Studying EWIMPs at Future Colliders
— Direct vs. Indirect Searches —

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1. Introduction

Electroweakly interacting massive particles (EWIMPs):

- Color-singlet
- n-plet of $SU(2)_L$

  $\Rightarrow$ Charged and neutral particles
- Neutral one is the lightest (DM candidate)

  $\Rightarrow$ Charged particles decay into neutral one

Difficulties in EWIMP searches at colliders

Particles in the same n-plet are highly degenerate

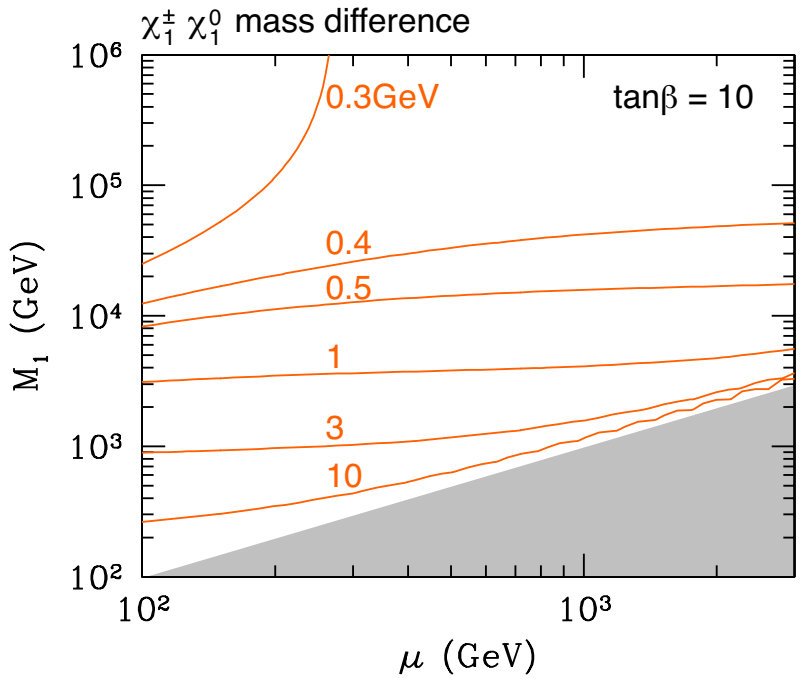
$\Rightarrow$ Only soft objects are produced by the decay

$\Rightarrow$ Typical decay length of charged one is $O(0.1-1)$ cm

Example: Higgsinos ($SU(2)_L$ doublets, with $Y = \pm 1/2$)

$\Rightarrow$ Neutral and charged particles: χ_1^0 (LSP), χ_2^0, $\chi_1^\pm$

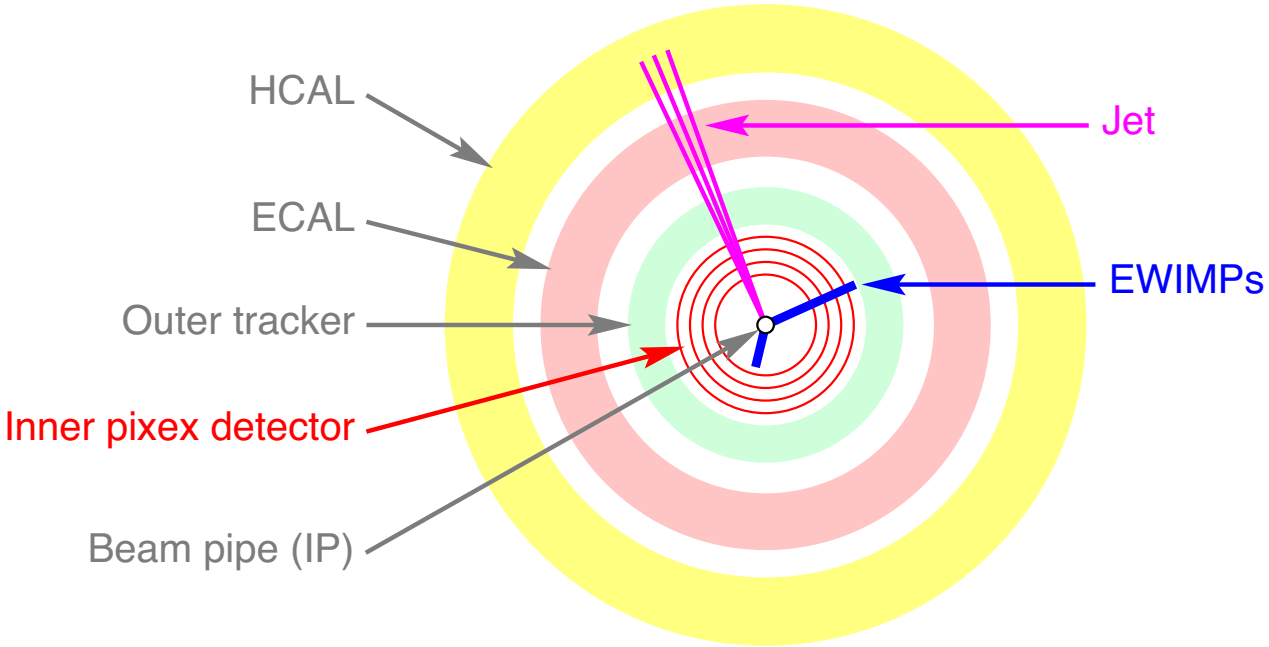
$\chi_1^\pm$ - χ_1^0 mass differences (with the GUT relation)



- Loop effects
- Mixing with gauginos

$$c\tau_{\tilde{H}^\pm \to \tilde{H}^0 \pi^\pm} \simeq 0.7\,\text{cm} \times \left(\frac{\Delta m_\pm}{340\,\text{MeV}}\right)^{-3} \left(1 - \frac{m_\pi^2}{\Delta m_\pm^2}\right)^{-1/2}$$

EWIMP production event (at pp collider)

