Search for GMSB NLSPs at LHC

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Abstract. NLSP – LSP decays could have dramatic influence on SUSY phenomenology at LHC. NLSP could have significant lifetime and could be charged. In at least two scenarios detectors must be used in a special way. They were not optimized for detection of heavy (semi)stable charged particles and decaying in flight (neutral or charged) NLSPs. During the last decade both ATLAS and CMS collaboration have developed strategies which allow for effective search within such scenarios.

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1 Introduction

Within Gauge-Mediated Supersymmetry Breaking models gravitino is the Lightest Supersymmetry Partner (LSP) whereas neutralino or stau plays the role of the Next to Lightest Supersymmetry Partner (NLSP). NLSP decays to its Standard Model partner and gravitino with a lifetime depending on the scale of the SUSY breaking. Detection of the NLSP and determination of its properties, in particular lifetime, can be of crucial importance for the physics program at LHC.

Minimal GMSB model is defined by six parameters: Λ – effective SUSY mass scale, N – number of messenger generations, M – messenger mass scale, tan β, sgn μ and Cg – ratio of the intrinsic SUSY breaking scale to messenger SB scale, governing goldstino coupling and hence – NLSP lifetime.

2 Long-lived charged NLSP at CMS

For large N, typically right sleptons are the lightest supersymmetric partners of SM particles. If, in addition, tan β has not too low value, ˜τ₁ is the NLSP which could have arbitrary long lifetime. In this way one obtains benchmark scenario in which every supersymmetric event cascade decays ends on pair of stable massive charged and not strongly interacting particles. These particles propagate through the detector like muons but with velocity β smaller than 1. Because of that their specific ionization is greater than for MIP and they arrive at given detector layer with a time delay. Both facts could be used to distinguish them from muons.

There are other theoretical scenarios with heavy stable charged particles. ATLAS and CMS searches for them were reported by Shikma Bressler in the same session [1]. I will cover only some details concerning search for staus using TOF method in the CMS detector. The first full detector simulation (based on GEANT3) analysis were performed already a decade ago [2, 3]. However specific ionization were not correctly simulated then. Because of that the analysis was based on originally developed method of TOF measurement by drift tubes of the barrel muon system of the CMS.

Here we present an update [4] of that analysis performed using OSCAR-ORCA version of CMS detector simulation (based on GEANT4), the same as used for CMS Physics TDR [5].

2.1 The TOF method

The barrel muon system of the CMS detector consist of four concentric muon stations inserted in the return yoke of the CMS solenoid. In each station there are three super-layers (SL) of four layers of drift tubes (DT) each. Two of SL measure $R_{\phi}$ coordinate and one z coordinate (there is no z SL in the outermost station). The tubes in each SL are staggered by half a tube. An average track pass alternatively on left and right side of the sensitive wire.

In a given SL hits due to muon should align if timing is correct whereas hits due to delayed particle do not align, they are shifted backward from the wire by $\delta x$ and form a zig-zag pattern. For each hit

$$\frac{\delta x}{v_{\text{drift}}} = \delta t = t_{\beta<1} - t_{c} = \frac{L}{c} \left( \frac{1}{\beta} - 1 \right)$$

and hence measuring $\delta x$ allows to estimate $\beta^{-1}$

$$\frac{1}{\beta} = 1 + \frac{\delta x}{L v_{\text{drift}}}.$$
It should be stressed, however, that real performance of the analysis could not be evaluated without checking the method against muons from real data. Another question is how well the $\tilde{\tau}_1$ mass could be determined. To test this 1000 pseudo-experiments corresponding to integrated luminosity $L = 0.5/fb$ for the lower mass point ($L = 4/fb$ for the higher mass point) were performed. The result are the following $M_{\tilde{\tau}_1} = \{153.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst})\}$ GeV for generated mass $M_{\tilde{\tau}_1} = 152.31$ GeV and $M_{\tilde{\tau}_1} = \{243.2 \pm 3.2(\text{stat}) \pm 1.4(\text{syst})\}$ GeV for generated mass $M_{\tilde{\tau}_1} = 242.93$ GeV. The test confirms that the method is well suited for the search for stable staus.

### 3 Non-pointing photons in ATLAS

Within GMSB if $N$ is small typically $\chi_1^0$ is the NLSP. Its lifetime is free parameter. By measuring lifetime it is possible to estimate the scale of supersymmetry breaking which is otherwise not accessible experimentally.

In the ATLAS analysis [2] very interesting technique was developed which allows to determine the masses of the slepton and neutralino from events with a lepton and converted photon arising from the cascade decay $\tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0 \rightarrow \ell \gamma G$.

The topology of $\chi_1^0$ decay inside ATLAS detector if the decay length is of the order of 1 m is shown in the Figure[2]. In the case of photon conversion the angle $\alpha$ could be precisely measured. ATLAS EMCAL allows also for precise determination of photon arrival time $\tau_\gamma$. Since the distance $L = |OA|$ is also known the angle $\psi$ could be determined [2].

$$
\cos \psi = \frac{1 - \xi^2}{1 + \xi^2} \quad \text{where} \quad \xi = \frac{c \tau_\gamma - L \cos \alpha}{L \sin \alpha}.
$$

If both angles $\alpha$ and $\psi$ are known for at least two reconstructed $\tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0 \rightarrow \ell \gamma G$ cascade decays it is possible to determine both $\tilde{\ell}$ and $\tilde{\chi}_1^0$ masses.

### 2.2 Results

Two points from the SPS7 line [3]: $\Lambda = 50$ TeV and $\Lambda = 80$ TeV were chosen for the full detector simulation. The mass of $\tilde{\tau}_1$ particle is equal to 152.31 GeV and 242.93 GeV respectively and the cross section is 1 pb and 0.1 pb. In the analysis a high mass ($M_{\mu\mu} > 110$ GeV) pair of energetic muons ($p_T^\mu > 60$ GeV) were searched for. Since most of the signal events contains products of a cascade decays of squarks or gluinos a high effective mass of the event were required ($M_{\text{eff}} > 360$ GeV) as well. Taking this into account the following background sources of muon pairs were considered: Drell-Yan above $Z^0$ resonance, $t\bar{t}$ and double vector boson production. Events were triggered on single muons with a default threshold of ($p_T^\mu > 80$ GeV).

Breakdown of number of events at different stages of the selection is given in the Table[1] A scatter plot $\beta^{-1}$ versus momentum for heavier mass point and $L = 4/fb$ is shown in the Figure[1] where clear separation of signal — staus and background — muons could be seen. The last column in the Table[1] correspond to highlighted area in that Figure.

The upper limit for number of expected background events in the region above the highest horizontal line in the figure ($\beta^{-1} > 1 + 3\sigma_{\beta^{-1}} = 1.132$) was evaluated to be 0.05 events for 1/fb which means that the 5$\sigma$ discovery could be claimed with 8 signal events. This correspond to integrated luminosity needed for a discovery $L = 52/fb$ for $\Lambda = 50 TeV$ and $L = 667/fb$ for $\Lambda = 80 TeV$.

### Table 1. Number of events at different stages of the selection for 1/fb. Columns correspond to: presel. — trigger and $p_T > 80$ GeV; quality — additional requirements at the pattern recognition stage that significantly reduce tails of $\beta^{-1}$ estimate (see ref. [4] for details); select. — requirements described in the text; $\beta^{-1}$ — highlighted area in the Figure[1]

| dataset     | presel. | quality | select. | $\beta^{-1}$ |
|-------------|---------|---------|---------|--------------|
| $\Lambda = 50$ TeV | 1714.1  | 956.4   | 666.4   | 155.054      |
| $\Lambda = 80$ TeV | 1088.1  | 59.8    | 45.0    | 12.019       |
| DY 2$\mu$   | 8105.6  | 4422.6  | 13.6    | 0.012        |
| $t\bar{t}$ 2$\mu$ | 2686.1  | 1624.4  | 33.7    | 0.029        |
| WW 2$\mu$   | 573.7   | 322.6   | 6.0     | 0.005        |
| ZZ 2$\mu$   | 202.0   | 110.1   | 0.1     | 0.000        |
| ZW 2$\mu$   | 231.6   | 121.3   | 0.0     | 0.000        |
| $\Sigma$    | 11798.9 | 6600.1  | 53.4    | 0.046        |
Knowing these masses it is possible to analytically calculate decay time and momentum of neutralino using the ECAL data and lepton momentum only, for each lepton non-pointing (converted or not) photon pair from slepton decay.

