Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for long-lived particles decaying to displaced, nonprompt jets and missing transverse momentum is presented. The data sample corresponds to an integrated luminosity of 137 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment at the CERN LHC in 2016–2018. Candidate signal events containing nonprompt jets are identified using the timing capabilities of the CMS electromagnetic calorimeter. The results of the search are consistent with the background prediction and are interpreted using a gauge-mediated supersymmetry breaking reference model with a gluino next-to-lightest supersymmetric particle. In this 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. These are the best limits to date for such massive gluinos with proper decay lengths greater than $\sim$0.5 m.

Submitted to Physics Letters B
1 Introduction

A large number of models for physics beyond the standard model predict long-lived particles that may be produced at the CERN LHC and decay into final states containing jets with missing transverse momentum, $\vec{p}_T^{\text{miss}}$ [1]. These models include supersymmetry (SUSY) with gauge-mediated SUSY breaking (GMSB) [2], split and stealth SUSY [3–5], and hidden valley models [6]. The $\vec{p}_T^{\text{miss}}$ may arise from a stable weakly interacting particle in the final state or from a heavy neutral long-lived particle that decays outside the detector.

The timing capabilities of the CMS electromagnetic calorimeter (ECAL) [7] are used to identify nonprompt or “delayed” jets produced by the displaced decays of heavy long-lived particles within the ECAL volume or within the tracking volume bounded by the ECAL. The delay is expected to be a few ns for a TeV scale particle that travels $\sim$1 m before decaying. A representative GMSB model is used as a benchmark to quantify the sensitivity of the search. In this model, pair-produced long-lived gluinos each decay into a gluon, which forms a jet, and a gravitino, which escapes the detector causing significant $\vec{p}_T^{\text{miss}}$ in the event. The leading order Feynman diagram for the benchmark model is shown in Fig. 1 (left).

![Diagram](image)

Figure 1: Leading order Feynman diagram for the GMSB signal model (left), and diagram of a typical event (right), expected to pass the signal region selection. The event has delayed energy depositions in the calorimeters but no tracks from a primary vertex.

There have been multiple searches for long-lived particles decaying to jets by the ATLAS [8], CMS [9] and LHCb [10] Collaborations at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV [11–26]. The use of calorimeter timing has so far been limited to searches targeting displaced photons at $\sqrt{s} = 8$ TeV [27,28]. The present study represents the first application of ECAL timing to a search for nonprompt jets from long-lived particle decays. This technique allows the reduction of backgrounds to the few event level, while retaining high efficiency for signal signatures of one or more displaced jets and $\vec{p}_T^{\text{miss}}$ in the final state. As detailed in Ref. [29], this approach brings significant new sensitivity to long-lived particle searches. A diagram of a characteristic event targeted by this analysis is shown in Fig. 1 (right). Such an event would escape reconstruction in a tracker-based search because of the difficulty in reconstructing tracks that originate from decay points separated from the primary vertex by more than $\sim$50 cm in the plane perpendicular to the beam axis. There are two effects that contribute to the time delay of jets from the decay of heavy long-lived particles, namely the increased path length arising from the indirect
trajectory, and the lower velocity associated with the high mass. The latter is the dominant effect for the signal models considered in this analysis.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal ECAL, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. The HCAL is segmented into individual calorimeter cells along pseudorapidity, $\eta$, azimuth, $\phi$, and depth. The barrel muon system is composed of drift-tubes (DTs) and resistive plate chambers (RPCs). These provide high resolution hit positioning and timing to determine the muon trajectory. In the forward region, RPCs are used along with cathode strip chambers (CSCs), which have greater resistance to the higher radiation flux occurring along the beamline than DTs. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematical variables, can be found in Ref. [9].

The CMS ECAL consists of 75,848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.00$ in two endcap regions (EE). This analysis relies on the timing capabilities of the EB [7]. The ECAL measures the energy of incoming electromagnetic particles through the scintillation light produced in the lead tungstate crystals. Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel region. These are capable of measuring the time of incoming particles with a resolution as low as $\sim 200 \text{ ps}$ for energy deposits above 50 GeV [30]. Each ECAL crystal with an APD unit attached is referred to as an ECAL cell.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in $\eta$ and 0.087 in $\phi$. In the $\eta$–$\phi$ plane, and for $|\eta| < 1.48$, the HCAL cells map on to $5 \times 5$ arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta \eta$ and $\Delta \phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system [31]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 $\mu$s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 Object and event reconstruction

The primary physics objects used in this analysis are jets reconstructed from the energy deposits in the calorimeter towers, clustered using the anti-$k_T$ algorithm [32] [33] with a distance parameter of 0.4. The contribution from each calorimeter tower is assigned the coordinates of the tower and a momentum, the absolute value and the direction of which are found from the energy measured in the tower assuming that the contributing particles originated at the center of the detector. The raw jet energy is obtained from the sum of the tower energies, and the raw
jet momentum by the vectorial sum of the tower momenta, which are found from the energy measured in the tower. The raw jet energies are then corrected to reflect a uniform relative response of the calorimeter in $\eta$ and a calibrated absolute response in transverse momentum $p_T$ [34]. Jets reconstructed using the CMS particle flow (PF) algorithm [35] are not used in this analysis because nonprompt jets do not produce reliable information in the tracker and out-of-time energy deposits are not included in the PF jet reconstruction.

All reconstructed vertices in the event, consistent with originating from a proton-proton (pp) interaction, are considered to be primary vertices (PVs) [36]. Each track that is identified as originating from a PV is associated with a jet if the separation of the track from the jet axis $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.4$, where $\Delta \eta$ and $\Delta \phi$ represent the difference (in radians) between the jet axis and the track in the pseudorapidity and in the azimuthal direction, respectively.

