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Discovering the Higgsino at CTAO-North within the Decade

Shotaro Abe,[a] **Tomohiro Inada,**[b,*] **Emmanuel Moulin,**[c] **Nicholas L. Rodd,**[d,e] **Benjamin R. Safdi**[d,e] **and Weishuang Linda Xu**[d,e,f,g]

[a] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[b] *Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan*
[c] *Irfu, CEA Saclay, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[d] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, U.S.A.*
[e] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.*
[f] *Kavli Institute for Particle Astrophysics & Cosmology, Stanford University, Stanford, CA 94305, U.S.A.*
[g] *Particle Theory Group, SLAC National Accelerator Laboratory, Stanford, CA 94305, U.S.A.*

E-mail: tomohiro.inada@cern.ch

Higgsino dark matter (DM) is a well-motivated candidate in supersymmetric theories, with a 1.1 TeV thermal higgsino naturally accounting for the observed DM abundance. Despite its strong theoretical foundation, detecting the higgsino remains challenging. The Cherenkov Telescope Array Observatory (CTAO), with CTAO-North in La Palma, Spain, and CTAO-South in Atacama, Chile, offers a promising indirect detection approach by probing gamma rays from potential DM annihilation, particularly in the Galactic Center. CTAO-North has achieved the first light with its first Large-Sized Telescope (LST), while CTAO-South, expected to be fully operational in the 2030s, will observe the Galactic Center under optimal conditions. Alternatively, CTAO-North can observe the Galactic Center at so-called large zenith angles —tracking the Galactic Center along the horizon— enhancing sensitivity at TeV energies at the cost of a higher energy threshold. With this observation mode, we regard that CTAO-North is capable of complementing the CTAO-South view. Using CTAO simulations of instrument responses, this study projects sensitivity of higgsino searches with CTAO-North and CTAO-South under a realistic observational timeline. In particular, considering the phased construction, we assume a two-stage telescope configuration for CTAO-North: the LST sub-array and the planned full array. Notably, our projections indicate that CTAO-North could achive the required sensitivity within the next decade, reinforcing gamma-ray observations as a viable method for higgsino DM detection. The findings and their implications are presented in this contribution.

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1. Introduction

The higgsino is among the most minimal and well-motivated weakly interacting massive particle (WIMP) candidates for dark matter (DM) in supersymmetric extensions of the Standard Model [1]. A nearly pure higgsino with mass $m_\chi \simeq 1.1$ TeV naturally yields the observed relic abundance through thermal freeze-out [2]. With alternatives like the wino increasingly constrained by indirect detection [3, 4], the higgsino remains a leading candidate for minimal DM [5]. Thermal higgsino DM is a key science driver for upcoming direct detection efforts [6], and collider programs [7]. However, its detection remains challenging. In the pure-state limit, the direct detection cross-section falls below the neutrino floor [8]. Even advanced future colliders like FCC-hh and 10 TeV muon colliders will only marginally probe thermal higgsinos [9, 10]. Indirect detection, by contrast, offers a more feasible route. Higgsinos can annihilate into W^+W^-, ZZ (tree level), and $\gamma\gamma$, γZ (loop level) [11]. The loop-induced gamma-ray lines are particularly compelling due to their distinctiveness and the lack of known astrophysical backgrounds producing such features near ~1.1 TeV. Hints of a possible signal have emerged in *Fermi*-LAT data [12], though continuum searches are hampered by background uncertainties. The Cherenkov Telescope Array Observatory (CTAO) represents the next generation of gamma-ray observatories [13], with full-sky coverage via dual sites: CTAO-South (Paranal, Chile) and CTAO-North (La Palma, Spain). It spans 20 GeV to 300 TeV using three telescope types (Large-Sized Telescope (LST), Medium-Sized Telescope (MST), Small-Sized Telescope (SST)). The Galactic Center—an optimal target for DM searches—is best viewed from the southern site, where it reaches zenith angles below 10° [14]. CTAO-South is expected to reach the required sensitivity to detect or exclude thermal higgsino DM across most plausible DM halo profiles [4, 15]. On the other hand, CTAO-North may contribute sooner. LST-1 has already achieved first light [16], with a 4-telescope setup operational by 2026. While observing the Galactic Center from La Palma (~58° zenith) presents challenges like higher thresholds and background rates, it also offers a larger effective area. The MAGIC telescope, also at La Palma, has demonstrated that reliable high-zenith-angle DM searches are possible [17, 18]. In this work, we assess CTAO-North's ability to search for thermal higgsino DM via such observations. CTAO-North may enable either discovery or strong constraints within a few years, contingent on the true DM profile near the Galactic Center.

2. Higgsino Annihilation Models and Instrument Response Functions

The properties of the higgsino are almost entirely specified by its electroweak representation and mass, allowing for precise predictions of both its annihilation cross-section and resulting photon spectrum. To compute this spectrum, we employ `DMγSpec` [11]; we briefly summarize the key physical contributions below. The gamma-ray signal from higgsino annihilation has three main components: line, endpoint, and continuum. The line component arises from two-body final states like $\gamma\gamma$ and γZ, which are generated at loop level and enhanced via the Sommerfeld effect [19–22]. This effect stems from the long-range electroweak force acting between non-relativistic higgsinos, boosting the annihilation rate at low velocities. For $m_\chi \sim 1.1$ TeV, the photon energies from these two channels differ by less than 0.2%. The endpoint contribution includes multi-body final states such as $\gamma + X$, where the photon energy approaches $E \sim m_\chi$. These events, once smeared by

CTAO's finite energy resolution [23], are observationally indistinguishable from the line signal. For example, in γW^+W^- final states with collimated W bosons, the photon may carry nearly all the energy. Resummation of large electroweak logarithms enhances this component at leading order, yielding $O(1)$ corrections to the line-like flux [11, 24, 25]. Lastly, the continuum arises from W^+W^- and ZZ tree-level channels. The subsequent decay and showering of these bosons produce a broad spectrum of lower-energy photons, many of which fall within CTAO's detection range. These are modeled using `PPPC4DMID` [26], as implemented in `DM`γ`Spec`.

3. CTAO setup: Instrument Response Functions

The performance of Imaging Atmospheric Cherenkov Telescopes (IACTs) depends strongly on the zenith angle. At CTAO-North (La Palma), the Galactic Center culminates at a zenith angle of 58°, which, though observationally challenging, significantly enhances the effective area due to the wider Cherenkov light pool [27]. However, the increased air mass attenuates the Cherenkov signal, raising the energy threshold. We adopt an average zenith angle of 60° and assume stereo observations involving all available LSTs and, later, MSTs. Instrument Response Functions (IRFs) for this configuration are drawn from the `prod5-v0.1` simulation suite [28], which encodes energy- and offset-dependent effective area, angular, and energy resolutions. The Alpha Configuration for CTAO-South includes 14 MSTs and 37 SSTs. For CTAO-North, we model a staged rollout: 4 LSTs operational by 2026, followed by 9 MSTs added by 2028. CTAO-South is assumed to begin full operations in 2031. As shown in Fig.2 [29], large zenith angles increase the effective area by up to an order of magnitude at TeV energies, which is critical for detecting higgsino-induced gamma-ray lines. Although MSTs do not improve the on-axis area near 1 TeV, they enhance the off-axis response (see Fig.B1 [29]), improving sensitivity under cored dark matter profiles. Notably, the large-zenith-angle effective area at CTAO-North becomes comparable to that of CTAO-South at low zenith angles, despite the southern site's larger array. This gain comes with reduced energy resolution and background rejection efficiency at large zenith angles (see Fig.B1 [29]). In particular, energy-dependent variations in cosmic-ray rejection must be characterized using OFF observations at similar zenith angles. A detailed treatment requires modeling ensemble-to-ensemble scatter in the residual background, which we defer to future work using real CTAO data. In this study, we adopt an idealized framework to illustrate the discovery potential under optimal assumptions.

4. Sensitivity with CTAO-North

At most, CTAO-North can observe the Galactic Center for ∼250 hrs/year during dark time between zenith angles of 58°–70° [30]. In this study, we conservatively assume 100 hrs/year of usable exposure. We consider four pointings offset from the Galactic Center, consistent with LST-1 monoscopic operation [31], though realistic observations will optimize pointing for broader science goals [32]. For full-array projections (North and South), we assume pointings offset by 1.2°; this choice has negligible effect in our simplified analysis. We adopt an energy resolution and model cosmic-ray-induced background using Monte Carlo IRFs from `prod5-v0.1` [33]. For diffuse Galactic gamma-ray emission, we use the *Fermi* `gll_iem_v07 (p8r3)` model, extrapolated above 2 TeV by a power-law [4]. This template is validated at TeV energies using LAT data. To capture astrophysical uncertainty in the DM profile, we consider high-resolution hydrodynamic simulations from Auriga [34, 35] and FIRE-2 [36]. For comparison, we also include DM-only Einasto and NFW profiles, normalized to 0.38 GeV/cm^3 at 8.3 kpc. Notably, FIRE-2 predicts significantly less central DM than Auriga. While some prior studies have adopted the Burkert profile [18], we omit it as its large core is disfavored by recent simulations [37].

Our sensitivity forecasts follow the approach of Ref. [4]. We simulate Asimov (expected) data binned into 100 logarithmically spaced energy bins from 100 GeV to 10 TeV, and spatially across five 1° annuli centered on the Galactic Center. Each energy–spatial bin is modeled using spectral templates for signal, cosmic-ray background, and diffuse Galactic emission. Point sources and small-scale extended emission are neglected as subdominant [4]. Both the continuum and line+endpoint components of the higgsino signal are included, the latter being more easily identifiable due to its narrow energy feature. The cosmic-ray background dominates at all radii except the very inner degree. To estimate discovery significance, we adopt a background-only null hypothesis and include the signal via a normalization factor μ, where $\mu = 1$ corresponds to the thermal higgsino flux. A joint likelihood is constructed from all annuli, and we apply Wilks' theorem to obtain the test statistic (TS) for discovery, with $\sqrt{\mathrm{TS}}$ approximating the number of σ [38, 39]. Our analysis assumes perfect knowledge of background components; in practice, nuisance parameters will degrade sensitivity [4]. Discovery prospects vary substantially with the assumed DM profile. Under the Auriga median J-factor, CTAO-North could detect higgsino DM at $> 5\sigma$ by 2028. The Einasto profile gives intermediate sensitivity, while the FIRE-2 median would require decades of data from CTAO-South or improved instrumentation to achieve comparable reach. These projections highlight the importance of both detector performance and DM distribution in the Galactic Center.

5. Discussion

CTAO represents a major step forward in the indirect detection of dark matter, and our results suggest that a discovery could be within reach in the near future. As shown in Fig.1 [29], CTAO-North has the potential to detect thermal higgsino dark matter before CTAO-South becomes operational, possibly within this decade. However, key uncertainties remain. Chief among them is the dark matter distribution in the inner Galaxy. Our projections also rely on an idealized analysis, assuming perfect background modeling. In practice, systematics—especially from misidentified cosmic rays, which dominate at TeV energies—may degrade sensitivity. Addressing this will require constructing accurate spectral models from OFF-source observations under similar conditions. Forthcoming data from CTAO-North will be essential to test this approach. Achieving robust sensitivity may ultimately depend on both CTAO sites operating at full capacity and prioritizing dark matter observations. For pessimistic halo profiles, CTAO-South might even require instrumentation beyond the planned Alpha Configuration. Given the strong theoretical motivation for the higgsino, one of the most compelling dark matter candidates, there is a clear scientific case for investing in such enhancements.

6. Summary

Thermal higgsinos are among the most compelling dark matter candidates, yet remain difficult to detect directly. In this work, we demonstrated that CTAO, particularly its northern site, may achieve a 5σ detection within the current decade under optimistic halo assumptions. Our projections rely on idealized background modeling and simplified observing strategies. Systematic uncertainties, especially from cosmic-ray contamination, could reduce sensitivity and will require detailed treatment with real data. The dark matter profile near the Galactic Center also introduces significant uncertainty, with J-factors spanning more than two orders of magnitude across simulations. Achieving full sensitivity will require coordinated operation of both CTAO sites and sufficient observing time dedicated to dark matter. For highly cored profiles, additional instrumentation beyond the current Alpha Configuration may be necessary. Given the theoretical motivation for higgsino dark matter, such efforts are well justified.

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