Snowmass2021 - A final word on minimal dark matter at future lepton colliders

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§ Intro Weakly Interacting Massive Particles (WIMPs) are one of the simplest example of dark matter (DM) candidates whose relic abundance is set by thermal freeze-out into Standard Model (SM) states. As a matter of fact, any WIMP may be dark matter, if a compelling reason for its stability on cosmological time-scales exists, and if a (possibly simple) cosmological history would yield the DM relic abundance today. In particular, assuming radiation domination in the early Universe, the s-wave annihilation cross section required for DM freeze-out is fixed to $\sigma_{\rm f.o.} = 2.2 \times 10^{-36} {\rm cm}^2$ and weakly dependent on the DM mass for DM masses above 10 GeV [1]. This type of cross sections offer the exciting possibility of producing directly the DM at collider facilities.

Here, very much in the spirit of Minimal Dark Matter (MDM) [2], we focus on a single $SU(2)$ n-plet whose thermal relic cross section goes as

$$\sigma_{\rm ann}({\rm DM} + {\rm DM} \leftrightarrow {\rm SM} + {\rm SM}) \propto \frac{g^4}{M^2} n^3 \,, \tag{1}$$

where imposing $\sigma_{\rm ann} = \sigma_{\rm f.o.}$ requires the mass M to get heavier as the size n of the multiplet grows. Our goal here is to bound n from above imposing $i)$ Dark Matter stability, $ii)$ calculability. As detailed below, we find that $n \leq 7$ where $n = 7$ is the largest multiplet allowed in the MDM framework which corresponds to the largest DM mass given the assumptions above. The latter lies in the tens of TeV range and possibly within the reach of an hypothetical future lepton collider. Our investigation will then set the required center-of-mass energy of the hypothetical future lepton collider to have a final word on MDM candidates.

§ The highest possible DM mass in Minimal Dark Matter The well known examples of pure Higgsino and Wino in the MSSM are particular cases of MDM for $n = 2$ and $n = 3$, where the DM stability is ensured by matter-parity. The mass prediction from thermal freeze-out, the possibility of probing these multiplets at future hadron colliders, and their signatures in direct and indirect detection have already been extensively studied in the literature [3–7]. Going to higher dimensional multiplets, the $n = 5$ multiplet stands out as a particularly theoretically appealing case, where the stabilization of the DM is based on an accidental symmetry without any *ad-hoc* matter-parity requirement [2], while the $n = 7$ multiplet can be made stable by assigning it a small electric charge [8].

As the size of the multiplet grows, the theory becomes strongly coupled at increasingly low scales, because each new charged state contributes to the RG evolution of the SM gauge couplings. Theories that become non-perturbative at scales too close to the WIMP mass lose their predictivity as theories of DM. The largest multiplet with a calculable relic abundance is $n = 7$ for which the prediction of thermal freeze-out is still not precisely known, but it is expected to lie in the tens of TeV range.

With these premises, we think that there are three main directions to explore. First, a precision computation of the thermal relic mass is still lacking for the 7-plet. Second, the discovery potential of these states at future high-energy colliders needs to be assessed. Third, the collider reach needs to be compared with the complementary constraints from indirect and direct detection.

§ Closing the gaps in Minimal Dark Matter predictions Heavy electroweak particles freeze-out when they are fully non-relativistic. In this regime, low-velocity non-perturbative corrections to their annihilation rate, such as Sommerfeld enhancement and bound-state formation (BSF), become important and modify substantially the annihilation cross section.

For large n-plet $n \geq 5$, in addition to the always relevant Sommerfeld enhancement, the formation and subsequent decay of WIMPonium bound states give $\mathcal{O}(1)$ correction to the thermal mass. For $n = 5$, bound states raise the DM mass required to reproduce the cosmological DM abundance from 9.4 TeV (w/o BSF) to roughly 14 TeV (w/ BSF computed in the $SU(2)$ invariant limit [9]). For $n = 7$ only the Sommerfeld-corrected DM relic density in the SU(2) invariant limit has been computed (see e.g. [10]), while the important corrections due to BSF have never been considered. Including them, would determine whether the predicted mass from freeze-out is within the discovery reach of a realistic high-energy collider.

§ Direct detection As far as direct detection is concerned, the spin-independent cross-section with nuclei of these candidates is accidentally suppressed [11]. The MDM thermal masses are expected to be probed only with multi-ton future detectors, such as XENONnT or DARWIN.

