COLLIDER LIMITS ON DARK MATTER

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Dark matter pair production at high energy colliders may leave observable signatures in the energy and momentum spectra of the objects recoiling against the dark matter. We discuss signatures of Dark Matter in the jets + missing energy and photon + missing energy channels at the Tevatron and at LEP. Working in a largely model-independent effective theory framework, we can convert the collider bounds into constraints on the dark matter–nucleon scattering cross section and on the dark matter annihilation cross section. Our bounds are highly competitive with those from direct and indirect dark matter searches, especially for light WIMPs and for WIMPs with spin-dependent or leptophilic interactions. For example, we show that LEP rules out light ($\lesssim$ 10 GeV) thermal relic dark matter if annihilation into electrons is among the dominant annihilation channels.

1 Introduction

Collider searches for dark matter are highly complementary to direct searches looking for dark matter–nucleon scattering and to indirect searches looking for signatures of dark matter annihilation or decay in stars or galaxies. The main advantage of collider searches is that they do not suffer from astrophysical uncertainties and that there is no lower limit to the dark matter masses to which they are sensitive.

In this talk, we discuss search strategies for dark matter at colliders and compare the obtained limits to those from direct and indirect searches. We work in a largely model-independent effective field theory framework, assuming the interactions between a dark matter Dirac fermion χ and standard model fermions f to be well described by contact operators of the form

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{f}\gamma^\mu f)}{\Lambda^2}\,, \qquad \text{(vector, } s\text{-channel)} \tag{1}$$

[a] Based on work done in collaboration with Yang Bai, Patrick Fox, Roni Harnik and Yuhsin Tsai

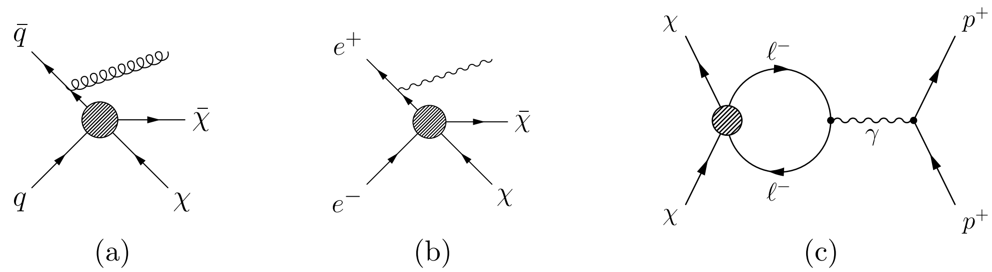


Figure 1: Dark matter production in association with (a) a mono-jet at a hadron colliders or with (b) a mono-photon at LEP. (c) Dark matter–nucleon scattering at one loop in models of leptophilic dark matter.

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{f}f)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)} \tag{2}$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)}{\Lambda^2}\,, \qquad \text{(axial vector, } s\text{-channel)} \tag{3}$$

$$\mathcal{O}_t = \frac{(\bar{\chi}f)(\bar{f}\chi)}{\Lambda^2}\,. \qquad \text{(scalar, } t\text{-channel)} \tag{4}$$

While this set of operators is not exhaustive, it encompasses the essential phenomenologically distinct scenarios: spin dependent and spin independent dark matter–nucleus scattering, as well as s- and p-wave annihilation. The classification of the effective operators as s-channel or t-channel refers to the renormalizable model from which they typically arise: (1)–(3) are most straightforwardly obtained if dark matter pair production is mediated by a new neutral particle propagating in the s-channel, while eq. (4) arises naturally if the mediator is a charged scalar exchanged in the t-channel (for instance a squark or slepton). With such a UV completion in mind, the suppression scale Λ can be interpreted as the mass of the mediator M, divided by the geometric mean of its couplings to standard model fermions, g_f, and dark matter, g_χ: $\Lambda = M/\sqrt{g_f g_\chi}$. Note that there is some degree of redundancy in eqs. (1)–(4) because $\mathcal{O}_t$ can be rewritten as a linear combination of s-channel type operator using the Fierz identities.

The experimental signatures we will investigate include events with a single jet or a single photon and a large amount of missing energy (fig. 1 (a) and (b)). In sec. 2, we will focus on searches at the Tevatron[1–3], while in sec. 3, we will derive limits from a reanalysis of LEP data[4].

2 Mono-jets at the Tevatron

Events in which dark matter is pair-produced can contribute to mono-jet events at CDF[5] through diagrams like the one in fig. 1 (a). By comparing the number of observed mono-jet events to the number of events expected from dark matter production and from standard model backgrounds, one can derive limits on the suppression scale Λ of the effective dark matter couplings as a function of the dark matter mass m_χ. These limits can then be converted into constraints on the dark matter–nucleon scattering cross section.

In fig. 2, we compare these constraints to the ones obtained from direct dark matter searches. We find that the Tevatron limits are stronger than those from direct searches if dark matter is lighter than a few GeV or has predominantly spin-dependent interactions. At $m_\chi \sim$ few $\times$ 100 GeV, the Tevatron's sensitivity deteriorates due to kinematic limitations.

Note that the Tevatron mono-jet search is limited by systematic uncertainties, so more data alone will not be sufficient to improve the limits considerably. However, some improvement can be expected from an analysis taking into account not only the total number of mono-jet events, but also the transverse momentum spectrum of the jets. Such an analysis would require good understanding of the uncertainties associated with the prediction of QCD backgrounds. Performing an inclusive rather than exclusive search may help to reduce the these uncertainties.

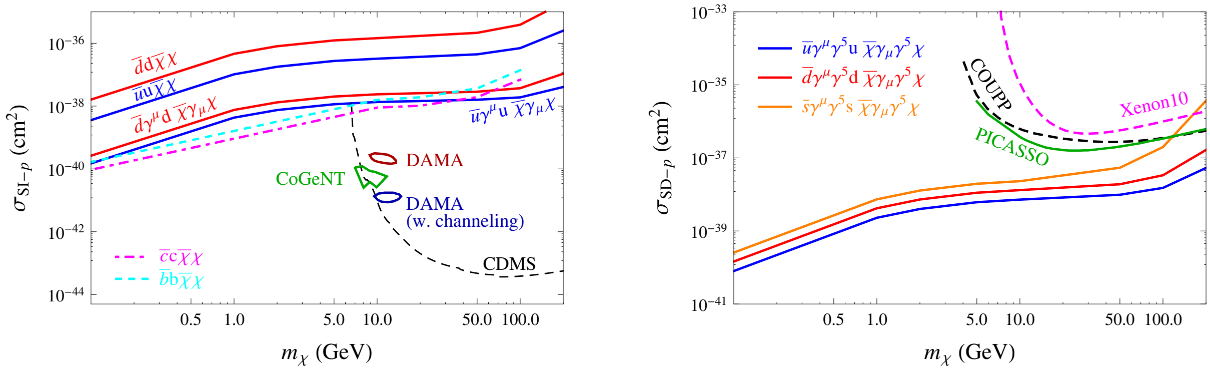


Figure 2: Limits on spin-independent (left) and spin-dependent (right) dark matter–proton interactions from a Tevatron mono-jet search[1;5]. We also show constraints from direct searches[6–8]. Plots taken from Bai et al.[1].

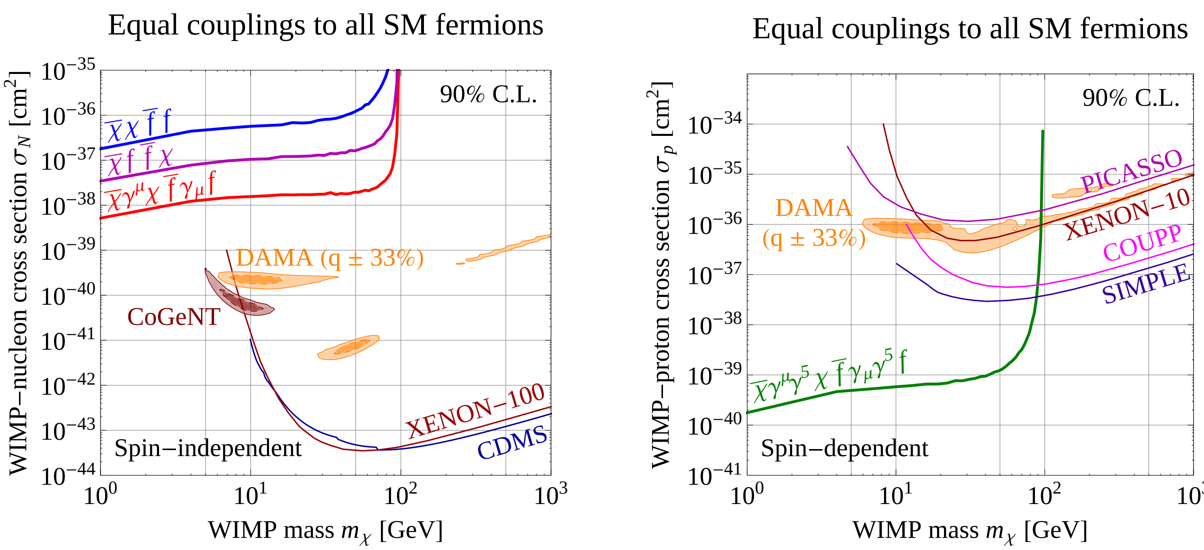


Figure 3: Limits on spin-independent (left) and spin-dependent (right) dark matter–nucleon interactions from a LEP mono-photon search[4;9]. Results are compared to constraints from various direct searches[6–8;10–15].

3 Mono-photons at LEP

Even though the total integrated luminosity of around 650 pb^{-1} recorded by the LEP experiments is smaller than the data set available at the Tevatron, we will now show that this data can still be used to set highly competitive limits on the properties of dark matter. Since initial state QCD radiation is absent at LEP, we will focus on final states with a single photon and a large amount of missing energy, *i.e.* we will study the process $e^+e^- \to \bar{\chi}\chi\gamma$ (fig. 1 (b)). Our analysis is based on the mono-photon spectrum observed by the DELPHI detector[9;16], which we will compare to predictions obtained using CompHEP[17], together with our own implementation of the DELPHI cuts, efficiencies, and energy resolutions in a modified version of the MadAnalysis framework[18]. Details on technical aspects of our analysis can be found in ref.[19]. We have verified our simulations by checking that we are able to reproduce the mono-photon distribution expected from the background process $e^+e^- \to Z\gamma$, with the Z decaying invisibly.

Like for the mono-jet channel, we first derive limits on the suppression scale Λ as a function of m_χ. While for mono-jets, a spectral analysis would have required detailed understanding of the systematic uncertainties in the background prediction, the mono-photon search at LEP is statistics-limited, and it is therefore straightforward to take into account the full mono-photon spectrum. This is advantageous because the distribution of signal events expected from dark

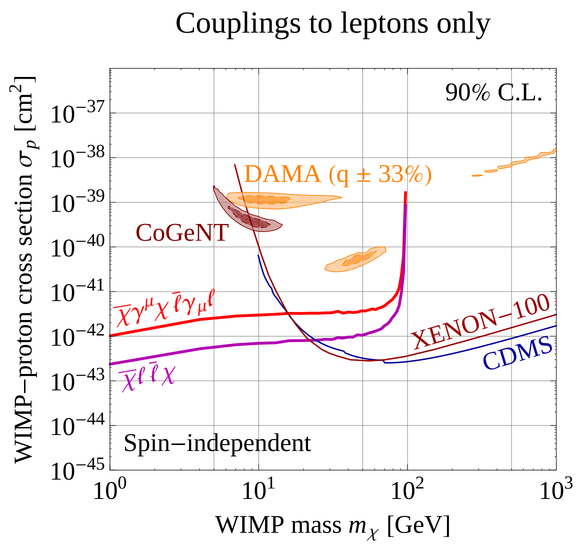


Figure 4: LEP constraints on dark matter with tree level couplings only to leptons[4], compared to limits from direct detection experiments[6–8;10;20;21].

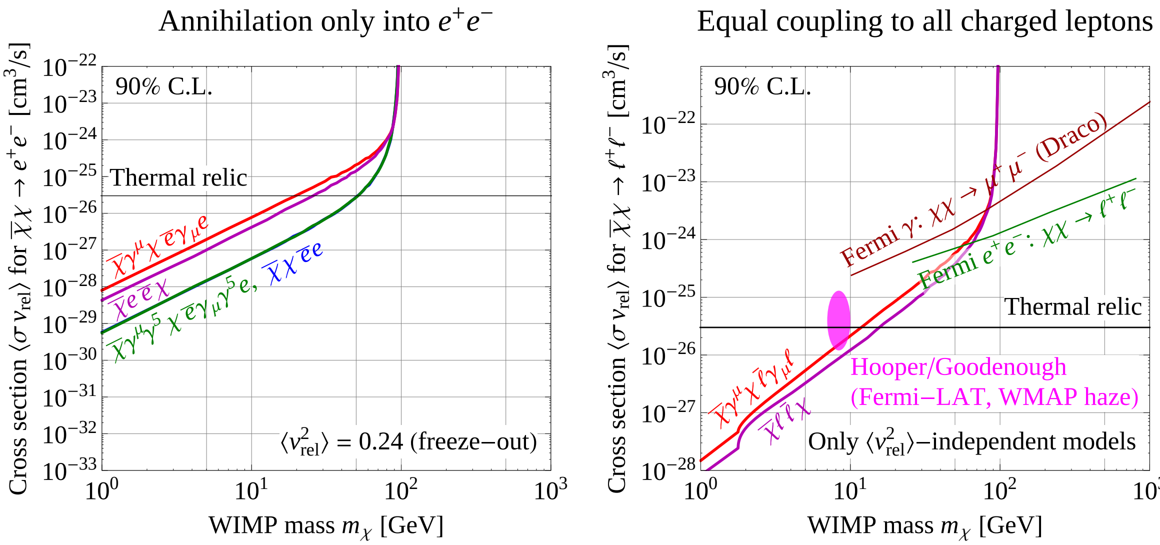
matter pair production is different from the shape of the $e^+e^- \to \bar{\nu}\nu\gamma$ background.

To convert the LEP bounds on Λ into limits on the dark matter–nucleon scattering cross section, we need to make some assumption on the relative strength of dark matter–quark couplings compared to dark matter–electron couplings. If these couplings are identical, as assumed in fig. 3, we find that the collider limits are again highly competitive for very light dark matter ($m_\chi \lesssim 4$ GeV) and for spin-dependent scattering up to the kinematic cut-off of LEP.

LEP can do even better in models where dark matter is leptophilic, *i.e.* has tree level couplings predominantly to leptons. Such models are, for example, motivated by recent anomalies in cosmic ray spectra.[22;23] Even though dark matter–nucleon scattering may be absent or suppressed in such models at the tree level, it can still occur at the loop level, mediated for instance by the diagram shown in fig. 1 (c).[21] The expected signal in direct detection experiments in this case is suppressed by a loop factor, so that LEP, which is probing unsuppressed tree level interactions, has a relative advantage and is competitive with direct searches even for spin-independent scattering up to its kinematic limit around $m_\chi \sim 80$ GeV (see fig. 4).

Besides the dark matter–nucleon scattering cross section, LEP can also set limits on the dark matter annihilation cross section. *Per se*, only bounds on annihilation into e^+e^- pairs can be derived (fig. 5 (a)), but it is easy to generalize these bounds, though not in a model-independent way. In particular, if there are other annihilation channels besides $\bar{\chi}\chi \to e^+e^-$, the LEP limits on the annihilation cross section are weakened by the inverse of the branching ratio for $\bar{\chi}\chi \to e^+e^-$. Since the cross sections for some types of dark matter interactions (in particular scalar and axial vector) depend strongly on the relative velocity $v_{\rm rel}$ of the annihilating dark matter particles, we have to specify the value of this quantity. In fig. 5, we take the average squared velocity $\langle v_{\rm rel}^2 \rangle$ to have a value of 0.24, corresponding to the time of electron–proton recombination in the early universe. (At later times, $\langle v_{\rm rel}^2 \rangle$ is smaller and the limits on scalar and axial vector interactions improve dramatically.[4]) We see that, if dark matter annihilates exclusively into e^+e^- pairs, LEP is able to rule out the annihilation cross section required for thermal relic dark matter, $\langle \sigma v_{\rm rel} \rangle = 3 \times 10^{-26}$ cm^3/s, if $m_\chi \lesssim \mathcal{O}(10\text{ GeV})$.

In fig. 5 (b) we compare LEP limits on the dark matter annihilation cross section to various astrophysical constraints[24–26]. We assume dark matter to couple equally to all charged leptons, but it would again be straightforward to rescale our limits if this is not the case. We see that for low m_χ LEP limits are stronger than constraints from gamma ray and e^+e^- observations



(a) (b)

Figure 5: LEP constraints on the dark matter annihilation cross section for the case where the branching ratio for $\bar{\chi}\chi \to e^+e^-$ is 100% (left), and for the case where dark matter couples equally to all charged leptons (right) [4].

by the Fermi-LAT collaboration, and that LEP is also able to disfavor a large portion of the parameter region that could potentially explain gamma ray signals from the galactic center.[26]

In fig. 6, we depart from the effective theory formalism and consider the implications of dark matter interactions mediated by a particle whose mass M is comparable to or below the LEP center of mass energy $\sqrt{s} \sim 200$ GeV. For $M \sim \sqrt{s}$, there is a regime where dark matter production at LEP is resonantly enhanced, so that the limit on the dark matter–nucleon scattering cross section σ_N improves compared to the contact operator case. For smaller M, the LEP constraint becomes generally weaker because the production cross section at LEP is proportional to s^{-1}, whereas σ_N is proportional to μ_N^2/M^4 (with the dark matter–nucleon invariant mass μ_N), giving direct detection experiments a relative advantage at small M. A special situation arises when $2m_\chi < M$, so that the mediator can be produced on-shell at LEP and then decay into dark matter. In that case, the LEP limit on σ_N is very sensitive to the width Γ of the mediator, which is a measure for its branching ratio into $\bar{\chi}\chi$ (larger Γ implies smaller branching ratio). We also note that on-shell production of the mediator with subsequent decay into standard model particles may impose independent constraints on models of this type.

4 Conclusions

In conclusion, we have shown that a largely model-independent search for dark matter is possible at high-energy hadron and lepton colliders by looking for an excess of events with large missing energy and a single jet or photon from initial state radiation. Working in an effective field theory framework, we have shown that the limits that LEP and the Tevatron can set on the mass and couplings of dark matter are superior to direct detection constraints if dark matter is very light ($\lesssim 4$ GeV) or has predominantly spin-dependent or leptophilic interactions. Above masses of $\mathcal{O}(100$ GeV), collider limits deteriorate due to kinematic limitations. We have also used LEP data to set limits on the dark matter annihilation cross section. For example, we were able to rule out a thermal relic with a mass below $\lesssim 10$ GeV if the e^+e^- final state is among the dominant annihilation channels. Our limits on dark matter annihilation are highly complementary to those from astrophysical searches since they extend to very low dark matter masses, whereas astrophysical experiment are most sensitive for dark matter masses above ~ 50 GeV. Finally, we

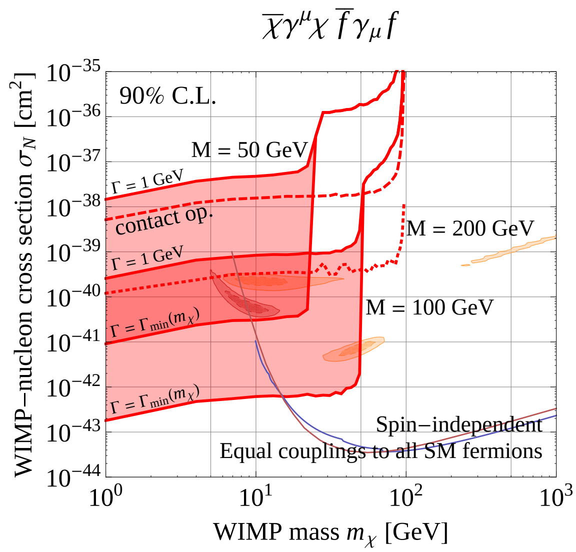


Figure 6: LEP constraints on the dark matter–nucleon scattering cross section in models where the interactions are mediated by a relatively light particle[4].

have also considered models in which dark matter interactions are mediated by a light particle and thus cannot be described in effective field theory. In this case, collider constraints can weaken, but depending on the details of the model may also become much stronger.

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