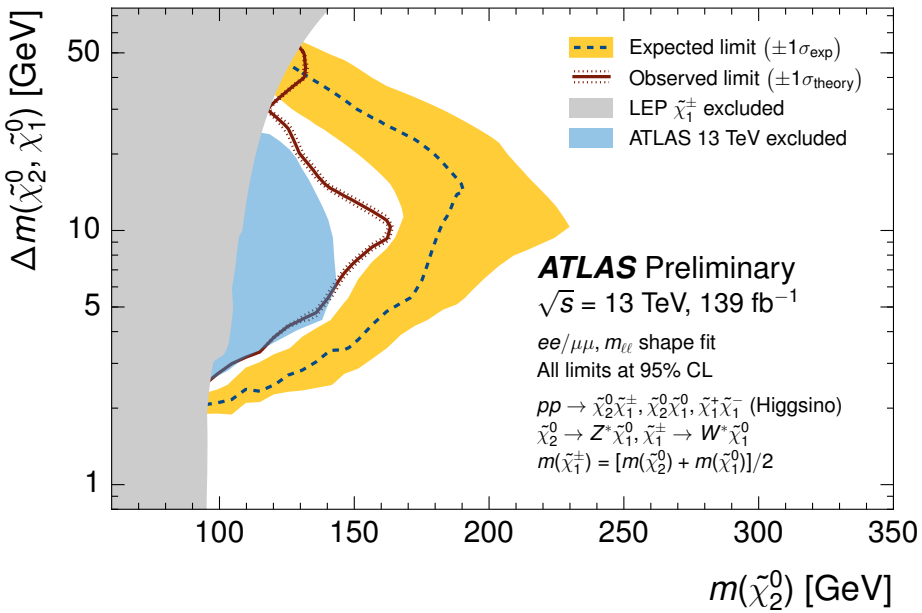


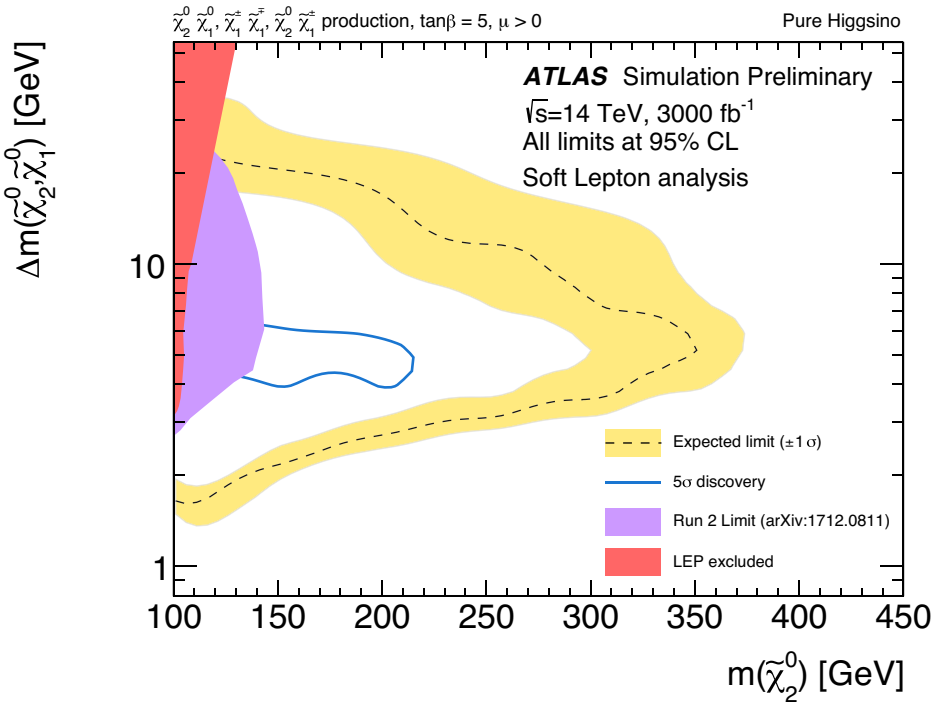
- Large MET events with soft leptons (for Higgsino)
- Mono-jet search
- Disappearing track search
- Indirect searches may be interesting

2. Direct Searches (Overview)

Current and future bounds with MET + soft $\ell^+\ell^-$

[ATLAS-CONF-2019-014, ATL-PHYS-PUB-2018-031]

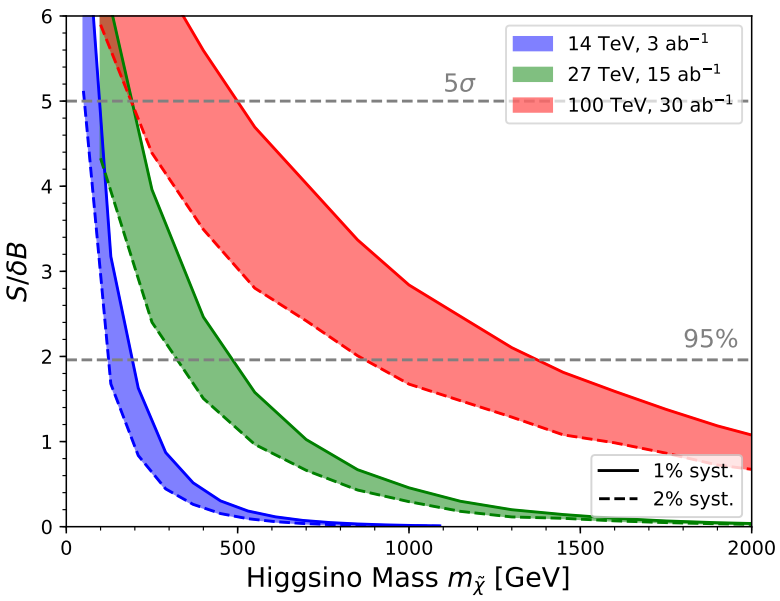




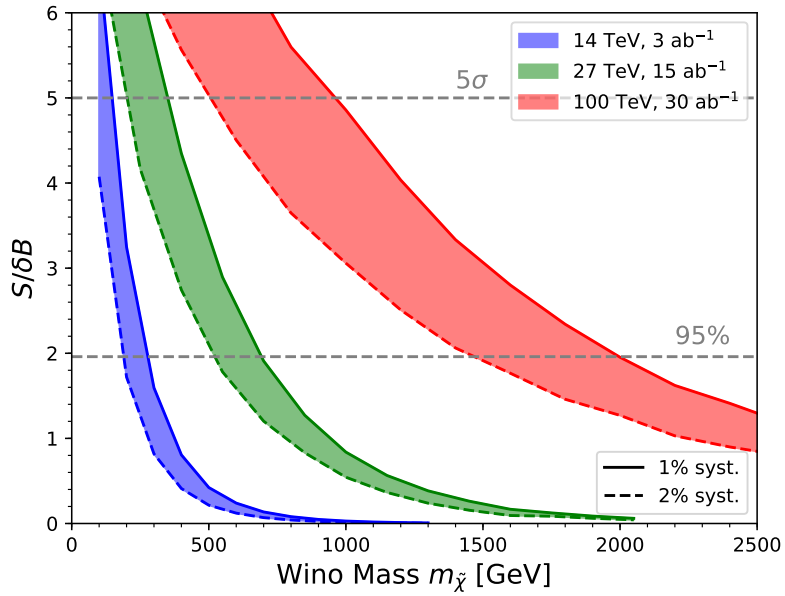
- High p_T jet(s) and MET
- Soft $\ell^+\ell^-$ pair, with $m_{\ell\ell} \sim O(1-10)$ GeV

