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Letter

Search for the lepton flavor violating $\tau \to 3\mu$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Geneva, Switzerland

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ABSTRACT

A search for the lepton flavor violating $\tau \to 3\mu$ decay is performed using proton-proton collision events at a center-of-mass energy of 13 TeV collected by the CMS experiment at the LHC in 2017–2018, corresponding to an integrated luminosity of 97.7 fb^{-1}. Tau leptons produced in both heavy-flavor hadron and W boson decays are exploited in the analysis. No evidence for the decay is observed. The results of this search are combined with an earlier null result based on data collected in 2016 to obtain a total integrated luminosity of 131 fb^{-1}. The observed (expected) upper limits on the branching fraction $\mathcal{B}(\tau \to 3\mu)$ at confidence levels of 90 and 95% are 2.9×10^{-8} (2.4×10^{-8}) and 3.6×10^{-8} (3.0×10^{-8}), respectively.

1. Introduction

There are no known symmetries that would strictly forbid lepton flavor violating decays, such as $\tau \to 3\mu$. However, the only source of lepton flavor violation in the standard model (SM) of particle physics is from neutrino transitions in loops, which implies a vanishingly small branching fraction for $\tau \to 3\mu$, around 10^{-55} [1–3]. Various extensions of the SM predict $\tau \to 3\mu$ decays with branching fractions as high as 10^{-10}–10^{-8} [4–6], which can be probed in present and near-future experiments.

The most stringent experimental upper limit on the branching fraction of the $\tau \to 3\mu$ decay, set by the Belle experiment, is $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% confidence level (CL) [7]. A similar upper limit of 3.3×10^{-8} at 90% CL [8] is reported by the BaBar experiment. While Belle and BaBar operated at asymmetric electron-positron B factories, proton-proton (pp) collisions offer another prolific source of tau leptons. The upper limits at 90% CL reported by the CERN LHC experiments are 4.6×10^{-8} from LHCb [9], 38×10^{-8} from ATLAS [10], and 8.0×10^{-8} from CMS [11].

In this Letter, we report a search for the $\tau \to 3\mu$ decay with the CMS experiment using data collected in 2017 and 2018, which correspond to integrated luminosities of 38.0 fb^{-1} and 59.7 fb^{-1}, respectively. The result is combined with a previously published analysis using data collected by the CMS experiment in 2016, which corresponds to an integrated luminosity of 33.2 fb^{-1} [11]. Both searches exploit tau leptons produced in heavy-flavor (charm and bottom) hadron decays and W boson decays. Heavy-flavor decays produce the vast majority of tau leptons at the LHC, and the $\tau \to 3\mu$ signal is characterized by the presence of low transverse momentum (p_T) muons in the final state, typically below 10 GeV, with high intrinsic background. While the tau lepton production rate from W boson decays is a few orders of magnitude smaller, the muons from the $\tau \to 3\mu$ signal have larger p_T, are typically isolated from hadronic activity, and are accompanied by significant missing transverse momentum in the event, resulting in a low intrinsic background. The background is dominated by events in which a pion or kaon misidentified as a muon is combined with two muons from a b hadron decay (usually one muon from the b hadron decay and one from the subsequent c hadron decay). Tabulated results are provided in the HEPData record for this analysis [12].

2. The CMS detector

The CMS apparatus [13] is a multipurpose, nearly hermetic detector, designed to trigger on [14,15] and identify electrons, muons, photons, and (charged and neutral) hadrons [16–18]. A global "particle-flow" algorithm [19] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build jets and measure the missing transverse momentum ($\vec{p}_T^{\,miss}$) [20–22], which is computed as the negative vector sum of the p_T of all the reconstructed particles in an event, with magnitude denoted as p_T^{miss}.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching measurements in the muon detectors to tracks measured in the tracker results in a relative p_T resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps [17].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [15].

3. Data and simulated samples

The data used in this analysis were collected in 2017–2018 from pp collisions at a center-of-mass energy of 13 TeV, and correspond to an integrated luminosity of 97.7 fb^{-1}. The heavy-flavor analysis uses $D_s^+ \to \tau^+\nu_\tau$ and $B^+/B^0 \to \tau + X$ as signal processes, accounting for about 60 and 40% of the τ lepton production from heavy-flavor decays, respectively, and $D_s^+ \to \phi(1020)\pi^+ \to \mu^+\mu^-\pi^+$ as a normalization process (ϕ(1020) is written as ϕ in the remainder of the Letter). Charge-conjugated processes are implied throughout this Letter. Simulated event samples are generated with Monte Carlo (MC) methods, using PYTHIA 8.226 [23] with the CP5 tune [24] at leading order (LO). The heavy-flavor decays are modeled with EVTGEN 1.6.0 [25], and a phase space model is used for the $\tau \to 3\mu$ decay. The $W^+ \to \tau^+\nu_\tau$ process is also simulated using PYTHIA with the CP5 tune. In addition, a smaller $W^+ \to \tau^+\nu_\tau$ sample is simulated using MADGRAPH5_aMC@NLO [26] at next-to-LO (NLO). All generated events are passed to a detailed GEANT4 [27] simulation of the CMS detector. The subsequent trigger selections and event reconstruction are performed with the same algorithms as those used with the data. The simulated events include multiple pp interactions within the same or nearby bunch crossings, known as pileup, and are reweighted to match the pileup distribution in data.

4. Search for the τ → 3μ decay in heavy-flavor hadron events

The search for $\tau \to 3\mu$ in heavy-flavor hadron decays uses low-p_T dimuon or trimuon triggers. The 2017 data were collected with L1 trigger requirements of either two oppositely charged muons having a pseudorapidity of $|\eta| < 1.5$ and a separation of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.4$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively, or three muons, with the p_T-(sub)leading muon having $p_T > 5(3)$ GeV (without any explicit p_T requirement for the third muon). At the HLT, two oppositely charged muons with $p_T > 3$ GeV and an additional track with $p_T > 1.2$ GeV were required. The three particles were fitted to a common vertex, which was required to have a vertex fit χ^2 per degree of freedom less than 8 and be separated from the beamline in the transverse plane by at least twice the uncertainty in the distance. The invariant mass of the three particles, assuming the muon mass for each, was required to be in the range of 1.60–2.02 GeV, which is wide enough to record both $\tau \to 3\mu$ and $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ candidate events. The two-dimensional pointing angle (α_{2D}), defined as the angle in the transverse plane between the three-particle momentum vector and the vector from the beamline to the three-particle common vertex, was required to satisfy $\cos\alpha_{2D} > 0.9$. For the 2018 data-taking period, an L1 trigger algorithm requiring two oppositely charged $p_T > 4$ GeV muons with $\Delta R < 1.2$ was added to complement the previous ones. The HLT algorithm was changed to require three muons, but with the same p_T and vertex requirements as those in 2017. The previous “2 muons and 1 track” trigger was prescaled by a factor of 20, i.e., storing only 5% of the events selected by the algorithm, in order to keep recording $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ candidate events.

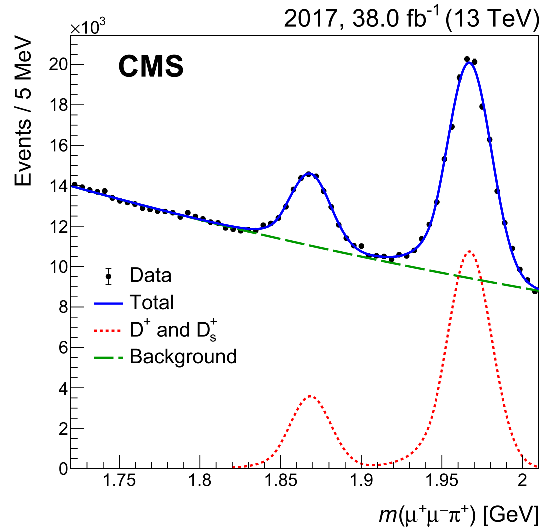

Fig. 1. The $\mu^+\mu^-\pi^+$ invariant mass distribution with the fits to the sum of the D^+(1.870 GeV) and D_s^+(1.968 GeV) [30] resonances and the background in 2017 data.

In the offline selection, three global muons [17] are required. A global muon combines a muon candidate reconstructed in the muon detectors with a track reconstructed in the silicon tracker. The three selected muons must have $|\eta| < 2.4$ and the minimum p_T is 3 GeV for the leading two muons and 2 GeV for the third, when ordered by decreasing p_T. Any muon with $|\eta| < 1.2$ must have $p_T > 3.5$ GeV. The muons must be matched to the objects that triggered the event by $\Delta R < 0.03$ and have a total charge of ±1. In about 1% of the cases, where more than one muon triplet candidate is found, the one with the smallest trimuon vertex fit χ^2 is selected. The tracks of the three muon candidates are refitted with a constraint that they originate from a common point [28]. This improves the mass resolution by about 10%. To match the trigger requirement, the two-dimensional distance of the trimuon vertex to the beamline is required to be at least twice its uncertainty. The primary vertex (PV) is chosen as the one with the smallest three-dimensional pointing angle (α_{3D}) between the trimuon momentum and the vector connecting the PV and the trimuon vertex.

