

# Search for a new heavy resonance decaying to a top quark and a neutral scalar boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

A first search at the LHC for a new heavy resonance decaying to a top quark and a neutral scalar boson  $\phi$  in the fully hadronic final state is presented, where the  $\phi$  boson is identified by its decay into a bottom quark-antiquark pair. The search is focused on final states in which the decay products of the highly Lorentz boosted top quark and  $\phi$  boson are each reconstructed as a single, large-radius jet with distinct substructure. The analysis is performed using proton-proton collision data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ , recorded with the CMS detector at the LHC in 2016–2018. The single production of a vector-like top quark,  $T'$ , is used as a benchmark model for the signal process. The results of this search are combined with those of a previous CMS search in which semileptonic decays of the top quark were used. No significant excess of data is observed with respect to the background prediction. For the case where the neutral scalar is a standard model Higgs boson and the  $T'$  quark width is 5% of its mass,  $T'$  quark masses between 0.85 and 1.3 TeV are excluded at 95% confidence level and the most stringent limits to date are set for masses above 2 TeV. For other  $\phi$  boson masses, upper limits as low as 0.1 fb are set on the product of the  $T'$  quark production cross section and branching fraction for its decay to a top quark and a  $\phi$  boson.

*Submitted to Physics Letters B*



# 1 Introduction

The standard model (SM) of particle physics has been extensively tested and shown to be consistent with experimental results, yet it does not explain why the Higgs boson mass ( $m_H$ ) lies near the electroweak (EW) scale, given the quadratic corrections arising from quantum loops. Naively, the Higgs boson mass would instead be expected to lie near the Planck scale, many orders of magnitude away from its measured value [1]. Of the many beyond-the-SM (BSM) theories attempting to address this hierarchy problem, those of particular interest to the search reported in this Letter introduce new particles called vector-like quarks (VLQs), which are nonchiral, color-charged, spin-1/2 partners of the third-generation SM quarks [2].

The nonchiral nature of VLQs allows for Lagrangian mass terms that do not arise from Yukawa couplings to the Higgs field. Therefore, they are free from the stringent constraints on the existence of sequential fourth-generation quarks set by precision EW measurements at the Fermilab Tevatron and the CERN LHC [3]. At the LHC, VLQs can be produced singly or in pairs via the EW and strong interactions, respectively, with the former typically dominating for VLQ masses greater than 1 TeV. One such VLQ, the hypothetical top quark partner  $T'$ , couples to the third-generation bottom (b) and top (t) quarks, and can decay to these quarks in association with a Higgs, W, or Z boson. In the case where the VLQ is a weak-isospin singlet, the branching fractions ( $\mathcal{B}$ ) are 50, 25, and 25% for the  $T' \rightarrow bW$ ,  $T' \rightarrow tH$ , and  $T' \rightarrow tZ$  decays, respectively. For the doublet state, the branching fractions into  $tH$  and  $tZ$  are both 50% [4]. Comprehensive reviews of searches for single and pair production of VLQs at  $\sqrt{s} = 13$  TeV have been published by the ATLAS [5] and CMS [6] Collaborations. These searches have targeted the direct decays of VLQs coupled predominantly to third-generation quarks and decaying through various bosonic channels.

However, the vector-like top quark partner need not couple solely to SM particles and in fact decays to new scalar or pseudoscalar particles are possible in nonminimal BSM scenarios [7–11]. One such example is a two-Higgs-doublet model [12] that is modified to include a VLQ [9]. The Higgs sector of such a model is extended to include an additional neutral scalar, neutral pseudoscalar, and two charged scalar bosons. The neutral scalar boson is predicted to decay to similar bosonic and fermionic final states as those of the SM Higgs boson, and the branching fraction of the VLQ decay to this scalar boson increases with the VLQ mass.

Motivated by such models, this Letter presents a search for the EW production of a single top quark partner  $T'$  in association with a bottom quark and decaying to a top quark and a neutral scalar boson  $\phi$ , wherein the top quark decays hadronically and the  $\phi$  boson is assumed to decay to a bottom quark-antiquark pair ( $b\bar{b}$ ). To take advantage of the larger VLQ single production cross sections at high mass, we target  $T'$  quark masses ( $m_{T'}$ ) ranging from 0.8 to 3 TeV and consider masses of the new scalar boson ( $m_\phi$ ) ranging from 75 to 500 GeV. In this regime, the top quark and  $\phi$  boson are each highly Lorentz boosted, such that their decay products merge, creating a dijet topology with large-radius jets in the final state.

Potential signal jet candidates are distinguished from background using neural network identification algorithms, referred to as “taggers”, which discriminate the jets originating from top quark or Higgs boson decays from those produced via quantum chromodynamics (QCD), referred to henceforth as the QCD multijet background. Since the final state includes one jet from the hadronic decay of a top quark and one  $\phi \rightarrow b\bar{b}$  candidate jet, which could be a misidentified hadronic top quark decay, events involving top quark pair production ( $t\bar{t}$ ) form the dominant background in this search. Although the selection on the tagging algorithm’s outputs is efficient at removing QCD multijet events, these events nonetheless remain the next most dominant background, followed by minor contributions from W and Z boson production

in association with jets, henceforth collectively termed V+jets.

We construct a binned likelihood model composed of QCD multijet,  $t\bar{t}$ , V+jets, and signal components in the plane spanned by the reconstructed mass of the scalar boson,  $m_\phi^{\text{rec}}$ , and the invariant mass of the system composed of the reconstructed scalar boson and top quark,  $m_{T'}^{\text{rec}}$ . This analysis targets a localized excess of events in the two-dimensional (2D) plane of  $(m_{T'}^{\text{rec}}, m_\phi^{\text{rec}})$  that would correspond to the presence of a  $T'$  quark resonance, decaying to a top quark and a  $\phi$  boson. The QCD multijet background in the signal region (SR) of this analysis is modeled using the prediction from a signal-depleted control region (CR) in data defined by inverting the tagger selection on the  $\phi$  candidate jet. All other background sources and the signal are modeled using Monte Carlo (MC) simulation.

The results from a combination of the fully hadronic channel with the channel wherein the top quark decays semileptonically, described in detail in Ref. [13], are presented. A charged-lepton veto in the fully hadronic channel ensures the orthogonality with the semileptonic channel by construction, and sources of systematic uncertainty that are common between the two channels are treated as correlated in the likelihood. Both analyses are performed using proton-proton (pp) collision data collected with the CMS detector in 2016–2018 at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$  [14, 15]. These are the first searches for the decay of a VLQ to a BSM particle.

This Letter is organized as follows. Section 2 provides an introduction to the CMS detector and event reconstruction. Section 3 describes the simulated signal and background samples used in this analysis. The event selection and object identification criteria are outlined in Section 4, followed by a description of the background estimation strategy in Section 5. Having thus introduced the search in the fully hadronic channel, a brief overview of the search performed in the semileptonic channel is provided in Section 6. Section 7 summarizes the sources of systematic uncertainty in the analysis, as well as the treatment of the combination of the fully hadronic and semileptonic channels. Finally, the results are presented in Section 8 and this Letter is summarized in Section 9. Tabulated results can be found in the HEPData record for this analysis [16].

## 2 The CMS detector and event reconstruction

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, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) 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. 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. [17, 18].

Events of interest are initially selected using a two-tiered trigger system. The first level (L1), 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  $4 \mu\text{s}$  [19]. The second level, known as the high-level trigger, 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 [20, 21].

The particle-flow (PF) algorithm [22] aims to reconstruct and identify each individual particle

in an event with an optimized combination of information from the various elements of the CMS detector. For each event, hadronic jets are clustered from these reconstructed particles (PF candidates) using the infrared- and collinear-safe anti- $k_T$  algorithm [23, 24]. Two different jet collections, referred to as AK4 and AK8 jets, are clustered using distance parameter values of 0.4 and 0.8, respectively. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole transverse momentum ( $p_T$ ) spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. The pileup per particle identification algorithm [25, 26] is used to mitigate the effect of pileup at the reconstructed particle level, making use of local shape information, event pileup properties, and tracking information.

Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [27]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [27]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [28]. In the case of AK8 jets, masses are calculated after applying a modified mass-drop algorithm [29, 30], known as the “soft-drop” algorithm [31], to remove wide-angle soft and collinear radiation from the jets.

### 3 Signal and background simulation

The signal process  $pp \rightarrow T' \rightarrow t\phi$  is generated at leading order for  $T'$  in a mass range of 0.8–3 TeV, in steps of 100 GeV, using the MC generator MADGRAPH5\_aMC@NLO [32] (version 2.6.5). The  $T'$  quark is treated as a weak-isospin singlet produced in association with a bottom quark, with a width of 1% of its mass. We assume  $\mathcal{B}(\phi \rightarrow b\bar{b}) = 100\%$  in the interpretation of the resulting cross sections in Section 8 except for the special case where the scalar is the Higgs boson,  $m_\phi = m_H = 125$  GeV, in which case the results are scaled by the SM branching fraction for the decay  $H \rightarrow b\bar{b}$ . When interpreting the results in the context of the  $T' \rightarrow tH$  decay, the cross sections are evaluated at next-to-leading order in the narrow-width approximation [33–35] for singlet  $T'$  VLQs with a fixed branching fraction of 25% to  $tH$ .

The  $\phi$  boson is generated with masses ranging from 75 to 500 GeV in varying steps, with a minimum step size of 25 GeV for lower-mass signals, but increasing to 100 GeV at higher masses. In order to decrease these gaps in the signal MC sample coverage, we perform interpolation between generated signal mass points in the region where  $m_{T'} \gtrsim 1$  TeV and  $m_\phi < 350$  GeV to produce signal shapes with 25 GeV spacing in  $m_\phi$ . To accomplish the interpolation, each generated signal mass point is first modeled by fitting a double-sided Crystal Ball function [36, 37] to its reconstructed  $m_\phi^{\text{rec}}$  and  $m_{T'}^{\text{rec}}$  spectra, which is then normalized to obtain a continuous probability distribution function representing the shape of the signal along each reconstructed mass axis. The shape of an interpolated signal of mass  $M$ , situated between two existing signals of masses  $M_1$  and  $M_2$ , such that  $M_1 < M < M_2$ , is then calculated along both axes following the method described in Ref. [38]. The final shape of the interpolated signal is derived as the product of these two distributions, yielding a 2D distribution as a function of  $(m_{T'}^{\text{rec}}, m_\phi^{\text{rec}})$ . The normalization of the signal is obtained by linear interpolation between the expected yields of the existing signals of masses  $M_1$  and  $M_2$ . The procedure is validated by running the algorithm

on the generated signal mass points and comparing the resulting distributions to the original. For all these signal mass points, the differences are negligible and the algorithm successfully reconstructs the original signal shape. We use the same interpolation strategy to produce the shape and normalization of the systematic uncertainty templates for each interpolated signal.

The two main backgrounds in this search arise from  $t\bar{t}$  production in which the top quarks decay hadronically and from QCD multijet events. Other sources of background, such as  $V$ +jets production, are found to have minimal contributions. To simulate SM  $t\bar{t}$  production, the next-to-leading-order POWHEG v2 [39–43] matrix element event generator is used, and for QCD multijet and  $V$ +jet simulation MADGRAPH5\_aMC@NLO [32] (versions 2.6.1 and 2.6.5, respectively) is used at leading order accuracy. The simulated QCD multijet samples are only used for checks of self-consistency of the background estimate and do not enter in the final likelihood model used to extract results.

Hadronization and parton showering are simulated using the PYTHIA (version 8.240) software package [44]. The NNPDF3.1 [45] parton distribution functions (PDFs) at next-to-next-to-leading order accuracy are used with the CP5 [46] underlying event tune for all simulations. The CMS detector simulation is performed with GEANT4 [47].

To simulate the effect of pileup, additional simulated inelastic pp collisions are superimposed on the hard scattering process using PYTHIA. Simulated samples are reweighted to correct the pileup simulation by using the total inelastic cross section of 69.2 mb [48, 49] to approximate the distribution of the number of pileup interactions in data, after which the simulated data are reconstructed in the same manner as the real data.

## 4 Event selection

Different sets of triggers based on jet properties are used for event selection across the three data-taking years. The first trigger criterion is based on the scalar  $p_T$  sum of all AK8 jets in the event ( $H_T$ ), requiring an  $H_T$  of at least 900 (1050) GeV for the 2016 (2017–2018) data set. An additional trigger used in the 2017 (2018) data set requires an event to possess  $H_T > 750$  (850) GeV as well as an AK8 jet with a trimmed jet mass of at least 50 GeV. For these triggers, the jet mass is calculated by a trimming algorithm [50] similar to the soft-drop algorithm described in Section 2.

The second trigger criterion requires a single AK8 jet above a given  $p_T$  threshold in the event. In both 2017 and 2018 a trigger requiring a single AK8 jet with  $p_T > 500$  GeV was used. An additional trigger required an AK8 jet with  $p_T > 400$  GeV together with a trimmed jet mass of at least 30 GeV. Such triggers with only a  $p_T$  criterion were not used in 2016. All these triggers are combined with a logical OR in order to maximize the trigger efficiency in each year. The trigger reaches full efficiency for a dijet invariant mass of approximately 1 TeV, and simulated events with dijet invariant masses below this threshold are weighted according to trigger efficiency correction factors measured in an orthogonal data set.