Mono-jet: future prospect

Higgsino



Wino



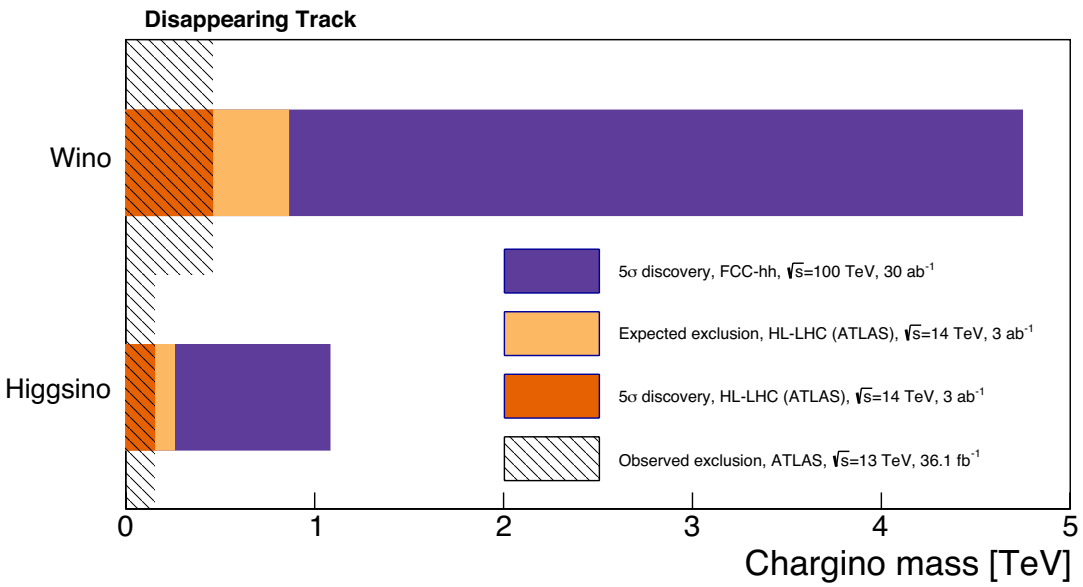
[Han, Mukhopadhyay & Wang ('18)]

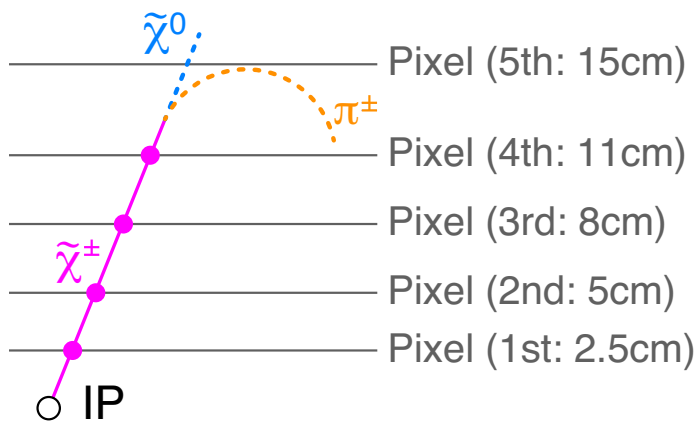
For Higgsino:

- 2σ exclusion at HL-LHC: $m_{\tilde{H}} \lesssim 100 - 200$ GeV
- 5σ discovery at FCC-hh: $m_{\tilde{H}} \lesssim 200 - 500$ GeV

Disappearing track searches at the HL-LHC and FCC-hh

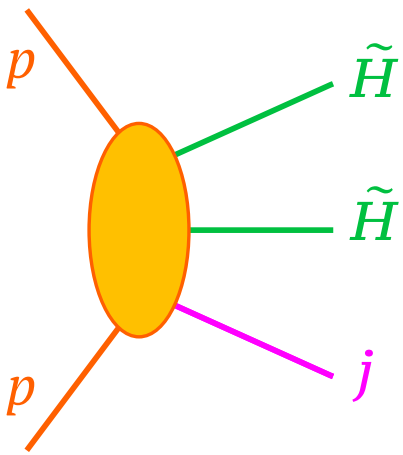
[Saito, Sawada, Terashi & Asai ('19); see also ATL-PHYS-PUB-2018-031]

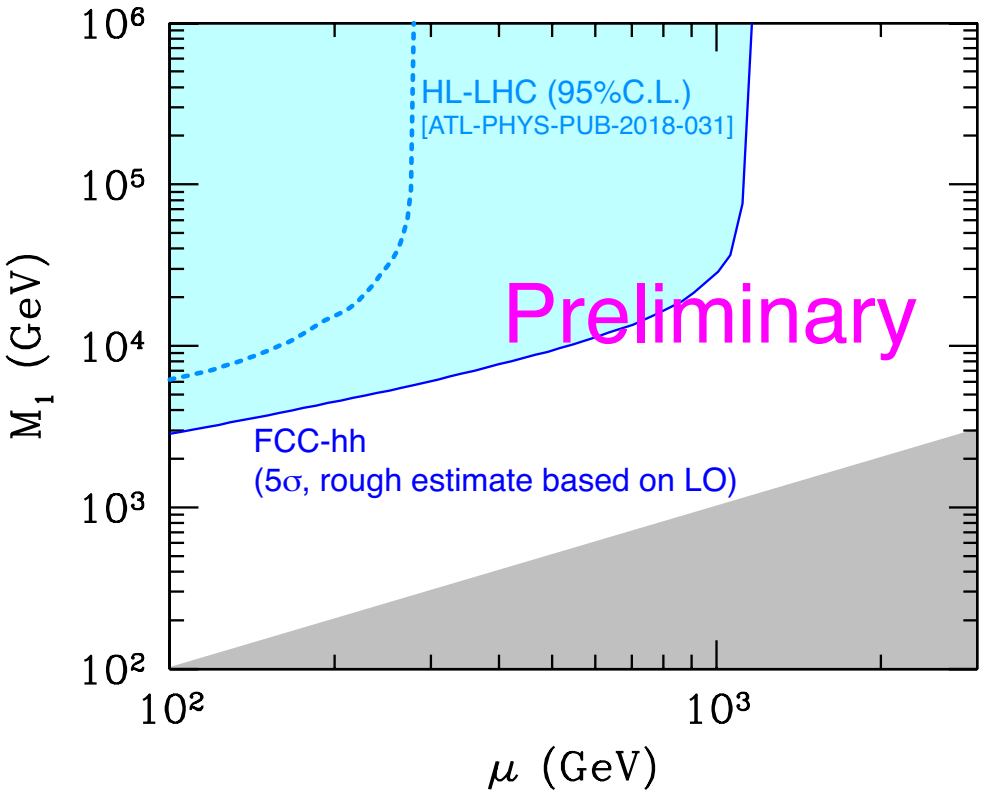




- Reaches for Higgsino with $\tau_{\tilde{H}^\pm} = 0.023\,\text{ns}$
  - $\mu \lesssim 260$ GeV at HL-LHC ($95\,\%$ C.L.)
  - $\mu \lesssim 1.1$ TeV at FCC-hh (5σ)
- The reach should become worse for shorter lifetime