The signal normalization strategy, detailed in Ref. [11], is summarized here. The dependence on the knowledge of D and B meson production cross sections, or trigger and selection efficiencies, is minimized by normalizing the signal yield to the $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ yield in data, separately for 2017 and 2018. The normalization channel $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ uses the same selection criteria with the following exceptions. Only two muons are required and they must be oppositely charged with an invariant mass between 1 and 1.04 GeV. The track associated with the pion must have $p_T > 2$ GeV and form a vertex with the two muons with a χ^2 per degree of freedom less than 5. Fig. 1 shows the $\mu^+\mu^-\pi^+$ invariant mass distribution using 2017 data with fits to the $D^+$and D_s^+signal peaks using Crystal Ball functions [29] for the peaks and an exponential function for the background.

The expected number of $\tau \to 3\mu$ signal events from D_s^+meson decays that pass the dimuon triggers, denoted as $N_{3\mu(D)}$, is related to $\mathcal{B}(\tau \to 3\mu)$ by

$$N_{3\mu(D)} = N_{\mu\mu\pi} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\text{reco}}_{3\mu(D)}}{\epsilon^{\text{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\text{trig}}_{3\mu(D)}}{\epsilon^{2\mu\text{trig}}_{\mu\mu\pi}} \times \frac{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \mathcal{B}(\tau \to 3\mu),$$

where $N_{\mu\mu\pi}$ is the measured $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ yield, $\mathcal{A}$ is the detector acceptance, ϵ^{reco} is the selection efficiency, ϵ^{trig} is the trigger efficiency, and the subscripts $3\mu(D)$ and $\mu\mu\pi$ indicate $\tau \to 3\mu$ and $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ decays, respectively. Similarly, the expected number of $\tau \to 3\mu$ signal events from decays of the form $B \to \tau + X$ coming from the dimuon triggers, denoted as $N_{3\mu(B)}$, is related to $\mathcal{B}(\tau \to 3\mu)$ by

$$N_{3\mu(B)} = N_{\mu\mu\pi}\, f\, \frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{reco}_{3\mu(B)}}{\epsilon^{reco}_{\mu\mu\pi}} \frac{\epsilon^{2\mu trig}_{3\mu(B)}}{\epsilon^{2\mu trig}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu) \times \frac{\mathcal{B}(B \to \tau + X)}{\mathcal{B}(B \to D_s^+ + X)\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)},$$

where $N_{\mu\mu\pi}$ is the measured $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ yield, f is the fraction of D_s^+ mesons from b hadron decays. The fraction f can be calculated as the ratio of cross sections (σ): $f = \sigma(pp \to B + X)\mathcal{B}(B \to D_s^+ + X)/\sigma(pp \to D_s^+ + X)$. Since D_s^+mesons produced from b hadron decays tend to decay farther from the PV than directly produced D_s^+mesons, we validate the simulation-predicted value of f by fitting the $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ proper decay length, $Lm(\mu^+\mu^-\pi^+)/p$, distribution in data, where L is the distance between the PV and the $\mu^+\mu^-\pi^+$ vertex, $m(\mu^+\mu^-\pi^+)$ is the $\mu^+\mu^-\pi^+$ invariant mass, and p is the $\mu^+\mu^-\pi^+$ momentum. The small contributions to signal events from $D^+ \to \tau + X$ and $B_s^0 \to \tau + X$ decays are added by scaling the $D_s^+ \to \tau^+\nu_\tau$ and $B \to \tau + X$ predictions by 1.04 and 1.12, respectively, as determined from simulation. Systematic uncertainties equal to these corrections are assigned.

The data collected using the trimuon trigger cannot be directly normalized to $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$. The simulation predicts that the fraction of signal events triggered exclusively by the trimuon trigger is about 28% of the events passing the dimuon triggers. When measured from events in a $D_s^+ \to \phi\mu^+\nu_\mu \to \mu^+\mu^-\mu^+\nu_\mu$ control region, this ratio is found to be 31%. The dimuon-triggered signal yields are therefore scaled up by 28%, and a systematic uncertainty of 3% is assigned on the total yields.

Selected events are categorized based on the calculated trimuon mass resolution, which primarily depends on the pseudorapidities of the reconstructed muon candidates. Three mass resolution categories are introduced: $\sigma_m/m < 0.7\%$, $0.7 < \sigma_m/m < 1.05\%$, and $\sigma_m/m > 1.05\%$, where m is the trimuon invariant mass and σ_m is its uncertainty. They are labeled A, B, and C, with average σ_m of 12, 19, and 25 MeV, respectively. The signal region (SR) for each category includes candidates with trimuon invariant masses within twice the average mass resolution. The sideband region includes candidates outside the SR but with trimuon invariant masses of 1.62–2.00 GeV. To remove $\phi \to \mu^+\mu^-$ contributions, candidates in which two oppositely charged muons have an invariant mass near the ϕresonance are rejected, with the exact requirement depending on the resolution category.

A study of simulated minimum-bias events reveals that the few events that pass our selection criteria usually have at least one muon candidate that is associated with a generated hadron. This can occur from the decay of a pion or kaon as well as from random matching between hadron tracks in the tracker and stubs in the muon detectors. Therefore, a boosted decision tree (BDT) is trained [31] based on muon reconstruction quality, using the lowest-p_T muon among the three in simulated $\tau \to 3\mu$ events as signal, and simulated B meson to charged pion or kaon decays as background, where hadrons wrongly identified as global muons are selected. The muon reconstruction quality BDT makes use of observables from the silicon tracker and muon detectors, as well as their compatibility. After that, another BDT, referred to as the analysis BDT, is trained for each mass resolution category to improve the signal-to-background ratio, using simulated signal events (with properly mixed D and B meson decays) and background events from the data sideband region. The analysis BDT training utilizes the following observables: trimuon p_T, the muon reconstruction quality BDT scores of each of the three muon candidates, additional muon quality criteria (each using the least signal-like value among the three muon candidates), number of hits in muon detectors for each of the three muon candidates, the normalized χ^2 of the trimuon vertex fit, α_{3D}, the distance between the PV and the trimuon vertex and its significance (defined as the distance divided by its uncertainty), the largest and smallest values of the transverse impact parameter of the three muons with respect to the PV, and their significances, and two isolation observables. The isolation observables measure the activity in terms of other particles in the vicinity of the trimuon vertex or the three muons. The first isolation observable is the smallest distance of closest approach to the trimuon vertex of all other tracks in the event with $p_T > 1$ GeV. The second isolation observable, which is maximized over the three muons, is defined by summing the p_T of all tracks with $p_T > 1$ GeV, and with $\Delta R < 0.3$ and a distance of closest approach below 1 mm with respect to the muon (the tracks associated with the other two muons are excluded), and by dividing this sum by the muon candidate p_T. The distributions of the observables providing the largest discrimination power between signal and background are shown in Fig. 2.

Each mass resolution category is divided into four subcategories based on the analysis BDT score. While the lowest analysis BDT score subcategory is discarded, the other three subcategories in each mass resolution category are retained for the statistical analysis, and assigned number labels from 1 to 3, such that label 1 corresponds to the highest (the most signal-enriched) BDT score subcategory. In this way, nine event categories are defined for each data-taking year.

The boundaries of the analysis BDT subcategories are optimized to give the largest expected combined signal significance, which is done before unblinding the signal region. For consistency with the W boson analysis, described in Section 5, $\omega(782) \to 2\mu$ contributions are vetoed by requiring the invariant masses of oppositely charged muon pairs to be away from the $\omega(782)$ peak by more than 10 MeV. This requirement has no impact on the result.

The trimuon invariant mass distributions for categories A1, B1, and C1 are shown in Fig. 3, along with a background-only fit with an exponential function, and the contribution expected from a signal with $\mathcal{B}(\tau \to 3\mu)$ set to 10^{-7}, which is chosen to enhance the visibility of the signal in the figures.

Events that do not have a τ candidate formed by three global muons but by two global muons and one tracker muon [17], which is reconstructed as a silicon tracker track extrapolated to match stubs in the muon detectors, are analyzed separately. The event selection is the same as in the case of three global muons. A tracker muon reconstruction quality BDT is trained to suppress misidentified muons. Events are then categorized based on mass resolution and using another analysis BDT, in the same way as in the case of three global muons, but defining three subcategories instead of four, with the lowest analysis BDT score subcategory discarded. Thus six event categories are defined for each year. The trimuon invariant mass distributions for these two global muons and one tracker muon analysis categories A1, B1, and C1 are shown in Fig. 4, along with a background-only fit, with an exponential function, and the contribution expected for a signal of $\mathcal{B}(\tau \to 3\mu)$ set to 10^{-7}.