This idea was tested with fast simulation of ATLAS detector for GMSB point: $A = 90 \text{ TeV}$, $M = 500 \text{ TeV}$, $N = 1$, $\tan \beta = 5$, $\mu > 0$. Neutralino and slepton masses for this point are $M(\tilde{\chi}_{1}^{0}) = 117 \text{ GeV}$, $M(\tilde{\ell}_{R}) = 162 \text{ GeV}$.

Longitudinal segmentation of the EMCAL of ATLAS allows for precise determination of the polar angle of a non-pointing photon with very good resolution of 0.06/√Eγ/GeV. More over, the arrival time could be measured with 100 ps resolution. This in turn allows for determination of $\tilde{\chi}_{1}^{0}$ decay time $t_D$. In the Figure 3 a correlation between reconstructed and generated $t_D$ is shown as well as distributions of $t_D/\gamma_{\chi}$ for three values of $c\tau$. In the Figure 4 the average $\langle t_D/\gamma_{\chi} \rangle$ and number of lepton non-pointing photon pairs in function of generated $\tilde{\chi}_{1}^{0}$ $c\tau$ is shown after the following selection: $E_{\gamma} > 30 \text{ GeV}$, $\Delta \theta > 0.2$, $\Delta t_{\gamma} > 1 \text{ ns}$ $M_{\text{eff}} > 400 \text{ GeV}$, $E_{T}^{\text{miss}} > 0.1M_{\text{eff}}$ for integrated luminosity $L = 13.9 \text{ fb}^{-1}$.

Both values shown in the Figure 4 could be parameterized and used for $\tilde{\chi}_{1}^{0}$ $c\tau$ determination. The reliability of both methods and absolute resolution (error bars) in function of generated $c\tau$ is shown in the Figure 5.

The relative resolution of $c\tau$ ranges from 3% to 17% for average proper time method $(t_D/\gamma_{\chi})$, and form 3% to 6% for lepton non-pointing $\gamma$ pair counting method.

![Fig. 2. The topology of $\tilde{\chi}_{1}^{0}$ decay inside ATLAS detector.](image)

![Fig. 3. Reliability of $t_D$ determination (a) and $t_D/\gamma_{\chi}$ distributions (b).](image)

![Fig. 4. Average $\langle t_D/\gamma_{\chi} \rangle$ (a) and number of lepton non-pointing photon pairs (b).](image)

![Fig. 5. Reliability of $c\tau$ determination methods.](image)

## 4 Non-pointing photons in CMS

A feasibility study of $\tilde{\chi}_{1}^{0}$ lifetime determination using CMS detector was done long ago [3]. However, only recently and only part of the original proposal was transformed into full detector simulation analysis [4]. The method is based on a difference between shapes of energy distributions among CMS ECAL crystals for pointing and non-pointing photons (see Fig. 6).

These energy distributions could be characterized by the covariance matrix. Variances along major and minor axes are given by

$$S_{\text{major}} = \frac{S_{\phi\phi} + S_{\eta\eta} \pm \sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\phi\eta}^2}}{2}$$

A measure of the elongation of the deposit is an asymmetry

$$\Delta = \frac{S_{\text{major}} - S_{\text{minor}}}{S_{\text{major}} + S_{\text{minor}}} = \frac{\sqrt{(S_{\phi\phi} - S_{\eta\eta})^2 + 4S_{\phi\eta}^2}}{S_{\phi\phi} + S_{\eta\eta}}$$

Another useful variable is the angle $\alpha$ (see Fig. 6) between the major axis and the $\phi$ axis which could be used to eliminate background due to converted photons for which $\alpha \approx 0$ and geometrical bias which gives an excess of deposits with large $\Delta$ for pointing photons for $\alpha \approx 0, \pm \pi$.

For the full simulation a point from SPS8 line [6] with $A = 140 \text{ TeV}$ was chosen and 6 different $\tilde{\chi}_{1}^{0}$ values of $c\tau$ were generated. The $\tilde{\chi}_{1}^{0}$ mass is 192.69 GeV and the cross section is 0.5 pb for this point.

The analysis is based on a search for energetic photons which are accompanied by at least four hard jets.
and missing energy, a consequence of cascade decays of squarks and gluinos. A breakdown of the number of events at different stages of the selection for signal and background samples is given in the Table 2.

The fraction of selected photons classified as non-pointing improves with growing \( c_T \) and background samples is given in the Table 2.

| dataset          | presel. | select. | non-p. | point. |
|------------------|---------|---------|--------|--------|
| \( c_T = 0 \)    | 2104.28 | 402.98  | 2.96   | 289.39 |
| \( c_T = 25 \text{ cm} \) | 2061.69 | 379.71  | 29.10  | 243.76 |
| \( c_T = 50 \text{ cm} \) | 1948.33 | 361.60  | 45.87  | 215.88 |
| \( c_T = 100 \text{ cm} \) | 1564.12 | 298.12  | 56.03  | 103.76 |
| \( c_T = 200 \text{ cm} \) | 1037.60 | 166.66  | 34.64  | 49.39  |
| \( c_T = 400 \text{ cm} \) | 645.77  | 114.89  | 26.16  | 67.19  |
| \( \Sigma Z_{jets} \) | 6137.93 | 0.65    | 0.00   | 0.37   |
| \( \Sigma W_{jets} \) | 8301.93 | 2.76    | 0.00   | 1.46   |
| \( \Sigma QCD \) | 787797.19 | 54.90 | 0.00 | 2.32 |
| \( VV_{jets, incl.} \) | 836.35  | 0.00    | 0.00   | 0.00   |
| \( t \bar{t} b, incl. \) | 4662.89 | 16.34   | 0.00   | 6.13   |
| \( \Sigma \text{total} \) | 807736.31 | 74.65 | 0.27 | 10.27 |

and missing energy, a consequence of cascade decays of squarks and gluinos. A breakdown of the number of events at different stages of the selection for signal and background samples is given in the Table 2.

The fraction of selected photons classified as non-pointing improves with growing \( c_T \) but at the same time more and more neutralinos decays outside ECAL. Non-pointing selection is almost background free.

An estimate of the minimal amount of integrated luminosity needed for \( 5 \sigma \) discovery versus simulated \( c_T \) is plotted in the Figure 7.

An integrated luminosity \( \mathcal{L} = 2 \text{ fb} \) is sufficient to claim discovery for \( c_T \leq 100 \text{ cm} \) and \( \mathcal{L} = 3.5 \text{ fb} \) for \( c_T = 400 \text{ cm} \).

To test CMS ECAL capability to estimate \( \chi_0^1 \) lifetime 100 likelihood fits of neighborhood \( c_T \) and background to the given \( c_T \) + background was done. The results are shown in the Figure 8. The precision of such procedure range from 15% to 40%. It will improve if more \( c_T \) points will be used, but one should remember that it depends on the knowledge of the shapes of distributions of variables used in the fit. These shapes depend (weakly) on other than \( c_T \) parameters of the model.

5 Conclusions

Gauge-Mediated Supersymmetry Breaking model is a generic framework for long-lived, heavy, charged, not strongly interacting particles and decaying in flight heavy (charged or neutral) particles.

During last decade both ATLAS and CMS have invented methods to tackle with such signatures, despite the fact that detectors had not been designed for them.

For long lived charged particles both detectors use synergy of specific ionization measurement and TOF method (for the full picture see also Ref. [1]). The ultimate goal before LHC startup should be development of model independent methods which could be tested on cosmics, \( Z \to \mu^+ \mu^- \) candle and other sources of energetic muons.

For non-pointing photons signature ATLAS and CMS successfully use their electromagnetic calorimeters. However, the ultimate resolution for lifetime determination of decaying in flight particles could be obtained only with tracking systems. Performance of such methods require full detector simulation with full background turned on.

There is just enough time to do that before LHC startup.

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