Spin-1 Thermal Targets for Dark Matter Searches at Beam Dump and Fixed Target Experiments

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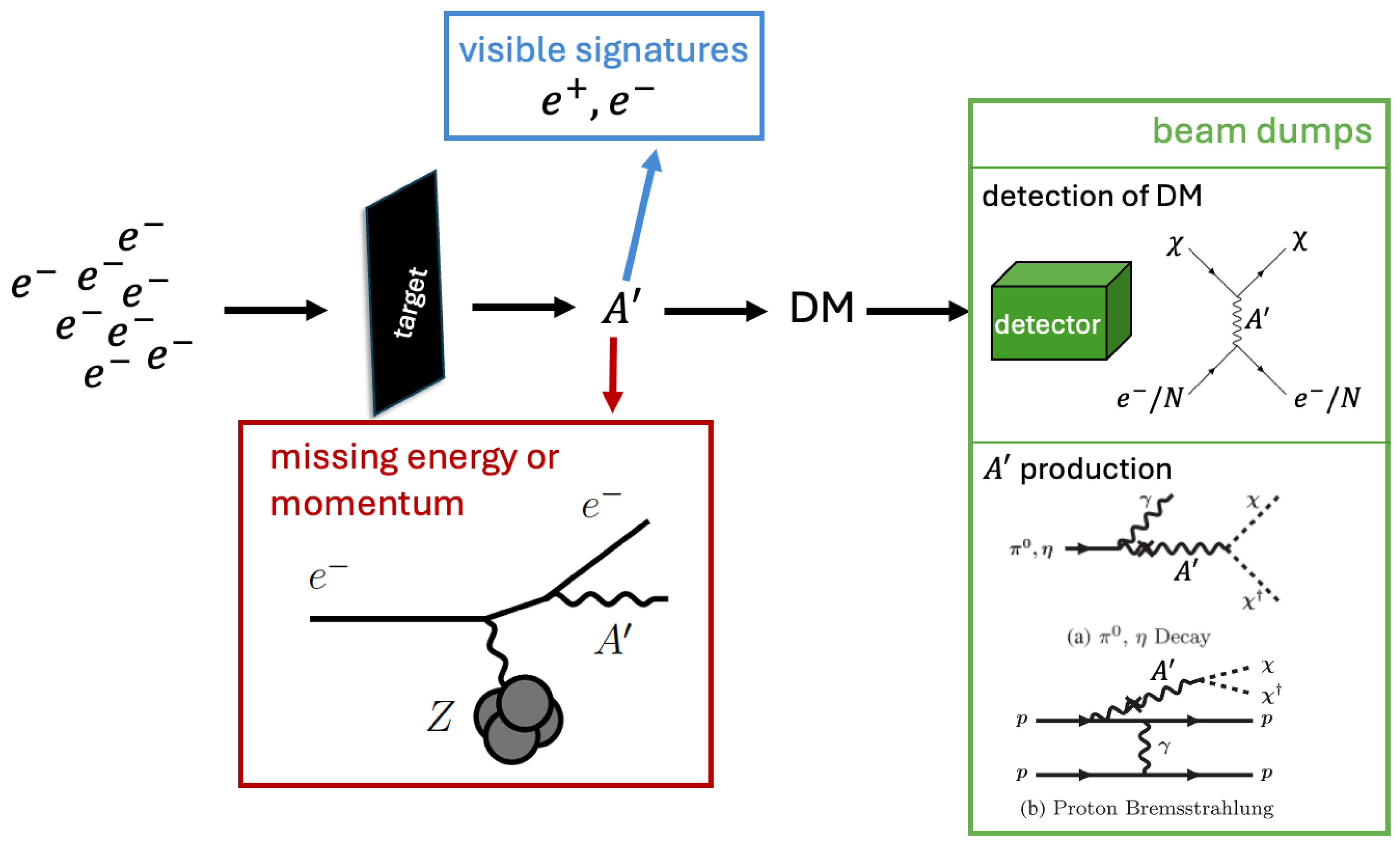
Sub-GeV Dark Matter

- Direct detection experiments are becoming more sensitive, with **no signal yet**.
- Instead of being GeV - TeV scale like the canonical WIMP, dark matter could have **sub-GeV** mass, **evading nuclear recoil direct detection** experiments.
- Sub-GeV dark matter is a plausible candidate which can account for the **thermal relic abundance** in the universe.
- Lee-Weinberg bound of electroweak mediators is circumvented by adding a new mediator, for example the **dark photon** A'.
- **Direct detection via electron recoils** and **accelerator based experiments** work complimentary to one another in probing sub-GeV dark matter.

Fixed Target Experiments

- Accelerator experiments involving a **fixed target** and a **beam** give some of the leading constraints and future sensitivity.
- An electron (or proton) beam is incident on a fixed target leading to interactions between the target nuclei and beam particles, with the goal to produce dark sector particles such as dark photons A'.



