

CERN-EP-2024-174
2025/08/22

CMS-TOP-22-002

Search for flavor-changing neutral current interactions of the top quark mediated by a Higgs boson in proton-proton collisions at 13 TeV

The CMS Collaboration*

Abstract

A search for flavor-changing neutral current interactions of the top quark (t) and the Higgs boson (H) is presented. The search is based on proton-proton collision data collected in 2016–2018 at a center-of-mass energy of 13 TeV with the CMS detector at the LHC, and corresponding to an integrated luminosity of 138 fb^{-1} . Events containing a pair of leptons with the same-sign electric charge and at least one jet are considered. The results are used to constrain the branching fraction ($\mathcal{B}$) of the top quark decaying to a Higgs boson and an up (u) or charm (c) quark. No significant excess above the estimated background was found. The observed (expected) upper limits at 95% confidence level are found to be 0.072% (0.059%) for $\mathcal{B}(t \rightarrow Hu)$ and 0.043% (0.062%) for $\mathcal{B}(t \rightarrow Hc)$. These results are combined with two other searches performed by the CMS Collaboration for flavor-changing neutral current interactions of top quarks and Higgs bosons in final states where the Higgs boson decays to either a pair of photons or a pair of bottom quarks. The resulting observed (expected) upper limits at 95% confidence level are 0.019% (0.027%) for $\mathcal{B}(t \rightarrow Hu)$ and 0.037% (0.035%) for $\mathcal{B}(t \rightarrow Hc)$.

Published in Physical Review D as doi:10.1103/95q6-vv1p.

1 Introduction

Quark decays mediated by flavor-changing neutral currents (FCNCs) are forbidden at tree level in the standard model (SM) and are suppressed at higher orders in the perturbative expansion by the Glashow–Iliopoulos–Maiani mechanism [1] and Cabibbo–Kobayashi–Maskawa unitarity constraints [2]. As a result, the SM branching fractions for the decay of a top quark (t) into a Higgs boson (H) and an up quark (u), $t \rightarrow Hu$, or a charm quark (c), $t \rightarrow Hc$, are expected to be of the order of 10^{-17} and 10^{-15} , respectively [3–6].

Many scenarios of physics beyond the SM may enhance these interactions, possibly by many orders of magnitude. Examples of such models include those of warped extra dimensions [7], composite Higgs boson models [8], two-Higgs-doublet models (2HDMs) [9–12] including supersymmetric models with R -parity violation [13], and quark-singlet models [14]. These scenarios may lead to sizable FCNC interactions of quarks with any of the neutral force mediators or with the Higgs boson. The Hct interaction in particular may be enhanced in 2HDMs [15–18], including scenarios of flavor-violating Yukawa couplings [19].

Searches for FCNC interactions of the top quark mediated by a Higgs boson have been performed by the ATLAS [20–23] and CMS [24–27] Collaborations. This paper presents searches for FCNC top quark interactions in a final state having at least two leptons (e, μ) with the same-sign (SS) electric charge and at least one jet. The CMS Collaboration previously reported a search in a similar final state, analyzing 19.7 fb^{-1} of 8 TeV proton-proton (pp) collision data [24]. The results presented here are obtained from the analysis of (pp) collisions at a center-of-mass energy of 13 TeV, targeting the decay of the Higgs boson to WW , ZZ , or $\tau\tau$ leading to the final states described above. The data were collected with the CMS detector at the CERN LHC in 2016–2018, and correspond to an integrated luminosity of 138 fb^{-1} .

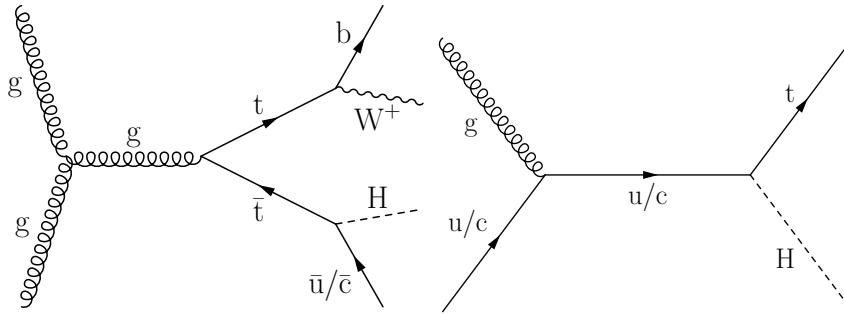


Figure 1: Representative Feynman diagrams for the production modes considered: $t\bar{t}$ production with the FCNC decay of the top quark to a Higgs boson and an up or charm quark (TT, left), and FCNC-associated production of a single top quark with a Higgs boson (ST, right).

Two channels for signal production are considered, the decay of a top quark to a Higgs boson and an up or charm quark in top quark-antiquark ($t\bar{t}$) pair production (TT production mode), as well as the associated production of a single top quark (ST production mode) with a Higgs boson via an up or charm quark, as shown in Fig. 1. The anomalous Hqt couplings enter through the top quark decay in the TT mode, while appearing in the matrix elements of the ST production mode with the single top quark subsequently decaying as normal, i.e. to a bottom quark and W boson. Other production modes are possible but are sub-dominant, such as the tW production mode which accounts for less than 4% of the signal. For the sake of consistency with other published searches for this phenomenon, only the TT and ST modes shown in Fig. 1 are considered. Results from a search in final states with leptons are combined with other FCNC searches performed by the CMS Collaboration targeting the decay of the Higgs boson to a pair of b quarks [26] or a pair of photons [27].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28].

Events of interest are selected using a two-tiered trigger system. The first level trigger, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μ s [29]. The second level trigger, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [30].

3 Simulated samples

Samples of simulated events are used in the design and validation of the analysis, the training and optimization of event classifiers, and in the estimate of expected yields from signal and rare SM background processes. Three separate sets of simulated events for each process are used in order to match the different data-taking conditions and algorithms used in 2016, 2017, and 2018.

The POWHEG v2 event generator [31–33] is used to simulate $t\bar{t}$ production [34], WZ and ZZ pair production [35], H production via gluon fusion [36], and $t\bar{t}H$ production [37] at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD). The JHUGEN generator [38] is used to simulate the decay of the Higgs boson into vector bosons in the gluon fusion production mode. Events with single top quarks produced in association with W bosons (tW) are simulated at NLO with POWHEG v1 [39] (2016) or POWHEG v2 (2017–2018). Samples of the Drell–Yan and W boson production processes are generated with up to four additional partons in the matrix element (ME) calculations using the MADGRAPH5_aMC@NLO event generator at leading order (LO) [40]. The MADGRAPH5_aMC@NLO v2.3.3 (v2.4.2) package is used for samples corresponding to 2016 (2017–2018) data-taking conditions. The production of $W^\pm W^\pm$, as well as the tWZ , $t\bar{t}\gamma$, and $t\bar{t} + XX$ (with $X = W, Z, H$) processes, are generated using MADGRAPH5_aMC@NLO at LO. Triple vector boson production (VVV, $V = Z, W$), diboson production in association with a photon ($WZ\gamma$, $WW\gamma$) as well as the $t\bar{t}Z$, tZq , $t\gamma$ and $t\bar{t}t\bar{t}$ processes are simulated using MADGRAPH5_aMC@NLO at NLO in QCD. The $t\bar{t}W$, $W\gamma$, $Z\gamma$, and VH processes are simulated at NLO with up to one or two extra partons in the ME calculations using MADGRAPH5_aMC@NLO.

The NNPDF3.0 [41] LO and NLO parton distribution function (PDF) sets are used to generate LO and NLO samples with 2016 data-taking conditions, while NNPDF3.1 next-to-NLO (NNLO) [42] is used for 2017–2018 samples. Event generators are interfaced with PYTHIA v8.226 [43] using the CUETP8M1 tune [44, 45] for 2016 and PYTHIA v8.230 using the CP5 tune [46] for 2017–2018 to simulate the parton shower, fragmentation, and hadronization of initial- and final-state partons, along with the underlying event. The MLM [47] and FxFx [48] prescriptions are employed to remove double counting of additional partons generated with MADGRAPH5_aMC@NLO and PYTHIA for the LO and NLO samples, respectively. The GEANT4

toolkit [49] is used to model the response of the CMS detector.

The effective Lagrangian with an FCNC coupling is:

$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} \left(F_{Hq}^L P_L + F_{Hq}^R P_R \right) q H + \text{h.c.} \quad (1)$$

Here, $P_L(P_R)$ are the left-hand (right-hand) projection operators defined as $P_L = (1 - \gamma_5)/2$ and $P_R = (1 + \gamma_5)/2$, and the notation h.c. indicates that the Hermitian conjugate terms are to be included in the sum. It is implemented in the FEYNRULES package [50], and the universal FEYNRULES output format [51] is used to generate the signal model. The complex chiral parameters are arbitrarily fixed to the values $F_{Hq}^L = 1$ and $F_{Hq}^R = 0$, as these parameters have no impact on the signal cross sections and usually have a small impact on kinematic distributions of objects in the event. Signal samples are generated in the TT and ST production modes assuming, for each mode, one of the two κ couplings is non-zero at a time. For the ST sample, the production and decays of the top quark and antiquark are simulated using MADGRAPH5_aMC@NLO at LO. The ST production mode cross section is calculated at LO precision with MADGRAPH5_aMC@NLO v2.6.0 as 72.6 (10.0) pb, equivalent to a coupling constant $\kappa_{Hut} = 1$ ($\kappa_{Hct} = 1$). The difference of the respective production cross sections originates from the up and charm quark parton distribution functions of the initial state protons. The TT production signal sample is generated with MADGRAPH5_aMC@NLO v2.4.2 at LO with up to two extra partons in the ME. The TT production mode cross section is taken to be 832 pb, as calculated at NNLO precision in perturbative QCD including soft-gluon resummation to next-to-next-to-leading-logarithm [52]. The SM and FCNC decays of the top quark and antiquark are simulated using MADSPIN [53]. The top quark and Higgs boson masses are set to 172.5 and 125.0 GeV, respectively. The Higgs boson decay is simulated using PYTHIA v8.226 (2016) or PYTHIA v8.230 (2017 and 2018). The generated signal samples are filtered to have one leptonically decaying top quark and one Higgs boson decaying to WW , ZZ , or $\tau\tau$. The cross sections applied in the analysis account for the branching fraction of the filtered LO decays. The adjusted cross sections are 12.08 pb for the TT production and 7.32 (1.01) pb for the ST Hut (Hct) production.

