Search for new physics with delayed jets in CMS Experiment with proton-proton collisions at $\sqrt{s} = 13$ TeV

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Introduction

- Many beyond the standard model (e.g. GMSB) predict long-lived particles that may decay into final states containing jets with missing transverse momentum, \( p_T^{\text{miss}} \).

- In this search a representative GMSB model is used, where pair-produced long-lived gluinos each decay into a gluon, which forms a jet, and a gravitino, which escapes the detector causing significant \( p_T^{\text{miss}} \) in the event.

- The delay in the appearance of the jet is expected to be a few ns for a TeV scale particle that travels \( \sim 1 \text{ m} \) before decaying.

- This location is within the CMS electromagnetic calorimeter (ECAL) volume or within the tracking volume bounded by the ECAL.

- The timing capabilities of the ECAL can be used to identify such nonprompt or “delayed” jets.

The analysis is performed with 137 fb\(^{-1}\) of data collected by the CMS experiment at a center-of-mass energy of 13 TeV.
Object and event reconstruction

- **Jets:**
  - The primary physics objects used in this analysis are jets reconstructed from the energy deposits in the calorimeter towers (ECAL+HCAL), clustered using the anti-\(k_T\) algorithm with a distance parameter of 0.4.
  - Jets are selected with \(p_T>30\) GeV and \(|\eta|<1.48\).

- **Jet timing \(t_{\text{jet}}\):**
  - For each cell within the ECAL detector, the timing offset is defined such that a particle traveling at the speed of light from the center of the collision region to the cell position arrives at time zero.
  - The jet timing is determined using all ECAL cells that satisfy \(\Delta R<0.4\) between the jet axis and cell position, that exceed an energy threshold of 0.5 GeV.
  - Energy deposits with a recorded time that is either less than \(-20\) ns or greater than 20 ns are rejected, to remove events originating from preceding or following bunch collisions, respectively.
  - The time of the jet, \(t_{\text{jet}}\), is defined by the median cell time.

- **\(p_T^{\text{miss}}\):**
  - Defined as the negative vector sum of calorimeter momenta deposits on the plane perpendicular to the beams.
Main Backgrounds and Cleaning Selection:

The main background contributions come from the following sources:

- ECAL time resolution tails,
- Electronic noise
- Direct APD hits
- In-time pileup
- Out-of-time pileup
- Satellite bunches
- Beam halo
- Cosmic muon hits

The cleaning selection criteria are optimized to reduce the background as much as possible without affecting the signal much. Following are the cleaning selection criteria:

- Number of ECAL cell hits \( N_{\text{cell}}^{\text{ECAL}} \) > 25, total EM energy > 20 GeV:
  - Improve jet time resolution, reject noise and direct APD hits
- PV\_Track\_Fraction < 1/12:
  - Rejection of prompt jets in timing tail, APD hits (from charged hadrons)
- RMS jet time/median jet time < 0.4\*, RMS jet time < 2.5 ns:
  - Reject widely spread jets due to e.g. prompt deposits overlapping with out of time cells
- Hadronic energy fraction > 0.2, Had energy > 50 GeV:
  - Reject APD hits, noise, beam halo, cosmics
- Jet EM energy fraction associated with CSC hits < 0.8:
  - Reject deposits from beam halo

- The final event selection contains:
  - At least one signal jet
  - \( p_T^{\text{miss}} > 300 \text{ GeV} \)
  - \( \text{max} \ (\Delta\phi_{\text{DT}}) < \pi/2 \) and \( \text{max} \ (\Delta\phi_{\text{RPC}}) < \pi/2 \) to reduce cosmic events
Background Estimation

- Three dominant backgrounds are estimated independently:
  - Beam halo
  - Satellite bunches
  - Cosmic muons

- ABCD method is used to predict the background contributions in the signal region by inverting the cleaning variables targeted for each background

Beam halo bkg estimation:

- Three independent regions B, C and D are selected by inverting one of the two cleaning selections: HEF and CSC EF but applying all other selections same as SR
- The bkg contribution in SR (A) is obtained using the following relation:
  \[ A = C \times \frac{B}{D} \]
- The overall beam halo prediction using this method in SR comes out to be
  \[ 0.02^{+0.04}_{-0.02} (stat)^{+0.05}_{-0.01} (syst) \]
Core and satellite background estimation

- Same method as the previous one but using the variables $t_{\text{jet}}$ and $\text{PV}_{\text{Track}}^\text{Fraction}$

### Validation

- The first validation region is defined with $t_{\text{jet}} < -3$ ns
- The number of predicted events in this VR comes out to be $0.09^{+0.2}_{-0.06}$
- But the observed event is 1,
- The event passing selection has no paired RPC or DT hits and is therefore unlikely to originate from a cosmic ray muon.

