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Detector and trigger challenge for supersymmetrical dark matter scenarios at the international linear collider

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Abstract. Two supersymmetrical (SUSY) dark matter scenarios are discussed to illustrate how challenging it is to detect and trigger these events out of standard model background events at a future international linear collider (ILC).

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1. Introduction

The existence of non-baryonic, non-relativistic (cold) and non-luminous (dark) matter appears now to be firmly established from the observations of the Wilkinson microwave anisotropy probe (WMAP) [1] together with data on the Hubble expansion and the density fluctuations in the Universe. The amount of such dark matter (DM) has been measured at the 10% level: $\Omega_{\rm DM}h^2 = 0.1126^{+0.0161}_{-0.0181}$ with h being the Hubble constant. The precision is expected to reduce down to 2% in the coming years by the Planck mission.

The nature of DM is one of the greatest unsolved mysteries of science. Since the standard model (SM) of particle physics cannot account for this, new physics has to be invoked to explain DM. Low energy SUSY provides an excellent solution to the origin of DM. Two scenarios are discussed here to show both the potential and the challenge at the ILC.

2. Neutralino dark matter

In the SUSY scenarios with R-parity conservation, the lightest SUSY particle (LSP) is stable and thus an ideal DM candidate. The lightest neutralino χ is considered as the most natural candidate to satisfy the cosmological constraints on DM in the

Universe. Within the minimal supergravity (mSUGRA) model, the precise data from WMAP have considerably reduced the corresponding SUSY phase space with a compatible SUSY DM contribution. In the mSUGRA model, one of the retained regions is 'co-annihilation' region, in which the amount of DM is dominantly regulated by the annihilation of χ with the scalar tau $\tilde{\tau}$ in particular when their mass difference is small.

Therefore, it is important to measure precisely the masses of χ and $\tilde{\tau}$. Previous studies have shown that the mass of χ as well as the mass of scalar muon $\tilde{\mu}$ can be precisely measured using the so-called end-point method [2]. The detection of $\tilde{\tau}$ is however more challenging and the mass measurement is more involved [3]. For example, the scenario D studied in [3] has $m_{\tilde{\tau}} = 217\,\mathrm{GeV}$ and $m_\chi = 212\,\mathrm{GeV}$ leading to a mass difference of 5 GeV. What is challenging is the small production cross-section $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ of about 10 fb at $\sqrt{s} = 500\,\mathrm{GeV}$ of the center-of-mass energy (0.46 fb at an optimum energy of $\sqrt{s} = 442\,\mathrm{GeV}$, see below). This cross-section is many orders of magnitude smaller than that of the SM processes (10^5–10^6 fb for the dominant SM processes $e^+e^- \to e^+e^-\tau^+\tau^-, e^+e^-\mu^+\mu^-$ and $e^+e^-q\overline{q}$). To efficiently suppress the SM background events, it is essential to be able to identify the energetic and forward going spectator electron and positron in the forward detectors down to a smallest possible angle (5 mrad). The background rejection is therefore very challenging in particular in the crossing angle collision mode. The other challenge is related to the fact that the resulting τ from $\tilde{\tau} \to \tau\chi$ and its visible final states in the subsequent τ decay are very soft.

To extract the $\tilde{\tau}$ mass with minimum luminosity, the method used in [3] consists of measuring the cross-section at one energy and deduce the mass from the value of β since, at the Born level, this cross-section depends on $\beta^3 = (1-4m^2/s)^{3/2}$, where m stands for the stau mass. Assuming the SM background to be negligible which could indeed be the case provided the efficient veto mentioned above [3] and for a given integrated luminosity, the best accuracy on the stau mass measurement using this method is achieved when the beam energy is just above the stau mass threshold (see [2] for a discussion of the other method). For scenario D with $m_{\tilde{\tau}} = 217\,\mathrm{GeV}$, the optimum $\sqrt{s}$ is at $\sim$442 GeV and the resulting error on the stau mass is $\sim$0.5 GeV for an integrated luminosity of 500 fb^{-1}. The gain in the precision with this choice of optimum beam energy is appreciable. At $\sqrt{s} = 500$ GeV the error would have been 1.2 GeV. For scenario D the resulting precision on the DM density of 6.9% is obtained [3] and the precision improves down to 1.6% for scenario G with larger mass difference at 9 GeV thus matching well the future precision expected from the Planck data.

3. Gravitino dark matter

However, the neutralino χ may not be the only possible DM candidate. Another candidate in SUSY models is the spin 3/2 gravitino $\tilde{G}$. The mass of $\tilde{G}$ is only described by the SUSY breaking scale F and the Planck scale M_P: $m_{\tilde{G}} = m_{3/2} = F/(\sqrt{3}M_\mathrm{P})$. Discovery of the gravitino would be therefore one of the most direct ways to prove the nature of the hidden sector of the SUSY models.

