EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2025-162
2025/08/11

CMS-BPH-24-011

First exclusive reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} mesons and precise measurement of their masses

The CMS Collaboration*

Abstract

Using proton-proton collision data collected by the CMS experiment at $\sqrt{s} = 13\,\mathrm{TeV}$ in 2016–2018, corresponding to an integrated luminosity of $140\,\mathrm{fb}^{-1}$, the first full reconstruction of the three vector B meson states, B^{*+}, B^{*0}, and B_s^{*0}, is performed. The mass differences between the excited mesons and their corresponding ground states are measured to be $m(B^{*+}) - m(B^{+}) = 45.277 \pm 0.039 \pm 0.027\,\mathrm{MeV}$, $m(B^{*0}) - m(B^{0}) = 45.471 \pm 0.056 \pm 0.028\,\mathrm{MeV}$, and $m(B_s^{*0}) - m(B_s^{0}) = 49.407 \pm 0.132 \pm 0.041\,\mathrm{MeV}$, where the first uncertainties are statistical and the second are systematic. These results improve on the precision of previous measurements by an order of magnitude.

Submitted to Physical Review Letters

*See Appendix D for the list of collaboration members

While the ground states of beauty mesons B^+, B^0, and B^0_s have been extensively studied, the corresponding excited vector mesons B^{*+}, B^{*0}, and B^{*0}_s are much less explored. The main challenge in the reconstruction of these excited states stems from the low-energy (40–50 MeV) photons emitted in $B^* \to B\gamma$ decays, with the energy below the detection thresholds in most experiments. Throughout this Letter, B^* corresponds to one of the B^{*+}, B^{*0}, or B^{*0}_s mesons, and B refers to one of the B^+, B^0, or B^0_s mesons; the inclusion of charge-conjugate states is implied. About 30 years ago, the four LEP experiments combined b jets with photons reconstructed from their conversions into e^+e^- pairs to measure the flavor-averaged mass difference $m(B^*) - m(B)$ [1–4], also known as the hyperfine splitting. Studies of the P-wave B^0_s mesons decaying into B^+K^- and $B^{*+}K^-$ by the LHCb and CMS experiments [5, 6], as well as to $B^0K^0_S$ and $B^{*0}K^0_S$ by CMS [6], provided the measurements of the mass differences $m(B^{*+}) - m(B^+)$ and $m(B^{*0}) - m(B^{*+})$ without reconstructing low-energy photons. Measurements at the dedicated B physics experiments CLEO and Belle, at the $\Upsilon(10860)$ energy, allowed indirect estimates of the B^{*0}_s meson mass [7, 8]; however, these two results are in tension with each other. Measurements of the properties of excited B mesons provide an important input to our understanding of the quantum chromodynamics (QCD) mechanisms responsible for quark dynamics and the formation of hadrons. In particular, precise measurements of the hyperfine splitting in the B meson system are an important input for quark models of hadrons [9–11].

In this Letter, the first exclusive reconstruction of the three excited vector mesons B^{*+}, B^{*0}, and B^{*0}_s, is presented. The analysis is performed using proton-proton (pp) collision data recorded by the CMS experiment during LHC Run 2 in 2016–2018 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 140 fb^{-1} [12–14]. Low-energy photons are reconstructed through their conversions into e^+e^- pairs in the beam pipe and detector material. Ground-state B mesons are reconstructed using the decays $B^+ \to \psi K^+$, $B^0 \to \psi K^{*0}$, and $B^0_s \to \psi\phi$, where ψ stands for the J/ψ and $\psi(2S)$ mesons detected using their decays to $\mu^+\mu^-$, and K^{*0} and ϕ refer to the $K^*(892)^0$ and $\phi(1020)$ mesons, reconstructed through their decays to $K^+\pi^-$ and K^+K^-, respectively. Tabulated results are provided in the HEPData record for this analysis [15].

The CMS apparatus [16, 17] is a multipurpose, nearly hermetic detector, designed to trigger on [18–20] and identify electrons, muons, photons, and charged and neutral hadrons [21–23]. A global "particle-flow" algorithm [24] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The procedure followed for aligning the detector is described in Ref. [25]. An improved pixel detector was installed before the 2017 data taking began [26].

Events of interest are selected using a two-tiered trigger system [18]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [19]. The second level, known as the high-level trigger (HLT), consists of a farm of computing processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. The events used in this analysis were selected at L1 by requiring the presence of at least two muons, and at the HLT by requiring two opposite-sign (OS) muons, with various pseudorapidity (η) and transverse momentum (p_T) thresholds, compatible with being produced in dimuon decays of either the J/ψ or $\psi(2S)$ meson.

The offline reconstruction requires two OS muons that form a vertex with fit χ^2 probability $P_{vtx} > 1\%$, each satisfying $p_T > 3.5$ GeV and $|\eta| < 2.5$ requirements, and passing a special selection optimized for low-p_{T} muons [27]. The dimuon invariant mass $m(\mu^+\mu^-)$ must be within 2.9–3.4 GeV for the J/ψ decay channels, and 3.4–3.9 GeV for the ψ(2S) decays. To build B candidates, the selected ψ candidate is combined with one or two OS high-purity tracks [23] with $p_{\mathrm{T}} > 1\,\mathrm{GeV}$ that do not match the selected muons. For the $\mathrm{B}^+ \to \psi\mathrm{K}^+$ and $\mathrm{B}^0_\mathrm{s} \to \psi\phi$ selection, one or both tracks are assigned the charged kaon mass hypothesis, with an additional requirement of $1.01 < m(\mathrm{K}^+\mathrm{K}^-) < 1.03\,\mathrm{GeV}$ for the latter. For the $\mathrm{B}^0 \to \psi\mathrm{K}^*(892)^0$ selection, the $\mathrm{K}^+\pi^-$ or $\mathrm{K}^-\pi^+$ mass assignment is made based on which combination has an invariant mass closer to the world-average K^{*0} meson mass of $M^{\mathrm{PDG}}_{\mathrm{K}^{*0}} = 895.55\,\mathrm{MeV}$ [28], followed by the requirement $0.81 < m(\mathrm{K}^\pm\pi^\mp) < 0.97\,\mathrm{GeV}$. In addition, a $\phi \to \mathrm{K}^+\mathrm{K}^-$ veto is applied in the $\mathrm{B}^0 \to \psi\mathrm{K}^*(892)^0$ channel to ensure that the selected $\mathrm{B}^{*0}_\mathrm{s} \to \mathrm{B}^0_\mathrm{s}\gamma$ candidates do not contribute to the $\mathrm{B}^0\gamma$ sample.

The B^+ (B^0 and B^0_s) candidates are obtained via a 3-track (4-track) vertex fit of the selected muons and track(s), which constrains the dimuon invariant mass to the world-average J/ψ or ψ(2S) mass [28]. From all reconstructed pp collision points, the primary vertex (PV) is chosen as the one with the smallest B pointing angle, defined as the angle between the B candidate momentum and the vector connecting the PV and the reconstructed B candidate vertex. Furthermore, if any of the 3 or 4 tracks used in the B candidate reconstruction is included in the fit of the chosen PV, they are removed and the PV position is refitted. The B candidates are required to have $p_{\mathrm{T}}(\mathrm{B}) > 10\,\mathrm{GeV}$, $P_{\mathrm{vtx}}(\mathrm{B}) > 1\%$, transverse vertex displacement from PV $L_{xy}(\mathrm{B})$ larger than 3 times its uncertainty, two-dimensional pointing angle $\cos[\vec{L}_{xy}(\mathrm{B}), \vec{p}_{\mathrm{T}}(\mathrm{B})] > 0.999$, and invariant mass within twice the average mass resolution of the corresponding B meson world-average mass $M^{\mathrm{PDG}}_{\mathrm{B}}$ [28].

