Electroweak dark matter at future hadron colliders

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Pheno 2018, May 7, 2018
Introduction

- Dark Matter and WIMP miracle
- SU(2) doublet $\tilde{H}$ or triplet $\tilde{W}$
- Only one free parameter: $M_\chi$

\[
\begin{align*}
\text{DM relic abundance} & \quad \Rightarrow & & \begin{cases} 
M_{\tilde{H}} \simeq 1 \text{ TeV} \\
\text{or} & \\
M_{\tilde{W}} \simeq 3 \text{ TeV}
\end{cases}
\end{align*}
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\begin{align*}
\begin{cases}
\text{DM relic abundance} & \Rightarrow M_{\tilde{H}} \simeq 1 \text{ TeV} \\
\text{thermal freeze-out} & \Rightarrow M_{\tilde{W}} \simeq 3 \text{ TeV}
\end{cases}
\end{align*}
\]
Spectrum

- Wino scenario
  - one Majorana neutralino + one chargino
- Higgsino scenario
  - one (pseudo-)Dirac neutralino + one chargino
- 1-loop radiative mass splitting $\sim \mathcal{O}(100 \text{ MeV})$
Direct Detection

- Direct detection loop-suppressed for pure states.
- No tree-level coupling to $h$ for Wino/Higgsino.
- No tree-level coupling to $Z$ for Wino.
- Large SI cross section for Higgsino via $Z$, already excluded.
- Pseudo-Dirac Higgsino. $\Delta m_{12} \gtrsim \mathcal{O}(100 \text{ keV})$
Indirect Detection

- Sensitive to the astro uncertainties (e.g. DM profile, propagation model)
- Complementary to collider searches.

Data from indirect detection can place significant constraints on any dark matter candidate in an SU(2)_L multiplet, due to the annihilation \( \chi^0 \chi^0 \rightarrow W^+ W^- \) (and ZZ, depending on the representation), which leads to copious production of gamma rays and antiprotons [4]. These searches are effective even for very small mass splittings within the SU(2)_L multiplet, and thus are complementary to direct detection. Here we will present the current constraints on a few scenarios on pure wino and pure higgsino dark matter. For the computation of wino annihilation, the Sommerfeld enhancement is crucial [52], and the one loop annihilation process \( \chi^0 \chi^0 \rightarrow \gamma \gamma \) may also be detectable [53, 54]. As a result, in recent years sophisticated effective field theory techniques have been applied to more accurate computation of these annihilation processes [55–60], especially in the case of gamma ray line searches.
Collider Searches

- Future hadron colliders
  - HL-LHC 14 TeV with $3 \text{ ab}^{-1}$
  - HE-LHC 27 TeV with $15 \text{ ab}^{-1}$
  - FCC/SppC 100 TeV $30 \text{ ab}^{-1}$
- Monojet
- Disappearing track
- Higher energies are very advantageous.

T. Han, S. Mukhopadhyay, XW, arXiv: 1805.00015

M. Low, L.T. Wang, arXiv: 1404.0682
M. Cirelli, et al. arXiv: 1407.7058

thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders
Mono-Jet

- One hard jet recoils against MET.
- Signal
  \[ \chi^0 \chi^0 / \chi^\pm \chi^0 / \chi^\pm \chi^\mp + \text{jets} \]
- Dominant background:
  \[ Z(\nu\nu) + \text{jets}, \quad W(\ell\nu) + \text{jets} \]
- Subdominant:
  \[ \bar{t}t, \quad Z(\ell\ell) + \text{jets}, \quad \text{diboson, multi-jets} \]
Mono-Jet

- One hard jet recoils against MET.

- Signal
  \[ \chi^0 \chi^0 / \chi^+ \chi^0 / \chi^\pm \chi^\mp + \text{jets} \]

- Dominant background:
  \[ Z(\nu \nu) + \text{jets}, \quad W(\ell \nu) + \text{jets} \]

- Subdominant:
  \[ t \bar{t}, \quad Z(\ell \ell) + \text{jets}, \quad \text{diboson, multi-jets} \]

- \( \lambda = 1 - 2\%, \quad \gamma = 10\% \)
Results

Figure 3: Comparative reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the mono-jet channel for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to optimistic values of the systematic uncertainties on the background estimate of 1% and 2% respectively, which might be achievable using data-driven methods with the accumulation of large statistics.

In Fig. 3 we compare the reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the monojet channel for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to systematic uncertainties on the background estimate of 1% and 2% respectively. In an optimistic scenario, we can expect to probe at the 95% C.L. wino-like DM mass of up to 280, 700, and 2000 GeV, at the 14, 27, and 100 TeV colliders respectively. For the Higgsino-like scenario, these numbers are reduced to 200, 490, and 1370 GeV, primarily due to the reduced production cross-section. Clearly, a 27 TeV collider can achieve a substantially improved reach by a factor of two or more compared to the HL-LHC, while the 100 TeV collider option will improve it further by another factor of three. Furthermore, a 100 TeV collider option may be able to completely cover the thermal Higgsino mass window using the monojet search, if the systematic uncertainties can be brought down to a percent level.

| 95% CL limit [GeV] | 14 TeV | 27 TeV | 100 TeV |
|-------------------|--------|--------|---------|
| Wino              | 190 – 280 | 530 – 700 | 1500 – 2000 |
| Higgsino          | 130 – 200 | 330 – 490 | 900 – 1370 |
Disappearing Track

- Long-lived chargino decays inside the tracker

\[ f(p_T) = \exp \left(-p_0 \cdot \log(p_T) - p_1 \cdot (\log(p_T))^2 \right) \]

- Scale according to $Z(\nu\nu) + \text{jets}$
- Vary background from 20% to 500%
- Systematics: $\lambda = 20\%$, $\gamma = 10\%$
Figure 4: Comparative reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the disappearing charged track analysis for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to modifying the central value of the background estimate by a factor of five, i.e., 20\% and 500\% of that obtained through the fit function in Eq. 2.9. With the lower value of the background estimate, the expected reach on wino-like DM mass at the 95\% C.L. is 0.9, 2.1 and 6.5 TeV at the 14, 27 and 100 TeV colliders respectively. For the Higgsino-like scenario, these numbers are reduced to 300, 600 and 1550 GeV, primarily due to the smaller length of the disappearing track and the reduced production rate. For the higher value of the background estimate, the mass reach for the wino-like states are modified to 500, 1500 and 4500 GeV, respectively, at the three collider energies. Similarly, for the Higgsino-like scenario, the reach is modified to 200, 450 and 1070 GeV. We note that the signal significance in the disappearing track search is rather sensitive to the wino and Higgsino mass values (thus making the reach very close in mass). This is because, as the chargino lifetime in the lab frame becomes shorter for heavier masses, the signal event rate decreases exponentially.

The improvements in going from the HL-LHC to the HE-LHC, and further from the HE-LHC to the FCC-hh/SppC are very similar to those obtained for the monojet analysis above, namely, around a factor of two and three, respectively. Although we have presented the reach at the 100 TeV collider without reference to the cosmology of these DM candidates, in order for a wino heavier than around 3 TeV and a Higgsino heavier than around 1 TeV not to overclose the Universe, one would require a non-standard thermal history, with late-time entropy production.

### Summary

| 95\% CL limit [GeV]   | 14 TeV   | 27 TeV   | 100 TeV  |
|-----------------------|----------|----------|----------|
| Wino                  | 500 – 900| 1500 – 2100| 4500 – 6500 |
| Higgsino              | 200 – 300| 450 – 600 | 1100 – 1550 |

References

[1] M. Cirelli, N. Fornengo and A. Strumia, Nucl. Phys. B 753, 178 (2006)
Summary

- Wino/Higgsino dark matter are simple but well-motivated models.
- Collider searches are important to cover the relevant parameter space, which is complementary to the indirect detection.
- Mono-jet and disappearing track are powerful channels.
- The possible LHC high energy upgrade would significantly extend the reach of wino/Higgsino searches.

| 95% C.L. | Wino Monojet | Wino Disappearing Track | Higgsino Monojet | Higgsino Disappearing Track |
|----------|--------------|-------------------------|-----------------|----------------------------|
| 14 TeV   | 280 GeV      | 900 GeV                 | 200 GeV         | 300 GeV                    |
| 27 TeV   | 700 GeV      | 2.1 TeV                 | 490 GeV         | 600 GeV                    |
| 100 TeV  | 2 TeV        | 6.5 TeV                 | 1.4 TeV         | 1.5 TeV                    |
Back-ups
Monojet

- Madgraph 5 + Pythia 6.4.28 + Delphes 3
- MLM matching up to 2 jets
- Selection cuts:
  - MET, $p_{T,j_1}$, $p_{T,j_2}$
  - $N_{\text{jets}} \leq 2$, $\Delta \phi_{j_1,j_2} < 2.5$
  - Lepton veto

| $\sqrt{s}$ (TeV) | $E_T^{\text{min}}$ (GeV) | $p_{T,j_1}$ (GeV) | $p_{T,j_2}$ (GeV) | $p_{T,\tau}$ (GeV) |
|------------------|-----------------|-----------------|-----------------|------------------|
| 14               | 650             | 300             | 30              | 30               |
| 27               | 1800–2700       | 400             | 60–160          | 30               |
| 100              | 4800–7000       | 1200            | 250–450         | 40               |

Table 1: Threshold values of different kinematic observables, namely, $E_T^{\text{min}}$, $p_{T,j_1}$, $p_{T,j_2}$, $p_{T,\tau}$, for different collider options in the monojet analysis, and the optimization range considered for the HE-LHC and FCC-hh/SppC colliders. See text for details.

The optimized set of kinematic cuts for the HE-LHC is given in Table 2, with the corresponding signal and background cross-sections. Here, basic cuts refers to the requirement –7–
Background

- Various backgrounds
- Hard to estimate

We do a naive estimation
- \( f(p_T) = \exp\left(-p_0 \cdot \log(p_T) - p_1 \cdot (\log(p_T))^2\right) \)
- Scale according to \( Z(\nu\nu) + \text{jets} \)
- Vary background from 20% to 500%.

Systematics: \( \lambda = 20\%, \quad \gamma = 10\% \)
Disappearing Track

- We follow the 13 TeV ATLAS analysis to extract the signal efficiency.
- Selection cuts:
  - MET, $p_{T,j_1}$, $p_{T,j_2}$, $p_{T,\text{track}}$
  - $\Delta \phi_{j,\text{MET}} > 1.5$
  - $0.1 < |\eta^{\text{track}}| < 1.9$
  - Track isolation $\Delta R = 0.4$
  - Track length $12 < d < 30$ cm

| $\sqrt{s}$ | $\slashed{E}_T$ [GeV] | $p_{T,j_1}$ [GeV] | $p_{T,j_2}$ [GeV] | $p_{T,\text{track}}$ [GeV] |
|------------|-----------------|-----------------|-----------------|-----------------|
| 14 TeV     | 150             | 150             | 70              | 250             |
| 27 TeV     | 400 – 700       | 400 – 600       | 140             | 400 – 700       |
| 100 TeV    | 1000 – 1400     | 700 – 1400      | 500             | 1000 – 1400     |

Systematics:
- $\lambda = 20\%$, $\gamma = 10\%$
Figure 4: Comparative reach of the HL-LHC, HE-LHC and FCC-hh/SppC options in the disappearing charged track analysis for wino-like (left panel) and Higgsino-like (right panel) DM search. The solid and dashed lines correspond to modifying the central value of the background estimate by a factor of five, i.e., 20% and 500% of that obtained through the fit function in Eq. 2.9.

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