Searches for light- and heavy-flavour three-jet resonances in pp collisions at $\sqrt{s} = 8$ TeV

CERN Collaboration*

CERN, Switzerland

1. Introduction

Hadronic multijet final states at hadron colliders offer a unique window on many possible extensions of the standard model (SM), although with the view partly obscured by large backgrounds due to SM processes. Many of these extensions predict resonances, such as heavy coloured fermions transforming as octets under $SU(3)_{C}$ [1–4] or supersymmetric gluinos that undergo $R$-parity-violating (RPV) decays to three quarks [5–7]. Recent studies from the Fermilab Tevatron Collider and the CERN Large Hadron Collider (LHC) employed the jet-ensemble technique. For this technique, jets are associated into unique combinations of three jets (triplets). Additional selection requirements are imposed to suppress the large backgrounds due to SM processes and to enhance sensitivity to strongly decaying resonances. These analyses set lower mass limits based upon resonance fits for gluinos undergoing RPV decays. The CDF Collaboration at the Tevatron excluded gluino masses below 144 GeV [8] using data from pp collisions at 1.96 TeV, while the CMS Collaboration at the LHC excluded masses below 460 GeV [9,10] with data from pp collisions at 7 TeV. An additional search at the LHC by the ATLAS Collaboration, also based on data collected with pp collisions at 7 TeV, has extended these limits to 666 GeV [11].

Presented here are the results of dedicated searches for pair-produced three-jet resonances in multijet events from pp collisions, with one search being inclusive with respect to parton flavours and the second requiring at least one jet from the resonance decay to be identified as a bottom-quark jet (b jet). This latter, heavy-flavour search is the first of its kind and probes additional RPV couplings. The results are based on a data sample of pp collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.4 ± 0.5 fb$^{-1}$ [12] collected with the CMS detector [13] at the LHC in 2012. Events with at least six jets, each with high transverse momentum ($p_{T}$) with respect to the beam direction, are selected and investigated for evidence of three-jet resonances consistent with strongly coupled supersymmetric particle decays. The event selection criteria are optimised in the context of the gluino signal mentioned above [5–7], using a simplified model where the gluinos decay with a branching fraction of 100% to quark jets. However, the generic features of the selection criteria provide a model-independent basis that can be used when examining extensions of the SM, since any exotic three-jet resonance with a narrow width, sufficient cross section, and high-$p_{T}$ jets would be expected to produce a significant bump on the smoothly falling SM background of our search. Additionally, low trigger thresholds and the application of b-jet identification make it possible to use SM top quark–antiquark (t$\bar{t}$) events to validate the analysis techniques.

2. The CMS experiment

The central feature of the CMS apparatus [13] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid are
a silicon pixel and strip tracker, a lead tungstate electromagnetic calorimeter (ECAL), and a hadron calorimeter (HCAL) that consists of brass layers and scintillator sampling calorimeters. Muons are measured in gas ionisation detectors embedded in the steel return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the centre of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle \( \theta \) is measured with respect to the positive z axis, the azimuthal angle \( \phi \) is measured in the x-y plane, and the pseudorapidity \( \eta \) is defined as \( \eta = -\ln(\tan(\theta/2)) \). Energy deposits from hadronic jets are measured using the ECAL and HCAL. The energy resolution for photons with \( E_T > 60 \) GeV varies between 1.1% and 2.6% over the solid angle of the ECAL barrel, and from 2.2% to 5% in the endcaps. The HCAL, when combined with the ECAL, measures jets with a resolution \( \Delta E/E \approx 60\%/\sqrt{E_T} (\text{GeV}) \oplus 5\% \) [14]. The ECAL provides coverage in pseudorapidity \( |\eta| < 1.479 \) in a barrel region and \( 1.479 < |\eta| < 3.0 \) in two endcap regions. 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 x 5 ECAL crystals arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of \( |\eta| \), the size of the towers increases, and the matching ECAL arrays contain fewer crystals. 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.

The CMS detector uses a two-tier trigger system to collect data. Events satisfying the requirements at the first level are passed to the high-level trigger (HLT), whose output is recorded and limited to a total rate of \( \sim 350 \) Hz. An HLT requirement based on at least six jets, reconstructed with only calorimeter information, is used to select events. With the jets ordered in descending \( p_T \) values, the \( p_T \) threshold at the HLT for the fourth jet is 60 GeV and, for the sixth jet, 20 GeV. For events passing all offline requirements described in Section 4, the total trigger efficiency is at least 95%.