Photon conversion candidates are formed from two OS tracks with a small angular separation, a small distance of closest approach, a conversion vertex at least 1.5 cm away from the beam axis, and a χ^2 probability above 0.05% for a kinematic fit that constrains the two tracks to originate from a common vertex with an invariant mass of zero. More details on the selection criteria are given in Ref. [29]. Only photon candidates with $p_{\mathrm{T}} > 300\,\mathrm{MeV}$ and $|\eta| < 1.5$ are kept, since conversions at more forward pseudorapidity are reconstructed with a significantly worse resolution. To improve the resolution, the $\mathrm{B}\gamma$ invariant mass is evaluated using the expression $M(\mathrm{B}\gamma) = m(\mathrm{B}\gamma) - m(\mathrm{B}) + M^{\mathrm{PDG}}_{\mathrm{B}}$, where the B meson and the conversion photon four-momenta are taken from the kinematic vertex fit that constrains the B meson, the photon candidate, and all tracks forming the chosen PV, to originate from the same vertex [30–32].

The momenta of the e^+ and e^- tracks measured by the tracker tend to be lower than the true momenta because the electrons and positrons lose energy while traversing the tracker, which results in a measured photon energy lower on average than the true photon energy [29, 33]. A photon energy scale (PES) correction is performed using $\pi^0 \to \gamma\gamma$ decays reconstructed from two converted photons in several ranges of photon p_{T} and $|\eta|$. The energy correction factor in each range is given by the ratio between the nominal π^0 mass [28] and the mean π^0 mass in data obtained from fitting the $\gamma\gamma$ invariant mass distribution. The PES correction is 1.002–1.04 in the kinematic range relevant for this analysis, i.e., $p_{\mathrm{T}}(\gamma) < 1.5\,\mathrm{GeV}$. Appendix A contains example fits to the $\gamma\gamma$ invariant mass distribution before and after the PES correction.

The PYTHIA 8.240 package [35] with the CP5 underlying event tune [36] is used to simulate the B^* meson production. The EVTGEN 1.6.0 [37] program models the decays $\mathrm{B}^* \to \mathrm{B}\gamma$, $\mathrm{B}^+ \to \psi\mathrm{K}^+$, $\mathrm{B}^0 \to \psi\mathrm{K}^*(892)^0$, and $\mathrm{B}^0_\mathrm{s} \to \psi\phi$ followed by the $\psi \to \mu^+\mu^-$ decays [28]. Final-state photon radiation is described using PHOTOS 3.61 [38, 39]. The generated Monte Carlo (MC) events are then passed to a detailed GEANT4-based simulation [40] of the CMS detector. The simulated events are then processed by the same reconstruction algorithms as used for the collision data. The simulation includes the effects of multiple pp interactions in the same or nearby bunch crossings (pileup) with a multiplicity distribution matching that observed in data. The simulated p_T and $|\eta|$ distributions of all three B^* mesons were adjusted using the corresponding B^{*+} meson distributions measured in data.

The $B\gamma$ mass resolution is found to depend strongly on $|\eta(\gamma)|$, ranging from about 0.7 MeV at $|\eta(\gamma)|$ close to zero to about 2 MeV at $|\eta(\gamma)|$ around 1.5. To improve the accuracy of the B^* meson mass measurements, a simultaneous fit of the $B\gamma$ mass distributions in several categories, defined by ranges of $|\eta(\gamma)|$, is performed. Pseudo-experiments were used to obtain a set of optimal $|\eta(\gamma)|$ ranges for each meson flavor. The resulting simultaneous fit structure includes: three $|\eta(\gamma)|$ ranges with boundaries at 0, 0.6, 1.0, and 1.4 for the B^{*+} signal; two $|\eta(\gamma)|$ ranges with boundaries at 0, 0.9, and 1.5 for the B^{*0} signal, and two $|\eta(\gamma)|$ ranges with boundaries at 0, 0.8, and 1.4 for the B_s^{*0} signal.

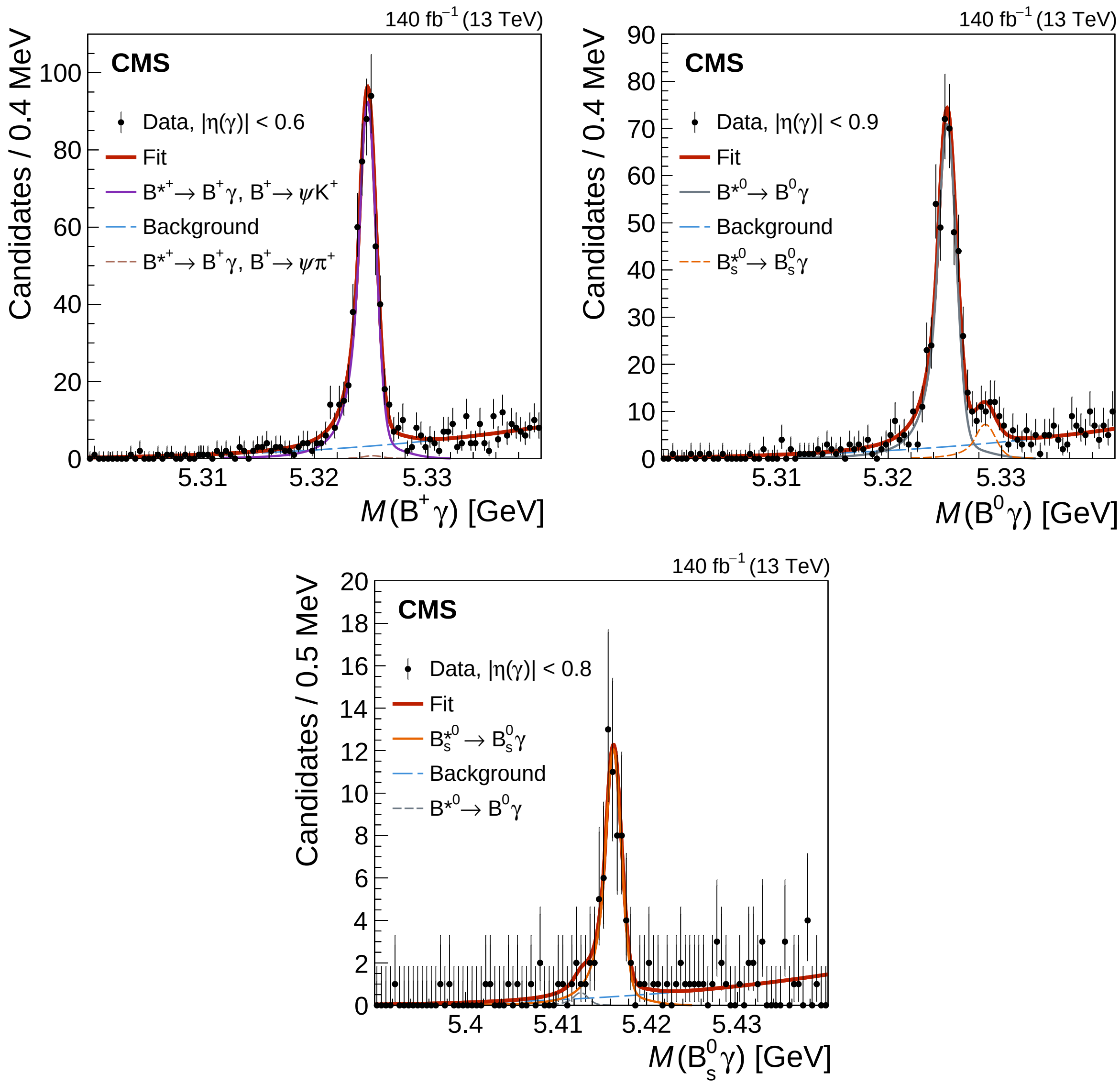

Figure 1: The measured distributions (filled circles) of the $B^+\gamma$ (upper left), $B^0\gamma$ (upper right), and $B_s^0\gamma$ (lower) invariant mass in the lowest $|\eta(\gamma)|$ range, which has the best invariant mass resolution. The simultaneous fit projections are shown with thick red lines, and the other components are described in the legends. The error bars represent statistical uncertainties in data.