Disappearing track search at FCC-hh (a rough estimate)





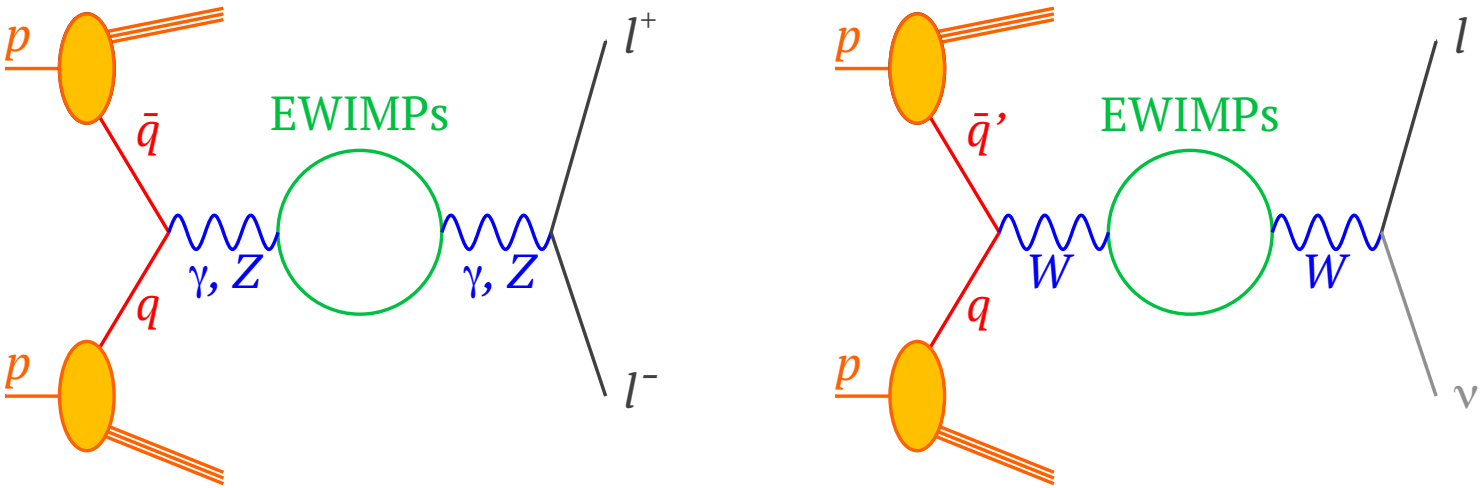
- $\tilde{H}^{\pm}$ with $L_T^{\tilde{H}^{\pm}} > 11\,\text{cm}$
- MET $> 4\,\text{TeV}$

$\Rightarrow$ Disappearing track search cannot access the region with relatively small gaugino masses

3. Indirect Searches with Drell-Yan Processes

Indirect search using Drell-Yan processes

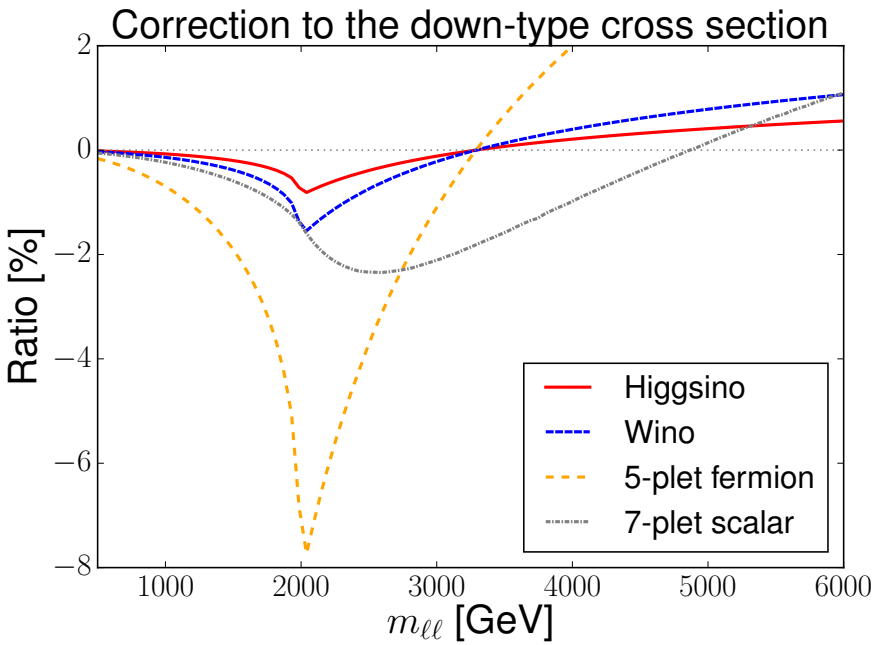
EWIMPs affect self energies of EW bosons



We may study

- Invariant-mass distributions of charged leptons
- Transverse-mass distributions of charged leptons

Effects of EWIMPs on Drell-Yan cross section



$$\text{Ratio} = \frac{d(\sigma_{\text{EWIMP}} - \sigma_{\text{SM}})/dm_{\ell\ell}}{d\sigma_{\text{SM}}/dm_{\ell\ell}}$$

$m_{\text{EWIMP}} = 1$ TeV

$\Rightarrow$ A "dip" at $m_{\ell\ell} \simeq 2m_{\text{EWIMP}}$ (or $m_T \simeq 2m_{\text{EWIMP}}$ for CC)

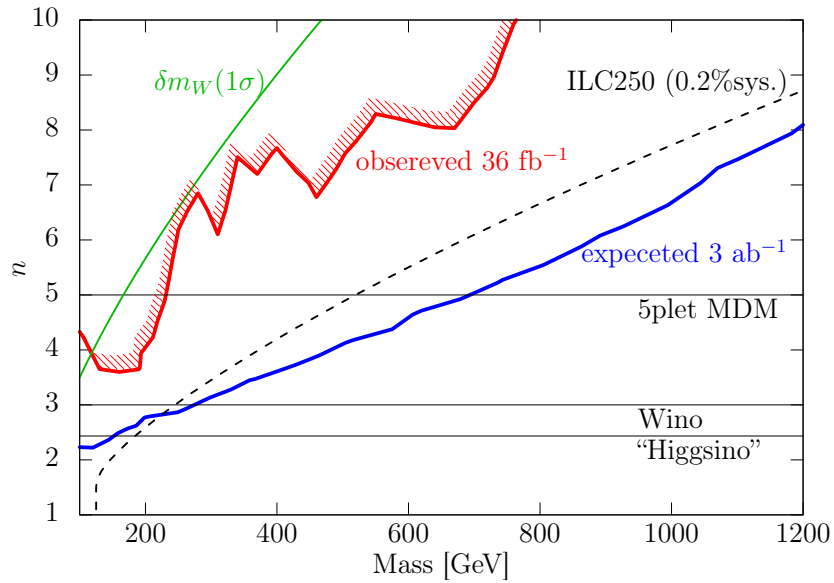
Likelihood (with discretizing $m_{\ell\ell}$ and m_T)

$$\chi^2 \simeq \sum_{f:\ell\ell,\ell\nu} \sum_{i:\text{bin}} \frac{(N_{f,i}^{(\text{EWIMP})} - N_{f,i}^{(\text{SM})})^2}{N_{f,i}}$$

