



Letter

# Measurement of the production cross section of a Higgs boson with large transverse momentum in its decays to a pair of $\tau$ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration <sup>\*</sup>

CERN, Geneva, Switzerland



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## ABSTRACT

A measurement of the production cross section of a Higgs boson with transverse momentum greater than 250 GeV is presented where the Higgs boson decays to a pair of  $\tau$  leptons. It is based on proton-proton collision data collected by the CMS experiment at the CERN LHC at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of  $138 \text{ fb}^{-1}$ . Because of the large transverse momentum of the Higgs boson the  $\tau$  leptons from its decays are boosted and produced spatially close, with their decay products overlapping. Therefore, a dedicated algorithm was developed to reconstruct and identify them. The observed (expected) significance of the measured signal with respect to the standard model background-only hypothesis is 3.5 (2.2) standard deviations. The product of the production cross section and branching fraction is measured to be  $1.64^{+0.68}_{-0.54}$  times the standard model expectation. The fiducial differential production cross section is also measured as functions of the Higgs boson and leading jet transverse momenta. This measurement extends the probed large-transverse-momentum region in the  $\tau\tau$  final state beyond 600 GeV.

## 1. Introduction

Since the discovery of a particle compatible with the standard model (SM) Higgs boson ( $H$ ) [1–3], many of its properties have been scrutinized, without evidence of deviations from the SM expectations [4,5]. Measuring the production of the Higgs boson with large transverse momentum ( $p_T$ ) tests the existence of physics beyond the SM (BSM) in the scalar sector, to which inclusive measurements could be insensitive [6]. Such measurements can shed light on the structure of the interactions of the Higgs boson with massive particles. In particular, the cross section of the gluon-gluon production mode of the Higgs boson ( $ggH$ ) is sensitive at large  $p_T$  to the structure of the effective  $ggH$  coupling [7,8].

The ATLAS and CMS Collaborations have reported measurements of the differential production cross section of the Higgs boson as a function of its transverse momentum  $p_T^H$  [9–21]. While the measurement precision at low  $p_T^H$  is driven by the  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ \rightarrow 4\ell$ , and  $H \rightarrow WW \rightarrow 2\ell 2\nu$  decay modes ( $\ell = e$  or  $\mu$ ), the sensitivity at larger  $p_T^H$  is improved by including the  $H \rightarrow \tau\tau$  and  $H \rightarrow b\bar{b}$  decay modes because of their larger branching fractions. In this Letter, a dedicated measurement of the production cross section of a Higgs boson with large  $p_T$  decaying to a pair of  $\tau$  leptons is presented. This measurement extends the probed large- $p_T$  region beyond 600 GeV [19]. Because of the large- $p_T$  of the

Higgs boson, the  $\tau$  leptons from its decays are boosted and produced spatially close with their decay products overlapping. A Higgs boson with  $p_T^H \gtrsim 250$  GeV leads to a separation  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.8$  between the  $\tau$  leptons. To handle overlapping  $\tau$  decay products, a dedicated algorithm to identify the close-by  $\tau$  leptons is employed. All four main Higgs boson production modes have been included in this measurement and four final states including hadronic and leptonic  $\tau$  decays are considered:  $\mu\tau_h$ ,  $e\tau_h$ ,  $\tau_h\tau_h$ , and  $e\mu$ , where  $\tau_h$  denotes the visible decay products of a  $\tau$  lepton decaying into hadrons. The results are extracted using a multiclass neural network (NN) categorizing the events into signal- and background-enriched regions. The analysis is based on proton-proton ( $pp$ ) collision data collected by the CMS experiment at the CERN LHC at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of  $138 \text{ fb}^{-1}$  [22–24].

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintil-

<sup>\*</sup> E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

lator 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 detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4  $\mu$ s [25]. 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 [26]. 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. [27].

### 3. Event simulation

The POWHEG 2.0 [28–31] generator is used to generate Higgs boson signal samples at next-to-leading order (NLO) in the four leading production modes. The distributions of  $p_T^H$  and jet multiplicity in the gluon fusion production simulation are corrected to match the predictions of the NNLOPS event generator based upon the POWHEG+MiNLO approach [32,33]. The  $W$  + jets and  $Z/\gamma^*$  + jets processes are modeled with MADGRAPH5\_AMC@NLO 2.2.2 (2.4.2) generator [34] with the MLM jet matching and merging scheme [35]. A combination of the POWHEG 2.0 [36,37] and MADGRAPH5\_AMC@NLO generators is used to model the diboson ( $WW$ ,  $WZ$ , and  $ZZ$ ) processes at NLO. Single top quark and  $t\bar{t}$  productions are modeled with the POWHEG [38,39] generator at NLO. The NNPDF 3.1 [40] parton distribution functions (PDF) are used, and all simulated samples are interfaced with PYTHIA 8.212 [41] to describe parton showering and hadronization. The CUETP8M1 [42] and CP5 [43] tunes are used for the 2016 and 2017–2018 samples, respectively. Additional inelastic  $pp$  interactions (pileup) generated by PYTHIA are overlaid on all simulated events, according to the luminosity profile of the analyzed data. The average pileup ranges from 23 interactions in 2016 to 32 in 2018. All the generated signal and background samples are processed with the simulation of the CMS detector based on GEANT4 [44]. Differences between data and simulation in trigger, particle identification, isolation efficiencies, and in the resolution of the jet  $p_T$  and missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ ) are corrected by applying scale factors to simulated events.

### 4. Event reconstruction and selection

The physics objects are reconstructed by the particle-flow (PF) algorithm [45], which combines information from all subdetectors to identify individual particles (PF candidates). The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [46]. Standard muon and electron reconstruction, identification, and isolation methods are used, and are similar to those described in Ref. [19]. Starting from PF candidates, AK4 and AK8 jets are reconstructed using the anti- $k_T$  FASTJET algorithm with a distance parameter of 0.4 and 0.8, respectively [47,48]. Jet energy corrections are applied to both simulation and data so that the average measured energy of jets becomes identical to that of simulated particle-level jets, to account for residual differences between the jet energy in data and in simulation [49,50], and to reduce pileup effects.

The PF candidates in AK4 jets are used to reconstruct  $\tau_h$  objects, using the hadrons-plus-strips (HPS) algorithm [51,52], which combines one or three charged particles with neutral pion candidates within a narrow signal cone, to identify the  $\tau_h$  decay modes. PF candidates inside a cone of size  $\Delta R = 0.5$ , defined as an isolation cone, around the  $\tau_h$  candidate are used to determine its isolation. To distinguish genuine  $\tau_h$  decays from jets originating from the hadronization of quarks or gluons, a multivariate analysis (MVA) discriminant is used [53], called “MVA

isolation” in the following. It combines information about the energy carried by PF candidates within the isolation cone with lifetime information. The lifetime information includes the impact parameter of the leading track of the tau candidate and its significance. In the case of 3-prong tau leptons, the secondary vertex is fitted using the tau tracks and a flight path length, i.e. a signed distance between the primary vertex and secondary vertex, and its significance are used in addition to the impact parameter. Electrons and muons reconstructed as  $\tau_h$  candidates are rejected with dedicated discriminants [53].

If a  $\tau$  lepton pair originates from a particle with high  $p_T$ , the decay products of the  $\tau$  leptons are emitted close to each other, forming a single jet. The separation of the  $\tau$  leptons is approximately equal to  $\frac{2m_H}{p_T^H}$ . The presence of two close-by  $\tau$  leptons spoils the isolation requirement, leading to a drop in efficiency. To recover this loss, a modified version of the HPS algorithm, relying on jet substructure techniques, has been developed [53]. Particles are first clustered in a large-radius jet with the Cambridge–Aachen algorithm [54] with a distance parameter of 0.8, and the jet is required to have  $p_T > 170$  GeV. The final step of the jet clustering is reversed to find two subjets consistent with  $\tau$  leptons. The subjets are then processed with the HPS algorithm to identify the  $\tau_h$  decay modes. A crucial step in the boosted  $\tau_h$  reconstruction algorithm is the requirement that the overlapping  $\tau$  leptons do not share any common PF candidate. This is, by construction, satisfied by the two subjets seeding the  $\tau$  lepton reconstruction algorithm. Thus, the isolation of a given  $\tau$  is computed after removal of the PF candidates that belong to the other  $\tau$  lepton. Since electrons and muons give rise to subjets, the method also excludes these leptons from the list of neighboring tau lepton isolation candidates in the  $e\tau_h$  and  $\mu\tau_h$  final states. The final step is to compute discriminants to reject jets, electrons, and muons mis-reconstructed as  $\tau_h$  candidates.

Fig. 1 compares the  $\tau_h\tau_h$  and  $\tau_h$  isolation efficiencies for the standard and boosted HPS algorithms as a function of  $p_T^H$ , in the  $\tau_h\tau_h$  (left) and  $\tau_h$  (right) final states. As  $p_T^H$  increases and the  $\tau$  leptons get spatially closer, the HPS  $\tau$  lepton isolation efficiency decreases while the boosted  $\tau$  lepton efficiency reaches a plateau and remains constant. This effect is more pronounced in the  $\tau_h\tau_h$  final state because of the presence of a pair of  $\tau_h$  candidates. A drop in the isolation efficiency of HPS  $\tau_h$  candidate around 450 GeV occurs when the distance between the  $\tau_h$  candidate becomes equal to the size of the  $\tau_h$  isolation cone of 0.5.

The  $\tau_h$  candidates must have  $p_T > 30$  GeV,  $|\eta| < 2.3$ , and pass an MVA isolation requirement that corresponds to a typical identification efficiency of 60% in  $Z/\gamma^* \rightarrow \tau\tau$  events for a 3% misidentification rate of jets. The loose working point of the discriminator against muons (electrons) is used, suppressing muons (electrons) by more than 90% and maintaining the  $\tau_h$  identification efficiency above 95%. The  $\vec{p}_T^{\text{miss}}$  is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as  $p_T^{\text{miss}}$  [55]. The  $\vec{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event. Another correction accounts for the effect of additional pileup interactions [50]. Two variables to quantify the hadronic activity in the event are used. The first one is the total visible hadronic activity  $H_T$ , which is defined as the scalar sum of transverse momenta of jets with  $p_T > 30$  GeV and  $|\eta| < 3$ . The second variable is the momentum imbalance  $\vec{H}_T^{\text{miss}}$  and is defined as the negative vector sum of the transverse momenta of jets with  $p_T > 30$  GeV and  $|\eta| < 5$ . Its magnitude is denoted as  $H_T^{\text{miss}}$ .

Collision events were collected using single-lepton (muon or electron) triggers in the  $\mu\tau_h$ ,  $e\tau_h$ , and  $e\mu$  channels, while a combination of triggers relying on  $p_T^{\text{miss}}$ , jet  $p_T$ ,  $H_T$ , and  $H_T^{\text{miss}}$  was used in the  $\tau_h\tau_h$  channel. In the  $\mu\tau_h$  ( $e\tau_h$ ) channel, events passing single-lepton triggers with  $p_T$  threshold of 50 (115) GeV and no isolation requirement must have an offline lepton with  $p_T > 52$  (120) GeV, while events passing single isolated lepton triggers must have an offline lepton with  $p_T$  between 28 (38) and 52 (120) GeV and passing isolation criteria, as well as  $p_T^{\text{miss}} > 30$  GeV. Events in the  $e\mu$  channel must pass any of the

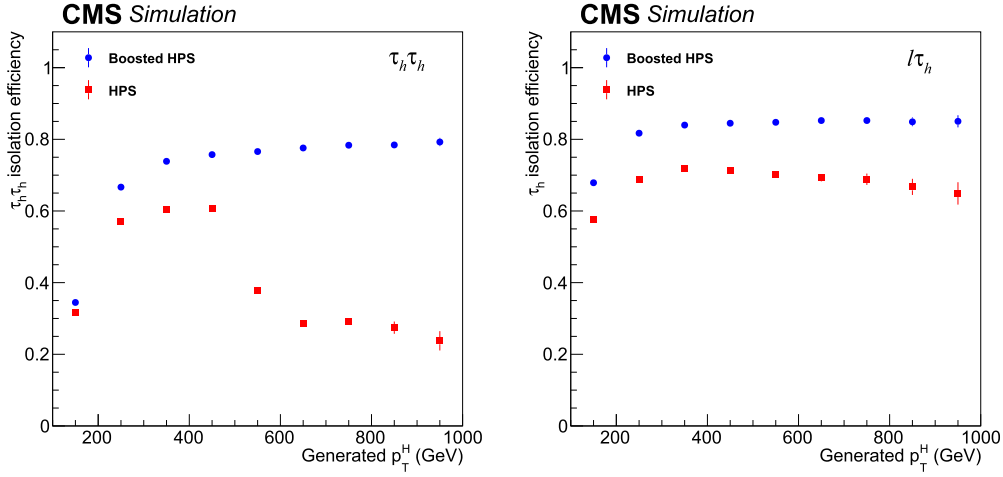


Fig. 1. Comparison of the isolation efficiencies for the standard and boosted HPS algorithms in the  $\tau_h \tau_h$  (left) and  $l \tau_h$  (right) final states.

Table 1

Selection requirements for the four  $\tau\tau$  final states. The relative isolation variable,  $I_{rel}^{\mu,e}$ , for muons and electrons is evaluated as the scalar sum of the  $p_T$  of the reconstructed particles in a cone around the lepton track relative to the  $p_T$  of the lepton. In the  $\tau_h \tau_h$  channel, the trigger requirement is defined by a combination of trigger candidates above a given threshold, indicated inside parentheses in GeV. The thresholds for the offline selection are driven by the trigger requirements. Except for the  $I_{rel}^{\mu,e}$ , the quantities are in units of GeV.

Final state	Trigger	Selection criteria
$\mu \tau_h$	$\mu(50)$	$p_T^{\mu} > 52, p_T^{\tau_h} > 30$
$\mu \tau_h$	Iso $\mu(27)$	$p_T^{\mu} > 28, p_T^{\tau_h} > 30, I_{rel}^{\mu} < 0.3, p_T^{\text{miss}} > 30$
$e \tau_h$	$e(115)$	$p_T^e > 120, p_T^{\tau_h} > 30$
$e \tau_h$	Iso $e(35)$	$p_T^e > 38, p_T^{\tau_h} > 30, I_{rel}^e < 0.3, p_T^{\text{miss}} > 30$
$\mu e$	$\mu(50)$	$p_T^{\mu} > 52, p_T^e > 10$
$\mu e$	Iso $\mu(27)$	$p_T^{\mu} > 28, p_T^e > 10, I_{rel}^{\mu,e} < 0.3, p_T^{\text{miss}} > 30$
$e \mu$	$e(115)$	$p_T^e > 120, p_T^{\mu} > 10$
$e \mu$	Iso $e(35)$	$p_T^e > 38, p_T^{\mu} > 10, I_{rel}^{\mu,e} < 0.3, p_T^{\text{miss}} > 30$
$\tau_h \tau_h$ (2016)	$p_T^{\text{AK8}}(360)$ & $m^{\text{AK8}}(30)$	$p_T^{\text{AK8}} > 450, m^{\text{AK8}} > 30$
$\tau_h \tau_h$ (2016)	$H_T(300)$ & $p_T^{\text{miss}}(110)$	$H_T > 400, p_T^{\text{miss}} > 180$
$\tau_h \tau_h$ (2017–2018)	$p_T^{\text{AK8}}(400)$ & $m^{\text{AK8}}(30)$	$p_T^{\text{AK8}} > 450, m^{\text{AK8}} > 30$
$\tau_h \tau_h$ (2017–2018)	$H_T(500)$ & $p_T^{\text{miss}}(100)$ & $H_T^{\text{miss}}(100)$	$H_T > 700, (p_T^{\text{miss}} + H_T^{\text{miss}}) > 280$

single-lepton triggers, with or without isolation, depending on the offline leading lepton  $p_T$ . The lepton not associated with the trigger must have  $p_T$  larger than 10 GeV and pass loose identification and isolation criteria.

In the  $\tau_h \tau_h$  channel, events triggered in 2016 (2017–2018) on the basis of an AK8 jet with  $p_T > 360$  (400) GeV and mass, using the soft drop algorithm [56], greater than 30 GeV are required to have an AK8 jet reconstructed offline with  $p_T > 450$  GeV and mass above 30 GeV. Events that do not pass the AK8 jet trigger are then checked against a combination of  $p_T^{\text{miss}}$ -based trigger criteria. Events that pass an online selection based on  $H_T > 300$  (500) GeV,  $p_T^{\text{miss}} > 110$  (100) GeV, and  $H_T^{\text{miss}} > 0$  (100) GeV, are required to have offline  $H_T > 400$  (700) GeV and  $p_T^{\text{miss}} > 180$  GeV ( $p_T^{\text{miss}} + H_T^{\text{miss}} > 280$  GeV). The trigger selection efficiency for events passing the offline requirements described here for the  $\tau_h \tau_h$  channel is about 90% across all three years. The trigger requirements and kinematic selection criteria are summarized in Table 1.

To reconstruct the Higgs boson candidates, the two identified objects ( $e, \mu$ , or  $\tau_h$  candidates) are required to have opposite charges. None of the jets in the event must be identified as originating from a bottom quark, using the medium (tight) working point of the DEEPCSV2 algorithm [57] in the  $\mu \tau_h$  and  $e \tau_h$  ( $e \mu$ ) final states. The quantity  $H_T$  must be greater than 200 GeV and the di- $\tau$  invariant mass, estimated from the visible momenta of the  $\tau$  lepton decay products and  $\vec{p}_T^{\text{miss}}$ , using a maximum likelihood technique [58], must exceed 50 GeV. The reconstructed  $p_T^H$  is defined as the magnitude of the vectorial sum of the  $p_T$  of the  $\tau$  leptons visible decay products and  $\vec{p}_T^{\text{miss}}$ , and must be larger than

250 GeV. Finally, to reduce the background with leptonically decaying  $W$  bosons, the transverse mass of the lepton and  $\vec{p}_T^{\text{miss}}$  in the  $\mu \tau_h$  and  $e \tau_h$  channels, and of the dilepton and  $\vec{p}_T^{\text{miss}}$  in the  $e \mu$  channel, must be less than 80 GeV. To ensure there is no overlap across different final states, events are vetoed in the presence of additional loosely identified and isolated lepton.

The dominant background in all four final states is the Drell–Yan process, which constitutes an irreducible background. This is followed by events with at least one jet being mis-identified as a  $\tau_h$ , muon, electron, and quantum chromodynamics (QCD) multijet events with nonprompt leptons. The  $t\bar{t}$  and diboson processes constitute the remaining background.

## 5. Background estimation

The Drell–Yan process is modeled using simulated samples. To correct the effect of missing higher order corrections in simulation, a scale factor that depends on the  $Z/\gamma^*$  boson mass and  $p_T$  is measured in a control region (CR) containing a pair of muons, and applied to the simulation in the signal region (SR). The  $t\bar{t}$  background is estimated from simulation. Simulated  $t\bar{t}$  events are weighted to reproduce the observed distribution of the top quark  $p_T$  and to account for any possible missing higher order corrections [59,60]. The background arising from the misidentification of leptons or  $\tau_h$  candidates, called “mis-ID background”, is estimated from data. It is mostly comprised of  $W$  + jets and QCD multijet events, where at least one jet is misidentified as an elec-

tron, muon, or  $\tau_h$  candidate. In events with at least one  $\tau_h$  candidate, a misidentification rate method is used to estimate the contribution of these two processes, collectively, in the SR. The probability for a jet that has passed a very loose isolation to pass the nominal isolation requirement of a  $\tau_h$  candidate, called the misidentification rate, is estimated in a region dominated by the mis-ID background, obtained by requiring one identified and isolated muon, and one jet separated from the muon by  $\Delta R > 0.8$ . This sample has a negligible signal component, while the small contribution from the other backgrounds is estimated from simulation and subtracted from data. The misidentification rate,  $f$ , is parameterized as a function of the  $p_T$  of the  $\tau_h$  candidate. To estimate the mis-ID background in the SR, an adjusted misidentification rate,  $\frac{f}{1-f}$ , is applied as a weight to events in the application region in data. The application region definition is identical to that of SR with the exception that the  $\tau_h$  candidate fails the nominal MVA isolation. The denominator accounts for the fraction  $(1-f)$  of mis-ID background events failing the isolation. The small contribution from the signal and other backgrounds is estimated from simulation and subtracted from data before the reweighting is applied.

To estimate the QCD multijet contribution in the  $e\mu$  channel, a sample is built from events that pass the signal selection criteria except that the requirement on the charge of two leptons is inverted. The small remaining contribution of the signal and other backgrounds is subtracted from data on the basis of simulation. The contribution of the QCD multijet background in the SR is derived by applying an opposite-sign to same-sign scale factor, measured in a region where the lepton isolation requirements are inverted.

## 6. Analysis strategy

A multiclass NN is used to construct a discriminant that separates the signal from the two dominant background processes, i.e. Drell-Yan and mis-ID backgrounds, following closely the method described in Ref. [61]. The NN is constructed with a feed-forward architecture containing two hidden layers and three output nodes. The number of nodes per layer is kept to a minimum to reduce the complexity of the neural network without compromising its performance. The value of each output node represents the probability for an event to belong to a given class. Ten variables are used as input to the NN: the  $p_T$  of the two leptons and leading jet,  $p_T^{\text{miss}}$ , the mass and  $p_T$  of the Higgs boson reconstructed from the  $\tau$  candidates and  $\vec{p}_T^{\text{miss}}$ ,  $S_T$  (defined as the scalar sum of the  $p_T$  of all leptons and jets with  $p_T > 30$  GeV and  $|\eta| < 3$  in the event), the transverse mass reconstructed from the lepton  $p_T$  and  $\vec{p}_T^{\text{miss}}$ , the value of the MVA isolation of the closest boosted  $\tau_h$  candidate to the muon (electron) in the  $\mu\tau_h$  and  $e\mu$  ( $e\tau_h$  and  $e\mu$ ) channels, and the di- $\tau$  mass. The NN is trained for the combination of the three data-taking years and separately for each final state.

Based on the maximum of the three output values, by construction larger than 1/3, events are sorted into one signal-enriched region and two background-dominated regions. The signal-enriched region is split into four bins depending on  $p_T^{\text{H}}$ , with lower bin boundaries of 250, 350, 450, and 600 GeV. To establish the presence of a signal a simultaneous binned maximum likelihood fit is performed to all three NN output distributions. The combined NN distributions in the signal-enriched region for all four  $p_T^{\text{H}}$  bins and three data-taking years are shown in Fig. 2.

## 7. Systematic uncertainties

Two types of systematic uncertainties are considered: normalization uncertainties in the event yields and uncertainties that affect both the shape and yield of the distributions. The uncertainties in the muon and electron trigger efficiencies, identification, and isolation, estimated with a tag-and-probe method [52], range from 1 to 5%, depending on the  $p_T$  and  $\eta$  of the lepton.

The uncertainty in the  $H_T$  and  $\vec{p}_T^{\text{miss}}$  trigger efficiencies in the  $\tau_h\tau_h$  channel is 10%, mostly arising from the difference in trigger efficiency

in data and simulation. The uncertainty in the efficiency of selecting boosted  $\tau_h$  candidates is parametrized as a function of  $p_T^{\text{H}}$ . To evaluate this uncertainty, a maximum likelihood fit is performed using the  $Z$  boson  $p_T$  distributions reconstructed using the dilepton four momenta and  $p_T^{\text{miss}}$ . The fit is performed in the Drell-Yan-dominated region, which is by definition orthogonal to the signal-enriched region. A large prefit uncertainty ( $U_{\text{prefit}}$ ) is assigned to the  $\tau_h$  identification efficiency, uncorrelated between final states, data-taking years, and bins of  $p_T^{\text{H}}$ . This is equivalent to letting this uncertainty freely float in the fit. After the fit, the magnitude of the postfit  $\tau_h$  identification efficiency uncertainty ( $U_{\text{postfit}}$ ) is compared to  $|U_{\text{prefit}} - U_{\text{postfit}}|$ . The largest value in each final state, data-taking years and  $p_T^{\text{H}}$  range is taken as the uncertainty in the  $\tau_h$  identification efficiency. It typically ranges between 10 and 20% except for the very last  $p_T^{\text{H}}$  bin in the  $\tau_h\tau_h$  final state where it reaches 50%.

The uncertainty in the integrated luminosity amounts to 1.2–2.5%, depending on the year [22–24]. A 2% normalization uncertainty is considered for the muon/electron energy scale, while a 3% uncertainty in the  $\tau_h$  energy scale is treated as a shape uncertainty that modifies final observable templates and propagated to the di- $\tau$  mass and  $\vec{p}_T^{\text{miss}}$ . Uncertainties associated with the jet energy scale and  $p_T^{\text{miss}}$  are also considered [62].

Uncertainties of 2.0, 4.2, 5.0, and 5.0% are used for the predicted cross sections of the Drell-Yan,  $t\bar{t}$ , single top quark, and diboson productions, respectively [63–66]. The PDF, renormalization and factorization scales, initial and final state radiation uncertainties are considered for the Drell-Yan and  $t\bar{t}$  processes. They vary from a few percent to about 20% depending on the final state, process, and data-taking year as they are evaluated with different Pythia tunes.

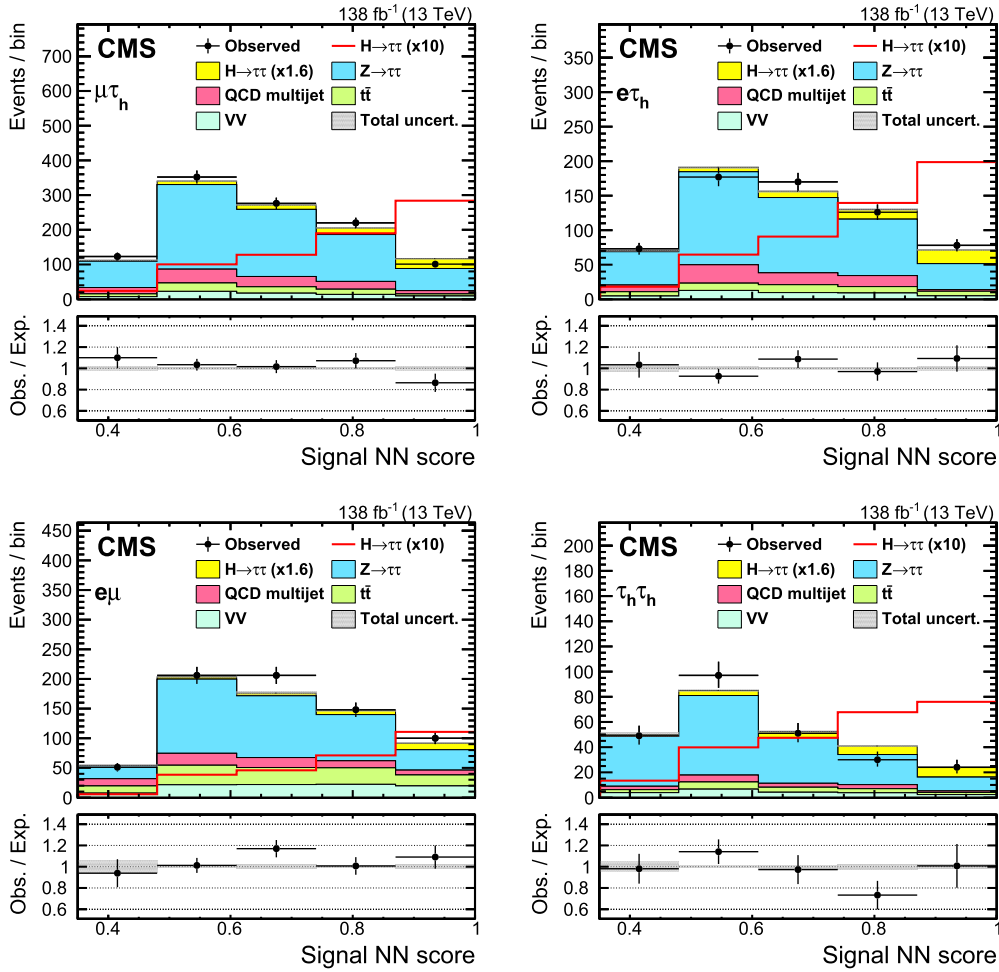
A 20% uncertainty is assigned to the QCD multijet background to cover for differences between the observed and predicted background rates in dedicated CRs. An additional uncertainty related to the probability for a jet to be misidentified as a  $\tau_h$  candidate, as well as an uncertainty in the normalization of the non-QCD background subtracted from data in the application region, are included and vary between 10 and 20%, depending on the final state. Uncertainties related to the top quark  $p_T$  reweighting in simulated  $t\bar{t}$  events are evaluated by varying the reweighting parameters between zero and twice their nominal values [59,60].

Theoretical uncertainties for the signal in the gluon fusion production mode are derived from the LHC Higgs Cross Section WG1 scheme [67]. Statistical uncertainties associated with the limited number of simulated events in the signal-enriched region or observed event yields in the control regions are accounted for as described in Ref. [68].

## 8. Results

A binned maximum likelihood fit is performed to all three NN output distributions to compute the probability of the compatibility of observed data with the background-only hypothesis [69,70]. The inclusion of the two background-dominated control regions helps to constrain the normalization and systematic uncertainties of the Drell-Yan and mis-ID backgrounds. The systematic uncertainties are taken as nuisance parameters. An observed significance of 3.5 standard deviations is obtained for a  $H \rightarrow \tau\tau$  signal with  $p_T^{\text{H}} \geq 250$  GeV by combining all channels and data-taking years, to be compared with an expected significance of 2.2 standard deviations. The best fit signal strength modifier, defined as the ratio of the inclusive Higgs boson production cross section to the SM expectation, is also extracted from a maximum likelihood fit to the same distributions and is found to be  $1.64^{+0.68}_{-0.54}$ , in agreement with the SM prediction. The sensitivity of this analysis is driven by the  $\mu\tau_h$  and  $e\tau_h$  channels in the low- $p_T$  region, and by the  $\tau_h\tau_h$  channel in the high- $p_T$  region. The sensitivity of the  $\tau_h\tau_h$  channel increases with the Higgs boson  $p_T$  because of the increase in efficiency of the  $H_T/p_T^{\text{miss}}$  triggers.

The differential production cross section is measured in a fiducial phase space that is defined per final state. Requirements on generator-

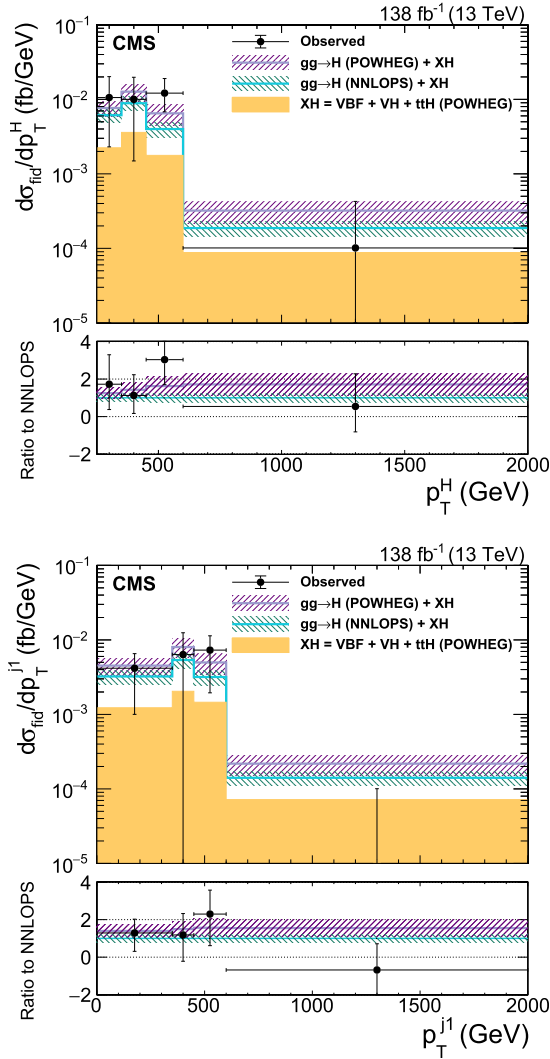


**Fig. 2.** Observed and expected NN distributions in the signal-enriched region, after combining all four  $p_T^H$  bins, in the  $\mu\tau_h$  (upper left),  $e\tau_h$  (upper right),  $e\mu$  (lower left), and  $\tau_h\tau_h$  (lower right) channels. The signal and background distributions are the result of a simultaneous binned maximum likelihood fit to all three output NN distributions, including all individual  $p_T$  bins and data-taking years. The bottom panel shows the ratio of the number of events observed in data to that of the expected background.

level variables are chosen to be close to the trigger and offline selections. In the  $\mu\tau_h$  ( $e\tau_h$ ) channel, the lepton is required to have generated  $p_T > 28$  (30) GeV and  $|\eta| < 2.4$  (2.5). If the generated  $p_T$  of the muon (electron) is less than 52 (115) GeV, a minimum threshold of 30 GeV is applied to the generated  $p_T^{\text{miss}}$  as well. The generated visible  $p_T$  of  $\tau_h$  leptons must exceed 30 GeV and their  $|\eta|$  must be less than 2.3 in the  $\mu\tau_h$ ,  $e\tau_h$ , and  $\tau_h\tau_h$  channels. In the  $\tau_h\tau_h$  channel, the generated  $p_T$  of the AK8 jet must be greater than 450 GeV or the generated  $H_T$  must be greater than 400 (700) GeV with a generated  $p_T^{\text{miss}}$  greater than 180 (140) GeV for 2016 (2017–2018) samples. In the  $e\mu$  channel, two sets of events are selected. The first set includes events with generated muon  $p_T > 52$  GeV, or between 28 and 52 GeV and  $p_T^{\text{miss}}$  above 30 GeV. The second set includes events with generated electron  $p_T > 115$  GeV, or between 38 and 115 GeV and  $p_T^{\text{miss}}$  above 30 GeV. In both sets, the other lepton must have generated  $p_T$  above 10 GeV. In all channels, the  $\Delta R$  between two leptons must be between 0.1 and 0.8, the generated  $p_T^H$  must be above 250 GeV, and there must be at least one jet with  $p_T$  larger than 30 GeV.

To derive the differential production cross section, the signal is split into four bins with lower bin boundaries of 250, 350, 450, and 600 GeV on the value of the generated (gen)  $p_T^H$  or with lower bin boundaries of 0, 350, 450, and 600 GeV on the value of the gen leading jet  $p_T$  ( $p_T^j$ ). The definitions of the signal- and background-dominated regions are identical to those used in the inclusive analysis. The same binning is used at reconstructed- (reco-) level to categorize events. The gen- and reco-level observable values are not perfectly aligned because

of the limited resolution, and events from one gen-level bin can migrate to a different reco-level bin. The contributions from the four gen-level bins are left floating independently from each other. By performing one simultaneous fit over all reco-level bin histograms of the NN distributions, the signal strength modifiers of the gen-level observable bins are determined utilizing the full statistical power of the data set. This is equivalent to extracting the signal in the reco-level bins and performing an unfolding to gen-level bins. The procedure follows the strategy adopted in Ref. [19]. Fiducial differential production cross sections measured as functions of  $p_T^H$  and  $p_T^j$  are shown in Fig. 3. Tabulated results are available in the HepData database [71]. The results are dominated by statistical uncertainties, especially in the highest- $p_T$  bins. The next dominant components, especially in the lowest- $p_T$  bins, are the tau energy scale uncertainty, which affects both the normalization and shape of the signal and background processes. Other important systematic uncertainties include theoretical uncertainties in the signal prediction arising from the infinite top mass assumption and initial and final state radiation. The ggH production mode contribution in the total signal yield reduces from 63% in the lowest  $p_T^H$  bin to 53% in the highest  $p_T^H$  bin, indicating the importance of other production modes at large  $p_T$  values. This measurement extends the probed large- $p_T$  region beyond 600 GeV. No significant deviation with respect to the SM predictions is observed and the measurements are compatible with both the POWHEG and NNLOPS expectations. The fit has a  $p$ -value with respect to the SM expectation



**Fig. 3.** Observed and expected differential fiducial cross sections in bins of  $p_T^H$  (upper) and  $p_T^{j_1}$  (lower). The last bins include the overflow. The uncertainty bands in the theoretical predictions include uncertainties from the following sources: PDF, renormalization and factorization scales, underlying event and parton showering, and the branching fraction  $B(H \rightarrow \tau\tau)$ .

from the NNLOPS prediction of 56 and 74% for the measurements with respect to  $p_T^H$  and  $p_T^{j_1}$ , respectively.

The inclusive fiducial production cross section is measured from the  $p_T^H$  distributions used in the differential analysis, by reformulating the parameters of interest such that one modifies the total inclusive fiducial production cross section. Its best fit value is  $3.88_{-1.35}^{+1.69}$  fb, which is consistent with the SM prediction of  $2.36 \pm 0.51$  fb obtained with the NNLOPS generator.

## 9. Summary

The measurement of the production cross section of a Higgs boson with large  $p_T$  decaying to a pair of  $\tau$  leptons has been performed using proton-proton collision data collected by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . A dedicated reconstruction algorithm has been used to resolve the overlapping decay products of the two close-by  $\tau$  leptons. The  $H \rightarrow \tau\tau$  signal with  $p_T^H > 250$  GeV is established with a significance of 3.5 standard deviations (2.2 expected). The best fit of the product of the observed  $H \rightarrow \tau\tau$  signal production cross section and branching fraction is  $1.64_{-0.54}^{+0.68}$  times the SM expectation. The fiducial inclusive production

cross section has been measured to be  $3.88_{-1.35}^{+1.69}$  fb, which is consistent with the SM prediction of  $2.36 \pm 0.51$  fb. The fiducial differential production cross section is also measured as functions of the Higgs boson and leading jet transverse momenta. This measurement extends the probed large-transverse-momentum region beyond 600 GeV. No significant deviation with respect to the SM predictions is observed in the transverse momentum distribution of the Higgs boson with large  $p_T^H$ .

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## 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](#).

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




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## CMS Collaboration

A. Hayrapetyan, A. Tumasyan 

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish <sup>3</sup>, T. Janssen , P. Van Mechelen 

Universiteit Antwerpen, Antwerpen, Belgium

E.S. Bols , J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , H. El Faham ,  
S. Lowette , I. Makarenko , D. Müller , A.R. Sahasransu , S. Tavernier , M. Tytgat <sup>4</sup>,  
S. Van Putte , D. Vannerom 

Vrije Universiteit Brussel, Brussel, Belgium



B. Clerbaux<sup>1</sup>, G. De Lentdecker<sup>1</sup>, L. Favart<sup>1</sup>, D. Hohov<sup>1</sup>, J. Jaramillo<sup>1</sup>, A. Khalilzadeh,  
K. Lee<sup>1</sup>, M. Mahdavihorrani<sup>1</sup>, A. Malara<sup>1</sup>, S. Paredes<sup>1</sup>, L. Pétré<sup>1</sup>, N. Postiau,  
L. Thomas<sup>1</sup>, M. Vanden Bemden<sup>1</sup>, C. Vander Velde<sup>1</sup>, P. Vanlaer<sup>1</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

M. De Coen<sup>2</sup>, D. Dobur<sup>2</sup>, Y. Hong<sup>2</sup>, J. Knolle<sup>2</sup>, L. Lambrecht<sup>2</sup>, G. Mestdach, C. Rendón,  
A. Samalan, K. Skovpen<sup>2</sup>, N. Van Den Bossche<sup>2</sup>, J. van der Linden<sup>2</sup>, L. Wezenbeek<sup>2</sup>

*Ghent University, Ghent, Belgium*

A. Benecke<sup>3</sup>, G. Bruno<sup>3</sup>, C. Caputo<sup>3</sup>, C. Delaere<sup>3</sup>, I.S. Donertas<sup>3</sup>, A. Giammanco<sup>3</sup>,  
K. Jaffel<sup>3</sup>, Sa. Jain<sup>3</sup>, V. Lemaître, J. Lidrych<sup>3</sup>, P. Mastrapasqua<sup>3</sup>, K. Mondal<sup>3</sup>,  
T.T. Tran<sup>3</sup>, S. Wertz<sup>3</sup>

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

G.A. Alves<sup>4</sup>, E. Coelho<sup>4</sup>, C. Hensel<sup>4</sup>, T. Menezes De Oliveira<sup>4</sup>, A. Moraes<sup>4</sup>,  
P. Rebello Teles<sup>4</sup>, M. Soeiro

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

W.L. Aldá Júnior<sup>5</sup>, M. Alves Gallo Pereira<sup>5</sup>, M. Barroso Ferreira Filho<sup>5</sup>,  
H. Brandao Malbouisson<sup>5</sup>, W. Carvalho<sup>5</sup>, J. Chinellato<sup>5</sup>, E.M. Da Costa<sup>5</sup>,  
G.G. Da Silveira<sup>5,6</sup>, D. De Jesus Damiao<sup>5</sup>, S. Fonseca De Souza<sup>5</sup>, R. Gomes De Souza,  
J. Martins<sup>5,7</sup>, C. Mora Herrera<sup>5</sup>, K. Mota Amarilo<sup>5</sup>, L. Mundim<sup>5</sup>, H. Nogima<sup>5</sup>,  
A. Santoro<sup>5</sup>, A. Sznajder<sup>5</sup>, M. Thiel<sup>5</sup>, A. Vilela Pereira<sup>5</sup>

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

C.A. Bernardes<sup>5,6</sup>, L. Calligaris<sup>5</sup>, T.R. Fernandez Perez Tomei<sup>5</sup>, E.M. Gregores<sup>5</sup>,  
P.G. Mercadante<sup>5</sup>, S.F. Novaes<sup>5</sup>, B. Orzari<sup>5</sup>, Sandra S. Padula<sup>5</sup>

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

A. Aleksandrov<sup>8</sup>, G. Antchev<sup>8</sup>, R. Hadjiiska<sup>8</sup>, P. Iaydjiev<sup>8</sup>, M. Misheva<sup>8</sup>, M. Shopova<sup>8</sup>,  
G. Sultanov<sup>8</sup>

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

A. Dimitrov<sup>8</sup>, L. Litov<sup>8</sup>, B. Pavlov<sup>8</sup>, P. Petkov<sup>8</sup>, A. Petrov<sup>8</sup>, E. Shumka<sup>8</sup>

*University of Sofia, Sofia, Bulgaria*

S. Keshri<sup>9</sup>, S. Thakur<sup>9</sup>

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

T. Cheng<sup>10</sup>, Q. Guo, T. Javaid<sup>10</sup>, L. Yuan<sup>10</sup>

*Beihang University, Beijing, China*

Z. Hu<sup>10</sup>, J. Liu, K. Yi<sup>10,8,9</sup>


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

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


*Institute of High Energy Physics, Beijing, China*

A. Agapitos<sup>10</sup>, Y. Ban<sup>10</sup>, A. Levin<sup>10</sup>, C. Li<sup>10</sup>, Q. Li<sup>10</sup>, Y. Mao, S.J. Qian<sup>10</sup>, X. Sun<sup>10</sup>,  
D. Wang<sup>10</sup>, H. Yang, L. Zhang<sup>10</sup>, C. Zhou<sup>10</sup>

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

Z. You 





Sun Yat-Sen University, Guangzhou, China

N. Lu 

University of Science and Technology of China, Hefei, China

G. Bauer <sup>14</sup>

Nanjing Normal University, Nanjing, China

X. Gao <sup>15</sup>, D. Leggat , H. Okawa , Y. Zhang 





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

Z. Lin , C. Lu , M. Xiao 





Zhejiang University, Hangzhou, Zhejiang, China

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

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

Universidad de Antioquia, Medellin, Colombia

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











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

M. Kovac , T. Sculac <sup>16</sup>

University of Split, Faculty of Science, Split, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra ,  
A. Starodumov <sup>17</sup>, T. Susa 

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis , K. Christoforou , S. Konstantinou , J. Mousa , C. Nicolaou , F. Ptochos ,  
P.A. Razis , H. Rykaczewski , H. Saka , A. Stepennov 


University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

E. Ayala 

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin 

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla <sup>18</sup>, Y. Assran <sup>19,20</sup>

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M.A. Mahmoud , Y. Mohammed 

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

R.K. Dewanjee <sup>21</sup>, K. Ehataht , M. Kadastik , T. Lange , S. Nandan , C. Nielsen ,  
J. Pata , M. Raidal , L. Tani , C. Veelken 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann , K. Osterberg , M. Voutilainen 

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar <sup>id</sup>, E. Brücken <sup>id</sup>, F. Garcia <sup>id</sup>, J. Havukainen <sup>id</sup>, K.T.S. Kallonen <sup>id</sup>, R. Kinnunen, T. Lampén <sup>id</sup>, K. Lassila-Perini <sup>id</sup>, S. Lehti <sup>id</sup>, T. Lindén <sup>id</sup>, M. Lotti, L. Martikainen <sup>id</sup>, M. Myllymäki <sup>id</sup>, M.m. Rantanen <sup>id</sup>, H. Siikonen <sup>id</sup>, E. Tuominen <sup>id</sup>, J. Tuominiemi <sup>id</sup>

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka <sup>id</sup>, H. Petrow <sup>id</sup>, T. Tuuva <sup>†</sup>

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon <sup>id</sup>, F. Couderc <sup>id</sup>, M. Dejardin <sup>id</sup>, D. Denegri, J.L. Faure, F. Ferri <sup>id</sup>, S. Ganjour <sup>id</sup>, P. Gras <sup>id</sup>, G. Hamel de Monchenault <sup>id</sup>, V. Lohezic <sup>id</sup>, J. Malcles <sup>id</sup>, J. Rander, A. Rosowsky <sup>id</sup>, M.Ö. Sahin <sup>id</sup>, A. Savoy-Navarro <sup>id,22</sup>, P. Simkina <sup>id</sup>, M. Titov <sup>id</sup>, M. Tornago <sup>id</sup>

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

C. Baldenegro Barrera <sup>id</sup>, F. Beaudette <sup>id</sup>, A. Buchot Perraguin <sup>id</sup>, P. Busson <sup>id</sup>, A. Cappati <sup>id</sup>, C. Charlot <sup>id</sup>, F. Damas <sup>id</sup>, O. Davignon <sup>id</sup>, A. De Wit <sup>id</sup>, G. Falmagne <sup>id</sup>, B.A. Fontana Santos Alves <sup>id</sup>, S. Ghosh <sup>id</sup>, A. Gilbert <sup>id</sup>, R. Granier de Cassagnac <sup>id</sup>, A. Hakimi <sup>id</sup>, B. Harikrishnan <sup>id</sup>, L. Kalipoliti <sup>id</sup>, G. Liu <sup>id</sup>, J. Motta <sup>id</sup>, M. Nguyen <sup>id</sup>, C. Ochando <sup>id</sup>, L. Portales <sup>id</sup>, R. Salerno <sup>id</sup>, J.B. Sauvan <sup>id</sup>, Y. Sirois <sup>id</sup>, A. Tarabini <sup>id</sup>, E. Vernazza <sup>id</sup>, A. Zabi <sup>id</sup>, A. Zghiche <sup>id</sup>

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

J.-L. Agram <sup>id,23</sup>, J. Andrea <sup>id</sup>, D. Apparú <sup>id</sup>, D. Bloch <sup>id</sup>, J.-M. Brom <sup>id</sup>, E.C. Chabert <sup>id</sup>, C. Collard <sup>id</sup>, S. Falke <sup>id</sup>, U. Goerlach <sup>id</sup>, C. Grimault, R. Haeberle <sup>id</sup>, A.-C. Le Bihan <sup>id</sup>, M. Meena <sup>id</sup>, G. Saha <sup>id</sup>, M.A. Sessini <sup>id</sup>, P. Van Hove <sup>id</sup>

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

S. Beauceron <sup>id</sup>, B. Blancon <sup>id</sup>, G. Boudoul <sup>id</sup>, N. Chanon <sup>id</sup>, J. Choi <sup>id</sup>, D. Contardo <sup>id</sup>, P. Depasse <sup>id</sup>, C. Dozen <sup>id,24</sup>, H. El Mamouni, J. Fay <sup>id</sup>, S. Gascon <sup>id</sup>, M. Gouzevitch <sup>id</sup>, C. Greenberg, G. Grenier <sup>id</sup>, B. Ille <sup>id</sup>, I.B. Laktineh, M. Lethuillier <sup>id</sup>, L. Mirabito, S. Perries, A. Purohit <sup>id</sup>, M. Vander Donckt <sup>id</sup>, P. Verdier <sup>id</sup>, J. Xiao <sup>id</sup>

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

D. Chokheli <sup>id</sup>, I. Lomidze <sup>id</sup>, Z. Tsamalaidze <sup>id,17</sup>

Georgian Technical University, Tbilisi, Georgia

V. Botta <sup>id</sup>, L. Feld <sup>id</sup>, K. Klein <sup>id</sup>, M. Lipinski <sup>id</sup>, D. Meuser <sup>id</sup>, A. Pauls <sup>id</sup>, N. Röwert <sup>id</sup>, M. Teroerde <sup>id</sup>

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

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

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

C. Dziwok<sup>id</sup>, G. Flügge<sup>id</sup>, W. Haj Ahmad<sup>id,26</sup>, T. Kress<sup>id</sup>, A. Nowack<sup>id</sup>, O. Pooth<sup>id</sup>,  
A. Stahl<sup>id</sup>, T. Ziemons<sup>id</sup>, A. Zotz<sup>id</sup>

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

H. Aarup Petersen<sup>id</sup>, M. Aldaya Martin<sup>id</sup>, J. Alimena<sup>id</sup>, S. Amoroso, Y. An<sup>id</sup>, S. Baxter<sup>id</sup>,  
M. Bayatmakou<sup>id</sup>, H. Becerril Gonzalez<sup>id</sup>, O. Behnke<sup>id</sup>, A. Belvedere<sup>id</sup>, S. Bhattacharya<sup>id</sup>,  
F. Blekman<sup>id,27</sup>, K. Borras<sup>id,28</sup>, D. Brunner<sup>id</sup>, A. Campbell<sup>id</sup>, A. Cardini<sup>id</sup>, C. Cheng,  
F. Colombina<sup>id</sup>, S. Consuegra Rodríguez<sup>id</sup>, G. Correia Silva<sup>id</sup>, M. De Silva<sup>id</sup>, G. Eckerlin,  
D. Eckstein<sup>id</sup>, L.I. Estevez Banos<sup>id</sup>, O. Filatov<sup>id</sup>, E. Gallo<sup>id,27</sup>, A. Geiser<sup>id</sup>, A. Giraldi<sup>id</sup>,  
G. Greau, V. Guglielmi<sup>id</sup>, M. Guthoff<sup>id</sup>, A. Hinzmann<sup>id</sup>, A. Jafari<sup>id,29</sup>, L. Jeppe<sup>id</sup>,  
N.Z. Jomhari<sup>id</sup>, B. Kaeck<sup>id</sup>, M. Kasemann<sup>id</sup>, H. Kaveh<sup>id</sup>, C. Kleinwort<sup>id</sup>, R. Kogler<sup>id</sup>,  
M. Komm<sup>id</sup>, D. Krücker<sup>id</sup>, W. Lange, D. Leyva Pernia<sup>id</sup>, K. Lipka<sup>id,30</sup>, W. Lohmann<sup>id,31</sup>,  
R. Mankel<sup>id</sup>, I.-A. Melzer-Pellmann<sup>id</sup>, M. Mendizabal Morentin<sup>id</sup>, J. Metwally, A.B. Meyer<sup>id</sup>,  
G. Milella<sup>id</sup>, A. Mussgiller<sup>id</sup>, L.P. Nair<sup>id</sup>, A. Nürnberg<sup>id</sup>, Y. Otariid, J. Park<sup>id</sup>,  
D. Pérez Adán<sup>id</sup>, E. Ranken<sup>id</sup>, A. Raspereza<sup>id</sup>, B. Ribeiro Lopes<sup>id</sup>, J. Rübenach, A. Saggio<sup>id</sup>,  
M. Scham<sup>id,32,28</sup>, S. Schnake<sup>id,28</sup>, P. Schütze<sup>id</sup>, C. Schwanenberger<sup>id,27</sup>, D. Selivanova<sup>id</sup>,  
M. Shchedrolosiev<sup>id</sup>, R.E. Sosa Ricardo<sup>id</sup>, D. Stafford, F. Vazzoler<sup>id</sup>, A. Ventura Barroso<sup>id</sup>,  
R. Walsh<sup>id</sup>, Q. Wang<sup>id</sup>, Y. Wen<sup>id</sup>, K. Wichmann, L. Wiens<sup>id,28</sup>, C. Wissing<sup>id</sup>, Y. Yang<sup>id</sup>,  
A. Zimmermann Castro Santos<sup>id</sup>

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

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

*University of Hamburg, Hamburg, Germany*

S. Brommer<sup>id</sup>, M. Burkart, E. Butz<sup>id</sup>, T. Chwalek<sup>id</sup>, A. Dierlamm<sup>id</sup>, A. Droll, N. Faltermann<sup>id</sup>,  
M. Giffels<sup>id</sup>, A. Gottmann<sup>id</sup>, F. Hartmann<sup>id,33</sup>, R. Hofsaess<sup>id</sup>, M. Horzela<sup>id</sup>, U. Husemann<sup>id</sup>,  
J. Kieseler<sup>id</sup>, M. Klute<sup>id</sup>, R. Koppenhöfer<sup>id</sup>, J.M. Lawhorn<sup>id</sup>, M. Link, A. Lintuluoto<sup>id</sup>,  
S. Maier<sup>id</sup>, S. Mitra<sup>id</sup>, M. Mormile<sup>id</sup>, Th. Müller<sup>id</sup>, M. Neukum, M. Oh<sup>id</sup>, M. Presilla<sup>id</sup>,  
G. Quast<sup>id</sup>, K. Rabbertz<sup>id</sup>, B. Regnery<sup>id</sup>, N. Shadskiy<sup>id</sup>, I. Shvetsov<sup>id</sup>, H.J. Simonis<sup>id</sup>,  
M. Toms<sup>id,34</sup>, N. Trevisani<sup>id</sup>, R. Ulrich<sup>id</sup>, R.F. Von Cube<sup>id</sup>, M. Wassmer<sup>id</sup>, S. Wieland<sup>id</sup>,  
F. Wittig, R. Wolf<sup>id</sup>, S. Wunsch, X. Zuo<sup>id</sup>

*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis<sup>id</sup>, A. Kyriakis, A. Papadopoulos<sup>33</sup>, A. Stakia<sup>id</sup>

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

P. Kontaxakis<sup>id</sup>, G. Melachroinos, A. Panagiotou, I. Papavergou<sup>id</sup>, I. Paraskevas<sup>id</sup>,  
N. Saoulidou<sup>id</sup>, K. Theofilatos<sup>id</sup>, E. Tziaferi<sup>id</sup>, K. Vellidis<sup>id</sup>, I. Zisopoulos<sup>id</sup>

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

G. Bakas<sup>ID</sup>, T. Chatzistavrou, G. Karapostoli<sup>ID</sup>, K. Kousouris<sup>ID</sup>, I. Papakrivopoulos<sup>ID</sup>,  
E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

*National Technical University of Athens, Athens, Greece*

K. Adamidis, I. Bestintzanos, I. Evangelou<sup>ID</sup>, C. Foudas, P. Gianneios<sup>ID</sup>, C. Kamtsikis,  
P. Katsoulis, P. Kokkas<sup>ID</sup>, P.G. Kosmoglou Kioseoglou<sup>ID</sup>, N. Manthos<sup>ID</sup>, I. Papadopoulos<sup>ID</sup>,  
J. Strologas<sup>ID</sup>

*University of Ioánnina, Ioánnina, Greece*

M. Bartók<sup>ID,35</sup>, C. Hajdu<sup>ID</sup>, D. Horvath<sup>ID,36,37</sup>, F. Sikler<sup>ID</sup>, V. Veszpremi<sup>ID</sup>

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

M. Csanád<sup>ID</sup>, K. Farkas<sup>ID</sup>, M.M.A. Gadallah<sup>ID,38</sup>, Á. Kadlecik<sup>ID</sup>, P. Major<sup>ID</sup>, K. Mandal<sup>ID</sup>,  
G. Pásztor<sup>ID</sup>, A.J. Rádl<sup>ID,39</sup>, G.I. Veres<sup>ID</sup>

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

P. Raics, B. Ujvari<sup>ID</sup>, G. Zilizi<sup>ID</sup>

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

G. Bencze, S. Czellar, J. Karancsi<sup>ID,35</sup>, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

T. Csorgo<sup>ID,39</sup>, F. Nemes<sup>ID,39</sup>, T. Novak<sup>ID</sup>

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

J. Babbar<sup>ID</sup>, S. Bansal<sup>ID</sup>, S.B. Beri, V. Bhatnagar<sup>ID</sup>, G. Chaudhary<sup>ID</sup>, S. Chauhan<sup>ID</sup>,  
N. Dhingra<sup>ID,40</sup>, A. Kaur<sup>ID</sup>, A. Kaur<sup>ID</sup>, H. Kaur<sup>ID</sup>, M. Kaur<sup>ID</sup>, S. Kumar<sup>ID</sup>, K. Sandeep<sup>ID</sup>,  
T. Sheokand, J.B. Singh<sup>ID</sup>, A. Singla<sup>ID</sup>

*Panjab University, Chandigarh, India*

A. Ahmed<sup>ID</sup>, A. Bhardwaj<sup>ID</sup>, A. Chhetri<sup>ID</sup>, B.C. Choudhary<sup>ID</sup>, A. Kumar<sup>ID</sup>, A. Kumar<sup>ID</sup>,  
M. Naimuddin<sup>ID</sup>, K. Ranjan<sup>ID</sup>, S. Saumya<sup>ID</sup>

*University of Delhi, Delhi, India*

S. Baradia<sup>ID</sup>, S. Barman<sup>ID,41</sup>, S. Bhattacharya<sup>ID</sup>, S. Dutta<sup>ID</sup>, S. Dutta, P. Palit<sup>ID</sup>, S. Sarkar

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

M.M. Ameen<sup>ID</sup>, P.K. Behera<sup>ID</sup>, S.C. Behera<sup>ID</sup>, S. Chatterjee<sup>ID</sup>, P. Jana<sup>ID</sup>, P. Kalbhor<sup>ID</sup>,  
J.R. Komaragiri<sup>ID,42</sup>, D. Kumar<sup>ID,42</sup>, L. Panwar<sup>ID,42</sup>, P.R. Pujahari<sup>ID</sup>, N.R. Saha<sup>ID</sup>, A. Sharma<sup>ID</sup>,  
A.K. Sikdar<sup>ID</sup>, S. Verma<sup>ID</sup>

*Indian Institute of Technology Madras, Madras, India*

S. Dugad, M. Kumar<sup>ID</sup>, G.B. Mohanty<sup>ID</sup>, P. Suryadevara

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

A. Bala<sup>ID</sup>, S. Banerjee<sup>ID</sup>, R.M. Chatterjee, M. Guchait<sup>ID</sup>, Sh. Jain<sup>ID</sup>, S. Karmakar<sup>ID</sup>,  
S. Kumar<sup>ID</sup>, G. Majumder<sup>ID</sup>, K. Mazumdar<sup>ID</sup>, S. Parolia<sup>ID</sup>, A. Thachayath<sup>ID</sup>

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

S. Bahinipati<sup>ID,43</sup>, A.K. Das, C. Kar<sup>ID</sup>, D. Maity<sup>ID,44</sup>, P. Mal<sup>ID</sup>, T. Mishra<sup>ID</sup>,  
V.K. Muraleedharan Nair Bindhu<sup>ID,44</sup>, K. Naskar<sup>ID,44</sup>, A. Nayak<sup>ID,44</sup>, P. Sadangi, P. Saha<sup>ID</sup>,  
S.K. Swain<sup>ID</sup>, S. Varghese<sup>ID,44</sup>, D. Vats<sup>ID,44</sup>

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

S. Acharya<sup>a,45</sup>, A. Alpana<sup>id</sup>, S. Dube<sup>id</sup>, B. Gomber<sup>id,45</sup>, B. Kansal<sup>id</sup>, A. Laha<sup>id</sup>, B. Sahu<sup>id,45</sup>,  
S. Sharma<sup>id</sup>

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

H. Bakhshiansohi<sup>id,46</sup>, E. Khazaie<sup>id,47</sup>, M. Zeinali<sup>id,48</sup>

Isfahan University of Technology, Isfahan, Iran

S. Chenarani<sup>id,49</sup>, S.M. Etesami<sup>id</sup>, M. Khakzad<sup>id</sup>, M. Mohammadi Najafabadi<sup>id</sup>

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

M. Grunewald<sup>id</sup>

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b, id</sup>, R. Aly<sup>a,c, id,50</sup>, A. Colaleo<sup>a,b, id</sup>, D. Creanza<sup>a,c, id</sup>, B. D'Anzi<sup>a,b, id</sup>,  
N. De Filippis<sup>a,c, id</sup>, M. De Palma<sup>a,b, id</sup>, A. Di Florio<sup>a,c, id</sup>, W. Elmetenawee<sup>a,b, id,50</sup>, L. Fiore<sup>a, id</sup>,  
G. Iaselli<sup>a,c, id</sup>, M. Louka<sup>a,b</sup>, G. Maggi<sup>a,c, id</sup>, M. Maggi<sup>a, id</sup>, I. Margjeka<sup>a,b, id</sup>,  
V. Mastrapasqua<sup>a,b, id</sup>, S. My<sup>a,b, id</sup>, S. Nuzzo<sup>a,b, id</sup>, A. Pellecchia<sup>a,b, id</sup>, A. Pompili<sup>a,b, id</sup>,  
G. Pugliese<sup>a,c, id</sup>, R. Radogna<sup>a, id</sup>, G. Ramirez-Sanchez<sup>a,c, id</sup>, D. Ramos<sup>a, id</sup>, A. Ranieri<sup>a, id</sup>,  
L. Silvestris<sup>a, id</sup>, F.M. Simone<sup>a,b, id</sup>, Ü. Sözbilir<sup>a, id</sup>, A. Stamerra<sup>a, id</sup>, R. Venditti<sup>a, id</sup>,  
P. Verwilligen<sup>a, id</sup>, A. Zaza<sup>a,b, id</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a, id</sup>, C. Battilana<sup>a,b, id</sup>, D. Bonacorsi<sup>a,b, id</sup>, L. Borgonovi<sup>a, id</sup>, R. Campanini<sup>a,b, id</sup>,  
P. Capiluppi<sup>a,b, id</sup>, A. Castro<sup>a,b, id</sup>, F.R. Cavallo<sup>a, id</sup>, M. Cuffiani<sup>a,b, id</sup>, G.M. Dallavalle<sup>a, id</sup>,  
T. Diotallevi<sup>a,b, id</sup>, F. Fabbri<sup>a, id</sup>, A. Fanfani<sup>a,b, id</sup>, D. Fasanella<sup>a,b, id</sup>, P. Giacomelli<sup>a, id</sup>,  
L. Giommi<sup>a,b, id</sup>, L. Guiducci<sup>a,b, id</sup>, S. Lo Meo<sup>a, id,51</sup>, L. Lunerti<sup>a,b, id</sup>, S. Marcellini<sup>a, id</sup>,  
G. Masetti<sup>a, id</sup>, F.L. Navarria<sup>a,b, id</sup>, A. Perrotta<sup>a, id</sup>, F. Primavera<sup>a,b, id</sup>, A.M. Rossi<sup>a,b, id</sup>,  
T. Rovelli<sup>a,b, id</sup>, G.P. Siroli<sup>a,b, id</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Costa<sup>a,b, id,52</sup>, A. Di Mattia<sup>a, id</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b, id,52</sup>, C. Tuve<sup>a,b, id</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

