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Lower Limit on Dark Matter Production at the CERN Large Hadron Collider

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We evaluate the prospects for finding evidence of dark matter production at the CERN Large Hadron Collider. We consider weakly interacting massive particles (WIMPs) and superWIMPs and characterize their properties through model-independent parametrizations. The observed relic density then implies lower bounds on dark matter production rates as functions of a few parameters. For WIMPs, the resulting signal is indistinguishable from background. For superWIMPs, however, this analysis implies significant production of metastable charged particles. For natural parameters, these rates may far exceed Drell-Yan cross sections and yield spectacular signals.

The energy density of nonbaryonic dark matter in the Universe is now known to be [1]

$$\Omega_{\mathrm{DM}} h^2 = 0.112 \pm 0.009, \qquad (1)$$

where Ω_{DM} is this energy density in units of the critical density, and $h \simeq 0.71$ is the normalized Hubble parameter. With accompanying constraints, this implies that nonbaryonic dark matter makes up about a quarter of the energy density of the Universe. Its microscopic identity is at present unknown, however, and is one of the outstanding questions in basic science today.

An exciting possibility is that particles that make up some or all of dark matter may be produced at high-energy colliders, such as the Tevatron at Fermilab or, beginning in 2007, the Large Hadron Collider (LHC) at CERN. Such prospects are particularly promising if dark matter is composed of WIMPs or superWIMPs, weakly or superweakly interacting massive particles, since these scenarios require new particles with masses near $M_{\mathrm{weak}} \sim 100$ GeV, the scale to be probed in detail at the LHC. Of course, the discovery of dark matter signals requires not only that dark matter be produced at colliders but also that it be produced with rates and signatures that allow it to be distinguished from background. Remarkably, however, WIMP and superWIMP production rates are also constrained by cosmology, because dark matter densities are determined (in part) by thermal freeze-out in these scenarios. Since WIMPs and superWIMPs cannot have relic densities in excess of $\Omega_{\mathrm{DM}} h^2$, they must have annihilated efficiently in the early Universe and, consequently, must be produced efficiently at colliders.

In this Letter, we analyze this argument quantitatively. We begin by characterizing the properties of WIMPs and superWIMPs through model-independent parametrizations. Our analysis is sufficiently general to accommodate concrete realizations of WIMP or superWIMP dark matter in supersymmetric, extra-dimensional, and many other frameworks. Using the observed relic density, we then determine, as functions of the few parameters entering

the analysis, the minimal dark matter production cross section and its observable consequences. This approach was applied in Ref. [2] to obtain conservative estimates for WIMP cross sections at the International Linear Collider (ILC). The results implied challenging rates for discovery. In this study, we focus on the more pressing case of the LHC and also analyze superWIMP scenarios, for which our conclusions will be far more promising.

In both the WIMP and superWIMP dark matter scenarios, the process of freeze-out plays a large role in determining the dark matter relic density. In WIMP scenarios, the dark matter is a stable, neutral WIMP with mass $m_{\mathrm{WIMP}} \sim M_{\mathrm{weak}}$ and pair annihilation cross section $\sigma_{\mathrm{A}} \sim \alpha_{\mathrm{weak}}^2 M_{\mathrm{weak}}^{-2}$. Beginning in thermal equilibrium in the early Universe, WIMPs annihilate until they become too dilute to find each other and "freeze out" at temperature T_F. Given the expansion rate determined by $M_{\mathrm{Pl}} \simeq 1.2 \times 10^{19}$ GeV, along with m_{WIMP} and σ_{A} given above, the thermal relic density $\Omega_{\mathrm{WIMP}} h^2$ is automatically near the observed $\Omega_{\mathrm{DM}} h^2$ of Eq. (1). In contrast to other dark matter scenarios, there is no need to introduce new energy scales to obtain the desired relic density.

SuperWIMP scenarios also begin with a weakly interacting particle, which we denote L, with mass $m_L \sim M_{\mathrm{weak}}$ and $\sigma_{\mathrm{A}} \sim \alpha_{\mathrm{weak}}^2 M_{\mathrm{weak}}^{-2}$ that freezes out with density $\Omega_L h^2 \sim \Omega_{\mathrm{DM}} h^2$. In contrast to WIMP scenarios, however, L particles are not stable but metastable, and they ultimately decay to superWIMPs, which form the dark matter we observe today [3]. SuperWIMPs are neutral and stable, but their interactions are much weaker than weak, typically gravitational. The resulting dark matter density is, then,

$$\Omega_{\mathrm{SWIMP}} h^2 = \frac{m_{\mathrm{SWIMP}}}{m_L} \Omega_L h^2. \qquad (2)$$

If, as is often natural, $m_{\mathrm{SWIMP}} \sim m_L$, superWIMPs are also produced with relic densities of the right order of magnitude. *A priori*, L particles may be either electrically charged or neutral. However, in the well-motivated cases of gravitino and Kaluza-Klein graviton superWIMPs [3–

5], the neutral case is typically excluded by contraints from big bang nucleosynthesis [3,4,6], and the most motivated L particles are charged sleptons and Kaluza-Klein leptons, respectively. In this study, we therefore consider only L particles with charge ± 1.

To determine the production rates at colliders, we must first find what annihilation cross sections are implied by the observed relic density $\Omega_{\mathrm{DM}}h^2$. Let X denote a generic particle that freezes out, either the WIMP in WIMP scenarios or L in superWIMP scenarios. The total $X\bar{X}$ annihilation cross section is

$$\sigma_{\mathrm{tot}} = \sum_{ij} \sigma(X\bar{X} \to ij; \hat{s}), \qquad (3)$$

where $\sqrt{\hat{s}}$ is the center-of-mass energy, and i, j are partons. We parametrize the thermal average of σ_{tot} as

$$\langle \sigma_{\mathrm{tot}} v_X \rangle \equiv \sigma_{\mathrm{an}} v_X^{2n} + \mathcal{O}(v_X^{2n+2}) \equiv \sigma_0 x^{-n} + \mathcal{O}(x^{-n-1}), \quad (4)$$

where v_X is the relative velocity of the initial X and $\bar{X}$ particles in their center-of-mass frame, and $x \equiv m_X/T = 6/v_X^2$. This expansion is valid in the common case where annihilation is dominated by a single angular momentum component (S-wave for $n = 0$, P-wave for $n = 1$, etc.). It is necessarily valid at freeze-out, where $x \sim 25$ and $v_X \sim \frac{1}{2}$, but, of course, breaks down if v_X is near 2.

With this parametrization, the annihilation cross section is related to the relic density through [7]

$$\Omega_X h^2 \simeq 1.07 \times 10^9 \ \mathrm{GeV}^{-1} \frac{n+1}{\sqrt{g_*} M_{\mathrm{Pl}}} \frac{x_F^{n+1}}{\sigma_0}, \qquad (5)$$

$$\sigma_0 = \frac{1}{c^2 - 1} \sqrt{\frac{8}{45}} \frac{2\pi^3}{g} \frac{g_*^{1/2} x_F^{n+1/2}}{m_X M_{\mathrm{Pl}}} e^{x_F}, \qquad (6)$$

where $x_F = m_X/T_F$, g_* is the effective number of relativistic degrees of freedom at freeze-out, g is the number of X degrees of freedom, and c is defined by $Y(x_F) \equiv cY_{\mathrm{EQ}}(x_F)$, with $Y(x)$ the X number density per entropy density and $Y_{\mathrm{EQ}}(x)$ its value if X had remained in thermal equilibrium. We set $c^2 - 1 = n + 1$, which reproduces numerical results to within 5% [7].

Given the annihilation cross section for X particles, their production rate at colliders is fixed by the principle of detailed balance, assuming time reversal symmetry [8]. Neglecting the i, j parton masses, we find

$$\sigma(ij \to X\bar{X}; \hat{s}) = \frac{\eta_{ij} v_X^2 (2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \sigma(X\bar{X} \to ij; \hat{s})$$

$$= \frac{\eta_{ij}(2S_X + 1)^2}{4(2S_i + 1)(2S_j + 1)} \kappa_{ij} \sigma_{\mathrm{an}} v_X^{2n+1}, \quad (7)$$

where $\kappa_{ij} = \sigma(X\bar{X} \to ij; \hat{s})/\sigma_{\mathrm{tot}}$, η_{ij} is $\frac{1}{2}$ if i and j are identical and 1 otherwise, S denotes spin, and all cross sections include averaging and summing over initial and final state spins, respectively, but do not include color factors. Note that Eq. (4) has been used, and so the final expression of Eq. (7) is not trustworthy for v_X near 2. Equations (5)–(7) determine the minimum production cross section, given the observed relic density, as a function of a few parameters that characterize the properties of X: its mass m_X and spin S_X, its dominant annihilation channel n, and the dynamical parameters κ_{ij}.

We now turn to the case of superWIMP dark matter produced in L decays. The L lifetime is extremely long (for gravitational decays, it is of the order of hours to months), and so L particles appear as stable charged particles in colliders. For the LHC, with $\sqrt{s} = 14$ TeV, the minimum cross section for L pair production is

$$\bar{\sigma}(pp \to L^+L^-; s) = \int_{4m_L^2/s}^{(4m_L^2/s)[1/(1-v_{\max}^2/4)]} du \int_u^1 \frac{dx}{x} \sum_{ij} [f_{q_i}^p(x)f_{\bar{q}_j}^p(u/x) + f_{\bar{q}_j}^p(x)f_{q_i}^p(u/x)]\bar{\sigma}(q_i\bar{q}_j \to L^+L^-; us), \qquad (8)$$

where f_i^p are proton parton distribution functions, and

$$\bar{\sigma}(q_i\bar{q}_j \to L^+L^-; us) = \frac{1}{N_c^2} \sum_{\mathrm{color}} \sigma(q_i\bar{q}_j \to L^+L^-; us) \quad (9)$$

is the color-averaged parton-level cross section, where $N_c = 3$, and the right-hand side is determined by Eq. (7) with X replaced by L. The upper limit of integration for u forces $v_L < v_{\max}$. We choose $v_{\max}^2 = 2$, so that the parametrization of Eq. (4) may reasonably be expected to be valid in the region of integration, and we conservatively neglect all contributions from $v_L > v_{\max}$. We also neglect subleading contributions from (loop-induced) gg fusion and three-body processes $qg \to L^+L^-q$. Tevatron cross sections are determined by replacing one proton with an antiproton and setting $\sqrt{s} = 2$ TeV.

To distinguish the metastable L signal from background, we require that *both* L^+ and L^- have pseudorapidity $|\eta| < 2.5$ and velocity $\beta < 0.7$, so that both tracks will be detected with ionization $-dE/dx$ more than double minimum ionizing. The β and v_X requirements are correlated but independent, since β is in the lab frame, and v_X is in the parton center-of-mass frame. These cuts, together with the requirement of isolated tracks in events free of hadronic activity, should leave the signal essentially background-free. The event rates depend weakly on the η cut, dropping by about 20% when requiring $|\eta| < 0.5$. For $\beta < 0.6$, the event rate drops by a factor of 2–5, depending on m_L.

In Fig. 1, we show the minimum cross sections for L pair production at the Tevatron and the LHC as functions of m_L for both S- and P-wave annihilation, assuming scalar L particles, velocity-independent $\kappa_{q\bar{q}} = 0.2$, for $q = d, u, s, c, b$, and $m_{\mathrm{SWIMP}}/m_L = 0.6$. As can be seen, P-wave annihilation in the early Universe is suppressed by v_L^2 relative to S-wave, and so must be compensated by larger σ_{an}, leading to larger minimum collider rates. D- and higher-wave annihilation will imply even larger minimum rates. The dependence on the other parameter as-
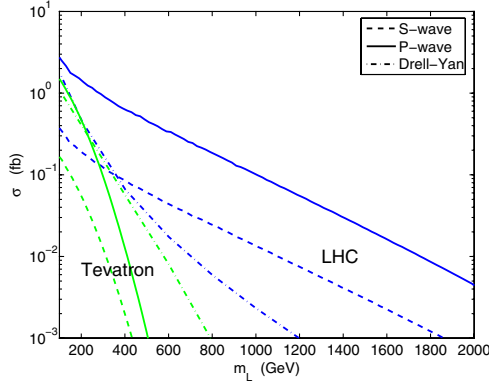
FIG. 1 (color online). Minimum Tevatron and LHC cross sections derived from cosmology, along with the Drell-Yan cross section, for L^+L^- production in the superWIMP scenario as functions of m_L. Each event has two highly ionizing tracks with velocity $\beta < 0.7$ and pseudorapidity $|\eta| < 2.5$. We assume $S_L = 0$, $m_{\text{SWIMP}}/m_L = 0.6$, and $\kappa_{q\bar{q}} = 0.2$, for $q = d, u, s, c, b$.
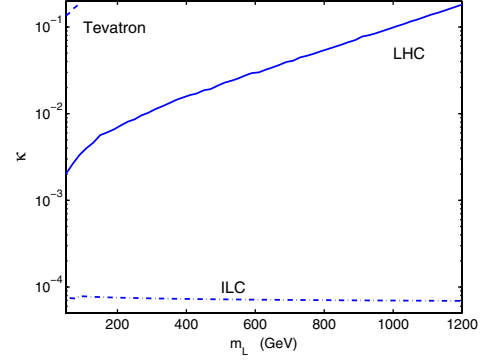

FIG. 2 (color online). Discovery limits for dark matter events in the superWIMP scenario at the Tevatron with $L = 30 \text{ fb}^{-1}$, LHC with $L = 1 \text{ ab}^{-1}$, and ILC with $L = 1 \text{ ab}^{-1}$. We require 10 events with two doubly minimum-ionizing tracks for discovery. For the ILC, the beam energy is assumed to be $\sqrt{s} \approx 2.8 m_L$, so that L particles are produced with $\beta = 0.7$. We assume $S_L = 0$, P-wave annihilation, and $m_{\text{SWIMP}}/m_L = 0.6$. The reach in κ scales linearly with $(2S_L + 1)^{-2}$ and, to an excellent approximation, $(m_{\text{SWIMP}}/m_L)^{-1}$.

sumptions is that the cross sections scale linearly with $(2S_L + 1)^2 \kappa_{q\bar{q}}$ and, to an excellent approximation, m_{SWIMP}/m_L. The L particles are assumed to be produced isotropically in the parton center-of-mass frame. We have checked that the results are insensitive to this assumption, varying by less than 10% for alternative distributions, such as $\sin^2\theta$ and $(1 \pm \cos\theta)^2$.

The cosmologically constrained L production cross sections shown in Fig. 1 are significant. For the LHC, even for $m_L \sim 1$ TeV, cross sections as large as 0.1 fb are predicted for P-wave annihilation. For comparison, the Drell-Yan production cross section $\sigma(pp \to \gamma, Z \to L^+L^-)$ is also shown in Fig. 1. At the LHC, for the parameters chosen, the minimum cross sections we have derived typically exceed the Drell-Yan cross sections; for P-wave annihilation, they are bigger by factors of 2–50, depending on m_L. Note that these minimum cross sections are parameter-dependent; no absolute minimum can be derived, as, for example, these cross sections may be made arbitrarily small by taking m_{SWIMP} to zero. However, if the fact that $\Omega_{\text{SWIMP}}h^2$ is around $\Omega_{\text{DM}}h^2$ is not merely a coincidence, it is natural to expect $m_{\text{SWIMP}} \sim m_L$, and it is significant that the predicted cross sections may be large for such natural choices.

The analysis above may be adapted easily to the case of the ILC, where the role of $\kappa_{q\bar{q}}$ is played by $\kappa_{e^+e^-}$. For the ILC, β and $v_{\text{max}}/2$ are nearly identical; the derivation of collider cross sections from the relic density is therefore reliable only when L particles are produced with $\beta < 0.7$. As examples, consider $S_L = 0$, $m_{\text{SWIMP}}/m_L = 0.6$, $\kappa_{e^+e^-} = 0.1$, and L particles produced with $\beta = 0.7$. For both $\sqrt{s} = 500$ GeV and 1 TeV, we find minimum cross sections of roughly 4 and 60 fb for S-wave and P-wave

annihilation, respectively. These imply hundreds to thousands of background-free events per year.

In Fig. 2, we give discovery limits in the (m_L, κ) plane, where $\kappa = \kappa_{q\bar{q}}$ for the Tevatron and LHC and $\kappa = \kappa_{e^+e^-}$ for the ILC. Given the cuts described above, we expect the signal to be background-free and so require 10 signal events for discovery. Even assuming a highly optimistic luminosity, the Tevatron can see the minimum dark matter signal only for $m_L \lesssim 100$ GeV and near maximal $\kappa_{q\bar{q}}$. The LHC does much better, probing $\kappa_{q\bar{q}} > 3 \times 10^{-3}$ for $m_L \sim 100$ GeV and $m_L < 1.2$ TeV for $\kappa_{q\bar{q}} \sim 0.2$. Finally, the ILC will provide phenomenal coverage down to $\kappa_{e^+e^-} \sim 10^{-4}$ for all m_L. The process $L^+L^- \to e^+e^-$ may be absent at tree level; in fact, all processes $L^+L^- \to f\bar{f}$ may be suppressed if annihilation to Higgs bosons dominates. However, even in these cases, since L must be weakly coupled to *some* standard model particles to explain $\Omega_L h^2 \sim \Omega_{\text{DM}} h^2$, we expect $\kappa_{e^+e^-} \sim 10^{-3}$ to be generated at loop level. Of course, this requires kinematically accessible L pairs. This is reasonable for the lower range of m_L plotted but requires later stages of the ILC program for the upper range.

We now consider WIMP dark matter scenarios. WIMP pair production is invisible at colliders. Here we consider the monojet signal of WIMP pairs produced in association with a gluon or quark. The cross section for $pp \to X\bar{X}j$ is not simply related to the cross section for $pp \to X\bar{X}$. However, for collinear or soft jets, these rates are related by splitting functions [2]. The color-averaged parton-level differential cross sections are, then,

$$\frac{d}{dz \, d\cos\theta} \bar{\sigma}(q(\bar{q} \to \bar{q}g) \to X\bar{X}g; \hat{s}) \approx F_{\bar{q} \to g}(z, \theta) \bar{\sigma}(q\bar{q} \to X\bar{X}; (1-z)\hat{s}), \qquad (10)$$

$$\frac{d}{dz \, d\cos\theta} \bar{\sigma}(q(g \to \bar{q}q) \to X\bar{X}q; \hat{s}) \approx F_{g \to q}(z, \theta) \frac{2S_q + 1}{2S_g + 1} \bar{\sigma}(q\bar{q} \to X\bar{X}; (1-z)\hat{s}), \qquad (11)$$

where the splitting functions are [9]

$$F_{q \to g}(z, \theta) = \frac{4}{N_c} \frac{\alpha_s}{\pi} \frac{1 + (1-z)^2}{z} \frac{1}{\sin^2\theta}, \qquad (12)$$

$$F_{g \to q}(z, \theta) = \frac{4}{N_c^2 - 1} \frac{\alpha_s}{\pi} \frac{z^2 + (1-z)^2}{\sin^2\theta}, \qquad (13)$$

with identical expressions for $q \to \bar{q}$. Here $i \to jk$ means that initial state parton i radiates parton k, which becomes the final state jet. The parameter $z = E_k/E_i$ varies from 0 to $1 - 4m_X^2/[s(1 - v_{\max}^2/4)]$ and θ is the angle between i and k; both are defined in the parton center-of-mass frame. Given these parton-level results, the LHC color-averaged differential cross section is

$$\frac{d}{dz\,d\cos\theta} \bar{\sigma}(pp \to X\bar{X}g, X\bar{X}q, X\bar{X}\bar{q}; s) \approx \int_{4m_X^2/(1-z)s}^{4m_X^2/(1-z)s(1-v_{\max}^2/4)} du \int_u^1 \frac{dx}{x}$$

$$\times \sum_{\substack{i,j=q,\bar{q},g \\ i \neq j}} f_i^p(x) f_j^p(u/x) \frac{d}{dz\,d\cos\theta} \bar{\sigma}(i(j \to \bar{i}k) \to X\bar{X}k; us). \qquad (14)$$

To ensure that the monojet events are detectable, we require the jets to have $\sin\theta_{\mathrm{lab}} > 0.1$ and $p_T > p_T^{\min}$. The factorization of Eqs. (10) and (11) holds formally only in the limit of soft or collinear jets, but it has been shown to be reasonably accurate even away from these limits in the region we have included [2]. In contrast to the superWIMP case, where the background is negligible, monojet events in the WIMP scenario suffer from a huge irreducible background from $pp \to \nu\bar{\nu}j$. At the ILC, the analogous single photon signal may be improved by an additional cut on the photon energy [2]. Unfortunately, this approach is not effective at the LHC because the parton center-of-mass energy is not fixed. Table I gives cross sections for the monojet signal for $m_{\mathrm{WIMP}} = 100$ GeV and two values of $p_T^{\min}$. The background, with the identical cuts implemented using the simulation package COMPHEP [10], is also given. Although thousands of WIMP monojet events are expected given integrated luminosity 1 ab^{-1}, the overwhelming background leads to very small $S/\sqrt{B}$, making discovery extremely difficult.

In summary, if stable WIMPs or superWIMPs exist, requiring that they not overclose the Universe implies efficient dark matter production rates at colliders. Using model-independent parametrizations, we have determined lower bounds on dark matter production rates as functions of a few parameters characterizing WIMP and superWIMP properties. For WIMP dark matter, the $X\bar{X}j$ signal is swamped by background. On the other hand, for natural parameters in the superWIMP scenario, the derived rate for

the production of two metastable charged particles may be much larger than the Drell-Yan cross section and implies spectacular signals at the LHC and, if kinematically accessible, the ILC. These superWIMP results imply promising prospects not only for detection of dark matter signals but also for detailed studies [11] of dark matter at future colliders.

[1] D. N. Spergel *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **148**, 175 (2003).

[2] A. Birkedal, K. Matchev, and M. Perelstein, Phys. Rev. D **70**, 077701 (2004).

[3] J. L. Feng, A. Rajaraman, and F. Takayama, Phys. Rev. Lett. **91**, 011302 (2003); Phys. Rev. D **68**, 063504 (2003); **68**, 085018 (2003).

[4] J. L. Feng, S. Su, and F. Takayama, Phys. Rev. D **70**, 075019 (2004); **70**, 063514 (2004).

[5] M. Fujii, M. Ibe, and T. Yanagida, Phys. Lett. B **579**, 6 (2004); J. R. Ellis *et al.*, Phys. Lett. B **588**, 7 (2004); W. Buchmuller *et al.*, Phys. Lett. B **588**, 90 (2004); F. Wang and J. M. Yang, Eur. Phys. J. C **38**, 129 (2004); L. Roszkowski, R. Ruiz de Austri, and K. Y. Choi, J. High Energy Phys. 08 (2005) 080.

[6] K. Jedamzik, Phys. Rev. D **70**, 063524 (2004); M. Kawasaki, K. Kohri, and T. Moroi, Phys. Lett. B **625**, 7 (2005).

[7] See, e.g., E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Reading, MA, 1990).

[8] W. Frazer, *Elementary Particles* (Prentice-Hall, Englewood Cliffs, NJ, 1966).

[9] See, e.g., F. Halzen and A. D. Martin, *Quarks and Leptons* (Wiley, New York, 1984).

[10] A. Pukhov *et al.*, hep-ph/9908288.

[11] K. Hamaguchi *et al.*, Phys. Rev. D **70**, 115007 (2004); J. L. Feng and B. T. Smith, Phys. Rev. D **71**, 015004 (2005); A. Brandenburg, L. Covi, K. Hamaguchi, L. Roszkowski, and F. D. Steffen, Phys. Lett. B **617**, 99 (2005).

TABLE I. The minimum monojet signal S from $pp \to X\bar{X}j$ at the LHC in the WIMP dark matter scenario. We assume scalar WIMPs with mass 100 GeV and P-wave annihilation and require jets to have $\sin\theta_{\mathrm{lab}} > 0.1$ and $p_T^{\min}$ as indicated. Also given are the standard model background B and the significance $S/\sqrt{B}$, assuming integrated luminosity 1 ab^{-1}.

$p_T^{\min}$	S	B	$S/\sqrt{B}$
30 GeV	18.6 fb	1300 pb	0.51
100 GeV	4.1 fb	130 pb	0.36