# *Measurement of the #b Polarization and Angular Parameters in #b→J/## Decays from Pp Collisions at $\sqrt{s}$ = 7 and 8 TeV*

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# Measurement of the $\Lambda_b$ polarization and angular parameters in $\Lambda_b \to J/\psi\Lambda$ decays from $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV

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An analysis of the bottom baryon decay $\Lambda_b \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi^-)$ is performed to measure the $\Lambda_b$ polarization and three angular parameters in data from $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV, collected by the CMS experiment at the Large Hadron Collider. The $\Lambda_b$ polarization is measured to be $0.00 \pm 0.06(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ and the parity-violating asymmetry parameter is determined to be $0.14 \pm 0.14(\mathrm{stat}) \pm 0.10(\mathrm{syst})$. The measurements are compared to various theoretical predictions, including those from perturbative quantum chromodynamics.

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## I. INTRODUCTION

The decay $\Lambda_b \to J/\psi\Lambda$ is a rich source of information about the effect of strong interactions in hadronic decays. For this particular decay, perturbative quantum chromodynamics can be applied and therefore a systematic approach can be taken to study its characteristics. Several techniques [1–10] are used to study and calculate the decay amplitudes and the effect of the $b$ quark polarization on this decay. The most interesting parameters that can be measured are the polarization, $P$, and the parity-violating decay asymmetry of the $\Lambda_b$, which is called $\alpha_b$ in some papers and is equal to $-\alpha_1$ in the notation used in this analysis. The LHCb and ATLAS experiments have reported measurements on this decay [11,12]. The LHCb Collaboration measured the $\Lambda_b$ polarization and the decay amplitudes, while ATLAS assumed a $\Lambda_b$ polarization of zero and measured the amplitudes. In this paper, a measurement of the $\Lambda_b$ transverse polarization is presented using the decay $\Lambda_b \to J/\psi\Lambda$, with $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$. Charge-conjugate modes are implied throughout this paper unless otherwise stated. The $\Lambda_b$ baryons used in this measurement come from both direct production in $pp$ collisions and decays of heavier $b$ baryons [1,13–16]. The data were collected with the CMS detector in $pp$ collisions at center-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 5.2 and 19.8 fb$^{-1}$, respectively.

## II. ANGULAR DISTRIBUTION

The $\Lambda_b \to J/\psi\Lambda$ decay into the $\mu^+\mu^-\ p\pi^-$ final state is illustrated in Fig. 1. In $pp$ collisions, we define the polarization of the $\Lambda_b$ as the mean value of the $\Lambda_b$ spin along the unit vector:

$$\hat{n} = \frac{\vec{p}_{\mathrm{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}_{\mathrm{beam}} \times \vec{p}_{\Lambda_b}|}, \tag{1}$$

normal to its production plane, where $\vec{p}_{\mathrm{beam}}$ is in the direction of the counterclockwise proton beam direction [17], and $\vec{p}_{\Lambda_b}$ is the $\Lambda_b$ momentum. The decay is described by four complex helicity amplitudes $T_{\lambda_1\lambda_2}$, with $\lambda_1 = \pm 1/2$ and $\lambda_2 = \pm 1, 0$ referring to the helicities of the $\Lambda$ and $J/\psi$ particles, respectively. The angular distribution is a function of five decay angles $(\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu)$ and has the form [8]

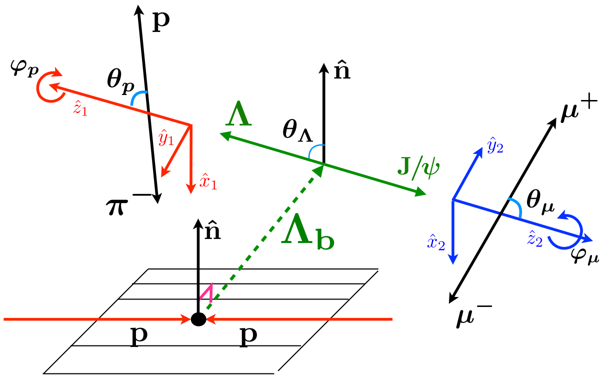

FIG. 1. Definition of the angles used to describe the $\Lambda_b \to J/\psi\Lambda$ decay into the $\mu^+\mu^-\ p\pi^-$ final state as explained in the text.

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$$\frac{d^5\Gamma}{d\cos\theta_\Lambda d\Omega_p d\Omega_\mu}(\theta_\Lambda,\theta_p,\theta_\mu,\varphi_p,\varphi_\mu) = \frac{1}{(4\pi)^3}\sum_{i=1}^{20} u_i(T_{\lambda_1\lambda_2})v_i(P,\alpha_\Lambda)w_i(\theta_\Lambda,\theta_p,\theta_\mu,\varphi_p,\varphi_\mu), \tag{2}$$