The initial event selection focuses on exploiting the kinematic properties of the decays of very heavy resonances, which are produced nearly at rest, causing their decay products to be highly Lorentz boosted and reconstructed roughly opposite to one another in the transverse plane. Therefore, events are required to have at least two AK8 jets, each with  $p_T > 350$  GeV,  $|\eta| < 2.4$ , and a soft-drop jet mass of at least 50 GeV. The jets are required to have an azimuthal angular separation  $> \pi/2$ . Additionally, all events must pass a set of standard data quality filters designed to remove events affected by noise in the various subdetectors [28]. Finally, all events

containing reconstructed leptons satisfying loose identification criteria [51, 52] are vetoed, in order to remain orthogonal to the selections imposed by the semileptonic channel [13].

After this initial selection, the two leading- $p_T$  jets are then subject to identification as the  $\phi \rightarrow b\bar{b}$  (“ $\phi$  jet”) and  $t \rightarrow bW(q\bar{q}')$  (“ $t$  jet”) candidates. Classification of the two jets as signal jet candidates is performed using the dynamic graph convolutional neural network PARTICLENET [53]. For every jet in an event, the PARTICLENET algorithm returns probability-like scores for the jet to have originated from the hadronic decay of some massive particle or from the hadronization of light quarks or gluons. In this search, the PARTICLENET “top quark score” is given by the algorithm’s default output for discrimination between jets originating from the hadronic decay of a top quark and from the hadronization of lighter quarks or gluons, referred to here as  $T_{bqq}^{\text{PNet}}$ . The PARTICLENET “ $\phi$  score” is given by a discriminant termed  $T_{\chi_{bb}}$ , defined by  $P(X_{\text{MD}} \rightarrow b\bar{b}) / (P(X_{\text{MD}} \rightarrow b\bar{b}) + P(\text{QCD}))$ , where  $P(\text{QCD})$  is the score corresponding to the QCD multijet background and  $P(X_{\text{MD}} \rightarrow b\bar{b})$  is the probability-like score corresponding to a jet arising from the decay of some massive resonance to  $b\bar{b}$ . The subscript MD indicates that the  $\phi$  score is mass decorrelated, meaning that the tagger response does not significantly change as a function of the jet mass, making this score criterion suitable to identify  $\phi \rightarrow b\bar{b}$  decays without biasing the background mass distributions.

Using these tagger scores, the dijet events are separated into one of three different analysis regions: a QCD multijet-enriched CR(QCD), a  $t\bar{t}$ -enriched CR( $t\bar{t}$ ), and the SR in which the search is performed. Because only two jets are considered in each event, selecting one jet as the  $t$  jet candidate naturally selects the other as the  $\phi$  jet candidate. To belong in the SR, events must contain at least one jet passing the high-purity (HP) working point (WP) of the PARTICLENET top quark tagger corresponding to a 0.1% mistagging rate,  $T_{bqq}^{\text{PNet}} \geq \text{HP WP}$ . If neither jet meets this criterion, the event is discarded. If only one jet passes the HP WP it is assigned as the  $t$  jet candidate. If both jets pass then the jet with the higher  $T_{bqq}^{\text{PNet}}$  score is assigned as the  $t$  jet candidate.

The CR(QCD) is defined by inverting the tagging requirement on the  $t$  jet, selecting only events in which the  $t$  jet candidate has a score passing only a very loose tagger selection of  $T_{bqq}^{\text{PNet}} > 0.2$ , denoted as the low-purity (LP) WP, such that  $\text{LP WP} < T_{bqq}^{\text{PNet}} < \text{HP WP}$ . An additional  $\phi$  tagging veto is placed on the  $t$  jet candidate in this region, using a similar LP WP definition  $T_{\chi_{bb}} > 0.2$  and requiring  $T_{\chi_{bb}} < \text{LP WP}$  to reduce possible signal contamination in the CR(QCD) introduced by the  $T_{bqq}^{\text{PNet}}$  score inversion.

Following the identification of the  $t$  jet candidate, additional  $\phi$  tagging selection is imposed on the  $\phi$  candidate jet in all events in both the SR and CR(QCD), dividing both regions into “Fail” and “Pass” regions. In the SR,  $\phi$  candidate jets with  $0.8 < T_{\chi_{bb}} < 0.98$  enter the Fail region of the SR, denoted  $\text{SR}_F$ , and jets with  $T_{\chi_{bb}} > 0.98$  enter the Pass region,  $\text{SR}_P$ . The Fail and Pass regions of the CR(QCD), denoted as  $\text{CR(QCD)}_F$  and  $\text{CR(QCD)}_P$ , are defined analogously. Events not belonging to either exclusive tagging category are not considered. The efficiency of the  $T_{\chi_{bb}}$  tagger is calibrated in a data set enriched in jets arising from gluon splitting to  $b\bar{b}$  pairs, the characteristics of which have been sculpted to resemble that of the new scalar using a boosted decision tree (BDT) [54]. These efficiencies are then used to scale the MC sample yields to what is expected from the data.

The dedicated CR( $t\bar{t}$ ) is used to constrain the systematic uncertainties affecting the dominant  $t\bar{t}$  background. The CR( $t\bar{t}$ ) is defined similarly to the SR at first, with one jet having  $T_{bqq}^{\text{PNet}} > \text{HP WP}$ . The second jet is then subject to a requirement of  $T_{\chi_{bb}} < 0.8$  to avoid overlap with the SR. The Pass and Fail regions of the CR( $t\bar{t}$ ),  $\text{CR}(t\bar{t})_P$ , and  $\text{CR}(t\bar{t})_F$ , are then populated by

events where this second jet passes or fails the HP WP of the mass-decorrelated DEEPAK8 [55] top quark tagger,  $T_{bqq}^{\text{DAK8}}$ , corresponding to a 0.1% mistagging rate.

## 5 Background estimation

A binned 2D likelihood model is constructed in the  $(m_{T'}^{\text{rec}}, m_{\phi}^{\text{rec}})$  plane from QCD multijet,  $t\bar{t}$ , V+jets, and signal components. The V+jets component appears mainly in the CR(QCD) because of the inversion of the top quark tagging requirements. The  $t\bar{t}$  and V+jets backgrounds are estimated from MC simulation, for which the effects of systematic uncertainties are incorporated in the fit by altered distributions obtained from the simulated samples, corresponding to variations in a given uncertainty source. The QCD multijet component is instead estimated using a method in which the distribution of multijet events taken from data in the  $T_{\chi_{bb}}$  Fail region is multiplied by a smooth, parametric transfer function (TF) to estimate the distribution in the  $T_{\chi_{bb}}$  Pass region. Because the  $T_{\chi_{bb}}$  tagger response is not correlated with the jet mass, the shape of the QCD multijet background in the Pass region can be obtained directly from the shape in the Fail region. The discussion in the following paragraph is intended to be generic for both the SR and CR( $t\bar{t}$ ), each of which has its own Pass and Fail tagging regions.

The TF is defined as the ratio of events passing to those failing the tagging requirement. For the SR and CR(QCD) this is the requirement on the second jet's  $T_{\chi_{bb}}$  score, and for the CR( $t\bar{t}$ ) this is the requirement on the second jet's  $T_{bqq}^{\text{DAK8}}$  score. To estimate the QCD multijet background in the Pass tagging region, the QCD multijet event yield in every bin of the  $(m_{T'}, m_{\phi})$  plane of the Fail region ( $n_F^{\text{QCD}}(i)$ ) is represented by an unconstrained parameter in the likelihood, whose initial value is given by the difference between the observed data ( $n_F^{\text{Data}}(i)$ ) and the total background from MC simulation ( $n_F^{\text{MC bkg}}(i)$ ) in that bin, prior to the fit. Thus, the number of QCD multijet events in a given bin  $i$  of any Pass tagging region,  $n_P^{\text{QCD}}(i)$ , is given by

$$n_P^{\text{QCD}}(i) = n_F^{\text{QCD}}(i) \text{TF}(m_{T'}, m_{\phi}), \quad (1)$$

where

$$n_F^{\text{QCD}}(i) = n_F^{\text{Data}}(i) - n_F^{\text{MC bkg}}(i). \quad (2)$$

A simultaneous maximum likelihood fit of the Pass and Fail regions is performed to determine the optimal parameters for  $n_F^{\text{QCD}}(i)$  and  $\text{TF}(m_{T'}, m_{\phi})$ , which also ensures that the QCD multijet estimates in the Fail regions are not strictly equal to the difference between the data and simulated background yields.

The CR(QCD) is used in the analysis only to validate the QCD multijet background estimation procedure described above, and to obtain an initial estimate for the TF in the SR before observing the actual data yields there, referred to as unblinding the analysis. The choice of parameterization for the TF was determined by Fisher tests [56] and found to be constant along both reconstructed mass axes in the CR(QCD). The constant TF and its postfit value were then used to generate pseudo-data in the SR before unblinding to help further validate the QCD multijet estimation procedure. A separate TF was measured in the CR( $t\bar{t}$ ) whose best fit polynomial representation was also found to be constant along both reconstructed mass axes.

The total background in the SR and CR( $t\bar{t}$ ) is then estimated by constructing a likelihood composed of the QCD multijet prediction and the  $t\bar{t}$  and V+jets contributions, which are represented by 2D histograms obtained from MC simulation and modified by the systematic uncertainties described in Section 7. The total background model, constructed as the sum of the

individual background contributions using a Poisson model for each bin of the  $(m_{T'}^{\text{rec}}, m_{\phi}^{\text{rec}})$  distribution, is then used to test the signal hypothesis by comparing the number of events from the background-only and signal-plus-background models, where the various signal mass hypotheses enter the likelihood as 2D histograms obtained from MC simulation.

In order to constrain the systematic uncertainties affecting the dominant  $t\bar{t}$  backgrounds, the SR and CR( $t\bar{t}$ ) are fit simultaneously. The QCD multijet background yields in both regions are estimated in parallel, but uncorrelated with one another, by using a separate TF for each region. The final TFs are determined to be constant factors for both the SR and CR( $t\bar{t}$ ).

## 6 Summary of the semileptonic result used in the combination

A brief summary of the search strategy for the semileptonic top quark decay channel is presented in this Section, together with a description of the procedure for its combination with the fully hadronic channel. A complete description of the semileptonic analysis can be found in Ref. [13].

The semileptonic analysis targets single production of a vector-like top quark partner decaying to a top quark and new scalar boson where the top quark decays to a bottom quark, charged lepton ( $\ell$ ), and neutrino ( $\nu$ ) via the  $t \rightarrow bW \rightarrow b\ell\nu$  channel and the scalar boson decays to  $b\bar{b}$ . The analysis targets events with an AK4 jet and an AK8 jet containing the hadronization products of the b quark and  $\phi$  boson, one electron or muon, and the presence of missing transverse momentum,  $\vec{p}_T^{\text{miss}}$ , defined as the negative vector  $p_T$  sum of all PF candidates in the event.

Similarly to the hadronic channel, the semileptonic analysis uses the mass-decorrelated PARTICLENET  $T_{\chi_{bb}}$  discriminant to identify boosted  $\phi$  or Higgs boson candidates reconstructed as AK8 jets. Top quark candidates are reconstructed using the information from the charged-lepton candidate, one AK4 jet, and the  $\vec{p}_T^{\text{miss}}$ , which is assumed to represent the neutrino  $p_T$ . A multiclass BDT algorithm is trained to distinguish genuine top quark candidates from the misidentified ones in QCD multijet events and all other types of background. The BDT output is used to define a top quark tagging discriminant used to distinguish the genuine from the misreconstructed top quark candidates.

Events are then categorized based on loose and tight WP thresholds of the  $T_{\chi_{bb}}$  and BDT top quark tagger scores. The loose and tight  $T_{\chi_{bb}}$  tagger WP thresholds separate events into validation and signal regions, respectively, with the former used to check the closure of the background estimation procedure and to constrain the background uncertainties in the final maximum likelihood fit. Events are further categorized based on the lepton flavor and the presence or absence of at least one forward jet ( $2.4 < |\eta| < 4$ ), a proxy for the light quark produced in association with the  $T'$  quark signal. A selection on  $m_{\phi}^{\text{rec}}$  of the  $\phi$  boson candidate is made separately for each  $\phi$  boson mass hypothesis, ensuring 95% signal efficiency in each case. The signal strength is then extracted from a simultaneous maximum likelihood fit to the invariant mass spectrum of the top quark and  $\phi$  boson candidates in all signal and validation regions formed by this event categorization.

## 7 Systematic uncertainties

The fully hadronic analysis takes into account several systematic uncertainties that can affect both the shape and normalization of the reconstructed mass distributions  $(m_{T'}^{\text{rec}}, m_{\phi}^{\text{rec}})$  in simulation, which are treated as nuisance parameters in the maximum likelihood fit used for signal

extraction. The uncertainty in the integrated luminosity, which affects only the overall normalization of the simulated processes, is implemented as a nuisance parameter with a log-normal probability distribution. All other uncertainties also affect the shape of the mass distributions, and they are constructed such that the  $\pm 1$  standard deviation of each distribution is mapped to the  $\pm 1$  standard deviation of the corresponding unit Gaussian constraint. The dominant sources of uncertainty in this search are that of the  $T_{\chi_{bb}}$  and  $T_{bqq}^{\text{PNet}}$  tagger efficiencies and the  $T_{\chi_{bb}}$  misidentification efficiency applied to the  $t\bar{t}$  simulation in the SR. Unless mentioned otherwise, all sources of uncertainty described here are applied to both the histograms obtained from the generated MC signal samples, as well as the interpolated signal histograms obtained by the procedure described in Section 3.

We consider several sources of theoretical uncertainties related to the modeling of the simulated signal and background processes. The uncertainty in the PDFs used to generate the simulated samples is derived from the PDF variations provided by the NNPDF3.1 set [45]. Uncertainties in the QCD renormalization and factorization scales are obtained via varying these scales independently by factors of 0.5 and 2 with respect to their default values, excluding the two extreme variations.

Experimental uncertainties related to the detector conditions are also considered and applied to MC simulated samples for both signal and background processes. The uncertainty in the integrated luminosity of the data set, taken to be 1.6% [14, 15], has a sub-percent impact on the results. The uncertainties in the jet energy scale and resolution are estimated as functions of  $p_T$  and  $\eta$  of the jets [27]. The uncertainty in the pileup description is evaluated by varying the total inelastic cross section by  $\pm 4.6\%$  [48].

During the 2016–2017 data-taking period, a gradual shift in the timing of the L1 trigger inputs from the ECAL in the  $|\eta| > 2.0$  region caused a trigger inefficiency, denoted as “prefiring” [19]. The trigger missed between 10% and 20% of the events containing an electron (of  $p_T \gtrsim 50$  GeV) or a jet (of  $p_T \gtrsim 100$  GeV) in the  $2.5 < |\eta| < 3.0$  range, the exact loss depending on the  $p_T$  and  $\eta$  of the trigger object. Correction factors were computed from data and applied to the acceptance evaluated by simulation. The uncertainties in these corrections are implemented as templates affecting the shape of the  $p_T$  and  $\eta$  distributions for 2016 and 2017 simulated samples.

The trigger efficiency is measured in an orthogonal data set as a 2D function of  $(m_{T'}^{\text{rec}}, m_{\phi}^{\text{rec}})$ . A parametric function is fit to the 2D efficiency curve, which serves to model the efficiency turn-on while simultaneously reducing statistical fluctuations in the measurement. The MC simulation based distributions are then corrected by evaluating the fitted efficiency function at each event’s reconstructed  $(m_{T'}^{\text{rec}}, m_{\phi}^{\text{rec}})$  invariant mass, and distributions corresponding to  $\pm 1$  standard deviations in the trigger efficiency are derived from the fit uncertainties.

A specific uncertainty in the  $t\bar{t}$  simulation arises from the top quark  $p_T$  reweighting procedure [57], which is extrapolated to high  $p_T$ . This accounts for the observed discrepancy where the  $p_T$  spectrum of  $t\bar{t}$  pairs in data is significantly softer than predicted by MC simulation. The uncertainty is implemented as uncorrelated variations of  $\pm 50\%$  in the correction factor derived from the ratio of the parton-level top quark  $p_T$  in data to the predictions from theory and POWHEG + PYTHIA simulation.

Additionally, uncertainties in the jet tagging and mistagging efficiencies of the various taggers used in this analysis are treated as shape effects on the signal and dominant  $t\bar{t}$  background. The efficiency of the  $T_{\chi_{bb}}$  tagger is calibrated in data using energetic gluons splitting to bottom quarks in data [54] as a proxy for the  $\phi \rightarrow b\bar{b}$  decay, with  $p_T$ -dependent correction factors and their uncertainties applied to signal MC as shape templates. The mistagging efficiency for the

$T_{\chi_{bb}}$  tagger, as well as the tagging efficiencies for the  $T_{bqq}^{\text{PNet}}$  and  $T_{bqq}^{\text{DAK8}}$  discriminants, are calibrated in data using the tag-and-probe method [58] with events enriched in  $t\bar{t}$  production. The  $T_{\chi_{bb}}$  mistagging uncertainty is applied only to  $t\bar{t}$  MC samples, as top quark induced jets have a nonnegligible,  $p_T$ -dependent, probability of being misidentified by this tagger as a  $\phi \rightarrow b\bar{b}$  candidate. The uncertainty in the  $T_{bqq}^{\text{DAK8}}$  tagging efficiency is applied only to the  $t\bar{t}$  background in the  $\text{CR}(t\bar{t})$ , which is the only analysis region where this tagger is employed.

Finally, the uncertainty in the QCD multijet background prediction in the SR is derived during the simultaneous fit to data of the SR and  $\text{CR}(t\bar{t})$ . The uncertainty in the best fit TF parameter values enter the Hessian matrix used to calculate the total background uncertainty. The TF parameters are uncorrelated between the SR and  $\text{CR}(t\bar{t})$  and are treated as nuisance parameters with uniform probability distribution functions in the likelihood.

The fully hadronic and semileptonic searches entering the combination are statistically independent from one another because of a lepton veto applied in the fully hadronic channel, which rejects any event with isolated muons or electrons. For all common  $m_{T'}$  and  $m_\phi$  hypotheses, a simultaneous maximum likelihood fit is performed to extract limits on the product of the cross section and branching fraction for the  $T' \rightarrow t\phi$  process, wherein systematic uncertainties that are common between the fully hadronic and semileptonic top quark decay channels are treated as fully correlated. These include uncertainties arising from reconstruction and calibration procedures such as the jet energy scale and resolution and the top quark  $p_T$  reweighting. Uncertainties in the  $T_{\chi_{bb}}$  tagging and mistagging efficiency correction factors are correlated between the two analyses, since both use this tagger at the same WP for boosted  $\phi$  boson identification. Theoretical uncertainties in both the renormalization and factorization scales as well as in the PDFs used in the generators are also taken to be correlated. Finally, uncertainties inherent to the accelerator and detector in both analyses are correlated, including those in the integrated luminosity and the L1 prefiring correction factors. Systematic uncertainties inherent to the QCD multijet background estimates are uncorrelated between the two channels, as these background estimates are performed in statistically independent regions. A detailed description of the uncertainty sources exclusive to the semileptonic channel, which include those arising from lepton identification and semileptonic top quark reconstruction, can be found in Ref. [13].

## 8 Results

A 2D binned maximum likelihood fit to data of the  $(m_{T'}^{\text{rec}}, m_\phi^{\text{rec}})$  distributions is performed simultaneously for events in the SR and  $\text{CR}(t\bar{t})$ , using MC simulation to model  $t\bar{t}$  and  $V$ +jets, and control samples in data to predict the QCD multijet background. The inclusion of the  $\text{CR}(t\bar{t})$  background model in the likelihood constrains the systematic uncertainties affecting  $t\bar{t}$  MC simulation, helping to model this dominant background in the SR more accurately. The product of a data-driven estimate in the  $T_{\chi_{bb}}$  Fail region and an unconstrained constant TF is used to predict the QCD multijet background yield in the  $T_{\chi_{bb}}$  Pass region of the SR, and the same estimation is performed in the  $\text{CR}(t\bar{t})$  using a separate constant TF.

The results of the 2D fit to data in the hadronic channel are represented in Fig. 1 as projections onto the reconstructed mass axes, and it is observed that the data are in agreement with the SM background prediction within uncertainties. The figure on the left shows the projection of the postfit distributions onto the  $m_\phi^{\text{rec}}$  axis and the one on the right the projection onto the  $m_{T'}^{\text{rec}}$  axis. The lower panels show the pull distributions, defined for each bin as the difference between the observed data and the postfit background prediction divided by the square root

of the difference between the squared Poisson uncertainty in the data and the squared postfit uncertainty in the total background estimate in that particular bin.

The results from the fully hadronic channel are combined with those from the semileptonic channel in a global maximum likelihood fit using the CMS statistical analysis tool COMBINE [59], which is based on the ROOFIT [60] and ROOSTATS [61] frameworks. Shared sources of systematic uncertainty are correlated between the two channels in the fit and are listed in Section 7, while those exclusive to each channel are considered uncorrelated. The signal strength for each  $m_{T'}$  hypothesis is extracted from a simultaneous fit of both channels' SRs, while utilizing their respective CRs to constrain the backgrounds.

The data are in agreement with the SM background prediction within uncertainties in both searches. The 95% confidence level (CL) expected and observed upper limits on the product of the cross section and branching fraction for  $T'$  quark production are calculated using the  $CL_s$  criterion [62, 63] with the profile likelihood ratio as the test statistic [64] using an asymptotic approximation [65]. The observed 95% CL upper limit is shown as a function of  $(m_{T'}, m_\phi)$  in Fig. 2. No assumption is made for  $\mathcal{B}(T' \rightarrow t\phi)$ , and  $\mathcal{B}(\phi \rightarrow b\bar{b})$  is assumed to be 100%. For  $m_{T'} < 1.5$  TeV, the combination achieves an improvement on the upper limits on the product of cross section and branching fraction for each channel by up to a factor of two for certain  $m_\phi$ . When interpreting the results in the case where the neutral scalar is the SM Higgs boson, the combination improves the mass exclusion limits by 100 GeV over the fully hadronic limits alone. For  $m_{T'} > 2$  TeV the combination converges to the results obtained by the semileptonic channel, which is more sensitive primarily due to lower backgrounds.

Limits at 95% CL on the product of the  $T'$  quark production cross section and branching fraction are shown in Fig. 3 as a function of  $m_{T'}$  for  $m_\phi = 125$  GeV, corresponding to the SM Higgs boson. The results are interpreted here in the context of the singlet  $T'$  quark, for resonances whose widths  $\Gamma$  are 1 and 5% of their mass. The limits for the two channels are shown alongside the results of the statistical combination. Masses of the  $T'$  quark between 0.85–1.3 TeV are excluded at 95% CL for the scenario where the  $T'$  quark mass is 5% of its width.

## 9 Summary

A search for single production of a vector-like top quark partner  $T'$  decaying to a top quark ( $t$ ) and a neutral scalar boson  $\phi$  in the fully hadronic final state is presented, using proton-proton collision data recorded by the CMS experiment at  $\sqrt{s} = 13$  TeV in 2016–2018 and corresponding to a total integrated luminosity of  $138 \text{ fb}^{-1}$ . The hadronic decay products of the top quark and  $\phi$  boson are expected to be highly Lorentz boosted from the decay of the massive  $T'$  resonance, resulting in two large-radius jets in the final state. The results of this hadronic search are combined with those from a previous search in the semileptonic channels in a simultaneous maximum likelihood fit. No significant excess of data with respect to the background prediction is observed. Upper limits at 95% confidence level (CL) are set on the product of the production cross section and branching fraction for the decay  $T' \rightarrow t\phi$ , representing the first results for the decay  $T' \rightarrow t(bq\bar{q}')\phi(b\bar{b})$  at the LHC. For the case where the neutral scalar is the standard model Higgs boson (H), upper limits are set on the product of the production cross section and the  $T' \rightarrow tH$  branching fraction between 10 and 0.4 fb at 95% CL for  $T'$  quark masses between 1 and 3 TeV. They exclude  $T'$  quark masses of 0.85–1.3 TeV assuming the  $T'$  quark is a weak-isospin singlet with a resonance width 5% of its mass, improving on all previous searches by the CMS Collaboration [6] by up to a factor of three and representing the most stringent limits to date for masses above 2 TeV. For other  $\phi$  boson masses, upper limits as

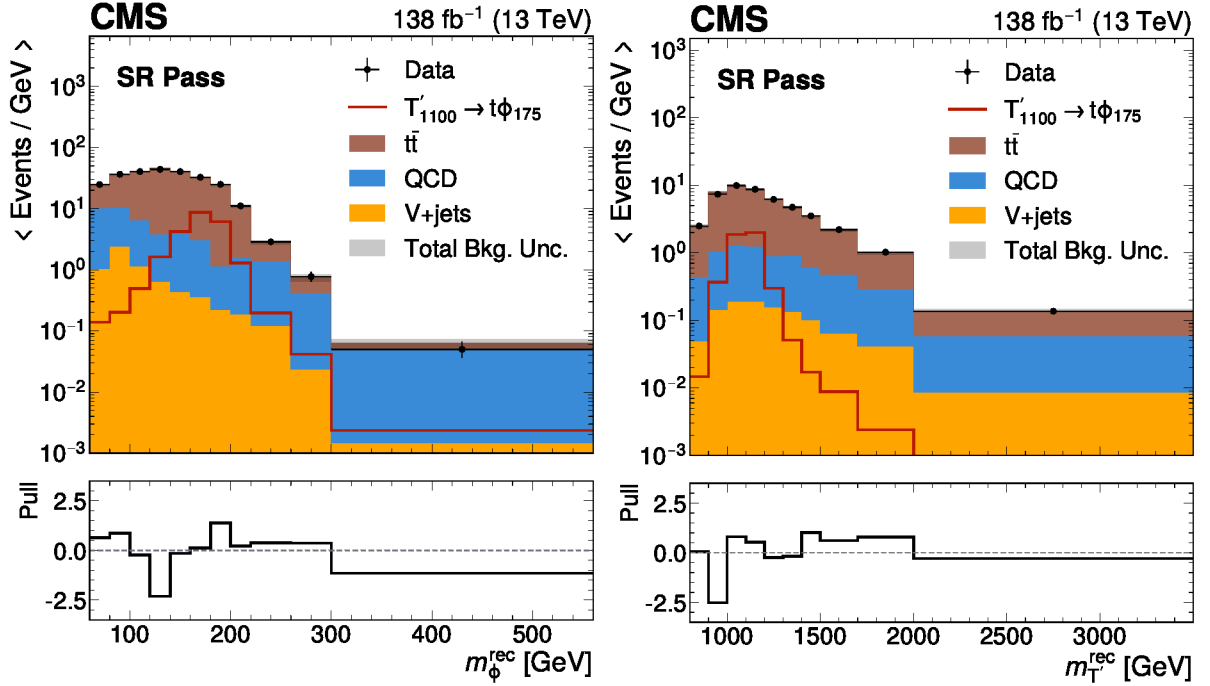


Figure 1: Postfit distributions of data and predicted background in the SR under the background-only hypothesis, projected onto the  $m_{\phi}^{\text{rec}}$  (left) and  $m_{T'}^{\text{rec}}$  (right) axes in the  $T_{\chi_{bb}}$  Pass tagging region,  $\text{SR}_P$ . A  $m_{\phi} = 175 \text{ GeV}$ ,  $m_{T'} = 1100 \text{ GeV}$  signal sample normalized to a cross section of  $220 \text{ fb}$  is overlaid for visualization. The  $y$  axes of the top panels have been rescaled to display the number of events per bin, divided by the width of each bin. The lower panels show the pull distributions, defined for each bin as the difference between the observed data and the postfit background prediction divided by the square root of the difference between the squared Poisson uncertainty in the data and the squared postfit uncertainty in the total background estimate in that particular bin.

