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Measurement of b-hadron masses with exclusive $J/\psi X$ decays in 2010 data

The LHCb Collaboration[1]

Abstract

We report b-hadron mass measurements with the exclusively reconstructed decays $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_S$, $B^0_s \to J/\psi \phi$, $\Lambda_b \to J/\psi \Lambda$ and $B^+_c \to J/\psi \pi^+$ using approximately 35 pb^{-1} of data collected with the LHCb detector during the 2010 physics run of the LHC. The momentum scale is calibrated with $J/\psi \to \mu^+\mu^-$ decays. The preliminary results are

$$\begin{aligned}
M(B^+ \to J/\psi K^+) &= 5279.27 \pm 0.11\,(\text{stat}) \pm 0.20\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0 \to J/\psi K^{*0}) &= 5279.54 \pm 0.15\,(\text{stat}) \pm 0.16\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0 \to J/\psi K^0_S) &= 5279.61 \pm 0.29\,(\text{stat}) \pm 0.20\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0_s \to J/\psi \phi) &= 5366.60 \pm 0.28\,(\text{stat}) \pm 0.21\,(\text{syst})\ \text{MeV}/c^2,\\
M(\Lambda_b \to J/\psi \Lambda) &= 5619.49 \pm 0.70\,(\text{stat}) \pm 0.19\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^+_c \to J/\psi \pi^+) &= 6268.0 \pm 4.0\,(\text{stat}) \pm 0.6\,(\text{syst})\ \text{MeV}/c^2.
\end{aligned}$$

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1 Introduction

In the Standard Model of particle physics, mesons and baryons are colourless objects made of quarks and gluons. They are bound together through the strong interaction described by Quantum ChromoDynamics (QCD). A property of hadrons that can be confronted to the theoretical predictions of QCD is their masses. Recent observations of strange b-baryons at Fermilab [1] triggered significant developments within the theory community (see for example Ref. [2]). The current knowledge of the masses of the b-hadrons observed so far at LHCb is reported in Table 1. The mass measurement of the exclusively reconstructed decays $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_{\rm S}$, $B^0_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$ and $B^+_c \to J/\psi\pi^+$ is reported in this analysis.

b-hadron	World-average mass
B^+	5279.17 ± 0.29 MeV/c^2
B^0	5279.50 ± 0.30 MeV/c^2
B^0_s	5366.3 ± 0.60 MeV/c^2
Λ_b	5620.2 ± 1.6 MeV/c^2
B^+_c	6277 ± 6 MeV/c^2

Table 1: Measured b-hadron masses, as quoted by the Particle Data Group [3].

2 Data samples and event selection

This analysis uses an integrated luminosity of approximately 35 pb^{-1} of pp-collision data recorded with the LHCb detector [4] at a centre-of-mass energy of $\sqrt{s} = 7$ TeV between July and November 2010. All detector components were fully operational and in stable conditions. The dataset comprises two distinct sub-samples recorded with opposite directions of the magnetic field in the spectrometer dipole, each of approximately 17 pb^{-1}.

The six decay channels considered in this analysis are $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_{\rm S}$, $B^0_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$ and $B^+_c \to J/\psi\pi^+$, with $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$, $K^{*0} \to K^-\pi^+$, $K^0_{\rm S} \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ (charge-conjugate modes are implied throughout the text). The event selections are strongly inspired from those developed for recent preliminary measurements of the B^+, B^0, B^0_s and Λ_b lifetimes [5] and of the relative B^+_c to B^+ production cross-section [6] performed with the same data sample. For the purpose of mass measurements, where a high signal purity is desired, only candidates with a measured proper time larger than 0.3 ps are used. In addition, to maximise the statistics, all events are used no matter which trigger algorithm retained them. However, most of the events have passed the single- or di-muon triggers. The mass resolution of the reconstructed b-hadron candidates is improved by constraining the J/ψ mass to its known value [3] in the vertex fit. An additional constraint is applied on the $K^0_{\rm S}$ and Λ mass when fitting $B^0 \to J/\psi K^0_{\rm S}$ and $\Lambda_b \to J/\psi\Lambda$ candidates, respectively.

