Search for long-lived particles using HCAL timing information

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Many new physics models give rise to the possibility of long-lived particles. If these particles are massive and weakly interacting, they can travel a considerable distance before decaying into visible particles and leave a signal of displaced non-prompt jets. A signal of this nature can be detected with the timing information and missing transverse momentum measurements. Recently, there was an attempt at ECAL to search for long-lived gluinos with such measurements. In this paper, we demonstrate that by also incorporating the HCAL data, we can significantly improve their exclusion limits.

I. INTRODUCTION

Supersymmetry(SUSY) is one of the most well-motivated possibilities for new physics beyond the Standard Model. However, no promising signatures of SUSY were found at 1 TeV scale, which brings us to consider less typical decay scenarios. Models such as gauge-mediated SUSY breaking(GMSB)[1], split and stealth SUSY[2], and hidden valley models[3] give rise to long-lived particles(LLP). LLPs from SUSY models have two distinctive decay signatures: non-prompt jets and missing transverse momentum p_T^{miss}[4]. Large p_T^{miss} occur when a stable weakly-interacting particle carries out the energy and decays outside the detector.

The efficiency of detecting such a particle depends exclusively on its mass m and decay length $c\tau$. An interesting thing to note is that both m and $c\tau$ should be in the 'Goldilocks zone' in order to have high efficiency. m must be comparable in scale to $\sqrt{s}$ in order to have β smaller than 1, but small enough so it can be produced with a reasonable cross section. $c\tau$ has to be large enough to cause a significant delay in jet production while still decaying inside the detector volume. When these conditions are satisfied, signals of this type benefit from very small number of background signals, since the chance of an energetic particle originating within the detector is extremely rare[4]. With adequate trigger selections, we can maintain high efficiency while reducing backgrounds to under a few events.

Recently, there was an attempt to detect these decay patterns using the timing capabilities of the CMS electromagnetic calorimeter(ECAL)[5]. We seek to verify whether we can further extend the sensitivity limit by incorporating the data from CMS hadronic calorimeter(HCAL). In this paper, we present a quantitative estimation result for detecting LLP with HCAL timing information through simplified generator-level simulation.

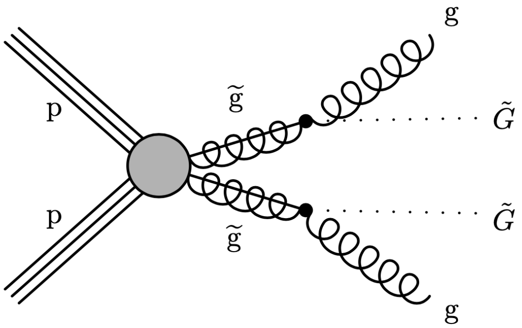

FIG. 1. Gluino production and decays from the GMSB signal model.

II. SIGNAL MODEL

To quantify our simulation, we will only consider the gluino production($pp \to \tilde{g}\tilde{g}$) and its decay to a gluon and gravitino pair($\tilde{g} \to g\tilde{G}$) within the GMSB model(Fig. 1). The long-lived $\tilde{g}$ will not be detected before it decays into a gluon jet. If the gluino is massive enough, it will produce displaced non-prompt jets with large p_T^{miss}.

From the schematics drawn in Fig. 2, we can calculate the timing difference of the LLP X and corresponding SM trajectories as follows[6]:

$$\Delta t = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}. \quad (1)$$

Typically, for light particles, $\beta_a \simeq \beta_{SM} \simeq 1$. Therefore, the timing delay is caused by two factors: a longer travel distance($l_a + l_X > l_{SM}$) and the slower speed of X($\beta_X < 1$). When there are multiple timing layers close to the decay vertex of X, l_a would be small and the latter will be dominant. For a gluino with a mass of 2300 TeV, the delay will be about 2 ns when it travels 1000 mm.

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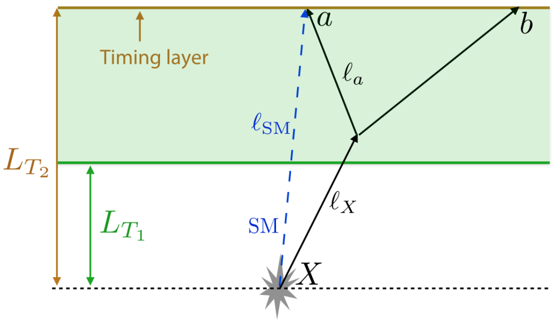

FIG. 2. An event with an LLP X decaying into two particles a and b. Two horizontal lines indicate the avalible timing layers. The blue dotted trajectory is a reference path for an SM particle and is used to calculate the prompt jet timing[6].

A. CMS Hadronic Calorimeter

Our detector of interest is located inside the Compact Muon Solenoid(CMS), one of the two general-purpose detectors at the LHC. CMS contains several concentric layers of detectors which operate independently. The innermost layer is the tracker, which measures the position of charged particles inside a magnetic field in order to identify their momentum and the position of primary vertices. Next is the electromagnetic calorimeter(ECAL), which stops the electrons and photons to identify them and measure the energies they carry.

Now we have the hadronic calorimeter(HCAL) composed of a Barrel region(HB) and endcap regions(HE)[7]. Its purpose is to measure the energy of hadronic jets, catching the majority of SM particles except muons and neutrinos. By acting as a 'catch all' detector, HCAL can provide missing energy measurements crucial for new physics searches. Since hadronic showers involve much more complex interactions, the energy and timing resolution is much worse that that of ECAL. This requires us to raise our Δt limit for our signal accordingly.

HB consists 16 alternating layers of brass absorber and scintillator tiles, covering the region between the outer extent of the ECAL(R = 1.77 m) and the inner extent of the magnetic coil(R = 2.95 m). There are four timing layers located at each R = 1.95 m, 2.25 m, 2.55 m, and 2.85 m. Due to its positional restrictions, the pseudorapidity coverage of HB is rather small($|\eta| < 1.3$). In our simulation, we will only consider HB since the majority of our signal is in the range $|\eta| < 1$.

B. Simulation Methods

We used `PYTHIA8`[8] for SUSY event generations. With all SM interactions turned off, only the production and decays mentioned above were allowed along with R-hadron formations. The properties of $\tilde{g}$ and other particles were manually allocated with a custom SLHA file.

Our goal is to calculate the percentage of events which satisfy the signal criterion; a jet delay time of over 3 ns/7 ns for detector radius 1200 mm/ 2850 mm and the decay vertex of $\tilde{g}$ inside the outermost HCAL timing layer(R = 2.85 m).

The main steps of our simulation are as follows.

- Generate 1000 events for $m_{\tilde{g}} = 1000$ GeV to 3000 GeV and $\log(c\tau) = 2.5$ to 6.0. Save all hard-scattered gluino particle informations.
- For every gluinos decaying inside the HCAL barrel raduis, calculate its delay time as
$$\Delta t = l_{\tilde{g}} \left(\frac{1}{\beta_{\tilde{g}}} - 1 \right). \tag{2}$$
- If at least one of the two gluinos produced from the events satisfy the signal criterion, mark the event as detected.
- Calculate the efficiency(ϵ) as (number of events detected/number of events generated).

The cls exclusion limit for the gluino cross section(σ) can then be calculated given the number of required signals(n_{cls}) and luminosity(L). Because the number of signals are

$$s = \epsilon \sigma L, \tag{3}$$

if we impose $s \geq n_{cls}$ we get

$$\sigma \leq \frac{n_{cls}}{\epsilon L}. \tag{4}$$

III. RESULTS

The simulated efficiency in the $c\tau - m$ plane is drawn in Fig. 3. We see that as the radius of the detector increases, the high efficiency domain shifts to longer decay lengths. For our CLs sensitivity limit, we refer to the studies of the background done in [5]. The reference also provides trigger sensitivity studies at detector levels, so we used it to calibrate our efficiency simulation results accordingly. Triggers such as cosmic ray veto and noise filter tend to be less sensitive at longer $c\tau$.

We drew sensitivity limits calculated at $m_{\tilde{g}} = 2400$ GeV along those from other experiments. After calibrating the trigger efficiencies, the simulation for R = 1200 mm agrees relatively well with observed ECAL results.

IV. CONCLUSION

Although it is difficult to directly compare our results with other experiments, we see that by increasing the detector radius, the sensitivity is significantly improved towards higher decay length regions.

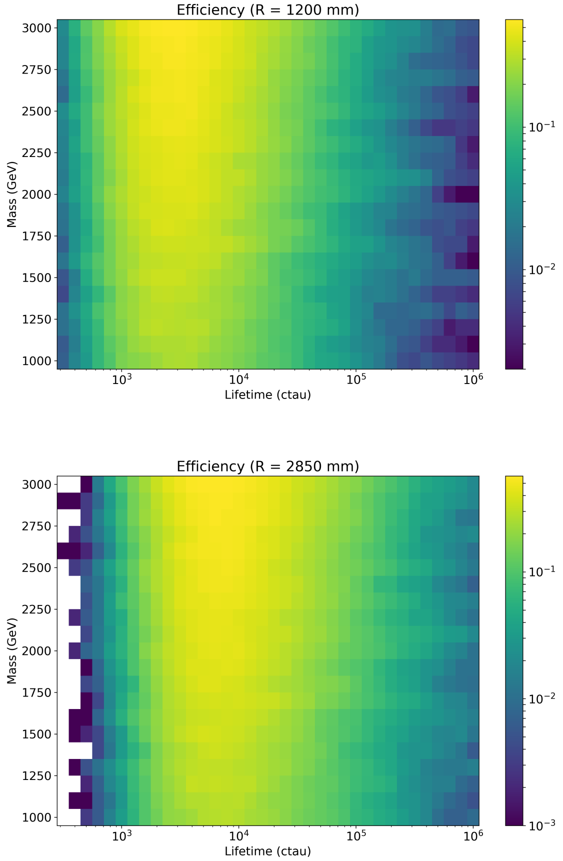

FIG. 3. Simulated efficiency in the mass and $c\tau$ plane for ECAL (R = 1200 mm) and HCAL (R = 2850 mm) radius. Empty region indicates $\epsilon = 0$.

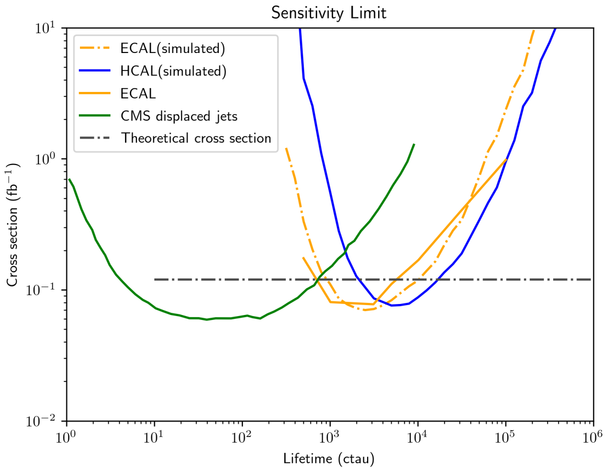

FIG. 4. The sensitivity limits for $m_{\tilde{g}} = 2400$ GeV from the two simulations along with previous experiment results.

A. Research limitations

Due to the lack of detector simulations of this study, there are some shortcomings.

- The simulation results for R=1200 mm was fitted to the results of [5] to calibrate the trigger sensitivity. Because there were only three data points available, we were restricted to first-order corrections which can negatively bias the results at high-R.
- We assumed that the majority of the gluinos decayed in the HCAL boundary will be rapidly detected by the closest timing layer. But a gluon traveling parallel to a layer can significantly effect jet timings.

ACKNOWLEDGMENTS

This paper was written as part of the Advanced Physics experiment class in Korea University. I thank Prof. Jaehyeok Yoo for providing an opportunity to work in a very interesting particle search.

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