The CMS particle-flow algorithm [15] combines calorimeter information with reconstructed tracks to identify individual particles such as photons, leptons, and neutral and charged hadrons. The photon energy is obtained directly from calibrated measurements in the ECAL. The energy of electrons is determined from a combination of the track momentum and the corresponding track momentum. The energy for a charged hadron is obtained from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects and calibrated for the nonlinear response of the calorimeters. Finally, the energy of a neutral hadron is obtained from the corresponding calibrated ECAL and HCAL energies. The particle-flow objects serve as input for jet reconstruction, performed using the anti-\( k_T \) algorithm [17–19] with a distance parameter of 0.5. The jet transverse momentum resolution is typically 15% at \( p_T = 10 \) GeV, 8% at 100 GeV, and 4% at 1 TeV; when jet clustering is based only upon the calorimeter energies, the corresponding resolutions are about 40%, 12%, and 5%.

Jet energy scale corrections [20] derived from data and Monte Carlo (MC) simulation are applied to account for the nonlinear and nonuniform response of the calorimeters. In data, a small residual correction factor is included to correct for differences in jet response between data and simulation. The combined corrections are approximately 5–10%, and their corresponding uncertainties range from 1–5%, depending on the pseudorapidity and energy of the jet. Jet quality criteria [21] are applied to remove misidentified jets, which arise primarily from calorimeter noise. In both data and simulated signal events, more than 99.8% of all selected jets satisfy these criteria.

3. Signal event simulation

Pair-produced gluinos are used to model the signal. Gluino production and decay are simulated using the Pythia [22] event generator (v6.424), with each gluino decaying to three quarks through the \( \lambda''_{ud} \) quark RPV coupling [23], where u and d refer to any up- or down-type quark, respectively. Two different scenarios are considered for this coupling, resulting in both an inclusive search similar to previous analyses [8–11] and a new heavy-flavour search. For the first case, the coupling of \( \lambda''_{ud} \), where the three numerical subscripts of \( \lambda'' \) refer to the quark generations of the corresponding u–d–d quarks, is set to a non-zero value, giving a branching fraction of 100% for the gluino decay to three light-flavour quarks. The second case, represented by \( \lambda''_{ud} \) or \( \lambda''_{cd} \), covers gluino decays to one b quark and two light-flavour quarks. The mass of the generated gluino signal ranges from 200 to 500 GeV in 50 GeV steps, with additional mass points at 750, 1000, 1250, and 1500 GeV. For the generation of this signal, all superpartners except the gluino are taken to be decoupled and heavy (i.e. beyond the reach of the LHC), the natural width of the gluino resonance is taken to be much smaller than the mass resolution of the detector. For the second case, represented by \( \lambda''_{cd} \), the mass range investigated, and no intermediate particles are produced in the gluino decay. Simulation of the CMS detector response is performed using the Geant4 [24] package.

4. Event selection

Events recorded with the six-jet trigger described above are required to contain at least one reconstructed primary vertex [16]. Since this analysis targets pair-produced three-jet resonances that naturally yield high jet multiplicity, we require events to contain at least six jets with \( |\eta| < 2.5 \). To ensure that the trigger is fully efficient, we impose minimal requirements that the \( p_T \) thresholds of the fourth and sixth jets are at least 80 and 60 GeV, respectively, though we impose higher thresholds for two of our three selections, as described below.

We use the jet-ensemble technique [8,9] in this analysis to combine the six highest-\( p_T \) jets in each event into all possible unique triplets. Each event that satisfies all selection requirements will yield 20 combinations of jet triplets. For signal events, no more than two of these triplets can be correct reconstructions of the pair-produced gluinos, with the remaining 18 triplets being incorrect combinations of jets. Thus, background triplets arising from SM multijet events are supplemented by “incorrect” jet-triplet combinations from the signal events themselves. To obtain sensitivity to the presence of a three-jet resonance, an additional requirement is placed on each jet triplet to preferentially remove SM background and incorrectly combined signal triplets. This selection criterion exploits the constant invariant mass of correctly reconstructed signal triplets and the observed linear correlation between the invariant mass and scalar sum of jet \( p_T \) for background triplets and incorrectly combined signal triplets:

\[
M_{jjj} < \left( \sum_{i=1}^{3} p_T^i \right) - \Delta,
\]

where \( M_{jjj} \) is the triplet invariant mass, the \( p_T \) sum is over the three jets in the triplet (triplet scalar \( p_T \)), and \( \Delta \) is an empirically
the expectations imposed by the trigger. We find that the peak position of as broad a range of gluino masses as possible given the restrictions.

This simple $\Delta$ window around the mass peak with a width corresponding to twice the number of signal and background triplets is calculated within a window from data. The number of background triplets obtained from data. The number of signal triplets to the square root of the number of signal triplets plus the expected gluino-mass resolution. This procedure is repeated for different thresholds on the sixth-jet $p_T$ in steps of 10 GeV, for a given gluino mass. For the inclusive search, the focus is on masses that are higher than those previously excluded by the jet-ensemble technique, so the mass range of the search starts around 400 GeV. We find that a requirement of $p_T \geq 110$ GeV on the sixth jet maximises the signal significance in this mass range.

The use of b-jet identification enables us to perform a heavy-flavour search in addition to our inclusive search for three-jet resonances. The combined secondary vertex (CSV) algorithm uses variables from reconstructed secondary vertices along with track-based lifetime information to identify b jets. The tagging efficiency for b jets changes with the $p_T$ of the jet, ranging from 70% for jets with $100 \leq p_T \leq 200$ GeV to 55% for jets with $p_T > 500$ GeV. We study different b-tagging requirements for signal events with simulated gluinos that have heavy-flavour decays and use the same definition of the signal significance as for the sixth-jet $p_T$ optimisation to determine the best choice. The CSV medium operating point, with a mistagging rate of about 1% for light-flavour jets, is found to be the optimal choice for detecting a potential signal in this analysis. The requirement that each event contain at least one b-tagged jet (b tag) increases the signal significance, and the additional requirement that all selected triplets have a b tag removes a large portion of the incorrectly combined signal triplets.

For the heavy-flavour analysis, we distinguish between a low-mass region covering gluino masses between 200 and 600 GeV and a high-mass region covering larger gluino masses. For the low-mass region, we maximise signal acceptance by using jet-$p_T$ cuts on the sixth jet, ranging from $100 \leq p_T \leq 200$ GeV and $p_T > 500$ GeV. We study different b-tagging requirements for signal events with simulated gluinos that have heavy-flavour decays and use the same definition of the signal significance as for the sixth-jet $p_T$ optimisation to determine the best choice. The CSV medium operating point, with a mistagging rate of about 1% for light-flavour jets, is found to be the optimal choice for detecting a potential signal in this analysis. The requirement that each event contain at least one b-tagged jet (b tag) increases the signal significance, and the additional requirement that all selected triplets have a b tag removes a large portion of the incorrectly combined signal triplets.

For the high-mass region, the sixth jet is required to have $p_T \geq 110$ GeV. For both the low- and high-mass regions, the value $\Delta = 110$ GeV is used. All-hadronic $t\bar{t}$ event production is a significant background in the low-mass region. We use $t\bar{t}$ events that produce triplets with masses in this region to help validate our analysis technique, as described below.
High-mass signal events, for both the light- and heavy-flavour signal models, have a more spherical shape than background events, which typically contain back-to-back jets and thus have a more linear shape. To significantly reduce the background in the high-mass searches, we use a sphericity variable, where the gluinos decay to light-flavour jets. Event-level selection requirements for the inclusive, low-mass search are applied, except for the triplet-level diagonal selection (Eq. (1)). All distributions are normalised to unit area. The simulated SM multijet events are generated using MadGraph [27] with showering performed by Pythia.

High-mass signal events, for both the light- and heavy-flavour signal models, have a more spherical shape than background events, which typically contain back-to-back jets and thus have a more linear shape. To significantly reduce the background in the high-mass searches, we use a sphericity variable, where the $\lambda_i$ variables are eigenvalues of the following tensor [22]:

$$S_{\alpha \beta} = \frac{\sum_i P_i^\alpha P_i^\beta}{\sum_i |P_i|^2},$$

(3)

where $\alpha$ and $\beta$ label separate jets, and the sphericity $S$ is calculated using all jets in each event. A comparison of the sphericity variable for data, simulated SM multijet events, and three different simulated gluino masses can be seen in Fig. 3. For the inclusive search and the high-mass, heavy-flavour search, selected events are required to have $S \geq 0.4$, which is based on the optimisation of the number of expected signal events divided by the square root of the number of signal-plus-background events. No sphericity requirement is used for the low-mass, heavy-flavour selection because low-mass signal events do not have a significant shape difference from background events.

