Light LSP and Heavy Higgs

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IOP, Bhubaneswar.

- Introduction.

- Low mass (mostly $m_{LSP} < m_{h_{SM}}/2$) DM in SUSY.

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

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

3 Heavy Higgs decays into Eweakinos

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.

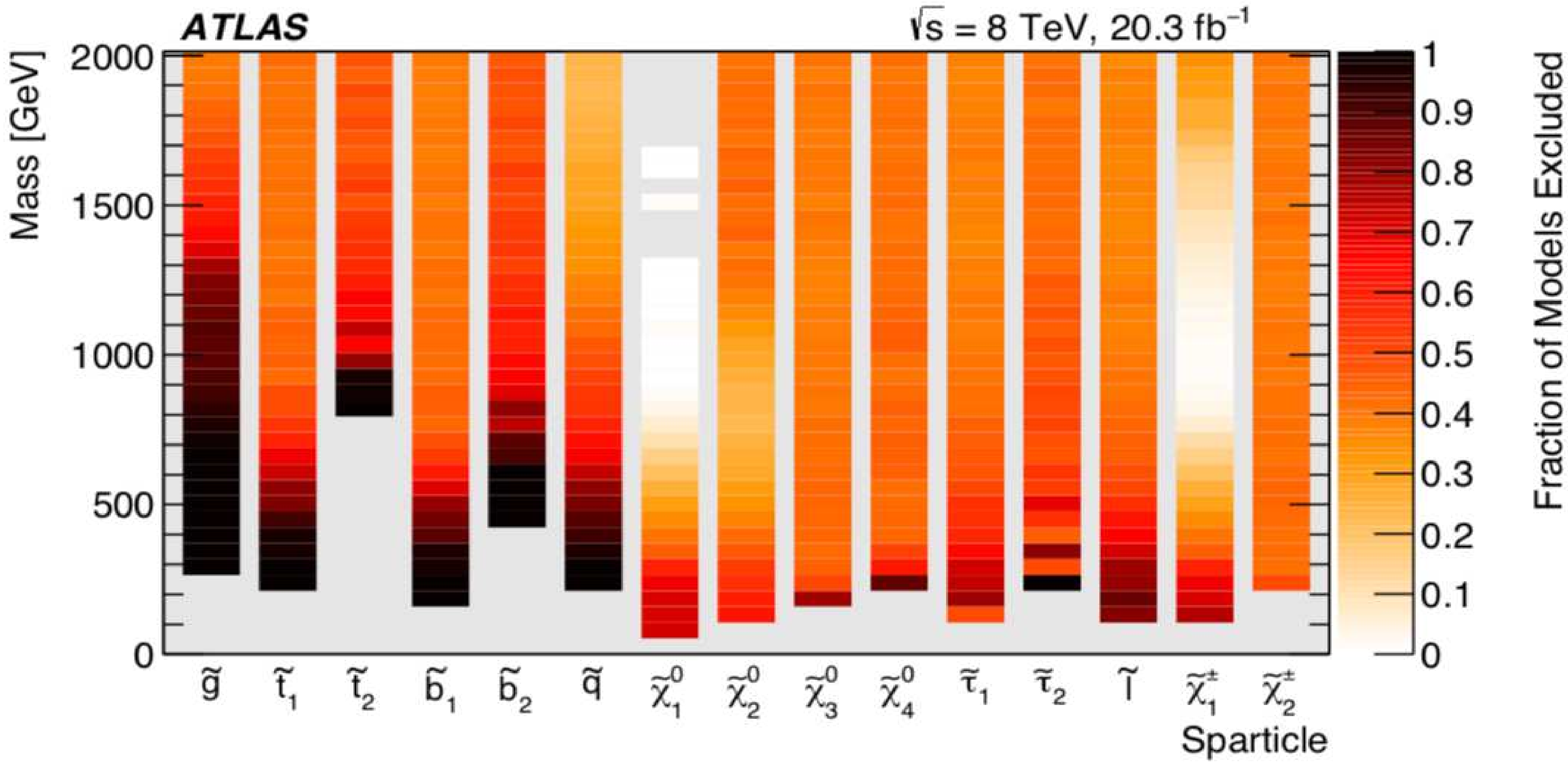
But LHC results have put the idea of 'natural' SUSY under stress and the XENON-1T, PandaX (4T), LZ results have put the WIMP paradigm under stress.

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! From the PDG

However, for the best fit points of various SUSY analyses LSP has mass a few hundred GeV! (Bagnaschi et al, arXiv: 1610.10084)

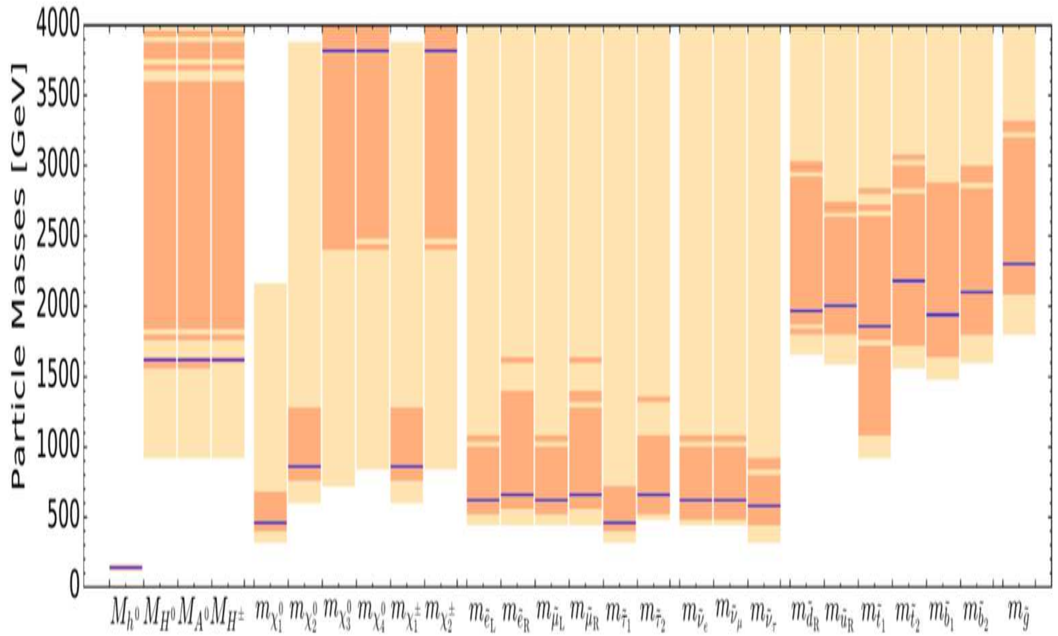
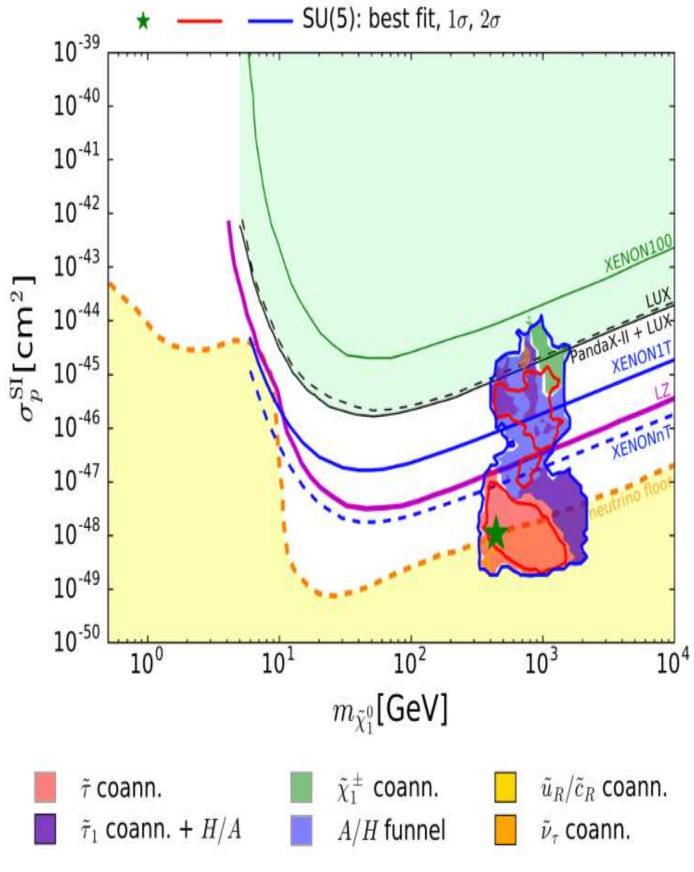


Fig. 12 The one-dimensional 68 and 95% CL ranges of masses we obtain for the current fit in the supersymmetric SU(5) model, shown in dark and light orange, respectively. The best-fit point is represented by blue lines



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).

There are newer (and higher) limits from analysis of hadronically decaying boosted bosons ATLAS, Phys. Rev. D, 104 (2021) 112010. with Wino mass limits going upto 1060 GeV (Higgsino upto 900 GeV), for LSP lighter than 400 (200) GeV. Need large mass difference with the LSP. Will comment about the effect of these results in the end

Critically evaluate the case of a light LSP (in general light EW sector). That is the subject of my talk: A light LSP ($2m_{\tilde{\chi}_1^0} < m_{h125}$)

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!

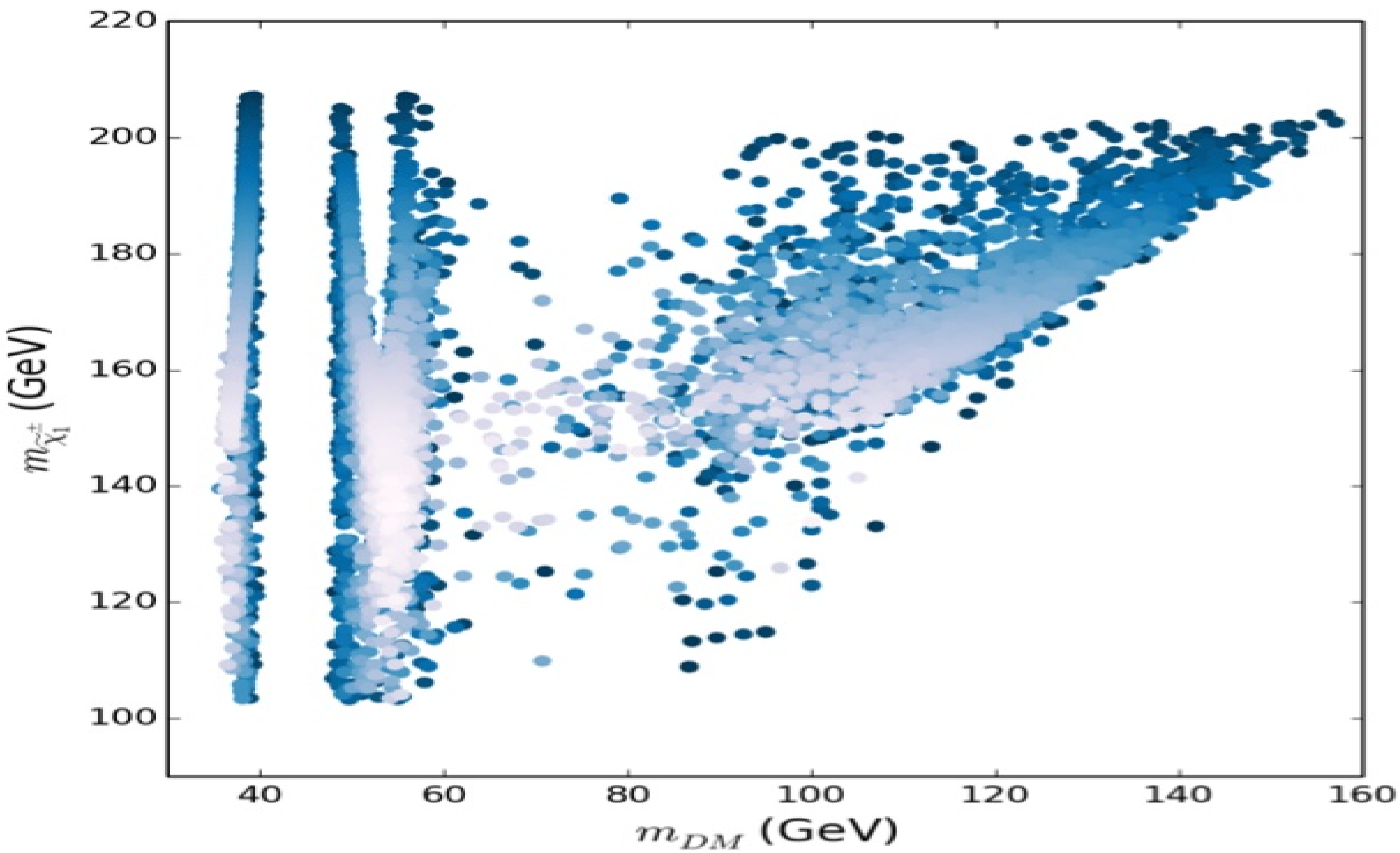
For many people this indicates 'unnaturalness' ! For example Dine: "Naturalness Under Stress"......

(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. More recent JHEP 01 (2020) 147 analysis shows similar results.

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



VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
Department of Physics, University of Texas, Austin, Texas 78712
(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^{\pm}$ and λ^0, lighter than or nearly degenerate with the $W^{\pm}$ and Z^0 gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^{\pm}$ is appreciably lighter than the $W^{\pm}$ it can be readily produced in $W^{\pm}$ decay, as well as in e^+-e^- collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

Weinberg was the first one to point out that the Eweakinos can be lightest part of the SUSY spectrum under certain conditions.

1)SUSY breaking happened through supergravity interactions in the hidden sector (Lykken, Weinberg, Hall, PRD 27, 1983)

2) Minimal Kinetic terms for the Yang Mills Superfields.

Co-GenT, CRESST, CDMS-SI, DAMA/LIBRA:

C.E. Aalseth et al. Phys. Rev. Lett., 106:131301, 2011. arXiv: 1002.4703. G. Angloher et al. Eur. Phys. J. C, 72:1971, 2012. arXiv: 1109.0702. Z. Ahmed et al. Science, 327:1619–1621, 2010. arXiv: 0912.3592. R. Agnese et al. Phys. Rev. Lett., 111(25):251301, 2013. arXiv: 1304.4279.

R. Bernabei et al. Eur. Phys. J. C, 67:39–49, 2010. arXiv: 1002.1028; R. Bernabei et al. Eur. Phys. J. C, 74(3):2827, 2014. arXiv: 1403.4733.

The DD reports are ruled out by Xenon, LUX

The indirect detection (Fermi-LAT) reports are 'clouded' by astro-physical uncertainties.

L. Goodenough et al. arXiv: 0910.2998. D. Hooper et al. Phys. Lett. B, 697:412–428, 2011. arXiv: 1010.2752, D. Hooper et al. Phys. Rev. D, 84:123005, 2011. aeXiv: 1110.0006, T. Daylan et al. Phys. Dark Univ., 12:1–23, 2016.

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 $\sim$ MeV and less than a few GeV $\tilde{\chi}_1^0$ (neutralino in SUSY) can be allowed.

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

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

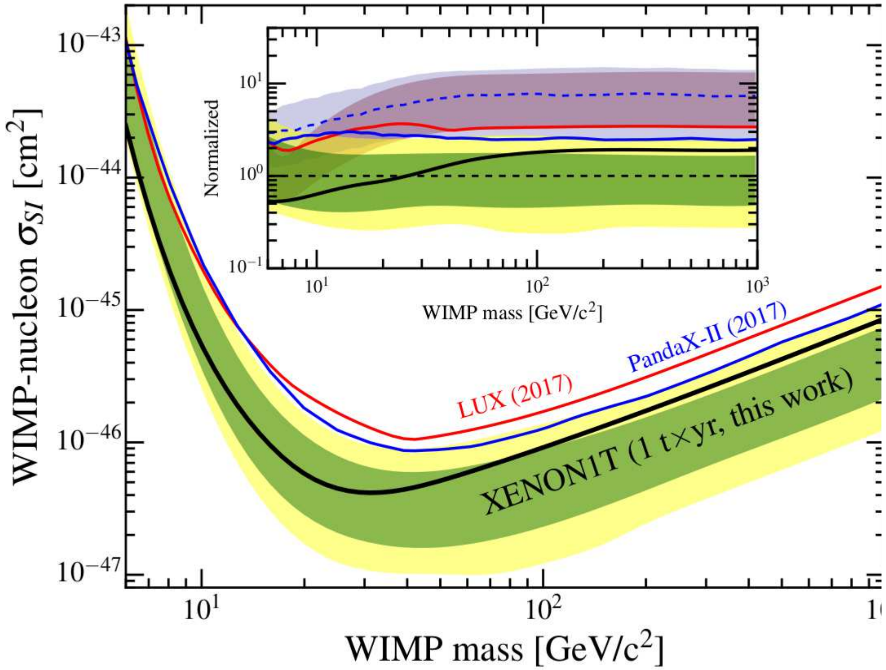
Major part of the discussion will talk about usual thermal relic.

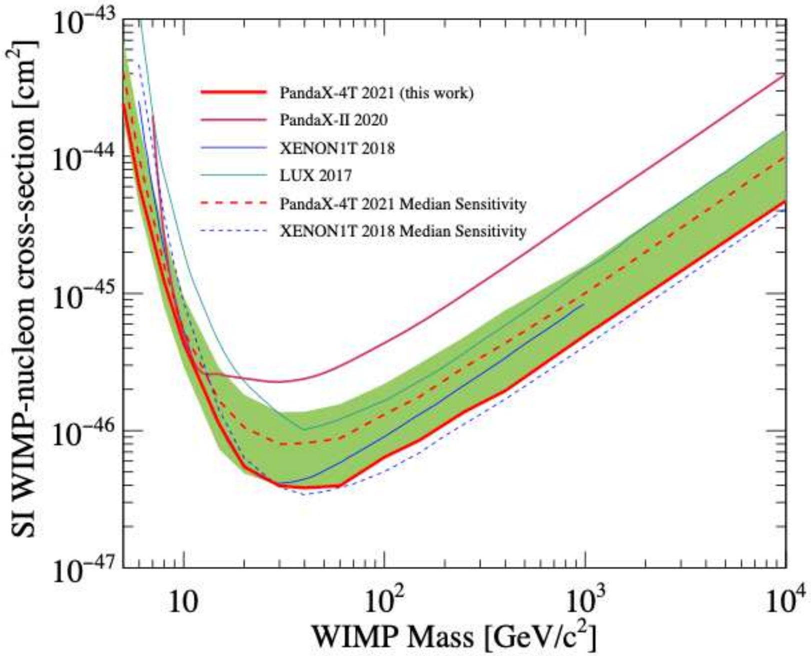
Recall:

Possibilities with freeze in and freeze out also exist.

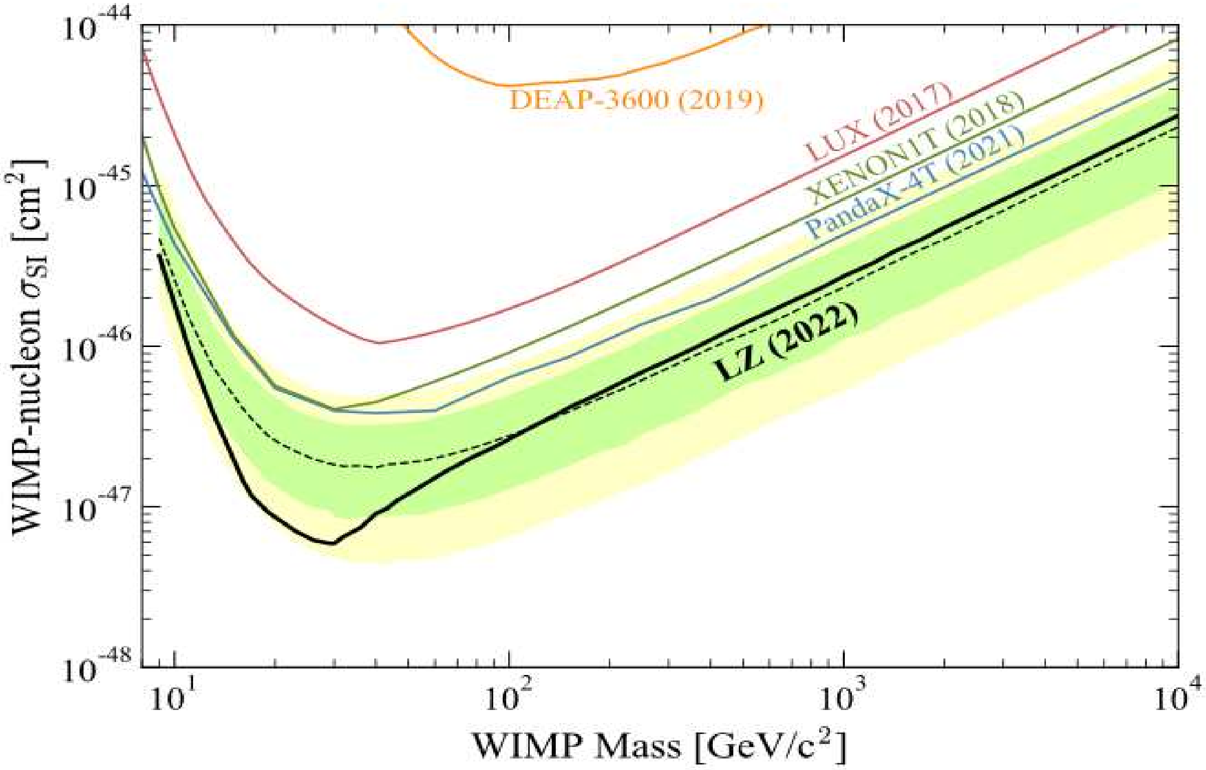
Further late time entropy injection can also make the relic consistent with observed relic.

The current status of the best limits from Direct Detection, straining the WIMP paradigm! Changing landscape of sitings of light DM in direct/indirect detection expts!





Xenon-1T(PRL, 111302 (2018)) PandaX-4T (PRL, 127, 261802, (2021))



This is data from only the first 60 days of exposure. The most stringent limit is set for spin-independent scattering at 30 GeV, excluding cross sections above $5.9 \times 10^{-48} cm^2$ at the 90% confidence level.

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.

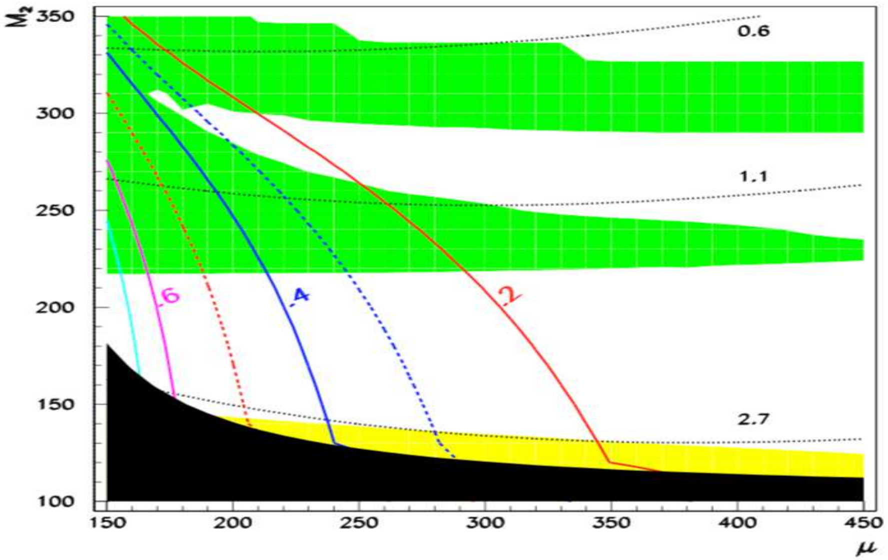
The extent of this mixing decides couplings of the $\tilde{\chi}_1^0$ with all the SM and (N)MSSM particles.

A Wino like or Higgsino like $\tilde{\chi}_1^0$ will have to be heavy ($\sim$ TeV) to explain the observed relic due to the high cross-sections. 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 its 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'.

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"

Till the DM detection experiments came in full swing the collider bounds dominated the story. 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. Focus moved to the pMSSM

G. Belanger, F. Boudjema, F. Donato R. M. Godbole and S. Rosier-Lees, Nucl. Phys. B **581**, 3 (2000), Phys. Lett. B 519 (2001) 93-102.

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

A light LSP can contribute to the 'invisible' decay of the Higgs.

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 limit from the LHC is ~13%. ATLAS-CONF-2020-008 and ~14.5% ATLAS: submitted to JHEP, 2202.07953

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 %

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

1)Look for Mono events or LLP. Not effective for light LSP.

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.

Now we have

1)precise determination of relic,

2)strong constraints from Direct Detection

3) LEP/LHC searches for electroweakinos

4)**Higgs detection and measurements**

5)precision calculations of the Higgs mass

6) measurements of the invisible width of the Higgs.

What is the situation now?

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 non observation 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 + $\tilde{\nu}_R$

A 'light' $\tilde{\chi}_1^0$ DM at the collider in pMSSM (2017):

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:

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

Analysis from 2017:

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.

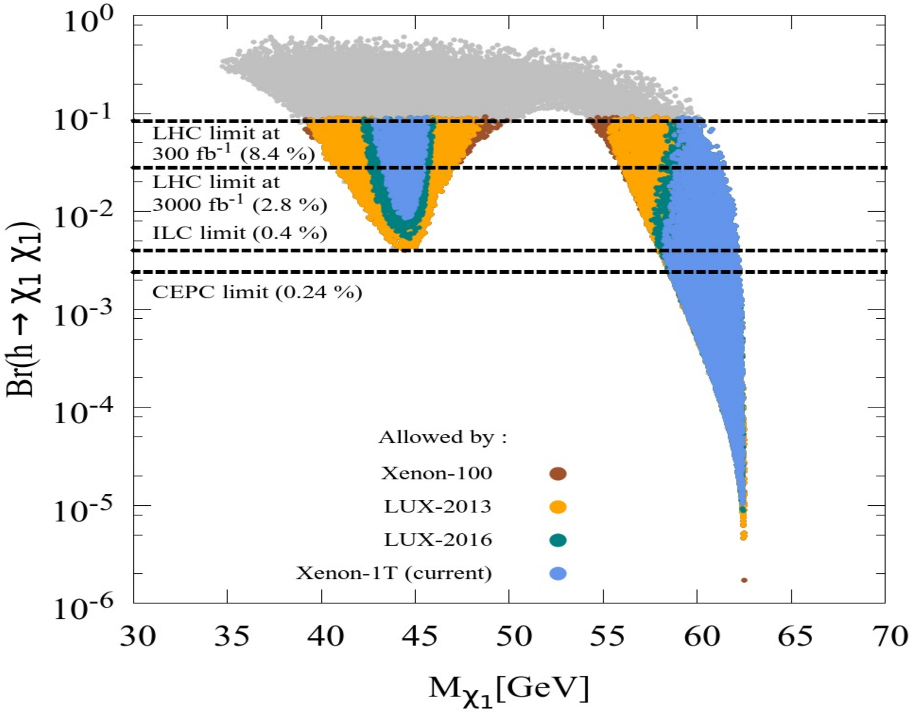
2)Calculate the invisible branching ratio for the Higgs.

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

4) Calculate the relic density for the given point.

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

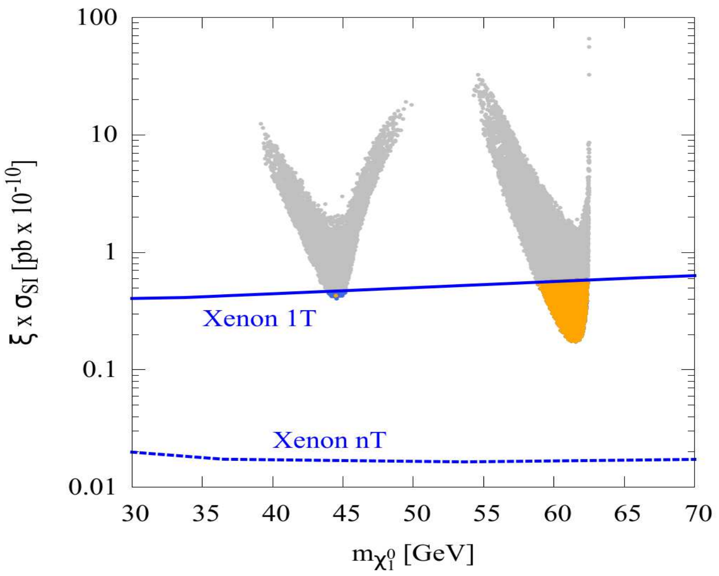
$\xi \leq 1$: Thermal DM



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.

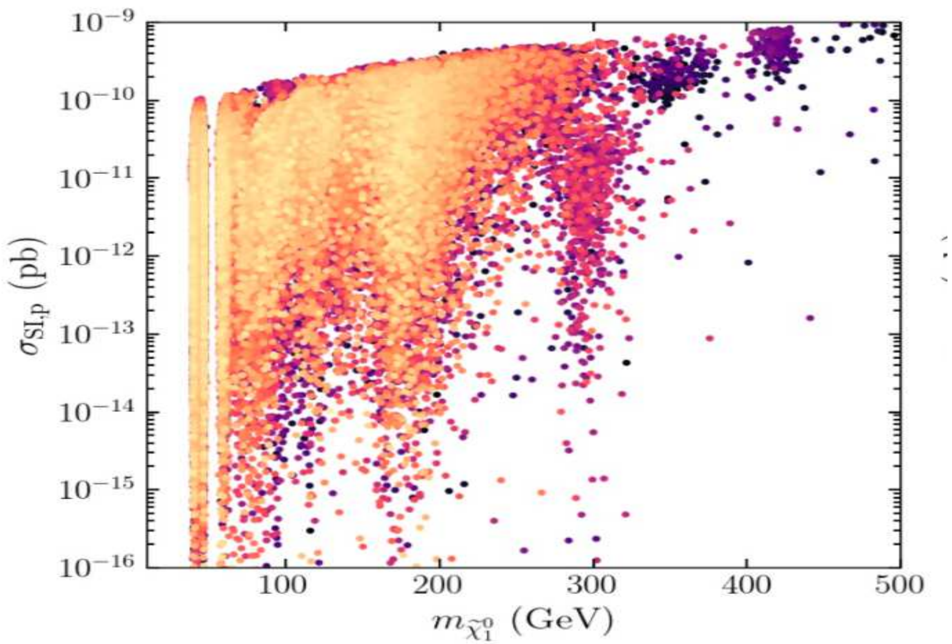


R, K. Barman, G. Bélanger, R. Godbole, 'Low mass LSP in SUSY' , Eur.Phys.J.ST 229 (2020) 21, 3159-3185

Xenon-1T all but rules out now the Z-funnel region. Points still allowed by current LHC Electro-weakino searches.

Production of electro weakino 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. HL/LHC can cover most of the region still allowed by the current electro-weakino searches and DD.

Situation for -ve μ slightly different. Currently investigating. (B., Bhattacharjee, R. K. Barman, G. Belanger, R. Godbole and R. Sengupta.)

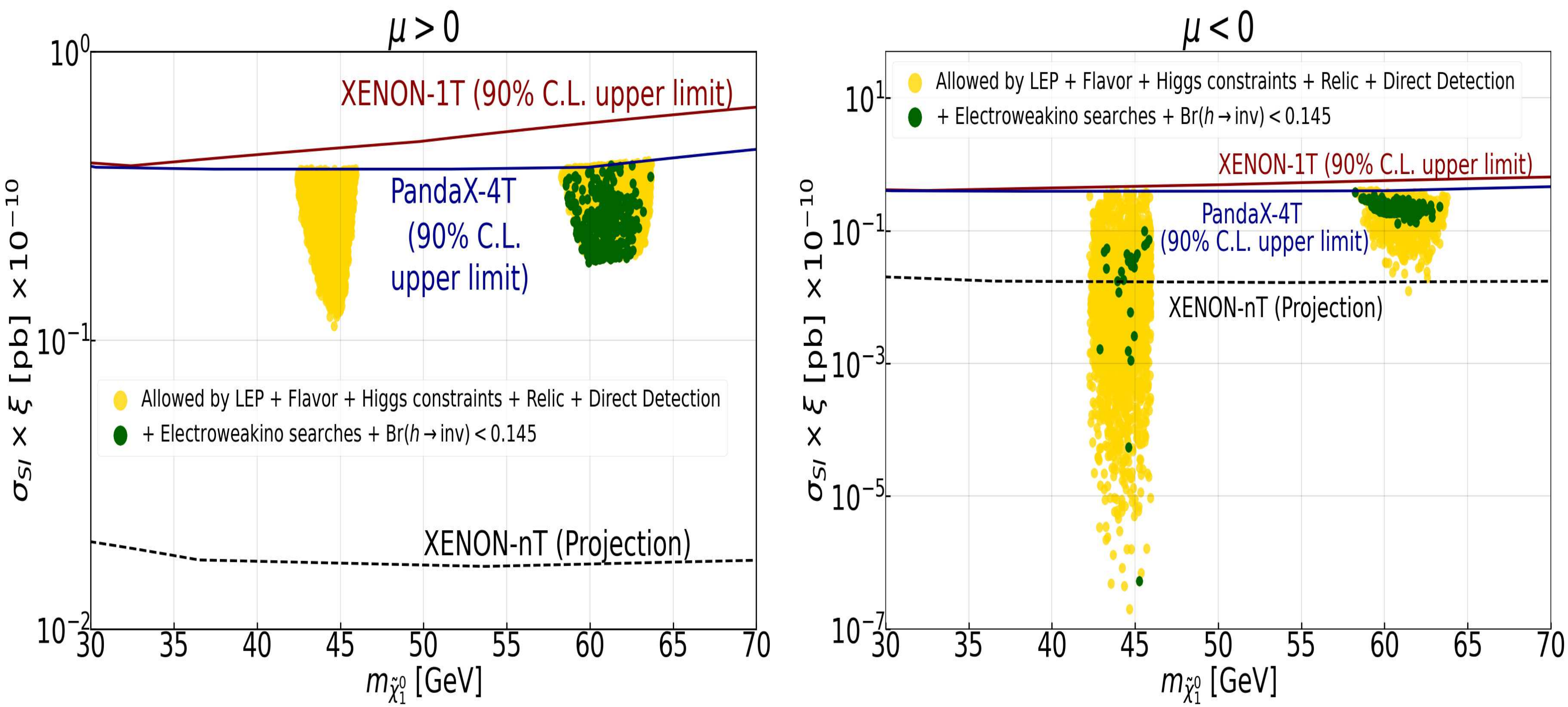


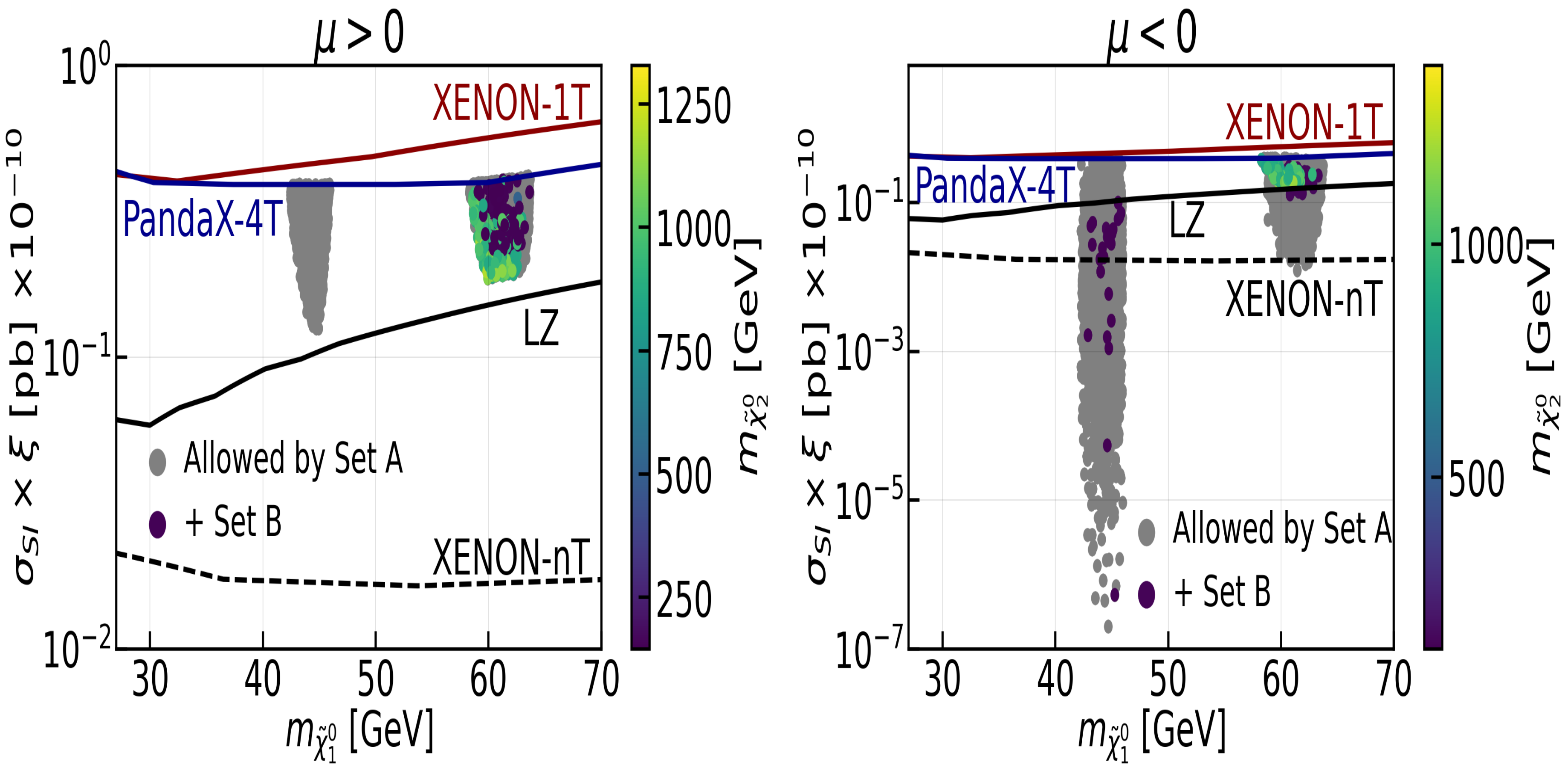
As said before we do need more scrutiny of the region $m_{\tilde{\chi}_1^0} \sim m_Z/2$.

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

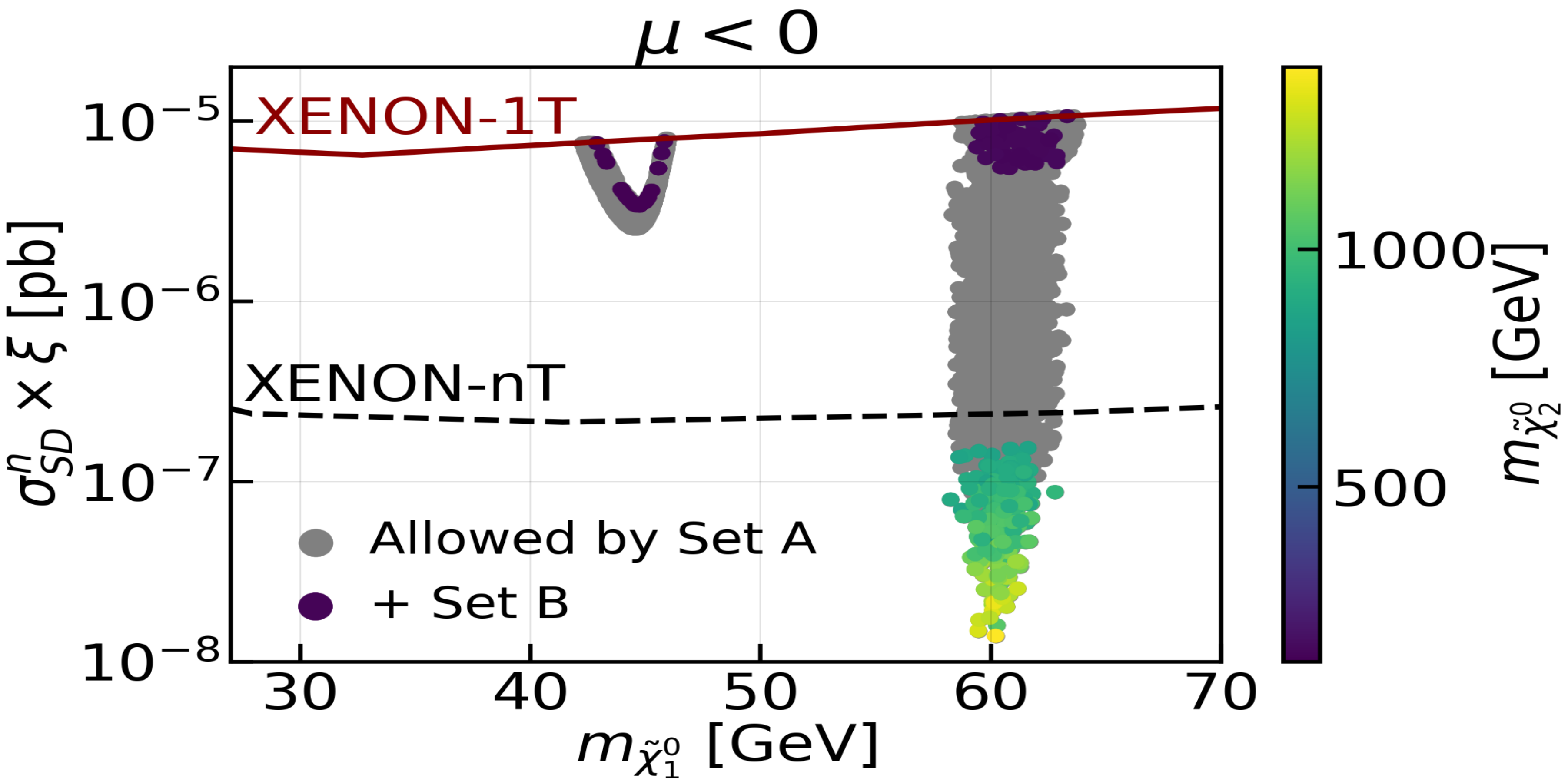
This analysis looks at PMSSM allowed spectra in light of current data and (g-2). The Δ_{EW} smallest if LSP is lighter than 100 GeV.

We extended the scan region by adding $\mu < 0$, have done more dedicated scanning to focus on light masses, applied the latest collider bounds on electroweakinos using Smodels. (R. Barman, G. Belanger, B. Bhattacharjee, R.G., Rhitaja Sengupta In Progress.)

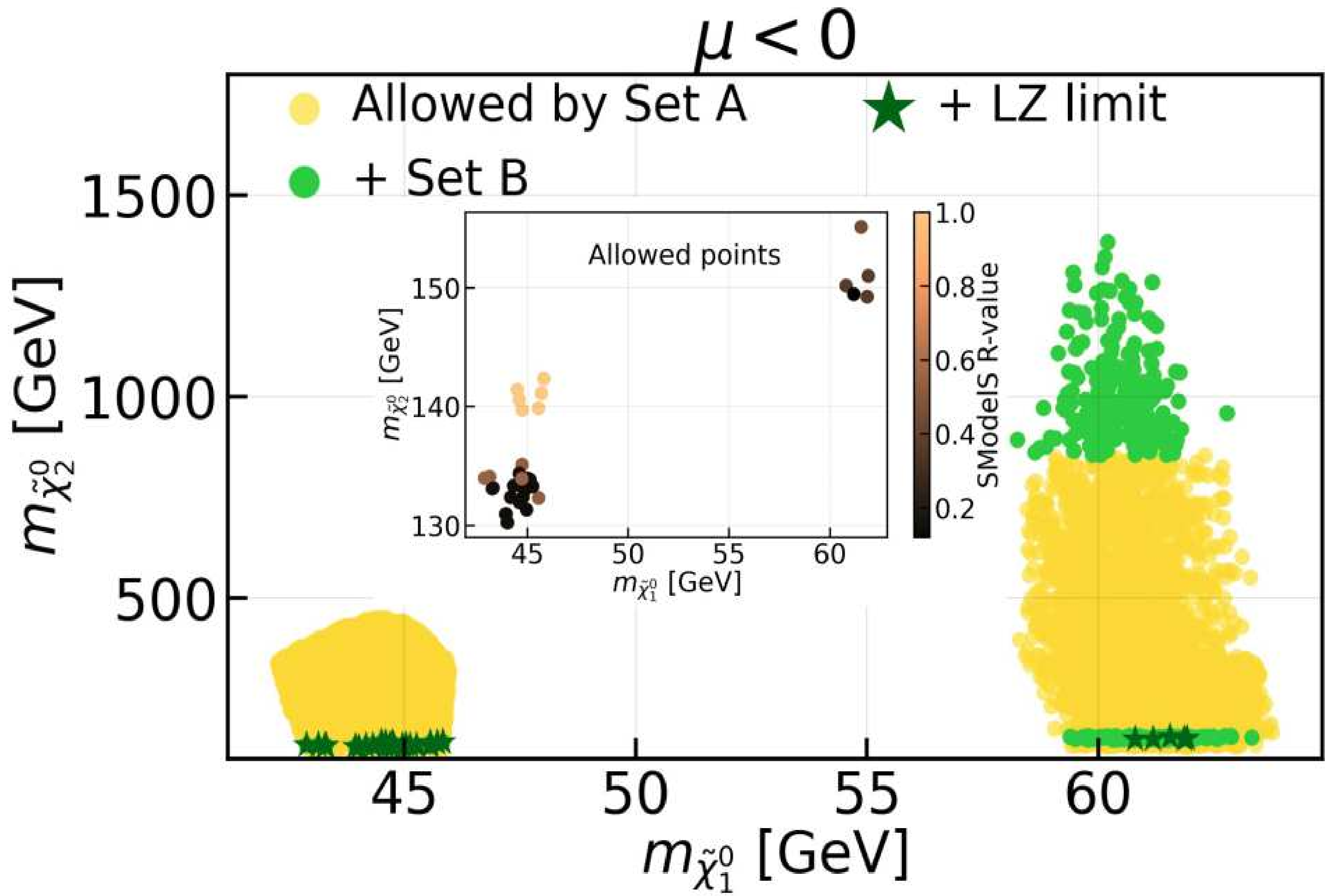




2207.06238 : R.K. Barman, G. Belanger, Biplob Bhattacharjee, R.G., Rhitaja Sengupta. Set A: without LHC EW searches, SET B: with EW searches.



2207.06238 : R.K. Barman, G. Belanger, Biplob Bhattacharjee, R.G., Rhitaja Sengupta



$\mu < 0$
Allowed by Set A
+ LZ limit
+ Set B
Allowed points
SModelS R-value
$m_{\tilde{\chi}_2^0}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]

2207.06238

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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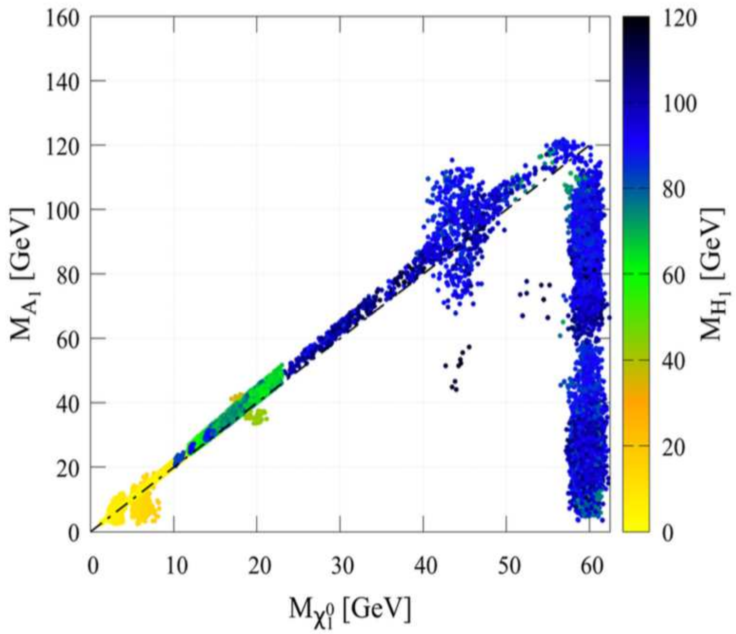
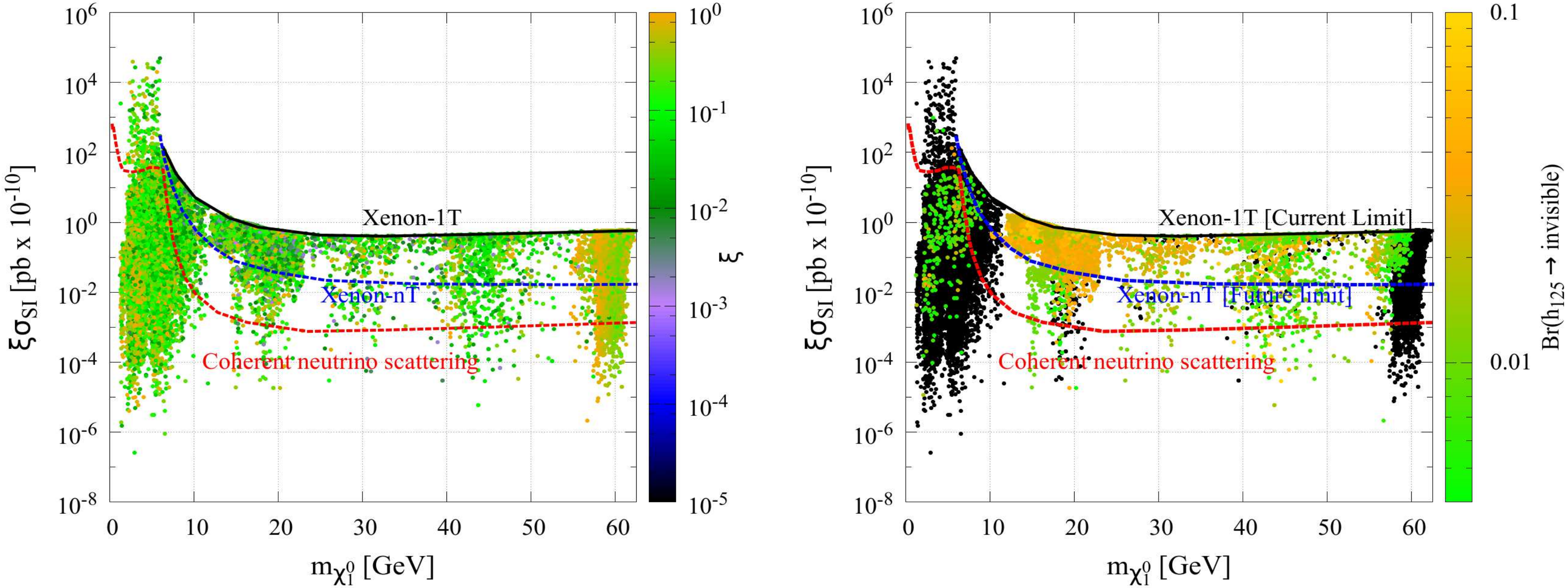


h_2 identified with the observed SM -like Higgs. Possibility of a light singlet dominated h_1, a_1 lighter than 122 GeV.

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

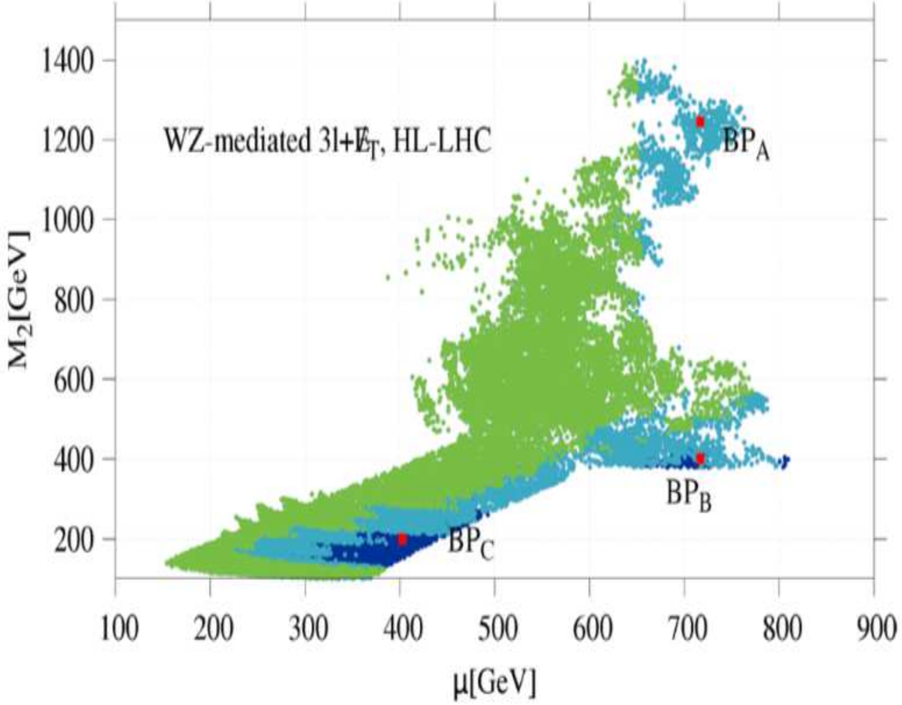


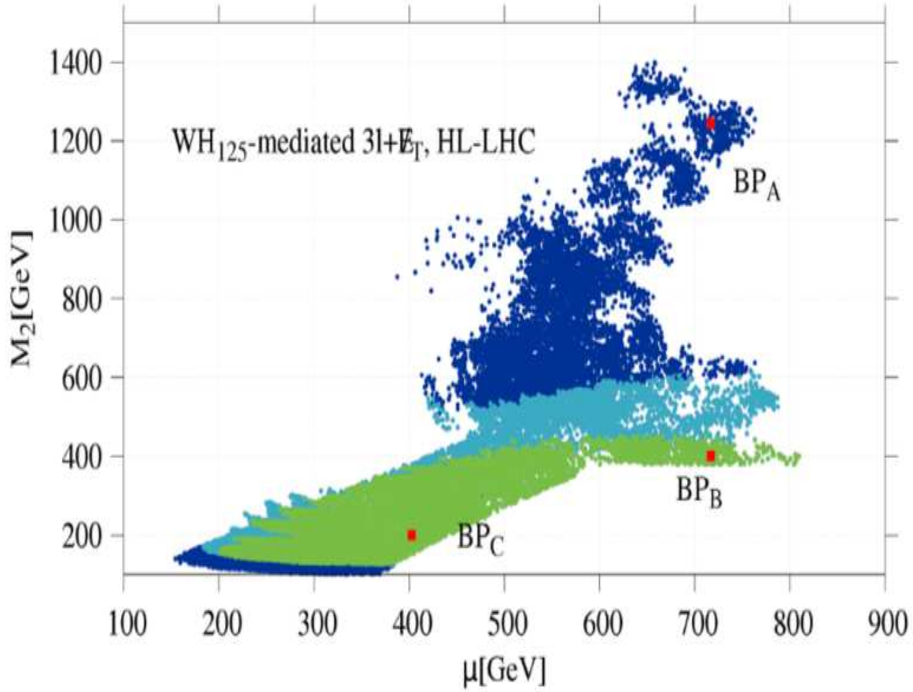
R. K. Barman, G. Bélanger, B. Bhattacherjee, R. Godbole, D. Sengupta and X. Tata, Phys. Rev. D **103**, no.1, 015029 (2021)

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!





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.

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.

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.

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

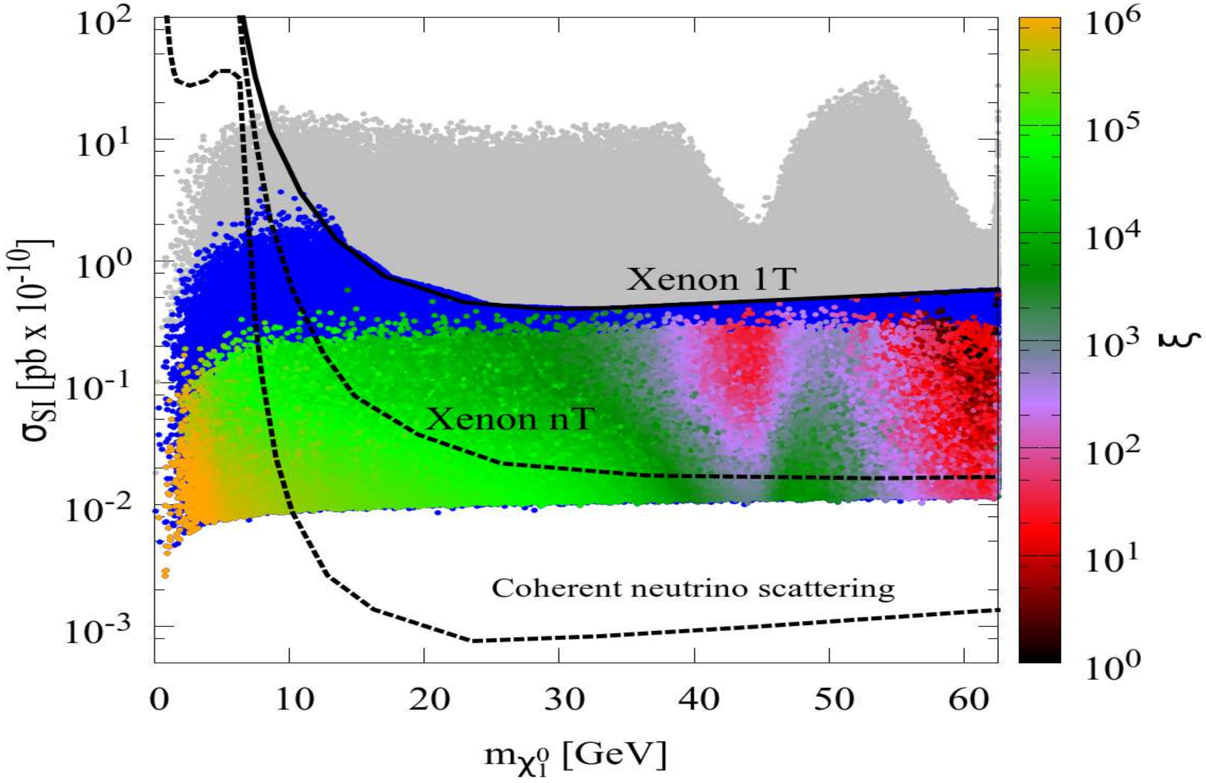
one can think of 'nonstandard cosmology'. The thermal relic might be above the observed relic, but there might be a period of entropy injection which will dilute the relic density to the 'measured' value.

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 can work!



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!

A light LSP in pMSSM is almost ruled out: light $\tilde{\chi}_1^0$. Both the h and Z funnel regions under stress in PMSSM. Allowed points not at the boundary of current exclusion. R values are small.

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 as **thermal** DM is all but ruled out. A very tiny region is allowed. Case different for NMSSM. For pMSSM light LSP as DM allowed only for non thermal scenario. Both can be tested at the HL/HE LHC, ILC/CEPC and DD experiments.

.Lot of work on heavy Higgs pheno:

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)

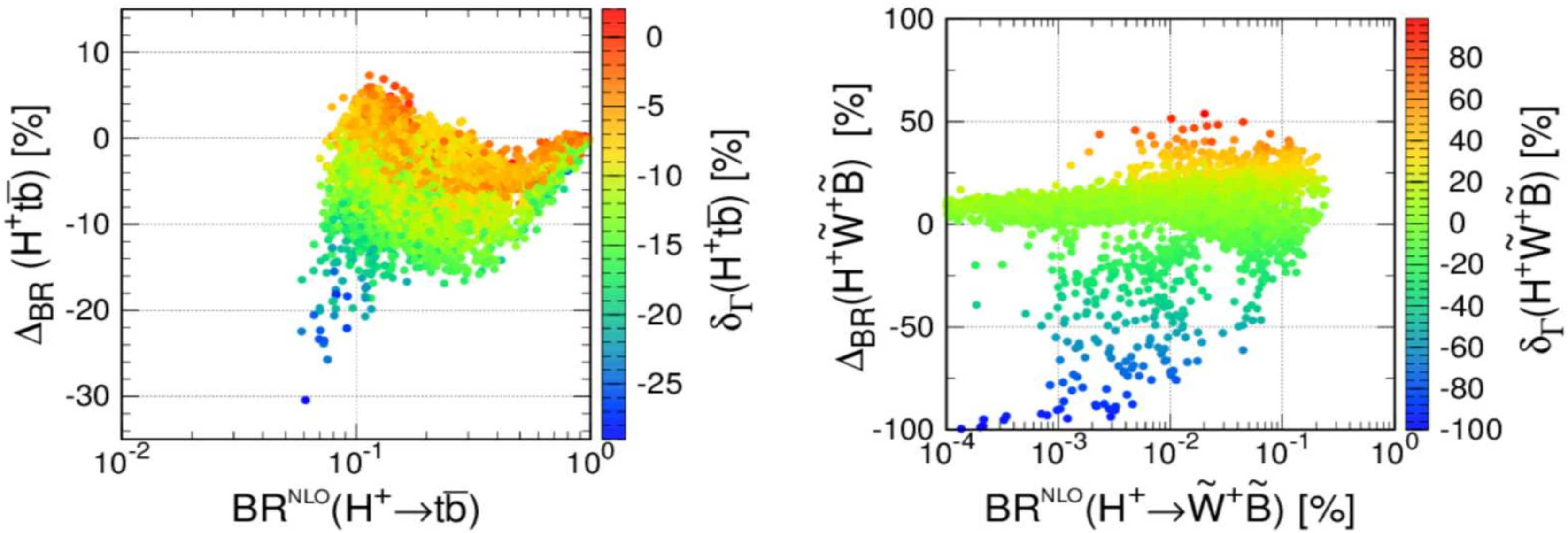
A very complete phenomenological analysis of heavy Higgs searches in SM final states , see eg., R. K. Barman, B. Bhattacherjee, A. Choudhury, D. Chowdhury, J. Lahiri and S. Ray, Eur. Phys. J. Plus **134**, no.4, 150 (2019).

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

i) 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)

ii) LLP final states?

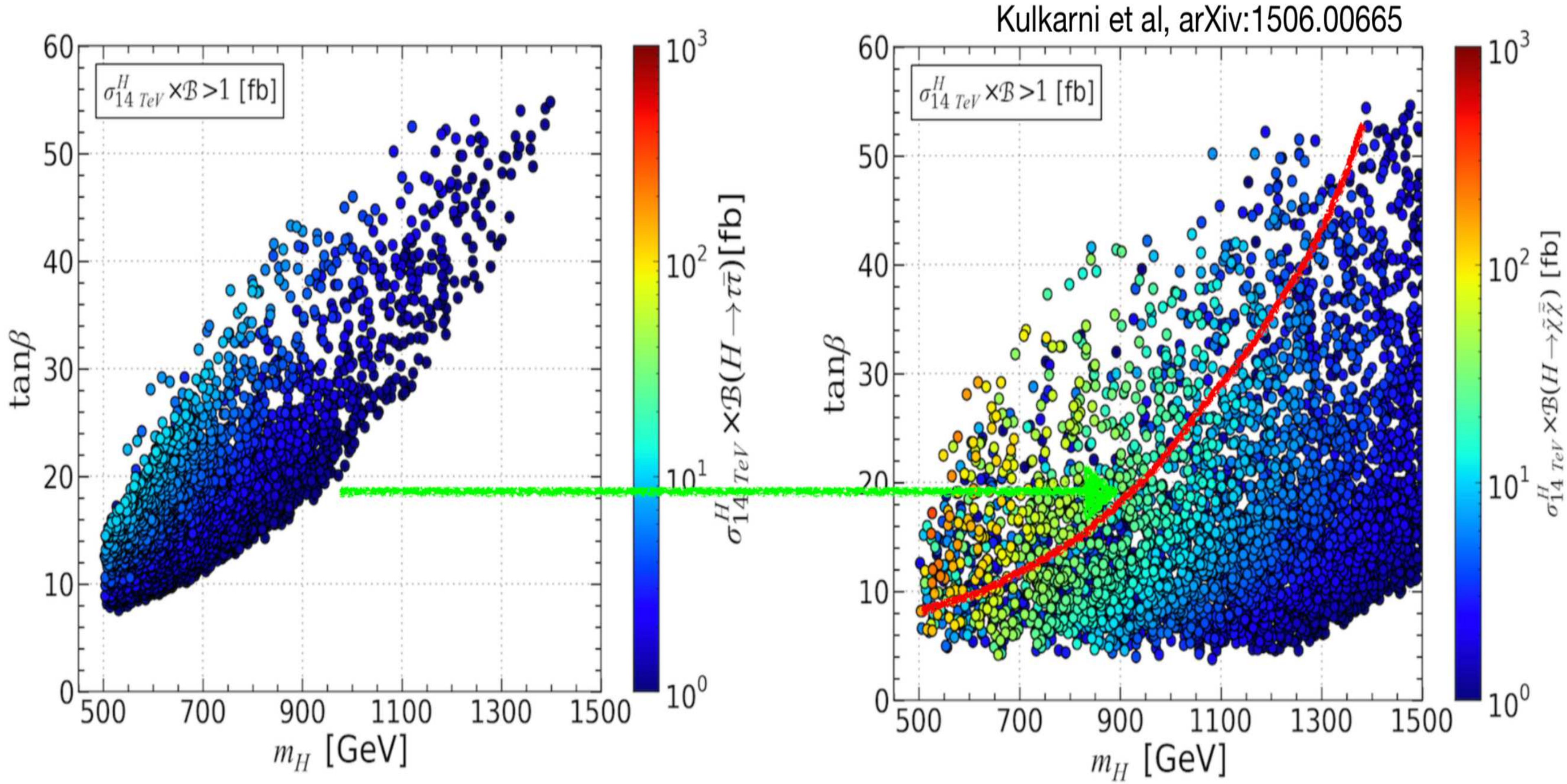
Impact of NLO on Branching ratios:



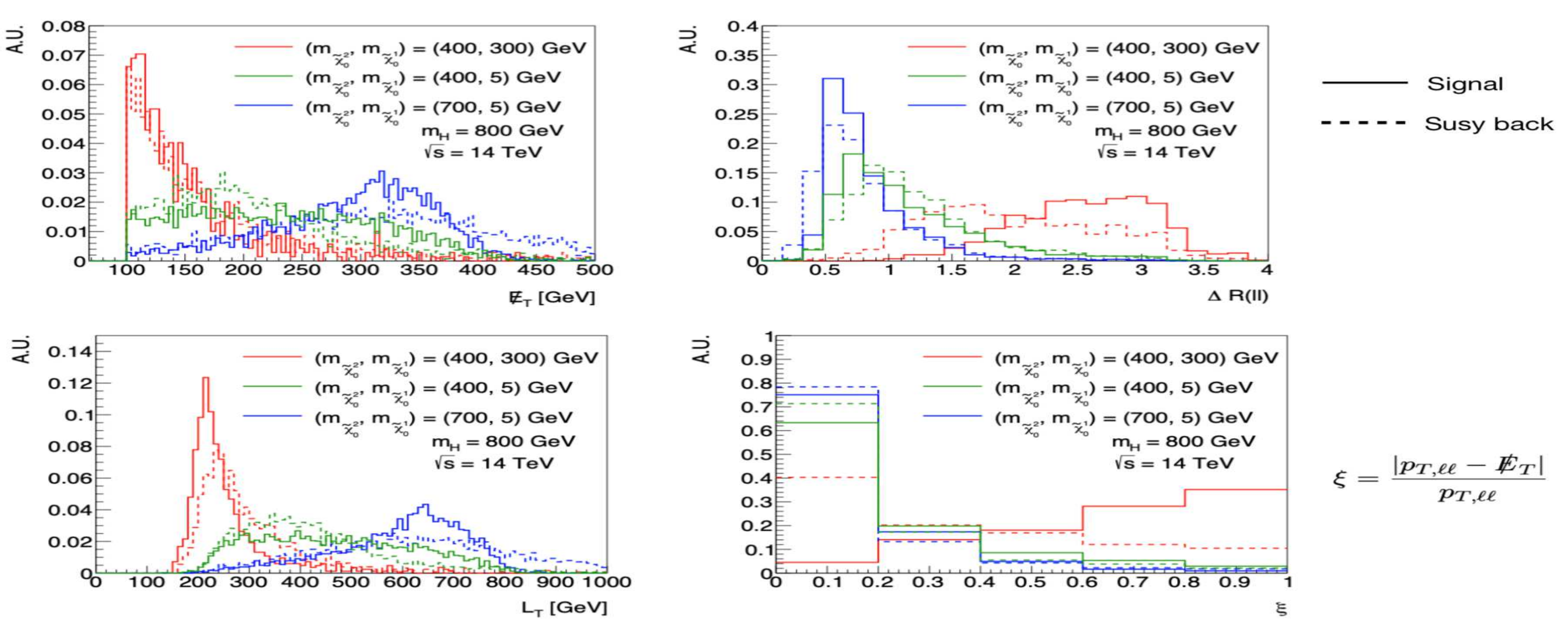
Ref: T. N. Dao, M. Muhlleitner, S. Patel and K. Sakurai, Eur. Phys. J. C **81**, no.4, 340 (2021)

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.Adhikary parallel session)



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