- The same exercise is repeated for the region $p_T^{\text{miss}} < 300$ GeV to investigate the issue more deeply.
- In this region the prediction $1.95 \pm 0.29$, which is comparable to the 1 event observed.

<table>
<thead>
<tr>
<th>A) Signal region</th>
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<tbody>
<tr>
<td>$t_{\text{jet}} &gt; 3$ ns, $\text{PV fraction} &gt; 1/12$</td>
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<th>B)</th>
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<th>D)</th>
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<tr>
<td>$-3$ ns $&lt; t_{\text{jet}} &lt; -1$ ns, $\text{PV fraction} &gt; 1/12$</td>
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Therefore the excess is considered to be consistent with a statistical fluctuation.
Core and satellite background estimation (2)

Validation (2)

- A second validation test is performed for the core and satellite background estimation because of the discrepancy found in the first test.

- In this validation region, the estimation from this method for the number of events in the validation region comes out to be $0.03 \pm 0.08$ which is in agreement with the zero events observed.

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<th>B)</th>
<th>A) VR(2)</th>
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<tbody>
<tr>
<td>$2 &lt; t_{\text{jet}} &lt; 3 \text{ ns}$</td>
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<td>$1 &lt; t_{\text{jet}} &lt; 2 \text{ ns}$</td>
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The final prediction for the core and satellite bunch background in the Signal Region is:

$$0.11^{+0.09}_{-0.05} (\text{stat})^{+0.02}_{-0.02} (\text{syst})$$
Cosmic background prediction

- Cosmic jets more widely spread in time due to hitting calorimeter at angle and depositing along length of crystal
- Use jet time RMS and muon system angular variables to define ABCD
- The method is validated in a validation region where events failed HBHE filter
- The predicted events in the validation region is $1.1^{+1.9}_{-1.1}$ which is consistent with the 1 observed events

The signal region prediction of cosmic background is:

$$1.0^{+1.8}_{-1.0} \text{ (stat)} +^{1.8}_{-1.0} \text{ (syst)}$$

The total background prediction is $1.1^{+2.5}_{-1.1}$ is consistent with 0 event observed
The observed upper limits at 95% CL for the gluino pair production cross section in the GMSB model, shown in the plane of gluino mass and $c\tau_0$.

A branching fraction of 100% for the gluino decay to a gluon and a gravitino is assumed.

The area below the thick black curve represents the observed exclusion region.

Masses up to 2100, 2500, and 1900 GeV are excluded at 95% confidence level for proper decay lengths of 0.3, 1, and 100 m, respectively.
Expected and observed limit on $\sigma \times BR^2$ after all signal region selections for a gluino GMSB model with $m_{\tilde{g}} = 2400$ GeV are shown in the dotted and solid black lines respectively.

- The dashed red line shows the theoretical value of $\sigma \times BR^2$.
- The region below the dashed red line is ruled out by the experiment.
Summary

- An inclusive search for long-lived particles has been presented, based on a data sample of proton-proton collisions collected at $\sqrt{13}$ TeV by the CMS experiment, corresponding to an integrated luminosity of $137 \text{ fb}^{-1}$.

- The search selects delayed jets from the decays of heavy long-lived particles using the timing capability of the electromagnetic calorimeter.

- The results are interpreted using the gluino gauge-mediated supersymmetry breaking signal model.

- Gluino masses up to 2100, 2500, and 1900 GeV are excluded at 95% confidence level for proper decay lengths of 0.3, 1, and 100 m, respectively.
Back Up
Few Definitions

- Hadronic energy fraction (HEF):
  \[ \frac{E_{HCAL}}{E_{ECAL} + E_{HCAL}} \]

- Jet EM energy fraction associated with CSC hits:
  \[ \text{The ratio of the total energy of ECAL cells matched to a CSC segment (}\Delta\varphi < 0.04\text{) to ECAL} \]

- \( PV_{Track} \) Fraction:
  \[ \text{Total momentum of all tracks originating from the primary vertex (PV) associated to the jet} \]
  \[ \text{the transverse energy of the jet} \]