Light LSP and Heavy Higgs: lamp posts for SUSY?

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- Introduction.

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

1 $\tilde{\chi}_1^0$ LSP: pMSSM, NMSSM (personal work)

2 $\tilde{\nu}_R$: cMSSM,pMSSM,NMSSM (review)

- Heavy Higgs with emphasis on electro weakino final state.(personal work)

Based on:

1)R. K. Barman, G. Belanger, B. Bhattacherjee, R. Godbole, G. Mendiratta and D. Sengupta, Phys. Rev. D 95 (2017) no.9, 095018; 1703.03838;

2)R. K. Barman, G. ,Belanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata,2006.07854, Phys. Rev. D 103, (2021) 015029;

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

4)B. Bhattacharjee, R. K. Barman, G. Belanger, R. Godbole, Rhitaja Senguptalight DM in pMSSM at the HL and HE LHC: thermal and non thermal case; In preparation.

These papers focus on $2m_{\tilde{\chi}_1^0} \leq m_h(125)$.

Heavy Higgs:

5)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)

An analytic continuation of sorts of work which I had started around 2000/2001.

G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000) [hep-ph/0002039]

G. Belanger, F. Boudjema, A. Cottrant, R. M. Godbole and A. Semenov, Phys. Lett. B **519**, 93 (2001) [hep-ph/0106275]

D. Albornoz Vasquez, G. Belanger, R. M. Godbole and A. Pukhov, Phys. Rev. D **85** (2012) 115013,[arXiv:1112.2200 [hep-ph]].

G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole, S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013) [arXiv:1308.3735 [hep-ph]]

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.

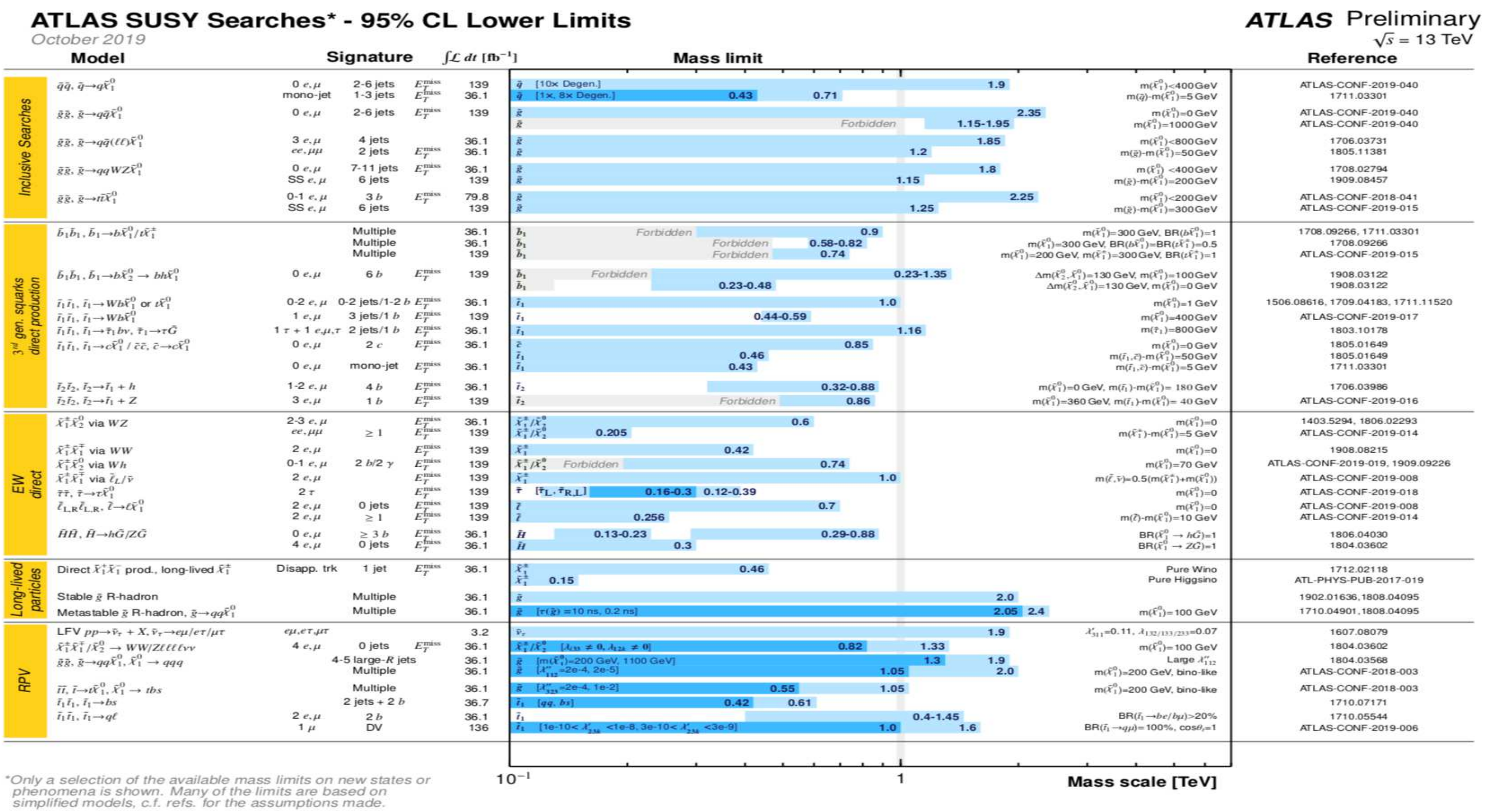
But LHC results have put the idea of ’natural’ SUSY under stress and the XENON-1T results have put the WIMP paradigm under stress.

Experimental constraints on masses of various sparticles from the LHC

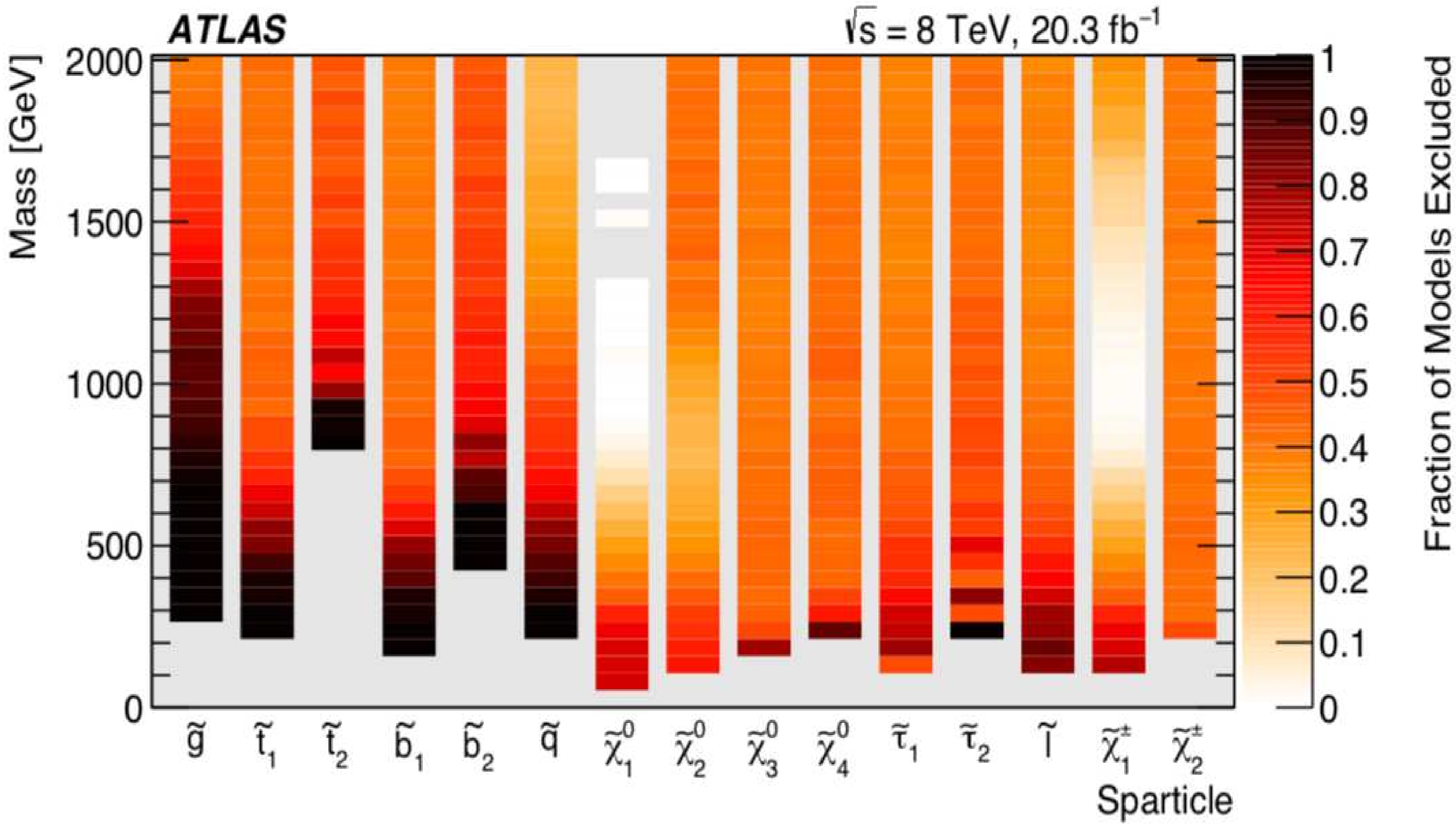
These translate into constraints on SUSY parameters.

Many are constrained to have very high values.

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



Limits from the PDG. But these are in simplified models. I can show similar plots for CMS!



A small mass $\tilde{\chi}_1^0$ still allowed in PMSSM!

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) and Heavy SUSY Higgses.

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

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)

- Should satisfy the Direct/Indirect detection constraints.

Planck measurements and the anisotropies tell us

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

In a model the predicted relic :

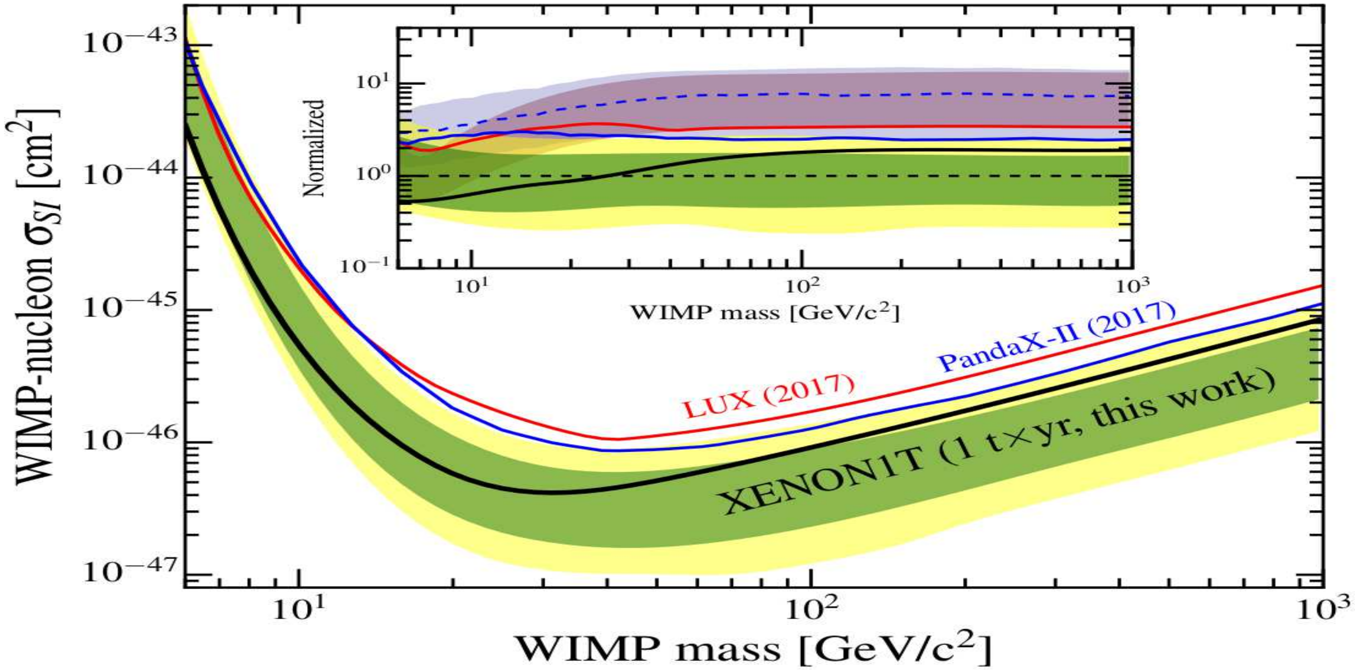
$$\Omega_{\tilde{\chi}}h^2 = \frac{m_{\tilde{\chi}}n_{\tilde{\chi}}}{\rho_c} \simeq \frac{3 \times 10^{-27}\mathrm{c}m^3 s^{-1}}{\langle \sigma_{ann} v \rangle},$$

One can calculate for a given model point the relic and check whether the calculated thermal relic is less than the measured value.

This expression above is for thermal relic, decided by the temperature at which it falls out of thermal equilibrium, ie. freezes out.

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!



Is there a cosmological limit on how light a CDM particle can be?

C. Boehm et al. J. Phys. G, 30:279–286, 2004. arXiv: astro-ph/0208458; C. Boehm, T.A. Ensslin, and J. Silk, J. Phys. G, 30:279–286, 2004, C. Boehm et al. JCAP, 08:041, 2013. arXiv: 1303.6270

Using PLANCK limit on N_{eff} ; effective number of ν species: masses for CDM as small as 2.5 MeV $\tilde{\chi}_1^0$ (neutralino in SUSY) can be allowed.

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.

The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with matter and also to the Higgs boson(s).

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 expts. 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?

Recall:

Predictions for relic density, Direct/Indirect detection and LHC phenomenology all decided by the same parameters.

So one can probe SUSY DM through its implications for all the four issues.

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.. 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.

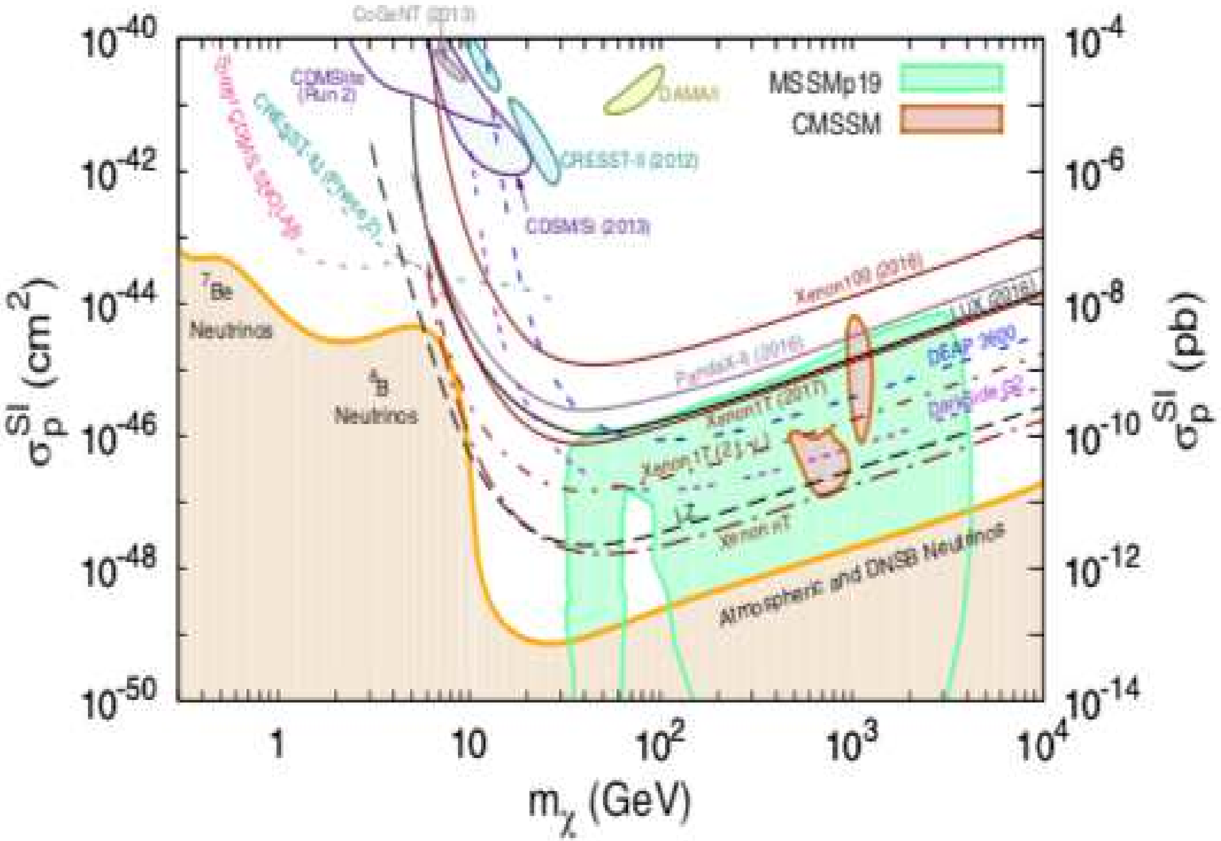
Early days:
In cMSSM the LEP constraint on $m_{\tilde{\chi}_1^\pm}$ and universal gaugino mass ruled out light $\tilde{\chi}_1^0$.So a light $\tilde{\chi}_1^0$ necessarily meant non universal gaugino masses. Hence focus moved to the pMSSM.

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

Higgsino-Bino mixture is 'liked' by relic so that we can try to get the right relic.

But it also means that the h **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),—-G. Belanger, G. D. La Rochelle, B. Dumont, R. M. Godbole, S. Kraml and S. Kulkarni, Phys. Lett. B **726** 773 (2013). So the higgsino-bino mixing 'liked' by relic requirements can also cause the Higgs to decay invisibly.

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 %

Produce the DM at the colliders. DM particles do not leave tracks in the detector. So their production is indicated by an imbalance of momentum. Produce events with a momentum imbalance: missing transverse energy

a)In the cascade decays of strongly interacting supersymmetric particles: Events with missing E_T. There are only constraints on this! Expts did not find anything here. Looking at compressed spectra. (ref. Ipsita's talk)

b)Direct production of electro weakinos and their decays: signals in the trilpeton + MET channel.

OR

c)in association with other SM particles: famous 'mono'events: mono W/Z/jets...

Example: for $m_{DM} < m_{h125}$:

$$pp \to hZ \to Z(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0),$$

$$pp \to hW \to W(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

$$pp \to h + jet \to jet + (h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$$

Mono Z/W and mono-jets.

So in the current situation two possibilities to look for light DM in SUSY:

1)Look for invisibly decaying Higgs say through 'mono' Z.

2)Direct production of the heavier Electroweakino states ($\tilde{\chi}_1^+ \tilde{\chi}_2^0$ etc) and their decays.

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.

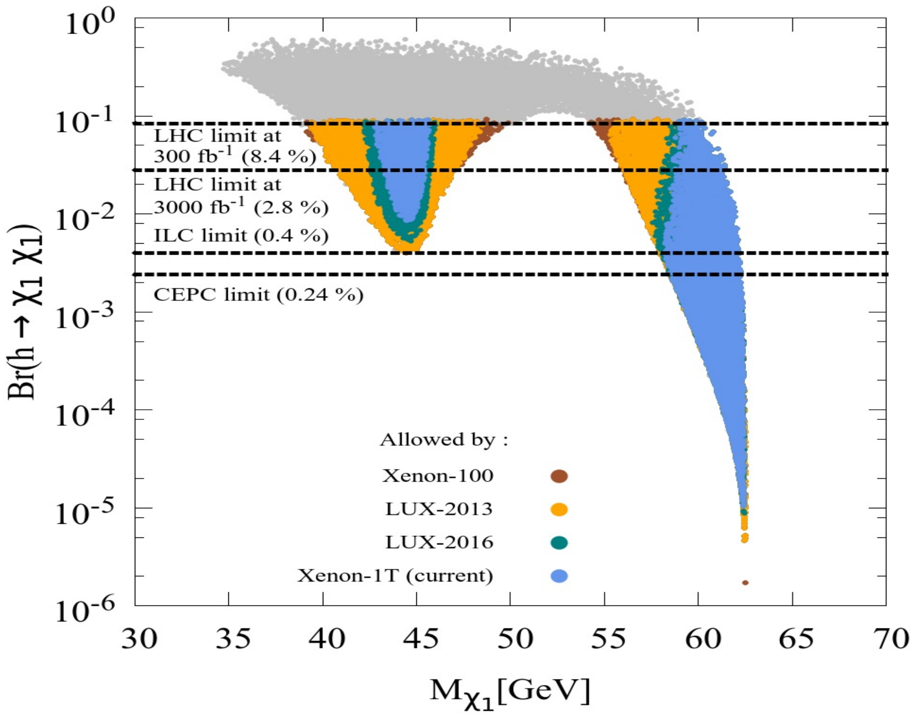
2)Calculate the invisible branching ratio for the Higgs.

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

4) Calculate the relic density for the given point.

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

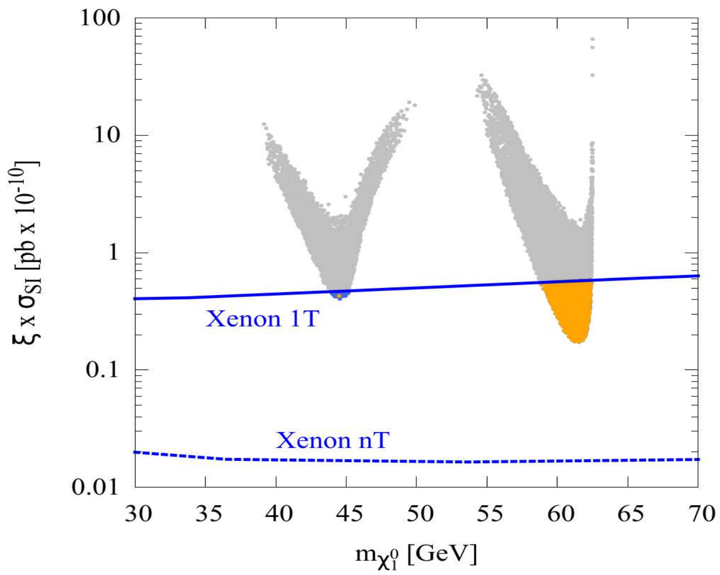
$\xi \leq 1$: Thermal DM



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.

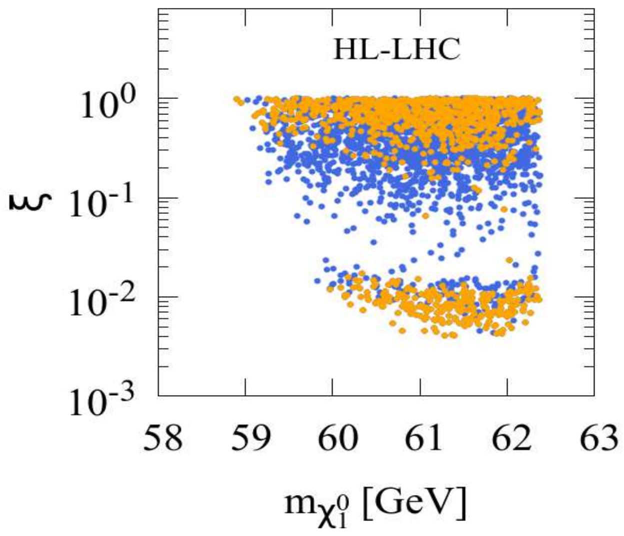
Collider signatures:
Production of electroweakino pairs which decay through mediation of WZ or Wh . WZ mediated 3l + MET or dilepton + MET searches and Wh_{125} mediated 1l + 2b + MET searches:

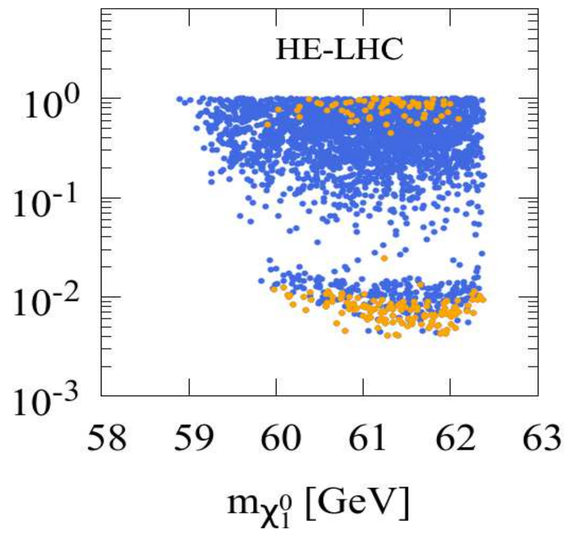
Run-II data 35fb^{-1} .

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%





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.

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

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

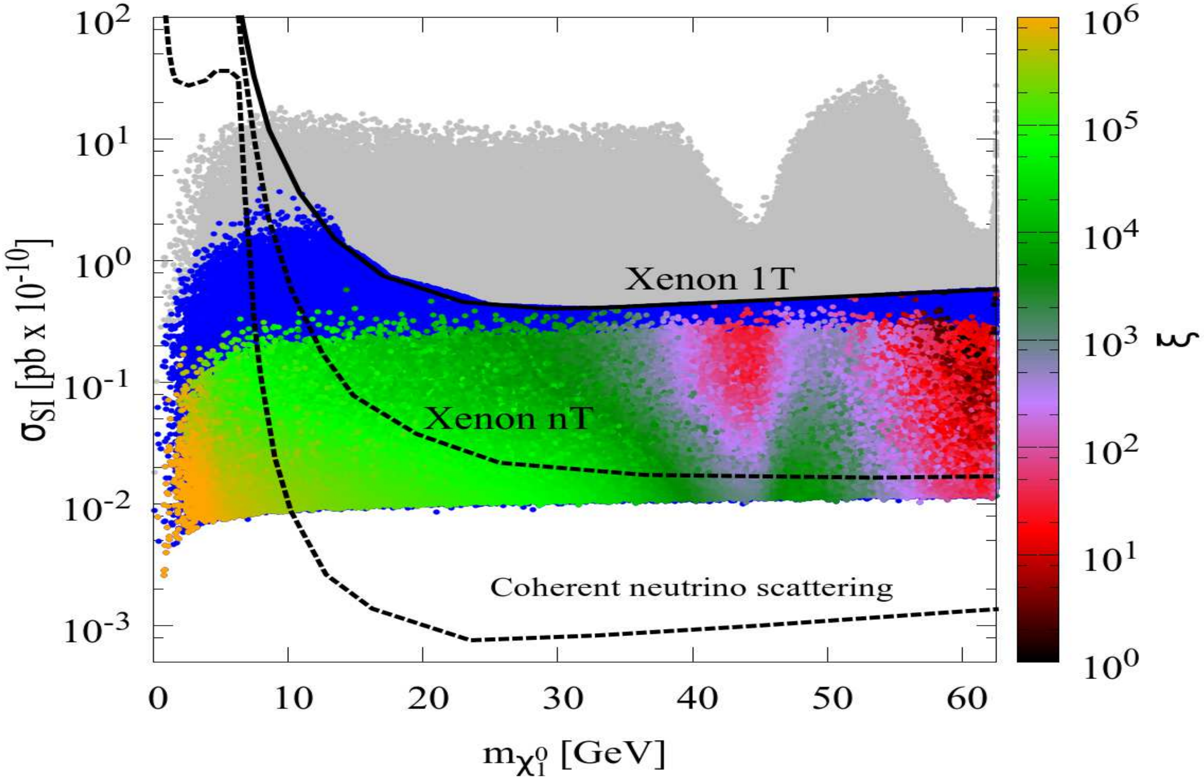
one can think of 'nonstandard cosmology'. The thermal relic might be above the observed relic, but there might be a period of entropy injection which will dilute the relic density to the 'measured' value.

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?



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!

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.

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.

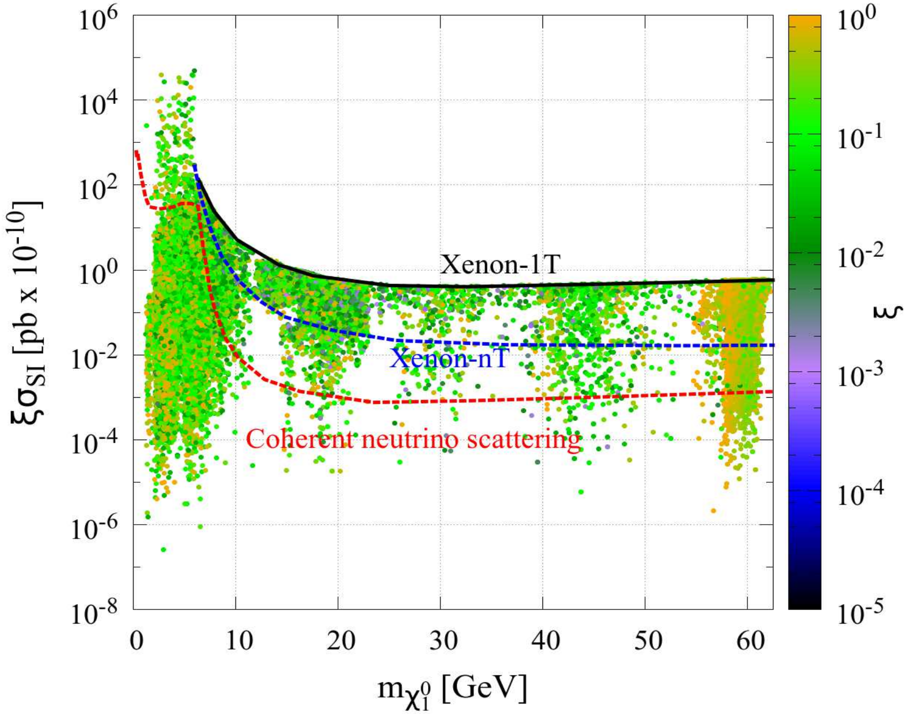
2)Connection with DD, Indirect detection and astrophysical probes of DM (galactic centre excess).Relic and consistence with DD a combination of annihilation through h_{SM} or A and 'blind spots' in SI DD due to interference effects.

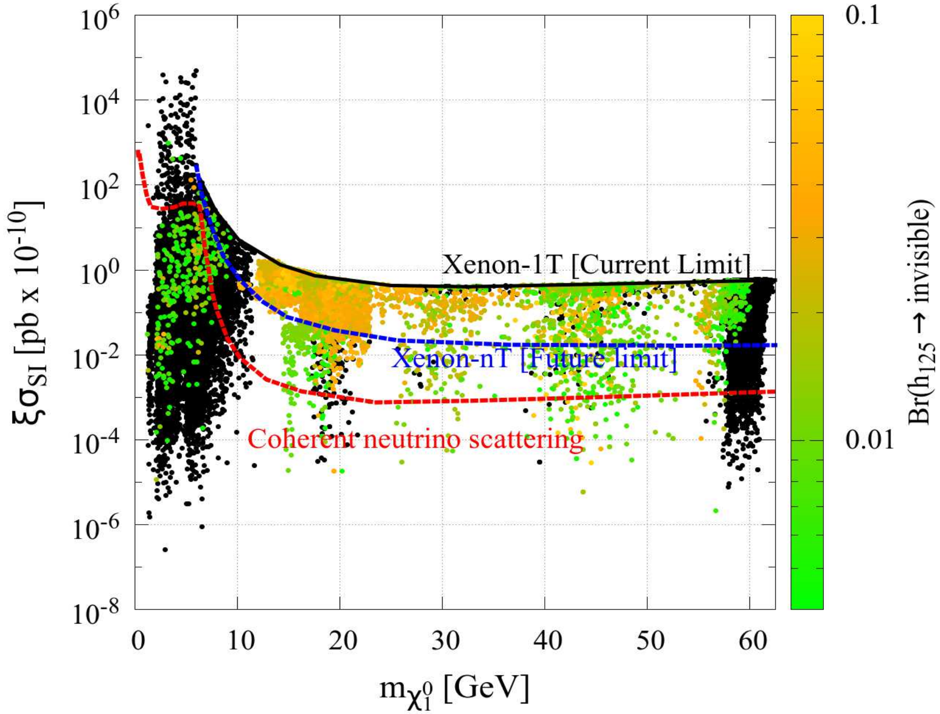
S. Baum, M. Carena, N. R. Shah and C. E. M. Wagner, JHEP **04**, 069 (2018); M. Carena, J. Osborne, N. R. Shah and C. E. M. Wagner, Phys. Rev. D **98**, no.11, 115010 (2018); M. Carena, J. Osborne, N. R. Shah and C. E. M. Wagner; Phys. Rev. D **100**, no.5, 055002 (2019)..... Did not focus on the 'light'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

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

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

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



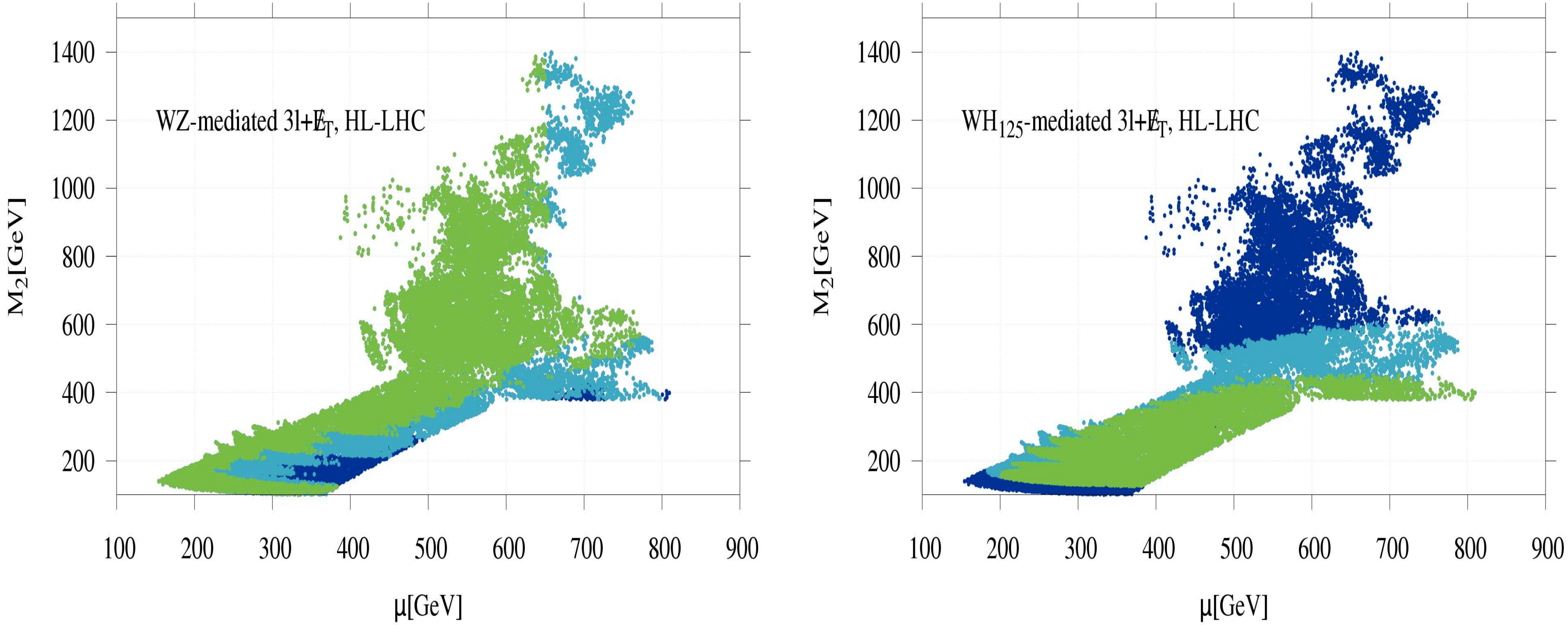


R. K. Barman, G. Bélanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata, Phys. Rev. D **103**, no.1, 015029 (2021)

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.



Green- Discovery reach, Light blue exclusion reach(ie 2 σ)

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. 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

Lot of work on heavy Higgs phenomenology. A very active area.

Prospects for Heavy Higgs searches with SM final states, inclusive of latest HO calculations: H. Bahl, P. Bechtle, S. Heinemeyer, S. Liebler, T. Stefaniak and G. Weiglein, "HL-LHC and ILC sensitivities in the hunt for heavy Higgs bosons," Eur. Phys. J. C **80**, no.10, 916 (2020)

A very complete phenomenological analysis of heavy Higgs searches in SM final states , see eg., R. K. Barman, B. Bhattacherjee, A. Choudhury, D. Chowdhury, J. Lahiri and S. Ray, Eur. Phys. J. Plus **134**, no.4, 150 (2019).

Interesting new phenomenological angles to be investigated: Focus on the decays of Heavy Higgs into electroweakinos.

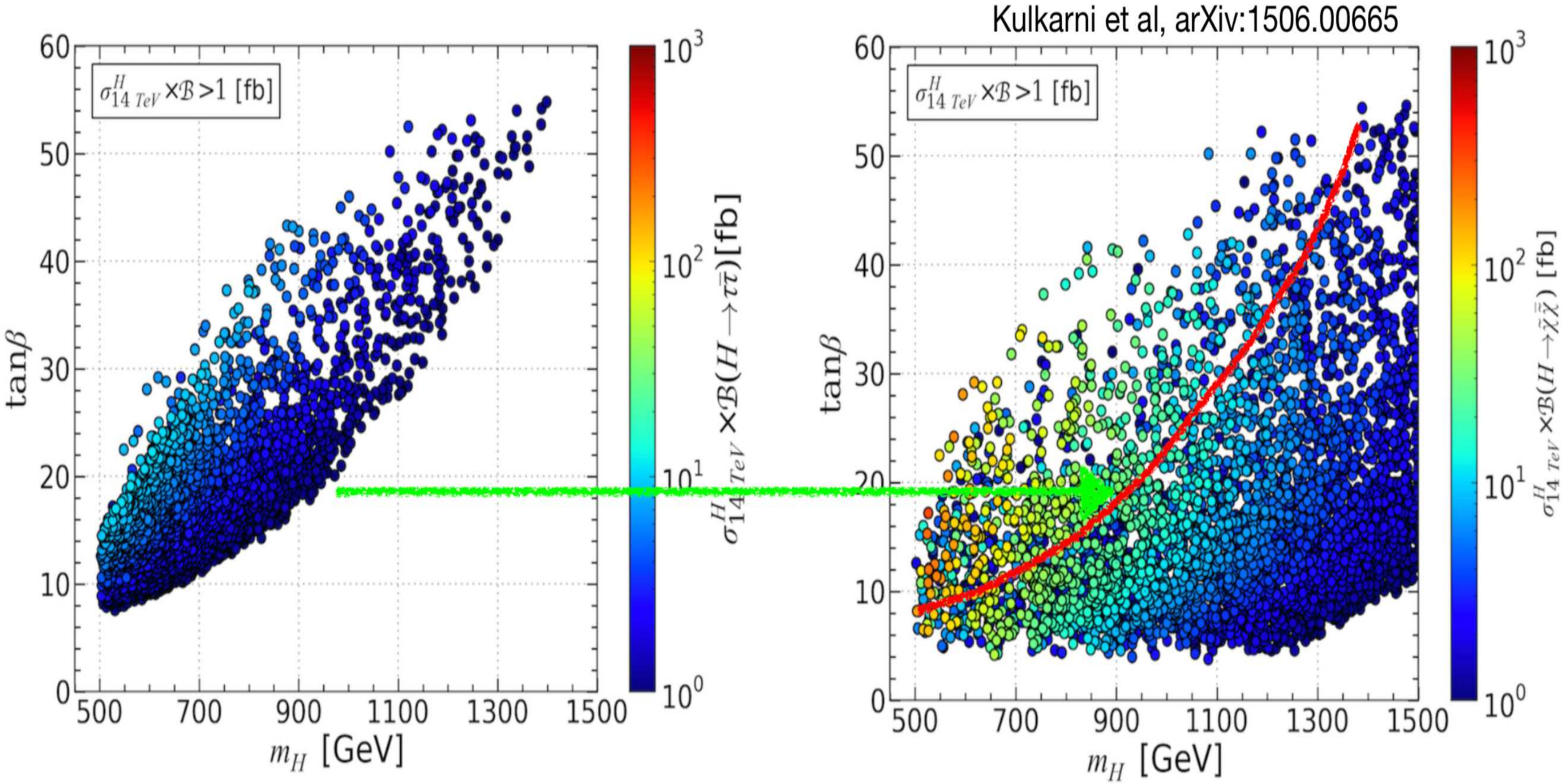
Mono-X S. Gori, Z. Liu and B. Shakya, JHEP **04** (2019), 049; **A. Adhikary et al, JHEP 04, 284 (2021)**; S. Baum, K. Freese, N. R. Shah and B. Shakya, Phys. Rev. D **95** (2017) no.11, 115036;R. K. Barman, B. Bhattacherjee, A. Chakraborty and A. Choudhury, Phys. Rev. D **94**, no.7, 075013 (2016)

We study resonant production of $pp \to H/A \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$, the $\tilde{\chi}_2^0$ further decaying to a $\tilde{\chi}_1^0 + h$ or $\tilde{\chi}_1^0 + Z$. The final state is $l^+ l^-$ or $b\bar{b}$ + missing E_T.

Please note here we are NOT restricting to the low mass $\tilde{\chi}_1^0$. But compared to others, we do take into account the SUSY background, which will give rise to the same final states. Also we study in detail the $bb \to H/A \tilde{\chi}_1^0 \tilde{\chi}_2^0$ as well.

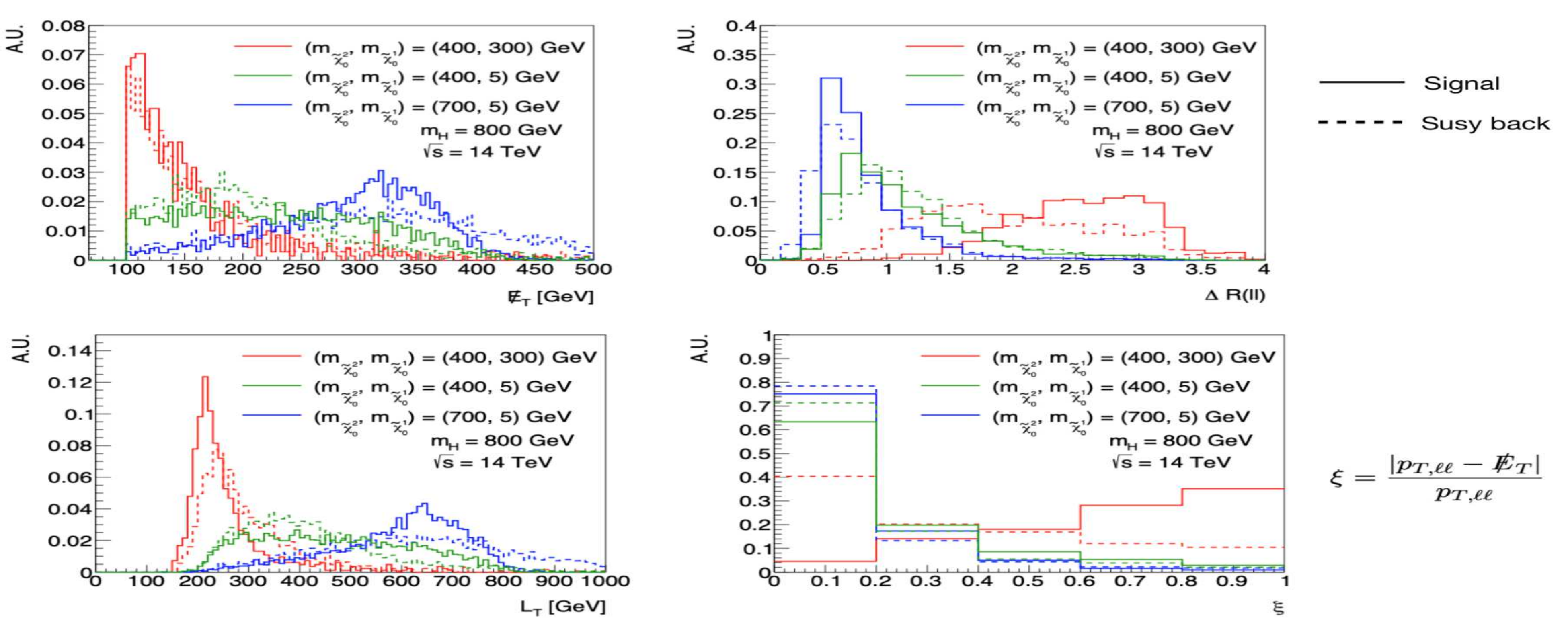
Heavy Higgs into electroweakinos complementary to SM final states.

(See also: Arbey et al. arXiv:1303.7450, Barman et al. arXiv:1607.00676, Bagnaschi arXiv:1808.07542).



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.



A light LSP in pMSSM is still possible: light $\tilde{\chi}_1^0$. Only h_{125} funnel region is allowed.

In NMSSM a light LSP is allowed. Only thermal scenario studied. Direct detection, LHC searches and invisible branching ratio of the Higgs all offer probes of the scenario.

pMSSM extended with a $\tilde{\nu}_R$: a light $\tilde{\nu}_R$ still possible. Characteristic signals.

We can see that this WIMP paradigm for a light LSP in pMSSM and NMSSM can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

Heavy Higgs decays into electroweakino final state an area of rich phenomenology.