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

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi<sup>id</sup>, S. Bianco<sup>id</sup>, S. Meola<sup>id,53</sup>, D. Piccolo<sup>id</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Chatagnon<sup>a, id</sup>, F. Ferro<sup>a, id</sup>, E. Robutti<sup>a, id</sup>, S. Tosi<sup>a,b, id</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

A. Benaglia<sup>a, id</sup>, G. Boldrini<sup>a,b, id</sup>, F. Brivio<sup>a, id</sup>, F. Cetorelli<sup>a, id</sup>, F. De Guio<sup>a,b, id</sup>,  
M.E. Dinardo<sup>a,b, id</sup>, P. Dini<sup>a, id</sup>, S. Gennai<sup>a, id</sup>, R. Gerosa<sup>a,b, id</sup>, A. Ghezzi<sup>a,b, id</sup>, P. Govoni<sup>a,b, id</sup>,

L. Guzzi <sup>a, [id](#)</sup>, M.T. Lucchini <sup>a, b, [id](#)</sup>, M. Malberti <sup>a, [id](#)</sup>, S. Malvezzi <sup>a, [id](#)</sup>, A. Massironi <sup>a, [id](#)</sup>,  
 D. Menasce <sup>a, [id](#)</sup>, L. Moroni <sup>a, [id](#)</sup>, M. Paganoni <sup>a, b, [id](#)</sup>, D. Pedrini <sup>a, [id](#)</sup>, B.S. Pinolini <sup>a</sup>, S. Ragazzi <sup>a, b, [id](#)</sup>,  
 T. Tabarelli de Fatis <sup>a, b, [id](#)</sup>, D. Zuolo <sup>a, [id](#)</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo <sup>a, [id](#)</sup>, A. Cagnotta <sup>a, b, [id](#)</sup>, F. Carnevali <sup>a, b</sup>, N. Cavallo <sup>a, c, [id](#)</sup>, A. De Iorio <sup>a, b, [id](#)</sup>,  
 F. Fabozzi <sup>a, c, [id](#)</sup>, A.O.M. Iorio <sup>a, b, [id](#)</sup>, L. Lista <sup>a, b, [id](#), 54</sup>, P. Paolucci <sup>a, [id](#), 33</sup>, B. Rossi <sup>a, [id](#)</sup>, C. Sciacca <sup>a, b, [id](#)</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Scuola Superiore Meridionale (SSM), Napoli, Italy

R. Ardino <sup>a, [id](#)</sup>, P. Azzi <sup>a, [id](#)</sup>, N. Bacchetta <sup>a, [id](#), 55</sup>, D. Bisello <sup>a, b, [id](#)</sup>, P. Bortignon <sup>a, [id](#)</sup>,  
 A. Bragagnolo <sup>a, b, [id](#)</sup>, R. Carlin <sup>a, b, [id](#)</sup>, P. Checchia <sup>a, [id](#)</sup>, T. Dorigo <sup>a, [id](#)</sup>, F. Gasparini <sup>a, b, [id](#)</sup>,  
 U. Gasparini <sup>a, b, [id](#)</sup>, E. Lusiani <sup>a, [id](#)</sup>, M. Margoni <sup>a, b, [id](#)</sup>, A.T. Meneguzzo <sup>a, b, [id](#)</sup>, M. Migliorini <sup>a, b, [id](#)</sup>,  
 J. Pazzini <sup>a, b, [id](#)</sup>, P. Ronchese <sup>a, b, [id](#)</sup>, R. Rossin <sup>a, b, [id](#)</sup>, F. Simonetto <sup>a, b, [id](#)</sup>, G. Strong <sup>a, [id](#)</sup>, M. Tosi <sup>a, b, [id](#)</sup>,  
 A. Triossi <sup>a, b, [id](#)</sup>, S. Ventura <sup>a, [id](#)</sup>, H. Yarar <sup>a, b</sup>, M. Zanetti <sup>a, b, [id](#)</sup>, P. Zotto <sup>a, b, [id](#)</sup>, A. Zucchetta <sup>a, b, [id](#)</sup>,  
 G. Zumerle <sup>a, b, [id](#)</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

S. Abu Zeid <sup>a, [id](#), 56</sup>, C. Aimè <sup>a, b, [id](#)</sup>, A. Braghieri <sup>a, [id](#)</sup>, S. Calzaferri <sup>a, [id](#)</sup>, D. Fiorina <sup>a, [id](#)</sup>,  
 P. Montagna <sup>a, b, [id](#)</sup>, V. Re <sup>a, [id](#)</sup>, C. Riccardi <sup>a, b, [id](#)</sup>, P. Salvini <sup>a, [id](#)</sup>, I. Vai <sup>a, b, [id](#)</sup>, P. Vitulo <sup>a, b, [id](#)</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

S. Ajmal <sup>a, b, [id](#)</sup>, P. Asenov <sup>a, [id](#), 57</sup>, G.M. Bilei <sup>a, [id](#)</sup>, D. Ciangottini <sup>a, b, [id](#)</sup>, L. Fanò <sup>a, b, [id](#)</sup>,  
 M. Magherini <sup>a, b, [id](#)</sup>, G. Mantovani <sup>a, b</sup>, V. Mariani <sup>a, b, [id](#)</sup>, M. Menichelli <sup>a, [id](#)</sup>, F. Moscatelli <sup>a, [id](#), 57</sup>,  
 A. Rossi <sup>a, b, [id](#)</sup>, A. Santocchia <sup>a, b, [id](#)</sup>, D. Spiga <sup>a, [id](#)</sup>, T. Tedeschi <sup>a, b, [id](#)</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

P. Azzurri <sup>a, [id](#)</sup>, G. Bagliesi <sup>a, [id](#)</sup>, R. Bhattacharya <sup>a, [id](#)</sup>, L. Bianchini <sup>a, b, [id](#)</sup>, T. Boccali <sup>a, [id](#)</sup>,  
 E. Bossini <sup>a, [id](#)</sup>, D. Bruschini <sup>a, c, [id](#)</sup>, R. Castaldi <sup>a, [id](#)</sup>, M.A. Ciocci <sup>a, b, [id](#)</sup>, M. Cipriani <sup>a, b, [id](#)</sup>,  
 V. D'Amante <sup>a, d, [id](#)</sup>, R. Dell'Orso <sup>a, [id](#)</sup>, S. Donato <sup>a, [id](#)</sup>, A. Giassi <sup>a, [id](#)</sup>, F. Ligabue <sup>a, c, [id](#)</sup>,  
 D. Matos Figueiredo <sup>a, [id](#)</sup>, A. Messineo <sup>a, b, [id](#)</sup>, M. Musich <sup>a, b, [id](#)</sup>, F. Palla <sup>a, [id](#)</sup>, A. Rizzi <sup>a, b, [id](#)</sup>,  
 G. Rolandi <sup>a, c, [id](#)</sup>, S. Roy Chowdhury <sup>a, [id](#)</sup>, T. Sarkar <sup>a, [id](#)</sup>, A. Scribano <sup>a, [id](#)</sup>, P. Spagnolo <sup>a, [id](#)</sup>,  
 R. Tenchini <sup>a, [id](#)</sup>, G. Tonelli <sup>a, b, [id](#)</sup>, N. Turini <sup>a, d, [id](#)</sup>, A. Venturi <sup>a, [id](#)</sup>, P.G. Verdini <sup>a, [id](#)</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

<sup>d</sup> Università di Siena, Siena, Italy

P. Barria <sup>a, [id](#)</sup>, M. Campana <sup>a, b, [id](#)</sup>, F. Cavallari <sup>a, [id](#)</sup>, L. Cunqueiro Mendez <sup>a, b, [id](#)</sup>, D. Del Re <sup>a, b, [id](#)</sup>,  
 E. Di Marco <sup>a, [id](#)</sup>, M. Diemoz <sup>a, [id](#)</sup>, F. Errico <sup>a, b, [id](#)</sup>, E. Longo <sup>a, b, [id](#)</sup>, P. Meridiani <sup>a, [id](#)</sup>,  
 J. Mijuskovic <sup>a, b, [id](#)</sup>, G. Organtini <sup>a, b, [id](#)</sup>, F. Pandolfi <sup>a, [id](#)</sup>, R. Paramatti <sup>a, b, [id](#)</sup>, C. Quaranta <sup>a, b, [id](#)</sup>,  
 S. Rahatlou <sup>a, b, [id](#)</sup>, C. Rovelli <sup>a, [id](#)</sup>, F. Santanastasio <sup>a, b, [id](#)</sup>, L. Soffi <sup>a, [id](#)</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Sapienza Università di Roma, Roma, Italy

N. Amapane <sup>a,b, ID</sup>, R. Arcidiacono <sup>a,c, ID</sup>, S. Argiro <sup>a,b, ID</sup>, M. Arneodo <sup>a,c, ID</sup>, N. Bartosik <sup>a, ID</sup>,  
 R. Bellan <sup>a,b, ID</sup>, A. Bellora <sup>a,b, ID</sup>, C. Biino <sup>a, ID</sup>, N. Cartiglia <sup>a, ID</sup>, M. Costa <sup>a,b, ID</sup>, R. Covarelli <sup>a,b, ID</sup>,  
 N. Demaria <sup>a, ID</sup>, L. Finco <sup>a, ID</sup>, M. Grippo <sup>a,b, ID</sup>, B. Kiani <sup>a,b, ID</sup>, F. Legger <sup>a, ID</sup>, F. Luongo <sup>a,b, ID</sup>,  
 C. Mariotti <sup>a, ID</sup>, S. Maselli <sup>a, ID</sup>, A. Mecca <sup>a,b, ID</sup>, E. Migliore <sup>a,b, ID</sup>, M. Monteno <sup>a, ID</sup>, R. Mulargia <sup>a, ID</sup>,  
 M.M. Obertino <sup>a,b, ID</sup>, G. Ortona <sup>a, ID</sup>, L. Pacher <sup>a,b, ID</sup>, N. Pastrone <sup>a, ID</sup>, M. Pelliccioni <sup>a, ID</sup>,  
 M. Ruspa <sup>a,c, ID</sup>, F. Siviero <sup>a,b, ID</sup>, V. Sola <sup>a,b, ID</sup>, A. Solano <sup>a,b, ID</sup>, A. Staiano <sup>a, ID</sup>, C. Tarricone <sup>a,b, ID</sup>,  
 D. Trocino <sup>a, ID</sup>, G. Umoret <sup>a,b, ID</sup>, E. Vlasov <sup>a,b, ID</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

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

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

S. Dogra <sup>ID</sup>, J. Hong <sup>ID</sup>, C. Huh <sup>ID</sup>, B. Kim <sup>ID</sup>, D.H. Kim <sup>ID</sup>, J. Kim, H. Lee, S.W. Lee <sup>ID</sup>,  
 C.S. Moon <sup>ID</sup>, Y.D. Oh <sup>ID</sup>, M.S. Ryu <sup>ID</sup>, S. Sekmen <sup>ID</sup>, Y.C. Yang <sup>ID</sup>

Kyungpook National University, Daegu, Korea

M.S. Kim <sup>ID</sup>

Department of Mathematics and Physics - GWNu, Gangneung, Korea

G. Bak <sup>ID</sup>, P. Gwak <sup>ID</sup>, H. Kim <sup>ID</sup>, D.H. Moon <sup>ID</sup>

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

E. Asilar <sup>ID</sup>, D. Kim <sup>ID</sup>, T.J. Kim <sup>ID</sup>, J.A. Merlin

Hanyang University, Seoul, Korea

S. Choi <sup>ID</sup>, S. Han, B. Hong <sup>ID</sup>, K. Lee, K.S. Lee <sup>ID</sup>, S. Lee <sup>ID</sup>, J. Park, S.K. Park, J. Yoo <sup>ID</sup>

Korea University, Seoul, Korea

J. Goh <sup>ID</sup>, S. Yang <sup>ID</sup>

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim <sup>ID</sup>, Y. Kim, S. Lee

Sejong University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi <sup>ID</sup>, W. Jun <sup>ID</sup>, J. Kim <sup>ID</sup>, J.S. Kim, S. Ko <sup>ID</sup>, H. Kwon <sup>ID</sup>, H. Lee <sup>ID</sup>,  
 J. Lee <sup>ID</sup>, J. Lee <sup>ID</sup>, B.H. Oh <sup>ID</sup>, S.B. Oh <sup>ID</sup>, H. Seo <sup>ID</sup>, U.K. Yang, I. Yoon <sup>ID</sup>

Seoul National University, Seoul, Korea

W. Jang <sup>ID</sup>, D.Y. Kang, Y. Kang <sup>ID</sup>, S. Kim <sup>ID</sup>, B. Ko, J.S.H. Lee <sup>ID</sup>, Y. Lee <sup>ID</sup>, I.C. Park <sup>ID</sup>, Y. Roh,  
 I.J. Watson <sup>ID</sup>

University of Seoul, Seoul, Korea

S. Ha <sup>ID</sup>, H.D. Yoo <sup>ID</sup>

Yonsei University, Department of Physics, Seoul, Korea

M. Choi <sup>ID</sup>, M.R. Kim <sup>ID</sup>, H. Lee, Y. Lee <sup>ID</sup>, I. Yu <sup>ID</sup>

Sungkyunkwan University, Suwon, Korea


T. Beyrouthy, Y. Maghrbi <sup>ID</sup>

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



K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns <sup>,58</sup>

Riga Technical University, Riga, Latvia

N.R. Strautnieks 







University of Latvia (LU), Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen , I. Yusuff <sup>,59</sup>, Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala , H. Castilla-Valdez , E. De La Cruz-Burelo , I. Heredia-De La Cruz <sup>,60</sup>,  
R. Lopez-Fernandez , C.A. Mondragon Herrera, A. Sánchez Hernández 

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

C. Oropeza Barrera , M. Ramírez García 

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bujanja , N. Raicevic 

University of Montenegro, Podgorica, Montenegro

P.H. Butler 








University of Canterbury, Christchurch, New Zealand

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







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

V. Avati, L. Grzanka , M. Malawski 

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szleper ,  
P. Zalewski 

















National Centre for Nuclear Research, Swierk, Poland

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

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

K. Pozniak , W. Zabolotny 

Warsaw University of Technology, Warsaw, Poland

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo ,  
T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo ,  
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