The measured invariant mass distributions of the selected $B^+\gamma$, $B^0\gamma$, and $B^0_s\gamma$ candidates are shown in Fig. 1 for the three categories with the best invariant mass resolution and in Appendix B for the four remaining ones. A clear signal is seen in each of them. A simultaneous extended unbinned maximum likelihood fit to the seven distributions is performed. Each signal is described by the sum of two Crystal Ball (CB) [41] functions, with common mean and tail parameters n and α. The three mean values, which are free parameters of the fit, correspond to the measured masses of the B^{*+}, B^{*0}, and B^{*0}_s mesons. The parameters n, α, and the relative contribution of the two CB functions (f) are fixed to the ones obtained from simulation. The widths of the CB functions (σ_1, σ_2) are multiplied by a common scale factor, which is a free parameter, to account for a possible data-simulation difference in the mass resolution. For the B^{*0} (B^{*0}_s) signals, the yield in the high $|\eta(\gamma)|$ range is set to be 41% (49%) of the yield in the low $|\eta(\gamma)|$ range, as found in simulation. No such constraint is applied to the B^{*+} signal since it has been used to correct the p_T and $|\eta|$ distributions in simulation. The peaking contribution from the Cabibbo-suppressed $B^+ \to \psi\pi^+$ decay in the $B^+\gamma$ mass spectrum is also modeled with the sum of two CB functions, with the shape parameters fixed to those found in simulation and the yield fixed relative to that for the B^{*+} signal, taking into account their relative branching fractions [28] and reconstruction efficiencies. In the $B^0\gamma$ mass distribution, the peaking contribution from $B^{*0}_s \to B^0_s\gamma \to \psi K^+K^-\gamma$ decays (with one of the B^0_s daughter kaons reconstructed as a pion candidate from the $B^0 \to \psi K^+\pi^-$ decay) is described by the sum of two CB functions with the shape parameters of the B^{*0}_s signal and the mass shifted by -87.78 MeV with respect to it, as found in the simulation. The normalization of this component is left free in the fit. In the $B^0_s\gamma$ mass distribution, the contribution from the B^{*0} decays is described by the sum of two CB functions with the shape parameters of the B^{*0} signal and the mass shifted by $+87.54$ MeV with respect to it. Its normalization is fixed to 0.7% of the B^{*0} signal, according to the studies based on simulated event samples. Finally, the background in all distributions is described with a standard threshold function $(m - m_0)^\beta$, where m_0 is specific to each meson flavor, set to the corresponding ground-state meson mass, and β is a free parameter, shared across the seven categories.

The fit returns the mass differences $\Delta m(B^{*+}) \equiv m(B^{*+}) - m(B^+) = 45.277 \pm 0.039$ MeV, $\Delta m(B^{*0}) \equiv m(B^{*0}) - m(B^0) = 45.471 \pm 0.056$ MeV, and $\Delta m(B^{*0}_s) \equiv m(B^{*0}_s) - m(B^0_s) = 49.41 \pm 0.13$ MeV, where the uncertainties are statistical only.

The measurement uncertainties are dominated by the statistical component. The leading systematic uncertainties are discussed below. To evaluate the systematic uncertainties related to the choice of the fit model, several alternative functions are tested, with different n or α in the CB functions, the sum of CB and Student's t distributions, a CB function plus a Gaussian function, or a CB function plus a Novosibirsk [42] function. In order to evaluate the uncertainties reflecting the simulated signal shape, an alternative fit is performed, no longer fixing the shape parameters but imposing that they are common to the (simultaneously fitted) measured and simulated distributions. The nominal fit fixes the yield ratios between the $|\eta(\gamma)|$ categories for B^{*0} and B^{*0}_s signals to the values expected from simulation; alternatively, these constraints are removed. Variations of the $B^+ \to J/\psi\pi^+$ contribution produce negligible changes in the results. The peak positions and yields of the B^{*0}_s to $B^0\gamma$ and B^{*0} to $B^0_s\gamma$ cross-feed contributions are varied. The alternative shape for the combinatorial background has seven independent β parameters, one for each $|\eta(\gamma)|$ category. For each of these sets of variations, the largest deviation in the measured quantities, with respect to the results of the baseline fit, is taken as the corresponding systematic uncertainty.

A cross-check is performed by splitting the data into subsamples matching each of the three data-taking years (2016, 2017, and 2018) and measuring the corresponding B^{*+} mass values.

This cross-check also provides a good estimate of the uncertainty due to the detector alignment, since the pixel detector was replaced between 2016 and 2017. The results are found to be in good agreement with each other and the baseline result.

The statistical uncertainty from the PES correction is evaluated by making alternative PES corrections, with a momentum scale factor in each $|\eta(\gamma)|$ and $p_{\mathrm{T}}(\gamma)$ range distributed as a Gaussian distribution, with mean equal to the baseline correction scale factor and RMS equal to its uncertainty. The simultaneous fit to the data is repeated each time, producing a set of $\Delta m(\mathrm{B}^*)$ measurements. The RMS values of these distributions are taken as the systematic uncertainties in the measured mass differences. The systematic uncertainty from the PES correction is evaluated by comparing the weighted average of the π^0 mass values in the $|\eta(\gamma)|$ and $p_{\mathrm{T}}(\gamma)$ ranges relevant for the analysis with the world-average value of the π^0 mass and scaling the difference by the ratio of $\Delta m(\mathrm{B}^*)$ to the π^0 mass.

All the systematic uncertainties described above are summarized in Table 1, together with the total systematic uncertainty, calculated as the sum in quadrature of the individual components. Systematic uncertainties in the various ratios or differences between the three reported mass differences are evaluated in the same way and are given in Appendix C.

Table 1: Systematic uncertainties in the measured mass differences, in keV.

Source	$m(\mathrm{B}^{*+}) - m(\mathrm{B}^+)$	$m(\mathrm{B}^{*0}) - m(\mathrm{B}^0)$	$m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}_\mathrm{s}^0)$
Signal model	4	8	21
Signal shape parameters	15	15	18
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	1	2	10
Background shape	2	<1	7
Cross-feed $\mathrm{B}_\mathrm{s}^{*0} \leftrightarrow \mathrm{B}^{*0}$	<1	1	10
Photon energy scale, statistical	12	14	16
Photon energy scale, systematic	18	18	19
Total	27	28	41

All the parameters measured in this analysis are presented in Table 2. The mass differences (entries 1–3 in Table 2) are consistent with, and an order of magnitude more precise than, the current world-average values [28]. The measured mass difference $m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}_\mathrm{s}^0)$ is in agreement with the Belle result [8], and about 2 standard deviations away from the CLEO result [7]. The masses of the vector states (rows 4–6) are determined by adding the measured difference between the excited and ground states to the world-average values of the ground-state masses [28].

In addition, the measurements of the differences between the vector state masses (rows 7–10 in Table 2), are reported, using the known mass differences between the B meson ground states [28]: $m(\mathrm{B}^0) - m(\mathrm{B}^+) = 0.31 \pm 0.05\,\mathrm{MeV}$ and $m(\mathrm{B}_\mathrm{s}^0) - [m(\mathrm{B}^0) + m(\mathrm{B}^+)]/2 = 87.37 \pm 0.12\,\mathrm{MeV}$, assuming their uncertainties to be uncorrelated. The result for $m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+})$ is consistent with the only previous measurement that used P-wave B_s^0 mesons [6], and is about 3 times more precise, while the other mass differences between vector states are measured for the first time. The differences and ratios between the mass differences are also measured for the first time (entries 11–18 in Table 2, which reflect the correlations between different uncertainties).

The measurements of $\Delta m(\mathrm{B}_\mathrm{s}^{*0})$, $\Delta m(\mathrm{B}^{*+})$, and $\Delta m(\mathrm{B}^{*0})$ agree with the predictions from lattice QCD [43–45] for $\Delta m(\mathrm{B}_\mathrm{s}^{*0})$ and $\Delta m(\mathrm{B}^{*+,0}) \equiv m(\mathrm{B}^{*+,0}) - m(\mathrm{B}^{+,0})$ (where $\mathrm{B}^{+,0}$ corresponds to either B^+ or B^0 since the predictions do not distinguish between the two), while the uncer-

Table 2: Results of the measurement. The first uncertainties are statistical, the second are systematic, and the third, where present, are related to the masses or mass differences of the ground states taken from Ref. [28].

	Parameter	Value
1	$\Delta m(\mathrm{B}^{*+}) \equiv m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+})$	$45.277 \pm 0.039 \pm 0.027\,\mathrm{MeV}$
2	$\Delta m(\mathrm{B}^{*0}) \equiv m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0})$	$45.471 \pm 0.056 \pm 0.028\,\mathrm{MeV}$
3	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) \equiv m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}_\mathrm{s}^{0})$	$49.407 \pm 0.132 \pm 0.041\,\mathrm{MeV}$
4	$m(\mathrm{B}^{*+})$	$5324.69 \pm 0.04 \pm 0.03 \pm 0.07\,\mathrm{MeV}$
5	$m(\mathrm{B}^{*0})$	$5325.19 \pm 0.06 \pm 0.03 \pm 0.08\,\mathrm{MeV}$
6	$m(\mathrm{B}_\mathrm{s}^{*0})$	$5416.34 \pm 0.13 \pm 0.04 \pm 0.10\,\mathrm{MeV}$
7	$m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+})$	$0.50 \pm 0.07 \pm 0.01 \pm 0.05\,\mathrm{MeV}$
8	$m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}^{*+})$	$91.66 \pm 0.14 \pm 0.03 \pm 0.12\,\mathrm{MeV}$
9	$m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}^{*0})$	$91.15 \pm 0.14 \pm 0.03 \pm 0.12\,\mathrm{MeV}$
10	$m(\mathrm{B}_\mathrm{s}^{*0}) - \frac{1}{2}\left[m(\mathrm{B}^{*0}) + m(\mathrm{B}^{*+})\right]$	$91.40 \pm 0.13 \pm 0.03 \pm 0.12\,\mathrm{MeV}$
11	$\Delta m(\mathrm{B}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$0.19 \pm 0.07 \pm 0.01\,\mathrm{MeV}$
12	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$4.13 \pm 0.14 \pm 0.03\,\mathrm{MeV}$
13	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) - \Delta m(\mathrm{B}^{*0})$	$3.94 \pm 0.14 \pm 0.03\,\mathrm{MeV}$
14	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) - \frac{1}{2}\left[\Delta m(\mathrm{B}^{*0}) + \Delta m(\mathrm{B}^{*+})\right]$	$4.03 \pm 0.13 \pm 0.03\,\mathrm{MeV}$
15	$\Delta m(\mathrm{B}^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0043 \pm 0.0015 \pm 0.0002$
16	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) / \Delta m(\mathrm{B}^{*+})$	$1.0912 \pm 0.0031 \pm 0.0007$
17	$\Delta m(\mathrm{B}_\mathrm{s}^{*0}) / \Delta m(\mathrm{B}^{*0})$	$1.0866 \pm 0.0031 \pm 0.0007$
18	$2\,\Delta m(\mathrm{B}_\mathrm{s}^{*0}) / \left[\Delta m(\mathrm{B}^{*+}) + \Delta m(\mathrm{B}^{*0})\right]$	$1.0889 \pm 0.0030 \pm 0.0007$

tainties in the predictions are 1–2 orders of magnitude larger than those of the measurement. Phenomenological models provide more precise predictions including $m(\mathrm{B}^{*0}) - m(\mathrm{B}^{*+}) = 0.6 \pm 0.2$ [10] and $0.31 \pm 0.07\,\mathrm{MeV}$ [11], close to our measurement (entry 7 in Table 2). Reference [10] also predicts hyperfine splittings $\Delta m(\mathrm{B}^{*+,0}) = 45.69 \pm 0.02\,\mathrm{MeV}$ (above both values 1 and 2 in Table 2) and $\Delta m(\mathrm{B}_\mathrm{s}^{*0}) = 46.73 \pm 0.08\,\mathrm{MeV}$ (below our measurement in line 3 of Table 2). Experimental systematic uncertainties are reduced by taking the ratios of the mass differences, as shown in entries 16–18 in Table 2. In addition, the theoretical uncertainties in the lattice QCD predictions from Ref. [44] are also reduced, giving a prediction of $\Delta m(\mathrm{B}_\mathrm{s}^{*0}) / \Delta m(\mathrm{B}^{*+,0}) = 1.007 \pm 0.034$, which is about 2.5 standard deviations below our results and with an uncertainty that remains an order of magnitude larger.

In summary, three vector B meson states, B^{*+}, B^{*0}, and $\mathrm{B}_\mathrm{s}^{*0}$, have been fully reconstructed in exclusive final states for the first time by detecting low-energy photons through their conversion to $\mathrm{e}^+\mathrm{e}^-$ pairs in the beam pipe and detector material. The data sample of $\sqrt{s} = 13\,\mathrm{TeV}$ proton-proton collisions was collected by the CMS experiment and corresponds to an integrated luminosity of $140\,\mathrm{fb}^{-1}$. The measurements benefit from a new photon energy scale calibration method that uses $\pi^0 \to \gamma\gamma$ decays in which both photons convert to $\mathrm{e}^+\mathrm{e}^-$ pairs. The masses of the three vector states are measured with respect to the corresponding ground states to be $m(\mathrm{B}^{*+}) - m(\mathrm{B}^{+}) = 45.277 \pm 0.039 \pm 0.027\,\mathrm{MeV}$, $m(\mathrm{B}^{*0}) - m(\mathrm{B}^{0}) = 45.471 \pm 0.056 \pm 0.028\,\mathrm{MeV}$, and $m(\mathrm{B}_\mathrm{s}^{*0}) - m(\mathrm{B}_\mathrm{s}^{0}) = 49.407 \pm 0.132 \pm 0.041\,\mathrm{MeV}$, where the first uncertainties are statistical and the second are systematic. A number of difference and ratio measurements between the reported masses and mass differences are also provided, where, due to cancellations in the computations of these quantities, both experimental and theoretical uncertainties are lower. These results are either the first measurement or an order of magnitude more precise than previous measurements. The new measurements are more precise than the available theoretical predictions and provide an important input to our understanding of heavy-quark systems.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

[1] L3 Collaboration, "B* production in Z decays at LEP", *Phys. Lett. B* **345** (1995) 589, doi:10.1016/0370-2693(95)01611-S.

[2] ALEPH Collaboration, "Production of excited beauty states in Z decays", *Z. Phys. C* **69** (1996) 393, doi:10.1007/BF02907419.

[3] DELPHI Collaboration, "B* production in Z decays", *Z. Phys. C* **68** (1995) 353, doi:10.1007/BF01620711.

[4] OPAL Collaboration, "B* production in Z^0 decays", *Z. Phys. C* **74** (1997) 413, doi:10.1007/s002880050404.

[5] LHCb Collaboration, "First observation of the decay $B_{s2}^*(5840)^0 \to B^{*+}K^-$ and studies of excited B_s^0 mesons", *Phys. Rev. Lett.* **110** (2013) 151803, doi:10.1103/PhysRevLett.110.151803, arXiv:1211.5994.

[6] CMS Collaboration, "Studies of $\mathrm{B}_{s2}^*(5840)^0$ and $\mathrm{B}_{s1}(5830)^0$ mesons including the observation of the $\mathrm{B}_{s2}^*(5840)^0 \to \mathrm{B}^0\mathrm{K}_S^0$ decay in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$", *Eur. Phys. J. C* **78** (2018) 939, doi:10.1140/epjc/s10052-018-6390-z, arXiv:1809.03578.

[7] CLEO Collaboration, "First measurements of the exclusive decays of the $\Upsilon(5S)$ to B meson final states and improved B_s^* mass measurement", *Phys. Rev. Lett.* **96** (2006) 152001, doi:10.1103/PhysRevLett.96.152001, arXiv:hep-ex/0601044.

[8] Belle Collaboration, "Measurement of the decay $B_s^0 \to D_s^- \pi^+$ and evidence for $B_s^0 \to D_s^{\pm} K^{\mp}$ in e^+e^- annihilation at $\sqrt{s} \approx 10.87\,\text{GeV}$", *Phys. Rev. Lett.* **102** (2009) 021801, doi:10.1103/PhysRevLett.102.021801, arXiv:0809.2526.

[9] J. L. Rosner and M. B. Wise, "Meson masses from SU(3) and heavy quark symmetry", *Phys. Rev. D* **47** (1993) 343, doi:10.1103/PhysRevD.47.343.

[10] J. L. Goity and C. P. Jayalath, "Strong and electromagnetic mass splittings in heavy mesons", *Phys. Lett. B* **650** (2007) 22, doi:10.1016/j.physletb.2007.04.037, arXiv:hep-ph/0701245.

[11] M. Karliner and J. L. Rosner, "Status of isospin splittings in mesons and baryons", *Phys. Rev. D* **100** (2019) 073006, doi:10.1103/PhysRevD.100.073006, arXiv:1906.07799.

[12] CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS", *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[13] CMS Collaboration, "CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[14] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[15] HEPData record for this analysis, 2025. doi:10.17182/hepdata.159543.

[16] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[17] CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.

[18] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[19] CMS Collaboration, "Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[20] CMS Collaboration, "Performance of the CMS high-level trigger during LHC Run 2", *JINST* **19** (2024) P11021, doi:10.1088/1748-0221/19/11/P11021, arXiv:2410.17038.

[21] CMS Collaboration, "Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC", *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[22] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[23] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[24] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[25] CMS Collaboration, "Strategies and performance of the CMS silicon tracker alignment during LHC Run 2", *Nucl. Instrum. Meth. A* **1037** (2022) 166795, doi:10.1016/j.nima.2022.166795, arXiv:2111.08757.

[26] CMS Tracker Group Collaboration, "The CMS phase-1 pixel detector upgrade", *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

[27] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\,\mathrm{TeV}$", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[28] Particle Data Group, S. Navas et al., "Review of particle physics", *Phys. Rev. D* **110** (2024) 030001, doi:10.1103/PhysRevD.110.030001.

[29] CMS Collaboration, "Measurement of the production cross section ratio $\sigma(\chi_{\mathrm{b2}}(1\mathrm{P}))/\sigma(\chi_{\mathrm{b1}}(1\mathrm{P}))$ in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$", *Phys. Lett. B* **743** (2015) 383, doi:10.1016/j.physletb.2015.02.048, arXiv:1409.5761.

[30] CMS Collaboration, "Study of excited Λ_{b}^{0} states decaying to $\Lambda_{\mathrm{b}}^{0}\pi^{+}\pi^{-}$ in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **803** (2020) 135345, doi:10.1016/j.physletb.2020.135345, arXiv:2001.06533.

[31] CMS Collaboration, "Observation of a new excited beauty strange baryon decaying to $\Xi_{\mathrm{b}}^{-}\pi^{+}\pi^{-}$", *Phys. Rev. Lett.* **126** (2021) 252003, doi:10.1103/PhysRevLett.126.252003, arXiv:2102.04524.

[32] CMS Collaboration, "Observation of the $\Xi_{\mathrm{b}}^{-} \to \psi(2\mathrm{S})\Xi^{-}$ decay and studies of the $\Xi_{\mathrm{b}}(5945)^{0}$ baryon in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$", *Phys. Rev. D* **110** (2024) 012002, doi:10.1103/PhysRevD.110.012002, arXiv:2402.17738.

[33] CMS Collaboration, "Observation of the $\chi_{\mathrm{b1}}(3\mathrm{P})$ and $\chi_{\mathrm{b2}}(3\mathrm{P})$ and measurement of their masses", *Phys. Rev. Lett.* **121** (2018) 092002, doi:10.1103/PhysRevLett.121.092002, arXiv:1805.11192.

[34] See Supplemental Material at [URL will be inserted by publisher] for the fit projections in extra rapidity ranges and systematic uncertainties in the differences and ratios of the mass differences.

[35] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[36] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[37] D. J. Lange, "The EvtGen particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[38] E. Barberio, B. van Eijk, and Z. Wąs, "PHOTOS: A universal Monte Carlo for QED radiative corrections in decays", *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

[39] E. Barberio and Z. Wąs, “PHOTOS: A universal Monte Carlo for QED radiative corrections. version 2.0”, *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4.

[40] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[41] M. J. Oreglia, “A study of the reactions $\psi' \to \gamma\gamma\psi$”. PhD thesis, Stanford University, 1980.

[42] Belle Collaboration, “A detailed test of the CsI(Tl) calorimeter for BELLE with photon beams of energy between 20 MeV and 5.4 GeV”, *Nucl. Instrum. Meth. A* **441** (2000) 401, doi:10.1016/S0168-9002(99)00992-4.

[43] F. Bernardoni et al., “B-meson spectroscopy in HQET at order 1/m”, *Phys. Rev. D* **92** (2015) 054509, doi:10.1103/PhysRevD.92.054509, arXiv:1505.03360.

[44] R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, “Precise heavy-light meson masses and hyperfine splittings from lattice QCD including charm quarks in the sea”, *Phys. Rev. D* **86** (2012) 094510, doi:10.1103/PhysRevD.86.094510, arXiv:1207.5149.

[45] Hadron Spectrum Collaboration, “Highly excited B, B_s and B_c meson spectroscopy from lattice QCD”, *JHEP* **01** (2025) 123, doi:10.1007/JHEP01(2025)123, arXiv:2408.02126.

A Example distributions of the $\pi^0 \to \gamma\gamma$ invariant mass

The distributions of the $\gamma\gamma$ invariant mass from two converted photons in 2018 data, showing the $\pi^0 \to \gamma\gamma$ peak in the kinematic range $0.8 < p_T(\gamma) < 0.9\,\text{GeV}$, $0.8 < |\eta(\gamma)| < 0.9$, are presented in Fig. A.1 before (left) and after (right) the PES correction. The distributions are fit with a sum of two Crystal Ball functions with a common mean for the signal and a polynomial multiplied by a power law function for the background.

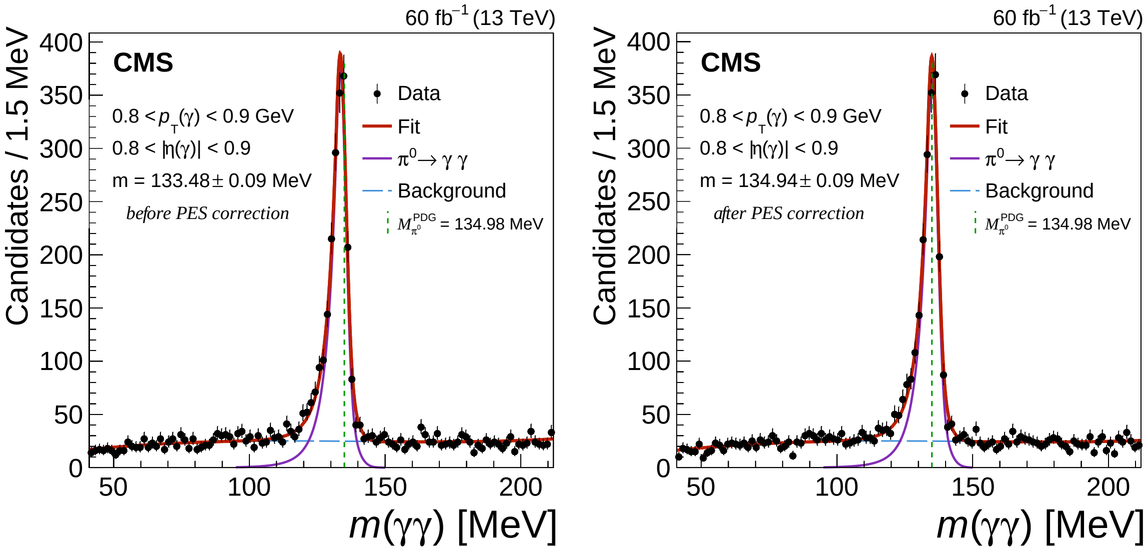

Figure A.1: The measured distributions of the diphoton invariant mass near the π^0 mass with the fit results overlaid, before (left) and after (right) the PES correction, in the kinematic range $0.8 < p_T(\gamma) < 0.9\,\text{GeV}$, $0.8 < |\eta(\gamma)| < 0.9$. The green vertical line shows the world-average value of the π^0 mass of 134.98 MeV [28].

B Fit projections in extra pseudorapidity ranges

The measured invariant mass distributions of the $B^+\gamma$, $B^0\gamma$, and $B^0_s\gamma$ candidates in the four additional categories of the simultaneous fit are shown in Fig. B.1.

C Systematic uncertainties in the differences and ratios of the mass differences

The systematic uncertainties for the differences and ratios of the mass differences (entries 11–18 in the tabulated list of results) are evaluated in the same manner as for the $\Delta m(B^*)$ uncertainties, with the variations to the baseline model applied simultaneously to all channels to account for correlations. The resulting uncertainties are shown in Tables C.1 and C.2. The experimental statistical and systematic uncertainties for lines 7–10 of the tabulated list of results are identical to those for lines 11–14 (Table C.1). As for the other measurements, the statistical uncertainties dominate.

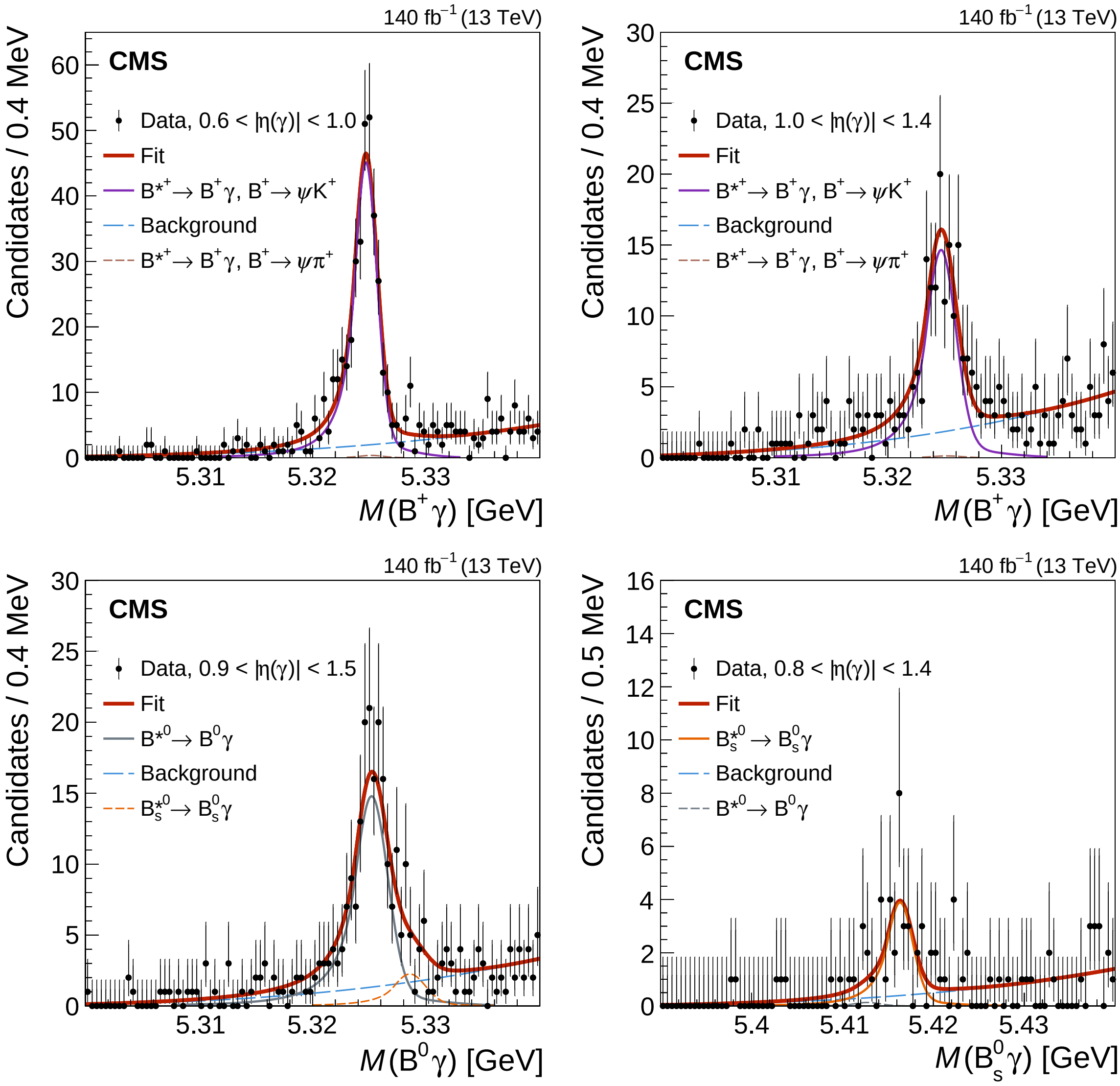

Figure B.1: The measured distributions (filled circles) of the $\mathrm{B}^+\gamma$ (upper), $\mathrm{B}^0\gamma$ (lower left), and $\mathrm{B}^0_\mathrm{s}\gamma$ (lower right) invariant mass corresponding to the most forward one or two $|\eta(\gamma)|$ regions, together with the simultaneous fit projections (thick red lines). The error bars represent statistical uncertainties in data.

Table C.1: Values, statistical, and systematic uncertainties, in keV, of the measured differences of the three mass differences.

Source	$\Delta m(\mathrm{B}^{*0}) - \Delta m(\mathrm{B}^{*+})$	$\Delta m(\mathrm{B}^{*0}_\mathrm{s}) - \Delta m(\mathrm{B}^{*+})$	$\Delta m(\mathrm{B}^{*0}_\mathrm{s}) - \Delta m(\mathrm{B}^{*0})$	$\Delta m(\mathrm{B}^{*0}_\mathrm{s}) - \frac{\Delta m(\mathrm{B}^{*0})+\Delta m(\mathrm{B}^{*+})}{2}$
Measured value	194	4130	3936	4033
Statistical uncertainty	68	138	139	134
Signal model	4	23	23	23
Signal shape parameters	1	3	3	3
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	3	11	7	9
Background shape	3	9	6	8
Cross-feed $\mathrm{B}^{*0}_\mathrm{s} \leftrightarrow \mathrm{B}^{*0}$	1	10	12	11
Photon energy scale, statistical	4	11	11	11
Photon energy scale, systematic	$<$1	2	2	2
Total systematic uncertainty	7	31	30	30

Table C.2: Values, statistical, and systematic uncertainties of the measured ratios of the three mass differences.

Source	$\Delta m(B^{*0})/\Delta m(B^{*+})$	$\Delta m(B_s^{*0})/\Delta m(B^{*+})$	$\Delta m(B_s^{*0})/\Delta m(B^{*0})$	$\frac{2\,\Delta m(B_s^{*0})}{\Delta m(B^{*+})+\Delta m(B^{*0})}$
Measured value	1.00428	1.09122	1.08656	1.08888
Statistical uncertainty	0.00151	0.00306	0.00309	0.00297
Signal model	0.00009	0.00050	0.00052	0.00052
Signal shape parameters	0.00002	0.00003	0.00004	0.00003
Yield ratios of $\lvert\eta(\gamma)\rvert$ ranges	0.00008	0.00023	0.00016	0.00020
Background shape	0.00005	0.00020	0.00014	0.00017
Cross-feed $B_s^{*0} \leftrightarrow B^{*0}$	0.00003	0.00023	0.00025	0.00015
Photon energy scale	0.00009	0.00025	0.00024	0.00024
Total systematic uncertainty	0.00016	0.00067	0.00066	0.00065

D The CMS Collaboration

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

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, M. Dragicevic, C. Giordano, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, 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, D. Ocampo Henao, 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, P. Kashko, 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, V. Lemaitre, J. Lidrych, P. Malek, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Barroso Ferreira Filho, E. Coelho, 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, 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, F. Torres Da Silva De Araujo[8]

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], F. Damas, 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, P. Danev, R. Hadjiiska, P. Iaydjiev, M. Shopova, G. Sultanov

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

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

Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
W. Brooks

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

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

Institute of High Energy Physics, Beijing, China
G.M. Chen[9], H.S. Chen[9], M. Chen[9], Y. Chen, Q. Hou, X. Hou, F. Iemmi, C.H. Jiang, A. Kapoor[10], H. Liao, G. Liu, Z.-A. Liu[11], J.N. Song[11], S. Song, J. Tao, C. Wang[9], 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, J. Wang, H. Yang, M. Zhang, 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[12,13], B. Li[14], H. Wang, K. Yi[15], 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[16]

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
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, 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.

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

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

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

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

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

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, N.T. Toikka, 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, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, 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, O. Davignon, A. De Wit, T. Debnath, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, 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,

G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, 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, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[22], Z. Tsamalaidze[23]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, P. Nattland, 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, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M.R. Beckers, C. Dziwok, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, A. Abel, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, I. Andreev, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K.-Y. Lin, K. Lipka[26], W. Lohmann[27], J. Malvaso, 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[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, M. Torkian, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, F. Labe, J. Lange, A. Lobanov, L. Moureaux, A. Nigamova, K. Nikolopoulos, A. Paasch, K.J. Pena Rodriguez, N. Prouvost, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt,

M. Sommerhalder, H. Stadie, G. Steinbrück, 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[29], R. Hofsaess, M. Horzela, F. Hummer, U. Husemann, J. Kieseler, M. Klute, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J.M. Lawhorn, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, 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, C. Verstege, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, 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

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, E. Tzovara, 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, 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[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, M. León Coello, 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[33], F. Nemes[33], T. Novak, I. Szanyi[35]

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, S. Phor, K. Ranjan, M.K. Saini

University of Hyderabad, Hyderabad, India

S. Acharya[37], B. Gomber[37], B. Sahu[37]

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, 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. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], T. Mishra, P.R. Pujahari, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

IISER Mohali, India, Mohali, India
B.K. Sirasva

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. Barman[39], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, M. Maity[39], G. Majumder, K. Mazumdar, S. Parolia, R. Saxena, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], D. Maity[41], P. Mal, K. Naskar[41], A. Nayak[41], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[41], D. Vats[41]

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

Indian Institute of Technology Hyderabad, Telangana, India
S. Ghosh

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], A. Jafari[43], V. Sedighzadeh Dalavi, M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[46]

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], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,17], N. Ferrara[a,c], L. Fiore[a], 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], F. Nenna[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], 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], C. Grandi[a], S. Lo Meo[a,47], 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,48], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,48]

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. Bianco, S. Meola[49], 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], V. Camagni[a,b], 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], M.R. Kim[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], 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], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,29], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
P. Azzi[a], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a,c], G. Bortolato[a,b], A.C.M. Bulla[a,c], R. Carlin[a,b], T. Dorigo[a,52], F. Gasparini[a,b], S. Giorgetti[a], M. Gulmini[a,53], 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], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], S. Calzaferri[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,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], 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], L. Calligaris[a,b], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], 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], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,55], T. Sarkar[a], A. Scribano[a], P. Solanki[a,b], 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], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], 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], 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], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[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], E. Vlasov[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, T. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, 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, J. Seo

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[56], T.J. Kim, Y. Ryou

Korea University, Seoul, Korea
S. Ha, S. Han, B. Hong, J. Kim, 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, H. Kim, J. Kim, T. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, J. Shin, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, D. Kim, 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, K. Hwang, B. Kim, S. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, 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, R. Plese, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

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

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[57], Z. Zolkapli

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, 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, 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, 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, L. Markovic, P. Milenovic, V. Milosevic

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
M. Alcalde Martinez, J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, J. Cuchillo Ortega, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, M. Gonzalez Hernandez, 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, R. Paz Herrera, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, 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, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, A. Soto Rodríguez, 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, C. Quintana San Emeterio, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[58], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[59], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, P.J. Fernández Manteca, W. Funk, A. Gaddi, 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[27], G. Karathanasis, S. Laurila, P. Lecoq, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, M. Mannelli, A. Mehta, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[61], J. Wang, S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[62], L. Caminada[62], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, L. Noehte[62], 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'archiacchiac[61], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, M. Malucchi, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[63], P. Bärtschi, F. Bilandzija, M.F. Canelli, G. Celotto, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, M. Missiroli, J. Motta, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

National Central University, Chung-Li, Taiwan
D. Bhowmik, C.M. Kuo, 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

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Dolek, I. Dumanoglu[64], Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[66], B. Tali[67], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[68]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi[69], E. Gülmez, M. Kaya[70], O. Kaya[71], M.A. Sarkisla[72], S. Tekten[73]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[64,74], S. Sen[75]

Istanbul University, Istanbul, Turkey
O. Aydilek[76], B. Hacisahinoglu, I. Hos[77], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[78], E. Simsek, D. Sunar Cerci, T. Yetkin[79]

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

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

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[42], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, 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, E. Leutgeb, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[81], 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[29], 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

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan[82]

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, S. Campbell, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, C.U. Perez, P. Rumerio[83], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
S. Cholak, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, J. Fulcher, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, E. Wurtz, 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, T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[84], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, O. Kukral, G. Mocellin, S. Ostrom, I. Salazar Segovia, 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, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[85], K. Downham, C. Grieco, M.M. Hussain, J. Incandela, M.W.K. Lai, A.J. Li, P. Masterson, 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, R. Kansal, J. Mao, H.B. New-

man, G. Reales Gutiérrez, T. Sievert, M. Spiropulu, J.R. Vlimant, R.A. Wynne, S. Xie

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, P. Meiring, 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, S. Kwan, 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, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, A. Ryd, J. Thom, P. Wittich, R. Zou, L. Zygala

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[86], C.E. Perez Lara, F. Ravera, A. Reinsvold Hall[87], 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. Goff, R. Hashmi, R.S. Kim, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, 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, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[88], O.K. Köseyan, A. Mestvirishvili[89], O. Neogi,

H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, S. Sekhar, M.V. Srivastav, 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[92], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G.G. Reddy, 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, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[93], A. Shevelev, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I.A. Cali, Y.c. Chen, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, G.M. Innocenti, 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, T.a. Sheng, G.S.F. Stephans, D. Walter, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, W.J. Jackson, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, 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

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, D. Yu

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, 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, 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, A. Ehnis, 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

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, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully

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

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

Purdue University Northwest, Hammond, Indiana, USA
N. Parashar, A. Pathak, E. Shumka

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, K.M. Ecklund, 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
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro[†], R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[93], H. Seo, R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, A. Kobert, S. Konstantinou, I. Laflotte, A. Lath, J. Martins, 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, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[94], A. Cagnotta, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, 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,

J. Zhang

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, 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, S. Lomte, R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, T. Nelson, 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[95], M. Danilov[95], T. Dimova[95], A. Ershov[95], S. Gninenko, I. Gorbunov, A. Gribushin[95], A. Kamenev, V. Karjavine, M. Kirsanov, V. Klyukhin[95], O. Kodolova[96,93], V. Korenkov, I. Korsakov, A. Kozyrev[95], N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev[95], A. Nikitenko[97,96], V. Palichik, V. Perelygin, S. Petrushanko[95], S. Polikarpov[95], O. Radchenko[95], M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], K. Slizhevskiy, V. Smirnov, O. Teryaev, I. Tlisova[95], A. Toropin, N. Voytishin, B.S. Yuldashev[†98], A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
E. Boos, V. Bunichev, M. Dubinin[86], V. Savrin, A. Snigirev, L. Dudko, K. Ivanov, V. Kim[23], V. Murzin, V. Oreshkin, D. Sosnov

†: 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 The University of the State of Amazonas, Manaus, Brazil
[9]Also at University of Chinese Academy of Sciences, Beijing, China
[10]Also at China Center of Advanced Science and Technology, Beijing, China
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at School of Physics, Zhengzhou University, Zhengzhou, China
[13]Now at Henan Normal University, Xinxiang, China
[14]Also at University of Shanghai for Science and Technology, Shanghai, China
[15]Now at The University of Iowa, Iowa City, Iowa, USA
[16]Also at Center for High Energy Physics, Peking University, Beijing, China
[17]Also at Helwan University, Cairo, Egypt
[18]Now at Zewail City of Science and Technology, Zewail, Egypt
[19]Also at British University in Egypt, Cairo, Egypt
[20]Also at Purdue University, West Lafayette, Indiana, USA

[21]Also at Université de Haute Alsace, Mulhouse, France
[22]Also at Tbilisi State University, Tbilisi, Georgia
[23]Also at an institute formerly covered by a cooperation agreement with CERN
[24]Also at University of Hamburg, Hamburg, Germany
[25]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[26]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[27]Also at Brandenburg University of Technology, Cottbus, Germany
[28]Also at Forschungszentrum Jülich, Juelich, Germany
[29]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[30]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[35]Also at The University of Kansas, Lawrence, Kansas, USA
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Hyderabad, Hyderabad, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at IIT Bhubaneswar, Bhubaneswar, India
[41]Also at Institute of Physics, Bhubaneswar, India
[42]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[43]Also at Isfahan University of Technology, Isfahan, Iran
[44]Also at Sharif University of Technology, Tehran, Iran
[45]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[46]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[47]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[48]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[49]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[50]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[52]Also at Lulea University of Technology, Lulea, Sweden
[53]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[54]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[55]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[56]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[57]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[58]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[59]Also at Saegis Campus, Nugegoda, Sri Lanka
[60]Also at National and Kapodistrian University of Athens, Athens, Greece
[61]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[62]Also at Universität Zürich, Zurich, Switzerland
[63]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[64]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

[65]Also at Konya Technical University, Konya, Turkey
[66]Also at Izmir Bakircay University, Izmir, Turkey
[67]Also at Adiyaman University, Adiyaman, Turkey
[68]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[69]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
[70]Also at Marmara University, Istanbul, Turkey
[71]Also at Milli Savunma University, Istanbul, Turkey
[72]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
[73]Also at Kafkas University, Kars, Turkey
[74]Now at Istanbul Okan University, Istanbul, Turkey
[75]Also at Hacettepe University, Ankara, Turkey
[76]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[77]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[78]Also at Yildiz Technical University, Istanbul, Turkey
[79]Also at Istinye University, Istanbul, Turkey
[80]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[81]Also at Monash University, Faculty of Science, Clayton, Australia
[82]Also at Bethel University, St. Paul, Minnesota, USA
[83]Also at Università di Torino, Torino, Italy
[84]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85]Also at California Lutheran University;, Thousand Oaks, California, USA
[86]Also at California Institute of Technology, Pasadena, California, USA
[87]Also at United States Naval Academy, Annapolis, Maryland, USA
[88]Also at Bingol University, Bingol, Turkey
[89]Also at Georgian Technical University, Tbilisi, Georgia
[90]Also at Sinop University, Sinop, Turkey
[91]Also at Erciyes University, Kayseri, Turkey
[92]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[93]Now at another institute formerly covered by a cooperation agreement with CERN
[94]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
[95]Also at another institute formerly covered by a cooperation agreement with CERN
[96]Also at Yerevan Physics Institute, Yerevan, Armenia
[97]Also at Imperial College, London, United Kingdom
[98]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan