

# Search for light long-lived particles decaying to displaced jets in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

The CMS Collaboration\*

## Abstract

A search for light long-lived particles decaying to displaced jets is presented, using a data sample of proton-proton collisions at a center-of-mass energy of 13.6 TeV, corresponding to an integrated luminosity of  $34.7 \text{ fb}^{-1}$ , collected with the CMS detector at the CERN LHC in 2022. Novel trigger, reconstruction, and machine-learning techniques were developed for and employed in this search. After all selections, the observations are consistent with the background predictions. Limits are presented on the branching fraction of the Higgs boson to long-lived particles that subsequently decay to quark pairs or tau lepton pairs. An improvement by up to a factor of 10 is achieved over previous limits for models with long-lived particle masses smaller than 60 GeV and proper decay lengths smaller than 1 m. The first constraints are placed on the fraternal twin Higgs and folded supersymmetry models, where the lower bounds on the top quark partner mass reach up to 350 GeV for the fraternal twin Higgs model and 250 GeV for the folded supersymmetry model.

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# 1 Introduction

Long-lived particles (LLPs) that have macroscopic decay lengths ( $\gtrsim 0.1$  mm) are ubiquitous in both the standard model (SM) and beyond-the-SM (BSM) scenarios. Many models of BSM physics naturally predict the production of hadronically decaying LLPs at the CERN LHC, which leads to displaced jets (DJs) whose origins are far from the interaction point. Examples include, but are not limited to, supersymmetry (SUSY) [1–17], dark sectors (DSs) or other models with dark matter candidates [18–31], models with heavy neutral leptons [32–35], baryogenesis triggered by weakly interacting massive particles [36–38], and models with a “high-quality” axion [39, 40]. In such cases, a displaced-jet search is a powerful tool to address numerous long-standing puzzles in particle physics.

In this paper, we present a search for at least one LLP produced in proton-proton (pp) collisions at the LHC and decaying inside the inner tracking system of the CMS detector [41, 42]. Data used in this search were collected at a center-of-mass energy of 13.6 TeV in 2022, corresponding to an integrated luminosity of  $34.7 \text{ fb}^{-1}$ . The target signature is a pair of jets, referred to as a dijet, arising from the LLP decay. Displaced vertices (DVs) can be reconstructed using the displaced tracks associated with the dijet. The properties of the tracks, DVs, and dijet are used to discriminate between exotic LLP signatures and SM background processes. We focus on light LLPs with masses  $m_{\text{LLP}} \lesssim 60 \text{ GeV}$  that decay to quarks or tau leptons, as this is an important and largely unconstrained phase space. This search introduces new trigger, reconstruction, and machine learning techniques to increase sensitivity to light LLPs, bringing up to a factor of 10 improvement compared to previous searches [43–46].

The benchmark signature for this search is an exotic decay of the 125 GeV Higgs boson to two long-lived neutral scalars  $S$  ( $H \rightarrow SS$ ), each of which further decays to a pair of SM fermions. The Feynman diagram for this process is shown in Fig. 1. We focus on hadronic final states, including bottom quarks ( $S \rightarrow b\bar{b}$ ), down quarks ( $S \rightarrow d\bar{d}$ ), and tau leptons ( $S \rightarrow \tau^+\tau^-$ , simply denoted as  $S \rightarrow \tau\tau$ ). The  $S \rightarrow b\bar{b}$  and  $S \rightarrow d\bar{d}$  decays are chosen as representative of LLP decays to heavy-flavor and light-flavor quarks, and the sensitivity of this search is similar for different quark flavor assumptions. This benchmark signature is motivated by the Higgs portal scenario [47], where the Higgs boson acts as a portal to DSs containing new SM gauge singlet particles. A well-motivated version of the Higgs portal scenario is “neutral naturalness” [28–30], realizations of which include the twin Higgs [26], folded SUSY [48], and quirky little Higgs [27] models. In neutral naturalness, the Higgs boson mass is protected by a global symmetry between the DS and the SM sector. This scenario also has important implications for the nature of dark matter [49–55], dark phase transitions and baryogenesis in the early universe [56–60], the origin of neutrino masses [61, 62], and proposed resolutions for tensions in cosmological measurements [54, 63]. The lightest hadronic state of the DS is usually a hidden glueball, which has a suppressed decay back to SM particles through the Higgs portal [64, 65]. Therefore, the hidden glueball is usually long-lived and decays to DJs, preferring displaced b jets because of mixing between the DS and the SM Higgs boson. The hidden glueball can be produced in decays of the Higgs boson and therefore equates to the generic  $S$  in the benchmark signature. The hidden glueball is theoretically preferred to have a mass between 10 and 60 GeV [29, 30, 66]. Because of hadronization in the DS, the Higgs boson can decay to more than two hidden glueballs, especially when the glueball mass is small [67]. Nevertheless, the two-body  $H \rightarrow SS$  decay is still the most common decay topology in the glueball mass range considered here and is therefore taken as the benchmark. This search is also sensitive to similar signatures with light hadronically decaying LLPs that appear in many other BSM scenarios.

The paper is organized as follows. A brief description of the CMS detector is introduced in

Section 2. The simulated samples are described in Section 3. Section 4 details the object reconstruction and displaced-jet triggers (DJTs). Section 5 describes the DV reconstruction and LLP identification algorithms. Section 6 describes the event selections and the background estimation method. The systematic uncertainties are presented in Section 7. The results and interpretations are described in Section 8. The paper is summarized in Section 9. Tabulated results are provided in the HEPData record for this analysis [68]. A glossary of the acronyms used in the paper is provided in Appendix A.

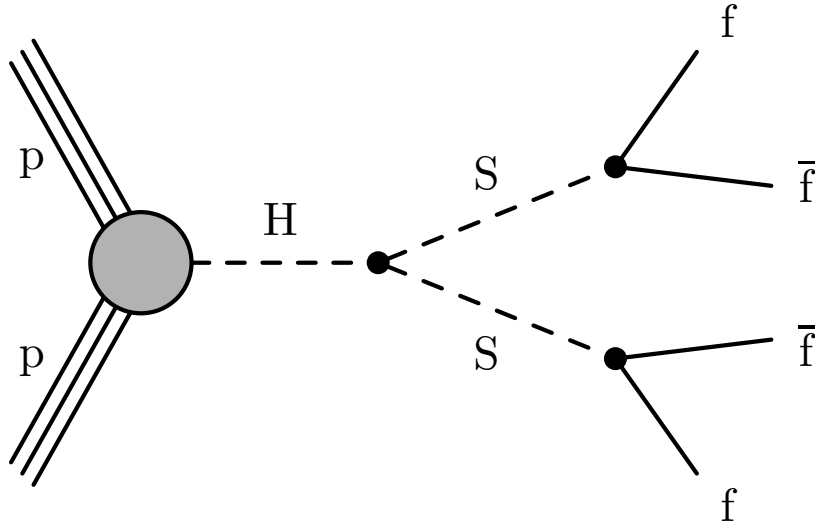


Figure 1: The Feynman diagram for the benchmark signal model, in which the SM-like Higgs boson with a mass of 125 GeV decays to two long-lived neutral scalars  $S$ , and each of them decays to a pair of SM fermions.

## 2 The CMS detector

The central feature of the CMS apparatus 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 electromagnetic calorimeter (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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range  $|\eta| < 3.0$ . During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1856 silicon pixel and 15 148 silicon strip detector modules. Details on the pixel detector can be found in Ref. [69]. For nonisolated particles with  $1 < p_T < 10$  GeV and  $|\eta| < 3.0$ , the track resolutions are typically 1.5% in  $p_T$  and 20–75  $\mu\text{m}$  in the transverse impact parameter ( $d_{xy}$ ) [70].

In the region  $|\eta| < 1.74$ , the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth ( $\phi$ ). 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, which are subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system. 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 fixed latency of about  $4\ \mu\text{s}$  [71]. 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 [72].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [41].

### 3 Event simulation

The backgrounds in this search include nuclear interactions, long-lived SM hadrons, and misreconstructed DVs formed by unrelated crossing tracks. Such phenomena mainly occur in SM events containing jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events. The simulated QCD multijet sample is generated at leading order (LO) with PYTHIA 8.306 [73]. Parton showering and hadronization are simulated with PYTHIA, using the CP5 underlying-event tune [74]. The simulated QCD multijet sample is mainly used to guide the analysis strategy, train the LLP-identification taggers, and estimate systematic uncertainties, while the background estimation for this search is purely determined from data.

The POWHEG 2.0 [75–78] program is used to generate events containing a 125 GeV Higgs boson via gluon-gluon fusion at next-to-LO, which is the dominant production mode of the SM-like Higgs boson. The process  $H \rightarrow S\bar{S}$  and the  $S \rightarrow b\bar{b}$ ,  $S \rightarrow d\bar{d}$ , and  $S \rightarrow \tau\tau$  decays are then simulated using PYTHIA. Signal samples are produced with LLP masses  $m_S$  of 15, 23, 30, 40, and 55 GeV, and mean proper decay lengths ( $c\tau_0$ ) from 1 mm to 1 m. The samples are normalized according to the gluon-gluon production cross section of a 125 GeV Higgs boson at a center-of-mass energy of 13.6 TeV [79].

Both generators use the NNPDF3.1 next-to-next-to-LO parton distribution functions [80]. The detailed CMS detector response is modeled with a GEANT4-based [81] simulation. The effects of additional pp interactions within the same or nearby bunch crossings (“pileup”) are included.

### 4 Object reconstruction and displaced-jet triggers

Jets are reconstructed from the energy deposits in the calorimeter towers, clustered using the anti- $k_T$  algorithm [82, 83] with a distance parameter of 0.4. Identification of the leading primary vertex (PV) is a prerequisite for the selection of DJs. The leading PV is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [84]. We consider tracks and jets reconstructed both at the HLT and using the full event reconstruction software, with the former objects used in the DJTs and the latter objects, described as “offline”, used for analyzing the events collected with the DJTs.

The data were collected with dedicated triggers aimed at selecting events with DJs from LLP

decays. In addition to the DJTs implemented in 2017–2018 [43], new DJTs were also been developed and implemented in 2022 [85] to significantly improve the trigger efficiencies for light LLPs. Displaced jets are identified, or “tagged”, in the HLT using two different requirements. The first, referred to as the “inclusive” tagging requirement, requires that the jet has at most one associated prompt track. Prompt tracks are defined to have  $p_T > 1$  GeV, a  $d_{xy}$  with respect to the leading PV smaller than 0.5 mm, and a  $d_{xy}$  significance ( $d_{xy}/\sigma_{xy}$ , the ratio of  $d_{xy}$  and its uncertainty) smaller than 5.0. The second, referred to as the “displaced” tagging requirement, encompasses the inclusive tagging requirement and additionally requires that if there is exactly one associated prompt track, there should also be at least one associated track with  $p_T > 1$  GeV and  $d_{xy} > 0.3$  mm.

Two DJTs are implemented. The first trigger requires  $H_T > 430$  GeV, where  $H_T$  is the scalar  $p_T$  sum of all jets with  $p_T > 40$  GeV and  $|\eta| < 2.5$ . The trigger also requires the presence of at least two jets satisfying  $p_T > 40$  GeV,  $|\eta| < 2.0$ , and the inclusive tagging requirement. The events selected by this trigger are further required to have an offline  $H_T > 450$  GeV to make sure the online  $H_T$  requirement reaches full efficiency and the difference between the observed and simulated efficiencies is negligible. The second trigger is seeded by a first-level trigger that requires  $H_T > 240$  GeV and the presence of a muon with  $p_T > 6$  GeV, in order to improve the trigger efficiencies for LLPs with heavy-flavor decays. The trigger further requires that there are at least two jets satisfying  $p_T > 40$  GeV,  $|\eta| < 2.0$ , and the displaced tagging requirement. The events selected by this trigger are further required to have an offline  $H_T > 240$  GeV.

The overall trigger efficiencies are  $\approx 0.4$ – $1.0\%$  for  $S \rightarrow b\bar{b}$  and  $S \rightarrow d\bar{d}$  in most of the considered mass and lifetime range. These efficiencies degrade to  $\approx 0.2$ – $0.7\%$  for  $S \rightarrow \tau\tau$ , because of the nonzero branching fraction for tau leptons to decay leptonically. Compared to the DJTs implemented in 2017–2018, the new trigger efficiencies are a factor of 4–17 higher for the  $H \rightarrow SS$ ,  $S \rightarrow b\bar{b}$  signature in the parameter ranges explored here.

## 5 Displaced-vertex reconstruction and long-lived particle identification

After the trigger selections, dijet candidates are formed from all possible pairs of offline jets in the event using the jets with  $p_T > 40$  GeV and  $|\eta| < 2.0$ . The track candidates used in this search are required to satisfy  $p_T > 1$  GeV and pass the high-purity selection [86]. For a given dijet candidate, the track candidates associated with each jet are selected by requiring that  $\Delta R < 0.5$ , where  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  is the angular distance between the jet axis and the track direction. When a track satisfies  $\Delta R < 0.5$  for both jets in the dijet candidate, it is associated with the jet with the smaller  $\Delta R$ .

For each dijet candidate, DVs are reconstructed using the associated displaced tracks that satisfy  $d_{xy} > 0.5$  mm and  $d_{xy}/\sigma_{xy} > 5.0$ . Two DV reconstruction approaches are taken. The first approach is to directly apply adaptive vertex reconstruction (AVR) [87, 88], which is an iterative application of the adaptive vertex fitter (AVF) [89], to all the associated displaced tracks. This approach efficiently reconstructs the LLP decay vertex. The second approach is to cluster the displaced tracks first, based on their distances of closest approach and points of closest approach (PCAs), which improves the efficiency to reconstruct the additional DVs arising from processes such as b hadron decays in  $S \rightarrow b\bar{b}$ . During the clustering, each displaced track is treated as a seed track, and a cluster is then formed by examining the compatibility between the seed track and other displaced tracks based on the distances of closest approach, PCAs, and the angles between the track directions and the PV-to-PCA direction. The AVR is then applied

to each cluster of tracks, resulting in another set of DVs. The DVs from the two approaches are then combined to form a single set of DVs. During the initial reconstruction, some displaced tracks originating from a given DV may not be associated with it after the vertex fitting. To mitigate this effect, all the displaced tracks and DVs are reexamined, and each DV is refitted with the AVF using all the displaced tracks that have a three-dimensional impact parameter significance ( $d_{xyz}/\sigma_{xyz}$ , the ratio of the three-dimensional impact parameter  $d_{xyz}$  and its uncertainty) smaller than 5.0 with respect to the DV. After the refitting, only the vertices with a  $\chi^2$  per degree of freedom ( $\chi^2/\text{dof}$ ) smaller than 5.0 are kept. To avoid duplicated vertices, a given DV is removed from the DV list if it shares at least 20% of its tracks with another DV and the significance of the distance between the two DVs is smaller than 3.0.

With the dijet candidates and their associated tracks and DVs as inputs, we employ graph neural networks (GNNs) [90, 91] as taggers to identify the dijets arising from LLP decays. The tracks and DVs associated with a given dijet candidate can naturally form graphs, where the tracks and DVs can be viewed as nodes of the graphs, while the track-to-vertex, vertex-to-track, and track-to-track relations can be viewed as the edges that connect two nodes. For each type of relation, a relation function can be built using the node and edge features. For example, for track-to-vertex relations  $R_{ik}$ , they can be described by a relation function  $f_{R_{\text{track-vertex}}}$ :

$$R_{ik} \equiv f_{R_{\text{track-vertex}}}(x_i, y_k, e_{ik}), \quad (1)$$

where  $x_i$  represents track features,  $y_k$  represents DV features,  $e_{ik}$  represents track-to-vertex edge features like the track-to-DV association, and  $i$  ( $k$ ) is the index of the tracks (DV). The DV features can then be updated based on the track-to-vertex relations using the message passing formalism [91]:

$$y'_k = f_{O_{\text{vertex}}}\left(y_k, \sum_i R_{ik}\right), \quad (2)$$

where  $y'_k$  represents the updated DV features, and  $f_{O_{\text{vertex}}}$  is referred to as the vertex objective function. The functions  $f_{R_{\text{track-vertex}}}$  and  $f_{O_{\text{vertex}}}$  are learned during the GNN training. The track-to-track and vertex-to-track relations are similarly incorporated and applied to track features. The updated DV and track features are further processed to provide the discrimination between the LLP signature and background processes.

Two GNN-based displaced-dijet taggers are implemented. The first one, referred to as the ‘‘displaced’’ tagger, only takes as input the associated displaced tracks and DVs. The second one, referred to as the ‘‘prompt-veto’’ tagger, only takes as input the associated tracks with  $d_{xy} < 0.3$  mm. The two taggers cover complementary characteristics of exotic LLPs: the presence of DVs from the LLP decays and the lack of prompt particles accompanying the LLP production. Moreover, the two taggers have negligible correlations for SM background processes, which is verified using simulated QCD multijet events, and thus they enable the estimation of the background yield from data.

For the displaced tagger, the input displaced tracks and input DVs are sorted according to their  $d_{xy}/\sigma_{xy}$  values in descending order. The input displaced track features include  $d_{xy}/\sigma_{xy}$ ;  $d_{xyz}/\sigma_{xyz}$ ; the distance from the PV to the crossing point of the track helix and the dijet direction in the transverse plane; whether the track is associated with the jet with a larger  $p_T$ ; and the ratio between the track energy and the energy sum of the tracks associated with the dijet. The input DV features include the vertex invariant mass and  $p_T$ ; the vertex track multiplicity; the transverse decay length significance;  $\chi^2/\text{dof}$  of the vertex fit; and the angles between the vertex momentum vector, the direction from the PV to DV, and the dijet candidate momentum direction. To characterize the track-to-vertex relations, the track-to-vertex edge features of the input

graph for each track-DV pair are taken to be the track-to-DV association;  $d_{xyz}$  and  $d_{xyz}/\sigma_{xyz}$  between the track and the DV; and the angle between the track direction and the direction of the DV displacement from the PV. The displaced tagger is built with two successive GNN blocks that update the track and DV features with track-to-track, track-to-vertex, and vertex-to-track relations, using the message passing formalism [91]. The outputs of this step are further processed with two parallel long short-term memory (LSTM) layers [92], which treat the processed track features and DV features as sequential data, representing decay chains within the LLP decay system. The LSTM outputs are further concatenated with two dijet global features: the total number of the DVs and the sum of  $d_{xy}/\sigma_{xy}$  for the tracks associated with DVs. The concatenated dijet, displaced track, and DV features are processed with a fully connected dense network to produce the final prediction score  $\mathcal{G}_{\text{displaced}}$ .

For the prompt-veto tagger, the input tracks are sorted according to  $d_{xy}/\sigma_{xy}$  in ascending order. The input track features include  $d_{xy}$ ;  $d_{xy}/\sigma_{xy}$ ; the track-to-PV associations for the leading PV and pileup vertices; the track-to-jet associations; and the ratio between the track energy and the total energy of the dijet candidate. In addition, for each pair of tracks, whether the two tracks are associated with the same PV is taken as the track-to-track edge feature for the input graph. The input track features are updated with a GNN message passing block that acts on the track-to-track relations. The outputs of the GNN block are processed with a single LSTM layer and then further processed with a fully-connected dense network, producing the final prediction score  $\mathcal{G}_{\text{prompt-veto}}$ .

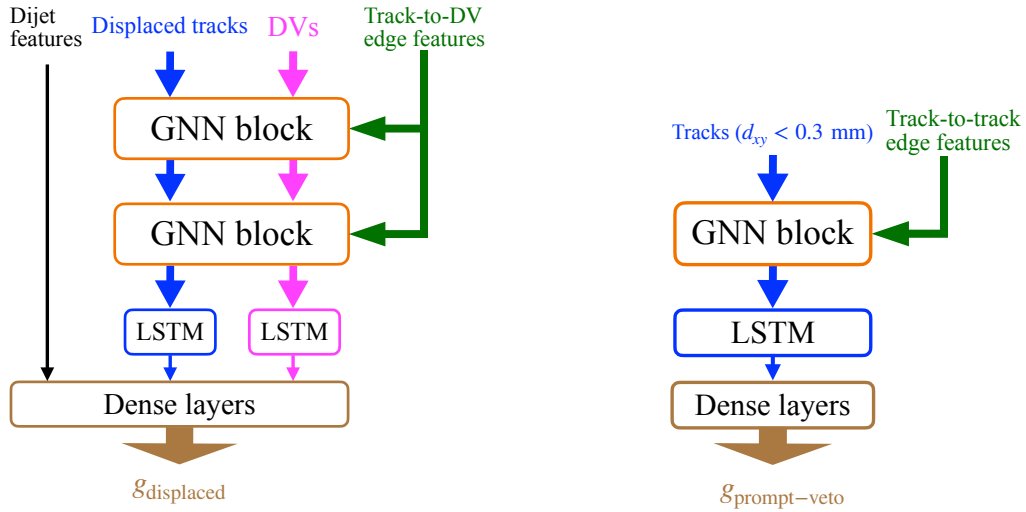


Figure 2: The architectures of the displaced (left) and prompt-veto (right) taggers. The displaced tagger takes as input the dijet global features, displaced tracks, and DVs. The prompt-veto tagger takes as input the tracks with  $d_{xy} < 0.3$  mm.