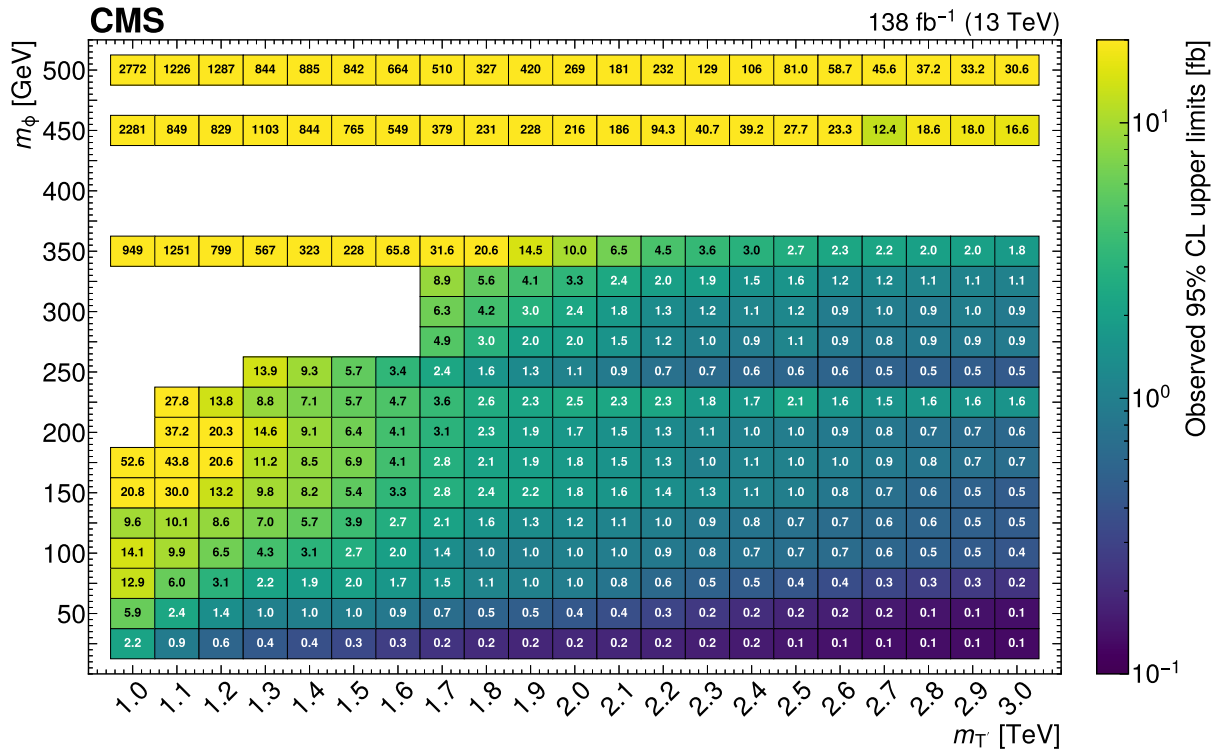


Figure 2: The upper limit at 95% CL on the product of cross section for the  $T' \rightarrow t\phi$  process and branching fraction  $\mathcal{B}(t \rightarrow bq\bar{q}')$  as a function of  $(m_{T'}, m_\phi)$ , assuming  $\mathcal{B}(\phi \rightarrow b\bar{b}) = 100\%$ . Masses of the  $\phi$  boson below 75 GeV are exclusive to the semileptonic channel, while  $m_\phi > 250$  GeV are exclusive to the fully hadronic channel. Besides  $m_\phi = 225$  GeV, also exclusive to the fully hadronic channel, upper limits for  $75 < m_\phi < 250$  GeV are obtained from the combination of the two channels. Gaps in  $m_\phi$  above 250 GeV are due to the limitations in the signal interpolation scheme in the hadronic channel, while gaps in  $m_\phi < 250$  GeV correspond to signals not considered by the semileptonic channel due to poor signal efficiency.

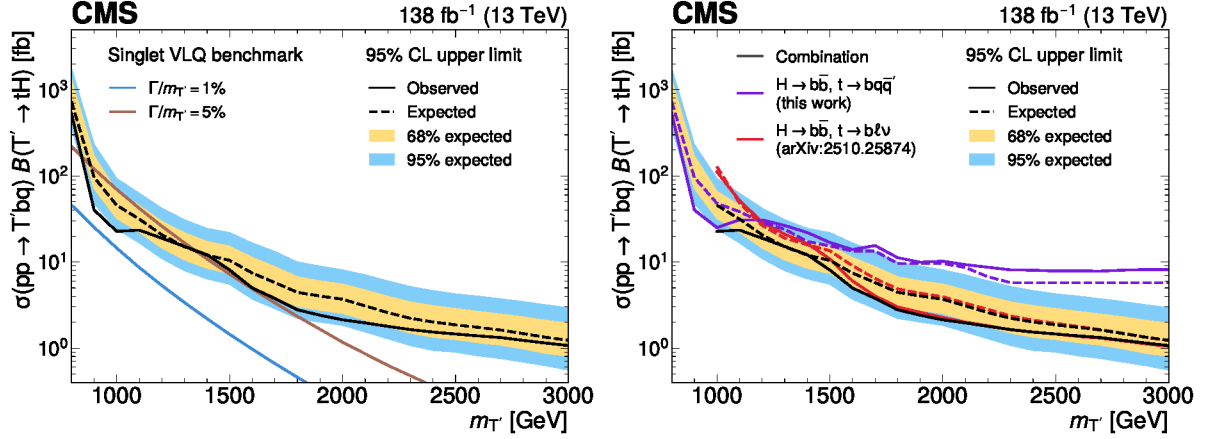


Figure 3: Upper limits at 95% CL on the product of the cross section and branching fraction for  $pp \rightarrow T' \rightarrow tH$  as functions of the  $T'$  quark mass for fixed  $m_\phi = m_H = 125$  GeV. In the left panel, the solid blue (brown) curves indicate the theoretical cross sections for the singlet  $T'$  quark model assuming its width is 1% (5%) of its mass [33, 34]. The contributions to the combination from the semileptonic (red) and fully hadronic (purple) channels are detailed in the right panel, where it is shown that upper limits for  $T'$  quark masses below 1 TeV are obtained from the fully hadronic channel only, while limits for all other mass points are obtained from the combination of the semileptonic and fully hadronic channels. The same holds for the shaded 68% and 95% expected upper limits in the right panel. In both panels, the median expected and the observed limits are depicted using dashed and solid lines, respectively.

low as 0.1 fb are set at 95% CL on the product of the  $T'$  production cross section and branching fraction to  $t\phi$ .

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); Minciencias (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG and PSG, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); MATE and NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, 101001205, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA) and Fonds voor Wetenschappelijk Onderzoek contract No. 1228724N (Belgium); the Beijing Municipal Science & Technology Commission, No. Z191100007219010, the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of China under Grant No. 2023YFA1605804, the Natural Science Foundation of China under Grant No. 12535004, and USTC Research Funds of the Double First-Class Initiative No. YD2030002017 (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 138136, K 143460, K 143477, K 147557, K 146913, K 146914, K 147048, TKP2021-NKTA-64, and 2025-1.1.5-NEMZ.KI-2025-00004, and MATE KKP and KKPCs Research Excellence and Flagship Research Groups grants (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, FAIR – Future Artificial Intelligence Research, and CUP I53D23001070006 (Mission 4 Component 1), funded by the NextGenerationEU program, the Italian Ministry of University and Research (MUR) under Bando PRIN 2022 – CUP I53C24002390006, PRIN PRIMULA 2022RBYK7T (Italy); the Latvian Council of Science; the Ministry of Science and Higher Education, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369, 2021/43/B/ST2/01552, 2023/49/B/ST2/03273, and the NAWA contract BPN/PPO/2021/1/00011 (Poland); the Fundação para a Ciência e a Tecnologia (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, “European Union NextGenerationEU/PRTR”, projects PID2022-142604OB-C21, PID2022-139519OB-C21, PID2023-147706NB-I00, PID2023-148896NB-I00, PID2023-146983NB-I00, PID2023-147115NB-I00, PID2023-148418NB-C41, PID2023-148418NB-C42, PID2023-148418NB-C43, PID2023-148418NB-C44, PID2024-158190NB-C22, RYC2021-033305-I, RYC2024-048719-I, CNS2023-144781, CNS2024-154769 and Plan de Ciencia, Tecnología e Innovación de Asturias, Spain; the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, the National Science, Research and Innovation Fund program IND\_FF\_68\_369\_2300\_097, and the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G680009 (Thailand); the Eric & Wendy Schmidt Fund for Strategic Innovation through the CERN Next Generation Triggers project under grant agreement number SIF-2023-004; the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

## References

- [1] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, “The Hierarchy problem and new dimensions at a millimeter”, *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.
- [2] Y. Okada and L. Panizzi, “LHC signatures of vector-like quarks”, *Adv. High Energy Phys.* **2013** (2013) 364936, doi:10.1155/2013/364936, arXiv:1207.5607.
- [3] O. Eberhardt et al., “Joint analysis of Higgs boson decays and electroweak precision observables in the standard model with a sequential fourth generation”, *Phys. Rev. D* **86** (2012) 013011, doi:10.1103/PhysRevD.86.013011, arXiv:1204.3872.
- [4] J.-A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Pérez-Victoria, “A handbook of vector-like quarks: mixing and single production”, *Phys. Rev. D* **88** (2013) 094010, doi:10.1103/PhysRevD.88.094010, arXiv:1306.0572.
- [5] ATLAS Collaboration, “Exploration at the high-energy frontier: ATLAS Run 2 searches investigating the exotic jungle beyond the Standard Model”, *Phys. Rept.* **1116** (2025) 301, doi:10.1016/j.physrep.2024.10.001, arXiv:2403.09292.
- [6] CMS Collaboration, “Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton–proton collisions at  $\sqrt{s} = 13$  TeV at the CMS experiment”, *Phys. Rept.* **1115** (2025) 570, doi:10.1016/j.physrep.2024.09.012, arXiv:2405.17605.
- [7] S. Fajfer, A. Greljo, J. F. Kamenik, and I. Mustac, “Light Higgs and vector-like quarks without prejudice”, *JHEP* **07** (2013) 155, doi:10.1007/JHEP07(2013)155, arXiv:1304.4219.
- [8] G. Cacciapaglia, T. Flacke, M. Park, and M. Zhang, “Exotic decays of top partners: mind the search gap”, *Phys. Lett. B* **798** (2019) 135015, doi:10.1016/j.physletb.2019.135015, arXiv:1908.07524.
- [9] R. Benbrik et al., “Signatures of vector-like top partners decaying into new neutral scalar or pseudoscalar bosons”, *JHEP* **05** (2020) 028, doi:10.1007/JHEP05(2020)028, arXiv:1907.05929.
- [10] J. A. Aguilar-Saavedra, J. Alonso-González, L. Merlo, and J. M. No, “Exotic vectorlike quark phenomenology in the minimal linear  $\sigma$  model”, *Phys. Rev. D* **101** (2020) 035015, doi:10.1103/PhysRevD.101.035015, arXiv:1911.10202.
- [11] A. Bhardwaj, T. Mandal, S. Mitra, and C. Neeraj, “Roadmap to explore vectorlike quarks decaying to a new scalar or pseudoscalar”, *Phys. Rev. D* **106** (2022) 095014, doi:10.1103/PhysRevD.106.095014, arXiv:2203.13753.
- [12] G. C. Branco et al., “Theory and phenomenology of two-Higgs-doublet models”, *Phys. Rept.* **516** (2012) 1, doi:10.1016/j.physrep.2012.02.002, arXiv:1106.0034.
- [13] CMS Collaboration, “Search for single production of a vector-like T quark decaying to a top quark and a neutral scalar boson in the lepton+jets final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, 2025. arXiv:2510.25874. Submitted to *JHEP*.

- [14] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [15] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the CMS detector”, CMS Physics Analysis Summary CMS-PAS-LUM-20-001, 2025.
- [16] HEPData record for this analysis, 2026. doi:10.17182/hepdata.167416.
- [17] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [18] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.
- [19] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [20] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [21] CMS Collaboration, “Performance of the CMS high-level trigger during LHC Run 2”, *JINST* **19** (2024) P11021, doi:10.1088/1748-0221/19/11/P11021, arXiv:2410.17038.
- [22] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [23] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_T$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [24] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [25] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [26] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.
- [27] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [28] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [29] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, “Jet substructure as a new Higgs search channel at the LHC”, *Phys. Rev. Lett.* **100** (2008) 242001, doi:10.1103/PhysRevLett.100.242001, arXiv:0802.2470.

- [30] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, “Towards an understanding of jet substructure”, *JHEP* **09** (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.
- [31] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft drop”, *JHEP* **05** (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.
- [32] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [33] M. Buchkremer, G. Cacciapaglia, A. Deandrea, and L. Panizzi, “Model independent framework for searches of top partners”, *Nucl. Phys. B* **876** (2013) 376, doi:10.1016/j.nuclphysb.2013.08.010, arXiv:1305.4172.
- [34] A. Carvalho et al., “Single production of vectorlike quarks with large width at the Large Hadron Collider”, *Phys. Rev. D* **98** (2018) doi:10.1103/physrevd.98.015029, arXiv:1805.06402.
- [35] A. Roy, N. Nikiforou, N. Castro, and T. Andeen, “Novel interpretation strategy for searches of singly produced vectorlike quarks at the LHC”, *Phys. Rev. D* **101** (2020) 115027, doi:10.1103/PhysRevD.101.115027, arXiv:2003.00640.
- [36] M. J. Oreglia, “A study of the reactions  $\psi' \rightarrow \gamma\gamma\psi$ ”, other thesis, Stanford University, 1980. SLAC Report SLAC-R-236.
- [37] J. E. Gaiser, “Charmonium Spectroscopy From Radiative Decays of the  $J/\psi$  and  $\psi'$ ”, other thesis, Stanford University, 1982. SLAC Report SLAC-R-255.
- [38] A. L. Read, “Linear interpolation of histograms”, *Nucl. Instrum. Meth. A* **425** (1999) 357, doi:10.1016/S0168-9002(98)01347-3.
- [39] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [40] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: The POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [41] S. Frixione, G. Ridolfi, and P. Nason, “A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction”, *JHEP* **09** (2007) 126, doi:10.1088/1126-6708/2007/09/126, arXiv:0707.3088.
- [42] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [43] E. Re, “Single-top  $Wt$ -channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [44] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.



- 
- [45] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [46] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [47] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [48] ATLAS Collaboration, “Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 13$  TeV with the ATLAS Detector at the LHC”, *Phys. Rev. Lett.* **117** (2016) 182002, doi:10.1103/PhysRevLett.117.182002, arXiv:1606.02625.
- [49] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 13$  TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [50] D. Krohn, J. Thaler, and L.-T. Wang, “Jet trimming”, *JHEP* **02** (2010) 084, doi:10.1007/JHEP02(2010)084, arXiv:0912.1342.
- [51] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [52] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/p06015, arXiv:1804.04528.
- [53] H. Qu and L. Gouskos, “Jet tagging via particle clouds”, *Phys. Rev. D* **101** (2020) 056019, doi:10.1103/PhysRevD.101.056019, arXiv:1902.08570.
- [54] CMS Collaboration, “Performance of heavy-flavour jet identification in Lorentz-boosted topologies in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **20** (2025) P11006, doi:10.1088/1748-0221/20/11/P11006, arXiv:2510.10228.
- [55] CMS Collaboration, “Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques”, *JINST* **15** (2020), no. 06, P06005, doi:10.1088/1748-0221/15/06/P06005, arXiv:2004.08262.
- [56] R. A. Fisher, “On the Interpretation of  $\chi^2$  from Contingency Tables, and the Calculation of P”, *J. Royal Stat. Soc.* **85** (1922) 87, doi:10.2307/2340521.
- [57] M. Czakon et al., “Top-pair production at the LHC through NNLO QCD and NLO EW”, *JHEP* **10** (2017) 186, doi:10.1007/JHEP10(2017)186, arXiv:1705.04105.
- [58] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [59] CMS Collaboration, “The CMS statistical analysis and combination tool: COMBINE”, *Comput. Softw. Big Sci.* **8** (2024) 19, doi:10.1007/s41781-024-00121-4, arXiv:2404.06614.

- [60] W. Verkerke and D. Kirkby, “The ROOFIT toolkit for data modeling”, in *Proc. 13th Int. Conf. on Computing in High Energy and Nuclear Physics (CHEP 2003): La Jolla CA, United States, March 24–28, 2003*. 2003. arXiv:physics/0306116.
- [61] L. Moneta et al., “The ROOSTATS project”, in *Proc. 13th Int. Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2010): Jaipur, India, February 22–27, 2010*. 2010. arXiv:1009.1003. doi:10.22323/1.093.0057.
- [62] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [63] A. L. Read, “Presentation of search results: The CL<sub>s</sub> technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [64] ATLAS and CMS Collaborations, and LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.
- [65] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].











## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

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









### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , L. Benato , T. Bergauer , M. Dragicevic , P.S. Hussain , M. Jeitler<sup>2</sup> , N. Krammer , A. Li , D. Liko , M. Matthewman, J. Schieck<sup>2</sup> , R. Schöfbeck<sup>2</sup> , M. Shooshitari , M. Sonawane , N. Van Den Bossche , W. Waltenberger , C.-E. Wulz<sup>2</sup> 









### Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , H. Kwon , D. Ocampo Henao , T. Van Laer , P. Van Mechelen 









### Vrije Universiteit Brussel, Brussel, Belgium

D. Ahmadi , J. Bierkens , N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , C. Gupta, F. Heyen, Y. Hong , P. Kashko , S. Lowette , I. Makarenko , S. Nandakumar , S. Tavernier , M. Tytgat<sup>3</sup> , G.P. Van Onsem , S. Van Putte , D. Vannerom , T. Wybouw 









### Université Libre de Bruxelles, Bruxelles, Belgium

A. Beshr, B. Bilin , F. Caviglia Roman, B. Clerbaux , A.K. Das, I. De Bruyn , G. De Lentdecker , E. Ducarme , H. Evard , L. Favart , A. Khalilzadeh, A. Malara , M.A. Shahzad, A. Sharma , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer , F. Zhang 









### Ghent University, Ghent, Belgium

A. Cauwels, M. De Coen , D. Dobur , C. Giordano , G. Gokbulut , K. Kaspar , D. Kavtaradze, D. Marckx , K. Skovpen , A.M. Tomaru, J. van der Linden , J. Vandenbroeck 









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

H. Aarup Petersen , S. Bein , A. Benecke , A. Bethani , G. Bruno , A. Cappati , J. De Favereau De Jeneret , C. Delaere , F. Gameiro Casalinho , A. Giammanco , A.O. Guzel , V. Lemaître, J. Lidrych , P. Malek , S. Turkcapar 









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

G.A. Alves , M. Barroso Ferreira Filho , E. Coelho , C. Hensel , D. Matos Figueiredo , T. Menezes De Oliveira , C. Mora Herrera , P. Rebello Teles , M. Soeiro , E.J. Tonelli Manganote<sup>4</sup> , A. Vilela Pereira 






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

W.L. Aldá Júnior , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>5</sup> , M. Costa Reis , E.M. Da Costa , D. Da Silva Dalto , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza , S. S. Jesus , T. Laux Kuhn<sup>6</sup> , K. Maslova , K. Mota Amarilo , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo<sup>7</sup> 

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






C.A. Bernardes , L. Calligaris , J. Carvalho Leite , F. Damas , T.R. Fernandez Perez Tomei , E.M. Gregores , B. Lopes Da Costa , I. Masetto Silverio , P.G. Mercadante , S.F. Novaes , Sandra S. Padula , V. Scheurer

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

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

G. Sultanov 

**University of Sofia, Sofia, Bulgaria**

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

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

S. Keshri , D. Laroze , M. Meena , S. Thakur 

**Universidad Tecnica Federico Santa Maria, Valparaiso, Chile**

W. Brooks 















**Beihang University, Beijing, China**

T. Cheng , T. Javaid , L. Wang , L. Yuan 














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

J. Gu , Z. Hu , Z. Liang, J. Liu, X. Wang , Y. Wang, H. Yang, S. Zhang 


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

G.M. Chen<sup>8</sup> , H.S. Chen<sup>8</sup> , M. Chen<sup>8</sup> , Y. Chen , Q. Hou , X. Hou, F. Iemmi , C.H. Jiang, H. Liao , G. Liu , Z.-A. Liu<sup>9</sup> , S. Song , J. Tao , C. Wang<sup>8</sup>, J. Wang , H. Zhang , J. Zhao 


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

A. Agapitos , Y. Ban , A. Carvalho Antunes De Oliveira , S. Deng , B. Guo, Q. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, C. Quaranta , X. Sun , D. Wang , J. Wang, M. Zhang, Y. Zhao, C. Zhou 

**State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China**

X. Hua, S. Yang 

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

Z. You 


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

N. Lu 

**Nanjing Normal University, Nanjing, China**

G. Bauer<sup>10,11</sup>, Z. Cui<sup>11</sup>, B. Li<sup>12</sup>, H. Wang , K. Yi<sup>13</sup> , J. Zhang 

**Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China**

C. Li 




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

Y. Li, Y. Zhou<sup>14</sup>





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

Z. Lin , C. Lu , M. Xiao<sup>15</sup> 

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

C. Avila , A. Cabrera , C. Florez , J.A. Reyes Vega




**Universidad de Antioquia, Medellin, Colombia**

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**

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 , D. Ferencek , K. Jakovic, A. Starodumov , T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , S. Konstantinou , C. Leonidou , L. Paizanos ,  
F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

M. Finger<sup>†</sup> , M. Finger Jr. 



**Escuela Politecnica Nacional, Quito, Ecuador**

E. Acurio 

**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**

S. Khalil<sup>16</sup> , E. Salama<sup>17,18</sup> 

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

A. Hussein , H. Mohammed 
















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

K. Jaffel , M. Kadastik, T. Lange , C. Nielsen , J. Pata , M. Raidal , N. Seeba , L. Tani 

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

E. Brücken , A. Milieva , K. Osterberg , M. Voutilainen 





















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

F. Garcia , P. Inkaew , K.T.S. Kallonen , R. Kumar Verma , T. Lampén , K. Lassila-Perini , B. Lehtela , S. Lehti , T. Lindén , N.R. Mancilla Xinto , M. Myllymäki ,  
M.m. Rantanen , S. Saariokari , N.T. Toikka , J. Tuominiemi 


























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

N. Bin Norjoharuddeen , H. Kirschenmann , P. Luukka , H. Petrow 

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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, P. Devouge, J.L. Faure , F. Ferri ,  
P. Gaigne, S. Ganjour , P. Gras , F. Guilloux , G. Hamel de Monchenault , M. Kumar ,  
V. Lohezic , Y. Maidannyk , J. Malcles , F. Orlandi , L. Portales , S. Ronchi ,  
M.Ö. Sahin , P. Simkina , M. Titov , M. Tornago 

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

R. Amella Ranz , F. Beaudette , G. Boldrini , P. Busson , C. Charlot , M. Chiusi ,  
T.D. Cuisset , O. Davignon , A. De Wit , T. Debnath , I.T. Ehle , S. Ghosh ,  
A. Gilbert , R. Granier de Cassagnac , M. Manoni , M. Nguyen , S. Obraztsov ,  
C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , G. Sokmen, Y. Song ,  
L. Urda Gómez , A. Zabi , A. Zghiche 


















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

J.-L. Agram<sup>19</sup> , J. Andrea , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , G. Coulon, S. Falke , U. Goerlach , A.-C. Le Bihan , G. Saha , A. Savoy-Navarro<sup>20</sup> , P. Vaucelle 

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

A. Di Florio , B. Orzari 

**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 , H. El Mamouni, J. Fay , E. Fillaudeau , S. Gascon , M. Gouzevitch , C. Greenberg , G. Grenier , B. Ille , E. Jourd'Huy, M. Lethuillier , B. Massoteau , L. Mirabito, A. Purohit , M. Vander Donckt , C. Verollet


























**Georgian Technical University, Tbilisi, Georgia**

G. Adamov, I. Lomidze , Z. Tsamalaidze<sup>21</sup> 

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

K.F. Adamowicz, V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , P. Nattland , V. Oppenländer, A. Pauls , D. Pérez Adán 


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

C. Daumann, S. Diekmann , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , M.Z. Farkas , B. Fischer , T. Hebbeker , K. Hoepfner , A. Jung , N. Kumar , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , A. Pozdnyakov , W. Redjeb , H. Reithler , U. Sarkar , V. Sarkisovi , A. Schmidt , C. Seth, A. Sharma , J.L. Spah , V. Vaulin, U. Willemsen , S. Zaleski, F.P. Zinn













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



M.R. Beckers , G. Flügge , N. Hoeflich , T. Kress , A. Nowack , O. Pooth , A. Stahl 

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**










































A. Abel, M. Aldaya Martin , J. Alimena , Y. An , I. Andreev , J. Bach , S. Baxter , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman<sup>22</sup> , K. Borras<sup>23</sup> , A. Campbell , S. Chatterjee , L.X. Coll Saravia , G. Eckerlin, D. Eckstein , E. Gallo<sup>22</sup> , A. Geiser , M. Guthoff , A. Hinzmann , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , F. Labe , W. Lange, D. Leyva Pernia , J.h. Li , K.-Y. Lin , K. Lipka<sup>24</sup> , W. Lohmann<sup>25</sup> , J. Malvaso , 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 , J. Park , E. Ranken , A. Raspereza , D. Rastorguev , L. Rygaard , M. Scham<sup>26,23</sup> , S. Schnake<sup>23</sup> , P. Schütze , C. Schwanenberger<sup>22</sup> , D. Schwarz , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford , M. Torkian, S. Vashishtha, A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , K. Wichmann, L. Wiens<sup>23</sup> , C. Wissing , Y. Yang , S. Zakharov , A. Zimmermann Castro Santos 

**University of Hamburg, Hamburg, Germany**

A.R. Alves Andrade , M. Antonello , S. Bollweg, M. Bonanomi , L. Ebeling, K. El Morabit , Y. Fischer , M. Frahm , E. Garutti , A. Grohsjean , A.A. Guvenli , J. Haller , D. Hundhausen, G. Kasieczka , P. Keicher , R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, J. Lange , A. Lobanov , J. Matthiesen, L. Moureaux , K. Nikolopoulos , K.J. Pena Rodriguez , N. Prouvost, B. Raciti , M. Rieger , D. Savoie , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , R. Ward 

B. Wiederspan, M. Wolf , C. Yede 

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

A. Brusamolino , E. Butz , Y.M. Chen , T. Chwalek , A. Dierlamm , G.G. Dincer , D. Druzhkin , U. Elicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann<sup>27</sup> , F. Hummer , U. Husemann , J. Kieseler , M. Klute , J. Knolle , R. Kunnilan Muhammed Rafeek, O. Lavoryk , J.M. Lawhorn , S. Maier , T. Mehner , M. Molch, A.A. Monsch , M. Mormile , Th. Müller , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , R. Schmieder, T. Selezneva, N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa , L. Stockmeier, K. Tauqeer, M. Toms , B. Topko , N. Trevisani , C. Verstege , T. Voigtländer , R.F. Von Cube , J. Von Den Driesch, C. Winter, R. Wolf , W.D. Zeuner , X. Zuo 





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

G. Anagnostou , G. Daskalakis , A. Kyriakis 

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

G. Melachroinos, Z. Painesis , I. Paraskevas , N. Plastiras , N. Saoulidou , K. Theofilatos , E. Tziaferi , E. Tzovara , K. Vellidis , I. Zisopoulos 

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

T. Chatzistavrou , G. Karapostoli , K. Kousouris , E. Siamarkou, G. Tsipolitis 

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou , C. Foudas, 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>28,29</sup> , Á. Kadlecik , C. Lee , K. Márton, A.J. Rád1<sup>30</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>31</sup> , M.M.A. Gadallah<sup>32</sup> , M. León Coello , G. Pásztor , G.I. Veres 

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

B. Ujvari , G. Zilizi 

**HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary**

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











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

T. Csorgo<sup>31</sup> , F. Nemes<sup>31</sup> , T. Novak , I. Szanyi<sup>33</sup> 

**IIT Bhubaneswar, Bhubaneswar, India**





























































S. Bahinipati , R. Raturi

**Panjab University, Chandigarh, India**

S. Bansal , S.B. Beri, V. Bhatnagar , B. Chauhan, S. Chauhan , N. Dhingra<sup>34</sup> , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J.B. Singh , A. Singla 




























**University of Delhi, Delhi, India**

A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , S. Phor , C. Prakash , K. Ranjan , M.K. Saini 






**Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India**P. Palni **University of Hyderabad, Hyderabad, India**S. Acharya<sup>35</sup> , B. Gomber **Indian Institute of Technology Kanpur, Kanpur, India**S. Ganguly , S. Mukherjee **Saha Institute of Nuclear Physics, HBNI, Kolkata, India**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. Chatterjee , G. Dash , A. Dattamunsi, P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri<sup>36</sup> , T. Mishra , P.R. Pujahari , A.K. Sikdar , R.K. Singh , P. Verma , S. Verma , A. Vijay **IISER Mohali, India, Mohali, India**S. Nayak , H. Rajpoot, B.K. Sirasva**Tata Institute of Fundamental Research-A, Mumbai, India**L. Bhatt, S. Dugad , G.B. Mohanty , M. Shelake , P. Suryadevara**Tata Institute of Fundamental Research-B, Mumbai, India**A. Bala , S. Banerjee , S. Barman<sup>37</sup> , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , M. Maity<sup>37</sup>, G. Majumder , K. Mazumdar , S. Parolia , R. Pramanik, R. Saxena , A. Thachayath **National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**D. Maity<sup>38</sup> , P. Mal , K. Naskar<sup>38</sup> , A. Nayak<sup>38</sup> , K. Pal , P. Sadangi, S.K. Swain , S. Varghese<sup>38</sup> , D. Vats<sup>38</sup> **Indian Institute of Science Education and Research (IISER), Pune, India**S. Dube , P. Hazarika , B. Kansal , A. Laha , R. Sharma , S. Sharma , K.Y. Vaish **Indian Institute of Technology Hyderabad, Telangana, India**S. Ghosh **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi<sup>39</sup> , A. Jafari<sup>40</sup> , V. Sedighzadeh Dalavi , M. Zeinali<sup>41</sup> **Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Bashiri , S. Chenarani<sup>42</sup> , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi , M. Nourbakhsh , S. Tizchang<sup>43</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> , M. Barbieri<sup>a,b</sup>, M. Buonsante<sup>a,b</sup> , A. Colaleo<sup>a,b</sup> , D. Creanza<sup>a,c</sup> , N. De Filippis<sup>a,c</sup> , M. De Palma<sup>a,b</sup> , W. Elmetenawee<sup>a,b,44</sup> , N. Ferrara<sup>a,c</sup> , L. Fiore<sup>a</sup> , L. Generoso<sup>a,b</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> , F. Nenna<sup>a,b</sup> , S. Nuzzo<sup>a,b</sup> , A. Pellecchia<sup>a,b</sup> , A. Pompili<sup>a,b</sup> , F.M. Procacci<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> , F.R. Cavallo<sup>a</sup> , M. Cruciani<sup>a,b</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> , R. Farinelli<sup>a</sup> , D. Fasanella<sup>a</sup> , L. Ferragina<sup>a,b</sup> , P. Giacomelli<sup>a</sup> , C. Grandi<sup>a</sup> , L. Guiducci<sup>a,b</sup> , S. Lo Meo<sup>a,45</sup> , M. Lorusso<sup>a,b</sup> , L. Lunerti<sup>a</sup> , S. Marcellini<sup>a</sup> , G. Masetti<sup>a</sup> , F.L. Navarria<sup>a,b</sup> , G. Paggi<sup>a,b</sup> , A. Perrotta<sup>a</sup> , A.M. Rossi<sup>a,b</sup> , S. Rossi Tisbeni<sup>a,b</sup> 





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

S. Costa<sup>a,b,46</sup> , A. Di Mattia<sup>a</sup> , A. Lapertosa<sup>a</sup> , R. Potenza<sup>a,b</sup> , A. Tricomi<sup>a,b,46</sup> 





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

J. Altork<sup>a,b</sup> , P. Assiouras<sup>a</sup> , G. Barbagli<sup>a</sup> , G. Bardelli<sup>a</sup> , M. Bartolini<sup>a,b</sup> , A. Calandri<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> , L. Damenti<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. Colafranceschi<sup>47</sup> , S. Meola<sup>48</sup> , D. Piccolo 









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

M. Alves Gallo Pereira<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> , V. Camagni<sup>a,b</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.R. Kim<sup>a</sup> , G. Lavizzari<sup>a,b</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> , 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> , F. Confortini<sup>a,b</sup> , C. Di Fraia<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , L. Favilla<sup>a,d</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,49</sup> , P. Paolucci<sup>a,27</sup> , B. Rossi<sup>a</sup> 











#### **INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università degli Studi di Cagliari<sup>c</sup>, Cagliari, Italy**

P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,50</sup> , D. Bisello<sup>a,b</sup> , L. Borella<sup>a</sup> , P. Bortignon<sup>a,c</sup> , G. Bortolato<sup>a,b</sup> , A.C.M. Bulla<sup>a,c</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a,51</sup> , F. Gasparini<sup>a,b</sup> , U. Gasparini<sup>a,b</sup> , S. Giorgetti<sup>a</sup> , N. Lai<sup>a</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , M. Michelotto<sup>a</sup> , J. Pazzini<sup>a,b</sup> , F. Primavera<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> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> 

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














A. Braghieri<sup>a</sup> , M. Brunoldi<sup>a,b</sup> , S. Calzaferri<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , M. Pelliccioni<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. Della Penna<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,52</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,b</sup> , C.A. Alexe<sup>a,c</sup> , P. Asenov<sup>a,b</sup> , P. Azzurri<sup>a</sup> , G. Bagliesi<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> , F. Cattafesta<sup>a,c</sup> , M.A. Ciocci<sup>a,d</sup> , M. Cipriani<sup>a,b</sup> , R. Dell'Orso<sup>a</sup> , S. Donato<sup>a,b</sup> , R. Forti<sup>a,b</sup> , A. Giassi<sup>a</sup> , F. Ligabue<sup>a,c</sup> , A.C. Marini<sup>a,b</sup> , A. Messineo<sup>a,b</sup> , S. Mishra<sup>a</sup> , V.K. Muraleedharan Nair Bindhu<sup>a,b</sup> , S. Nandan<sup>a</sup> , F. Palla<sup>a</sup> , M. Riggirello<sup>a,c</sup> , A. Rizzi<sup>a,b</sup> , G. Rolandi<sup>a,c</sup> , S. Roy Chowdhury<sup>a,53</sup> , T. Sarkar<sup>a</sup> , A. Scribano<sup>a</sup> , P. Solanki<sup>a,b</sup> , P. Spagnolo<sup>a</sup> , F. Tenchini<sup>a,b</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**

P. Akrap<sup>a,b</sup> , C. Basile<sup>a,b</sup> , S.C. Behera<sup>a</sup> , F. Cavallari<sup>a</sup> , L. Cunqueiro Mendez<sup>a,b</sup> , F. De Ruggi<sup>a,b</sup> , D. Del Re<sup>a,b</sup> , M. Del Vecchio<sup>a,b</sup> , E. Di Marco<sup>a</sup> , M. Diemoz<sup>a</sup> , F. Errico<sup>a</sup> , L. Frosina<sup>a,b</sup> , R. Gargiulo<sup>a,b</sup> , B. Harikrishnan<sup>a,b</sup> , F. Lombardi<sup>a,b</sup> , E. Longo<sup>a,b</sup> , L. Martikainen<sup>a,b</sup> , G. Organtini<sup>a,b</sup> , N. Palmeri<sup>a,b</sup> , R. Paramatti<sup>a,b</sup> , T. Pauletto<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> , V. Vladimirov<sup>a,b</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,c</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> , E. Ferrando<sup>a,b</sup> , L. Finco<sup>a</sup> , M. Grippo<sup>a,b</sup> , B. Kiani<sup>a,b</sup> , L. Lanteri<sup>a,b</sup> , F. Legger<sup>a</sup> , F. Luongo<sup>a,b</sup> , C. Mariotti<sup>a</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> , M.M. Obertino<sup>a,b</sup> , G. Ortona<sup>a</sup> , L. Pacher<sup>a,b</sup> , N. Pastrone<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> , E. Vlasov<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,53</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> , R. Delli Gatti<sup>a,b</sup> , C. Giraladin<sup>a,b</sup> 

**Kyungpook National University, Daegu, Korea**

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

**Department of Mathematics and Physics - GWNu, 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 , J. Seo 

**Hanyang University, Seoul, Korea**

E. Asilar , F. Carnevali , J. Choi<sup>54</sup> , T.J. Kim , Y. Ryou , J. Song 




**Korea University, Seoul, Korea**

S. Ha , S. Han , B. Hong , J. Kim , K. Lee , K.S. Lee , S. Lee , J. Padmanaban , J. Yoo 















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

J. Goh , J. Shin , S. Yang 

**Sejong University, Seoul, Korea**

L. Kalipoliti , Y. Kang , H. S. Kim , Y. Kim , B. Ko, S. Lee 







**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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

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

G. Cho, Y. Eo , K. Hwang , H. Jang , B. Kim , D. Kim, S. Kim, K. Lee , H.D. Yoo 


**Sungkyunkwan University, Suwon, Korea**

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 , O.M. Eberlins , A. Gaile , M. Klevs , C. Munoz Diaz , D. Osite , G. Pikurs , R. Plese , A. Potrebko , M. Seidel , D. Sidiropoulos Kontos 