(Systematic error should be included)

$95\,\%$ exclusion reach of ILC and HL-LHC

[Matsumoto, Shirai & Takeuchi ('17); See also Harigaya, Ichikawa, Kundu, Matsumoto & Shirai ('15)]



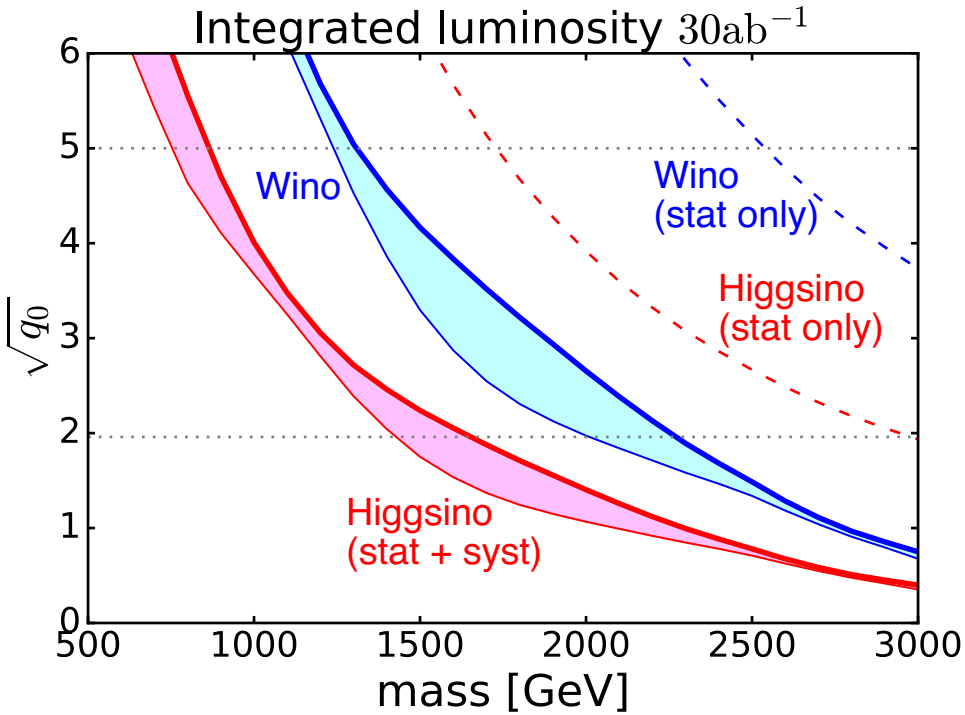
n: n-plet of $SU(2)_L$

For Higgsino:

- ILC250 may cover Higgsino mass up to $\mu \lesssim 185\,\text{GeV}$
- Higgsino mass of ~ 1 TeV is far beyond the reach

Case with $100\,\text{TeV}$ pp colliders (like FCC-hh), using

- $m_{\ell\ell}$, for $pp \to \ell^+\ell^-$
- $m_T^2 \equiv 2p_{T,\ell}\, p_{T,\text{miss}}(1 - \cos\phi_{\ell,\text{miss}})$, for $pp \to \ell^\pm\nu$



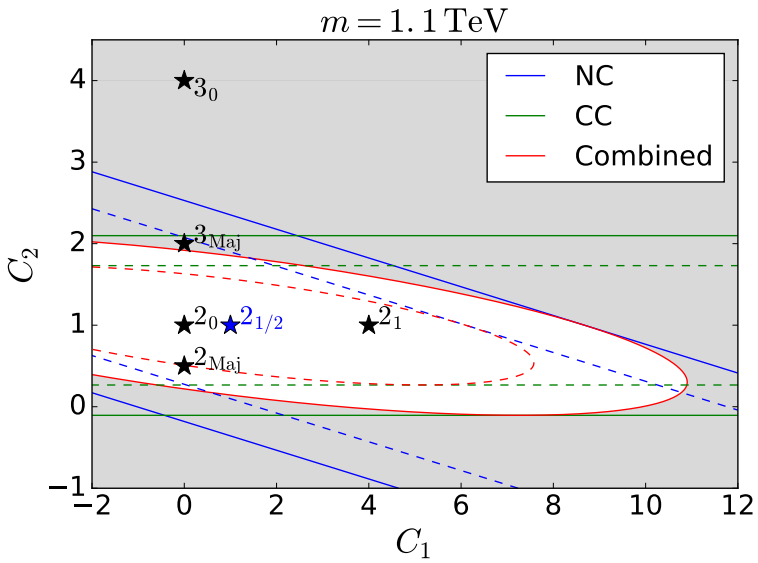
[Chigusa, Ema & TM ('18); Abe, Chigusa, Ema & TM ('19)]

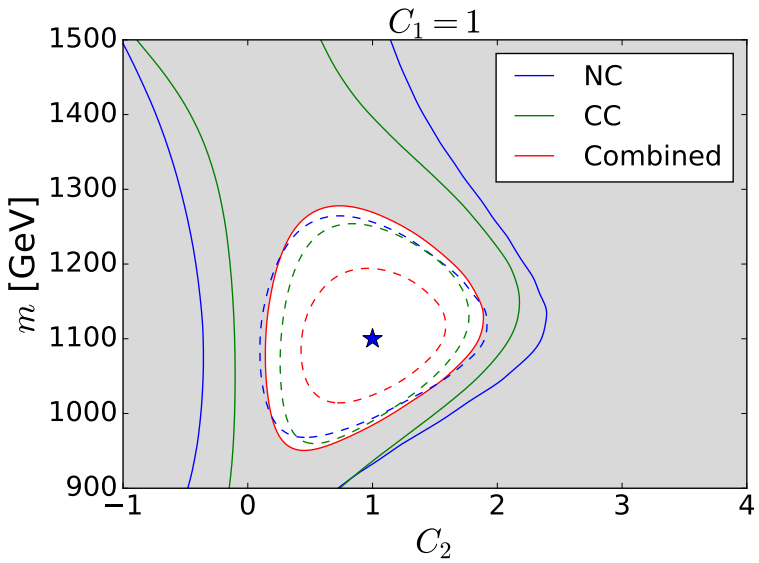
After discovery, we may determine mass and couplings

$$\Delta\mathcal{L}_{\text{eff}} = C_2\, g^2\, W^a_{\mu\nu} f\left(-\frac{D^2}{m^2}\right) W^{a\mu\nu} + C_1\, g'^2\, B_{\mu\nu} f\left(-\frac{\partial^2}{m^2}\right) B^{\mu\nu}$$

