Light Singlino Dark Matter at Future Colliders

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Snowmass21: Letter of interest

Future collider reach for light DM in the NMSSM via light Higgs searches and direct electroweakino searches[*]

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Thematic areas:

☑ EF08: BSM: Model specific explorations

☑ EF10: BSM: Dark Matter at colliders

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arXiv : 2006.07854

THE SALES PITCH

- NMSSM light neutralino sector is different from MSSM
- An expanded Higgs and neutralino sector.
- Phenomenologically richer and well motivated.
- Offers scope for exploration in complementary experiments
- The light neutralino DM in NMSSM will largely remain unexplored without future colliders and next generation DD experiments
- A pitch for measuring the Invisible decay of the Higgs

NMSSM Higgses

$$W_{MSSM} = y_u^{ij}\hat{u}_i\hat{Q}_j\cdot\hat{H}_u - y_d^{ij}\hat{d}_i\hat{Q}_j\cdot\hat{H}_d - y_e^{ij}\hat{E}_i\hat{L}_j\cdot\hat{H}_d + \boxed{\mu\hat{H}_u\cdot\hat{H}_d}$$

→ An accidental weak scale parameter

$$W_{NMSSM} = W_{MSSM}(\mu=0) + \boxed{\lambda\hat{S}\hat{H}_u\cdot\hat{H}_d} + \frac{k}{3}\hat{S}^3$$

- Instead generate a weak scale parameter by a SUSY breaking term
- Additional quartic Higgs doublet with self coupling λ^2
- Additional contribution to SM Higgs
- Lower fine tuning

A phenomenologically richer Higgs sector compared to MSSM:
7 Higgs bosons: 3 CP-even states (h_1, h_2 and h_3), 2 CP-odd states (a_1 and a_2) and 2 charged Higgses ($H^\pm$).

Possible to have singlet dominated light psuedoscalar or light CP even state

$$M_A^2 = \frac{\mu}{\sin\beta\cos\beta}\left(A_\lambda + \frac{\kappa\mu}{\lambda}\right)$$

The tree level Higgs sector is driven by:

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta,\ \mu$$

A_λ and A_κ are the trilinear soft-breaking parameters.

$$M_{H^\pm}^2 = M_A^2 + M_W^2 - \frac{1}{2}\lambda^2 v^2$$

NMSSM Higgses

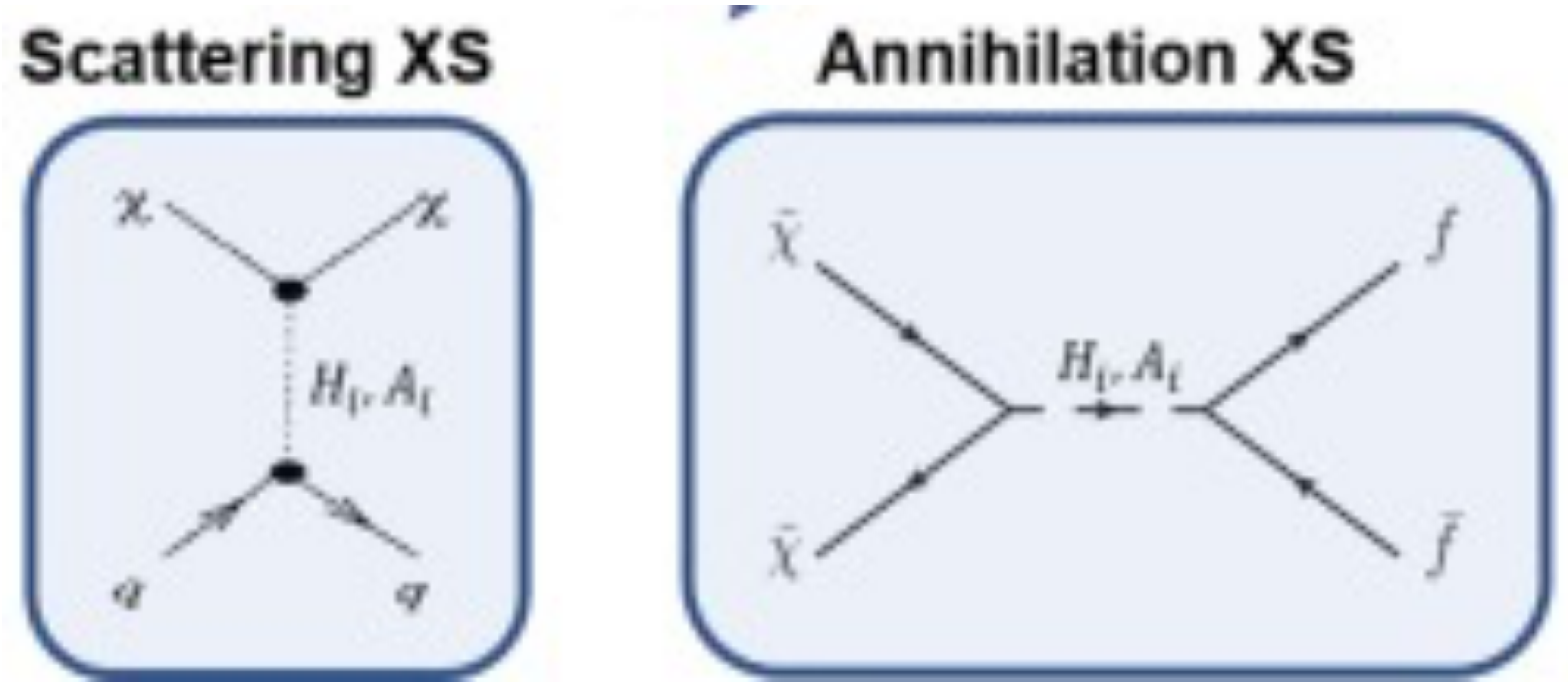
The neutralino mass matrix:

$$M_{\chi_i^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu & -\lambda v \sin\beta \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 & -\lambda v \cos\beta \\ 0 & 0 & -\lambda v \sin\beta & -\lambda v \cos\beta & 2\kappa v_s \end{pmatrix}$$

The neutralinos can be admixtures of *singlino*, bino, wino and higgsinos.

At the tree level, the EW ino sector is controlled by: M_1, M_2, $\mu, \tan\beta$, λ, κ

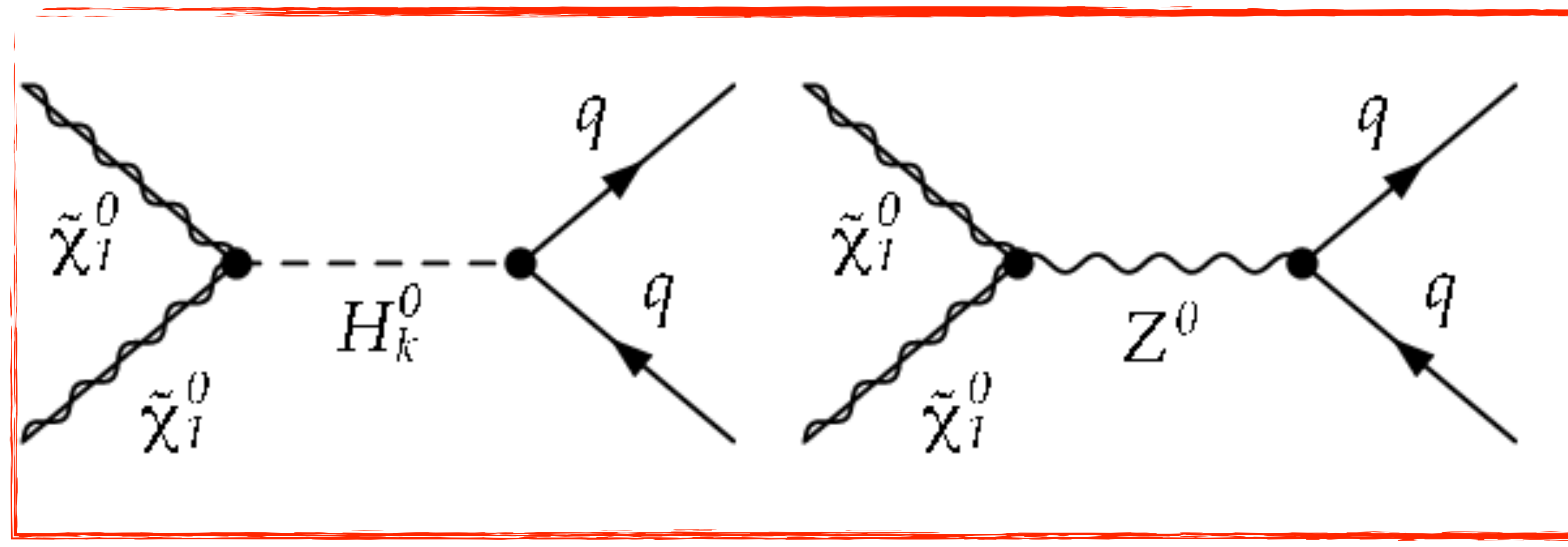
- Light neutralino can be dominantly singlet, as light as a few GeV
- Small direct detection cross section
- Relic via s channel pseudo-scalar and CP even scalar



MSSM light neutralinos

Light Neutralinos mostly Bino, some admixture with Higgsinos

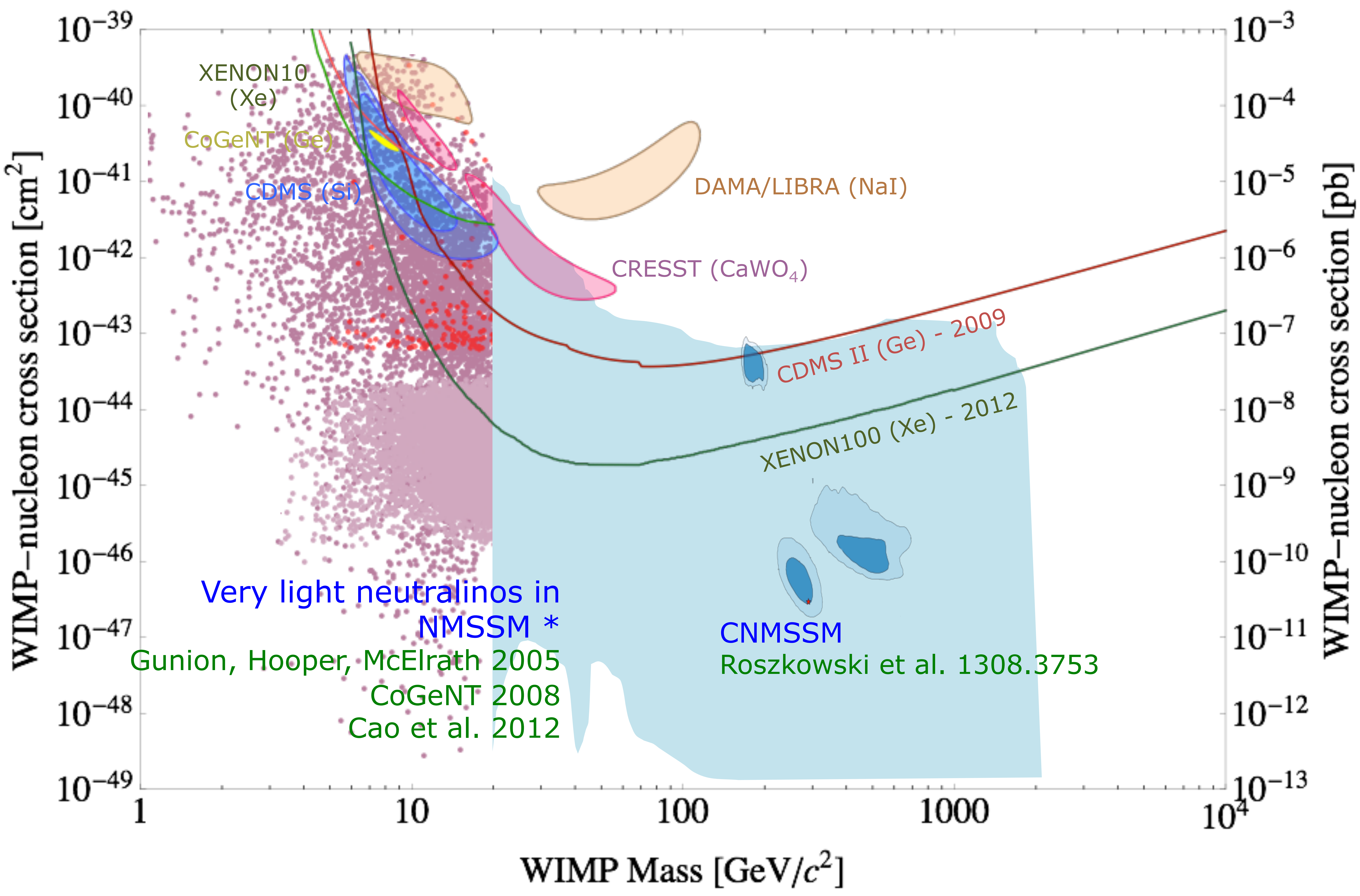
Constrained by a combination of DD, relic and and chargino constraints



$$M_{\tilde{\chi}_1^0} \gtrsim 34 \text{ GeV}$$

arXiv: 1703.03838
G.Belanger, R. K Barman, B. Bhattacharjee, R. Godbole, D. Sengupta

NMSSM vs others



* without constrains on the Higgs sector

Analyzing the space

- Standard Cosmology with $\Omega h^2 \leq 0.120$ and focus on the $M_{\tilde{\chi}_1^0} \leq 62.5$ GeV
- Constraints and prospects from Invisible Higgs decays
- Collider, astrophysical and cosmological constraints.