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

P. Adzic , P. Milenovic 

Faculty of Physics, University of Belgrade, Belgrade, Serbia

M. Dordevic , J. Milosevic , V. Rekovic














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

M. Aguilar-Benitez, J. Alcaraz Maestre , Cristina F. Bedoya , M. Cepeda , M. Cerrada ,  
N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle ,  
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



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

J.F. de Trocóniz 

Universidad Autónoma de Madrid, Madrid, Spain

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




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

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



















































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

M.K. Jayananda , B. Kailasapathy ,<sup>61</sup> D.U.J. Sonnadara , D.D.C. Wickramarathna 

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna ,<sup>62</sup> K. Liyanage , N. Perera , N. Wickramage 

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

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney ,  
A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci ,  
E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria ,  
A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson ,  
F. Fallavollita <sup>63</sup>, L. Forthomme , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill ,  
F. Glege , L. Gouskos , M. Haranko , J. Hegeman , B. Huber, V. Innocente , T. James ,  
P. Janot , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri ,  
M. Mannelli , A.C. Marini , M. Matthewman, F. Meijers , S. Mersi , E. Meschi ,  
V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli,  
F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , H. Qu , D. Rabady ,  
G. Reales Gutiérrez, M. Rovere , H. Sakulin , S. Scarfi , C. Schwick, M. Selvaggi ,  
A. Sharma , K. Shchelina , P. Silva , P. Sphicas ,<sup>64</sup> A.G. Stahl Leiton , A. Steen ,  
S. Summers , D. Treille , P. Tropea , A. Tsiros, D. Walter , J. Wanczyk ,<sup>65</sup> J. Wang,  
S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua<sup>ID,66</sup>, L. Caminada<sup>ID,66</sup>, A. Ebrahimi<sup>ID</sup>, W. Erdmann<sup>ID</sup>, R. Horisberger<sup>ID</sup>,  
Q. Ingram<sup>ID</sup>, H.C. Kaestli<sup>ID</sup>, D. Kotlinski<sup>ID</sup>, C. Lange<sup>ID</sup>, M. Missiroli<sup>ID,66</sup>, L. Noehte<sup>ID,66</sup>,  
T. Rohe<sup>ID</sup>

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad<sup>ID</sup>, K. Androsov<sup>ID,65</sup>, M. Backhaus<sup>ID</sup>, A. Calandri<sup>ID</sup>, C. Cazzaniga<sup>ID</sup>, K. Datta<sup>ID</sup>,  
A. De Cosa<sup>ID</sup>, G. Dissertori<sup>ID</sup>, M. Dittmar, M. Donegà<sup>ID</sup>, F. Eble<sup>ID</sup>, M. Galli<sup>ID</sup>, K. Gedia<sup>ID</sup>,  
F. Glessgen<sup>ID</sup>, C. Grab<sup>ID</sup>, D. Hits<sup>ID</sup>, W. Lustermann<sup>ID</sup>, A.-M. Lyon<sup>ID</sup>, R.A. Manzoni<sup>ID</sup>,  
M. Marchegiani<sup>ID</sup>, L. Marchese<sup>ID</sup>, C. Martin Perez<sup>ID</sup>, A. Mascellani<sup>ID,65</sup>, F. Nessi-Tedaldi<sup>ID</sup>,  
F. Pauss<sup>ID</sup>, V. Perovic<sup>ID</sup>, S. Pigazzini<sup>ID</sup>, M. Reichmann<sup>ID</sup>, C. Reissel<sup>ID</sup>, T. Reitenspiess<sup>ID</sup>,  
B. Ristic<sup>ID</sup>, F. Riti<sup>ID</sup>, D. Ruini, D.A. Sanz Becerra<sup>ID</sup>, R. Seidita<sup>ID</sup>, J. Steggemann<sup>ID,65</sup>,  
D. Valsecchi<sup>ID</sup>, R. Wallny<sup>ID</sup>

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

C. Amsler<sup>ID,67</sup>, P. Bäertschi<sup>ID</sup>, C. Botta<sup>ID</sup>, D. Brzhechko, M.F. Canelli<sup>ID</sup>, K. Cormier<sup>ID</sup>,  
R. Del Burgo, J.K. Heikkilä<sup>ID</sup>, M. Huwiler<sup>ID</sup>, W. Jin<sup>ID</sup>, A. Jofrehei<sup>ID</sup>, B. Kilminster<sup>ID</sup>,  
S. Leontsinis<sup>ID</sup>, S.P. Liechti<sup>ID</sup>, A. Macchiolo<sup>ID</sup>, P. Meiring<sup>ID</sup>, V.M. Mikuni<sup>ID</sup>, U. Molinatti<sup>ID</sup>,  
A. Reimers<sup>ID</sup>, P. Robmann, S. Sanchez Cruz<sup>ID</sup>, K. Schweiger<sup>ID</sup>, M. Senger<sup>ID</sup>, Y. Takahashi<sup>ID</sup>,  
R. Tramontano<sup>ID</sup>

Universität Zürich, Zurich, Switzerland

C. Adloff<sup>68</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout<sup>ID</sup>, P.C. Tiwari<sup>ID,42</sup>, S.S. Yu<sup>ID</sup>

National Central University, Chung-Li, Taiwan

L. Ceard, Y. Chao<sup>ID</sup>, K.F. Chen<sup>ID</sup>, P.s. Chen, Z.g. Chen, W.-S. Hou<sup>ID</sup>, T.h. Hsu, Y.w. Kao,  
R. Khurana, G. Kole<sup>ID</sup>, Y.y. Li<sup>ID</sup>, R.-S. Lu<sup>ID</sup>, E. Paganis<sup>ID</sup>, X.f. Su<sup>ID</sup>, J. Thomas-Wilsker<sup>ID</sup>,  
L.s. Tsai, H.y. Wu, E. Yazgan<sup>ID</sup>

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee<sup>ID</sup>, N. Srimanobhas<sup>ID</sup>, V. Wachirapusanand<sup>ID</sup>

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

D. Agyel<sup>ID</sup>, F. Boran<sup>ID</sup>, Z.S. Demiroglu<sup>ID</sup>, F. Dolek<sup>ID</sup>, I. Dumanoglu<sup>ID,69</sup>, E. Eskut<sup>ID</sup>,  
Y. Guler<sup>ID,70</sup>, E. Gurpinar Guler<sup>ID,70</sup>, C. Isik<sup>ID</sup>, O. Kara, A. Kayis Topaksu<sup>ID</sup>, U. Kiminsu<sup>ID</sup>,  
G. Onengut<sup>ID</sup>, K. Ozdemir<sup>ID,71</sup>, A. Polatoz<sup>ID</sup>, B. Tali<sup>ID,72</sup>, U.G. Tok<sup>ID</sup>, S. Turkcapar<sup>ID</sup>,  
E. Uslan<sup>ID</sup>, I.S. Zorbakir<sup>ID</sup>

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

M. Yalvac<sup>ID,73</sup>

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun<sup>ID</sup>, I.O. Atakisi<sup>ID</sup>, E. Gülmez<sup>ID</sup>, M. Kaya<sup>ID,74</sup>, O. Kaya<sup>ID,75</sup>, S. Tekten<sup>ID,76</sup>

Bogazici University, Istanbul, Turkey

A. Cakir<sup>ID</sup>, K. Cankocak<sup>ID,69,77</sup>, Y. Komurcu<sup>ID</sup>, S. Sen<sup>ID,78</sup>

Istanbul Technical University, Istanbul, Turkey

O. Aydilek<sup>ID</sup>, S. Cerci<sup>ID,72</sup>, V. Epshteyn<sup>ID</sup>, B. Hacisahinoglu<sup>ID</sup>, I. Hos<sup>ID,79</sup>, B. Kaynak<sup>ID</sup>,  
S. Ozkorucuklu<sup>ID</sup>, O. Potok<sup>ID</sup>, H. Sert<sup>ID</sup>, C. Simsek<sup>ID</sup>, D. Sunar Cerci<sup>ID,72</sup>, C. Zorbilmez<sup>ID</sup>

Istanbul University, Istanbul, Turkey

B. Isildak , <sup>80</sup>















Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev , B. Grynyov 


















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

L. Levchuk 



































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

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans ,  
H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , S. Paramesvaran ,  
S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou , <sup>81</sup>, K. Walkingshaw Pass, R. White 

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev , <sup>82</sup>, C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg , <sup>83</sup>, J. Linacre ,  
K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh,  
C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 












Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio,  
C.A. Carrillo Montoya , G.S. Chahal , <sup>84</sup>, D. Colling , J.S. Dancu, I. Das , P. Dauncey ,  
G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi ,  
A. Howard, G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons ,  
A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , J. Nash , <sup>85</sup>, M. Pesaresi ,  
B.C. Radburn-Smith , A. Richards, A. Rose , C. Seez , R. Shukla , A. Tapper ,  
K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee , <sup>33</sup>, M. Vojinovic , N. Wardle ,  
D. Winterbottom 






Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama ,  
J. Hiltbrand , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 






















Baylor University, Waco, TX, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal ,  
A.M. Vargas Hernandez 

Catholic University of America, Washington, DC, USA

B. Bam , R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio , <sup>86</sup>,  
E. Usai , R. Yi 

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Benelli<sup>1b</sup>, X. Coubez<sup>28</sup>, D. Cutts<sup>1b</sup>, M. Hadley<sup>1b</sup>, U. Heintz<sup>1b</sup>, J.M. Hogan<sup>1b,87</sup>, T. Kwon<sup>1b</sup>,  
G. Landsberg<sup>1b</sup>, K.T. Lau<sup>1b</sup>, D. Li<sup>1b</sup>, J. Luo<sup>1b</sup>, S. Mondal<sup>1b</sup>, M. Narain<sup>1b,†</sup>, N. Pervan<sup>1b</sup>,  
S. Sagir<sup>1b,88</sup>, F. Simpson<sup>1b</sup>, M. Stamenkovic<sup>1b</sup>, W.Y. Wong, X. Yan<sup>1b</sup>, W. Zhang

Brown University, Providence, RI, USA

S. Abbott<sup>1b</sup>, J. Bonilla<sup>1b</sup>, C. Brainerd<sup>1b</sup>, R. Breedon<sup>1b</sup>, M. Calderon De La Barca Sanchez<sup>1b</sup>,  
M. Chertok<sup>1b</sup>, M. Citron<sup>1b</sup>, J. Conway<sup>1b</sup>, P.T. Cox<sup>1b</sup>, R. Erbacher<sup>1b</sup>, F. Jensen<sup>1b</sup>, O. Kukral<sup>1b</sup>,  
G. Mocellin<sup>1b</sup>, M. Mulhearn<sup>1b</sup>, D. Pellett<sup>1b</sup>, W. Wei<sup>1b</sup>, Y. Yao<sup>1b</sup>, F. Zhang<sup>1b</sup>

University of California, Davis, Davis, CA, USA

M. Bachtis<sup>1b</sup>, R. Cousins<sup>1b</sup>, A. Datta<sup>1b</sup>, G. Flores Avila, J. Hauser<sup>1b</sup>, M. Ignatenko<sup>1b</sup>,  
M.A. Iqbal<sup>1b</sup>, T. Lam<sup>1b</sup>, E. Manca<sup>1b</sup>, A. Nunez Del Prado, D. Saltzberg<sup>1b</sup>, V. Valuev<sup>1b</sup>

University of California, Los Angeles, CA, USA

R. Clare<sup>1b</sup>, J.W. Gary<sup>1b</sup>, M. Gordon, G. Hanson<sup>1b</sup>, W. Si<sup>1b</sup>, S. Wimpenny<sup>1b,†</sup>

University of California, Riverside, Riverside, CA, USA

J.G. Branson<sup>1b</sup>, S. Cittolin<sup>1b</sup>, S. Cooperstein<sup>1b</sup>, D. Diaz<sup>1b</sup>, J. Duarte<sup>1b</sup>, L. Giannini<sup>1b</sup>,  
J. Guiang<sup>1b</sup>, R. Kansal<sup>1b</sup>, V. Krutelyov<sup>1b</sup>, R. Lee<sup>1b</sup>, J. Letts<sup>1b</sup>, M. Masciovecchio<sup>1b</sup>,  
F. Mokhtar<sup>1b</sup>, S. Mukherjee<sup>1b</sup>, M. Pieri<sup>1b</sup>, M. Quinnan<sup>1b</sup>, B.V. Sathia Narayanan<sup>1b</sup>,  
V. Sharma<sup>1b</sup>, M. Tadel<sup>1b</sup>, E. Vourliotis<sup>1b</sup>, F. Würthwein<sup>1b</sup>, Y. Xiang<sup>1b</sup>, A. Yagil<sup>1b</sup>

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

A. Barzdukas<sup>1b</sup>, L. Brennan<sup>1b</sup>, C. Campagnari<sup>1b</sup>, A. Dorsett<sup>1b</sup>, J. Incandela<sup>1b</sup>, J. Kim<sup>1b</sup>,  
A.J. Li<sup>1b</sup>, P. Masterson<sup>1b</sup>, H. Mei<sup>1b</sup>, J. Richman<sup>1b</sup>, U. Sarica<sup>1b</sup>, R. Schmitz<sup>1b</sup>, F. Setti<sup>1b</sup>,  
J. Shephlock<sup>1b</sup>, D. Stuart<sup>1b</sup>, T.Á. Vámi<sup>1b</sup>, S. Wang<sup>1b</sup>

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

A. Bornheim<sup>1b</sup>, O. Cerri, A. Latorre, J. Mao<sup>1b</sup>, H.B. Newman<sup>1b</sup>, M. Spiropulu<sup>1b</sup>,  
J.R. Vlimant<sup>1b</sup>, C. Wang<sup>1b</sup>, S. Xie<sup>1b</sup>, R.Y. Zhu<sup>1b</sup>

California Institute of Technology, Pasadena, CA, USA

J. Alison<sup>1b</sup>, S. An<sup>1b</sup>, M.B. Andrews<sup>1b</sup>, P. Bryant<sup>1b</sup>, M. Cremonesi, V. Dutta<sup>1b</sup>, T. Ferguson<sup>1b</sup>,  
A. Harilal<sup>1b</sup>, C. Liu<sup>1b</sup>, T. Mudholkar<sup>1b</sup>, S. Murthy<sup>1b</sup>, M. Paulini<sup>1b</sup>, A. Roberts<sup>1b</sup>, A. Sanchez<sup>1b</sup>,  
W. Terrill<sup>1b</sup>

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat<sup>1b</sup>, W.T. Ford<sup>1b</sup>, A. Hassani<sup>1b</sup>, G. Karathanasis<sup>1b</sup>, E. MacDonald, N. Manganelli<sup>1b</sup>,  
F. Marini<sup>1b</sup>, A. Perloff<sup>1b</sup>, C. Savard<sup>1b</sup>, N. Schonbeck<sup>1b</sup>, K. Stenson<sup>1b</sup>, K.A. Ulmer<sup>1b</sup>,  
S.R. Wagner<sup>1b</sup>, N. Zipper<sup>1b</sup>

University of Colorado Boulder, Boulder, CO, USA

J. Alexander<sup>1b</sup>, S. Bright-Thonney<sup>1b</sup>, X. Chen<sup>1b</sup>, D.J. Cranshaw<sup>1b</sup>, J. Fan<sup>1b</sup>, X. Fan<sup>1b</sup>,  
D. Gadkari<sup>1b</sup>, S. Hogan<sup>1b</sup>, P. Kotamnives, J. Monroy<sup>1b</sup>, M. Oshiro<sup>1b</sup>, J.R. Patterson<sup>1b</sup>,  
J. Reichert<sup>1b</sup>, M. Reid<sup>1b</sup>, A. Ryd<sup>1b</sup>, J. Thom<sup>1b</sup>, P. Wittich<sup>1b</sup>, R. Zou<sup>1b</sup>

Cornell University, Ithaca, NY, USA

M. Albrow<sup>1b</sup>, M. Alyari<sup>1b</sup>, O. Amram<sup>1b</sup>, G. Apollinari<sup>1b</sup>, A. Apresyan<sup>1b</sup>, L.A.T. Bauerdick<sup>1b</sup>,  
D. Berry<sup>1b</sup>, J. Berryhill<sup>1b</sup>, P.C. Bhat<sup>1b</sup>, K. Burkett<sup>1b</sup>, J.N. Butler<sup>1b</sup>, A. Canepa<sup>1b</sup>, G.B. Cerati<sup>1b</sup>,

H.W.K. Cheung<sup>id</sup>, F. Chlebana<sup>id</sup>, G. Cummings<sup>id</sup>, J. Dickinson<sup>id</sup>, I. Dutta<sup>id</sup>, V.D. Elvira<sup>id</sup>,  
 Y. Feng<sup>id</sup>, J. Freeman<sup>id</sup>, A. Gandrakota<sup>id</sup>, Z. Gece<sup>id</sup>, L. Gray<sup>id</sup>, D. Green, A. Grummer<sup>id</sup>,  
 S. Grünendahl<sup>id</sup>, D. Guerrero<sup>id</sup>, O. Gutsche<sup>id</sup>, R.M. Harris<sup>id</sup>, R. Heller<sup>id</sup>, T.C. Herwig<sup>id</sup>,  
 J. Hirschauer<sup>id</sup>, L. Horyn<sup>id</sup>, B. Jayatilaka<sup>id</sup>, S. Jindariani<sup>id</sup>, M. Johnson<sup>id</sup>, U. Joshi<sup>id</sup>,  
 T. Klijnsma<sup>id</sup>, B. Klima<sup>id</sup>, K.H.M. Kwok<sup>id</sup>, S. Lammel<sup>id</sup>, D. Lincoln<sup>id</sup>, R. Lipton<sup>id</sup>, T. Liu<sup>id</sup>,  
 C. Madrid<sup>id</sup>, K. Maeshima<sup>id</sup>, C. Mantilla<sup>id</sup>, D. Mason<sup>id</sup>, P. McBride<sup>id</sup>, P. Merkel<sup>id</sup>,  
 S. Mrenna<sup>id</sup>, S. Nahn<sup>id</sup>, J. Ngadiuba<sup>id</sup>, D. Noonan<sup>id</sup>, V. Papadimitriou<sup>id</sup>, N. Pastika<sup>id</sup>,  
 K. Pedro<sup>id</sup>, C. Pena<sup>id,89</sup>, F. Ravera<sup>id</sup>, A. Reinsvold Hall<sup>id,90</sup>, L. Ristori<sup>id</sup>,  
 E. Sexton-Kennedy<sup>id</sup>, N. Smith<sup>id</sup>, A. Soha<sup>id</sup>, L. Spiegel<sup>id</sup>, S. Stoynev<sup>id</sup>, J. Strait<sup>id</sup>,  
 L. Taylor<sup>id</sup>, S. Tkaczyk<sup>id</sup>, N.V. Tran<sup>id</sup>, L. Uplegger<sup>id</sup>, E.W. Vaandering<sup>id</sup>, I. Zoi<sup>id</sup>

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

C. Aruta<sup>id</sup>, P. Avery<sup>id</sup>, D. Bourilkov<sup>id</sup>, L. Cadamuro<sup>id</sup>, P. Chang<sup>id</sup>, V. Cherepanov<sup>id</sup>,  
 R.D. Field, E. Koenig<sup>id</sup>, M. Kolosova<sup>id</sup>, J. Konigsberg<sup>id</sup>, A. Korytov<sup>id</sup>, K.H. Lo, K. Matchev<sup>id</sup>,  
 N. Menendez<sup>id</sup>, G. Mitselmakher<sup>id</sup>, K. Mohrman<sup>id</sup>, A. Muthirakalayil Madhu<sup>id</sup>, N. Rawal<sup>id</sup>,  
 D. Rosenzweig<sup>id</sup>, S. Rosenzweig<sup>id</sup>, K. Shi<sup>id</sup>, J. Wang<sup>id</sup>

*University of Florida, Gainesville, FL, USA*

T. Adams<sup>id</sup>, A. Al Kadhim<sup>id</sup>, A. Askew<sup>id</sup>, N. Bower<sup>id</sup>, R. Habibullah<sup>id</sup>, V. Hagopian<sup>id</sup>,  
 R. Hashmi<sup>id</sup>, R.S. Kim<sup>id</sup>, S. Kim<sup>id</sup>, T. Kolberg<sup>id</sup>, G. Martinez, H. Prosper<sup>id</sup>, P.R. Prova,  
 O. Viazlo<sup>id</sup>, M. Wulansatiti<sup>id</sup>, R. Yohay<sup>id</sup>, J. Zhang

*Florida State University, Tallahassee, FL, USA*

B. Alsufyani, M.M. Baarmand<sup>id</sup>, S. Butalla<sup>id</sup>, T. Elkafrawy<sup>id,56</sup>, M. Hohlmann<sup>id</sup>,  
 R. Kumar Verma<sup>id</sup>, M. Rahmani, E. Yanes

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

M.R. Adams<sup>id</sup>, A. Baty<sup>id</sup>, C. Bennett, R. Cavanaugh<sup>id</sup>, S. Dittmer<sup>id</sup>, R. Escobar Franco<sup>id</sup>,  
 O. Evdokimov<sup>id</sup>, C.E. Gerber<sup>id</sup>, D.J. Hofman<sup>id</sup>, J.h. Lee<sup>id</sup>, D.S. Lemos<sup>id</sup>, A.H. Merrit<sup>id</sup>,  
 C. Mills<sup>id</sup>, S. Nanda<sup>id</sup>, G. Oh<sup>id</sup>, B. Ozek<sup>id</sup>, D. Pilipovic<sup>id</sup>, R. Pradhan<sup>id</sup>, T. Roy<sup>id</sup>,  
 S. Rudrabhatla<sup>id</sup>, M.B. Tonjes<sup>id</sup>, N. Varelas<sup>id</sup>, X. Wang<sup>id</sup>, Z. Ye<sup>id</sup>, J. Yoo<sup>id</sup>

*University of Illinois Chicago, Chicago, USA*

M. Alhusseini<sup>id</sup>, D. Blend, K. Dilsiz<sup>id,91</sup>, L. Emediato<sup>id</sup>, G. Karaman<sup>id</sup>, O.K. Köseyan<sup>id</sup>,  
 J.-P. Merlo, A. Mestvirishvili<sup>id,92</sup>, J. Nachtman<sup>id</sup>, O. Neogi, H. Ogul<sup>id,93</sup>, Y. Onel<sup>id</sup>,  
 A. Penzo<sup>id</sup>, C. Snyder, E. Tiras<sup>id,94</sup>

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

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

*Johns Hopkins University, Baltimore, MD, USA*

A. Abreu<sup>id</sup>, L.F. Alcerro Alcerro<sup>id</sup>, J. Anguiano<sup>id</sup>, P. Baringer<sup>id</sup>, A. Bean<sup>id</sup>, Z. Flowers<sup>id</sup>,  
 D. Grove<sup>id</sup>, J. King<sup>id</sup>, G. Krintiras<sup>id</sup>, M. Lazarovits<sup>id</sup>, C. Le Mahieu<sup>id</sup>, C. Lindsey,  
 J. Marquez<sup>id</sup>, N. Minafra<sup>id</sup>, M. Murray<sup>id</sup>, M. Nickel<sup>id</sup>, M. Pitt<sup>id</sup>, S. Popescu<sup>id,95</sup>, C. Rogan<sup>id</sup>,  
 C. Royon<sup>id</sup>, R. Salvatico<sup>id</sup>, S. Sanders<sup>id</sup>, C. Smith<sup>id</sup>, Q. Wang<sup>id</sup>, G. Wilson<sup>id</sup>

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

B. Allmond<sup>ID</sup>, A. Ivanov<sup>ID</sup>, K. Kaadze<sup>ID</sup>, A. Kalogeropoulos<sup>ID</sup>, D. Kim, Y. Maravin<sup>ID</sup>, K. Nam,  
J. Natoli<sup>ID</sup>, D. Roy<sup>ID</sup>, G. Sorrentino<sup>ID</sup>

Kansas State University, Manhattan, KS, USA

F. Rebassoo<sup>ID</sup>, D. Wright<sup>ID</sup>

Lawrence Livermore National Laboratory, Livermore, CA, USA

A. Baden<sup>ID</sup>, A. Belloni<sup>ID</sup>, A. Bethani<sup>ID</sup>, Y.M. Chen<sup>ID</sup>, S.C. Eno<sup>ID</sup>, N.J. Hadley<sup>ID</sup>, S. Jabeen<sup>ID</sup>,  
R.G. Kellogg<sup>ID</sup>, T. Koeth<sup>ID</sup>, Y. Lai<sup>ID</sup>, S. Lascio<sup>ID</sup>, A.C. Mignerey<sup>ID</sup>, S. Nabili<sup>ID</sup>, C. Palmer<sup>ID</sup>,  
C. Papageorgakis<sup>ID</sup>, M.M. Paranjpe, L. Wang<sup>ID</sup>

University of Maryland, College Park, MD, USA

J. Bendavid<sup>ID</sup>, W. Busza<sup>ID</sup>, I.A. Cali<sup>ID</sup>, Y. Chen<sup>ID</sup>, M. D'Alfonso<sup>ID</sup>, J. Eysermans<sup>ID</sup>, C. Freer<sup>ID</sup>,  
G. Gomez-Ceballos<sup>ID</sup>, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskiy<sup>ID</sup>,  
J. Krupa<sup>ID</sup>, L. Lavezzo<sup>ID</sup>, Y.-J. Lee<sup>ID</sup>, K. Long<sup>ID</sup>, C. Mironov<sup>ID</sup>, C. Paus<sup>ID</sup>, D. Rankin<sup>ID</sup>,  
C. Roland<sup>ID</sup>, G. Roland<sup>ID</sup>, S. Rothman<sup>ID</sup>, Z. Shi<sup>ID</sup>, G.S.F. Stephans<sup>ID</sup>, Z. Wang<sup>ID</sup>,  
B. Wyslouch<sup>ID</sup>, T.J. Yang<sup>ID</sup>

Massachusetts Institute of Technology, Cambridge, MA, USA

B. Crossman<sup>ID</sup>, B.M. Joshi<sup>ID</sup>, C. Kapsiak<sup>ID</sup>, M. Krohn<sup>ID</sup>, D. Mahon<sup>ID</sup>, J. Mans<sup>ID</sup>,  
B. Marzocchi<sup>ID</sup>, S. Pandey<sup>ID</sup>, M. Revering<sup>ID</sup>, R. Rusack<sup>ID</sup>, R. Saradhy<sup>ID</sup>, N. Schroeder<sup>ID</sup>,  
N. Strobbe<sup>ID</sup>, M.A. Wadud<sup>ID</sup>

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi<sup>ID</sup>

University of Mississippi, Oxford, MS, USA

K. Bloom<sup>ID</sup>, M. Bryson, D.R. Claes<sup>ID</sup>, G. Haza<sup>ID</sup>, J. Hossain<sup>ID</sup>, C. Joo<sup>ID</sup>, I. Kravchenko<sup>ID</sup>,  
J.E. Siado<sup>ID</sup>, W. Tabb<sup>ID</sup>, A. Vagnerini<sup>ID</sup>, A. Wightman<sup>ID</sup>, F. Yan<sup>ID</sup>, D. Yu<sup>ID</sup>

University of Nebraska-Lincoln, Lincoln, NE, USA

H. Bandyopadhyay<sup>ID</sup>, L. Hay<sup>ID</sup>, I. Iashvili<sup>ID</sup>, A. Kharchilava<sup>ID</sup>, M. Morris<sup>ID</sup>, D. Nguyen<sup>ID</sup>,  
S. Rappoccio<sup>ID</sup>, H. Rejeb Sfar, A. Williams<sup>ID</sup>

State University of New York at Buffalo, Buffalo, NY, USA

G. Alverson<sup>ID</sup>, E. Barberis<sup>ID</sup>, J. Dervan, Y. Haddad<sup>ID</sup>, Y. Han<sup>ID</sup>, A. Krishna<sup>ID</sup>, J. Li<sup>ID</sup>,  
M. Lu<sup>ID</sup>, G. Madigan<sup>ID</sup>, R. McCarthy<sup>ID</sup>, D.M. Morse<sup>ID</sup>, V. Nguyen<sup>ID</sup>, T. Orimoto<sup>ID</sup>,  
A. Parker<sup>ID</sup>, L. Skinnari<sup>ID</sup>, A. Tishelman-Charny<sup>ID</sup>, B. Wang<sup>ID</sup>, D. Wood<sup>ID</sup>

Northeastern University, Boston, MA, USA

S. Bhattacharya<sup>ID</sup>, J. Bueghly, Z. Chen<sup>ID</sup>, K.A. Hahn<sup>ID</sup>, Y. Liu<sup>ID</sup>, Y. Miao<sup>ID</sup>, D.G. Monk<sup>ID</sup>,  
M.H. Schmitt<sup>ID</sup>, A. Taliercio<sup>ID</sup>, M. Velasco

Northwestern University, Evanston, IL, USA

G. Agarwal<sup>ID</sup>, R. Band<sup>ID</sup>, R. Bucci, S. Castells<sup>ID</sup>, A. Das<sup>ID</sup>, R. Goldouzian<sup>ID</sup>, M. Hildreth<sup>ID</sup>,  
K.W. Ho<sup>ID</sup>, K. Hurtado Anampa<sup>ID</sup>, T. Ivanov<sup>ID</sup>, C. Jessop<sup>ID</sup>, K. Lannon<sup>ID</sup>, J. Lawrence<sup>ID</sup>,  
N. Loukas<sup>ID</sup>, L. Lutton<sup>ID</sup>, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley<sup>ID</sup>, C. Mcgrady<sup>ID</sup>,  
C. Moore<sup>ID</sup>, Y. Musienko<sup>ID</sup>,<sup>17</sup> H. Nelson<sup>ID</sup>, M. Osherson<sup>ID</sup>, A. Piccinelli<sup>ID</sup>, R. Ruchti<sup>ID</sup>,  
A. Townsend<sup>ID</sup>, Y. Wan, M. Wayne<sup>ID</sup>, H. Yockey, M. Zarucki<sup>ID</sup>, L. Zygala<sup>ID</sup>

University of Notre Dame, Notre Dame, IN, USA

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

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

F.M. Addesa <sup>id</sup>, H. Bouchamaoui <sup>id</sup>, P. Das <sup>id</sup>, G. Dezoort <sup>id</sup>, P. Elmer <sup>id</sup>, A. Frankenthal <sup>id</sup>,  
B. Greenberg <sup>id</sup>, N. Haubrich <sup>id</sup>, G. Kopp <sup>id</sup>, S. Kwan <sup>id</sup>, D. Lange <sup>id</sup>, A. Loeliger <sup>id</sup>,  
D. Marlow <sup>id</sup>, I. Ojalvo <sup>id</sup>, J. Olsen <sup>id</sup>, A. Shevelev <sup>id</sup>, D. Stickland <sup>id</sup>, C. Tully <sup>id</sup>

*Princeton University, Princeton, NJ, USA*

S. Malik <sup>id</sup>

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

A.S. Bakshi <sup>id</sup>, V.E. Barnes <sup>id</sup>, S. Chandra <sup>id</sup>, R. Chawla <sup>id</sup>, S. Das <sup>id</sup>, A. Gu <sup>id</sup>, L. Gutay,  
M. Jones <sup>id</sup>, A.W. Jung <sup>id</sup>, D. Kondratyev <sup>id</sup>, A.M. Koshy, M. Liu <sup>id</sup>, G. Negro <sup>id</sup>,  
N. Neumeister <sup>id</sup>, G. Paspalaki <sup>id</sup>, S. Piperov <sup>id</sup>, V. Scheurer, J.F. Schulte <sup>id</sup>, M. Stojanovic <sup>id</sup>,  
J. Thieman <sup>id</sup>, A.K. Viridi <sup>id</sup>, F. Wang <sup>id</sup>, W. Xie <sup>id</sup>

*Purdue University, West Lafayette, IN, USA*

J. Dolen <sup>id</sup>, N. Parashar <sup>id</sup>, A. Pathak <sup>id</sup>

*Purdue University Northwest, Hammond, IN, USA*

D. Acosta <sup>id</sup>, T. Carnahan <sup>id</sup>, K.M. Ecklund <sup>id</sup>, P.J. Fernández Manteca <sup>id</sup>, S. Freed, P. Gardner,  
F.J.M. Geurts <sup>id</sup>, W. Li <sup>id</sup>, O. Miguel Colin <sup>id</sup>, B.P. Padley <sup>id</sup>, R. Redjimi, J. Rotter <sup>id</sup>,  
E. Yigitbasi <sup>id</sup>, Y. Zhang <sup>id</sup>

*Rice University, Houston, TX, USA*

A. Bodek <sup>id</sup>, P. de Barbaro <sup>id</sup>, R. Demina <sup>id</sup>, J.L. Dulemba <sup>id</sup>, C. Fallon, A. Garcia-Bellido <sup>id</sup>,  
O. Hindrichs <sup>id</sup>, A. Khukhunaishvili <sup>id</sup>, N. Parmar, P. Parygin <sup>id,34</sup>, E. Popova <sup>id,34</sup>, R. Taus <sup>id</sup>,  
G.P. Van Onsem <sup>id</sup>

*University of Rochester, Rochester, NY, USA*

K. Goulios <sup>id</sup>

*The Rockefeller University, New York, NY, USA*

B. Chiarito, J.P. Chou <sup>id</sup>, Y. Gershtein <sup>id</sup>, E. Halkiadakis <sup>id</sup>, A. Hart <sup>id</sup>, M. Heindl <sup>id</sup>,  
D. Jaroslawski <sup>id</sup>, O. Karacheban <sup>id,31</sup>, I. Laflotte <sup>id</sup>, A. Lath <sup>id</sup>, R. Montalvo, K. Nash,  
H. Routray <sup>id</sup>, S. Salur <sup>id</sup>, S. Schnetzer, S. Somalwar <sup>id</sup>, R. Stone <sup>id</sup>, S.A. Thayil <sup>id</sup>, S. Thomas,  
J. Vora <sup>id</sup>, H. Wang <sup>id</sup>

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

H. Acharya, D. Ally <sup>id</sup>, A.G. Delannoy <sup>id</sup>, S. Fiorendi <sup>id</sup>, S. Higginbotham <sup>id</sup>, T. Holmes <sup>id</sup>,  
A.R. Kanuganti <sup>id</sup>, N. Karunaratna <sup>id</sup>, L. Lee <sup>id</sup>, E. Nibigira <sup>id</sup>, S. Spanier <sup>id</sup>

*University of Tennessee, Knoxville, TN, USA*

D. Aebi <sup>id</sup>, M. Ahmad <sup>id</sup>, O. Bouhali <sup>id,96</sup>, M. Dalchenko <sup>id</sup>, R. Eusebi <sup>id</sup>, J. Gilmore <sup>id</sup>,  
T. Huang <sup>id</sup>, T. Kamon <sup>id,97</sup>, H. Kim <sup>id</sup>, S. Luo <sup>id</sup>, S. Malhotra, R. Mueller <sup>id</sup>, D. Overton <sup>id</sup>,  
D. Rathjens <sup>id</sup>, A. Safonov <sup>id</sup>

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

N. Akchurin <sup>id</sup>, J. Damgov <sup>id</sup>, V. Hegde <sup>id</sup>, A. Hussain <sup>id</sup>, Y. Kazhykarim, K. Lamichhane <sup>id</sup>,  
S.W. Lee <sup>id</sup>, A. Mankel <sup>id</sup>, T. Peltola <sup>id</sup>, I. Volobouev <sup>id</sup>, A. Whitbeck <sup>id</sup>



Texas Tech University, Lubbock, TX, USA

E. Appelt<sup>1b</sup>, S. Greene, A. Gurrola<sup>1b</sup>, W. Johns<sup>1b</sup>, R. Kunnawalkam Elayavalli<sup>1b</sup>, A. Melo<sup>1b</sup>,  
F. Romeo<sup>1b</sup>, P. Sheldon<sup>1b</sup>, S. Tuo<sup>1b</sup>, J. Velkovska<sup>1b</sup>, J. Viinikainen<sup>1b</sup>

Vanderbilt University, Nashville, TN, USA

B. Cardwell<sup>1b</sup>, B. Cox<sup>1b</sup>, J. Hakala<sup>1b</sup>, R. Hirosky<sup>1b</sup>, A. Ledovsky<sup>1b</sup>, C. Neu<sup>1b</sup>,  
C.E. Perez Lara<sup>1b</sup>

University of Virginia, Charlottesville, VA, USA

P.E. Karchin<sup>1b</sup>

Wayne State University, Detroit, MI, USA

A. Aravind, S. Banerjee<sup>1b</sup>, K. Black<sup>1b</sup>, T. Bose<sup>1b</sup>, S. Dasu<sup>1b</sup>, I. De Bruyn<sup>1b</sup>, P. Everaerts<sup>1b</sup>,  
C. Galloni, H. He<sup>1b</sup>, M. Herndon<sup>1b</sup>, A. Herve<sup>1b</sup>, C.K. Koraka<sup>1b</sup>, A. Lanaro, R. Loveless<sup>1b</sup>,  
J. Madhusudanan Sreekala<sup>1b</sup>, A. Mallampalli<sup>1b</sup>, A. Mohammadi<sup>1b</sup>, S. Mondal, G. Parida<sup>1b</sup>,  
D. Pinna, A. Savin, V. Shang<sup>1b</sup>, V. Sharma<sup>1b</sup>, W.H. Smith<sup>1b</sup>, D. Teague, H.F. Tsoi<sup>1b</sup>,  
W. Vetens<sup>1b</sup>, A. Warden<sup>1b</sup>

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev<sup>1b</sup>, V. Andreev<sup>1b</sup>, Yu. Andreev<sup>1b</sup>, T. Aushev<sup>1b</sup>, M. Azarkin<sup>1b</sup>, I. Azhgirey<sup>1b</sup>,  
A. Babaev<sup>1b</sup>, A. Belyaev<sup>1b</sup>, V. Blinov<sup>98</sup>, E. Boos<sup>1b</sup>, V. Borshch<sup>1b</sup>, D. Budkouski<sup>1b</sup>,  
V. Bunichev<sup>1b</sup>, M. Chadeeva<sup>1b,98</sup>, V. Chekhovsky, R. Chistov<sup>1b,98</sup>, A. Dermenev<sup>1b</sup>,  
T. Dimova<sup>1b,98</sup>, D. Druzhkin<sup>1b,99</sup>, M. Dubinin<sup>1b,89</sup>, L. Dudko<sup>1b</sup>, G. Gavrilov<sup>1b</sup>, V. Gavrilov<sup>1b</sup>,  
S. Gninenko<sup>1b</sup>, V. Golovtsov<sup>1b</sup>, N. Golubev<sup>1b</sup>, I. Golutvin<sup>1b</sup>, I. Gorbunov<sup>1b</sup>, A. Gribushin<sup>1b</sup>,  
Y. Ivanov<sup>1b</sup>, V. Kachanov<sup>1b</sup>, V. Karjavine<sup>1b</sup>, A. Karneyeu<sup>1b</sup>, V. Kim<sup>1b,98</sup>, M. Kirakosyan,  
D. Kirpichnikov<sup>1b</sup>, M. Kirsanov<sup>1b</sup>, V. Klyukhin<sup>1b</sup>, O. Kodolova<sup>1b,100</sup>, D. Konstantinov<sup>1b</sup>,  
V. Korenkov<sup>1b</sup>, A. Kozyrev<sup>1b,98</sup>, N. Krasnikov<sup>1b</sup>, A. Lanev<sup>1b</sup>, P. Levchenko<sup>1b,101</sup>,  
N. Lychkovskaya<sup>1b</sup>, V. Makarenko<sup>1b</sup>, A. Malakhov<sup>1b</sup>, V. Matveev<sup>1b,98</sup>, V. Murzin<sup>1b</sup>,  
A. Nikitenko<sup>1b,102,100</sup>, S. Obraztsov<sup>1b</sup>, V. Oreshkin<sup>1b</sup>, V. Palichik<sup>1b</sup>, V. Perelygin<sup>1b</sup>, M. Perfilov,  
S. Petrushanko<sup>1b</sup>, S. Polikarpov<sup>1b,98</sup>, V. Popov<sup>1b</sup>, O. Radchenko<sup>1b,98</sup>, R. Ryutin, M. Savina<sup>1b</sup>,  
V. Savrin<sup>1b</sup>, V. Shalaev<sup>1b</sup>, S. Shmatov<sup>1b</sup>, S. Shulha<sup>1b</sup>, Y. Skovpen<sup>1b,98</sup>, S. Slabospitskii<sup>1b</sup>,  
V. Smirnov<sup>1b</sup>, A. Snigirev<sup>1b</sup>, D. Sosnov<sup>1b</sup>, V. Sulimov<sup>1b</sup>, E. Tcherniaev<sup>1b</sup>, A. Terkulov<sup>1b</sup>,  
O. Teryaev<sup>1b</sup>, I. Tlisova<sup>1b</sup>, A. Toropin<sup>1b</sup>, L. Uvarov<sup>1b</sup>, A. Uzunian<sup>1b</sup>, A. Volkov, A. Vorobyev<sup>†</sup>,  
N. Voytishin<sup>1b</sup>, B.S. Yuldashev<sup>103</sup>, A. Zarubin<sup>1b</sup>, I. Zhizhin<sup>1b</sup>, A. Zhokin<sup>1b</sup>

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

<sup>†</sup> 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 Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

<sup>4</sup> Also at Ghent University, Ghent, Belgium.

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

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

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

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

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

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

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

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

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

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

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

<sup>16</sup> Also at University of Latvia (LU), Riga, Latvia.

<sup>17</sup> Also at an institute or an international laboratory covered by a cooperation agreement with CERN.

<sup>18</sup> Also at Cairo University, Cairo, Egypt.

- <sup>19</sup> Also at Suez University, Suez, Egypt.
- <sup>20</sup> Now at British University in Egypt, Cairo, Egypt.
- <sup>21</sup> Also at Birla Institute of Technology, Mesra, Mesra, India.
- <sup>22</sup> Also at Purdue University, West Lafayette, Indiana, USA.
- <sup>23</sup> Also at Université de Haute Alsace, Mulhouse, France.
- <sup>24</sup> Also at Department of Physics, Tsinghua University, Beijing, China.
- <sup>25</sup> Also at The University of the State of Amazonas, Manaus, Brazil.
- <sup>26</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- <sup>27</sup> Also at University of Hamburg, Hamburg, Germany.
- <sup>28</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- <sup>29</sup> Also at Isfahan University of Technology, Isfahan, Iran.
- <sup>30</sup> Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
- <sup>31</sup> Also at Brandenburg University of Technology, Cottbus, Germany.
- <sup>32</sup> Also at Forschungszentrum Jülich, Juelich, Germany.
- <sup>33</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- <sup>34</sup> Now at an institute or an international laboratory covered by a cooperation agreement with CERN.
- <sup>35</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- <sup>36</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- <sup>37</sup> Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania.
- <sup>38</sup> Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
- <sup>39</sup> Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>40</sup> Also at Punjab Agricultural University, Ludhiana, India.
- <sup>41</sup> Also at University of Visva-Bharati, Santiniketan, India.
- <sup>42</sup> Also at Indian Institute of Science (IISc), Bangalore, India.
- <sup>43</sup> Also at IIT Bhubaneswar, Bhubaneswar, India.
- <sup>44</sup> Also at Institute of Physics, Bhubaneswar, India.
- <sup>45</sup> Also at University of Hyderabad, Hyderabad, India.
- <sup>46</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- <sup>47</sup> Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
- <sup>48</sup> Also at Sharif University of Technology, Tehran, Iran.
- <sup>49</sup> Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- <sup>50</sup> Also at Helwan University, Cairo, Egypt.
- <sup>51</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- <sup>52</sup> Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- <sup>53</sup> Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- <sup>54</sup> Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
- <sup>55</sup> Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- <sup>56</sup> Also at Ain Shams University, Cairo, Egypt.
- <sup>57</sup> Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy.
- <sup>58</sup> Also at Riga Technical University, Riga, Latvia.
- <sup>59</sup> Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- <sup>60</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- <sup>61</sup> Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- <sup>62</sup> Also at Saegis Campus, Nugegoda, Sri Lanka.
- <sup>63</sup> Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- <sup>64</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>65</sup> Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- <sup>66</sup> Also at Universität Zürich, Zurich, Switzerland.
- <sup>67</sup> Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- <sup>68</sup> Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- <sup>69</sup> Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- <sup>70</sup> Also at Konya Technical University, Konya, Turkey.
- <sup>71</sup> Also at Izmir Bakircay University, Izmir, Turkey.
- <sup>72</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>73</sup> Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- <sup>74</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>75</sup> Also at Milli Savunma University, Istanbul, Turkey.
- <sup>76</sup> Also at Kafkas University, Kars, Turkey.
- <sup>77</sup> Now at stanbul Okan University, Istanbul, Turkey.
- <sup>78</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>79</sup> Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- <sup>80</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>81</sup> Also at Vrije Universiteit Brussel, Brussel, Belgium.
- <sup>82</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>83</sup> Also at University of Bristol, Bristol, United Kingdom.
- <sup>84</sup> Also at IPPP Durham University, Durham, United Kingdom.
- <sup>85</sup> Also at Monash University, Faculty of Science, Clayton, Australia.
- <sup>86</sup> Also at Università di Torino, Torino, Italy.
- <sup>87</sup> Also at Bethel University, St. Paul, Minnesota, USA.
- <sup>88</sup> Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- <sup>89</sup> Also at California Institute of Technology, Pasadena, California, USA.
- <sup>90</sup> Also at United States Naval Academy, Annapolis, Maryland, USA.
- <sup>91</sup> Also at Bingol University, Bingol, Turkey.
- <sup>92</sup> Also at Georgian Technical University, Tbilisi, Georgia.
- <sup>93</sup> Also at Sinop University, Sinop, Turkey.
- <sup>94</sup> Also at Erciyes University, Kayseri, Turkey.
- <sup>95</sup> Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
- <sup>96</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>97</sup> Also at Kyungpook National University, Daegu, Korea.
- <sup>98</sup> Also at another institute or international laboratory covered by a cooperation agreement with CERN.

<sup>99</sup> Also at Universiteit Antwerpen, Antwerpen, Belgium.

<sup>100</sup> Also at Yerevan Physics Institute, Yerevan, Armenia.

<sup>101</sup> Also at Northeastern University, Boston, Massachusetts, USA.

<sup>102</sup> Also at Imperial College, London, United Kingdom.

<sup>103</sup> Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.