First Exclusive Reconstruction of the B^{*+}, B^{*0}, and B_s^{*0} Mesons and Precise Measurement of Their Masses

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(Received 7 August 2025; accepted 16 December 2025; published 22 January 2026)

Using proton-proton collision data collected by the CMS experiment at $\sqrt{s} = 13$ TeV in 2016–2018, corresponding to an integrated luminosity of 140 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 $m(B^{*+}) - m(B^{+}) = 45.277 \pm 0.039 \pm 0.027$ MeV, $m(B^{*0}) - m(B^{0}) = 45.471 \pm 0.056 \pm 0.028$ MeV, and $m(B_s^{*0}) - m(B_s^{0}) = 49.407 \pm 0.132 \pm 0.041$ 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.

DOI: 10.1103/njf9-4zfv

While the ground states of beauty mesons B^{+}, B^{0}, and B_s^{0} have been extensively studied, the corresponding excited vector mesons B^{*+}, B^{*0}, and B_s^{*0} are much less explored. The main challenge in the reconstruction of these excited states stems from the low-energy (40–50 MeV in the B^* meson rest frame) 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_s^{*0} mesons, and B refers to one of the B^{+}, B^{0}, or B_s^{0} 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_s^0 mesons decaying into B^+K^- and $B^{*+}K^-$ by the LHCb and CMS experiments [5,6], as well as to $B^0K_S^0$ and $B^{*0}K_S^0$ 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_s^{*0} 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_s^{*0}, 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 $B_s^0 \to \psi\phi$, 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. Tracks are reconstructed from hits in the tracker and muons are reconstructed by matching tracks with muon candidates found in the muon detectors. 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

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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 $\psi(2\mathrm{S})$ meson.

The offline reconstruction requires two OS muons that form a vertex with fit χ^2 probability $P_{\mathrm{vtx}} > 1\%$, each satisfying $p_{\mathrm{T}} > 3.5$ 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 $\psi(2\mathrm{S})$ decays. To build B^+ (B^0 and B_s^0) candidates, the selected ψ candidate is combined with one (two OS) high-purity tracks [23] with $p_{\mathrm{T}} > 1$ GeV that do not match the selected muons. For the $B^+ \to \psi K^+$ and $B_s^0 \to \psi\phi$ selection, one or both tracks are assigned the charged kaon mass hypothesis, with an additional requirement of $1.01 < m(K^+K^-) < 1.03$ GeV for the latter. For the $B^0 \to \psi K^*(892)^0$ selection, the $K^+\pi^-$ or $K^-\pi^+$ mass assignment is made based on which combination has an invariant mass closer to the world-average K^{*0} meson mass of $M_{K^{*0}}^{\mathrm{PDG}} = 895.55$ MeV [28], followed by the requirement $0.81 < m(K^\pm\pi^\mp) < 0.97$ GeV. In addition, a $\phi \to K^+K^-$ veto is applied in the $B^0 \to \psi K^*(892)^0$ channel (by changing the track mass hypothesis) to ensure that the $B_s^0\gamma$ and $B^0\gamma$ samples do not overlap.

The B^+ (B^0 and B_s^0) candidates are obtained via a three-track (four-track) vertex fit of the selected muons and track(s), which constrains the dimuon invariant mass to the world-average J/ψ or $\psi(2\mathrm{S})$ 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 three or four 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 $p_{\mathrm{T}}(B) > 10$ GeV, $P_{\mathrm{vtx}}(B) > 1\%$, transverse vertex displacement from PV $L_{xy}(B)$ larger than 3 times its uncertainty, two-dimensional pointing angle $\cos[\vec{L}_{xy}(B), \vec{p}_{\mathrm{T}}(B)] > 0.999$, and invariant mass within twice the average mass resolution of the corresponding B meson world-average mass M_B^{PDG} [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 $p_{\mathrm{T}} > 300$ 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 $B\gamma$ invariant mass is evaluated using the expression $M(B\gamma) = m(B\gamma) - m(B) + M_B^{\mathrm{PDG}}$, 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., $p_{\mathrm{T}}(\gamma) < 1.5$ GeV. Supplemental Material [34] 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 $B^* \to B\gamma$, $B^+ \to \psi K^+$, $B^0 \to \psi K^*(892)^0$, and $B_s^0 \to \psi\phi$ 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, as the data-simulation differences in the kinematic spectra are expected to be similar for the three states.

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. Pseudoexperiments were used to obtain a set of optimal $|\eta(\gamma)|$ ranges for each meson

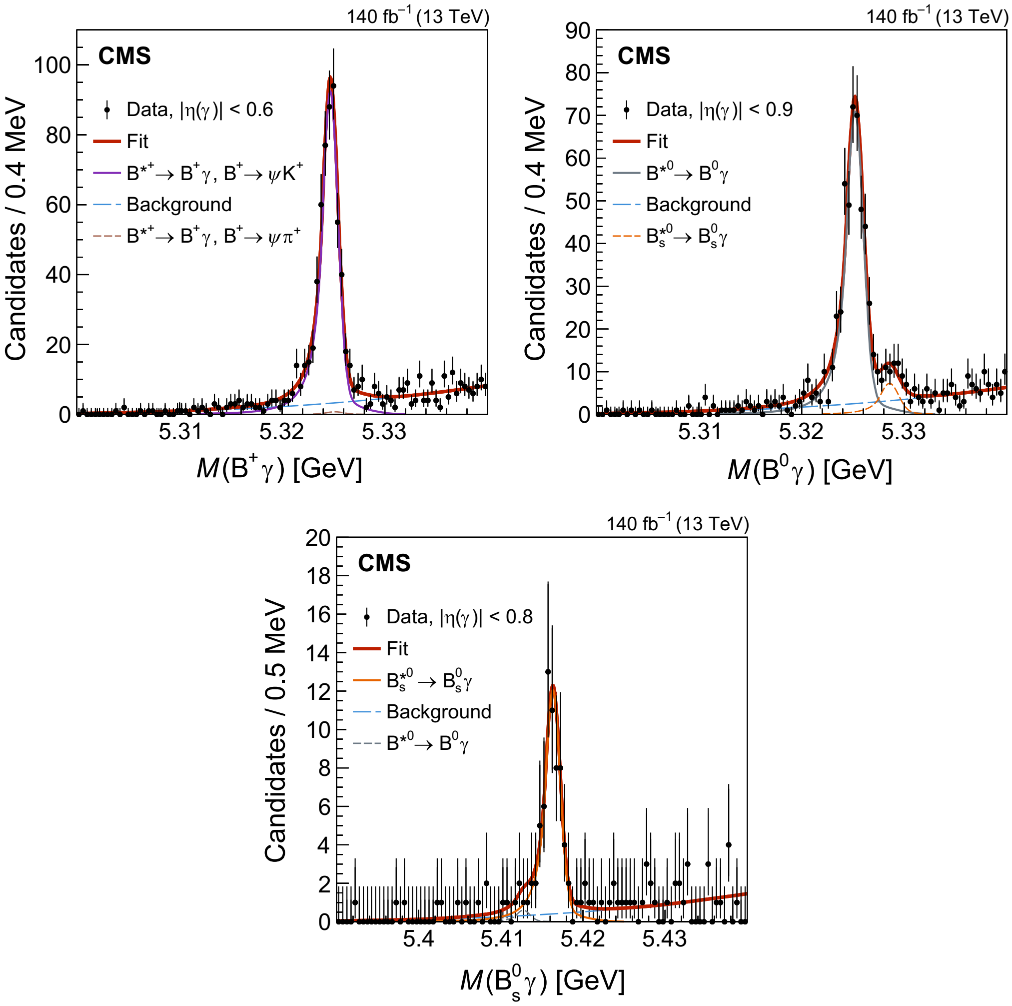

FIG. 1. The measured distributions (filled circles) of the $B^+\gamma$ (upper left), $B^0\gamma$ (upper right), and $B_s^0\gamma$ (lower) invariant mass in the lowest $|\eta(\gamma)|$ range, which has the best invariant mass resolution. The simultaneous fit projections are shown with thick red lines,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

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.

The measured invariant mass distributions of the selected $B^+\gamma$, $B^0\gamma$, and $B_s^0\gamma$ candidates are shown in Fig. 1 for the three categories with the best invariant mass resolution and in Supplemental Material [34] 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_s^{*0} 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_s^{*0}) 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 $B_s^{*0} \to B_s^0\gamma \to \psi K^+K^-\gamma$ decays (with one of the B_s^0 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_s^{*0} signal and the mass shifted by -87.78 MeV with

TABLE I. Systematic uncertainties in the measured mass differences, in keV.

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

respect to it, as found in the simulation. The normalization of this component is left free in the fit. In the $B_s^0\gamma$ 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 combinatorial background produced by random photons paired with a B meson is described in all distributions 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. Including all three meson flavors in a single fit allows for better control of cross contribution between B^{*0} and B_s^{*0} and more precise modeling of signal and background shapes that are expected to be the same.

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 $\Delta m(B_s^{*0}) \equiv m(B_s^{*0}) - m(B_s^{0}) = 49.407 \pm 0.132$ 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 signal 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 in the signal shape from the limited number of simulated events, 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_s^{*0} 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_s^{*0} to $B^0\gamma$ and B^{*0} to $B_s^0\gamma$ cross-feed contributions are varied. The alternative combinatorial background shape 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 $\Delta m(B^*)$ 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, obtained after the PES correction, 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 $\Delta m(B^*)$ to the π^0 mass.

All the systematic uncertainties described above are summarized in Table I, 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 Supplemental Material [34].

All the parameters measured in this analysis are presented in Table II. The mass differences (entries 1–3 in Table II) are consistent with, and an order of magnitude more precise than, the current world-average values [28]. The measured mass difference $m(B_s^{*0}) - m(B_s^0)$ is in agreement with the Belle result [8], and about two standard deviations away from the CLEO result [7]. The masses of

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

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 II), are reported, using the known mass differences between the B meson ground states [28]: $m(B^0) - m(B^+) = 0.31 \pm 0.05$ MeV and $m(B_s^0) - [m(B^0) + m(B^+)]/2 = 87.37 \pm 0.12$ MeV, assuming their uncertainties to be uncorrelated. The result for $m(B^{*0}) - m(B^{*+})$ 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 II), taking advantage of the cancellation of some uncertainties in these quantities.

The measurements of $\Delta m(B_s^{*0})$, $\Delta m(B^{*+})$, and $\Delta m(B^{*0})$ agree with the predictions from lattice QCD [43–45] for $\Delta m(B_s^{*0})$ and $\Delta m(B^{*+,0}) \equiv m(B^{*+,0}) - m(B^{+,0})$ (where $B^{+,0}$ corresponds to either B^+ or B^0 since the predictions do not distinguish between the two), while the uncertainties in the predictions are 1–2 orders of magnitude larger than those of the measurement. Phenomenological models provide more precise predictions including $m(B^{*0}) - m(B^{*+}) = 0.6 \pm 0.2$ [10] and 0.31 ± 0.07 MeV [11], close to our measurement (entry 7 in Table II). Reference [10] also predicts hyperfine splittings $\Delta m(B^{*+,0}) = 45.69 \pm 0.02$ MeV (above both values 1 and 2 in Table II) and $\Delta m(B_s^{*0}) = 46.73 \pm 0.08$ MeV (below our measurement in line 3 of Table II). Experimental systematic uncertainties are reduced by taking the ratios of the mass differences, as shown in entries 16–18 in Table II. In addition, the theoretical uncertainties in the lattice QCD predictions from Ref. [44] are also reduced, giving a prediction of $\Delta m(B_s^{*0})/\Delta m(B^{*+,0}) = 1.007 \pm 0.034$, 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 B_s^{*0}, have been fully reconstructed in exclusive final states for the first time by detecting low-energy photons through their conversion to e^+e^- pairs in the beam pipe and detector material. The data sample of $\sqrt{s} = 13$ TeV proton-proton collisions was collected by the CMS experiment and corresponds to an integrated luminosity of 140 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 e^+e^- pairs. The masses of the three vector states are measured with respect to the corresponding ground states to be $m(B^{*+}) - m(B^+) = 45.277 \pm 0.039 \pm 0.027$ MeV, $m(B^{*0}) - m(B^0) = 45.471 \pm 0.056 \pm 0.028$ MeV, and $m(B_s^{*0}) - m(B_s^0) = 49.407 \pm 0.132 \pm 0.041$ 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).

Data availability—Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse, and open access policy [46].

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