1. future multi-ton direct detection experiments.
2. invisible Higgs decay width measurement at the future LHC, FCC, ILC and CEPC.
3. direct light Higgs searches and direct electroweakino searches at the HL-LHC and the HE-LHC.

Light States in NMSSM

Analyzing current constraints for light DM in NMSSM

$$0.01 < \lambda < 0.7,\ 10^{-5} < \kappa < 0.05\quad 3 < \tan\beta < 40$$

$$100\ \text{GeV} < \mu < 1\ \text{TeV},\ 1.5\ \text{TeV} < M_3 < 10\ \text{TeV}$$

$$2\ \text{TeV} < A_\lambda < 10.5\ \text{TeV},\ \ -150\ \text{GeV} < A_\kappa < 100\ \text{GeV}$$

$$M_1 = 2\ \text{TeV},\ 70\ \text{GeV} < M_2 < 2\ \text{TeV}$$

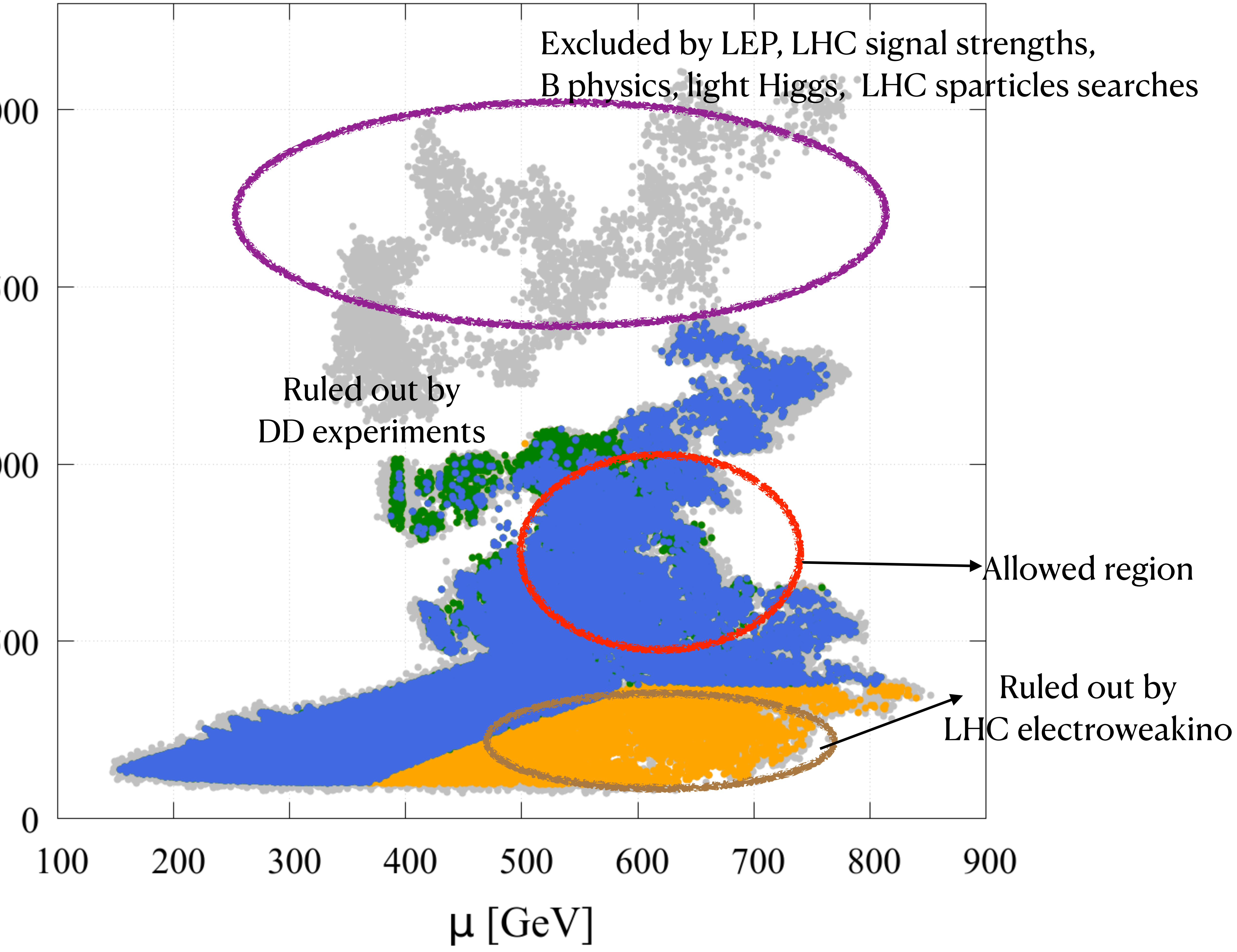
$$A_t = 2\ \text{TeV},\ A_{b,\tilde{\tau}} = 0,\ M_{U^3_R}, M_{D^3_R}, M_{Q^3_L} = 2\ \text{TeV},\ M_{e^3_L}, M_{e^3_R} = 3\ \text{TeV}$$

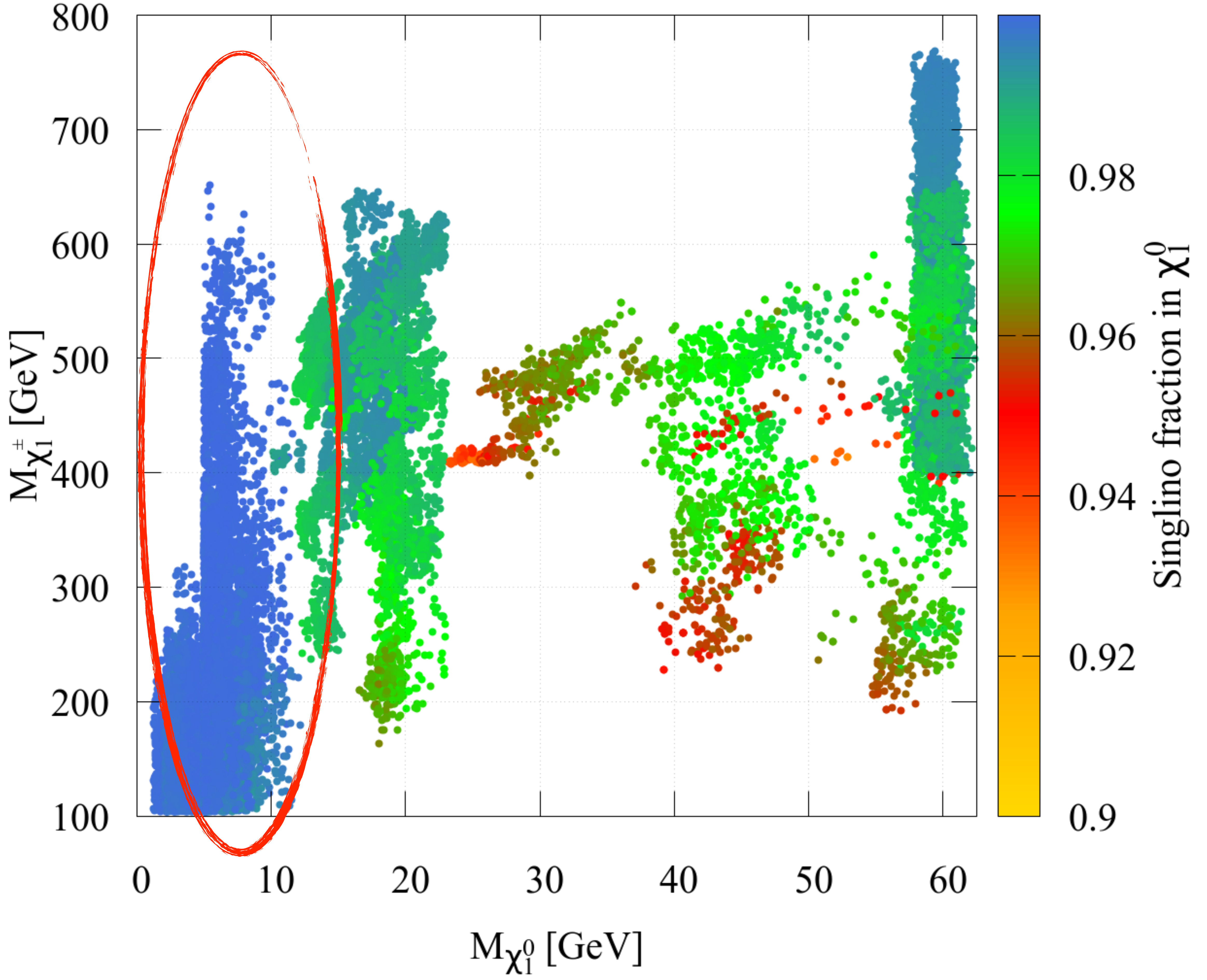
→ Scan Parameters

Light States in NMSSM : constraints

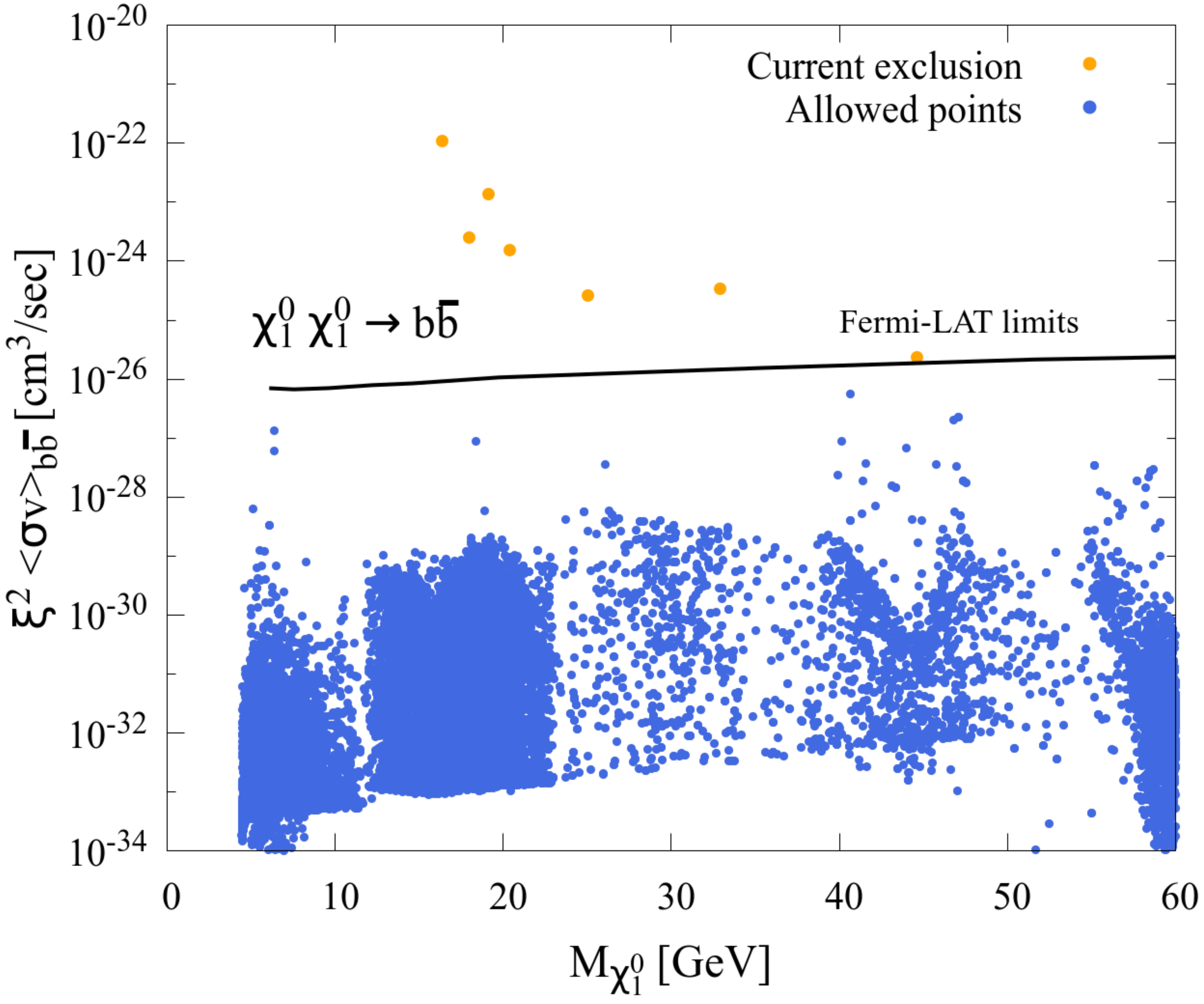
- An SM like Higgs, the heavier CP even, a lighter CP odd.
- LEP limit on chargino < 103.5 GeV
- LEP limit : $\sigma_{\tilde{\chi}_1^0 \tilde{\chi}_2^0} \lesssim 0.1$ pb
- Upper bound on relic $\Omega^{obs.}_{DM(\tilde{\chi}_1^0)} h^2 \leq 0.122$
- Flavor constraints : $Br(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ $Br(B^+ \to \tau^+\nu_\tau) = (1.06 \pm 0.19) \times 10^{-4}$ $Br(B \to X_s\gamma) = (3.32 \pm 0.16) \times 10^{-4}$
- Higgs signal strengths $b\bar{b}$, $\tau^+\tau^-$, ZZ, W^+W^- and $\gamma\gamma$
- Invisible decays of the Higgs : VBF < 13 % $\Gamma_{H_{125}} < 22$ MeV
- Light Higgs searches at the LHC $\sigma_{H_{125}}/\sigma_{H_{SM}} \times Br(H_{125} \to A_1 A_1 \to 2b2\mu)$
- Electroweakino searches at the LHC. $pp \to (\tilde{\chi}_i^0 \to Z/H_{125}\tilde{\chi}_1^0)(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0)$ $3l + \not{E}_T$
- Direct Detection bounds from Xenon 1T

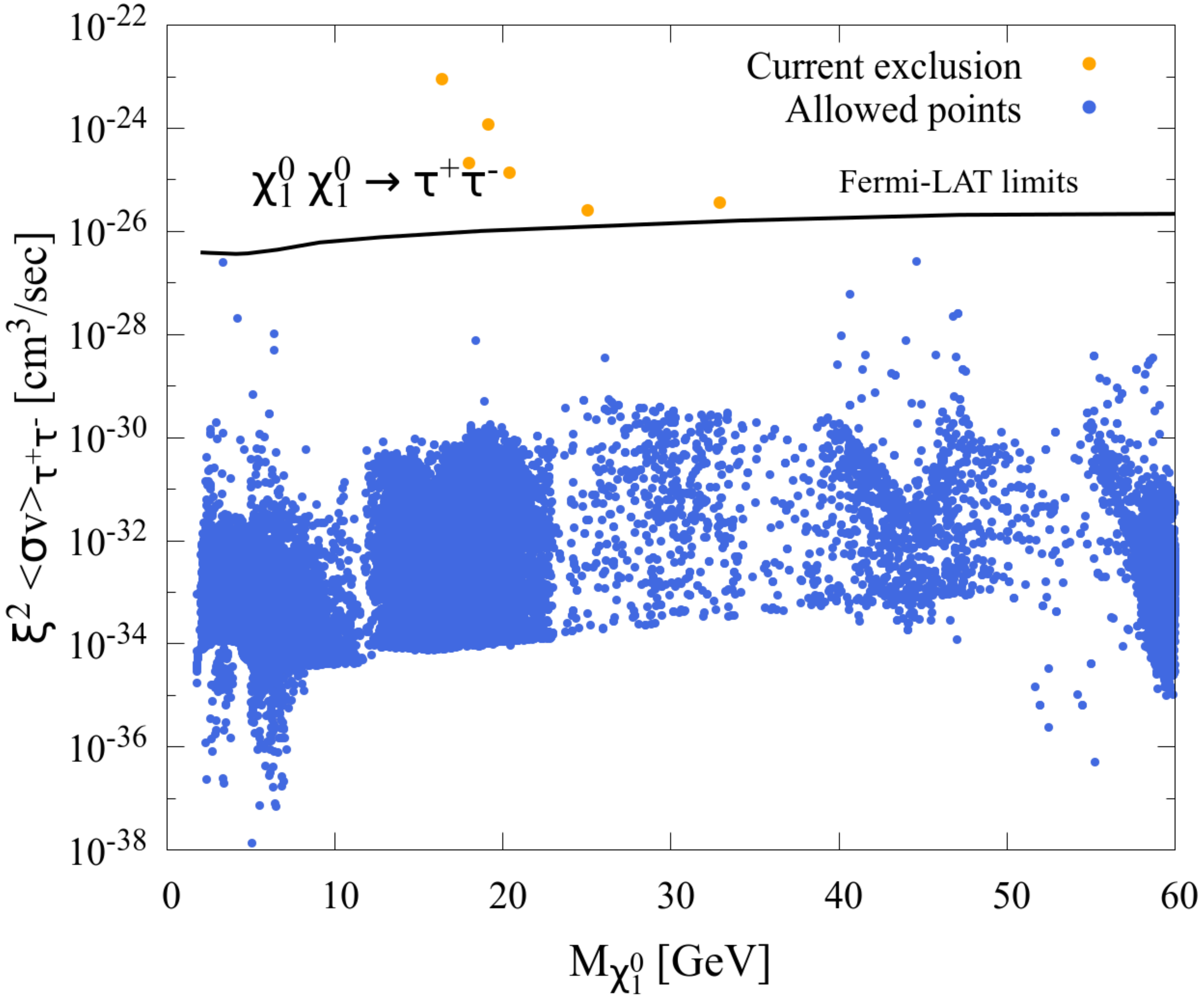
Light States in NMSSM : constraints





Light States in NMSSM : Indirect detection





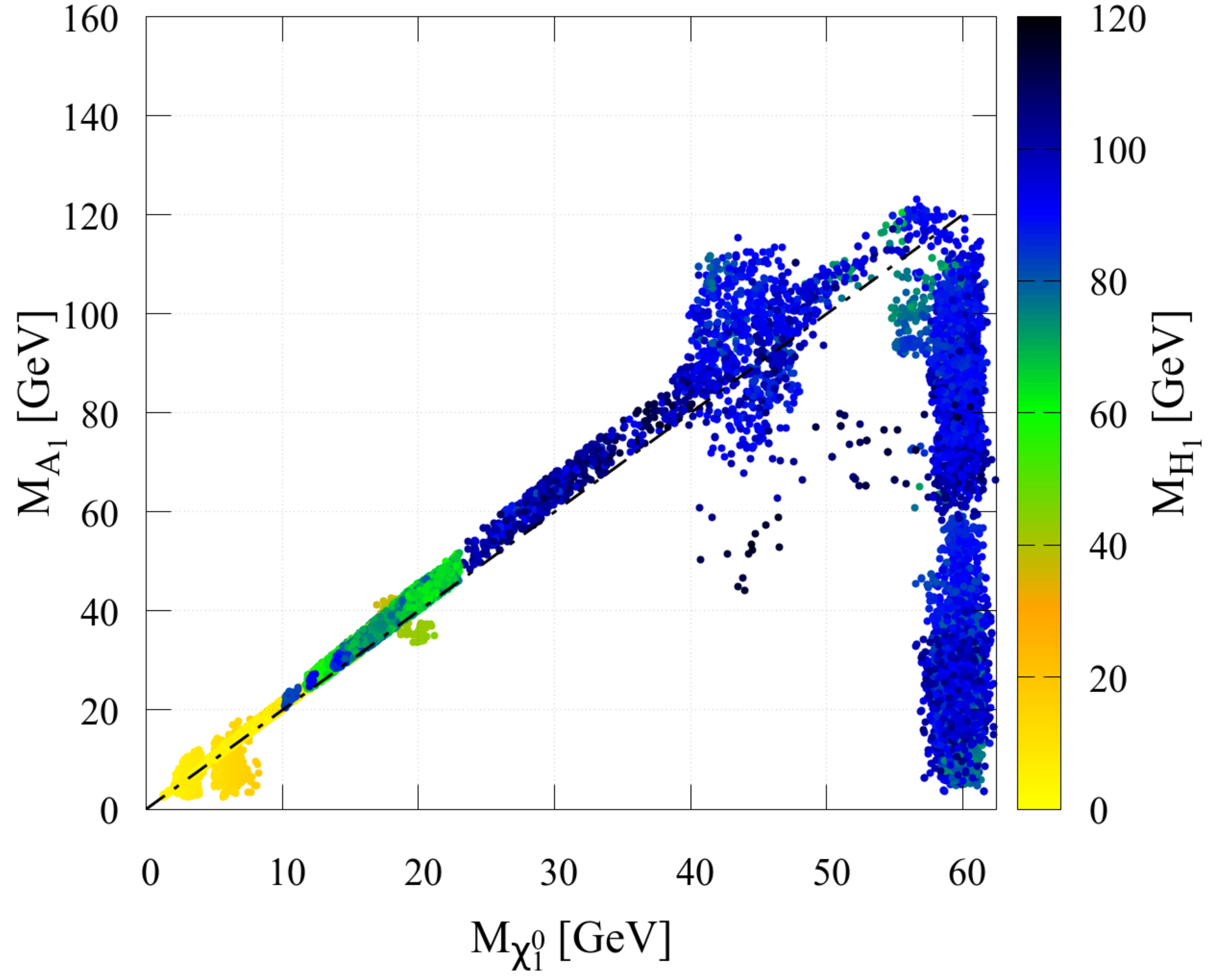
$$\xi = \Omega^{\text{thermal}}_{\tilde{\chi}_1^0}/0.12$$

Light States in NMSSM : Relic

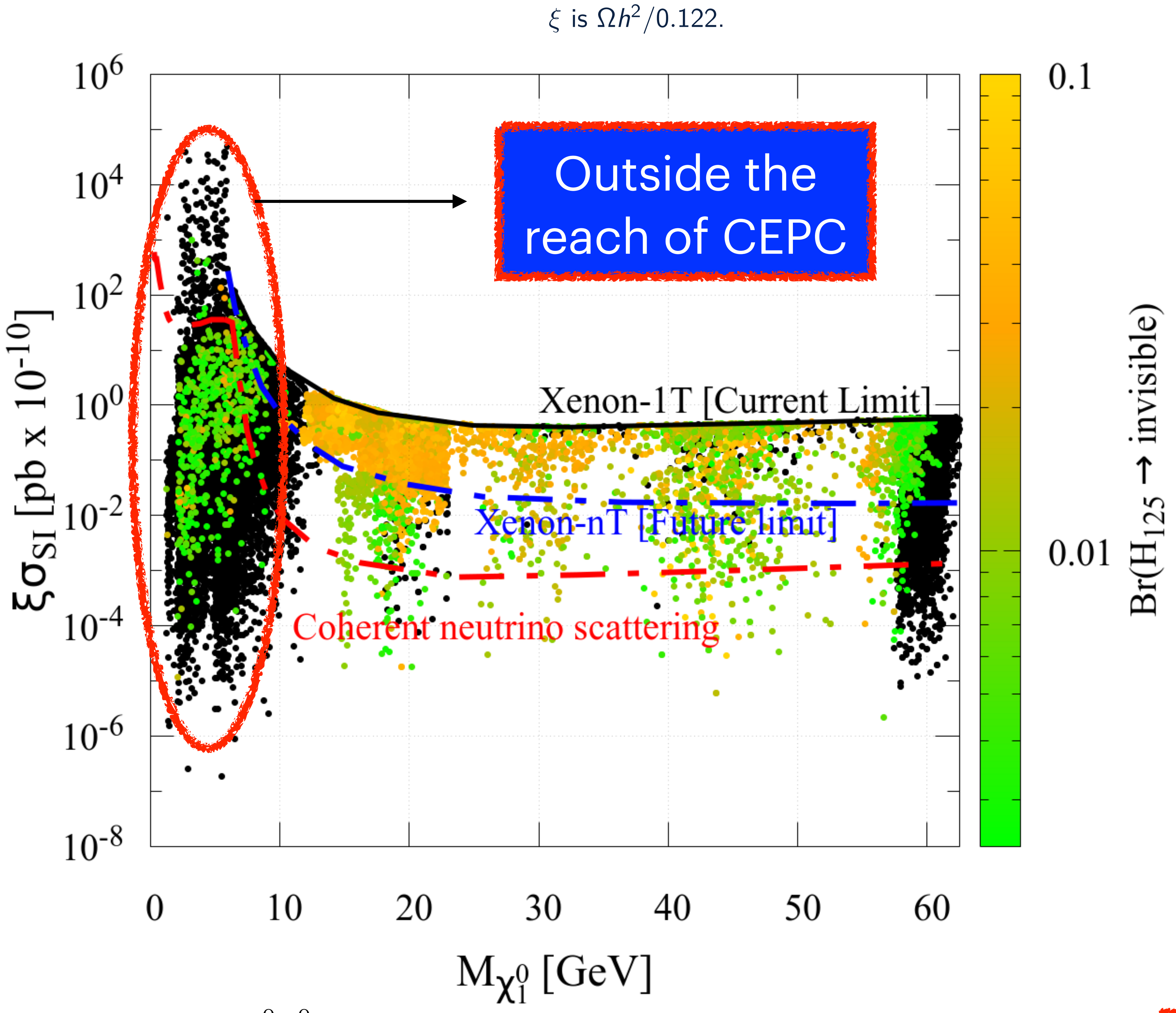
MSSM light neutralinos ⟶ Lower bound $M_{\widetilde{\chi}_1^0} \gtrsim 34$ GeV Z funnel $(\sim M_Z/2)$ Higgs-funnel $(M_{H_{125}}/2)$