To conclude, we define three different search regions for this analysis with specific selection criteria applied as previously discussed and summarised in Table 1.

5. Background estimation and signal extraction

The dominant background for this search comes from SM multijet events, which arise from perturbative QCD processes of order $O(\alpha_s^2)$ and higher. The invariant mass shape of incorrectly combined signal triplets is found to be similar to that of the background from SM multijet processes, such that the combined distribution is consistent with that of SM multijets alone. Moreover, because the normalisation of the background component ($P_0$ in Eq. (2)) is unconstrained, any incorrectly combined signal triplets, if present, would be absorbed into the background estimate. The triplet invariant mass distribution for the background decreases smoothly with increasing mass, and we model this background using a four-parameter function (Eq. (2)) fit directly to the data, except in the case of the low-mass, heavy-flavour search.

For the low-mass, heavy-flavour search, there is an additional background contribution from all-hadronic $t\bar{t}$ events. These events are modelled using the MadGraph [27] generator, and the expected number of $t\bar{t}$ events is determined from the next-to-next-to-leading-order (NNLO) cross section of $245.8^{+8.7}_{-10.5}$ pb [28]. The shape of the contribution from SM multijet processes is modelled with a statistically independent data sample, constructed by imposing a veto on b-tagged jets while retaining all other selection requirements. This sample is referred to as the b-jet control region, and the combination of simulated $t\bar{t}$ events and the background from SM multijet processes, modelled by this control region, gives the total SM background estimate for the low-mass, heavy-flavour analysis.

A comparison of the background estimate to the data is performed, in which the data are fit using a binned maximum likelihood method with either the four-parameter function of Eq. (2) for the inclusive analysis and the high-mass, heavy-flavour analysis, or
the background shape described above for the low-mass, heavy-flavour analysis. Fig. 4 shows a comparison between the three-jet invariant mass distribution in data and the background estimate for the inclusive analysis. Fig. 5 shows the comparisons between data and background estimates for the low- and high-mass heavy-flavour analyses. In all three cases, no statistically significant deviations from the data are observed.

As a validation of the analysis technique, we consider the $t\bar{t}$ triplets as a signal with the background solely composed of triplets from SM multijet processes, whose shape is modelled by the b-jet control region, with the small amount of simulated $t\bar{t}$ events without b tags subtracted. The $t\bar{t}$ cross section is extracted based on the contribution of its signal triplets and is compared with the theoretical prediction for the cross section of $245^{+8}_{-8} \text{ pb}$. The measurement yields a result of $205^{\pm 28} \text{ pb}$ (combined statistical and systematic uncertainties), which is within less than two standard deviations from the theoretical value, thereby showing our technique can successfully reconstruct hadronically decaying $t\bar{t}$ events.

To obtain an estimate of the number of signal triplets expected after all selection criteria are applied, the sum of a Gaussian function that represents the signal and a four-parameter function (Eq. (2)) that models the incorrectly combined signal triplets is fit to the simulated $M_{jjj}$ distribution for each gluino mass. The Gaussian component of the fit provides the estimate for the expected number of signal triplets. The factors in this overall triplet signal efficiency ($A \times \epsilon$) are both parametrised as functions of gluino mass, as shown in Fig. 6. The width of the Gaussian function modelling the signal varies according to the detector resolution, ranging from 17 to 70 GeV for gluino masses from 200 to 1500 GeV. The $A \times \epsilon$ ranges from about 0.003 to 0.033 for the inclusive search for gluino masses from 400–1500 GeV, and, for the heavy-flavour search, from 0.005 to 0.04 for masses from 200–600 GeV, and from 0.008 to 0.015 for masses from 600–1500 GeV. For high-mass gluinos, the $A \times \epsilon$ flattens slightly because of the decreased efficiency to reconstruct triplets in the Gaussian signal peak.