$f(x)$: Loop function

Case of $1.1\,\text{TeV}$ Higgsino at FCC-hh ($C_1 = C_2 = 1$)

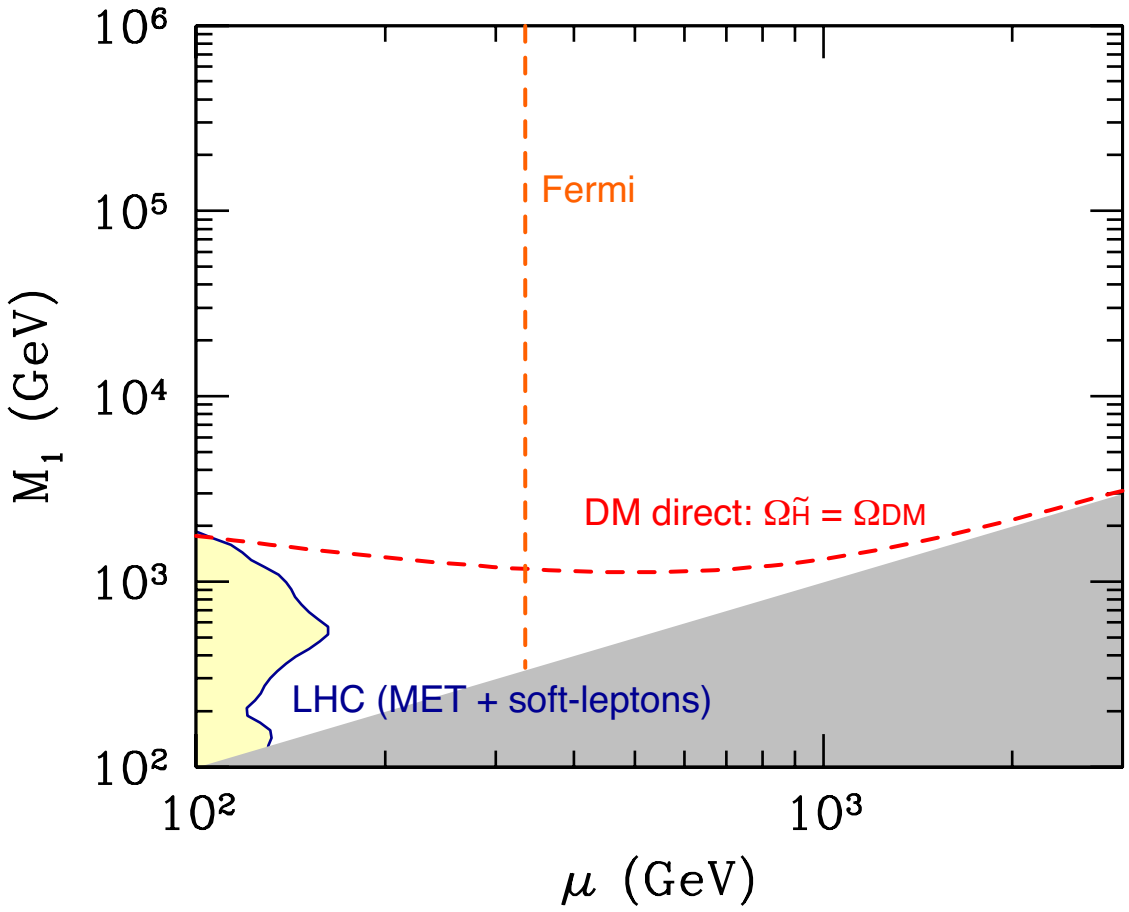




[Abe, Chigusa, Ema & TM ('19)]