Additional simulated minimum bias pp interactions within the same or adjacent bunch crossings (pileup) are included in the simulated events, and events are reweighted according to the observed instantaneous luminosity and the total inelastic pp cross section of 69.2 mb [54].

4 Event selection and search strategy

This analysis considers events with at least two leptons (electron or muon) with the SS electric charge and at least one jet. The main backgrounds are from detector effects (namely non-prompt leptons and charge misidentified leptons) and SM processes that produce an SS lepton pair, including processes producing multiple gauge bosons and/or top quarks. Backgrounds are suppressed by making requirements on the kinematic variables of reconstructed physics objects, the same as those presented in Refs. [55–57].

Events are reconstructed using the particle-flow (PF) algorithm [58], which combines information from the CMS subdetectors to identify charged and neutral hadrons, photons, electrons, and muons, collectively referred to as PF candidates. These candidates are associated with reconstructed vertices. 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. [59]. The physics objects used include jets clustered from PF candidates associated with the PV and the magnitude of missing transverse momentum, $\vec{p}_T^{\text{miss}}$ [60]. The $\vec{p}_T^{\text{miss}}$ is computed

as the negative vector sum of the transverse momentum ($\vec{p}_T$) of all the PF candidates, excluding charged-hadron candidates that do not originate from the PV. The magnitude of this vector is referred to as p_T^{miss} .

Electron candidates are reconstructed by combining clusters of energy deposits in the ECAL with tracks [61]. The electron identification is performed using shower shape variables, track-cluster matching variables, and track quality variables. To reject electrons originating from photon conversions inside the detector, electron candidates are required to have at most one missing measurement in the innermost tracker layers and to be incompatible with any conversion-like secondary vertices. Muon candidates are reconstructed by geometrically matching tracks from measurements in the muon system and tracker, and fitting them to form a global muon track. Good muon candidates are selected using the qualities of the geometrical matching and of the track [62].

Selected electrons (muons) are required to have $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$ (2.5) and originate from the PV. Additionally, electrons in the transition region $1.442 < |\eta| < 1.556$, between the barrel and endcaps of the ECAL, are excluded since the reconstruction of an electron object in this region is not optimal. Leptons are required to be isolated using a logical combination of three isolation variables: the energy surrounding the lepton candidate in a fixed cone size $\Delta R = 0.4$, the energy surrounding the lepton candidate in a cone size that depends on the candidate p_T , and the transverse momentum of the lepton candidate relative to the residual momentum of the nearest jet after lepton momentum subtraction. This definition is designed to distinguish leptons produced in decays of W or Z bosons (“prompt leptons”) from leptons produced in hadron decays, in conversions of photons in jets, or hadrons misidentified as leptons (“nonprompt leptons”). Lepton selection efficiencies are in the ranges of 45–80 (70–90)% for electrons (muons), increasing as a function of the lepton p_T and reaching a maximum value for $p_T > 60 \text{ GeV}$. Details of the lepton isolation requirements can be found in [55].

Hadronic jets are clustered from neutral and charged PF candidates associated with the PV, using the anti- k_T algorithm [63, 64] and a distance parameter of 0.4. The jet momentum is determined as the vector sum of all PF candidate momenta in the jet. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, $\gamma + \text{jets}$, $Z + \text{jets}$, and multijet events are used to determine any residual differences between the observed and simulated jet energy scale, and appropriate corrections are made [65]. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures. The $\vec{p}_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. The H_T is defined as the scalar p_T sum of jets in an event.

Selected jets must have $p_T > 25 \text{ GeV}$, $|\eta| < 2.4$, and be separated from isolated leptons by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$, where ϕ is the azimuthal angle in radians. Jets containing the decay of a b hadron are identified as bottom quark jets (b-tagged jets) using a deep neural network algorithm, DEEPJET [66–68]. The discriminator working point is chosen so that the misidentification rate to tag light-flavor or gluon jets is approximately 1%. This choice results in an efficiency to identify a bottom quark jet in the range 75–85% for jets with p_T of 25–400 GeV, and a misidentification rate of about 15% for jets originating from a charm quark. Jets failing the b tagging requirement are further required to have $p_T > 30 \text{ GeV}$ to improve signal purity. The DEEPJET algorithm is also used to identify jets containing the decay of a c-flavored hadron (c-tagged jets) [69]. The DeepJet algorithm is a multiclassifier, allowing for a b tagging discriminator score and a c tagging discriminator score to be returned by the same algorithm. Jets

Table 1: Summary of the trigger thresholds used to select the analysis data set. The triggers require two isolated leptons, with different p_T requirements depending on their flavors. For each trigger, the p_T threshold 1 corresponds to the lepton listed first, and the p_T threshold 2 to the lepton listed last.

Trigger	$p_{T,1}$ threshold	$p_{T,2}$ threshold
ee	23 GeV	12 GeV
$e\mu$	23 GeV	8 GeV
μe	23 GeV	12 GeV
$\mu\mu$	17 GeV	8 GeV

Table 2: Baseline analysis selections.

Physics objects	Selection criteria
Lepton	Pair of isolated SS leptons (e or μ), lead $p_T > 25$ GeV, else $p_T > 20$ GeV, $ \eta_e < 2.4$, $ \eta_\mu < 2.5$
Jet	≥ 2 in SS events or ≥ 1 in multilepton events, $p_T > 30$ GeV, $ \eta < 2.4$
b-tagged jet	$p_T > 25$ GeV, $ \eta < 2.4$
$m_{\ell\ell}$ (SF)	> 12 GeV
$m_{\ell\ell}$ (any flavor, any charge)	> 8 GeV
m_{ee} (SS)	< 75 or > 105 GeV

arising from b and c hadrons tend to be amongst the hardest jets in the event and thus the b and c tagging discriminator scores for the leading three jets are used for event classification.

Events containing at least three leptons, referred to as multilepton events, or a pair of leptons with the same-sign electric charged are selected using a logical OR of triggers requiring the presence of two isolated leptons. The trigger efficiency for electrons is 90–98%, reaching its maximum value for $p_T > 30$ GeV. For muons, the trigger efficiency is around 92%. The uncertainty in the trigger efficiency measurement is 1–5% per trigger lepton. The trigger requirements are summarized in Table 1.

Events are vetoed if any pair of leptons in the events is consistent with coming from a known resonance. Events with a pair of leptons with an invariant mass less than 8 GeV are vetoed, irrespective of lepton flavor or charge. Additionally, events with a pair of same-flavor leptons of any charge are vetoed if the invariant mass of the pair is greater than 12 GeV. Finally, events with a pair of electrons with the same-sign electric charge are vetoed if the invariant mass of the pair is between 75 and 105 GeV. A baseline analysis selection defined in terms of requirements on these objects is summarized in Table 2. The main SM processes that contribute at this stage of the selection are dibosons, associated production of gauge bosons with top quarks, $t\bar{t}$, $W + \text{jets}$, and Drell–Yan.

Events passing the baseline selection are classified using a boosted decision tree (BDT) trained on simulated samples of signal and background processes. Training is performed using a mixture of the two signal production modes weighted according to the cross sections in Section 3. Two BDTs are trained: one for identifying the Htt signal and one the Hct signal. Both BDTs are trained using the XGBOOST [70] framework with 33 input features, which were selected for their expected differences between signal and background events:

- The number of electrons, jets, and b-tagged jets in the event,

- kinematic features of up to three leptons including the p_T , $|\eta|$, transverse and longitudinal impact parameters, and the transverse mass of the lepton and the p_T^{miss} ,
- features of the leading three jets: p_T , b and c tagging discriminator score,
- invariant mass of the two p_T -leading leptons,
- p_T of the jet with the largest $|\eta|$,
- b tagging discriminator score of the p_T -leading b-tagged jet,
- p_T of the jet with the highest b tagging discriminator score,
- p_T^{miss} ,
- H_T .

The input features above are primarily numbers, kinematics, and other properties of selected leptons and jets. These are among the most important discriminating variables between signal and backgrounds that are nearly entirely from processes containing one or more top quarks. Separate trainings for the ST and TT signal modes were evaluated and did not yield significant improvement.

Search regions (SRs) are defined by bins in the BDT discriminator value. Bin edges are determined using the SCIKITLEARN [71] quantile transformation function so that the signal acceptance is approximately uniform across SRs, reducing the effects of outlier events. Expected yields of the signal process in these SRs are determined from simulation after applying scale factors (SFs) that correct for differences between data and simulation in the efficiencies of the applied triggers, lepton selection, and b tagging.