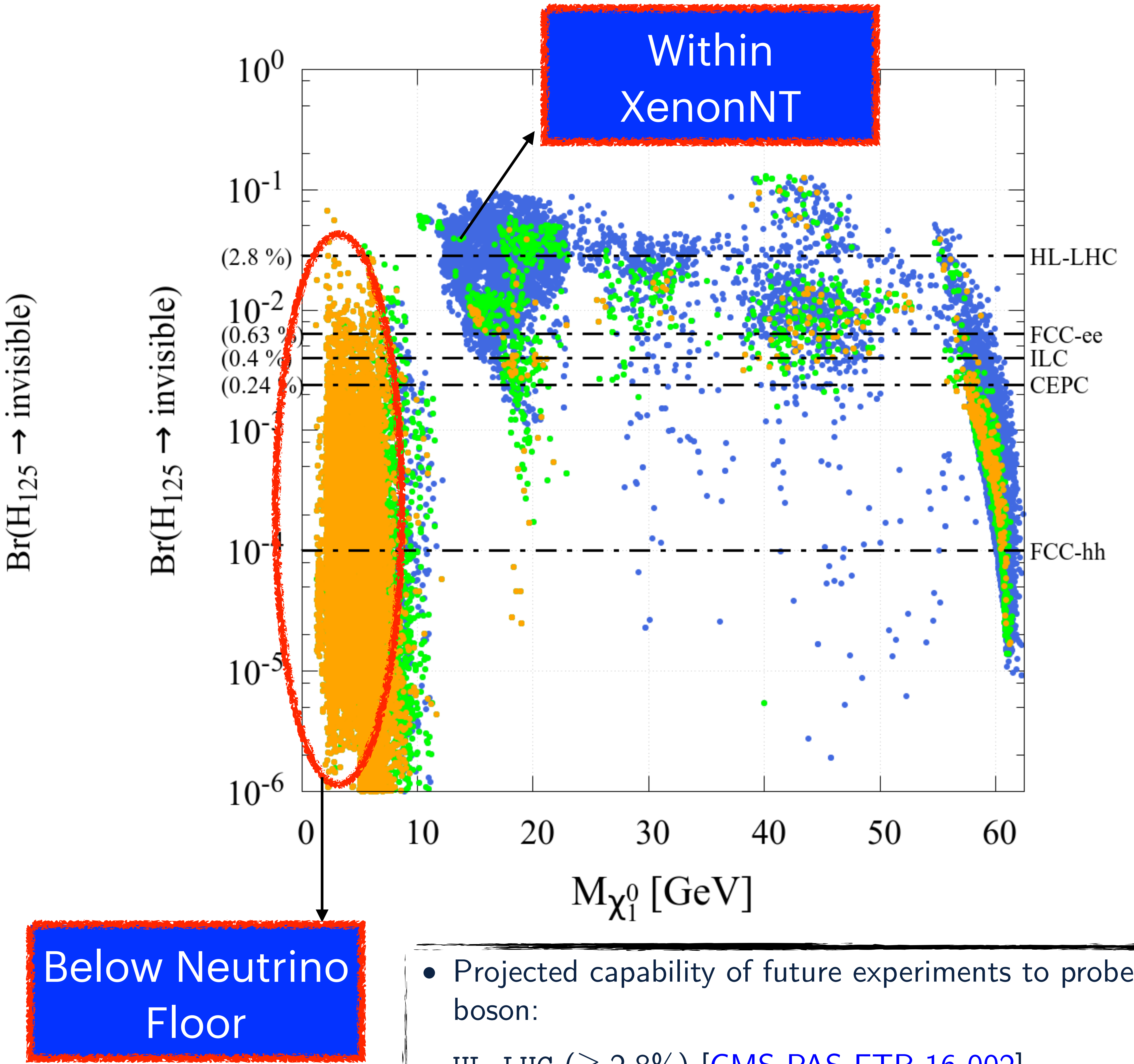
- The $\widetilde{\chi}_1^0$ has to be bino or singlino dominated.
- In such cases, $\Omega h^2 \leq 0.122$ can be satisfied only through co-annihilation or annihilation via resonance.
- For our parameter space, co-annihilation $\longrightarrow$ *not feasible*
- Only possibility $\rightarrow$ annihilation via resonance.
- We fix M_1 at 2 TeV $\rightarrow \widetilde{\chi}_1^0$ is always singlino dominated.
- a_1 and h_1 is always singlet dominated.

- Below the Z funnel region:
  1. the allowed points are mostly populated along $M_{a_1} \sim 2M_{\widetilde{\chi}_1^0}$.
  2. points away from the above correlation have $M_{h_1} \sim 2M_{\widetilde{\chi}_1^0}$.



Light States in NMSSM : Invisible Higgs constraints



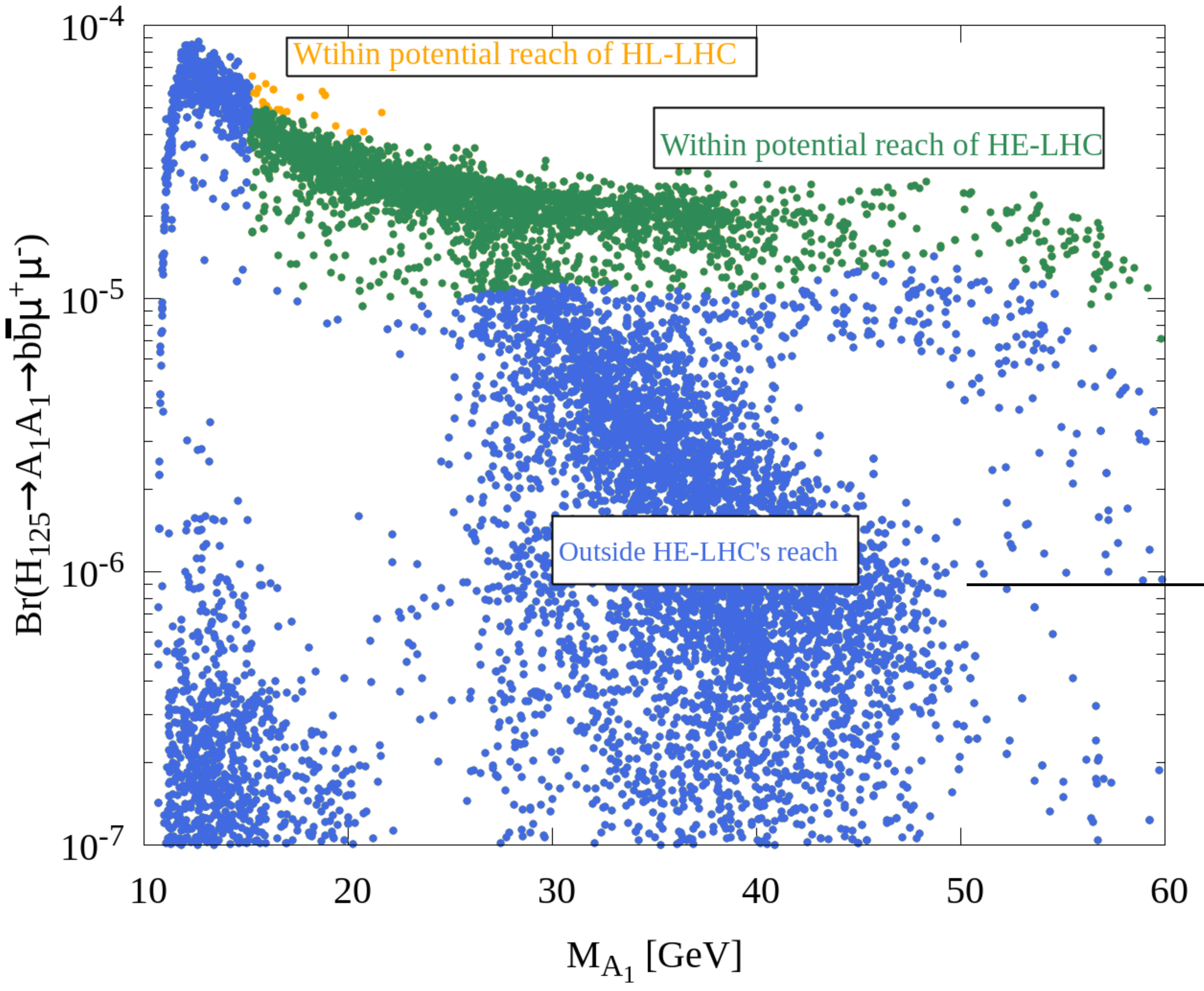


- $H_{125} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $H_{125} \to A_1 A_1 \to 4\tilde{\chi}_1^0$
- $H_{125} \to H_1 H_1 \to 4\tilde{\chi}_1^0$
- $H_{125} \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to (\tilde{\chi}_2^0 \to H_1 \tilde{\chi}_1^0)\tilde{\chi}_1^0 \to (H_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) 2\tilde{\chi}_1^0 \to 4\tilde{\chi}_1^0$
- $H_{125} \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to (\tilde{\chi}_2^0 \to A_1 \tilde{\chi}_1^0)\tilde{\chi}_1^0 \to (A_1 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) 2\tilde{\chi}_1^0 \to 4\tilde{\chi}_1^0$

- Projected capability of future experiments to probe invisibly decaying Higgs boson:

  HL-LHC ($\gtrsim$ 2.8%) [CMS-PAS-FTR-16-002],
  FCC-ee ($\gtrsim$ 0.63%) [1605.00100],
  ILC ($\gtrsim$ 0.4%) [1310.0763],
  CEPC ($\gtrsim$ 0.24%) [1811.10545],
  FCC-hh ($\gtrsim$ 0.01%) [CERN-ACC-2018-045].

Light States in NMSSM : constraints



Not optimized, room for improvement
Dedicated simulation required

The future projections have been taken from *1902.00134 (Report from WG 2: Higgs Physics at the HL-LHC and HE-LHC, M. Cepeda et. al.)* *and translated to our allowed parameter space.*

Light States in NMSSM : Projections

Collider reach of HE-LHC and HL-LHC

- Simple cut based optimized analysis
- Target WZ and WH mediated 3l + MET channel for Higgsino production
- Projections translated to allowed NMSSM parameter space
- Map out Efficiency grids in the Higgsino-LSP mass plane

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

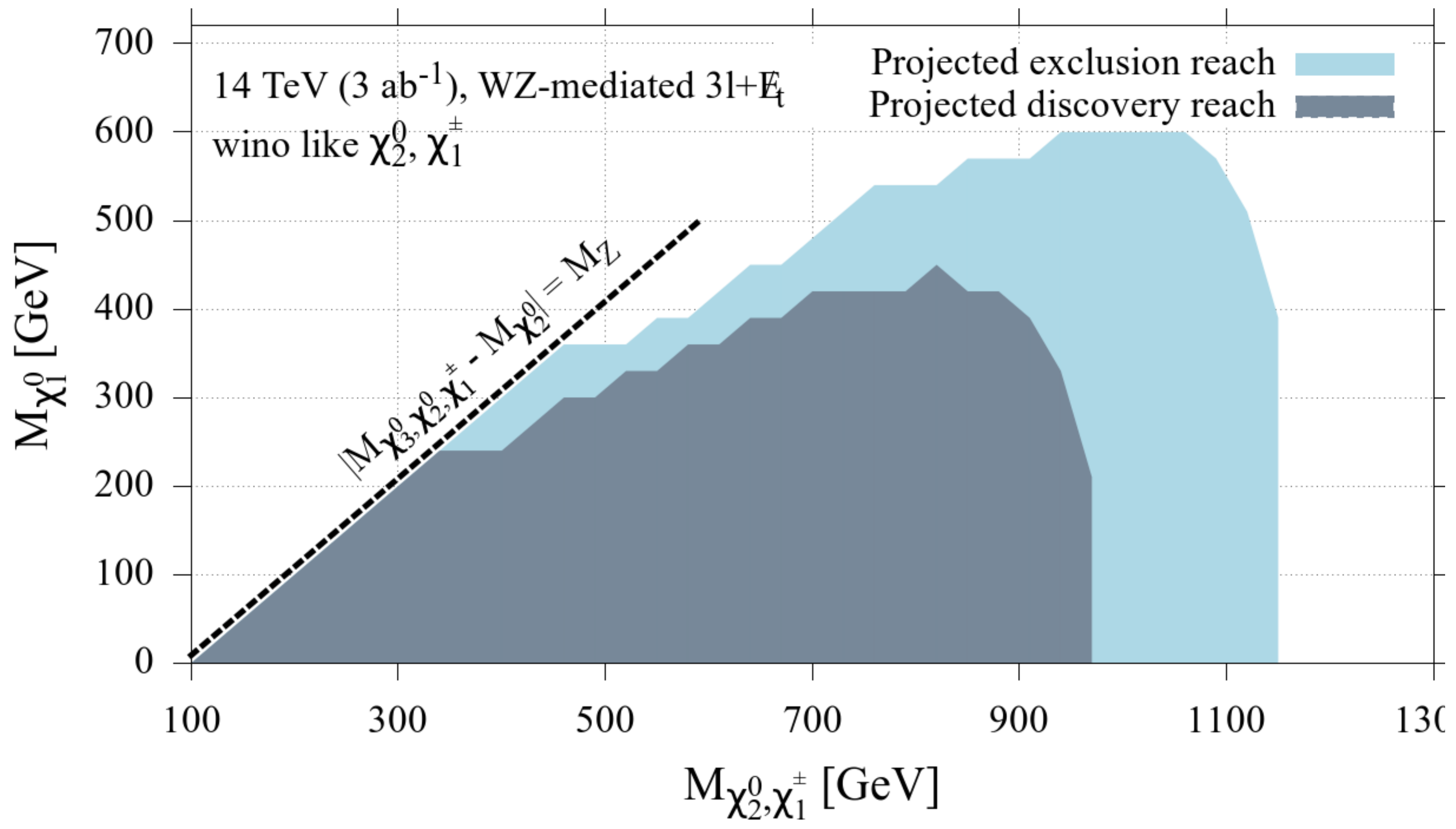
The following signal regions (SR) are used. We choose SRs optimized for large (BPB1, BPD1, BPG1), intermediate (BPE1, BPF1, BPH1) and small (BPA1, BPC1, BPF1) mass difference between NLSPs and the LSP.

