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DEEPLY INELASTIC DARK MATTER: BEAM DUMPS AS WIMP CANNONS

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Abstract

We consider a phenomenological approach to constraining dark matter interactions with quarks by the exchange of a light mediator particle. We find that, for low WIMP masses, an old beam dump experiment provides stronger bounds than currently obtainable at the LHC with monojet searches.

1 A toy model for light dark matter

The search for particle dark matter (DM) benefits from many and diverse approaches, both theoretically and experimentally. Recently, there has been much theoretical interest in scenarios for light, "secluded" DM 1), where the DM – generally a hypothesized Weakly Interacting Massive Particle (WIMP) – interacts with the SM only by the exchange of a mediator particle. There are several viable portals for such an interaction. For example, the WIMP candidate could be charged under an additional $U(1)'$ gauge boson which mixes kinetically with the $U(1)_Y$ of the Standard Model (SM) (e.g. [2]).

We propose a phenomenological approach to the mediation of dark matter interactions with the SM, and do not specify a particular portal. We consider Dirac fermionic dark matter (though the analysis is easily extendable to Majorana or scalar DM) which interacts with the SM quarks by the exchange of a mediator particle that is of scalar, vector, pseudo-scalar or axial-vector type. The corresponding interaction terms in the Lagrangian are:

$$\mathcal{L}_{\rm V} = V_\mu \left(g_q \sum_q \bar{q}\gamma^\mu q + g_\chi \, \bar{\chi}\gamma^\mu \chi \right) , \qquad \mathcal{L}_{\rm S} = \phi \left(g_q \sum_q \bar{q}q + g_\chi \bar{\chi}\chi \right) , \quad (1)$$

with similar terms for axial-vector and pseudo-scalar mediators[1]. For the vector case, this framework encompasses the physics of the popular kinetic mixing paradigm. As a simplifying assumption, we take the couplings to all quark flavours, g_q, to be equal.

One sensitive testing ground for light dark matter is the current generation of neutrino fixed target experiments [3, 4]. Here, we will consider a predecessor to the current facilities, the proton beam dump experiment E613, which ran in the 1980s at Fermilab [5, 6]. The relatively high beam energy at E613 (400 GeV) allows the probing of WIMP masses in the $\sim$ few GeV range, whereas the current generation operate at much lower energy (the highest being MINOS which uses the 30 GeV NuMI beamline [7]).

2 Dark matter production and rescattering

WIMP production, $pp \to \chi\bar{\chi}$, in the target proceeds through the s-channel via quark annihilation directly to the mediator particle, which subsequently splits into two WIMPs. We study only the kinematic regime where the mass of the mediator is less than twice the final state mass of the WIMPs, $m_{\rm med} < 2m_\chi$, meaning there is no resonant production. The alternate kinematic regime, $2m_\chi > m_{\rm med}$ was covered in the context of current neutrino experiments recently in [4]. The production process was implemented in MadGraph 5 [8].

After production, the WIMPs may rescatter in 15m of iron shielding (atomic number $A_{\rm Fe} = 56$, density $\rho_{\rm Fe} = 7.87$ g/cm^3) before passing through

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[1] Subject to appropriate factors of γ_5.

Quantity	E613
Beam Energy (E_B)	400 GeV
Protons on Target (POT)	10^{17}
Target Material	tungsten
Target Nucleon Density (n_T)	$1.15 \times 10^{25}/\text{cm}^3$
Target Length (L_T)	43 cm
Distance to Detector (L)	55.8 m
(Effective) Detector Area	1.77 m^2
Detector Length	166 cm

Table 1: Relevant details concerning the E613 experiment 5, 6).

the detector (with a lead-dominated fiducial mass, $A_{\text{Pb}} = 208$, density $\rho_{\text{Pb}} = 11.34$ g/cm^3) 56m down the beam tunnel. A WIMP scattering in the detector appears indistinguishably from a neutrino neutral current (NC) event – this allows us constrain the strength of the WIMP interaction with quarks. In lieu of a reliable model of the neutrino NC background, we conservatively require that the predicted number of WIMP NC events is lower than the total number of detected NC events at E613, i.e. less than 156.