The dominant systematic uncertainty is related to the signal normalization, including the statistical uncertainty in the yield of $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ decays and its variation over different data-taking periods; the uncertainties in various heavy-flavor decay branching fractions [30] that affect the signal normalization; the uncertainty in the muon reconstruction efficiency, measured using a tag-and-probe method [32] applied to $J/\psi \to \mu^+\mu^-$ data events; and the uncertainty in the BDT requirement efficiency, studied by training a BDT for the $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ process using the same observables and comparing the $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ efficiencies as functions of the BDT requirement in data and simulated events. The uncertainties in the mean and width of the signal trimuon invariant mass distribution are determined by comparing $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ shapes in data and simulated events in each mass resolution category. The trimuon mass distribution of the background in each event category can be modeled analytically using an exponential, a power-law, or a second-order poly-

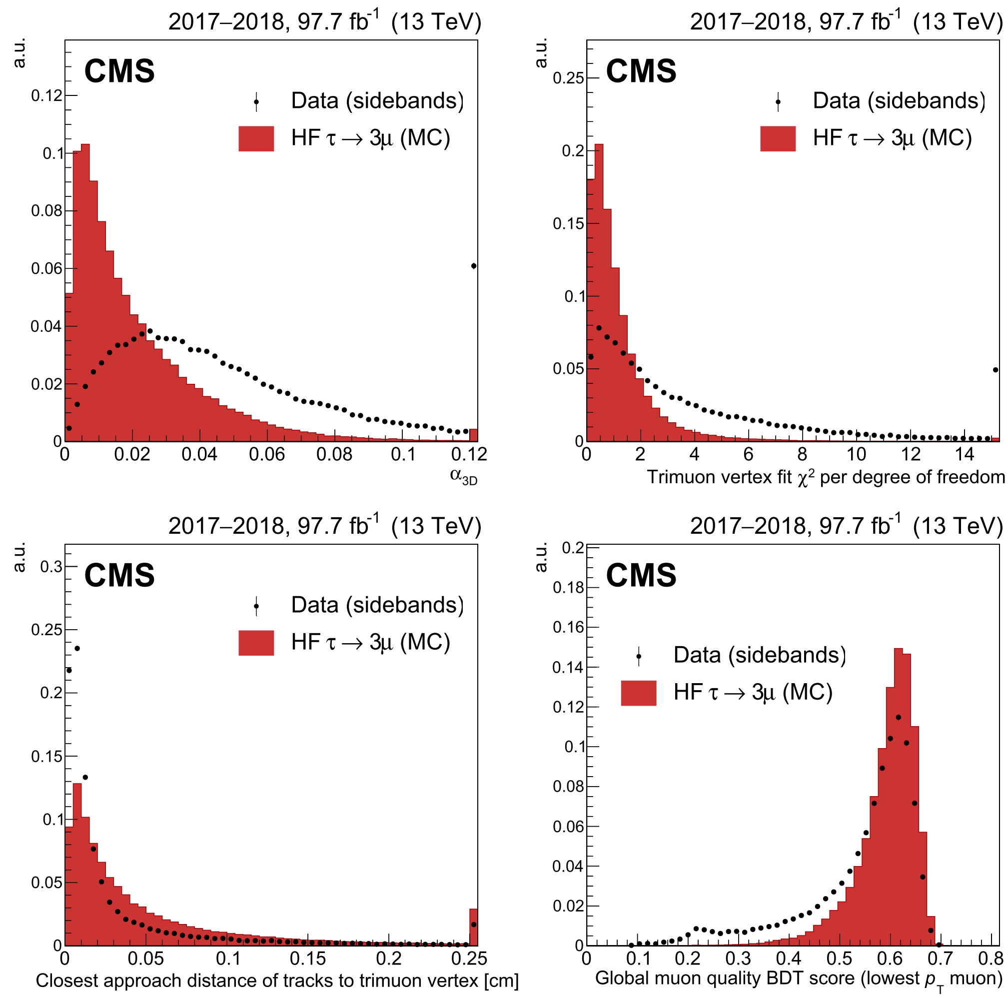

Fig. 2. Signal and background distributions for the four observables with the highest discrimination power used for the heavy-flavor (HF) analysis BDT training: α_{3D} (upper left), χ^2 per degree of freedom of the trimuon vertex fit (upper right), the smallest distance of closest approach to the trimuon vertex of all the other tracks in the event with $p_T > 1$ GeV (lower left), and the muon reconstruction quality BDT score of the lowest p_T muon of the triplet (lower right). The signal and background distributions are obtained respectively from MC simulation and from the mass-sideband regions in data. All distributions are normalized to unit area. The rightmost bins include overflow.

nomial function. The systematic uncertainty associated with the choice of the function is treated as a discrete nuisance parameter in the fit [33].

5. Search for the $\tau \to 3\mu$ decay in W boson events

The $W^+ \to \tau^+\nu_\tau \to \mu^+\mu^-\mu^+\nu_\tau$ signal features three collimated muons with relatively high p_T. The trimuon system is isolated from any hadronic activity in the event and associated with large missing momentum carried away by the neutrino.

A dedicated HLT path was used in 2017–2018 in the search for the $\tau \to 3\mu$ decay in W boson events collected with the same L1 trigger requirements as those described in Section 4, as well as events collected with L1 trigger criteria targeting single-muon events with a muon p_T greater than 22 (25) GeV in 2017 (2018). Three muons were required to be reconstructed at the HLT, each with $p_T > 1$ GeV, and at least one with $p_T > 7$ GeV. The p_T of the trimuon system was required to be greater than 15 GeV and the resulting τ candidate was required to have an invariant mass between 1.3 and 2.1 GeV. The three muons were required to have a total charge of ± 1. An isolation variable, defined as the p_T sum of all tracks, other than those associated with the three muons, with $\Delta R < 0.8$ with respect to the τ candidate, and with a distance of closest approach with respect to the τ candidate below 3 mm along the beam direction, was required to be smaller than 20% of the τ candidate p_T.

The offline selection requires three muons with $p_T > 3.5\,(2.0)$ GeV for $|\eta| < 1.2$ $(1.2 < |\eta| < 2.4)$, with the three muons matching those that triggered the event. Tau lepton candidates are formed by combining all possible triplets of muons that pass the selection and can be successfully fitted to a common vertex. To remove contamination from dimuon resonances, a τ candidate is discarded if the mass of any pair of oppositely charged muons belonging to the τ candidate lies within 20 MeV of the ϕor the $\omega(782)$ masses. No more than one τ candidate per event is considered. Preference is given to candidates with the largest transverse mass $m_T = \sqrt{2 p_T^\tau p_T^{miss} [1 - \cos\Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss})]}$, which is one of the most sensitive observables to distinguish the W boson decay from other processes. The tracks of the three muon candidates are then refitted using the common vertex constraint.

The expected number of $\tau \to 3\mu$ signal events from W boson decays, denoted as $N_{3\mu(W)}$, is related to $\mathcal{B}(\tau \to 3\mu)$ by

$$N_{3\mu(W)} = \mathcal{L}\,\sigma(pp \to W + X)\,\mathcal{B}(W \to \tau\nu_\tau) \times \mathcal{A}_{3\mu(W)}\,\epsilon_{3\mu(W)}\,\mathcal{B}(\tau \to 3\mu),$$

where $\mathcal{L}$ is the integrated luminosity [34–36], $\sigma(pp \to W + X)$ is the W boson production cross section, $\mathcal{B}(W \to \tau\nu_\tau)$ is the branching fraction of the W boson decay to $\tau\nu_\tau$, $\mathcal{A}_{3\mu(W)}$ is the acceptance, and $\epsilon_{3\mu(W)}$ is the combined trigger and selection efficiency for the three muons. The product of $\sigma(pp \to W + X)$ and $\mathcal{B}(W \to \tau\nu_\tau)$ is obtained from the

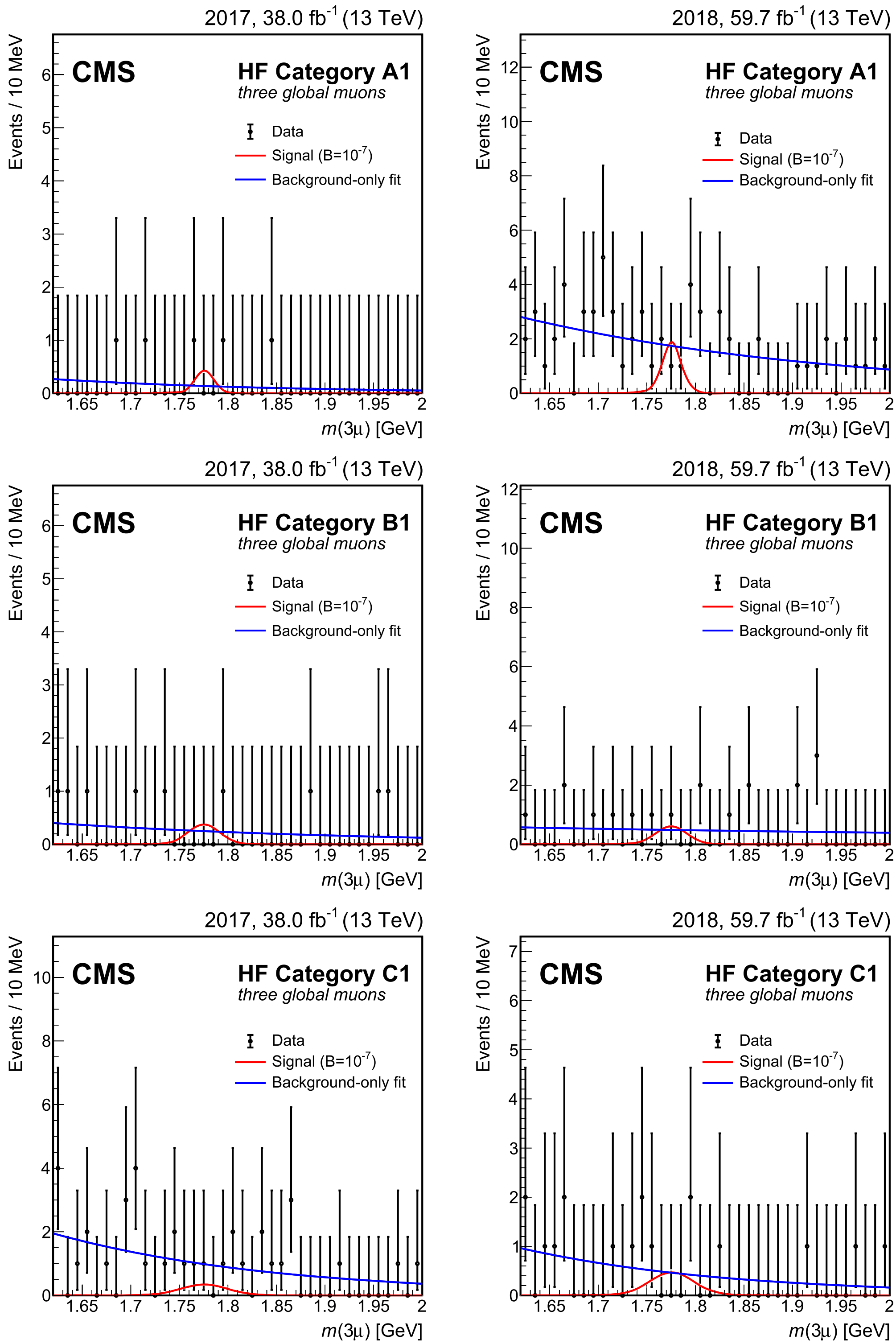

Fig. 3. Trimuon mass distributions in the highest BDT score subcategory of each of the three mass resolution categories of the heavy-flavor (HF) analysis: A1 (upper), B1 (middle), and C1 (lower) for 2017 (left) and 2018 (right) candidate events with three global muons. Data are shown with black markers. The background-only fit and the expected signal for $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$ are shown with blue and red lines, respectively.

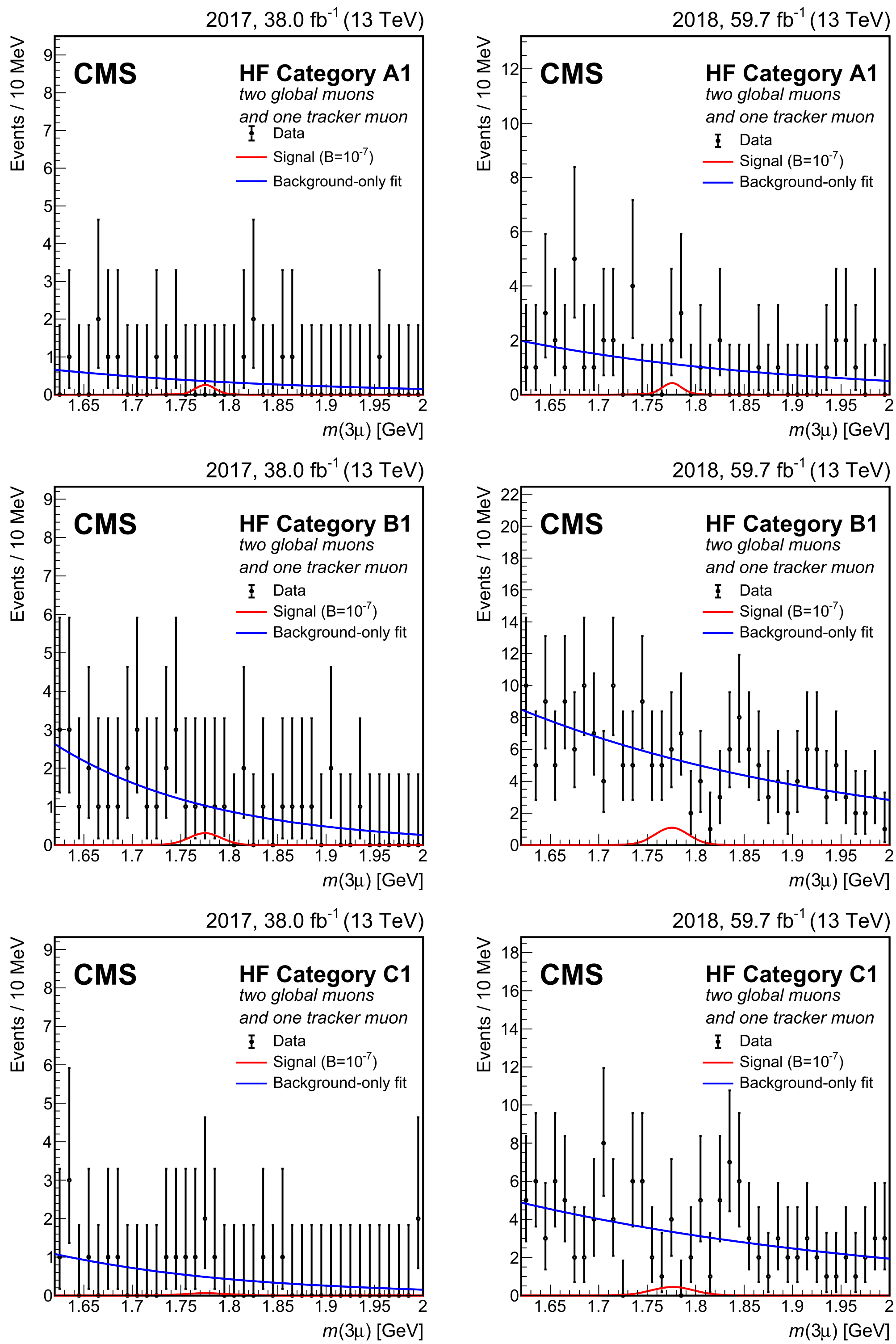

Fig. 4. Trimuon mass distributions in the highest BDT score subcategories of each of the three mass resolution categories of the heavy-flavor (HF) analysis: A1 (upper), B1 (middle), and C1 (lower) for 2017 (left) and 2018 (right) candidate events with two global muons and one tracker muon. Data are shown with black markers. The background-only fit and the expected signal for $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$ are shown with blue and red lines, respectively.

ATLAS measurement of $\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{X})\mathcal{B}(\mathrm{W} \to \mu\nu_\mu)$ at 13 TeV [37] and the world-average value of the ratio $\mathcal{B}(\mathrm{W} \to \tau\nu_\tau)/\mathcal{B}(\mathrm{W} \to \mu\nu_\mu)$ [30]. The p_T and η distributions of the W boson sample generated at LO are reweighted to match the distributions obtained from the smaller sample simulated at NLO precision.

Residual backgrounds are further reduced using a BDT, trained on simulated $\mathrm{W}^+ \to \tau^+\nu_\tau \to \mu^+\mu^-\mu^+\nu_\tau$ signal events and a background sample from data with the trimuon invariant mass within the 1.60–1.74 or 1.82–2.00 GeV range. The inputs to the BDT can be categorized into three different classes, related to either: $\mathrm{W}^+ \to \tau^+\nu_\tau$ decay, τ decay vertex, or quality of muon reconstruction. The $\mathrm{W}^+ \to \tau^+\nu_\tau$ related observables are: the p_T, η, and relative isolation of the τ candidate, along with m_T, $p_\mathrm{T}^\mathrm{miss}$ and the W boson p_T (defined as the magnitude of the vector sum of $\vec{p}_\mathrm{T}$ of the three muons and $\vec{p}_\mathrm{T}^\mathrm{miss}$). The isolation observable is defined as the scalar p_T sum of photons and tracks with $\Delta R < 0.8$ around the τ candidate direction, excluding the three muon candidates themselves, and is corrected for the pileup contribution. The relative isolation value is obtained by dividing the absolute isolation by the τ candidate p_T. In addition, the longitudinal component of the missing momentum is used: this is inferred from solving the energy-momentum equation for the τ candidate and the $\vec{p}_\mathrm{T}^\mathrm{miss}$ after imposing the nominal W boson mass [30] constraint. Observables related to the τ decay vertex are the χ^2 of the vertex fit, the significance of the distance in the transverse plane between the beamline and the decay vertex, and α_2D. The quality of muon reconstruction input is a single bit for each muon indicating whether the muon has passed the tight muon identification requirement [17]. The distributions of the observables providing the largest discrimination power between signal and background are shown in Fig. 5.

The events are separated into categories A, B, and C, in the same way as for the heavy-flavor analysis, from higher to lower mass resolutions. For each mass resolution category, an optimal BDT cut value is chosen, with events below the cut value rejected. It is found that optimizing for the largest expected signal significance or the most stringent expected upper limit has very little effect on the cut value obtained. The signal efficiency and background rejection of the BDT are checked to be uniform in τ candidate mass to avoid bias.

All selection criteria described above were determined in a blind way, without looking at data events with trimuon invariant mass in the range 1.74–1.82 GeV. Once the data were unblinded, it was observed that a significant fraction of events after the BDT selection had the trimuon vertex not displaced from the beamline, in spite of the distance in the transverse plane between the beamline and the trimuon vertex divided by its uncertainty being one of the BDT input features. These events were found to be consistent with the MC simulation prediction of $\mathrm{W}^+ \to \mu^+\mu^-\mu^+\nu_\mu$ events, where a W boson decays to a muon and a neutrino, and the emission of final-state radiation from the muon results in the production of two additional muons. To reduce this background, the distance in the transverse plane between the beamline and the trimuon vertex is required to be larger than twice its uncertainty.

The trimuon invariant mass distributions, after final selections, in categories A, B, and C are shown in Fig. 6, along with a background-only fit with a flat function, and the contribution expected for a signal of $\mathcal{B}(\tau \to 3\mu)$ set to 10^{-7}.

The major systematic uncertainties include the uncertainties in single-muon reconstruction efficiencies, measured using the tag-and-probe method applied to $J/\psi \to \mu^+\mu^-$ data events; the uncertainty in the HLT isolation selection efficiency, studied by comparing the trigger efficiency for $\mathrm{D}_\mathrm{s}^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$ events in data and simulation selected by an alternative version of the HLT path that contains no isolation requirements; the uncertainty in the NLO reweighting, which arises from the statistical uncertainty in the NLO simulation. The uncertainties in the mean and width of the signal trimuon invariant mass distribution are determined in the same way as in the heavy-flavor analysis.

6. Results

The branching fraction $\mathcal{B}(\tau \to 3\mu)$ is obtained from a simultaneous unbinned maximum likelihood fit to the trimuon mass distributions in a range 1.6–2.0 GeV in all 36 event categories of the heavy-flavor analysis and the W boson analysis. For the heavy-flavor analysis, the signal model is a Gaussian plus Crystal Ball function [29], while for the Wboson analysis it is a Gaussian function. Both signal models have fixed mean and width, as determined from fitting the simulated events in the corresponding category. The background normalizations are free parameters in the fit.

Upper limits on $\mathcal{B}(\tau \to 3\mu)$ are determined using a frequentist method [38] based on a modified profile likelihood test statistic and the $\mathrm{CL_s}$ criterion [39,40]. Uncertainties are incorporated via nuisance parameters, and are assumed to be uncorrelated between the heavy-flavor analysis and the W boson analysis. The nuisance parameters for the low-expected-background W boson analysis are treated with the strategy described in Ref. [41]. Events from data and simulation that pass the selection criteria of both analyses are removed from the heavy-flavor analysis in the combined fit, to benefit from the higher signal-to-background ratio in the W analysis.

The analysis sensitivity is limited by the statistical uncertainty, while the total impact of the systematic uncertainties is found to be a few percent.

The heavy-flavor analysis results in an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of $3.4\ (3.6) \times 10^{-8}$. The W boson analysis yields an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of $8.0\ (5.6) \times 10^{-8}$. The combination of the two analyses leads to an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of $3.1\,(2.7) \times 10^{-8}$.

The previously published result based on 2016 data [11] is combined with the new results by performing a simultaneous unbinned maximum likelihood fit to the trimuon mass distributions, leading to an observed (expected) upper limit at 90% CL on $\mathcal{B}(\tau \to 3\mu)$ of $2.9\,(2.4) \times 10^{-8}$. The upper limits at 90% CL are summarized in Fig. 7. The observed (expected) upper limit at 95% CL is $3.6\,(3.0) \times 10^{-8}$.

7. Summary

A search has been presented for the lepton flavor violating decay $\tau \to 3\mu$, using proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the CMS experiment at the LHC in 2017–2018. Tau leptons produced in heavy-flavor hadron decays and W boson decays are exploited in the analysis. The results from this analysis are combined with those of an earlier analysis using 2016 data, which gives a combined total integrated luminosity of 131 fb^{-1}. The observed (expected) upper limit on the branching fraction $\mathcal{B}(\tau \to 3\mu)$ is $2.9\ (2.4) \times 10^{-8}$ at 90% confidence level, and $3.6\,(3.0) \times 10^{-8}$ at 95% confidence level. The result obtained in this search is the best from a hadron collider experiment, and comparable with the current most restrictive one from the Belle experiment. As this limit is dominated by the statistical uncertainty, the additional data now being collected will provide even more stringent tests of the standard model with this decay channel.

Declaration of competing interest

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

Data availability

will be supplied at proof stage

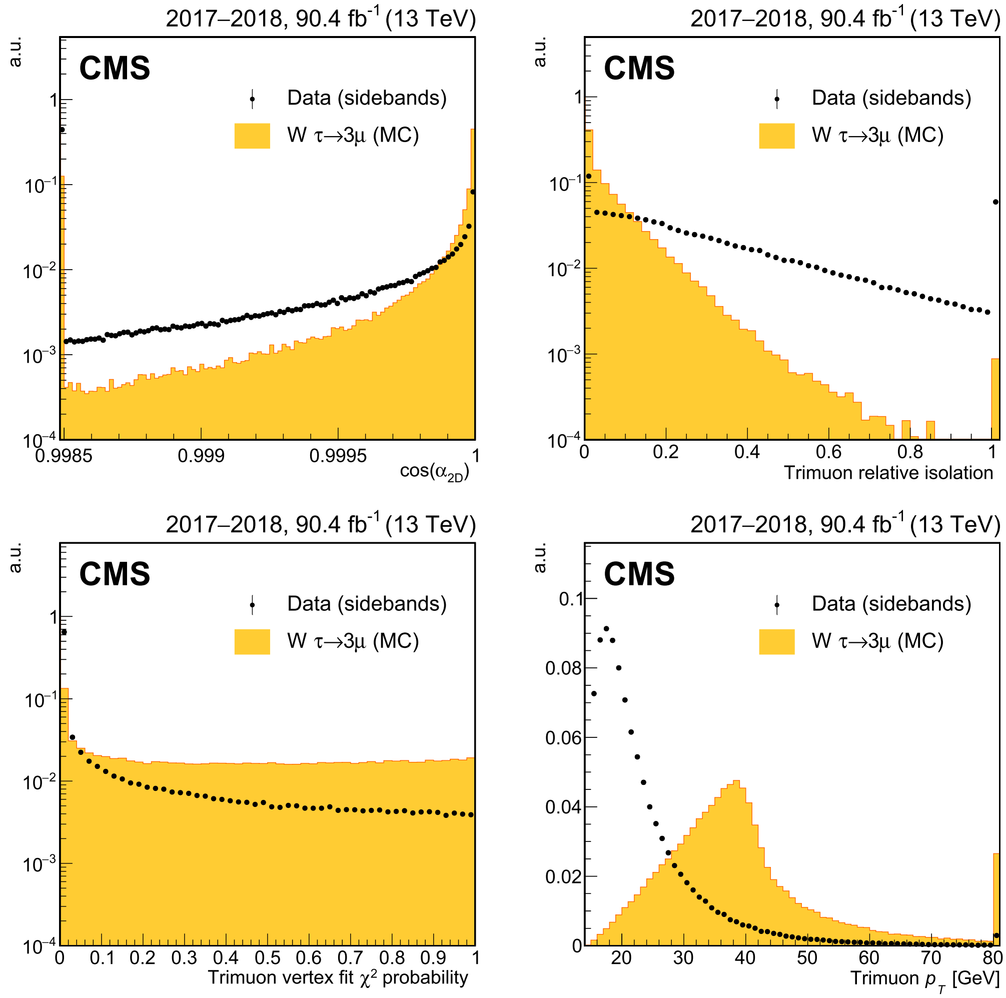

Fig. 5. Signal and background distributions for the four observables with the highest discrimination power used for the W boson analysis BDT training: cos(α_{2D}) (upper left), relative isolation observable of the trimuon system (upper right), trimuon vertex fit χ^2 probability (lower left), trimuon p_T (lower right). The signal and background distributions are obtained respectively from MC simulation and from the mass-sideband regions in data. All distributions are normalized to unit area. The leftmost (rightmost) bins include underflow (overflow).

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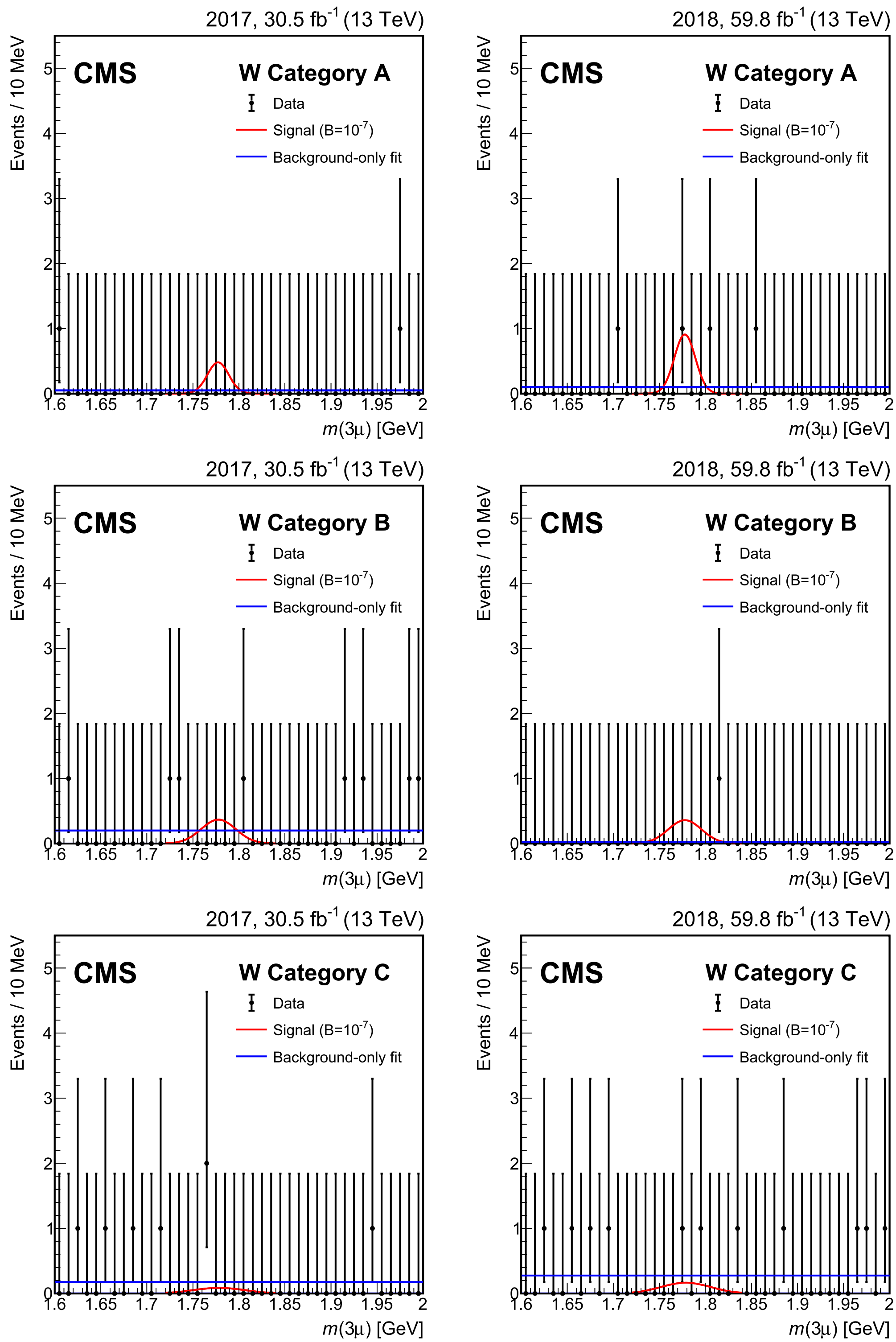

Fig. 6. Trimuon mass distributions of the 2017 (left) and 2018 (right) data events in the three mass resolution categories A (upper), B (middle), and C (lower) of the W boson analysis. Data are shown with black markers. The background-only fit and the expected signal for $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$ are shown with blue and red lines, respectively.

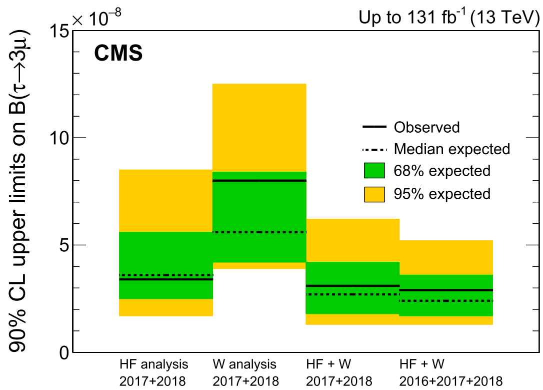

Fig. 7. Observed and expected upper limits on $\mathcal{B}(\tau \to 3\mu)$ at 90% CL, from the heavy-flavor (HF) analysis, the W boson analysis, the combination of the two analyses, as well as their combination with the previously published result using 2016 data.

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References

[1] X.-Y. Pham, Lepton flavor changing in neutrinoless τ decays, Eur. Phys. J. C 8 (1999) 513, https://doi.org/10.1007/s100529901088, arXiv:hep-ph/9810484.
[2] G. Hernández-Tomé, G. López Castro, P. Roig, Flavor violating leptonic decays of τ and μ leptons in the Standard Model with massive neutrinos, Eur. Phys. J. C 79 (2019) 84, https://doi.org/10.1140/epjc/s10052-019-6563-4, arXiv:1807.06050.
[3] P. Blackstone, M. Fael, E. Passemar, $\tau \to \mu\mu\mu$ at a rate of one out of 10^{14} tau decays?, Eur. Phys. J. C 80 (2020) 506, https://doi.org/10.1140/epjc/s10052-020-8059-7, arXiv:1912.09862.
[4] W.J. Marciano, T. Mori, J.M. Roney, Charged lepton flavor violation experiments, Annu. Rev. Nucl. Part. Sci. 58 (2008) 315, https://doi.org/10.1146/annurev.nucl.58.110707.171126.
[5] M. Raidal, et al., Flavour physics of leptons and dipole moments, Eur. Phys. J. C 57 (2008) 13, https://doi.org/10.1140/epjc/s10052-008-0715-2, arXiv:0801.1826.
[6] E. Arganda, M.J. Herrero, Testing supersymmetry with lepton flavor violating τ and μ decays, Phys. Rev. D 73 (2006) 055003, https://doi.org/10.1103/PhysRevD.73.055003, arXiv:hep-ph/0510405.
[7] K. Hayasaka, et al., Belle, Search for lepton flavor violating τ decays into three leptons with 719 million produced $\tau^+\tau^-$ pairs, Phys. Lett. B 687 (2010) 139, https://doi.org/10.1016/j.physletb.2010.03.037, arXiv:1001.3221.
[8] J.P. Lees, et al., BaBar, Limits on τ lepton-flavor violating decays in three charged leptons, Phys. Rev. D 81 (2010) 111101, https://doi.org/10.1103/PhysRevD.81.111101, arXiv:1002.4550.
[9] LHCb Collaboration, Search for the lepton flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$, J. High Energy Phys. 02 (2015) 121, https://doi.org/10.1007/JHEP02(2015)121, arXiv:1409.8548.
[10] ATLAS Collaboration, Probing lepton flavour violation via neutrinoless $\tau \to 3\mu$ decays with the ATLAS detector, Eur. Phys. J. C 76 (2016) 232, https://doi.org/10.1140/epjc/s10052-016-4041-9, arXiv:1601.03567.
[11] CMS Collaboration, Search for the lepton flavor violating decay $\tau \to 3\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 01 (2021) 163, https://doi.org/10.1007/JHEP01(2021)163, arXiv:2007.05658.
[12] HEPData record for this analysis, https://doi.org/10.17182/hepdata.145641, 2023.
[13] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[14] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
[15] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
[16] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. 16 (2021) P05014, https://doi.org/10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
[17] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, https://doi.org/10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
[18] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
[19] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
[20] CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P10005, https://doi.org/10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
[21] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
[22] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. 14 (2019) P07004, https://doi.org/10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
[23] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
[24] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
[25] D.J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A 462 (2001) 152, https://doi.org/10.1016/S0168-9002(01)00089-4.
[26] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.
[27] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[28] K. Prokofiev, T. Speer, A kinematic fit and a decay chain reconstruction library, in: Vol1 Proceedings of Computing in High Energy and Nuclear Physics 2004, 2005, cERN-2005-002.
[29] M.J. Oreglia, A study of the reactions $\psi' \to \gamma\gamma\psi$, Ph.D. thesis, Stanford University, 1980, http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-236.pdf, SLAC Report SLAC-R-236.
[30] Particle Data Group, R.L. Workman, et al., Review of particle physics, Prog. Theor. Exp. Phys. 2022 (2022) 083C01, https://doi.org/10.1093/ptep/ptac097.
[31] T. Chen, 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, ACM, New York, NY, USA, 2016, p. 785.
[32] CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 10 (2011) 132, https://doi.org/10.1007/JHEP10(2011)132, arXiv:1107.4789.
[33] P.D. Dauncey, M. Kenzie, N. Wardle, G.J. Davies, Handling uncertainties in background shapes: the discrete profiling method, J. Instrum. 10 (2015) P04015, https://doi.org/10.1088/1748-0221/10/04/P04015, arXiv:1408.6865.
[34] 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, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
[35] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, in: CMS Physics Analysis Summary CMS-PAS-LUM-17–004, 2018, https://cds.cern.ch/record/2621960.

[36] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, in: CMS Physics Analysis Summary CMS-PAS-LUM-18–002, 2019, https://cds.cern.ch/record/2676164.
[37] ATLAS Collaboration, Measurement of $W^{\pm}$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 759 (2016) 601, https://doi.org/10.1016/j.physletb.2016.06.023, arXiv:1603.09222.
[38] ATLAS and CMS Collaborations, and LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011, https://cds.cern.ch/record/1379837.
[39] A.L. Read, Presentation of search results: the CL_s technique, J. Phys. G 28 (2002) 2693, https://doi.org/10.1088/0954-3899/28/10/313.
[40] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A 434 (1999) 435, https://doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[41] R.D. Cousins, V.L. Highland, Incorporating systematic uncertainties into an upper limit, Nucl. Instrum. Methods Phys. Res., Sect. A 320 (1992) 331, https://doi.org/10.1016/0168-9002(92)90794-5.

The CMS Collaboration

A. Hayrapetyan, A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [3], T. Janssen, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

A. Benecke, G. Bruno, C. Caputo, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, K. Mondal, T.T. Tran, S. Wertz

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

C.A. Bernardes [6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

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

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

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

University of Sofia, Sofia, Bulgaria

S. Keshri, S. Thakur

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

T. Cheng, Q. Guo, T. Javaid, L. Yuan

Beihang University, Beijing, China

Z. Hu, J. Liu, K. Yi [8,9]

Department of Physics, Tsinghua University, Beijing, China

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

Institute of High Energy Physics, 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

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

Z. You

Sun Yat-Sen University, Guangzhou, China

N. Lu

University of Science and Technology of China, Hefei, China

G. Bauer [14]

Nanjing Normal University, Nanjing, China

X. Gao [15], D. Leggat, H. Okawa, Y. Zhang

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

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

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

Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

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

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

M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, A. Starodumov [16], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Elgammal [17], A. Ellithi Kamel [18]

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

M. Abdullah Al-Mashad, M.A. Mahmoud

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

R.K. Dewanjee [19], K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva [†]

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [20], P. Simkina, M. Titov, M. Tornago

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

C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, A. De Wit, G. Falmagne, 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

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

J.-L. Agram [21], 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

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

S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen [22], 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

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

G. Adamov, I. Lomidze, Z. Tsamalaidze[16]

Georgian Technical University, Tbilisi, Georgia

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

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, L. Mastrolorenzo, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, A. Novak, 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 Araujo[23], L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad[24], T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

RWTH Aachen University, III. Physikalisches Institut B, Aachen, 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. Blekman[25], K. Borras[26], D. Brunner, 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. Gallo[25], A. Geiser, A. Giraldi, G. Greau, V. Guglielmi, M. Guthoff, A. Hinzmann, A. Jafari[27], L. Jeppe, N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[28], W. Lohmann[29], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, A. Mussgiller, L.P. NAIR, A. Nürnberg, Y. Otarid, J. Park, D. Pérez Adán, E. Ranken, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Scham[30,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, M. Eich, K. El Morabit, Y. Fischer, A. Fröhlich, C. Garbers, E. Garutti, A. Grohsjean, M. Hajheidari, 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. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[31], 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, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy,

I. Shvetsov, H.J. Simonis, M. Toms[32], N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, S. Wunsch, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[31], A. Stakia

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

M. Bartók[33], C. Hajdu, D. Horvath[34,35], F. Sikler, V. Veszpremi

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

M. Csanád, K. Farkas, M.M.A. Gadallah[36], Á. Kadlecsik, P. Major, K. Mandal, G. Pásztor, A.J. Rádl[37], G.I. Veres

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

P. Raics, B. Ujvari, G. Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G. Bencze, S. Czellar, J. Karancsi[33], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

T. Csorgo[37], F. Nemes[37], T. Novak

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

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[38], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Baradia, S. Barman[39], S. Bhattacharya, S. Dutta, S. Dutta, P. Palit, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, P. Jana, P. Kalbhor, J.R. Komaragiri[40], D. Kumar[40], L. Panwar[40], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Indian Institute of Technology Madras, Madras, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [41], A.K. Das, C. Kar, D. Maity [42], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [42], K. Naskar [42], A. Nayak [42], P. Sadangi, P. Saha, S.K. Swain, S. Varghese [42], D. Vats [42]

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

S. Acharya [43], A. Alpana, S. Dube, B. Gomber [43], B. Kansal, A. Laha, B. Sahu [43], S. Sharma

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

H. Bakhshiansohi [44], E. Khazaie [45], M. Zeinali [46]

Isfahan University of Technology, Isfahan, Iran

S. Chenarani [47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,c,48], 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,48], 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. Pellecchia [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]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], 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,49], 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]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Costa [a,b,50], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,50], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, 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]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Meola [51], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Chatagnon [a], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, 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]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo [a], A. Cagnotta [a,b], F. Carnevali [a,b], N. Cavallo [a,c], A. De Iorio [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,52], P. Paolucci [a,31], B. Rossi [a], C. Sciacca [a,b]

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

R. Ardino [a], P. Azzi [a], N. Bacchetta [a,53], D. Bisello [a,b], P. Bortignon [a], A. Bragagnolo [a,b], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], S. Fantinel [a], F. Gasparini [a,b], U. Gasparini [a,b], G. Grosso [a], E. Lusiani [a], M. Margoni [a,b], 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], H. Yarar [a,b], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, Italy

S. Abu Zeid [a,54], 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]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

S. Ajmal [a,b], P. Asenov [a,55], 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,55], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

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], A. Venturi [a], P.G. Verdini [a]

[a] INFN Sezione di Pisa, Pisa, Italy
[b] Università di Pisa, Pisa, Italy
[c] Scuola Normale Superiore di Pisa, Pisa, Italy
[d] Università di Siena, Siena, Italy

P. Barria [a], 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]

[a] INFN Sezione di Roma, Roma, Italy
[b] Sapienza Università di Roma, Roma, 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], 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], 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]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, Italy

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], K. De Leo [a,b], G. Della Ricca [a,b]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Korea

M.S. Kim

Department of Mathematics and Physics – GWNU, Gangneung, Korea

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

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh, S. Yang

Kyung Hee University, Department of Physics, Seoul, Korea

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

Sejong University, Seoul, Korea

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

Seoul National University, 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

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Maghrbi

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

K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns [56]

Riga Technical University, Riga, Latvia

N.R. Strautnieks

University of Latvia (LU), Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, I. Yusuff[57], Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[58], R. Lopez-Fernandez, C.A. Mondragon Herrera, A. Sánchez Hernández

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

C. Oropeza Barrera, M. Ramírez García

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, N. Raicevic

University of Montenegro, Podgorica, Montenegro

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Pozniak, W. Zabolotny

Warsaw University of Technology, Warsaw, Poland

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

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

P. Adzic, P. Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

M. Dordevic, J. Milosevic, V. Rekovic

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

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

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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

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

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

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

M.K. Jayananda, B. Kailasapathy[59], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna[60], K. Liyanage, N. Perera, N. Wickramage

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

D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, F. Fallavollita[61], L. Forthomme, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, B. Huber, V. Innocente, T. James, P. Janot, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, M. Matthewman, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, H. Qu, D. Rabady, G. Reales Gutiérrez, M. Rovere, H. Sakulin, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[62], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[63], S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua[64], L. Caminada[64], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[64], L. Noehte[64], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov[63], 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, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese,

C. Martin Perez, A. Mascellani[63], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, R. Seidita, J. Steggemann[63], D. Valsecchi, R. Wallny

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

C. Amsler[65], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi, R. Tramontano

Universität Zürich, Zurich, Switzerland

C. Adloff[66], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[40], S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, Z.g. Chen, 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

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

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

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[67], E. Eskut, Y. Guler[68], E. Gurpinar Guler[68], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[69], A. Polatoz, B. Tali[70], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

M. Yalvac[71]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[72], O. Kaya[73], S. Tekten[74]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak[67,75], Y. Komurcu, S. Sen[76]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek, S. Cerci[70], V. Epshteyn, B. Hacisahinoglu, I. Hos[77], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, D. Sunar Cerci[70], C. Zorbilmez

Istanbul University, Istanbul, Turkey

B. Isildak[78]

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev, B. Grynyov

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

L. Levchuk

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

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[79], K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[81], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[82], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, J. Nash[83], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[31], M. Vojinovic, N. Wardle, D. Winterbottom

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, TX, USA

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

Catholic University of America, Washington, DC, USA

B. Bam, R. Chudasama, S.I. Cooper, S.V. Gleyzer, C.U. Perez, P. Rumerio[84], E. Usai, R. Yi

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Benelli, X. Coubez[26], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[85], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, S. Sagir[86], F. Simpson, M. Stamenkovic, W.Y. Wong, X. Yan, W. Zhang

Brown University, Providence, RI, USA

S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, 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, Davis, Davis, CA, 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, Los Angeles, CA, USA

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

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

A. Barzdukas, L. Brennan, C. Campagnari, A. Dorsett, 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

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

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

California Institute of Technology, Pasadena, CA, USA

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

Carnegie Mellon University, Pittsburgh, PA, USA

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

University of Colorado Boulder, Boulder, CO, USA

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

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[87], F. Ravera, A. Reinsvold Hall[88], 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, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, 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.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang

University of Florida, Gainesville, FL, USA

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

Florida State University, Tallahassee, FL, USA

B. Alsufyani, M.M. Baarmand, S. Butalla, T. Elkafrawy[54], M. Hohlmann, R. Kumar Verma, M. Rahmani, E. Yanes

Florida Institute of Technology, Melbourne, FL, USA

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

University of Illinois Chicago, Chicago, USA

M. Alhusseini, D. Blend, K. Dilsiz[89], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[90], J. Nachtman, O. Neogi, H. Ogul[91], Y. Onel, A. Penzo, C. Snyder, E. Tiras[92]

The University of Iowa, Iowa City, IA, USA

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

Johns Hopkins University, Baltimore, MD, 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, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[93], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

The University of Kansas, Lawrence, KS, USA

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

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA

A. Baden, A. Belloni, A. Bethani, 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. Paranjpe, L. Wang

University of Maryland, College Park, MD, USA

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

Massachusetts Institute of Technology, Cambridge, MA, 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 Minnesota, Minneapolis, MN, USA

L.M. Cremaldi

University of Mississippi, Oxford, MS, USA

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

University of Nebraska-Lincoln, Lincoln, NE, USA

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

State University of New York at Buffalo, Buffalo, NY, 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, A. Tishelman-Charny, B. Wang, D. Wood

Northeastern University, Boston, MA, USA

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

Northwestern University, Evanston, IL, USA

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

University of Notre Dame, Notre Dame, IN, 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

The Ohio State University, Columbus, OH, 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

Princeton University, Princeton, NJ, USA

S. Malik

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, S. Das, 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. Virdi, F. Wang, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar, A. Pathak

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Baty, 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

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[32], E. Popova[32], R. Taus, G.P. Van Onsem

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[29], I. Laflotte, A. Lath, R. Montalvo, K. Nash, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

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

University of Tennessee, Knoxville, TN, USA

D. Aebi, M. Ahmad, O. Bouhali[94], M. Dalchenko, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[95], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

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

Texas Tech University, Lubbock, TX, USA

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

Vanderbilt University, Nashville, TN, USA

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

University of Virginia, Charlottesville, VA, USA

P.E. Karchin

Wayne State University, Detroit, MI, 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, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

University of Wisconsin – Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[96], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov[96], M. Danilov[96], A. Dermenev, T. Dimova[96], D. Druzhkin[97], M. Dubinin[87], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, V. Karjavine, A. Karneyeu, V. Kim[96], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[98], V. Korenkov, A. Kozyrev[96], N. Krasnikov, A. Lanev, P. Levchenko[99], N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[96], V. Murzin, A. Nikitenko[100,98], S. Obraztsov, V. Oreshkin, V. Palichik, V. Perelygin, S. Polikarpov[96], V. Popov, O. Radchenko[96], M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[96], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, A. Vorobyev[†], G. Vorotnikov, N. Voytishin, B.S. Yuldashev[101], A. Zarubin, I. Zhizhin, A. Zhokin

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

† Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Ghent University, Ghent, Belgium.
[5] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[6] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[7] Also at UFMS, Nova Andradina, Brazil.
[8] Also at Nanjing Normal University, Nanjing, China.
[9] Now at The University of Iowa, Iowa City, Iowa, USA.
[10] Also at University of Chinese Academy of Sciences, Beijing, China.
[11] Also at China Center of Advanced Science and Technology, Beijing, China.
[12] Also at University of Chinese Academy of Sciences, Beijing, China.
[13] Also at China Spallation Neutron Source, Guangdong, China.
[14] Now at Henan Normal University, Xinxiang, China.
[15] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[16] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[17] Now at British University in Egypt, Cairo, Egypt.
[18] Now at Cairo University, Cairo, Egypt.
[19] Also at Birla Institute of Technology, Mesra, Mesra, India.
[20] Also at Purdue University, West Lafayette, Indiana, USA.
[21] Also at Université de Haute Alsace, Mulhouse, France.
[22] Also at Department of Physics, Tsinghua University, Beijing, China.
[23] Also at The University of the State of Amazonas, Manaus, Brazil.
[24] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[25] Also at University of Hamburg, Hamburg, Germany.
[26] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[27] Also at Isfahan University of Technology, Isfahan, Iran.
[28] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[29] Also at Brandenburg University of Technology, Cottbus, Germany.
[30] Also at Forschungszentrum Jülich, Juelich, Germany.
[31] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[32] Now at an institute or an international laboratory covered by a cooperation agreement with CERN.
[33] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[34] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[35] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[36] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[37] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[38] Also at Punjab Agricultural University, Ludhiana, India.
[39] Also at University of Visva-Bharati, Santiniketan, India.
[40] Also at Indian Institute of Science (IISc), Bangalore, India.
[41] Also at IIT Bhubaneswar, Bhubaneswar, India.
[42] Also at Institute of Physics, Bhubaneswar, India.
[43] Also at University of Hyderabad, Hyderabad, India.
[44] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[45] Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[46] Also at Sharif University of Technology, Tehran, Iran.
[47] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[48] Also at Helwan University, Cairo, Egypt.
[49] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[50] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[51] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[52] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[53] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[54] Also at Ain Shams University, Cairo, Egypt.
[55] Also at Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy.
[56] Also at Riga Technical University, Riga, Latvia.
[57] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[58] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[59] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[60] Also at Saegis Campus, Nugegoda, Sri Lanka.
[61] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[62] Also at National and Kapodistrian University of Athens, Athens, Greece.
[63] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[64] Also at Universität Zürich, Zurich, Switzerland.
[65] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[66] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[67] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[68] Also at Konya Technical University, Konya, Turkey.
[69] Also at Izmir Bakircay University, Izmir, Turkey.
[70] Also at Adiyaman University, Adiyaman, Turkey.
[71] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[72] Also at Marmara University, Istanbul, Turkey.
[73] Also at Milli Savunma University, Istanbul, Turkey.
[74] Also at Kafkas University, Kars, Turkey.
[75] Now at Istanbul Okan University, Istanbul, Turkey.
[76] Also at Hacettepe University, Ankara, Turkey.
[77] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.

[78] Also at Yildiz Technical University, Istanbul, Turkey.
[79] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[80] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[81] Also at University of Bristol, Bristol, United Kingdom.
[82] Also at IPPP Durham University, Durham, United Kingdom.
[83] Also at Monash University, Faculty of Science, Clayton, Australia.
[84] Also at Università di Torino, Torino, Italy.
[85] Also at Bethel University, St. Paul, Minnesota, USA.
[86] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[87] Also at California Institute of Technology, Pasadena, California, USA.
[88] Also at United States Naval Academy, Annapolis, Maryland, USA.
[89] Also at Bingol University, Bingol, Turkey.
[90] Also at Georgian Technical University, Tbilisi, Georgia.
[91] Also at Sinop University, Sinop, Turkey.
[92] Also at Erciyes University, Kayseri, Turkey.
[93] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[94] Also at Texas A&M University at Qatar, Doha, Qatar.
[95] Also at Kyungpook National University, Daegu, Republic of Korea.
[96] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[97] Also at Universiteit Antwerpen, Antwerpen, Belgium.
[98] Also at Yerevan Physics Institute, Yerevan, Armenia.
[99] Also at Northeastern University, Boston, Massachusetts, USA.
[100] Also at Imperial College, London, United Kingdom.
[101] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.