5 Background estimation

Events containing an SS lepton pair and jets arise from several SM processes. The first category consists of events that contain one or more nonprompt leptons. Events containing a pair of prompt leptons with the SS electric charge arise from SM processes including diboson and triboson production and associated production of a boson with a $t\bar{t}$. This background is subdominant and is estimated from simulation. The smallest category of background consists of dilepton events from $t\bar{t}$, Drell–Yan, and WW processes with a charge-misidentified prompt electron. Descriptions of the methods used to estimate each category of background and the validation studies follow.

Semileptonic $t\bar{t}$ and leptonic W + jets processes with an additional nonprompt lepton with the same-sign electric charge as a prompt lepton constitute the largest background in this search. This background is estimated using the “tight-to-loose” (TL) ratio method [55]. The tight identification and isolation requirements used to select prompt leptons are relaxed to define a loose lepton selection that is enriched in nonprompt leptons. The efficiency, ϵ_{TL} , for a nonprompt lepton that satisfies the loose selection to also pass the tight requirement is measured in a control sample of single-lepton events, as a function of the lepton flavor, p_T , and $|\eta|$. Contamination from processes producing a prompt lepton, mostly W + jets and followed by Drell–Yan, is subtracted using the simulation. The loose-lepton definition was optimized to achieve an ϵ_{TL} that is approximately the same for lepton candidates arising from heavy or light flavor hadrons. Furthermore, for leptons that fail the tight selection, the lepton p_T is redefined as the sum of the lepton p_T and the energy in the isolation cone, where the isolation cone is an angular distance $\Delta R = 0.4$ from the lepton p_T . The redefinition accounts for the momentum of the parent parton. Together, the criteria allow constructing an ϵ_{TL} that is approximately independent of sample and SR. See Ref. [55] for further details. For each SR, a control region (CR) is constructed

with the same selection criteria as the SR but requiring that at least one lepton passes the loose selection but fails the tight requirement. The number of events with a nonprompt lepton in each SR is estimated by weighting each loose-not-tight lepton in a corresponding CR event by a factor of $\epsilon_{\text{TL}}/(1 - \epsilon_{\text{TL}})$.

The simulation is used to evaluate the performance of the method. A TL efficiency, measured from simulated samples of multijet production, is used to predict the number of events with a nonprompt lepton expected to enter the SRs. The estimate is compared with the observed number of events with a nonprompt lepton in simulated $t\bar{t}$ and $W + \text{jets}$ samples. The predicted and observed rates of events with a nonprompt lepton are compared in each SR and as functions of kinematic properties. These rates are found to agree within 30%, which is taken as a flat systematic uncertainty in the final nonprompt-lepton background estimate.

The second category of background consists of SM processes that produce a pair of prompt SS leptons. Diboson and triboson processes and associated production of a boson with $t\bar{t}$ are the most significant processes in this background category. Smaller contributions arise from processes including a genuine photon such as $W\gamma, Z\gamma, t\gamma$ via photon conversion, and “rare” processes, such as tWZ and $t\bar{t}\bar{t}$.

As it is not possible to construct a CR enriched in these processes with a large number of events and high purity, the backgrounds are estimated from simulation. Expected yields are estimated after applying SFs that account for small differences between data and simulation in the measured trigger, lepton selection, and b tagging efficiencies, with associated systematic uncertainties described in Section 6.

The smallest category of background consists of dilepton $t\bar{t}$ and Drell–Yan events where the charge of an electron is misidentified, thus misclassifying a pair of prompt leptons with opposite-sign electric charge as an SS pair. Referred to as the “charge flip” background, it is estimated using a method similar to that described above for estimating the nonprompt-lepton background. The probability, ϵ_q , to misidentify the charge of an electron is estimated in simulation, as a function of electron p_T and $|\eta|$. This probability ranges between 10^{-5} and 10^{-3} for electrons and is at least an order of magnitude smaller for muons. For each SR requiring two SS leptons, a CR is constructed with the same selections except that the two leptons have opposite electric charge. The number of events with a lepton whose charge is misidentified is estimated by scaling each CR event by a weight obtained by summing terms of $\epsilon_q/(1 - \epsilon_q)$ for each lepton in the event.

Because the charge misidentification rate is estimated using simulation, the performance is evaluated in a CR enriched in $Z \rightarrow e^+e^-$ events with the charge of the electron or positron misidentified. For each data collection year, a single SF inclusive in p_T and $|\eta|$ is derived from a comparison of the observed and estimated number of such electron pairs. For 2016 (2017–2018) the correction factor is approximately 1.1 (1.4). A flat 30% uncertainty in the estimate is assumed in all regions based on these and other studies described in the following section.

6 Systematic uncertainties

Sources of systematic uncertainties related to signal and background processes and their impact on the results are summarized in Table 3. The change in SR yields is reported as a one standard deviation range. A description of the uncertainties considered are summarized in this section, first in backgrounds estimated using CRs (charge-misidentified and nonprompt-lepton) followed by yields estimated from simulation.

The nonprompt-lepton background is assigned an uncertainty of 30% based on the agreement observed in closure tests of the TL method using simulated QCD multijet, $t\bar{t}$, and $W + \text{jets}$ samples. The simulation is used to subtract contamination from prompt leptons, which is less than 1% in the CR, but is typically between 10% and 20% in the ϵ_{TL} measurement control sample, with uncertainties in ϵ_{TL} as large as 50% in the least statistically significant bins. This uncertainty leads to a 7–10% impact on the predicted yields in the SR. Uncertainties in the subtracted prompt contamination are considered separately for electrons and muons and correlated across bins of ϵ_{TL} for each lepton flavor. The charge-misidentified lepton background is assigned an uncertainty of 30% based on the agreement observed between the estimate and data in a control sample enriched in $Z \rightarrow e^+e^-$ events with one electron or positron having a misidentified charge. An uncertainty $<5\%$ in the rate at which the electron charge is misidentified results from the limited number of events in the simulated samples in which this rate is measured. The statistical uncertainty in the CRs used to estimate the charge-misidentified and nonprompt-lepton backgrounds is included in the total uncertainty. The statistical uncertainties in the nonprompt-lepton background and the charge-misidentified lepton background are treated as fully uncorrelated. The other uncertainties in these backgrounds are treated as correlated between SR bins but uncorrelated between data taking periods. The uncertainty in the estimate of the contribution of processes with a nonprompt lepton is the dominant uncertainty in the background.

The remaining uncertainties described here apply only for the estimate of yields of the signal process and backgrounds arising from SM processes with a prompt, SS lepton pair, which are estimated using simulation. Statistical uncertainties originating from the finite size of simulated samples are accounted for in each SR bin and for signal and background separately [72]. The integrated luminosities of the 2016, 2017, and 2018 data-taking periods are individually known with uncertainties in the 1.2–2.5% range [73–75], while the total 2016–2018 integrated luminosity has an uncertainty of 1.6%, the improvement in precision reflecting the (uncorrelated) time evolution of some systematic effects. The simulated samples are reweighted according to the observed instantaneous luminosity and the minimum bias cross section. The uncertainty in the total inelastic pp cross section leads to changes $<2\%$ in the expected signal and background yields.

The efficiency of the trigger requirements is measured with an uncertainty of 2%, using an independent data sample selected with single-lepton triggers. The efficiencies of the lepton reconstruction and identification requirements are measured using data samples enriched in $Z \rightarrow \ell\ell$ events, with uncertainties of up to 5 (3)% per electron (muon). Varying the lepton efficiency SFs results in a 2–3% effect on the SR yields. The jet energy scale is varied within its uncertainty resulting in a 1–8% effect in signal yields and $<5\%$ in background yields for rare SM processes.

The tagging efficiencies for b, c, and light-flavor jets are measured in dedicated data samples [67]. Varying these efficiencies within their measured uncertainties results in variations between 6–16% of the SR yields.

Uncertainties in the normalization and shape distribution of events across SRs are considered for each background process estimated from simulation. Flat uncertainties are applied to specific background processes to account for the uncertainty in the total cross section: 5% for WZ [76], 10% for SS WW [77], 12% for $t\bar{t}W$ [78], and 8% for $t\bar{t}Z$ [78]. These flat uncertainties also account for the normalization changes due to the choice of the renormalization (μ_R) and factorization (μ_F) scales. The uncertainties in the shape distribution of events for each background process from the choice of the μ_R , μ_F , and α_S scales is accounted for separately and are

obtained by taking the envelope of the distributions obtained with modified scales. The typical effect of varying the μ_F and μ_R scales on the shapes of the BDT distributions is 10 to 15%. The impact of variations of the PDFs [79] is 4 to 6%.

For signal events, the total cross section uncertainty in the TT production mode is 6%, estimated from the uncertainty in the $t\bar{t}$ NNLO cross section, caused by the variation of the PDFs and the strong coupling α_S [80–82]. The uncertainty in the cross section for signal production in the ST mode is estimated to be 30%, resulting from missing higher-order corrections. The total impact in the normalization of the signal yields ranges from 6 to 10% across SRs. The typical effect of varying the μ_F and μ_R scales on the shapes of the BDT distributions is 2 to 9% for signal processes. The impact of variations of the PDFs [79] is $<2\%$.

All systematic uncertainties are correlated between the SR bins. With the exception of the μ_F and μ_R scales and cross section uncertainties, every systematic effect is correlated between signal and the rare SM background. The trigger efficiency uncertainties are assumed as being uncorrelated between the data taking periods. The uncertainty in the integrated luminosity is partially correlated between years, while all remaining uncertainties are correlated.

Table 3: Sources of systematic uncertainties in the yields of signal and background processes, as well as their impact on the yields in the SRs. The impact is expressed as a one standard deviation range.

Source	Uncertainty in tcH prediction	Uncertainty in tuH prediction	Uncertainty in SM SS prediction	Uncertainty in nonprompt estimate	Uncertainty in charge flip estimate
Estimate normalization	—	—	—	30%	30%
ϵ_{TL}/ϵ_q	—	—	—	7–10%	$<5\%$
Integrated luminosity	1.6%	1.6%	1.6%	—	—
Pileup	$<2\%$	$<2\%$	$<2\%$	—	—
Trigger efficiency	2%	2%	2%	—	—
Lepton efficiency	2–3%	2–3%	2–3%	—	—
Jet energy scale	1–6%	$<8\%$	$<5\%$	—	—
b/c tagging	10–16%	6–13%	7–14%	—	—
Theory normalization	6–10%	6–10%	5–25%	—	—
Renormalization and factorization	7–9%	2–6%	10–15%	—	—
scale shape	—	—	—	—	—
PDF shape	$<2\%$	$<2\%$	4–6%	—	—
Total	14–16%	11–14%	20–28%	31–35%	29–31%

7 Results

A binned likelihood fit is constructed using yields from the signal and control regions, incorporating the theoretical and experimental uncertainties described in Section 6 as nuisance parameters. The number of observed events and of simulated events in the SRs and CRs are Poisson distributed. Expected yields of signal events are estimated using a mixture of simulated samples of TT and ST production modes weighed according to the cross sections in Section 3. Figure 2 shows that the estimated backgrounds and observed data are consistent within statistical and systematic uncertainties as a function of the BDT score, before (“prefit”) and after maximizing the likelihood function (“postfit”). Knowledge of the backgrounds, particularly the non-prompt background, is improved considering the signal and control region

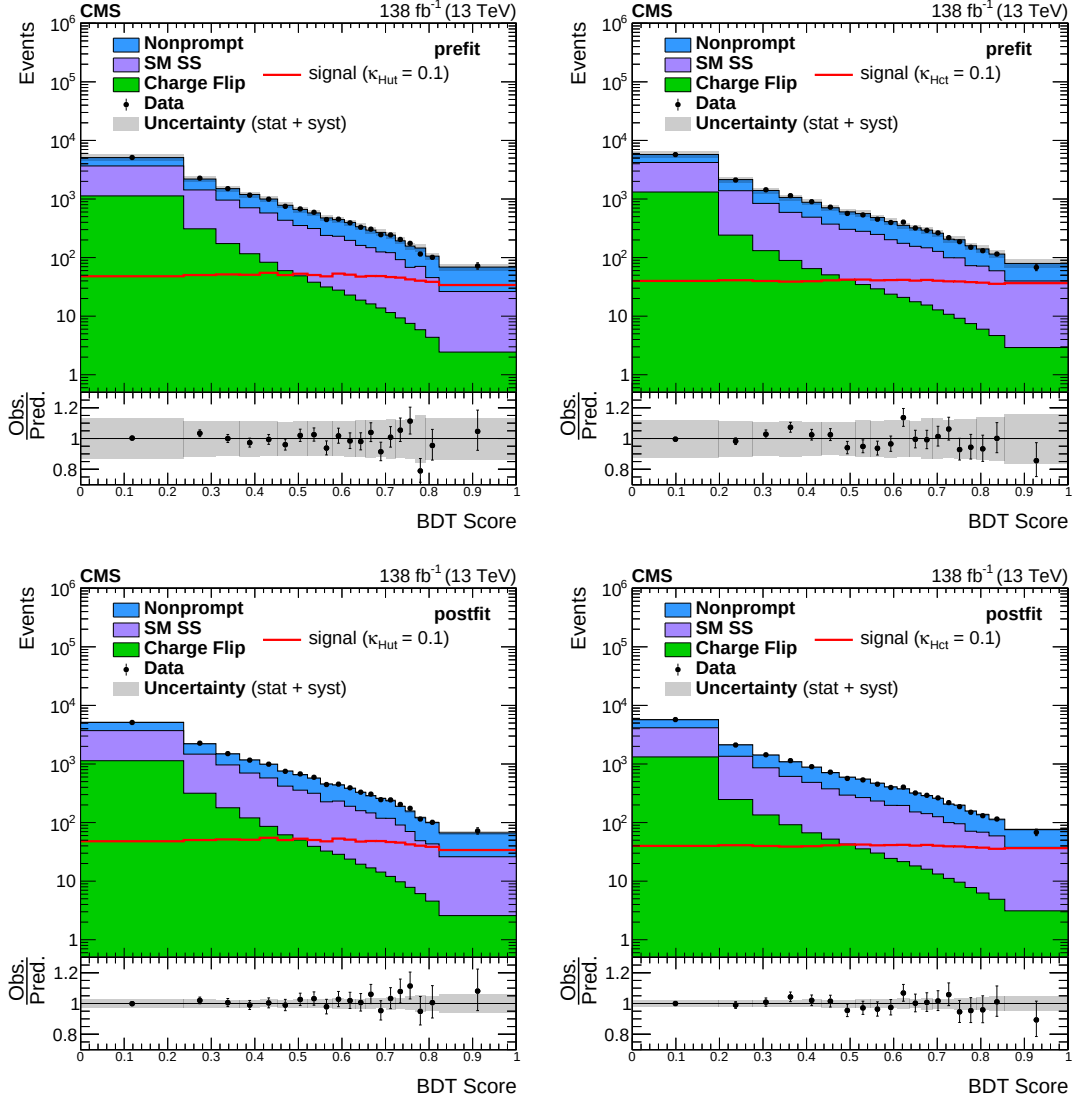


Figure 2: The prefit (upper) and postfit (lower) observed and expected distributions of BDT score in the SR for 2016–2018 data are shown. The $t \rightarrow H_u$ signal is shown on the left and $t \rightarrow H_c$ is shown on the right, normalized with a coupling $\kappa_{H_{qt}} = 0.1$ for illustration. The uncertainty bands include statistical and systematic uncertainties in the estimated backgrounds.

yields in the fit. Overlaid are distributions of signal, normalized assuming a coupling strength of 0.1 between the top quark, the Higgs boson, and an up or charm quark. While the presence of FCNC interactions would affect other Higgs boson couplings, existing experimental constraints on FCNC interactions limit the potential impact on the Higgs boson decay modes, rendering the effects negligible.

Results are obtained using the CMS statistical analysis tool COMBINE [83] which is based on the RooFit [84] and RooStats [85] frameworks. Upper limits on the coupling strengths and branching fractions are set at 95% confidence level (CL), using the CL_s criterion with the LHC profile likelihood ratio as a test statistic in the asymptotic formulation [86–89]. Observed (expected) limits are 0.072 (0.059)% on the $\mathcal{B}(t \rightarrow H_u)$ and 0.043 (0.062)% on the $\mathcal{B}(t \rightarrow H_c)$. The limits can be cast as observed (expected) constraints on the anomalous coupling strengths: $\kappa_{H_{ut}} < 0.071(0.064)$ and $\kappa_{H_{ct}} < 0.055(0.065)$. The limits agree within one standard deviation,

see Fig. 3, which shows the expected and observed limits, as well as the one and two standard deviation bands on the coupling strength and on the branching fraction for each anomalous coupling. The exclusion curves shown in Fig. 3 are obtained by interpolating the limits with only a single coupling present, assuming a linear relationship in the branching fractions.

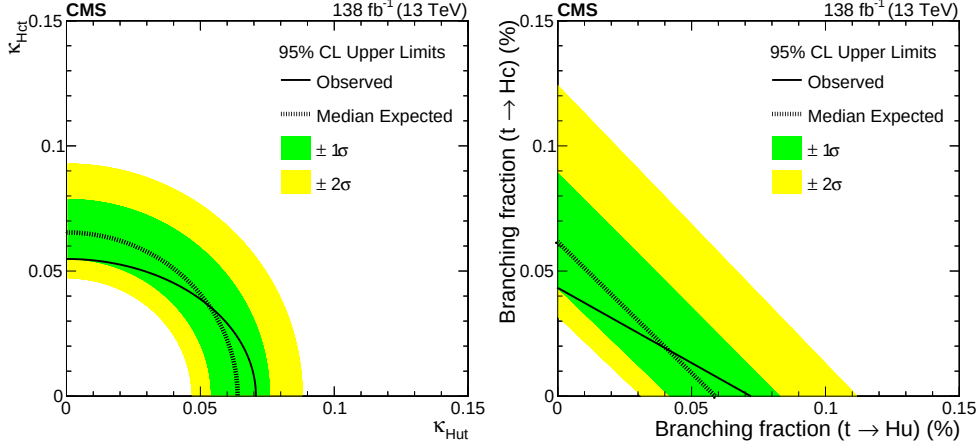


Figure 3: The expected (dashed line) and observed (solid line) limits on the coupling strength (left) and on the branching fraction (right) are shown. The green (yellow) bands show the 68 (95)% confidence level ranges of the expected limits. The area to the right and above the solid line is excluded.

8 Combination

In addition to the results presented in the previous section, the CMS Collaboration has reported the results of two other searches for Higgs-mediated FCNC decays of the top quark, in which the Higgs boson decays to bottom quark pairs [26] or to a pair of photons [27]. The results of these searches and the new search presented are summarized in Table 4. A statistical combination of the results of the three searches is performed. As the three results target different and distinct decay modes of the Higgs boson, there is no overlap between the SRs of the three analyses. Correlations of systematic uncertainties in the signal and background yields are studied and accounted for. Uncertainties are correlated between the three analyses if the object definitions and approaches to measuring uncertainties are the same; otherwise, they are uncorrelated. Uncertainties in the jet energy scale and p_T^{miss} resolution, the integrated luminosity, the lepton identification efficiencies, and per-process theoretical uncertainties are treated as fully correlated. Remaining uncertainties are treated as uncorrelated. The impact of the choice of the correlation scheme on the combination result was studied and found to be $<1\%$. The results of the combination are reported in Table 4. A summary and comparison of the results of the individual analyses and the combination is shown in Fig. 4.

9 Summary

This paper presents the results of a search for flavor changing neutral current interactions of the top quark (t), Higgs boson (H), and an up (u) or charm (c) quark. The search is performed in a final state with a pair of leptons of same electric charge and at least one jet. Expected yields from backgrounds emerging from detector effects are estimated by extrapolating yields observed in control regions using transfer factors measured in orthogonal data or simulated samples. Expected yields from standard model processes producing a pair of prompt leptons with the

Table 4: Observed and expected limits on the $t \rightarrow Hu$ and $t \rightarrow Hc$ branching fractions for the three searches in different Higgs boson decay channels performed by the CMS Collaboration. A statistical combination of the results is also reported.

Analysis	95% CL limit on $\mathcal{B}(t \rightarrow Hu)$	95% CL limit on $\mathcal{B}(t \rightarrow Hc)$
	observed (expected)	observed (expected)
$H \rightarrow b\bar{b}$ [26]	0.079 (0.11)%	0.094 (0.086)%
$H \rightarrow \gamma\gamma$ [27]	0.019 (0.031)%	0.073 (0.051)%
Leptonic (this analysis)	0.072 (0.059)%	0.043 (0.062)%
Combination	0.019 (0.027)%	0.037 (0.035)%

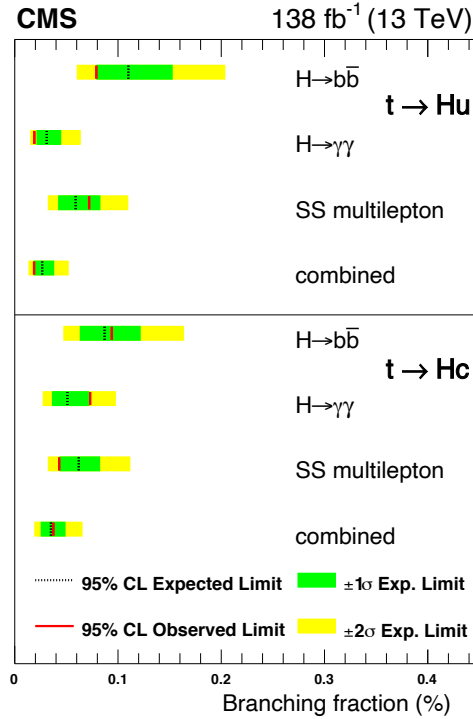


Figure 4: Summary of the observed and expected results from the three individual analyses and their combination. The dotted line shows the expected limits and the solid red lines shows the observed limits. The green and yellow bands show the 68 and 95% confidence level ranges of the expected limits.

same-sign electric charge are estimated from simulation. Two trained boosted decision trees are used to evaluate and classify each event. No excess above the estimated background from standard model processes is observed. The observed (expected) upper limits at 95% confidence level (CL) on the branching fraction are found to be 0.072% (0.059%) for $\mathcal{B}(t \rightarrow Hu)$ and 0.043% (0.062%) for $\mathcal{B}(t \rightarrow Hc)$. The limits can be cast as observed (expected) constraints on the anomalous coupling strengths: $\kappa_{Hut} < 0.071(0.064)$ and $\kappa_{Hct} < 0.055(0.065)$.

The ATLAS Collaboration has performed a similar search, including a targeted $H \rightarrow \tau^+\tau^-$ final state [23]. A combination of ATLAS searches in different final states obtained observed (expected) limits at 95% CL of $\mathcal{B}(t \rightarrow Hu) < 0.026\%(0.018\%)$ and $\mathcal{B}(t \rightarrow Hc) < 0.034\%(0.023\%)$. A statistical combination of the results of the search in leptonic final states with those of pre-

vious CMS publications searching for the same phenomena where the Higgs boson decays to a bottom quark-antiquark pair or to a pair of photons is performed. The results of the combination lead to observed (expected) exclusion limits at the 95% CL on the branching fractions $\mathcal{B}(t \rightarrow Hb) < 0.019\%(0.027\%)$ and $\mathcal{B}(t \rightarrow H\gamma) < 0.037\%(0.035\%)$ and represent the most stringent constraints on these interactions from the CMS Collaboration.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); 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); LMTLT (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 (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-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 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); 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 B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] S. L. Glashow, J. Iliopoulos, and L. Maiani, “Weak interactions with lepton-hadron symmetry”, *Phys. Rev. D* **2** (1970) 1285, doi:10.1103/PhysRevD.2.1285.
- [2] M. Kobayashi and T. Maskawa, “CP violation in the renormalizable theory of weak interaction”, *Prog. Theor. Phys.* **49** (1973) 652, doi:10.1143/PTP.49.652.
- [3] G. Eilam, J. L. Hewett, and A. Soni, “Rare decays of the top quark in the standard and two Higgs doublet models”, *Phys. Rev. D* **44** (1991) 1473, doi:10.1103/PhysRevD.44.1473. [Erratum: doi:10.1103/PhysRevD.59.039901].
- [4] B. Mele, S. Petrarca, and A. Soddu, “A new evaluation of the decay width in the standard model”, *Phys. Lett. B* **435** (1998) 401, doi:10.1016/S0370-2693(98)00822-3.
- [5] J. A. Aguilar-Saavedra, “Top flavor-changing neutral interactions: theoretical expectations and experimental detection”, *Acta Phys. Polon. B* **35** (2004) 2695, doi:10.48550/arXiv.hep-ph/0409342, arXiv:hep-ph/0409342.
- [6] C. Zhang and F. Maltoni, “Top-quark decay into Higgs boson and a light quark at next-to-leading order in QCD”, *Phys. Rev. D* **88** (2013) 054005, doi:10.1103/physrevd.88.054005, arXiv:1305.7386.
- [7] A. Azatov, M. Toharia, and L. Zhu, “Higgs mediated flavor changing neutral currents in warped extra dimensions”, *Phys. Rev. D* **80** (2009) 035016, doi:10.1103/physrevd.80.035016, arXiv:0906.1990.
- [8] A. Azatov, G. Panico, G. Perez, and Y. Soreq, “On the flavor structure of natural composite Higgs models & top flavor violation”, *JHEP* **12** (2014) 082, doi:10.1007/jhep12(2014)082, arXiv:1408.4525.
- [9] S. Bejar, J. Guasch, and J. Solà, “Loop induced flavor changing neutral decays of the top quark in a general two Higgs doublet model”, *Nucl. Phys. B* **600** (2001) 21, doi:10.1016/S0550-3213(01)00044-X, arXiv:hep-ph/0011091.
- [10] J. Guasch and J. Solà, “FCNC top quark decays in the MSSM: a door to SUSY physics in high luminosity colliders?”, *Nucl. Phys. B* **562** (1999) 3, doi:10.1016/S0550-3213(99)00579-9.

- [11] J. J. Cao et al., “Supersymmetry-induced flavor-changing neutral-current top-quark processes at the CERN Large Hadron Collider”, *Phys. Rev. D* **75** (2007) 075021, doi:10.1103/physrevd.75.075021, arXiv:hep-ph/0702264.
- [12] J. Cao et al., “SUSY induced top quark FCNC decay $t \rightarrow cH$ after Run I of LHC”, *Eur. Phys. J. C* **74** (2014) 3058, doi:10.1140/epjc/s10052-014-3058-1, arXiv:1404.1241.
- [13] G. Eilam et al., “Top-quark rare decay $t \rightarrow cH$ in R-parity-violating SUSY”, *Phys. Lett. B* **510** (2001) 227, doi:10.1016/s0370-2693(01)00598-6, arXiv:hep-ph/0102037.
- [14] J. A. Aguilar-Saavedra, “Effects of mixing with quark singlets”, *Phys. Rev. D* **67** (2003) 035003, doi:10.1103/PhysRevD.69.099901, arXiv:hep-ph/0210112. [Erratum: doi:10.1103/PhysRevD.67.035003].
- [15] W.-S. Hou, “Tree level $t \rightarrow c h$ or $h \rightarrow t c$ decays”, *Phys. Lett. B* **296** (1992) 179, doi:10.1016/0370-2693(92)90823-M.
- [16] I. Baum, G. Eilam, and S. Bar-Shalom, “Scalar flavor changing neutral currents and rare top quark decays in a two Higgs doublet model ‘for the top quark’”, *Phys. Rev. D* **77** (2008) 113008, doi:10.1103/PhysRevD.77.113008, arXiv:0802.2622.
- [17] C. Kao, H.-Y. Cheng, W.-S. Hou, and J. Sayre, “Top decays with flavor changing neutral Higgs interactions at the LHC”, *Phys. Lett. B* **716** (2012) 225, doi:10.1016/j.physletb.2012.08.032, arXiv:1112.1707.
- [18] B. Altunkaynak et al., “Flavor changing heavy Higgs interactions at the LHC”, *Phys. Lett. B* **751** (2015) 135, doi:10.1016/j.physletb.2015.10.024, arXiv:1506.00651.
- [19] K.-F. Chen, W.-S. Hou, C. Kao, and M. Kohda, “When the Higgs meets the top: Search for $t \rightarrow ch^0$ at the LHC”, *Phys. Lett. B* **725** (2013) 378, doi:10.1016/j.physletb.2013.07.060, arXiv:1304.8037.
- [20] ATLAS Collaboration, “Search for top quark decays $t \rightarrow qH$, with $H \rightarrow \gamma\gamma$, in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector”, *JHEP* **10** (2017) 129, doi:10.1007/JHEP10(2017)129, arXiv:1707.01404.
- [21] ATLAS Collaboration, “Search for flavor-changing neutral currents in top quark decays $t \rightarrow Hc$ and $t \rightarrow Hu$ in multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **98** (2018) 032002, doi:10.1103/PhysRevD.98.032002, arXiv:1805.03483.
- [22] ATLAS Collaboration, “Search for top-quark decays $t \rightarrow Hq$ with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **05** (2019) 123, doi:10.1007/JHEP05(2019)123, arXiv:1812.11568.
- [23] ATLAS Collaboration, “Search for flavour-changing neutral-current couplings between the top quark and the Higgs boson in multi-lepton final states in 13 TeV pp collisions with the ATLAS detector”, *Eur. Phys. J. C* **84** (2024) 757, doi:10.1140/epjc/s10052-024-12994-1, arXiv:2404.02123.
- [24] CMS Collaboration, “Search for top quark decays via Higgs-boson-mediated flavor-changing neutral currents in pp collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **02** (2017) 079, doi:10.1007/JHEP02(2017)079, arXiv:1610.04857.

-
- [25] 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, doi:10.1007/JHEP06(2018)102, arXiv:1712.02399.
- [26] CMS Collaboration, “Search for flavor-changing neutral current interactions of the top quark and the Higgs boson decaying to a bottom quark-antiquark pair at $\sqrt{s} = 13$ TeV”, *JHEP* **02** (2022) 169, doi:10.1007/JHEP02(2022)169, arXiv:2112.09734.
- [27] 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, doi:10.1103/physrevlett.129.032001, arXiv:2111.02219.
- [28] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [29] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [30] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [31] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [32] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [33] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [34] S. Frixione, P. Nason, and G. Ridolfi, “A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction”, *JHEP* **09** (2007) 126, doi:10.1088/1126-6708/2007/09/126, arXiv:0707.3088.
- [35] P. Nason and G. Zanderighi, “ W^+W^- , WZ and ZZ production in the POWHEG-BOX-V2”, *Eur. Phys. J. C* **74** (2014) 2702, doi:10.1140/epjc/s10052-013-2702-5, arXiv:1311.1365.
- [36] E. Bagnaschi, G. Degrandi, 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, doi:10.1007/JHEP02(2012)088, arXiv:1111.2854.
- [37] H. B. Hartanto, B. Jager, L. Reina, and D. Wackeroth, “Higgs boson production in association with top quarks in the POWHEG BOX”, *Phys. Rev. D* **91** (2015) 094003, doi:10.1103/PhysRevD.91.094003, arXiv:1501.04498.
- [38] S. Bolognesi et al., “On the spin and parity of a single-produced resonance at the LHC”, *Phys. Rev. D* **86** (2012) 095031, doi:10.1103/PhysRevD.86.095031, arXiv:1208.4018.

- [39] E. Re, “Single-top Wt-channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [40] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [41] NNPDF Collaboration, “Parton distributions for the LHC run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [42] R. D. Ball et al., “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [43] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [44] P. Skands, S. Carrazza, and J. Rojo, “Tuning PYTHIA 8.1: the Monash 2013 Tune”, *Eur. Phys. J. C* **74** (2014) 3024, doi:10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.
- [45] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [46] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [47] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [48] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [49] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [50] A. Alloul et al., “Feynrules 2.0 — a complete toolbox for tree-level phenomenology”, *Comput. Phys. Commun.* **185** (2014) 2250, doi:10.1016/j.cpc.2014.04.012, arXiv:1310.1921.
- [51] C. Degrande et al., “UFO — the universal FeynRules output”, *Comput. Phys. Commun.* **183** (2012) 1201, doi:10.1016/j.cpc.2012.01.022, arXiv:1108.2040.
- [52] M. Czakon and A. Mitov, “Top++: A program for the calculation of the top-pair cross-section at hadron colliders”, *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.
- [53] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, “Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations”, *JHEP* **03** (2013) 015, doi:10.1007/JHEP03(2013)015, arXiv:1212.3460.

-
- [54] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.
- [55] CMS Collaboration, “Search for new physics in same-sign dilepton events in proton–proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **76** (2016) 439, doi:10.1140/epjc/s10052-016-4261-z, arXiv:1605.03171.
- [56] CMS Collaboration, “Search for physics beyond the standard model in events with jets and two same-sign or at least three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **80** (2020) doi:10.1140/epjc/s10052-020-8168-3.
- [57] CMS Collaboration, “Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **80** (2020) 75, doi:10.1140/epjc/s10052-019-7593-7, arXiv:1908.06463.
- [58] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [59] CMS Collaboration, “Technical proposal for the phase-II upgrade of the Compact Muon Solenoid”, CMS Technical proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.
- [60] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [61] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/p05014, arXiv:2012.06888.
- [62] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [63] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [64] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [65] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [66] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [67] E. Bols et al., “Jet flavour classification using deepjet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [68] CMS Collaboration, “Performance of the DeepJet b tagging algorithm using 41.9 fb⁻¹ of data from proton-proton collisions at 13 TeV with Phase-1 CMS detector”, CMS Detector Performance Note CMS-DP-2018-058, 2018.

- [69] CMS Collaboration, “A new calibration method for charm jet identification validated with proton-proton collision events at $\sqrt{s}=13$ TeV”, *JINST* **17** (2022) P03014, doi:10.1088/1748-0221/17/03/P03014, arXiv:2111.03027.
- [70] T. Chen and C. Guestrin, “Xgboost: A scalable tree boosting system”, in *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, KDD '16*, p. 785?794. Association for Computing Machinery, New York, NY, USA, 2016. doi:10.1145/2939672.2939785.
- [71] F. Pedregosa et al., “Scikit-learn: Machine learning in Python”, *J. Mach. Learn. research* **12** (2011) 2825, doi:10.48550/arXiv.1201.0490, arXiv:1201.0490.
- [72] R. J. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comput. Phys. Commun.* **77** (1993) 219, doi:10.1016/0010-4655(93)90005-W.
- [73] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s}=13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [74] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s}=13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [75] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s}=13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [76] CMS Collaboration, “Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s}=13$ TeV”, *JHEP* **07** (2022) 032, doi:10.1007/JHEP07(2022)032, arXiv:2110.11231.
- [77] B. Biedermann, A. Denner, and M. Pellen, “Complete NLO corrections to W^+W^+ scattering and its irreducible background at the LHC”, *JHEP* **10** (2017) 124, doi:10.1007/JHEP10(2017)124, arXiv:1708.00268.
- [78] LHC Higgs Cross Section Working Group Collaboration, D. de Florian et al., “Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector”. CERN Yellow Reports: Monographs. CERN, Geneva, 2017. doi:10.23731/CYRM-2017-002.
- [79] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [80] S. Catani, D. de Florian, M. Grazzini, and P. Nason, “Soft gluon resummation for Higgs boson production at hadron colliders”, *JHEP* **07** (2003) 028, doi:10.1088/1126-6708/2003/07/028, arXiv:hep-ph/0306211.
- [81] M. Cacciari et al., “The t anti-t cross-section at 1.8-TeV and 1.96-TeV: A Study of the systematics due to parton densities and scale dependence”, *JHEP* **04** (2004) 068, doi:10.1088/1126-6708/2004/04/068, arXiv:hep-ph/0303085.
- [82] A. Kalogeropoulos and J. Alwall, “The syscalc code: A tool to derive theoretical systematic uncertainties”, 2018. arXiv:1801.08401.
- [83] CMS Collaboration, “The CMS statistical analysis and combination tool: COMBINE”, 2024. arXiv:2404.06614. Submitted to *Comput. Softw. Big Sci.*

- [84] W. Verkerke and D. P. Kirkby, “The RooFit toolkit for data modeling”, 2003.
arXiv:physics/0306116.
- [85] L. Moneta et al., “The RooStats Project”, *PoS ACAT2010* (2010) 057,
doi:10.22323/1.093.0057, arXiv:1009.1003.
- [86] T. Junk, “Confidence level computation for combining searches with small statistics”,
Nucl. Instrum. Meth. A **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2.
- [87] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Physics G* **28** (2002)
2693, doi:10.1088/0954-3899/28/10/313.
- [88] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for
likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554,
doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum:
doi:10.1140/epjc/s10052-013-2501-z].
- [89] ATLAS, CMS, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson
search combination in Summer 2011”, technical report, CERN, Geneva, 2011.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck² , R. Schöffbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat⁴ , G.P. Van Onsem , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , C. Delaere , I.S. Donertas , A. Giammanco , Sa. Jain , V. Lemaître, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , T. Menezes De Oliveira , A. Moraes , P. Rebello Teles , M. Soeiro

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. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, J. Martins⁷ , C. Mora Herrera , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel , A. Vilela Pereira 

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

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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

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

University of Sofia, Sofia, Bulgaria

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

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

S. Keshri , S. Thakur 

Beihang University, Beijing, China

T. Cheng , T. Javaid , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

Z. Hu , J. Liu, K. Yi^{8,9} 

Institute of High Energy Physics, Beijing, China

G.M. Chen¹⁰ , H.S. Chen¹⁰ , M. Chen¹⁰ , F. Iemmi , C.H. Jiang, A. Kapoor¹¹ , H. Liao , Z.-A. Liu¹² , R. Sharma¹³ , J.N. Song¹², J. Tao , C. Wang¹⁰, J. Wang , Z. Wang¹⁰, H. Zhang 

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

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

Sun Yat-Sen University, Guangzhou, China

Z. You 

University of Science and Technology of China, Hefei, China

K. Jaffel , N. Lu 

Nanjing Normal University, Nanjing, China

G. Bauer¹⁴

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

X. Gao¹⁵ 

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

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 , A. Sculac 

University of Split, Faculty of Science, Split, Croatia

M. Kovac , T. Sculac 

Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, S. Mishra , A. Starodumov¹⁶ , T. Susa 

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech RepublicM. 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**A.A. Abdelalim^{17,18} , E. Salama^{19,20} **Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M. Abdullah Al-Mashad , M.A. Mahmoud **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , E. Brücken , F. Garcia , K.T.S. Kallonen , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow **IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro²¹ , P. Simkina , M. Titov , M. Tornago **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram²² , J. Andrea , D. Apparu , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , C. Grimault, R. Haeberle , A.-C. Le Bihan , M. Meena , G. Saha , M.A. Sessini , P. Van Hove **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen²³ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao **Georgian Technical University, Tbilisi, Georgia**

A. Khvedelidze²⁴ , I. Lomidze , Z. Tsamalaidze²⁴ 

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 , F. Engelke , J. Erdmann ,
M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone ,
A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee ,
D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler ,
U. Sarkar , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein ,
F. Torres Da Silva De Araujo²⁵ , S. Wiedenbeck , S. Zaleski

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

C. Dziwok , G. Flügge , W. Haj Ahmad²⁶, T. Kress , A. Nowack , O. Pooth , A. Stahl ,
T. Ziemons , A. Zotz 

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , S. Baxter ,
M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya ,
F. Blekman²⁷ , K. Borras²⁸ , A. Campbell , A. Cardini , C. Cheng , F. Colombina ,
S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein ,
L.I. Estevez Banos , O. Filatov , E. Gallo²⁷ , A. Geiser , A. Giraldi , V. Guglielmi ,
M. Guthoff , A. Hinzmann , A. Jafari²⁹ , L. Jeppe , N.Z. Jomhari , B. Kaech ,
M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange,
D. Leyva Pernia , K. Lipka³⁰ , W. Lohmann³¹ , R. Mankel , I.-A. Melzer-Pellmann ,
M. Mendizabal Morentin , A.B. Meyer , G. Milella , A. Mussgiller , L.P. Nair ,
A. Nürnberg , Y. Otariid, J. Park , D. Pérez Adán , E. Ranken , A. Raspereza ,
B. Ribeiro Lopes , J. Rübenach, A. Saggio , M. Scham^{32,28} , S. Schnake²⁸ , P. Schütze ,
C. Schwanenberger²⁷ , D. Selivanova , K. Sharko , M. Shchedrolosiev , R.E. Sosa Ric-
cardo , D. Stafford , F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen ,
K. Wichmann, L. Wiens²⁸ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg,
M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean ,
J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher , R. Klanner , W. Korcari ,
T. Kramer , 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 , B. Raciti , M. 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 , T. Chwalek , A. Dierlamm , A. Droll, N. Fal-
termann , M. Giffels , A. Gottmann , F. Hartmann³³ , R. Hofsaess , M. Horzela ,
U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link,
A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh ,
E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy ,
I. Shvetsov , H.J. Simonis , M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer ,
S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis , A. Papadopoulos³³, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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

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

M. Bartók³⁴ , C. Hajdu , D. Horvath^{35,36} , K. Márton, A.J. RádI³⁷ , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , M.M.A. Gadallah³⁸ , Á. Kadlecsek , P. Major , K. Mandal , G. Pásztor , G.I. Veres 

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari , G. Zilizi 

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

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

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

T. Csorgo³⁹ , F. Nemes³⁹ , T. Novak 

Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra⁴⁰ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman⁴¹ , S. Bhattacharya , S. Dutta , S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , P. Jana , P. Kalbhor , J.R. Komaragiri⁴² , D. Kumar⁴² , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, R.K. Dewanjee⁴³ , M. Guchait , Sh. Jain 

A. Jaiswal, S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

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

S. Bahinipati⁴⁴ , C. Kar , D. Maity⁴⁵ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁵ , K. Naskar⁴⁵ , A. Nayak⁴⁵ , P. Sadangi, S.K. Swain , S. Varghese⁴⁵ , D. Vats⁴⁵ 

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

S. Acharya⁴⁶ , A. Alpana , S. Dube , B. Gomber⁴⁶ , B. Kansal , A. Laha , B. Sahu⁴⁶ , S. Sharma , K.Y. Vaish 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴⁷ , E. Khazaie⁴⁸ , M. Zeinali⁴⁹ 

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

S. Chenarani⁵⁰ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 

University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,c,17} , A. Colaleo^{a,b} , D. Creanza^{a,c} , B. D'Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,c} , W. Elmetenawee^{a,b,17} , L. Fiore^a , G. Iaselli^{a,c} , M. Louka^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellicchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^a , G. Ramirez-Sanchez^{a,c} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a , A. Zaza^{a,b} 

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borghonovi^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,51} , L. Lunerti^{a,b} , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Costa^{a,b,52} , A. Di Mattia^a , R. Potenza^{a,b} , A. Tricomi^{a,b,52} , C. Tuve^{a,b} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵³ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

P. Chatagnon^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a , G. Boldrini^{a,b} , F. Brivio^a , F. Cetorelli^a , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^a , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a, S. Ragazzi^{a,b} , T. Tabarelli de Fatis^{a,b} , D. Zuolo^a 

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,54} , P. Paolucci^{a,33} , B. Rossi^a , C. Sciacca^{a,b} 

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,55} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Gasparini^{a,b} , A. Gozzelino^a , M. Gulmini^{a,56} , E. Lusiani^a , M. Margoni^{a,b} , F. Marini^a , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , H. Yarar^{a,b}, P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b} 

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S. Abu Zeid^{a,20} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

S. Ajmal^{a,b} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,57} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , F. Vaselli^{a,c} , A. Venturi^a , P.G. Verdini^a 

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , M. Campana^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , F. Errico^{a,b} , E. Longo^{a,b} , P. Meridiani^a , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a 

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , C. Borca^{a,b} , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , L. Finco^a , M. Grippo^{a,b} , B. Kiani^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , L. Markovic^{a,b} , S. Maselli^a , A. Mecca^{a,b} , E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a 

L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , F. Siviero^{a,b} ,
V. Sola^{a,b} , A. Solano^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , D. Trocino^a , G. Umoret^{a,b} ,
E. Vlasov^{a,b} , R. White^a 

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a ,
G. Della Ricca^{a,b} 

Kyungpook National University, Daegu, Korea

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

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim 

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

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

Hanyang University, Seoul, Korea

E. Asilar , D. Kim , T.J. Kim , J.A. Merlin

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

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

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

T. Beyrouthy 

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 

Vilnius University, Vilnius, Lithuania

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

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

N. Bin Norjoharuddeen , I. Yusuff⁵⁸ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁹ , R. Lopez-Fernandez , C.A. Mondragon Herrera, A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , M. Ramírez García 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja , N. Raicevic 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

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

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

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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , 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 , A. Muhammad 

Warsaw University of Technology, Warsaw, Poland

K. Pozniak , W. Zabolotny 

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

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

Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , P. Milenovic 

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

M. Dordevic , J. Milosevic , V. Rekovic

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

M. Aguilar-Benitez, J. Alcaraz Maestre , Cristina F. Bedoya , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix 

M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , 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 , P. Leguina , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 

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

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

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁶⁰ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

W.G.D. Dharmaratna⁶¹ , K. Liyanage , N. Perera , N. Wickramage 

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , L. Forthomme , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , B. Huber , V. Innocente , T. James , P. Janot , O. Kaluzinska , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , M. Matthewman, F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , H. Qu , D. Rabady , G. Reales Gutiérrez, M. Rovere , H. Sakulin , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶² , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsirou, D. Walter , J. Wanczyk⁶³ , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T. Bevilacqua⁶⁴ , L. Caminada⁶⁴ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶⁴ , L. Noehte⁶⁴ , T. Rohe 

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

T.K. Aarrestad , K. Androso⁶³ , M. Backhaus , A. Calandri , C. Cazzaniga , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez 