The jet timing is determined using all ECAL cells that satisfy $\Delta R < 0.4$ between the jet axis and cell position and that satisfy an energy threshold of 0.5 GeV. 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. 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, $t_{jet}$, is defined by the median cell time. The jet-based requirements used to reject the dominant backgrounds, referred to as the signal jet requirements, are detailed in Section 5.

The value of $p_T^{miss}$ used for this analysis is defined as the projection on the plane perpendicular to the beams of the negative vector sum of calorimeter momenta deposits in an event, with no rejection of out-of-time ECAL cells. Its magnitude is referred to as $p_T^{miss}$.

4 Data sets and simulated samples

The data sample was collected in 2016, 2017, and 2018 by the CMS detector in pp collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $137 \pm 3.3$ fb$^{-1}$ [37–39]. The trigger required the events to satisfy $p_T^{miss}$ (trigger) $> 120$ GeV. This is computed as the negative vector $p_T$ sum of all HLT PF candidates, which, contrary to the offline PF candidates, include out-of-time deposits [40].

The search is interpreted using the GMSB signal model with samples produced with gluino masses from 1000 to 3000 GeV, and proper decay lengths ($c\tau_0$) varying from 0.3 to 100 m. The gluino pair production cross sections are determined at next-to-leading-order (NLO) plus next-to-leading-logarithm (NLL) precision [41–46]. All other SUSY particles, apart from the gravitino, are assumed to be heavy and decoupled from the interaction. Signal samples are produced with PYTHIA 8.212 [47], and NNPDF3.1LO [48] is used for parton distribution function (PDF) modeling. When a gluino or top squark is long-lived, it will have enough time to form a hadronic state, an R-hadron [49–51], which is simulated with PYTHIA 8.212. For underlying event modeling the CP2 tune is used [52].

The modeling of the jet-based variables discussed in Section 5 is validated using a simulated sample of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events. This sample is simulated with MadGraph5_aMC@NLO 2.2.2 [53] event generator at leading-order (LO) accuracy. This generator is interfaced with PYTHIA 8.212 for hadronization and fragmentation. The jets from the matrix element calculations are matched to parton shower jets using the MLM algorithm [53]. The underlying event is modeled using the CUETP8M1 (CP5) tune [52] for simulation with NNPDF3.0NLO.
(NNPDF3.1NNLO) used for PDF modeling for the 2016 (2017 and 2018) detector operating conditions.

The description of the detector response is implemented using the GEANT4 package for all simulated processes. To model the effect of additional pp interactions within the same bunch crossing (in-time pileup) or nearby bunch crossings (out-of-time pileup), minimum bias events generated with PYTHIA are added to the simulated event sample, with a frequency distribution per bunch crossing weighted to match that observed in data.

5 Event and object selection

The selection criteria are optimized taking into account the principal background sources that produce delayed timing signals, which are detailed below.

- **ECAL time resolution tails**: these tails affect the collisions of in-time ("core") bunches and arise from intercalibration uncertainties, crystal-dependent variations in scintillation rise time, loss of crystal transparency because of radiation, and run-by-run shifts associated with the readout electronics.

- **Electronic noise**: electronic noise in the ECAL can cause individual cells to record deposits at arbitrary times, typically with low energies, and uncorrelated with surrounding cells.

- **Direct ionization in the APD**: the traversal of a charged particle produces a signal that is \( \sim 11 \) ns earlier than the signal from scintillation light. However, the ionization signal may arrive later if the associated charged particle travels back from the HCAL, or is associated with a later bunch crossing.

- **In-time pileup**: additional pp collisions in the same bunch crossing can produce particles with a spread in collision time and with varying flight paths, depending on the point of origin along the beam axis. These effects result in timing shifts of up to a few hundred ps.

- **Out-of-time pileup**: additional pp collisions in neighboring bunch crossings can result in deposits that are delayed by integer multiples of the bunch spacing (25 ns).

- **Satellite bunches**: the LHC radiofrequency (RF) cavities operate at a frequency of 400 MHz, such that RF “buckets” are separated by \( \sim 2.5 \) ns. In order to achieve the desired bunch spacing, only one in ten of these buckets (separated by 25 ns) is filled. However, adjacent “satellite” bunches may also contain protons at a level corresponding to \( O(10^{-5}) \) times that of the main bunch.

- **Beam halo**: collisions between beam protons and an LHC collimator can result in muons that pass through the detector approximately parallel to the beam line. These “beam halo” muons can deposit energy within the ECAL, causing an early signal if the beam halo is from the current or previous bunch or a delayed signal if the beam halo originates from a following bunch.

- **Cosmic ray muon hits**: cosmic ray muons may cause deposits in the ECAL that occur at random times.

The events considered in this analysis as including candidate long-lived particles are required to satisfy a series of selections that define the signal region (SR). Each requirement is chosen to be at least \( \sim 90\% \) efficient for jets from the decay of a TeV scale long-lived particle while allowing at least a factor \( \sim 10 \) rejection of the identified background process. In order to predict background contributions to the SR, some of these requirements are inverted to enhance
particular background processes, as detailed in Section 6.

5.1 Jet selection

5.1.1 Baseline jet selection

All jets considered in this analysis must pass baseline $p_T$ and $\eta$ requirements. A requirement of $p_T > 30 \text{ GeV}$ is made to reduce contributions from pileup jets. The jets are required to satisfy $|\eta| < 1.48$ so that they are reconstructed in the EB. The barrel requirement is made because the timing resolution is significantly better in this region compared with the endcap [30], and jets of the targeted signal model are strongly peaked in the central $\eta$ region.