where $w_i$ are trigonometric functions, $u_i$ are bilinear combinations of the helicity amplitudes $T_{\lambda_1\lambda_2}$, and $v_i$ stands for 1, $P$, $\alpha_\Lambda$, or $P\alpha_\Lambda$; $P$ is the $\Lambda_b$ polarization and $\alpha_\Lambda$ is the asymmetry parameter in the decay $\Lambda \to p\pi^-$. The angle $\theta_\Lambda$ is the polar angle of the $\Lambda$ momentum relative to $\hat{n}$ in the $\Lambda_b$ rest frame; $\theta_p$ and $\varphi_p$ are the polar and azimuthal angles of the proton, respectively, defined with respect to the axes $\hat{z}_1 = \vec{p}_\Lambda/|\vec{p}_\Lambda|$ and $\hat{y}_1 = (\hat{n}\times\vec{p}_\Lambda)/|\hat{n}\times\vec{p}_\Lambda|$ in the rest frame of the $\Lambda$; and the angles $\theta_\mu$ and $\varphi_\mu$ are the polar and azimuthal angles, respectively, of the positively charged muon, defined with respect to the axes $\hat{z}_2 = \vec{p}_{J/\psi}/|\vec{p}_{J/\psi}|$ and $\hat{y}_2 = (\hat{n}\times\vec{p}_{J/\psi})/|\hat{n}\times\vec{p}_{J/\psi}|$ in the $J/\psi$ rest frame. Here, $\vec{p}_\Lambda$ and $\vec{p}_{J/\psi}$ are the momenta of the $\Lambda$ and $J/\psi$, respectively, and $d\Omega_p = d(\cos\theta_p)d\varphi_p$ and $d\Omega_\mu = d(\cos\theta_\mu)d\varphi_\mu$ are differential solid angles. Assuming uniform detector acceptance over the azimuthal angles $\varphi_p$ and $\varphi_\mu$, the angular distribution can be simplified through an integration over these two angles:

$$\begin{aligned}\frac{d^3\Gamma}{d\cos\theta_\Lambda d\cos\theta_p d\cos\theta_\mu}(\theta_\Lambda,\theta_p,\theta_\mu) &= \int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\frac{d^5\Gamma}{d\cos\theta_\Lambda d\Omega_p d\Omega_\mu}(\theta_\Lambda,\theta_p,\theta_\mu,\varphi_p,\varphi_\mu)d\varphi_p d\varphi_\mu \\ &\sim \sum_{i=1}^{8} u_i(|T_{\lambda_1\lambda_2}|^2)v_i(P,\alpha_\Lambda)w_i(\theta_\Lambda,\theta_p,\theta_\mu).\end{aligned} \tag{3}$$

The eight functional forms of $u_i$, $v_i$, and $w_i$ are listed in Table I. The $u_i$ factors are written in terms of the three angular decay parameters $\alpha_1$, $\alpha_2$, and $\gamma_0$ proposed in Ref. [8], and the constant 1, which themselves can be written in terms of the $T_{\lambda_1\lambda_2}$ amplitudes as

$$\begin{aligned} 1 &= |T_{++}|^2 + |T_{+0}|^2 + |T_{-0}|^2 + |T_{--}|^2, \\ \alpha_1 &= |T_{++}|^2 - |T_{+0}|^2 + |T_{-0}|^2 - |T_{--}|^2, \\ \alpha_2 &= |T_{++}|^2 + |T_{+0}|^2 - |T_{-0}|^2 - |T_{--}|^2, \\ \gamma_0 &= |T_{++}|^2 - 2|T_{+0}|^2 - 2|T_{-0}|^2 + |T_{--}|^2, \end{aligned} \tag{4}$$

where $\alpha_1$ is the asymmetry parameter for the decay $\Lambda_b \to J/\psi\Lambda$, $\alpha_2$ represents the longitudinal polarization of the $\Lambda$, and $\gamma_0$ is a parameter that depends on the longitudinal and transverse polarizations of the $J/\psi$ [9]. The $CP$ invariance of Eq. (3) implies that the parameters for $\Lambda_b$ and $\bar{\Lambda}_b$ are related as follows:

TABLE I. Functions used in Eq. (3) to describe the angular distribution in the decay $\Lambda_b \to J/\psi\Lambda$, with $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$.

| $i$ | $u_i$ | $v_i$ | $w_i$ |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | $\alpha_2$ | $\alpha_\Lambda$ | $\cos\theta_p$ |
| 3 | $-\alpha_1$ | $P$ | $\cos\theta_\Lambda$ |
| 4 | $-(1+2\gamma_0)/3$ | $\alpha_\Lambda P$ | $\cos\theta_\Lambda\cos\theta_p$ |
| 5 | $\gamma_0/2$ | 1 | $(3\cos^2\theta_\mu - 1)/2$ |
| 6 | $(3\alpha_1 - \alpha_2)/4$ | $\alpha_\Lambda$ | $\cos\theta_p(3\cos^2\theta_\mu - 1)/2$ |
| 7 | $(\alpha_1 - 3\alpha_2)/4$ | $P$ | $\cos\theta_\Lambda(3\cos^2\theta_\mu - 1)/2$ |
| 8 | $(\gamma_0 - 4)/6$ | $\alpha_\Lambda P$ | $\cos\theta_\Lambda\cos\theta_p(3\cos^2\theta_\mu - 1)/2$ |

$$\bar{P} = -P, \quad \bar{\alpha}_1 = -\alpha_1, \quad \bar{\alpha}_2 = -\alpha_2, \quad \bar{\gamma}_0 = \gamma_0. \tag{5}$$

In addition, $CP$ conservation in $\Lambda \to p\pi^-$ decays implies that $\bar{\alpha}_\Lambda = -\alpha_\Lambda$ [18]. In this analysis, the four parameters $(P, \alpha_1, \alpha_2, \gamma_0)$ are extracted from an analysis of the angular distribution given in Eq. (3), where $\alpha_\Lambda$ is fixed to its world-average value of $0.642 \pm 0.013$ [18].

## III. THE CMS DETECTOR

The CMS detector is used to study a wide range of phenomena produced in high-energy collisions, with its central feature being a superconducting solenoid of $6m$ internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate scintillating crystal electromagnetic calorimeter, and a brass and scintillator sampling hadron calorimeter, including a central barrel and endcap detectors, are located within the magnetic volume.

The silicon tracker detects charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles with transverse momentum of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in $p_T$ and 25–90 (45–150) $\mu$m in the transverse (longitudinal) impact parameter [19]. Muons are detected in gas-ionization chambers within the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers [20]. The global event reconstruction (also called particle-flow event reconstruction [21]) consists of reconstructing and identifying each individual particle with an optimized combination of all subdetector information. In this process, muons are identified as a track in the silicon tracker consistent with either a track or several hits in the muon system, associated with an energy deficit in the calorimeters.

Events of interest are selected using a two-tiered trigger system [22]. 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 time interval of less than 4 $\mu$s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17].

## IV. DATA AND SIMULATED EVENTS

We use data collected with a trigger designed for events containing a $J/\psi$ meson decaying to two muons that form a displaced vertex relative to the mean $pp$ collision point (beamspot). The requirement on the displacement does not affect the angular distributions of the reconstructed $\Lambda_b$ decay products. The dimuon trigger configurations were changed during the data taking at different center-of-mass energies, with increasingly stringent requirements to maintain an acceptable trigger rate as the instantaneous luminosity increased. The requirements of the different trigger versions are as follows: the $J/\psi$ candidates are selected in the invariant mass window 2.5–4.0 GeV and 2.9–3.3 GeV depending on the version; the angle ($\beta$) between the reconstructed momentum vector of the dimuon system and the vector pointing from the beamspot position to the dimuon vertex must have a value of $\cos\beta > 0.9$; the distance between the beamspot and the dimuon vertex in the transverse plane must have a value that is at least a factor of 3 larger than its uncertainty (standard deviation or SD); the muon pair must satisfy $p_{\mathrm{T}}^{\mu\mu} > 6.5$ or 6.9 GeV in the different versions; the $\chi^2$ probability of the fit of the two muons to a common vertex must exceed 0.05, 0.10, or 0.15 from the earliest to the latest version; each muon must be in $|\eta(\mu)| < 2.2$ and have $p_{\mathrm{T}}^{\mu} > 3.5$ or 4 GeV; and the distance of closest approach of each muon to the common vertex in the transverse plane must be less than 0.5 cm.

Simulated events of the signal decay are used to study the effects of detector acceptance and selection on the reconstructed angular distributions. The events are generated using PYTHIA 6.4[23] for production and hadronization, and EVTGEN [24] is used to describe the $b$ and $c$ hadron decays. The generated events are passed through the full CMS detector simulation based on GEANT4 [25]. The simulated event samples are generated to reproduce $\sqrt{s} = 7$ and 8 TeV data-taking conditions, where additional simulation of $pp$ interactions in the same or nearby beam crossings and the impact of the HLT are included. Simulated events are reconstructed and selected using the same algorithms and requirements as used for data.

## V. RECONSTRUCTION AND EVENT SELECTION

The offline selection requires pairs of oppositely charged muons originating from a common vertex to form the $J/\psi$ candidates. The standard CMS muon reconstruction procedure [20] is used to identify the muons. Since the trigger changed slightly over the different data-taking periods, the offline selection is required to be more restrictive than the most-stringent trigger, and is summarized as follows: (i) each muon must have $p_{\mathrm{T}}^{\mu} > 4$ GeV and the dimuon transverse momentum must satisfy $p_{\mathrm{T}}^{\mu\mu} > 8$ GeV; (ii) the $\chi^2$ probability must exceed 0.15; and (iii) the dimuon invariant mass must lie within ±150 MeV of the world-average $J/\psi$ mass [18]. Additional requirements are the same as the trigger selection and, to reduce background, the $J/\psi$ candidates must satisfy $\cos\beta > 0.99$.

The $\Lambda$ candidates are constructed from pairs of oppositely charged tracks that have a successful fit to a common vertex. Since the default CMS algorithms cannot distinguish between pions and protons, the higher- and lower-momentum tracks are assumed to have the proton and pion masses [18], respectively. The selections used for $\Lambda$ and $K_S^0$ particles are detailed in Ref. [26]. They are optimized to reduce background using the following additional requirements: (i) each track is required to have at least 6 hits in the silicon tracker and a $\chi^2$ track fit per degree of freedom $< 7$; (ii) the tracks coming from the $\Lambda$ decay are required to have $p_{\mathrm{T}}^{\pi} > 0.3$ GeV, $p_{\mathrm{T}}^{p} > 1.0$ GeV; (iii) the transverse impact parameter of the tracks relative to the beamspot is required to be greater than 3 SD; (iv) the probability of the two-track vertex fit must exceed 2%; (v) the transverse separation of the two-track vertex from the beamspot is required to be larger than 15 SD; (vi) the invariant mass of the $\Lambda$ candidate is selected to lie within ±9 MeV of the world-average value [18] and satisfy $p_{\mathrm{T}}^{p\pi} > 1.3$ GeV; and (vii) to reduce the contamination of $K_S^0 \to \pi^+\pi^-$ decays, events are removed if their invariant mass falls within ±20 MeV of the $K_S^0$ mass when the proton candidate is given the charged pion mass.

The $\Lambda_b$ candidates are fitted to a common vertex by combining the $J/\psi$ and $\Lambda$ candidates, with the respective mass constraints to the world-average values of the $J/\psi$ and $\Lambda$ masses [18]. The selection of $\Lambda_b$ candidates is optimized to reduce background with the additional requirements: $p_{\mathrm{T}}^{J/\psi\Lambda} > 10$ GeV, a $\chi^2$ probability of the fit to the $J/\psi\Lambda$ vertex $> 3\%$, and the $J/\psi\Lambda$ invariant mass $5.40 < m_{J/\psi\Lambda} < 5.84$ GeV.

To extract the number of signal and background events and to define the signal and sidebands regions, unbinned maximum likelihood fits to the reconstructed invariant mass ($m_{J/\psi\Lambda}$) distributions are performed, using separate data sets of the $\Lambda_b$ and $\bar{\Lambda}_b$ candidates at $\sqrt{s} = 7$ and 8 TeV. The signal shape is modeled by two Gaussian functions with different SDs, $\sigma_1$ and $\sigma_2$, but common mean $\mu_{J/\psi\Lambda}$, and the background by a first-order polynomial. We define in the four data sets the signal region as $\mu_{J/\psi\Lambda} \pm 16$ MeV, the lower sideband region as [5.46, 5.54] GeV, and the upper sideband region as

[5.70, 5.78] GeV. From the fits the $\Lambda_b$ yields are $981 \pm 39$ and $2072 \pm 55$ signal events, and the $\bar{\Lambda}_b$ yields are $916 \pm 40$ and $1974 \pm 53$ signal events at $\sqrt{s} = 7$ and 8 TeV, respectively.

## VI. MEASUREMENT OF THE POLARIZATION AND ANGULAR PARAMETERS

The analysis extracts the $\Lambda_b$ polarization, $P$, and the angular decay parameters $\alpha_1$, $\alpha_2$, and $\gamma_0$. The results are obtained from an unbinned maximum likelihood fit to the $J/\psi\Lambda$ invariant mass distribution and the three angular variables $\Theta_3 = (\cos\theta_\Lambda, \cos\theta_p, \cos\theta_\mu)$, using the extended likelihood function:

$$L = \exp\left(-N_{\mathrm{sig}} - N_{\mathrm{bkg}}\right)\prod^{N}[N_{\mathrm{sig}}PDF_{\mathrm{sig}} + N_{\mathrm{bkg}}PDF_{\mathrm{bkg}}], \tag{6}$$

where N is the total number of events, $N_{\mathrm{sig}}$ and $N_{\mathrm{bkg}}$ are the yields of signal and background events, respectively, determined from the fit in Sec. V, and $PDF_{\mathrm{sig}}$ and $PDF_{\mathrm{bkg}}$ represent the probability density functions (PDFs) for the signal and background, respectively. The $PDF_{\mathrm{sig}}$ has the form

$$PDF_{\mathrm{sig}} = F_{\mathrm{sig}}(\Theta_3)\epsilon(\Theta_3)G(m_{J/\psi\Lambda}), \tag{7}$$

where $F_{\mathrm{sig}}$ represents the theoretical angular distribution given by Eq. (3) and $G$ is the sum of two Gaussian functions used to model the $J/\psi\Lambda$ invariant mass distribution, as mentioned in Sec. V. The effect of the detector on the angular distribution is taken into account by the factor $\epsilon$ that represents the efficiency as a function of the angles.

To estimate the angular efficiency, simulated events of $\Lambda_b \to J/\psi\Lambda$ decays are generated with uniform distributions in $\cos\theta_\Lambda$, $\cos\theta_p$, and $\cos\theta_\mu$. After full detector simulation, reconstruction, and implementation of the final selection requirements, the slight differences between the simulated events and the background-subtracted data are minimized through a weighting procedure where weights are assigned to the simulated events to match the data. The weights are computed with an iterative process in which, for each iteration, the histograms of a selection variable in background-subtracted data and simulated events are used to calculate the ratio bin by bin (weight) with its propagated statistical uncertainty. The final weight per event is the product of the weights in each iteration. The efficiency distributions as a function of the variables are fit with a product of Chebyshev polynomials, where the coefficients are obtained for $\Lambda_b$ and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV in separate likelihood fits. The simulated efficiency distributions and the results of these fits are shown in Fig. 2 for the $\Lambda_b$ candidates at $\sqrt{s} = 8$ TeV.

The background $PDF_{\mathrm{bkg}}$ is given by the product of a first-order polynomial $\mathcal{P}(m_{J/\psi\Lambda})$ for the invariant mass and an angular distribution function $F_{\mathrm{bkg}}(\Theta_3)$:

$$PDF_{\mathrm{bkg}} = \mathcal{P}(m_{J/\psi\Lambda})F_{\mathrm{bkg}}(\Theta_3). \tag{8}$$

The background angular distributions $F_{\mathrm{bkg}}(\Theta_3)$ are estimated using events from the $m_{J/\psi\Lambda}$ invariant mass sidebands. They are modeled using Chebyshev polynomials for $\cos\theta_\Lambda$ and $\cos\theta_p$, and a product of two complementary error functions for $\cos\theta_\mu$, as shown in Fig. 3 for $\Lambda_b$ candidates at $\sqrt{s} = 8$ TeV.

The complete likelihood function in Eq. (6) is maximized by fitting simultaneously the four data sets for $\Lambda_b$ and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV, allowing for the extraction of the common parameters $P$, $\alpha_1$, $\alpha_2$, and $\gamma_0$. The simultaneous fit is performed in the enriched signal mass range within 3.5 SDs of the mean $\Lambda_b$ mass. This range contains more than 99.9% of the signal events, and significantly reduces the number of background events. As a result, the fit is less sensitive to the modeling discussed above. The fit parameters for the background and efficiency distributions

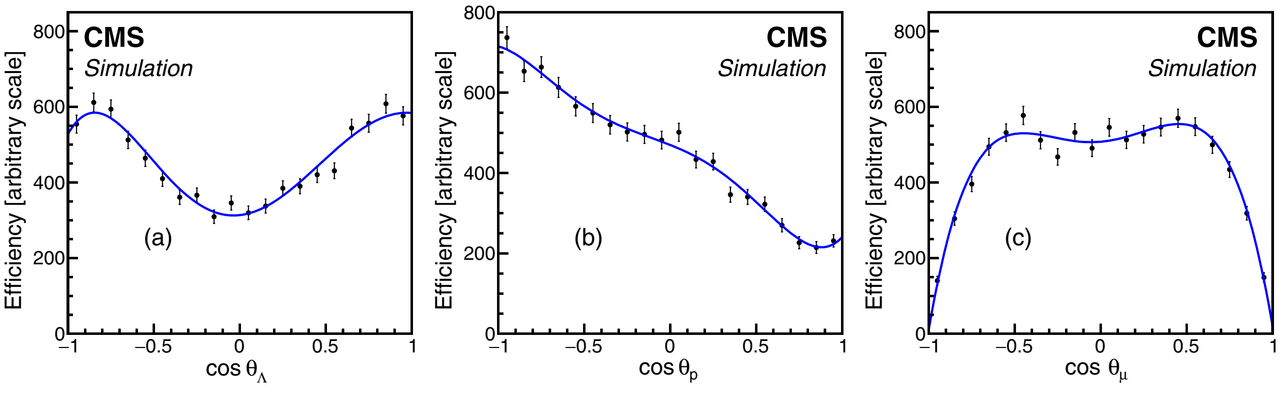

FIG. 2. The efficiencies as a function of (a) $\cos\theta_\Lambda$, (b) $\cos\theta_p$, and (c) $\cos\theta_\mu$ obtained from simulated $\Lambda_b \to J/\psi\Lambda$ decays at $\sqrt{s} = 8$ TeV. The vertical bars on the points are the statistical uncertainties in the simulated data, and the lines show the projections of a 3D fit to the distributions using Chebyshev polynomials. The scales of the vertical axes are arbitrary.

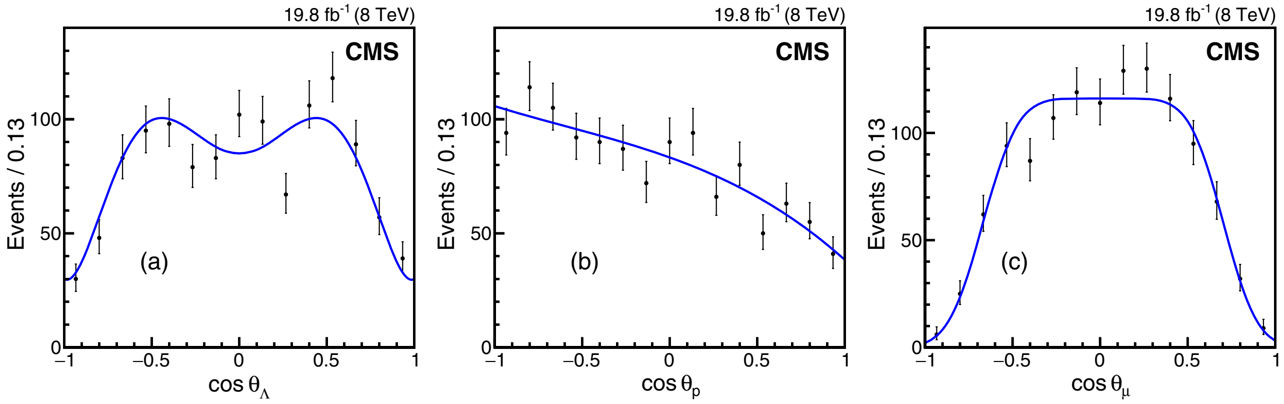

FIG. 3. The background angular distributions of (a) $\cos\theta_\Lambda$, (b) $\cos\theta_p$, and (c) $\cos\theta_\mu$ are shown, as obtained from the sidebands in the $J/\psi\Lambda$ invariant mass distribution at $\sqrt{s}=8$ TeV. The vertical bars on the points represent the statistical uncertainties, and the solid lines are the results of the fits to data as described in the text.

are fixed to those found in the previous fits. The signal and background mass parameters are obtained from previous fits to the mass distribution within 10 SDs, and the numbers of signal and backgrounds events are fixed to the propagated values in the signal mass region. The resulting fit values of the polarization and the three angular decay parameters are

$$P = 0.00 \pm 0.06, \qquad \alpha_1 = 0.14 \pm 0.14,$$
$$\alpha_2 = -1.11 \pm 0.04, \qquad \gamma_0 = -0.27 \pm 0.08,$$

where the uncertainties are statistical only. The correlation matrix of the fitted parameters is shown in Table II. No strong correlations are found among these parameters. Translating these values to the squares of the helicity amplitudes, the results are

$$|T_{++}|^2 = 0.05 \pm 0.04, \qquad |T_{+0}|^2 = -0.10 \pm 0.04,$$
$$|T_{-0}|^2 = 0.51 \pm 0.03, \qquad |T_{--}|^2 = 0.52 \pm 0.04,$$

where the uncertainties are statistical only. The projections of the fit are shown in Figs. 4 and 5 for $\Lambda_b$ and $\bar{\Lambda}_b$, respectively, using the combined data at $\sqrt{s} = 7$ and 8 TeV.

## VII. SYSTEMATIC UNCERTAINTIES

Various sources of systematic uncertainty that affect the measurement of the parameters $P$, $\alpha_1$, $\alpha_2$, and $\gamma_0$ are discussed below.

TABLE II. Correlation matrix for the fitted parameters.

| Parameter | $P$ | $\alpha_1$ | $\alpha_2$ | $\gamma_0$ |
|---|---|---|---|---|
| $P$ | 1 | −0.039 | −0.029 | 0.116 |
| $\alpha_1$ | | 1 | −0.207 | −0.030 |
| $\alpha_2$ | | | 1 | 0.285 |
| $\gamma_0$ | | | | 1 |

*Fit bias.*—The bias introduced through the fitting procedure is studied by generating 1000 pseudoexperiments using the measured parameters as inputs. The difference between the input and the mean of the fitted values is taken as the systematic uncertainty.

*Asymmetry parameter $\alpha_\Lambda$.*—This parameter is varied up and down by its uncertainty and the maximum deviation in the final result for each parameter is taken as the systematic uncertainty.

*Model for the background $m_{J/\psi\Lambda}$ distribution.*—An exponential function is used instead of the first-order polynomial in the likelihood fit. The parameter of the exponential and the background yield are varied by their uncertainties. The fit is redone taking into account this variation on the background model for the mass, and the differences between these results and the nominal fit results are taken as the systematic uncertainty for this source.

*Model for the background angular distributions.*—Alternative parametrizations of the background angular distributions are used to estimate the systematic uncertainty. For $\cos\theta_\Lambda$ and $\cos\theta_\mu$ the alternative models comprise a superposition of Gaussian kernels, as implemented in Roofit RooKeysPdf [27], while for $\cos\theta_p$ the alternative model is an error function. The differences relative to the nominal results are taken as the systematic uncertainties from the modeling of the background angular distributions.

*Model for the signal $m_{J/\psi\Lambda}$ distribution.*—We estimate this uncertainty by changing the parameters by their uncertainties, taking into account their correlations. In each sample of $\Lambda_b$ and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV, we use the parameter of the signal mass model with the largest global correlation and add 1 SD to its nominal value if the correlation is positive and subtract 1 SD if the correlation is negative. The difference relative to the nominal result is quoted as a systematic uncertainty.

*Angular efficiencies.*—The values of the Chebyshev polynomial coefficients that model the angular dependence of the efficiencies are changed by their uncertainties. The

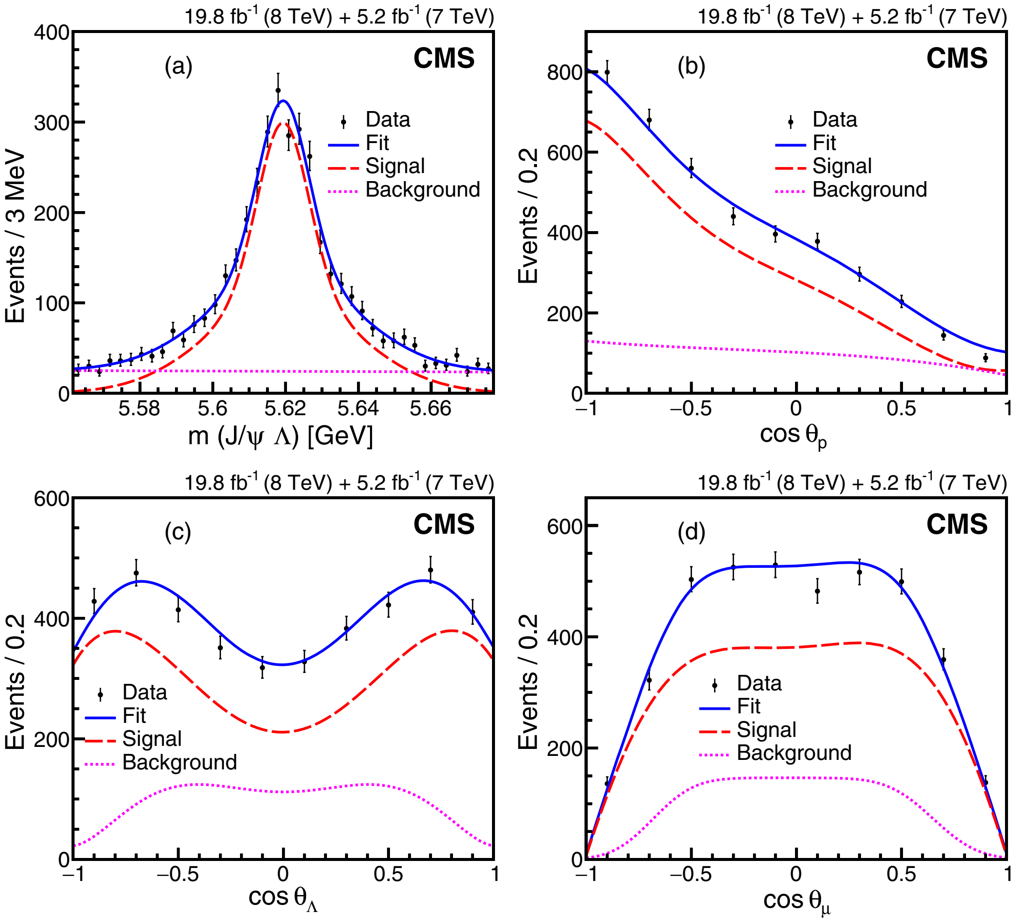

FIG. 4. Distributions in (a) $m_{J/\psi\Lambda}$, (b) $\cos\theta_p$, (c) $\cos\theta_\Lambda$, and (d) $\cos\theta_\mu$ for $\Lambda_b$ candidates in the combined $\sqrt{s} = 7$ and 8 TeV data. The vertical bars on the points are the statistical uncertainties in the data, the solid line shows the result of the fit, and the dashed and dotted lines represent, respectively, the signal and background contributions from the fit.

difference relative to the nominal fitted result is taken as the systematic uncertainty.

*Angular resolution.*—We study the systematic uncertainty in the angular resolution of the measured observables $\cos\theta_\Lambda$, $\cos\theta_p$, and $\cos\theta_\mu$ by first determining the resolution using simulated events, then taking the difference between the generated (before detector simulation) and reconstructed (fully simulated) distributions of the cosines of the three polar angles, and fitting the resulting distributions to Gaussian functions. Using these models, we generate random numbers that are added to the three polar angles of the events at generation. The difference between the obtained parameters from the likelihood fits using the same events, with and without the added random terms, is quoted as the systematic uncertainty from the angular resolution.

*Azimuthal angle efficiency.*—Uniform azimuthal efficiencies are assumed throughout the analysis. Besides simplifying the measurement from a five- to a three-dimensional angular analysis, this assumption also reduces the number of angular parameters from 6 to 3. The effect of the nonuniformity in the $\varphi_p$ and $\varphi_\mu$ efficiencies is investigated with 500 pseudoexperiments generated using the five-dimensional angular distribution, multiplied by the polar and azimuthal efficiencies obtained from the full simulation, as well as initializing the 3 extra parameters to values away from the physical boundary. The resulting distributions are then fitted to the nominal three-dimensional angular model. Differences in the mean values of $P$, $\alpha_1$, $\alpha_2$, and $\gamma_0$ relative to the input values (set to the nominal results) are taken as the systematic uncertainties from the impact of the nonuniformity of the azimuthal efficiencies.

*Weighting procedure.*— To estimate the uncertainty from the weighting procedure, we vary each weight by its uncertainty and use this as a new weight to correct the efficiencies, then redo the fit with these new values. The differences between the results of this fit and the nominal values are taken as the systematic uncertainty in each parameter.

*Reconstruction bias.*—Possible unaccounted reconstruction biases are also considered. To estimate this systematic uncertainty, we use a simulated event sample with input values of the helicity amplitudes and polarization similar to those observed in data. Then, after reconstruction and selection as in data, we fit the simulated events and take

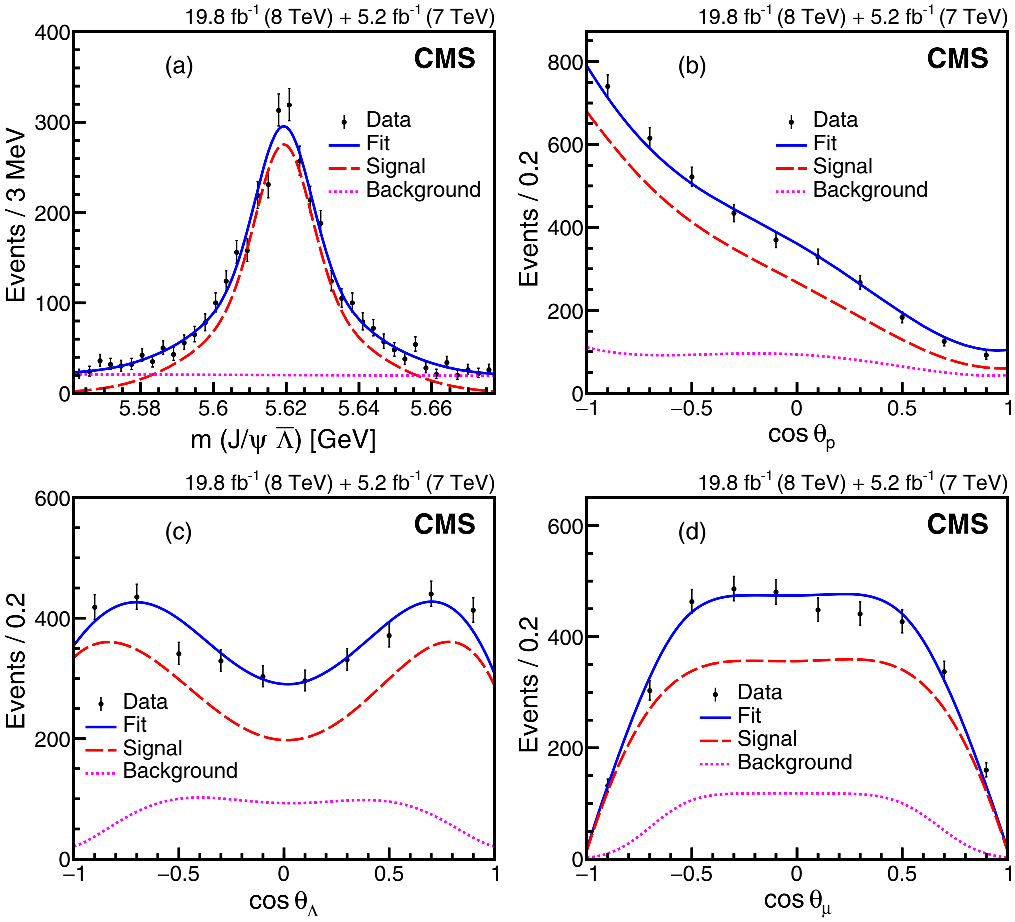

FIG. 5. Distributions in (a) $m_{J/\psi\bar{\Lambda}}$, (b) $\cos\theta_p$, (c) $\cos\theta_\Lambda$, and (d) $\cos\theta_\mu$ for $\bar{\Lambda}_b$ candidates in the combined $\sqrt{s} = 7$ and 8 TeV data. The vertical bars on the points are the statistical uncertainties in the data, the solid line shows the result of the fit, and the dashed and dotted lines represent, respectively, the signal and background contributions from the fit.

the differences between the input and fit values for every angular parameter and polarization. Since we are using the full reconstruction of the simulated events, we subtract in quadrature the systematic sources involved in the fit from those observed differences, and finally take the square root of this subtraction as the estimate of the systematic uncertainty component due to reconstruction bias. This systematic uncertainty is by far the largest uncertainty; however, it is still smaller or comparable to the corresponding statistical uncertainty.

TABLE III. The sources and values of the systematic uncertainties in each parameter and the total uncertainty. Each value in the table should be multiplied by $10^{-2}$ to obtain the corresponding systematic uncertainty.

| Source | $P(\times 10^{-2})$ | $\alpha_1(\times 10^{-2})$ | $\alpha_2(\times 10^{-2})$ | $\gamma_0(\times 10^{-2})$ |
|---|---|---|---|---|
| Fit bias | 0.1 | 0.3 | 0.1 | 0.2 |
| Asymmetry parameter $\alpha_\Lambda$ | 0.4 | 0.7 | 2.0 | 0.6 |
| Background $m_{J/\psi\Lambda}$ distribution | 0.01 | 0.5 | 1.0 | 0.9 |
| Background angular distribution | 0.4 | 0.5 | 0.9 | 5.0 |
| Signal $m_{J/\psi\Lambda}$ distribution | 0.01 | 0.3 | 1.0 | 1.0 |
| Angular efficiencies | 0.1 | 0.3 | 3.0 | 1.0 |
| Angular resolution | 1.0 | 0.1 | 2.6 | 0.8 |
| Azimuthal angle efficiency | 0.1 | 1.0 | 0.3 | 0.1 |
| Weighting procedure | 0.1 | 1.3 | 0.4 | 2.0 |
| Reconstruction bias | 5.7 | 9.8 | 2.0 | 9.1 |
| Total (quadrature sum) | 5.8 | 10.0 | 5.1 | 11.1 |

The contributions from the different uncertainty sources are assumed to be independent and the total systematic uncertainty is calculated as the quadrature sum of all uncertainties. The values of the systematic uncertainties in each parameter from the individual sources and their quadrature sum are given in Table III.

## VIII. SUMMARY AND CONCLUSIONS

Based on an angular analysis of about 6000 $\Lambda_b \to J/\psi(\to\mu^+\mu^-)\Lambda(\to p\pi^-)$ events collected by the CMS experiment at $\sqrt{s}=7$ and 8 TeV, a measurement of the $\Lambda_b$ polarization $P$, the parity-violating asymmetry parameter in the $\Lambda_b$ decay $\alpha_1$, the $\Lambda$ longitudinal polarization $\alpha_2$, and the parameter $\gamma_0$ has been performed. The obtained values are

$$\begin{aligned} P &= 0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}),\\ \alpha_1 &= 0.14 \pm 0.14(\text{stat}) \pm 0.10(\text{syst}),\\ \alpha_2 &= -1.11 \pm 0.04(\text{stat}) \pm 0.05(\text{syst}),\\ \gamma_0 &= -0.27 \pm 0.08(\text{stat}) \pm 0.11(\text{syst}), \end{aligned}$$

corresponding to the squares of the helicity amplitudes

$$\begin{aligned} |T_{++}|^2 &= 0.05 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}),\\ |T_{+0}|^2 &= -0.10 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}),\\ |T_{-0}|^2 &= 0.51 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}),\\ |T_{--}|^2 &= 0.52 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}). \end{aligned}$$

The measured $\Lambda_b$ polarization value given above is consistent with the LHCb measurement [11] and theoretical predictions of 0.10 [5] and 0.20 [6]. Note that in our notation, $\alpha_1$ is the negative value of $\alpha_b$ referred to in the theory [9,10,28–31], LHCb [11], and ATLAS [12] papers. To compare with the theoretical predictions and the other measurements, we use the negative of our measured value of $\alpha_1$. The many theoretical predictions for $-\alpha_1$ include −0.2 to −0.1 from quark model techniques [9,28–31], −0.17 to −0.14 from perturbative quantum chromodynamics calculations [10], and 0.78 from heavy-quark effective theory [4,6]. The measured value is inconsistent at more than 5 standard deviations with the heavy-quark effective theory prediction, but is consistent at less than one standard deviation with the other predictions. The presented measurement of $\alpha_1$ is also consistent with the measurements $0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$ and $0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ by LHCb [11] and ATLAS [12], respectively, and with no parity violation at the level of one standard deviation. The measurement of $\alpha_2$, compatible with $-1$, indicates that the positive-helicity states of the $\Lambda$ coming from the $\Lambda_b$ decay are suppressed.

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