Higgsino LSP / Higgsino DM
— Current Status and Future Prospects —

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Dark matter searches in the 2020s © Kashiwa, ’19.11.11
1. Introduction
Higgsinos: Superpartners of Higgs bosons in SUSY model

- **Gauge eigenstates:** \( \tilde{H}_u = (\tilde{H}_u^+ \tilde{H}_u^0) \) and \( \tilde{H}_d = (\tilde{H}_d^0 \tilde{H}_d^-) \)

- **Mass eigenstates:**

\[
\begin{align*}
\chi_1^0 & \approx \frac{1}{\sqrt{2}} \left( \tilde{H}_u^0 \pm \tilde{H}_d^0 \right) \\
\chi_2^0 & \approx \frac{1}{\sqrt{2}} \left( \tilde{H}_u^0 \mp \tilde{H}_d^0 \right) \\
\chi_1^+ & \approx \left( \tilde{H}_u^+ \right)
\end{align*}
\]

- \( \chi_1^0 \) can be DM

I will discuss phenomenology of Higgsino LSP / DM

- **Properties of Higgsinos**
- **Higgsino DM:** Relic density and observational constraints
- **Higgsino LSP searches at colliders**
2. Properties of Higgsinos
Higgsino mass is highly related to the naturalness of EWSB

\[ W = \mu \hat{H}_d (i \sigma_2) \hat{H}_u \]

\( \mu \) is (approximately) equal to masses of Higgsinos

For successful EWSB (tree level):

\[
\frac{1}{2} m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \approx -m_{H_u}^2 - \mu^2 \quad \text{(for } \tan \beta \gg 1) 
\]

⇒ From naturalness point of view, \( \mu \) is preferred to be close to the EW scale

\( m_{H_u}^2 \) receives renormalization-group effects

⇒ Naively, \( |m_{H_u}^2|^{1/2} \) becomes as large as other SUSY breaking parameters
Small $\mu$ due to focus-point mechanism

[Feng & TM ('98); Feng, Matchev & TM ('99)]

- $m_{H_u}^2$ becomes insensitive to the scale of SUSY breaking, adopting the universal scalar mass at the GUT scale

\[
m_{H_u}^2 (m_{\text{weak}}) \approx c_0 m_0^2 + O(M_{1/2}^2)
\]

\[|c_0| \ll 1\]

- Gaugino-mediated focus-point scenario is also possible

[Yanagida & Yokozaki ('13)]
Hereafter, Higgsino is assumed to be the LSP

⇒ Masses of $\chi^0_1$, $\chi^0_2$, $\chi^\pm_1$ are quite degenerate

$\chi^\pm_1$ - $\chi^0_1$ mass difference (with the GUT relation)

- Loop effects
- Mixing with gauginos

$$c T_{H^\pm \rightarrow H^0 \pi^\pm} \simeq 7 \text{ mm} \times \left( \frac{\Delta m_\pm}{340 \text{ MeV}} \right)^{-3} \left( 1 - \frac{m^2_\pi}{\Delta m^2_\pm} \right)^{-1/2}$$
3. Higgsino DM
Thermal relic abundance

\[ \Omega^{(\text{thermal})}_{\tilde{H}} = \Omega_{\text{DM}} \text{ requires } \mu \approx 1.1 - 1.2 \text{ TeV} \]

Results of detailed calculation (for Higgsino-Wino system)

[Beneke, Hellmann & Ruiz-Femeni (’14)]

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<th>(M_2)</th>
<th>(m_{\text{LSP}})</th>
<th>(\Delta m_\pm)</th>
<th>(\Omega_{\text{LSP}} h^2)</th>
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<td>1382</td>
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</table>

Masses are all in units of GeV
Possibility of non-thermal production

⇒ Higgsino DM is possible with $\mu \lesssim 1\,\text{TeV}$

**Example: decay of primordial gravitino**

\[ \Omega_{\tilde{H}} \simeq \frac{\mu n_{3/2}}{\rho_{\text{crit}}} \]