5.1.2 Signal jet selection

The SR requirement on the jet time is $t_{\text{jet}} > 3 \text{ ns}$. The timing resolution improves for higher energy ECAL deposits before reaching a plateau [30]. A requirement on the ECAL energy component of the jet of $E_{\text{ECAL}} > 20 \text{ GeV}$ is applied as this threshold was found to optimize the timing resolution of the jets while ensuring high signal efficiency.

Jets from signal events are expected to have a large number of ECAL cells ($N_{\text{cell,ECAL}}$) hit, while jets dominated by direct APD hits or ECAL noise often have a low number of cells hit. A threshold of $N_{\text{cell,ECAL}} > 25$ is applied to reject these backgrounds.

Jets from signal events will typically have similar energy depositions in the ECAL and HCAL, while jets originating from noise or beam halo typically have a small or zero HCAL energy component ($E_{\text{HCAL}}$). In order to reject such backgrounds, jets are required to have a hadronic energy fraction $\text{HEF} = E_{\text{HCAL}} / (E_{\text{ECAL}} + E_{\text{HCAL}}) > 0.2$. An additional requirement of $E_{\text{HCAL}} > 50 \text{ GeV}$ is made to reject backgrounds from noise and beam halo as well as to ensure a well-measured hadronic component.

Signal jets typically have a small RMS in the time of the constituent cells ($t_{\text{RMS,jet}}$) as all the component cells originate from the same delayed jet. Jets that are significantly delayed because of contributions from uncorrelated noise often contain cells that are widely spread in time. In such cases the $t_{\text{RMS,jet}}$ will be correlated with $t_{\text{jet}}$, so backgrounds are rejected by applying a requirement of both $t_{\text{RMS,jet}} < 0.4t_{\text{jet}}$ and of $t_{\text{RMS,jet}} < 2.5 \text{ ns}$.

Jets that originate from a PV and have a mismeasured time or originate from satellite bunch collisions typically contain significant total momentum in tracks associated with their PV. The $\text{PV}_{\text{track}}$ fraction, defined as the ratio of the total $p_T$ of all PV tracks matched to the jet ($\Delta R < 0.5$) to the transverse calorimeter energy of the jet, is used to select potential signal jets that do not originate from a PV. A requirement of $\text{PV}_{\text{track}} < 0.083$ is applied.

Beam halo muons will travel directly through the CSCs before leaving energy deposits in the ECAL, so the fraction of ECAL energy that can be associated with CSC track segments provides rejection of backgrounds from beam halo. The ratio of the total energy of ECAL cells matched to a CSC segment ($\Delta \phi < 0.04$) to $E_{\text{ECAL}}$, defined as $E_{\text{ECAL}}^\text{CSC}/E_{\text{ECAL}}$, is used to discriminate beam halo backgrounds. A requirement of $E_{\text{ECAL}}^\text{CSC}/E_{\text{ECAL}} < 0.8$ is applied.

5.2 Event selection

A requirement of $p_T^{\text{miss}} > 300 \text{ GeV}$ is applied to reject backgrounds from multijet production from core and satellite bunch collisions.

The DT and RPC muon systems are used to reduce the background contribution from cosmic
ray muons. Signal events could also have deposits in the muon systems if the jets contain muons, if there is “punch-through” of jet constituents to the muon system, or if the long-lived particle decays within the muon system. To mitigate the inefficiency for signal events, only the DT segments and RPC hits with \( r > 560 \) cm (where \( r \) is the transverse radial distance to the interaction point) and RPC stations with \( |z| > 600 \) cm (where \( z \) is the distance along the beamline to the interaction point) are considered. In order to reduce the effect of noise, DT segments and RPC hits are required to be within \( \Delta R < 0.5 \) of a DT segment with a hit. The maximal \( \Delta \phi \) between such “paired” DT segments and RPC hits is defined as \( \max(\Delta \phi_{\text{DT}}) \) and \( \max(\Delta \phi_{\text{RPC}}) \), respectively. Events satisfying \( \max(\Delta \phi_{\text{DT}}) > \pi/2 \) or \( \max(\Delta \phi_{\text{RPC}}) > \pi/2 \) are rejected to reduce the contribution of cosmic ray muon events.

Finally, events are required to satisfy a series of filters designed to ensure that the reconstruction is of good quality and contains at least one jet satisfying the requirements outlined in Section 5.1. These requirements are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Summary of the requirements used to define the signal region.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline jet selection</strong></td>
</tr>
<tr>
<td>(</td>
</tr>
<tr>
<td>( p_T &gt; 30 ) GeV</td>
</tr>
<tr>
<td><strong>Signal jet selection</strong></td>
</tr>
<tr>
<td>( E_{\text{ECAL}} &gt; 20 ) GeV</td>
</tr>
<tr>
<td>( N_{\text{cell}}^{\text{ECAL}} &gt; 25 )</td>
</tr>
<tr>
<td>( \text{HEF} &gt; 0.2 ) and ( E_{\text{HCAL}} &gt; 50 ) GeV</td>
</tr>
<tr>
<td>( t_{\text{jet}}^{\text{RMS}} / t_{\text{jet}} &lt; 0.4 ) and ( t_{\text{jet}}^{\text{RMS}} &lt; 2.5 ) ns</td>
</tr>
<tr>
<td>( \text{PV fraction}_{\text{track}} &lt; 0.083 )</td>
</tr>
<tr>
<td>( E_{\text{CSC}}^{\text{ECAL}} / E_{\text{ECAL}} &lt; 0.8 )</td>
</tr>
<tr>
<td>( t_{\text{jet}} &gt; 3 ) ns</td>
</tr>
<tr>
<td><strong>Event level selection</strong></td>
</tr>
<tr>
<td>At least one signal jet</td>
</tr>
<tr>
<td>( p_{\text{miss}}^{T} &gt; 300 ) GeV</td>
</tr>
<tr>
<td>Quality filters</td>
</tr>
<tr>
<td>( \max(\Delta \phi_{\text{DT}}) &lt; \pi/2 )</td>
</tr>
<tr>
<td>( \max(\Delta \phi_{\text{RPC}}) &lt; \pi/2 )</td>
</tr>
</tbody>
</table>

