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Measurement of the ratio of the $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ branching fractions using three-prong τ lepton decays

The CMS Collaboration*

Abstract

The ratio between the $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ branching fractions is measured using a data sample of proton-proton collisions collected by CMS at a center-of-mass energy of 13 TeV in the years 2016–2018 and corresponding to an integrated luminosity of 138 fb^{-1}. The J/ψ meson is identified through its $J/\psi \to \mu^+\mu^-$ decay and the tau lepton is reconstructed in the hadronic three-prong final state. The measured ratio of branching fractions in this tau decay mode, $\mathcal{R}^{had}_{J/\psi} = 1.04^{+0.50}_{-0.44}$, is combined with the previous analysis based on the $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ leptonic decay channel, leading to $\mathcal{R}_{J/\psi} = 0.49 \pm 0.26$. As this result is consistent with the standard model prediction of 0.258 ± 0.004, no evidence of lepton flavor universality violation is found.

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*See Appendix A for the list of collaboration members

The standard model (SM) of particle physics provides an excellent description of physical processes up to the electroweak scale and was completed by the discovery of the Higgs boson [1–3] by the ATLAS and CMS Collaborations at the CERN LHC. The Yukawa couplings of the Higgs boson to fermions are proportional to the fermion masses and can contain complex phases that contribute to charge-conjugation and parity violation, particularly through the Cabibbo–Kobayashi–Maskawa matrix [4, 5] in the quark sector. The Yukawa couplings are also the only source of lepton flavor universality (LFU) violation in the SM, and so far the measurements of the coupling are consistent with the SM predictions for the second and third lepton generations [6, 7]. Given that LFU is not explained by any underlying structure of the SM, it is natural to consider whether a more elaborate mechanism for LFU could exist. An observation of LFU violation in B meson decays would point to physics beyond the SM.

To experimentally test LFU, the LHCb Collaboration measured the branching ratio $\mathcal{R}_{J/\psi} = \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, using $J/\psi \to \mu^+\mu^-$ and $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ decays, which ensures both decay modes have the same visible final state (three muons). The result, $0.71 \pm 0.17\,\text{(stat)} \pm 0.18\,\text{(syst)}$ [8], exceeds the value predicted by the SM, 0.258 ± 0.004 [9–13], by about 2 standard deviations. The CMS Collaboration subsequently measured $\mathcal{R}_{J/\psi} = 0.17^{+0.18}_{-0.17}\,\text{(stat)}^{+0.21}_{-0.22}\,\text{(syst)}^{+0.19}_{-0.18}\,\text{(theo)}$ [14] in the same final states, using a data sample collected in 2018, corresponding to an integrated luminosity of $59.7\,\text{fb}^{-1}$ [15] (referred to as the "leptonic τ analysis" in this Letter).

The measurement presented in this Letter, which is also provided in a HEPData record [16], is based on a sample of proton-proton (pp) collisions at $\sqrt{s} = 13\,\text{TeV}$ collected by CMS in 2016–2018 and corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$ [15, 17, 18]. We identify and reconstruct the decay $B_c^+ \to J/\psi\tau^+\nu_\tau$ with subsequent decays of the J/ψ meson to a pair of muons and of the τ lepton to its hadronic three-prong final state, reconstructed from three charged pions, referred to as τ^+_{had}. Besides the neutrino, additional (unreconstructed) pions may also be present in the decay. The data used in Ref. [14] to evaluate the $B_c^+ \to J/\psi\mu^+\nu_\mu$ yield are also used to derive the denominator of $\mathcal{R}_{J/\psi}$ in this measurement. The result is combined with that of the leptonic τ analysis [14]. In this Letter, wherever a particle or its decay mode is specified, the charge conjugate is also implied, unless otherwise indicated.

The CMS apparatus [19, 20] is a multipurpose, nearly hermetic detector, designed to trigger on [21–23] and identify electrons, muons, photons, and (charged and neutral) hadrons [24–26]. A global "particle-flow" (PF) algorithm [27] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the lead-tungstate crystal electromagnetic, and brass and 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. Objects such as hadronically decaying τ leptons [28] are built from the reconstructed particles.

For each data taking year, a corresponding sample of simulated events, containing B_c^+ mesons, has been produced with the BCVEGPY [29, 30] Monte Carlo (MC) event generator, interfaced with EVTGEN 1.6.0 [31, 32] for decays of weakly decaying hadrons, and with PYTHIA 8.240 [33] for parton showering, hadronization, and modeling of the underlying event using the CP5 tune [34]. The events include the signal modes, $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$, and other $B_c^+ \to J/\psi H_c X$ decays, where H_c indicates a (possibly excited) charm meson and X indicates additional products. The TAUOLA 1.1.5 program is used to simulate τ lepton decays [35, 36]. Contributions from $\psi(2S)$, $\chi_{c1}(1P)$, and $\chi_{c2}(1P)$ feed-down decays to J/ψ mesons are also included. The branching fractions of the decays are obtained from their measured values or theoretical predictions [37–41]. Most of the contributions that satisfy our selection criteria come from $B_c^+ \to J/\psi D_s^{(*)+}$ decays, where the D_s^+ meson might be in an excited state. Contributions from other B_c^+ decays are referred to as "$B_c^+ \to$ others" and mainly include the $B_c^+ \to J/\psi D^{(*)+}$, $B_c^+ \to J/\psi D^+ K^{(*)0}$, and $B_c^+ \to J/\psi D^{(*)0} K^+$ decays. To account for decays not included in the simulation, the $B_c^+ \to$ others yields are scaled up with a factor calculated from an investigation of the effect in simulation of other expected but unobserved B_c^+ decay modes: $B_c^+ \to J/\psi H_c X$, where H_c includes charm meson excited states above the $D^{(*)}$ and X includes up to two pions or kaons, either neutral or charged, with a phase space model for the decays. The $B_c^+ \to J/\psi \ell \nu$ ($\ell = \mu, \tau$) decay was generated with an hadronic model using the Kiselev form factor parameterization [42]. We update to the parameterization in Ref. [43] by reweighting the generated events in the simulated sample using the HAMMER [44] framework. The events are also reweighted so that the average of the B_c^+ meson lifetime distribution matches the world-average value of 0.510 ps [45]. As the B_c^+ cross section is not well known, we initially normalize the B_c^+ MC samples to match the data in a two step process. First, the normalization of the 2018 MC sample is taken from the leptonic τ analysis [14] by comparing the $B_c^+ \to J/\psi \mu^+ \nu_\mu$ yields in the measured and simulated event samples. To normalize the 2016 and 2017 MC samples, we reconstruct and select $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$ candidates, fit the invariant mass distributions of data and MC to obtain the yields for each of the three years, calculate the data/MC ratio of yields, calculate the ratio of the 2016 and 2017 results to the 2018 result, and multiply by the 2018 normalization value.

