

## Test of Anomaly Mediation at the LHC

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### Abstract

In the anomaly-mediated supersymmetry breaking model with the assumption of the generic form of Kähler potential, gauginos are the only kinematically accessible superparticles to the LHC. We consider the LHC phenomenology of such a model assuming that the gluino is lighter than 1 TeV. We show that a significant number of charged Winos, which may travel  $O(10\text{ cm})$  before the decay, are produced from the gluino production processes. Thus, in this class of model, it will be very important to search for short charged tracks using inner detectors. We also show that, if a large number of the charged Wino tracks are identified, the lifetime of the charged Wino can be measured, which provides us a test of anomaly mediation.

# 1 Introduction

Once supersymmetry (SUSY) is broken in a hidden sector, the SUSY-breaking effects are automatically transferred to the SUSY standard model (SSM) sector by the tree-level supergravity (SUGRA) interactions. That is, squarks and sleptons acquire soft SUSY-breaking masses of order of the gravitino masses  $m_{3/2}$ . However, the gauginos are all massless at this level and hence one usually introduces couplings between a hidden field  $Z$  and the gauge-field-strength superfield  $W_\alpha^i$  as  $(Z/M_{\text{PL}})W^{i\alpha}W_\alpha^i$ . Here,  $M_{\text{PL}} \simeq 2.4 \times 10^{18}$  GeV is the reduced Planck mass and the hidden field  $Z$  is supposed to have a SUSY-breaking  $F$  term. Provided that the  $F$  term is the dominant component of the SUSY breaking, one obtains the gaugino masses of order of the gravitino mass  $m_{3/2}$ . In this scenario the hidden field  $Z$  must be completely neutral to have the above coupling to the gauge kinetic functions. However, the neutrality of the hidden field  $Z$  causes serious cosmological problems; the so-called modulus problem [1] and the over-production of the gravitinos in inflaton decays [2].

It was sometimes ago pointed out [3, 4] that the one-loop quantum effects induce the gaugino masses in the SSM without the neutral hidden field. This mechanism is called as "anomaly mediation". Namely, the anomaly mediation always takes place in the quantum SUGRA and the gauginos become massive without any neutral hidden field once the SUSY is broken. Therefore, the model is free from the above cosmological problems since there is no need to introduce a neutral hidden field.

The anomaly mediation predicts so-called split SUSY spectrum where squarks and sleptons may have masses of the order 100 TeV while the masses of gauginos are in the range of 100 GeV – 1 TeV. (The gaugino masses is suppressed, since they are generated at the one-loop level.) Because of the relatively large masses of squarks we need a very precious fine-tuning of parameters to obtain the correct electro-weak symmetry breaking, but on the other hand it solves many serious problems in the SSM. First of all the flavor-changing neutral current and CP-violation problems become very milder due to the large masses of squarks and sleptons. We may naturally explain no discovery of Higgs at LEP and no discovery of proton decays induced by dimension-five operators. Furthermore, the gravitino mass is also predicted at the order of 100 TeV, which makes another cosmological

gravitino problems much less severe [6]. (The gravitinos are also produced by particle scatterings in the thermal bath in early universe. We have upper bounds of the reheating temperature  $T_R$  to avoid over-production of the gravitinos depending on the gravitino mass.) In fact, it has been pointed out [5] that the leptogenesis does work in the anomaly-mediation model, since the reheating temperature  $T_R$  can be as high as  $10^{10}$  GeV without any conflict with cosmology.

Although the squarks and sleptons are so heavy as explained above, the masses of gauginos may be in the accessible range to the LHC experiments. The anomaly mediation predicts a certain relation among the gaugino masses such as  $M_2 < M_1 < M_3$  (where  $M_1$ ,  $M_2$ , and  $M_3$  are gaugino masses for  $U(1)_Y$ ,  $SU(2)_L$ , and  $SU(3)_C$  gauge groups, respectively) in a large region of the parameter space [7]. And the charged wino has a considerably long lifetime as  $c\tau_{\tilde{W}^\pm} \sim 5$  cm (with  $c$  being the speed of light). Interesting enough is that the lifetime is almost independent of the parameters in the anomaly-mediation model. Thus, we consider that not only the observation of such a long-lived charged particle but also the measurement of its lifetime at the LHC provide a serious test of the anomaly-mediation model.

In the previous work [7] we consider a very pessimistic situation where the gluino  $\tilde{g}$  is too heavy to be produced at the LHC and hence the number of produced winos  $\tilde{W}$  is limited. In this letter we assume that the gluino is lighter than 1 TeV and they are efficiently produced at the LHC. And we show that the large number of winos are produced through the gluino production and the lifetime of the charged wino may be measured at the LHC to test the anomaly mediation.

We also note that it will be difficult to confirm supersymmetry even at the LHC experiment, if the present anomaly-mediation model is realized. Thus, it is important to see if the properties of the unstable charged particle, observed as short charged tracks, are consistent with the prediction of the anomaly-mediation model.

## 2 Properties of Gauginos

First, we summarize the mass spectrum of superparticles in our analysis. In the anomaly-mediation model where the Higgsinos (as well as sfermions) acquire masses of  $O(10 \text{ TeV})$ ,

radiative correction due to the Higgs-Higgsino loop diagram significantly changes the gaugino-mass relation predicted in the pure anomaly-mediation model [8]. In our study, we consider the case  $M_2 < M_1 < M_3$ , but the ratio  $M_3/M_2$  is assumed to be much smaller than the predicted value from the pure anomaly-mediation model. In our following numerical study, we use the gaugino mass parameters

$$M_2 = 200 \text{ GeV}, \quad M_3 = 1 \text{ TeV}, \quad (1)$$

and consider the case where gluino dominantly decays as  $\tilde{g} \rightarrow \tilde{W}q\bar{q}$  (and hence the bino is irrelevant in our study). In this case, a large number of winos are produced from the gluino production processes at the LHC, contrary to the assumption used in [7]. Then, detailed studies of the properties of wino may be possible. For example, with the gluino mass of 1 TeV, the gluino production cross section at the LHC is  $\sigma_{pp \rightarrow \tilde{g}\tilde{g}} \simeq 220 \text{ fb}$ . (Here, we have taken the renormalization scale to be the gluino mass.) Since the gluino decays into the charged wino with the branching ratio of 2/3, charged winos of  $O(10^5)$  is produced with the Luminosity of  $100 \text{ fb}^{-1}$  (although many of them decay without being detected).

Next, let us discuss the properties of winos in the anomaly-mediation model. The mass difference between charged and neutral winos originates dominantly from 1-loop Feynmann diagrams with electro-weak bosons in the loop. Then, charged wino becomes heavier than neutral one, and the mass difference is given by [9]

$$\delta m_{\tilde{W}} = m_{\tilde{W}^\pm} - m_{\tilde{W}^0} = \frac{g_2^2}{16\pi^2} M_2 \left[ f(r_W) - \cos^2 \theta_W f(r_Z) - \sin^2 \theta_W f(0) \right], \quad (2)$$

where  $f(r) = \int_0^1 dx (2 + 2x^2) \ln[x^2 + (1-x)r^2]$  and  $r_i = m_i/M_2$ . The mass difference is in the range  $155 \text{ MeV} \lesssim \delta m_{\tilde{W}} \lesssim 170 \text{ MeV}$ , which is much smaller than the (expected) wino mass parameter  $M_2$ . If  $\tilde{W}^0$  is the LSP,  $\tilde{W}^\pm$  dominantly decays as  $\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm$  and its lifetime becomes very long; in such a case, the lifetime of  $\tilde{W}^\pm$  is given by

$$\tau_{\tilde{W}^\pm}^{-1} = \frac{2G_F^2}{\pi} \cos^2 \theta_c f_\pi^2 \delta m_{\tilde{W}}^3 \left( 1 - \frac{m_\pi^2}{\delta m_{\tilde{W}}^2} \right)^{1/2}, \quad (3)$$

where  $f_\pi \simeq 130 \text{ MeV}$ , and  $\theta_c$  is the Cabbibo angle. Numerically, the lifetime is of  $\mathcal{O}(10^{-10} \text{ sec})$ . Importantly, the mass difference  $\delta m_{\tilde{W}}$ , and hence the lifetime  $\tau_{\tilde{W}^\pm}$ , are insensitive to the wino mass parameter  $M_2$ . Thus, if the lifetime of charged wino is experimentally determined, it provides an important test of the anomaly-mediation model.

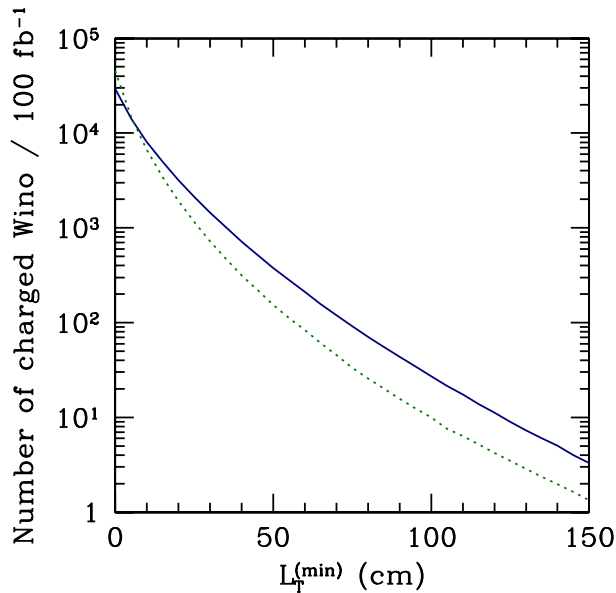


Figure 1: Number of charged winos produced at the LHC, which travel transverse distance longer than  $L_T^{(\min)}$ . The solid line is for the process  $pp \rightarrow \tilde{g}\tilde{g}$ , while the dotted line is for  $pp \rightarrow \tilde{W}\tilde{W}_{j_{pT} > 100 \text{ GeV}}$ . Here, we use the luminosity of  $100 \text{ fb}^{-1}$ .

The smallness of the mass difference has a significant implication for collider experiments when the neutral wino  $\tilde{W}^0$  is the LSP. In this case, the NLSP, charged wino  $\tilde{W}^\pm$ , decays into the neutral one  $\tilde{W}^0$  by emitting very soft  $\pi^\pm$  which easily escape the detection. This fact makes the discovery of  $\tilde{W}^\pm$  at the LHC very challenging. However, with the lifetime estimated above, the charged winos produced in the LHC experiment are expected to travel  $\sim \mathcal{O}(1 - 10 \text{ cm})$  before they decay. Thus, they travel for macroscopic distances and some of them may decay after traveling through some of the detectors. In such a case, charged winos may be observed as energetic short charged tracks.

In Fig. 1, we plot the number of  $\tilde{W}^\pm$  from the gluino production process  $pp \rightarrow \tilde{g}\tilde{g}$ , requiring that the transverse travel length of  $\tilde{W}^\pm$  be longer than  $L_T^{(\min)}$  (with the luminosity of  $100 \text{ fb}^{-1}$ ). There are still a few hundred of the non-decay winos at even  $L_T^{(\min)} = 54 \text{ cm}$ , at which the transition radiation tracker (TRT) is set in the ATLAS detector. By using these samples, we may be able to extract information on the winos as we will discuss in the following section. This may provide quantitative tests of the anomaly-mediation model. For comparison, we also plot the number of  $\tilde{W}^\pm$  from the Drell-Yan induced process  $pp \rightarrow \tilde{W}^\pm\tilde{W}^\mp_{j_{pT} > 100 \text{ GeV}}$  and  $pp \rightarrow \tilde{W}^0\tilde{W}^\mp_{j_{pT} > 100 \text{ GeV}}$ , where

$j_{p_T > 100 \text{ GeV}}$  denotes the energetic jet with the transverse momentum larger than 100 GeV. (The jet is a necessary trigger for the event [10].) With the mass spectrum we have adopted, the gluino production process produces a larger amount of charged winos than the wino + jet production process if  $L_T^{(\text{min})} \gtrsim 10 \text{ cm}$ . In the following numerical analysis, for simplicity, we only consider the winos produced by the process  $pp \rightarrow \tilde{g}\tilde{g}$ .

### 3 Measurement of the Lifetime

Now, we are at the position to discuss LHC phenomenology with the wino LSP. Since we are interested in the charged wino whose lifetime is  $O(10^{-10} \text{ sec})$ , most of the charged winos produced at the LHC experiment will decay inside the detectors. Thus, we should look for short charged tracks with high momentum which disappear inside the detector. If we can obtain a large number of samples of short charged tracks, we may check if the properties of the observed short-lived charged particle are consistent with the prediction of anomaly-mediation model.

However, in the actual situation, such a study will be non-trivial. This is because, first of all, it will be challenging to find such short charged tracks and, second, accurate measurements of the travel length should be also non-trivial.

Importantly, the ATLAS detector has the TRT which may be useful for the detailed study of the properties of charged wino. The TRT is located at 54 – 107 cm from the beam axis [11] and continuously follows charged tracks. The TRT may be used to find charged-wino tracks. In the following, we show how well we can study properties of charged wino, assuming that the charged-wino tracks can be found with high efficiency with the TRT. We have checked the tracking efficiencies and precision of the track resolution for the various decay position in TRT, and they are found to be stable. So this assumption is reasonable.

First, as discussed in [12], once the wino tracks are found, wino mass can be determined by combining the time-of-flight information with the momentum information. The resolution of the velocity  $\beta$  is about 0.1 if  $\beta < 0.85$ . Then, the mass can be determined with the accuracy of 10% if enough samples of the exotic tracks are available.

If a large number of samples of the charged wino are obtained in the form of short

charged tracks, distribution of the length of those tracks  $L$  can be derived. From the distribution of  $L$ , the lifetime of charged wino may be also determined. As we have mentioned, the lifetime of charged wino in the anomaly-mediated model is accurately calculated, an interesting test of the anomaly-mediation model is possible by comparing the experimentally determined lifetime with the theoretical prediction.

If a large number of charged winos *at rest* are available, the number of  $\tilde{W}^\pm$  decreases with time as  $N_{\tilde{W}^\pm} \propto e^{-t/\tau_{\tilde{W}^\pm}}$ . Thus, by fitting the survival probability with the exponential function, one may be able to determine the lifetime. However, in the LHC experiment, charged winos are produced with various velocities, and hence we have to take into account the effect of  $\gamma$ -factor. In addition, probably the precise determination of the travel length is possible only if (i) charged wino travels some amount of length in the TRT, and (ii) charged wino decays inside the TRT.

In the following discussion, let us consider how we can determine the lifetime by using only such limited samples. For this purpose, we assume that the charged winos satisfying (i) and (ii) can be identified by the off-line analysis and that their travel length can be determined.

In order to quantize the conditions (i) and (ii), we define the transverse travel length  $L_T$  as

$$L_T = L \sin \theta, \quad (4)$$

where  $\theta$  is the direction of the charged wino with respect to the beam axis. Then, the conditions (i) and (ii) becomes that the  $L_T$  is in the “fiducial” volume of the TRT;  $L_T^{(\min)} < L_T < L_T^{(\max)}$  (with some relevant constraint on  $\theta$ ). In our numerical study, we take  $L_T^{(\min)} = 60$  cm and  $L_T^{(\max)} = 100$  cm.

Using the fact that the momentum of individual charged track is measurable, we parametrize the observable constructed from  $L_T$  and the momentum as

$$\frac{L_T - L_T^{(\min)}}{|\mathbf{p}_T|} \equiv t_D m_{\tilde{W}^\pm}^{-1}, \quad (5)$$

where  $\mathbf{p}_T$  is the transverse momentum, i.e.,  $|\mathbf{p}_T| = |\mathbf{p}| \sin \theta$ . The physical meaning of  $t_D$  is the time interval in the rest frame of  $\tilde{W}^\pm$  between the moment corresponding to  $L_T = L_T^{(\min)}$  and that of the decay. Importantly, when  $L_T^{(\max)} \rightarrow \infty$ , the distribution of

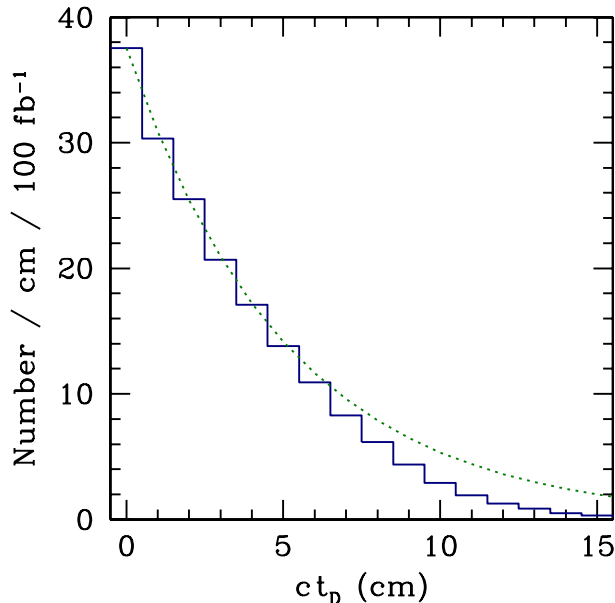


Figure 2: The histogram is the distribution of the variable  $t_D$  multiplied by the speed of light. The dotted line is the number of events expected from the exponential distribution (i.e., in the case of  $L_T^{(\max)} \rightarrow \infty$ ).

the variable  $t_D$  obeys  $P(t_D) = P_0 e^{-t_D/\tau_{\tilde{W}^\pm}}$ , where  $P_0$  is the normalization constant. Thus, from the distribution of the variable  $t_D m_{\tilde{W}^\pm}^{-1}$ , we obtain information about the combination  $\tau_{\tilde{W}^\pm} m_{\tilde{W}^\pm}^{-1}$ .

In the actual situation,  $L_T^{(\max)}$  is finite, and hence the distribution  $P(t_D)$  does not exactly follow the exponential behavior. However, even in that case, we may be able to constrain  $\tau_{\tilde{W}^\pm} m_{\tilde{W}^\pm}^{-1}$ . In Fig. 2, we plot the distribution of  $t_D$  for  $L_T^{(\max)} = 100$  cm. Here, using MadGraph/MadEvent package [13], we have generated  $10^7$  signal events and calculated the distribution with Monte Carlo analysis. In addition, in the same figure, we show the distribution for the case  $L_T^{(\max)} \rightarrow \infty$ . As one can see, for  $ct_D \lesssim 10$  cm,  $P(t_D)$  is well approximated by the exponential function. Thus, if the distribution of  $t_D$  is obtained, we may be able to extract the information about the lifetime of the charged wino.

In order to see how well the lifetime (more accurately, the combination  $\tau_{\tilde{W}^\pm} m_{\tilde{W}^\pm}^{-1}$ ) can be constrained, we first generate event samples using the underlying parameters given in (1) for the luminosity of  $100 \text{ fb}^{-1}$  and calculate the distribution  $t_D$ ,  $P(t_D)$ . For the statistical analysis, we classify the events into four bins, which are



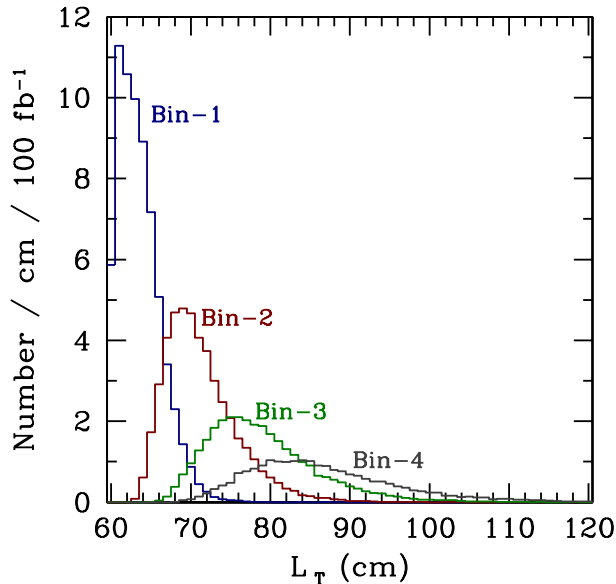


Figure 3: Distributions of the variable  $L_T$  for samples in bins 1 – 4. Here, the luminosity of  $100 \text{ fb}^{-1}$  is used.

1.  $0 \text{ cm} < ct_D \leq 2 \text{ cm}$  ( $0 \text{ cm/GeV} < ct_D m_{\tilde{W}^\pm}^{-1} \leq 0.01 \text{ cm/GeV}$ ),
2.  $2 \text{ cm} < ct_D \leq 4 \text{ cm}$  ( $0.01 \text{ cm/GeV} < ct_D m_{\tilde{W}^\pm}^{-1} \leq 0.02 \text{ cm/GeV}$ ),
3.  $4 \text{ cm} < ct_D \leq 6 \text{ cm}$  ( $0.02 \text{ cm/GeV} < ct_D m_{\tilde{W}^\pm}^{-1} \leq 0.03 \text{ cm/GeV}$ ),
4.  $6 \text{ cm} < ct_D \leq 8 \text{ cm}$  ( $0.03 \text{ cm/GeV} < ct_D m_{\tilde{W}^\pm}^{-1} \leq 0.04 \text{ cm/GeV}$ ).

We denote the number of events in each bin as  $n_k$  ( $k = 1 - 4$ ). Distributions of the variable  $L_T$  for samples in bins 1 – 4 are shown in Fig. 3. We can see that most of the charged winos in the sample events decay within the TRT. Then, we compare  $n_k$  ( $k = 1 - 4$ ) with the expected number of events estimated with the postulated lifetime  $\tau$ . Expected number of events in four bins are denoted as  $\bar{n}_k(\tau) \propto e^{-kd_{\text{bin}}/c\tau} - e^{-(k+1)d_{\text{bin}}/c\tau}$ , where  $d_{\text{bin}}$  is the width of the bins and is  $d_{\text{bin}} = 2 \text{ cm}$ . With  $n_k$  and  $\bar{n}_k$ , we calculate the  $\chi^2$  variable. In order to use only the shape information of the distribution, we treat the normalization as a free parameter, and the  $\chi^2$  variable is defined as

$$\chi^2(\tau) = \sum_k \frac{[n_k - N_0 \bar{n}_k(\tau)]^2}{n_k} = \sum_k n_k - \frac{[\sum_k \bar{n}_k(\tau)]^2}{\sum_k [\bar{n}_k^2(\tau)/n_k]}, \quad (6)$$

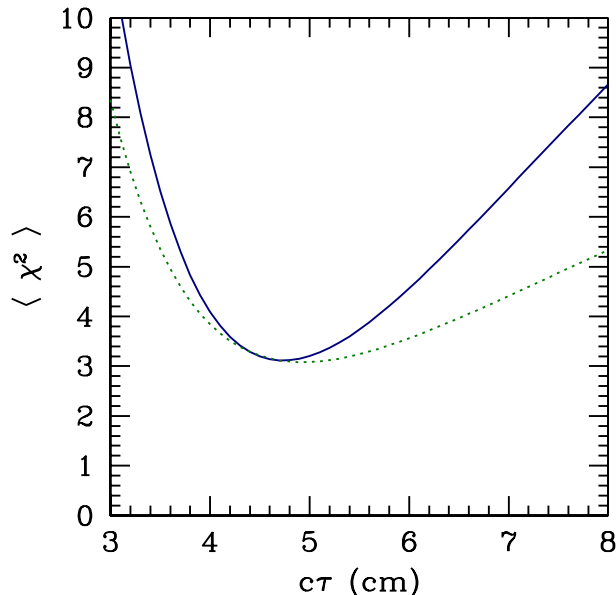


Figure 4: The averaged value of the  $\chi^2$  variable as a function of the postulated value of the lifetime  $\tau$ . Here, the  $\chi^2$  variable is calculated with four bins with  $d_{\text{bin}} = 2$  cm (solid) and 1.5 cm (dotted) with the luminosity of  $100 \text{ fb}^{-1}$ . The input value of the lifetime of the charged wino is  $c\tau_{\tilde{W}^\pm} = 5.1$  cm.

where  $N_0$  is the normalization constant which minimizes  $\chi^2$ . The  $\chi^2$  variable obtained above fluctuates, depending on the set of event samples  $\{n_k\}$ . In order to estimate the typical uncertainty in the determination of the lifetime, we repeat the above process to obtain the averaged value of  $\chi^2(\tau)$  for each postulated value of  $\tau$ .

The averaged value of  $\chi^2(\tau)$  is shown in Fig. 4. The typical constraint on the lifetime is estimated from  $\delta\langle\chi^2(\tau)\rangle \equiv \langle\chi^2(\tau)\rangle - \langle\chi^2\rangle_{\text{min}} < 1$  where  $\langle\chi^2\rangle_{\text{min}}$  is the minimum value of  $\langle\chi^2(\tau)\rangle$ . (Notice that  $\langle\chi^2\rangle_{\text{min}} \simeq 3$ , which is consistent with the expected value of the  $\chi^2$  variable with three degrees of freedom.) Then, we obtain the constraint  $4.0 \text{ cm} < c\tau < 5.7 \text{ cm}$  (or  $0.020 \text{ cm/GeV} < c\tau m_{\tilde{W}^\pm}^{-1} < 0.029 \text{ cm/GeV}$ , if no information about the wino mass is available). Thus, the lifetime is constrained with the uncertainty of about 10 – 20 %.

The best-fit value of the lifetime, which is  $c\tau_{\text{best}} \simeq 4.8 \text{ cm}$ , is smaller than the input value of the lifetime. This is probably due to the fact that the number of events in higher bins (in particular, that of 4th bin) are smaller than the expectation values from the exponential distribution because only the events with  $L_T < 100$  cm are adopted (see Fig.

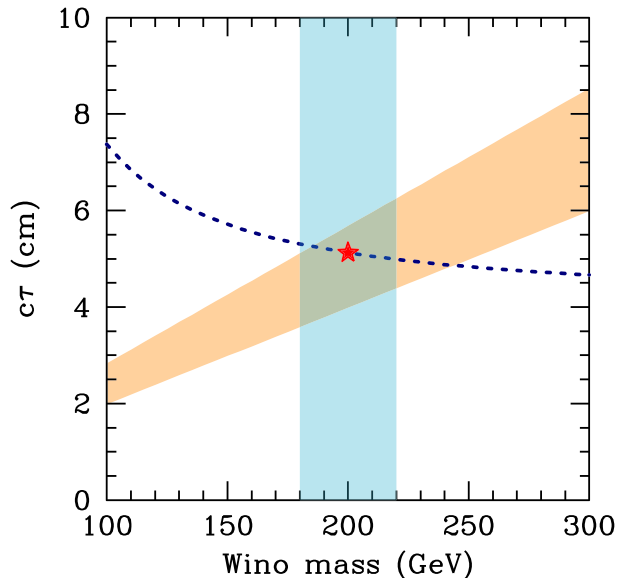


Figure 5: Expected experimental and theoretical constraints on the wino mass vs.  $c\tau$  plane. The vertical band is the constraint on the wino mass using the velocity and momentum information, while another band is from the bound on the wino lifetime as a function of the wino mass. The dotted line is the theoretical prediction of the lifetime of the wino (multiplied by the speed of light). The star at the center is the input point.

2). If we limit ourselves to the samples with smaller value of  $t_D$ , the best-fit value of the lifetime becomes closer to the input value. To see this, we also calculate the averaged value of the  $\chi^2$  variable with the four bins with the interval of 1.5 cm, instead of 2 cm, and the result is also shown in Fig. 4. In this case, the best-fit value becomes 5.0 cm and is closer to the input value. However, since the number of events decreases in this case, the uncertainty becomes larger.

Finally, in Fig. 5, we summarize expected experimental constraints on the wino mass vs.  $c\tau$  plane. In the same figure, we also plot the theoretical prediction on the lifetime of the wino as a function of the wino mass. We can see that, if the (short) charged wino tracks can be identified with a sizable efficiency, we can provide an interesting test of the anomaly-mediation model.

## 4 Conclusions

In this letter, we have proposed a new procedure to test the anomaly-mediation model in which only gauginos are kinematically accessible to the LHC. We have paid particular attention to the study of the charged Wino, which is expected to behave as a short charged track in the detectors. As we have discussed, the mass of the charged wino may be determined from the velocity and momentum information while the information about the lifetime of the charged wino may be obtained from the distribution of the travel length. Combining these two, non-trivial test of the anomaly-mediation model may be possible. Thus, we emphasize the importance of the search and the study of short charged tracks using the TRT (and other detector components).

Here, we have concentrated on informations available from the charged Wino tracks observed by the TRT. However, constraints on the gaugino masses (in particular, those on the wino mass) is also obtained from the invariant-mass distribution of the jets produced by the decay process of the gluino:  $\tilde{g} \rightarrow \tilde{W}q\bar{q}$  [12]. Such informations also provide important and independent test of the anomaly-mediation model.

In this letter, possibility of determining the lifetime of the charged wino has been discussed. However, we have not included any detailed detector effects in the present analysis. In addition, we have assumed that the short charged track can be easily identified irrespective of  $L_T$ . In the realistic situation, however, more detailed understanding of the efficiency to discover the short charged tracks is necessary. Such a study will be performed elsewhere [14].

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