Missing Energy/Momentum

- We consider the future experimental reach of **LDMX** and the current experiment **NA64**, where the recoil electron p_T and/or E is measured to search for signals from dark photon bremsstrahlung.

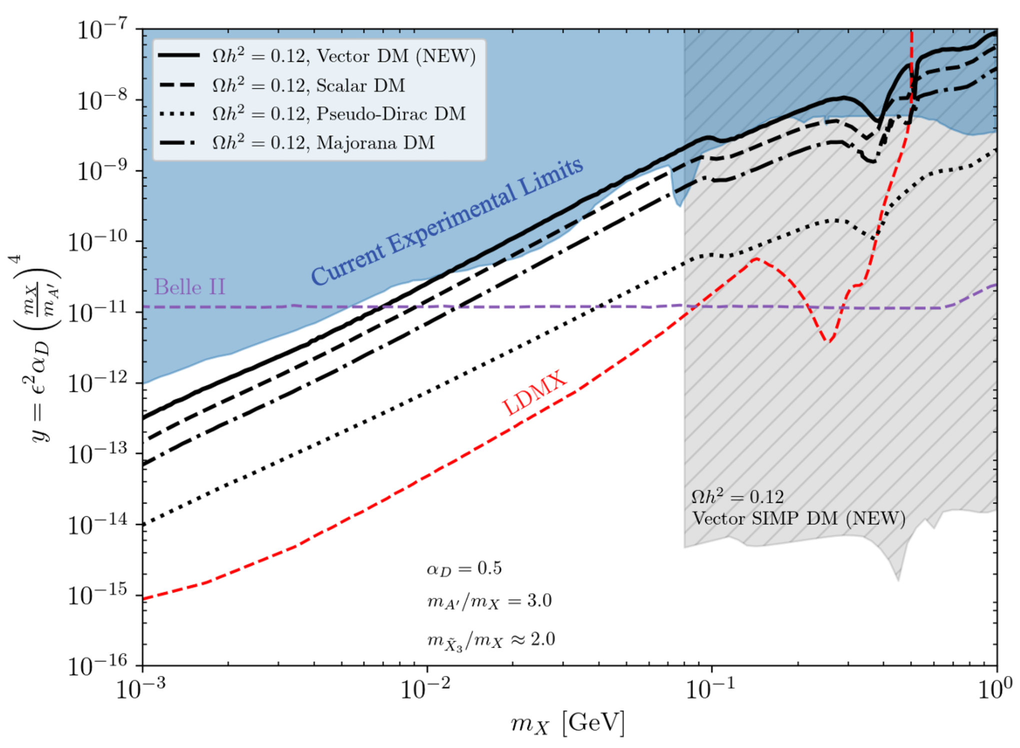
Proton Beam Dumps

- The absence of significant signal over background at **LSND** and **MiniBooNE** has lead to the constraints considered here. Dark photons can be produced through meson decays, and in the case of MiniBooNE (where the beam energy is sufficient) through dark bremsstrahlung.

Thermal Targets

Fixed target experiments search for signatures which are also compatible with **relic density** observations of the CMB from Planck, namely **thermal targets**.

Here we include the relic targets of various dark matter models (including vector/spin-1 dark matter which is from this work) with current and **future** experimental limits [LDMX and Belle II]:



- LDMX Full Luminosity with 1.6×10^{15} EOT and a 8 GeV electron beam.

Spin-1 Dark Matter

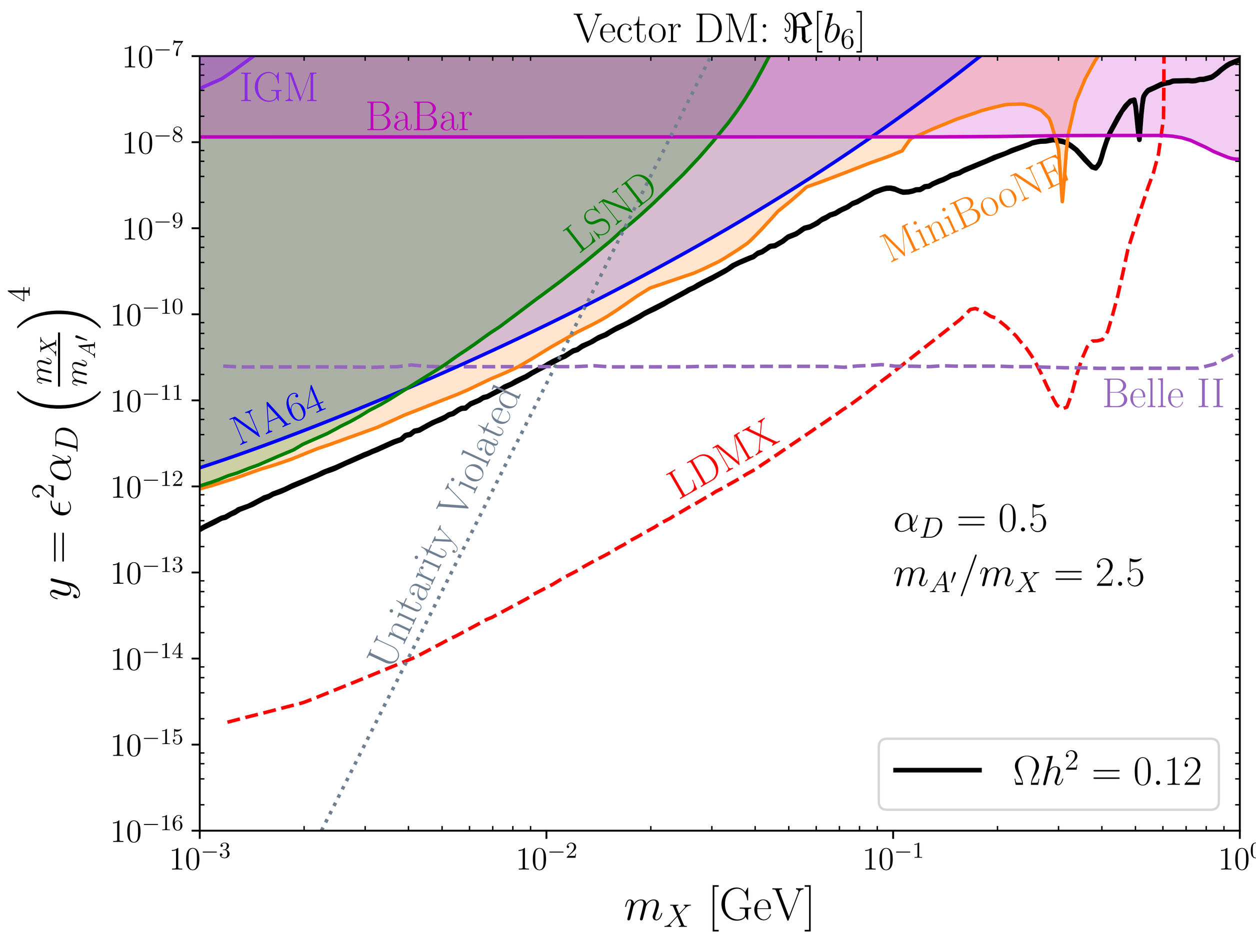
We **extend** the existing studies on sub-GeV dark matter at fixed target experiments, which include spin-0 and spin-1/2 dark matter models, to include spin-1 dark matter. We consider simplified spin-1 models which are directly comparable to the previously studied models, and an **ultraviolet complete model** based on a non-abelian gauge group where dark matter is a spin-1 Strongly Interacting Massive Particle (SIMP).

Simplified Spin-1 Dark Matter Models

- The SM is extended by a single dark matter particle, X and a mediator particle, A'.

$$\begin{aligned}\mathscr{L} = &- \left[ib_5 X^\dagger_\nu \partial_\mu X^\nu A'^\mu + b_6 X^\dagger_\mu \partial^\mu X_\nu A'^\nu + h.c.\right] \\ &- \left[b_7 \epsilon_{\mu\nu\rho\sigma} \left(X^{\dagger\mu} \partial^\nu X^\rho\right) A'^\sigma + h.c.\right] \\ &- e\epsilon A'_\mu \bar{f} \gamma^\mu f,\end{aligned}$$

- Certain simplified models are **highly constrained** by **beam dump experiments**, and/or **energy injection** into the CMB, while others are the **first to be probed by LDMX**.
- **Unitarity** ***bounds*** **are strong** in these models due to energy dependent vertices and polarization vectors for dark matter.

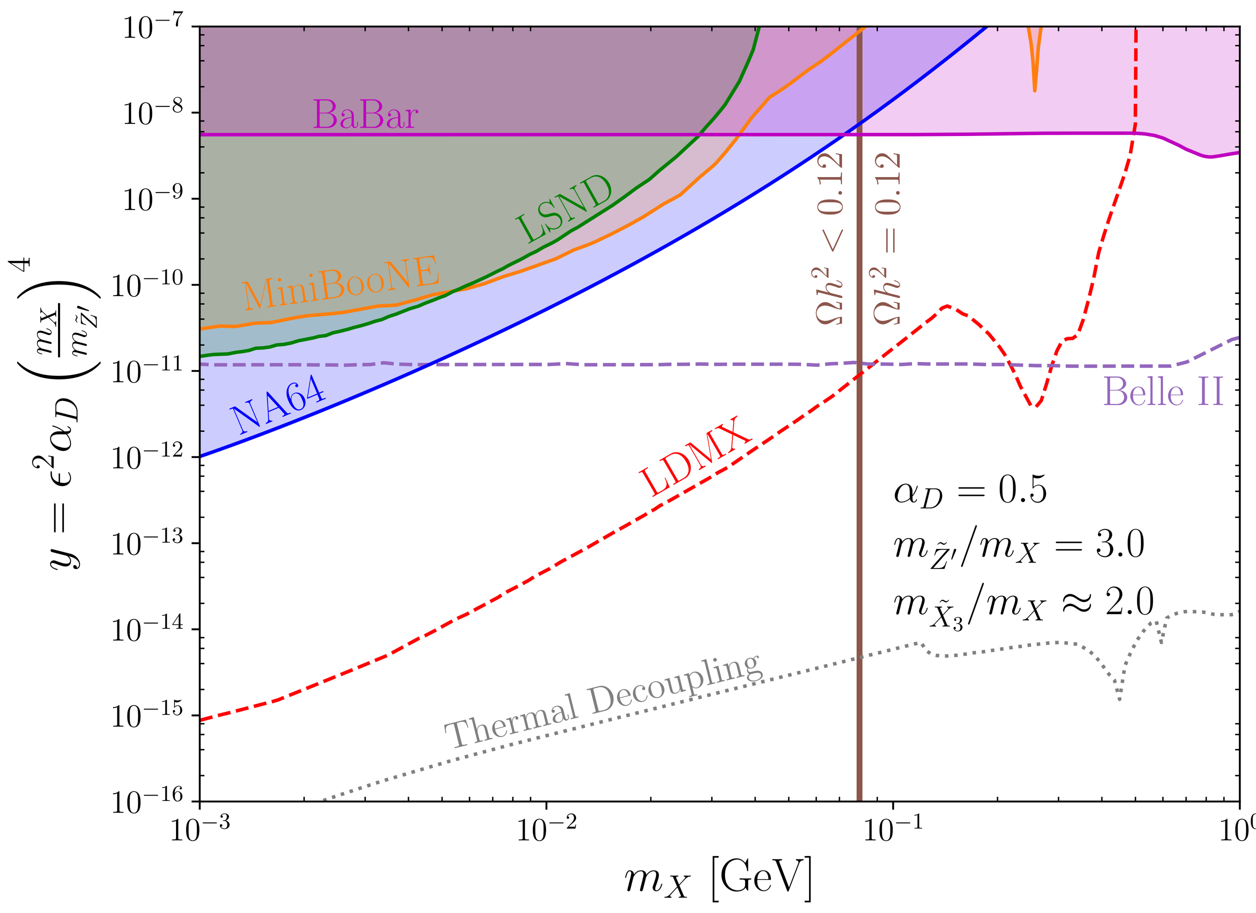


SIMP Spin-1 Dark Matter

- The SM is extended by a dark $SU_X(2) \times U_{Z'}(1)$
- We get an **extended Higgs sector**, and **two new mediators**, A' and $\tilde{X}_3$
- Not subject to strong energy dependent *unitarity bounds*.

$$\begin{aligned}\mathscr{L} = &- ig_X \cos\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{X}_{3,\nu} - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{X}_{3,\nu} \right. \\ &\left. + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{X}^\nu_3 - \partial^\nu \tilde{X}^\mu_3\right)\right] \\ &- ig_X \sin\theta'_X \left[\left(\partial^\mu X^\nu - \partial^\nu X^\mu\right) X^\dagger_\mu \tilde{Z}'_\nu - \left(\partial^\mu X^{\nu\dagger} - \partial^\nu X^{\mu\dagger}\right) X_\mu \tilde{Z}'_\nu \right. \\ &\left. + X_\mu X^\dagger_\nu \left(\partial^\mu \tilde{Z}'^\nu - \partial^\nu \tilde{Z}'^\mu\right)\right] \\ &- e\varepsilon \cos(\theta'_X)\, \tilde{Z}'_\mu\, \bar{f}\gamma^\mu f + e\varepsilon \sin(\theta'_X)\, \tilde{X}_{3\mu}\, \bar{f}\gamma^\mu f\end{aligned}$$

- Relic target is **independent of** ϵ since relic density is dominantly set by $3 \to 2$ or $2 \to 2$ annihilations to $\tilde{X}_3$.
- **Weaker beam dump limits** due to cancellations between diagrams for e^-/N dark matter scattering.



Summary

- We have **extended the current landscape of sub-GeV DM models** considered in the context of **fixed target experiments**,
- to include spin-1 sub-GeV DM [with $m_{A'} > 2m_{DM}$].
  - Simplified models
  - UV complete SIMP model
- Spin-1 dark matter are the first models to be probed at upcoming LDMX!

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