- $T_R \sim 10^9 - 10^{10}$ GeV for $\Omega_{\tilde{H}}^{(\text{gravitino})} = \Omega_{\text{DM}}$
- $m_{3/2} \gtrsim O(10)\,\text{TeV}$ to avoid BBN constraints
Direct detection of the Higgsino DM

Spin-independent (SI) process via Higgs exchange

The scattering occurs via diagrams with virtual gauginos

$\Rightarrow$ The SI cross section decreases with heavier gauginos

$Z$-exchange process is irrelevant if $\Delta m_0 \gtrsim O(100) \text{ keV}$

$\Rightarrow$ It can be neglected if $M_{1,2} \lesssim 10^7 \text{ GeV}$
The present bound and future prospects (assuming $\Omega_{\tilde{H}} = \Omega_{\text{DM}}$)

- Current bound already excludes the region with the gaugino masses of $O(1)\,\text{TeV}$
- The region with the gaugino masses of $O(10)\,\text{TeV}$ can be covered, if we can go down to the neutrino floor
Indirect detection using cosmic rays

Pair annihilation of DM is a source of cosmic rays

\[ \tilde{H} (\text{DM}) \rightarrow W, Z \rightarrow \text{Cosmic Rays} \]

\[ \Rightarrow \gamma\text{-ray} \]

\[ \Rightarrow \text{Anti-proton} \]
Indirect: $\gamma$-ray (present and future)

Continuum Gamma Rays: $\chi^0\chi^0 \rightarrow WW+ZZ$

- **Currently**, $\mu \gtrsim 340$ GeV with Fermi data
- **CTA** will cover up to $\mu \sim 1$ TeV
4. Higgsino LSP at Colliders
Higgsino-LSP searches at colliders are challenging

- $\chi_{1}^{\pm}$ and $\chi_{2}^{0}$ decay into soft objects (and $\chi_{1}^{0}$)
- $\chi_{1}^{\pm}$ is likely to decay before reaching detectors

Events to be used for direct search

⇒ MET + soft $\ell^{+}\ell^{-}$
⇒ Mono-jet events
⇒ Disappearing track
Disappearing track searches with $cT_{\tilde{H}^{\pm}} \simeq 7$ mm

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

- $\mu \lesssim 260$ GeV at HL-LHC (95% C.L.)
- $\mu \lesssim 1.1$ TeV at FCC-hh (5$\sigma$)

The reach should become worse for shorter lifetime
Indirect search: Higgsinos affect self-energies of EW bosons

\[ p \quad \tilde{q} \quad \tilde{H} \quad \gamma, Z \quad l^+ \quad l^- \]

\[ p \quad q \quad \gamma, Z \quad \tilde{H} \quad l^+ \quad l^- \]

\[ \Rightarrow \text{A “dip” at } m_{\ell\ell} \simeq 2\mu \text{ for NC (or at } m_T \simeq 2\mu \text{ for CC)} \]

We may study Drell-Yan processes precisely

- Invariant-mass distributions of charged leptons
- Transverse-mass distributions of charged leptons
Future prospects for HL-LHC, ILC, and FCC-hh

- LH-LHC will cover $\mu \lesssim 150$ GeV
- ILC250 may cover $\mu \lesssim 185$ GeV
  
  [See also Harigaya, Ichikawa, Kundu, Matsumoto & Shirai ('15)]
- FCC-hh may cover $\mu \sim 1$ TeV

[Matsumoto, Shirai & Takeuchi ('17)]

[Abe, Chigusa, Ema & TM ('19)]
5. Summary (with Three Figures)
Higgsino LSP: current bound

\[ \Omega H = \Omega_{\text{DM}} \]

LHC (MET + soft-leptons)

\[ \Rightarrow \text{Large parameter region is still unexplored} \]
Higgsino LSP: future prospect (in a next few decades)

$\Omega_H = \Omega_{DM}$ (ν-floor x 10)