	Benchmark points							
	BPA1	BPB1	BPC1	BPD1	BPE1	BPF1	BPG1	BPH1
$M_{\widetilde{\chi}_2^0,\widetilde{\chi}_3^0,\widetilde{\chi}_1^\pm}$ [GeV]	130	310	310	610	610	610	1000	1000
$M_{\widetilde{\chi}_1^0}$ [GeV]	30	0	210	0	300	510	0	420
Kinematic variables	Signal regions							
	SRA1	SRB1	SRC1	SRD1	SRE1	SRF1	SRG1	SRH1
$\Delta\Phi_{l_W \not{E}_T}$	≤ 0.2	-	≤ 1.5	-	-	-	-	-
$\Delta\Phi_{SFOS-\not{E}_T}$	-	$[2.7 : \pi]$	$[1.8 : \pi]$	$[1.5 : \pi]$	$[1.8 : \pi]$	-	$[1.6 : \pi]$	$[1.5 : \pi]$
ΔR_{SFOS}	[1.4 : 3.8]	[0.3 : 2.1]	-	[0.1 : 1.3]	[0.1 : 1.3]	[1.6 : 4.0]	[0.1 : 1.0]	[0.1 : 1.3]
$\not{E}_T$ [GeV]	[50 : 290]	≥ 220	[100 : 380]	≥ 200	≥ 250	-	≥ 200	≥ 200
$M_T^{l_W}$ [GeV]	-	≥ 100	[100 : 225]	≥ 300	≥ 150	[150 : 350]	≥ 150	≥ 200
$M_{CT}^{l_W}$ [GeV]	-	≥ 100	-	≥ 100	≥ 150	[100 : 400]	≥ 200	≥ 200
$p_T^{l_1}$ [GeV]	[50 : 150]	≥ 120	[60 : 110]	≥ 150	≥ 150	[60 : 150]	≥ 210	≥ 200
$p_T^{l_2}$ [GeV]	[50 : 110]	≥ 60	≥ 30	≥ 100	≥ 100	[50 : 80]	≥ 150	≥ 100
$p_T^{l_3}$ [GeV]	≥ 30	≥ 30	≥ 30	≥ 50	≥ 50	[30 : 60]	≥ 50	≥ 50

Background generation (at LO) done using `MadGraph5_aMC@NLO`. Signal generated using `Pythia-6` and detector effects simulated with `Delphes-3.4.2`.

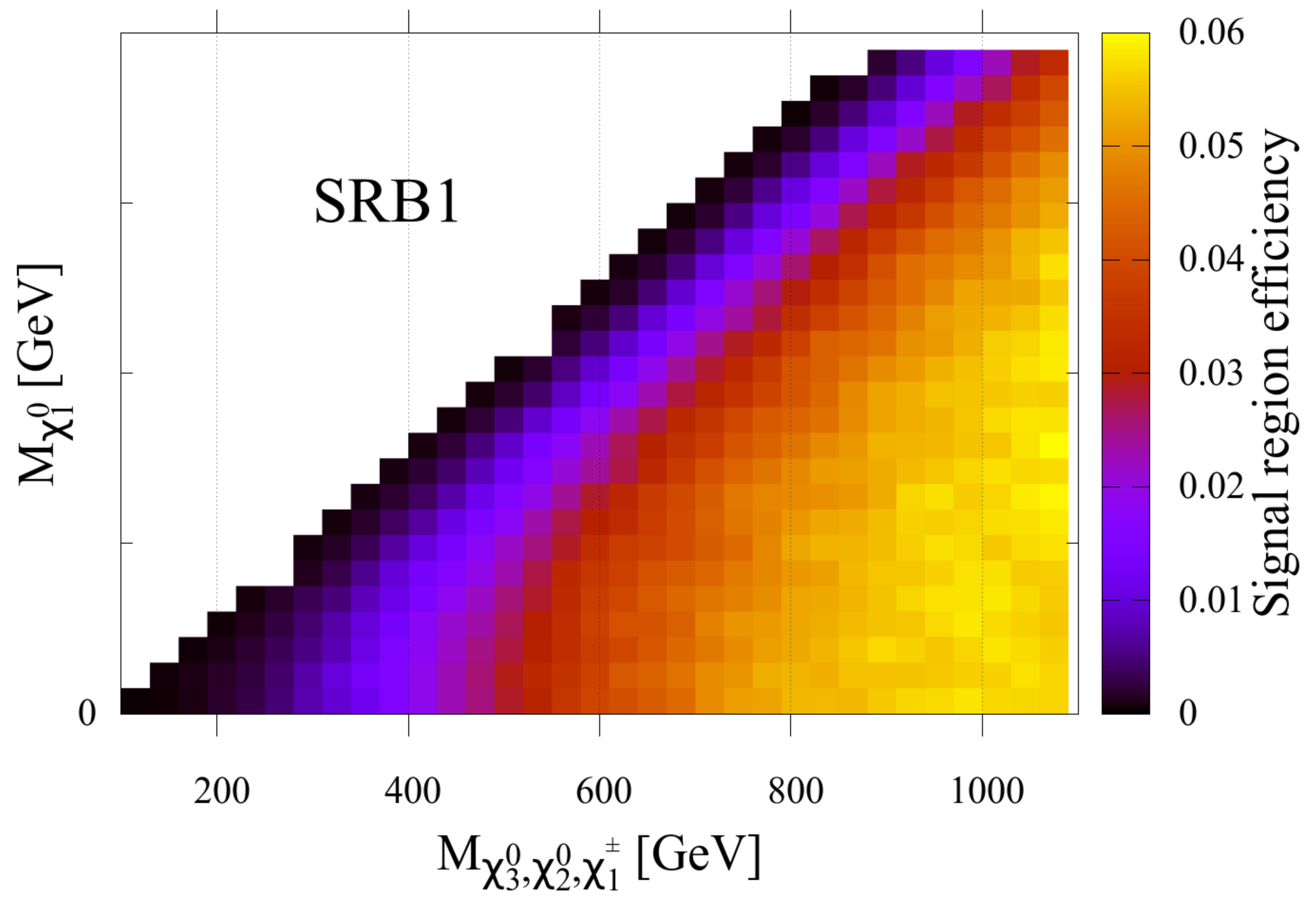
WZ-mediated $3l + \not{E}_T$ at the HL-LHC

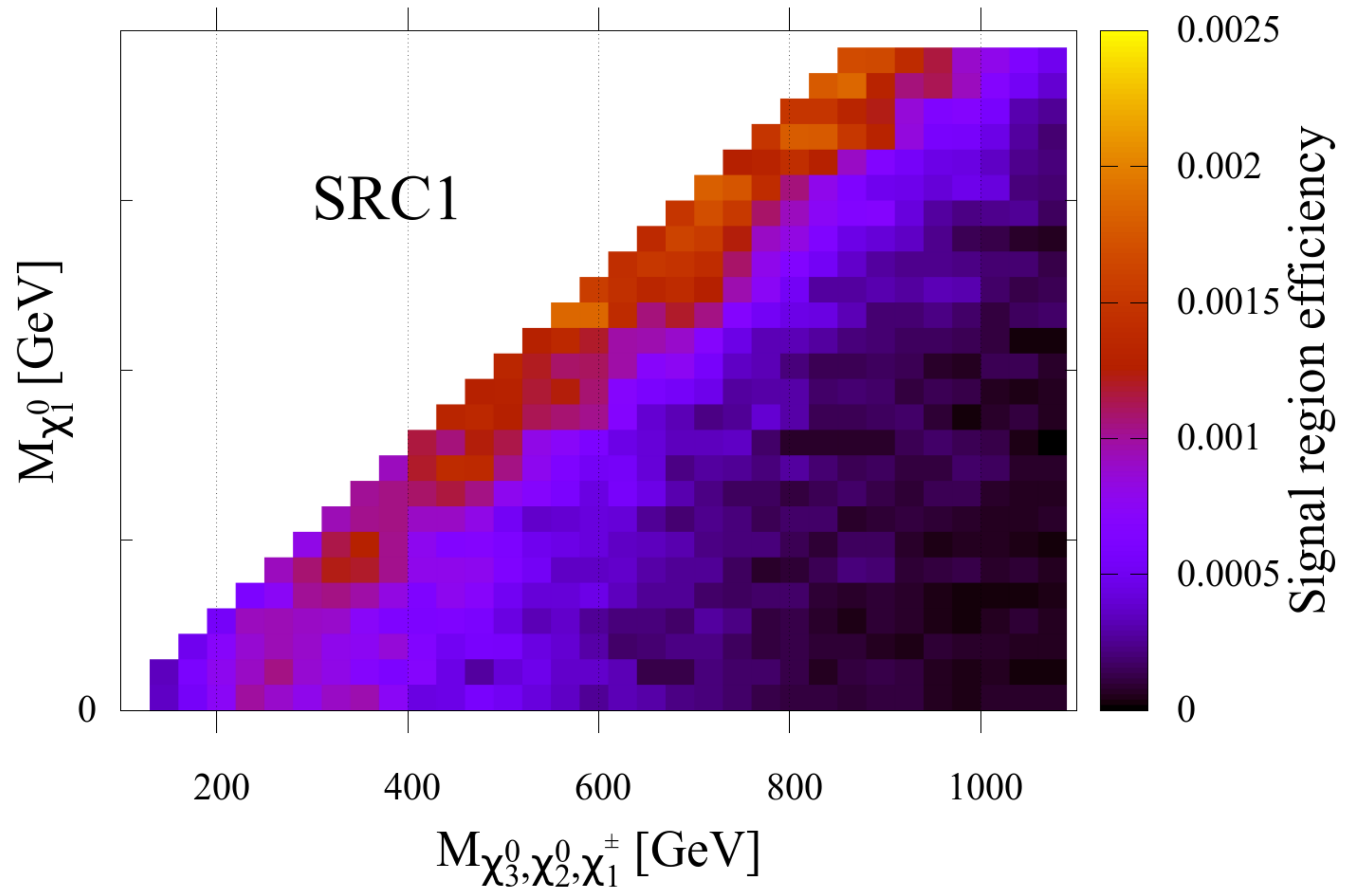
Projected reach of wino searches in the WZ mediated $3l + \not{E}_T$ final state at the HL-LHC.



Our projection results are comparable with the ATLAS projections in ATL-PHYS-PUB-2018-048 (discovery (exclusion) upto $\sim$950 ($\sim$ 1110) GeV for massless LSP at 95% C.L.).

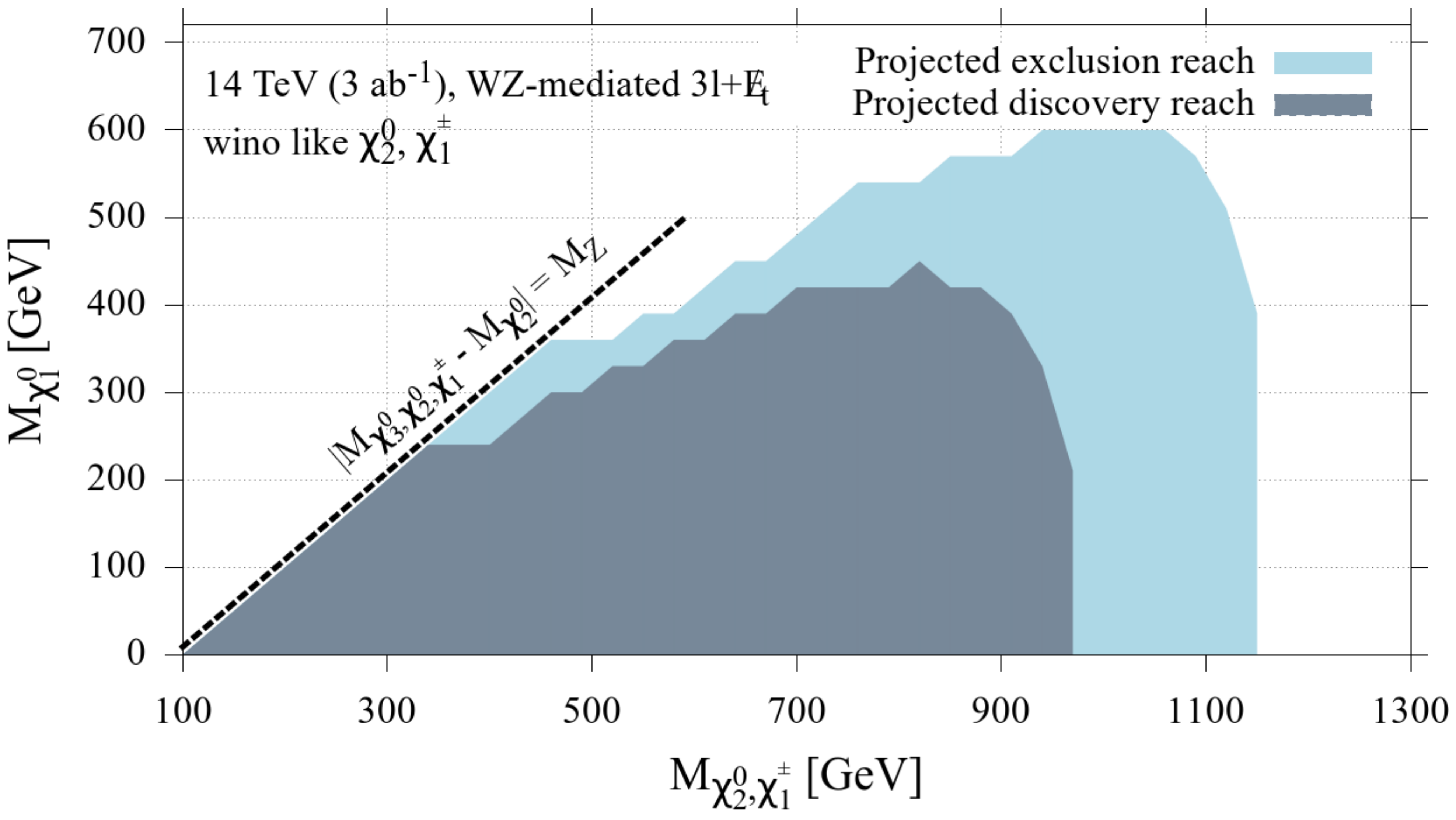
Efficiency maps:





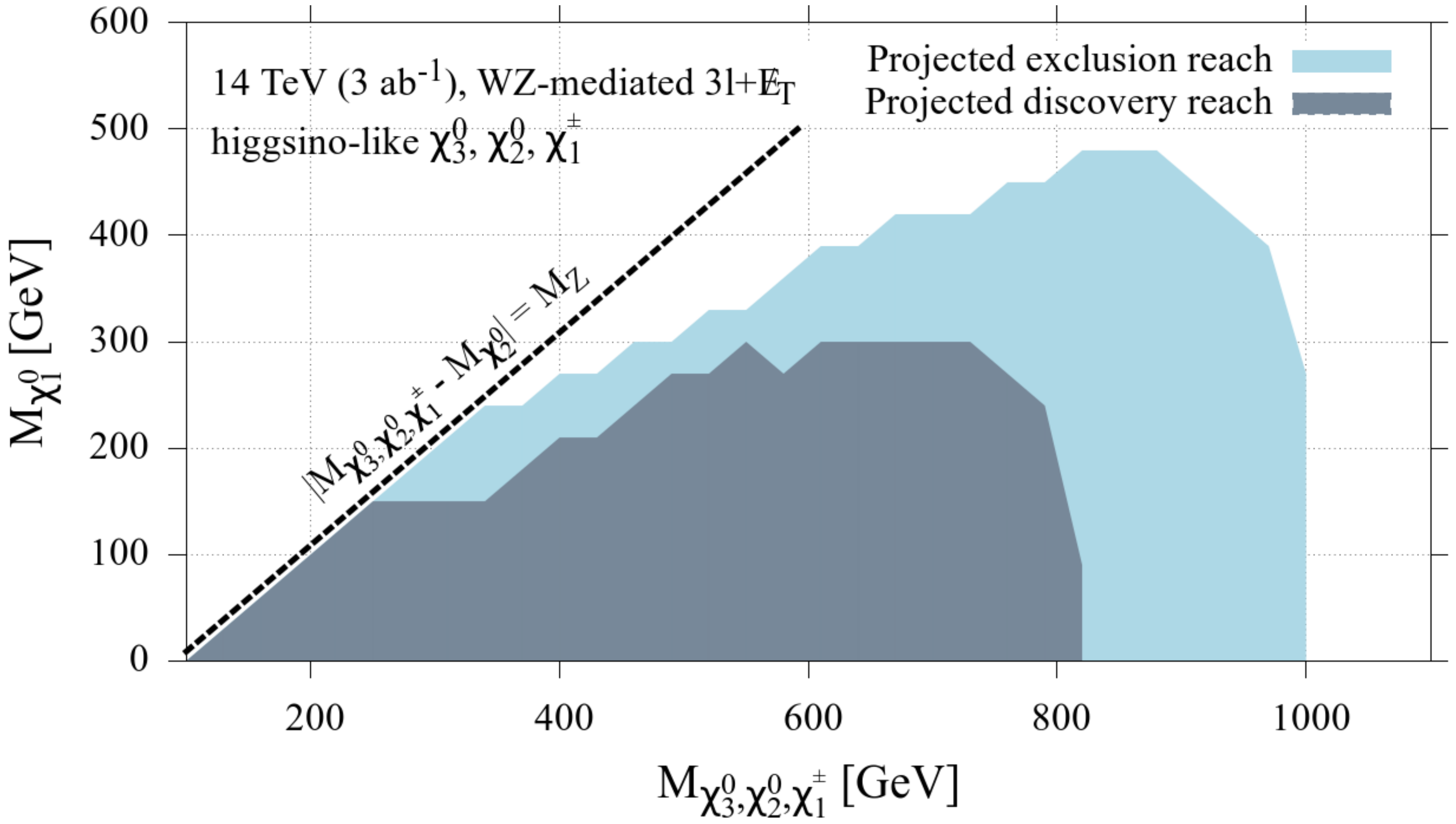
WZ-mediated $3l + \not{E}_T$ at the HL-LHC

Projected reach of wino searches in the WZ mediated $3l + \not{E}_T$ final state at the HL-LHC.



Our projection results are comparable with the ATLAS projections in ATL-PHYS-PUB-2018-048 (discovery (exclusion) upto $\sim$950 ($\sim$ 1110) GeV for massless LSP at 95% C.L.).

Projected reach of higgsino searches in the WZ mediated $3l + \not{E}_T$ final state at the HL-LHC.



A systematic uncertainty of 5% has been assumed in these analyses.

Impact on allowed NMSSM parameter space

- In our allowed parameter region, $\widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0, \widetilde{\chi}_1^\pm, \widetilde{\chi}_2^\pm$ are either higgsino-like, wino-like or wino-higgsino admixtures.
- Direct chargino-neutralino pair production modes which can potentially contribute to WZ mediated $3l + \not{E}_{\mathrm{T}}$: $\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_2^0\widetilde{\chi}_2^\pm$, $\widetilde{\chi}_3^0\widetilde{\chi}_1^\pm$, $\widetilde{\chi}_3^0\widetilde{\chi}_2^\pm$, $\widetilde{\chi}_4^0\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_4^0\widetilde{\chi}_2^\pm$
- The direct production cross-section ($\sigma_{\widetilde{\chi}_i^0\widetilde{\chi}_j^\pm}$) is computed by scaling the pure higgsino cross-section with the respective reduced squared $W\widetilde{\chi}_i^0\widetilde{\chi}_j^\pm$ couplings:

$$C^2_{W\widetilde{\chi}_i^0\widetilde{\chi}_j^\pm} = \left\{\left(N_{i3}\ V_{j2} - N_{i2}\ V_{j1}\sqrt{2}\right)^2 + \left(N_{i4}\ U_{j2} + N_{i2}\ U_{j1}\sqrt{2}\right)^2\right\}$$

U/V are the chargino mixing matrices while N represents the neutralino mixing matrix.

- The signal yield for a particular parameter space point is computed for all the signal regions through:

$$S = \sigma_{\widetilde{\chi}_i^0\widetilde{\chi}_j^\pm} \times (Relevant\ Br\ ratios) \times (\mathcal{L} = 3000\ \mathrm{fb}^{-1}) \times Signal\ efficiency \quad (1)$$

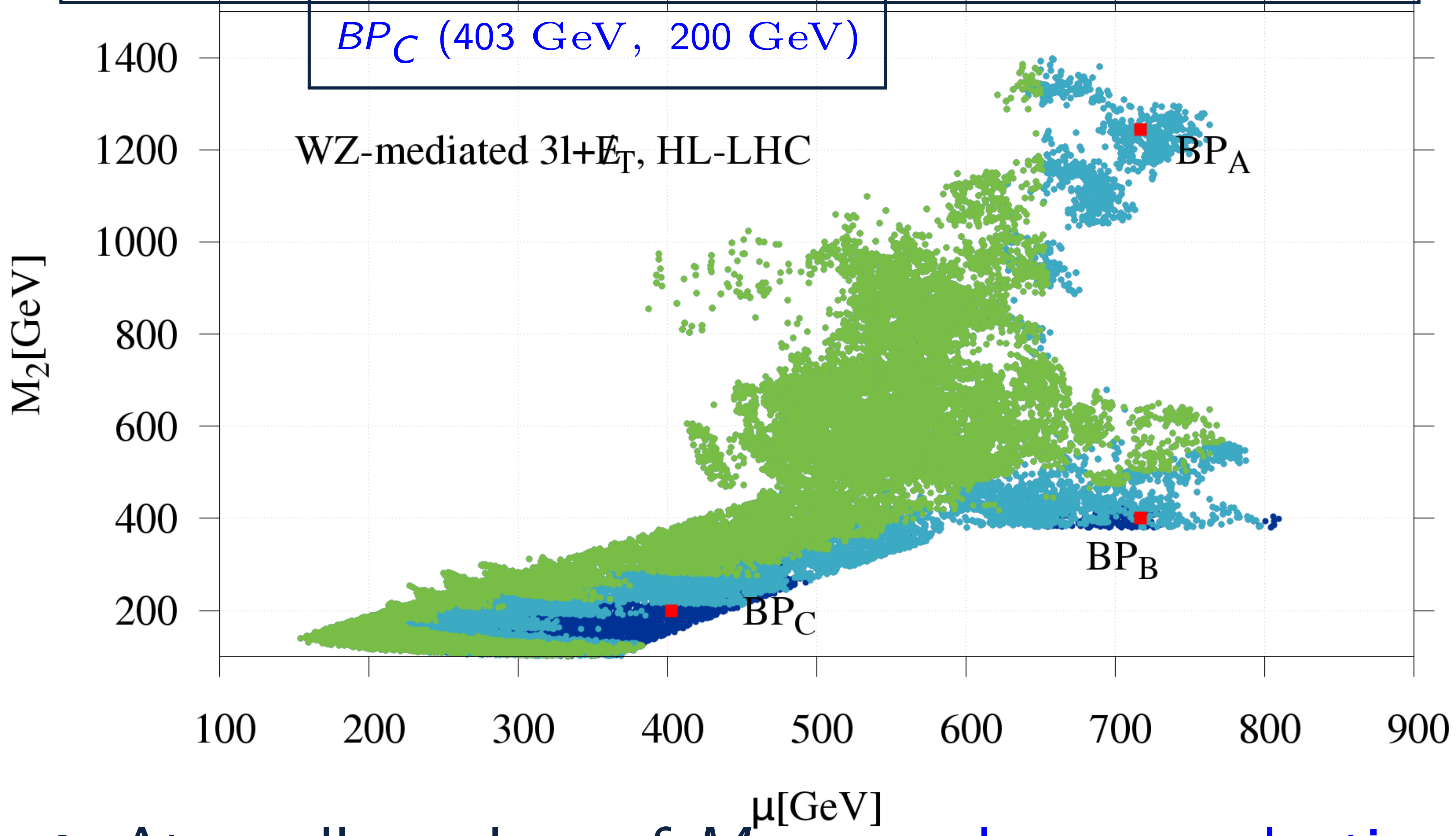
- The signal efficiency is obtained from the efficiency maps shown earlier.
- The signal significance (S_σ) is computed as: $S/\sqrt{B + (B \cdot sys\_un)^2}$, by adopting the signal region that yields the highest S_σ. Here, B stands for background.

Impact on allowed NMSSM parameter space

Color code: Green: $S_\sigma > 5$, light blue: $2 < S_\sigma < 5$, dark blue: $S_\sigma < 2$

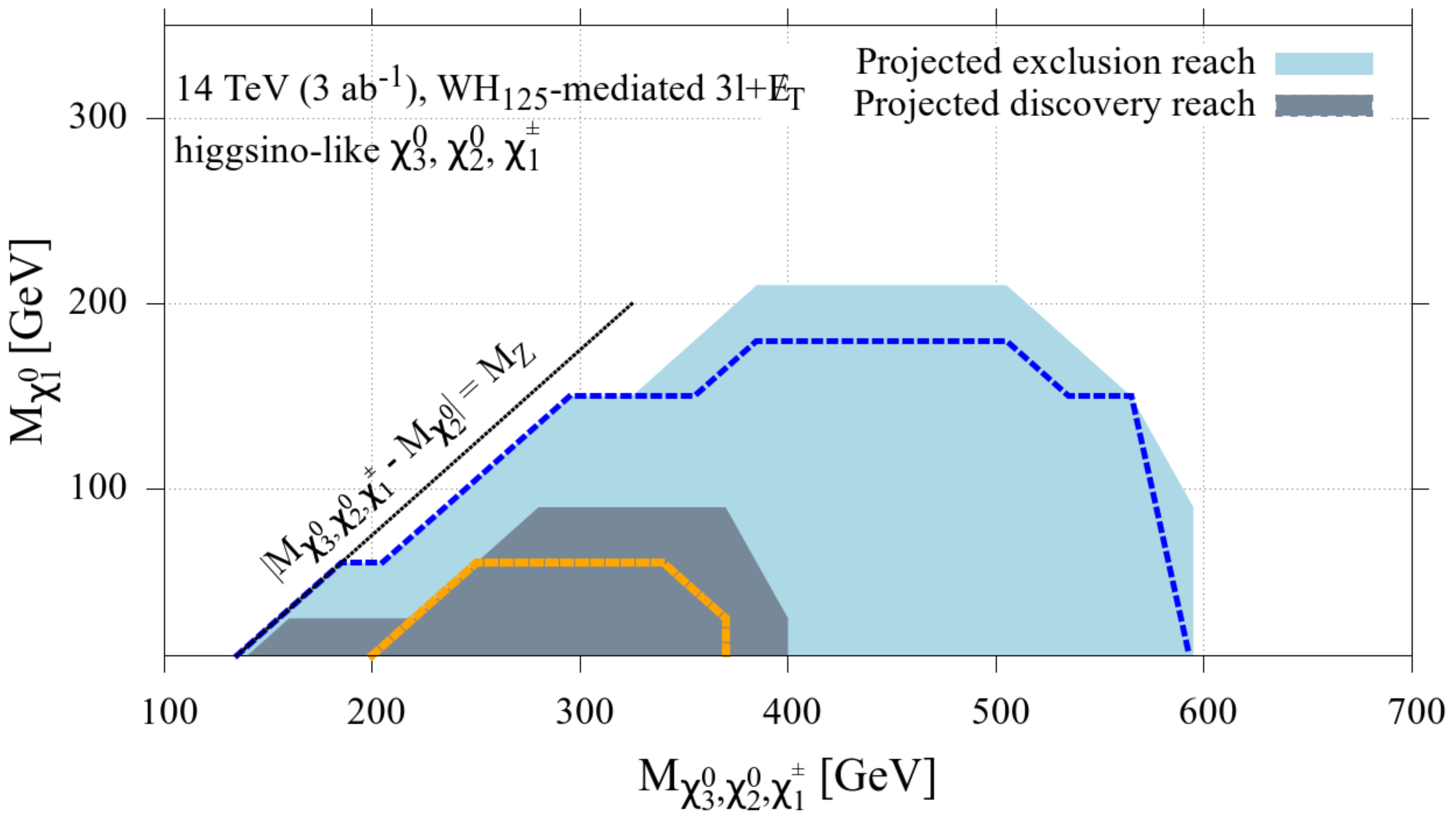
BP_A ($\mu \sim 717$ GeV, $M_2 \sim 1244$ GeV), BP_B (717 GeV, 400 GeV)

BP_C (403 GeV, 200 GeV)



- The observation of a signal is an interplay between the production cross-section and signal efficiency.
- At large values of M_2, μ (near BP_A) $\rightarrow$ large efficiency but smaller production cross-section $\rightarrow$ kinematically suppressed signal.
- At smaller values of M_2, μ, $\rightarrow$ larger production cross-section but signal efficiencies reduce.
- The dark blue points near BP_C have S_σ marginally less than 2σ on account of smaller efficiency from SRB1 and suppressed $\widetilde{\chi}_2^0 \rightarrow Z\widetilde{\chi}_1^0$.
- In BP_B and BP_C, the dominant production mode is $\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm$, and $\widetilde{\chi}_2^0$ dominantly decays into $H_{125} + \widetilde{\chi}_1^0$ with branching rates of 82% and 92%, respectively $\rightarrow$ reduced sensitivity in WZ mediated channels.
- Direct searches in WH_{125} mediated channels could be more effective for these benchmarks.

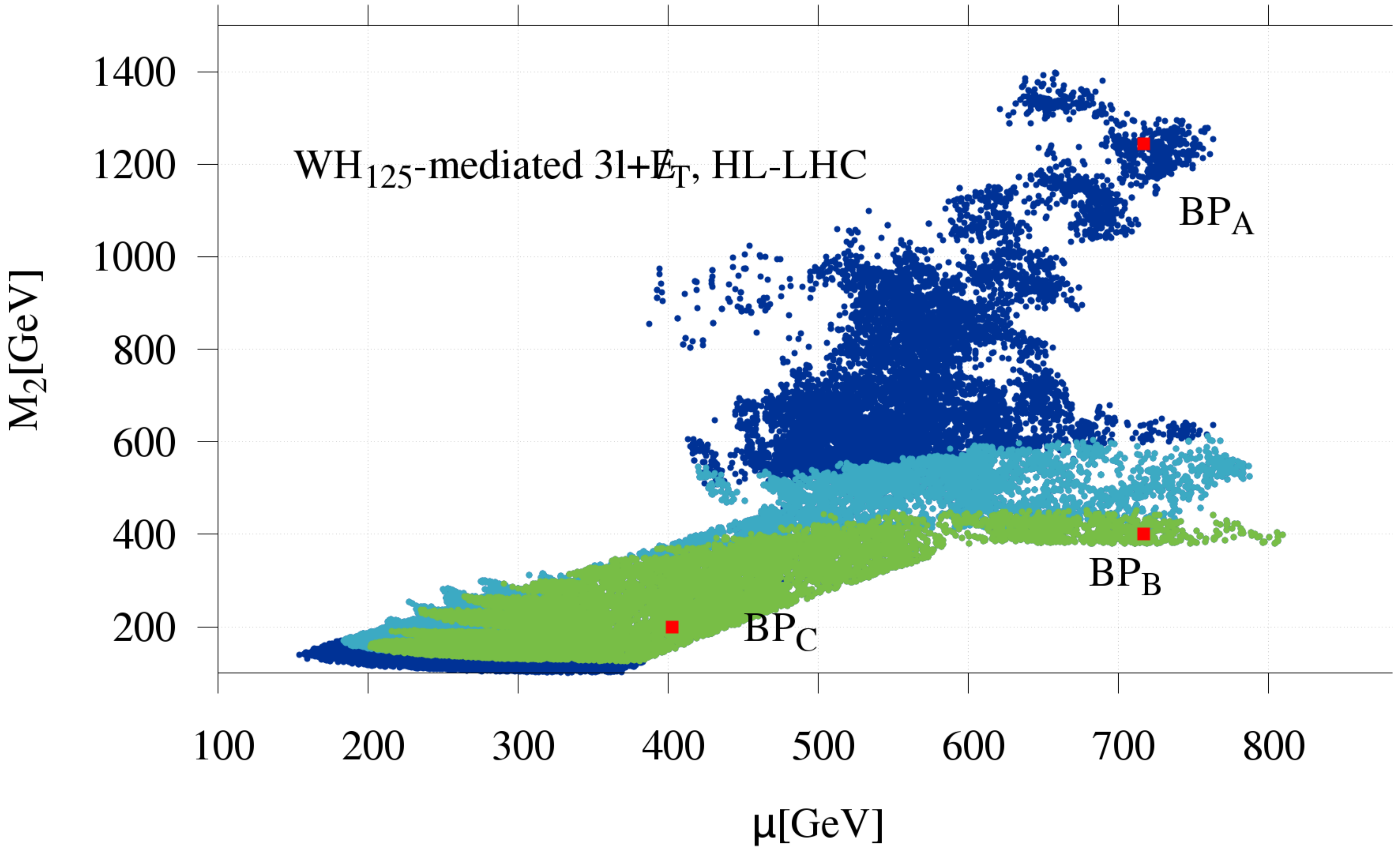
WH_{125}-mediated $3l + \not{E}_T$ at the HL-LHC



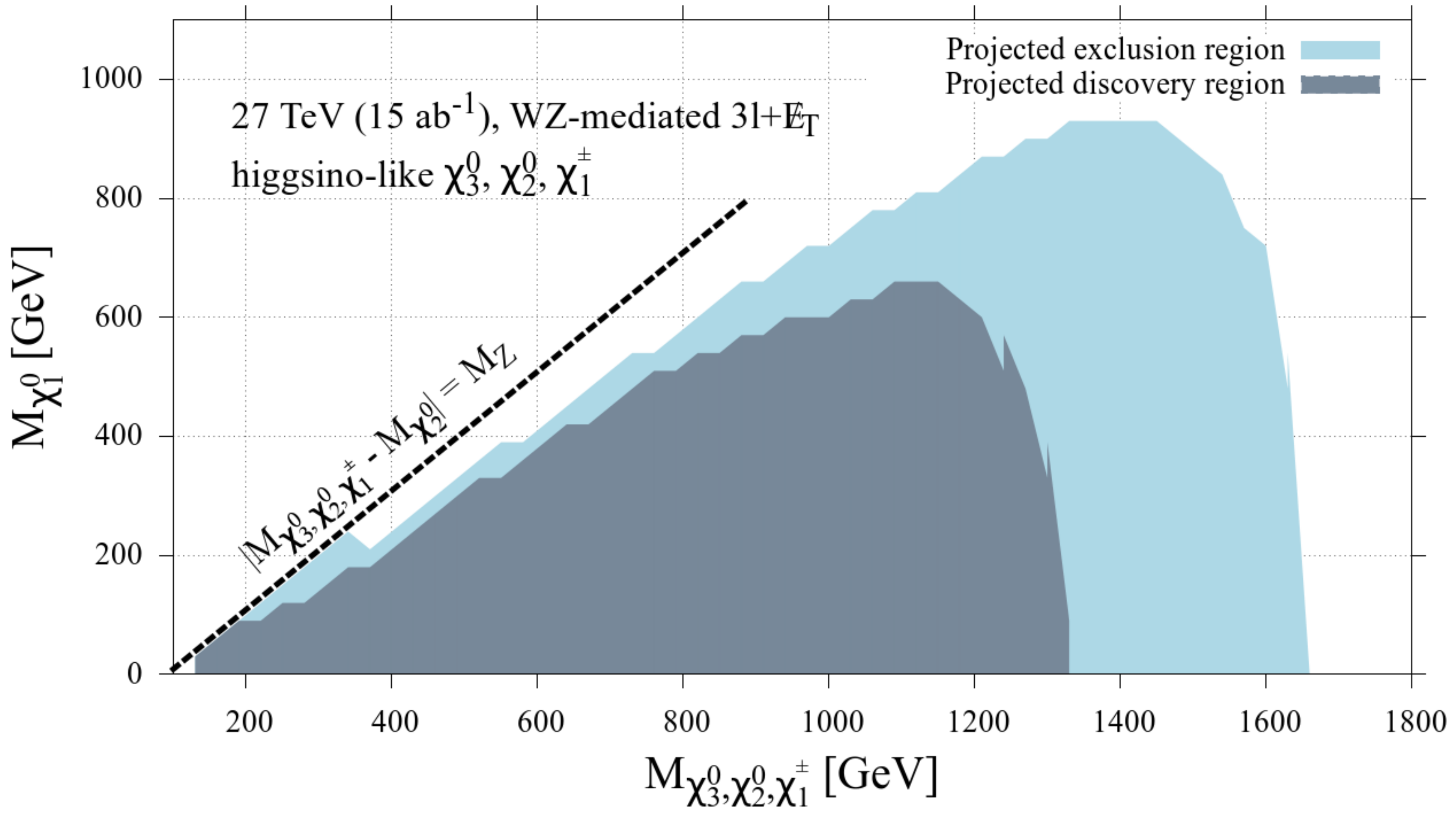
- Here, we use the optimized signal region cuts from ATL-PHYS-PUB-2014-010.

The figure at the bottom shows the projected reach on the currently allowed region $\rightarrow$ direct searches in the WH_{125} mediated $3l + \not{E}_T$ channel are more effective in probing the $M_2 \lesssim \mu$ region of parameter space.

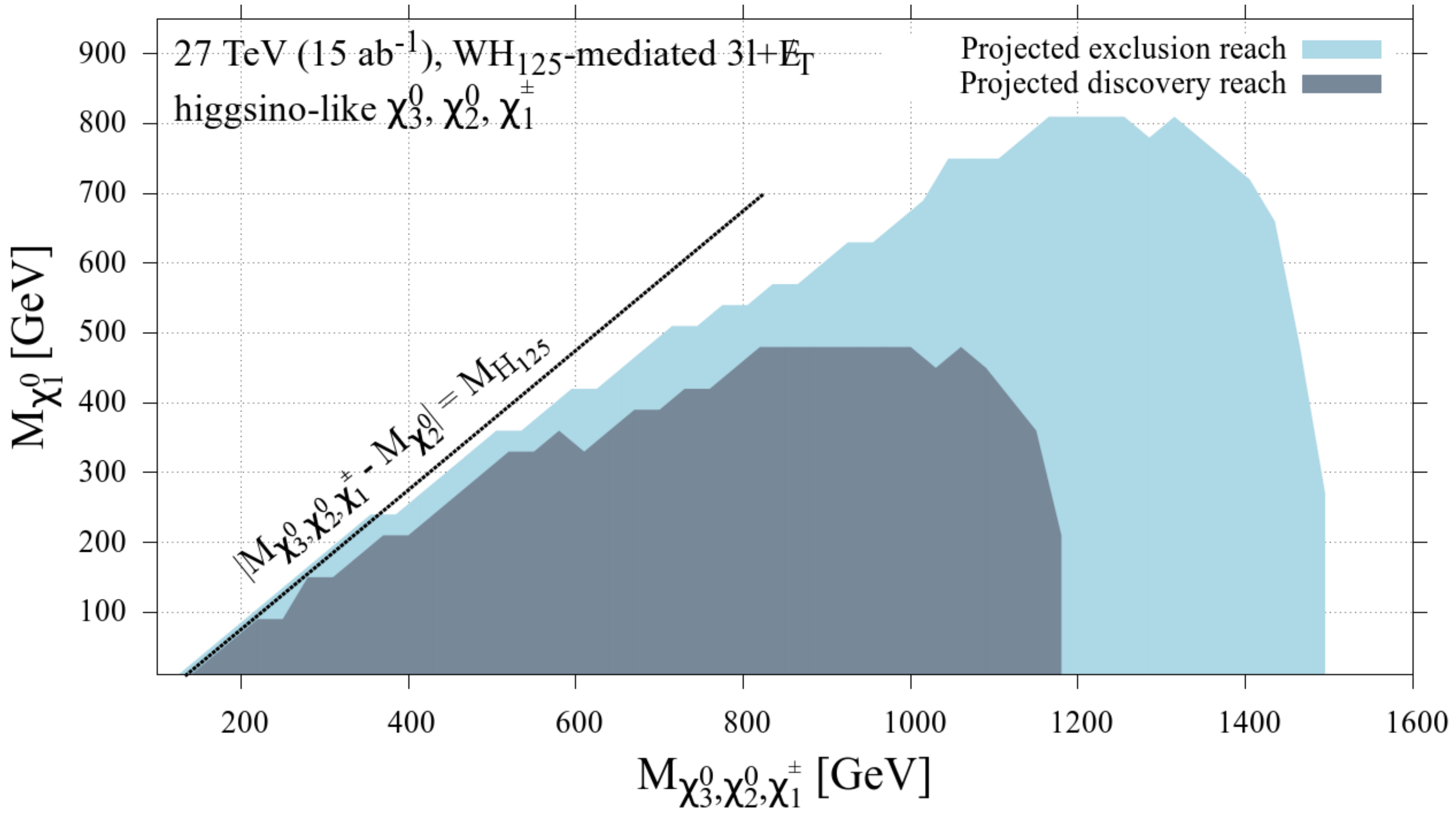
- BP_B and BP_C: outside the reach of direct searches in WZ mediated $3l + \not{E}_T$, but fall within the discovery reach of direct searches in the WH_{125} mediated channel.
- Similarly, the $M_2 \lesssim 150$ GeV region in this figure shows 5σ sensitivity via the WZ mediated $3l + \not{E}_T$ search channel.
- We observe a striking complementarity in the search power via WZ and WH_{125} mediated $3l + \not{E}_T$ search channels..



Color code: Grey: projected discovery region, light blue: projected exclusion region



- We perform our own collider analysis and 10 optimized signal regions are considered.
- Considerable improvement over its HL-LHC counterpart. Projected exclusion reach at the HL-LHC was only up to ~ 1000 GeV for massless $\widetilde{\chi}_1^0$.



- We optimize 7 different signal regions to perform this search.
- Projected exclusion reach at the HL-LHC was only up to ~ 600 GeV.

Scope of other complementary search channels in BP_B

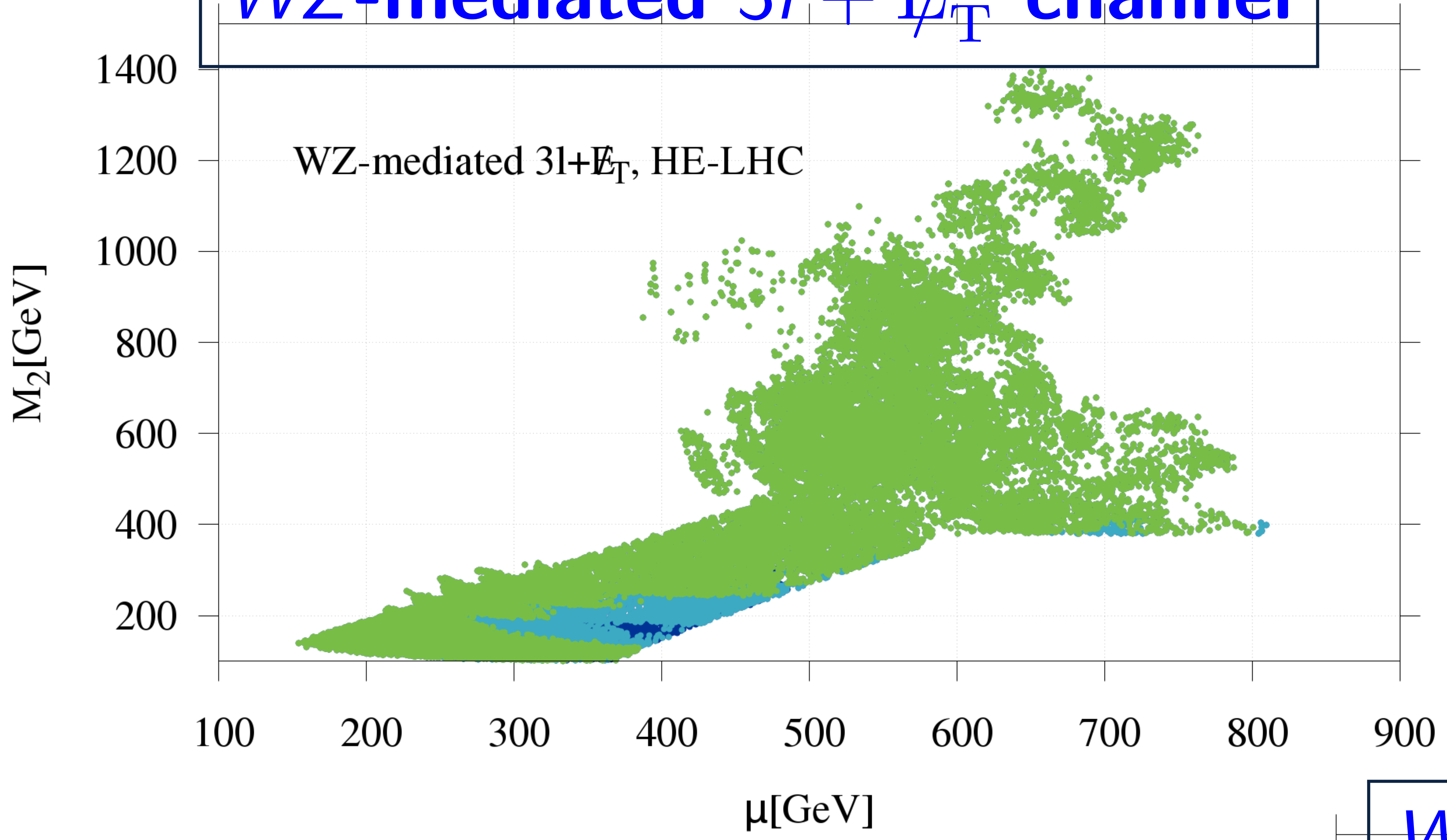
	$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{\chi}_3^0$	$\widetilde{\chi}_4^0$	$\widetilde{\chi}_1^\pm$	$\widetilde{\chi}_2^\pm$
Mass [GeV]	60.4	421	734	742	421	741
wino %	10^{-5}	0.96	2×10^{-3}	0.04	0.94	0.06
higgsino %	10^{-4}	0.04	0.99	0.96	0.06	0.94
Singlino fraction in $\widetilde{\chi}_1^0$: 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.

Projected reach of EW ino searches at the HE-LHC on the allowed parameter space

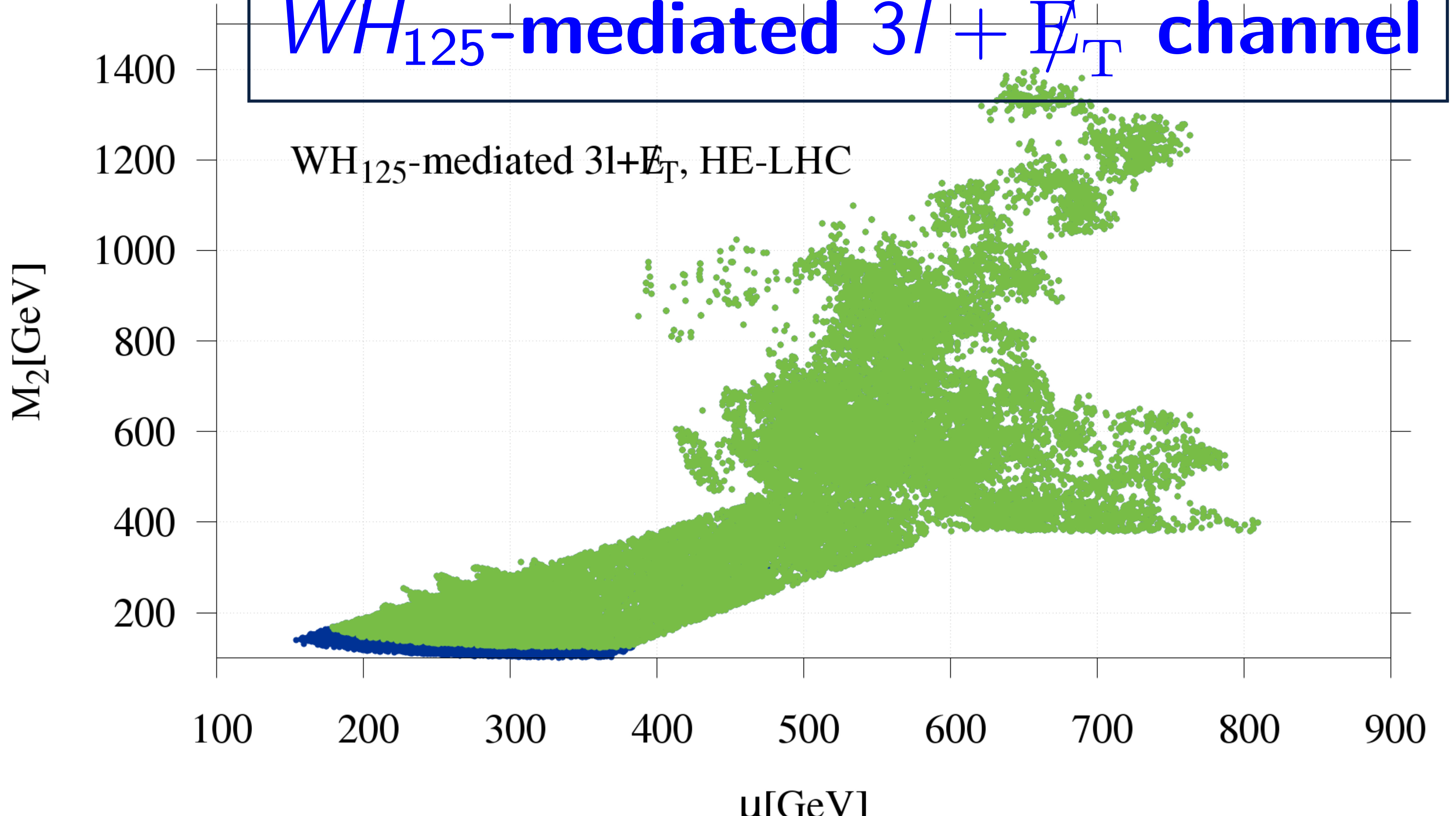
Color code: Green: $S_\sigma > 5$, light blue: $2 < S_\sigma < 5$, dark blue: $S_\sigma < 2$

WZ-mediated $3l + \not{E}_T$ channel



The HE-LHC provides a larger discovery opportunity than the HL-LHC for the detection of NMSSM inos with light LSP.

WH_{125}-mediated $3l + \not{E}_T$ channel



Combination of EW ino searches in the WZ and WH_{125} mediated $3l + \not{E}_T$ channel will probe all the currently allowed parameter space points at discovery potential.

Future directions

Light Higgs phenomenology

- Benchmark studies focused on exploring the parameter region with light H_1/A_1 at the future high-energy colliders through dedicated searches in various final states, viz. the 4τ final state.
- Study of complementarity between the direct light Higgs search projections and the invisible Higgs width measurement capability of the linear colliders.

The alternate probes for electroweakino searches

- Benchmark points BP_B and BP_C indicated towards the possibility of having cascade decays which culminate in final states which are different from the traditional search channels.
- These novel search modes might provide complementary probes for benchmark points with cascade decays and could increase the discovery reach at the future colliders.

A comprehensive study of the light singlino region of parameter space

- We find light singlino-like LSPs with mass as small as $\sim$1 GeV compatible with the current collider, astrophysical and cosmological constraints.
- Despite having a pseudoscalar Higgs as the mediator, the annihilation cross-section of these light singlinos is found to be small enough to avoid any implications from the current indirect constraints while also generating an under-abundant relic.
- This sector would require a more careful study.

Benchmark points

Benchmark points	Input parameters
BP_A	$\lambda = 0.3$, $\kappa = 0.01$, $\tan\beta = 9.5$, $A_\lambda = 6687$ GeV, $A_\kappa = 5.2$ GeV, $\mu = 717$ GeV, $M_2 = 1244$ GeV, $M_3 = 2301$ GeV
BP_B	$\lambda = 0.44$, $\kappa = 0.02$, $\tan\beta = 11.8$, $A_\lambda = 8894$ GeV, $A_\kappa =$ -57 GeV, $\mu = 717$ GeV, $M_2 = 400$ GeV, $M_3 = 4323$ GeV
BP_C	$\lambda = 0.08$, $\kappa = 3 \times 10^{-4}$, $\tan\beta = 18$, $A_\lambda = 6563$ GeV, $A_\kappa =$ -7.9 GeV, $\mu = 403$ GeV, $M_2 = 200$ GeV $M_3 = 3080$ GeV
BP_D	$\lambda = 0.44$, $\kappa = 0.02$, $\tan\beta = 15.6$, $A_\lambda = 585$ GeV, $A_\kappa = 9501$ GeV, $\mu = 585$ GeV, $M_2 = 952$ GeV, $M_3 = 4457$ GeV
BP_E	$\lambda = 0.27$, $\kappa = 0.02$, $\tan\beta = 11.6$, $A_\lambda = 5875$ GeV, $A_\kappa = 12$ GeV, $\mu = 518$ GeV, $M_2 = 696$ GeV, $M_3 = 3634$ GeV
BP_F	$\lambda = 0.30$, $\kappa = 0.01$, $\tan\beta = 11.2$, $A_\lambda = 6319$ GeV, $A_\kappa = 17$ GeV, $\mu = 571$ GeV, $M_2 = 555$ GeV, $M_3 = 2687$ GeV
BP_G	$\lambda = 0.42$, $\kappa = 0.02$, $\tan\beta = 15.9$, $A_\lambda = 8638$ GeV, $A_\kappa = 43.4$ GeV, $\mu = 515$ GeV, $M_2 = 396$ GeV, $M_3 = 2903$ GeV
BP_H	$\lambda = 0.02$, $\kappa = 7 \times 10^{-5}$, $\tan\beta = 25.5$, $A_\lambda = 7348$ GeV, $A_\kappa =$ -7.3 GeV, $\mu = 302$ GeV, $M_2 = 204$ GeV, $M_3 = 2239$ GeV
BP_I	$\lambda = 0.02$, $\kappa = 6 \times 10^{-5}$, $\tan\beta = 27.6$, $A_\lambda = 6924$ GeV, $A_\kappa =$ -5.7 GeV, $\mu = 262$ GeV, $M_2 = 210$ GeV, $M_3 = 2217$ GeV