The phenomenology of the gravitino dark matter (GDM) models depends on the nature of the next-to-lightest SUSY particle (NLSP). Cosmological constraints favor charged sleptons as NLSP. Assuming $\tilde{\tau}$ to be NLSP, every SUSY cascade would end in a $\tilde{\tau}$ and the dominant decay in which $\tilde{G}$ is produced is $\tilde{\tau} \to \tau\tilde{G}$. The decay width depends only on the stau mass $m_{\tilde{\tau}}$, the gravitino mass $m_{\tilde{G}}$, and the Planck scale M_{P} and is given by

$$\Gamma_{\tilde{\tau}\to\tau\tilde{G}} = \frac{1}{48\pi M_{\mathrm{P}}^2} \frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2} \left[1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right]^4 . \tag{1}$$

Since the decay width is suppressed by M_{P}^{-2}, the lifetime of $\tilde{\tau}$ ($\tau_{\tilde{\tau}} = 1/\Gamma_{\tilde{\tau}}$) could be long, ranging from seconds to years. The charged stau with low velocity lose their kinetic energy by ionization loss and could be stopped in detectors depending on its lifetime. The ILC has the advantage that the beam energy can be tuned to produce low momentum staus.

The analysis strategy [4] is described briefly here. The numbers quoted below are the analysis results of [4] based on the LDC (large detector concept) and are for scenario GDM ϵ which has the following parameters: the common scalar mass m_0 has the same mass of gravitino $m_0 = m_{3/2} = 20\,\mathrm{GeV}$, the common gaugino mass $M_{1/2} = 440\,\mathrm{GeV}$, the common trilinear coupling $A_0 = 25\,\mathrm{GeV}$, the ratio of the vacuum expectation values of the two Higgs fields $\tan\beta = 15$ and the sign of the Higgsino mass parameter μ is positive. The experimental conditions are an integrated luminosity of $100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$. The corresponding inclusive $\tilde{\tau}$ production cross-section is 300 fb.

The stau is identified by the characteristic heavy ionization $-\mathrm{d}E/\mathrm{d}x \propto 1/\beta^2$ in the time projection chamber. The stau mass is determined from two-body kinematics of $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ production, i.e. those staus produced directly with relatively large velocity leaving the detector before decaying. The resulting mass value $m_{\tilde{\tau}} = 157.6 \pm 0.2\,\mathrm{GeV}$.

On the other hand, the stau lifetime measurement has to be based on a different sample of staus which have small velocity and are stopped in the detector. More specifically, one has to follow low momentum stau candidate until it stops inside the detector and record its location and the time stamp t_0. In the next step, one has to trigger decay $\tilde{\tau} \to \tau\tilde{G}$ at t_{trig} which is uncorrelated to beam collision time and associate the stopping point in space with the decay point to get the time difference $t_{\mathrm{trig}} - t_0$. A fit to the time difference distribution gives a lifetime result of $\tau_{\tilde{\tau}} = (2.60 \pm 0.05) \times 10^6\,\mathrm{s}$ assuming that both the calorimeters and the iron return yoke can be used in the analysis.

In practice, the measurement may be less precise since it may only be feasible using the instrumented iron return yoke if the corresponding readout can be switched on all the time. The triggering of the stau decay in the calorimeters which are operated in a pulsed mode may not be possible. Indeed, to cope with the heat production of the electronics, it is foreseen that the amplifiers and readout channels of the calorimeter detector parts are switched on and read out only during one bunch train for 2 ms while remaining off for the rest of 198 ms before the next bunch train.

A direct gravitino mass measurement can be performed by exploiting the tau recoil of the decay $\tilde{\tau} \to \tau\tilde{G}$. The upper endpoints of the energy spectra which coincide with the primary tau are directly related to the masses involved. For this measurement, the tau hadronic decay modes to heavy final states $\tau \to \rho\nu_\tau$ and $\tau \to 3\pi\nu_\tau$ are better than those decay modes $\tau \to e\nu_e\nu_\tau$ and $\tau \to \pi\nu_\tau$. A fit to the energy spectra using either an analytical formula for the endpoint or a complete simulation yields a gravitino mass of $m_{\tilde{G}} = 20 \pm 4\,\text{GeV}$.

These measured $m_{\tilde{\tau}}$, $\tau_{\tilde{\tau}}$ and $m_{\tilde{G}}$ can be used in eq. (1) to determine supergravity Planck scale with the value of $(2.4{\pm}0.5){\times}10^{18}$ GeV for the considered scenario where the error being dominated by the precision on the gravitino mass measurement. This determination can be compared with the macroscopically determined Planck scale of Einstein gravity, $M_{\text{P}} = (8\pi G_{\text{N}})^{-1/2} = 2.43534(18) \times 10^{18}\,\text{GeV}$ [5] with G_{N} being Newton's constant. The comparison constitutes a crucial test of supergravity.

In the case that the gravitino mass cannot be directly measured, an indirect but more precise determination of $m_{\tilde{G}}$ can be obtained from the stau mass and lifetime measurements assuming the gravitational coupling and the macroscopic value of M_{P}. The resulting gravitino mass $m_{\tilde{G}} = 20 \pm 0.2\,\text{GeV}$, where the error is dominated by the lifetime measurement.

The challenge lies here on the triggering of late and beam-collision-time uncorrelated $\tilde{\tau}$ decays. This would need a major change of the data acquisition strategy resulting in a considerable increase in the data volume to collect as all beam uncorrelated backgrounds (e.g. the cosmic ray events) will enter. However, given the importance of such a measurement, a possible solution should be found.

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