The number of WIMPs produced at the target is (see Table 1 for experimental parameters):

$$N_{\text{prod}} = 2 \times \sigma(pp \to \chi\bar{\chi}) \times L_T \times n_T \times \text{POT} \tag{2}$$

The number of expected NC events in the detector from this flux may be found by calculating the probability that the WIMP scatters in the detector, but not in the intervening shielding, i.e.

$$N_{\text{detected}} = \epsilon \times (1 - P_{\text{Fe}}) \times P_{\text{Pb}} \times N_{\text{prod}} \ . \tag{3}$$

The geometric acceptance of the detector is represented schematically by the parameter ϵ, which accounts for the rapidity cut on the WIMPs. In order for a WIMP to hit the detector face, conservatively modelled as a circle of radius 0.75 m, it must be produced with an opening angle of $\Delta\theta = \frac{0.75 \text{ m}}{55.8 \text{ m}} = 0.0134$ radians in the lab frame. The leading-twist probability for a WIMP to scatter is:

$$P = \int_0^L dx \, \frac{1}{\lambda} \, e^{-\frac{x}{\lambda}} \, , \qquad \text{where} \qquad \lambda = \frac{A}{N_A \times \rho \times \sigma\,(\chi N \to \chi N)}. \tag{4}$$

N_A is Avagadro's number, 6.022×10^{23}, and $\sigma\left(\chi N \rightarrow \chi N\right)$ is the cross section for the deep inelastic scattering of a WIMP from a nucleon, N. λ is the mean free path in a material with atomic mass number A and density ρ.

A Monte Carlo simulation was employed to calculate the number of WIMP NC events expected in the detector. The simulation (implemented in `C++`) accounted for the geometric considerations above and the rescattering in both the shielding and the detector, though it was found that the shielding causes a negligible loss, $(1 - P_{\mathrm{Fe}}) \sim 1$.

3 Results

Figure 1 displays the bounds obtained on the WIMP coupling-mass plane for a mediator particle of mass 1 GeV. Also shown is a bound from the LHC, calculated using the monojet analysis of the CMS collaboration 9). Here, WIMPs are created in a *pp* collision and leave no trace in the detector; the signal is a single jet with missing transverse energy. The CMS analysis permits 660 monojet events above the SM background, from which we derive our bound, which is consistent with other recent work 10).

The constraints from E613 shown in Figure 1 get stronger as the WIMP mass decreases, clearly suggesting the investigation of MeV scale WIMPs, which already well theoretically motivated (e.g. 2)). However, with a 400 GeV proton beam and such light WIMPs, one can run into a region of small Bjorken-x. Here, parton-level deep inelastic scattering is no longer an appropriate description, owing to the gluon saturation of the parton distribution functions. A new model of the nucleus must be employed, whereby the interaction of the mediator and nucleon occurs via a colour dipole 11). With such a model in hand, one could reliably probe MeV-scale WIMP and mediator masses 12).

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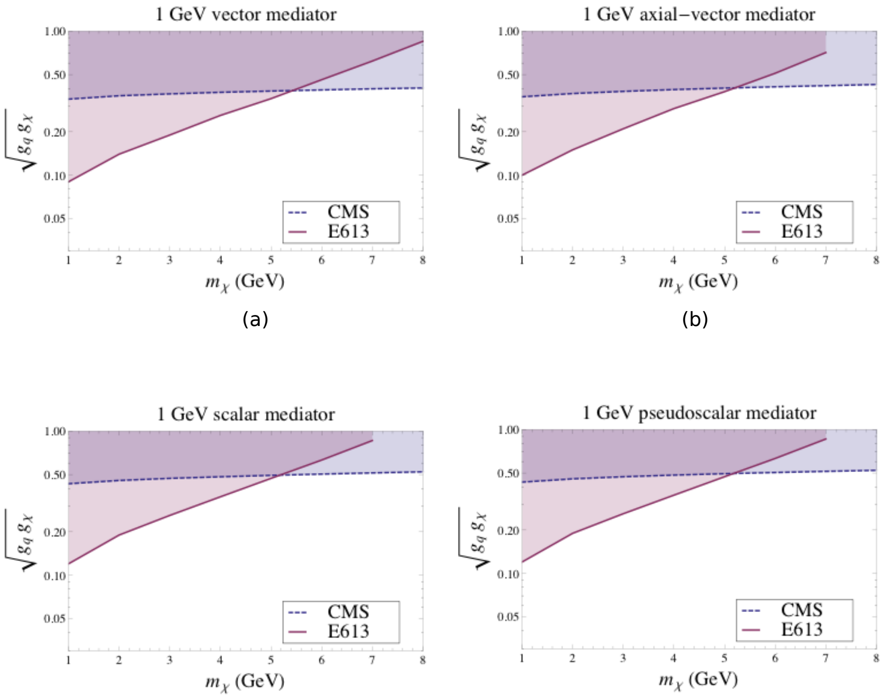

(a) (b)

(c) (d)

Figure 1: Limits on a combination of coupling parameters for 1 GeV (a) vector (b) axial-vector (c) scalar and (d) pseudo-scalar mediators. The shaded regions represent areas of parameter space ruled out by the respective experiment.

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