Measurement of the Dependence of the Hadron Production Fraction Ratios f_s/f_u and f_d/f_u on B Meson Kinematic Variables in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.*[*]
(CMS Collaboration)

(Received 5 December 2022; revised 27 March 2023; accepted 20 June 2023; published 19 September 2023)

The dependence of the ratio between the B_s^0 and B^+ hadron production fractions, f_s/f_u, on the transverse momentum (p_T) and rapidity of the B mesons is studied using the decay channels $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$. The analysis uses a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment in 2018 and corresponding to an integrated luminosity of 61.6 fb^{-1}. The f_s/f_u ratio is observed to depend on the B p_T and to be consistent with becoming asymptotically constant at large p_T. No rapidity dependence is observed. The ratio of the B^0 to B^+ meson production fractions, f_d/f_u, is also measured, for the first time in proton-proton collisions, using the $B^0 \to J/\psi K^{*0}$ decay channel. The result is found to be within 1 standard deviation of unity and independent of p_T and rapidity, as expected from isospin invariance.

DOI: 10.1103/PhysRevLett.131.121901

When a b quark is produced with sufficient momentum, it undergoes a process, referred to as fragmentation or hadronization, that results in the creation of a b hadron. The relative rates of the various flavors of b hadrons are referred to as hadron production fractions or fragmentation functions. The fractions of B^+, B^0, and B_s^0 mesons are denoted by f_u, f_d, and f_s, respectively. Experiments at the B factories use the characteristics of B meson production at the $\Upsilon(4S)$ to set the scale of the measured B^+ and B^0 branching fractions, allowing precision measurements at both B factories and hadron colliders. For the B_s^0, however, the limited event samples at the $\Upsilon(10860)$ and uncertainties in the fraction of B_s^0 mesons produced do not allow the same approach. As a result, precision B_s^0 branching fraction measurements at hadron colliders rely on ratios to B^+ or B^0 decay modes, which require knowledge of f_s/f_u or f_s/f_d, respectively. In fact, measurements of the rare decay $B_s^0 \to \mu^+\mu^-$, which is used to search for physics beyond the standard model, are currently limited by the uncertainty in f_s/f_u [1–5]. Besides providing information about the nature of the strong interaction, precise f_s/f_u values are also needed to measure the $B_s^0 \to \mu^+\mu^-$ and other B_s^0 branching fractions.

A variety of measurements obtained from Z boson decays by the LEP experiments have been combined by the Heavy Flavor Averaging Group to obtain values for the hadron production fractions and the ratio f_s/f_d [6]. Subsequent central-rapidity measurements by CDF (for pseudorapidity $|\eta| < 1$) in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV [7] and by ATLAS (for $|\eta| < 2.5$) in proton-proton (pp) collisions at $\sqrt{s} = 7$ TeV [8] were compatible with the LEP result, with no evidence of a dependence on transverse momentum (p_T). Instead, measurements of f_s/f_d in the forward-rapidity region ($2 < \eta < 6.4$) by LHCb in pp collisions at $\sqrt{s} = 7$, 8, and 13 TeV [9] (combining results from Refs. [10–13]) give strong evidence for a p_T dependence of these quantities, the values decreasing as the p_T of the B meson increases.

This Letter presents an analysis aimed at establishing if and how the relative B_s^0 and B^+ production rates change with p_T in a kinematic region relevant for the ATLAS and CMS experiments at the CERN LHC, $p_T > 12$ GeV and $|y| < 2.4$, approximately complementary to that of the LHCb detector. Additionally, we perform the first test of the isospin invariance in B meson production in pp collisions, by measuring the f_d/f_u ratio. These measurements use a sample of pp collisions collected by the CMS experiment in 2018 at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 61.6 fb^{-1} [14,15].

Throughout this Letter, charge-conjugate states are implicitly included, and K^{*0} and ϕ represent the $K^{*0}(892)^0$ and $\phi(1020)$, respectively. The B^+ and B_s^0 mesons are reconstructed using the $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$ decay channels, with the J/ψ and ϕ mesons decaying as $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The respective event yields, N_{B^+} and $N_{B_s^0}$, are measured with corresponding detection efficiencies ϵ_{B^+} and $\epsilon_{B_s^0}$. The ratio of the efficiency-corrected meson

[*]Full author list given at the end of the Letter.

yields, $\mathcal{R}_s = (N_{B_s^0}/\epsilon_{B_s^0})/(N_{B^+}/\epsilon_{B^+})$, is directly proportional to the f_s/f_u ratio,

$$\mathcal{R}_s = f_s/f_u \frac{\mathcal{B}(B_s^0 \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi K^+)}, \quad (1)$$

where $\mathcal{B}(B_s^0 \to J/\psi\phi)$, $\mathcal{B}(\phi \to K^+K^-)$, and $\mathcal{B}(B^+ \to J/\psi K^+)$ are the branching fractions of the indicated decay channels; the $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ factor cancels in the ratio. Given that the available measurements of the $B_s^0 \to J/\psi\phi$ branching fraction and of f_s are correlated, we report measurements of $\mathcal{R}_s$ rather than of f_s/f_u.

The analysis also includes a measurement of the ratio between the B^0 and B^+ hadron fractions, f_d/f_u, using the B^0 yield determined with $B^0 \to J/\psi K^{*0}$ events, where the K^{*0} mesons are reconstructed in the $K^{*0} \to \pi^- K^+$ decay channel. Using notations analogous to those used above,

$$\begin{aligned}\mathcal{R}_d &= \frac{N_{B^0}}{\epsilon_{B^0}} \Big/ \frac{N_{B^+}}{\epsilon_{B^+}} \\ &= f_d/f_u \frac{\mathcal{B}(B^0 \to J/\psi K^{*0})\mathcal{B}(K^{*0} \to \pi^- K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}. \quad (2)\end{aligned}$$

Under the assumption of strong isospin symmetry, the f_d/f_u ratio is expected to be independent of kinematic variables and identical to unity. Given that the branching fractions used to calculate f_d/f_u from $\mathcal{R}_d$ are (independently) obtained from high-precision B factory measurements, we report the more relevant quantity f_d/f_u.

The CMS apparatus is a multipurpose detector [16] designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons [17–19]. A superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of 100 kHz within a fixed latency of about 4 μs [20]. The second level, consisting of a farm of processors running a faster version of the full event reconstruction software, reduces the rate to around 1 kHz, before data storage [21].

The events used in the analysis were selected by a trigger requiring two oppositely charged muons with $|\eta| < 2.5$ and $p_T > 4$ GeV, a distance of closest approach between the two muons smaller than 0.5 cm, a dimuon vertex fit χ^2 probability larger than 10%, a dimuon invariant mass in the range 2.9–3.3 GeV, and a transverse distance between the dimuon vertex and the beam axis, L_{xy}, larger than three times its uncertainty. In addition, the dimuon $\vec{p}_T$ and transverse displacement vector, $\vec{L}_{xy}$, must be aligned with each other: $\cos\theta \equiv \vec{L}_{xy} \cdot \vec{p}_T/(L_{xy} p_T) > 0.9$. The trigger also requires a third track in the event, compatible with being produced at the dimuon vertex, having $p_T >$ 1.2 GeV and a transverse impact parameter significance larger than 2. Finally, the dimuon-plus-track vertex fit χ^2 probability must be larger than 10%.

The charged tracks used to reconstruct the B mesons must pass high-purity criteria [19], have five or more hits in the silicon tracker, at least one of them in the pixel layers, and have $|\eta| < 2.4$. They must also match the tracks that triggered the data readout. The muons used to reconstruct the J/ψ candidates must fulfill soft-muon identification requirements [18], which include the (loose) matching between the track reconstructed in the silicon tracker and the one reconstructed in the muon detectors. They must also have $p_T > 4$ GeV and an impact parameter smaller than 0.3 cm in the transverse plane and smaller than 20 cm along the beam axis.

The J/ψ candidate is combined with one track to reconstruct $B^+ \to J/\psi K^+$ decays or with a pair of oppositely charged tracks to reconstruct the $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ decays. All three tracks must have $p_T > 1.2$ GeV. They are fitted together with the dimuon, imposing a common (secondary) vertex (SV, the B meson decay point), constraining the dimuon invariant mass to the J/ψ world-average mass, $m_{J/\psi}^{\mathrm{PDG}}$ [22], and assigning to each of the other tracks the $\pi^\pm$ or $K^\pm$ masses, as suitable. Furthermore, the invariant mass of the pair of tracks must satisfy $|M(K^+K^-) - m_\phi^{\mathrm{PDG}}| < 10$ MeV for B_s^0 decays and $|M(\pi K) - m_{K^{*0}}^{\mathrm{PDG}}| < 50$ MeV for B^0 decays, where m_ϕ^{PDG} and $m_{K^{*0}}^{\mathrm{PDG}}$ are, respectively, the ϕ and K^{*0} world-average masses [22]. In the latter case, lack of particle identification implies that both combinations are possible (π^+K^- and $K^+\pi^-$); if both match the mass window requirement, only the one with mass closer to $m_{K^{*0}}^{\mathrm{PDG}}$ is kept.

The primary vertex (PV) is selected among the several reconstructed pp collisions as the one that minimizes the pointing angle of the B meson, defined as the angle between the B momentum and the vector joining the primary and secondary vertices. The PV is refitted without the tracks of the B candidate before computing the B decay length as the distance between the PV and the SV. We select B meson candidates with $12 < p_T < 70$ GeV, $|y| < 2.4$, a decay length larger than 5 times its uncertainty, and a dimuon-plus-track(s) vertex χ^2 probability larger than 10%. For each decay channel, if more than one B meson candidate is reconstructed in an event (occurring in less than 1% of the events), only the one with the highest fit χ^2 probability is kept.

The event selection criteria described above were optimized through the study of Monte Carlo (MC) event samples, which were also used to evaluate the detection

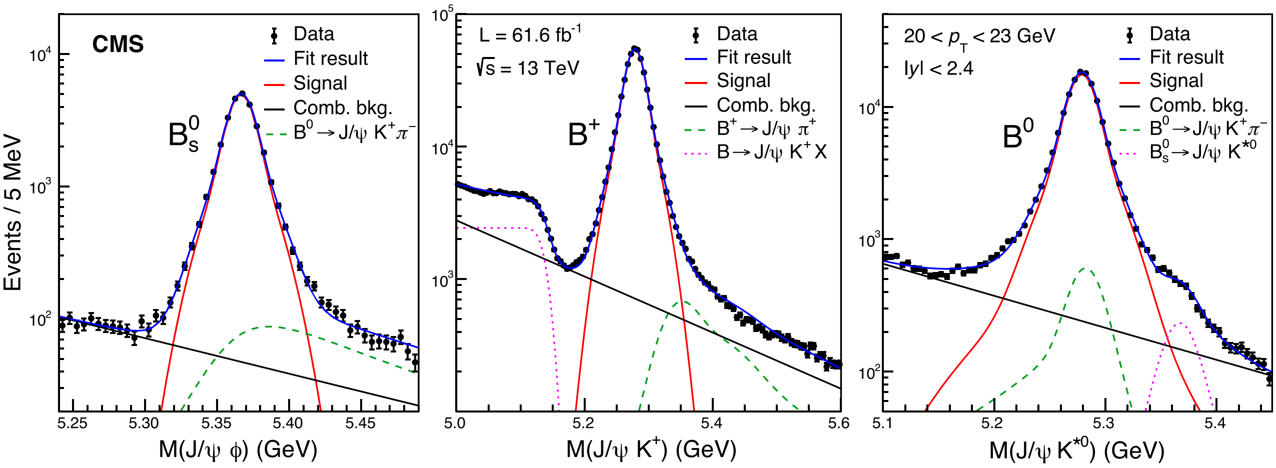

FIG. 1. The $J/\psi\phi$, $J/\psi K^+$, and $J/\psi K^{*0}$ invariant mass distributions for B meson candidates with $20 < p_T < 23$ GeV, and associated fits as described in the text.

efficiencies and the shapes of the invariant mass distributions of some background contributions. They were generated with PYTHIA8.230 [23] for the production and hadronization steps, with EVTGEN1.6.0 [24] for the decay of the b hadrons, and with PHOTOS3.61 [25] for the final-state radiation modeling. The response of the CMS detector to the generated events, including the trigger and reconstruction steps, was simulated with GEANT4 [26], using algorithms identical to those used on the data. The simulated events include multiple pp interactions in the same or nearby beam crossings, with a distribution matching the one observed in the collected data.

The B_s^0, B^+, and B^0 meson yields are measured by fitting, with unbinned maximum likelihood techniques, the $J/\psi\phi$, $J/\psi K^+$, and $J/\psi K^{*0}$ invariant mass distributions, respectively. These distributions are fitted for 12 p_T bins (integrated over y) or 7 $|y|$ bins (integrated over p_T), with ranges defined so as to keep a similar number of events in each bin. Figure 1 shows the three invariant mass distributions for the 20–23 GeV p_T bin.

The signal peak is fitted by the sum of two Gaussian functions with a common mean and independent widths, reflecting the shapes observed in the simulated event samples; the mean and widths are left free in the fit. The underlying combinatorial background is fitted by an exponential function. The $J/\psi K^+$ sample includes a background term due to events where B mesons decay through $J/\psi K^+ X$ channels and the X particle is not reconstructed. This contribution is described by an error function, with two free shape parameters. Some of the $J/\psi K^{*0}$ candidates have swapped pion-kaon mass assignments. They are included in the fit model by adding a component with shape and normalization (12% relative to the unswapped yield) fixed from simulation. The $J/\psi K^{*0}$ sample also includes (Cabibbo-suppressed) $B_s^0 \to J/\psi K^{*0}$ decays, with normalization as a free parameter and described by a shape identical to that of the B^0 signal peak, except for the shifted mass and for a small width broadening to account for the change of mass resolution, as determined from simulation.