The architectures of the displaced and prompt-veto taggers are illustrated in Fig. 2. Both taggers are implemented and trained using the TENSORFLOW v2.6.0 package [93]. For the training, the binary cross entropy [94] is used as the loss function. The simulated QCD multijet sample is used as the background sample. Simulated  $H \rightarrow SS$  samples with  $S \rightarrow b\bar{b}$ ,  $m_S = 30, 40,$  and  $55$  GeV, and  $c\tau_0 = 1, 10, 100,$  and  $1000$  mm are combined to form the signal sample. In a given signal event, the dijet candidate that is the most compatible with the generated LLP decay is selected for the training, according to the distance between the reconstructed DVs and the generated LLP decay vertex, as well as the angular distance between the momenta of the dijet candidate and the generated LLP. The GNNs are trained for the  $S \rightarrow b\bar{b}$  signature because this is the most important decay channel in the Higgs portal scenarios, and the resulting GNNs



are also directly applied to the signatures with other decay channels. The DJT selections are applied to the events used for the training, and both jets in each dijet candidate are required to satisfy  $p_T > 40$  GeV and  $|\eta| < 2.0$ . Event weights are assigned during the training such that the total sums of the weights are identical for the signal and background samples. The output scores of the GNN taggers range between 0 and 1, with larger values indicating that the dijet is more likely to arise from an LLP decay.

In general, the displaced tagger achieves a background rejection factor of  $10^4$  when the signal efficiency is  $\approx 55\%$ , while the prompt-veto tagger can achieve a background rejection factor of  $10^3$  when the signal efficiency is  $\approx 30\%$ . The agreement between data and simulation is verified for the input variables and the GNN output scores, using the events collected with a prescaled control trigger that requires  $H_T > 425$  GeV.

## 6 Event selection and background estimation

In this search, after the trigger selections, we select the dijet candidates that have at least one reconstructed DV with  $\chi^2/\text{dof} < 5.0$ . The displaced and prompt-veto tagger scores are computed for each dijet candidate, and the one with the largest  $g_{\text{prompt-veto}}$  in a given event is selected. We then require that the selected dijet candidate satisfies  $g_{\text{displaced}} > 0.9985$  and  $g_{\text{prompt-veto}} > 0.985$ , determined by maximizing the 5-standard-deviation discovery potential for the  $H \rightarrow SS$ ,  $S \rightarrow b\bar{b}$  signature using the Punzi formula [95], according to the expected signal efficiencies and background yields after the selection.

We define four exclusive regions to employ the ‘‘ABCD’’ background estimation method [96].

- Region A: events with  $0.95 < g_{\text{displaced}} < 0.9985$ ,  $0.95 < g_{\text{prompt-veto}} < 0.985$ ;
- Region B: events with  $0.95 < g_{\text{displaced}} < 0.9985$ ,  $0.985 < g_{\text{prompt-veto}} < 1.0$ ;
- Region C: events with  $0.9985 < g_{\text{displaced}} < 1.0$ ,  $0.95 < g_{\text{prompt-veto}} < 0.985$ ; and
- Region D, the signal region (SR): events with  $0.9985 < g_{\text{displaced}} < 1.0$ ,  $0.985 < g_{\text{prompt-veto}} < 1.0$ .

The estimated background yield in the SR is thus:

$$N_D^{\text{exp}} = N_B N_C / N_A, \quad (3)$$

where  $N_X$  is the event yield in region X. In Eq. (3), it is assumed that there is no signal contribution to regions A–C. When interpreting the results for a given signal point, signal contributions are taken into account by performing a simultaneous fit in all regions A–D, which will be discussed in Section 8.1.

The predicted background yields and the number of observed events in the SR are shown in Fig. 3. The uncertainties in the predicted background yields come from the statistical uncertainties in regions A, B, and C. Predictions and observations are also shown for regions with smaller  $g_{\text{displaced}}$  ranges below 0.9985, achieved by corresponding adjustments to the  $g_{\text{displaced}}$  boundaries of regions A–D, in order to validate the background estimation method. The predictions and observations are summarized in Table 1. For each observation, a  $p$ -value is computed based on the lower tail of a Poisson distribution convolved with a normalized Gaussian function for the statistical uncertainty of the background prediction. The  $p$ -value is then converted to a  $Z$ -value according to the Gaussian error function, which represents the observed significance with an equivalent number of standard deviations [97]. The  $Z$ -values are also listed in Table 1, with absolute values all below 1.3 standard deviations, indicating good agreement between the predictions and observations.

Table 1: The predicted background yields and observations in the region with  $g_{\text{prompt-veto}} > 0.985$  for different  $g_{\text{displaced}}$  ranges. The background predictions are shown with their statistical uncertainties. The significance of any deviation between the observation and prediction for each  $g_{\text{displaced}}$  range is shown as a Z-value.

$g_{\text{displaced}}$	Predicted background	Observation	Z-value
(0.96, 0.97)	$68.39 \pm 12.60$	52	-1.06
(0.97, 0.98)	$67.55 \pm 9.46$	77	0.80
(0.98, 0.99)	$76.18 \pm 8.95$	72	-0.27
(0.99, 0.995)	$38.82 \pm 5.08$	45	0.84
(0.995, 0.998)	$25.41 \pm 3.87$	26	0.22
(0.998, 0.9985)	$2.83 \pm 1.17$	5	1.25
(0.9985, 1.0)	$3.34 \pm 1.28$	3	0.19

The background estimation was additionally validated using simulated QCD and signal events, both with and without the effect of signal contamination, as well as using observed data in signal-depleted regions with small  $g_{\text{prompt-veto}}$  values. In all cases, the estimated background and the observed value agree within statistical uncertainties. Therefore, no additional systematic uncertainty is assigned to the predicted background yields.

## 7 Systematic uncertainties

The systematic uncertainty in the integrated luminosity for 13.6 TeV pp collision data in 2022 is 1.4% [98], which is taken as one of the systematic uncertainties in the signal yield. The systematic uncertainty arising from the pileup modeling is estimated by varying the inelastic pp cross section by 4.6% [99]; the resulting variation in the signal yield is found to be 1–8% and is taken as the corresponding systematic uncertainty. The jet energy scale uncertainty is propagated to the simulated signal samples by varying the jet energy and  $p_T$  by one standard deviation, and the resulting systematic uncertainty in the signal yield is found to be 5–10%.

Measurements of the efficiency of the online requirements of the DJTs are compared between data and the simulated QCD multijet sample. Events collected with an isolated single-muon trigger are used for the online  $H_T$  requirement, and events collected with a prescaled  $H_T$  trigger requiring  $H_T > 425$  GeV are used for the online jet  $p_T$  requirement. The differences in the measured efficiencies between data and simulation are found to be small, and their impacts on the predicted signal yields are negligible, so no corresponding uncertainty is assigned.

To estimate the systematic uncertainty in the predicted signal yields from the online tracking requirement of the DJTs, the per-jet efficiencies of this requirement are measured as functions of the number of offline prompt tracks and displaced tracks, using events collected with the prescaled  $H_T$  trigger. The difference between data and simulated QCD multijet events is applied to the simulated signal events as a bias for the probability of a single jet to pass the online tracking requirements. The variation of the efficiency for signal events to have at least two jets passing the online tracking requirements is found to be 0.1–5% and is taken as the corresponding systematic uncertainty.

The impact of the possible mismodeling of the GNN scores in the simulation on the predicted signal yields is measured similarly, using events collected with the prescaled  $H_T$  trigger. The GNN scores in the simulated samples are varied by the magnitude of the measured discrepancy between data and QCD multijet simulation. The effect on the signal yields is found to be 4–14% and is taken as the corresponding systematic uncertainty.

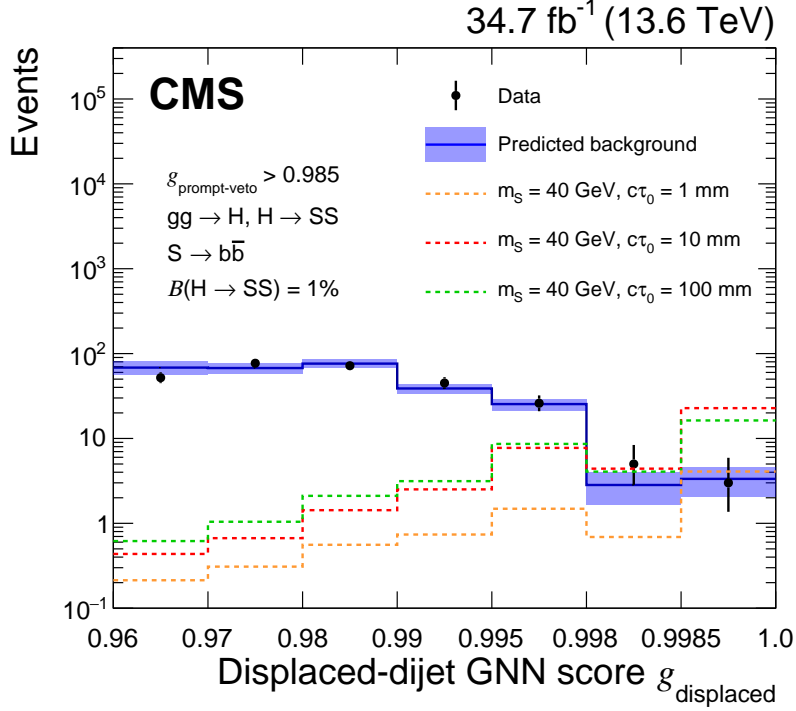


Figure 3: The predicted background yields and the number of observed events for the data with  $g_{\text{prompt-veto}} > 0.985$ , shown for different bins of the displaced-dijet GNN score  $g_{\text{displaced}}$ . Expected signal yields for the  $H \rightarrow SS$ ,  $S \rightarrow b\bar{b}$  signature are also shown for models with  $m_S = 40 \text{ GeV}$  and  $c\tau_0 = 1, 10, \text{ or } 100 \text{ mm}$ , assuming a branching fraction of 1% for the  $H \rightarrow SS$  decay.

The various systematic uncertainties in the signal yields are summarized in Table 2.

Table 2: Summary of the systematic uncertainties in the signal yields.

Source	Uncertainty (%)
Integrated luminosity	1.4
Pileup modeling	1–8
Jet energy scale	5–10
Online tracking requirements	0.1–5
GNN modeling	4–14

## 8 Results

The observed event yields in regions A, B, and C are  $N_A = 722$ ,  $N_B = 344$ , and  $N_C = 7$ , respectively. The predicted background yield in the SR with  $g_{\text{displaced}} > 0.9985$  and  $g_{\text{prompt-veto}} > 0.985$  is therefore  $3.34 \pm 1.28$ . We observe 3 events, which is consistent with the prediction. The signal efficiencies for representative  $H \rightarrow SS$  signal points in the SR can be found in Table 3.

