Long-lived unstable superparticles at the LHC

Koji Ishiwata, Takumi Ito [*], Takeo Moroi

Department of Physics, Tohoku University, Sendai 980-8578, Japan

ARTICLE INFO

ABSTRACT

In various models of supersymmetry (SUSY), the lightest superparticle in the minimal SUSY standard model sector, which we call MSSM-LSP, becomes unstable. Then, we may observe the decay of the MSSM-LSP in the detector at the LHC experiment. We show that the discovery of such a decay process (and the determination of the lifetime of the MSSM-LSP) may be possible at the LHC even if the decay length of the MSSM-LSP is much longer than the size of the detector; sizable number of the MSSM-LSPs decay inside the detector if the lifetime is shorter than $10^{-(3-5)}$ s. We also discuss the implications of the study of the MSSM-LSP decay for several well-motivated SUSY models.

Supersymmetry (SUSY) is a well-motivated target of the LHC experiment. Indeed, not only the discovery but also detailed studies of the superparticles are possible at the LHC experiment if superparticles are within the kinematical reach [1,2]. In many of the studies, it is assumed that R-parity is conserved, and that the lightest superparticle (LSP) is the lightest neutralino. If so, all the produced superparticles cascade down to the lightest neutralino just after the production and SUSY events are characterized by large missing p_T.

Even though the lightest superparticle in the minimal-SUSY-Standard Model (MSSM) sector, which we call MSSM-LSP, is often assumed to be the lightest neutralino and is stable, it is not always the case. Various scenarios where the MSSM-LSP becomes unstable have been proposed. One important example is the gauge-mediated SUSY breaking scenario [3], where the SUSY breaking in the MSSM sector is mediated via the standard-model gauge interaction so that SUSY-induced flavor violation are strongly suppressed. In the gauge-mediated model, the gravitino becomes the LSP and the MSSM-LSP decays into the gravitino.

Another example is R-parity violation, with which the MSSM-LSP becomes unstable. Usually, R-parity conservation is assumed to realize the LSP dark matter scenario. However, LSP can be dark matter even if the R-parity is violated; if the R-parity violation is weak enough, the lifetime of the LSP becomes longer than the present age of the universe. This possibility becomes important when the gravitino is the LSP [4,5], because it has several advantages. In such a case, the thermal leptogenesis [6], which requires relatively high reheating temperature [7], may be possible without conflicting with the constraints from big-bang nucleosynthesis [8]

and the overproduction of the gravitino [9]. In addition, if the gravitino is dark matter with R-parity violation, a fraction of gravitino dark matter decays until the present epoch. The decay becomes a source of the high energy cosmic rays. In particular, recently, it has been shown that the anomalous excesses of the γ-ray and positron fluxes observed by EGRET [10] and HEAT [11] experiments, respectively, can be simultaneously explained in the gravitino dark matter scenario with R-parity violation if the lifetime of the gravitino is about 10^{26} s [12,13]. In such a scenario, the MSSM-LSP decays mainly via the R-parity violating interaction with the lifetime of $10^{-(5-6)}$ s. Discovery of the MSSM-LSP with such a lifetime may give us a hint to understand the origin of high energy cosmic rays.

The experimental search for the decay of the MSSM-LSP gives important test of the scenarios with unstable MSSM-LSP. Since the superparticles are expected to be copiously produced at the LHC, we may have a chance to find the signal of the decay of MSSM-LSP. With long-lived unstable MSSM-LSP, we may see the decay at the LHC experiment in the form of a displaced vertex from the interaction point, non-pointing particle, and/or a disappearance of high p_T tracks. Discovery of the MSSM-LSP decay is very important to understand the property of the MSSM-LSP. However, if the decay length of the MSSM-LSP is much longer than the size of the detector, most of the MSSM-LSPs escape from the detector before they decay. In such a case, the typical signal of the SUSY events are the same as the case where the MSSM-LSP is stable, and the discovery of the decay becomes statistically non-trivial.

In this Letter, we discuss the possibility of discovering the decay of the MSSM-LSP at the LHC experiment, paying particular attention to the case where the decay length is much longer than the size of the detector. We will show that the discovery may be possible if the lifetime is shorter than $\tau \lesssim 10^{-(3-5)}$ s. Then, we consider the implication of the result for several types of models with unstable MSSM-LSP. Furthermore, if the decay is observed, the life-

* Corresponding author.
E-mail address: takuito@tuhep.phys.tohoku.ac.jp (T. Ito).

time of the MSSM-LSP can be constrained [14,15]; we also discuss the possibility of determining the lifetime of long-lived MSSM-LSP.

Let us start with discussing the basic formulae. If the MSSM-LSP is unstable, a fraction of the MSSM-LSPs produced at the LHC experiment decay inside the detector. If the MSSM-LSP (with its lifetime τ) has the velocity v, the decay probability before propagating the distance L is given by $P_{\text{dec}}(L) = 1 - e^{-L/v\gamma\tau}$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ (with $c \simeq 3.0 \times 10^8$ m/s being the speed of light). Then, denoting the pseudo-rapidity of the MSSM-LSP as $\eta \equiv -\ln\tan(\theta/2)$ (with θ being the angle from the beam axis), the number of the MSSM-LSPs which decay inside the detector is given by

$$N_{\text{dec}} = N_{\text{tot}} \int d\eta \, dv \, f(\eta, v)\left(1 - e^{-l^{(\max)}(\eta)/v\gamma\tau}\right), \tag{1}$$

where N_{tot} is the total number of MSSM-LSP, $l^{(\max)}(\eta)$ is the distance to the outer boundary of the detector from the interaction point, and $f(\eta, v) \equiv N_{\text{tot}}^{-1} dN/d\eta \, dv$ is the distribution function of the MSSM-LSP; $\int d\eta \, dv \, f(\eta, v) = 1$.[1]

In our following discussion, it is convenient to define

$$L^{(\text{eff})} \equiv \int d\eta \, dv \, f(\eta, v)\frac{cl^{(\max)}(\eta)}{v\gamma}. \tag{2}$$

Then, when the size of the detector is much smaller than the decay length $c\tau$, we obtain

$$N_{\text{dec}} = N_{\text{tot}}\frac{L^{(\text{eff})}}{c\tau}. \tag{3}$$

When $c\tau \lesssim N_{\text{tot}}L^{(\text{eff})}$, we expect several decay events inside the detector. Since, typically, $v \sim c$ and $\gamma \sim O(1-10)$, $L^{(\text{eff})}$ becomes comparable to the size of the detector, as we will see in the following. Thus, roughly speaking, the number of the decay inside the detector is determined by the size of the detector and the total cross section for the SUSY events. In our analysis, for simplicity, we approximate the shape of the detector as a cylinder with the radius $l_T^{(\max)}$ and the half-length (to the z-direction) $l_z^{(\max)} \equiv l_T^{(\max)}/\tan\theta_{\text{edge}}$:

$$l^{(\max)}(\eta) = \begin{cases} l_T^{(\max)}/\sin\theta: & \eta < \eta_{\text{edge}}, \\ l_z^{(\max)}/|\cos\theta|: & \eta > \eta_{\text{edge}}, \end{cases} \tag{4}$$

where $\eta_{\text{edge}} = -\ln\tan(\theta_{\text{edge}}/2)$. From the muon chamber layout of the ATLAS detector, in our Monte Carlo (MC) analysis, we take [1][2]

$$l_T^{(\max)} = 10 \text{ m}, \qquad \eta_{\text{edge}} = 1.0. \tag{5}$$

Now, we calculate how many MSSM-LSPs decay inside the detector. The details depend on the MSSM parameters, and on what the MSSM-LSP is. When the MSSM-LSP is unstable, charged (or even colored) MSSM-LSP is phenomenologically viable. In the following, we discuss two of the important cases; one is the case where the lightest neutralino χ_1^0 is the MSSM-LSP while in the other case, the lighter stau $\tilde{\tau}$ is the MSSM-LSP. For example, in the gauge-mediated model, they are two of the important candidates of the MSSM-LSP.

Fig. 1. Distribution of p_T of the final-state lightest neutralino with 10^4 samples for the χ_1^0-MSSM-LSP case. We take $m_{\tilde{g}} = 1$ TeV (shaded) and 2 TeV (unshaded).

First, we consider the case where the lightest neutralino χ_1^0 is the MSSM-LSP, and is a long-lived unstable particle. Even though χ_1^0 is invisible, spectacular signal may arise if χ_1^0 decays inside the detector. For example, in the models mentioned above (i.e., the gauge-mediated model or the model with R-parity violation), χ_1^0 decays into γ or Z boson and an invisible particle. If we can find a production of high energy γ or the decay products of Z from the point which is displaced from the interaction point, like non-pointing photon [15], it can be identified as the signal of the decay of χ_1^0. (The study of these signals may require that the decay occurs at an inner region of the detector, which reduces the fiducial volume compared to Eqs. (4) and (5). For more details, see later discussion.) Signal of those events should be searched at the offline analysis. In order to record those events, trigger may be an issue. One possibility is to use the missing p_T trigger. Because two χ_1^0s are produced in the SUSY events, even if one of χ_1^0 decays inside the detector to be the signal event, the other χ_1^0 is expected to escape from the detector. (Notice that we consider the case that $c\tau$ is much longer than the size of the detector.) Such a non-decaying χ_1^0 should be a source of large missing p_T. With the MC analysis, we calculate the distribution of the p_T of χ_1^0. The distribution for $m_{\tilde{g}} = 1$ TeV and 2 TeV are shown in Fig. 1. With the present choice of parameters, more than 80–90% of χ_1^0s have p_T larger than 100 GeV for $m_{\tilde{g}} = 1$–2 TeV. Thus, assuming that the escaping χ_1^0 is the dominant source of the missing p_T, most of the signal events have large missing p_T. Thus, if a relevant missing p_T trigger is implemented, the event can be recorded.

In order to estimate how many χ_1^0s decay inside the detector, we perform MC analysis. At the LHC experiment, MSSM-LSP is mostly from the productions of colored superparticles: $pp \to \tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}'$ (with $\tilde{g}$ and $\tilde{q}$ being the gluino and squark, respectively). The cross sections for these processes as well as the decay chains of the superparticles depend on the MSSM parameters. Here, as a well-motivated example, we adopt the gauge-mediated model to calculate these quantities. (Notice that, even though we use the gauge-mediated model to fix the underlying parameters, it is just for simplicity.) In our study, the SUSY events are generated as follows:

1. Mass spectrum of the superparticles and their decay rates are calculated in the framework of the gauge-mediated model. Here, the simplest gauge-mediated model is adopted where the model is parametrized by $\tan\beta$ (i.e., the ratio of the vacuum expectation values (VEVs) of up- and down-type Higgs bosons), number of

---

[1] Here, we neglect the effect of the energy loss of charged MSSM-LSP in matter via ionization, which may stop the charged MSSM-LSP in the detector when the velocity is small (i.e., typically, $\beta \lesssim 0.3$–0.35) [16]. As we will show in Fig. 4, most of the produced MSSM-LSPs have relatively large velocity. Thus, the following results (in particular, the results shown in Fig. 3) are almost unchanged even if we only use the samples with sufficiently large velocity (i.e., typically, $\beta \gtrsim 0.3$–0.35). However, it should be noted that the study of the charged MSSM-LSP stopped in matter via ionization may also provide interesting information about the charged MSSM-LSP [16].

[2] The end-cap of the ATLAS detector covers only up to $|\eta| < 2.7$ [1]. We have checked that most of the MSSM-LSPs are within this region, and hence we do not impose a cut on η for simplicity.
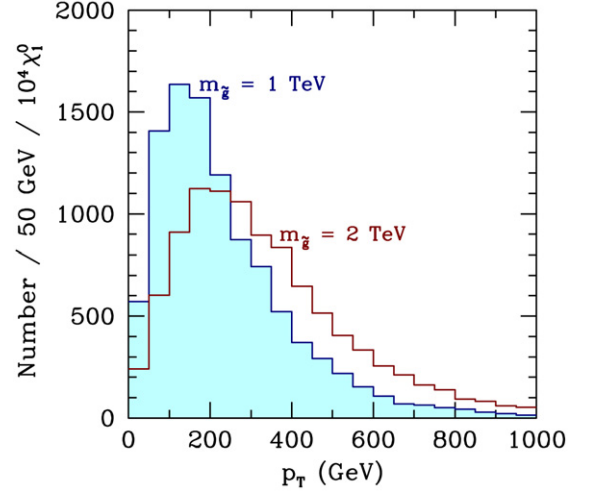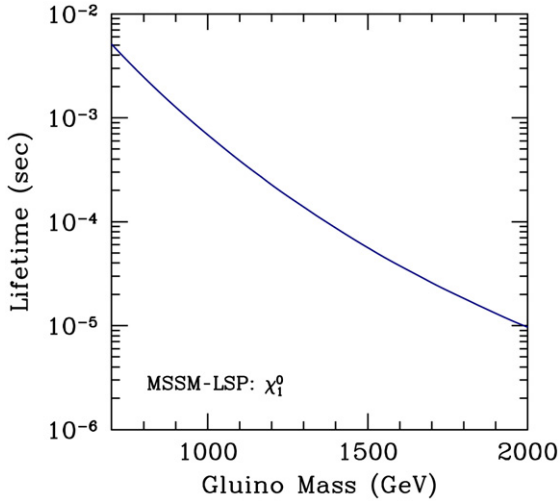
Fig. 2. The lifetime of χ_1^0 which gives $N_{dec} = 10$ (with $\mathcal{L} = 100 \text{ fb}^{-1}$) as a function of the gluino mass.
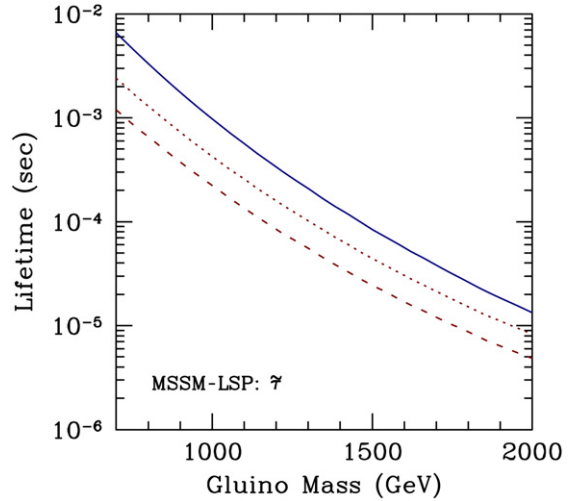

Fig. 3. The lifetime of $\tilde{\tau}$ which gives $N_{dec} = 10$ as a function of the gluino mass (solid), and that which corresponds to $N_{dec}^{(v' < v_{max})} = 10$ with $v_{max} = 0.9$ (dotted) and 0.8 (dashed). The integrated luminosity is taken to be $\mathcal{L} = 100 \text{ fb}^{-1}$.

vector-like messenger multiplets (in $\mathbf{5} + \bar{\mathbf{5}}$ representation of grand-unified $SU(5)$ group) $N_{\mathbf{5}}$, the messenger scale M_{mess}, and Λ which is the ratio of the F-component of the SUSY breaking field to its VEV.

2. SUSY events expected at the LHC experiment are generated with $\sqrt{s} = 14$ TeV.

3. In each event, decay chains of superparticles are followed and the resultant momentum distribution of the MSSM-LSP is obtained. Then, $L^{(eff)}$ is calculated.

4. From the event samples, we calculate the number of the MSSM-LSP decay inside the detector as a function of τ.

In our analysis, we use ISAJET package [17] for the first step while, for second and third steps, HERWIG package [18] is used.

For the study of the χ_1^0-MSSM-LSP case, we take $\tan\beta = 20$, $N_{\mathbf{5}} = 1$, $M_{mess} = 10^7$ GeV, and Λ is fixed to determine the mass scale of MSSM particles (in particular, in the present analysis, the gluino mass). With the above choice of parameters, the MSSM-LSP is Bino-like lightest neutralino, and its mass is given by $m_{\chi_1^0} = 175$ GeV, 360 GeV, and 500 GeV for the gluino mass $m_{\tilde{g}} = 1$ TeV, 1.5 TeV, and 2 TeV, respectively.[3]

With the MC analysis, we found that $L^{(eff)}$ is not sensitive to the mass spectrum of superparticles, and is ~ 10 m; $L^{(eff)} = 8.5$ m, 9.9 m, and 11.4 m for $m_{\tilde{g}} = 1$ TeV, 1.5 TeV, and 2 TeV, respectively. We can see that $L^{(eff)}$ is slightly enhanced as $m_{\tilde{g}}$ increases, which is due to the decrease of the averaged velocity of the MSSM-LSP for larger value of $m_{\tilde{g}}$. On the contrary, the total cross section for the SUSY events strongly depends on the masses of superparticles; the total cross section is given by 1240 fb, 80 fb, and 10 fb, for $m_{\tilde{g}} = 1$ TeV, 1.5 GeV, and 2 TeV, respectively.

In Fig. 2, we plot the value of τ which gives $N_{dec} = 10$ (with $\mathcal{L} = 100 \text{ fb}^{-1}$) as a function of the gluino mass. (Since $N_{dec} \propto \tau^{-1}$, the lifetime which gives a different value of N_{dec} can be calculated from the figure.) For $m_{\tilde{g}} = 1$ TeV, 1.5 TeV, and 2 TeV, $N_{dec} \geqslant 10$ requires τ to be smaller than 7×10^{-4} s, 6×10^{-5} s, and 1×10^{-5} s,

respectively. Thus, when the lifetime is shorter than $10^{-(3-5)}$ s, the number of the decay of the MSSM-LSP inside the detector turns out to be larger than $\sim O(1)$.

Next, we consider the decay of $\tilde{\tau}$-MSSM-LSP. We expect several possibilities to find the signal of the decay of $\tilde{\tau}$. In the models we introduced, $\tilde{\tau}$ decays into tau lepton and an invisible particle. For example, in the gauge-mediated model, the invisible particle is the gravitino while, in the scenario with the R-parity violation, it is a neutrino. In those cases, we may find a displaced decay vertex by observing decay product(s) of the tau lepton.[4] In addition, if $\tilde{\tau}$ propagates $O(10\text{ cm})$ or so, hits in inner trackers should exist. Then, if we do not observe corresponding hits in calorimeters or in muon detector, we may identify such a short track as a signal of the $\tilde{\tau}$ decay inside the detector. Furthermore, using the fact that two staus are produced, we can simply look for events with only one $\tilde{\tau}$ track (which may be useful to count the number of staus which decay very inside the detector for the determination of τ). For the case of $\tilde{\tau}$-MSSM-LSP, the trigger may not be an issue because at least one high p_T charged track (i.e., $\tilde{\tau}$) exists in the SUSY event; then, we expect that we can use the muon trigger.

Here and hereafter, in the study of the case where $\tilde{\tau}$ is the MSSM-LSP, we adopt the underlying parameters of $\tan\beta = 20$, $N_{\mathbf{5}} = 2$, and $M_{mess} = 10^7$ GeV, with which $\tilde{\tau}$ becomes the MSSM-LSP. With such a choice of parameters, the mass of $\tilde{\tau}$ becomes larger than 100 GeV when $m_{\tilde{g}} \gtrsim 650$ GeV, and is 170 GeV, 270 GeV, and 370 GeV, for $m_{\tilde{g}} = 1$ TeV, 1.5 TeV, and 2 TeV, respectively. We follow the same procedure as the case of χ_1^0-MSSM-LSP. For $m_{\tilde{g}} = 1$ TeV, 1.5 TeV, and 2 TeV, $L^{(eff)}$ and the cross section for the SUSY events are given by 7.1 m and 2050 fb, 8.1 m and 150 fb, and 9.4 m and 20 fb, respectively. As in the case of χ_1^0-MSSM-LSP, we can see that $L^{(eff)}$ is insensitive to the mass spectrum of the superparticles. In Fig. 3, we show the lifetime which gives $N_{dec} = 10$. Again, when $\tau \lesssim O(10^{-(3-5)}$ s), we can expect the decay of the MSSM-LSP inside the detector.

Comparing Figs. 2 and 3, it is understood that N_{dec} does not depend much on the mass spectrum of the superparticles as far as the masses of the colored superparticles are fixed. This fact indicates that N_{dec} is mostly determined by the total cross section for

---

[3] With the present choice of parameters, the Higgs mass becomes smaller than the present experimental bound of 114.4 GeV [19] when $m_{\tilde{g}} \lesssim 950$ GeV. Because we choose the gauge-mediated model just as an example of the SUSY model to fix the mass spectrum of MSSM particles, and also because the Higgs mass is sensitive to the masses of stops, we do not take the Higgs-mass constraint so seriously and extend our study to the parameter region of $m_{\tilde{g}} \lesssim 950$ GeV. If one is interested in the case of the gauge-mediated model, only the results for $m_{\tilde{g}} \gtrsim 950$ GeV are relevant.

[4] Otherwise, if selectron (smuon) is the MSSM-LSP, it decays into electron (muon) and an invisible particle. Then, energetic charged tracks from displaced vertices are the target.

the SUSY events (as well as by the lifetime of the MSSM-LSP). (See Eq. (3).)

So far, we have seen that a sizable number of MSSM-LSPs decay inside the detector when $\tau \lesssim 10^{-(3-5)}$ s. However, this does not necessarily mean that the decay of the MSSM-LSP can be easily observed. In particular, in our calculation of $L^{(\mathrm{eff})}$, we have assumed that the typical size of the fiducial region is ~ 10 m. (More accurately, see Eqs. (4) and (5).) This implies that, in the case of the ATLAS detector, the decay of the MSSM-LSP may have to be identified by using only the last layer of the muon chamber. Such an analysis requires very high efficiency of detecting signals of the decay in the muon detector. In some cases, more conservative procedure to confirm the decay may be necessary. For example, for the case of the χ_1^0-MSSM-LSP, some possibilities are (i) to require the decay of χ_1^0 inside the inner tracker region so that we can detect non-pointing photon using the electromagnetic calorimeter [15], or (ii) to look for a decay in the calorimeters to see the decay vertex. For the case of $\tilde{\tau}$-MSSM-LSP, as we have mentioned, we can require (i) no hits in the muon detector for high p_T charged particles observed by the inner detectors, or (ii) the discovery of the decay vertex of $\tilde{\tau}$ in the calorimeters or inner trackers. Then, the size of the fiducial volume to study the decay is reduced. At the ATLAS detector, the inner radius of the muon chamber, the outer radius of the hadron calorimeter, and the outer radius of the inner tracker region are about 5 m, 4.25 m, and 103 cm, respectively [1]. Importantly, $L^{(\mathrm{eff})}$ given in Eq. (2) is proportional to the (typical) length of the fiducial region. Thus, if the MSSM-LSP is required to decay in the calorimeters or in the inner tracker, $L^{(\mathrm{eff})}$ is expected to be reduced by the factor of 2–10, and hence the maximum value of the lifetime with which sizable decay events are expected is. Even with such a smaller value of $L^{(\mathrm{eff})}$, as Figs. 2 and 3 indicate, a significant number of the MSSM-LSP may decay in the fiducial region in the models we are interested in, as we see in the following. The understanding of the efficiency to find the signal of the decay should require extensive studies of the detector effects, which is beyond the scope of this Letter. Here, we simply assume that the signals of the decay can be somehow identified in the following discussion.

Let us now consider implications of the search for the decay of the long-lived MSSM-LSP. First, we consider the gauge-mediated model. When the Bino-like neutralino is the MSSM-LSP, it decays into gravitino and a gauge boson (i.e., photon or Z-boson), and the lifetime of χ_1^0 is estimated as

$$\tau \simeq 2 \times 10^{-5} \text{ s} \times \left(\frac{m_{\chi_1^0}}{200 \text{ GeV}} \right)^{-5} \left(\frac{m_{3/2}}{100 \text{ keV}} \right)^2, \qquad (6)$$

where $m_{3/2}$ is the gravitino mass. In the case where $\tilde{\tau}$ is the MSSM-LSP, it decays into gravitino and the tau–lepton, and the lifetime of $\tilde{\tau}$ is given by

$$\tau \simeq 2 \times 10^{-5} \text{ s} \times \left(\frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-5} \left(\frac{m_{3/2}}{100 \text{ keV}} \right)^2. \qquad (7)$$

Thus, a sizable amount the MSSM-LSP decay is possible in both cases if $m_{3/2} \lesssim O(100 \text{ keV}-1 \text{ MeV})$; in particular, using the fact that too large $m_{\tilde{g}}$ is not preferred from the naturalness point of view, the number of the decay events can be as large as $O(100)$ in such a case.

Another important case is with R-parity violation. In particular, with the introduction of the following bi-linear R-parity breaking interaction into the SUSY breaking terms:

$$\mathcal{L}_{\mathrm{RPV}} = B_{\mathrm{RPV}} \tilde{L} H_u + \mathrm{h.c.}, \qquad (8)$$

with $\tilde{L}$ and H_u being the slepton and the up-type Higgs boson, respectively, it was pointed out that the EGRET and HEAT anomalies can be simultaneously explained if the gravitino is the LSP [12,13].

(Here and hereafter, we neglect the generation index for sleptons for simplicity.) Such a scenario works for any kind of the MSSM-LSP as far as the lifetime of the gravitino is $\sim 10^{26}$ s. With the R-parity violating interaction given in Eq. (8), gravitino ψ_μ dominantly decays as $\psi_\mu \to \nu Z$ or $l^\pm W^\mp$. When the gravitino is heavier than the weak bosons, the lifetime of the gravitino is estimated as [13]

$$\tau_{3/2} \simeq 7 \times 10^{25} \text{ s} \times \left(\frac{\kappa}{10^{-9}} \right)^{-2} \left(\frac{m_{3/2}}{200 \text{ GeV}} \right)^{-3}, \qquad (9)$$

where $\kappa = B_{\mathrm{RPV}}/m_{\tilde{\nu}}^2$ (with $m_{\tilde{\nu}}$ being the sneutrino mass) is the VEV of the sneutrino in units of the VEV of the standard-model like Higgs boson. With the R-parity violation given in Eq. (8), the MSSM-LSP may also decay dominantly via the R-parity violating interaction. Then, when the Bino-like neutralino is the MSSM-LSP, it decays into a neutrino and a standard-model boson with the lifetime

$$\tau \simeq 1 \times 10^{-6} \text{ s} \times \left(\frac{\kappa}{10^{-9}} \right)^{-2} \left(\frac{m_{\chi_1^0}}{200 \text{ GeV}} \right)^{-1}. \qquad (10)$$

When $\tilde{\tau}$ is the MSSM-LSP, it decays into the tau lepton and a neutrino, and the lifetime is given by

$$\tau \simeq 3 \times 10^{-5} \text{ s} \times \left(\frac{\kappa}{10^{-9}} \right)^{-2} \left(\frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-1} \left(\frac{m_{\tilde{B}}}{300 \text{ GeV}} \right)^2, \qquad (11)$$

where $m_{\tilde{B}}$ is the mass of the Bino-like neutralino. Requiring $\tau_{3/2} \sim 10^{26}$ s to simultaneously explain the EGRET and HEAT anomalies, κ is required to be $\sim 10^{-9}$ for $m_{3/2} \sim 200$ GeV, resulting in $\tau \sim O(10^{-6} \text{ s})$ $(O(10^{-5} \text{ s}))$ when the MSSM-LSP is Bino-like neutralino (stau). From the study of N_{dec} given above, we expect sizable amount of the decay of the MSSM-LSP inside the detector with such a lifetime. In particular, when masses of superparticles are at most ~ 1 TeV to solve the naturalness problem, the number of the MSSM-LSP decay inside the detector is expected to be ~ 100–1000. Thus, the search for the decay of the long-lived MSSM-LSP should give an important test of the scenario to explain the origins of anomalous γ-ray and positron fluxes.

So far, we have discussed the discovery of the decay of long-lived MSSM-LSP. Importantly, once the decay is found, we can also constrain the lifetime of the MSSM-LSP. This fact can be easily understood from Eq. (3); once the total number of the produced MSSM-LSP and the number of the decay in the detector are both determined, the lifetime τ is constrained using Eq. (3).

A relatively good determination of the lifetime is expected in particular when the MSSM-LSP is $\tilde{\tau}$ (or other charged superparticles) even if the decay length is much longer than the size of the detector [14].[5] The tracking information about the long-lived charged particle will be available if it travels transverse length longer than $O(10 \text{ cm})$. Thus, once large amounts of $\tilde{\tau}$ samples become available, we expect that the distribution function f can be directly determined from the experimental data. Since we consider the case where $c\tau$ is much longer than the size of the detector, most of the staus do not decay inside the detector, and are observed as energetic charged particles. Then, if enough amounts of $\tilde{\tau}$s are identified with the measurement of their momenta, we can determine $f(\eta, v)$.

In discussing the identification of long-lived $\tilde{\tau}$ tracks, it should be noted that the stau may be confused with the muon in particular when $\tilde{\tau}$ does not decay inside the detector. This fact makes the determination of N_{tot} (or, more accurately, the number of events in

---

[5] If the decay length $c\tau$ of the MSSM-LSP is comparable or smaller than the size of the detector, decrease of the decay point may be experimentally observed. Then, the lifetime is determined by using the distribution of the decay points when $c\tau \gtrsim$ a few cm [20].

which both of $\tilde{\tau}$s do not decay inside the detector) non-trivial. One possibility to distinguish $\tilde{\tau}$ from the muon is to use the time-of-flight information; for this purpose, the transition radiation tracker and the muon system are useful in the ATLAS detector. If the velocity of $\tilde{\tau}$ is small enough, it takes sizable time to reach trackers, calorimeters, and muon chamber after the production. If the velocity information is combined with the momentum information, $\tilde{\tau}$ with small enough velocity can be distinguished from energetic muon. In our study, we require that the velocity of at least one of the two staus should be smaller than v_{max} so that the event can be identified as a SUSY event; we assume that, with the velocity measurement, $\tilde{\tau}$ with $v < v_{max}$ can be distinguished from high p_T muon whose velocity is almost the speed of light. We adopt several values of v_{max} to see how the results depend on v_{max}. On the contrary, if one of the staus decays inside the detector, it provides a striking signal, as we have discussed.

Based on the above argument, we assume that the SUSY events can be identified if there exists at least one $\tilde{\tau}$ which escapes from the detector with $v < v_{max}$, or if one of $\tilde{\tau}$s decays inside the detector. (Since we consider the case $c\tau \gg L^{(eff)}$, we safely neglect the case where both of $\tilde{\tau}$s decay inside the detector.) Then, we expect that we can experimentally count the number of events where one of the $\tilde{\tau}$s decays inside the detector and the other escapes from the detector with its velocity smaller than v_{max}. We denote the number of such events as $N_{dec}^{(v' < v_{max})}$. Importantly, $N_{dec}^{(v' < v_{max})}$ can be calculated as a function of τ after the experimental determination of the velocity distribution of $\tilde{\tau}$ with the above-mentioned type of SUSY events. Thus, with the measurement of $N_{dec}^{(v' < v_{max})}$, a determination of τ is possible. Since we are interested in the case where $N_{dec}^{(v' < v_{max})}$ is much smaller than the total number of $\tilde{\tau}$s observed, the statistical error in the determination of the lifetime is dominantly from $N_{dec}^{(v' < v_{max})}$; $\delta\tau \simeq \tau / \sqrt{N_{dec}^{(v' < v_{max})}}$.

If the correlation of the velocities of two staus is weak, $N_{dec}^{(v' < v_{max})}$ is given by

$$N_{dec}^{(v' < v_{max})} \simeq N_{tot}^{(v < v_{max})} \frac{L^{(eff)}}{c\tau}, \qquad (12)$$

where $N_{tot}^{(v < v_{max})}$ is the number of $\tilde{\tau}$s which satisfy $v < v_{max}$, which is also experimentally measurable. With our MC analysis, we have confirmed that Eq. (12) holds with a good accuracy. Thus, even though more accurate relation between $N_{dec}^{(v' < v_{max})}$ and τ can be obtained once the experimental data become available, we use Eq. (12) to estimate how well the lifetime can be constrained for simplicity.

In order to see the effect of the velocity cut, we show the distribution of $v\gamma$ of $\tilde{\tau}$. The parameter Λ is taken to be 66 TeV and 141 TeV so that the gluino mass is given by $m_{\tilde{g}} = 1$ TeV and 2 TeV, respectively. The result is shown in Fig. 4. From the figure, we can see that $\tilde{\tau}$ acquires large velocity in average. Thus, if one imposes relatively severe cut on the velocity of $\tilde{\tau}$ to reduce the muon background, significant amounts of the stau events will be also discarded. (See the following discussion.)

Next, we calculate $N_{tot}^{(v < v_{max})}$ for $v_{max} = 0.8c$ and $0.9c$; the lifetime which gives $N_{tot}^{(v < v_{max})} = 10$ is also shown in Fig. 3. (Notice that N_{dec} corresponds to $N_{dec}^{(v' < v_{max})}$ with $v_{max} = c$.) Assuming that all the decay events are identified, Fig. 3 shows contours on $m_{\tilde{g}}$ vs. τ plane on which the statistical uncertainty in the determination of τ is about 30% (i.e., $\delta\tau = \tau / \sqrt{10}$). In order to determine τ at this level, the lifetime is required to be, for $v_{max} = c$ and $0.9c$, for example, shorter than 1×10^{-3} and 4×10^{-4} s (8×10^{-5} and 4×10^{-5} s, 1×10^{-5} and 8×10^{-6} s) for $m_{\tilde{g}} = 1$ TeV (1.5 TeV, 2 TeV), respectively. Notice that, with a smaller input value of τ, better determination of the lifetime is expected.
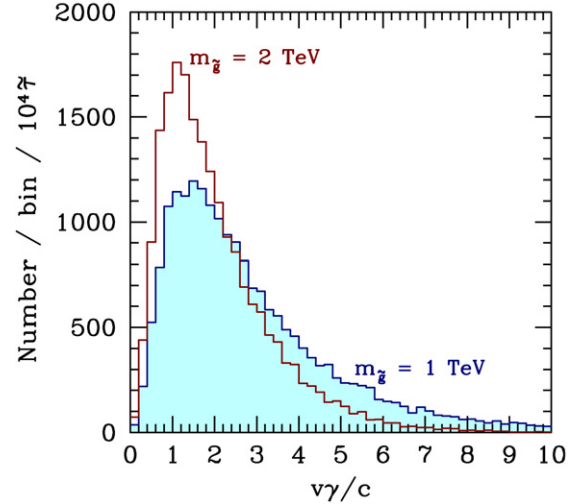

Fig. 4. Distribution of $v\gamma/c$ of the final-state stau with 10^4 samples. We take $m_{\tilde{g}} = 1$ TeV (shaded) and 2 TeV (unshaded).

As one can see, the sensitivity becomes worse as we require smaller value of v_{max}. This is because most of the staus are produced with relatively large velocity. (See Fig. 4.) Importantly, the muon system of the ATLAS detector is expected to have a good time resolution of about 0.7 ns, and the velocity measurement is possible with the accuracy of $\delta v / v^2 \simeq 0.03 c^{-1}$ [1]. Thus, good separation of $\tilde{\tau}$ from μ may be possible even with a relatively large value of v_{max}. In addition, as we have mentioned, the SUSY event may be identified even without imposing the velocity cut if one of the staus decays inside the detector. Thus, if the total number of staus (with any velocity) can be somehow determined, the velocity cut is unnecessary. For example, if the correlation of the velocities of two staus is experimentally checked to be negligible, the total number of stau events can be calculated from the number of events with $v_1 < v_{max} < v_2$ and that of $v_1, v_2 < v_{max}$, where v_1 and v_2 are velocities of two staus (with $v_1 < v_2$). In such a case, we can adopt the result with $v_{max} = c$.

Such a measurement of the lifetime provide a quantitative information about underlying parameters. For example, in the gauge-mediated model, the measurement of the lifetime is possible when the gravitino is lighter than $O(100 \text{ keV–1 MeV})$, and consequently, the gravitino mass can be determined assuming that $\tilde{\tau}$ decays into the gravitino. Then, we can obtain an important information about the SUSY breaking scale.[6] In addition, in the model with R-parity violation, the size of the R-parity violating coupling constant can be determined.

Finally, we comment on the case where the lightest neutralino is the MSSM-LSP. Even though the discovery of the decay of (long-lived) χ_1^0, which is already very spectacular, may be possible, the precise determination of N_{tot}, which is necessary for the determination of the lifetime of χ_1^0, is very non-trivial. This is because χ_1^0 is neutral and we cannot directly count the number of χ_1^0s which do not decay inside the detector. If the total number of SUSY events can be somehow estimated, however, the discovery of the decay of χ_1^0 gives significant information about the property of the MSSM-LSP. Once the SUSY events are found, we expect that the order-of-magnitude estimation of the number of SUSY events can be performed, which gives a bound on N_{tot}. Then, the measurement of N_{dec} gives some information about the lifetime.

---

[6] For other possibilities, see [16,21].

Acknowledgements

References

[1] ATLAS Collaboration, ATLAS Detector and Physics Performance, Technical Design Report, CERN/LHCC 99-14 and CERN/LHCC 99-15 (1999).
[2] CMS Collaboration, CMS Physics, Technical Design Report, CERN/LHCC 2006-001 and CERN/LHCC 2006-002 (2006).
[3] M. Dine, A.E. Nelson, Y. Shirman, Phys. Rev. D 51 (1995) 1362;
    M. Dine, A.E. Nelson, Y. Nir, Y. Shirman, Phys. Rev. D 53 (1996) 2658.
[4] F. Takayama, M. Yamaguchi, Phys. Lett. B 485 (2000) 388.
[5] W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra, T. Yanagida, JHEP 0703 (2007) 037.
[6] M. Fukugita, T. Yanagida, Phys. Lett. B 174 (1986) 45.
[7] W. Buchmuller, P. Di Bari, M. Plumacher, Ann. Phys. 315 (2005) 305;
    G.F. Giudice, A. Notari, M. Raidal, A. Riotto, A. Strumia, Nucl. Phys. B 685 (2004) 89.
[8] For the recent study, see, for example, K. Kohri, T. Moroi, A. Yotsuyanagi, Phys. Rev. D 73 (2006) 123511;
    M. Kawasaki, K. Kohri, T. Moroi, A. Yotsuyanagi, arXiv: 0804.3745 [hep-ph].
[9] T. Moroi, H. Murayama, M. Yamaguchi, Phys. Lett. B 303 (1993) 289.
[10] P. Sreekumar, et al., EGRET Collaboration, Astrophys. J. 494 (1998) 523.
[11] S.W. Barwick, et al., HEAT Collaboration, Astrophys. J. 482 (1997) L191.
[12] A. Ibarra, D. Tran, arXiv: 0804.4596 [astro-ph].
[13] K. Ishiwata, S. Matsumoto, T. Moroi, arXiv: 0805.1133 [hep-ph].
[14] S. Ambrosanio, B. Mele, S. Petrarca, G. Polesello, A. Rimoldi, JHEP 0101 (2001) 014.
[15] K. Kawagoe, T. Kobayashi, M.M. Nojiri, A. Ochi, Phys. Rev. D 69 (2004) 035003.
[16] W. Buchmuller, K. Hamaguchi, M. Ratz, T. Yanagida, Phys. Lett. B 588 (2004) 90;
    K. Hamaguchi, Y. Kuno, T. Nakaya, M.M. Nojiri, Phys. Rev. D 70 (2004) 115007;
    J.L. Feng, B.T. Smith, Phys. Rev. D 71 (2005) 015004;
    J.L. Feng, B.T. Smith, Phys. Rev. D 71 (2005) 019904, Erratum;
    A. Arvanitaki, S. Dimopoulos, A. Pierce, S. Rajendran, J.G. Wacker, Phys. Rev. D 76 (2007) 055007.
[17] F.E. Paige, S.D. Protopopescu, H. Baer, X. Tata, hep-ph/0312045.
[18] G. Corcella, et al., JHEP 0101 (2001) 010, hep-ph/0210213;
    S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour, B.R. Webber, JHEP 0204 (2002) 028.
[19] W.M. Yao, et al., Particle Data Group, J. Phys. G 33 (2006) 1.
[20] S. Asai, T. Moroi, T.T. Yanagida, Phys. Lett. B 664 (2008) 185.
[21] K. Hamaguchi, S. Shirai, T.T. Yanagida, Phys. Lett. B 651 (2007) 44;
    K. Hamaguchi, M.M. Nojiri, A. de Roeck, JHEP 0703 (2007) 046;
    K. Hamaguchi, S. Shirai, T.T. Yanagida, Phys. Lett. B 663 (2008) 86.