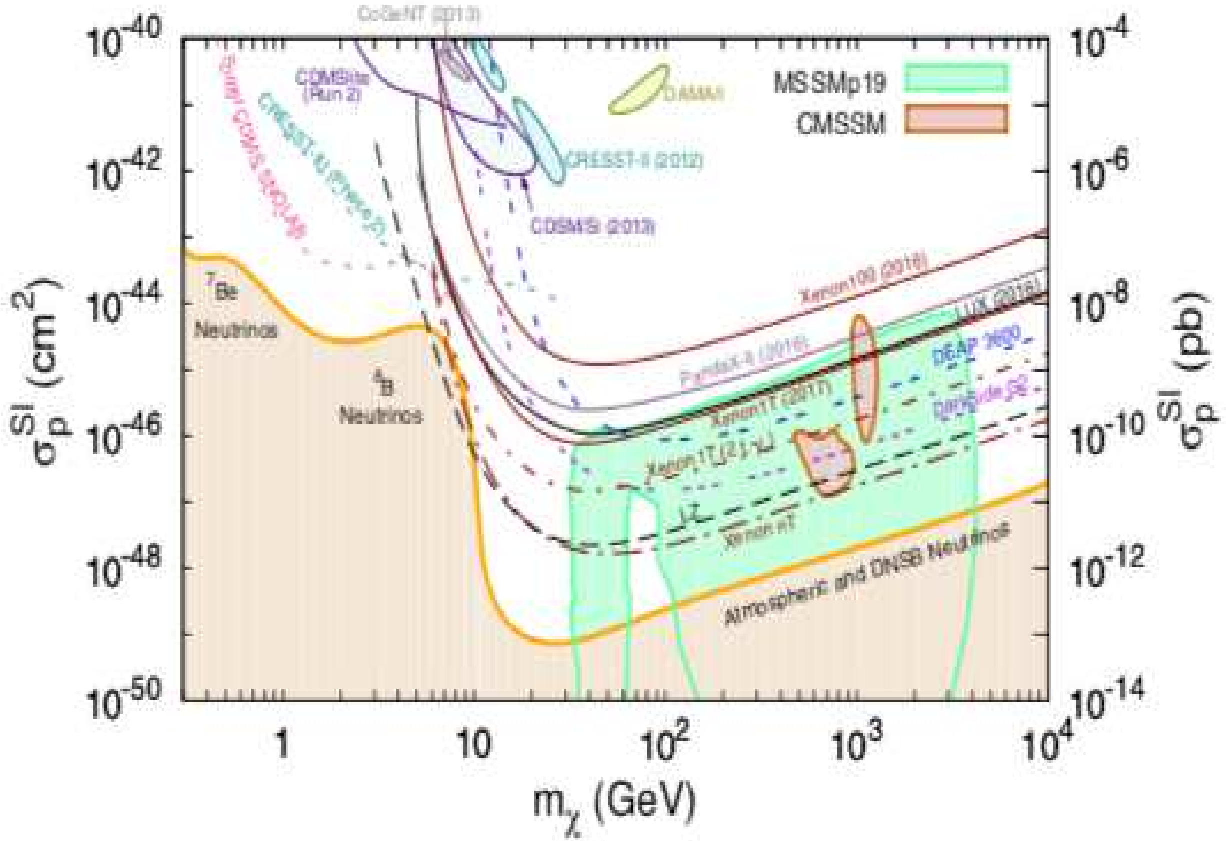
Early days:
In cMSSM the LEP constraint on $m_{\tilde{\chi}_1^\pm}$ and universal gaugino mass ruled out light $\tilde{\chi}_1^0$.So a light $\tilde{\chi}_1^0$ necessarily meant non universal gaugino masses. Hence focus moved to the pMSSM.

Before Xenon 1T and LHC results, older relic measurements:
Lower limit of 30 GeV on the mass of the $\tilde{\chi}_1^0$. L. Calibbi, T. Ota, Y. Takanishi, JHEP 07, 013 (2011); D.A. Vasquez, G. Belanger, C. Boehm, Phys. Rev. D 84, 095015 (2011)

Now we have precise determination of relic, strong constraints from Direct Detection as well as LEP/LHC measurements, **higgs detection** and precision calculations of the Higgs mass.

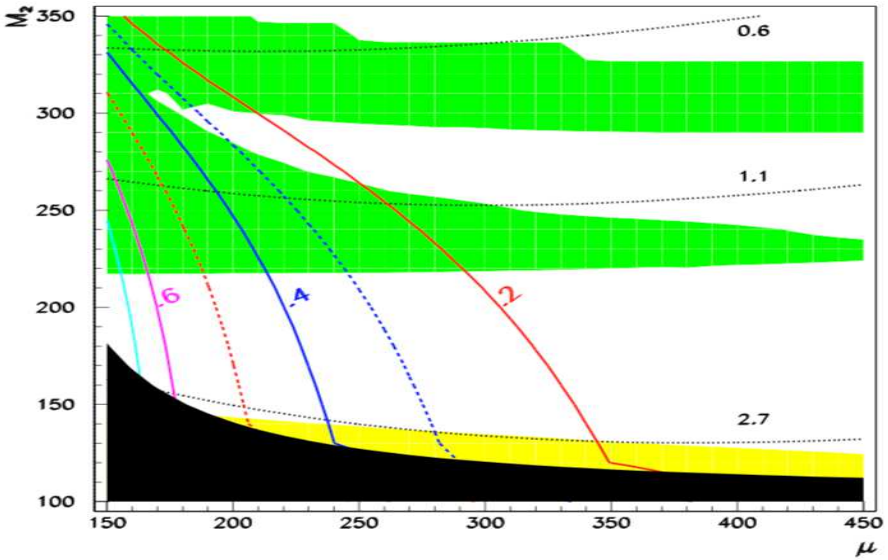
What is the situation now?

A summary from L. Roszkowski, E. M. Sessolo and S. Trojanowski,Rept. Prog. Phys. **81** (2018) no.6, 066201 1707.06277 which shows the regions of different reported low mass detections and relic predictions.



This is Pre Xenon-1T result showed earlier

For the Higgsino-Bino well tempered relic, h_{125} **can** have appreciable branching fraction into invisible neutralino pair. In fact this was the focus of our early papers! G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000)



Green : Relic < 0.1, White: $0.1 < $ relic < 0.3, yellow : relic > 0.3

Phys. Lett. B 519 (2001) 93-102 "The MSSM invisible Higgs in the light of dark matter and g-2"

After the Higgs discovery:

, G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole, S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013)

Invisible decay of the Higgs can also be searched for at the LHC:

E.g. : R. M. Godbole, M. Guchait, K. Mazumdar, S. Moretti and D. P. Roy (2003), Phys. Lett. B **571**; D. Ghosh, R. Godbole, M. Guchait, K. Mohan and D. Sengupta, Phys. Lett. B 725, arXiv:1211.7015 [hep-ph] (2013)

Current best limits from the LHC is ~13%. ATLAS-CONF-2020-008

Future for looking for this 'dark' higgs is 'bright'.