6. Systematic uncertainties

Systematic uncertainties in the signal acceptance are assigned in the following manner. For uncertainties related to the jet energy scale (JES) [20], the jet energy corrections are varied within their uncertainties for each signal mass, and then the entire selection procedure is repeated to determine the parametrised values of the $A \times \epsilon$. The largest difference from the nominal values is taken as a systematic uncertainty. To evaluate the systematic uncertainty associated with the level of simulated ISR and FSR for signal events, i.e. the spontaneous emission of gluons from incoming or outgoing participants of the hard interaction, dedicated signal samples are generated where the relative amounts of ISR and FSR are coherently increased or decreased with respect to the nominal setting of the Pythia event generator [29]. The parameter controlling the amount of ISR (PARP(67)) is varied around its central value of 2.5 by $\pm 0.5$ and that for the FSR (PARP(71)) is varied from 2.5 to 8, with a nominal value of 4.0. For each sample, the rederived $A \times \epsilon$ is compared to the nominal value, and the difference is taken as the systematic uncertainty. Analogously, an uncertainty is assigned to account for the effects of multiple pp
collisions in an event (pileup) by reweighting all MC signal samples such that the distribution of the number of interactions per bunch crossing is shifted, high and low, by one standard deviation compared with that found in data [30]. For the analyses using b tagging, an uncertainty is assigned based on the scale factor that comprises the differences in b-tagging efficiencies in data compared with simulation [26]. The same procedure as outlined above is repeated, where the b-tagging scale factors are varied within their uncertainties, and the effect on $A \times \epsilon$ is evaluated. Uncertainties in the fit parameters of the Gaussian signal are used as an additional systematic uncertainty for each mass point. Finally, an overall systematic uncertainty of 2.6% is assigned to the integrated luminosity measurement [12]. The ranges in the values of these uncertainties are summarised in Table 2. Systematic uncertainties related to the signal and background shapes are discussed in Section 7.

7. Results and limits

The three-jet invariant mass distributions are examined for a Gaussian signal peak on top of the smoothly falling background distribution. As has been described, this analysis uses different selection criteria to search for resonances coupling to light-flavour and to heavy-flavour quarks, with the latter search done separately in low-mass and high-mass regions. In the analysis of each of the three selections, the background normalisation parameter is unconstrained and is therefore determined by the SM multijet component of the combined fit. For the function describing the background, the initial values of its parameters are taken from the background-only hypothesis fit to the data, while they are allowed to float in the background-plus-signal hypothesis fits for the limit calculation. The signal is modelled with Gaussians defined by the width and $A \times \epsilon$ curves shown in Fig. 6. The uncertainties in the expected number of signal triplets are included as log-normal constraints, where the uncertainty for the width of the Gaussian includes a 10% systematic uncertainty to account for jet resolution effects [20]. For the $t\bar{t}$ background estimate, uncertainties in both the shape and normalisation are included. In addition to those already discussed in the previous section, uncertainties due to ambiguities in the parton shower matching procedure between the MADGRAPH and PYTHIA event generators, as well as those due to the dependence on the renormalisation and factorisation scale, are taken into account.

Upper limits are placed on the cross section times branching fraction for the production of three-jet resonances. A modified-frequentist approach, using the CLs [31,32] technique and a profile likelihood as the test statistic, is employed. Limits are calculated with the frequentist asymptotic calculator implemented in the RooStats [33,34] package. The full CLs calculations give similar limits within a few percent, and closure tests where a fixed signal is injected yield consistent coverage. The observed and expected 95% confidence level (CL) upper limits on the gluino pair-production cross section times branching fraction as a function of gluino mass are presented in Fig. 7. The solid red lines in the figure show the next-to-leading-order (NLO) plus next-to-leading-logarithm (NLL) cross sections for gluino pair production [35–39], and the dashed red lines indicate the corresponding one-standard-deviation ($\sigma$) uncertainties, which range between 15% and 43%. To quote final results, we use the points where the $-1\sigma$-uncertainty curve for the NLO + NLL cross section crosses the expected- and observed-limit curves. We additionally quote the result where the central theoretical curve intersects the limit curves.

The production of gluinos undergoing RPV decays into light-flavour jets is excluded at 95% CL for gluino masses below 650 GeV, with a less conservative exclusion of 670 GeV based upon the theory value at the central scale. The respective expected limits are 755 and 795 GeV. These results extend the limit of 460 GeV [10] obtained with the 7 TeV CMS dataset. Gluinos whose decay includes a heavy-flavour jet are excluded for masses between 200 and 835 GeV, which is the most stringent mass limit to date for this model of RPV gluino decay, with the less conservative exclusion up to 855 GeV from the central theoretical value. The respective expected limits are 825 and 860 GeV. While a smaller phase space is probed in the heavy-flavour search, the limits extend to higher masses because of the reduction of the background.

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**Table 2**

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<tr>
<th>Source of systematic uncertainty</th>
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<td>ISR/FSR</td>
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<td>Pileup</td>
<td>1–5%</td>
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<td>b tagging</td>
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<td>Luminosity</td>
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**Figure 6.** The signal parametrisation shown as a function of gluino mass for the inclusive search. The Gaussian signal width (left) and the $A \times \epsilon$ parametrisation (right) versus signal mass are both shown. The hatched bands represent the combined statistical and systematic uncertainties.
include a heavy-flavour jet in their decay have been excluded at 95% CL for masses between 200 and 835 GeV, which is the most stringent limit to date for this model of gluino decay.

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8. Summary

A search for hadronic resonance production in pp collisions at a centre-of-mass energy of 8 TeV has been conducted by the CMS experiment at the LHC with a data sample corresponding to an integrated luminosity of 19.4 fb\(^{-1}\). The approach is model independent, with event selection criteria optimised using the RPV supersymmetric model for gluino pair production in a six-jet final state. Two different scenarios for this RPV decay have been considered: gluinos decaying exclusively to light-flavour jets, and gluinos decaying to one b-quark jet and two light-flavour jets, with the assumption in both cases of a 100% branching fraction for gluinos decaying to quark jets. Methods based on data have been used to derive estimates of background from SM multijet processes. Events with high jet multiplicity and a large scalar sum of jet \(p_T\) have been analysed for the presence of signal events, and no deviation has been found between the standard model background expectations and the measured mass distributions. The production of gluinos undergoing RPV decay into light-flavour jets has been excluded at the 95% CL for masses below 650 GeV. Gluinos that

**References**


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


Institut für Experimentelle Kernphysik, Karlsruhe, Germany


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

L. Gouskos, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Athens, Athens, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioannina, Ioannina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary
S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S.B. Beri, V. Bhatnagar, N. Dholiya, R. Gupta, M. Kaur, M.Z. Mehta, M. Mittal, N. Nishu, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shrivastava

University of Delhi, Delhi, India


Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India


Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei, H. Bakhshiansohi, S.M. Etesamii, A. Fahim, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Grunewald

University College Dublin, Dublin, Ireland


INFN Sezione di Bari, Bari, Italy
Università di Bari, Bari, Italy
Politecnico di Bari, Bari, Italy


INFN Sezione di Bologna, Bologna, Italy
Università di Bologna, Bologna, Italy

S. Albergo, G. Cappello, M. Chiorboli, S. Costa, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Catania, Catania, Italy
Università di Catania, Catania, Italy
G. Barbaglia, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, E. Gallo, S. Gonzi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, A. Trofiano

G. Barbaglia, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, E. Gallo, S. Gonzi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, A. Trofiano

INFN Sezione di Firenze, Firenze, Italy
Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbrì, D. Piccolo
INFN Laboratori Nazionali di Frascati, Frascati, Italy


INFN Sezione di Genova, Genova, Italy
Università di Genova, Genova, Italy


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Università di Genova, Genova, Italy


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Università di Genova, Genova, Italy

S. Buontempo, N. Cavallo, F. Fabozzi, A.O.M. Iorio, L. Lista, S. Meola, M. Merola, P. Paolucci

INFN Sezione di Napoli, Napoli, Italy
Università di Napoli ‘Federico II’, Napoli, Italy
Università della Basilicata (Potenza), Napoli, Italy
Università G. Marconi (Roma), Napoli, Italy

S. Buontempo, N. Cavallo, F. Fabozzi, A.O.M. Iorio, L. Lista, S. Meola, M. Merola, P. Paolucci

INFN Sezione di Napoli, Napoli, Italy
Università di Napoli ‘Federico II’, Napoli, Italy
Università della Basilicata (Potenza), Napoli, Italy
Università G. Marconi (Roma), Napoli, Italy

