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Dark matter wants Linear Collider

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Summary. — One of the main purposes of physics at the International Linear Collider (ILC) is to study the property of dark matter such as its mass, spin, quantum numbers, and interactions with particles of the standard model. We discuss how the property can or cannot be investigated at the ILC using two typical cases of dark matter scenario: i) most of new particles predicted in physics beyond the standard model are heavy and only dark matter is accessible at the ILC, and ii) not only dark matter but also other new particles are accessible at the ILC. We find that, as can be easily imagined, dark matter can be detected without any difficulties in the latter case. In the former case, it is still possible to detect dark matter when the mass of dark matter is less than a half mass of the higgs boson.

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1. – Introduction

Dark matter, which accounts for about 23% of energy density of the present universe [1], has been one of great mysteries not only in particle physics but also in astrophysics and cosmology. While various well-motivated candidates for dark matter have been discussed theoretically, its detailed nature is still unknown. One of the main purposes at collider experiments is to reveal the property of dark matter such as its mass, spin, quantum numbers (gauge charges), and interactions with particles of the standard model (SM). For instance, at the Large Hadron Collider (LHC), it is expected that the mass of dark matter can be measured. On the other hand, the International Liner Collider (ILC) enables us not only to measure the mass very accurately, but also to determine the spin of dark matter [2]. It may be even possible to measure quantum numbers and coupling constant of each interaction between dark matter and SM particle.

It is, therefore, very important to evaluate how dark matter can be detected and how accurately its nature can be determined at the ILC. The answer to this question depends on the scenario of dark matter. For instance, when many new particles involving dark matter particle, which are predicted in physics beyond the SM, are within the range of the ILC, investigation of the nature of dark matter is expected not to be difficult. This is because these new particles eventually decay into dark matter and, as a result, many dark matter particles will be produced at the ILC. On the other hand, when the most of new particles are not accessible at the ILC, this investigation will be difficult.

In this report, we deal with these two cases and clarify the detectability of dark matter at the ILC. We use a model independent method as far as we can. In addition, we also try to estimate how accurately the property of dark matter can be determined if the detection turns out to be possible. In the next section, we first consider the case that only dark matter is accessible at the ILC (case (i)). After that, we consider another case that not only dark matter but also other new particles are accessible at the ILC in sect. **3** (case (ii)). Finally, we summarize our results in sect. **4**.

2. – The case i)

We first consider the case that all new particles except dark matter are heavy and not accessible at the ILC. In this case, it is convenient to use the method using effective lagrangian for investigating dark matter signals at the ILC. By postulating a global Z_2 symmetry to guarantee the stability of dark matter, where the dark matter particle has odd charge while SM particles have even one, and considering invariance under SM gauge groups, effective lagrangians for three cases of the spin of dark matter (scalar dark matter ϕ, fermion dark matter χ, and vector dark matter V_μ), are given by

$$(1)\quad \mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial\phi)^2 - \frac{M_S^2}{2}\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{d_S}{4!}\phi^4 + \mathcal{O}(1/\Lambda),$$

$$(2)\quad \mathcal{L}_F = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - M_F\right)\chi - \frac{c_F}{2\Lambda}|H|^2\bar{\chi}\chi - \frac{d_F}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu} + \mathcal{O}(1/\Lambda^2),$$

$$(3)\quad \mathcal{L}_V = \mathcal{L}_{\rm SM} - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{M_V^2}{2}V_\mu V^\mu + \frac{c_V}{2}|H|^2 V_\mu V^\mu - \frac{d_V}{4!}(V_\mu V^\mu)^2 + \mathcal{O}(1/\Lambda),$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $B_{\mu\nu}$ is the field strength tensor of hypercharge gauge boson, and $\mathcal{L}_{\rm SM}$ is the lagrangian of SM with H being the higgs boson. Dark matter is assumed to be an identical particle in all cases of the spin of dark matter for simplicity, so that these are described by real Klein-Gordon, Majorana, and real Proca fields, respectively. The cutoff scale of above effective Lagrangians is denoted by Λ, which should be $\gtrsim 1\,\mathrm{TeV}$. We have also assumed that the dark matter particle does not carry any charges of SM gauge interactions. Otherwise, the dark matter particle accompanies $SU(2)_L$ partners, which are necessarily predicted due to charge and color neutralities of the dark matter particle, and this fact conflict with the case we are considering in this section.