### 8.1 Interpretations of the results

Upper limits at 95% confidence level (CL) are set on the branching fraction  $\mathcal{B}(H \rightarrow SS)$  for different signal models, computed using the  $\text{CL}_s$  criterion [100, 101], with an LHC-style profile

Table 3: Signal efficiencies scaled by a factor of  $10^4$  for the  $H \rightarrow SS$  signature with  $S \rightarrow b\bar{b}$ ,  $S \rightarrow d\bar{d}$ , and  $S \rightarrow \tau\tau$  decays in the signal region D, shown for representative signal points with different  $m_S$  and  $c\tau_0$  values. Only statistical uncertainties are listed.

Decay channel	$m_S$ (GeV)	$c\tau_0$			
		1 mm	10 mm	100 mm	1000 mm
$S \rightarrow b\bar{b}$	55	$2.82 \pm 0.06$	$15.46 \pm 0.14$	$12.52 \pm 0.12$	$2.17 \pm 0.05$
	40	$2.25 \pm 0.05$	$11.96 \pm 0.12$	$8.60 \pm 0.10$	$1.06 \pm 0.04$
	23	$0.48 \pm 0.02$	$4.42 \pm 0.07$	$2.71 \pm 0.06$	$0.20 \pm 0.01$
$S \rightarrow d\bar{d}$	55	$2.80 \pm 0.06$	$12.48 \pm 0.13$	$10.30 \pm 0.11$	$1.89 \pm 0.05$
	40	$2.47 \pm 0.05$	$11.76 \pm 0.12$	$8.13 \pm 0.09$	$1.06 \pm 0.04$
	23	$0.59 \pm 0.03$	$5.14 \pm 0.07$	$2.89 \pm 0.06$	$0.19 \pm 0.02$
$S \rightarrow \tau\tau$	55	$0.28 \pm 0.02$	$2.17 \pm 0.05$	$1.40 \pm 0.04$	$0.24 \pm 0.02$
	40	$0.23 \pm 0.02$	$1.77 \pm 0.05$	$1.08 \pm 0.04$	$0.15 \pm 0.01$
	23	$0.09 \pm 0.01$	$0.75 \pm 0.03$	$0.39 \pm 0.02$	$0.023 \pm 0.005$

likelihood ratio [102] as the test statistic. Systematic uncertainties are incorporated through the use of nuisance parameters, which are profiled according to the frequentist paradigm. The asymptotic approximation [103] is used for calculating the  $CL_s$  values and has been verified with full-frequentist results for representative signal points. To account for possible signal contributions in regions A–C, a simultaneous fit is performed for the signal strength and the background yields in all regions A–D, enforcing the ABCD relationship from Eq. (3) for the background yields, while allowing for a signal component in all regions with relative proportions dictated by the signal simulation. The differences between the results of the simultaneous fit and those obtained only using the yields in the SR are smaller than 10%. These calculations are performed using the COMBINE package [104].

The upper limits on  $\mathcal{B}(H \rightarrow SS)$  for the  $S \rightarrow b\bar{b}$ ,  $S \rightarrow d\bar{d}$ , and  $S \rightarrow \tau\tau$  decay scenarios are shown in Fig. 4 for different  $m_S$  and  $c\tau_0$  values. The limits become weaker for smaller  $c\tau_0$  because only displaced tracks are used to reconstruct DVs, and for larger  $c\tau_0$  because the tracking efficiency decreases with increasing displacement of the displaced tracks. The limits also become less stringent at smaller  $m_S$  because the boost of the LLP decay system increases, so the two quarks or hadronically decaying tau leptons are more likely to be reconstructed as a single jet.

The upper limits for the  $S \rightarrow b\bar{b}$  decay scenario are within 20% of the  $S \rightarrow d\bar{d}$  limits when  $m_S > 20$  GeV, while in the previous search [43] the  $S \rightarrow b\bar{b}$  limits were much weaker than the  $S \rightarrow d\bar{d}$  limits. The difference in sensitivity between the  $S \rightarrow b\bar{b}$  and  $S \rightarrow d\bar{d}$  final states is mitigated by the new DV reconstruction algorithm and the GNN taggers, which better capture information from the B hadron decay vertices. The new DJTs accept more signal events, increasing the signal yield compared to previous searches even in this smaller data set. The upper limits for the  $S \rightarrow \tau\tau$  decay scenario are weaker than the  $S \rightarrow b\bar{b}$  and  $S \rightarrow d\bar{d}$  limits because there is less displaced activity in  $S \rightarrow \tau\tau$  decays, as there is no hadronization when tau leptons are produced at the LLP decay vertex.

This search provides the first exclusions of hadronically decaying displaced tau leptons arising from LLPs with decay lengths smaller than  $\approx 1$  m. The  $S \rightarrow b\bar{b}$  and  $S \rightarrow d\bar{d}$  observed limits are compared to other results [43, 44] for representative signal points in Fig. 5. Although the integrated luminosity of the data analyzed in this search is only  $\approx 25\%$  of that used in the other searches, the obtained limits are much stronger, thanks to the new trigger, reconstruction, and

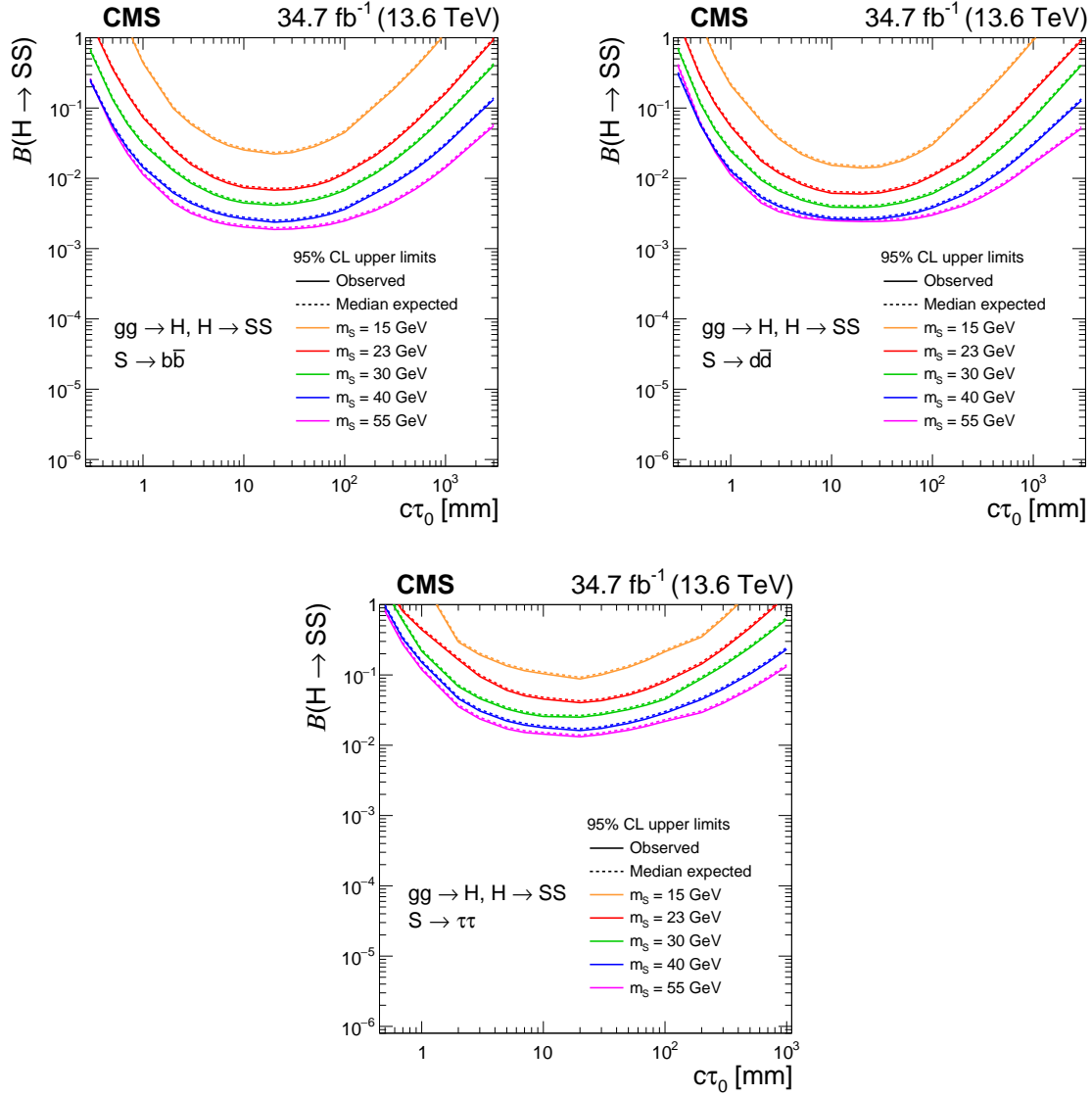


Figure 4: The 95% CL upper limits on the branching fraction  $B(H \rightarrow SS)$  for  $S \rightarrow b\bar{b}$  (upper left),  $S \rightarrow d\bar{d}$  (upper right), and  $S \rightarrow \tau\tau$  (lower), for different LLP masses  $m_S$  and proper decay lengths  $c\tau_0$ . The solid (dashed) lines represent the observed (median expected) limits.

machine-learning techniques. The  $S \rightarrow b\bar{b}$  ( $S \rightarrow d\bar{d}$ ) limits are better than those obtained previously by a factor of up to 10 (8).