S. Buontempo, N. Cavallo, F. Fabozzi, A.O.M. Iorio, L. Lista, S. Meola, M. Merola, P. Paolucci

INFN Sezione di Napoli, Napoli, Italy
Università di Napoli ‘Federico II’, Napoli, Italy
Università della Basilicata (Potenza), Napoli, Italy
Università G. Marconi (Roma), Napoli, Italy

M. Gabusi, S.P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy

M. Gabusi, S.P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy

M. Gabusi, S.P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy

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INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy

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INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy

M. Gabusi, S.P. Ratti, C. Riccardi, P. Vitulo

INFN Sezione di Padova, Padova, Italy
Università di Padova, Padova, Italy
Università di Trento (Trento), Padova, Italy


INFN Sezione di Pisa, Pisa, Italy
Università di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy


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Scuola Normale Superiore di Pisa, Pisa, Italy


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Università di Pisa, Pisa, Italy
Scuola Normale Superiore di Pisa, Pisa, Italy


INFN Sezione di Roma, Roma, Italy
Università di Roma, Roma, Italy
N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, R. Bellan\textsuperscript{a,b}, C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, S. Casasso\textsuperscript{a,b}, M. Costa\textsuperscript{a,b}, A. Degano\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, M. Musich\textsuperscript{a}, M.M. Obertino\textsuperscript{a,c}, G. Ortona\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a,2}, A. Potenza\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, A. Solano\textsuperscript{a,b}, A. Staiano\textsuperscript{a}, U. Tamponi\textsuperscript{a}\textsuperscript{a}\textsuperscript{INFN Sezione di Torino, Torino, Italy}\textsuperscript{b}\textsuperscript{Università di Torino, Torino, Italy}\textsuperscript{c}\textsuperscript{Università del Piemonte Orientale (Novara), Torino, Italy}\textsuperscript{S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a,2}, G. Della Ricca\textsuperscript{a,b}, B. Gobbo\textsuperscript{a}, C. La Licata\textsuperscript{a,b}, M. Marone\textsuperscript{a,b}, D. Montanino\textsuperscript{a,b}, A. Penzo\textsuperscript{a}, A. Schizzi\textsuperscript{a,b}, T. Umer\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}\textsuperscript{INFN Sezione di Trieste, Trieste, Italy}\textsuperscript{b}\textsuperscript{Università di Trieste, Trieste, Italy}\textsuperscript{S. Chang, T.Y. Kim, S.K. Nam}\textsuperscript{Kangwon National University, Chunchon, Republic of Korea}\textsuperscript{D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, D.C. Son}\textsuperscript{Kyungpook National University, Daegu, Republic of Korea}\textsuperscript{J.Y. Kim, Zero J. Kim, S. Song}\textsuperscript{Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea}\textsuperscript{S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, S.K. Park, Y. Roh}\textsuperscript{Korea University, Seoul, Republic of Korea}\textsuperscript{M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu}\textsuperscript{University of Seoul, Seoul, Republic of Korea}\textsuperscript{Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu}\textsuperscript{Sungkyunkwan University, Suwon, Republic of Korea}\textsuperscript{I. Grigelionis, A. Juodagalvis}\textsuperscript{Vilnius University, Vilnius, Lithuania}\textsuperscript{H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz\textsuperscript{34}, R. Lopez-Fernandez, J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas}\textsuperscript{Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico}\textsuperscript{S. Carrillo Moreno, F. Vazquez Valencia}\textsuperscript{Universidad Iberoamericana, Mexico City, Mexico}\textsuperscript{H.A. Salazar Ibarguen}\textsuperscript{Benemérita Universidad Autónoma de Puebla, Puebla, Mexico}\textsuperscript{E. Casimiro Linares, A. Morelos Pineda}\textsuperscript{Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico}\textsuperscript{D. Krofcheck}\textsuperscript{University of Auckland, Auckland, New Zealand}\textsuperscript{P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood}\textsuperscript{University of Canterbury, Christchurch, New Zealand}

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, Santa Barbara, USA


California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA


University of Colorado at Boulder, Boulder, USA


Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA


Fermi National Accelerator Laboratory, Batavia, USA