§ Indirect detection Indirect detection of DM with gamma-rays from the Galactic Center (GC) and from Milky Way's dwarf Spheroidal galaxies (dSphs) are, at present, the most promising strategies to probe EW multiplets (see e.g. [7, 12–14]). For example, H.E.S.S. observations of γ-ray lines from the GC [15] already exclude all the MDM multiplets, if a cuspy profile is assumed. However, these limits suffer from an large uncertainty related to the choice of the galactic DM profile which is to large extent irreducible. For instance, all the MDM multiplets are still viable if a cored profile is assumed.

More robust limits can be obtained from dSphs that are the cleanest laboratories to look for DM in high energy gamma-rays. At present, the exclusion power is rather limited and does not directly affect the MDM predictions [16]. Future observations, together with important refinements of the theoretical computations of the annihilation cross section have the power of improving substantially the present status.

Experimentally, indirect detection experiments are entering in the realm of very high energetic gamma-ray astronomy thanks to satellites such as Fermi-LAT and Cherenkov telescope arrays such as H.E.S.S. and the upcoming construction of CTA and LHAASO.

Theoretically, the non-perturbative effects discussed for thermal freeze-out are largely enhanced for DM annihilations in deeply non-relativistic environments such as the GC and dSphs. These make the gamma-ray spectrum of EW multiplets quite complex and peculiar. The expected features are: i) gamma-ray continuum from the showering, hadronization and decays of heavy electroweak gauge bosons as result of DM annihilation; ii) gamma-ray lines, peaking at the DM mass, from the loop-induced annihilations; iii) a series of gamma-ray lines (in the GeV energy range) due to the WIMPonium formation.

Analyzing all the proposed signatures with a critical, conservative and, when possible, multi-messenger approach will lead to a robust conclusions about indirect detection searches of MDM.

§ Collider reach While the LHC currently only excludes masses lighter than few hundreds of GeV, WIMP masses in the 10-20 TeV ballpark are a clear physics target for a high-energy collider of the next generation. Given the electroweak nature of the signal, a multi-TeV lepton collider such as a muon collider would be an ideal machine for the exploration of this scenario.

Possible production of quasi-degenerate electroweak states include:

- production of the neutral components of the multiplet, plus accompanying radiation, i.e. $\ell^+\ell^- \to \chi^0\chi^0 + X$;
- production of the charged components $\ell^+\ell^- \to \chi^\pm\chi^{0,\pm} + X$, for a suitable charge of X.

Both these productions may be initiated by the beam leptons, or by the weak partons they contain, e.g. by weak boson scattering. However, for large masses of χ close to the kinematic limit, we expect direct production in a $2 \to 2$ process to be the dominant mechanism.

The decay of the charged particles determines the observable signal to be sought in the data. When the charged states do not give observable hits in the detectors we generally search for the production of X recoiling against "nothing" – this is the so-called "mono-X" search strategy. This strategy is sensitive both to the production of purely neutral states and to the production of charged ones, hence probes the full spectrum of the n-plet, and the expected signal rates are larger as n grows. The possibility of reconstructing (to a good extent) the full event kinematics at a lepton collider should allow to isolate the signal from the SM background much more efficiently than what is possible at a hadron collider.

In case charged states of the multiplet decay and leave some observable trace in the detectors it is possible to further scrutinize the events and reject backgrounds more effectively requiring the presence of:

- single or multiple charged tracks of characteristic length,
- anomalous dE/dx energy depositions,
- peculiar calorimeter showers,
- time or space displacement of the decay products.

In this contribution we will evaluate the production rates of the electroweak multiplets whose interactions are calculable in perturbation theory. Taking into account the most important backgrounds, we will provide estimates for the bounds on generic BSM sources of "mono-X" signals, along the line of Refs. [17, 18]. These generic bounds will be translated into specific ones for each n-plet, and compared with the mass range for which each n-plet can be a thermal relic Dark Matter, in view of the results that we expect to attain from improved calculations discussed above.

In addition we will compute production rates for the peculiar signals that originate from the charged states – which can be rather exotic in the case of large multiplets – and we will present detector target performances that need to be attained in order to detect a convincing number of such peculiar events. This effort is especially aimed at finding out what the necessary challenges to be dealt with in the design of the experiments are.

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