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Constraints on light Majorana dark matter from colliders

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ABSTRACT

We explore model-independent collider constraints on light Majorana dark matter particles. We find that colliders provide a complementary probe of WIMPs to direct detection, and give the strongest current constraints on light DM particles. Collider experiments can access interactions not probed by direct detection searches, and outperform direct detection experiments by about an order of magnitude for certain operators in a large part of parameter space. For operators which are suppressed at low momentum transfer, collider searches have already placed constraints on such operators limiting their use as an explanation for DAMA.

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1. Introduction

Recently, there has been much interest in light (order \sim GeV) mass dark matter [1–5]. This interest is partly spurred by the fact that the DAMA signal of annual modulation [6] may be understood as consistent with null results reported by CDMS [7] and Xenon 10 [8] if the dark matter is a weakly interacting massive particle (WIMP) of mass \lesssim 10 GeV [9]. Further excitement is motivated by the signal reported by CoGeNT, which favors a WIMP in the same mass range [10] as DAMA with moderate channeling (however, unpublished data from a pair of CDMS Si detectors [11] provides some tension, see [4]).

A WIMP which is relevant for direct detection experiments necessarily has substantial coupling to nucleons, and thus can be produced in high energy particle physics experiments such as the Tevatron and Large Hadron Collider (LHC). In particular, light WIMP states can be produced with very large rates. These WIMPs escape undetected, and hence the most promising signals involve missing energy from a pair of WIMPs recoiling against Standard Model (SM) radiation from the initial state quarks/gluons [12–14]. While such searches are complicated by large SM backgrounds producing missing energy, we will find that colliders can provide stringent restrictions on the parameter space of light dark matter models. Colliders can also access interactions which are irrelevant for direct detection (either because they lead to vanishing matrix elements in non-relativistic nucleon states or are suppressed at low momentum transfer).

In this Letter, we explore the bounds colliders can place on a light Majorana fermion WIMP, which we assume interacts with

the SM largely through higher dimensional operators. By exploring the complete set of leading operators, we arrive at a model-independent picture (up to our assumptions) of WIMP interactions with SM particles in the case where the WIMP is somewhat lighter than any other particles in the dark sector. We show that colliders can outperform direct detection searches significantly over a large area of parameter space.

2. The effective theory

We assume that the WIMP (χ) is the only degree of freedom beyond the SM accessible to the experiments of interest. Under this assumption, the interactions between WIMPs and SM fields are mediated by higher dimensional operators, which are non-renormalizable in the strict sense, but may remain predictive with respect to experiments whose energies are low compared to the mass scale of their coefficients. We assume the WIMP is an SM singlet, and examine operators of the form [13,15,16]

$$\begin{aligned}\mathcal{L}_{\text{int},qq}^{(\text{dim } 6)} &= G_\chi [\bar{\chi} \Gamma^\chi \chi] \times [\bar{q} \Gamma^q q], \\ \mathcal{L}_{\text{int},GG}^{(\text{dim } 7)} &= G_\chi [\bar{\chi} \Gamma^\chi \chi] \times (GG \text{ or } G\tilde{G}).\end{aligned}\quad (1)$$

Here q denotes the quarks $q = u, d, s, c, b, t$, and G and \tilde{G} the field strength of the gluon with $\tilde{G}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} G_{\rho\sigma} / 2$. Ten independent Lorentz-invariant interactions are allowed; by applying Fierz transformations, all other operators can be rewritten as a linear combination of operators of the desired form. In Table 1, we present couplings G_χ and $\Gamma^{\chi,q}$ for these ten operators, where we have expressed G_χ 's in terms of an energy scale M_* . In the table, we have assumed that the coefficients of the scalar operators, M1–M4, are proportional to the quark masses, in order to avoid large flavor changing neutral currents. We will assume that the interaction is dominated by only one of the above operators in the table.

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Table 1
The list of the effective operators defined in Eq. (1).

