

## MIT Open Access Articles

*Search for a vector-like quark  $T \rightarrow tH$  via the diphoton decay mode of the Higgs boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** Journal of High Energy Physics. 2023 Sep 11;2023(9):57

**As Published:** [https://doi.org/10.1007/JHEP09\(2023\)057](https://doi.org/10.1007/JHEP09(2023)057)

**Publisher:** Springer Berlin Heidelberg

**Persistent URL:** <https://hdl.handle.net/1721.1/152193>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of use:** Creative Commons Attribution



RECEIVED: February 24, 2023

REVISED: July 31, 2023

ACCEPTED: August 22, 2023

PUBLISHED: September 11, 2023

# Search for a vector-like quark $T' \rightarrow tH$ via the diphoton decay mode of the Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

---



## The CMS collaboration

*E-mail:* [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch)

**ABSTRACT:** A search for the electroweak production of a vector-like quark  $T'$ , decaying to a top quark and a Higgs boson is presented. The search is based on a sample of proton-proton collision events recorded at the LHC at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . This is the first  $T'$  search that exploits the Higgs boson decay to a pair of photons. For narrow isospin singlet  $T'$  states with masses up to 1.1 TeV, the excellent diphoton invariant mass resolution of 1–2% results in an increased sensitivity compared to previous searches based on the same production mechanism. The electroweak production of a  $T'$  quark with mass up to 960 GeV is excluded at 95% confidence level, assuming a coupling strength  $\kappa_T = 0.25$  and a relative decay width  $\Gamma/M_{T'} < 5\%$ .

**KEYWORDS:** Beyond Standard Model, Hadron-Hadron Scattering, Top Physics

ARXIV EPRINT: [2302.12802](https://arxiv.org/abs/2302.12802)

---

## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>The CMS detector</b>	<b>3</b>
<b>3</b>	<b>Simulated samples</b>	<b>3</b>
<b>4</b>	<b>Event selection</b>	<b>4</b>
<b>5</b>	<b>Discrimination between signal and background</b>	<b>5</b>
<b>6</b>	<b>Signal and background modeling</b>	<b>8</b>
<b>7</b>	<b>Systematic uncertainties</b>	<b>9</b>
<b>8</b>	<b>Results</b>	<b>9</b>
<b>9</b>	<b>Summary</b>	<b>12</b>
	<b>The CMS collaboration</b>	<b>18</b>

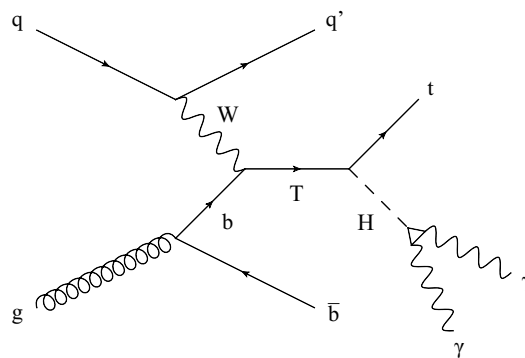
---

## 1 Introduction

The Higgs boson (H) was discovered by the ATLAS and CMS Collaborations in 2012 [1–3]. With this discovery, the standard model (SM) is now in principle complete as a low-energy effective theory, describing all known fundamental particles and their interactions. However, the stability of the Higgs boson mass at the electroweak (EW) scale remains unexplained: as the SM is extrapolated to high energies, quantum loop corrections to the Higgs boson self-energy quadratically diverge [4]. Various theories beyond the SM predict additional particles that can affect these quantum corrections to the Higgs boson mass. One such new particle is a vector-like quark (VLQ).

The VLQs are hypothetical spin- $\frac{1}{2}$ , colored particles whose left- and right-handed components transform in the same way under the SM gauge group. Therefore, unlike the chiral quarks in the SM, their masses are not generated by a Yukawa coupling to the Higgs boson and have a lower contribution to the production cross section of the Higgs boson. A variety of new physics models, such as composite Higgs models [5–9], little Higgs models [10–12], and models with a warped extra dimension [13], incorporate VLQs which provide solutions to the above mentioned Higgs boson mass stability problem. In minimal models, the VLQs may only exist as electroweak singlets, denoted as  $T'$  and  $B'$ , and doublets, carrying respective electric charges of  $2/3e$  and  $-1/3e$ ; further doublets and triplets may also exist where the VLQs can have exotic charges.

Here, we present a search for the production of a vector-like top quark partner  $T'$  at the LHC. These could either be pair-produced by the strong interaction or singly-produced by the electroweak one. For pair production through the strong interaction, the available



**Figure 1.** Leading-order Feynman diagram for single  $T'$  production in  $Wb$  fusion and its subsequent decay into  $tH$  ( $H \rightarrow \gamma\gamma$ ).

parton level center-of-mass energy is shared between the two heavy particles. In contrast, in the EW production of a single  $T'$ , a larger kinematic phase space is available and heavier masses can, in principle, be probed. The  $T'$  quark can couple to SM quarks and charged or neutral bosons, resulting in decays to  $bW$ ,  $tZ$ , and  $tH$  channels. For the EW production of an isospin singlet  $T'$  VLQ, considered in this paper, the  $T'$  branching fractions ( $\mathcal{B}$ ) are assumed to be 50, 25, and 25%, respectively, for  $bW$ ,  $tZ$ , and  $tH$  decays [14]. The leading order Feynman diagram for the electroweak  $T'$  production along with the  $H \rightarrow \gamma\gamma$  decay is shown in figure 1. The EW production cross section depends explicitly on the couplings of the VLQ to third-generation quarks [14, 15], henceforth referred as  $\kappa_T$ . Here, the coupling  $\kappa_T$  can significantly change based on the choice of the VLQ mass and width. In this study, the VLQ production and decay are parametrized using the narrow width approximation (NWA) [16], where the  $T'$  natural width ( $\Gamma$ ) is approximately 1% relative to its mass ( $M_{T'}$ ). The NWA is valid up to  $\Gamma/M_{T'} \approx 10\text{--}15\%$ , beyond which the large width of  $T'$  and its interference with the SM background become important [15, 17]. However, the sensitivity of this analysis extends up to  $\Gamma/M_{T'} \approx 5\%$ , which roughly corresponds to the experimental resolution of  $M_{T'}$ .

This search is based on the  $pp$  collision data recorded with the CMS detector during LHC operations from 2016–2018, corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . The study focuses on the EW production of  $T'$  in proton-proton ( $pp$ ) collisions at  $\sqrt{s} = 13 \text{ TeV}$ ,  $pp \rightarrow T' b q$ , followed by the decay of  $T' \rightarrow tH$ , where the Higgs boson decays into a pair of photons ( $H \rightarrow \gamma\gamma$ ). The leptonic and hadronic decay modes of the top quark are treated separately to achieve the best possible search sensitivity. It is the first  $T'$  search by the LHC experiments in  $H \rightarrow \gamma\gamma$  channel. The ATLAS and CMS Collaborations have previously performed searches for strong and EW production of VLQs at  $\sqrt{s} = 13 \text{ TeV}$  [18–23]. The most recent results on pair production [22, 23] exclude  $T'$  masses below 1.48 TeV at 95% confidence level (CL), assuming branching fractions of 50, 25 and 25% for  $bW$ ,  $tZ$ , and  $tH$  decays, respectively.

These previous searches used the reconstructed  $T'$  invariant mass or transverse mass as the main observable. The present analysis exploits the excellent resolution of 1–2% for the

reconstructed H mass in the diphoton decay channel to search for a signal characterized by a peak at the H mass above the falling diphoton mass ( $m_{\gamma\gamma}$ ) continuum. The statistical methodologies and the non-Higgs background determination techniques are identical to the ones used in the SM  $H \rightarrow \gamma\gamma$  measurements [24].

## 2 The CMS detector

The CMS apparatus [25] is a multipurpose, nearly hermetic detector, designed to trigger on [26, 27] and identify electrons, muons, photons, and charged and neutral hadrons [28–30]. A global “particle-flow” (PF) algorithm [31] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker, by the crystal electromagnetic calorimeters (ECAL), and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The first level of the trigger system, composed of special hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a time interval of less than  $4 \mu\text{s}$ . The second level, known as the high-level trigger, consists of a farm of processors that further decreases the event rate from around 100 kHz to less than 1 kHz [27], running a version of the full event reconstruction software optimized for fast processing. 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. [32]. The 2017 and 2018 data sets benefit from the upgrade of the pixel tracking detector in the winter of 2016–2017 [33], improving the acceptance, redundancy, and resolution. The updated tracker greatly enhances the performance of b jet identification [34], which is essential to analysis and online event selection.

## 3 Simulated samples

The data analysis strategy has been optimized using Monte Carlo (MC) simulation, where specific pp event generators and a GEANT4-based detector simulation [35] have been utilized. The signal process,  $pp \rightarrow T'(\rightarrow tH)bq$  [15], is generated to leading order and with  $\Gamma/M_{T'} \approx 1\%$ . Samples of events are generated with MADGRAPH5\_AMC@NLO 2.3.3 [36, 37] at ten  $M_{T'}$  points, from 600 to 1200 GeV, using NNPDF3.1 [38] as the parton distribution function (PDF) set. The Higgs boson and top quark masses are set to 125.0 and 172.5 GeV, respectively. The SM background processes contributing to the  $m_{\gamma\gamma}$  spectrum are categorized in two types: SM Higgs boson (SMH) background and SM nonresonant background (NRB). The MADGRAPH5\_AMC@NLO generator has been utilized to simulate the SM Higgs boson production, including gluon fusion (ggH) [39], vector-boson fusion (VBF) [40], production in association with top quarks (tH, t $\bar{t}$ H) [41], or with a vector boson (VH) [42] at next-to-leading order in quantum chromodynamics (QCD). The total cross sections and branching fractions, as recommended by the LHC Higgs boson cross section working group [43], have been adopted for the SMH production processes. The background processes,  $t + X$ ,

$t\bar{t} + X$ ,  $W\gamma$ , and  $Z\gamma$ , are simulated with MADGRAPH5\_aMC@NLO, whereas diboson events are produced at the leading order with PYTHIA 8.205 [44]. The nonresonant diphoton samples are simulated with SHERPA 2.2.4 [45] which includes tree-level processes with up to three additional partons, as well as box diagrams. For all MC samples generated with MADGRAPH5\_aMC@NLO, the parton showering and hadronization have been implemented via PYTHIA, with the underlying event tune CUETP8M1 [46] and CP5 [47] respectively for the 2016 and the 2017–2018 datasets. The nonresonant background samples are used to train a multivariate analysis (MVA) discriminant, while the corresponding yields are extracted using sidebands, defined by  $m_{\gamma\gamma} < 115$  or  $m_{\gamma\gamma} > 135$  GeV, in data.

## 4 Event selection

The online event selection of the diphoton triggers requires at least two photons with asymmetric conditions on the photon transverse momenta:  $p_T(\gamma_1) > 30$  GeV and  $p_T(\gamma_2) > 18$  or  $>22$  GeV, depending on the data taking period. Moreover, requirements [24] on the isolation in the calorimeter and on the shape of the electromagnetic shower are imposed. The  $m_{\gamma\gamma}$  is required to be above 90 GeV, assuming both photons originate from the primary vertex.

For efficient selection of photons associated with the primary vertex, a separate MVA based on the isolation and photon shower shape variables, called the photon ‘ID MVA’ [24], is used in the offline event selection. Events are selected with at least two ID MVA selected photons within the ECAL and the tracker fiducial region (pseudorapidity  $|\eta| < 2.5$ , but excluding the ECAL barrel-endcap transition region,  $1.44 < |\eta| < 1.57$ ). The photon pairs are further required to satisfy the criteria:  $100 < m_{\gamma\gamma} < 180$  GeV,  $p_T(\gamma_1)/m_{\gamma\gamma} > 1/3$ , and  $p_T(\gamma_2)/m_{\gamma\gamma} > 1/4$ ; in the case of multiple diphoton pairs, the one with highest  $p_T(\gamma\gamma)$  is chosen [24].

Reconstructed particles are used to form jets using the anti- $k_T$  algorithm with a distance parameter of 0.4 [48, 49], and to estimate the missing transverse momentum ( $p_T^{\text{miss}}$ ) [50–52]. This search uses energy-corrected jet candidates with  $p_T > 25$  GeV and  $|\eta| < 4.5$ , with stringent requirements imposed to remove spurious jets [53]. Jets must be separated from photons and leptons in the event, with  $\Delta R(j, \gamma) \equiv \sqrt{(\eta_\gamma - \eta_j)^2 + (\phi_\gamma - \phi_j)^2} > 0.4$  and  $\Delta R(j, \ell) > 0.4$ , where  $\phi$  is the azimuthal angle in radians. For the identification (tagging) of jets from b quark hadronization and decay (b jets), the deep neural network based DEEPCSV algorithm [54] is applied, for jets with  $|\eta| < 2.5$ . This search utilizes the b-tagged jets with DEEPCSV scores exceeding a minimum value corresponding to a misidentification probability of 10% for light quark and gluon jets, and to an identification efficiency for b jets of 75–90% depending on the jet  $p_T$  [54].

Isolated leptons with  $p_T > 10$  GeV and within appropriate fiducial volumes ( $|\eta| < 1.44$  or  $1.57 < |\eta| < 2.40$ , and  $|\eta| < 2.40$ , respectively, for electrons and muons) are considered in this search. These leptons are further required to be separated from any photon or jet considered in the analysis:  $\Delta R(\ell, \gamma) > 0.4$  and  $\Delta R(\ell, j) > 0.4$ . Neutrinos are accounted for through the reconstruction of  $p_T^{\text{miss}}$ . The  $\vec{p}_T^{\text{miss}}$  vector is computed as the negative vector

$p_T$  sum of all the PF candidates in an event [52]. The  $\bar{p}_T^{\text{miss}}$  is modified to account for corrections to the energy scale of the reconstructed jets in the event.

As mentioned above, this search categorizes events based on the leptonic or hadronic decays of the top quark. Events containing a pair of photons and at least one electron or muon are defined as the leptonic category; those with a pair of photons and no lepton form the hadronic category. To target the  $t \rightarrow bW$  decay, at least one b-tagged jet is required in the leptonic channel, and three jets, of which at least one is b tagged, are required in the hadronic channel. Events with two leptons from the Drell–Yan processes contribute to the background in the leptonic category and are rejected by requiring  $|m_{ee/\mu\mu} - M_Z| > 5 \text{ GeV}$ . In the leptonic category, the QCD,  $\gamma$  + jets, and  $\gamma\gamma$  + jets processes constitute 25% of the total background yield. In the hadronic category, however, these background contributions amount to 95% of the total. Owing to imperfect MC modeling of the  $\gamma$  + jets and multi-jets processes, those backgrounds are estimated from data in a phase space region defined by inverting the selection on the photon ID MVA, which consists of a sample of events with a significant contribution from jets with at least one of them misidentified as a photon. For each of these events, the photon ID MVA value of the photon candidate failing the ID MVA selection is substituted with a value generated from the MC distribution of photon ID MVA for misidentified jets passing the photon ID requirement. This is the same procedure used in the previous  $H \rightarrow \gamma\gamma$  related studies [55, 56]. Since the simulation of the  $\gamma\gamma$  + jets process is performed only at leading order [24], additional normalization factors accounting for higher orders are derived from a simultaneous template fit to the photon ID MVAs. The normalization factors are then applied to the control samples in data ( $\gamma$  + jets and multi-jets) and the  $\gamma\gamma$  + jets samples when using those samples to provide the background in the MVA training. However, these normalization factors have no role in creating the final background model of the analysis.

## 5 Discrimination between signal and background

At this level of selection,  $t\bar{t}H$  with  $H \rightarrow \gamma\gamma$  is the dominant background among the SMH production processes for both categories, since it also leads to a peak in the  $m_{\gamma\gamma}$  spectrum at the Higgs boson mass. The  $m_{\gamma\gamma}$  spectrum from  $T'$  signal also peaks at  $M_H$  due to  $T' \rightarrow tH$  decay. To separate the overlapping  $T'$  signal from the SMH background processes, MVA discriminants based on boosted decision trees (BDTs) are implemented [57] separately for each category (BDT-SMH). Furthermore, an additional BDT (BDT-NRB) is trained to suppress the sizeable nonresonant background contributions in the hadronic category. In the leptonic channel, discrimination against the background exploits characteristic features of the kinematic properties of each of the objects contributing to the signal (two prompt photons, b jet, lepton and neutrino) and on energy and momentum conservation. Similarly for the hadronic channel, the input features of both BDT-SMH and BDT-NRB include the kinematic properties of the physics objects: photons, jets, diphotons, reconstructed top quark candidates, jet multiplicities,  $p_T^{\text{miss}}$ , b-tagging scores of jets from the DeepCSV algorithm, and the output of the photon ID MVA for both photons. In order to prevent a possible correlation between  $m_{\gamma\gamma}$  and the BDT score, the ratios  $p_T(\gamma_1)/m_{\gamma\gamma}$ ,  $p_T(\gamma_2)/m_{\gamma\gamma}$ ,

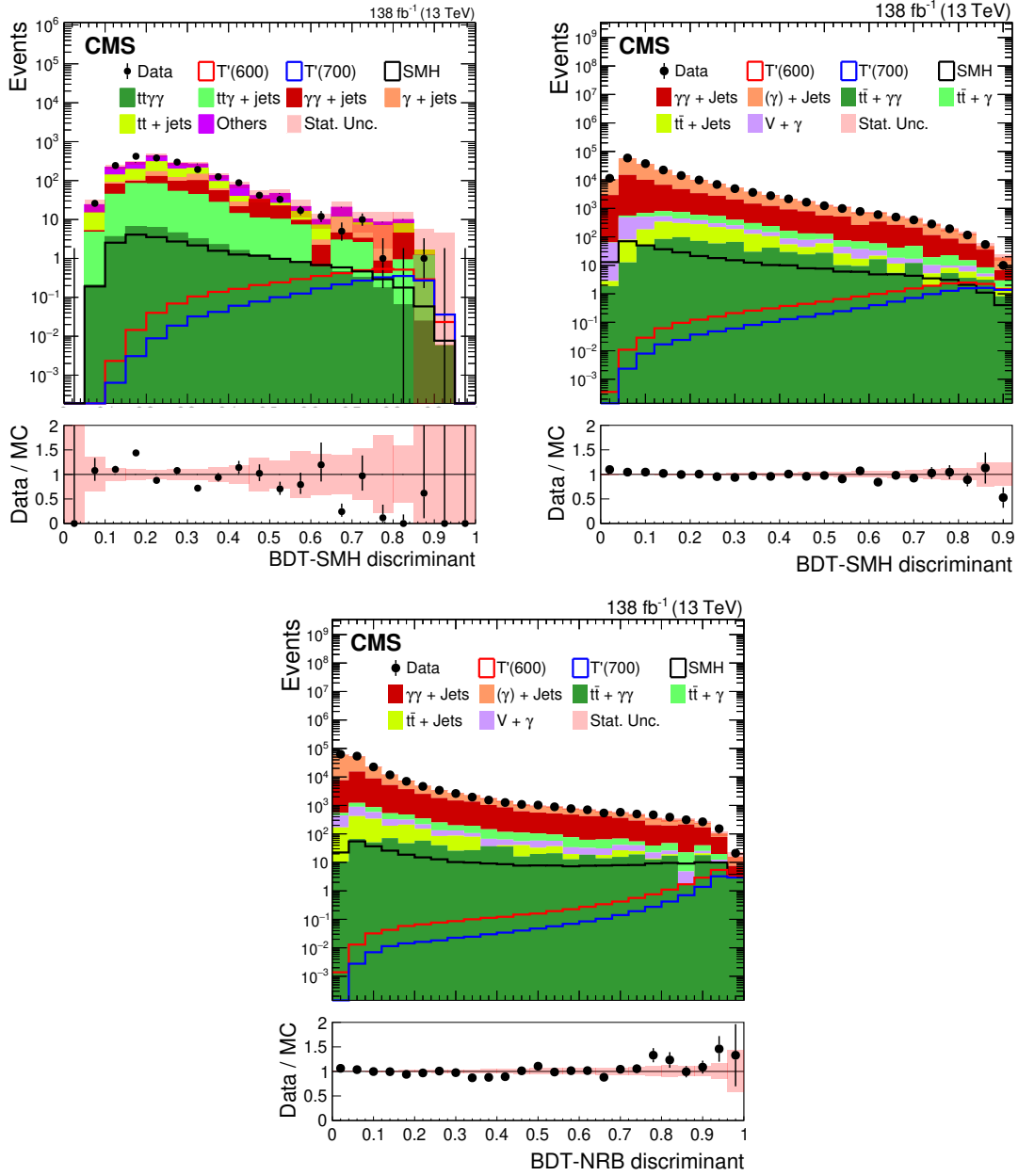


and  $p_T(\gamma\gamma)/m_{\gamma\gamma}$  are provided as input to the BDT training, rather than using  $m_{\gamma\gamma}$  directly. The linear correlation between the BDT score and  $m_{\gamma\gamma}$  is found to be less than 5% in all samples. As the kinematic distributions of the signal vary among different  $M_{T'}$  values, separate BDTs have been used in three  $M_{T'}$  ranges: 600–700, 700–1000, and 1000–1200 GeV. In the leptonic category, the trained BDT-SMH yields a signal efficiency of more than 75%, for a background efficiency of 10%. Similarly, in the hadronic category, the trained BDT-SMH and BDT-NRB yield a signal efficiency of more than 96% and 98%, respectively, for a background efficiency of 10%. Furthermore, each BDT output distribution of the hadronic and leptonic categories in the  $m_{\gamma\gamma}$  sideband region shows an overall statistical agreement between data and simulation with a  $\chi^2$  p-value of 5%. The fluctuations observed in some of the distributions are associated with a limited simulated sample size. Figure 2 shows the distribution of the well-separated BDT output scores for signal and background processes when the training is performed over the  $T'$  samples having masses between 600 and 700 GeV.

The kinematic properties of each Higgs boson candidate are always reconstructed from the momenta of the photons. However, the kinematic distributions of the top quark candidates are reconstructed differently for leptonic and hadronic channels; the leptonic channel uses constraints on the event  $p_T$  conservation and the W boson mass [58]; the hadronic channel uses the minimum  $\chi^2$  method [59] to choose the correct combination of jets. The reconstructed top quark mass is also used as one of the input variables for the BDTs in the hadronic channel. The candidate  $T'$  mass,  $m_{tH}$ , is reconstructed by combining the four-momenta of the top quark and the H candidates, with an overall experimental resolution of 5–7% in both leptonic and hadronic channels. To maximize the selection efficiency, the events considered by each optimized BDT are required to fall within a broad window in  $m_{tH}$  that extends beyond the range of  $M_{T'}$  for which that BDT was trained with.

The primary experimental observable for this search is the diphoton invariant mass,  $m_{\gamma\gamma}$ . Higgs bosons from both SM processes and  $T'$  decay are expected to peak on a smoothly falling  $m_{\gamma\gamma}$  distribution in the range  $100 < m_{\gamma\gamma} < 180$  GeV. The selection criteria on the BDT discriminants for the three different  $M_{T'}$  ranges, labelled I, II, III in table. 1, have been optimized to maximize signal sensitivity with respect to the background, separately for the leptonic and hadronic categories. For statistically robust modelling of the NRB from data, the optimization requires at least eight events in the signal sideband regions of  $m_{\gamma\gamma}$ . The  $m_{tH}$  window criterion is the same between leptonic and hadronic channels. The complete list of selection criteria on BDT score and the  $m_{tH}$  window are provided in table. 1. The expected yield of a  $T'$  for  $\kappa_T$  fixed at 0.2, nonresonant background, and the SM Higgs boson background processes within the signal region (SR),  $m_{\gamma\gamma} \in [115, 135]$  GeV, for each signal window are shown in the table. 2 together with the observed number of events in the SR.





**Figure 2.** The BDT output distributions for data, backgrounds and signal events in the leptonic and the hadronic categories: leptonic BDT trained against the SM Higgs boson backgrounds (upper left), hadronic BDT trained against the SM Higgs boson backgrounds (upper right), and hadronic BDT trained against the nonresonant background processes (lower). For the leptonic category, MC-estimated nonresonant backgrounds are normalized to the number of observed data events. For the hadronic category, the control samples in data have been adapted for  $\gamma$  + jets backgrounds, while all other MC samples are normalized to an integrated luminosity of 138 fb<sup>-1</sup>. The shaded region in the lower panels represents the statistical uncertainties of the different samples.

BDT	I	II	III
$M_{T'}(\text{GeV})$	[600, 700]	[700, 1000]	[1000, 1200]
Hadronic analysis			
BDT-NRB score	> 0.94	>0.96	>0.95
BDT-SMH score	>0.80	>0.80	>0.80
$m_{tH}$ window (GeV)	[480, 800]	[550, 1150]	[650, 1600]
Leptonic analysis			
BDT score	>0.60	>0.40	>0.40
$m_{tH}$ window (GeV)	[480, 800]	[550, 1150]	[650, 1600]

**Table 1.** Signal selection criteria for the three BDTs and  $m_{tH}$  windows.

BDT	$M_{T'}(\text{GeV})$	Leptonic yield				Hadronic yield			
		$T'$	Nonres. bkgd.	SM H bkgd.	Obs.	$T'$	Nonres. bkgd.	SM H bkgd.	Obs.
I	600	1.7				3.2			
	625	1.7				3.5			
	650	1.6	$11.0 \pm 9.0$	$1.3 \pm 0.1$	1	3.6	$1.6 \pm 0.9$	$1.8 \pm 0.1$	4
	675	1.6				3.7			
	700	1.5				3.6			
II	800	1.6				2.9			
	900	1.2	$19.0 \pm 14.4$	$2.3 \pm 0.1$	16	3.0	$7.3 \pm 4.0$	$2.0 \pm 0.1$	6
	1000	0.8				2.5			
III	1100	0.7	$14.4 \pm 13.7$	$1.4 \pm 0.1$	10	2.3	$9.0 \pm 5.3$	$2.4 \pm 0.2$	7
	1200	0.5				1.8			

**Table 2.** The expected yields of different processes in each signal window for events with a  $T'$  with mass in the range  $M_{T'} \in [600, 1200]$  GeV, and the observed number of events in the signal region  $m_{\gamma\gamma} \in [115, 135]$ . Here, the yields for the  $T'$  are for  $\kappa_T$  fixed at 0.2.

## 6 Signal and background modeling

Models of the signal and SMH background processes are obtained by fitting the  $m_{\gamma\gamma}$  distributions in simulation with a sum of at most five Gaussian functions, separately for each category.

The models used to describe the nonresonant background processes are extracted from the observed  $m_{\gamma\gamma}$  spectrum in the region  $m_{\gamma\gamma} \in [100, 180]$  GeV using a discrete profiling method [60]. This technique accounts for the systematic uncertainty in the background estimate associated with choosing a particular analytic function to describe the  $m_{\gamma\gamma}$  spectrum. The chosen functions are from a list of families of functions: exponentials, power laws,

polynomials, and Laurent series [60]. However, the degrees of freedom for these functions are decided in each case using a detailed  $\mathcal{F}$ -test [61] with a loose requirement on the goodness-of-fit.

## 7 Systematic uncertainties

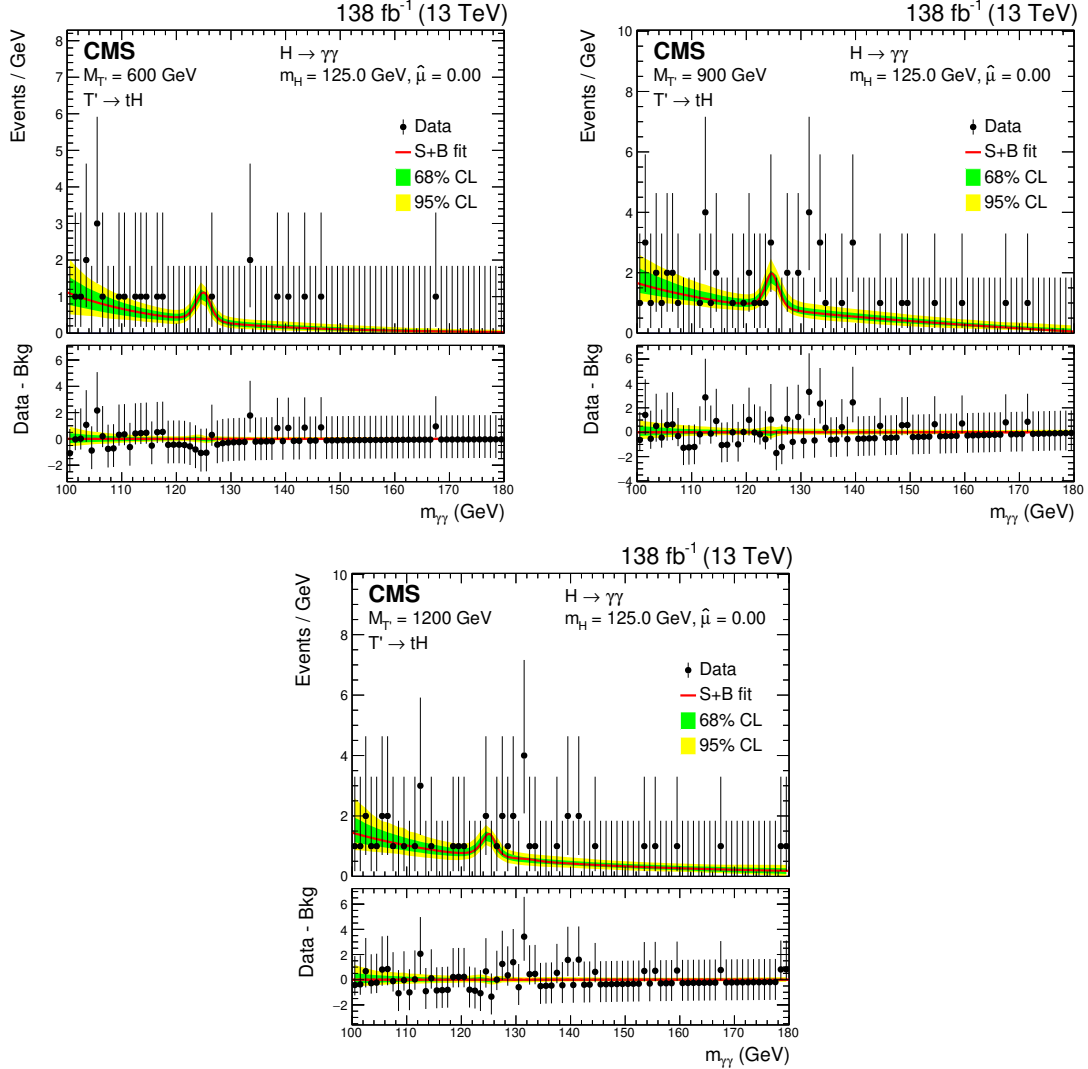
Systematic uncertainties that modify the  $m_{\gamma\gamma}$  distributions are incorporated in the signal shape and normalization as nuisance parameters. The dominant experimental uncertainties affecting the event yields and signal shape are those associated with: the integrated luminosity [62–64], the photon identification MVA ID score, the jet energy scale and resolution, the trigger efficiency, the dependence of the selection efficiency on photon shower-shape variables, the estimation of  $p_T^{\text{miss}}$ , the corrections to the photon energy scale and resolution, and the b jet identification efficiency.

In addition, theoretical uncertainties arise from the variations of the QCD renormalization and factorization scales involved in the cross section computation of the SM processes. The uncertainties that account for the limited knowledge of the PDFs and the  $H \rightarrow \gamma\gamma$  branching fractions are also included. The impact of each systematic uncertainty on the final signal strength ( $\mu = \sigma/\sigma_{\text{th}}$ ) is less than 5%, and the results are limited only by the statistical uncertainties.

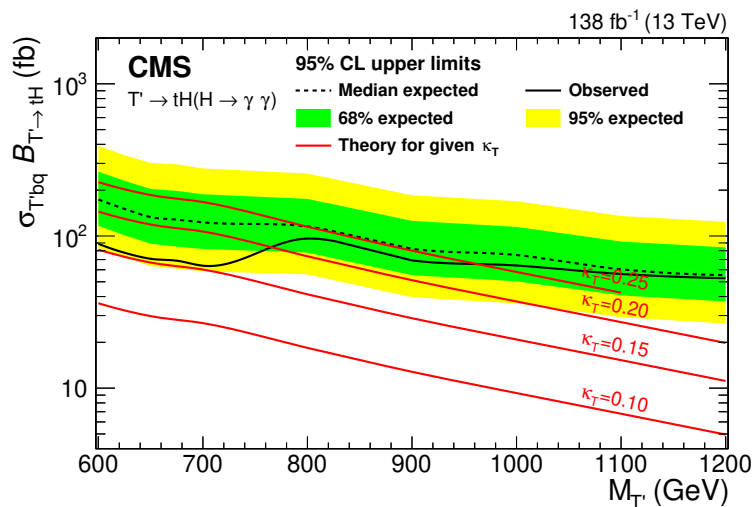
## 8 Results

The combined (leptonic and hadronic analyses) data distributions and the corresponding signal-plus-background model fits of the  $m_{\gamma\gamma}$  distribution are shown in figure 3 for  $M_{T'}$  values of 600, 900, and 1200 GeV. No statistically significant excesses above the SM backgrounds in any of the channels or mass ranges are observed. Upper limits on the signal strength modifiers  $\mu_{\text{obs}} = (\sigma)_{\text{obs}}/(\sigma)_{\text{th}}$  and  $\mu_{\text{exp}} = (\sigma)_{\text{exp}}/(\sigma)_{\text{th}}$ , are derived for different  $M_{T'}$ , using a maximum likelihood fit of the  $m_{\gamma\gamma}$  distributions, keeping the  $M_H$  parameter of the model fixed at 125 GeV. The expected and observed upper limits are estimated at the 95% CL based on the  $\text{CL}_s$  criterion [65, 66] using the asymptotic approximation [67, 68] for the test statistic. The results are verified with pseudoexperiments and are cross-checked with detailed bias studies on the parameter  $\mu$ .

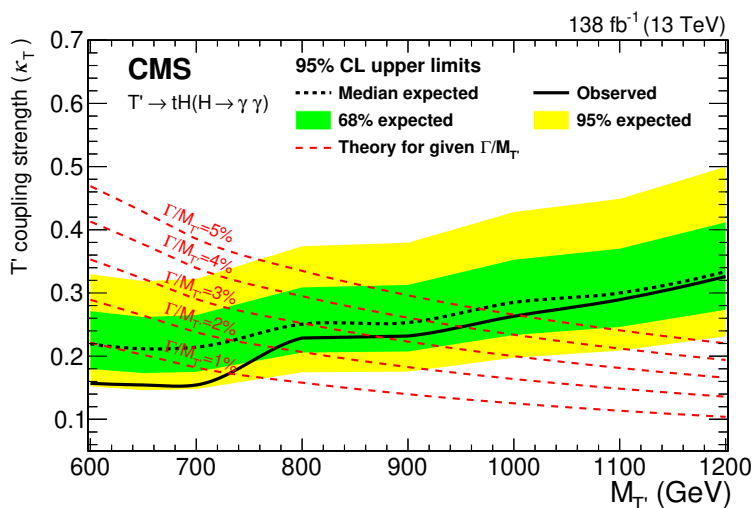
Finally, the upper limits on  $\mu_{\text{obs}}$  and  $\mu_{\text{exp}}$  are translated into the upper limits on  $\sigma_{T'\text{bq}} \mathcal{B}_{T' \rightarrow tH}$ , as displayed in figure 4 together with the theoretical cross sections for the singlet  $T'$  production with representative  $\kappa_T$ -values fixed at 0.1, 0.15, 0.2 and 0.25 (for  $\Gamma/M_{T'} < 5\%$ ). Similarly, the upper limits on the coupling parameter of  $T'$  with the SM particles ( $\kappa_T$ ) under the narrow width approximation is displayed in figure 5 with theoretical  $\kappa_T$ -values corresponding to the  $\Gamma/M_{T'}$ -values fixed at 1, 2, 3, 4, and 5%. Tabulated results are provided in the HEPData record for this analysis [69]. The limits obtained separately in the leptonic and hadronic channels are available in the HEPData record, where it can be seen that the hadronic channel dominates the sensitivity.



**Figure 3.** The combined, leptonic plus hadronic, distributions for data (black dots) and  $m_{\gamma\gamma}$  signal-plus-background model fits (red line) for a VLQ signal with  $M_{T'}$  of 600 (upper left), 900 (upper right), and 1200 GeV (lower). The green (yellow) band represents the 68% (95%) CL in the background component of the fit. The peak in the background component shows the considered irreducible SM Higgs boson (ggH, VBF, VH,  $t\bar{t}H$  and  $tH$ ) contribution. Here,  $\hat{\mu}$  is the best fit value of the signal strength parameter  $\mu$ , which is zero for the three  $M_{T'}$  values considered. The lower panel shows the residuals after the subtraction of the background component.



**Figure 4.** The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on  $\sigma_{T'_{bq}} \mathcal{B}_{T' \rightarrow tH}$  are displayed as a function of  $M_{T'}$ . The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical cross sections for the singlet  $T'$  production with representative  $\kappa_{T'}$ -values fixed at 0.1, 0.15, 0.2 and 0.25 (for  $\Gamma/M_{T'} < 5\%$ ) are shown as red lines.



**Figure 5.** The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on the  $T'$  coupling to third-generation quarks,  $\kappa_{T'}$ , under the narrow width approximation displayed as a function of  $M_{T'}$ . The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis. The theoretical  $\kappa_{T'}$  values corresponding to the  $\Gamma/M_{T'}$ -values fixed at 1, 2, 3, 4, and 5% are shown as red dashed lines.

## 9 Summary

A search for a vector-like quark decaying to a top quark and a Higgs boson that decays into two photons,  $T' \rightarrow tH$  ( $H \rightarrow \gamma\gamma$ ), has been performed using proton-proton collision data at  $\sqrt{s} = 13$  TeV recorded with the CMS detector in 2016–2018, and corresponding to an integrated luminosity of  $138 \text{ fb}^{-1}$ . The search has been carried out based on a model of  $T'$  electroweak production in a narrow width approximation with a ratio of  $T'$  width relative to its mass ( $\Gamma/M_{T'} \approx 1\%$ ). The sensitivity of this analysis extends up to  $\Gamma/M_{T'} \approx 5\%$ , which roughly corresponds to the experimental resolution of  $M_{T'}$ . Both the hadronic and leptonic decay modes of the top quark are considered in the search. A novel multivariate analysis incorporating three separately optimized boosted decision trees is exploited to separate likely signal events from background processes, including the standard model production of Higgs bosons. No statistically significant excess over the expected background prediction is observed. Assuming a coupling to third generation quarks of  $\kappa_T = 0.25$  and a relative decay width of  $\Gamma/M_{T'} < 5\%$ , the electroweak production of a singlet  $T'$  quark is excluded up to a mass of 960 GeV at 95% confidence level. This search for a vector-like quark,  $T'$ , is the most sensitive to date for  $M_{T'}$  up to 1.1 TeV, among searches exploring the same production mechanism.

## Acknowledgments

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

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316,

765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science — EOS” — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany’s Excellence Strategy — EXC 2121 “Quantum Universe” — 390833306, and under project number 400140256 — GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program — ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](https://arxiv.org/abs/1207.7214)] [[INSPIRE](#)].
- [2] CMS collaboration, *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](https://arxiv.org/abs/1207.7235)] [[INSPIRE](#)].
- [3] CMS collaboration, *Observation of a New Boson with Mass Near 125 GeV in pp Collisions at  $\sqrt{s} = 7$  and 8 TeV*, *JHEP* **06** (2013) 081 [[arXiv:1303.4571](https://arxiv.org/abs/1303.4571)] [[INSPIRE](#)].
- [4] L. Susskind, *Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory*, *Phys. Rev. D* **20** (1979) 2619 [[INSPIRE](#)].



- [5] R. Contino, L. Da Rold and A. Pomarol, *Light custodians in natural composite Higgs models*, *Phys. Rev. D* **75** (2007) 055014 [[hep-ph/0612048](#)] [[INSPIRE](#)].
- [6] R. Contino, T. Kramer, M. Son and R. Sundrum, *Warped/composite phenomenology simplified*, *JHEP* **05** (2007) 074 [[hep-ph/0612180](#)] [[INSPIRE](#)].
- [7] D.B. Kaplan, *Flavor at SSC energies: A new mechanism for dynamically generated fermion masses*, *Nucl. Phys. B* **365** (1991) 259 [[INSPIRE](#)].
- [8] M.J. Dugan, H. Georgi and D.B. Kaplan, *Anatomy of a Composite Higgs Model*, *Nucl. Phys. B* **254** (1985) 299 [[INSPIRE](#)].
- [9] S. Blasi and F. Goertz, *Softened Symmetry Breaking in Composite Higgs Models*, *Phys. Rev. Lett.* **123** (2019) 221801 [[arXiv:1903.06146](#)] [[INSPIRE](#)].
- [10] M. Perelstein, M.E. Peskin and A. Pierce, *Top quarks and electroweak symmetry breaking in little Higgs models*, *Phys. Rev. D* **69** (2004) 075002 [[hep-ph/0310039](#)] [[INSPIRE](#)].
- [11] O. Matsedonskyi, G. Panico and A. Wulzer, *Light Top Partners for a Light Composite Higgs*, *JHEP* **01** (2013) 164 [[arXiv:1204.6333](#)] [[INSPIRE](#)].
- [12] M. Schmaltz and D. Tucker-Smith, *Little Higgs review*, *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 229 [[hep-ph/0502182](#)] [[INSPIRE](#)].
- [13] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [[hep-ph/9905221](#)] [[INSPIRE](#)].
- [14] J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer and M. Pérez-Victoria, *Handbook of vectorlike quarks: Mixing and single production*, *Phys. Rev. D* **88** (2013) 094010 [[arXiv:1306.0572](#)] [[INSPIRE](#)].
- [15] A. Deandrea et al., *Single production of vector-like quarks: the effects of large width, interference and NLO corrections*, *JHEP* **08** (2021) 107 [*Erratum ibid.* **11** (2022) 028] [[arXiv:2105.08745](#)] [[INSPIRE](#)].
- [16] A. Roy, N. Nikiforou, N. Castro and T. Andeen, *Novel interpretation strategy for searches of singly produced vectorlike quarks at the LHC*, *Phys. Rev. D* **101** (2020) 115027 [[arXiv:2003.00640](#)] [[INSPIRE](#)].
- [17] S. Banerjee et al., *Phenomenological analysis of multi-pseudoscalar mediated dark matter models*, *JHEP* **07** (2022) 111 [[arXiv:2110.15391](#)] [[INSPIRE](#)].
- [18] ATLAS collaboration, *Combination of the searches for pair-produced vector-like partners of the third-generation quarks at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Rev. Lett.* **121** (2018) 211801 [[arXiv:1808.02343](#)] [[INSPIRE](#)].
- [19] CMS collaboration, *Search for pair production of vectorlike quarks in the fully hadronic final state*, *Phys. Rev. D* **100** (2019) 072001 [[arXiv:1906.11903](#)] [[INSPIRE](#)].
- [20] CMS collaboration, *Search for electroweak production of a vector-like T quark using fully hadronic final states*, *JHEP* **01** (2020) 036 [[arXiv:1909.04721](#)] [[INSPIRE](#)].
- [21] ATLAS collaboration, *Search for single production of a vectorlike T quark decaying into a Higgs boson and top quark with fully hadronic final states using the ATLAS detector*, *Phys. Rev. D* **105** (2022) 092012 [[arXiv:2201.07045](#)] [[INSPIRE](#)].
- [22] CMS collaboration, *Search for pair production of vector-like quarks in leptonic final states in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2023) 020 [[arXiv:2209.07327](#)] [[INSPIRE](#)].

- [23] ATLAS collaboration, *Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector*, *Eur. Phys. J. C* **83** (2023) 719 [[arXiv:2212.05263](#)] [[INSPIRE](#)].
- [24] CMS collaboration, *Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2021) 027 [[arXiv:2103.06956](#)] [[INSPIRE](#)].
- [25] CMS collaboration, *The CMS Experiment at the CERN LHC, 2008* *JINST* **3** S08004 [[INSPIRE](#)].
- [26] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, 2020 *JINST* **15** P10017 [[arXiv:2006.10165](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *The CMS trigger system, 2017* *JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [28] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, 2021* *JINST* **16** P05014 [[arXiv:2012.06888](#)] [[INSPIRE](#)].
- [29] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV*, 2018 *JINST* **13** P06015 [[arXiv:1804.04528](#)] [[INSPIRE](#)].
- [30] CMS collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker, 2014* *JINST* **9** P10009 [[arXiv:1405.6569](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector, 2017* *JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].
- [32] CMS collaboration, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, CERN-LHCC-2015-010 (2015) [[DOI:10.17181/CERN.VU8I.D59J](#)] [[INSPIRE](#)].
- [33] CMS collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade*, CERN-LHCC-2012-016 (2012) [[DOI:10.2172/1151650](#)] [[INSPIRE](#)].
- [34] CMS collaboration, *Performance of b tagging algorithms in proton-proton collisions at 13 TeV with Phase 1 CMS detector*, CMS-DP-2018-033 (2018).
- [35] GEANT4 collaboration, *GEANT4—a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [36] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [37] P. Artoisenet, R. Frederix, O. Mattelaer and R. Rietkerk, *Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations*, *JHEP* **03** (2013) 015 [[arXiv:1212.3460](#)] [[INSPIRE](#)].
- [38] NNPDF collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663 [[arXiv:1706.00428](#)] [[INSPIRE](#)].
- [39] E. Bagnaschi, G. Degrossi, P. Slavich and A. Vicini, *Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM*, *JHEP* **02** (2012) 088 [[arXiv:1111.2854](#)] [[INSPIRE](#)].
- [40] P. Nason and C. Oleari, *NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG*, *JHEP* **02** (2010) 037 [[arXiv:0911.5299](#)] [[INSPIRE](#)].

- [41] H.B. Hartanto, B. Jager, L. Reina and D. Wackerroth, *Higgs boson production in association with top quarks in the POWHEG BOX*, *Phys. Rev. D* **91** (2015) 094003 [[arXiv:1501.04498](#)] [[INSPIRE](#)].
- [42] G. Luisoni, P. Nason, C. Oleari and F. Tramontano,  *$HW^\pm/HZ + 0$  and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO*, *JHEP* **10** (2013) 083 [[arXiv:1306.2542](#)] [[INSPIRE](#)].
- [43] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, [arXiv:1610.07922](#) [[DOI:10.23731/CYRM-2017-002](#)] [[INSPIRE](#)].
- [44] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [45] SHERPA collaboration, *Event Generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [[arXiv:1905.09127](#)] [[INSPIRE](#)].
- [46] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [[arXiv:1512.00815](#)] [[INSPIRE](#)].
- [47] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [[arXiv:1903.12179](#)] [[INSPIRE](#)].
- [48] M. Cacciari, G.P. Salam and G. Soyez, *The anti- $k_t$  jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [49] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [50] CMS collaboration, *Performance of reconstruction and identification of  $\tau$  leptons decaying to hadrons and  $\nu_\tau$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV*, 2018 *JINST* **13** P10005 [[arXiv:1809.02816](#)] [[INSPIRE](#)].
- [51] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in  $pp$  collisions at 8 TeV*, 2017 *JINST* **12** P02014 [[arXiv:1607.03663](#)] [[INSPIRE](#)].
- [52] CMS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at  $\sqrt{s} = 13$  TeV using the CMS detector*, 2019 *JINST* **14** P07004 [[arXiv:1903.06078](#)] [[INSPIRE](#)].
- [53] CMS collaboration, *Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS*, 2011 *JINST* **6** P11002 [[arXiv:1107.4277](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in  $pp$  collisions at 13 TeV*, 2018 *JINST* **13** P05011 [[arXiv:1712.07158](#)] [[INSPIRE](#)].
- [55] CMS collaboration, *Measurements of  $t\bar{t}H$  Production and the CP Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel*, *Phys. Rev. Lett.* **125** (2020) 061801 [[arXiv:2003.10866](#)] [[INSPIRE](#)].
- [56] CMS collaboration, *Search for Flavor-Changing Neutral Current Interactions of the Top Quark and Higgs Boson in Final States with Two Photons in Proton-Proton Collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **129** (2022) 032001 [[arXiv:2111.02219](#)] [[INSPIRE](#)].
- [57] H. Voss, A. Hocker, J. Stelzer and F. Tegenfeldt, *TMVA, the Toolkit for Multivariate Data Analysis with ROOT*, *PoS ACAT* (2007) 040 [[physics/0703039](#)] [[INSPIRE](#)].























- [58] CMS collaboration, *Evidence for the associated production of a single top quark and a photon in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **121** (2018) 221802 [[arXiv:1808.02913](#)] [[INSPIRE](#)].
- [59] CMS collaboration, *Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at  $\sqrt{s} = 13$  TeV*, *JHEP* **06** (2018) 102 [[arXiv:1712.02399](#)] [[INSPIRE](#)].
- [60] P.D. Dauncey, M. Kenzie, N. Wardle and G.J. Davies, *Handling uncertainties in background shapes: the discrete profiling method*, 2015 *JINST* **10** P04015 [[arXiv:1408.6865](#)] [[INSPIRE](#)].
- [61] R.A. Fisher, *On the Interpretation of  $\chi^2$  from Contingency Tables, and the Calculation of P*, *J. Roy. Statist. Soc.* **85** (1922) 87.
- [62] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [[arXiv:2104.01927](#)] [[INSPIRE](#)].
- [63] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at  $\sqrt{s} = 13$  TeV*, CMS-PAS-LUM-17-004, CERN, Geneva (2018).
- [64] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at  $\sqrt{s} = 13$  TeV*, CMS-PAS-LUM-18-002, CERN, Geneva (2019).
- [65] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [[hep-ex/9902006](#)] [[INSPIRE](#)].
- [66] A.L. Read, *Presentation of search results: The  $CL_s$  technique*, *J. Phys. G* **28** (2002) 2693 [[INSPIRE](#)].
- [67] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].
- [68] G.J. Feldman and R.D. Cousins, *A unified approach to the classical statistical analysis of small signals*, *Phys. Rev. D* **57** (1998) 3873 [[physics/9711021](#)] [[INSPIRE](#)].
- [69] HEPData record for this analysis, DOI:[10.17182/HEPDATA.134009](#), (2022).

## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan <sup>1</sup>














### Institut für Hochenergiephysik, Vienna, Austria

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

















### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish <sup>3</sup>, T. Janssen , T. Kello <sup>4</sup>, H. Rejeb Sfar , P. Van Mechelen 


### Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette ,  
S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck ,  
D. Vannerom 

















### Université Libre de Bruxelles, Bruxelles, Belgium

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

### Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , C. Rendón , A. Samalan , K. Skovpen ,  
M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 






















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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas ,  
A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre , K. Mondal , A. Taliercio , T.T. Tran <sup>6</sup>,  
P. Vischia , S. Wertz 








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

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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

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

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

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


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

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





**University of Sofia, Sofia, Bulgaria**

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




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

S.Thakur 
















**Beihang University, Beijing, China**

T. Cheng , T. Javaid <sup>8</sup>, M. Mittal , L. Yuan 











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

M. Ahmad , G. Bauer<sup>9</sup>, Z. Hu , S. Lezki , K. Yi<sup>9,10</sup>

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

G.M. Chen <sup>8</sup>, H.S. Chen <sup>8</sup>, M. Chen <sup>8</sup>, F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao ,  
Z.-A. Liu <sup>11</sup>, V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker ,  
J. Wang , H. Zhang , J. Zhao 

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

A. Agapitos , Y. An , Y. Ban , A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian ,  
X. Sun , D. Wang , J. Xiao , H. Yang




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

M. Lu , Z. You 

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


















N. Lu 

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

X. Gao <sup>4</sup>, D. Leggat, H. Okawa , Y. Zhang 

















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

Z. Lin , C. Lu , M. Xiao 

**Universidad de Los Andes, Bogota, Colombia**C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga **Universidad de Antioquia, Medellin, Colombia**J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez **University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**D. Giljanovic , N. Godinovic , D. Lelas , I. Puljak **University of Split, Faculty of Science, Split, Croatia**Z. Antunovic, M. Kovac , T. Sculac **Institute Rudjer Boskovic, Zagreb, Croatia**V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov <sup>12</sup>,  
T. Susa **University of Cyprus, Nicosia, Cyprus**A. Attikis , K. Christoforou , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou,  
F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov **Charles University, Prague, Czech Republic**M. Finger , M. Finger Jr. , A. Kveton **Escuela Politecnica Nacional, Quito, Ecuador**E. Ayala **Universidad San Francisco de Quito, Quito, Ecuador**E. Carrera Jarrin **Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**H. Abdalla <sup>13</sup>, Y. Assran<sup>14,15</sup>**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M.A. Mahmoud , Y. Mohammed **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, T. Lange , S. Nandan ,  
C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 


















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

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,  
T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen ,  
M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 















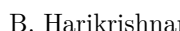






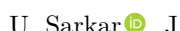






**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow , T. Tuuva







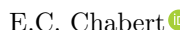




**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri ,  
S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander,  
A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro <sup>16</sup>, P. Simkina , M. Titov 


















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

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

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

J.-L. Agram <sup>17</sup>, J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom ,  
E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan ,  
P. Van Hove 

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

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo ,  
P. Depasse , C. Dozen <sup>18</sup>, H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch ,  
G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot ,  
M. Vander Donckt , P. Verdier , S. Viret























**Georgian Technical University, Tbilisi, Georgia**

D. Chokheli , I. Lomidze , Z. Tsamalaidze <sup>12</sup>

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










V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert ,  
M. Teroerde 

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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey ,  
D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee ,  
L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll ,  
A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt 

S.C. Schuler, A. Sharma , A. Stein , F. Torres Da Silva De Araujo <sup>19</sup>, L. Vigilante,  
S. Wiedenbeck , S. Zaleski

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

C. Dziwok , G. Flügge , W. Haj Ahmad <sup>20</sup>, O. Hlushchenko, T. Kress , A. Nowack ,  
O. Pooth , A. Stahl , T. Ziemons , A. Zotz 
































### Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou ,  
O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman <sup>21</sup>,  
K. Borras <sup>22</sup>, D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina,  
S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin,  
D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo <sup>21</sup>, A. Geiser , A. Giraldi ,  
G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari <sup>23</sup>, N.Z. Jomhari ,  
B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm ,  
D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka <sup>24</sup>, W. Lohmann <sup>25</sup>, R. Mankel ,  
I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella ,  
M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza ,  
B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham <sup>26,22</sup>,  
V. Scheurer, S. Schnake <sup>22</sup>, P. Schütze , C. Schwanenberger <sup>21</sup>, M. Shchedrolosiev ,  
R.E. Sosa Ricardo , D. Stafford, N. Tonon <sup>†</sup>, M. Van De Klundert , F. Vazzoler ,  
A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann,  
L. Wiens <sup>22</sup>, C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

### University of Hamburg, Hamburg, Germany

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









### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll,  
N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann <sup>27</sup>, M. Horzela ,  
U. Husemann , M. Klute , R. Koppenhöfer , M. Link, A. Lintuluoto , S. Maier , S. Mitra ,  
Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , J. Rauser, M. Schnepf,  
I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube ,  
M. Wassmer , S. Wieland , R. Wolf , S. Wozniewski , S. Wunsch, X. Zuo 

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

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 








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

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 


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

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






**University of Ioánnina, Ioánnina, Greece**

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

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

M. Csanád , K. Farkas , M.M.A. Gadallah <sup>28</sup>, S. Lökös <sup>29</sup>, P. Major , K. Mandal , G. Pásztor , A.J. Rádl <sup>30</sup>, O. Surányi , G.I. Veres 


**Wigner Research Centre for Physics, Budapest, Hungary**

M. Bartók <sup>31</sup>, G. Bencze, C. Hajdu , D. Horvath <sup>32,33</sup>, F. Sikler , V. Veszpremi 

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

N. Beni , S. Czellar, J. Karancsi <sup>31</sup>, J. Molnar, Z. Szillasi, D. Teyssier 


















**Institute of Physics, University of Debrecen, Debrecen, Hungary**

P. Raics, B. Ujvari <sup>34</sup>









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

T. Csorgo <sup>30</sup>, F. Nemes <sup>30</sup>, T. Novak 










**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra <sup>35</sup>, R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh <sup>36</sup>, A. Singla , A. K. Viridi 















**University of Delhi, Delhi, India**








































































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

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


















S. Baradia , S. Barman <sup>37</sup>, S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber <sup>38</sup>, M. Maity <sup>37</sup>, P. Palit , G. Saha , B. Sahu , S. Sarkar

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

P.K. Behera , S.C. Behera , S. Chatterjee , P. Kalbhor , J.R. Komaragiri <sup>39</sup>, D. Kumar <sup>39</sup>, A. Muhammad , L. Panwar <sup>39</sup>, R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari <sup>39</sup>, S. Verma 

**Bhabha Atomic Research Centre, Mumbai, India**K. Naskar <sup>40</sup>**Tata Institute of Fundamental Research-A, Mumbai, India**T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara**Tata Institute of Fundamental Research-B, Mumbai, India**S. Banerjee , R. Chudasama , M. Guchait , S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Mukherjee , A. Thachayath **National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India**S. Bahinipati <sup>41</sup>, A.K. Das, C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu <sup>42</sup>, A. Nayak <sup>42</sup>, P. Saha , S.K. Swain, D. Vats <sup>42</sup>**Indian Institute of Science Education and Research (IISER), Pune, India**A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi <sup>43</sup>, E. Khazaie , M. Zeinali <sup>44</sup>**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani <sup>45</sup>, S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi **University College Dublin, Dublin, Ireland**M. Grunewald **INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**M. Abbrescia <sup>a,b</sup>, R. Aly <sup>a,c,46</sup>, C. Aruta <sup>a,b</sup>, A. Colaleo <sup>a</sup>, D. Creanza <sup>a,c</sup>, N. De Filippis <sup>a,c</sup>, M. De Palma <sup>a,b</sup>, A. Di Florio <sup>a,b</sup>, W. Elmetenawee <sup>a,b</sup>, F. Errico <sup>a,b</sup>, L. Fiore <sup>a</sup>, G. Iaselli <sup>a,c</sup>, G. Maggi <sup>a,c</sup>, M. Maggi <sup>a</sup>, I. Margjeka <sup>a,b</sup>, V. Mastrapasqua <sup>a,b</sup>, S. My <sup>a,b</sup>, S. Nuzzo <sup>a,b</sup>, A. Pellecchia <sup>a,b</sup>, A. Pompili <sup>a,b</sup>, G. Pugliese <sup>a,c</sup>, R. Radogna <sup>a</sup>, D. Ramos <sup>a</sup>, A. Ranieri <sup>a</sup>, G. Selvaggi <sup>a,b</sup>, L. Silvestris <sup>a</sup>, F.M. Simone <sup>a,b</sup>, Ü. Sözbilir <sup>a</sup>, A. Stamerra <sup>a</sup>, R. Venditti <sup>a</sup>, P. Verwilligen <sup>a</sup>**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**G. Abbiendi <sup>a</sup>, C. Battilana <sup>a,b</sup>, D. Bonacorsi <sup>a,b</sup>, L. Borgonovi <sup>a</sup>, R. Campanini <sup>a,b</sup>, P. Capiluppi <sup>a,b</sup>, A. Castro <sup>a,b</sup>, F.R. Cavallo <sup>a</sup>, C. Ciocca <sup>a</sup>, M. Cuffiani <sup>a,b</sup>, G.M. Dallavalle <sup>a</sup>, T. Diotallevi <sup>a,b</sup>, F. Fabbri <sup>a</sup>, A. Fanfani <sup>a,b</sup>, P. Giacomelli <sup>a</sup>, L. Giommi <sup>a,b</sup>, C. Grandi <sup>a</sup>, L. Guiducci <sup>a,b</sup>, S. Lo Meo <sup>a,47</sup>, L. Lunerti <sup>a,b</sup>, S. Marcellini <sup>a</sup>, G. Masetti <sup>a</sup>, F.L. Navarria <sup>a,b</sup>, A. Perrotta <sup>a</sup>, F. Primavera <sup>a,b</sup>, A.M. Rossi <sup>a,b</sup>, T. Rovelli <sup>a,b</sup>, G.P. Siroli <sup>a,b</sup>**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**S. Costa <sup>a,b,48</sup>, A. Di Mattia <sup>a</sup>, R. Potenza <sup>a,b</sup>, A. Tricomi <sup>a,b,48</sup>, C. Tuve <sup>a,b</sup>






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

G. Barbagli <sup>a</sup>, G. Bardelli <sup>a,b</sup>, B. Camaiani <sup>a,b</sup>, A. Cassese <sup>a</sup>, R. Ceccarelli <sup>a,b</sup>, V. Ciulli <sup>a,b</sup>,  
 C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, G. Latino <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, M. Lizzo <sup>a,b</sup>,  
 M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, R. Seidita <sup>a,b</sup>, G. Sguazzoni <sup>a</sup>, L. Viliani <sup>a</sup>

























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

L. Benussi <sup>a</sup>, S. Bianco <sup>a</sup>, S. Meola <sup>49</sup>, D. Piccolo <sup>a</sup>








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

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



























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

A. Benaglia <sup>a</sup>, G. Boldrini <sup>a</sup>, F. Brivio <sup>a,b</sup>, F. Cetorelli <sup>a,b</sup>, F. De Guio <sup>a,b</sup>,  
 M.E. Dinardo <sup>a,b</sup>, P. Dini <sup>a</sup>, S. Gennai <sup>a</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, L. Guzzi <sup>a,b</sup>,  
 M.T. Lucchini <sup>a,b</sup>, M. Malberti <sup>a</sup>, S. Malvezzi <sup>a</sup>, A. Massironi <sup>a</sup>, D. Menasce <sup>a</sup>,  
 L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</sup>, B.S. Pinolini <sup>a</sup>, S. Ragazzi <sup>a,b</sup>, N. Redaelli <sup>a</sup>,  
 T. Tabarelli de Fatis <sup>a,b</sup>, D. Zuolo <sup>a,b</sup>












**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli ‘Federico II’<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo <sup>a</sup>, F. Carnevali <sup>a,b</sup>, N. Cavallo <sup>a,c</sup>, A. De Iorio <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>,  
 A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a,b,50</sup>, P. Paolucci <sup>a,27</sup>, B. Rossi <sup>a</sup>, C. Sciacca <sup>a,b</sup>
















**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi <sup>a</sup>, N. Bacchetta <sup>a,51</sup>, D. Bisello <sup>a,b</sup>, P. Bortignon <sup>a</sup>, A. Bragagnolo <sup>a,b</sup>,  
 P. Checchia <sup>a</sup>, T. Dorigo <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, G. Govi <sup>a</sup>, G. Grosso <sup>a</sup>,  
 L. Layer <sup>a,52</sup>, E. Lusiani <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, J. Pazzini <sup>a,b</sup>,  
 P. Ronchese <sup>a,b</sup>, R. Rossin <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, G. Strong <sup>a</sup>, M. Tosi <sup>a,b</sup>, H. Yarar <sup>a,b</sup>,  
 M. Zanetti <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>











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

S. Abu Zeid <sup>a,53</sup>, C. Aimè <sup>a,b</sup>, A. Braghieri <sup>a</sup>, S. Calzaferri <sup>a,b</sup>, D. Fiorina <sup>a,b</sup>,  
 P. Montagna <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a</sup>, P. Vitulo <sup>a,b</sup>

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

P. Asenov <sup>a,54</sup>, G.M. Bilei <sup>a</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, M. Magherini <sup>a,b</sup>,  
 G. Mantovani <sup>a,b</sup>, V. Mariani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Moscatelli <sup>a,54</sup>, A. Piccinelli <sup>a,b</sup>,  
 M. Presilla <sup>a,b</sup>, A. Rossi <sup>a,b</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga <sup>a</sup>, T. Tedeschi <sup>a,b</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy; Università di Siena<sup>d</sup>, Siena, Italy**

P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, V. Bertacchi <sup>a,c</sup>, R. Bhattacharya <sup>a</sup>, L. Bianchini <sup>a,b</sup>,  
 T. Boccali <sup>a</sup>, E. Bossini <sup>a,b</sup>, D. Bruschini <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,b</sup>,

V. D'Amante<sup>a,d</sup>, R. Dell'Orso<sup>a</sup>, M.R. Di Domenico<sup>a,d</sup>, S. Donato<sup>a</sup>, A. Giassi<sup>a</sup>,  
 F. Ligabue<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, D. Matos Figueiredo<sup>a</sup>, A. Messineo<sup>a,b</sup>, M. Musich<sup>a,b</sup>,  
 F. Palla<sup>a</sup>, S. Parolia<sup>a</sup>, G. Ramirez-Sanchez<sup>a,c</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>,  
 S. Roy Chowdhury<sup>a</sup>, T. Sarkar<sup>a</sup>, A. Scribano<sup>a</sup>, N. Shafiei<sup>a,b</sup>, P. Spagnolo<sup>a</sup>,  
 R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini<sup>a,d</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

### INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Roma, Italy

P. Barria<sup>a</sup>, M. Campana<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a</sup>, M. Diemoz<sup>a</sup>,  
 E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>,  
 C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a</sup>,  
 R. Tramontano<sup>a,b</sup>

### INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Torino, Italy; Università del Piemonte Orientale<sup>c</sup>, Novara, Italy

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

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

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>,  
 G. Della Ricca<sup>a,b</sup>, G. Sorrentino<sup>a,b</sup>

### Kyungpook National University, Daegu, Korea

S. Dogra<sup>b</sup>, C. Huh<sup>b</sup>, B. Kim<sup>b</sup>, D.H. Kim<sup>b</sup>, G.N. Kim<sup>b</sup>, J. Kim, J. Lee<sup>b</sup>, S.W. Lee<sup>b</sup>,  
 C.S. Moon<sup>b</sup>, Y.D. Oh<sup>b</sup>, S.I. Pak<sup>b</sup>, M.S. Ryu<sup>b</sup>, S. Sekmen<sup>b</sup>, Y.C. Yang<sup>b</sup>

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

H. Kim<sup>b</sup>, D.H. Moon<sup>b</sup>

### Hanyang University, Seoul, Korea

E. Asilar<sup>b</sup>, T.J. Kim<sup>b</sup>, J. Park<sup>b</sup>

### Korea University, Seoul, Korea

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


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

J. Goh<sup>b</sup>










### Sejong University, Seoul, Korea

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

**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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


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

S. Ha , H.D. Yoo 

**Sungkyunkwan University, Suwon, Korea**

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

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

T. Beyrouthy, Y. Maghrbi 

**Riga Technical University, Riga, Latvia**

K. Dreimanis , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns 







**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius ,  
G. Tamulaitis 

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

N. Bin Norjoharuddeen , S.Y. Hoh <sup>55</sup>, I. Yusuff <sup>55</sup>, Z. Zolkapli

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

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

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

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz <sup>56</sup>, R. Lopez-Fernandez ,  
C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**

C. Oropeza Barrera , F. Vazquez Valencia 

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








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

**University of Montenegro, Podgorica, Montenegro**


I. Bubanja, J. Mijuskovic<sup>57</sup>, N. Raicevic 



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

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





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

V. Avati, L. Grzanka , M. Malawski 













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

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

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

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





























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

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,  
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 

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

P. Adzic <sup>58</sup>, M. Dordevic , P. Milenovic , J. Milosevic 













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

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández , M. Barrio Luna, Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada , N. Colino ,  
B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix ,  
M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa ,  
J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,  
J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas ,  
J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott


















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

J.F. de Trocóniz 

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

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

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros ,  
M. Fernandez , C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasasoa García ,  
C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas ,  
J. Piedra Gomez , C. Prieels, A. Ruiz-Jimeno , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

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

M.K. Jayananda , B. Kailasapathy <sup>59</sup>, D.U.J. Sonnadara , D.D.C. Wickramarathna 





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

W.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage 





































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

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon<sup>†</sup>, D. Barney ,  
J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi ,  
G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , L. Cristella ,  
D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranichis , M. Deile ,  
M. Dobson , M. Dünser , N. Dupont, F. Fallavollita<sup>60</sup>, A. Florent , L. Forthomme ,  
G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos ,  
E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot ,  
J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb ,  
C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi ,  
E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez,  
M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt ,  
H. Qu , T. Quast, D. Rabaday , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin ,  
J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas <sup>61</sup>,  
A.G. Stahl Leitner , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea ,  
A. Tsirou, J. Wanczyk <sup>62</sup>, K.A. Wozniak , W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

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

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

T.K. Aarrestad , K. Androsov <sup>62</sup>, M. Backhaus , P. Berger, A. Calandri , K. Datta ,  
A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia ,  
F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon ,  
R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani <sup>62</sup>, F. Nessi-Tedaldi ,  
J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann ,  
C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra ,  
J. Steggemann <sup>62</sup>, D. Valsecchi <sup>27</sup>, R. Wallny 

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>64</sup>, P. Bärtshi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier,  
 A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei,  
 B. Kilminster, S. Leontsinis, S.P. Liechi, A. Macchiolo, P. Meiring, V.M. Mikuni,  
 U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger,  
 M. Senger, Y. Takahashi

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

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

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

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, Y.W. Kao, R. Khurana,  
 G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan,  
 P.r. Yu

**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusanand

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

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

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

G. Karapinar<sup>70</sup>, K. Ocalan<sup>71</sup>, M. Yalvac<sup>72</sup>

**Bogazici University, Istanbul, Turkey**

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya<sup>73</sup>, O. Kaya<sup>74</sup>, S. Tekten<sup>75</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>66</sup>, Y. Komurcu, S. Sen<sup>66</sup>

**Istanbul University, Istanbul, Turkey**

O. Aydilek, S. Cerci<sup>69</sup>, B. Hacisahinoglu, I. Hos<sup>76</sup>, B. Isildak<sup>77</sup>, B. Kaynak,  
 S. Ozkorucuklu, C. Simsek, D. Sunar Cerci<sup>69</sup>
















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

B. Grynyov


















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

L. Levchuk
































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

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher ,  
M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran ,  
S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou <sup>78</sup>, K. Walkingshaw Pass, R. White 

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

A.H. Ball, K.W. Bell , A. Belyaev <sup>79</sup>, C. Brew , R.M. Brown , D.J.A. Cockerill ,  
C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg <sup>80</sup>, Sh. Jain , 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 













**Imperial College, London, United Kingdom**

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio,  
V. Cepaitis , G.S. Chahal <sup>81</sup>, D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies,  
M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles ,  
J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen ,  
D.G. Monk , J. Nash <sup>82</sup>, M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards,  
A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley ,  
L.H. Vage, T. Virdee <sup>27</sup>, M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

**Brunel University, Uxbridge, United Kingdom**

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








**Baylor University, Waco, Texas, U.S.A.**

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

















**Catholic University of America, Washington, DC, U.S.A.**

R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez 



















**The University of Alabama, Tuscaloosa, Alabama, U.S.A.**

S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio <sup>83</sup>,  
C. West 


















**Boston University, Boston, Massachusetts, U.S.A.**

A. Akpinar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , E. Fontanesi ,  
D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez ,  
A. Tsatsos , S. Yuan 















**Brown University, Providence, Rhode Island, U.S.A.**

G. Benelli , B. Burkle , X. Coubez<sup>22</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan <sup>84</sup>,  
T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan ,  
S. Sagir <sup>85</sup>, F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang








**University of California, Davis, Davis, California, U.S.A.**

J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok ,  
 J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin ,  
 M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 
























**University of California, Los Angeles, California, U.S.A.**

M. Bachtis , R. Cousins , A. Datta , D. Hamilton , J. Hauser , M. Ignatenko ,  
 M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , S. Regnard , D. Saltzberg , B. Stone ,  
 V. Valuev 

















**University of California, Riverside, Riverside, California, U.S.A.**

R. Clare , J.W. Gary , M. Gordon , G. Hanson , G. Karapostoli , O.R. Long ,  
 N. Manganelli , W. Si , S. Wimpenny 














**University of California, San Diego, La Jolla, California, U.S.A.**

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









**University of California, Santa Barbara — Department of Physics, Santa Barbara, California, U.S.A.**

N. Amin , C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta , J. Incandela ,  
 M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , M. Quinnan ,  
 J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy , D. Stuart ,  
 S. Wang 














**California Institute of Technology, Pasadena, California, U.S.A.**

A. Bornheim , O. Cerri , I. Dutta , A. Latorre , J.M. Lawhorn , J. Mao , H.B. Newman ,  
 T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 


















**Carnegie Mellon University, Pittsburgh, Pennsylvania, U.S.A.**

J. Alison , S. An , M.B. Andrews , P. Bryant , T. Ferguson , A. Harilal , C. Liu ,  
 T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 






































































**University of Colorado Boulder, Boulder, Colorado, U.S.A.**

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



















**Cornell University, Ithaca, New York, U.S.A.**

J. Alexander , S. Bright-Thomney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan ,  
 D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid ,  
 A. Ryd , J. Thom , P. Wittich , R. Zou 











**Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.**

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry ,  
 J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati ,  
 H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng ,  
 J. Freeman , A. Gandrakota , Z. Geese , L. Gray , D. Green, S. Grünendahl , D. Guerrero ,  
 O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn ,  
 B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima ,  
 K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima ,  
 C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba ,  
 D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena <sup>86</sup>, F. Ravera ,  
 A. Reinsvold Hall <sup>87</sup>, L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel ,  
 J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

**University of Florida, Gainesville, Florida, U.S.A.**

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field, M. Kim, E. Koenig ,  
 J. Konigsberg , A. Korytov , E. Kuznetsova , K.H. Lo, K. Matchev , N. Menendez ,  
 G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig ,  
 K. Shi , J. Wang , Z. Wu 



















**Florida State University, Tallahassee, Florida, U.S.A.**

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg ,  
 G. Martinez, H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang












**Florida Institute of Technology, Melbourne, Florida, U.S.A.**

M.M. Baarmand , S. Butalla , T. Elkafrawy <sup>53</sup>, M. Hohlmann , R. Kumar Verma ,  
 M. Rahmani, F. Yumiceva 












**University of Illinois at Chicago (UIC), Chicago, Illinois, U.S.A.**

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , S. Dittmer , O. Evdokimov ,  
 C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy ,  
 S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 

**The University of Iowa, Iowa City, Iowa, U.S.A.**

M. Alhusseini , K. Dilsiz <sup>88</sup>, L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo,  
 A. Mestvirishvili <sup>89</sup>, J. Nachtman , O. Neogi, H. Ogul <sup>90</sup>, Y. Onel , A. Penzo , C. Snyder,  
 E. Tiras <sup>91</sup>

**Johns Hopkins University, Baltimore, Maryland, U.S.A.**


O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou ,  
 P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

**The University of Kansas, Lawrence, Kansas, U.S.A.**

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers ,  
 T. Isidori , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey,

J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 



















### **Kansas State University, Manhattan, Kansas, U.S.A.**

B. Allmond , S. Duric , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim , Y. Maravin , T. Mitchell , A. Modak , K. Nam , D. Roy 



























### **Lawrence Livermore National Laboratory, Livermore, California, U.S.A.**

F. Rebassoo , D. Wright 
















### **University of Maryland, College Park, Maryland, U.S.A.**

E. Adams , A. Baden , O. Baron , A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 

### **Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.**

D. Abercrombie , W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov , P. Harris , M. Hu , D. Kovalskiy , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang , Z. Wang , B. Wyslouch , T. J. Yang 

















### **University of Minnesota, Minneapolis, Minnesota, U.S.A.**

R.M. Chatterjee , B. Crossman , A. Evans , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 












### **University of Mississippi, Oxford, Mississippi, U.S.A.**

L.M. Cremaldi 




















### **University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.**

K. Bloom , M. Bryson , D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin , I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow<sup>†</sup> , W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 










### **State University of New York at Buffalo, Buffalo, New York, U.S.A.**

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 

### **Northeastern University, Boston, Massachusetts, U.S.A.**





















G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , T. Wamorkar , B. Wang , A. Wisecarver , D. Wood 

### **Northwestern University, Evanston, Illinois, U.S.A.**










S. Bhattacharya , J. Bueghly , Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco 



















**University of Notre Dame, Notre Dame, Indiana, U.S.A.**

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth ,  
 K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton ,  
 J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore ,  
 Y. Musienko <sup>12</sup>, R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

**The Ohio State University, Columbus, Ohio, U.S.A.**

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




















**Princeton University, Princeton, New Jersey, U.S.A.**

F.M. Addesa , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg ,  
 N. Haubrich , S. Higginbotham , G. Kopp , S. Kwan , D. Lange , D. Marlow , I. Ojalvo ,  
 J. Olsen , D. Stickland , C. Tully 

**University of Puerto Rico, Mayaguez, Puerto Rico, U.S.A.**

S. Malik , S. Norberg















**Purdue University, West Lafayette, Indiana, U.S.A.**

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung ,  
 D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,  
 S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , F. Wang , R. Xiao ,  
 W. Xie 














**Purdue University Northwest, Hammond, Indiana, U.S.A.**

J. Dolen , N. Parashar 

**Rice University, Houston, Texas, U.S.A.**

D. Acosta , A. Baty , T. Carnahan , S. Dildick , K.M. Ecklund , P.J. Fernández Manteca ,  
 S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi,  
 J. Rotter , S. Yang , E. Yigitbasi , L. Zhang<sup>92</sup>, Y. Zhang 

















**University of Rochester, Rochester, New York, U.S.A.**

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, T. Ferbel , M. Galanti,  
 A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova ,  
 E. Ranken , R. Taus , G.P. Van Onsem 

**The Rockefeller University, New York, New York, U.S.A.**

K. Goulianos 

**Rutgers, The State University of New Jersey, Piscataway, New Jersey, U.S.A.**














B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl ,  
 D. Jaroslawski , O. Karacheban <sup>25</sup>, I. Laflotte , A. Lath , R. Montalvo, K. Nash,  
 M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil ,  
 S. Thomas, H. Wang 












**University of Tennessee, Knoxville, Tennessee, U.S.A.**

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 

**Texas A&M University, College Station, Texas, U.S.A.**

O. Bouhali <sup>93</sup>, M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon <sup>94</sup>, H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,  
A. Safonov 











**Texas Tech University, Lubbock, Texas, U.S.A.**

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke,  
S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

**Vanderbilt University, Nashville, Tennessee, U.S.A.**

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon ,  
S. Tuo , J. Velkovska , J. Viinikainen 






















**University of Virginia, Charlottesville, Virginia, U.S.A.**

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovsky , A. Li ,  
C. Neu , C.E. Perez Lara , B. Tannenwald 

**Wayne State University, Detroit, Michigan, U.S.A.**











P.E. Karchin , N. Poudyal 

**University of Wisconsin — Madison, Madison, Wisconsin, U.S.A.**

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

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

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev ,  
A. Belyaev , V. Blinov <sup>95</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev ,  
V. Chekhovsky, R. Chistov <sup>95</sup>, M. Danilov <sup>95</sup>, A. Dermenev , T. Dimova <sup>95</sup>, I. Dremin ,  
M. Dubinin <sup>86</sup>, L. Dudko , V. Epshteyn , G. Gavrilov , V. Gavrilov , S. Gninenko ,  
V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , Y. Ivanov , V. Kachanov ,  
L. Kardapoltsev <sup>95</sup>, V. Karjavine , A. Karneyev , V. Kim <sup>95</sup>, M. Kirakosyan,  
D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova <sup>96</sup>, D. Konstantinov ,  
V. Korenkov , A. Kozyrev <sup>95</sup>, N. Krasnikov , A. Lanev , P. Levchenko , A. Litomin,  
N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev <sup>95</sup>, V. Murzin ,  
A. Nikitenko <sup>97</sup>, S. Obraztsov , A. Oskin, I. Ovtin <sup>95</sup>, V. Palichik , V. Perelygin ,  
M. Perfilov, S. Petrushanko , S. Polikarpov <sup>95</sup>, V. Popov, O. Radchenko <sup>95</sup>, M. Savina ,  
V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen <sup>95</sup>, S. Slabospitskii ,  
V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov 

O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov , A. Vorobyev, N. Voytishin , B.S. Yuldashev<sup>98</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

<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 Université Libre de Bruxelles, Bruxelles, 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 University of Chinese Academy of Sciences, Beijing, China

<sup>9</sup> Also at Nanjing Normal University Department of Physics, Nanjing, China

<sup>10</sup> Now at The University of Iowa, Iowa City, Iowa, U.S.A.

<sup>11</sup> Also at University of Chinese Academy of Sciences, Beijing, China

<sup>12</sup> Also at an institute or an international laboratory covered by a cooperation agreement with CERN

<sup>13</sup> Also at Cairo University, Cairo, Egypt

<sup>14</sup> Also at Suez University, Suez, Egypt

<sup>15</sup> Now at British University in Egypt, Cairo, Egypt

<sup>16</sup> Also at Purdue University, West Lafayette, Indiana, U.S.A.

<sup>17</sup> Also at Université de Haute Alsace, Mulhouse, France

<sup>18</sup> Also at Department of Physics, Tsinghua University, Beijing, China

<sup>19</sup> Also at The University of the State of Amazonas, Manaus, Brazil

<sup>20</sup> Also at Erzincan Binali Yildirim University, Erzincan, Turkey

<sup>21</sup> Also at University of Hamburg, Hamburg, Germany

<sup>22</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

<sup>23</sup> Also at Isfahan University of Technology, Isfahan, Iran

<sup>24</sup> Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

<sup>25</sup> Also at Brandenburg University of Technology, Cottbus, Germany

<sup>26</sup> Also at Forschungszentrum Jülich, Juelich, Germany

<sup>27</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

<sup>28</sup> Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

<sup>29</sup> Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

<sup>30</sup> Also at Wigner Research Centre for Physics, Budapest, Hungary

<sup>31</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

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

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

<sup>34</sup> Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary

<sup>35</sup> Also at Punjab Agricultural University, Ludhiana, India

<sup>36</sup> Also at UPES — University of Petroleum and Energy Studies, Dehradun, India

<sup>37</sup> Also at University of Visva-Bharati, Santiniketan, India

<sup>38</sup> Also at University of Hyderabad, Hyderabad, India

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

<sup>40</sup> Also at Indian Institute of Technology (IIT), Mumbai, India

<sup>41</sup> Also at IIT Bhubaneswar, Bhubaneswar, India

<sup>42</sup> Also at Institute of Physics, Bhubaneswar, India

<sup>43</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

<sup>44</sup> Also at Sharif University of Technology, Tehran, Iran

<sup>45</sup> Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran

<sup>46</sup> Also at Helwan University, Cairo, Egypt

<sup>47</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy

- <sup>48</sup> Also at *Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
- <sup>49</sup> Also at *Università degli Studi Guglielmo Marconi, Roma, Italy*
- <sup>50</sup> Also at *Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy*
- <sup>51</sup> Also at *Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.*
- <sup>52</sup> Also at *Università di Napoli ‘Federico II’, Napoli, Italy*
- <sup>53</sup> Also at *Ain Shams University, Cairo, Egypt*
- <sup>54</sup> Also at *Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
- <sup>55</sup> Also at *Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
- <sup>56</sup> Also at *Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
- <sup>57</sup> Also at *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- <sup>58</sup> Also at *Faculty of Physics, University of Belgrade, Belgrade, Serbia*
- <sup>59</sup> Also at *Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
- <sup>60</sup> Also at *INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
- <sup>61</sup> Also at *National and Kapodistrian University of Athens, Athens, Greece*
- <sup>62</sup> Also at *Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
- <sup>63</sup> Also at *Universität Zürich, Zurich, Switzerland*
- <sup>64</sup> Also at *Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
- <sup>65</sup> Also at *Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
- <sup>66</sup> Also at *Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
- <sup>67</sup> Also at *Konya Technical University, Konya, Turkey*
- <sup>68</sup> Also at *Izmir Bakircay University, Izmir, Turkey*
- <sup>69</sup> Also at *Adiyaman University, Adiyaman, Turkey*
- <sup>70</sup> Also at *Istanbul Gedik University, Istanbul, Turkey*
- <sup>71</sup> Also at *Necmettin Erbakan University, Konya, Turkey*
- <sup>72</sup> Also at *Bozok Universitetesi Rektörlüğü, Yozgat, Turkey*
- <sup>73</sup> Also at *Marmara University, Istanbul, Turkey*
- <sup>74</sup> Also at *Milli Savunma University, Istanbul, Turkey*
- <sup>75</sup> Also at *Kafkas University, Kars, Turkey*
- <sup>76</sup> Also at *Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
- <sup>77</sup> Also at *Ozyegin University, Istanbul, Turkey*
- <sup>78</sup> Also at *Vrije Universiteit Brussel, Brussel, Belgium*
- <sup>79</sup> Also at *School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
- <sup>80</sup> Also at *University of Bristol, Bristol, United Kingdom*
- <sup>81</sup> Also at *IPPP Durham University, Durham, United Kingdom*
- <sup>82</sup> Also at *Monash University, Faculty of Science, Clayton, Australia*
- <sup>83</sup> Also at *Università di Torino, Torino, Italy*
- <sup>84</sup> Also at *Bethel University, St. Paul, Minnesota, U.S.A.*
- <sup>85</sup> Also at *Karamanoğlu Mehmetbey University, Karaman, Turkey*
- <sup>86</sup> Also at *California Institute of Technology, Pasadena, California, U.S.A.*
- <sup>87</sup> Also at *United States Naval Academy, Annapolis, Maryland, U.S.A.*
- <sup>88</sup> Also at *Bingol University, Bingol, Turkey*
- <sup>89</sup> Also at *Georgian Technical University, Tbilisi, Georgia*
- <sup>90</sup> Also at *Sinop University, Sinop, Turkey*
- <sup>91</sup> Also at *Erciyes University, Kayseri, Turkey*
- <sup>92</sup> Also at *Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China*
- <sup>93</sup> Also at *Texas A&M University at Qatar, Doha, Qatar*
- <sup>94</sup> Also at *Kyungpook National University, Daegu, Korea*
- <sup>95</sup> Also at *another institute or international laboratory covered by a cooperation agreement with CERN*
- <sup>96</sup> Also at *Yerevan Physics Institute, Yerevan, Armenia*

<sup>97</sup> Also at Imperial College, London, United Kingdom

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