A second (background) simulated sample contains events with $H_b \to J/\psi X$ decays, where H_b indicates a ground state hadron with a b quark other than a B_c^+ meson, and the J/ψ decays to a pair of muons. The PYTHIA 8.240 generator [33] is used to simulate the production and hadronization of the b quark into H_b with the "SoftQCD:nonDiffractive" process. To increase the generation efficiency, one of the H_b hadrons in each event is forced to decay in modes that include a J/ψ meson. The $H_b \to J/\psi X$ decays are simulated with EVTGEN 1.6.0, including contributions from feed-down decays of heavier charmonium states. This sample is primarily used to derive corrections in the estimation of the inclusive $H_b \to J/\psi X$ background.

The simulated samples include effects from additional pp interactions in the same or nearby bunch crossings (pileup), generated with PYTHIA, with a multiplicity distribution tuned to match the data. The simulated events are reweighted to match the pileup profile observed in data. Final-state photon radiation is modeled by PHOTOS 3.61 [46]. The interactions between particles and the CMS detector are simulated using GEANT4 [47] and the output is processed through the standard CMS reconstruction software.

Events are collected using a trigger that requires a pair of oppositely-charged muons, each with transverse momentum $p_T > 4$ GeV. The two muons are used to form a J/ψ candidate, which must have vertex fit probability above 10%, $p_T > 6.9$ GeV, and an invariant mass in the 2.9–3.3 GeV range. The displacement in the transverse plane between the beam axis and the dimuon vertex is required to be at least 3 times the uncertainty in the displacement. An additional track with $p_T > 1.2$ GeV is required to be present, form a vertex with the J/ψ candidate muons, and be displaced with respect to the beam axis with a significance greater than 2.

At the offline reconstruction level, the two muons are required to match the muons used in the trigger, satisfy the trigger requirements, pass a set of loose identification (ID) criteria [25], and have an invariant mass in the 2.95–3.25 GeV range. If more than one J/ψ candidate is found in an event (around 1% of the events), we select the one with the highest p_T. We define the primary vertex (PV) as the pp collision vertex with the shortest distance along the beam axis to the line defined by the J/ψ candidate momentum direction that intersects the dimuon vertex. Corrections to the simulated events (scale factors) are applied to match the efficiencies found in data. The trigger efficiency is determined from events that pass a different trigger than used for the signal, while the offline muon reconstruction and identification efficiency is determined using the tag and probe method from prompt J/ψ events. Scale factors are derived for each data-taking year. Three trigger scale factors are applied, one related to the J/ψ selection, which is binned in muon p_T and $|\eta|$, one related to the J/ψ displacement, which is binned in the significance of the displacement in the transverse plane between the beam axis and the dimuon vertex, and one related to the hadron track, which is binned in track p_T, $|\eta|$, and impact parameter significance. The muon scale factor is applied to both muons in the event and is binned in muon p_T and $|\eta|$.

Potential τ^+_{had} candidates are obtained by selecting triplets of PF charged hadrons, with each charged hadron required to have $p_T > 0.5\,\text{GeV}$, pseudorapidity $|\eta| < 2.5$, pass within 1.2 mm of the PV in the longitudinal direction, have $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1$, where $\Delta\eta$ and $\Delta\phi$ are measured with respect to the J/ψ candidate momentum (ϕ is the azimuthal angle in radians), and a distance of closest approach with respect to the J/ψ vertex between -0.4 and 0.6 mm, where the sign depends on the angle between the track and the J/ψ momentum direction. The triplet is required to have electrical charge equal to unity, to have a vertex fit probability greater than 10%, $p_T > 3\,\text{GeV}$, a three-dimensional displacement with respect to the PV greater than 3 times its uncertainty, and an invariant mass less than 1.7 GeV. At least one of the three pion candidates is required to match the track object reconstructed at the trigger level. In cases where more than one triplet satisfies these criteria, we select the highest-p_T triplet. This occurs in about 20% of the simulated signal events and the selection is correct for about 70% of these events.

After this baseline event selection, more than 99.98% of the events are inclusive B^0 and B^+ background events with a J/ψ meson candidate in the final state. We use a discriminator based on a boosted decision tree (BDT) trained with the XGBOOST algorithm [48] to suppress the background. The $B_c^+ \to J/\psi\tau^+\nu_\tau$ simulated sample for the 2018 data-taking period is used as signal for the training. The selected τ lepton candidate is required to be matched to the generator-level τ^+_{had}. The simulated sample of the $H_b \to J/\psi X$ background for the 2018 data-taking period is used as the background process. The BDT hyperparameters were optimized using a Bayesian technique and comparisons between data and simulation on control regions not used in the analysis were used to check the agreement. A training using background events from data was also performed and yielded similar results. The background sample also includes processes with genuine hadronically decaying τ leptons, which can lead to final states similar to that of the signal. However, in most cases these can easily be discriminated from the $B_c^+ \to J/\psi\tau^+\nu_\tau$ process and result in a low BDT score, s_{BDT}. The training is performed using 18 input variables related to the kinematic and topological properties of the B meson and τ lepton candidates, as well as global event-level observables. The s_{BDT} distribution is depicted in Fig. 1, where expected simulated events are compared to 2018 data considering just the statistical uncertainties before the fit for $\mathcal{R}_{J/\psi}$.

Using the s_{BDT} variable, two regions are defined in each data-taking period: for the 2016 (2017–2018) data a signal-enriched region (SR) with $s_{\text{BDT}} > 3.5$ ($s_{\text{BDT}} > 4.2$) and a background-enriched sideband region (SB) with $2 < s_{\text{BDT}} < 3$ ($2.5 < s_{\text{BDT}} < 3.5$). The SR region is optimized to maximize the signal significance, while the SB region is defined so that it includes a sufficiently large number of events with s_{BDT} values close enough to the SR to ensure that it represents the background in that region, but far enough from the SR to minimize signal contamination. In the SR, the signal and background efficiencies relative to the baseline selection are about 10% and 0.01%, respectively. The 2016 and 2017–2018 s_{BDT} regions differ because of the upgraded pixel system installed after the 2016 data-taking period [49]. For simulated signal events in the SR, about 90% of the τ^+_{had} candidates are created from the three pions from the τ

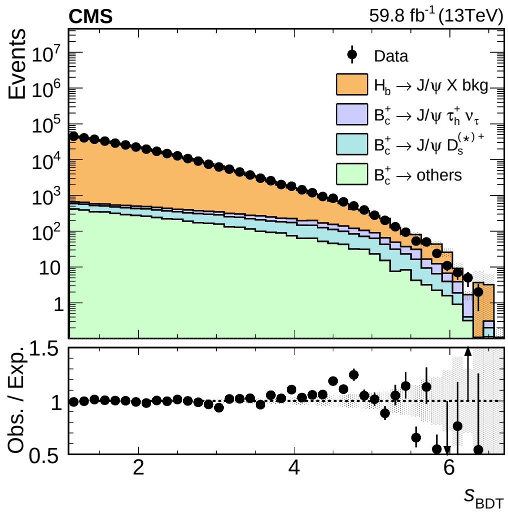

Figure 1: The s_{BDT} distribution. The data are shown by closed circles, with vertical bars representing the statistical uncertainties. The simulated $\mathrm{H_b} \to \mathrm{J}/\psi\mathrm{X}$ contribution is normalized to match the yield in data after applying all event selection criteria except the BDT. The $\mathrm{B_c^+} \to \mathrm{J}/\psi\mathrm{X}$ processes are normalized before the $\mathcal{R}_{\mathrm{J}/\psi}$ fit. The ratio between the data and the sum of expected signal and background contributions is shown in the lower panel. The statistical uncertainty in the sum of the simulated contributions is shown as a gray band.

lepton decay, while 10% of the τ^+_{had} candidates are created from two pions from the τ lepton decay along with an unrelated track. Both types of events are considered as signal. The SB is used to derive the contribution of $\mathrm{H_b} \to \mathrm{J}/\psi\mathrm{X}$ backgrounds in the SR.

We exploit the dominant three-prong hadronic τ lepton decay $\tau^+ \to \mathrm{a_1}(1260)^+\overline{\nu}_\tau$ [50] for the signal extraction, where $\mathrm{a_1}(1260)^+ \to \rho(770)^0(\to \pi^+\pi^-)\pi^+$. A one-dimensional unrolled distribution is built starting from the ρ_1 vs. ρ_2 invariant masses two-dimensional distribution, where ρ_1 and ρ_2 are the two possible $\rho(770)^0 \to \pi^+\pi^-$ meson candidates built from each τ^+_{had} candidate and ordered in p_{T}. We consider the mass range 0.2–1.5 GeV for ρ_1 and ρ_2, each split into four bins with widths of 0.225 GeV for the first three and 0.625 GeV for the last. We refer to this distribution as the unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distribution. Genuine τ lepton decays are likely to produce a resonant structure either in the ρ_1 or in the ρ_2 invariant mass distributions. This is not the case for background events, which typically do not include genuine τ lepton decays. Neither the ρ_1 nor the ρ_2 invariant masses are included in the BDT and both variables are found to be independent with s_{BDT}.

To obtain the final results, maximum likelihood fits are performed using the COMBINE tool [51]. The data used by the fit are the same as used in the leptonic τ analysis [14] plus six unrolled ρ^0 mass distributions (SB and SR for three data taking periods). The signal strength parameter r is proportional to the parameter of interest, $\mathcal{R}_{\mathrm{J}/\psi}$ and therefore only scales the $\mathrm{B_c^+} \to \mathrm{J}/\psi\tau^+\nu_\tau$ yield. Another free parameter, $r_{\mathrm{B_c^+}}$, multiplies the initial normalization of all $\mathrm{B_c^+}$ MC events, including the $\mathrm{B_c^+}$ background as well as the $\mathrm{B_c^+} \to \mathrm{J}/\psi\mu^+\nu_\mu$ and $\mathrm{B_c^+} \to \mathrm{J}/\psi\tau^+\nu_\tau$ contributions. The value of $r_{\mathrm{B_c^+}}$ is primarily determined by the (large) number of $\mathrm{B_c^+} \to \mathrm{J}/\psi\mu^+\nu_\mu$ events. The fit model for the leptonic τ distributions is the same as in Ref. [14]. For the hadronic τ distributions, the $\mathrm{B_c^+}$ MC sample is split into $\mathrm{B_c^+} \to \mathrm{J}/\psi\tau^+\nu_\tau$ signal, $\mathrm{B_c^+} \to \mathrm{J}/\psi\mathrm{D_s^{(*)+}}$ background, and other $\mathrm{B_c^+}$ backgrounds, with the unrolled $m(\rho_1)$ vs. $m(\rho_2)$ shapes for each contribution determined from simulation and the normalization set by r and $r_{\mathrm{B_c^+}}$.

The expected yield of $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ events in each bin of the unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distribution in the SR is derived from the SB data after subtracting the expected number of $\mathrm{B_c^+}$ events:

$$N_{\mathrm{H_b}}(\mathrm{SR}, i) = f_{\mathrm{ext}}(i) \left(N_{\mathrm{data}}(\mathrm{SB}, i) - r_{\mathrm{B_c^+}}\, N_{\mathrm{B_c^+,bkg}}(\mathrm{SB}, i) - r_{\mathrm{B_c^+}}\, r\, N_{\mathrm{B_c^+,sig}}(\mathrm{SB}, i) \right). \quad (1)$$

The parameters $N_{\mathrm{B_c^+,bkg}}$ and $N_{\mathrm{B_c^+,sig}}$ denote the number of $\mathrm{B_c^+}$ background events ($\mathrm{B_c^+} \rightarrow \mathrm{J}/\psi\mathrm{D_s^{(*)+}}$ and $\mathrm{B_c^+} \rightarrow$ others) and signal events, respectively. The factors $f_{\mathrm{ext}}(i)$, typically in 0.06–0.11 range, control the extrapolation of the $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ background from the SB to the SR. The values of $f_{\mathrm{ext}}(i)$ are calculated from the simulated $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ events. However, the s_{BDT} distributions for data and MC are not entirely consistent and therefore the MC samples must be reweighted. First, we compute the ratio between the measured and the $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ simulated s_{BDT} distributions, after subtracting from the measured distribution the expected $\mathrm{B_c^+}$ contribution. Next, a third order polynomial function is fit to the ratio in the region of $0 < s_{\mathrm{BDT}} < 3.5$ for 2017–2018 and $0 < s_{\mathrm{BDT}} < 3$ for 2016. Finally, the fitted function is used to reweight all MC $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ events in the SB and SR regions before calculating $f_{\mathrm{ext}}(i)$.

To validate the background extrapolation method, two studies are performed using different control regions in the data. First, we use the SB data to predict the backgrounds in the "gap" region between the SB and the SR, i.e., $3.0 < s_{\mathrm{BDT}} < 3.5$ for 2016 and $3.5 < s_{\mathrm{BDT}} < 4.2$ for 2017–2018. Second, we select events by inverting at least one of the requirements on the vertex probability and the displacement significance with respect to the PV of the τ lepton in the SR and SB. The modified SB is used to predict the background in the modified SR. In both cases, agreement is found between the predicted and observed background. In addition, the background predicted from the nominal SB is seen to agree with the simulated background within the statistical uncertainty in the simulation.

Systematic uncertainties for both the normalization and shapes of the model are implemented as nuisance parameters in the fit. The log-normal function is used to constrain normalization nuisance parameters. Table 1 provides a summary of the systematic uncertainties, including information on the type of systematic uncertainty (affecting shape or normalization), which samples it affects, and its correlation across the different analysis channels. All systematic uncertainties are fully correlated between the SB and SR.

The uncertainty related to the $\mathrm{B_c^+}$ form factors is implemented using the HAMMER framework [44]. Ten independent variations are considered. These modify both the $\mathrm{B_c^+} \rightarrow \mathrm{J}/\psi\mu^+\nu_\mu$ and $\mathrm{B_c^+} \rightarrow \mathrm{J}/\psi\tau^+\nu_\tau$ decays, with each variation corresponding to an eigenvector of the ten different BGL parameters [43].

While it is known that $\tau^+ \rightarrow \mathrm{a_1(1260)^+}\overline{\nu}_\tau$, $\mathrm{a_1(1260)^+} \rightarrow \rho(770)^0(\rightarrow \pi^+\pi^-)\pi^+$ dominates the $\tau^+ \rightarrow \mathrm{a_1(1260)^+}\overline{\nu}_\tau \rightarrow \pi^+\pi^-\pi^+\nu_\tau$ final state, the nonresonant $\mathrm{a_1(1260)^+} \rightarrow \pi^+\pi^-\pi^+$ decay has also been observed, and the relative contributions are unknown [37]. Variations in the relative abundance of these two decay modes would cause shape distortions in the signal templates. To account for this effect, generator-level events are simulated with an alternative TAUOLA setting (changing "TauolaCurrentOption" from 1 (BaBar-tuned) to 0 (CLEO-tuned)), and an alternative signal template is built by reweighting events based on the generator-level unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distribution.

The $\mathrm{H_b} \rightarrow \mathrm{J}/\psi\mathrm{X}$ background is estimated using data in the SB region. Possible shape differences in the ρ^0 mass distributions between SB and SR are corrected via the bin-by-bin extrapolation factors $f_{\mathrm{ext}}(i)$, which are obtained from simulation. These factors are varied within their

Table 1: Systematic uncertainties considered in this analysis. The upper and lower entries in the table are the uncertainties affecting the shape and normalization of the processes given in the third column. A given uncertainty treated as correlated between analysis channels is marked with a check mark (✓).

Source	Type	Affected proc.	Channel			
			τ_μ 2018	τ_h 2018	τ_h 2017	τ_h 2016
Form factor	shape	$B_c^+ \to J/\psi \ell \nu_\ell$	✓	✓	✓	✓
TAUOLA model	shape	$B_c^+ \to J/\psi \tau^+ \nu_\tau$	—	✓	✓	✓
$H_b \to J/\psi X$ shape	shape	$H_b \to J/\psi X$ (data)	—	✓	✓	✓
Pileup weight	shape	All MC	✓	✓	✓	✓
B_c^+ lifetime	shape	All B_c^+ procs.	✓	✓	✓	✓
$B_c^+ \to$ others	shape	$B_c^+ \to$ others	—	✓	✓	✓
Finite MC size	shape	All	✓	✓	✓	✓
Triplet reco. eff.	norm.	$B_c^+ \to J/\psi \tau^+ \nu_\tau$	—	6.9% (✓)	6.9% (✓)	6.9% (✓)
$B_c^+ \to J/\psi D_s^{(*)+}$ normalization	norm.	$B_c^+ \to J/\psi D_s^{(*)+}$	38% (✓)	38% (✓)	38% (✓)	38% (✓)
$B_c^+ \to$ others normalization	norm.	$B_c^+ \to$ others	—	50% (✓)	50% (✓)	50% (✓)
Trigger ($\mu^+\mu^-$)	norm.	All MC	10% (✓)	10%(✓)$\oplus$ 5%	10%	10%
Trigger (track)	norm.	All MC	—	10%	10%	10%
Trigger (J/ψ)	norm.	All MC	—	10%	10%	10%
Muon ID	norm.	All MC	4%	4%	4%	4%
Muon reco.	norm.	All MC	4% (✓)	4% (✓)	4%	4%
$H_b \to J/\psi X$ norm.	norm.	$H_b \to J/\psi X$ (data)	—	30%	30%	30%
B_c^+ MC norm.	norm.	All B_c^+	—	5%	30%	30%

uncertainties and the resulting templates are included as a systematic uncertainty. They are treated as uncorrelated between all bins of the unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distribution, as they are dominated by the statistical uncertainties in the number of simulated events. Across all bins, the uncertainties are typically in the 5–20% range.

For all B_c^+ decays, a systematic uncertainty related to the variation of the B_c^+ lifetime within its measured uncertainty is considered.

For all simulated processes, systematic uncertainties related to the pileup modeling are taken into account by varying the total inelastic cross section used to generate the pileup distributions [52].

As previously described, the unknown contributions to $B_c^+ \to$ others are accounted for by scaling up the generated MC events. Uncertainties on the normalization (amounting to half of the scaling) and shape are assessed.

The statistical uncertainties from the limited number of events in the simulated samples are included independently in each bin. In addition, this uncertainty is propagated to the $H_b \to J/\psi X$ background estimate as the B_c^+ signal and background are subtracted from the data in the SB region in Eq. (1).

The hadronic τ decay contains three pions of relatively low momenta compared to the normalization channel of one muon. Therefore, discrepancies in the track reconstruction efficiency between data and simulation will affect the result. A 2.3% uncertainty [53] is assumed per track, yielding a total normalization uncertainty of 6.9% affecting the $B_c^+ \to J/\psi \tau^+ \nu_\tau$

process. A further check is performed by measuring the yields of the $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$ processes, as the only difference between the two processes is the track multiplicity, which itself depends on the track reconstruction. After selecting corresponding events in data and simulation, the resonant mass peaks are fitted to obtain the total number of $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$ events in data and simulation. The ratios of the yields of the two processes in data and simulation differ by 4.4%, corresponding to an uncertainty of 2.2% per track, compatible with the assumed 2.3% uncertainty per track.

The normalization uncertainty for the $B_c^+ \to J/\psi D_s^{(*)+}$ background originates from experimentally measured branching fractions as derived in the leptonic τ analysis [14].

Uncertainties in the efficiencies of the muon reconstruction (4%), ID (4%), and trigger selection (10%) are considered. These uncertainties are considered to be uncorrelated across years of data taking. For 2018, the muon trigger uncertainties are partly correlated between this analysis and the leptonic τ analysis because the event selection is similar, with an additional uncorrelated 5% uncertainty owing to the difference in the online muon selection. The muon reconstruction uncertainty is also correlated between the two, whereas the uncertainty in the muon ID is uncorrelated as two different ID criteria are used. Uncertainties in the trigger efficiencies related to the track reconstruction and selection (10%) and the requirement that the J/ψ candidate vertex be displaced from the beam axis (10%) are also considered.

Given the uncertainty in the check of the backgrounds predicted from the SBs in the "gap" regions and those with the inverted τ lepton selection, a 30% uncertainty is assigned to the $H_b \to J/\psi X$ background normalization, uncorrelated across years.

The normalization of the B_c^+ MC samples for 2016 and 2017 relative to 2018 is obtained from the ratio of the yields of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ events in data and MC in each year. These relative correction factors for 2016 and 2017 are also calculated using the $B_c^+ \to J/\psi\pi^+$ invariant mass peak, and the difference with respect to the ones from $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ is used to determine a B_c^+ MC normalization systematic uncertainty of 30% for each of 2016 and 2017 periods, uncorrelated by year.

Other considered systematic uncertainties are found to be negligible. The leading systematic uncertainties for the hadronic τ analysis are the ones related to the $H_b \to J/\psi X$ background estimation, obtained from data, and its extrapolation from the SB to the SR, which is based on simulation.

Several fits have been performed using different subsets of the data. As the hadronic τ analysis relies on the leptonic τ data to determine the $B_c^+ \to J/\psi\mu^+\nu_\mu$ yield, we cannot obtain a completely independent hadronic τ value for $\mathcal{R}_{J/\psi}$. However, we can fit the hadronic τ and leptonic τ data with separate $\mathcal{R}_{J/\psi}$ parameters for each. In this case, the two results share a common denominator ($B_c^+ \to J/\psi\mu^+\nu_\mu$ yield), but the $B_c^+ \to J/\psi\tau^+\nu_\tau$ yields are independent. Incorporating just the 2018 data to match the leptonic τ analysis, this fit returns $\mathcal{R}_{J/\psi}^{\text{had},2018} = 0.74^{+0.57}_{-0.53}$. Including the hadronic τ decay data recorded in 2016 and 2017, a value of $\mathcal{R}_{J/\psi}^{\text{had}} = 1.04^{+0.50}_{-0.44}$ is obtained. We verified that this result is stable against inflating the prefit uncertainty in the $B_c^+ \to J/\psi X$ normalization. Given the uncertainties, this result is compatible with that of the leptonic τ analysis, 0.17 ± 0.33. We compared the likelihoods of the fits to the data of this analysis and to the data of the leptonic τ analysis when assuming one common parameter r or two independent parameters r_{lep} and r_{had}. The likelihood ratio, expressed as $-2\ln\mathcal{L}(\text{data}|r)/\mathcal{L}(\text{data}|r_{\text{lep}}, r_{\text{had}})$, is 2.06, corresponding to a p-value [54] of 0.15, indicating that the two measurements are compatible.

Finally, we perform a simultaneous fit in all analysis regions of this and of the leptonic τ analysis to obtain

$$\mathcal{R}_{J/\psi} = 0.49 \pm 0.11\,(\text{stat}) \pm 0.23\,(\text{syst}) \pm 0.07\,(\text{theo}),$$

where the last uncertainty corresponds to the B_c^+ form factors and the systematic uncertainty includes the other systematic uncertainties. Figure 2 shows the SR unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distributions of the data and of the final fit for each of the three data-taking years. This result is in agreement with the SM prediction of 0.258 ± 0.004, as shown in Fig. 3, where a summary of the CMS measurements in each τ decay channel, their combination, the prediction from the SM, and the comparison with the LHCb result are presented.

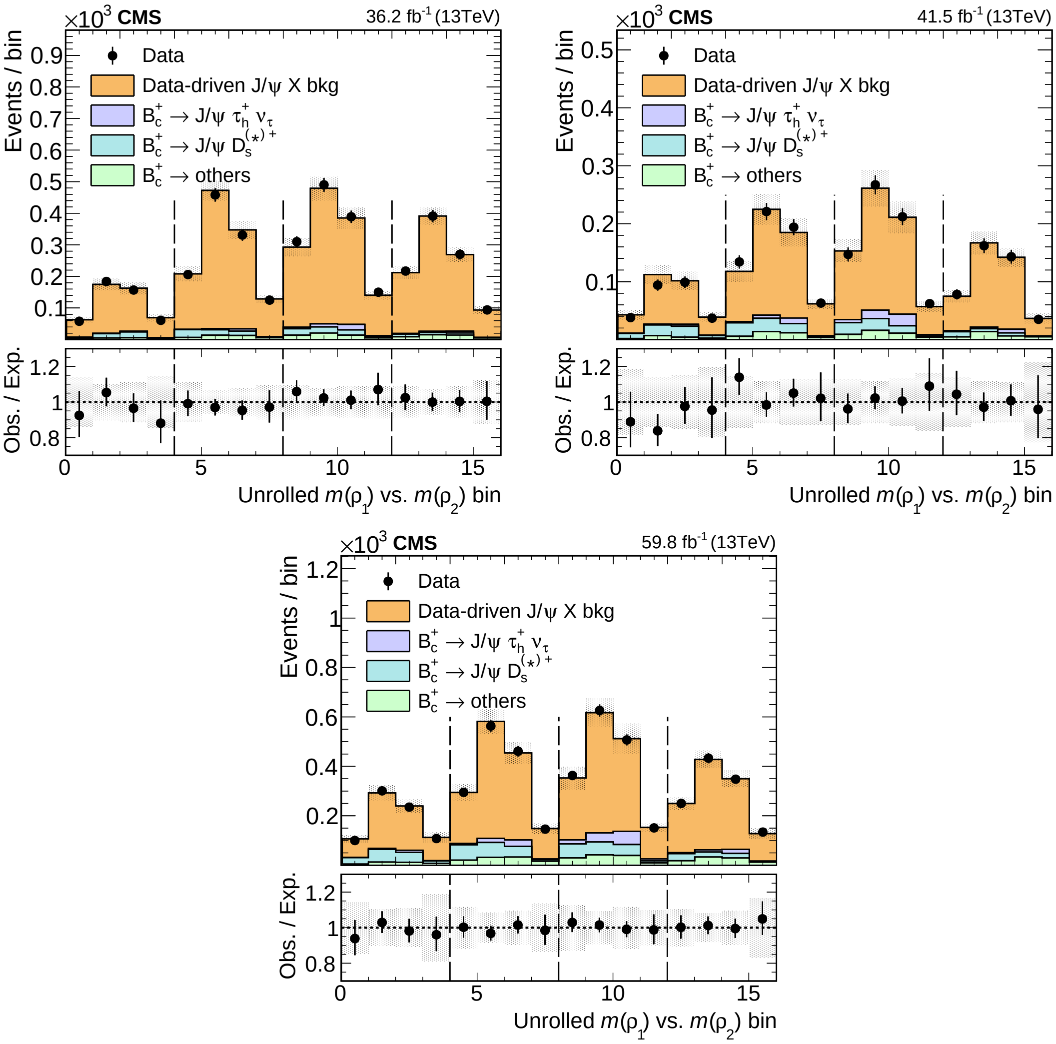

Figure 2: Distribution of the SR unrolled $m(\rho_1)$ vs. $m(\rho_2)$ distribution for the 2016 (upper left), 2017 (upper right), and 2018 (lower) data-taking periods. The dashed vertical lines indicate bins in $m(\rho_1)$. The data (black markers) are compared to the postfit expected yields of the $H_b \to J/\psi X$ background estimated from data and simulated $B_c^+ \to J/\psi\tau^+\nu_\tau$, $B_c^+ \to J/\psi D_s^{(*)+}$, and $B_c^+ \to$ others processes (stacked histograms). The ratio between the data and the sum of postfit signal and background is shown in the lower panel. The total uncertainty in the expected event yield is shown by the gray band.

In summary, the branching fraction ratio $\mathcal{R}_{J/\psi} = \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ has been measured using $J/\psi \to \mu^+\mu^-$ decays for both the numerator and denominator, and the

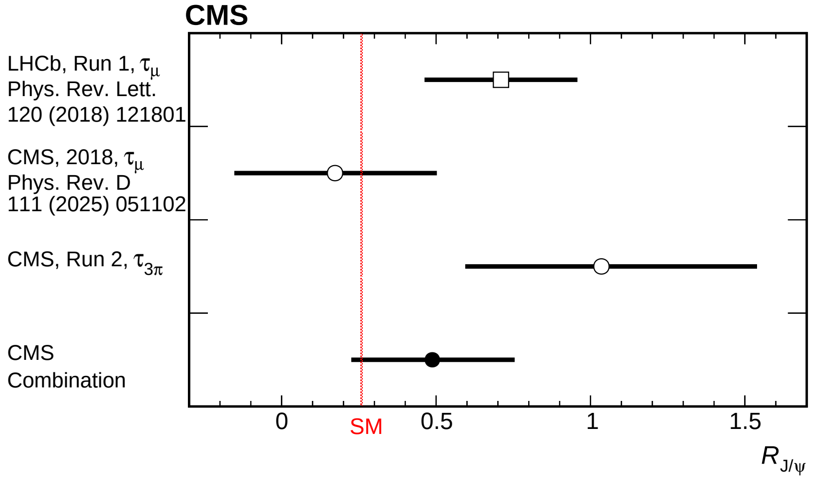

Figure 3: Summary of $\mathcal{R}_{J/\psi}$ measurements from LHCb leptonic τ decays [8], CMS leptonic τ decays [14], CMS hadronic τ decays, and the CMS combination. The total uncertainties in the measured values are indicated by the horizontal lines. The vertical red line is the SM prediction.

three-prong hadronic τ decay for the numerator. Proton-proton collision data corresponding to an integrated luminosity of 138 fb^{-1} for the numerator and 59.7 fb^{-1} for the denominator, both collected at $\sqrt{s} = 13$ TeV by the CMS experiment, are used. This measurement is the first contribution to lepton flavor universality tests in $\mathrm{B_c^+}$ meson decays with hadronic τ decays. The ratio is measured to be $\mathcal{R}^{\mathrm{had}}_{J/\psi} = 1.04^{+0.50}_{-0.44}$. Combined with our previous measurement using leptonic τ decays from Ref. [14], the result is $\mathcal{R}_{J/\psi} = 0.49 \pm 0.26$. No deviation from the standard model prediction (0.258 ± 0.004) is observed.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Chekhovsky, A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, K. Damanakis, M. Dragicevic, C. Giordano, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck[2], D. Schwarz, M. Shooshtari, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
J. Bierkens, N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, S. Lowette, I. Makarenko, D. Müller, J. Song, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, F. Zhang

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, J. Knolle, L. Lambrecht, D. Marckx, K. Skovpen, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], M. Costa Reis, E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[7], M. Macedo, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, B. Lopes Da Costa, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula, V. Scheurer

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen[8], Q. Hou, F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, Q. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, Y. Zhao, C. Zhou

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

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[12], B. Li[13], H. Wang, K. Yi[14], J. Zhang

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

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[15]

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov,

T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[16,17], R. Aly[18,16], B. El-mahdy[19]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. Abdullah Al-Mashad, A. Hussein, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
H. Kirschenmann, P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T.D. Cuisset, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, G. Liu, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, J. Xiao

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[23]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, V. Oppenländer, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, F. Torres Da Silva De Araujo[24], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[25], K. Borras[26], A. Campbell, S. Chatterjee, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, E. Gallo[25], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[27], W. Lohmann[28], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[29,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, M. Antonello, S. Bollweg, M. Bonanomi, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, J. Haller, D. Hundhausen, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, K. Nikolopoulos, 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, R. Ward, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[30], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, W.D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[30], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, E. Siamarkou, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
D. Druzhkin, C. Hajdu, D. Horvath[31,32], K. Márton, A.J. Rádl[33], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[34], M.M.A. Gadallah[35], Á. Kadlecsik, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[34], F. Nemes[34], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia, S. Barman[37], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], T. Mishra, B. Parida[39], P.R. Pujahari, N.R. Saha, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Bhowmik[40], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[41], D. Maity[42], P. Mal, K. Naskar[42], A. Nayak[42], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[42], D. Vats[42]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[43], A. Alpana, S. Dube, B. Gomber[43], P. Hazarika, B. Kansal, A. Laha, B. Sahu[43], R. Sharma, S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44], A. Jafari[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[47], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[48]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,16], N. Ferrara[a,b], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], 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,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,50], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,50]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], P. Assiouras[a], G. Barbagli[a], G. Bardelli[a], M. Bartolini[a,b], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Colafranceschi[51], S. Meola[52], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], F. Cetorelli[a,b], 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], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,53], P. Paolucci[a,30], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,54], M. Biasotto[a,55], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,56], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], M. Pelliccioni[a], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,57], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
C. Aimè[a,b], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], M. Musich[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,40], T. Sarkar[a],

A. Scribano[a], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[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], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a,c], R. Bellan[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], 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. 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], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, J. Choi[58], D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, J. Shin, S. Yang

Sejong University, Seoul, Korea
Y. Kang, H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, J. Shin, U.K. Yang, I. Yoon

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

Yonsei University, Department of Physics, Seoul, Korea

G. Cho, S. Ha, K. Hwang, B. Kim, S. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O.M. Eberlins, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[59], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[60], R. Lopez-Fernandez, J. Mejia Guisao, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, W.A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, A. Bellora[61], L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Sastre, J. Vazquez Escobar

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, A. Cardini, J. Cuevas, J. Del Riego Badas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[62], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[63], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, E. Brondolin, C.E. Brown, C. Caillol, G. Cerminara, N. Chernyavskaya, P. Connor, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[28],

G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, M. Magherini, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, M. Migliorini, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, B. Ribeiro Lopes, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[64], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[65], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[66], L. Caminada[66], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[66], L. Noehte[66], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[65], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, A.-M. Lyon, M. Malucchi, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[65], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[65], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[67], P. Bärtschi, M.F. Canelli, G. Celotto, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[68], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, S. Taj, P.C. Tiwari[38]

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

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[69], E. Eskut, Y. Guler[70], E. Gurpinar Guler[70], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[71], A. Polatoz, B. Tali[72], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[73]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[74], O. Kaya[75], S. Tekten[76]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[69,77], S. Sen[78]

Istanbul University, Istanbul, Turkey
O. Aydilek[79], B. Hacisahinoglu, I. Hos[80], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[81], D. Sunar Cerci, T. Yetkin[22]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[82], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[83], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[30], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, C.U. Perez, P. Rumerio[84], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[85], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[86], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo

University of California, Los Angeles, California, USA
K. Adamidis, M. Bachtis, D. Campos, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, M.M. Hussain, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA
A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, J. Mao, H.B. Newman, G. Reales Gutiérrez, T. Sievert, M. Spiropulu, J.R. Vlimant, R.A. Wynne, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA

J. Alexander, X. Chen, D.J. Cranshaw, J. Dickinson, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

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

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, V. Sulimov, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, T. Elkafrawy[89], M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, N. Barnett, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, C. Mills, S. Nanda, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[90], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[91], O. Neogi, H. Ogul[92], Y. Onel, A. Penzo, C. Snyder, E. Tiras[93]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[94], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[95], A. Shevelev, L. Wang, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, J. Bendavid, S. Bright-Thonney, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, D. Walter, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, P. Levchenko, J. Li, M. Lu, N. Manganelli, R. Mccarthy, D.M. Morse, T. Orimoto, A. Parker, L. Skinnari, C.S. Thoreson, E. Tsai, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, D. Li, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco, J. Wang

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[23], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, M. Carrigan, R. De Los Santos, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, K. Coldham, P. Das, G. Dezoort, P. Elmer, P. Fackeldey,

A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully, L.H. Vage

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, J.F. Schulte, A. K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, T. Huang, I. Krommydas, N. Lewis, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[95], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, J. Martins, R. Montalvo, K. Nash, B. Rand, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA
D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[96], R. Eusebi, J. Gilmore, T. Kamon, H. Kim, S. Luo, R. Mueller, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, Y. Kazhykarim, K. Lamichhane, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, S. Lomte,

R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

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

S. Afanasiev, V. Alexakhin, Yu. Andreev, T. Aushev, D. Budkouski, R. Chistov[97], M. Danilov[97], T. Dimova[97], A. Ershov[97], S. Gninenko, I. Golutvin[†], I. Gorbunov, A. Gribushin[97], V. Karjavine, M. Kirsanov, V. Klyukhin[97], O. Kodolova[98], V. Korenkov, A. Kozyrev[97], N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev[97], A. Nikitenko[99,98], V. Palichik, V. Perelygin, S. Petrushanko[97], S. Polikarpov[97], O. Radchenko[97], M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[97], V. Smirnov, O. Teryaev, I. Tlisova[97], A. Toropin, N. Voytishin, B.S. Yuldashev[†100], A. Zarubin, I. Zhizhin

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

E. Boos, V. Bunichev, M. Dubinin[87], V. Savrin, A. Snigirev

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[5]Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
[6]Also at Universidade Estadual de Campinas, Campinas, Brazil
[7]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[8]Also at University of Chinese Academy of Sciences, Beijing, China
[9]Also at China Center of Advanced Science and Technology, Beijing, China
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at China Spallation Neutron Source, Guangdong, China
[12]Now at Henan Normal University, Xinxiang, China
[13]Also at University of Shanghai for Science and Technology, Shanghai, China
[14]Now at The University of Iowa, Iowa City, Iowa, USA
[15]Also at Center for High Energy Physics, Peking University, Beijing, China
[16]Also at Helwan University, Cairo, Egypt
[17]Now at Zewail City of Science and Technology, Zewail, Egypt
[18]Also at British University in Egypt, Cairo, Egypt
[19]Also at Cairo University, Cairo, Egypt
[20]Also at Purdue University, West Lafayette, Indiana, USA
[21]Also at Université de Haute Alsace, Mulhouse, France
[22]Also at Istinye University, Istanbul, Turkey
[23]Also at an institute formerly covered by a cooperation agreement with CERN
[24]Also at The University of the State of Amazonas, Manaus, Brazil
[25]Also at University of Hamburg, Hamburg, Germany
[26]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[27]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[28]Also at Brandenburg University of Technology, Cottbus, Germany
[29]Also at Forschungszentrum Jülich, Juelich, Germany
[30]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[31]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[32]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

[33]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[34]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[35]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at Amity University Uttar Pradesh, Noida, India
[40]Also at UPES - University of Petroleum and Energy Studies, Dehradun, 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 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 Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[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 James Madison University, Harrisonburg, Maryland, USA
[52]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[53]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[54]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[55]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[56]Also at Lulea University of Technology, Lulea, Sweden
[57]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[58]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[59]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[60]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[61]Also at INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy
[62]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[63]Also at Saegis Campus, Nugegoda, Sri Lanka
[64]Also at National and Kapodistrian University of Athens, Athens, Greece
[65]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[66]Also at Universität Zürich, Zurich, Switzerland
[67]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[68]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[69]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[70]Also at Konya Technical University, Konya, Turkey
[71]Also at Izmir Bakircay University, Izmir, Turkey
[72]Also at Adiyaman University, Adiyaman, Turkey
[73]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[74]Also at Marmara University, Istanbul, Turkey

[75]Also at Milli Savunma University, Istanbul, Turkey
[76]Also at Kafkas University, Kars, Turkey
[77]Now at Istanbul Okan University, Istanbul, Turkey
[78]Also at Hacettepe University, Ankara, Turkey
[79]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[80]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[81]Also at Yildiz Technical University, Istanbul, Turkey
[82]Also at School of Physics and Astronomy, University of Southampton, Southampton, 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 Ain Shams University, Cairo, Egypt
[90]Also at Bingol University, Bingol, Turkey
[91]Also at Georgian Technical University, Tbilisi, Georgia
[92]Also at Sinop University, Sinop, Turkey
[93]Also at Erciyes University, Kayseri, Turkey
[94]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[95]Now at another institute formerly covered by a cooperation agreement with CERN
[96]Also at Texas A&M University at Qatar, Doha, Qatar
[97]Also at another institute formerly covered by a cooperation agreement with CERN
[98]Also at Yerevan Physics Institute, Yerevan, Armenia
[99]Also at Imperial College, London, United Kingdom
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan