Probing the NMSSM and MSSM with light neutralino DM through Higgs invisible measurements

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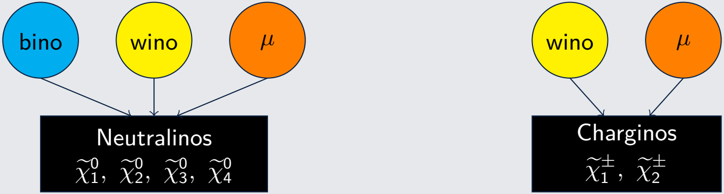
- Searches at the LHC have unambiguously confirmed the existence of a scalar boson at 125 GeV.
- Numerous measurements indicate that the properties of the observed resonance is consistent with the predictions from SM.
- The current data still leaves enough space for the observed Higgs to have non-standard decays.
- Higgs decaying to invisible particles provides one such exciting prospect.
- Invisible particles, if stable, could also be the dark matter candidate.
- Within R-parity conserved SUSY scenarios, the lightest stable particle, typically χ_1^0 (lightest neutralino), naturally provides a DM candidate.
- Correlations between invisible Higgs measurements at the future linear colliders, Dark Matter direct detection and direct/indirect collider probes, can provide interesting directions towards exploring the SUSY landscape.

- MSSM parameters which capture the relevant physics of the Higgs and electroweakino sector :
  the gaugino masses (M_1, M_2), the higgsino mass (μ), $\tan\beta$, pseudoscalar mass (M_A), third generation squarks, trilinear coupling of stop (A_t) and gluino mass (M_3).
- The Higgs sector features 5 Higgs bosons: 2 neutral scalars (H_1, H_2), 1 neutral pseudoscalar (A_1), and charged Higgses ($H^\pm$).

- The electroweakino sector:



$\tilde{\chi}_1^0$ can be a viable DM candidate if R-parity conservation is assumed.

- Our region of interest : $M_{\widetilde{\chi}_1^0} < M_h/2$:
  Below 62.5 GeV, the $\widetilde{\chi}_1^0$ has to be bino dominated due to the chargino mass constraint.
- Small bino annihilation cross-section $\rightarrow$ not large enough to be compatible with observed relic abundance.
- Compatibility with relic abundance requires specific resonances at $\sim 2M_{\widetilde{\chi}_1^0} \rightarrow$ annihilation through Z-boson or Higgs boson.

Range of parameter space

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

Relevant couplings:

- $\widetilde{\chi}_1^0$-Higgs-$\widetilde{\chi}_1^0$ coupling: $g_{h\widetilde{\chi}_1^0\widetilde{\chi}_1^0} = g\,(N_{11} - \tan\theta_W N_{12})\,(\sin\alpha N_{13} + \cos\alpha N_{14})$
- $\widetilde{\chi}_1^0$-Z-$\widetilde{\chi}_1^0$ coupling: $g_{Z\widetilde{\chi}_1^0\widetilde{\chi}_1^0} = \frac{g}{2\cos\theta_W}\left(|N_{13}|^2 - |N_{14}|^2\right)$

α : Higgs mixing angle, N_{11} : bino component, N_{12} : wino components, N_{13}, N_{14} : higgsino components

Limits from LEP:

- $M_{\widetilde{\chi}_1^\pm} \gtrsim 103.5\ \mathrm{GeV}$.
- Upper limits on $\sigma(e^+e^- \to \widetilde{\chi}_i^0 \widetilde{\chi}_1^0)$ at 95% CL.
- Upper limits from searches in $e^+e^- \to ZH_j/A_iH_j$

Flavor constraints:

- $3.00 \times 10^{-4} < Br(B \to X_s\gamma) < 3.64 \times 10^{-4}$.
- $1.73 \times 10^{-9} < Br(B_s \to \mu^+\mu^-) < 4.33 \times 10^{-9}$.
- $0.68 \times 10^{-4} < Br(B^+ \to \tau^+\nu_\tau) < 1.44 \times 10^{-4}$.

Limits from LHC

- Higgs signal strength constraints.
- Limits from sparticle searches at the LHC.
- $Br(h_{125} \to inv.) < 19\%$.

Limits from LEP:

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Limits from LHC

- Constraints from direct electroweakino searches
  - $pp \to (\chi_i^0 \to Z/h\chi_1)(\chi_1^{\pm} \to W^{\pm}\chi_1^0)$ 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.

- LHC : Direct Searches

Current limit
$Br(H \to inv.) \sim 11\ \%$

Projections
High Luminosity LHC: $\sim$ 4%.

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

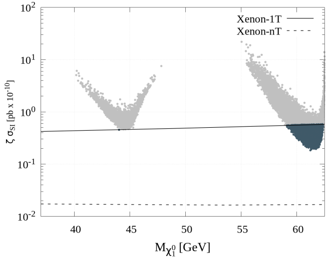
ILC : $Br(H \to inv.) \sim 0.4\ \%$.
CEPC : $Br(H \to inv.) \sim 0.28\ \%$.

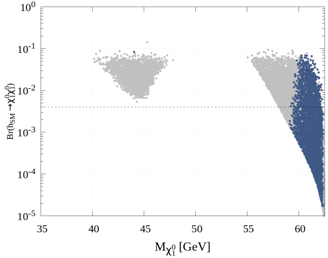
Aim of this work

To shed some light on the nature of DM and its discovery prospect, the complimentarity among the following future experiments is studied:

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

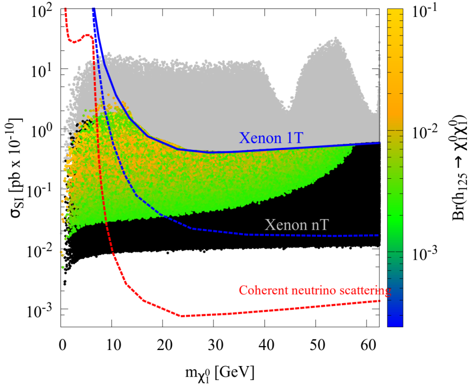
*In this work, we do not perform any detailed investigation of any specific mechanism which will eventually generate the correct relic density.





- Imposing the upper bound on relic density sets a lower limit on $M_{\tilde{\chi}_1^0} \gtrsim 40$ GeV.
- Efficient DM annihilation could be achieved only through Z or Higgs exchange $\rightarrow$ points populated in the $M_{h_{SM}}/2$ and $M_Z/2$ regions.
- Higgs signal strength measurements restrict $Br(h \rightarrow inv.) \lesssim 10\%$ $\rightarrow$ stronger than the current direct limit.
- The current Xe-1T limits exclude almost all the points in the Z funnel region and significant fraction of points in the Higgs funnel region.
- Future linear colliders will be able to completely probe the Z funnel region and a small fraction of currently allowed points in the Higgs funnel region.

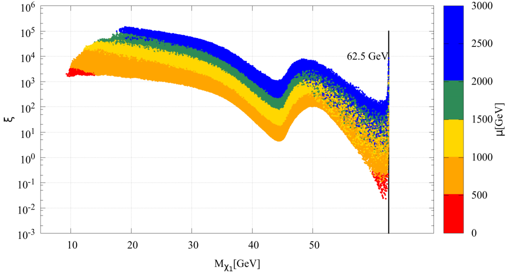
1. Lifting the relic density constraint makes it possible to obtain low LSP masses as well.
2. Black points: $Br(h_{125} \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0) < 0.4\%$.
3. Higgs invisible measurements at the future linear colliders will be able to probe points which are outside the projected reach of future direct detection experiments over the entire $\widetilde{\chi}_1^0$ mass range.



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.



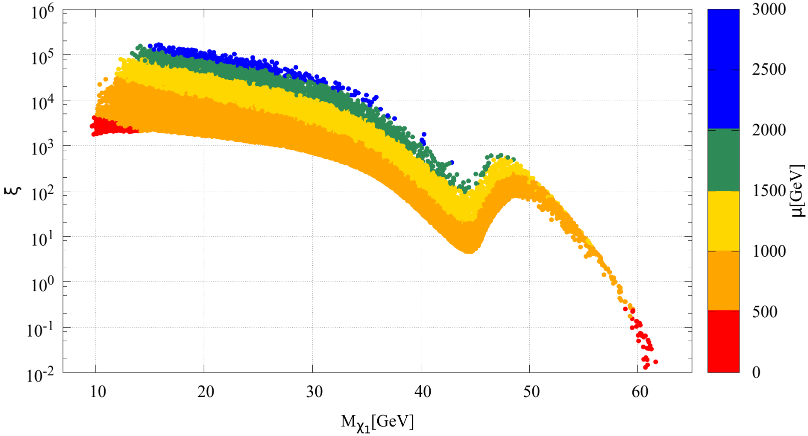
The red coloured points will be sensitive to electroweakino searches at ILC.
An observation within this scenario would be able to demarcate between a thermal DM and a non standard DM.

A similar spectrum is observed for parameter points with :

- $Br(h \to inv.) > 0.4\%$.(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)



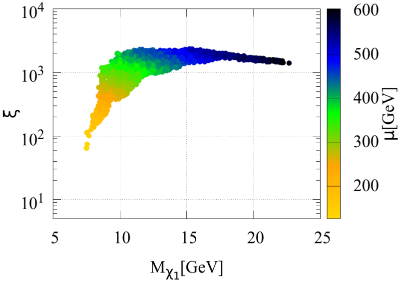
The following parameter space points are visible to

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

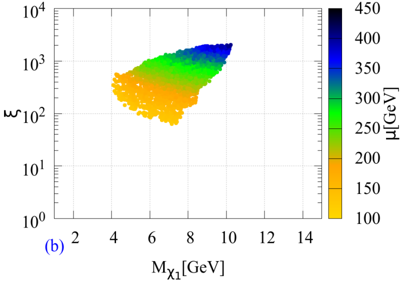
however, evade detection by

- LZ (through SD WIMP-neutron interaction)

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

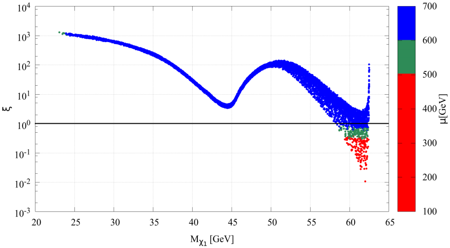


Evades Xe-nT

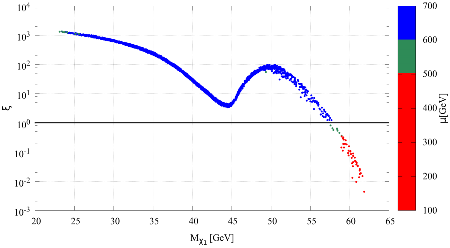


An observation within this scenario would be indicative of being a relic from non-thermal history.

These parameter points are accessible to Xe-nT and LZ only.



Accessible to Xe-nT, LZ and ILC,



- A signal in the non-resonant and Z resonance region would indicate towards the DM being a relic from $\Omega h^2 > 0.12$.
- In the first case, observation in the Higgs resonance region complemented by an observation in electroweakino search at ILC will be indicative of a thermal DM.

Next, lets take a look at the NMSSM parameter space with light $\widetilde{\chi}_1^0$ DM.

1. Solves the μ problem in MSSM: The NMSSM offers an elegant solution to the μ-problem in MSSM through the introduction of an additional singlet superfield ($\hat{S}$).

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

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

It naturally generates an effective μ term when S develops a non-zero vev $\langle S \rangle$.

2. Less tuning required for a 125 GeV SM-like Higgs boson:

$$M^2_{h_{SM}} \sim M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(ln\left(\frac{m^2_{stop}}{m_t^4}\right) + ...\right)$$

MSSM (Tree level): $M_h < M_Z \cdot |\cos 2\beta| \lesssim M_Z$
NMSSM (Tree level): $M_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

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It naturally generates an **effective μ term** ($\mu \sim \lambda\langle S\rangle$) when S develops a non-zero vev $\langle S\rangle$. NMSSM is the simplest SUSY extension of the SM in which the weak scale is generated by M_{SUSY}.

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Why NMSSM?

Richer Higgs sector

- 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 admixtures of doublets and singlet.

Richer electroweakino sector

- 5 neutralinos (MSSM + singlino) and 2 charginos $(\widetilde{\chi}_1^{\pm},\ \widetilde{\chi}_2^{\pm})$:

$$\chi_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_d^0 + N_{i4}\tilde{H}_u^0 + N_{i5}\tilde{S} \quad (1)$$

- At the tree level, the EW ino sector is parametrized by: $M_1,\ M_2,\ \mu, \tan\beta,\ \lambda, \kappa$.

- Possible to have light singlet-dominated a_1/h_1 below 125 GeV which can couple with singlinos $\rightarrow$ possibile to obtain singlino-like $\widetilde{\chi}_1^0$ $(O(1)\ GeV)$ with $\Omega h^2 < 0.122$..
- Added complication: More input parameters are required to parametrize the tree level Higgs and electroweakino sector:

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \tan\beta,\ \mu,\ M_1,\ M_2$$

Parameter space scan

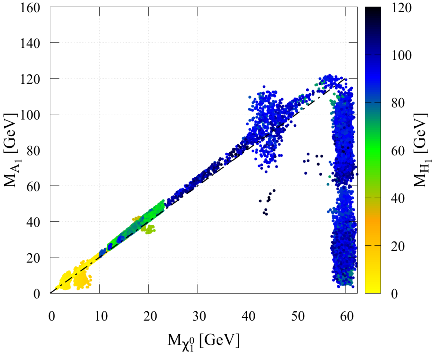
- We choose the parameter space with:
  - $M_{\tilde{\chi}_1^0} < 62.5$ GeV
  - $\Omega h^2 \leq 0.120$
  - M_{h_1} and M_{a_1} below 122 GeV
- h_2 is identified with the SM-like Higgs boson.
- heavy squarks and sleptons to decouple their effects on the light neutralino sector.

The scan is performed over the following range of input parameters:

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

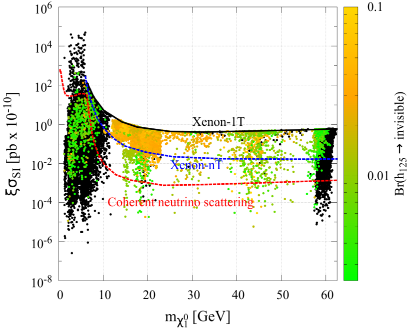
- Below 62.5 GeV, the $\widetilde{\chi}_1^0$ has to be bino or singlino dominated.
- $\Omega h^2 \leq 0.122$ can be satisfied only through co-annihilation or annihilation via resonance.
- For our parameter space,
  co-annihilation $\longrightarrow$ *not feasible*
- Only possibility $\rightarrow$ annihilation via resonance.
- We fix M_1 at 2 TeV $\rightarrow$ $\widetilde{\chi}_1^0$ is always singlino dominated.
- The singlino-like $\widetilde{\chi}_1^0$ below $M_Z/2$ can undergo annihilation through a_1 or h_1.
- To evade the current constraints, light a_1 and h_1 must be 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 $M_{h_1} \sim 2M_{\widetilde{\chi}_1^0}$.



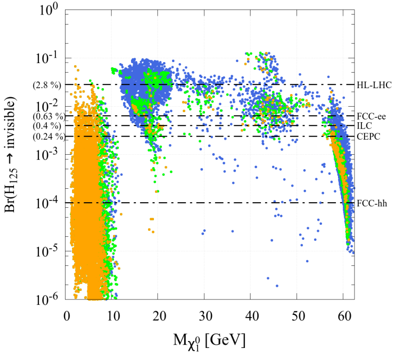
Complementarity between future direct detection experiments and invisible Higgs measurements

Black points: $Br(H_{125} \to inv.) < 0.4\% \to$ outside the projected Higgs invisible measurement capability of ILC.



- ILC will be able to probe the green colored points in the $M_{\tilde{\chi}_1^0} \lesssim$ 10 GeV region which may be forever outside the reach of DM detectors.
- ILC will also be able to probe points which are outside Xenon-nT's future reach.

Complementarity between future direct detection experiments and invisible Higgs measurements



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]

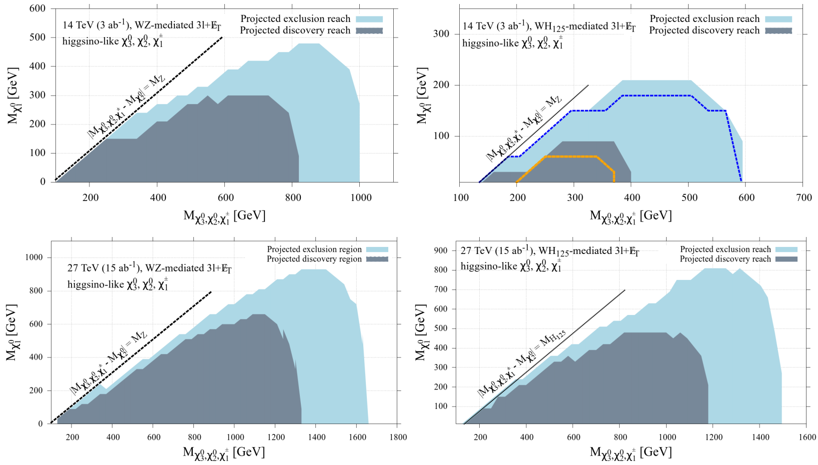
- Orange: points below the coherent neutrino scattering floor.
- Green: points outside Xenon-nT's projected reach but above the neutrino scattering floor.

Conclusion

- In MSSM with light bino-like neutralino DM, imposing the upper limit on relic density leads to allowed points in the Higgs and Z pole regions.
- Direct detection experiments exclude most of the points in the Z funnel region, however, a significant fraction of points survive in the Higgs funnel region.
- Higgs invisible measurements at the future linear colliders alongside future direct detection measurements will be able to probe a considerable fraction of these allowed parameter points.
- Higgs invisible measurements would also be able to cover parameter points in the $\Omega h^2 > 0.12$ region which are outside the projected reach of future DD experiments.
- In NMSSM with singlino-like $\widetilde{\chi}_1^0$ and $\Omega h^2 < 0.12$, Higgs invisible measurements at the future linear colliders would be able to probe points which are outside the projected reach of future DD experiments and also those points which fall below the coherent neutrino scattering floor.

Thank you

Backup slides


14 TeV (3 ab^{-1}), WZ-mediated 3l+$\not{E}_T$
higgsino-like $\chi_3^0, \chi_2^0, \chi_1^\pm$
Projected exclusion reach
Projected discovery reach
$|M_{\chi_3^0,\chi_2^0,\chi_1^\pm} - M_{\chi_1^0}| = M_Z$
$M_{\chi_1^0}$ [GeV]
$M_{\chi_3^0,\chi_2^0,\chi_1^\pm}$ [GeV]
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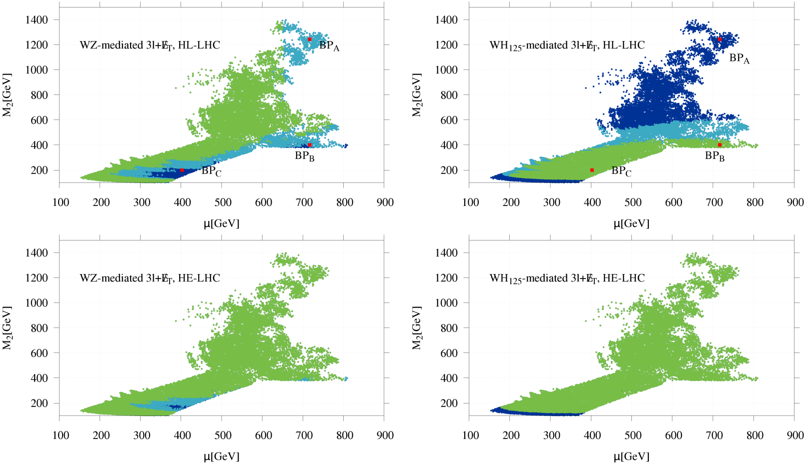
Projected exclusion reach
Projected discovery reach
$|M_{\chi_3^0,\chi_2^0,\chi_1^\pm} - M_{\chi_1^0}| = M_{H_{125}}$


WZ-mediated 3l+$\not{E}_T$, HL-LHC
BP$_A$
BP$_B$
BP$_C$
WH$_{125}$-mediated 3l+$\not{E}_T$, HL-LHC
WZ-mediated 3l+$\not{E}_T$, HE-LHC
WH$_{125}$-mediated 3l+$\not{E}_T$, HE-LHC
M$_2$[GeV]
μ[GeV]
100
200
300
400
500
600
700
800
900
1000
1200
1400