All the other background contributions have shapes determined from the simulated event samples. The $B^+ \to J/\psi\pi^+$ curve in the B^+ panel represents (Cabibbo-suppressed) decays where the pion track is misinterpreted as a kaon; its normalization is fixed to that of the B^+ signal yield, scaled by the ratio of the two branching fractions [22]. The misidentification of a pion as a kaon is also the reason why sometimes a $B^0 \to J/\psi K\pi$ decay is incorrectly assigned to the B_s^0 sample. This small contribution is described by a Johnson function [27], with a normalization constrained, in each p_T or $|y|$ bin, to that of the B_s^0 signal yield, the scaling factor being the relative yield found in a fit to the integrated event sample. The background to the B_s^0 sample from $\Lambda_b^0 \to J/\psi K^- p$ decays where the proton is misidentified as a kaon has been found to be negligible. A background from $B^0 \to J/\psi K\pi$ decays also contributes to the $B^0 \to J/\psi K^{*0}$ distributions. This peaking background is modeled with a double-sided Crystal Ball [28] function plus a Gaussian function. Its normalization is constrained, in each p_T or $|y|$ bin, to that of the B^0 signal yield, scaled by the yield ratio obtained in the fit of the integrated event sample.

As seen in Eqs. (1) and (2), only the ratios of detection efficiencies, $\epsilon_{B_s^0}/\epsilon_{B^+}$ and $\epsilon_{B^0}/\epsilon_{B^+}$, are needed to convert the ratios of signal event yields, obtained from the fits illustrated in Fig. 1, into the $\mathcal{R}_s$ and $\mathcal{R}_d$ observables. These efficiency ratios are evaluated using the simulated event samples, reflecting the trigger and reconstruction steps, as well as the detector acceptance. Both ratios increase by around a factor of 3.5 between the lowest and highest p_T bins, while the variation with $|y|$ is only at the 10% level.

The $\mathcal{R}_s$ and $\mathcal{R}_d$ measurements are affected by systematic uncertainties in the determination of the fitted signal yields and in the evaluation of the efficiency ratios.

The systematic uncertainties affecting the signal yields are evaluated by repeating the fits of the mass distributions in alternative conditions and computing the difference between the obtained results and those of the baseline fit. Two main variations of the fit model are independently considered: first, the modeling of the signal peaks is changed from the default double Gaussian to a student's *t* distribution [29]; second, the combinatorial background is fitted by a first-order Chebyshev polynomial instead of the baseline exponential function. An additional systematic uncertainty in the B^0 meson yield, of less than 1%, is evaluated by fitting the $J/\psi K^{*0}$ mass distribution changing the normalization of the "π-K swap" term, relative to that of the B^0 signal term, by the uncertainty in the default value, which exclusively reflects the sizes of the MC event samples; other systematic effects were found to be negligible. The fit procedure itself is seen to provide unbiased results, for each of the bins, both for the central values and the uncertainties, through a study involving fits of 1000 event samples randomly generated using the nominal functions with the best fit parameters and with sizes corresponding to the number of measured events. The result is that the uncertainties in the fitted B_s^0, B^+, and B^0 signal yields contribute systematic uncertainties to the $\mathcal{R}_s$ and $\mathcal{R}_d$ measurements that are, respectively, in the 1.6%–2.6% and 2.0%–5.0% ranges.

For the efficiency ratios, $\epsilon_{B_s^0}/\epsilon_{B^+}$ and $\epsilon_{B^0}/\epsilon_{B^+}$, a systematic uncertainty, ≈1% for all p_T and $|y|$ bins, reflects the size of the simulated event samples. As the B_s^0 and B^0 decays lead to one more track than the B^+ decays, a single-track reconstruction efficiency uncertainty is assigned to both efficiency ratios. This 2.3% uncertainty is not found to depend on p_T or $|y|$ [30]. Several other potential sources of uncertainty were considered and found to have negligible effects on the efficiency *ratios*. The muon identification and reconstruction efficiencies, in particular, cancel out. The efficiencies were also recomputed with varied B_s^0 p_T distributions and with the decay angular distributions reweighed to match the data; both variations have negligible effects. Finally, the simulated events were reweighed (with weights dependent on the y and p_T of the B meson, as well as on the p_T of the kaons) so that the B_s^0, B^+, and B^0 MC distributions match the measured ones. This procedure leads to systematic uncertainties in the 1%–2% and 2%–5% ranges for the $\mathcal{R}_s$ and $\mathcal{R}_d$ measurements, respectively.

Apart from the uncertainty in the track reconstruction efficiency, assumed to be independent of p_T and $|y|$, the bin-to-bin systematic uncertainties are added in quadrature. For the $\mathcal{R}_s$ measurement, they are in the 2.3%–3.2% and 1.8%–4.4% ranges for the p_T and $|y|$ results, respectively, while for $\mathcal{R}_d$ the corresponding ranges are 2.4%–7.8% and 2.3%–4.9%. The larger $\mathcal{R}_d$ uncertainties arise from the more complex background composition of the B^0 decay. Both measurements have ≈1% statistical uncertainties in each bin.

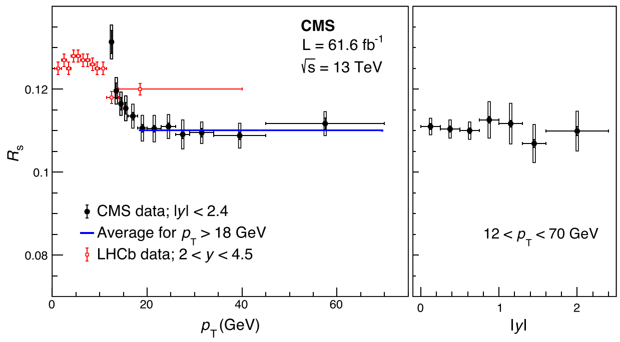

FIG. 2. Efficiency-corrected yield ratio $\mathcal{R}_s$, as a function of p_T (left) and $|y|$ (right). The vertical bars (boxes) represent the statistical (bin-to-bin systematic) uncertainties, while the horizontal bars give the bin widths. The global uncertainty (of 2.3%) is not graphically represented. The blue line represents the average for $p_T > 18$ GeV. For comparison, the LHCb measurement [12] is also shown.

The measured $\mathcal{R}_s$ values, presented in Fig. 2, do not show any signs of a rapidity dependence. In contrast, they show a clear p_T dependence at low p_T, followed by a flat high-p_T trend. Averaging the $p_T > 18$ GeV measurements gives $\mathcal{R}_s = 0.1102 \pm 0.0027$, where the uncertainty includes all contributions, added in quadrature. The low-p_T dependence is compatible with the LHCb measurements (for $2 < y < 4.5$) [12], also shown in Fig. 2.

The measured $\mathcal{R}_d$ ratio can be used to probe isospin invariance in B meson production, converting it into the f_d/f_u observable with Eq. (2), as long as the needed ratio of B meson branching fractions, $\mathcal{B}(B^+ \to J/\psi K^+)/\mathcal{B}(B^0 \to J/\psi K^{*0})$, is evaluated without the isospin invariance assumption. For $\mathcal{B}(B^0 \to J/\psi K^{*0})$, we take the world-average value [22], which is dominated by measurements at the $\Upsilon(4S)$ that assume isospin invariance: $\mathcal{R}^{\pm,0} = \mathcal{B}[\Upsilon(4S) \to B^+B^-]/\mathcal{B}[\Upsilon(4S) \to B^0\bar{B}^0] = 1$. For $\mathcal{B}(B^+ \to J/\psi K^+)$, we use its most precise measurement [31], after correcting for their assumption, $\mathcal{R}^{\pm,0} = 1.058 \pm 0.024$ [6], to make it compatible with the branching fractions that use $\mathcal{R}^{\pm,0} = 1$. The ratio of branching fractions in Eq. (2) is then divided [32] by the most recent $\mathcal{R}^{\pm,0}$ value (1.059 ± 0.027) [33] to remove the isospin conservation assumption. The obtained f_d/f_u ratios are plotted versus p_T and $|y|$ in Fig. 3, with no dependence on either variable observed. The average value of 0.998 ± 0.063, with the uncertainty including all contributions, is compatible with unity within the 6% precision of the measurement, consistent with isospin invariance in B meson production at hadron colliders.

The numerical results corresponding to Figs. 2 and 3 are tabulated in [34] and in the HEPData record for this analysis [35].

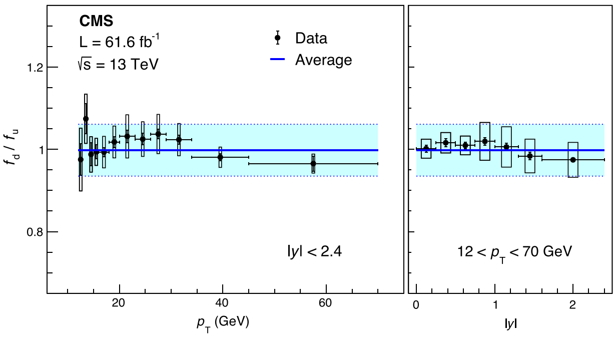

FIG. 3. The ratio of the B^0 to B^+ hadron production fractions f_d/f_u, as a function of p_T (left) and $|y|$ (right). The vertical bars (boxes) represent the statistical (bin-to-bin systematic) uncertainties, while the horizontal bars give the bin widths. The horizontal blue line and band represent the average value and uncertainty. The global uncertainty (of 5.7%) is included in the blue bands but not in the individual data points.

In summary, the ratio of the B_s^0 and B^+ hadron production fractions, f_s/f_u, directly proportional to the ratio of the efficiency-corrected meson yields, $\mathcal{R}_s$, is studied as a function of the B meson transverse momentum p_T and rapidity, using the $B_s^0 \to J/\psi\phi$ and $B^+ \to J/\psi K^+$ decay channels. The analysis uses an event sample of pp collisions at a center-of-mass energy of 13 TeV, collected by CMS in 2018 and corresponding to an integrated luminosity of 61.6 fb^{-1}. While no $\mathcal{R}_s$ dependence on the B meson rapidity is seen, a strong variation is observed in the $12 < p_T < 18$ GeV range, followed by a flat trend for higher p_T values. The f_d/f_u ratio, measured for the first time in proton-proton collisions using the $B^0 \to J/\psi K^{*0}$ decay channel, is found to be compatible with unity and independent of rapidity and p_T. This is the first direct measurement of isospin invariance in B meson production at hadron colliders. The b hadron production fractions presented in this Letter also provide a crucial input to measurements by ATLAS and CMS of the $B_s^0 \to \mu^+\mu^-$ branching fraction.

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

[1] CMS and LHCb Collaborations, Observation of the rare $B_s^0 \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data, Nature (London) **522**, 68 (2015).
[2] ATLAS Collaboration, Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector, J. High Energy Phys. 04 (2019) 098.
[3] CMS Collaboration, Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment, J. High Energy Phys. 04 (2020) 188.
[4] LHCb Collaboration, Measurement of the $B_s^0 \to \mu^+\mu^-$ Branching Fraction and Effective Lifetime and Search for $B^0 \to \mu^+\mu^-$ Decays, Phys. Rev. Lett. **118**, 191801 (2017).
[5] LHCb Collaboration, Measurement of the $B_s^0 \to \mu^+\mu^-$ decay properties and search for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ decays, Phys. Rev. D **105**, 012010 (2022).
[6] Y. S. Amhis *et al.* (HFLAV Collaboration), Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018, Eur. Phys. J. C **81**, 226 (2021).
[7] T. Aaltonen *et al.* (CDF Collaboration), Measurement of ratios of fragmentation fractions for bottom hadrons in pp collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D **77**, 072003 (2008).
[8] ATLAS Collaboration, Determination of the Ratio of b-Quark Fragmentation Fractions f_s/f_d in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector, Phys. Rev. Lett. **115**, 262001 (2015).
[9] LHCb Collaboration, Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions, Phys. Rev. D **104**, 032005 (2021).
[10] LHCb Collaboration, Measurement of b-hadron production fractions in 7 TeV pp collisions, Phys. Rev. D **85**, 032008 (2012).
[11] LHCb Collaboration, Measurement of the fragmentation fraction ratio f_s/f_d and its dependence on B meson kinematics, J. High Energy Phys. 04 (2013) 001.
[12] LHCb Collaboration, Measurement of f_s/f_u Variation with Proton-Proton Collision Energy and B-Meson Kinematics, Phys. Rev. Lett. **124**, 122002 (2020).

[13] LHCb Collaboration, Measurement of b-hadron fractions in 13 TeV pp collisions, Phys. Rev. D **100**, 031102 (2019).
[14] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-18-002, 2019, https://cds.cern.ch/record/2676164.
[15] 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**, 800 (2021).
[16] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. **3**, S08004 (2008).
[17] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. **16**, P05014 (2021).
[18] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **13**, P06015 (2018).
[19] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. **9**, P10009 (2014).
[20] CMS Collaboration, Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **15**, P10017 (2020)}.
[21] CMS Collaboration, The CMS trigger system, J. Instrum. **12**, P01020 (2017).
[22] R. L. Workman *et al.* (Particle Data Group), Review of particle physics, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[23] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA8.2, Comput. Phys. Commun. **191**, 159 (2015).
[24] D. Lange, The EVTGEN particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[25] N. Davidson, T. Przedzinski, and Z. Wąs, PHOTOS interface in C++: Technical and physics documentation, Comput. Phys. Commun. **199**, 86 (2016).
[26] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[27] N. L. Johnson, Systems of frequency curves generated by methods of translation, Biometrika **36**, 149 (1949).
[28] M. J. Oreglia, A study of the reactions $\psi' \to \gamma\gamma\psi$, Ph.D. thesis, Stanford University, 1980 [Report No. SLAC-R-236].
[29] S. Jackman, *Bayesian Analysis for the Social Sciences* (John Wiley & Sons, New Jersey, USA, 2009).
[30] CMS Collaboration, Tracking POG results for pion efficiency with the $D*$ meson using data from 2016 and 2017, CMS Detector Performance Report, Report No. CMS-DP-2018-050, 2018.
[31] S. Choudhury *et al.* (BELLE Collaboration), Test of lepton flavor universality and search for lepton flavor violation in $B \to Kll$ decays, J. High Energy Phys. 03 (2021) 105.
[32] M. Jung, Branching ratio measurements and isospin violation in B-meson decays, Phys. Lett. B **753**, 187 (2016).
[33] Y. Amhis *et al.* (HFLAV Collaboration), Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021, Phys. Rev. D **107**, 052008 (2023).
[34] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.121901 for numerical results in bins of p_T and $|y|$.
[35] HEPData record for this analysis (2022), 10.17182/hepdata.134069.

A. Tumasyan,[1,b] W. Adam,[2] J. W. Andrejkovic,[2] T. Bergauer,[2] S. Chatterjee,[2] K. Damanakis,[2] M. Dragicevic,[2] A. Escalante Del Valle,[2] P. S. Hussain,[2] M. Jeitler,[2,c] N. Krammer,[2] L. Lechner,[2] D. Liko,[2] I. Mikulec,[2] P. Paulitsch,[2] J. Schieck,[2,c] R. Schöfbeck,[2] D. Schwarz,[2] M. Sonawane,[2] S. Templ,[2] W. Waltenberger,[2] C.-E. Wulz,[2,c] M. R. Darwish,[3,d] T. Janssen,[3] T. Kello,[3,e] H. Rejeb Sfar,[3] P. Van Mechelen,[3] E. S. Bols,[4] J. D'Hondt,[4] A. De Moor,[4] M. Delcourt,[4] H. El Faham,[4] S. Lowette,[4] A. Morton,[4] D. Müller,[4] A. R. Sahasransu,[4] S. Tavernier,[4] W. Van Doninck,[4] S. Van Putte,[4] D. Vannerom,[4] B. Clerbaux,[5] G. De Lentdecker,[5] L. Favart,[5] D. Hohov,[5] J. Jaramillo,[5] K. Lee,[5] M. Mahdavikhorrami,[5] I. Makarenko,[5] A. Malara,[5] S. Paredes,[5] L. Pétré,[5] N. Postiau,[5] L. Thomas,[5] M. Vanden Bemden,[5] C. Vander Velde,[5] P. Vanlaer,[5] D. Dobur,[6] J. Knolle,[6] L. Lambrecht,[6] G. Mestdach,[6] C. Rendón,[6] A. Samalan,[6] K. Skovpen,[6] M. Tytgat,[6] N. Van Den Bossche,[6] B. Vermassen,[6] L. Wezenbeek,[6] A. Benecke,[7] G. Bruno,[7] F. Bury,[7] C. Caputo,[7] P. David,[7] C. Delaere,[7] I. S. Donertas,[7] A. Giammanco,[7] K. Jaffel,[7] Sa. Jain,[7] V. Lemaitre,[7] K. Mondal,[7] A. Taliercio,[7] T. T. Tran,[7] P. Vischia,[7] S. Wertz,[7] G. A. Alves,[8] E. Coelho,[8] C. Hensel,[8] A. Moraes,[8] P. Rebello Teles,[8] W. L. Aldá Júnior,[9] M. Alves Gallo Pereira,[9] M. Barroso Ferreira Filho,[9] H. Brandao Malbouisson,[9] W. Carvalho,[9] J. Chinellato,[9,f] E. M. Da Costa,[9] G. G. Da Silveira,[9,g] D. De Jesus Damiao,[9] V. Dos Santos Sousa,[9] S. Fonseca De Souza,[9] J. Martins,[9,h] C. Mora Herrera,[9] K. Mota Amarilo,[9] L. Mundim,[9] H. Nogima,[9] A. Santoro,[9] S. M. Silva Do Amaral,[9] A. Sznajder,[9] M. Thiel,[9] A. Vilela Pereira,[9] C. A. Bernardes,[10,g] L. Calligaris,[10] T. R. Fernandez Perez Tomei,[10] E. M. Gregores,[10] P. G. Mercadante,[10] S. F. Novaes,[10] Sandra S. Padula,[10] A. Aleksandrov,[11] G. Antchev,[11] R. Hadjiiska,[11] P. Iaydjiev,[11] M. Misheva,[11] M. Rodozov,[11] M. Shopova,[11] G. Sultanov,[11] A. Dimitrov,[12] T. Ivanov,[12] L. Litov,[12] B. Pavlov,[12] P. Petkov,[12] A. Petrov,[12] E. Shumka,[12] S. Thakur,[13] T. Cheng,[14] T. Javaid,[14,i]

M. Mittal,[14] L. Yuan,[14] M. Ahmad,[15] G. Bauer,[15,j] Z. Hu,[15] S. Lezki,[15] K. Yi,[15,k,j] G. M. Chen,[16,i] H. S. Chen,[16,i] M. Chen,[16,i] F. Iemmi,[16] C. H. Jiang,[16] A. Kapoor,[16] H. Liao,[16] Z.-A. Liu,[16,l] V. Milosevic,[16] F. Monti,[16] R. Sharma,[16] J. Tao,[16] J. Thomas-Wilsker,[16] J. Wang,[16] H. Zhang,[16] J. Zhao,[16] A. Agapitos,[17] Y. An,[17] Y. Ban,[17] A. Levin,[17] C. Li,[17] Q. Li,[17] X. Lyu,[17] Y. Mao,[17] S. J. Qian,[17] X. Sun,[17] D. Wang,[17] J. Xiao,[17] H. Yang,[17] M. Lu,[18] Z. You,[18] N. Lu,[19] X. Gao,[20,e] D. Leggat,[20] H. Okawa,[20] Y. Zhang,[20] Z. Lin,[21] C. Lu,[21] M. Xiao,[21] C. Avila,[22] D. A. Barbosa Trujillo,[22] A. Cabrera,[22] C. Florez,[22] J. Fraga,[22] J. Mejia Guisao,[23] F. Ramirez,[23] M. Rodriguez,[23] J. D. Ruiz Alvarez,[23] D. Giljanovic,[24] N. Godinovic,[24] D. Lelas,[24] I. Puljak,[24] Z. Antunovic,[25] M. Kovac,[25] T. Sculac,[25] V. Brigljevic,[26] B. K. Chitroda,[26] D. Ferencek,[26] S. Mishra,[26] M. Roguljic,[26] A. Starodumov,[26,m] T. Susa,[26] A. Attikis,[27] K. Christoforou,[27] S. Konstantinou,[27] J. Mousa,[27] C. Nicolaou,[27] F. Ptochos,[27] P. A. Razis,[27] H. Rykaczewski,[27] H. Saka,[27] A. Stepennov,[27] M. Finger,[28,m] M. Finger Jr.,[28,m] A. Kveton,[28] E. Ayala,[29] E. Carrera Jarrin,[30] A. A. Abdelalim,[31,n,o] E. Salama,[31,p,q] M. Abdullah Al-Mashad,[32] M. A. Mahmoud,[32] S. Bhowmik,[33] R. K. Dewanjee,[33] K. Ehataht,[33] M. Kadastik,[33] T. Lange,[33] S. Nandan,[33] C. Nielsen,[33] J. Pata,[33] M. Raidal,[33] L. Tani,[33] C. Veelken,[33] P. Eerola,[34] H. Kirschenmann,[34] K. Osterberg,[34] M. Voutilainen,[34] S. Bharthuar,[35] E. Brücken,[35] F. Garcia,[35] J. Havukainen,[35] M. S. Kim,[35] R. Kinnunen,[35] T. Lampén,[35] K. Lassila-Perini,[35] S. Lehti,[35] T. Lindén,[35] M. Lotti,[35] L. Martikainen,[35] M. Myllymäki,[35] M. m. Rantanen,[35] H. Siikonen,[35] E. Tuominen,[35] J. Tuominiemi,[35] P. Luukka,[36] H. Petrow,[36] T. Tuuva,[36,a] C. Amendola,[37] M. Besancon,[37] F. Couderc,[37] M. Dejardin,[37] D. Denegri,[37] J. L. Faure,[37] F. Ferri,[37] S. Ganjour,[37] P. Gras,[37] G. Hamel de Monchenault,[37] V. Lohezic,[37] J. Malcles,[37] J. Rander,[37] A. Rosowsky,[37] M. Ö. Sahin,[37] A. Savoy-Navarro,[37,r] P. Simkina,[37] M. Titov,[37] C. Baldenegro Barrera,[38] F. Beaudette,[38] A. Buchot Perraguin,[38] P. Busson,[38] A. Cappati,[38] C. Charlot,[38] F. Damas,[38] O. Davignon,[38] B. Diab,[38] G. Falmagne,[38] B. A. Fontana Santos Alves,[38] S. Ghosh,[38] R. Granier de Cassagnac,[38] A. Hakimi,[38] B. Harikrishnan,[38] G. Liu,[38] J. Motta,[38] M. Nguyen,[38] C. Ochando,[38] L. Portales,[38] R. Salerno,[38] U. Sarkar,[38] J. B. Sauvan,[38] Y. Sirois,[38] A. Tarabini,[38] E. Vernazza,[38] A. Zabi,[38] A. Zghiche,[38] J.-L. Agram,[39,s] J. Andrea,[39] D. Apparu,[39] D. Bloch,[39] G. Bourgatte,[39] J.-M. Brom,[39] E. C. Chabert,[39] C. Collard,[39] D. Darej,[39] U. Goerlach,[39] C. Grimault,[39] A.-C. Le Bihan,[39] P. Van Hove,[39] S. Beauceron,[40] B. Blancon,[40] G. Boudoul,[40] A. Carle,[40] N. Chanon,[40] J. Choi,[40] D. Contardo,[40] P. Depasse,[40] C. Dozen,[40,t] H. El Mamouni,[40] J. Fay,[40] S. Gascon,[40] M. Gouzevitch,[40] G. Grenier,[40] B. Ille,[40] I. B. Laktineh,[40] M. Lethuillier,[40] L. Mirabito,[40] S. Perries,[40] L. Torterotot,[40] M. Vander Donckt,[40] P. Verdier,[40] S. Viret,[40] I. Lomidze,[41] T. Toriashvili,[41,u] Z. Tsamalaidze,[41,m] V. Botta,[42] L. Feld,[42] K. Klein,[42] M. Lipinski,[42] D. Meuser,[42] A. Pauls,[42] N. Röwert,[42] M. Teroerde,[42] S. Diekmann,[43] A. Dodonova,[43] N. Eich,[43] D. Eliseev,[43] M. Erdmann,[43] P. Fackeldey,[43] D. Fasanella,[43] B. Fischer,[43] T. Hebbeker,[43] K. Hoepfner,[43] F. Ivone,[43] M. y. Lee,[43] L. Mastrolorenzo,[43] M. Merschmeyer,[43] A. Meyer,[43] S. Mondal,[43] S. Mukherjee,[43] D. Noll,[43] A. Novak,[43] F. Nowotny,[43] A. Pozdnyakov,[43] Y. Rath,[43] W. Redjeb,[43] F. Rehm,[43] H. Reithler,[43] A. Schmidt,[43] S. C. Schuler,[43] A. Sharma,[43] A. Stein,[43] F. Torres Da Silva De Araujo,[43,v] L. Vigilante,[43] S. Wiedenbeck,[43] S. Zaleski,[43] C. Dziwok,[44] G. Flügge,[44] W. Haj Ahmad,[44,w] O. Hlushchenko,[44] T. Kress,[44] A. Nowack,[44] O. Pooth,[44] A. Stahl,[44] T. Ziemons,[44] A. Zotz,[44] H. Aarup Petersen,[45] M. Aldaya Martin,[45] J. Alimena,[45] P. Asmuss,[45] S. Baxter,[45] M. Bayatmakou,[45] H. Becerril Gonzalez,[45] O. Behnke,[45] S. Bhattacharya,[45] F. Blekman,[45,x] K. Borras,[45,y] D. Brunner,[45] A. Campbell,[45] A. Cardini,[45] C. Cheng,[45] F. Colombina,[45] S. Consuegra Rodríguez,[45] G. Correia Silva,[45] M. De Silva,[45] G. Eckerlin,[45] D. Eckstein,[45] L. I. Estevez Banos,[45] O. Filatov,[45] E. Gallo,[45,x] A. Geiser,[45] A. Giraldi,[45] G. Greau,[45] A. Grohsjean,[45] V. Guglielmi,[45] M. Guthoff,[45] A. Jafari,[45,z] N. Z. Jomhari,[45] B. Kaech,[45] M. Kasemann,[45] H. Kaveh,[45] C. Kleinwort,[45] R. Kogler,[45] M. Komm,[45] D. Krücker,[45] W. Lange,[45] D. Leyva Pernia,[45] K. Lipka,[45,aa] W. Lohmann,[45,bb] R. Mankel,[45] I.-A. Melzer-Pellmann,[45] M. Mendizabal Morentin,[45] J. Metwally,[45] A. B. Meyer,[45] G. Milella,[45] M. Mormile,[45] A. Mussgiller,[45] A. Nürnberg,[45] Y. Otarid,[45] D. Pérez Adán,[45] E. Ranken,[45] A. Raspereza,[45] B. Ribeiro Lopes,[45] J. Rübenach,[45] A. Saggio,[45] M. Savitskyi,[45] M. Scham,[45,cc,y] V. Scheurer,[45] S. Schnake,[45,y] P. Schütze,[45] C. Schwanenberger,[45,x] M. Shchedrolosiev,[45] R. E. Sosa Ricardo,[45] D. Stafford,[45] N. Tonon,[45,a] M. Van De Klundert,[45] F. Vazzoler,[45] A. Ventura Barroso,[45] R. Walsh,[45] D. Walter,[45] Q. Wang,[45] Y. Wen,[45] K. Wichmann,[45] L. Wiens,[45,y] C. Wissing,[45] S. Wuchterl,[45] Y. Yang,[45] A. Zimermmane Castro Santos,[45] A. Albrecht,[46] S. Albrecht,[46] M. Antonello,[46] S. Bein,[46] L. Benato,[46]

M. Bonanomi,[46] P. Connor,[46] K. De Leo,[46] M. Eich,[46] K. El Morabit,[46] F. Feindt,[46] A. Fröhlich,[46] C. Garbers,[46] E. Garutti,[46] M. Hajheidari,[46] J. Haller,[46] A. Hinzmann,[46] H. R. Jabusch,[46] G. Kasieczka,[46] P. Keicher,[46] R. Klanner,[46] W. Korcari,[46] T. Kramer,[46] V. Kutzner,[46] F. Labe,[46] J. Lange,[46] A. Lobanov,[46] C. Matthies,[46] A. Mehta,[46] L. Moureaux,[46] M. Mrowietz,[46] A. Nigamova,[46] Y. Nissan,[46] A. Paasch,[46] K. J. Pena Rodriguez,[46] T. Quadfasel,[46] M. Rieger,[46] O. Rieger,[46] D. Savoiu,[46] J. Schindler,[46] P. Schleper,[46] M. Schröder,[46] J. Schwandt,[46] M. Sommerhalder,[46] H. Stadie,[46] G. Steinbrück,[46] A. Tews,[46] M. Wolf,[46] S. Brommer,[47] M. Burkart,[47] E. Butz,[47] T. Chwalek,[47] A. Dierlamm,[47] A. Droll,[47] N. Faltermann,[47] M. Giffels,[47] J. O. Gosewisch,[47] A. Gottmann,[47] F. Hartmann,[47,dd] M. Horzela,[47] U. Husemann,[47] M. Klute,[47] R. Koppenhöfer,[47] M. Link,[47] A. Lintuluoto,[47] S. Maier,[47] S. Mitra,[47] Th. Müller,[47] M. Neukum,[47] M. Oh,[47] G. Quast,[47] K. Rabbertz,[47] J. Rauser,[47] I. Shvetsov,[47] H. J. Simonis,[47] N. Trevisani,[47] R. Ulrich,[47] J. van der Linden,[47] R. F. Von Cube,[47] M. Wassmer,[47] S. Wieland,[47] R. Wolf,[47] S. Wozniewski,[47] S. Wunsch,[47] X. Zuo,[47] G. Anagnostou,[48] P. Assiouras,[48] G. Daskalakis,[48] A. Kyriakis,[48] A. Stakia,[48] M. Diamantopoulou,[49] D. Karasavvas,[49] P. Kontaxakis,[49] A. Manousakis-Katsikakis,[49] A. Panagiotou,[49] I. Papavergou,[49] N. Saoulidou,[49] K. Theofilatos,[49] E. Tziaferi,[49] K. Vellidis,[49] I. Zisopoulos,[49] G. Bakas,[50] T. Chatzistavrou,[50] G. Karapostoli,[50] K. Kousouris,[50] I. Papakrivopoulos,[50] G. Tsipolitis,[50] A. Zacharopoulou,[50] K. Adamidis,[51] I. Bestintzanos,[51] I. Evangelou,[51] C. Foudas,[51] P. Gianneios,[51] C. Kamtsikis,[51] P. Katsoulis,[51] P. Kokkas,[51] P. G. Kosmoglou Kioseoglou,[51] N. Manthos,[51] I. Papadopoulos,[51] J. Strologas,[51] M. Csanád,[52] K. Farkas,[52] M. M. A. Gadallah,[52,ee] S. Lökös,[52,ff] P. Major,[52] K. Mandal,[52] G. Pásztor,[52] A. J. Rádl,[52,gg] O. Surányi,[52] G. I. Veres,[52] M. Bartók,[53,hh] G. Bencze,[53] C. Hajdu,[53] D. Horvath,[53,ii,jj] F. Sikler,[53] V. Veszpremi,[53] N. Beni,[54] S. Czellar,[54] J. Karancsi,[54,hh] J. Molnar,[54] Z. Szillasi,[54] D. Teyssier,[54] P. Raics,[55] B. Ujvari,[55,kk] G. Zilizi,[55] T. Csorgo,[56,gg] F. Nemes,[56,gg] T. Novak,[56] J. Babbar,[57] S. Bansal,[57] S. B. Beri,[57] V. Bhatnagar,[57] G. Chaudhary,[57] S. Chauhan,[57] N. Dhingra,[57,ll] R. Gupta,[57] A. Kaur,[57] A. Kaur,[57] H. Kaur,[57] M. Kaur,[57] S. Kumar,[57] P. Kumari,[57] M. Meena,[57] K. Sandeep,[57] T. Sheokand,[57] J. B. Singh,[57,mm] A. Singla,[57] A. Ahmed,[58] A. Bhardwaj,[58] A. Chhetri,[58] B. C. Choudhary,[58] A. Kumar,[58] M. Naimuddin,[58] K. Ranjan,[58] S. Saumya,[58] S. Baradia,[59] S. Barman,[59,nn] S. Bhattacharya,[59] D. Bhowmik,[59] S. Dutta,[59] S. Dutta,[59] B. Gomber,[59,oo] M. Maity,[59,nn] P. Palit,[59] G. Saha,[59] B. Sahu,[59] S. Sarkar,[59] P. K. Behera,[60] S. C. Behera,[60] S. Chatterjee,[60] P. Kalbhor,[60] J. R. Komaragiri,[60,pp] D. Kumar,[60,pp] A. Muhammad,[60] L. Panwar,[60,pp] R. Pradhan,[60] P. R. Pujahari,[60] N. R. Saha,[60] A. Sharma,[60] A. K. Sikdar,[60] S. Verma,[60] K. Naskar,[61,qq] T. Aziz,[62] I. Das,[62] S. Dugad,[62] M. Kumar,[62] G. B. Mohanty,[62] P. Suryadevara,[62] S. Banerjee,[63] M. Guchait,[63] S. Karmakar,[63] S. Kumar,[63] G. Majumder,[63] K. Mazumdar,[63] S. Mukherjee,[63] A. Thachayath,[63] S. Bahinipati,[64,rr] A. K. Das,[64] C. Kar,[64] P. Mal,[64] T. Mishra,[64] V. K. Muraleedharan Nair Bindhu,[64,ss] A. Nayak,[64,ss] P. Saha,[64] S. K. Swain,[64] D. Vats,[64,ss] A. Alpana,[65] S. Dube,[65] B. Kansal,[65] A. Laha,[65] S. Pandey,[65] A. Rastogi,[65] S. Sharma,[65] H. Bakhshiansohi,[66,tt,uu] E. Khazaie,[66,uu] M. Zeinali,[66,vv] S. Chenarani,[67,ww] S. M. Etesami,[67] M. Khakzad,[67] M. Mohammadi Najafabadi,[67] M. Grunewald,[68] M. Abbrescia,[69a,69b] R. Aly,[69a,69c,n] C. Aruta,[69a,69b] A. Colaleo,[69a] D. Creanza,[69a,69c] L. Cristella,[69a,69b] N. De Filippis,[69a,69c] M. De Palma,[69a,69b] A. Di Florio,[69a,69b] W. Elmetenawee,[69a,69b] F. Errico,[69a,69b] L. Fiore,[69a] G. Iaselli,[69a,69c] G. Maggi,[69a,69c] M. Maggi,[69a] I. Margjeka,[69a,69b] V. Mastrapasqua,[69a,69b] S. My,[69a,69b] S. Nuzzo,[69a,69b] A. Pellecchia,[69a,69b] A. Pompili,[69a,69b] G. Pugliese,[69a,69c] R. Radogna,[69a] D. Ramos,[69a] A. Ranieri,[69a] G. Selvaggi,[69a,69b] L. Silvestris,[69a] F. M. Simone,[69a,69b] Ü. Sözbilir,[69a] A. Stamerra,[69a] R. Venditti,[69a] P. Verwilligen,[69a] G. Abbiendi,[70a] C. Battilana,[70a,70b] D. Bonacorsi,[70a,70b] L. Borgonovi,[70a] L. Brigliadori,[70a] R. Campanini,[70a,70b] P. Capiluppi,[70a,70b] A. Castro,[70a,70b] F. R. Cavallo,[70a] M. Cuffiani,[70a,70b] G. M. Dallavalle,[70a] T. Diotalevi,[70a,70b] F. Fabbri,[70a] A. Fanfani,[70a,70b] P. Giacomelli,[70a] L. Giommi,[70a,70b] C. Grandi,[70a] L. Guiducci,[70a,70b] S. Lo Meo,[70a,xx] L. Lunerti,[70a,70b] S. Marcellini,[70a] G. Masetti,[70a] F. L. Navarria,[70a,70b] A. Perrotta,[70a] F. Primavera,[70a,70b] A. M. Rossi,[70a,70b] T. Rovelli,[70a,70b] G. P. Siroli,[70a,70b] S. Costa,[71a,71b,yy] A. Di Mattia,[71a] R. Potenza,[71a,71b] A. Tricomi,[71a,71b,yy] C. Tuve,[71a,71b] G. Barbagli,[72a] G. Bardelli,[72a,72b] B. Camaiani,[72a,72b] A. Cassese,[72a] R. Ceccarelli,[72a,72b] V. Ciulli,[72a,72b] C. Civinini,[72a] R. D'Alessandro,[72a,72b] E. Focardi,[72a,72b] G. Latino,[72a,72b] P. Lenzi,[72a,72b] M. Lizzo,[72a,72b] M. Meschini,[72a] S. Paoletti,[72a] G. Sguazzoni,[72a] L. Viliani,[72a] L. Benussi,[73] S. Bianco,[73] S. Meola,[73,zz] D. Piccolo,[73] M. Bozzo,[74a,74b] P. Chatagnon,[74a] F. Ferro,[74a] E. Robutti,[74a] S. Tosi,[74a,74b] A. Benaglia,[75a] G. Boldrini,[75a] F. Brivio,[75a,75b] F. Cetorelli,[75a,75b] F. De Guio,[75a,75b]

M. E. Dinardo,[75a,75b] P. Dini,[75a] S. Gennai,[75a] A. Ghezzi,[75a,75b] P. Govoni,[75a,75b] L. Guzzi,[75a,75b] M. T. Lucchini,[75a,75b] M. Malberti,[75a] S. Malvezzi,[75a] A. Massironi,[75a] D. Menasce,[75a] L. Moroni,[75a] M. Paganoni,[75a,75b] D. Pedrini,[75a] B. S. Pinolini,[75a] S. Ragazzi,[75a,75b] N. Redaelli,[75a] T. Tabarelli de Fatis,[75a,75b] D. Zuolo,[75a,75b] S. Buontempo,[76a] F. Carnevali,[76a,76b] N. Cavallo,[76a,76c] A. De Iorio,[76a,76b] F. Fabozzi,[76a,76c] A. O. M. Iorio,[76a,76b] L. Lista,[76a,76b,aaa] P. Paolucci,[76a,dd] B. Rossi,[76a] C. Sciacca,[76a,76b] P. Azzi,[77a] N. Bacchetta,[77a,bbb] D. Bisello,[77a,77b] P. Bortignon,[77a] A. Bragagnolo,[77a,77b] R. Carlin,[77a,77b] P. Checchia,[77a] T. Dorigo,[77a] F. Gasparini,[77a,77b] U. Gasparini,[77a,77b] G. Grosso,[77a] M. Gulmini,[77a,ccc] L. Layer,[77a,ddd] E. Lusiani,[77a] M. Margoni,[77a,77b] A. T. Meneguzzo,[77a,77b] J. Pazzini,[77a,77b] P. Ronchese,[77a,77b] R. Rossin,[77a,77b] F. Simonetto,[77a,77b] G. Strong,[77a] M. Tosi,[77a,77b] H. Yarar,[77a,77b] M. Zanetti,[77a,77b] P. Zotto,[77a,77b] A. Zucchetta,[77a,77b] S. Abu Zeid,[78a,p] C. Aimè,[78a,78b] A. Braghieri,[78a] S. Calzaferri,[78a,78b] D. Fiorina,[78a,78b] P. Montagna,[78a,78b] V. Re,[78a] C. Riccardi,[78a,78b] P. Salvini,[78a] I. Vai,[78a] P. Vitulo,[78a,78b] P. Asenov,[79a,eee] G. M. Bilei,[79a] D. Ciangottini,[79a,79b] L. Fanò,[79a,79b] M. Magherini,[79a,79b] G. Mantovani,[79a,79b] V. Mariani,[79a,79b] M. Menichelli,[79a] F. Moscatelli,[79a,eee] A. Piccinelli,[79a,79b] M. Presilla,[79a,79b] A. Rossi,[79a,79b] A. Santocchia,[79a,79b] D. Spiga,[79a] T. Tedeschi,[79a,79b] P. Azzurri,[80a] G. Bagliesi,[80a] V. Bertacchi,[80a,80c] R. Bhattacharya,[80a] L. Bianchini,[80a,80b] T. Boccali,[80a] E. Bossini,[80a,80b] D. Bruschini,[80a,80c] R. Castaldi,[80a] M. A. Ciocci,[80a,80b] V. D'Amante,[80a,80d] R. Dell'Orso,[80a] S. Donato,[80a] A. Giassi,[80a] F. Ligabue,[80a,80c] D. Matos Figueiredo,[80a] A. Messineo,[80a,80b] M. Musich,[80a,80b] F. Palla,[80a] S. Parolia,[80a] G. Ramirez-Sanchez,[80a,80c] A. Rizzi,[80a,80b] G. Rolandi,[80a,80c] S. Roy Chowdhury,[80a] T. Sarkar,[80a] A. Scribano,[80a] P. Spagnolo,[80a] R. Tenchini,[80a] G. Tonelli,[80a,80b] N. Turini,[80a,80d] A. Venturi,[80a] P. G. Verdini,[80a] P. Barria,[81a] M. Campana,[81a,81b] F. Cavallari,[81a] D. Del Re,[81a,81b] E. Di Marco,[81a] M. Diemoz,[81a] E. Longo,[81a,81b] P. Meridiani,[81a] G. Organtini,[81a,81b] F. Pandolfi,[81a] R. Paramatti,[81a,81b] C. Quaranta,[81a,81b] S. Rahatlou,[81a,81b] C. Rovelli,[81a] F. Santanastasio,[81a,81b] L. Soffi,[81a] R. Tramontano,[81a,81b] N. Amapane,[82a,82b] R. Arcidiacono,[82a,82c] S. Argiro,[82a,82b] M. Arneodo,[82a,82c] N. Bartosik,[82a] R. Bellan,[82a,82b] A. Bellora,[82a,82b] C. Biino,[82a] N. Cartiglia,[82a] M. Costa,[82a,82b] R. Covarelli,[82a,82b] N. Demaria,[82a] M. Grippo,[82a,82b] B. Kiani,[82a,82b] F. Legger,[82a] C. Mariotti,[82a] S. Maselli,[82a] A. Mecca,[82a,82b] E. Migliore,[82a,82b] M. Monteno,[82a] R. Mulargia,[82a] M. M. Obertino,[82a,82b] G. Ortona,[82a] L. Pacher,[82a,82b] N. Pastrone,[82a] M. Pelliccioni,[82a] M. Ruspa,[82a,82c] K. Shchelina,[82a] F. Siviero,[82a,82b] V. Sola,[82a,82b] A. Solano,[82a,82b] D. Soldi,[82a,82b] A. Staiano,[82a] M. Tornago,[82a,82b] D. Trocino,[82a] G. Umoret,[82a,82b] A. Vagnerini,[82a,82b] E. Vlasov,[82a,82b] S. Belforte,[83a] V. Candelise,[83a,83b] M. Casarsa,[83a] F. Cossutti,[83a] G. Della Ricca,[83a,83b] G. Sorrentino,[83a,83b] S. Dogra,[84] C. Huh,[84] B. Kim,[84] D. H. Kim,[84] G. N. Kim,[84] J. Kim,[84] J. Lee,[84] S. W. Lee,[84] C. S. Moon,[84] Y. D. Oh,[84] S. I. Pak,[84] M. S. Ryu,[84] S. Sekmen,[84] Y. C. Yang,[84] H. Kim,[85] D. H. Moon,[85] E. Asilar,[86] T. J. Kim,[86] J. Park,[86] S. Choi,[87] S. Han,[87] B. Hong,[87] K. Lee,[87] K. S. Lee,[87] J. Lim,[87] J. Park,[87] S. K. Park,[87] J. Yoo,[87] J. Goh,[88] H. S. Kim,[89] Y. Kim,[89] S. Lee,[89] J. Almond,[90] J. H. Bhyun,[90] J. Choi,[90] S. Jeon,[90] J. Kim,[90] J. S. Kim,[90] S. Ko,[90] H. Kwon,[90] H. Lee,[90] S. Lee,[90] B. H. Oh,[90] S. B. Oh,[90] H. Seo,[90] U. K. Yang,[90] I. Yoon,[90] W. Jang,[91] D. Y. Kang,[91] Y. Kang,[91] D. Kim,[91] S. Kim,[91] B. Ko,[91] J. S. H. Lee,[91] Y. Lee,[91] J. A. Merlin,[91] I. C. Park,[91] Y. Roh,[91] D. Song,[91] I. J. Watson,[91] S. Yang,[91] S. Ha,[92] H. D. Yoo,[92] M. Choi,[93] M. R. Kim,[93] H. Lee,[93] Y. Lee,[93] I. Yu,[93] T. Beyrouthy,[94] Y. Maghrbi,[94] K. Dreimanis,[95] G. Pikurs,[95] A. Potrebko,[95] M. Seidel,[95] V. Veckalns,[95] M. Ambrozas,[96] A. Carvalho Antunes De Oliveira,[96] A. Juodagalvis,[96] A. Rinkevicius,[96] G. Tamulaitis,[96] N. Bin Norjoharuddeen,[97] S. Y. Hoh,[97,fff] I. Yusuff,[97,fff] Z. Zolkapli,[97] J. F. Benitez,[98] A. Castaneda Hernandez,[98] H. A. Encinas Acosta,[98] L. G. Gallegos Maríñez,[98] M. León Coello,[98] J. A. Murillo Quijada,[98] A. Sehrawat,[98] L. Valencia Palomo,[98] G. Ayala,[99] H. Castilla-Valdez,[99] I. Heredia-De La Cruz,[99,ggg] R. Lopez-Fernandez,[99] C. A. Mondragon Herrera,[99] D. A. Perez Navarro,[99] A. Sánchez Hernández,[99] C. Oropeza Barrera,[100] F. Vazquez Valencia,[100] I. Pedraza,[101] H. A. Salazar Ibarguen,[101] C. Uribe Estrada,[101] I. Bubanja,[102] J. Mijuskovic,[102,hhh] N. Raicevic,[102] A. Ahmad,[103] M. I. Asghar,[103] A. Awais,[103] M. I. M. Awan,[103] M. Gul,[103] H. R. Hoorani,[103] W. A. Khan,[103] V. Avati,[104] L. Grzanka,[104] M. Malawski,[104] H. Bialkowska,[105] M. Bluj,[105] B. Boimska,[105] M. Górski,[105] M. Kazana,[105] M. Szleper,[105] P. Zalewski,[105] K. Bunkowski,[106] K. Doroba,[106] A. Kalinowski,[106] M. Konecki,[106] J. Krolikowski,[106] M. Araujo,[107] P. Bargassa,[107] D. Bastos,[107] A. Boletti,[107] P. Faccioli,[107] M. Gallinaro,[107] J. Hollar,[107] N. Leonardo,[107] T. Niknejad,[107] M. Pisano,[107] J. Seixas,[107] J. Varela,[107] P. Adzic,[108,iii] M. Dordevic,[108] P. Milenovic,[108] J. Milosevic,[108] M. Aguilar-Benitez,[109] J. Alcaraz Maestre,[109] M. Barrio Luna,[109] Cristina F. Bedoya,[109] M. Cepeda,[109] M. Cerrada,[109] N. Colino,[109] B. De La Cruz,[109] A. Delgado Peris,[109] D. Fernández Del Val,[109] J. P. Fernández Ramos,[109] J. Flix,[109] M. C. Fouz,[109] O. Gonzalez Lopez,[109] S. Goy Lopez,[109] J. M. Hernandez,[109] M. I. Josa,[109] J. León Holgado,[109] D. Moran,[109] C. Perez Dengra,[109] A. Pérez-Calero Yzquierdo,[109] J. Puerta Pelayo,[109] I. Redondo,[109] D. D. Redondo Ferrero,[109] L. Romero,[109] S. Sánchez Navas,[109] J. Sastre,[109] L. Urda Gómez,[109] J. Vazquez Escobar,[109] C. Willmott,[109] J. F. de Trocóniz,[110] B. Alvarez Gonzalez,[111] J. Cuevas,[111] J. Fernandez Menendez,[111] S. Folgueras,[111] I. Gonzalez Caballero,[111] J. R. González Fernández,[111] E. Palencia Cortezon,[111] C. Ramón Álvarez,[111] V. Rodríguez Bouza,[111] A. Soto Rodríguez,[111] A. Trapote,[111] C. Vico Villalba,[111] J. A. Brochero Cifuentes,[112] I. J. Cabrillo,[112] A. Calderon,[112] J. Duarte Campderros,[112] M. Fernandez,[112] C. Fernandez Madrazo,[112] A. García Alonso,[112] G. Gomez,[112] C. Lasaosa García,[112] C. Martinez Rivero,[112] P. Martinez Ruiz del Arbol,[112] F. Matorras,[112] P. Matorras Cuevas,[112] J. Piedra Gomez,[112] C. Prieels,[112] L. Scodellaro,[112] I. Vila,[112] J. M. Vizan Garcia,[112] M. K. Jayananda,[113] B. Kailasapathy,[113,jjj] D. U. J. Sonnadara,[113] D. D. C. Wickramarathna,[113] W. G. D. Dharmaratna,[114] K. Liyanage,[114] N. Perera,[114] N. Wickramage,[114] D. Abbaneo,[115] E. Auffray,[115] G. Auzinger,[115] J. Baechler,[115] P. Baillon,[115,a] D. Barney,[115] J. Bendavid,[115] A. Bermúdez Martínez,[115] M. Bianco,[115] B. Bilin,[115] A. A. Bin Anuar,[115] A. Bocci,[115] E. Brondolin,[115] C. Caillol,[115] T. Camporesi,[115] G. Cerminara,[115] N. Chernyavskaya,[115] S. S. Chhibra,[115] S. Choudhury,[115] M. Cipriani,[115] D. d'Enterria,[115] A. Dabrowski,[115] A. David,[115] A. De Roeck,[115] M. M. Defranchis,[115] M. Deile,[115] M. Dobson,[115] M. Dünser,[115] N. Dupont,[115] F. Fallavollita,[115,kkk] A. Florent,[115] L. Forthomme,[115] G. Franzoni,[115] W. Funk,[115] S. Ghosh,[115] S. Giani,[115] D. Gigi,[115] K. Gill,[115] F. Glege,[115] L. Gouskos,[115] E. Govorkova,[115] M. Haranko,[115] J. Hegeman,[115] V. Innocente,[115] T. James,[115] P. Janot,[115] J. Kaspar,[115] J. Kieseler,[115] N. Kratochwil,[115] S. Laurila,[115] P. Lecoq,[115] E. Leutgeb,[115] C. Lourenço,[115] B. Maier,[115] L. Malgeri,[115] M. Mannelli,[115] A. C. Marini,[115] F. Meijers,[115] S. Mersi,[115] E. Meschi,[115] F. Moortgat,[115] M. Mulders,[115] S. Orfanelli,[115] L. Orsini,[115] F. Pantaleo,[115] E. Perez,[115] M. Peruzzi,[115] A. Petrilli,[115] G. Petrucciani,[115] A. Pfeiffer,[115] M. Pierini,[115] D. Piparo,[115] M. Pitt,[115] H. Qu,[115] T. Quast,[115] D. Rabady,[115] A. Racz,[115] G. Reales Gutiérrez,[115] M. Rovere,[115] H. Sakulin,[115] J. Salfeld-Nebgen,[115] S. Scarfi,[115] M. Selvaggi,[115] A. Sharma,[115] P. Silva,[115] P. Sphicas,[115,lll] A. G. Stahl Leiton,[115] S. Summers,[115] K. Tatar,[115] D. Treille,[115] P. Tropea,[115] A. Tsirou,[115] J. Wanczyk,[115,mmm] K. A. Wozniak,[115] W. D. Zeuner,[115] L. Caminada,[116,nnn] A. Ebrahimi,[116] W. Erdmann,[116] R. Horisberger,[116] Q. Ingram,[116] H. C. Kaestli,[116] D. Kotlinski,[116] C. Lange,[116] M. Missiroli,[116,nnn] L. Noehte,[116,nnn] T. Rohe,[116] T. K. Aarrestad,[117] K. Androsov,[117,mmm] M. Backhaus,[117] A. Calandri,[117] K. Datta,[117] A. De Cosa,[117] G. Dissertori,[117] M. Dittmar,[117] M. Donegà,[117] F. Eble,[117] M. Galli,[117] K. Gedia,[117] F. Glessgen,[117] T. A. Gómez Espinosa,[117] C. Grab,[117] D. Hits,[117] W. Lustermann,[117] A.-M. Lyon,[117] R. A. Manzoni,[117] L. Marchese,[117] C. Martin Perez,[117] A. Mascellani,[117,mmm] F. Nessi-Tedaldi,[117] J. Niedziela,[117] F. Pauss,[117] V. Perovic,[117] S. Pigazzini,[117] M. G. Ratti,[117] M. Reichmann,[117] C. Reissel,[117] T. Reitenspiess,[117] B. Ristic,[117] F. Riti,[117] D. Ruini,[117] D. A. Sanz Becerra,[117] R. Seidita,[117] J. Steggemann,[117,mmm] D. Valsecchi,[117] R. Wallny,[117] C. Amsler,[118,ooo] P. Bärtschi,[118] C. Botta,[118] D. Brzhechko,[118] M. F. Canelli,[118] K. Cormier,[118] A. De Wit,[118] R. Del Burgo,[118] J. K. Heikkilä,[118] M. Huwiler,[118] W. Jin,[118] A. Jofrehei,[118] B. Kilminster,[118] S. Leontsinis,[118] S. P. Liechti,[118] A. Macchiolo,[118] P. Meiring,[118] V. M. Mikuni,[118] U. Molinatti,[118] I. Neutelings,[118] A. Reimers,[118] P. Robmann,[118] S. Sanchez Cruz,[118] K. Schweiger,[118] M. Senger,[118] Y. Takahashi,[118] C. Adloff,[119,ppp] C. M. Kuo,[119] W. Lin,[119] P. K. Rout,[119] P. C. Tiwari,[119,pp] S. S. Yu,[119] L. Ceard,[120] Y. Chao,[120] K. F. Chen,[120] P. s. Chen,[120] H. Cheng,[120] W.-S. Hou,[120] R. Khurana,[120] G. Kole,[120] Y. y. Li,[120] R.-S. Lu,[120] E. Paganis,[120] A. Psallidas,[120] A. Steen,[120] H. y. Wu,[120] E. Yazgan,[120] C. Asawatangtrakuldee,[121] N. Srimanobhas,[121] V. Wachirapusitanand,[121] D. Agyel,[122] F. Boran,[122] Z. S. Demiroglu,[122] F. Dolek,[122] I. Dumanoglu,[122,qqq] E. Eskut,[122] Y. Guler,[122,rrr] E. Gurpinar Guler,[122,rrr] C. Isik,[122] O. Kara,[122] A. Kayis Topaksu,[122] U. Kiminsu,[122] G. Onengut,[122] K. Ozdemir,[122,sss] A. Polatoz,[122] A. E. Simsek,[122] B. Tali,[122,ttt] U. G. Tok,[122] S. Turkcapar,[122] E. Uslan,[122] I. S. Zorbakir,[122] G. Karapinar,[123,uuu] K. Ocalan,[123,vvv] M. Yalvac,[123,www] B. Akgun,[124] I. O. Atakisi,[124] E. Gülmez,[124] M. Kaya,[124,xxx] O. Kaya,[124,yyy] S. Tekten,[124,zzz] A. Cakir,[125] K. Cankocak,[125,qqq] Y. Komurcu,[125] S. Sen,[125,aaaa] O. Aydilek,[126] S. Cerci,[126,ttt] B. Hacisahinoglu,[126] I. Hos,[126,bbbb] B. Isildak,[126,cccc] B. Kaynak,[126] S. Ozkorucuklu,[126] C. Simsek,[126] D. Sunar Cerci,[126,ttt] B. Grynyov,[127] L. Levchuk,[128] D. Anthony,[129] J. J. Brooke,[129] A. Bundock,[129]

E. Clement,[129] D. Cussans,[129] H. Flacher,[129] M. Glowacki,[129] J. Goldstein,[129] H. F. Heath,[129] L. Kreczko,[129] B. Krikler,[129] S. Paramesvaran,[129] S. Seif El Nasr-Storey,[129] V. J. Smith,[129] N. Stylianou,[129,dddd] K. Walkingshaw Pass,[129] R. White,[129] A. H. Ball,[130] K. W. Bell,[130] A. Belyaev,[130,eeee] C. Brew,[130] R. M. Brown,[130] D. J. A. Cockerill,[130] C. Cooke,[130] K. V. Ellis,[130] K. Harder,[130] S. Harper,[130] M.-L. Holmberg,[130,ffff] Sh. Jain,[130] J. Linacre,[130] K. Manolopoulos,[130] D. M. Newbold,[130] E. Olaiya,[130] D. Petyt,[130] T. Reis,[130] G. Salvi,[130] T. Schuh,[130] C. H. Shepherd-Themistocleous,[130] I. R. Tomalin,[130] T. Williams,[130] R. Bainbridge,[131] P. Bloch,[131] S. Bonomally,[131] J. Borg,[131] C. E. Brown,[131] O. Buchmuller,[131] V. Cacchio,[131] C. A. Carrillo Montoya,[131] V. Cepaitis,[131] G. S. Chahal,[131,gggg] D. Colling,[131] J. S. Dancu,[131] P. Dauncey,[131] G. Davies,[131] J. Davies,[131] M. Della Negra,[131] S. Fayer,[131] G. Fedi,[131] G. Hall,[131] M. H. Hassanshahi,[131] A. Howard,[131] G. Iles,[131] J. Langford,[131] L. Lyons,[131] A.-M. Magnan,[131] S. Malik,[131] A. Martelli,[131] M. Mieskolainen,[131] D. G. Monk,[131] J. Nash,[131,hhhh] M. Pesaresi,[131] B. C. Radburn-Smith,[131] D. M. Raymond,[131] A. Richards,[131] A. Rose,[131] E. Scott,[131] C. Seez,[131] R. Shukla,[131] A. Tapper,[131] K. Uchida,[131] G. P. Uttley,[131] L. H. Vage,[131] T. Virdee,[131,dd] M. Vojinovic,[131] N. Wardle,[131] S. N. Webb,[131] D. Winterbottom,[131] K. Coldham,[132] J. E. Cole,[132] A. Khan,[132] P. Kyberd,[132] I. D. Reid,[132] S. Abdullin,[133] A. Brinkerhoff,[133] B. Caraway,[133] J. Dittmann,[133] K. Hatakeyama,[133] A. R. Kanuganti,[133] B. McMaster,[133] M. Saunders,[133] S. Sawant,[133] C. Sutantawibul,[133] M. Toms,[133] J. Wilson,[133] R. Bartek,[134] A. Dominguez,[134] C. Huerta Escamilla,[134] R. Uniyal,[134] A. M. Vargas Hernandez,[134] R. Chudasama,[135] S. I. Cooper,[135] D. Di Croce,[135] S. V. Gleyzer,[135] C. Henderson,[135] C. U. Perez,[135] P. Rumerio,[135,iiii] E. Usai,[135] C. West,[135] A. Akpinar,[136] A. Albert,[136] D. Arcaro,[136] C. Cosby,[136] Z. Demiragli,[136] C. Erice,[136] E. Fontanesi,[136] D. Gastler,[136] S. May,[136] J. Rohlf,[136] K. Salyer,[136] D. Sperka,[136] D. Spitzbart,[136] I. Suarez,[136] A. Tsatsos,[136] S. Yuan,[136] G. Benelli,[137] X. Coubez,[137,y] D. Cutts,[137] M. Hadley,[137] U. Heintz,[137] J. M. Hogan,[137,jjjj] T. Kwon,[137] G. Landsberg,[137] K. T. Lau,[137] D. Li,[137] J. Luo,[137] M. Narain,[137] N. Pervan,[137] S. Sagir,[137,kkkk] F. Simpson,[137] W. Y. Wong,[137] X. Yan,[137] D. Yu,[137] W. Zhang,[137] S. Abbott,[138] J. Bonilla,[138] C. Brainerd,[138] R. Breedon,[138] M. Calderon De La Barca Sanchez,[138] M. Chertok,[138] J. Conway,[138] P. T. Cox,[138] R. Erbacher,[138] G. Haza,[138] F. Jensen,[138] O. Kukral,[138] G. Mocellin,[138] M. Mulhearn,[138] D. Pellett,[138] B. Regnery,[138] Y. Yao,[138] F. Zhang,[138] M. Bachtis,[139] R. Cousins,[139] A. Datta,[139] J. Hauser,[139] M. Ignatenko,[139] M. A. Iqbal,[139] T. Lam,[139] E. Manca,[139] W. A. Nash,[139] D. Saltzberg,[139] B. Stone,[139] V. Valuev,[139] R. Clare,[140] J. W. Gary,[140] M. Gordon,[140] G. Hanson,[140] O. R. Long,[140] N. Manganelli,[140] W. Si,[140] S. Wimpenny,[140] J. G. Branson,[141] S. Cittolin,[141] S. Cooperstein,[141] D. Diaz,[141] J. Duarte,[141] R. Gerosa,[141] L. Giannini,[141] J. Guiang,[141] R. Kansal,[141] V. Krutelyov,[141] R. Lee,[141] J. Letts,[141] M. Masciovecchio,[141] F. Mokhtar,[141] M. Pieri,[141] M. Quinnan,[141] B. V. Sathia Narayanan,[141] V. Sharma,[141] M. Tadel,[141] E. Vourliotis,[141] F. Würthwein,[141] Y. Xiang,[141] A. Yagil,[141] N. Amin,[142] C. Campagnari,[142] M. Citron,[142] G. Collura,[142] A. Dorsett,[142] J. Incandela,[142] M. Kilpatrick,[142] J. Kim,[142] A. J. Li,[142] P. Masterson,[142] H. Mei,[142] M. Oshiro,[142] J. Richman,[142] U. Sarica,[142] R. Schmitz,[142] F. Setti,[142] J. Sheplock,[142] P. Siddireddy,[142] D. Stuart,[142] S. Wang,[142] A. Bornheim,[143] O. Cerri,[143] I. Dutta,[143] A. Latorre,[143] J. M. Lawhorn,[143] J. Mao,[143] H. B. Newman,[143] T. Q. Nguyen,[143] M. Spiropulu,[143] J. R. Vlimant,[143] C. Wang,[143] S. Xie,[143] R. Y. Zhu,[143] J. Alison,[144] S. An,[144] M. B. Andrews,[144] P. Bryant,[144] V. Dutta,[144] T. Ferguson,[144] A. Harilal,[144] C. Liu,[144] T. Mudholkar,[144] S. Murthy,[144] M. Paulini,[144] A. Roberts,[144] A. Sanchez,[144] W. Terrill,[144] J. P. Cumalat,[145] W. T. Ford,[145] A. Hassani,[145] G. Karathanasis,[145] E. MacDonald,[145] F. Marini,[145] A. Perloff,[145] C. Savard,[145] N. Schonbeck,[145] K. Stenson,[145] K. A. Ulmer,[145] S. R. Wagner,[145] N. Zipper,[145] J. Alexander,[146] S. Bright-Thonney,[146] X. Chen,[146] D. J. Cranshaw,[146] J. Fan,[146] X. Fan,[146] D. Gadkari,[146] S. Hogan,[146] J. Monroy,[146] J. R. Patterson,[146] J. Reichert,[146] M. Reid,[146] A. Ryd,[146] J. Thom,[146] P. Wittich,[146] R. Zou,[146] M. Albrow,[147] M. Alyari,[147] G. Apollinari,[147] A. Apresyan,[147] L. A. T. Bauerdick,[147] D. Berry,[147] J. Berryhill,[147] P. C. Bhat,[147] K. Burkett,[147] J. N. Butler,[147] A. Canepa,[147] G. B. Cerati,[147] H. W. K. Cheung,[147] F. Chlebana,[147] K. F. Di Petrillo,[147] J. Dickinson,[147] V. D. Elvira,[147] Y. Feng,[147] J. Freeman,[147] A. Gandrakota,[147] Z. Gecse,[147] L. Gray,[147] D. Green,[147] S. Grünendahl,[147] D. Guerrero,[147] O. Gutsche,[147] R. M. Harris,[147] R. Heller,[147] T. C. Herwig,[147] J. Hirschauer,[147] L. Horyn,[147] B. Jayatilaka,[147] S. Jindariani,[147] M. Johnson,[147] U. Joshi,[147] T. Klijnsma,[147] B. Klima,[147] K. H. M. Kwok,[147] S. Lammel,[147] D. Lincoln,[147] R. Lipton,[147] T. Liu,[147] C. Madrid,[147] K. Maeshima,[147] C. Mantilla,[147] D. Mason,[147] P. McBride,[147] P. Merkel,[147] S. Mrenna,[147] S. Nahn,[147] J. Ngadiuba,[147] D. Noonan,[147] S. Norberg,[147]