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

N.R. Strautnieks 

**Vilnius University, Vilnius, Lithuania**

M. Ambrozias , A. Juodagalvis , S. Nargelas , S. Nayak , A. Rinkevicius , G. Tamulaitis 

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

I. Yusuff<sup>55</sup> , Z. Zolkapli



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

J.F. Benitez , A. Castaneda Hernandez , A. Cota Rodriguez , L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma , R. Lopez-Fernandez , J. Mejia Guisao , R. Reyes-Almanza , 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 , F.E. Neri Huerta , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

**University of Montenegro, Podgorica, Montenegro**

I. Bubanja , J. Mijuskovic , 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, W.A. Khan 









**AGH University of Krakow, Krakow, Poland**

V. Avati, L. Forthomme , L. Grzanka , M. Malawski , K. Piotrkowski 

**National Centre for Nuclear Research, Swierk, Poland**

M. Bluj , M. Ghimiray , 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 , W. Matyszkiewicz , A. Muhammad , S. Slawinski 





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

P. Fokow , K. Pozniak , W. Zabolotny 

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

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
































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

P. Adzic , L. Markovic , P. Milenovic , V. Milosevic 

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

D. Devetak , M. Dordevic , J. Milosevic , L. Nadderd , V. Rekoivic, M. Stojanovic 

















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

M. Alcalde Martinez , 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 , M. Gonzalez Hernandez , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. Llorente Merino , C. Martin Perez , E. Martin Viscasilas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , R. Paz Herrera , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , 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**

E. Aller Gutierrez , B. Alvarez Gonzalez , J. Ayllon Torresano , A. Cardini , J. Cuevas , J. Del Riego Badas , D. Estrada Acevedo , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina , M. Obeso Menendez , E. Palencia Cortezon , J. Prado Pico , A. Soto Rodríguez , P. Vischia 














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

S. Blanco Fernández , I.J. Cabrillo , A. Calderon , M. Caserta, J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasaosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , C. Quintana San Emeterio , V. Rodriguez, L. Scodellaro , I. Vila , R. Vilar Cortabitarte , J.M. Vizan Garcia 































**University of Colombo, Colombo, Sri Lanka**B. Kailasapathy<sup>56</sup> , D.D.C. Wickramarathna **University of Ruhuna, Department of Physics, Matara, Sri Lanka**W.G.D. Dharmaratna<sup>57</sup> , K. Liyanage , N. Perera **CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo , C. Amendola , R. Ardino , E. Auffray , J. Baechler, D. Barney ,  
 J. Bendavid , I. Bestintzanos, M. Bianco , A. Bocci , L. Borgonovi , C. Botta ,  
 A. Bragagnolo , C.E. Brown , C. Caillol , G. Cerminara , P. Connor , K. Cormier ,  
 D. d'Enterria , A. Dabrowski , P. Das , A. David , A. De Roeck , M.M. Defranchis ,  
 M. Deile , M. Dobson , P.J. Fernández Manteca , B.A. Fontana Santos Alves ,  
 E. Fontanesi , W. Funk , A. Gaddi, S. Giani, D. Gigi, K. Gill , F. Glege , M. Glowacki,  
 A. Gruber , J. Hegeman , J.K. Heikkilä , R. Hofsaess , B. Huber , T. James , P. Janot ,  
 L. Jeppe , O. Kaluzinska , O. Karacheban<sup>25</sup> , G. Karathanasis , S. Laurila , P. Lecoq ,  
 E. Leutgeb , C. Lourenço , A.-M. Lyon , M. Magherini , L. Malgeri , M. Mannelli ,  
 A. Mehta , F. Meijers , J.A. Merlin, S. Mersi , E. Meschi , M. Migliorini , F. Monti ,  
 F. Moortgat , M. Mulders , M. Musich , I. Neutelings , S. Orfanelli, F. Pantaleo ,  
 M. Pari , G. Petrucciani , A. Pfeiffer , M. Pierini , M. Pitt , H. Qu , D. Rabadý ,  
 A. Reimers , B. Ribeiro Lopes , F. Riti , P. Rosado , M. Rovere , H. Sakulin ,  
 R. Salvatico , S. Sanchez Cruz , S. Scarfi , M. Selvaggi , K. Shchelina , P. Silva ,  
 P. Sphicas<sup>58</sup> , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea ,  
 E. Vernazza , J. Wanczyk<sup>59</sup> , S. Wuchterl , M. Zarucki , P. Zehetner , P. Zejdl ,  
 G. Zevi Della Porta 




















**PSI Center for Neutron and Muon Sciences, Villigen, Switzerland**



L. Caminada<sup>60</sup> , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli ,  
 D. Kotlinski , C. Lange , U. Langenegger , A. Nigamova , L. Noehte<sup>60</sup> , L. Redard-  
 Jacot , T. Rohe , A. Samalan 













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

T.K. Aarrestad , M. Backhaus , T. Bevilacqua<sup>60</sup> , G. Bonomelli , C. Cazzaniga ,  
 K. Datta , P. De Bryas Dexmiers D'Archiacchiac<sup>59</sup> , A. De Cosa , G. Dissertori ,  
 M. Dittmar, M. Donegà , F. Glessgen , C. Grab , N. Härringer , T.G. Harte ,  
 M.Köppel , W. Lustermann , M. Malucchi , R.A. Manzoni , L. Marchese ,  
 A. Mascellani<sup>59</sup> , F. Nessi-Tedaldi , F. Paus , A.A. Petre, J. Prendi , B. Ristic ,  
 S. Rohletter, P.M. Sander, R. Seidita , J. Steggemann<sup>59</sup> , A. Tarabini , C.Z. Tee ,  
 D. Valsecchi , P.H. Wagner, R. Wallny 

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>61</sup> , P. Bäertschi , F. Bilandzija , M.F. Canelli , G. Celotto , T.A. Gold-  
 schmidt, V. Guglielmi , A. Jofrehei , B. Kilminster , T.H. Kwok , S. Leontsinis ,  
 V. Lukashenko , A. Macchiolo , F. Meng , M. Missiroli , J. Motta , P. Robmann,  
 E. Shokr , F. Stäger , R. Tramontano , P. Viscone 


**National Central University, Chung-Li, Taiwan**D. Bhowmik, C.M. Kuo, P.K. Rout , S. Taj , P.C. Tiwari<sup>36</sup> **National Taiwan University (NTU), Taipei, Taiwan**

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
















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

C. Asawatangtrakuldee , N. Srimanobhas 

**Tunis El Manar University, Tunis, Tunisia**

Y. Maghrbi 


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

D. Agyel , F. Dolek , I. Dumanoglu<sup>62</sup> , Y. Guler<sup>63</sup> , E. Gurpınar Guler<sup>63</sup> , C. Isik , O. Kara<sup>64</sup> , A. Kayis Topaksu , Y. Komurcu , G. Onengut , K. Ozdemir<sup>65</sup> , B. Tali<sup>66</sup> , U.G. Tok , E. Uslan , I.S. Zorbakir 

**Hacettepe University, Ankara, Turkey**

S. Sen 

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

M. Yalvac<sup>67</sup> 









**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi<sup>68</sup> , E. Gülmez , M. Kaya<sup>69</sup> , O. Kaya<sup>70</sup> , M.A. Sarkisla<sup>71</sup>, S. Tekten<sup>72</sup> 



**Istanbul Technical University, Istanbul, Turkey**

D. Boncukcu , A. Cakir , K. Cankocak<sup>62,73</sup> 

**Istanbul University, Istanbul, Turkey**

B. Hacisahinoglu , I. Hos<sup>74</sup> , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 

**Yildiz Technical University, Istanbul, Turkey**

S. Cerci , C. Dozen<sup>75</sup> , B. Isildak , E. Simsek , D. Sunar Cerci , T. Yetkin<sup>75</sup> 














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

A. Boyaryntsev , O. Dadazhanova, B. Grynyov 






















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

L. Levchuk 























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























J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , D. Dharmender, H. Flacher , J. Goldstein , H.F. Heath , M.-L. Holmberg , A. Karakoulaki, L. Kreczko , S. Paramesvaran , L. Robertshaw , M.S. Sanjrani<sup>39</sup>, J. Segal, V.J. Smith 

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

A.H. Ball, K.W. Bell , A. Belyaev<sup>76</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , A. Elliot , K.V. Ellis, J. Gajownik , K. Harder , S. Harper , J. Linacre , K. Manolopoulos, M. Moallemi , 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 , O. Buchmuller, C.A. Carrillo Montoya , D. Colling , I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , H.R. Hoorani , A. Howard, G. Iles , C.R. Knight , P. Krueper , J. Langford , K.H. Law , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios 

A. Mastronikolis , M. Mieskolainen , J. Nash<sup>77</sup> , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , T.B. Runting , L. Russell , K. Savva , R. Schmitz , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , T. Virdee<sup>27</sup> , M. Vojinovic , N. Wardle , D. Winterbottom , J. Xiao 


#### **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 , J. Dittmann , K. Hatakeyama , V. Hegde , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 















#### **Bethel University, St. Paul, Minnesota, USA**

J.M. Hogan 



















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

R. Bartek , A. Dominguez , S. Raj , B. Sahu , A.E. Simsek , S.S. Yu 
























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

B. Bam , A. Buchot Perraguin , S. Campbell , R. Chudasama , S.I. Cooper , C. Crovella , G. Fidalgo , S.V. Gleyzer , A. Khukhunaishvili , K. Matchev , E. Pearson , P. Rumerio<sup>78</sup> , E. Usai , R. Yi 























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

S. Cholak , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , J. Fulcher , F. Golf , S. Jeon , J. O'Cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , I. Suarez , A. Tsatsos , E. Wurtz , A.G. Zecchinelli 
















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

G. Barone , G. Benelli , D. Cutts , S. Ellis , L. Gouskos , M. Hadley , U. Heintz , K.W. Ho , T. Kwon , L. Lambrecht , G. Landsberg , K.T. Lau , M. LeBlanc , J. Luo , S. Mondal , J. Roloff , T. Russell , S. Sagir<sup>79</sup> , X. Shen , M. Stamenkovic , S. Sunnarborg , J. Tang , N. Venkatasubramanian 




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

S. Abbott , S. Baradia , B. Barton , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , E. Cannaert , M. Chertok , M. Citron , J. Conway , P.T. Cox , F. Eble , R. Erbacher , C. Fairchild , O. Kukral , G. Mocellin , S. Ostrom , I. Salazar Segovia , J.H. Steenis , J.S. Tafoya Vargas , W. Wei , S. Yoo 



























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

K. Adamidis , M. Bachtis , D. Campos , R. Cousins , S. Crossley , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo , E. Manca , A. Nunez Del Prado , D. Saltzberg , V. Valuev 
















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

R. Clare , J.W. Gary , G. Hanson 












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

A. Aportela , A. Arora , J.G. Branson , S. Cittolin , B. D'Anzi , D. Diaz , J. Duarte , L. Giannini , Y. Gu , J. Guiang , V. Krutelyov , R. Lee , J. Letts , H. Li , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch , M. Quinnan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , A. Yagil , Z. Zhao 


















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

A. Barzdukas , L. Brennan , C. Campagnari , S. Carron Montero<sup>80</sup> , K. Downham , C. Grieco , M.M. Hussain, J. Incandela , M.W.K. Lai, A.J. Li , P. Masterson , J. Richman , S.N. Santpur , D. Stuart , T.Á. Vámi , X. Yan , D. Zhang 

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

A. Albert , S. Bhattacharya , A. Bornheim , O. Cerri, Z. Hao , R. Kansal , L. Mori, H.B. Newman , G. Reales Gutiérrez, T. Sievert, M. Spiropulu , C. Sun , J.R. Vlimant , R.A. Wynne , S. Xie 



















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

J. Alison , S. An , M. Cremonesi, V. Dutta , E.Y. Ertorer , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, M. Kanemura, C. Liu , M. Marchegiani , P. Meiring , S. Murthy , P. Palit , K. Park , M. Paulini , A. Roberts , A. Sanchez , Y. Zhou 

















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

J.P. Cumalat , W.T. Ford , J. Fraticelli , A. Hart , S. Kwan , 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 , X. Chen , J. Dickinson , A. Duquette, J. Fan , X. Fan , J. Grassi , P. Kotamnives , J. Monroy , G. Niendorf , M. Oshiro , J.R. Patterson , A. Ryd , J. Thom , H.A. Weber , B. Weiss , P. Wittich , R. Zou , L. Zygala 












**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 , C. Cosby , G. Cummings , I. Dutta , V.D. Elvira , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , J. Hirschauer , V. Innocente , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , R.S. Kim , B. Klima , S. Lammel , D. Lincoln , R. Lipton , T. Liu , K. Maeshima , 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>81</sup> , C.E. Perez Lara , V. Perovic , F. Ravera , A. Reinsvold Hall<sup>82</sup> , L. Ristori , M. Safdari , E. Sexton-Kennedy , E. Smith , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , C. Wang , 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 , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , V. Sulimov , Y. Takahashi , J. Wang 

























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

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Goff, R. Hashmi , A. Hassani , T. Kolberg , G. Martinez , M. Mazza , H. Prosper , P.R. Prova, R. Yohay 










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

B. Alsufyani , S. Das , S. Demarest, L. Hasa , M. Hohlmann , M. Lavinsky, E. Yanes












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

M.R. Adams , N. Barnett, A. Baty , C. Bennett , N. Brandman-hughes, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , H. Gupta , M. Hawksworth , A. Hingrajiya, D.J. Hofman , Z. Huang , J.h. Lee , C. Mills , S. Nanda , G. Nigmatkulov , B. Ozek , T. Phan, D. Pilipovic , R. Pradhan , E. Prifti, P. Roy, T. Roy , D. Shekar, N. Singh, F. Strug, A. Thielen, M.B. Tonjes , N. Varelas , M.A. Wadud , A. Wang , J. Yoo 
























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

M. Alhusseini , D. Blend , K. Dilsiz<sup>83</sup> , O.K. Köseyan , A. Mestvirishvili<sup>84</sup> , O. Neogi, H. Ogul<sup>85</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>86</sup> 









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

B. Blumenfeld , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , A. Mitra, N. Pinto , M. Roguljic , S. Sekhar , M.V. Srivastav , M. Swartz 
















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

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , R. Bhattacharya , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , S. Popescu<sup>87</sup> , C. Rogan , C. Royon , S. Rudrabhatla , S. Sanders , C. Smith , G. Wilson 



































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

A. Ahmad, B. Allmond , N. Islam, A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , G.G. Reddy , D. Roy , G. Sorrentino 












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

A. Baden , A. Belloni , J. Bistany-riebman, S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, S. Lascio , P. Major , A.C. Mignerey , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova<sup>88</sup> , A. Shevelev , L. Zhang 














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

C. Baldenegro Barrera , H. Bossi , S. Bright-Thonney , I.A. Cali , Y.c. Chen , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso , P. Harris, D. Hoang , G.M. Innocenti , K. Ivanov , G. Kopp , D. Kovalskiy , L. Lavezzo , Y.-J. Lee , K. Long , P. Lugato, C. Mcginn , E. Moreno , A. Novak , M.I. Park , C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , T.a. Sheng , G.S.F. Stephans , D. Walter , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 















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

A. Alpana , B. Crossman , W.J. Jackson, C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , R. Rusack , O. Sancar , R. Saradhy , N. Strobbe 

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

K. Bloom , D.R. Claes , S.V. Dixit , G. Haza , J. Hossain , C. Joo , I. Kravchenko , K.H.M. Kwok , Y. Mehra, J. Morris , A. Rohilla , J.E. Siado , A. Vagnerini , A. Wightman 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia , I. Iashvili , A. Kalogeropoulos , A. Kharchilava , A. Mandal , M. Morris , D. Nguyen , O. Poncet , S. Rappoccio , H. Rejeb Sfar, W. Terrill , A. Williams , D. Yu 

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



























A. Aarif , G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , M. Lu , N. Manganelli , R. Mccarthy 

D.M. Morse , T. Orimoto , L. Skinnari , C.S. Thoreson , E. Tsai , D. Wood 








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

S. Dittmer , K.A. Hahn , S. King, M. McGinnis , Y. Miao , D.G. Monk , M.H. Schmitt ,  
A. Taliercio , M. Velasco , J. Wang 
















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

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , A. Datta , A. Ehnis,  
R. Goldouzian , M. Hildreth , K. Hurtado Anampa , T. Ivanov , C. Jessop ,  
A. Karneyeu , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano ,  
N. Marinelli, P. Mastrapasqua , A. Masud, T. McCauley , C. Mcgrady , C. Moore ,  
Y. Musienko<sup>21</sup> , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend ,  
Y. Wan, M. Wayne , H. Yockey

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

M. Carrigan , R. De Los Santos , L.S. Durkin , C. Hill , M. Joyce , D.A. Wenzl,  
B.L. Winer , B. R. Yates 






















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

H. Bouchamaoui , G. Dezoort , P. Elmer , A. Frankenthal , M. Galli , B. Greenberg ,  
K. Kennedy, Y. Lai , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen ,  
F. Simpson , D. Stickland , C. Tully 

**University of Puerto Rico, Mayaguez, Puerto Rico, USA**

S. Malik , R. Sharma 



















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

S. Chandra , A. Gu , L. Gutay, M. Huwiler , M. Jones , A.W. Jung , I.G. Karslioglu ,  
D. Kondratyev , J. Li , M. Liu , M. Macedo , G. Negro , N. Neumeister ,  
G. Paspalaki , S. Piperov , N.R. Saha , J.F. Schulte , F. Wang , A. Wildridge , W. Xie ,  
Y. Yao , Y. Zhong 












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

N. Parashar , A. Pathak , E. Shumka 





















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

D. Acosta , A. Agrawal , C. Arbour , T. Carnahan , K.M. Ecklund , F.J.M. Geurts ,  
T. Huang , I. Krommydas , N. Lewis, W. Li , J. Lin , O. Miguel Colin , B.P. Padley ,  
R. Redjimi , J. Rotter , C. Vico Villalba , M. Wulansatiti , E. Yigitbasi , Y. Zhang 

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

O. Bessidskaia Bylund, A. Bodek , P. de Barbaro<sup>†</sup> , R. Demina , A. Garcia-Bellido ,  
H.S. Hare , O. Hindrichs , N. Parmar , P. Parygin<sup>88</sup> , H. Seo , R. Taus , Y.h. Yu 


















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

B. Chiarito, J.P. Chou , S.V. Clark , S. Donnelly, D. Gadkari , Y. Gershtein ,  
E. Halkiadakis , C. Houghton , D. Jaroslawski , A. Kobert , I. Laflotte , A. Lath ,  
J. Martins , P. Meltzer, M. Perez Prada , B. Rand , J. Reichert , P. Saha , S. Salur ,  
S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora 











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

D. Ally , A.G. Delannoy , S. Fiorendi , J. Harris, T. Holmes , A.R. Kanuganti ,  
N. Karunarathna , J. Lawless, L. Lee , E. Nibigira , B. Skipworth, S. Spanier 










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

D. Aebi , M. Ahmad , T. Akhter , K. Androsov , A. Basnet , A. Bolshov, O. Bouhali<sup>89</sup> , A. Cagnotta , S. Cooperstein , V. D'Amante , R. Eusebi , P. Flanagan , J. Gilmore , Y. Guo, T. Kamon , S. Luo , R. Mueller , G. Pizzati , A. Safonov 


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

N. Akchurin , J. Damgov , Y. Feng , N. Gogate , W. Jin , S.W. Lee , C. Madrid , 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 , D. Rathjens , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen , J. Zhang


















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

B. Cardwell , H. Chung , B. Cox , J. Hakala , G. Hamilton Ilha Machado, R. Hirosky , M. Jose, A. Ledovskoy , C. Mantilla , C. Neu , C. Ramón Álvarez , Z. Wu











#### 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 , E. Chavez , R. Cruz, S. Dasu , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , S. Lomte , R. Loveless , A. Mallampalli , J. Marquez, A. Mohammadi , S. Mondal, T. Nelson, G. Parida , L. Pétré , D. Pinna , A. Savin, V. Shang , V. Sharma , R. Simeon, W.H. Smith , D. Teague, A. Thete , A. Warden 

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

S. Afanasiev , V. Alexakhin , Yu. Andreev , T. Aushev , D. Budkouski , R. Chistov , M. Danilov , T. Dimova , A. Ershov , S. Gninenko , I. Gorbunov , A. Kamenev , V. Karjavine , M. Kirsanov , V. Klyukhin , O. Kodolova<sup>90</sup> , V. Korenkov , I. Korsakov, A. Kozyrev , N. Krasnikov , A. Lanev , A. Malakhov , V. Matveev , A. Nikitenko<sup>91,90</sup> , V. Palichik , V. Perelygin , S. Petrushanko , O. Radchenko , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen , K. Slizhevskiy, V. Smirnov , O. Teryaev , I. Tlisova , A. Toropin , N. Voytishin , A. Zarubin , I. Zhizhin 

#### Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

L. Dudko , V. Kim<sup>21</sup> , V. Murzin , V. Oreshkin , D. Sosnov , E. Boos , V. Bunichev , M. Dubinin<sup>81</sup> , A. Gribushin , V. Savrin , A. Snigirev 

†: 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 FACAMP - Faculdades de Campinas, Sao Paulo, 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 The University of the State of Amazonas, Manaus, Brazil

<sup>8</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>9</sup>Also at University of Chinese Academy of Sciences, Beijing, China

<sup>10</sup>Also at School of Physics, Zhengzhou University, Zhengzhou, China

- <sup>11</sup>Now at Henan Normal University, Xinxiang, China
- <sup>12</sup>Also at University of Shanghai for Science and Technology, Shanghai, China
- <sup>13</sup>Also at The University of Iowa, Iowa City, Iowa, USA
- <sup>14</sup>Also at Nanjing Normal University, Nanjing, China
- <sup>15</sup>Also at Center for High Energy Physics, Peking University, Beijing, China
- <sup>16</sup>Also at Zewail City of Science and Technology, Zewail, Egypt
- <sup>17</sup>Also at British University in Egypt, Cairo, Egypt
- <sup>18</sup>Now at Ain Shams University, Cairo, Egypt
- <sup>19</sup>Also at Université de Haute Alsace, Mulhouse, France
- <sup>20</sup>Also at Purdue University, West Lafayette, Indiana, USA
- <sup>21</sup>Also at an institute formerly covered by a cooperation agreement with CERN
- <sup>22</sup>Also at University of Hamburg, Hamburg, Germany
- <sup>23</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>24</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- <sup>25</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>26</sup>Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>27</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>28</sup>Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
- <sup>29</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>30</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- <sup>31</sup>Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- <sup>32</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>33</sup>Also at The University of Kansas, Lawrence, Kansas, USA
- <sup>34</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>35</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>36</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>37</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>38</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>39</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>40</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>41</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>42</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>43</sup>Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>44</sup>Also at Helwan University, Cairo, Egypt
- <sup>45</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>46</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>47</sup>Also at James Madison University, Harrisonburg, Maryland, USA
- <sup>48</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>49</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>50</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>51</sup>Also at Lulea University of Technology, Lulea, Sweden
- <sup>52</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>53</sup>Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- <sup>54</sup>Also at Institut de Physique des 2 Infinis de Lyon (IP2I ), Villeurbanne, France
- <sup>55</sup>Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia

- 
- <sup>56</sup> Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- <sup>57</sup> Also at Saegis Campus, Nugegoda, Sri Lanka
- <sup>58</sup> Also at National and Kapodistrian University of Athens, Athens, Greece
- <sup>59</sup> Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- <sup>60</sup> Also at Universität Zürich, Zurich, Switzerland
- <sup>61</sup> Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- <sup>62</sup> Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- <sup>63</sup> Also at Konya Technical University, Konya, Turkey
- <sup>64</sup> Also at Istanbul Topkapi University, Istanbul, Turkey
- <sup>65</sup> Also at Izmir Bakircay University, Izmir, Turkey
- <sup>66</sup> Also at Adiyaman University, Adiyaman, Turkey
- <sup>67</sup> Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- <sup>68</sup> Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
- <sup>69</sup> Also at Marmara University, Istanbul, Turkey
- <sup>70</sup> Also at Milli Savunma University, Istanbul, Turkey
- <sup>71</sup> Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
- <sup>72</sup> Also at Kafkas University, Kars, Turkey
- <sup>73</sup> Now at Istanbul Okan University, Istanbul, Turkey
- <sup>74</sup> Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- <sup>75</sup> Also at Istinye University, Istanbul, Turkey
- <sup>76</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- <sup>77</sup> Also at Monash University, Faculty of Science, Clayton, Australia
- <sup>78</sup> Also at Università di Torino, Torino, Italy
- <sup>79</sup> Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- <sup>80</sup> Also at California Lutheran University, Thousand Oaks, California, USA
- <sup>81</sup> Also at California Institute of Technology, Pasadena, California, USA
- <sup>82</sup> Also at United States Naval Academy, Annapolis, Maryland, USA
- <sup>83</sup> Also at Bingol University, Bingol, Turkey
- <sup>84</sup> Also at Georgian Technical University, Tbilisi, Georgia
- <sup>85</sup> Also at Sinop University, Sinop, Turkey
- <sup>86</sup> Also at Erciyes University, Kayseri, Turkey
- <sup>87</sup> Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- <sup>88</sup> Now at another institute formerly covered by a cooperation agreement with CERN
- <sup>89</sup> Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
- <sup>90</sup> Also at Yerevan Physics Institute, Yerevan, Armenia
- <sup>91</sup> Also at Imperial College, London, United Kingdom