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Observation of a New Ξ_b Baryon

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The observation of a new b baryon via its strong decay into $\Xi_b^- \pi^+$ (plus charge conjugates) is reported. The measurement uses a data sample of pp collisions at $\sqrt{s} = 7$ TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 5.3 fb^{-1} . The known Ξ_b^- baryon is reconstructed via the decay chain $\Xi_b^- \rightarrow J/\psi \Xi^- \rightarrow \mu^+ \mu^- \Lambda^0 \pi^-$, with $\Lambda^0 \rightarrow p \pi^-$. A peak is observed in the distribution of the difference between the mass of the $\Xi_b^- \pi^+$ system and the sum of the masses of the Ξ_b^- and π^+ , with a significance exceeding 5 standard deviations. The mass difference of the peak is $14.84 \pm 0.74(\text{stat}) \pm 0.28(\text{syst}) \text{ MeV}$. The new state most likely corresponds to the $J^P = 3/2^+$ companion of the Ξ_b .

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According to the well-established quark model and corresponding spectroscopy of baryons, there are several predicted baryons containing one strange and one beauty valence quark. These include the Ξ_b (ground state) and Ξ_b' , both with total angular momentum and parity $J^P = 1/2^+$, a $J^P = 3/2^+$ state with angular momentum $L = 0$ (often referred to, as will be done in this Letter, as Ξ_b^*), and two states with $J^P = 1/2^-$ and $3/2^-$, both with angular momentum $L = 1$. These baryons can be neutral (valence quark content $u - s - b$) or negatively charged ($d - s - b$). At the Tevatron, baryons with masses and decay modes consistent with the theoretical predictions for the ground state Ξ_b baryons have been observed [1–3], although their quantum numbers have not yet been established. The allowed decays of the experimentally missing Ξ_b states should be analogous to the charmed sector [4–6]. In addition, theoretical calculations [7–11] predict the mass difference between the Ξ_b' and Ξ_b to be smaller than the mass of the pion, in which case the strong decay $\Xi_b' \rightarrow \Xi_b$ is kinematically forbidden. The mass difference between the Ξ_b^* and Ξ_b , however, is expected to be large enough to allow such a decay.

This Letter presents a search for the decay $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$, with $\Xi_b^- \rightarrow J/\psi \Xi^-$, $J/\psi \rightarrow \mu^+ \mu^-$, $\Xi^- \rightarrow \Lambda^0 \pi^-$, and $\Lambda^0 \rightarrow p \pi^-$. Charge conjugate states are implied throughout. The reconstruction of such decays involves the presence of three secondary vertices, where the Ξ_b^- , Ξ^- , and Λ^0 decay, which are well separated from the primary interaction vertex. The analysis is based on a data sample of pp collisions at $\sqrt{s} = 7$ TeV, collected in 2011 by the Compact Muon Solenoid (CMS) experiment at the

Large Hadron Collider (LHC), corresponding to an integrated luminosity of 5.3 fb^{-1} .

The CMS apparatus is described in detail in Ref. [12]. Its central feature is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. The main subdetectors used in this analysis are the silicon tracker and the muon systems. The silicon tracker, composed of pixel and strip detector modules, is immersed in the magnetic field, and enables the measurement of charged particle momenta over the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln(\tan\theta/2)$ and θ is the polar angle of the track relative to the counterclockwise beam direction. Muons are identified in the range $|\eta| < 2.4$ using gas-ionization detectors embedded in the steel return yoke of the magnet.

The events used in this analysis were collected using the two-level trigger system of CMS. The first level consists of custom hardware processors and uses information from the muon systems to select events with two muons. The “high-level trigger” processor farm further decreases the event rate before data storage, requiring two opposite-sign muons compatible with being the decay products of a J/ψ , either promptly produced or displaced from the primary vertex (PV). The nonprompt J/ψ trigger requires two opposite-sign muons with an invariant mass within 200 MeV of the J/ψ mass [13], single muon transverse momentum $p_T > 3, 3.5, 4, \text{ or } 5 \text{ GeV}$, and dimuon vertex fit χ^2 probability larger than 10% or 15%. The requirements were made tighter depending on the LHC instantaneous luminosity so as to limit the trigger rate. In addition, the dimuon vertex must be separated from the beam line by more than 3 times the uncertainty on the separation σ_{vertex} , which includes the transverse vertex resolution (independently estimated for each event) and the beam line position uncertainty. Finally, the requirement $\cos\alpha > 0.9$ is also applied, where α is the angle, in the plane transverse to the beam, between the dimuon momentum and the direction from the beam line to the dimuon vertex. The prompt J/ψ trigger requires two opposite-sign muons with an

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invariant mass within 250 MeV of the J/ψ mass [13], dimuon $p_T > 10$ or 13 GeV (depending on the instantaneous luminosity), dimuon rapidity $|y| < 1.25$, and dimuon vertex fit χ^2 probability greater than 0.5%.

The reconstruction of the $\Xi_b^- \rightarrow J/\psi \Xi^-$ candidates begins by identifying $J/\psi \rightarrow \mu^+ \mu^-$ decays. The candidate J/ψ mesons are built by combining pairs of oppositely charged muons (tracks in the silicon tracker matched to tracks in the muon detectors) satisfying the trigger conditions and having an invariant mass within 150 MeV of the J/ψ mass. Candidate Λ^0 baryons are reconstructed in decays to a pion (π_Λ) and a proton (p) with opposite charges, where the higher momentum track is assumed to be the proton. Both tracks are required to have a track fit $\chi^2/\text{ndf} < 5$, where ndf is the number of degrees of freedom, and at least six hits in the silicon tracker. The Λ^0 candidate vertex must have a fit $\chi^2/\text{ndf} < 7$ and be displaced from the beam line by more than $10\sigma_{\text{vertex}}$. Possible contamination from misreconstructed K_S mesons is removed by requiring that the candidate mass, when assuming that both tracks are pions, differs from the K_S mass [13] by more than 20 MeV. Candidate Ξ^- baryons are reconstructed by combining a Λ^0 candidate with a track (π_Ξ) of the same charge as the π_Λ . A kinematic vertex fit [14] is performed, assuming that the track is a pion, and with the Λ^0 candidate mass constrained to its world-average value [13]. A veto window of 20 MeV around the Ω^- mass [13] is applied when assuming that the π_Ξ candidate is a kaon. The Ξ^- is then combined with the J/ψ to form a Ξ_b^- candidate, with a kinematic vertex fit constraining their masses to the world-average values [13]. On average, the events used in this analysis have around eight reconstructed primary vertices (PV). The PV closest in three dimensions to the Ξ_b^- trajectory is taken as the one where the Ξ_b^- was produced.

The Ξ_b^- signal selection criteria are chosen by an iterative algorithm that maximizes both the signal yield and the significance, calculated as $S/\sqrt{S+B}$, where the signal (S) and background (B) yields are evaluated in a window of ± 40 MeV around the Ξ_b^- mass, 5790.5 ± 2.7 MeV [13]. The value of B is linearly interpolated to this signal region from the two mass sidebands, located between 40 and 100 MeV away from the peak value. Thirty variables are used to optimize the Ξ_b^- signal selection. At every iteration, two variables are chosen randomly, where one of them is tightened and the other loosened. If S and the significance increase, the new set of values is accepted. To avoid ending up in a local maximum, an iteration is accepted if the significance decreases by less than a random number uniformly generated between 0 and 10%. The variables used for the selection include the p_T of both muons, and of the J/ψ , p , π_Λ , π_Ξ , Ξ^- , and Ξ_b^- . The muons and Ξ_b^- can have different p_T selections in the pseudorapidity regions $|\eta| < 1.2$ and $|\eta| > 1.2$, where $|\eta| = 1.2$ is the transition between the barrel and endcap detectors. The algorithm

also tunes the requirements on the differences between the reconstructed masses and the world-average masses for the Λ^0 , Ξ^- , and J/ψ , with the latter case being different for $|\eta(J/\psi)| < 1.2$ and $|\eta(J/\psi)| > 1.2$. Also, the total J/ψ pseudorapidity coverage can be adjusted to be smaller than the full $|\eta(J/\psi)| < 2.4$ range.

To select a Ξ_b^- sample with a good signal-over-background ratio, it is important to reject promptly produced tracks. This is done via a selection on their transverse impact parameter significances $D_{\text{ip}}/\sigma_{D_{\text{ip}}}$, where the impact parameter D_{ip} is calculated with respect to the beam line and $\sigma_{D_{\text{ip}}}$ is its uncertainty. This procedure is applied to the p , π_Λ , and π_Ξ tracks, as well as to the Λ^0 and Ξ^- trajectories. Long-lived particles (Λ^0 , Ξ^- , and Ξ_b^-) are selected by requirements on their transverse decay lengths and on the significance $L_{xy}/\sigma_{L_{xy}}$ of the transverse distance between their production and decay vertices L_{xy} , where $\sigma_{L_{xy}}$ is the uncertainty of L_{xy} . Minimal fit confidence levels are required on the Λ^0 , Ξ^- , and Ξ_b^- decay vertices, while the three-dimensional distance significance must be smaller than the optimized thresholds for the distances between the Ξ^- trajectory and the J/ψ decay vertex, as well as between the Ξ_b^- trajectory and the chosen PV.

The $J/\psi \Xi^-$ invariant-mass distribution for the Ξ_b^- candidates passing the selection criteria is shown in Fig. 1, together with the result of a fit with a Gaussian function representing the signal plus a second-order polynomial representing the background, which gives a signal yield of 108 ± 14 events. The same figure also displays the invariant-mass distribution for background events, in which the π_Ξ and proton have the same charge, giving

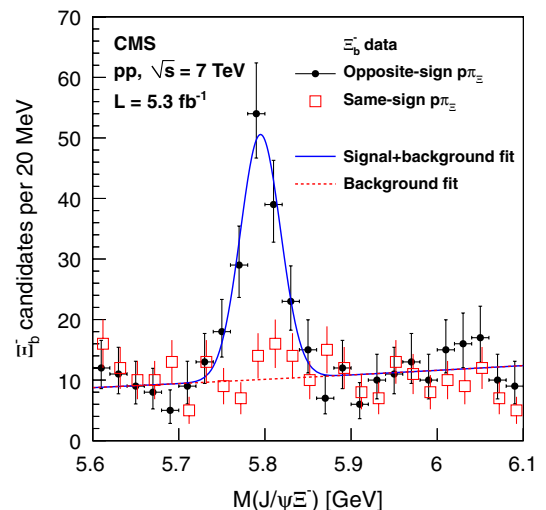


FIG. 1 (color online). Invariant-mass distributions of the selected Ξ_b^- candidates (closed circles) and of the $J/\psi \Xi^-$ pairs where the proton and π_Ξ have the same charge (open squares). The blue solid curve represents the result of the signal-plus-background fit to the Ξ_b^- distribution, while the red dashed line shows the corresponding background component.

further evidence that the observed peak corresponds to a real Ξ_b^- signal. The Ξ_b^- mass extracted from the fit is $5795.0 \pm 3.1(\text{stat})$ MeV, in good agreement with the world-average value [13]. The corresponding mass resolution is $23.7 \pm 3.2(\text{stat})$ MeV, in agreement with the value 22.5 ± 4.7 MeV, obtained from a detailed Monte Carlo (MC) simulation of the CMS detector response, using PYTHIA 6.409 [15], EVTGEN [16], and GEANT4 [17].

To search for Ξ_b^{*0} baryons, the Ξ_b^- candidates with a mass within 2.5 standard deviations of the fitted peak value are combined with tracks, assumed to be pions, with a charge opposite to the π_Ξ charge (opposite-sign pairs) and coming from the selected PV, with a significance less than 3 standard deviations on the distance between the track trajectory and the PV. Other quality requirements applied to the tracks are $p_T > 0.25$ GeV, at least two hits in the silicon pixel layers, at least five hits in the entire tracker, and a track fit $\chi^2/\text{ndf} < 2.5$.

The Ξ_b^{*0} search uses the mass difference Q between the measured $J/\psi \Xi_b^- \pi^+$ invariant mass and the sum of the masses of the decay products, $Q = M(J/\psi \Xi_b^- \pi^+) - M(J/\psi \Xi_b^-) - M(\pi)$, where $M(\pi)$ is the charged-pion mass [13]. The search for new resonances in the Q distribution requires a reliable background shape. A background model is built using candidates where the prompt pion and the Ξ_b^- have the same charge (same-sign pairs), given that the background is expected to be dominated by combinatorial sources, as checked by MC studies. The measured momentum distributions of Ξ_b^- candidates and same-sign pions ($p(\Xi_b^-)$, $p(\pi)$), together with the distribution of the angle between them (α), are used to randomly generate uncorrelated values for $p(\Xi_b^-)$, $p(\pi)$, and α . Given the limited statistical precision of the Ξ_b^- momentum distribution, the corresponding random numbers are generated from a parametrized version using the fit function $f_{\Xi_b^-}(p) = p^{k_1} e^{-k_2 p}$, where k_i are free parameters. The three random values are then combined to calculate a Q value for predicting the combinatorial background distribution. One hundred million Q values are generated in this way and the resulting distribution is fitted to the function $Q^{c_1}(e^{-c_2 Q} + e^{-c_3 Q} + e^{-c_4 Q})$, where c_i are free parameters. Figure 2(a) compares the Q distribution of the same-sign Ξ_b^{*0} candidates with the predicted background shape. Alternative functional forms of $f_{\Xi_b^-}(p)$ are used to estimate the systematic uncertainty associated with this method, which contributes to the determination of the background parameters.

The measured opposite-sign Q distribution is displayed in Fig. 2(b) for the range 0–50 MeV. The 21 events observed in the region $12 < Q < 18$ MeV represent a clear excess with respect to the expected background yield of 3.0 ± 1.4 events, evaluated by integrating the background function in this Q window. An unbinned maximum-likelihood fit is performed to the opposite-sign Q distribution with a Breit-Wigner distribution convolved with a

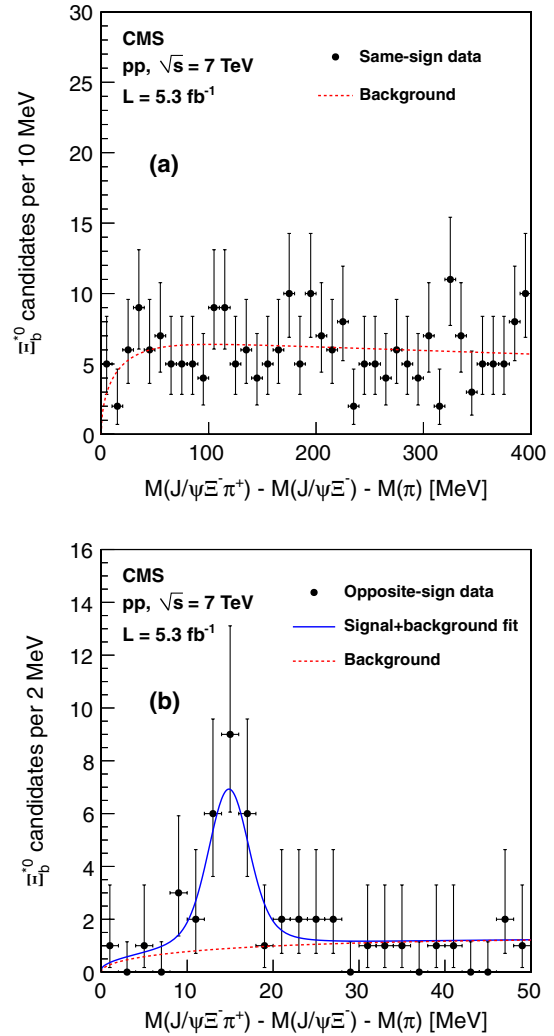


FIG. 2 (color online). (a) Same-sign Q distribution (closed circles) and result of a fit with the background model (red dashed curve) in the range $0 < Q < 400$ MeV. (b) Opposite-sign Q distribution (closed circles) in the $0 < Q < 50$ MeV range, along with the result of the signal-plus-background fit (blue solid curve); the background term is also shown (red dashed curve).

Gaussian function, added to the background function previously described. The Gaussian resolution of the peak is constrained to 1.91 ± 0.11 MeV, as determined in the signal MC simulation, and the background parameters are allowed to float within their total uncertainties (statistical plus systematic, added in quadrature). Figure 2(b) also shows the result of the fit. A peak is clearly visible above the background continuum. The fitted parameters of the peak are $Q = 14.84 \pm 0.74(\text{stat})$ MeV and Breit-Wigner width $\Gamma = 2.1 \pm 1.7(\text{stat})$ MeV. The fitted Breit-Wigner width agrees with $\Gamma = 0.51 \pm 0.16$ MeV, the value obtained following Eq. (102) of Ref. [18], based on lattice quantum chromodynamic calculations.

To evaluate the significance of the signal, the likelihood L_{s+b} of the signal-plus-background fit is determined. The

fit is then repeated using the background-only model to obtain a new likelihood L_b . The parameters obtained from the background fit are allowed to float so that their uncertainties and correlations contribute to the calculation of the significance. The logarithmic likelihood ratio $\sqrt{\ln(L_{s+b}/L_b)}$ would indicate a statistical significance of 6.9 standard deviations (σ), corresponding to a probability of 2.5×10^{-12} for a background fluctuation of this significance or more to be observed. The significance remains the same if the fit is repeated using the theoretically expected width, allowing it to vary within the range of the theoretical uncertainty. The signal significance is also evaluated by generating pseudoexperiments in which the background distribution is varied within its statistical uncertainty, and determining the background fluctuation probability (“ p value”) as the number of experiments that give a fit with the same significance or higher than in the data. The “look-elsewhere effect” [19] is assessed by searching for a peak, of width Γ between 0 and 25 MeV, in the extended mass range $0 < Q < 50$ MeV, where the Ξ_b^{*0} is theoretically expected. The resulting background fluctuation probability is $p = 1.3 \times 10^{-8}$, which corresponds to a 5.7σ equivalent Gaussian significance. If the search range is further extended to $0 < Q < 400$ MeV, the equivalent Gaussian significance becomes 5.3σ .

This analysis has been repeated using simulated B^+ , B^0 , B_s , and Λ_b samples, obtained by the detailed MC simulation of the CMS detector already mentioned. The samples contain events in which the b hadron is forced to decay to a J/ψ , which decays to $\mu^+\mu^-$. No evidence of peaks due to partially reconstructed b -hadron decays is observed in these samples. The opposite-sign Q distribution obtained using Ξ_b^- candidates from the lower- and higher-mass sidebands of the signal peak also shows no excess, indicating that the observed peak is not caused by fake Ξ_b^- candidates.

The systematic uncertainty on the measured Q value is evaluated through the signal MC simulation. The reconstructed Q value in MC simulations is measured to be 0.23 ± 0.10 MeV above the generated value. This is consistent with the observation that the measured Λ^0 and Ξ^- masses are 0.16 ± 0.05 and 0.18 ± 0.14 MeV, respectively, above their world averages. The sum in quadrature of the shift and its statistical uncertainty, 0.25 MeV, is considered as the systematic uncertainty due to this effect. As an extreme fitting scenario, a flat function is used for the background shape, leading to a Q value 0.12 MeV higher than the value measured with the nominal background model. Adding in quadrature this uncertainty with the previous one results in a total Q systematic uncertainty of 0.28 MeV.

The observation of this resonance, corresponding to the one observed in the charm sector [4], and its mass measurement add valuable information to the understanding of the interactions between quarks within a baryon.

In summary, a new Ξ_b^- baryon has been observed in pp collisions at $\sqrt{s} = 7$ TeV, using data collected by the CMS experiment, corresponding to an integrated luminosity of 5.3 fb^{-1} . The signal is observed with a significance exceeding 5 standard deviations. The measured $Q = M(J/\psi \Xi^- \pi^+) - M(J/\psi \Xi^-) - M(\pi)$ value is $14.84 \pm 0.74(\text{stat}) \pm 0.28(\text{syst})$ MeV. Given the charged-pion and Ξ_b^- masses [13], the resulting b -baryon mass is $5945.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.7(\text{PDG})$ MeV, where the last uncertainty reflects the present accuracy of the Ξ_b^- mass from the Particle Data Group [13]. While the width of the new baryon is not measured with good statistical precision, it is compatible with theoretical expectations [18]. Given its measured mass and decay mode, the new baryon is likely to be the Ξ_b^{*0} , with $J^P = 3/2^+$.

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