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	–
M8	GG	$i\alpha_s/8M_*^3$	γ_5	–
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	–
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	–

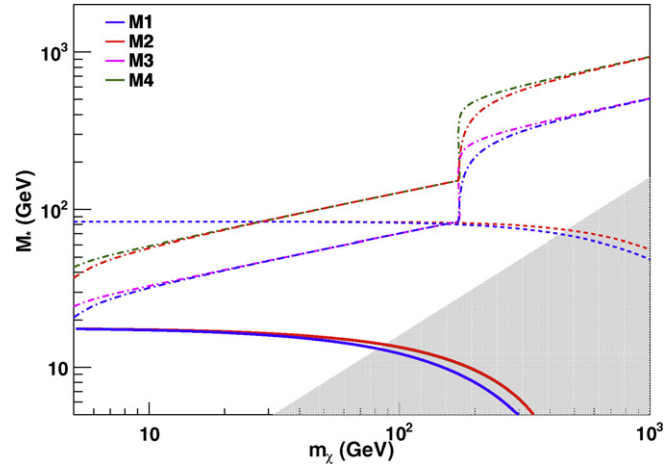


Fig. 1. Constraints on M_* for operators M1–M4. Solid lines are Tevatron 2σ constraints. Dashed lines show LHC 5σ reach. Results for M1 and M2 are largely degenerate with M3 and M4, respectively. The dash-dotted lines show the value of M_* which reproduce the thermal relic density ($\Omega h^2 = 0.11$). In the shaded region, the effective theory breaks down.

Our effective theory description will break down at energies of order the mass of whatever virtual particles mediate the χ – SM interactions. If we imagine that the interactions are mediated at tree-level by some heavy state with couplings of order g and mass M , we can identify $M_* \sim M/g$. In order for perturbation theory to be trustworthy, $g \lesssim 2\pi$, and thus the effective theory description can at best be valid for $M_* \geq m_\chi/(2\pi)$, providing an upper limit on collider cross sections for which there can be any effective theory description.

3. Collider constraints

We put constraints on each operator in Table 1 by considering the pair production of WIMPs at hadron colliders together with associated hard jets,

$$p\bar{p}(pp) \rightarrow \chi\chi + \text{jets}. \quad (2)$$

We generate signal events for each operator using CompHEP [17, 18] and shower them with PYTHIA [19] with the help of the CompHEP–PYTHIA interface [20]. Detector effects are simulated using PGS [21] with the CDF detector model.

The largest and irreducible Standard Model background is Z + jets with $Z \rightarrow \nu\nu$. The next important background comes from W + jets where the charged lepton from W -decay is lost. The QCD multi-jet production with mismeasured transverse momentum also contributes to the background, but is expected to be subdominant for our cuts [22,23].

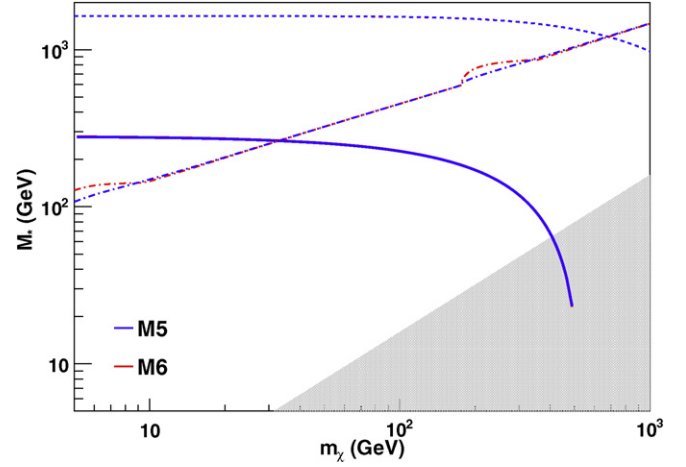


Fig. 2. Same as Fig. 1, but for the largely degenerate operators M5 and M6.

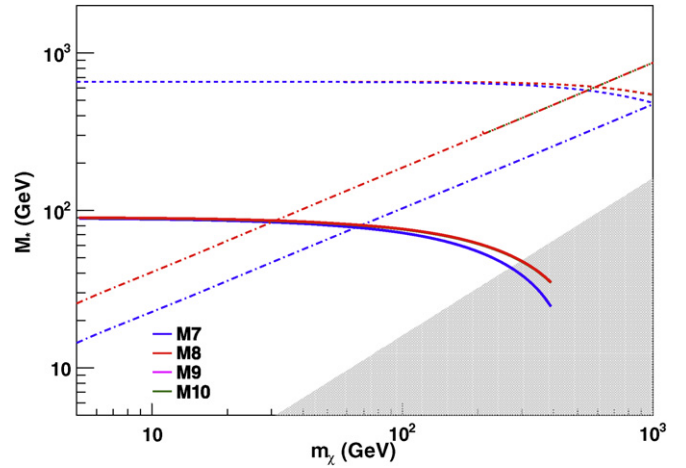


Fig. 3. Same as Fig. 1, but for the operators M7 and M8 which are largely degenerate with M9 and M10, respectively.