A. Mascellani⁶³ , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶³ , D. Valsecchi , R. Wallny 

Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁵ , P. Bäertschi , M.F. Canelli , K. Cormier , J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , U. Molinatti , A. Reimers , P. Robmann , S. Sanchez Cruz , M. Senger , F. Stäger , Y. Takahashi , R. Tramontano 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁶ , D. Bhowmik , C.M. Kuo , W. Lin , P.K. Rout , P.C. Tiwari⁴² , S.S. Yu 

National Taiwan University (NTU), Taipei, Taiwan

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

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

C. Asawatrangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁷ , E. Eskut , Y. Guler⁶⁸ , E. Gurpinar Guler⁶⁸ , C. Isik , O. Kara , A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁹ , A. Polatoz , B. Tali⁷⁰ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

M. Yalvac⁷¹ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷² , O. Kaya⁷³ , S. Tekten⁷⁴ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{67,75} , G.G. Dincer , Y. Komurcu , S. Sen⁷⁶ 

Istanbul University, Istanbul, Turkey

O. Aydilek²⁶ , S. Cerci⁷⁰ , V. Epshteyn , B. Haciasahinoglu , I. Hos⁷⁷ , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 

Yildiz Technical University, Istanbul, Turkey

B. Isildak⁷⁸ , D. Sunar Cerci⁷⁰ 

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

A. Boyaryntsev , B. Grynyov 

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

L. Levchuk 

University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou⁷⁹ , K. Walkingshaw Pass 

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁸⁰ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Malik, M. Mieskolainen , J. Nash⁸² , M. Pesaresi , B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee³³ , M. Vojinovic , N. Wardle , D. Winterbottom 

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

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

Catholic University of America, Washington, DC, USA

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

The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸³ , E. Usai , R. Yi 

Boston University, Boston, Massachusetts, USA

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

Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²⁸, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , S. Sagir⁸⁵ , F. Simpson , M. Stamenkovic , X. Yan , W. Zhang

University of California, Davis, Davis, California, USA

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

University of California, Los Angeles, California, USA

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

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si , S. Wimpenny[†] 

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

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

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

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

California Institute of Technology, Pasadena, California, USA

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

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

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

University of Colorado Boulder, Boulder, Colorado, USA

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

Cornell University, Ithaca, New York, USA

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

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , 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. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , A. Whitbeck , I. Zoi 

University of Florida, Gainesville, Florida, USA

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

Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Habibullah , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez , H. Prosper , P.R. Prova 

M. Wulansatiti , R. Yohay , J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy²⁰ , M. Hohlmann ,
R. Kumar Verma , M. Rahmani, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA

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

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend, K. Dilsiz⁸⁸ , L. Emediato , G. Karaman , O.K. Köseyan , J.-
P. Merlo, A. Mestvirishvili⁸⁹ , J. Nachtman , O. Neogi, H. Ogul⁹⁰ , Y. Onel , A. Penzo ,
C. Snyder, E. Tiras⁹¹ 

Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers ,
D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez ,
N. Minafra , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹² , C. Rogan , C. Royon ,
R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 

Kansas State University, Manhattan, Kansas, USA

B. Allmond , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin ,
J. Natoli , D. Roy , G. Sorrentino 

Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 

University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , Y.M. Chen , 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 , M.M. Paranipe, L. Wang 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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

University of Minnesota, Minneapolis, Minnesota, USA

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

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado 

W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

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

H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams 

Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Dervan , Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , R. McCarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , B. Wang , D. Wood 

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko¹⁶ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

The Ohio State University, Columbus, Ohio, USA

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

Princeton University, Princeton, New Jersey, USA

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

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 

Purdue University, West Lafayette, Indiana, USA

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

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, Texas, USA

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

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar , P. Parygin⁹³ , E. Popova⁹³ , R. Taus 

The Rockefeller University, New York, New York, USA

K. Goulianos 

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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslawski , O. Karacheban³¹ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

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

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

D. Aebi , M. Ahmad , O. Bouhali⁹⁴ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁵ , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

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

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA

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

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

Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu , D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin , V. Gavrilov , N. Lychkovskaya , A. Nikitenko^{96,97} , V. Popov , A. Zhokin 

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

S. Afanasiev , D. Budkouski , I. Golutvin , I. Gorbunov , V. Karjavine , V. Korenkov , A. Lanev , A. Malakhov , V. Matveev⁹⁸ , V. Palichik , V. Perelygin , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B.S. Yuldashev⁹⁹, A. Zarubin , I. Zhizhin , G. Gavrilov , V. Golovtcov , Y. Ivanov , V. Kim¹⁰⁰ , P. Levchenko¹⁰¹ , V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov , A. Vorobyev[†], T. Aushev , R. Chistov¹⁰⁰ , M. Danilov¹⁰⁰ , S. Polikarpov¹⁰⁰ , V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov , A. Belyaev , E. Boos , V. Bunichev , M. Dubinin⁸⁶ , L. Dudko , A. Ershov , A. Gribushin , V. Klyukhin , S. Obraztsov , M. Perfilov , V. Savrin , P. Volkov , G. Vorochnikov , V. Blinov¹⁰⁰, T. Dimova¹⁰⁰ , A. Kozyrev¹⁰⁰ , O. Radchenko¹⁰⁰ , Y. Skovpen¹⁰⁰ , I. Azhgirey , V. Kachanov , D. Konstantinov , R. Ryutin, S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin¹⁰² , E. Tcherniaev , V. Chekhovsky, V. Makarenko 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Ghent University, Ghent, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at Nanjing Normal University, Nanjing, China

⁹Now at The University of Iowa, Iowa City, Iowa, USA

¹⁰Also at University of Chinese Academy of Sciences, Beijing, China

¹¹Also at China Center of Advanced Science and Technology, Beijing, China

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at China Spallation Neutron Source, Guangdong, China

¹⁴Now at Henan Normal University, Xinxiang, China

¹⁵Also at Université Libre de Bruxelles, Bruxelles, Belgium

¹⁶Also at an international laboratory covered by a cooperation agreement with CERN

¹⁷Also at Helwan University, Cairo, Egypt

¹⁸Now at Zewail City of Science and Technology, Zewail, Egypt

¹⁹Also at British University in Egypt, Cairo, Egypt

²⁰Now at Ain Shams University, Cairo, Egypt

²¹Also at Purdue University, West Lafayette, Indiana, USA

²²Also at Université de Haute Alsace, Mulhouse, France

²³Also at Istinye University, Istanbul, Turkey

²⁴Also at an institute formerly covered by a cooperation agreement with CERN

²⁵Also at The University of the State of Amazonas, Manaus, Brazil

²⁶Also at Erzincan Binali Yildirim University, Erzincan, Turkey

²⁷Also at University of Hamburg, Hamburg, Germany

²⁸Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁹Also at Isfahan University of Technology, Isfahan, Iran

³⁰Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

³¹Also at Brandenburg University of Technology, Cottbus, Germany

³²Also at Forschungszentrum Jülich, Juelich, Germany

³³Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

³⁴Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

³⁵Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

³⁶Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

³⁷Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

³⁸Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

³⁹Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

⁴⁰Also at Punjab Agricultural University, Ludhiana, India

⁴¹Also at University of Visva-Bharati, Santiniketan, India

⁴²Also at Indian Institute of Science (IISc), Bangalore, India

⁴³Also at Birla Institute of Technology, Mesra, Mesra, India

⁴⁴Also at IIT Bhubaneswar, Bhubaneswar, India

⁴⁵Also at Institute of Physics, Bhubaneswar, India

⁴⁶Also at University of Hyderabad, Hyderabad, India

- ⁴⁷Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁸Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁹Also at Sharif University of Technology, Tehran, Iran
- ⁵⁰Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁵¹Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁵²Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵³Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵⁴Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁵Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁶Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- ⁵⁷Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁸Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁹Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁶⁰Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁶¹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶²Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶³Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶⁴Also at Universität Zürich, Zurich, Switzerland
- ⁶⁵Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁶Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁷Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁸Also at Konya Technical University, Konya, Turkey
- ⁶⁹Also at Izmir Bakircay University, Izmir, Turkey
- ⁷⁰Also at Adiyaman University, Adiyaman, Turkey
- ⁷¹Also at Bozok Universiteleri Rektörlüğü, Yozgat, Turkey
- ⁷²Also at Marmara University, Istanbul, Turkey
- ⁷³Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁴Also at Kafkas University, Kars, Turkey
- ⁷⁵Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁶Also at Hacettepe University, Ankara, Turkey
- ⁷⁷Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁸Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁹Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁸⁰Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸¹Also at IPPP Durham University, Durham, United Kingdom
- ⁸²Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸³Also at Università di Torino, Torino, Italy
- ⁸⁴Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁶Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁸Also at Bingöl University, Bingöl, Turkey
- ⁸⁹Also at Georgian Technical University, Tbilisi, Georgia

⁹⁰Also at Sinop University, Sinop, Turkey

⁹¹Also at Erciyes University, Kayseri, Turkey

⁹²Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

⁹³Now at another institute formerly covered by a cooperation agreement with CERN

⁹⁴Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁵Also at Kyungpook National University, Daegu, Korea

⁹⁶Also at Imperial College, London, United Kingdom

⁹⁷Now at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at another international laboratory covered by a cooperation agreement with CERN

⁹⁹Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

¹⁰⁰Also at another institute formerly covered by a cooperation agreement with CERN

¹⁰¹Also at Northeastern University, Boston, Massachusetts, USA

¹⁰²Also at Universiteit Antwerpen, Antwerpen, Belgium