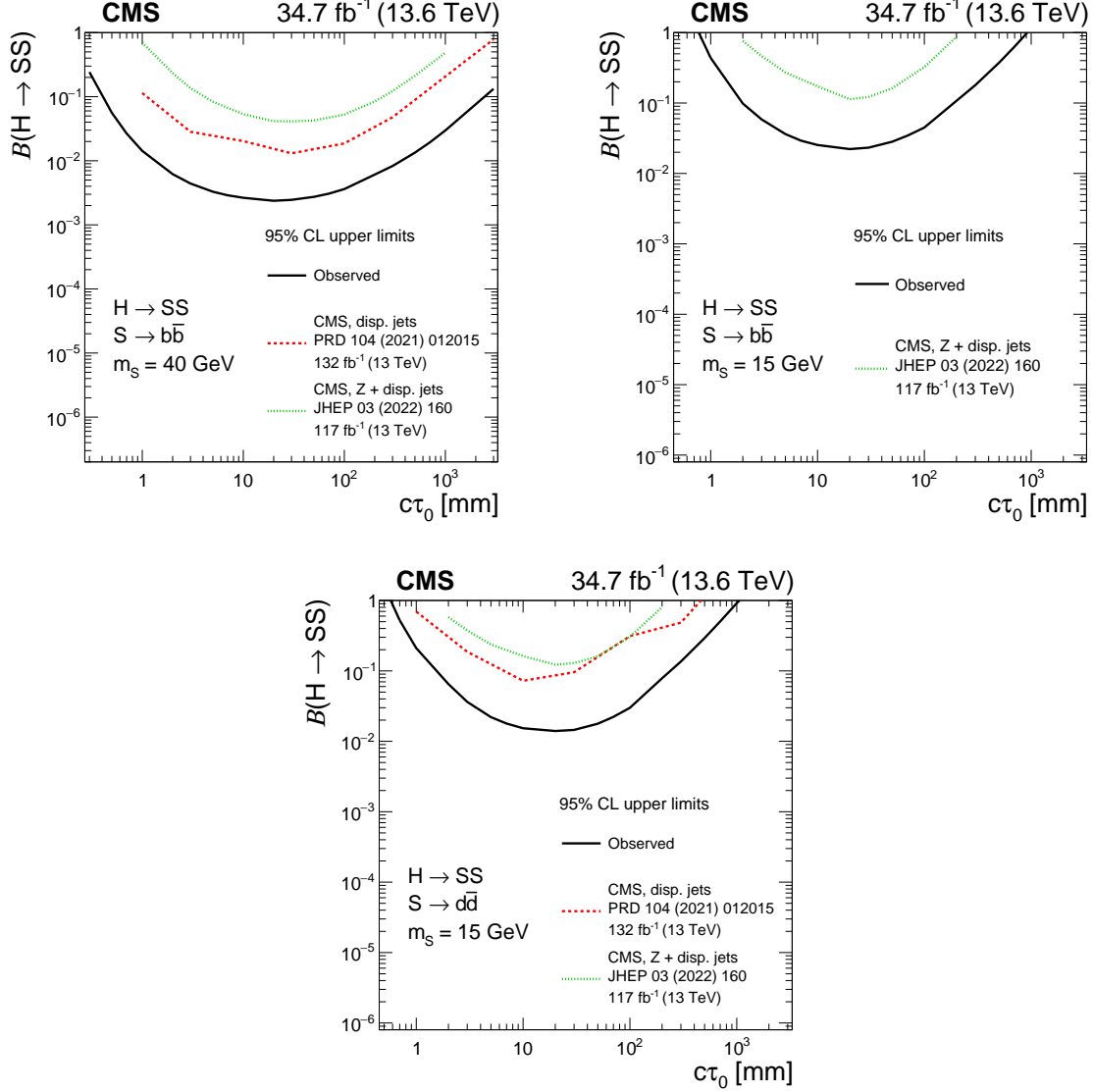


Figure 5: Comparisons of the observed limits from this search and other results, for  $S \rightarrow b\bar{b}$ ,  $m_S = 40$  GeV (upper left);  $S \rightarrow b\bar{b}$ ,  $m_S = 15$  GeV (upper right); and  $S \rightarrow d\bar{d}$ ,  $m_S = 15$  GeV (lower). The other results include the previous CMS displaced-jets search [43] (red dashed lines) and the CMS Z + displaced-jets search [44] (green dotted lines), where the observed limits agree with the median expected limits within 15% and are within the regions containing 68% of the distributions of the limits expected under the background-only hypothesis.

Figure 6 shows the 95% CL limits on  $m_S$  for different  $c\tau_0$  assuming a branching fraction of 1% for the  $H \rightarrow SS$  decay, with subsequent  $S \rightarrow b\bar{b}$  or  $S \rightarrow d\bar{d}$  decays. When  $m_S$  is larger than 40 GeV,  $B(H \rightarrow SS)$  larger than 1% is excluded for  $c\tau_0$  between 1.5 and 370 mm with  $S \rightarrow b\bar{b}$  decays, or for  $c\tau_0$  between 1.3 and 380 mm with  $S \rightarrow d\bar{d}$  decays.

We also interpret the search with the fraternal twin Higgs (FTH) [29] and folded SUSY (FSUSY) [48] models, which are two benchmarks for the neutral-naturalness scenario. For this interpretation, the scalar  $S$  is interpreted as the lightest glueball  $G_0$  in the DS. The branching

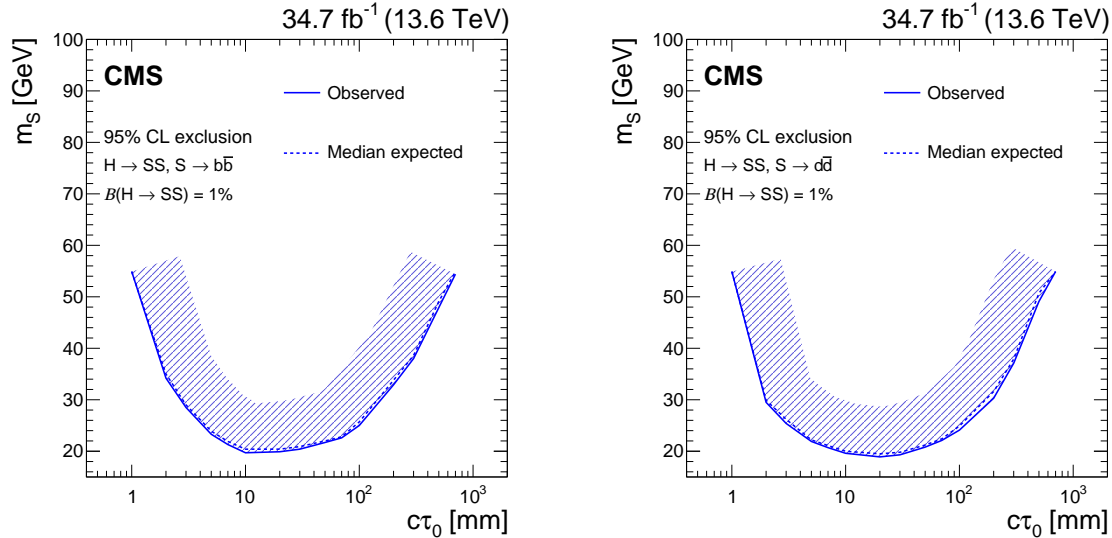


Figure 6: The 95% CL limits on the LLP mass  $m_S$  for different proper decay lengths  $c\tau_0$  assuming a branching fraction of 1% for the  $H \rightarrow SS$  decay, and with subsequent  $S \rightarrow b\bar{b}$  (left) or  $S \rightarrow d\bar{d}$  (right) decays. The solid (dashed) lines represent the observed (median expected) limits. The hashed areas indicate the direction of the excluded area from the observed limits.

fraction for the Higgs boson decay to  $G_0$  ( $\mathcal{B}(H \rightarrow G_0 G_0)$ ) and the  $c\tau_0$  of  $G_0$  both depend on the glueball mass  $m_0$  and the mass  $m_T$  of the top quark partner  $T$  in the DS. These dependencies are taken from Ref. [66], assuming  $\mathcal{B}(H \rightarrow G_0 G_0)$  is the same as the branching fraction for the Higgs boson to decay to hidden gluons multiplied by a phase space factor  $\sqrt{1 - 4m_0^2/m_H^2}$ . For simplicity we also assume the branching fraction for  $G_0 \rightarrow b\bar{b}$  is 100%, since this is the dominant decay channel of  $G_0$  in the considered mass range because of the Higgs-portal interaction. In this way, the  $S \rightarrow b\bar{b}$  limits are translated into 95% CL exclusions in the  $m_0$ - $m_T$  plane, as shown in Fig. 7. Top quark partner masses up to 350 (250) GeV are excluded for the FTH (FSUSY) model.

The data analyzed in this search was collected in the first year of the ongoing LHC Run 3. The results in this paper already achieve an order-of-magnitude improvement over existing results, which represents a significant step forward in probing the phase space of exotic LLPs. The full LHC Run-3 data set will correspond to a much larger integrated luminosity, which is expected to increase the sensitivity of this search significantly. The techniques introduced in this paper, together with newer techniques such as additional DJTs in a separate parking data stream dedicated to LLP searches [105], will help realize the full potential of the complete Run-3 data set and expand the coverage of exotic LLP signatures.

## 9 Summary

A search for light long-lived particles decaying into jets has been performed using proton-proton collision data corresponding to an integrated luminosity of  $34.7 \text{ fb}^{-1}$ , collected with the CMS experiment at a center-of-mass energy of 13.6 TeV in 2022. Novel techniques in trigger, reconstruction, and machine learning were developed for and employed in this search, leading to significant improvements over existing results.

The observed yields are consistent with the background predictions. The best limits to date are set for long-lived particles with masses between 15 and 55 GeV and with proper decay lengths

smaller than  $\approx 1$  m. The search provides the first exclusions of hadronically decaying displaced tau leptons arising from LLPs with decay lengths smaller than  $\approx 1$  m. For the signature where the Higgs boson decays to two long-lived particles that further decay to bottom (down) quark pairs, branching fractions greater than 1% for the exotic Higgs boson decay are excluded for a long-lived particle mass larger than 40 GeV and mean proper decay lengths between 1.5 (1.3) and 370 (380) mm. For these signatures, the branching fraction limits are better than those obtained previously by a factor of up to 10 (8). Exclusions are also placed on the parameter space of the fraternal twin Higgs and folded supersymmetry models in the neutral naturalness scenario, giving lower limits on top quark partner masses of up to 350 and 250 GeV, respectively. The results are the first constraints placed on these models.

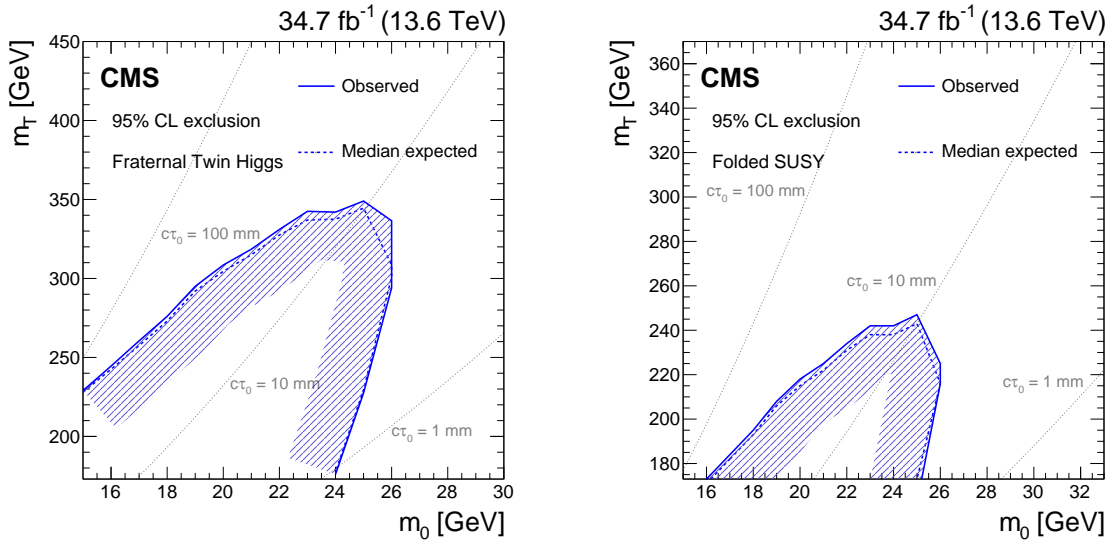


Figure 7: The 95% CL limits on the dark-sector top quark partner mass  $m_T$  for different hidden glueball masses  $m_0$ , in the fraternal twin Higgs model [29] (left) and the folded SUSY model [48] (right). The solid (dashed) lines represent the observed (median expected) limits. The hashed areas indicate the direction of the excluded area from the observed limits.