HL-LHC (MET + soft-leptons, 95% C.L.)
HL-LHC (track, 95% C.L.)
ILC250 (indirect, 95% CL)
HL-LHC (mono-jet)

$\Rightarrow$ Significant improvements may be possible in next decades
Collider and DM experiments are both important.
back ups
Focus-point scenario with non-universal gaugino masses

[Yanagida & Yokozaki]

\[ m_{H_u}^2 (m_{\text{weak}}) \simeq -1.21 M_3^2 + 0.21 M_2^2 - 0.02 M_1^2 - 0.10 M_2 M_3 + \cdots \]

If \( M_3 : M_2 : M_1 \simeq 0.4 : 1 : 1 \), for e.g., \( m_{H_u}^2 \) may be suppressed

\[ M_1 = M_2 \]

[Yanagida & Yokozaki (’14)]
DM direct detection experiments: summary

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

- **\( \nu \) floor:** \( \sigma_{SI} \sim 2 \times 10^{-48} \text{ cm}^2 \times \left( \frac{m_{WIMP}}{1 \text{ TeV}} \right) \)
Indirect: anti-proton (using AMS-02 results)

\[ \langle \sigma v \rangle_{\text{wino}} \]

\[ \langle \sigma v \rangle_{\text{Higgsino}} \]

\[ M_{\chi} < 10^{-26} \text{cm}^3\text{s}^{-1} \]

\[ \sigma v \]

\[ \sigma v_{\text{max}} \]

\[ \sigma v_{\text{max}} \text{ (AMS-02 \bar{p})} \]

\[ \sigma v_{H} \text{ (theory)} \]

\[ \sigma v_{\text{max}} \text{ (Fermi } \gamma) \]

\[ 95\% \text{ Upper-bound (MIN)} \]

\[ \text{Best fit (MIN)} \]

\[ \text{MED} \]

\[ \text{MAX} \]

[Ibe, Matsumoto, Shirai & Yanagida ('15)]

[Krall & Reece ('17), based on Cuoco, Kramer & Korsmeiner ('17)]

⇒ Anti-proton constraint is sensitive to the propagation model
Current and future bounds with MET + soft $\ell^+\ell^-$


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

For Higgsino:

- $2\sigma$ exclusion at HL-LHC: $m_{\tilde{H}} \lesssim 100 - 200$ GeV
- $5\sigma$ discovery at FCC-hh: $m_{\tilde{H}} \lesssim 200 - 500$ GeV
Disappearing track search: HL-LHC (future prospect)

The image shows a plot of the disappearing track analysis for neutralino production, $\tan \beta = 5$, $\mu > 0$. The plot includes expected limits and discovery limits with $\pm 1 \sigma_{\text{exp}}$. The analysis is performed at the LHC with $s=14$ TeV, $3000$ fb$^{-1}$, and $\mu = 200$. All limits are set at 95% confidence level (CL).

The figures are labeled with references: [ATL-PHYS-PUB-2018-031].
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 $\tau_{\tilde{H}^\pm} = 0.023$ ns (i.e., $c\tau_{\tilde{H}^\pm} \simeq 7$ mm)
  - $\mu \lesssim 260$ GeV at HL-LHC (95% C.L.)
  - $\mu \lesssim 1.1$ TeV at FCC-hh (5$\sigma$)
- The reach should become worse for shorter lifetime
Disappearing track search for $cT_{\tilde{H}^\pm} < 7 \text{ mm}$ (a rough estimate)

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

⇒ Disappearing track search cannot access the region of relatively small gaugino masses
Systematic errors in our FCC-hh analysis

- Systematic effects are assumed to be smooth

Real number of events in $i$-th bin in the SM ($p = m_{\ell\ell}$ or $m_T$)

$$N_i^{(\text{true})} = N_i^{(\text{MC})} \times e^{\theta_1 (1 - p_i)} \theta_2 p_i^{(\theta_3 + \theta_4 \ln p_i + \theta_5 \ln^2 p_i)}$$

$\Rightarrow \theta$'s absorb systematic uncertainties

Sources of systematic uncertainties

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