LHC can reach 'invisible' BR upto 3.8%

ILC/CLIC/FCC can reach upto 0.2-0.4 %

So in the current situation different possibilities to look for light $\tilde{\chi}_1^0$ in SUSY:

1) Look for Mono events or LLP

2)Look for invisibly decaying Higgs.

3)Direct production of the heavier Electroweakino states ($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ etc) and their decays. WZ mediated and WH mediated decays of heavier charginos and neutralinos.

A 'light' $\tilde{\chi}_1^0$ DM at the collider in pMSSM:

Light $\tilde{\chi}_1^0$: pure Bino, will over close the universe. Mixed bino-higgsino efficient annihilation via Z or h_{125}. Hence a light $\tilde{\chi}_1^0$ in pMSSM has to be necessarily a 'mixed' state.

Consider parameter range consistent with $m_h \simeq 125$ GeV and no SUSY observation:

$$\begin{aligned} 1 \text{ GeV} < M_1 < 100 \text{ GeV}, \; 90 \text{ GeV} < M_2 < 3 \text{ TeV}, \\ 1 < \tan\beta < 55, \; 70 \text{ GeV} < \mu < \; 3 \text{ TeV}, \\ 800 \text{ GeV} < M_{\tilde{Q}_{3l}} < 10 \text{ TeV}, 800 \text{ GeV} < M_{\tilde{t}_R} < 10 \text{ TeV}, \\ 800 \text{ GeV} < M_{\tilde{b}_R} < 10 \text{ TeV}, \\ 2 \text{ TeV} < M_3 < 5 \text{ TeV}, -10 \text{ TeV} < A_t < 10 \text{ TeV} \end{aligned}$$

1) Make sure given point is allowed by a variety of current constraints: LHC constraints, LEP constraints, flavour constraints coming from B sector, Higgs sector constraints.

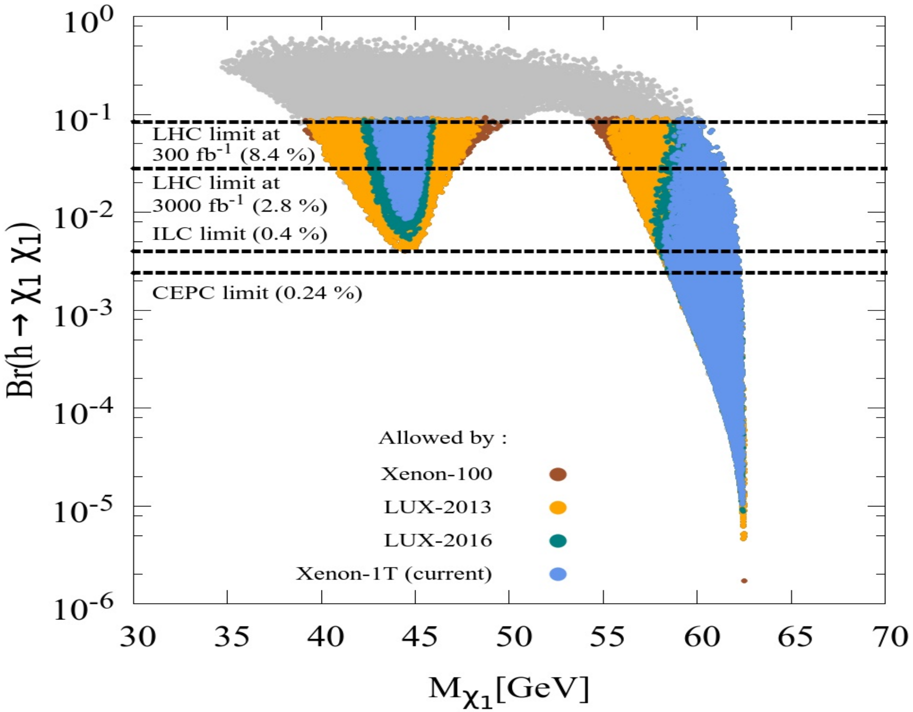
2)Calculate the invisible branching ratio for the Higgs.

3) Calculate the expected 'direct detection cross-sections.

4) Calculate the relic density for the given point.

Calculate $\xi = \Omega_{cal}h^2/\Omega_{obs}h^2 = \Omega_{cal}h^2/0.122$

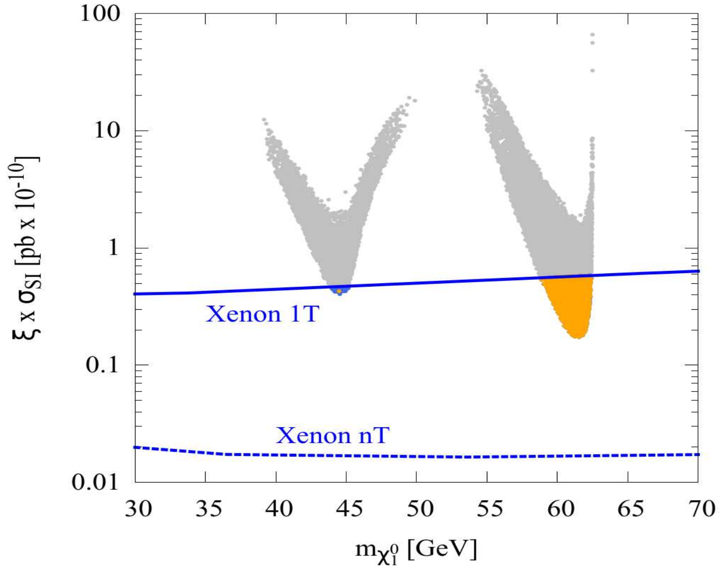
$\xi \leq 1$: Thermal DM



R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838 Projection for 13/14 TeV: 1310.8361 + HL LHC CMS/ATLAS studies:

300 1/fb, 0.15; 3000 1/fb, 0.06 and the ILC: 0.3 %.

Since then LHC run-II data became available and Xenon 1T came up with its result.



R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Eur.Phys.J.ST 229 (2020) 21, 3159-3185

Xenon-1T all but rules out now the Z-funnel region. Points still allowed by current LHC Electro-weakino searches. situation for -ve μ slightly different. Currently investigating. B., Bhattacharjee, R. K. Barman, G. Belanger, R. Godbole and R. Sengupta.

Collider signatures:
Production of electroweakino pairs which decay through mediation of WZ or Wh . WZ mediated 3l + MET or dilepton + MET searches and Wh_{125} mediated 1l + 2b + MET searches:

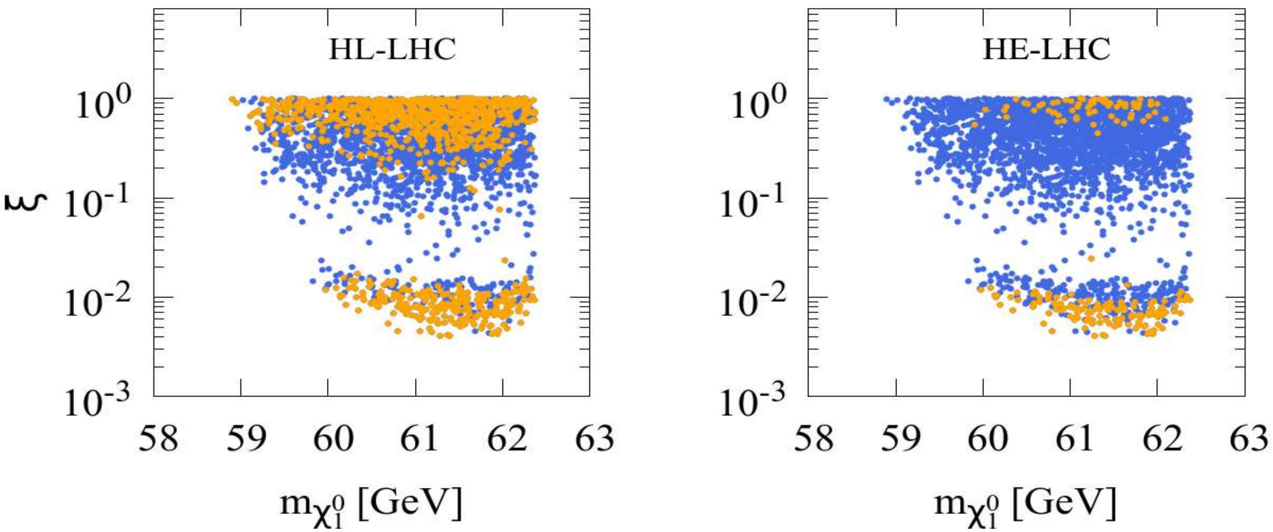
Run-II data 35fb^{-1} .

Higgsino upto 390 GeV ruled out. G. Pozzo et al. Phys. Lett. B, 789:582–591, 2019. arXiv: 1807.01476 : Pure Wino upto 650 GeV ruled out (CMS data).

Translated this to our parameter region.

Exclude points where $m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}$ and $m_{\tilde{\chi}_1^\pm}$ is $\leq$ 390 GeV and all three, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_1^\pm$, have a higgsino composition $\geq$ 90%. We also exclude points where $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^\pm}$ are $\leq$ 650 GeV and both $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ have wino composition $\geq$ 90%

(should do a more clean job of recasting)



R. Kumar Barman, G. Belanger and R. M. Godbole, Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020)

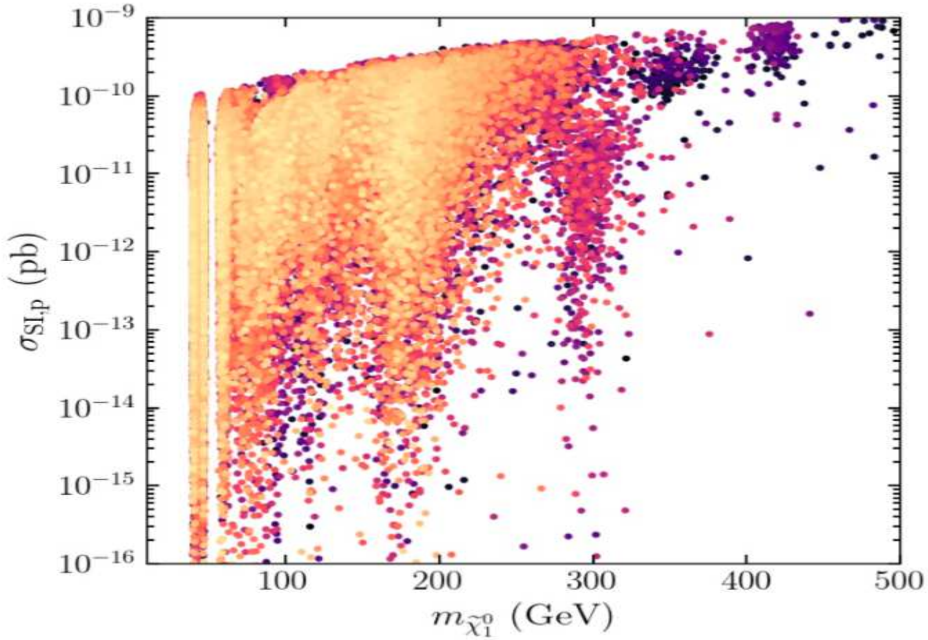
How can one test it at HL/HE LHC? Use efficiency maps we made in R. K. Barman, G. Bélanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata, Phys. Rev. D **103**, no.1, 015029 (2021) (validated by comparing with ATLAS analysis). Combined use of EWeakino production.

Blue within the discovery reach of 3 l + MET channel.

$\xi > 0.1$: $M_2 < 250, \mu > 400$. Small $h\tilde{\chi}_1^0\chi_1^0$ couplings and hence relic is a bit higher. The heavier states are Wino-Higgsino mixed states and still allowed.

$\xi < 0.02$: $\mu < 150, M_2 > 650$ GeV, but the Higgsino content is $< 90\%$. Hence survive the current bounds.

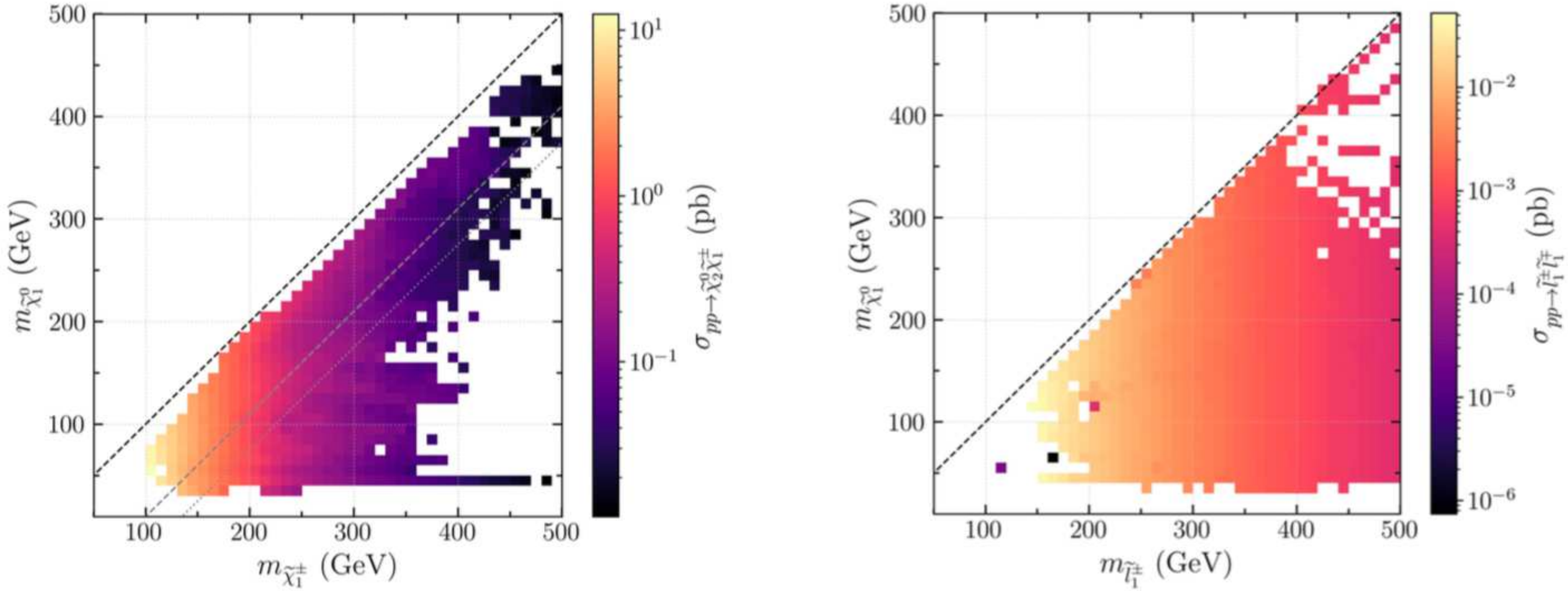
Still need to do the recasting of allowed points to see whether some of these points which we have concluded as allowed by the current searches are excluded or vice versa.



As said before we do need more scrutiny of the region $m_{\tilde{\chi}_1^0} \sim m_Z/2$.

A recent analysis by Melissa Van Beekveld and collaborators (hep-ph/2104.03245) does have allowed points in this mass range.

This analysis looks at PMSSM allowed spectra in light of current data and (g-2). The Δ_{EW} smallest if LSP is lighter than 100 GeV.



The cross-sections for their allowed points for slepton pair and chargino-neutralino pair production.

NMSSM superpotential extended from MSSM by adding terms $\lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$

Now the neutralino mass matrix is five dimensional. There is one more neutral fermion : the singlino. The LSP is a superposition of all the five.

Has one more pseudoscalar and scalar in addition to the MSSM Higgses. Thus in principle two 'lighter states A_1, H_1 become available for resonant annihilation. Thus additional annihilation channels become possible.

Much studied subject. Next slide shows some recent papers. Our focus was looking in detail at the low mass LSP region in light of all the current constraints and connection with invisible width of the Higgs. See if (small) LSP masses other than those approximately $M_Z/2$ or $M_{h125}/2$ are allowed

1)Semi constrained NMSSM:

S. Ma, K. Wang and J. Zhu, Chin. Phys. C **45**, no.2, 023113 (2021), K. Wang and J. Zhu, JHEP **06**, 078 (2020),Chin. Phys. C **44**, no.6, 061001 (2020). Looked at the light LSP but in a constrained version of the NMSSM.

2)Connection with DD, Indirect detection and astrophysical probes of DM (galactic centre excess).Relic and consistence with DD a combination of annihilation through h_{SM} or A and 'blind spots' in SI DD due to interference effects.

S. Baum, M. Carena, N. R. Shah and C. E. M. Wagner, JHEP **04**, 069 (2018); M. Carena, J. Osborne, N. R. Shah and C. E. M. Wagner, Phys. Rev. D **98**, no.11, 115010 (2018); M. Carena, J. Osborne, N. R. Shah and C. E. M. Wagner; Phys. Rev. D **100**, no.5, 055002 (2019)..... Did not focus on the 'light' LSP region.

We focussed on the light LSP region and in the full NMSSM.

$$
\begin{aligned}
0.01 < \lambda < 0.7,\ 10^{-5} < \kappa < 0.05,\ 3 < \tan\beta < 40 \\
100\ \text{GeV} < \mu < 1\ \text{TeV},\ 1.5\ \text{TeV} < M_3 < 10\ \text{TeV} \\
2\ \text{TeV} < A_\lambda < 10.5\ \text{TeV},\ -150\ \text{GeV} < A_\kappa < 100\ \text{GeV} \quad (1) \\
M_1 = 2\ \text{TeV},\ 70\ \text{GeV} < M_2 < 2\ \text{TeV} \\
A_t = 2\ \text{TeV},\ A_{b,\tilde{\tau}} = 0,\ M_{U_R^3}, M_{D_R^3}, M_{Q_L^3} = 2\ \text{TeV},\ M_{e_L^3}, M_{e_R^3} = 3\ \text{TeV}
\end{aligned}
$$

The $\tilde{\chi}_1^0$ is a linear combination of singlino, bino and higgsino/wino.

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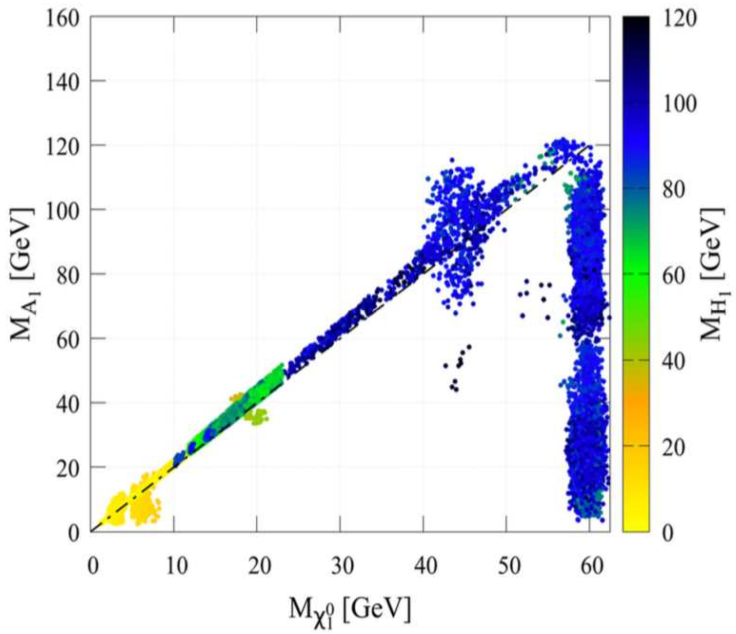
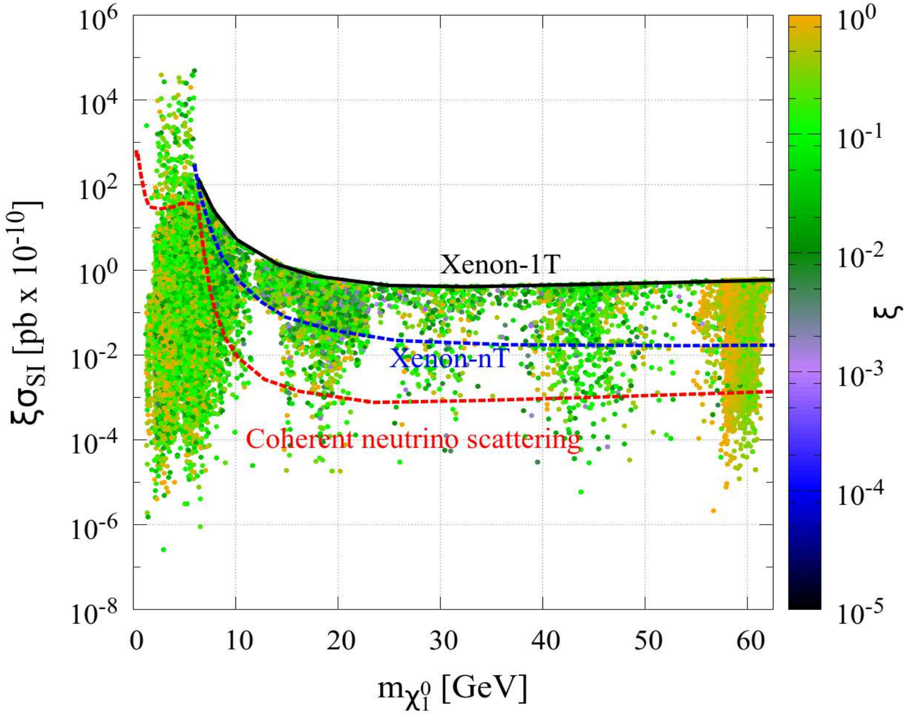
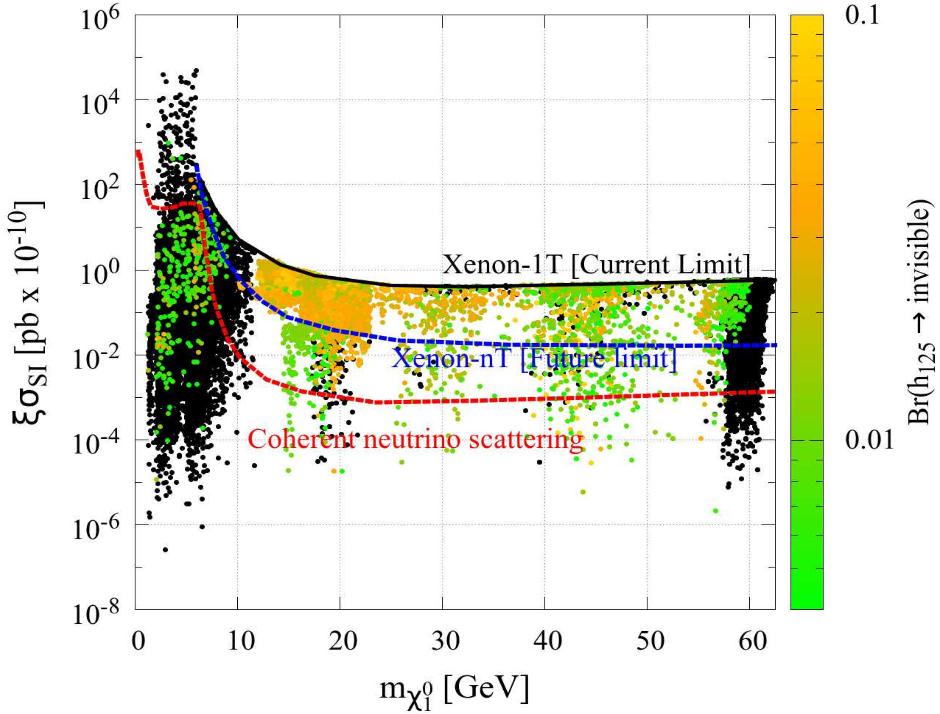


h_2 identified with the observed SM -like Higgs. Possibility of a light singlet dominated h_1, a_1 lighter than 122 GeV.

$\tilde{\chi}_1^0$ Singlino or Bino dominated. Annihilations through a_1, h_1 provide the right relic No co-annihilations for our choice . Only resonance annihilations.

Along the line $2M_{\tilde{\chi}_1^0} = m_{a_1}$. Away from this it is the h_1 which provides efficient annihilation.



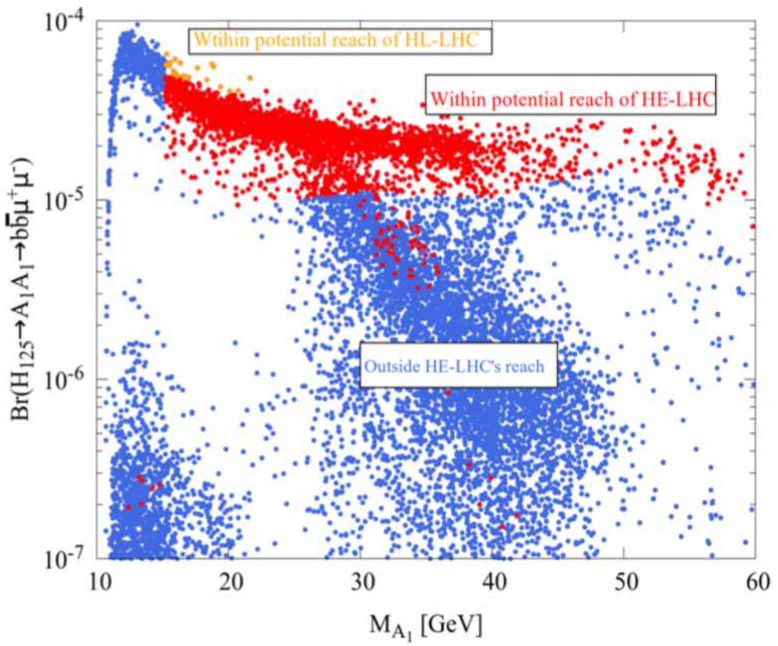


R. K. Barman, G. Bélanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata, Phys. Rev. D **103**, no.1, 015029 (2021)

Annihilation through A_1, H_1 gives allowable relic.

Low mass LSP regions allowed by DD as well as relic. Black points not reachable even by CEPC in the invisible channel.

How can they be probed at HL/LHC or HE/LHC? Again through WZ mediated and WH mediated EWeakino signals as well as light Higgses!



Future projections from 1902.00134 (Report from WG 2: Higgs Physics at the HL-LHC and HE-LHC, M. Cepeda et. al.). Translated to our allowed parameter space.