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## A Glossary of acronyms

AVF	Adaptive vertex fitter
AVR	Adaptive vertex reconstruction
BSM	Beyond the standard model
CL	Confidence level
DJ	Displaced jet
DJT	Displaced-jet trigger
DS	Dark sector
DV	Displaced vertex
ECAL	Electromagnetic calorimeter
FTH	Fraternal twin Higgs
FSUSY	Folded supersymmetry
GNN	Graph neural network
HCAL	Hadron calorimeter
HLT	High-level trigger
LLP	Long-lived particle
LO	Leading order
LSTM	Long short-term memory
PCA	Point of the closest approach
PV	Primary vertex
QCD	Quantum chromodynamics
SM	Standard model
SR	Signal region
SUSY	Supersymmetry




















## B The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan<sup>1</sup> 













### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler<sup>2</sup> , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck<sup>2</sup> , R. Schöfbeck , D. Schwarz , M. Sonawane , W. Waltenberger , C.-E. Wulz<sup>2</sup> 

















### Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , T. Van Laer, P. Van Mechelen 













### Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat<sup>3</sup> , G.P. Van Onsem , S. Van Putte , D. Vannerom 















### Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 











### Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 

















### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










### Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera<sup>4</sup> , A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira<sup>4</sup> 

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

W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>5</sup>, E.M. Da Costa , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, T. Laux Kuhn, M. Macedo , J. Martins<sup>7</sup> , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

### Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes<sup>6</sup> , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maitto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 




### Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. Shopova , G. Sultanov 




**University of Sofia, Sofia, Bulgaria**

A. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 



**Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile**

S. Keshri , D. Laroze , S. Thakur 













**Beihang University, Beijing, China**

T. Cheng , T. Javaid , L. Yuan 

**Department of Physics, Tsinghua University, Beijing, China**

Z. Hu , Z. Liang, J. Liu, K. Yi<sup>8,9</sup> 


**Institute of High Energy Physics, Beijing, China**

G.M. Chen<sup>10</sup> , H.S. Chen<sup>10</sup> , M. Chen<sup>10</sup> , F. Iemmi , C.H. Jiang, A. Kapoor<sup>11</sup> , H. Liao , Z.-A. Liu<sup>12</sup> , R. Sharma<sup>13</sup> , J.N. Song<sup>12</sup>, J. Tao , C. Wang<sup>10</sup>, J. Wang , Z. Wang<sup>10</sup>, H. Zhang , J. Zhao 

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou 

**Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**

S. Yang 

**Sun Yat-Sen University, Guangzhou, China**

Z. You 

**University of Science and Technology of China, Hefei, China**

K. Jaffel , N. Lu 

**Nanjing Normal University, Nanjing, China**

G. Bauer<sup>14</sup>, B. Li, J. Zhang 

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

X. Gao<sup>15</sup> , Y. Li

**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , C. Lu , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega



**Universidad de Antioquia, Medellin, Colombia**

F. Ramirez , C. Rendón, M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 

**University of Split, Faculty of Science, Split, Croatia**

M. Kovac , A. Petkovic, T. Sculac 




**Institute Rudjer Boskovic, Zagreb, Croatia**

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov<sup>16</sup> , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 



**Charles University, Prague, Czech Republic**

M. Finger , M. Finger Jr. , A. Kveton 

**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**

H. Abdalla<sup>17</sup> , S. Abu Zeid<sup>18</sup> , Y. Assran<sup>19,20</sup>

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

M.A. Mahmoud , Y. Mohammed 
















**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

**Department of Physics, University of Helsinki, Helsinki, Finland**

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















**Helsinki Institute of Physics, Helsinki, Finland**

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 




























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow 
















**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro<sup>21</sup> , P. Simkina , M. Titov , M. Tornago 

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Hari Krishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 


















**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>22</sup> , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

A. Di Florio 

**Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France**

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen<sup>23</sup> , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourd’huy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 






























### Georgian Technical University, Tbilisi, Georgia

I. Lomidze , T. Toriashvili<sup>24</sup> , Z. Tsamalaidze<sup>16</sup> 









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

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 























































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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , C. Seth, A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo<sup>25</sup> , S. Wiedenbeck , S. Zaleski







































### RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 










### Deutsches Elektronen-Synchrotron, Hamburg, Germany




























H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman<sup>26</sup> , K. Borras<sup>27</sup> , A. Campbell , A. Cardini , C. Cheng, F. Colombina , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>26</sup> , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka<sup>28</sup> , W. Lohmann<sup>29</sup> , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham<sup>30,27</sup> , S. Schnake<sup>27</sup> , P. Schütze , C. Schwanenberger<sup>26</sup> , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens<sup>27</sup> , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

### University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoiiu , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 

### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, U. Elicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann<sup>31</sup> , R. Hofsaess 

M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos<sup>31</sup>, A. Stakia 

**National and Kapodistrian University of Athens, Athens, Greece**

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






**National Technical University of Athens, Athens, Greece**

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsipolitis , A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

**HUN-REN Wigner Research Centre for Physics, Budapest, Hungary**

C. Hajdu , D. Horvath<sup>32,33</sup> , K. Márton, A.J. Rádl<sup>34</sup> , F. Sikler , V. Veszpremi 

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**

M. Csanád , K. Farkas , A. Fehérkuti<sup>35</sup> , M.M.A. Gadallah<sup>36</sup> , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 

**Faculty of Informatics, University of Debrecen, Debrecen, Hungary**

B. Ujvari , G. Zilizi 













**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

**Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary**

F. Nemes<sup>35</sup> , T. Novak 

**Panjab University, Chandigarh, India**

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>37</sup> , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J.B. Singh , A. Singla 


















**University of Delhi, Delhi, India**

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M.K. Saini, S. Saumya 

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

S. Baradia , S. Barman<sup>38</sup> , S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar

**Indian Institute of Technology Madras, Madras, India**

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri<sup>39</sup> , D. Kumar<sup>39</sup> , T. Mishra , B. Parida , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay











**Tata Institute of Fundamental Research-A, Mumbai, India**

S. Dugad, G.B. Mohanty , M. Shelake, P. Suryadevara










**Tata Institute of Fundamental Research-B, Mumbai, India**

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

**National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**

S. Bahinipati<sup>40</sup> , C. Kar , D. Maity<sup>41</sup> , P. Mal , V.K. Muraleedharan Nair Bindhu<sup>41</sup> , K. Naskar<sup>41</sup> , A. Nayak<sup>41</sup> , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese<sup>41</sup> , D. Vats<sup>41</sup> 








**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Acharya<sup>42</sup> , A. Alpana , S. Dube , B. Gomber<sup>42</sup> , P. Hazarika , B. Kansal , A. Laha , B. Sahu<sup>42</sup> , S. Sharma , K.Y. Vaish 


**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>43</sup> , A. Jafari<sup>44</sup> , M. Zeinali<sup>45</sup> 



















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

S. Bashiri, S. Chenarani<sup>46</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie<sup>47</sup> , M. Mohammadi Najafabadi , S. Tizchang<sup>48</sup> 











**University College Dublin, Dublin, Ireland**

M. Felcini , M. Grunewald 





**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup> , A. Colaleo<sup>a,b</sup> , D. Creanza<sup>a,c</sup> , B. D'Anzi<sup>a,b</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,49</sup> , L. Fiore<sup>a</sup> , G. Iaselli<sup>a,c</sup> , L. Longo<sup>a</sup> , M. Louka<sup>a,b</sup>, G. Maggi<sup>a,c</sup> , M. Maggi<sup>a</sup> , I. Margjeka<sup>a</sup> , V. Mastrapasqua<sup>a,b</sup> , S. My<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , G. Pugliese<sup>a,c</sup> , R. Radogna<sup>a,b</sup> , D. Ramos<sup>a</sup> , A. Ranieri<sup>a</sup> , L. Silvestris<sup>a</sup> , F.M. Simone<sup>a,c</sup> , Ü. Sözbilir<sup>a</sup> , A. Stamerra<sup>a,b</sup> , D. Troiano<sup>a,b</sup> , R. Venditti<sup>a,b</sup> , P. Verwilligen<sup>a</sup> , A. Zaza<sup>a,b</sup> 


















**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup> , C. Battilana<sup>a,b</sup> , D. Bonacorsi<sup>a,b</sup> , P. Capiluppi<sup>a,b</sup> , A. Castro<sup>+a,b</sup> , F.R. Cavallo<sup>a</sup> , M. Cuffiani<sup>a,b</sup> , G.M. Dallavalle<sup>a</sup> , T. Diotallevi<sup>a,b</sup> , F. Fabbri<sup>a</sup> , A. Fanfani<sup>a,b</sup> , D. Fasanella<sup>a</sup> , P. Giacomelli<sup>a</sup> , L. Giommi<sup>a,b</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,50</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarra<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , F. Primavera<sup>a,b</sup> , A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> , T. Rovelli<sup>a,b</sup> , G.P. Siroli<sup>a,b</sup> 

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Costa<sup>a,b,51</sup> , A. Di Mattia<sup>a</sup> , A. Lapertosa<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,51</sup> , C. Tuve<sup>a,b</sup> 

























































**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**






























P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a,b</sup> , B. Camaiani<sup>a,b</sup> , A. Cassese<sup>a</sup> , R. Ceccarelli<sup>a</sup> , V. Ciulli<sup>a,b</sup> , C. Civinini<sup>a</sup> , R. D'Alessandro<sup>a,b</sup> , E. Focardi<sup>a,b</sup> , T. Kello<sup>a</sup>, G. Latino<sup>a,b</sup> , P. Lenzi<sup>a,b</sup> , M. Lizzo<sup>a</sup> , M. Meschini<sup>a</sup> , S. Paoletti<sup>a</sup> , A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni<sup>a</sup> , L. Viliani<sup>a</sup> 