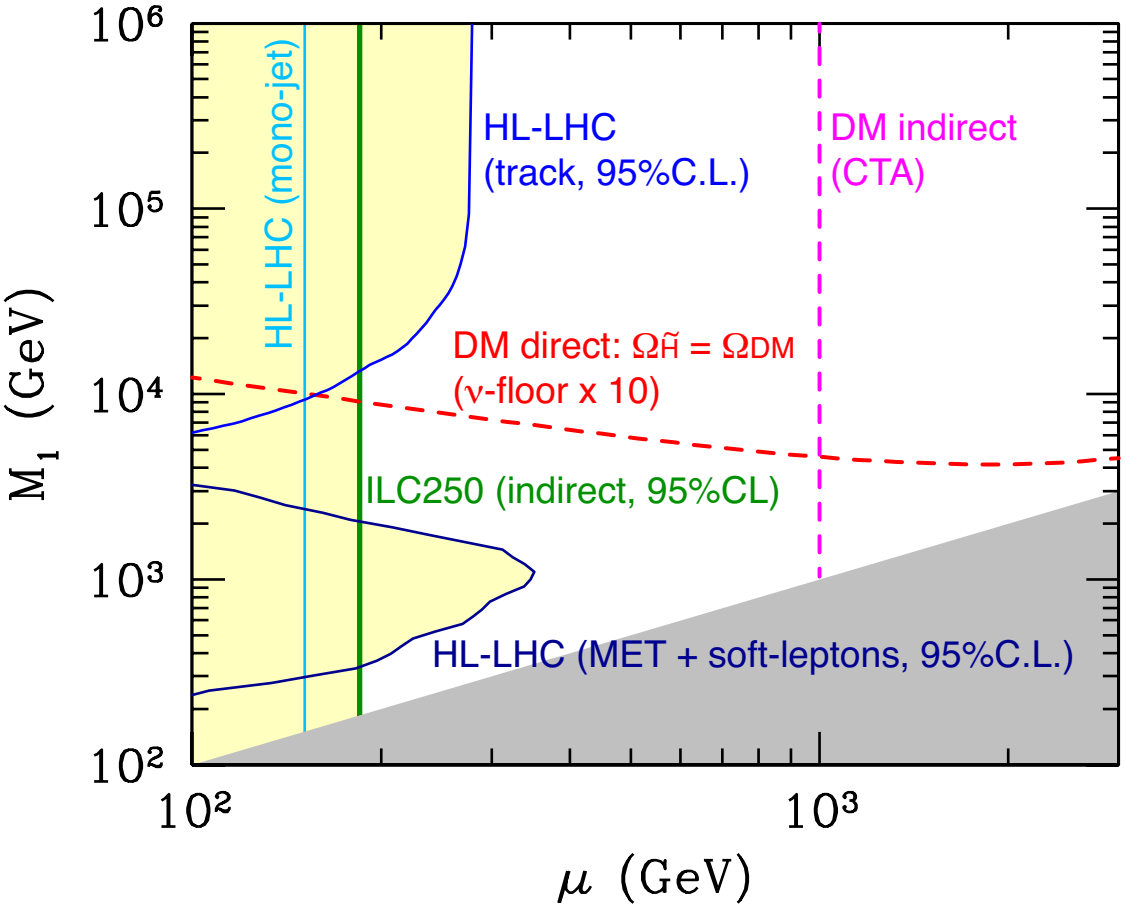
4. Comparisons: Case of Higgsino

Higgsino LSP: current bound



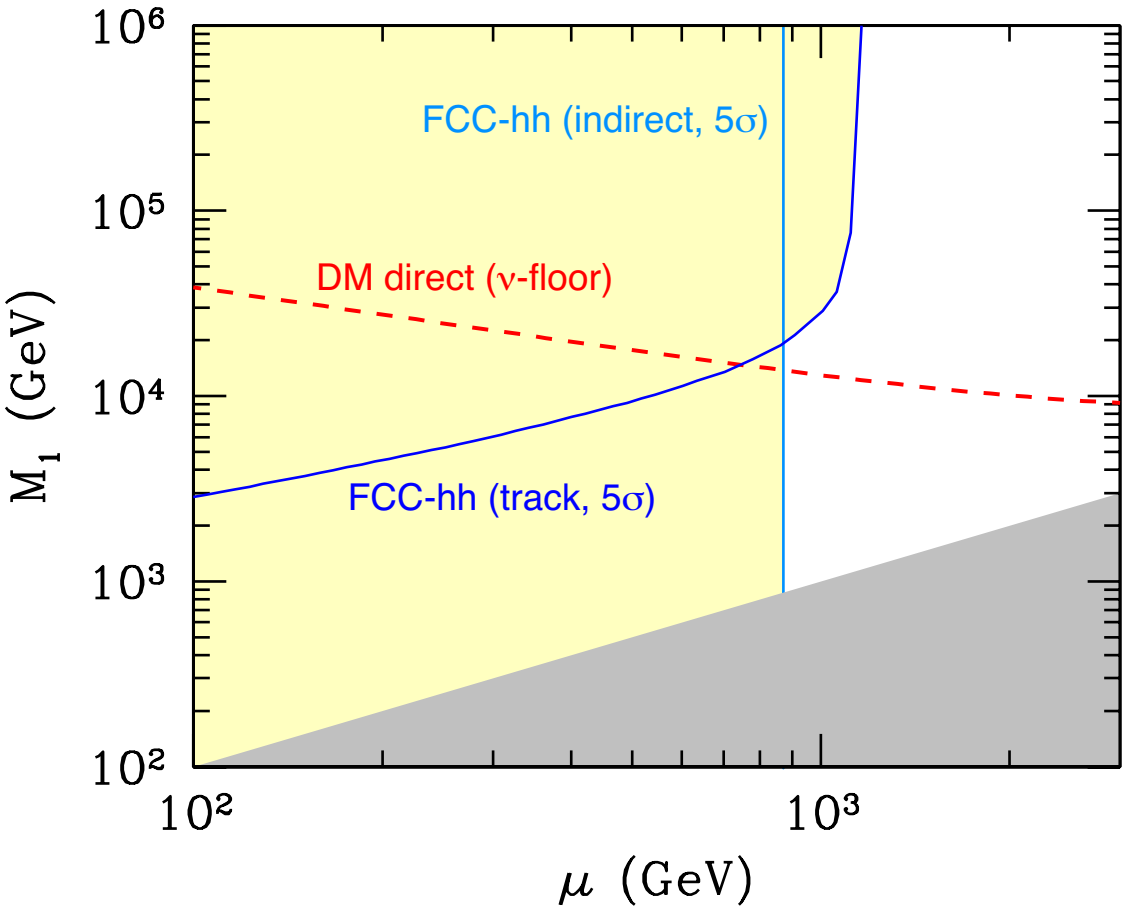
$\Rightarrow$ Large parameter region is still unexplored

Higgsino LSP: future prospect (in next few decades)



$\Rightarrow$ Significant improvements may be possible in next decades

Higgsino LSP: future prospect (ultimate)



$\Rightarrow$ We may ultimately reach Higgsino mass of ~ 1 TeV

5. Summary

There are many ideas of the EWIMP searches

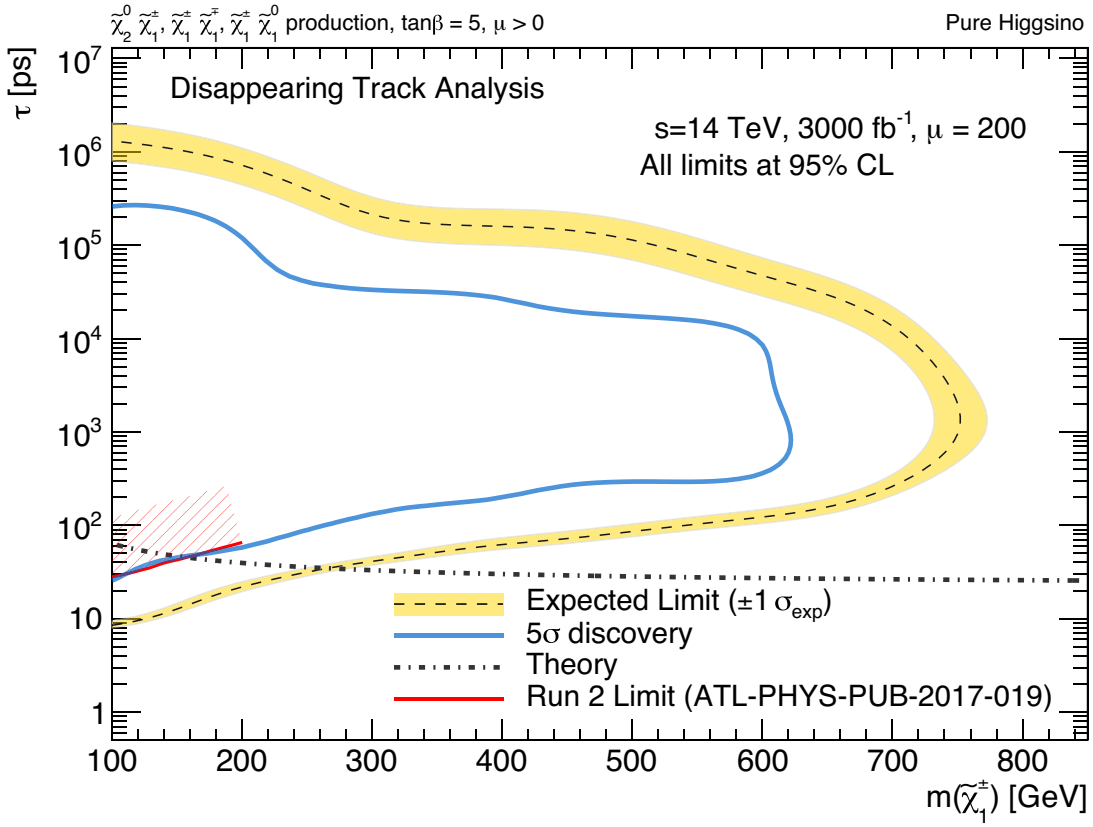
- MET with soft leptons
- Mono-jet
- Disappearing track search
- Indirect search with Drell-Yan process
- $\cdots$
- (DM direct detection)
- (DM indirect searches using cosmic ray)

EWIMPs searches are challenging even in future

- We should do everything we can do
- Collider and DM experiments are both important

Back Ups

Disappearing track search: HL-LHC



[ATL-PHYS-PUB-2018-031]

Statistical analysis (with discretizing $m_{\ell\ell}$ and m_T)

$$\chi^2 \simeq \sum_{f:\ell\ell,\ell\nu} \sum_{i:\text{bin}} \frac{(N_{f,i}^{(\text{EWIMP})} - N_{f,i}^{(\text{SM})} f_{f,i}^{(\text{sys})})^2}{N_{f,i}}$$

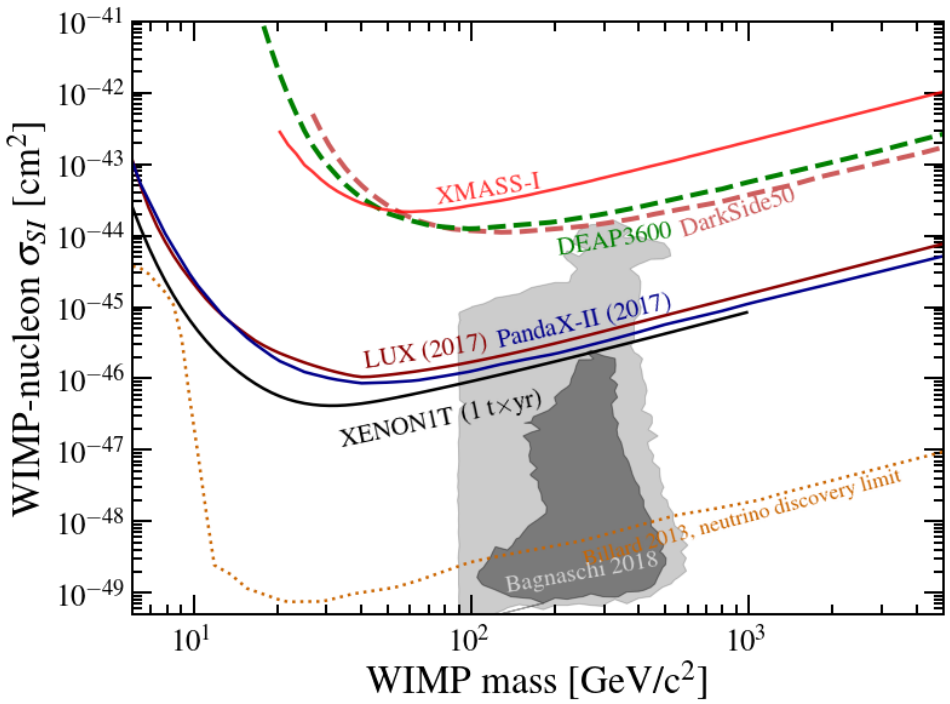
$f_i^{(\text{sys})}(\theta) = e^{\theta_1}(1-p_i)^{\theta_2} p_i^{(\theta_3+\theta_4 \ln p_i + \theta_5 \ln^2 p_i)}$ with $p_i = 2m_i/\sqrt{s}$

$\Rightarrow$ θ's absorb systematic uncertainties

Sources of systematic uncertainties

- Luminosity
- Renormalization and factorization scales
- PDF choice
- Lepton ID

DM direct detection experiments: summary

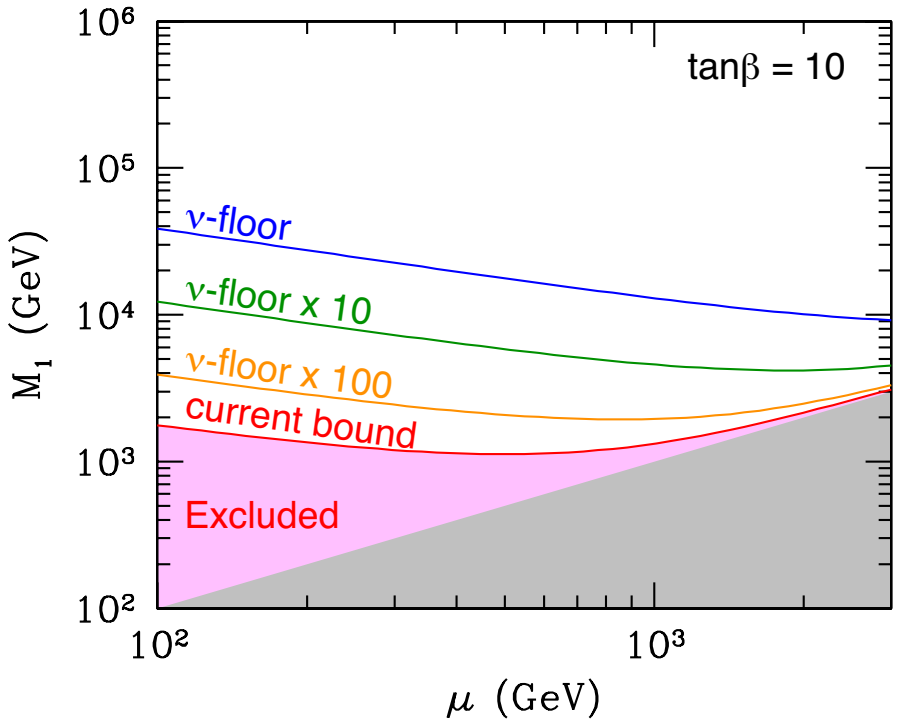


[from T. Yamashita's talk @ TAUP 2019]

- Current: $\sigma_{\mathrm{SI}} \lesssim 1 \times 10^{-45}\,\mathrm{cm}^2 \times \left(\frac{m_{\mathrm{WIMP}}}{1\,\mathrm{TeV}}\right)$

- ν floor: $\sigma_{\mathrm{SI}} \sim 2 \times 10^{-48}\,\mathrm{cm}^2 \times \left(\frac{m_{\mathrm{WIMP}}}{1\,\mathrm{TeV}}\right)$

Direct detection of Higgsino DM



- Current bound already excludes the region with the gaugino masses of $O(1)$ TeV
- The region with the gaugino masses of $O(10)$ TeV can be covered, if we can go down to the neutrino floor