The results indicate that the discovery potential of light Higgs bosons produced via direct decays of H125 is not very strong.

No attempt to optimize the analysis for increased luminosity or increased energy. So, our conclusion must be viewed with caution.

Light Higgs searches in the future lepton colliders may have an improved projected reach.

How did we compute the projected reach?

We derive the projected reach at the HL-LHC and the HE-LHC for doublet higgsino production via the WZ and WH125 mediated $3l + \not{E}_T$ channels through cut-based collider analyses using optimized signal regions.

The projections are translated to the allowed NMSSM parameter space by considering the actual production cross-sections and branching ratios of the mixed states.

In order to do so, we map out the efficiency grids in the doublet-higgsino LSP mass plane.

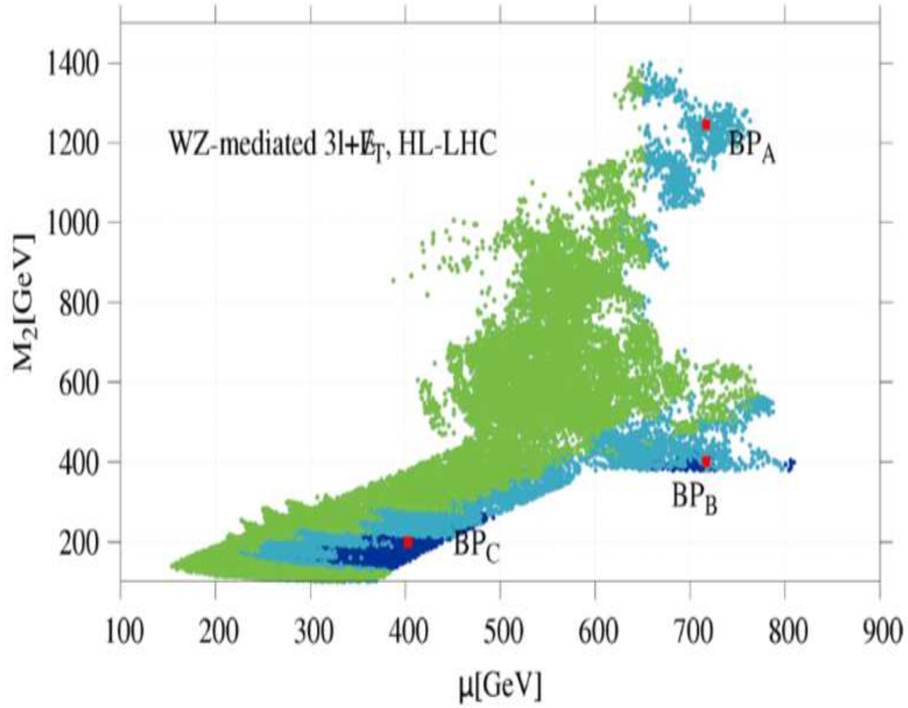
In our allowed parameter region, $\tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ as well as$\tilde{\chi}_1^{\pm}, \chi_2^{\pm}$ are either higgsino-like, wino-like or wino-higgsino admixtures.

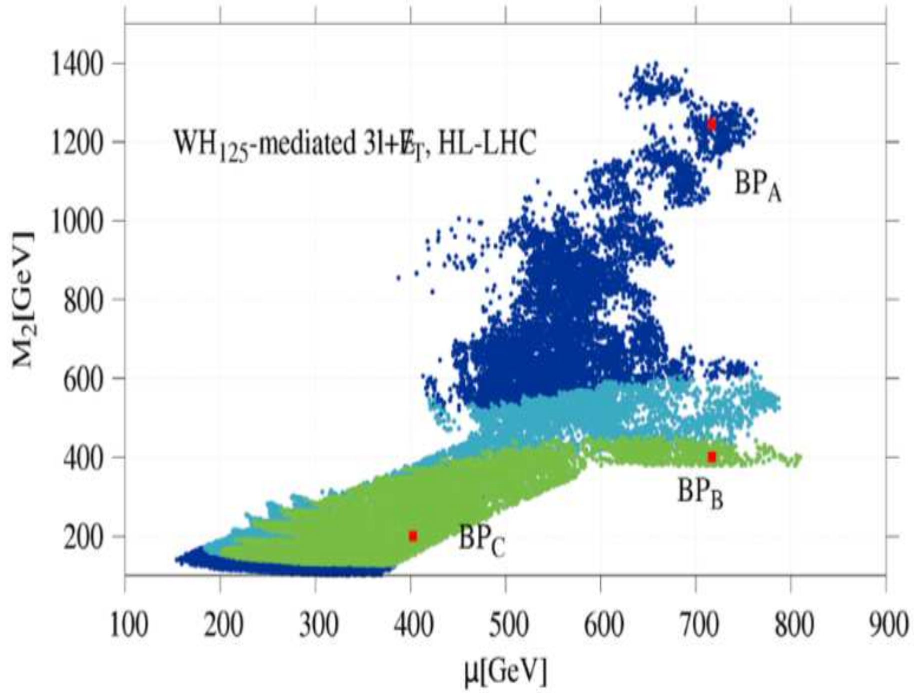
Direct chargino-neutralino pair production modes which can potentially contribute to WZ mediated 3l + E/T signal are $\tilde{\chi}_2^0\chi_1^{\pm}, \chi_2^0\chi_2^{\pm}, \tilde{\chi}_3^0\chi_1^{\pm}$ and $\chi_3^0\chi_2^{\pm}$ and $\tilde{\chi}_4^0\chi_1^{\pm}, \chi_4^0\chi_2^{\pm}$.

The direct production cross-section is computed by scaling the pure Higgsino cross-sections $\sigma(\tilde{\chi}_i^0\tilde{\chi}_j^+)$ with the respective reduced squared couplings consisting of elements of the mixing matrix.

The signal yield for a particular parameter space point is computed for all the signal regions by multiplying this cross-section by branching ratio, luminosity and signal efficiency.

The signal efficiency is obtained from the efficiency maps we constructed and validated using ATL-PHYS-PUB-2018- 048 and used their optimised cuts.





Green- Discovery reach $S_\sigma > 5$, Light blue $2 < S < 5$ and dark blue $S < 2$. $BP_A : \mu \sim 717, M_2 \sim 1245$ GeV, $BP_B : \mu \sim 717, M_2 \sim 400$ GeV and $BP_C : \mu \sim 403, M_2 = 200$ GeV.

Complementarity between the WZ and Wh_{125} mediated channels.

The observation of a signal is an interplay between the production cross-section and signal efficiency.

At large values of M_2, μ (near BPA) we have large efficiency but smaller production cross-section due to kinematically suppressed signal.

At smaller values of M_2, μ larger production cross-section but signal efficiencies reduce.

In BP_B and BP_C, the dominant production mode is $\tilde{\chi}_2\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0 \to h_{125} + \tilde{\chi}_1^0$ with branching rates of 82% and 92%, respectively. Hence reduced sensitivity in WZ mediated channels. Direct searches in Wh_{125} mediated channels could be more effective for these benchmark points.

Scope of other complementary search channels in BP_B

	$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{\chi}_3^0$	$\widetilde{\chi}_4^0$	$\widetilde{\chi}_1^\pm$	$\widetilde{\chi}_2^\pm$
Mass [GeV]	60.4	421	734	742	421	741
wino %	10^{-5}	0.96	2×10^{-3}	0.04	0.94	0.06
higgsino %	10^{-4}	0.04	0.99	0.96	0.06	0.94
Singlino fraction in $\widetilde{\chi}_1^0$: 0.99			$M_{H_1}=97.2$ GeV, $M_{A_1}=99$ GeV			
Cross-section (fb)	$\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm$	$\widetilde{\chi}_2^0\widetilde{\chi}_2^\pm$	$\widetilde{\chi}_3^0\widetilde{\chi}_1^\pm$	$\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm$	$\widetilde{\chi}_4^0\widetilde{\chi}_1^\pm$	$\widetilde{\chi}_4^0\widetilde{\chi}_2^\pm$
$\sqrt{s}=14$ TeV	104	0.27	0.28	2.1	0.25	2.3
$\sqrt{s}=27$ TeV	363	1.1	1.1	10.2	1.0	11.2
Branching ratio	$\widetilde{\chi}_2^0\to\widetilde{\chi}_1^0 Z$ (0.04), $\widetilde{\chi}_1^0 H_{125}$ (0.82), $\widetilde{\chi}_1^0 H_1$ (0.14)					
	$\widetilde{\chi}_3^0\to\widetilde{\chi}_1^0 Z$ (0.13), $\widetilde{\chi}_1^0 H_{125}$ (0.10), $\widetilde{\chi}_1^0 H_1$ (0.01), $\widetilde{\chi}_1^\pm W^\mp$ (0.51), $\widetilde{\chi}_2^0 Z$ (0.23), $\widetilde{\chi}_2^0 H_{125}$ (0.01)					
	$\widetilde{\chi}_4^0\to\widetilde{\chi}_1^0 Z$ (0.12), $\widetilde{\chi}_1^0 H_{125}$ (0.11), $\widetilde{\chi}_1^\pm W^\mp$ (0.53) $\widetilde{\chi}_4^0\to\widetilde{\chi}_2^0 Z$ (0.02), $\widetilde{\chi}_2^0 H_{125}$ (0.21)					
Significance at HL-LHC: WZ mediated $3l+\not{E}_T$: 1.5, WH_{125} mediated $3l+\not{E}_T$: 5.3 Significance at HE-LHC: WZ mediated $3l+\not{E}_T$: 4.4, WH_{125} mediated $3l+\not{E}_T$: 34						

- Notice the presence of other cascade decay modes:
  1. $\widetilde{\chi}_3^0$ can decay into $\widetilde{\chi}_2^0 Z$, while $\widetilde{\chi}_2^0$ can decay into $\widetilde{\chi}_1^0 H_1$ or $\widetilde{\chi}_1^0 H_{125}$.
  2. $\widetilde{\chi}_3^0$ is dominantly produced in association with $\widetilde{\chi}_2^\pm$, which can decay into $Z/H_{125}+\widetilde{\chi}_1^\pm$ or $W^\pm+\widetilde{\chi}_2^0/\widetilde{\chi}_1^0$ with appreciable rates.
  3. $\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm$ can eventually lead to rich final states including $VV+\not{E}_T$ or $V/Z/H_1+\not{E}_T$. Although, $\sigma(\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm)$ is small for BP_B, but one obtain points with relatively larger $\sigma(\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm)$, for. eg. BP_C with $\sigma(\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm)\sim 24.8$ fb.
- $3l+\not{E}_T$ channels might not be most the efficient ones in the presence of these cascade decay channels.
- Dedicated searches beyond the scope of this work will be needed to explore these novel signals.

So in NMSSM a light LSP is easily accommodated.

Question: Light A_1, H_1 obtained with low values of κ, λ. Is that natural?

Our LSP is mostly singlino. Difficulty to search for a mixed, light LSP region.

Plan to do first a simplified model analysis and then perhaps go back to NMSSM again to understand it.

Light $\tilde{\nu}_R$ can be LSP. Avoid DD constraints by small Yukawa couplings of the $\tilde{\nu}_R$ (pMMSM,cMSSM). Have an NLSP $\tilde{\tau}_1$. Correct relic by a freeze in mechanism or Decay of long lived $\tilde{\tau}_1$. Interesting phenomenology at the LHC. $\tilde{\nu}_R \sim 30 - 40$ GeV. S. Banerjee et al. JHEP, 07:095, 2016. arXiv: 1603.08834, S. Banerjee et al. JHEP, 09:143, 2018. arXiv: 1806.04488.

Light $\tilde{\nu}_R$ can be LSP in NMSSM. Interactions of $\tilde{\nu}_R$ with SM particles through additional Higgses: D. G. Cerdeno et al. Phys. Rev. D, 79:023510, 2009. arXiv: 0807.3029, D.G. Cerdeo et al. JCAP, 08:005, 2014. arXiv: 1404.2572, D.G. Cerdeno et al. Phys. Rev. D, 91(12):123530, 2015. arXiv: 1501.01296.
No recent analysis of this scenario is available. Would be good to have this analysis. The invisible width measurement of the Higgs can constrain this picture.

Some of these scenarios give unusual signatures at the LHC. Discussed in a White paper "Unveiling Hidden Physics at the LHC - Whitepaper", Bruce Mellado and Oliver Fischer. arXiv/hep-ph/ 2109.06065

One can, however, think of various possibilities which will then give a relic different than the thermal case.

Freeze in OR Out of equilibrium decay.

OR

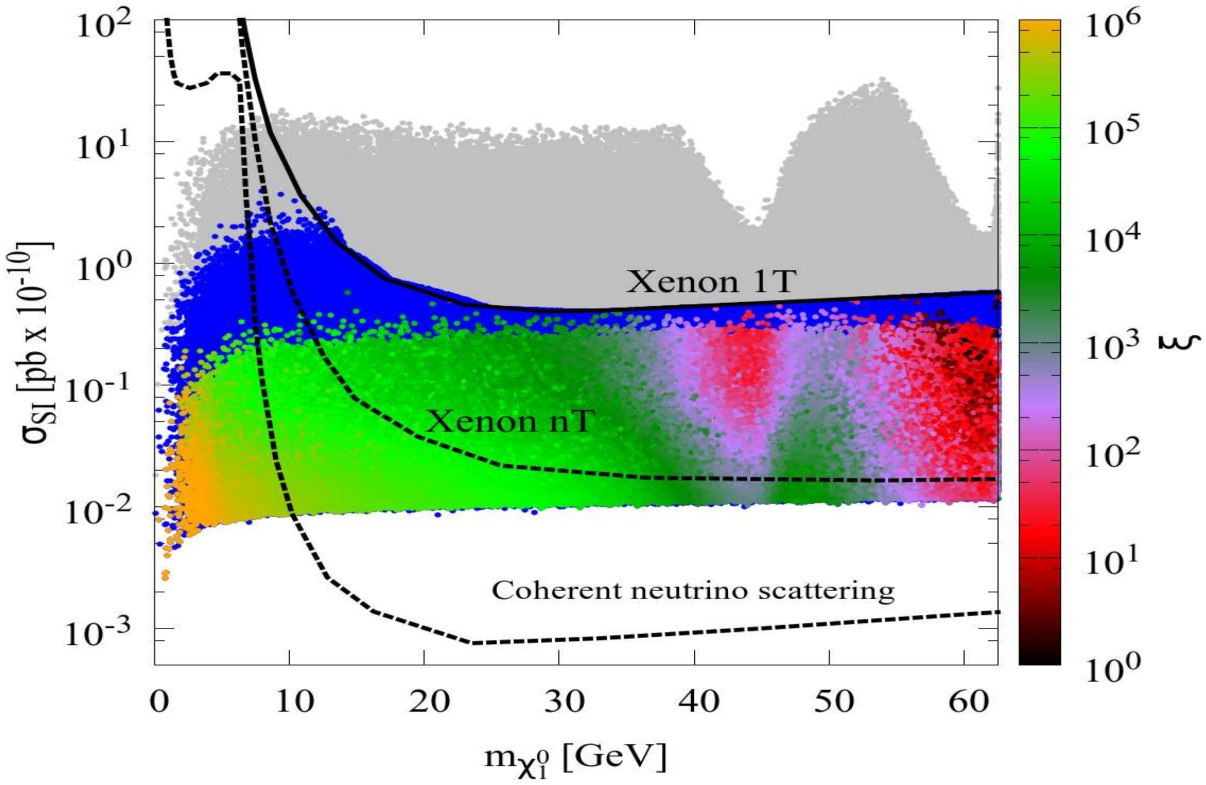
one can think of 'nonstandard cosmology'. The thermal relic might be above the observed relic, but there might be a period of entropy injection which will dilute the relic density to the 'measured' value.

Calculate $\xi = \Omega_{cal}h^2/\Omega_{obs}h^2 = \Omega_{cal}h^2/0.122$

So far I presented the results for $\xi < 1$.

What happens for $\xi > 1$ (Non thermal) I.e. assume there is a mechanism of (say) entropy injection to reduce Ω_{DM}.

Can this be probed at HL/LHC? As we discussed in a paper in 2015 this gives rise to different interesting search strategies. Not discussing that here. But just the classic trilepton, dilepton with missing E_T signal

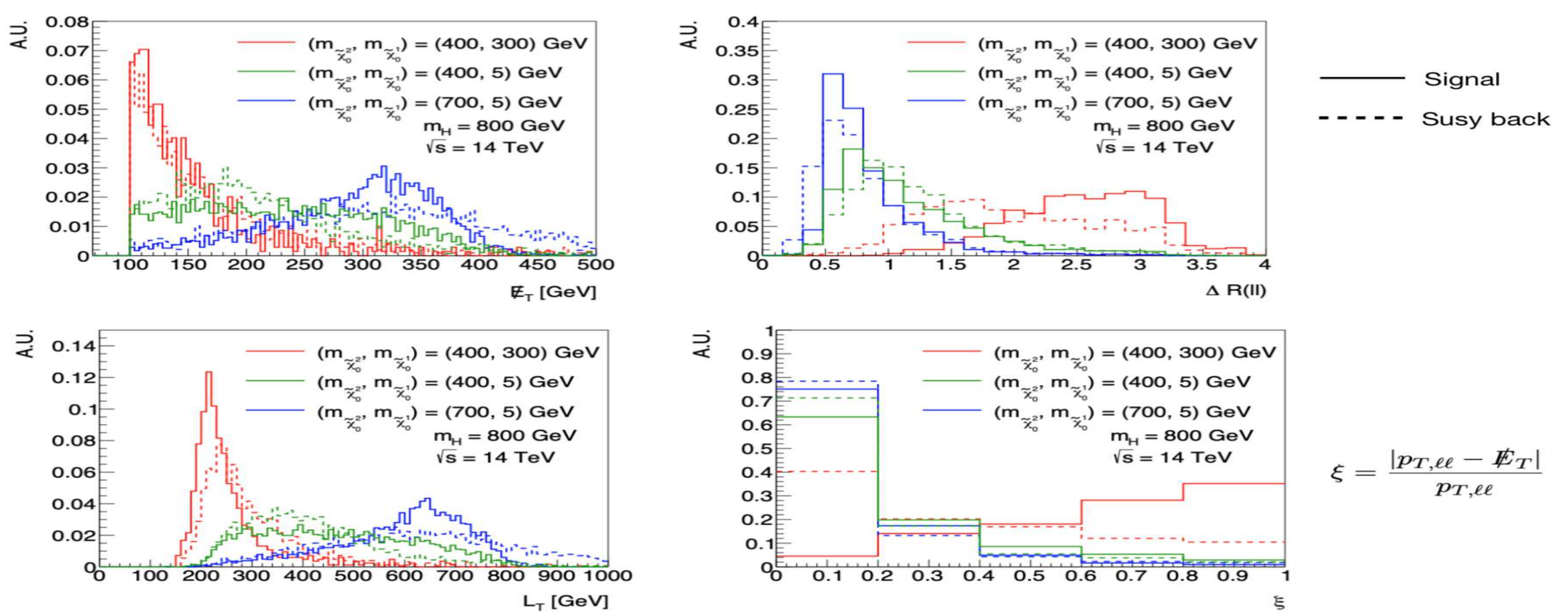


R. Kumar Barman, G. Belanger and R. M. Godbole, Eur. Phys. J. ST **229**, no.21, 3159-3185 (2020)

Reach of HL LHC through trilepton, dilepton + MET and 1 l + 2b + MET indicated by blue points. Can not be reached by Xenon nT DD, some even below the Neutrino floor!

Analysed in A. Adhikary, B. Bhattacherjee, R. M. Godbole, N. Khan and S. Kulkarni, "Searching for heavy Higgs in supersymmetric final states at the LHC," JHEP **04**, 284 (2021)

SUSY backgrounds and also viability of using final states with b's by tagging the b's. Also interesting LLP signals for heavy charged Higgs.



$$\xi = \frac{|p_{T,\ell\ell} - \not{E}_T|}{p_{T,\ell\ell}}$$