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**








L. Benussi , S. Bianco , S. Meola<sup>52</sup> , D. Piccolo 



**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**P. Chatagnon<sup>a</sup> , F. Ferro<sup>a</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> **INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup> , F. Brivio<sup>a</sup> , F. Cetorelli<sup>a,b</sup> , F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , R. Gerosa<sup>a,b</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a</sup> , M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup> , S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , S. Palluotto<sup>a,b</sup> , D. Pedrini<sup>a</sup> , A. Perego<sup>a,b</sup> , B.S. Pinolini<sup>a</sup>, G. Pizzati<sup>a,b</sup>, S. Ragazzi<sup>a,b</sup> , T. Tabarelli de Fatis<sup>a,b</sup> **INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy**S. Buontempo<sup>a</sup> , A. Cagnotta<sup>a,b</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,53</sup> , P. Paolucci<sup>a,31</sup> , B. Rossi<sup>a</sup> **INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,54</sup> , D. Bisello<sup>a,b</sup> , P. Bortignon<sup>a</sup> , G. Bortolato<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup> , A.C.M. Bulla<sup>a</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , S. Giorgetti<sup>a</sup>, A. Gozzelino<sup>a</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , M. Migliorini<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> **INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a</sup> , D. Fiorina<sup>a</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a,b</sup> , P. Vitulo<sup>a,b</sup> **INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**S. Ajmal<sup>a,b</sup> , M.E. Ascioti<sup>a,b</sup>, G.M. Bilei<sup>a</sup> , C. Carrivale<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,55</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> **INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**C. Aimè<sup>a</sup> , C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<sup>a</sup> , R. Bhattacharya<sup>a</sup> , L. Bianchini<sup>a,b</sup> , T. Boccali<sup>a</sup> , E. Bossini<sup>a</sup> , D. Bruschini<sup>a,c</sup> , R. Castaldi<sup>a</sup> , M.A. Ciocci<sup>a,b</sup> , M. Cipriani<sup>a,b</sup> , V. D'Amante<sup>a,d</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a</sup> , D. Matos Figueiredo<sup>a</sup> , A. Messineo<sup>a,b</sup> , S. Mishra<sup>a</sup> , M. Musich<sup>a,b</sup> , F. Palla<sup>a</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Spagnolo<sup>a</sup> , R. Tenchini<sup>a</sup> , G. Tonelli<sup>a,b</sup> , N. Turini<sup>a,d</sup> , F. Vaselli<sup>a,c</sup> , A. Venturi<sup>a</sup> , P.G. Verdini<sup>a</sup> **INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy**C. Baldenegro Barrera<sup>a,b</sup> , P. Barria<sup>a</sup> , C. Basile<sup>a,b</sup> , F. Cavallari<sup>a</sup> , L. Cunqueiro Mendez<sup>a,b</sup> , D. Del Re<sup>a,b</sup> , E. Di Marco<sup>a,b</sup> , M. Diemoz<sup>a</sup> , F. Errico<sup>a,b</sup> , E. Longo<sup>a,b</sup> , J. Mijuskovic<sup>a,b</sup> , G. Organtini<sup>a,b</sup> , F. Pandolfi<sup>a</sup> , R. Paramatti<sup>a,b</sup> , C. Quaranta<sup>a,b</sup> , S. Rahatlou<sup>a,b</sup> , C. Rovelli<sup>a</sup> , F. Santanastasio<sup>a,b</sup> , L. Soffi<sup>a</sup> **INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**N. Amapane<sup>a,b</sup> , R. Arcidiacono<sup>a,c</sup> , S. Argiro<sup>a,b</sup> , M. Arneodo<sup>a,c</sup> , N. Bartosik<sup>a</sup> , R. Bellan<sup>a,b</sup> , A. Bellora<sup>a,b</sup> , C. Biino<sup>a</sup> , C. Borca<sup>a,b</sup> , N. Cartiglia<sup>a</sup> , M. Costa<sup>a,b</sup> 

R. Covarelli<sup>a,b</sup> , N. Demaria<sup>a</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , F. Legger<sup>a</sup> ,  
 F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</sup> , L. Markovic<sup>a,b</sup> , S. Maselli<sup>a</sup> , A. Mecca<sup>a,b</sup> , L. Menzio<sup>a,b</sup>,  
 P. Meridiani<sup>a</sup> , E. Migliore<sup>a,b</sup> , M. Monteno<sup>a</sup> , R. Mulargia<sup>a</sup> , M.M. Obertino<sup>a,b</sup> ,  
 G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<sup>a</sup> , M. Pelliccioni<sup>a</sup> , M. Ruspa<sup>a,c</sup> ,  
 F. Siviero<sup>a,b</sup> , V. Sola<sup>a,b</sup> , A. Solano<sup>a,b</sup> , A. Staiano<sup>a</sup> , C. Tarricone<sup>a,b</sup> , D. Trocino<sup>a</sup> ,  
 G. Umoret<sup>a,b</sup> , R. White<sup>a,b</sup> 

**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**

J. Babbar<sup>a,b</sup> , S. Belforte<sup>a</sup> , V. Candelise<sup>a,b</sup> , M. Casarsa<sup>a</sup> , F. Cossutti<sup>a</sup> , K. De Leo<sup>a</sup> ,  
 G. Della Ricca<sup>a,b</sup> 


**Kyungpook National University, Daegu, Korea**

S. Dogra , J. Hong , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon , Y.D. Oh ,  
 M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

**Department of Mathematics and Physics - GWNNU, Gangneung, Korea**

M.S. Kim 






**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

G. Bak , P. Gwak , H. Kim , D.H. Moon 

**Hanyang University, Seoul, Korea**

E. Asilar , J. Choi , D. Kim , T.J. Kim , J.A. Merlin, Y. Ryou

**Korea University, Seoul, Korea**

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Yoo 













**Kyung Hee University, Department of Physics, Seoul, Korea**

J. Goh , S. Yang 








**Sejong University, Seoul, Korea**

H. S. Kim , Y. Kim, S. Lee



**Seoul National University, Seoul, Korea**

J. Almond, J.H. Bhyun, J. Choi , J. Choi, W. Jun , J. Kim , Y.W. Kim, S. Ko , H. Kwon ,  
 H. Lee , J. Lee , J. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 

**University of Seoul, Seoul, Korea**

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh,  
 I.J. Watson 

**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha , H.D. Yoo 


**Sungkyunkwan University, Suwon, Korea**

M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 

**College of Engineering and Technology, American University of the Middle East (AUM),  
 Dasman, Kuwait**

T. Beyrouthy, Y. Gharbia

**Kuwait University - College of Science - Department of Physics, Safat, Kuwait**


F. Alazemi 

**Riga Technical University, Riga, Latvia**

K. Dreimanis , A. Gaile , C. Munoz Diaz, D. Osite , G. Pikurs, A. Potrebko , M. Seidel 

D. Sidiropoulos Kontos

**University of Latvia (LU), Riga, Latvia**

N.R. Strautnieks 







**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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

I. Yusuff<sup>56</sup> , Z. Zolkapli



**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 



**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz<sup>57</sup> , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera, A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**

C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Bautista , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**

I. Bubanja , N. Raicevic 

**University of Canterbury, Christchurch, New Zealand**

P.H. Butler 

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan 







**AGH University of Krakow, 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 , M. Górski , M. Kazana , M. Szleper , P. Zalewski 

















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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski , A. Muhammad 



**Warsaw University of Technology, Warsaw, Poland**

K. Pozniak , W. Zabolotny 

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff































**Faculty of Physics, University of Belgrade, Belgrade, Serbia**

P. Adzic , P. Milenovic 


**VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**

D. Devetak, M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic





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

J. Alcaraz Maestre , Cristina F. Bedoya , J.A. Brochero Cifuentes , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. Llorente Merino , E. Martin Viscasillas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 



















**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz 



**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina , E. Palencia Cortezon , J. Prado Pico, C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 

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

S. Bhowmik , S. Blanco Fernández , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasasa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

**University of Colombo, Colombo, Sri Lanka**

B. Kailasapathy<sup>58</sup> , D.D.C. Wickramarathna 













**University of Ruhuna, Department of Physics, Matara, Sri Lanka**

W.G.D. Dharmaratna<sup>59</sup> , K. Liyanage , N. Perera 



































**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Boronovi , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , J. Hegeman , J.K. Heikkilä , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban<sup>29</sup> , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabadý , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas<sup>60</sup> , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk<sup>61</sup> , J. Wang, K.A. Wozniak<sup>62</sup> , S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner




















**Paul Scherrer Institut, Villigen, Switzerland**

T. Bevilacqua<sup>63</sup> , L. Caminada<sup>63</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>63</sup> , L. Noehte<sup>63</sup> , T. Rohe , A. Samalan




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

T.K. Aarrestad , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazzaniga , K. Datta , P. De Bryas Dexmiers D'archiac<sup>61</sup> , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte, D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani<sup>61</sup> , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , B. Ristic , F. Riti , R. Seidita , J. Steggemann<sup>61</sup> , A. Tarabini , D. Valsecchi , R. Wallny 












**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>64</sup> , P. Bärttschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 



**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>65</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>39</sup> , S.S. Yu 




















**National Taiwan University (NTU), Taipei, Taiwan**

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsiou, H.y. Wu, E. Yazgan 


**High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand**

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu<sup>66</sup> , E. Eskut , Y. Guler<sup>67</sup> , E. Gurpınar Guler<sup>67</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , Y. Komurcu , G. Onengut , K. Ozdemir<sup>68</sup> , A. Polatoz , B. Tali<sup>69</sup> , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Sokmen, M. Yalvac<sup>70</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>71</sup> , O. Kaya<sup>72</sup> , S. Tekten<sup>73</sup> 





**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>66,74</sup> , G.G. Dincer<sup>66</sup> , S. Sen<sup>75</sup> 

**Istanbul University, Istanbul, Turkey**

O. Aydilek<sup>76</sup> , B. Hacisahinoglu , I. Hos<sup>77</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 


**Yildiz Technical University, Istanbul, Turkey**

S. Cerci , B. Isildak<sup>78</sup> , D. Sunar Cerci , T. Yetkin 















**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine**

A. Boyaryntsev , B. Grynyov 




















**National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine**

L. Levchuk 





































**University of Bristol, Bristol, United Kingdom**

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou<sup>79</sup> , K. Walkingshaw Pass

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

A.H. Ball, K.W. Bell , A. Belyaev<sup>80</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 













**Imperial College, London, United Kingdom**

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal<sup>81</sup> , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , C.R. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios, M. Mieskolainen , J. Nash<sup>82</sup> , M. Pesaresi , P.B. Pradeep, B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee<sup>31</sup> , M. Vojinovic , N. Wardle , D. Winterbottom 




**Brunel University, Uxbridge, United Kingdom**

J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

**Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish<sup>83</sup> , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 



















**Catholic University of America, Washington, DC, USA**

R. Bartek , A. Dominguez , A.E. Simsek 


















**The University of Alabama, Tuscaloosa, Alabama, USA**

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson, C.U. Perez , P. Rumerio<sup>84</sup> , E. Usai , R. Yi 



















**Boston University, Boston, Massachusetts, USA**

A. Akpinar , C. Cosby , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 






**Brown University, Providence, Rhode Island, USA**

G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan<sup>85</sup> , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell, S. Sagir<sup>86</sup> , X. Shen, F. Simpson , M. Stamenkovic , N. Venkatasubramanian, X. Yan 

**University of California, Davis, Davis, California, USA**

S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo , F. Zhang 

























**University of California, Los Angeles, California, USA**

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

**University of California, Riverside, Riverside, California, USA**

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 










**University of California, San Diego, La Jolla, California, USA**

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang















**California Institute of Technology, Pasadena, California, USA**

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 


































































**University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalata , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 


















**Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 













**Fermi National Accelerator Laboratory, Batavia, Illinois, USA**

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>87</sup> , F. Ravera , A. Reinsvold Hall<sup>88</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






**University of Florida, Gainesville, Florida, USA**

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 
























#### **Florida State University, Tallahassee, Florida, USA**

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











#### **Florida Institute of Technology, Melbourne, Florida, USA**

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy<sup>18</sup> , M. Hohlmann , E. Yanes












#### **University of Illinois Chicago, Chicago, Illinois, USA**

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , N. Singh, M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























#### **The University of Iowa, Iowa City, Iowa, USA**

M. Alhousseini , D. Blend, K. Dilsiz<sup>89</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>90</sup> , O. Neogi, H. Ogul<sup>91</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>92</sup> 









#### **Johns Hopkins University, Baltimore, Maryland, USA**

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 


















#### **The University of Kansas, Lawrence, Kansas, USA**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu<sup>93</sup> , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson 
























#### **Kansas State University, Manhattan, Kansas, USA**

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

#### **University of Maryland, College Park, Maryland, USA**

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova<sup>94</sup> , A. Shevelev , L. Wang 

#### **Massachusetts Institute of Technology, Cambridge, Massachusetts, USA**













J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn, A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang 

#### **University of Minnesota, Minneapolis, Minnesota, USA**














B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans ,  
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











#### **University of Nebraska-Lincoln, Lincoln, Nebraska, USA**

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado ,  
W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

#### **State University of New York at Buffalo, Buffalo, New York, USA**

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos ,  
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





















#### **Northeastern University, Boston, Massachusetts, USA**

G. Alverson , E. Barberis , J. Bonilla , M. Campana , J. Dervan, Y. Haddad , Y. Han ,  
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


#### **Northwestern University, Evanston, Illinois, USA**

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , M. McGinnis , Y. Miao , D.G. Monk ,  
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










#### **University of Notre Dame, Notre Dame, Indiana, USA**

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,  
K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence ,  
N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady ,  
C. Moore , Y. Musienko<sup>16</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,  
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

#### **The Ohio State University, Columbus, Ohio, USA**

A. Basnet , B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas ,  
K. Wei, B.L. Winer , B. R. Yates 




















#### **Princeton University, Princeton, New Jersey, USA**

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,  
B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange ,  
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#### **University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik 














#### **Purdue University, West Lafayette, Indiana, USA**

A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung ,  
A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov ,  
V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang ,  
A. Wildridge , W. Xie , Y. Yao 

#### **Purdue University Northwest, Hammond, Indiana, USA**

J. Dolen , N. Parashar , A. Pathak 





















#### **Rice University, Houston, Texas, USA**

D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner,  
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







#### **University of Rochester, Rochester, New York, USA**

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin<sup>94</sup> , R. Taus 
















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

#### **University of Tennessee, Knoxville, Tennessee, USA**

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 












#### **Texas A&M University, College Station, Texas, USA**

D. Aebi , M. Ahmad , T. Akhter , K. Androsov<sup>61</sup> , O. Bouhali<sup>95</sup> , R. Eusebi , J. Gilmore , T. Huang , T. Kamon<sup>96</sup> , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 

#### **Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

#### **Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























#### **University of Virginia, Charlottesville, Virginia, USA**

B. Cardwell , H. Chung, B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu 

#### **Wayne State University, Detroit, Michigan, USA**

S. Bhattacharya , P.E. Karchin 

#### **University of Wisconsin - Madison, Madison, Wisconsin, USA**

A. Aravind, S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , L. Pétré , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

#### **Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN**

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin<sup>†</sup> , I. Gorbunov , V. Karjavine , V. Korenkov , A. Lanev , A. Malakhov , V. Matveev<sup>97</sup> , V. Palichik , V. Perelygin , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B.S. Yuldashev<sup>98</sup>, A. Zarubin , I. Zhizhin , G. Gavrilo , V. Golovtcov , Y. Ivanov , V. Kim<sup>97</sup> , P. Levchenko<sup>99</sup> , V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov , A. Vorobyev<sup>†</sup>, Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyev , D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin , T. Aushev , V. Gavrilo , N. Lychkovskaya , A. Nikitenko<sup>100,101</sup> , V. Popov , A. Zhokin , M. Chadeeva<sup>97</sup> , R. Chistov<sup>97</sup> , S. Polikarpov<sup>97</sup> , V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov , E. Boos , V. Bunichev , M. Dubinin<sup>87</sup> , L. Dudko , A. Ershov , V. Klyukhin , O. Kodolova<sup>101</sup> , S. Obraztsov , M. Perfilov, S. Petrushanko , V. Savrin , G. Vorotnikov , V. Blinov<sup>97</sup>, T. Dimova<sup>97</sup> , A. Kozyrev<sup>97</sup> , O. Radchenko<sup>97</sup> , Y. Skovpen<sup>97</sup> , V. Kachanov , D. Kon-

stantinov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin<sup>102</sup> 

**Authors affiliated with an institute formerly covered by a cooperation agreement with CERN**  
V. Chekhovsky, V. Makarenko 

†: Deceased

<sup>1</sup>Also at Yerevan State University, Yerevan, Armenia

<sup>2</sup>Also at TU Wien, Vienna, Austria

<sup>3</sup>Also at Ghent University, Ghent, Belgium

<sup>4</sup>Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

<sup>5</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup>Also at UFMS, Nova Andradina, Brazil

<sup>8</sup>Also at Nanjing Normal University, Nanjing, China

<sup>9</sup>Now at The University of Iowa, Iowa City, Iowa, USA

<sup>10</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>11</sup>Also at China Center of Advanced Science and Technology, Beijing, China

<sup>12</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>13</sup>Also at China Spallation Neutron Source, Guangdong, China

<sup>14</sup>Now at Henan Normal University, Xinxiang, China

<sup>15</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium

<sup>16</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>17</sup>Also at Cairo University, Cairo, Egypt

<sup>18</sup>Also at Ain Shams University, Cairo, Egypt

<sup>19</sup>Also at Suez University, Suez, Egypt

<sup>20</sup>Now at British University in Egypt, Cairo, Egypt

<sup>21</sup>Also at Purdue University, West Lafayette, Indiana, USA

<sup>22</sup>Also at Université de Haute Alsace, Mulhouse, France

<sup>23</sup>Also at Istinye University, Istanbul, Turkey

<sup>24</sup>Also at Tbilisi State University, Tbilisi, Georgia

<sup>25</sup>Also at The University of the State of Amazonas, Manaus, Brazil

<sup>26</sup>Also at University of Hamburg, Hamburg, Germany

<sup>27</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>28</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

<sup>29</sup>Also at Brandenburg University of Technology, Cottbus, Germany

<sup>30</sup>Also at Forschungszentrum Jülich, Juelich, Germany

<sup>31</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

<sup>32</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

<sup>33</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

<sup>34</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

<sup>35</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

<sup>36</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

<sup>37</sup>Also at Punjab Agricultural University, Ludhiana, India

<sup>38</sup>Also at University of Visva-Bharati, Santiniketan, India

<sup>39</sup>Also at Indian Institute of Science (IISc), Bangalore, India

<sup>40</sup>Also at IIT Bhubaneswar, Bhubaneswar, India

<sup>41</sup>Also at Institute of Physics, Bhubaneswar, India

<sup>42</sup>Also at University of Hyderabad, Hyderabad, India

- <sup>43</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>44</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>45</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>46</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>47</sup>Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>48</sup>Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>49</sup>Also at Helwan University, Cairo, Egypt
- <sup>50</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>51</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>52</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>53</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>54</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>55</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>56</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- <sup>57</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- <sup>58</sup>Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>59</sup>Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>60</sup>Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>61</sup>Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>62</sup>Also at University of Vienna, Vienna, Austria
- <sup>63</sup>Also at Universität Zürich, Zurich, Switzerland
- <sup>64</sup>Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>65</sup>Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- <sup>66</sup>Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>67</sup>Also at Konya Technical University, Konya, Turkey
- <sup>68</sup>Also at Izmir Bakircay University, Izmir, Turkey
- <sup>69</sup>Also at Adiyaman University, Adiyaman, Turkey
- <sup>70</sup>Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>71</sup>Also at Marmara University, Istanbul, Turkey
- <sup>72</sup>Also at Milli Savunma University, Istanbul, Turkey
- <sup>73</sup>Also at Kafkas University, Kars, Turkey
- <sup>74</sup>Now at Istanbul Okan University, Istanbul, Turkey
- <sup>75</sup>Also at Hacettepe University, Ankara, Turkey
- <sup>76</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>77</sup>Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>78</sup>Also at Yildiz Technical University, Istanbul, Turkey
- <sup>79</sup>Also at Vrije Universiteit Brussel, Brussel, Belgium
- <sup>80</sup>Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>81</sup>Also at IPPP Durham University, Durham, United Kingdom
- <sup>82</sup>Also at Monash University, Faculty of Science, Clayton, Australia
- <sup>83</sup>Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
- <sup>84</sup>Also at Università di Torino, Torino, Italy

---

<sup>85</sup>Also at Bethel University, St. Paul, Minnesota, USA

<sup>86</sup>Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

<sup>87</sup>Also at California Institute of Technology, Pasadena, California, USA

<sup>88</sup>Also at United States Naval Academy, Annapolis, Maryland, USA

<sup>89</sup>Also at Bingöl University, Bingöl, Turkey

<sup>90</sup>Also at Georgian Technical University, Tbilisi, Georgia

<sup>91</sup>Also at Sinop University, Sinop, Turkey

<sup>92</sup>Also at Erciyes University, Kayseri, Turkey

<sup>93</sup>Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

<sup>94</sup>Now at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>95</sup>Also at Texas A&M University at Qatar, Doha, Qatar

<sup>96</sup>Also at Kyungpook National University, Daegu, Korea

<sup>97</sup>Also at another institute or international laboratory covered by a cooperation agreement with CERN

<sup>98</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

<sup>99</sup>Also at Northeastern University, Boston, Massachusetts, USA

<sup>100</sup>Also at Imperial College, London, United Kingdom

<sup>101</sup>Now at Yerevan Physics Institute, Yerevan, Armenia

<sup>102</sup>Also at Universiteit Antwerpen, Antwerpen, Belgium