6 Background estimation

This section details the characterization of the dominant background sources and the methods used to estimate residual contributions to the SR. The backgrounds are investigated by inverting the requirements on the discriminating variables summarized in Table 1 to define control regions (CRs) enriched in particular background processes. There are three main background sources: beam halo backgrounds, which typically have low HEF and large \( E_{\text{ECAL}}^{\text{CSC}} / E_{\text{ECAL}} \); out-of-time backgrounds from core and satellite bunch collisions, which have large PV fraction, and jets originating from cosmic ray muons, which have high \( \max(\Delta \phi_{\text{DT/RPC}}) \) and \( t_{\text{jet}}^{\text{RMS}} \). The backgrounds are estimated from the CRs using methods that rely on data. These predictions are
tested using validation regions (VRs) that do not overlap with the SRs to ensure they are unbiased. The agreement of the observation with prediction in the VRs is used to estimate systematic uncertainties in the prediction in the SR. For jets in the CRs with \( |t_{\text{jet}}| < 3 \text{ ns} \), the \( t_{\text{jet}}^{\text{RMS}} / t_{\text{jet}} < 0.4 \) requirement is replaced with a requirement of \( t_{\text{jet}}^{\text{RMS}} < 1.2 \) ns.

### 6.1 Beam halo

The beam halo contribution is estimated by measuring the pass/fail ratio of the \( E_{\text{CSC}/\text{ECAL}} / E_{\text{ECAL}} > 0.8 \) requirement for events with HEF < 0.2 and applying it to the observed number of events with HEF > 0.2. The SR prediction is made using all events with \( t_{\text{jet}} > 3 \text{ ns} \). The prediction is made without any requirement on \( E_{\text{HCAL}} \) and can therefore be considered an upper limit on the contribution from the beam halo background.

The VR for this prediction is defined by selecting events with \( t_{\text{jet}} < -2 \text{ ns} \) and applying all signal requirements except those on \( E_{\text{CSC}/\text{ECAL}}, \text{HEF}, \) and \( E_{\text{HCAL}} \). To enhance the contribution of beam halo events relative to the contributions from satellite bunches and cosmic ray muons in the VR, the \( \phi \) values of the jets are required to be within 0.2 radians of 0 or \( \pm \pi \). The correlation between \( E_{\text{CSC}/\text{ECAL}} / E_{\text{ECAL}} \) and HEF in the VR is consistent with zero, meaning they can be used to make an unbiased prediction. The prediction from this method for the number of events passing signal thresholds on \( E_{\text{CSC}/\text{ECAL}} / E_{\text{ECAL}} \) and HEF in the VR is \( 0.02^{+0.06}_{-0.02} \) events, in agreement with the 0 events observed.

The level of agreement between prediction and observation in the VR is used to derive a systematic uncertainty in the prediction. The slope of a linear fit to the pass/fail ratio of the \( E_{\text{CSC}/\text{ECAL}} / E_{\text{ECAL}} > 0.8 \) requirement as a function of HEF is found to be consistent with zero. The uncertainty is then propagated to the region with \( E_{\text{CSC}/\text{ECAL}} / E_{\text{ECAL}} > 0.8 \) and HEF > 0.2. The final prediction for the SR is \( 0.02^{+0.06}_{-0.02} \) (stat) \( +0.05_{-0.01} \) (syst) events.

### 6.2 Core and satellite bunch background prediction

The core and satellite bunch background contribution is estimated by measuring the pass/fail ratio of the \( \text{PV}_{\text{track}}^{\text{fraction}} < 0.083 \) requirement for events with \( 1 < t_{\text{jet}} < 3 \text{ ns} \) and applying it to the observed number of events with \( t_{\text{jet}} > 3 \text{ ns} \) and \( \text{PV}_{\text{track}}^{\text{fraction}} > 0.083 \). Two VRs are defined to verify the prediction of the satellite bunch and timing tail backgrounds.

The first VR is selected to contain events with \( t_{\text{jet}} < -1 \text{ ns} \) and passing all signal requirements except for that on \( \text{PV}_{\text{track}}^{\text{fraction}} < 0.083 \). The pass/fail ratio of the \( \text{PV}_{\text{track}}^{\text{fraction}} < 0.083 \) requirement is measured for events with \( -3 < t_{\text{jet}} < -1 \text{ ns} \) and applied to the number of events with \( t_{\text{jet}} < -3 \text{ ns} \) and \( \text{PV}_{\text{track}}^{\text{fraction}} > 0.083 \). The upper bound on \( t_{\text{jet}} \) ensures the sample is enriched with jets in the tail of the \( t_{\text{jet}} \) distribution. The correlation between the variables in the VR is confirmed to be consistent with zero, which allows an unbiased prediction to be made. The prediction from this method for the number of events passing \( t_{\text{jet}} < -3 \text{ ns} \) and \( \text{PV}_{\text{track}}^{\text{fraction}} < 0.083 \) is \( 0.09^{+0.2}_{-0.06} \) events, to be compared with 1 observed event. The event passing selection has no paired RPC or DT hits and is therefore unlikely to originate from a cosmic ray muon. The compatibility with expectation is within two standard deviations, however, to ensure the prediction is unbiased, a further validation is carried out. The requirement of \( p_{\text{T}}^{\text{miss}} > 300 \text{ GeV} \) is inverted and the prediction repeated. The events must still satisfy the \( p_{\text{T}}^{\text{miss}} \) (trigger) > 120 GeV requirement. In this region \( 1.95 \pm 0.29 \) events are predicted and 1 event is observed. The observation in the negative time region for \( p_{\text{T}}^{\text{miss}} > 300 \text{ GeV} \) is therefore considered to be consistent with a statistical fluctuation.
A second VR is defined using events with $1 < t_{\text{jet}} < 3$ ns. The pass/fail ratio of the $\text{PV}^\text{fraction}_{\text{track}} < 0.083$ requirement is measured for events with $1 < t_{\text{jet}} < 2$ ns and applied to the number of events with $2 < t_{\text{jet}} < 3$ ns and $\text{PV}^\text{fraction}_{\text{track}} > 0.083$. The estimation from this method for the number of events passing $2 < t_{\text{jet}} < 3$ ns and $\text{PV}^\text{fraction}_{\text{track}} < 0.083$ is $0.03^{+0.08}_{-0.03}$ events, in agreement with the 0 events observed.

The prediction for the SR relies on using the efficiency of the $\text{PV}^\text{fraction}_{\text{track}}$ requirement of events with $1 < t_{\text{jet}} < 3$ ns to predict the efficiency of the $\text{PV}^\text{fraction}_{\text{track}}$ requirement for $t_{\text{jet}} > 3$ ns. Because of differences in the reconstruction of the calorimeter energy and tracker $p_T$, this efficiency may be expected to have some small time dependence. In order to measure any such $t_{\text{jet}}$ dependence and derive an associated systematic uncertainty, a data sample with the offline $p_T^\text{miss}$ requirement inverted (but passing trigger requirements) and $t_{\text{jet}} > 2$ ns is used. The region of $\text{PV}^\text{fraction}_{\text{track}} < 0.083$ is not included to avoid contamination from cosmic ray or beam halo muon deposits. The slope of a linear fit to the pass/fail ratio of a looser requirement of $\text{PV}^\text{fraction}_{\text{track}} < 0.5$ against $t_{\text{jet}}$ is consistent with zero. As for the beam halo prediction, the uncertainty from the fit is propagated to the region with $t_{\text{jet}} > 3$ ns and $\text{PV}^\text{fraction}_{\text{track}} > 0.083$. The final prediction for the core and satellite bunch background is $0.11^{+0.09}_{-0.05}$ (stat)$^{+0.02}_{-0.02}$ (syst) events.

### 6.3 Cosmic ray events

The discriminating variables used for the cosmic background prediction are the $t_{\text{jet}}^{\text{RMS}}$ of the jet and the larger of $\text{max}(\Delta\phi_{\text{DT}})$ and $\text{max}(\Delta\phi_{\text{RPC}})$, labelled as $\text{max}(\Delta\phi_{\text{DT/RPC}})$. The pass/fail ratio of the $t_{\text{jet}}^{\text{RMS}} < 2.5$ ns requirement is measured for events with $\text{max}(\Delta\phi_{\text{DT/RPC}}) > \pi/2$ and applied to events with $\text{max}(\Delta\phi_{\text{DT/RPC}}) < \pi/2$. Cosmic ray muons passing through the HCAL will typically deposit significant energy in a single isolated cell. The HCAL noise rejection quality filters are designed to reject events containing such isolated deposits, thus inverting these filters, with all other requirements applied, provides a validation region enriched in events with cosmic ray muons.

The correlation between $t_{\text{jet}}^{\text{RMS}}$ and $\text{max}(\Delta\phi_{\text{DT/RPC}})$ in the validation sample is consistent with zero, allowing them to be used to make an unbiased prediction. The estimation in the VR for the number of events passing signal thresholds in $t_{\text{jet}}^{\text{RMS}}$ and $\text{max}(\Delta\phi_{\text{DT/RPC}})$ is $1.1^{+1.9}_{-1.1}$ events, in agreement with the 1 event observed. A systematic uncertainty is applied to account for the small number of events in the VR. The final prediction in the SR is $1.0^{+1.8}_{-1.0}$ (stat)$^{+1.8}_{-1.0}$ (syst) events.

### 6.4 Background summary

The estimated background yields are summarized in Table 2. The total background prediction is $1.1^{+2.5}_{-1.1}$ events.

<table>
<thead>
<tr>
<th>Background source</th>
<th>Events predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam halo muons</td>
<td>$0.02^{+0.06}<em>{-0.02}$ (stat)$^{+0.09}</em>{-0.01}$ (syst)</td>
</tr>
<tr>
<td>Core and satellite bunch collisions</td>
<td>$0.11^{+0.09}<em>{-0.05}$ (stat)$^{+0.02}</em>{-0.02}$ (syst)</td>
</tr>
<tr>
<td>Cosmic ray muons</td>
<td>$1.0^{+1.8}<em>{-1.0}$ (stat)$^{+1.8}</em>{-1.0}$ (syst)</td>
</tr>
</tbody>
</table>
7 Results and interpretation

Figure 2: The timing distribution of the backgrounds predicted to contribute to the signal region, compared to those for a representative signal model. The time is defined by the jet in the event with the largest $t_{\text{jet}}$ passing the relevant selection. The distributions for the major backgrounds are taken from control regions and normalized to the predictions detailed in Section 6. The observed data is shown by the black points. No events are observed in data for $t_{\text{jet}} > 3$ ns (indicated with a vertical black line).

Figure 2 shows the timing distribution for events with jets passing all the SR requirements. The background shapes are shown for illustration only and are not used for the statistical interpretation. The overall background prediction for the SR is $1.1^{+2.5}_{-1.1}$ events, which is consistent with the observation of 0 events.

The model used for the interpretation is the GMSB SUSY model in which gluinos are pair produced and form R-hadrons. The long-lived gluinos then decay to a gluon and gravitino producing a delayed jet and $p_T^{\text{miss}}$. Interactions of the R-hadrons with the detector lead to signatures exploited by searches for heavy stable charged particles and are not considered for the interpretation of this analysis.

The trigger efficiency for the simulated samples is evaluated from an emulation. The inefficiency due to the $p_T^{\text{miss}}$ trigger requirement ranges from $\sim$5 to $\sim$15% for $c\tau_0 = 1$ and 10 m, respectively. The trigger emulation is validated with data using an independent sample collected with a single muon reference trigger.

The product of the experimental acceptance and efficiency ($A\epsilon$), shown in Fig. 3, is evaluated independently for each model point, defined in terms of the gluino mass ($m_{\tilde{g}}$) and proper decay length. The efficiency is maximized for high gluino masses and for a range in $c\tau_0$ bounded by the requirements that the gluino must have sufficient lifetime for its decay products to pass the $t_{\text{jet}} > 3$ ns requirement and that the gluino must decay before or within the ECAL. For a gluino model with $m_{\tilde{g}} = 2400$ GeV the efficiency is highest (up to $\sim$50%) for the range $1 < c\tau_0 < 10$ m. The efficiency is larger for higher masses because of the increased $p_T^{\text{miss}}$ in the event and the reduced velocity of the gluino.
Figure 3: The product, $A_e$, of the acceptance and efficiency in the $c\tau_0$ vs. $m_{\tilde{g}}$ plane for the GMSB model, after all requirements.

Table 3: The derived uncertainty in the product, $A_e$, of the acceptance and efficiency from the modeling of the variables discussed in Section 5.1.2 for a representative model with $m_{\tilde{g}} = 2400$ GeV.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Derived uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau_0 = 1$ m</td>
<td>$c\tau_0 = 10$ m</td>
</tr>
<tr>
<td>$P_{\text{fraction}}$</td>
<td>0.01 0.03</td>
</tr>
<tr>
<td>$N_{\text{cell}}$</td>
<td>3.2 4.2</td>
</tr>
<tr>
<td>HEF</td>
<td>2.8 2.5</td>
</tr>
<tr>
<td>$E_{\text{ECAL}} / E_{\text{ECAL}}$</td>
<td>0.9 0.9</td>
</tr>
<tr>
<td>$\mu_{\text{RMS}}$</td>
<td>22 15</td>
</tr>
</tbody>
</table>

Interactions of the R-hadrons with the detector would be expected to reduce the efficiency of the $P_{\text{fraction}}$ and $\max(\Delta\phi_{DT/RPC})$ requirements. The impact of such interactions was evaluated for two benchmark signal points, $m_{\tilde{g}} = 1500$ GeV and $c\tau_0 = 1$ m, and $m_{\tilde{g}} = 1500$ GeV and $c\tau_0 = 10$ m, using the “cloud” model of R-hadron/matter interactions [50, 56], which assumes that the R-hadron is surrounded by a cloud of colored, light constituents that interact during scattering. The fraction of $\tilde{g}$ which hadronize to a neutral $\tilde{g}$-gluon state was taken to be 0.1. Compared to non-interacting R-hadrons, the relative reduction in selection efficiency for both benchmark signal points was found to be $\sim 15\%$.

In order to evaluate systematic uncertainties in the modeling of the variables used to select signal jets (defined in Section 5.1.2), the corresponding distributions for events from the multijet simulation are compared with data. For each variable, the threshold used for the selection is varied in the simulation to match the efficiency measured in data. The change in acceptance from this variation is shown for each of the jet-based variables in Table 3, using an example model point. This variation is taken as a systematic uncertainty in the signal model acceptance. In addition, the variation in $t_{\text{jet}}^{\text{RMS}}$ is propagated to $t_{\text{jet}}^{\text{RMS}} / t_{\text{jet}}$. 
In addition to the uncertainty in the modeling of the variables used to select signal jets, the systematic uncertainties in the signal $A\varepsilon$ are summarized below.

- Integrated luminosity: 2.5% [37], 2.3% [38], and 2.5% [39] uncorrelated uncertainties for the 2016, 2017, and 2018 data taking periods, respectively.
- Trigger inefficiency: typically 5–15%.
- Limited simulated sample size: up to $\sim$10%, depending on SR $A\varepsilon$.
- Pileup reweighting: 4.6% uncertainty in the total inelastic pp cross section [57], which corresponds to an uncertainty in the SR $A\varepsilon$ of 1–5%.
- Jet energy resolution/scale: a 1–5% percent uncertainty [34].

Under the signal+background hypothesis, a modified frequentist approach is used to determine observed upper limits at 95% confidence level (CL) on the cross section ($\sigma$) to produce a pair of gluinos, each decaying with 100% branching fraction to a gluon and a gravitino, as a function of $m_{\tilde{g}}$ and $c_{\tau_0}$. The approach uses the LHC-style profile likelihood ratio as the test statistic [58] and the CL$_s$ criterion [59, 60]. The expected and observed upper limits are evaluated through the use of pseudodata sets. Potential signal contributions to event counts in the SR and CRs are taken into consideration.

Figure 4 shows the observed upper limit on $\sigma$ as a function of lifetime and gluino mass for the GMSB model. Gluino masses below 2100 GeV are excluded at 95% confidence level for $c_{\tau_0}$ between 0.3 and 30 m. The dependence of the expected and observed upper limit as a function of $c_{\tau_0}$ is shown in Fig. 5 for $m_{\tilde{g}} = 2400$ GeV. The observed limit is compared to the results of the CMS displaced jet search [24], based on a data sample with integrated luminosity of 36.1 fb$^{-1}$, showing the complementary coverage. These results extend the reach beyond previous searches for models with jets and significant $\vec{p}_{T}^{miss}$ in the final state for $c_{\tau_0} \gtrsim 0.5$ m [21, 24, 25].