At the Tevatron, monojet searches [23,24] have looked for events with leading jet $E_T > 80$ GeV, missing $E_T > 80$ GeV, 2nd jet with $p_T < 30$ GeV, and vetoing any 3rd jet with $E_T > 20$ GeV. CDF analyzed 1.0 fb^{-1} of data with 8449 observed events. The expected number of SM background events is $N_{\text{SM}} = 8663 \pm 332$. Based on this result, we put a 2σ upper limit on the new physics cross section of $\sigma_{\text{new}} < 0.664 \text{ pb}$ (after cuts), which we translate into bounds on M_* .

For the LHC, we simulate jets + missing energy events (without vetoing extra jet activity) for $\sqrt{s} = 14$ TeV and compare them with the analysis in Ref. [25]. In Ref. [25], the number of SM background events with missing p_T larger than 500 GeV was about $B = 2 \times 10^4$ for integrated luminosity 100 fb^{-1} , while the signal acceptance is better than 90%. We assume that the signal acceptance remains 90%, that is, $S = 0.9 \times \sigma_{j\chi\chi} \times 100 \text{ fb}^{-1}$, where $\sigma_{j\chi\chi}$ is the parton-level cross section. We define the 5σ reach at the LHC by $S/\sqrt{B} > 5$, which we translate into reaches on M_* .

The Tevatron constraints and LHC reaches on M_* for each operator in Table 1 are summarized in Figs. 1–3. These bounds on M_* can be applied generically to models of dark matter, and can be used to place constraints. In the following, we apply them to find new constraints on direct detection cross sections.

4. Implications for direct detection

Only operators M1, M6, and M7 contribute to direct detection in the limit of zero momentum transfer. Through standard calculations [34] we find that the single-nucleon cross sections due to these operators are

$$\sigma_{SD;M6}^N = \frac{16\mu_\chi^2}{\pi} (0.015) \left(\frac{1}{2M_*^2} \right)^2, \quad (3)$$

$$\sigma_{SI;M1}^N = \frac{4\mu_\chi^2}{\pi} (0.082 \text{ GeV}^2) \left(\frac{1}{2M_*^3} \right)^2, \quad (4)$$

$$\sigma_{SI;M7}^N = \frac{4\mu_\chi^2}{\pi} (5.0 \text{ GeV}^2) \left(\frac{1}{8M_*^3} \right)^2, \quad (5)$$

where μ_χ is the reduced mass. We translate our limits on M_* for each operator into a constraint on the direct detection cross section (for the relevant operators) which can be induced by that operator. In Figs. 4–6, we plot the constraints from the Tevatron and the discovery reach of the LHC on the cross sections, as well as other existing constraints.

The most striking feature of our collider-derived constraints is the fact that they are sensitive to arbitrarily light DM particles. They are thus highly complementary to direct detection experiments, which have limited sensitivity to light DM due to their finite energy threshold. For light Majorana WIMPs, colliders make definite and important statements about the properties of DM. More generally, models with very low WIMP masses are most efficiently probed at colliders.

For WIMPs of mass less than 10 GeV, the Tevatron constraints already rule out cross sections above $\sim 10^{-37} \text{ cm}^2$, which are allowed by all other constraints. If the DM couples through an operator like $\chi\chi G^2$, the LHC will be able to place bounds far superior to any near-future DM experiment searching for spin-independent scattering, even for DM masses up to a TeV. Spin-dependent experiments are already outperformed in much of parameter space by current Tevatron bounds, while the LHC can place bounds several orders of magnitude better than near-future spin-dependent experiments.

5. Conclusions

We have derived new constraints on generic Majorana DM models based on null search results for monojets at the Tevatron, and explored corresponding discovery reaches at the LHC. Our bounds cover regions of parameter space which were previously not constrained by experimental efforts and strongly constrain some kinds of low mass WIMPs as an explanation for the DAMA and CoGeNT signals. In particular, we have derived constraints on the direct detection scattering of light Majorana WIMPs which are significantly stronger than experimental bounds (and near-future prospects) for spin-dependent scattering.

Colliders are particularly good experiments for testing DM models which are suppressed at small momentum transfer, whether the suppression is kinematic in nature as in models of light DM, or if the momentum dependence is inherent in the induced operator itself, as is the case with momentum-dependent DM [35]. It would be interesting to study the collider constraints on these models in detail.

6. Note added

During the final stages of preparing this manuscript, the Xenon 100 Collaboration released data constraining the low WIMP mass region of parameter space [36].

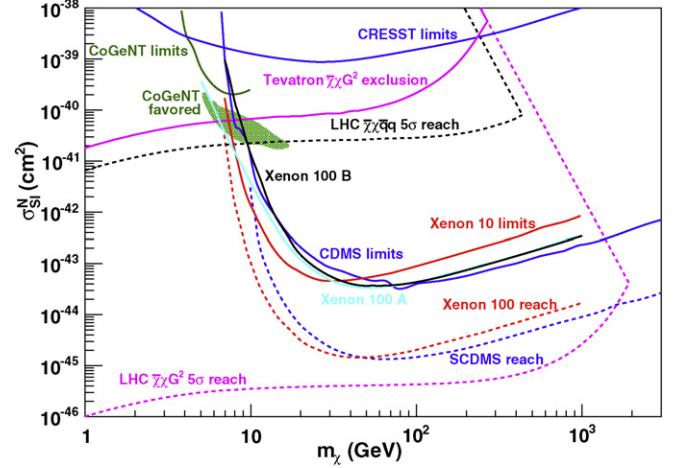


Fig. 4. Regions of parameter space excluded by Tevatron searches, CDMS/Xenon 10 [7,8], CoGeNT [26], and CRESST [27] (solid lines as indicated). The shaded region is the parameter space favored by a WIMP interpretation of the CoGeNT signal [10]. Also shown are projected bounds for the LHC, (S)CDMS [28], and Xenon 100 [29] (dotted lines as indicated).

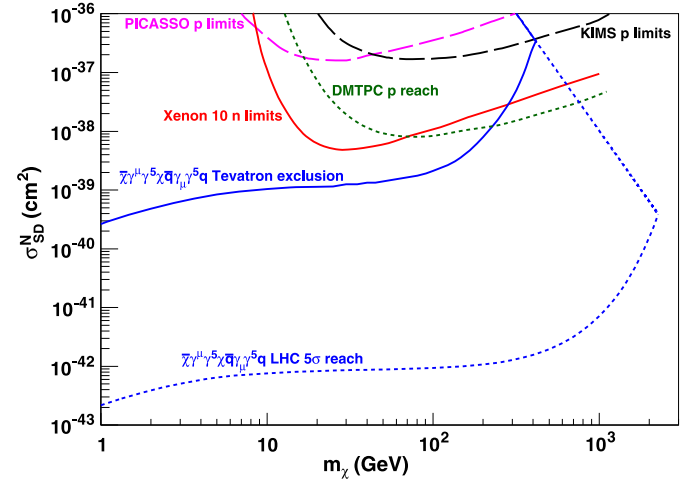


Fig. 5. Regions of parameter space excluded by Tevatron searches, Xenon 10 [8], KIMS [30] and PICASSO [31]. Also shown are projected bounds for the LHC and DMTPC [32].

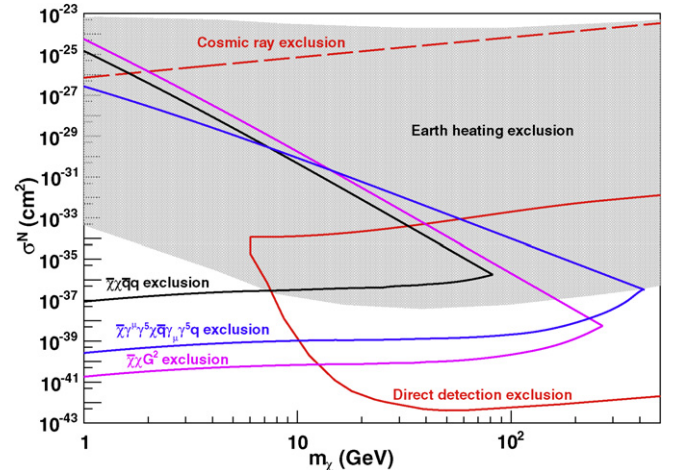


Fig. 6. The regions of parameter space excluded by Tevatron and other constraints (taken from [33]).

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