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Dark Matter prospects in MSSM, NMSSM and $U(1)$ extended SM.

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Outline

1. Invisibly decaying Higgs boson in MSSM
2. The current status and future prospects of neutralino DM in NMSSM
3. Strongly-interacting thermal WIMPs in $U(1)_D$ extended SM

Outline for Section 1

1. Invisibly decaying Higgs boson in MSSM
   - Based on Phys. Rev. D 95, 095018,
     RKB, Genevieve Belanger, Biplob Bhattacherjee, Rohini Godbole, Gaurav Mendiratta, Dipan Sengupta
2. The current status and future prospects of neutralino DM in NMSSM
3. Strongly-interacting thermal WIMPs in $U(1)_D$ extended SM

Motivation

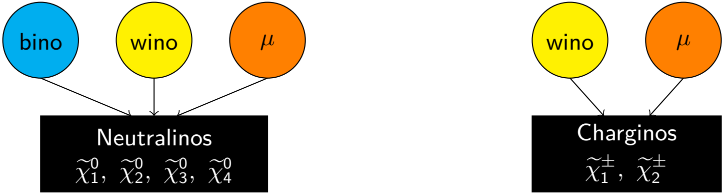
1. The ATLAS and CMS collaborations have umambiguously confirmed the existence of a scalar boson at 125 GeV.
2. The current data still leaves enough space for the Higgs to have non-standard decays.
3. Higgs decaying to invisible particles provides one such exciting prospect.
4. Invisible particles, if stable, could also be the dark matter candidate.
5. Within R-parity conserved SUSY scenarios, the lightest stable particle, typically χ_1^0, naturally provides a DM candidate.
6. Correlations between invisible Higgs, Dark Matter and collider signatures of SUSY, can provide interesting clues towards understanding the nature of DM.

The MSSM parameter space

- Our region of interest: The Higgs and electroweakino sectors.

- gaugino mass parameter (M_1, M_2)
- $\tan\beta$
- stop trilinear coupling (A_t)
- higgsino mass parameter(μ)
- third generation squark mass parameter
- gluino mass parameter(M_3)

Relevant input parameters



We focus upon the region with

$$M_{\widetilde{\chi}_1^0} < (M_{H_{SM}}/2 \sim 62.5 \text{ GeV})$$

Parameter space scan

- LEP data excludes a chargino mass below ~ 103.5 GeV $\rightarrow$ forces light $\widetilde{\chi}_1^0$ ($M_{\widetilde{\chi}_1^0} \lesssim 62.5$ GeV) to be dominantly bino.
- Annihilation cross-section of a bino-dominated $\widetilde{\chi}_1^0$ is not large enough to be compatible with the observed relic abundance.

Compatibility with relic abundance requires:

Specific mass relations: $M_{\widetilde{\chi}_1^0} \sim M_{res.}/2$, or co-annihilation

Possibilities: $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ annihilation through an intermediate $M_{res.}$ = Z-boson or Higgs boson.

1. Gaugino-higgsino admixture required for coupling with Higgs.
2. higgsino composition solely controls the coupling with Z boson.

Range of parameter space

$$1 \text{ GeV} < M_1 < 100 \text{ GeV}, \quad 90 \text{ GeV} < M_2 < 3 \text{ TeV}$$
$$1 < \tan\beta < 55, \quad 70 \text{ GeV} < \mu < 3 \text{ TeV}$$

Limits on invisibly decaying Higgs

- LHC : Direct Searches

Current limits

CMS : $Br(H \to inv.) \sim 24$ %, ATLAS : $Br(H \to inv.) \sim 28$ %

Projections

CMS : $Br(H \to inv.) \sim 17 - 28$ % at 14 TeV, 300 fb^{-1} and $6 - 17$ % at 14 TeV, 3000 fb^{-1}.

ATLAS : $Br(H \to inv.) \sim 23 - 32$ % at 14 TeV, 300 fb^{-1} and $8 - 16$ % at 14 TeV, 3000 fb^{-1}.

- Global fits to the Higgs coupling measurements offers '*indirect*' probe of the 'Higgs invisible' branching ratio : Stronger limits [Current : ~ 10 %, Projections for HL-LHC : ~ 5%]
- e^+e^- colliders offer the best sensitivity :

ILC : $Br(H \to inv.) \sim 0.4$ %.
CEPC : $Br(H \to inv.) \sim 0.28$ %.

Constraints

- Higgs mass is restricted between $122 - 128$ GeV.
- Flavor Physics Observables:
  Allowing 2σ uncertainty with respect to the measured values, we imposed
  - $B_d \to X_s \gamma = (3.32 \pm 0.15) \times 10^{-4}$
  - $B_s \to \mu^+\mu^- = 2.8^{+0.7}_{-0.6} \times 10^{-9}$.
- LEP limits :
  - Chargino mass : $M_{\tilde{\chi}_1^\pm} > 103$ GeV .
  - The neutralino pair production cross-section : $\sigma_{\tilde{\chi}_1^0 \tilde{\chi}_2^0} < 0.1$ pb
- An upper limit on the Higgs boson width is imposed, $\Gamma_h < 22$ MeV.
- Higgs data: Limits have been obtained by CMS and ATLAS, corresponding to LHC Run I data, on signal strength parameters, defined as :

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \times (\mathrm{BR}^f)_{\mathrm{SM}}},$$

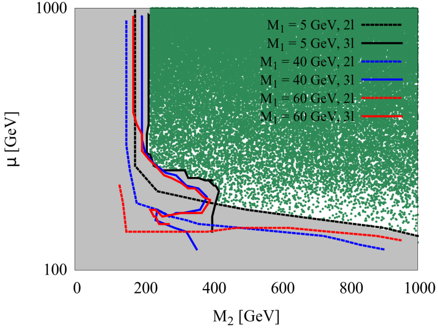
Production modes : ggF, VBF, VH , $t\bar{t}h$
Decay channels : $\gamma\gamma$, $b\bar{b}$, $\tau^+\tau^-$, ZZ^*, W^+W^{-*}

Constraints from direct electroweakino searches

The processes of interest for us are :

- $pp \to \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^{\pm} \to l^+l^- + \not{E}_{\mathrm{T}}$
- $pp \to \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^{0} \to 3l + \not{E}_{\mathrm{T}}$

- Three discrete value : $M_1 = 5,\ 40,\ 60\ \mathrm{GeV}$ were chosen, and the $\mu - M_2$ plane was randomly scanned. Exclusion lines were derived for the dilepton and the trilepton searches.
- The recasted LHC 8 TeV results in publicly available analyses database of MadAnalysis5 and Checkmate was used.



The thermal and non-thermal region

The allowed parameter space is divided into two regions based on their relic densities :

- $\Omega h^2 \leq 0.122$ [Underabundant : The thermal scenario]
- $\Omega h^2 > 0.122$ [Overabundant : The non-thermal scenario]

In this work, we do not perform any detailed investigation of any specific mechanism which will eventually generate the correct relic density.

We only attempt to decipher clues concerning the characteristics of these two scenarios through a study of complimentarity among the following future experiments:

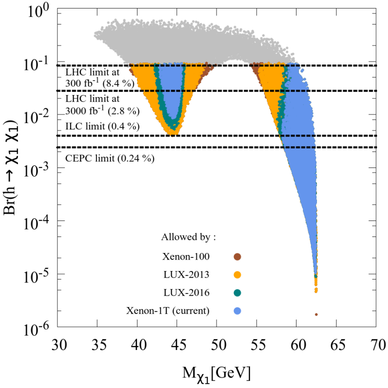
- Higgs invisible width measurements at ILC.
- Future projections of Xenon-nT, PICO-250 and LZ, through SI WIMP-nucleon, SD WIMP-proton and SD WIMP-neutron interactions.

Our motive is to shed some light on the nature of DM and its discovery prospect.

$\Omega h^2 < 0.122$

1. Within our framework, efficient DM annihilation could be achieved only through Z or Higgs exchange.

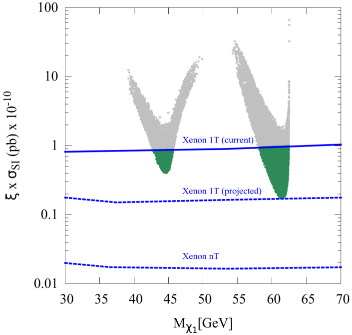
Imposing the relic density bound sets a lower limit on $M_{\tilde{\chi}_1^0} \gtrsim 34$ GeV.

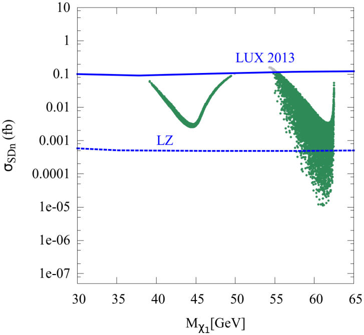


- The signal strength measurements restrict $Br(h \to inv.) \lesssim 10\%$.

  [The 'indirect' constraint in action.]
- The current Xe-1T limits also strongly constrain the parameter space.
- ILC will be able to probe the entire Z funnel region through its sensitivity in the Higgs invisible branching.

Constraints from direct detection





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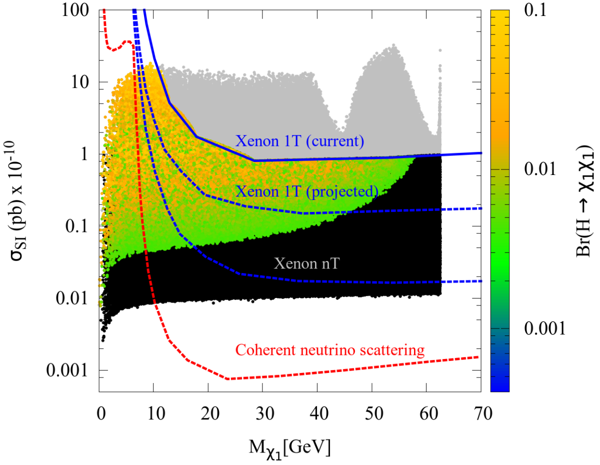
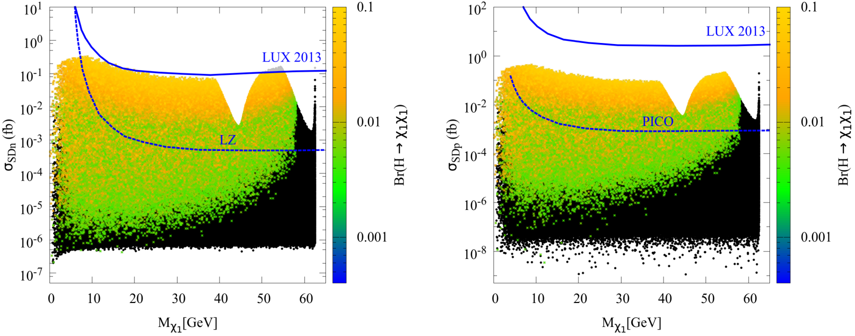
The projected limits from Xe-1T will be able to probe the entire region.

LZ and PICO will also be able to probe the entire Z resonance regions.

1. Lifting the relic density constraint makes it possible to obtain low LSP masses as well.
2. In the low $M_{\tilde{\chi}_1^0}$ region, the Higgs invisible probe at ILC will be much stronger than the sensitivity of the DD experiments.



Constraints from Spin-dependent interactions



Complimentarity of future experiments in probing dark matter

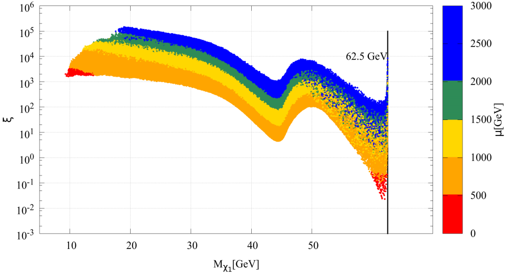
1. In the next few slides, we characterize the different possibilities to identify the nature of dark matter by exploiting the complimentarity between the ILC (through Higgs invisible width or detection of electroweakinos), and the future SI (Xenon-nT) and SD (PICO-250, LZ) direct detection experiments.
2. The limit of detectability for electroweakinos at the ILC : $\mu < 500$ GeV
3. ILC is also projected to have an excellent electroweakino mass measurement capability with an uncertainty of $\lesssim 1$ GeV.
4. Direct detection experiments have a relatively larger uncertainty in LSP mass measurement.

An interesting case :

The following parameter points evade detection at

- PICO-250 (through SD WIMP-proton interaction)
- LZ (through SD WIMP-neutron interaction)
- ILC (through Higgs invisible branching)

However, they are within the sensitivity reach of Xe-nT through SI WIMP-nucleon interaction.



The red coloured points will be sensitive to electroweakino searches at ILC.

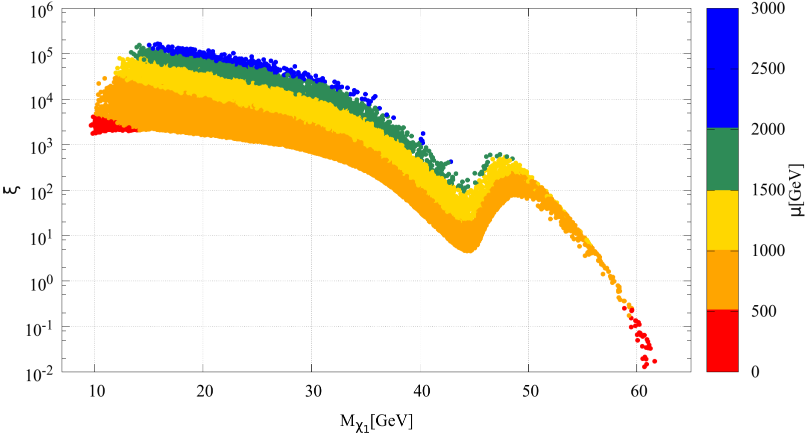
An observation within this scenario would be able to clearly demarcate between a thermal DM and a non standard DM.

A similar spectrum is observed for parameter points with :

- $Br(h \rightarrow inv.) > 0.4\%$.(Sensitive to ILC search)
- Detectable at Xe-nT (through SI WIMP-nucleon interaction)

however, evades detection by

- PICO-250 (through SD WIMP-proton interaction)
- LZ (through SD WIMP-neutron interaction)



Some more constrained scenarios

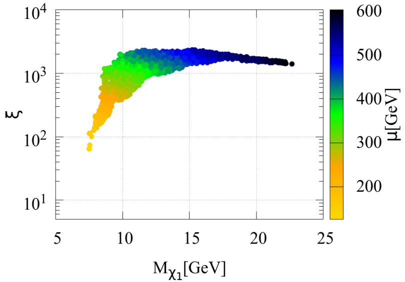
The following parameter space points are visible to

- PICO-250 (through SD WIMP-proton interaction)
- ILC (through Higgs invisible branching)

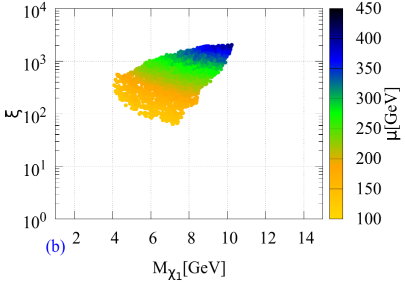
however, evade detection by

- LZ (through SD WIMP-neutron interaction)

Visible to Xe-nT (through SI WIMP-nucleon interaction)



Evades Xe-nT



Taking advantage of the LSP mass resolution capability, an observation here, would be indicative of it being a relic from non-thermal history.

- We choose a benchmark point (BP1) from the allowed points, which evades all DD experiments, and has $Br(h \to inv.) = 0.35\%$.

$$M_1 = 10.6 \text{ GeV}, \quad M_2 = 812.6 \text{ GeV}, \quad \tan\beta = 42.8, \quad \mu = 442 \text{ GeV},$$
$$m_{\tilde{Q}_{3l}} = 8.42 \text{ TeV}, \quad m_{\tilde{t}_R} = 3.42 \text{ TeV}, \quad m_{\tilde{b}_R} = 4.93 \text{ TeV}, \quad M_3 = 4.36 \text{ TeV},$$
$$A_t = 2.42 \text{ TeV}, \quad A_b = 0 \text{ TeV} = A_\tau$$
$$m_{\tilde{Q}_{2l,1l}} = 3.00 \text{ TeV}, \quad m_{\tilde{c},u_R} = 3.00 \text{ TeV}, \quad m_{\tilde{s},d_R} = 3.00 \text{ TeV}, \quad m_{slepton} = 3 \text{ TeV}$$

- We investigated the cascade decay of the directly produced wino-type chargino/neutralino pairs, $pp \to \widetilde{\chi}_4^0 \widetilde{\chi}_2^\pm$, through the intermediate higgsino-type inos.
- $\widetilde{\chi}_4^0 \widetilde{\chi}_2^\pm$ would result in a $ZZWh + \not{E}_{\mathrm{T}}$ final state with a branching fraction of 15%.
- With $\sigma(pp \to \widetilde{\chi}_4^0 \widetilde{\chi}_2^\pm) \sim 3\ fb^{-1}$, ~ 1350 events are expected at HL-LHC.
- Other final states like $VVVW + \not{E}_{\mathrm{T}}$ or $VWWW + \not{E}_{\mathrm{T}}$ $(V = Z, h)$, having minimal SM background, are also possible.
- An observation in these channels at LHC, complemented by measurements of μ and $M_{\widetilde{\chi}_1^0}$ at ILC, might open up the possibility of obtaining some estimate on M_2

Outline for Section 2

1. Invisibly decaying Higgs boson in MSSM

2. The current status and future prospects of neutralino DM in NMSSM
   - Ongoing work in collaboration with: Genevieve Belanger, Biplob Bhattacherjee, Rohini Godbole, Dipan Sengupta, Xerxes Tata

3. Strongly-interacting thermal WIMPs in $U(1)_D$ extended SM

The NMSSM superpotential

$$W = W_{MSSM} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{k}{3} \hat{S}^3$$

Richer Higgs and electroweakino sectors

- 7 Higgs bosons: 3 neutral scalars (H_1, H_2, H_3), 2 neutral pseudoscalars (A_1, A_2), and charged Higgses $(H^{\pm})$
  The scalars and pseudoscalars are an admixture of doublets and singlet.
- 2 charginos $(\widetilde{\chi}_1^{\pm}, \ \widetilde{\chi}_2^{\pm})$ and 5 neutralinos:

$$\chi_i^0 = N_{i1} \tilde{B} + N_{i2} \tilde{W}^3 + N_{i3} \tilde{H}_d^0 + N_{i4} \tilde{H}_u^0 + N_{i5} \tilde{S} \quad (2)$$

- Compared to MSSM, new terms $\propto \lambda, \kappa, v_s$ are introduced in the couplings of the Higgs with other Higgses and electroweakinos.

- In MSSM without prospects of co-annihilation, relic density constraints restrict the light neutralino to values above $\sim 34\ \mathrm{GeV}$.
- Within the next-to-minimal SUSY (NMSSM), much lighter neutralinos ($\sim 1\ \mathrm{GeV}$) can also satisfy the upper bounds on relic density.
- The additional CP-even and CP-odd states in NMSSM provide an efficient annihilation mechanism for lighter neutralinos.
- These light Higgs states, if are dominantly singlet in nature $\rightarrow$ evade collider constraints.

The aim of this work

Evaluate the impact of current constraints and reach of future projections for a variety of experiments to discover a light neutralino in beyond the MSSM-like NMSSM.

Light neutralino refers to: $M_{\tilde{\chi}_1^0} \leq M_{H_{SM}}/2 \sim 62.5\ \mathrm{GeV}$

Future experiments considered:

- Invisible Higgs width measurement at CEPC.
- Multi-ton direct detection experiments.
- Direct light Higgs searches at the future upgrades of LHC *viz* HL-LHC ($\sqrt{s} = 14\ \mathrm{TeV}$, $3000\ fb^{-1}$) and HE-LHC ($\sqrt{s} = 27\ \mathrm{TeV}$, $15\ ab^{-1}$).
- Direct electroweakino searches in the $3l + \not{E}_{\mathrm{T}}$ final state at HL-LHC and HE-LHC.

Current constraints

The Higgs mass constraint, LEP limits, Flavour physics constraints, Relic density constraints, Higgs signal strength constraints, direct detection constraints.

Direct search of light Higgs bosons at LHC

Limits from searches in $H_2 \to A_1 A_1 \to 2b2\mu,\ 2b2\tau,\ 2\mu2\tau,\ 4\mu$ channels.
Favours a singlet-like light Higgs boson

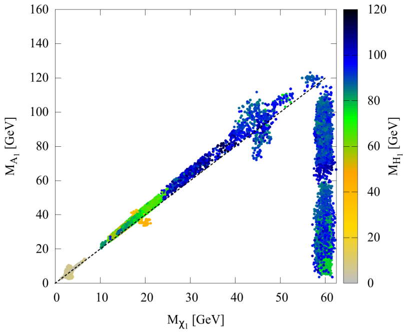
Direct electroweakino searches at LHC

- $pp \to (\chi_i^0 \to Z/h\chi_1)(\chi_1^\pm \to W^\pm \chi_1^0)$ resulting in $3l + E_{miss}^t$ final state. $\to$ Excludes a wino upto ~ 600 GeV for $M_{\widetilde{\chi}_1^0} \lesssim 60$ GeV.
- Direct chargino pair-production in OS di-lepton$+\not{E}_T$ final state $\to$ excludes wino-like $\widetilde{\chi}_1^\pm$ below $\lesssim 400$ GeV for bino-like $M_{\widetilde{\chi}_1^0} \sim 50$ GeV.

Light neutralino LSP

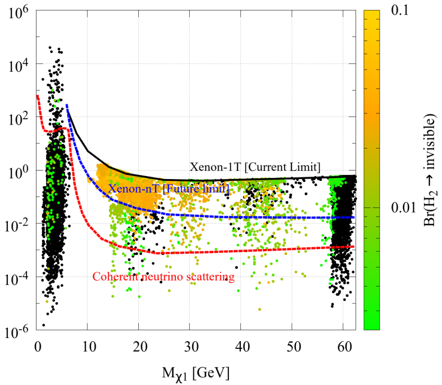
- We obtain parameter space points compatible with relic density constraints at $M_{\tilde{\chi}_1^0}$ as low as ~ 1 GeV.

  Facilitated via the exchange of light Higgses, H_1 or A_1, in the $M_{\tilde{\chi}_1^0} \leq M_Z/2$ region.



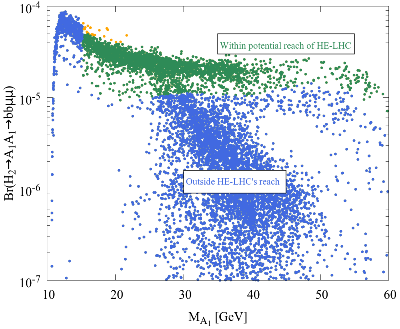
- The LSP is dominantly singlino in nature.
- The light Higgses are singlet in nature

- Black colored points feature $Br(H_2 \to invisible) \lesssim 0.24\%$ $\to$ Outside CEPC's projected reach in invisible Higgs searches.
- Poits below the blue dashed line are outside the projected reach of Xenon-nT.
- Invisible Higgs measurements in e^+-e^- colliders will be able to probe the $M_{\tilde{\chi}_1^0} \lesssim 10$ GeV region, otherwise inaccessible to DD experiments.

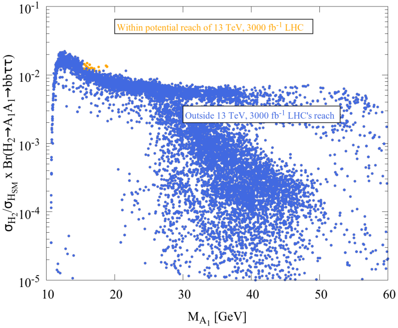


Future direct light Higgs searches

Green: Within HE-LHC's projected reach (95% C.L.)
Orange: within HL-LHC's projected reach (95% C.L.)
Blue: outside HE-LHC's projected reach



Orange: within potential reach of $\sqrt{s} = 13$ TeV, 3000 fb^{-1} LHC (95% C.L.)
Blue: outside $\sqrt{s} = 13$ TeV, 3000 fb^{-1} LHC's projected reach.



- We derive the projected reach of direct electroweakino searches in both, WZ and Wh_{125} mediated $3l + \not{E}_T$ channels, at HE-LHC, and evaluate their projected impact on the currently allowed NMSSM parameter space.

Optimized selection cuts for searches in the Wh_{125}-mediated $3l + \not{E}_T$ channel

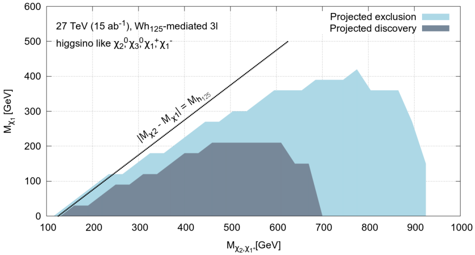
Cuts	SRA4	SRB4	SRC4	SRD4	SRE4	SRF4	SRG4
M_μ [GeV]	310	610	610	610	1210	1210	1210
$M_{\tilde{\chi}_1^0}$ [GeV]	00	00	300	480	00	600	1080
ΔR_{OS}^{min}	≤ 0.1	≤ 0.6	≤ 0.6	≤ 1.0	≤ 0.4	≤ 0.6	≤ 1.0
ΔR_{OS}^{max}	-	[0.1-2.5]	[0.2-2.6]	-	[0.1-2.9]	[0.2-2.6]	-
$M_{OS,min}^{inv.}$ [GeV]	≤ 20	-	-	≤ 60	-	-	≤ 60
$M_T^{l_1}$ [GeV]	-	≥ 200	≥ 100	-	≥ 200	≥ 200	-
$M_{CT}^{l_1}$ [GeV]	≤ 50	-	-	-	-	-	-
$p_T^{l_1}$ [GeV]	[20 − 290]	≥ 150	≥ 100	[20-290]	≥ 150	≥ 100	[20-290]
$p_T^{l_2}$ [GeV]	≥ 20	≥ 90	≥ 80	[20-120]	≥ 140	≥ 90	[20-70]
$p_T^{l_3}$ [GeV]	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20

The background yields

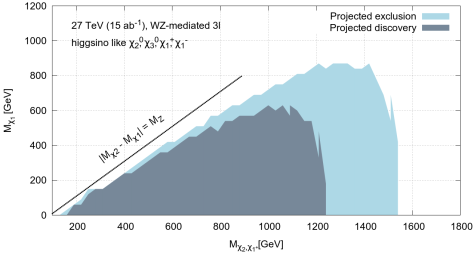
Background process	Cross section [LO]	Background yield (27 TeV, 15 ab^{-1})						
		SRA	SRB	SRC	SRD	SRE	SRF	SRG
$t\bar{t}V$ $(V = W, Z)$ $(W \to l\nu, Z \to ll)$	1384 fb	0	0	0	186.84	0	0	124.56
VVV $(V = W, Z)$	679.5 fb	3.09	3.09	3.09	485.36	0.00	3.09	377.16
$l\nu ll$	835.4 fb	150.36	12.53	12.53	16890.98	12.53	12.53	13871.16
$l\nu h_{125}$ $(h_{125} \to WW^*)$ $(W \to l\nu)$	0.287 fb	1.18	0.007	0.237	72.26	0.12	0.12	57.62
Total Background		154.64	15.62	15.86	17635.44	12.65	15.74	14430.50

HE-LHC projections from direct electroweakino searches

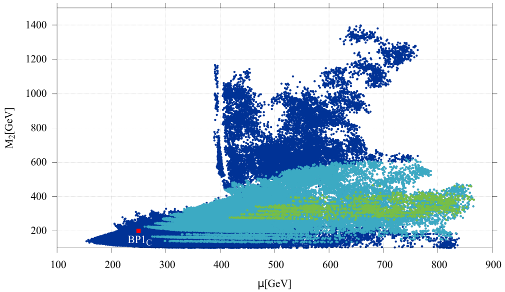
Projected exclusion and discovery contours from direct electroweakino searches in the Wh_{125}-mediated $3l + \not{E}_T$ final state at HE-LHC.



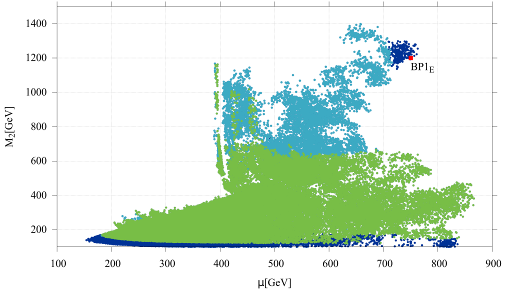
Projected exclusion and discovery contours from direct electroweakino searches in the WZ-mediated $3l + \not{E}_T$ final state at HE-LHC



Projected reach of direct EWino searches

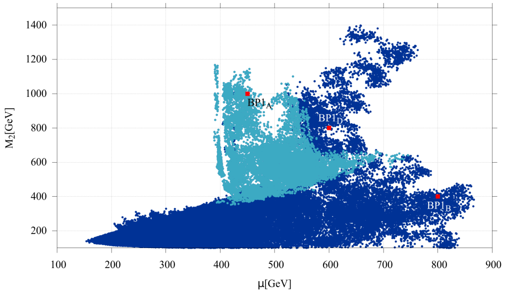


Wh_{125}-mediated $3l + \not{E}_T$ searches at HL-LHC.

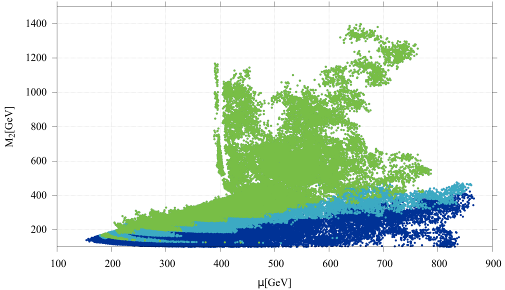


Wh_{125}-mediated $3l + \not{E}_T$ searches at HE-LHC.

Projected reach of direct EWino searches



WZ-mediated $3l + \not{E}_T$ searches at HL-LHC.



WZ-mediated $3l + \not{E}_T$ searches at HE-LHC.

Summary

- It is possible to obtain allowed points with LSP neutralino masses as low as $\sim 1~\mathrm{GeV}$ in the NMSSM framework.
- The parameter space explored by us features dominantly singlino-like LSP's and singlet-like light Higgses.
- Future e^{+}-e^{-} colliders and future DD experiments will be sensitive over a significant area of the currently allowed parameter space region.
- The strongest future reach is exhibited by direct electroweakino searches at the high energy luminosity run of LHC $\rightarrow$ projected to be capable of probing the entire region of currently allowed parameter space.

Outline for Section 3

1. Invisibly decaying Higgs boson in MSSM
2. The current status and future prospects of neutralino DM in NMSSM
3. Strongly-interacting thermal WIMPs in $U(1)_D$ extended SM
   - Based on J. High Energ. Phys. (2019) 2019: 177.
     RKB, Biplob Bhattacherjee, Arindam Chatterjee, Arghya Choudhury, Aritra Gupta

The status so far

- So far, no evidence of new physics at the LHC.
- No evidence of particle DM from direct or indirect searches.

The possibilities:

New physics is beyond the reach of current LHC, and can only be probed via their contribution to higher dimensional effective operators.

OR

New physics exists within the electroweak scale and is weakly coupled to the SM.

Motivation

The status so far

- So far, no evidence of new physics at the LHC.
- No evidence of particle DM from direct or indirect searches.

The possibilities:

New physics exists within the electroweak scale and is weakly coupled to the SM.

We explore this particular possibility and study the phenomenological prospects of SM extended with a local $U(1)_D$ gauge group.

Motivation

- Inspite of the enormous success of ΛCDM in the cosmological scales, there have been concerns, in particular when it comes to the small scale structures *viz* *Core-vs-cusp* and *Too-big-to-fail*.

Self-interacting DM, have been argued to be capable of resolving these issues.

- Light mediators can generate large self-interaction among the DM particles through Sommerfeld enhancement.

We choose a parameter space such that the $U(1)_D$ extended Dark sector consists of at least one light mediator to facilitate adequate self-interaction.

The model

The Dark sector

- An extra neutral Z like boson, Z_D.
- An extra neutral scalar boson, H_1.
- Two fermions.

The Dark sector interacts with the SM sector via:

$$\mathcal{L}_{\text{portal}} = -\frac{\epsilon_g}{4} F^{\mu\nu} F_{D\mu\nu} - \frac{\lambda_{\text{mix}}}{4} (\varphi^* \varphi)(H^\dagger H), \tag{3}$$

ϵ_g: Kinetic gauge mixing, φ: The complex scalar field

DM self-interaction: Allowed regions

Following three cases are possible :

Small M_{Z_D}, but heavier M_{H_1}

Not a good choice.
Requires a small value of $g_D \rightarrow$ suppresses the $\chi_+\chi_-Z_D$ coupling.

Both, Z_D and H_1, are lighter

Not a good choice from collider perspective.

Small M_{H_1}, heavier Z_D

The preferred choice for studying self-interactions.

For large self-interactions

- preferred choice of M_{H_1} : $10\ \mathrm{MeV} - 10\ \mathrm{GeV}$
- DM mass accommodated upto $\lesssim 1\ \mathrm{TeV}$

Possible non-standard decay modes of SM-like Higgs:

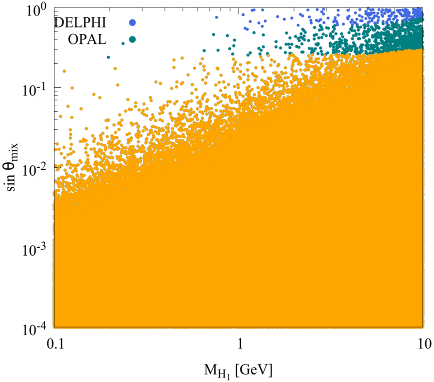
- $H_2 \to H_1 H_1 \propto \lambda_{mix}$
- $H_2 \to Z_D Z_D \propto \epsilon_g^2$
- $H_2 \to \chi \pm \chi \pm \propto f \sin\theta_{mix}$

$$-0.10 < \lambda_H < -0.16, \quad -10^{-8} < \lambda_\phi < -0.7, \quad 10^{-12} < \lambda_{mix} < 0.3$$
$$10^{-6} < g_D < 0.6, \quad 10^{-4} < \epsilon_g < 10^{-10}$$
$$1\ \mathrm{GeV} < v_D < 1000\ \mathrm{GeV}, \quad 10^{-6} < f < 10^{-1}, \quad 1\ \mathrm{GeV} < M < 500\ \mathrm{GeV}$$

Impact of current constraints

LEP limits

DELPHI: U.L. on ζ^2, ζ : Normalized $H_1 VV$ coupling. (Excludes $\sin\theta_{mix} > 0.5$)
OPAL: U.L. on κ, κ: $\sigma_{H_1^{VH}}/\sigma_{H_{SM}^{VH}}$. (Excludes $\sin\theta_{mix} > 0.2$)

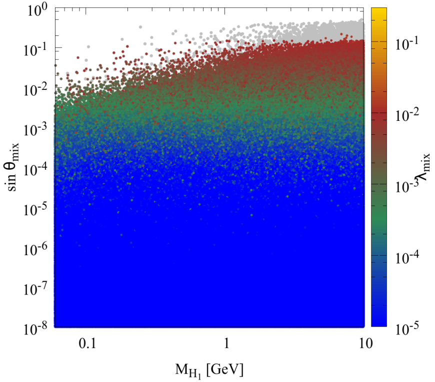


Impact of current constraints

Higgs signal strength

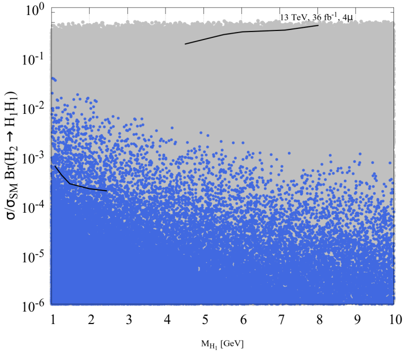
Constraints from Run-I and Run-II data are imposed through a global χ^2-fit.

$H_2 \to Z_D Z_D$: $\propto g_D^2 \sin\theta_{mix}$ and ϵ_g^2
$H_2 \to H_1 H_1$: $\propto \lambda_{mix} v_H$

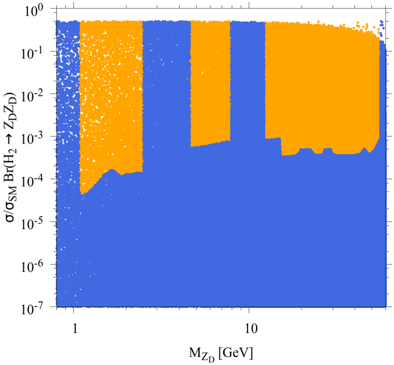


Direct searches at LHC

Channel: $H_2 \to H_1 H_1 \to 4\mu$



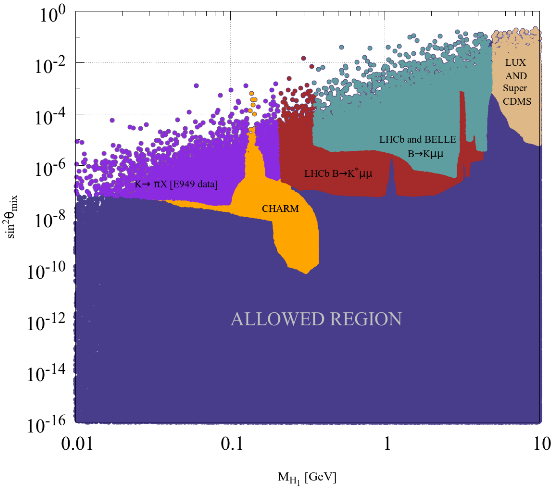
Channel: $H_2 \to Z_D Z_D \to 4l$



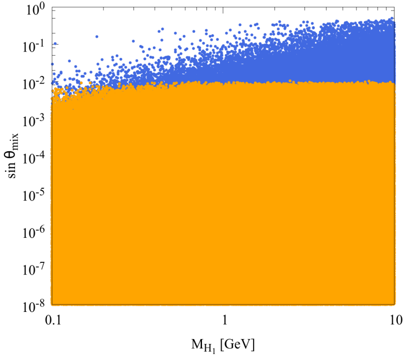
Searches in the $H_2 \to ZZ_D$ can effectively probe ϵ_g, however, are marred by the huge ZZ^* continuum background.

Impact of current constraints

Constraints from beam-dump and B-factories



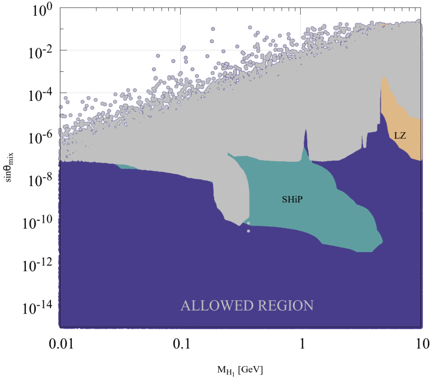
Combination of measurements at the future 300 fb^{-1} run of LHC, and 500 GeV run of ILC, is projected to confine *HZZ* coupling within 0.3%.



Projected reach: $\sin\theta_{mix} \gtrsim 0.007$

Future prospects of SHiP and LZ experiments

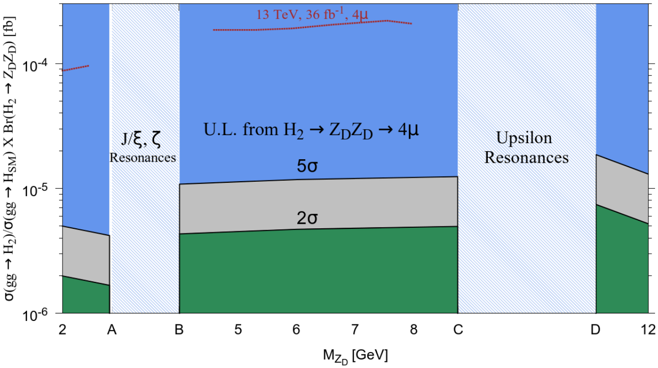
- For $M_{H_1} \sim 1\,\mathrm{GeV}$, current limits exclude $\sin\theta_{mix} \gtrsim\sim 10^{-3}$, whereas, SHiP is projected to probe until $\sin\theta_{mix} \sim 10^{-5}$.
- LZ is expected to gain effectiveness in the $O(10)$ GeV region, and is expected to improve upon the existing sensitivity by around an order of magnitude.



Future prospects at HL-LHC: $H_2 \to Z_D Z_D \to 4l$

We performed a detailed search analysis to probe Z_D at HL-LHC, using the process: $pp \to H_2 \to Z_D Z_D \to 4l$[1].

U.L. on $\sigma_{ggH_2}/\sigma_{ggH_{SM}} \times Br(H_2 \to Z_D Z_D)$ derived from Z_D search in the 4μ final state at HL-LHC



[1] arXiv: 1802.03388, ATLAS coll.

Comparison of projected U.L.'s at HL-LHC from searches in $H_2 \to \chi_+\chi_+ \to Z_D\chi_- Z_D\chi_-$

$H_2 \to Z_D Z_D \to 4l$ furnishes stronger limits as compared to $H_2 \to \chi_+\chi_+ \to \chi_- Z_D \chi_- Z_D \to 4l + \not{E}_T$

M_{Z_D} [GeV]	$H_2 \to \chi_+\chi_+ \to 4\mu + \not{E}_T$		$H_2 \to Z_D Z_D \to 4\mu$	
	5σ [fb]	2σ [fb]	5σ [fb]	2σ [fb]
2.40	1.03	0.41	0.181	0.072

The possibility of invariant mass reconstruction in the former case filters out the background more efficiently, furnishing stronger U.L.

Late decaying Z_D

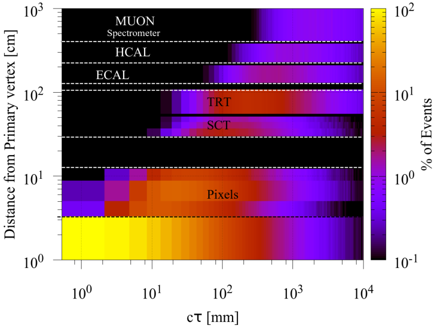
- In general, a particle is said to be long-lived if its proper decay length exceeds $c\tau > 10^{-4}$ m.
- The proper decay length of $Z_D \propto \epsilon^{-2}$,
  viz $M_{Z_D} \sim 2$ GeV, *a value of* $\epsilon_g \gtrsim (10^{-5} - 10^{-6})$ *will result in the* Z_D *to become a LLP.*
- The decay can occur in different segments of the LHC based on kinematic distribution and decay length.

Decay length: $l_d = \beta\gamma c\tau$

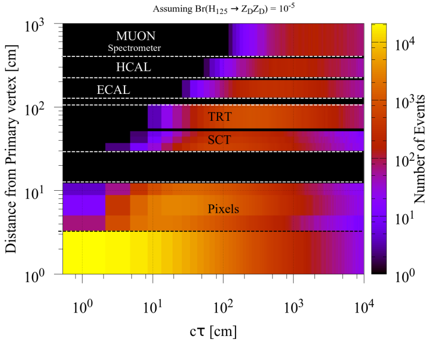
- Identification of the point of decay of LLP within the detector and its boost can be used to estimate the proper life-time of the particle.
- The total number of decay events, $N = N_0 e^{-\tau_i/\tau}$.
  The fraction of events undergoing decay in different segments of the detector will be a characteristic reflection of the proper decay length.

Late decaying Z_D

HL-LHC



HE-LHC



Summary

- The $U(1)_D$-extended SM offers a wide region of parameter space with strong self-interaction, also being compatible with the current constraints.
- Future probes exhibit a tremendous potential in exploring the strongly self-interacting allowed parameter space.

A very complicated but interesting road ahead in the search of new physics.

Thank you.