8 Summary

An inclusive search for long-lived particles has been presented, based on a data sample of proton-proton collisions collected at $\sqrt{s} = 13$ TeV by the CMS experiment, corresponding to an integrated luminosity of 137 fb$^{-1}$. The search uses the timing of energy deposits in the electromagnetic calorimeter to select delayed jets from the decays of heavy long-lived particles, with residual backgrounds estimated using measurements in control regions in the data. The results are interpreted using the gluino gauge-mediated supersymmetry breaking signal model and 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. The reach for models that predict significant missing transverse momentum in the final state is significantly extended beyond all previous searches, for proper decay lengths greater than $\sim$0.5 m [21, 24, 25].

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the
Figure 4: The observed upper limits at 95% CL for the gluino pair production cross section in the GMSB model, shown in the plane of $m_{\tilde{g}}$ 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, while the dashed red lines indicate the expected limits and their ±1 standard deviation ranges. The thin black lines show the effect of the theoretical uncertainties on the signal cross section.
Figure 5: The observed and expected upper limits at 95% CL on the gluino pair production cross section for a gluino GMSB model with $m_{\tilde{g}} = 2400$ GeV. The one (two) standard deviation variation in the expected limit is shown in the inner green (outer yellow) band. The blue solid line shows the observed limit obtained by the CMS displaced jet search \cite{24}.

References


References


A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut fr Hochenergiephysik, Wien, Austria

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Universit Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Universit Catholique de Louvain, Louvain-la-Neuve, Belgium

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Estadual Paulista, Universidade Federal do ABC, So Paulo, Brazil
C.A. Bernardes, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, SandraS. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Tsinghua University, Beijing, China
Z. Hu, Y. Wang

Universidad de los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. Gonzalez Hernandez, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar Gonzalez, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgammal

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Universit Paris-Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Universit Paris-Saclay, Palaiseau, France

Universit de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Universit de Lyon, Universit Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nuclaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsalalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

National and Kapodistrian University of Athens, Athens, Greece

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ionnina, Ionnina, Greece

MTA-ELTE Lendlet CMS Particle and Nuclear Physics Group, Etv L Lornd University, Budapest, Hungary

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, F. Sikler, T. Vmi, V. Veszpremi, G. Vesztorgombi†
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

Panjab University, Chandigarh, India

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

Indian Institute of Technology Madras, Madras, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Universit di Bari, Politecnico di Bari, Bari, Italy
A. Pompili\textsuperscript{a,b}, G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwille\textsuperscript{a}

INFN Sezione di Bologna \textsuperscript{a}, Universit\`{a} di Bologna \textsuperscript{b}, Bologna, Italy
G. Abbiendi\textsuperscript{a}, C. Battilana\textsuperscript{a,b}, D. Bonacorsi\textsuperscript{a,b}, L. Borgonovi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, R. Campanini\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, C. Ciocca\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, E. Fontanesi, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, F. Iememi\textsuperscript{a,b}, S. Lo Meo\textsuperscript{a,29}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, A. Perrotta\textsuperscript{a}, F. Primavera\textsuperscript{a,b}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{a}

INFN Sezione di Catania \textsuperscript{a}, Universit\`{a} di Catania \textsuperscript{b}, Catania, Italy
S. Albergo\textsuperscript{a,b,30}, S. Costa\textsuperscript{a,b}, A. Di Mattia\textsuperscript{a}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b,30}, C. Tuve\textsuperscript{a,b}

INFN Sezione di Firenze \textsuperscript{a}, Universit\`{a} di Firenze \textsuperscript{b}, Firenze, Italy
G. Barbagli\textsuperscript{a}, R. Ceccarelli, K. Chatterjee\textsuperscript{a,b}, V. Ciu\textsuperscript{a}, C. Cividini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, G. Latino, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Vili\textsuperscript{a}

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benucci, S. Bianco, D. Piccolo

INFN Sezione di Genova \textsuperscript{a}, Universit\`{a} di Genova \textsuperscript{b}, Genova, Italy
M. Bozzo\textsuperscript{a,b}, F. Ferro\textsuperscript{a}, R. Mulargia\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

INFN Sezione di Milano-Bicocca \textsuperscript{a}, Universit\`{a} di Milano-Bicocca \textsuperscript{b}, Milano, Italy
A. Benaglia\textsuperscript{a}, A. Beschi\textsuperscript{a,b}, F. Brivio\textsuperscript{a,b,v}, V. Ciriolo\textsuperscript{a,b,16}, S. Di Guida\textsuperscript{a,b,16}, M.E. Dinardo\textsuperscript{a,b}, P. Dini\textsuperscript{a}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, L. Guzzi\textsuperscript{a,b}, M. Malberti\textsuperscript{a}, S. Malvezzi\textsuperscript{a}, D. Menasce\textsuperscript{a}, F. Monti\textsuperscript{a,b}, L. Moroni\textsuperscript{a}, G. Ortona\textsuperscript{a,b}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, T. Tabarelli de Fatis\textsuperscript{a,b}, D. Zuolo\textsuperscript{a,b}

INFN Sezione di Napoli \textsuperscript{a}, Universit\`{a} di Napoli ‘Federico II’ \textsuperscript{b}, Napoli, Italy, Universita della Basilicata \textsuperscript{c}, Potenza, Italy, Universit\`{a} di Marconi \textsuperscript{d}, Roma, Italy
S. Buontempo\textsuperscript{a}, N. Cavollo\textsuperscript{a,c}, A. De Iorio\textsuperscript{a,b}, A. Di Crescenzo\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a}, G. Galati\textsuperscript{a}, A.O.M. Iorio\textsuperscript{a,b}, L. Lista\textsuperscript{a,b}, S. Meola\textsuperscript{a,d,16}, P. Paolucci\textsuperscript{a,16}, B. Rossi\textsuperscript{a,c}, C. Sciaccia\textsuperscript{a,b}, E. Voevodina\textsuperscript{a,b}

INFN Sezione di Padova \textsuperscript{a}, Universit\`{a} di Padova \textsuperscript{b}, Padova, Italy, Universit\`{a} di Trento \textsuperscript{c}, Trento, Italy
P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a}, D. Bisello\textsuperscript{a,b}, A. Boletti\textsuperscript{a,b}, A. Bragagnolo, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Gasparini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, S.Y. Hoh, P. Lujan, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, M. Presilla\textsuperscript{a}, P. Ronchese\textsuperscript{a,b}, R. Rossin\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, A. Tiko, M. Tosi\textsuperscript{a,b}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

INFN Sezione di Pavia \textsuperscript{a}, Universit\`{a} di Pavia \textsuperscript{b}, Pavia, Italy
A. Braghieri\textsuperscript{a}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}

INFN Sezione di Perugia \textsuperscript{a}, Universit\`{a} di Perugia \textsuperscript{b}, Perugia, Italy
M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fan\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}

INFN Sezione di Pisa \textsuperscript{a}, Universit\`{a} di Pisa \textsuperscript{b}, Scuola Normale Superiore di Pisa \textsuperscript{c}, Pisa, Italy
K. Androsov\textsuperscript{a}, P. Azzurri\textsuperscript{a}, G. Bagliesi\textsuperscript{a}, V. Bertacchi\textsuperscript{a,c}, L. Bianchini\textsuperscript{a}, T. Boccal\textsuperscript{a}, R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,b}, R. Dell’Orso\textsuperscript{a}, G. Fedi\textsuperscript{a}, L. Giannini\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a},

INFN Sezione di Roma, Sapienza Universit di Roma, Rome, Italy

INFN Sezione di Torino, Universit di Torino, Torino, Italy, Universit del Piemonte Orientale, Novara, Italy

INFN Sezione di Trieste, Universit di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, A. Da Rold, G. Della Ricca, F. Vazzoler, A. Zanetti

Kyungpook National University, Daegu, Korea

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

Kyung Hee University, Department of Physics
J. Goh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea

University of Seoul, Seoul, Korea

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns
Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autonoma de San Luis Potos, San Luis Potos, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Grski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratorio de Instrumentacao e Fisica Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chchhipounov, V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev
Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Steppenov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
O. Bychkova, R. Chistov, M. Danilov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov, V. Blinov, T. Dimova, L. Kardapoltsev, Y. Skovpen

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tscherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autonoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocni

Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

University of Colombo, Colombo, Sri Lanka
K. Malagalage

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

Universitats Zrich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan
T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee
ukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, M. Yalcin

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Glmez, M. Kaya, O. Kaya, B. Kaynak, . zelik, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, Y. Komurcu, S. Seri

Istanbul University, Istanbul, Turkey
S. Ozkorucuklu

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West
Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA
Y.R. Joshi

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebsasso, D. Wright

University of Maryland, College Park, USA
Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar
Rice University, Houston, USA

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA

Rutgers, The State University of New Jersey, Piscataway, USA
H. Acharya, A.G. Delannoy, G. Riley, S. Spanier

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

University of Wisconsin - Madison, Madison, WI, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Universit Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidad Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS/CPNA Federal University of Mato Grosso do Sul/Campus of Nova Andradina, Nova Andradina, Brazil
6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Universit Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Suez University, Suez, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Also at Purdue University, West Lafayette, USA
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Erzincan Binali Yıldırım University, Erzincan, Turkey
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at MTA-ELTE Lendulet CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Now at INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Bari, Italy
29: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
30: Also at CENTRO SICILIANO DI FISICA NUCLEARE E DI STRUTTURA DELLA MATERIA, Catania, Italy
31: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
32: Also at Riga Technical University, Riga, Latvia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, USA
40: Also at Imperial College, London, United Kingdom
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, USA
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at Universit degli Studi di Siena, Siena, Italy
46: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
47: Also at National and Kapodistrian University of Athens, Athens, Greece
48: Also at Universiteit Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Simak University, SIRNAK, Turkey
52: Also at Beykent University, Istanbul, Turkey
53: Also at Istanbul Aydin University, Istanbul, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Gaziosmanpasa University, Tokat, Turkey
57: Also at Ozyegin University, Istanbul, Turkey
58: Also at Izmir Institute of Technology, Izmir, Turkey
59: Also at Marmara University, Istanbul, Turkey
60: Also at Kafkas University, Kars, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at Vrije Universiteit Brussel, Brussel, Belgium
64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
65: Also at Institute for Particle Physics Phenomenology Durham University, Durham, United Kingdom
66: Also at Monash University, Faculty of Science, Clayton, Australia
67: Also at Bethel University, St. Paul, USA
68: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
69: Also at Vilnius University, Vilnius, Lithuania
70: Also at Bingol University, Bingol, Turkey
71: Also at Georgian Technical University, Tbilisi, Georgia
72: Also at Sinop University, Sinop, Turkey
73: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
74: Also at Texas A&M University at Qatar, Doha, Qatar
75: Also at Kyungpook National University, Daegu, Korea
76: Also at University of Hyderabad, Hyderabad, India