V. Papadimitriou,[147] N. Pastika,[147] K. Pedro,[147] C. Pena,[147,llll] F. Ravera,[147] A. Reinsvold Hall,[147,mmmm] L. Ristori,[147] E. Sexton-Kennedy,[147] N. Smith,[147] A. Soha,[147] L. Spiegel,[147] S. Stoynev,[147] J. Strait,[147] L. Taylor,[147] S. Tkaczyk,[147] N. V. Tran,[147] L. Uplegger,[147] E. W. Vaandering,[147] I. Zoi,[147] P. Avery,[148] D. Bourilkov,[148] L. Cadamuro,[148] P. Chang,[148] V. Cherepanov,[148] R. D. Field,[148] E. Koenig,[148] M. Kolosova,[148] J. Konigsberg,[148] A. Korytov,[148] E. Kuznetsova,[148] K. H. Lo,[148] K. Matchev,[148] N. Menendez,[148] G. Mitselmakher,[148] A. Muthirakalayil Madhu,[148] N. Rawal,[148] D. Rosenzweig,[148] S. Rosenzweig,[148] K. Shi,[148] J. Wang,[148] Z. Wu,[148] T. Adams,[149] A. Askew,[149] N. Bower,[149] R. Habibullah,[149] V. Hagopian,[149] T. Kolberg,[149] G. Martinez,[149] H. Prosper,[149] O. Viazlo,[149] M. Wulansatiti,[149] R. Yohay,[149] J. Zhang,[149] M. M. Baarmand,[150] S. Butalla,[150] T. Elkafrawy,[150,p] M. Hohlmann,[150] R. Kumar Verma,[150] M. Rahmani,[150] F. Yumiceva,[150] M. R. Adams,[151] R. Cavanaugh,[151] S. Dittmer,[151] O. Evdokimov,[151] C. E. Gerber,[151] D. J. Hofman,[151] D. S. Lemos,[151] A. H. Merrit,[151] C. Mills,[151] G. Oh,[151] T. Roy,[151] S. Rudrabhatla,[151] M. B. Tonjes,[151] N. Varelas,[151] X. Wang,[151] Z. Ye,[151] J. Yoo,[151] M. Alhusseini,[152] K. Dilsiz,[152,nnnn] L. Emediato,[152] G. Karaman,[152] O. K. Köseyan,[152] J.-P. Merlo,[152] A. Mestvirishvili,[152,oooo] J. Nachtman,[152] O. Neogi,[152] H. Ogul,[152,pppp] Y. Onel,[152] A. Penzo,[152] C. Snyder,[152] E. Tiras,[152,qqqq] O. Amram,[153] B. Blumenfeld,[153] L. Corcodilos,[153] J. Davis,[153] A. V. Gritsan,[153] S. Kyriacou,[153] P. Maksimovic,[153] J. Roskes,[153] S. Sekhar,[153] M. Swartz,[153] T. Á. Vámi,[153] A. Abreu,[154] L. F. Alcerro Alcerro,[154] J. Anguiano,[154] P. Baringer,[154] A. Bean,[154] Z. Flowers,[154] J. King,[154] G. Krintiras,[154] M. Lazarovits,[154] C. Le Mahieu,[154] C. Lindsey,[154] J. Marquez,[154] N. Minafra,[154] M. Murray,[154] M. Nickel,[154] C. Rogan,[154] C. Royon,[154] R. Salvatico,[154] S. Sanders,[154] C. Smith,[154] Q. Wang,[154] G. Wilson,[154] B. Allmond,[155] S. Duric,[155] A. Ivanov,[155] K. Kaadze,[155] A. Kalogeropoulos,[155] D. Kim,[155] Y. Maravin,[155] T. Mitchell,[155] A. Modak,[155] K. Nam,[155] D. Roy,[155] F. Rebassoo,[156] D. Wright,[156] E. Adams,[157] A. Baden,[157] O. Baron,[157] A. Belloni,[157] A. Bethani,[157] S. C. Eno,[157] N. J. Hadley,[157] S. Jabeen,[157] R. G. Kellogg,[157] T. Koeth,[157] Y. Lai,[157] S. Lascio,[157] A. C. Mignerey,[157] S. Nabili,[157] C. Palmer,[157] C. Papageorgakis,[157] L. Wang,[157] K. Wong,[157] W. Busza,[158] I. A. Cali,[158] Y. Chen,[158] M. D'Alfonso,[158] J. Eysermans,[158] C. Freer,[158] G. Gomez-Ceballos,[158] M. Goncharov,[158] P. Harris,[158] M. Hu,[158] D. Kovalskyi,[158] J. Krupa,[158] Y.-J. Lee,[158] K. Long,[158] C. Mironov,[158] C. Paus,[158] D. Rankin,[158] C. Roland,[158] G. Roland,[158] Z. Shi,[158] G. S. F. Stephans,[158] J. Wang,[158] Z. Wang,[158] B. Wyslouch,[158] T. J. Yang,[158] R. M. Chatterjee,[159] B. Crossman,[159] J. Hiltbrand,[159] B. M. Joshi,[159] C. Kapsiak,[159] M. Krohn,[159] Y. Kubota,[159] D. Mahon,[159] J. Mans,[159] M. Revering,[159] R. Rusack,[159] R. Saradhy,[159] N. Schroeder,[159] N. Strobbe,[159] M. A. Wadud,[159] L. M. Cremaldi,[160] K. Bloom,[161] M. Bryson,[161] D. R. Claes,[161] C. Fangmeier,[161] L. Finco,[161] F. Golf,[161] C. Joo,[161] R. Kamalieddin,[161] I. Kravchenko,[161] I. Reed,[161] J. E. Siado,[161] G. R. Snow,[161,a] W. Tabb,[161] A. Wightman,[161] F. Yan,[161] A. G. Zecchinelli,[161] G. Agarwal,[162] H. Bandyopadhyay,[162] L. Hay,[162] I. Iashvili,[162] A. Kharchilava,[162] C. McLean,[162] M. Morris,[162] D. Nguyen,[162] J. Pekkanen,[162] S. Rappoccio,[162] A. Williams,[162] G. Alverson,[163] E. Barberis,[163] Y. Haddad,[163] Y. Han,[163] A. Krishna,[163] J. Li,[163] J. Lidrych,[163] G. Madigan,[163] B. Marzocchi,[163] D. M. Morse,[163] V. Nguyen,[163] T. Orimoto,[163] A. Parker,[163] L. Skinnari,[163] A. Tishelman-Charny,[163] T. Wamorkar,[163] B. Wang,[163] A. Wisecarver,[163] D. Wood,[163] S. Bhattacharya,[164] J. Bueghly,[164] Z. Chen,[164] A. Gilbert,[164] K. A. Hahn,[164] Y. Liu,[164] N. Odell,[164] M. H. Schmitt,[164] M. Velasco,[164] R. Band,[165] R. Bucci,[165] M. Cremonesi,[165] A. Das,[165] R. Goldouzian,[165] M. Hildreth,[165] K. Hurtado Anampa,[165] C. Jessop,[165] K. Lannon,[165] J. Lawrence,[165] N. Loukas,[165] L. Lutton,[165] J. Mariano,[165] N. Marinelli,[165] I. Mcalister,[165] T. McCauley,[165] C. Mcgrady,[165] K. Mohrman,[165] C. Moore,[165] Y. Musienko,[165,m] R. Ruchti,[165] A. Townsend,[165] M. Wayne,[165] H. Yockey,[165] M. Zarucki,[165] L. Zygala,[165] B. Bylsma,[166] M. Carrigan,[166] L. S. Durkin,[166] C. Hill,[166] M. Joyce,[166] A. Lesauvage,[166] M. Nunez Ornelas,[166] K. Wei,[166] B. L. Winer,[166] B. R. Yates,[166] F. M. Addesa,[167] P. Das,[167] G. Dezoort,[167] P. Elmer,[167] A. Frankenthal,[167] B. Greenberg,[167] N. Haubrich,[167] S. Higginbotham,[167] G. Kopp,[167] S. Kwan,[167] D. Lange,[167] A. Loeliger,[167] D. Marlow,[167] I. Ojalvo,[167] J. Olsen,[167] D. Stickland,[167] C. Tully,[167] S. Malik,[168] A. S. Bakshi,[169] V. E. Barnes,[169] R. Chawla,[169] S. Das,[169] L. Gutay,[169] M. Jones,[169] A. W. Jung,[169] D. Kondratyev,[169] A. M. Koshy,[169] M. Liu,[169] G. Negro,[169] N. Neumeister,[169] G. Paspalaki,[169] S. Piperov,[169] A. Purohit,[169] J. F. Schulte,[169] M. Stojanovic,[169] J. Thieman,[169] A. K. Virdi,[169] F. Wang,[169] R. Xiao,[169] W. Xie,[169] J. Dolen,[170] N. Parashar,[170] D. Acosta,[171] A. Baty,[171] T. Carnahan,[171] S. Dildick,[171] K. M. Ecklund,[171] P. J. Fernández Manteca,[171] S. Freed,[171] P. Gardner,[171] F. J. M. Geurts,[171] A. Kumar,[171] W. Li,[171]

B. P. Padley,[171] R. Redjimi,[171] J. Rotter,[171] S. Yang,[171] E. Yigitbasi,[171] Y. Zhang,[171] A. Bodek,[172] P. de Barbaro,[172] R. Demina,[172] J. L. Dulemba,[172] C. Fallon,[172] A. Garcia-Bellido,[172] O. Hindrichs,[172] A. Khukhunaishvili,[172] P. Parygin,[172] E. Popova,[172] R. Taus,[172] G. P. Van Onsem,[172] K. Goulianos,[173] B. Chiarito,[174] J. P. Chou,[174] Y. Gershtein,[174] E. Halkiadakis,[174] A. Hart,[174] M. Heindl,[174] D. Jaroslawski,[174] O. Karacheban,[174,bb] I. Laflotte,[174] A. Lath,[174] R. Montalvo,[174] K. Nash,[174] M. Osherson,[174] H. Routray,[174] S. Salur,[174] S. Schnetzer,[174] S. Somalwar,[174] R. Stone,[174] S. A. Thayil,[174] S. Thomas,[174] H. Wang,[174] H. Acharya,[175] A. G. Delannoy,[175] S. Fiorendi,[175] T. Holmes,[175] E. Nibigira,[175] S. Spanier,[175] O. Bouhali,[176,rrrr] M. Dalchenko,[176] A. Delgado,[176] R. Eusebi,[176] J. Gilmore,[176] T. Huang,[176] T. Kamon,[176,ssss] H. Kim,[176] S. Luo,[176] S. Malhotra,[176] R. Mueller,[176] D. Overton,[176] D. Rathjens,[176] A. Safonov,[176] N. Akchurin,[177] J. Damgov,[177] V. Hegde,[177] K. Lamichhane,[177] S. W. Lee,[177] T. Mengke,[177] S. Muthumuni,[177] T. Peltola,[177] I. Volobouev,[177] A. Whitbeck,[177] E. Appelt,[178] S. Greene,[178] A. Gurrola,[178] W. Johns,[178] A. Melo,[178] F. Romeo,[178] P. Sheldon,[178] S. Tuo,[178] J. Velkovska,[178] J. Viinikainen,[178] B. Cardwell,[179] B. Cox,[179] G. Cummings,[179] J. Hakala,[179] R. Hirosky,[179] A. Ledovskoy,[179] A. Li,[179] C. Neu,[179] C. E. Perez Lara,[179] P. E. Karchin,[180] A. Aravind,[181] S. Banerjee,[181] K. Black,[181] T. Bose,[181] S. Dasu,[181] I. De Bruyn,[181] P. Everaerts,[181] C. Galloni,[181] H. He,[181] M. Herndon,[181] A. Herve,[181] C. K. Koraka,[181] A. Lanaro,[181] R. Loveless,[181] J. Madhusudanan Sreekala,[181] A. Mallampalli,[181] A. Mohammadi,[181] S. Mondal,[181] G. Parida,[181] D. Pinna,[181] A. Savin,[181] V. Shang,[181] V. Sharma,[181] W. H. Smith,[181] D. Teague,[181] H. F. Tsoi,[181] W. Vetens,[181] A. Warden,[181] S. Afanasiev,[182] V. Andreev,[182] Yu. Andreev,[182] T. Aushev,[182] M. Azarkin,[182] A. Babaev,[182] A. Belyaev,[182] V. Blinov,[182,m] E. Boos,[182] V. Borshch,[182] D. Budkouski,[182] V. Chekhovsky,[182] R. Chistov,[182,m] M. Danilov,[182,m] A. Dermenev,[182] T. Dimova,[182,m] I. Dremin,[182] M. Dubinin,[182,llll] L. Dudko,[182] V. Epshteyn,[182] A. Ershov,[182] G. Gavrilov,[182] V. Gavrilov,[182] S. Gninenko,[182] V. Golovtcov,[182] N. Golubev,[182] I. Golutvin,[182] I. Gorbunov,[182] A. Gribushin,[182] Y. Ivanov,[182] V. Kachanov,[182] L. Kardapoltsev,[182,m] V. Karjavine,[182] A. Karneyeu,[182] V. Kim,[182,m] M. Kirakosyan,[182] D. Kirpichnikov,[182] M. Kirsanov,[182] V. Klyukhin,[182] O. Kodolova,[182,tttt] D. Konstantinov,[182] V. Korenkov,[182] A. Kozyrev,[182,m] N. Krasnikov,[182] A. Lanev,[182] P. Levchenko,[182] A. Litomin,[182] N. Lychkovskaya,[182] V. Makarenko,[182] A. Malakhov,[182] V. Matveev,[182,m] V. Murzin,[182] A. Nikitenko,[182,tttt,uuuu] S. Obraztsov,[182] I. Ovtin,[182,m] V. Palichik,[182] V. Perelygin,[182] S. Petrushanko,[182] S. Polikarpov,[182,m] V. Popov,[182] O. Radchenko,[182,m] M. Savina,[182] V. Savrin,[182] D. Selivanova,[182] V. Shalaev,[182] S. Shmatov,[182] S. Shulha,[182] Y. Skovpen,[182,m] S. Slabospitskii,[182] V. Smirnov,[182] A. Snigirev,[182] D. Sosnov,[182] V. Sulimov,[182] E. Tcherniaev,[182] A. Terkulov,[182] O. Teryaev,[182] I. Tlisova,[182] A. Toropin,[182] L. Uvarov,[182] A. Uzunian,[182] A. Vorobyev,[182,a] N. Voytishin,[182] B. S. Yuldashev,[182,vvvv] A. Zarubin,[182] I. Zhizhin,[182] and A. Zhokin[182]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

[18]*Sun Yat-Sen University, Guangzhou, China*
[19]*University of Science and Technology of China, Hefei, China*
[20]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China*
[21]*Zhejiang University, Hangzhou, Zhejiang, China*
[22]*Universidad de Los Andes, Bogota, Colombia*
[23]*Universidad de Antioquia, Medellin, Colombia*
[24]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[25]*University of Split, Faculty of Science, Split, Croatia*
[26]*Institute Rudjer Boskovic, Zagreb, Croatia*
[27]*University of Cyprus, Nicosia, Cyprus*
[28]*Charles University, Prague, Czech Republic*
[29]*Escuela Politecnica Nacional, Quito, Ecuador*
[30]*Universidad San Francisco de Quito, Quito, Ecuador*
[31]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[32]*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
[33]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[34]*Department of Physics, University of Helsinki, Helsinki, Finland*
[35]*Helsinki Institute of Physics, Helsinki, Finland*
[36]*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
[37]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[38]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[39]*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
[40]*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
[41]*Georgian Technical University, Tbilisi, Georgia*
[42]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
[43]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[44]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
[45]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[46]*University of Hamburg, Hamburg, Germany*
[47]*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
[48]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
[49]*National and Kapodistrian University of Athens, Athens, Greece*
[50]*National Technical University of Athens, Athens, Greece*
[51]*University of Ioánnina, Ioánnina, Greece*
[52]*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[53]*Wigner Research Centre for Physics, Budapest, Hungary*
[54]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[55]*Institute of Physics, University of Debrecen, Debrecen, Hungary*
[56]*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[57]*Panjab University, Chandigarh, India*
[58]*University of Delhi, Delhi, India*
[59]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[60]*Indian Institute of Technology Madras, Madras, India*
[61]*Bhabha Atomic Research Centre, Mumbai, India*
[62]*Tata Institute of Fundamental Research-A, Mumbai, India*
[63]*Tata Institute of Fundamental Research-B, Mumbai, India*
[64]*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
[65]*Indian Institute of Science Education and Research (IISER), Pune, India*
[66]*Isfahan University of Technology, Isfahan, Iran*
[67]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[68]*University College Dublin, Dublin, Ireland*
[69]*INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy*
[69a]*INFN Sezione di Bari, Bari, Italy*
[69b]*Università di Bari, Bari, Italy*
[69c]*Politecnico di Bari, Bari, Italy*
[70a]*INFN Sezione di Bologna, Bologna, Italy*
[70b]*Università di Bologna, Bologna, Italy*

[71a]INFN Sezione di Catania, Catania, Italy
[71b]Università di Catania, Catania, Italy
[72a]INFN Sezione di Firenze, Firenze, Italy
[72b]Università di Firenze, Firenze, Italy
[73]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[74a]INFN Sezione di Genova, Genova, Italy
[74b]Università di Genova, Genova, Italy
[75a]INFN Sezione di Milano-Bicocca, Milano, Italy
[75b]Università di Milano-Bicocca, Milano, Italy
[76a]INFN Sezione di Napoli, Napoli, Italy
[76b]Università di Napoli 'Federico II', Napoli, Italy
[76c]Università della Basilicata, Potenza, Italy
[76d]Università G. Marconi, Roma, Italy
[77a]INFN Sezione di Padova, Padova, Italy
[77b]Università di Padova, Padova, Italy
[77c]Università di Trento, Trento, Italy
[78a]INFN Sezione di Pavia, Pavia, Italy
[78b]Università di Pavia, Pavia, Italy
[79a]INFN Sezione di Perugia, Perugia, Italy
[79b]Università di Perugia, Perugia, Italy
[80a]INFN Sezione di Pisa, Pisa, Italy
[80b]Università di Pisa, Pisa, Italy
[80c]Scuola Normale Superiore di Pisa, Pisa, Italy
[80d]Università di Siena, Siena, Italy
[81a]INFN Sezione di Roma, Roma, Italy
[81b]Sapienza Università di Roma, Roma, Italy
[82a]INFN Sezione di Torino, Torino, Italy
[82b]Università di Torino, Torino, Italy
[82c]Università del Piemonte Orientale, Novara, Italy
[83a]INFN Sezione di Trieste, Trieste, Italy
[83b]Università di Trieste, Trieste, Italy
[84]Kyungpook National University, Daegu, Korea
[85]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[86]Hanyang University, Seoul, Korea
[87]Korea University, Seoul, Korea
[88]Kyung Hee University, Department of Physics, Seoul, Korea
[89]Sejong University, Seoul, Korea
[90]Seoul National University, Seoul, Korea
[91]University of Seoul, Seoul, Korea
[92]Yonsei University, Department of Physics, Seoul, Korea
[93]Sungkyunkwan University, Suwon, Korea
[94]College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
[95]Riga Technical University, Riga, Latvia
[96]Vilnius University, Vilnius, Lithuania
[97]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[98]Universidad de Sonora (UNISON), Hermosillo, Mexico
[99]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[100]Universidad Iberoamericana, Mexico City, Mexico
[101]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[102]University of Montenegro, Podgorica, Montenegro
[103]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[104]AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
[105]National Centre for Nuclear Research, Swierk, Poland
[106]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[107]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[108]VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[109]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[110]Universidad Autónoma de Madrid, Madrid, Spain
[111]Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
[112]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

[113]*University of Colombo, Colombo, Sri Lanka*
[114]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[115]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[116]*Paul Scherrer Institut, Villigen, Switzerland*
[117]*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[118]*Universität Zürich, Zurich, Switzerland*
[119]*National Central University, Chung-Li, Taiwan*
[120]*National Taiwan University (NTU), Taipei, Taiwan*
[121]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[122]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[123]*Middle East Technical University, Physics Department, Ankara, Turkey*
[124]*Bogazici University, Istanbul, Turkey*
[125]*Istanbul Technical University, Istanbul, Turkey*
[126]*Istanbul University, Istanbul, Turkey*
[127]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
[128]*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
[129]*University of Bristol, Bristol, United Kingdom*
[130]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[131]*Imperial College, London, United Kingdom*
[132]*Brunel University, Uxbridge, United Kingdom*
[133]*Baylor University, Waco, Texas, USA*
[134]*Catholic University of America, Washington, DC, USA*
[135]*The University of Alabama, Tuscaloosa, Alabama, USA*
[136]*Boston University, Boston, Massachusetts, USA*
[137]*Brown University, Providence, Rhode Island, USA*
[138]*University of California, Davis, Davis, California, USA*
[139]*University of California, Los Angeles, California, USA*
[140]*University of California, Riverside, Riverside, California, USA*
[141]*University of California, San Diego, La Jolla, California, USA*
[142]*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
[143]*California Institute of Technology, Pasadena, California, USA*
[144]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[145]*University of Colorado Boulder, Boulder, Colorado, USA*
[146]*Cornell University, Ithaca, New York, USA*
[147]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[148]*University of Florida, Gainesville, Florida, USA*
[149]*Florida State University, Tallahassee, Florida, USA*
[150]*Florida Institute of Technology, Melbourne, Florida, USA*
[151]*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
[152]*The University of Iowa, Iowa City, Iowa, USA*
[153]*Johns Hopkins University, Baltimore, Maryland, USA*
[154]*The University of Kansas, Lawrence, Kansas, USA*
[155]*Kansas State University, Manhattan, Kansas, USA*
[156]*Lawrence Livermore National Laboratory, Livermore, California, USA*
[157]*University of Maryland, College Park, Maryland, USA*
[158]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[159]*University of Minnesota, Minneapolis, Minnesota, USA*
[160]*University of Mississippi, Oxford, Mississippi, USA*
[161]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[162]*State University of New York at Buffalo, Buffalo, New York, USA*
[163]*Northeastern University, Boston, Massachusetts, USA*
[164]*Northwestern University, Evanston, Illinois, USA*
[165]*University of Notre Dame, Notre Dame, Indiana, USA*
[166]*The Ohio State University, Columbus, Ohio, USA*
[167]*Princeton University, Princeton, New Jersey, USA*
[168]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[169]*Purdue University, West Lafayette, Indiana, USA*
[170]*Purdue University Northwest, Hammond, Indiana, USA*
[171]*Rice University, Houston, Texas, USA*
[172]*University of Rochester, Rochester, New York, USA*

[173]*The Rockefeller University, New York, New York, USA*
[174]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[175]*University of Tennessee, Knoxville, Tennessee, USA*
[176]*Texas A&M University, College Station, Texas, USA*
[177]*Texas Tech University, Lubbock, Texas, USA*
[178]*Vanderbilt University, Nashville, Tennessee, USA*
[179]*University of Virginia, Charlottesville, Virginia, USA*
[180]*Wayne State University, Detroit, Michigan, USA*
[181]*University of Wisconsin - Madison, Madison, Wisconsin, USA*
[182]*An institute or international laboratory covered by a cooperation agreement with CERN*

[a]Deceased.
[b]Also at Yerevan State University, Yerevan, Armenia.
[c]Also at TU Wien, Vienna, Austria.
[d]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[e]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[h]Also at UFMS, Nova Andradina, Brazil.
[i]Also at University of Chinese Academy of Sciences, Beijing, China.
[j]Also at Nanjing Normal University Department of Physics, Nanjing, China.
[k]Also at The University of Iowa, Iowa City, Iowa, USA.
[l]Also at University of Chinese Academy of Sciences, Beijing, China.
[m]Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
[n]Also at Helwan University, Cairo, Egypt.
[o]Also at Zewail City of Science and Technology, Zewail, Egypt.
[p]Also at Ain Shams University, Cairo, Egypt.
[q]Also at British University in Egypt, Cairo, Egypt.
[r]Also at Purdue University, West Lafayette, Indiana, USA.
[s]Also at Université de Haute Alsace, Mulhouse, France.
[t]Also at Department of Physics, Tsinghua University, Beijing, China.
[u]Also at Tbilisi State University, Tbilisi, Georgia.
[v]Also at The University of the State of Amazonas, Manaus, Brazil.
[w]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[x]Also at University of Hamburg, Hamburg, Germany.
[y]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[z]Also at Isfahan University of Technology, Isfahan, Iran.
[aa]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[bb]Also at Brandenburg University of Technology, Cottbus, Germany.
[cc]Also at Forschungszentrum Jülich, Juelich, Germany.
[dd]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[ee]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[ff]Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
[gg]Also at Wigner Research Centre for Physics, Budapest, Hungary.
[hh]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[ii]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[jj]Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[kk]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[ll]Also at Punjab Agricultural University, Ludhiana, India.
[mm]Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
[nn]Also at University of Visva-Bharati, Santiniketan, India.
[oo]Also at University of Hyderabad, Hyderabad, India.
[pp]Also at Indian Institute of Science (IISc), Bangalore, India.
[qq]Also at Indian Institute of Technology (IIT), Mumbai, India.
[rr]Also at IIT Bhubaneswar, Bhubaneswar, India.
[ss]Also at Institute of Physics, Bhubaneswar, India.
[tt]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[uu]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[vv]Also at Sharif University of Technology, Tehran, Iran.

[ww]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[xx]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[yy]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[zz]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[aaa]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[bbb]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[ccc]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[ddd]Also at Università di Napoli 'Federico II', Napoli, Italy.
[eee]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[fff]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[ggg]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[hhh]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[iii]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[jjj]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[kkk]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[lll]Also at National and Kapodistrian University of Athens, Athens, Greece.
[mmm]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[nnn]Also at Universität Zürich, Zurich, Switzerland.
[ooo]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[ppp]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[qqq]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[rrr]Also at Konya Technical University, Konya, Turkey.
[sss]Also at Izmir Bakircay University, Izmir, Turkey.
[ttt]Also at Adiyaman University, Adiyaman, Turkey.
[uuu]Also at Istanbul Gedik University, Istanbul, Turkey.
[vvv]Also at Necmettin Erbakan University, Konya, Turkey.
[www]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[xxx]Also at Marmara University, Istanbul, Turkey.
[yyy]Also at Milli Savunma University, Istanbul, Turkey.
[zzz]Also at Kafkas University, Kars, Turkey.
[aaaa]Also at Hacettepe University, Ankara, Turkey.
[bbbb]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[cccc]Also at Yildiz Technical University, Istanbul, Turkey.
[dddd]Also at Vrije Universiteit Brussel, Brussel, Belgium.
[eeee]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[ffff]Also at University of Bristol, Bristol, United Kingdom.
[gggg]Also at IPPP Durham University, Durham, United Kingdom.
[hhhh]Also at Monash University, Faculty of Science, Clayton, Australia.
[iiii]Also at Università di Torino, Torino, Italy.
[jjjj]Also at Bethel University, St. Paul, Minnesota, USA.
[kkkk]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[llll]Also at California Institute of Technology, Pasadena, California, USA.
[mmmm]Also at United States Naval Academy, Annapolis, Maryland, USA.
[nnnn]Also at Bingol University, Bingol, Turkey.
[oooo]Also at Georgian Technical University, Tbilisi, Georgia.
[pppp]Also at Sinop University, Sinop, Turkey.
[qqqq]Also at Erciyes University, Kayseri, Turkey.
[rrrr]Also at Texas A&M University at Qatar, Doha, Qatar.
[ssss]Also at Kyungpook National University, Daegu, Korea.
[tttt]Also at Yerevan Physics Institute, Yerevan, Armenia.
[uuuu]Also at Imperial College, London, United Kingdom.
[vvvv]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.