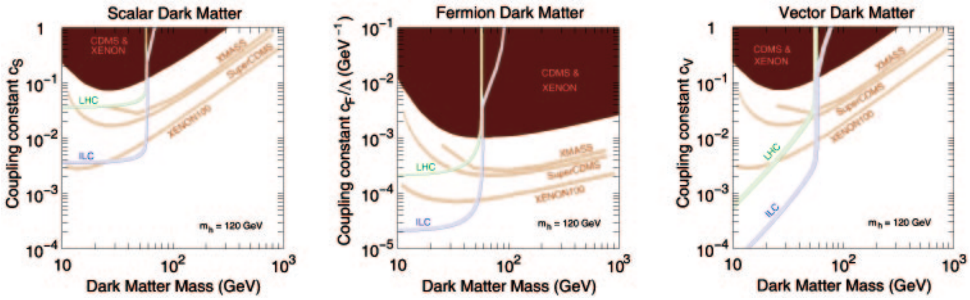

Fig. 1. – (Colour on-line) Sensitivities to detect dark matter signals at the ILC and LHC. Constraints and expected sensitivities from several direct detection experiments for dark matter are also shown.

Interaction terms proportional to coefficients d_S and d_V in eqs. (1) and (3) represent self-interactions of dark matter, which are not relevant for present colder phenomenology. The last term in RHS of eq. (2), which is proportional to coefficient d_F, is the interaction between dark matter and hypercharge gauge boson, however this term is most likely to be obtained by 1-loop diagrams of new physics dynamics at the cutoff scale Λ and can be ignored in comparison with the term proportional to c_F. As a result, in any case, dark matter interacts only through the Higgs boson at the leading order of $1/\Lambda$. After the electroweak symmetry breaking, masses of dark matters are given by $m_S^2 = M_S^2 + c_S v^2/2$, $m_F = M_F + c_F v^2/(2\Lambda)$, and $m_V^2 = M_V^2 + c_V v^2/2$, respectively, where the vacuum expectation value is $\langle H \rangle = (0, v)^T/\sqrt{2}$ with being $v \simeq 246\,\text{GeV}$. Model parameters relevant to our discussion are, thus, m and c with the subscript being S, F, or V.

Now we discuss dark matter signals at the ILC. When the mass of dark matter is less than a half mass of the Higgs boson (H), the branching ratio of H is significantly altered due to the interaction with dark matter. On the other hand, the production cross section of H remains the same. Since partial decay widths of H into quarks and leptons are suppressed due to small Yukawa couplings, many Higgs bosons produced at the ILC decay invisibly. One of the important processes for the invisible decay is the higgs-strahlung, $e^+e^- \to ZH$. In ref. [3], it has been shown that, using $500\,\text{fb}^{-1}$ data with 350 GeV center-of-mass energy, the invisible decay can be detected at the 95% CL when its branching ratio exceeds 0.95%. Here, the mass of H is fixed to be 120 GeV.

On the other hand, when the mass of dark matter is heavier than a half mass of the Higgs boson (H), H no longer decays into a pair of dark matters. Even in such a case, the Higgs-strahlung process, $e^+e^- \to H^*Z \to 2\text{DM} + q\bar{q}$ with H^* being a virtual Higgs boson, seems to be still important to detect dark matter at the ILC, because dark matter interacts only with H. After taking care of several SM backgrounds against the signal, which are coming from $e^+e^- \to W^+W^-$, ZZ, $\nu\nu Z$, e^+e^-Z, and $e^\pm \nu W^\mp$, we found that the signal will be detected at 95% CL when the cross section of the signal exceeds 0.7–0.8 fb after applying several kinematical cuts [4], where the center-of-mass energy of 300 GeV and the integrated luminosity of $2\,\text{ab}^{-1}$ are assumed. The Higgs mass is fixed to be 120 GeV, while the mass of dark matter is varied from 60 to 90 GeV.

All results are summarized in fig. 1, where the experimental sensitivity to detect dark matter signals at the ILC is shown as a blue line. For comparison, we plot the sensitivity of the LHC for the invisible decay of H as a green line [5]. Constraints and future prospective to detect dark matter at direct detection experiments of dark matter are also shown in the figure with assuming that scattering between dark matter and nucleon is

TABLE I. – *Spin combinations of new particles χ^0 and $\chi^\pm$ and examples of new physics models.*

Particles	Spins	Representative models
$(\chi_S^\pm, \chi_S^0)$	(0, 0)	Inert Higgs model
$(\chi_F^\pm, \chi_F^0)$	(1/2, 1/2)	Supersymmetric model
$(\chi_V^\pm, \chi_V^0)$	(1, 1)	Littlest Higgs model
$(\chi_V^\pm, \chi_S^0)$	(1, 0)	No well-known models
$(\chi_S^\pm, \chi_V^0)$	(0, 1)	No well-known models

dominated by the H exchanging process. It can be seen that the wide parameter region will be covered at the ILC when the mass of the dark matter is less than a half mass of H.

3. – The case ii)

We next consider the case that not only dark matter but also other new particles, which are expected to be introduced in new physics model at the TeV scale, are accessible at the ILC. Since there are many possibilities to realize this case, it is not easy to investigate dark matter signals at the ILC in a completely model-independent way. Instead, we focus on a new charged particle which decays into dark matter and W boson. Both dark matter and new particles are assumed to have odd charge under Z_2 symmetry which guarantees the stability of dark matter. SM particles are assumed to have even charge under the symmetry. Existence of such a new particle is predicted in the most of new physics models. We particularly consider the process, $e^+e^- \to \chi^+\chi^- \to \chi^0\chi^0W^+W^-$, where dark matter is denoted by χ^0 while the new charged particle is $\chi^\pm$. The process turns out to be useful to detect dark matter signals and investigate its nature.

Spins of χ^0 and $\chi^\pm$ particles depend on new physics model. All possible combinations for the spins up to spin 1 are shown in table I. As a first step of our study towards the evaluation of ILC's potential to detect dark matter signals and investigate its nature [6], we consider the following three models: the inert Higgs doublet model [7], the supersymmetric model [8], and the littlest Higgs model with T-parity [9]. These models contain a dark matter particle with spin 0, 1/2, and 1, respectively. The crucial difference from the $(1,0)$ or $(0,1)$ models in table I only appears in what relates to the $\chi^\pm\chi^0W^\mp$ vertex (*e.g.*, the shape of W boson energy distribution reconstructed). Strategy developed in this report can be applied to models with $(1,0)$ or $(0,1)$ spin combinations, as shown later.

Mass spectrum of dark matter (χ^0) and charged particle ($\chi^\pm$) used in our analysis is shown in table II. This mass spectrum is adopted in all the new physics models. Though the three new physics models predict different cross section values for $\chi^\pm$ pair production, we use a common value for the cross section with 100% branching ratio

TABLE II. – *Representative point used in our simulation study. See ref.* [6] *for more details.*

$M_{\chi^\pm}$ (GeV)	M_{χ^0} (GeV)	Cross section (fb)	$\sqrt{s}$ (GeV)
232	44.0	200	500

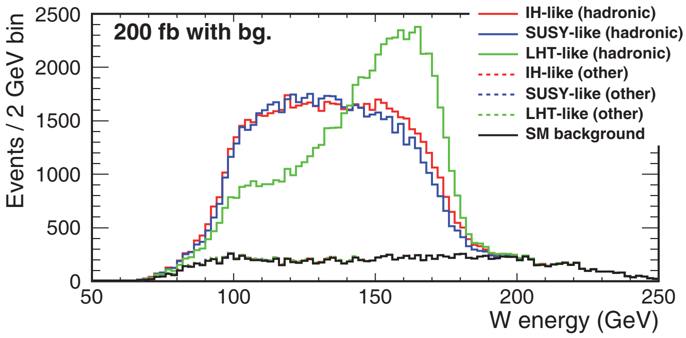

Fig. 2. – Distributions of reconstructed energy of W boson for IH-, SUSY-, and LHT-like models.

for the decay $\chi^{\pm} \to \chi^0 W^{\pm}$(1). At the ILC, χ^+ and χ^- are produced in pairs through s-channel exchanges of photon (γ) and Z boson. In addition, if there is another new particle which has a lepton number such as the sneutrino in the supersymmetric model or the heavy neutrino in the littlest Higgs model with T-parity, the diagram in which the new particle is exchanged in the t-channel contributes to the $\chi^{\pm}$ pair production. In our analysis, we simply assume that such a particle is heavy enough and ignore its contribution. For details of interaction vertex, χ^+-χ^--$Z(\gamma)$, see ref. [6].

We first consider the detection of dark matter signals at the ILC. The most useful (physical) quantity for the detection is the energy distribution of W boson emitted by the decay of $\chi^{\pm}$. Solving kinematics of the process $e^+e^- \to \chi^+\chi^- \to \chi^0\chi^0W^+W^-$, we can find the maximum and minimum of W energy. Finding both the edges on reconstructed W boson energy is nothing but the detection of dark matter. Furthermore, both masses of $\chi^{\pm}$ and χ^0 can be estimated from positions of the edges. Figure 2 shows the distribution of W energy for each model on top of SM background. Clear edges can be seen in the distribution of every model. The edge positions are obtained by a fit using an empirical function with kinematical edges. The fitting results are summarized in table III.

We next consider the threshold behavior of $\chi^{\pm}$ pair production. Since the total angular momentum along beam axis is one in energetic e^+e^- collisions, the cross section for the production behaves as $(s-4M^2_{\chi^{\pm}})^{1/2}$ in the threshold region when $\chi^{\pm}$ is fermionic. On the other hand, when $\chi^{\pm}$ is scalar or vector particle, the behavior is changing to $(s-4M^2_{\chi^{\pm}})^{3/2}$. Notice that, since $\chi^{\pm}_V$ is expected to be a gauge boson, its production vertex is coming from gauge self-interactions. In addition, there is also a vertex between SM gauge boson and would-be Nambu-Goldstone bosons which are absorbed in the longitudinal mode of $\chi^{\pm}_V$. In both cases, the final state with the total spin one cannot be composed by the vertices alone, which leads to the threshold behavior $\sigma \propto (s-4M^2_{\chi^{\pm}})^{3/2}$. As a result, information of the spin of $\chi^{\pm}$, which immediately leads to that about χ^0 because of Lorentz invariance, can be obtained by observing the threshold behavior.

Figure 3 shows how the cross section of each model depends on the center-of-mass energy $\sqrt{s}$. A clear difference can be seen between the SUSY-like model whose production cross section has the $(s-s_0)^{1/2}$ dependence, and the other two whose cross sections have the $(s-s_0)^{3/2}$ dependence where s_0 is the threshold energy, twice the mass of $\chi^{\pm}$.

(1) We therefore call the models the inert Higgs-like (IH-like), supersymmetric-like (SUSY-like), and littlest Higgs with T parity-like (LHT-like) models, respectively, in following discussions.

TABLE III. – *Measurement accuracies for* $\chi^{\pm}$ *and* χ^0 *masses.* (*Luminosity is set to be* $500\,\mathrm{fb}^{-1}$.)

	IH-like	SUSY-like	LHT-like
$M_{\chi^{\pm}}$ (GeV)	232.9 ± 0.1	232.7 ± 0.1	232.1 ± 0.1
M_{χ^0} (GeV)	44.2 ± 0.6	43.6 ± 0.7	43.8 ± 0.5

We finally consider the production angle of $\chi^{\pm}$, which can be reconstructed up to two-fold ambiguities from reconstructed W boson momenta. The distribution of the angle allow us to investigate the property of $\chi^{\pm}$, because it depends on the spin of $\chi^{\pm}$. The angular distribution in each case of IH-, SUSY-, or LHT-like model turns out to be

$$\frac{\mathrm{d}\sigma}{\mathrm{d}(\cos\theta)} \propto \begin{cases} 1-\cos^2\theta & \text{(for IH-like)}, \\ (1+x/4)-(1-x/4)\cos^2\theta & \text{(for SUSY-like)}, \\ (1+x+x^2/12)-(1-x/3+x^2/12)\cos^2\theta & \text{(for LHT-like)}, \end{cases} \tag{4}$$

where $x = s/M^2_{\chi^{\pm}}$ with s being the center-of-mass energy, and θ is the angle between $\chi^{\pm}$ momentum and beam axis. The angular distribution turns out to be a quite powerful tool to discriminate new physics models as we will show in the following.

In order to derive the production angle, we have to solve a quadratic equation using masses of new particles and momenta of W bosons with assuming a back-to-back ejection of the $\chi^{\pm}$ pair. The equation gives either two solutions which contain one correct production angle or no solutions when the discriminant of the equation is negative. Unphysical negative discriminant comes from missing reconstructing W momenta or imperfect back-to-back condition of two $\chi^{\pm}$ mainly due to initial state radiation. Fractions of 23.9% (IH-like), 20.8% (SUSY-like), 23.7% (LHT-like), and 64.4% (SM background) of events have negative discriminant. In order to estimate the separation power between the models, we have used the distribution of two-dimensional production angle, where two angles are obtained by solving the quadratic equation in each event. We compare the distribution for one model (dubbed as "dataset") against another model ("template").

In order to quantify the difference between a dataset of the model M_D and a template of the model M_T, We defined the chi-square value χ^2, the reduced chi-square $\tilde{\chi}^2$

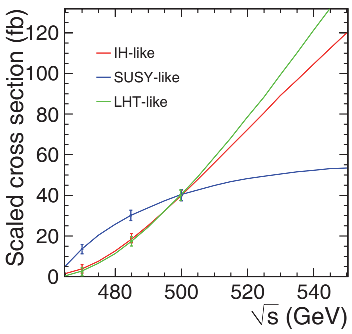

Fig. 3. – Threshold behavior of $\chi^+\chi^-$ production for IH-, SUSY-, and LHT-like models.

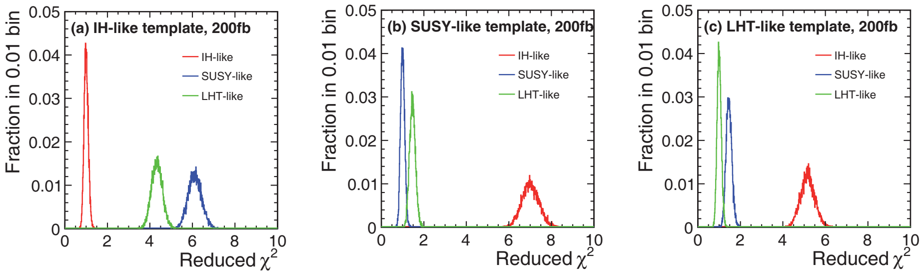

Fig. 4. – Distribution of $\tilde{\chi}^2(M_D, M_T)$ in each model. Luminosity is assumed to be $500\,\text{fb}^{-1}$.

and the separation power P as $\chi^2(M_D, M_T) = \sum_i^{\text{bins}} \{D_i(M_D) - T_i(M_T)\}^2/|T_i(M_T)|$, $\tilde{\chi}^2(M_D, M_T) = \chi^2(M_D, M_T)/(N-1)$, and $P(M_D, M_T) = (\tilde{\chi}^2(M_D, M_T) - 1)/\sigma(M_T)$, where $D_i(M)$ and $T_i(M)$ are the number of dataset and template events in the i-th bin of the model M, $N = 210$ is the number of bins, and $\sigma(M)$ is the standard deviation of $\tilde{\chi}^2(M, M)$. Since we use a high-statistics sample (10^6 events for each model) for the template, the effect of MC statistics of the templates can be ignored. The template distributions are normalized to the integral of the data events before calculating the χ^2 value. Figure 4 shows the obtained $\tilde{\chi}^2$ distribution with 10000 datasets for every combination of three models. It can be seen that separation is possible for every model.

Table IV tabulates the expected value of separation power $\bar{P}$. Despite the similar angular distribution of SUSY- and the LHT-like models, all three models can be identified. These values do not include the effect of the mass uncertainty of new particles, which is not significant with $< 5\%$ mass uncertainty obtained in our mass determination analysis.

4. – Conclusions

We have investigated dark matter signals at the ILC with especially focusing on two cases of dark matter scenario: i) only dark matter is accessible at the ILC and other new particles, which are predicted in physics beyond the SM, are much heavier, and ii) not only dark matter but also (some of) other new particles are accessible at the ILC.

In the first case, we found that dark matter is detectable at the ILC if the mass of dark matter is lighter than a half mass of the Higgs boson, and the dark matter signal appears as the invisible decay width of the Higgs boson. It is yet not clear whether the property of dark matter can be determined or not. We will leave the problem as a future work. On the other hand, if the mass of dark matter is heavier than a half mass of the Higgs boson, the detection of dark matter becomes challenging. We have shown that

Table IV. – *Expectation value of separation power $\bar{P}$ among three models obtained by the distribution of 2-dimensional production angle. Luminosity is assumed to be $500\,\text{fb}^{-1}$.*

$M_D \backslash M_T$	IH-like	SUSY-like	LHT-like
IH-like	–	63	43
SUSY-like	53	–	4.9
LHT-like	35	4.9	–

the detection may be possible if the mass of dark matter is less than 100 GeV and the coupling constant between dark matter and Higgs boson is not suppressed. Very recently, it has been pointed out that the Z-boson fusion process to produce a dark matter pair (instead of the Higgs-strahlung process) may overcome the problem if very energetic linear collider is available [10]. We also have another possibility. Our analysis about the detectability of dark matter at the ILC is based on dimension-5 operators. The detection using dimension-6 operators may help us to detect dark matter at the ILC.

In the next case, we have investigated dark matter signals at the ILC based on the fact that various new physics models predict the existence of a process $e^+e^- \to \chi^+\chi^- \to W^+W^-\chi^0\chi^0$. Using the process, we have considered IH-, SUSY-, and LHT-like models as typical examples of the case. We have shown that dark matter can be easily detected by observing the energy distribution of reconstructed W-boson. Furthermore, the distribution enables us to measure both χ^0 and $\chi^\pm$ masses accurately. We have also considered threshold behavior and scattering angle of the $\chi^\pm$ pair production, and found that the discrimination of the models, namely, that of the spin of dark matter, is possible using these two measurements. Extension of the analysis developed here to those for more general models are important to investigate the detectability of dark matter signals in a completely model-independent way. We also remain the problem as a future work.

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