Decay mode	Yield	Uncorrected mass (MeV/c^2)	Mass resolution (MeV/c^2)
$B^+ \to J/\psi K^+$	11151 ± 115	5278.39 ± 0.11	10.50 ± 0.10
$B^0 \to J/\psi K^*$	3308 ± 65	5278.71 ± 0.17	7.73 ± 0.15
$B^0 \to J/\psi K_S$	1184 ± 38	5278.68 ± 0.30	8.62 ± 0.26
$B_s^0 \to J/\psi \phi$	816 ± 30	5366.26 ± 0.28	6.96 ± 0.25
$\Lambda_b \to J/\psi \Lambda$	279 ± 19	5628.37 ± 0.70	9.00 ± 0.61
$B_c^+ \to J/\psi \pi^+$	25.1 ± 6.6	6266.1 ± 4.0	13.9 ± 3.7

Table 2: Fitted values of the signal yields, uncorrected mass values and mass resolutions.

Decay mode	Measured mass [MeV/c^2]	PDG average [MeV/c^2]
$\Upsilon \to \mu^+\mu^-$	9459.90 ± 0.54	9460.30 ± 0.26
$\psi(2S) \to J/\psi(\mu\mu)\pi^+\pi^-$	3686.12 ± 0.06	3686.09 ± 0.04
$J/\psi \to \mu^+\mu^-$	3096.97 ± 0.01	3096.916 ± 0.011
$D^0 \to K^-\pi^+$	1864.75 ± 0.07	1864.83 ± 0.14
$K_S^0 \to \pi^+\pi^-$	497.62 ± 0.01	497.61 ± 0.02

Table 3: Measured masses of different decays after the momentum scale calibration procedure, compared to the PDG averages [3]. The errors quoted in the middle column are statistical only; systematics errors are expected to be larger than the statistical errors.

Unbinned maximum likelihood fits, where the signal is described with a Gaussian function and the background with an exponential function, are performed on the reconstructed mass distributions of the six considered decay modes to extract the number of signal events, the mass values and the mass resolutions reported in Table 2.

3 Momentum scale calibration

The momentum scale is calibrated using a large sample of $J/\psi \to \mu^+\mu^-$ decays. This calibration, obtained as an average overall scale factor to be applied on all raw measurements of the track momenta, accounts for a mixture of effects related to imperfections in the knowledge of the magnetic field map and of the alignment of the tracking system. After calibration, the relative difference between the measured average J/ψ mass and the known value is 2×10^{-5} (see Table 3), which is a factor 5 smaller than the systematic uncertainty of 0.1 per mille assigned on the momentum scale factor. The calibration is checked to be valid for two-body decays of the Υ, D^0 and K_S^0, as well as for the decay $\psi(2S) \to J/\psi\pi^+\pi^-$ (see Table 3). The measured J/ψ mass after alignment and calibration is checked to be stable over the whole 2010 data-taking period (see Fig. 1).

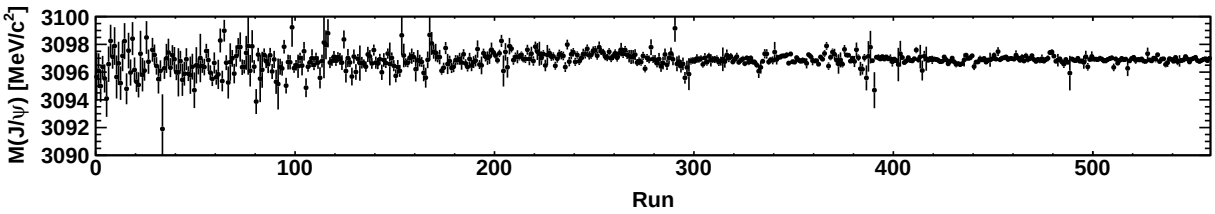

Figure 1: Measured J/ψ mass as a function of run number during the entire 2010 data-taking period. Error bars are statistical.

4 Results and systematic uncertainties

The fitted b-hadron mass distributions after the calibration of the momentum scale are shown in Fig. 2. The following sources of systematic uncertainty are considered:

Mass fitting: The default fitting function assumes a Gaussian signal and an exponential background component. To test the dependence of the results on the fit model fits are performed assuming a double Gaussian signal and/or a flat background component. In each case the difference with respect to the default results is assigned as a systematic error.

Momentum calibration: Fits are performed varying the momentum scale factor within its ± 0.1 per mille uncertainty, determined from the J/ψ calibration procedure. The difference of the results to the central value is taken as an estimate of the systematic error. In addition, a residual bias on the momentum scale is observed as a function of track pseudo-rapidity η. To estimate the impact on the result the bias is parameterized and used to give an η-dependent momentum scale calibration. Again the difference of the result of this fit to that obtained with the constant calibration is taken as an estimate of the systematic error.

Detector description: The amount of material assumed by the track reconstruction for the energy loss correction is varied by 10% (representing the current uncertainty on the knowledge of the material) and the analysis is repeated. The difference to the nominal result is used as an estimate of the systematic error.

Detector alignment: Three further checks are made related to the quality of the alignment. Firstly, the track slopes, which are essentially determined from measurements in the vertex detector, are changed by 1 per mille, corresponding to the precision with which the length scale along the beam axis is known. The shift in the mass measurement is assigned as a systematic uncertainty. Secondly, any hits from the tracking station before the magnet (TT), whose function is to improve the momentum resolution, are removed from the tracks forming the candidate and the track fit is rerun. In this case no significant effect is observed, and the statistical precision of this test is assigned as a systematic uncertainty. Finally, it is observed

that the ϕ mass peak is shifted with respect to its expected position; this is most likely due to a bias on the opening angle. It is expected that this bias is present in all channels containing a ϕ. This has been checked using $D^+ \to \phi\pi^+$ decays. Compared to the central value of the D^+ mass as quoted by the PDG [3], a shift of 0.328 ± 0.200 MeV/c^2 is seen, consistent with the bias observed for the inclusive ϕ sample of 0.285 ± 0.010 MeV/c^2. This shift is corrected for and a systematic uncertainty of 0.16 MeV/c^2, the error quoted by the PDG on the D^+ mass, is assigned.

The systematic uncertainties assigned on the measured mass for each mode and on the mass differences are summarized in Tables 4 and 5.

The stability of the measured b-hadron masses is studied by dividing the data samples according to the magnet polarity, final state flavour (for cases where the final state is flavour specific) as well as whether the K^0_S and Λ daughter tracks have vertex detector hits. In addition for high statistics decays, B^+ and B^0, the measurement is repeated in bins of b-hadron kinematics. For all these additional checks, no systematic bias is observed. Therefore, no systematic error is assigned.

5 Summary

The b-hadron masses are measured using data collected at a centre-of-mass of energy $\sqrt{s} = 7$ TeV during the 2010 LHCb data-taking period. The preliminary mass results are

$$\begin{aligned}
M(B^+ \to J/\psi K^+) &= 5279.27 \pm 0.11\,(\text{stat}) \pm 0.20\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0 \to J/\psi K^{*0}) &= 5279.54 \pm 0.15\,(\text{stat}) \pm 0.16\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0 \to J/\psi K^0_S) &= 5279.61 \pm 0.29\,(\text{stat}) \pm 0.20\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0_s \to J/\psi \phi) &= 5366.60 \pm 0.28\,(\text{stat}) \pm 0.21\,(\text{syst})\ \text{MeV}/c^2,\\
M(\Lambda_b \to J/\psi \Lambda) &= 5619.49 \pm 0.70\,(\text{stat}) \pm 0.19\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^+_c \to J/\psi \pi^+) &= 6268.0 \pm 4.0\,(\text{stat}) \pm 0.6\,(\text{syst})\ \text{MeV}/c^2.
\end{aligned}$$

An important systematic error is related to the determination of the average momentum scale in the tracking system. This error largely cancels if mass differences are considered. This gives

$$\begin{aligned}
M(B^0 \to J/\psi K^*) - M(B^+ \to J/\psi K^+) &= 0.27 \pm 0.19\,(\text{stat}) \pm 0.12\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0 \to J/\psi K^0_S) - M(B^+ \to J/\psi K^+) &= 0.34 \pm 0.31\,(\text{stat}) \pm 0.10\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^0_s \to J/\psi \phi) - M(B^+ \to J/\psi K^+) &= 87.33 \pm 0.30\,(\text{stat}) \pm 0.19\,(\text{syst})\ \text{MeV}/c^2,\\
M(\Lambda_b \to J/\psi \Lambda) - M(B^+ \to J/\psi K^+) &= 340.22 \pm 0.71\,(\text{stat}) \pm 0.08\,(\text{syst})\ \text{MeV}/c^2,\\
M(B^+_c \to J/\psi \pi^+) - M(B^+ \to J/\psi K^+) &= 988.7 \pm 4.0\,(\text{stat}) \pm 0.5\,(\text{syst})\ \text{MeV}/c^2.
\end{aligned}$$

The results are in agreement with the world averages quoted in Ref. [3]. In many cases they represent significant improvements on the precision compared to the previous measurements.

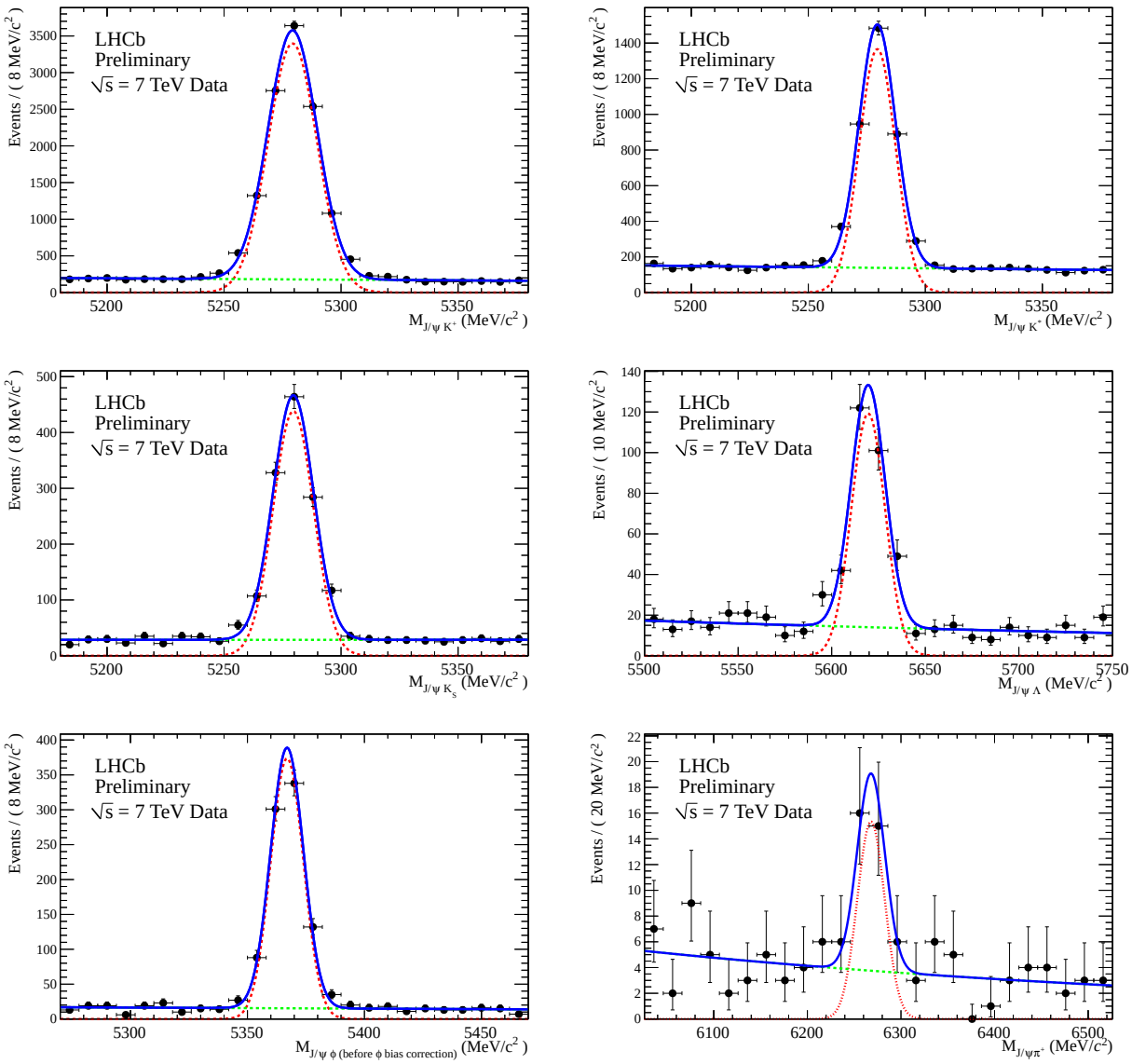

Figure 2: Corrected reconstructed mass of $B^+ \to J/\psi K^+$ (top left), $B^0 \to J/\psi K^*$ (top right), $B^0 \to J/\psi K^0_S$ (middle left), $\Lambda_b \to J/\psi \Lambda$ (middle right), $B^0_s \to J/\psi \phi$ before applying the ϕ bias correction (bottom left), and $B^+_c \to J/\psi \pi^+$ (bottom right) candidates, with superimposed fit.

Source of uncertainty	$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K^{*0}$	$B^0 \to J/\psi K^0_S$	$B^0_s \to J/\psi\phi$	$\Lambda_b \to J/\psi\Lambda$	$B^+_c \to J/\psi\pi^+$
Mass fitting:						
Background model	0.04	0.03	0.00	0.01	0.00	0.32
Signal model	0.01	0.02	0.06	0.02	0.07	0.07
Momentum calibration:						
Average momentum scale	0.15	0.14	0.15	0.11	0.14	0.23
η dependence of momentum scale	0.04	0.00	0.09	0.03	0.02	0.44
Detector description:						
Energy loss correction	0.10	0.00	0.05	0.03	0.09	0.11
Detector alignment:						
Vertex detector (track slopes)	0.05	0.04	0.04	0.03	0.04	0.06
Tracking stations (TT information)	0.05	0.05	0.05	0.05	0.05	0.05
ϕ bias	–	–	–	0.16	–	–
Quadratic sum	0.20	0.16	0.20	0.21	0.19	0.61

Table 4: Systematic uncertainties (in MeV/c^2) on the mass measurements.

Source of uncertainty	$B^0 \to J/\psi K^{*0}$	$B^0 \to J/\psi K^0_S$	$B^0_s \to J/\psi\phi$	$\Lambda_b \to J/\psi\Lambda$	$B^+_c \to J/\psi\pi^+$
Mass fitting:					
Background model	0.05	0.04	0.04	0.04	0.32
Signal model	0.02	0.06	0.02	0.07	0.07
Momentum calibration:					
Average momentum scale	0.01	0.00	0.04	0.01	0.08
η dependence of momentum scale	0.04	0.05	0.01	0.02	0.40
Detector description:					
Energy loss correction	0.10	0.05	0.07	0.01	0.01
Detector alignment:					
Vertex detector (track slopes)	0.01	0.01	0.02	0.01	0.01
Tracking stations (TT information)	0.00	0.00	0.00	0.00	0.00
ϕ bias	–	–	0.16	–	–
Quadratic sum	0.12	0.10	0.19	0.08	0.52

Table 5: Systematic uncertainties (in MeV/c^2) on the differences of mass measurements, expressed with respect to the $B^+ \to J/\psi K^+$ mass (*e.g.* the last column gives the systematic uncertainties on $M(B^+_c \to J/\psi\pi^+) - M(B^+ \to J/\psi K^+)$).

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