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Heavy-flavour spectroscopy (X, Y, Z, B_c, B^{**})

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Summary. — The LHCb measurements in the area of heavy-flavour spectroscopy (X, Y, Z, B_c, B^{**}) with part of the data collected in 2010 and 2011 are described in this paper. We first summarise the recent results for $X(3872)$ mass and production and searches for $X(4140)$. We then show the results of the search for orbitally excited mesons ($B^{**}_{(s)}$) and their mass measurements. We also measure the mass and production of B^+_c meson and report the first observation of $B^+_c \to J/\psi\pi^+\pi^+\pi^-$ decay channel.

PACS 14.40.Nd – Bottom mesons ($|B| > 0$).
PACS 14.40.Rt – Exotic mesons.

1. – The LHCb Experiment

The LHCb experiment [1], one of the four large detector experiments at the LHC, is optimized for heavy-quark physics with the unique coverage in the forward region. It collected around $0.04\,\mathrm{fb}^{-1}$ data in 2010 and $1\,\mathrm{fb}^{-1}$ data in 2011 with proton-proton collisions at a centre-of-mass energy of 7 TeV. With the large amount of b events in its acceptance ($O(10^{11})/\mathrm{fb}$), LHCb is shedding new light in the field of heavy flavour spectroscopy.

2. – X, Y, Z states

Recently, discoveries or evidences of new resonance structures have been made in the charmonium or bottomonium systems which can not be included in the quark model. The new resonance structures are denoted as "X, Y, Z" to indicate their unknown nature. Many models [2] are discussed to explain these resonance structures such as tetraquark models [3], molecular states [4] or charmonium hybrids with an excited degree of freedom [5]. LHCb has a program to understand the nature of these states. The current results for the $X(3872)$ and $X(4140)$ states are described here.

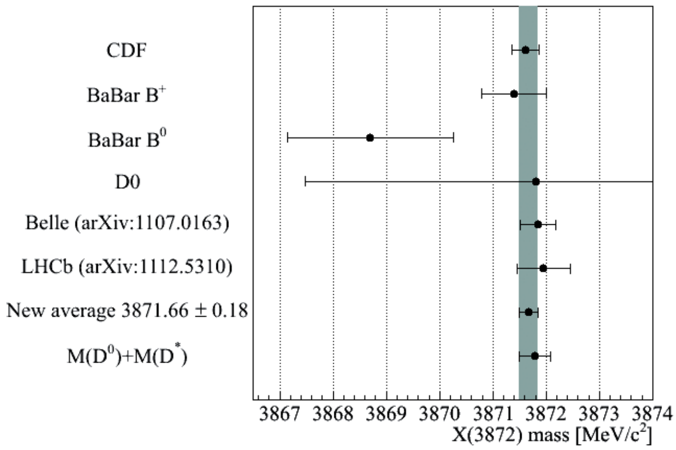

Fig. 1. – Published measurements of the $X(3872)$ mass in the $J/\psi\pi^+\pi^-$ mode, by the Belle [6], D0 [8], BaBar [13] and CDF [14] collaborations, and their comparision with the current LHCb measurement. The average including the LHCb measurement is performed according to the prescription given in ref. [15]. The sum of the D^0 and D^{*0} masses [15] is also shown.

2˙1. $X(3872)$. – The $X(3872)$ meson was discovered in 2003 by the Belle Collaboration with $B^\pm \to X(3872)K^\pm$ and $X(3872) \to J/\psi\pi^+\pi^-$ [6]. It was quickly confirmed by other collaborations [7-9]. Some properties of $X(3872)$ have been measured: for example, the dipion mass spectrum by CDF [10], the quantum numbers constrained to either $J^{PC} = 2^{-+}$ or 1^{++} [11], but its nature remains unknown. One possibility is that the $X(3872)$ state is a loosely bounded $D^{*0}\bar{D}^0$ molecular [12] motivated by the proximity of its mass to the $D^{*0}\bar{D}^0$ threshold. In this case the $X(3872)$ mass should be smaller than the $D^{*0}\bar{D}^0$ threshold to have a negative binding energy. It is thus important to measure $X(3872)$ mass precisely to test it. The first measurement of the $X(3872)$ mass in LHCb is done with $37\,\text{pb}^{-1}$ data collected in 2010 and yields:

$$M_{X(3872)} = 3871.96 \pm 0.46_{\text{stat}} \pm 0.10_{\text{syst}}\,\text{MeV}/c^2. \quad (1)$$

We summarise the current experiment measurements of the mass of $X(3872)$ in fig. 1. The LHCb measurement is in good agreement with the published results [6, 8, 13, 14]. Adding our and the recent Belle [6] results, the world average of the mass of $X(3872)$ is improved from $3871.57 \pm 0.25\,\text{MeV}/c^2$ [15] to $3871.66 \pm 0.18\,\text{MeV}/c^2$. It is still indistinguishable from the sum of the D^0 and D^{*0} masses obtained from the results of the global PDG fit [15]. More precise measurements are needed to solve the puzzle. The current LHCb result is dominated by the statistical error. With the collected 2011 data and coming 2012 data, our precision will be significantly improved.

Besides the measurement of the mass of $X(3872)$, the inclusive production cross-section is also studied in the phase space region $p_T \in [5, 20]\,\text{GeV}/c$ and $\eta \in [2.5, 4.5]$ where p_T and η are the transverse momentum and rapidity of the $X(3872)$. The measurement gives

$$\sigma(pp \to X(3872) + X) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 4.7 \pm 1.1_{\text{stat}} \pm 0.7_{\text{syst}}\,\text{nb}. \quad (2)$$

The result is compared with the current available calculation for LHC using a non-relativistic QCD model assuming that the cross-section is dominated by the production of charm quark paris with negligible relative momentum [16]. The calculated results are summed in our measured region and yield 13.0 ± 2.7 nb, which exceeds our measurement by 2.8σ.

2˙2. $X(4140)$. – The observation of the $X(4140)$ state (also referred to as $Y(4140)$) is claimed by the CDF Collaboration with 3.8σ evidence [17] using $p\bar{p}$ collision data collected at the Tevatron at a centre-of-mass energy of 1.96 TeV. A preliminary update with $6.0\,\text{fb}^{-1}$ data increases the significance to more than 5σ with 115 ± 12 reconstructed $B^+ \to J/\psi\phi K^+$ events and 19 ± 6 $X(4140)$ candidates. The measured mass and width are $4143.4^{+2.9}_{-3.0} \pm 0.6\,\text{MeV}/c^2$ and $15.3^{+10.4}_{-6.1} \pm 2.5\,\text{MeV}/c^2$ respectively. The relative branching fraction was measured to be $\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)/\mathcal{B}(B^+ \to J/\psi\phi K^+) = 0.149 \pm 0.039_{\text{stat}} \pm 0.024_{\text{syst}}$. There is also a claim of a 3.1σ evidence of a second resonance state ($X(4274)$) in higher mass region with mass and width to be $4274.4^{+8.4}_{-6.7} \pm 1.9\,\text{MeV}/c^2$ and $32.3^{+21.9}_{-15.3} \pm 7.6\,\text{MeV}/c^2$, respectively. The observation of the two resonance states near threshold has triggered widespread interest as charmonium states above the open charm threshold are generally broad [18].

Using $0.37\,\text{fb}^{-1}$ data collected in 2011, LHCb performed a similar search with 346 ± 20 reconstructed $B^+ \to J/\psi\phi K^+$ events. The invariant mass difference $(M(J/\psi\phi) - M(J/\psi))$ distribution for the $B^+ \to J/\psi\phi K^+$ in the B^+ ($\pm2.5\sigma$) and ϕ ($\pm15\,\text{MeV}/c^2$) mass window is shown in fig. 2. To ease the comparison with CDF, we employ the same fit model using a spin-zero relativistic Breit-Wigner shape for signal distribution together with a three-body phase-space function for background distribution. Both are convolved with the detector resolution ($1.5\pm0.1\,\text{MeV}/c^2$). The efficiency is obtained from full simulation and coped into the distribution. Using the central value of the mass and width from CDF, a binned maximum likelihood yields 6.4 ± 4.9 $X(4140)$ candidates while the expected number from CDF gives $35 \pm 9 \pm 6$. The fitted distribution and expected distribution are shown on the top plot of fig. 2. An alternative background model is also tried using a quadratic function multiplied by the three-body phase space factor, the fit results are shown on the bottom plot of fig. 2. It gives a fit yield of 0.6 events with a positive error of 7.1 events. Taking into account statistical and systematic errors of both experiments, we conclude a 2.4σ (2.7σ with the alternative background modelling) disagreement with the CDF result. We do not confirm the exsitence of $X(4140)$. An upper limit on the branching fraction at 90% confidence level is set to be

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi)} < 0.07. \tag{3}$$

Similar results are obtained for $X(4274)$, we expect 53 ± 19 $X(4274)$ events using the measurements from CDF while the fit results give $3.4^{+6.5}_{-3.4}$ and 0^{+10}_{-0} respectively using two different background modellings. This yields an upper limit of

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi)} < 0.08, \tag{4}$$

at 90% confidence level.

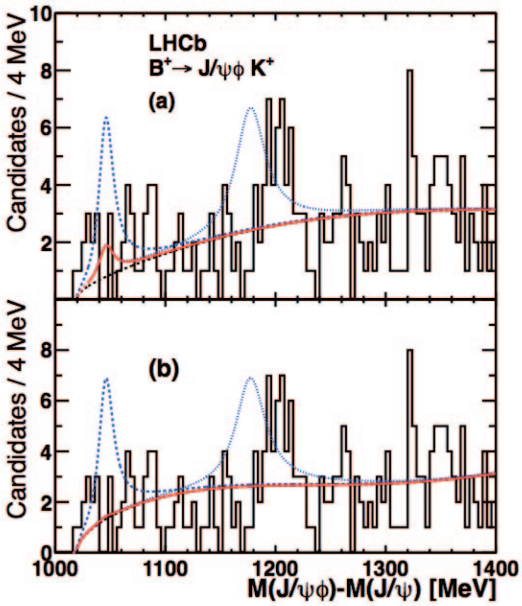

Fig. 2. – Invariant-mass difference $M(J/\psi\phi) - M(J/\psi)$ distribution for the $B^+ \to J/\psi\phi K^+$ in the B^+ ($\pm 2.5\sigma$) and ϕ ($\pm 15\,\mathrm{MeV}/c^2$) mass window. The dashed black line on top shows the background distribution using the same model as in CDF (three-body phase space) and the dashed black line on bottom shows the background distribution using a quadratic function multiplied by the three-body phase space. The dotted blue lines shows the expected distribution using the central value from CDF while the red solid line gives our fit results. Both fit functions on top and bottom are corrected with efficiencies obtained from simulation.

3. – Orbitally excited $B_{(s)}$ mesons

Properties of excited $B_{(s)}$ mesons containing a light quark (B^0_s, B^0, B^+) have been well predicted by heavy quark effective theory [19-21]. The system is described by three quantum numbers: the orbital angular momentum L, the angular momentum of the light quark $j_q = |L \pm 1/2|$ and the total angular momentum $J = |j_q \pm 1/2|$. In the heavy-quark limit, an essential idea is that the heavy-quark spin and j_q are conserved separately. For $j_q = 1/2 = L \pm 1/2$, the ground-state pesudo-scalar and vector mesons are with $L = 0$ while the orbital excited states ($L = 1$) are labelled as $B^{**}_{(s)}$. There are two more $L = 1$ orbital excitations with $j_q = 3/2$, they are all parity-even excited states.

Among the $B^{**}_{(s)}$ states, $B_1(5721)^0$ and $B^*_2(5747)^0$ have been observed by both CDF [22] and D0 [23]; $B_{s1}(5830)^0$ has been seen by CDF [24] and $B^*_{s2}(5840)^0$ has been seen by both CDF [24] and D0 [25]. The isospin partners of $B_1(5721)^0$ and $B^*_2(5747)^0$ are expected but not observed previously. In both experiments, the $B^{**}_{(s)}$ are reconstructed using $B + h$ ($h = \pi, K$). The soft photon from $B^* \to B + \gamma$ is ignored during the reconstruction if $B^{**}_{(s)}$ decays to B^*. The reconstructed mass in this case is shifted by $45.78 \pm 0.35\,\mathrm{MeV}/c^2$ ($M(B^*) - M(B)$).

The LHCb search is performed with $0.34\,\mathrm{fb}^{-1}$ data collected in 2011 and we search for B^{**}_s with decay channel $B^{(*)-} + K^+$, B^{**0} with decay channel $B^{(*)-} + \pi^+$ and B^{**+} with decay channel $B^{(*)0} + \pi^+$. The invariant-mass distribution $Q(h) = M(Bh^+) - M(B) - M(h^+)$ for the three processes are shown in fig. 3 and 4, respectively. In fig. 3,

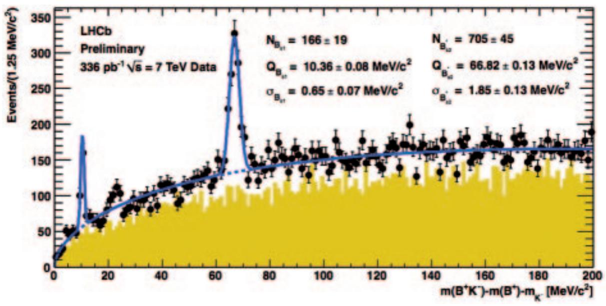

Fig. 3. – Invariant-mass distribution of $M(B^+K^-) - M(B^+) - M(K^-)$. The data distribution is labelled with black points. The yellow hist is the wrong sign combination. The solid blue line shows the fitted distribution.

two narrow peaks which corresponds to $B_{s1}(5830)^0$ and $B^*_{s2}(5840)^0$ could be clearly seen. The widths of the peaks are around $1\,\mathrm{MeV}/c^2$, mainly due to detector resolution and we model the signal distributions using Gaussian functions. As there is no visible sign of the $B^{*0}_{s2} \to B^{*-} + K^+$ mass peak, we do not include it in our analysis. The measured masses and significances are summarised in table I.

Due to the large width of B^{**0} and B^{**+} mesons, decays from different excited states overlap as shown in fig. 4 and we use a Breit-Wigner function to fit signal distributions. The three Breit-Wigner distributions shown at the bottom of each plot correspond to $B_1^{0(+)} \to B^{*-(0)}\pi^+$, $B_2^{0(+)} \to B^{*-(0)}\pi^+$ and $B_2^{0(+)} \to B^{-(0)}\pi^+$ from left to right. During the fit, the mass difference between two B^*_2 decay channels are fixed to be $45.78\,\mathrm{MeV}/c^2$ and the widths of the resonance are fixed to be the same. The relative yields of the two decay channels are fixed to be 0.93 ± 0.18 based on the theoretical predictions [26]. The ratio of the widths of the two excited states are fixed to be 0.9 ± 0.2 [27]. The left plot of fig. 4 gives the invariant-mass difference distribution for $B^{*-} + \pi^+$ with fitted function superimposed. The fitted masses and significances for B^{**0} mesons are also summarised in table I. The measured masses agree with previous measurements [22, 23]. The invariant-mass difference distribution for the isospin partner of B^{**0} is shown in

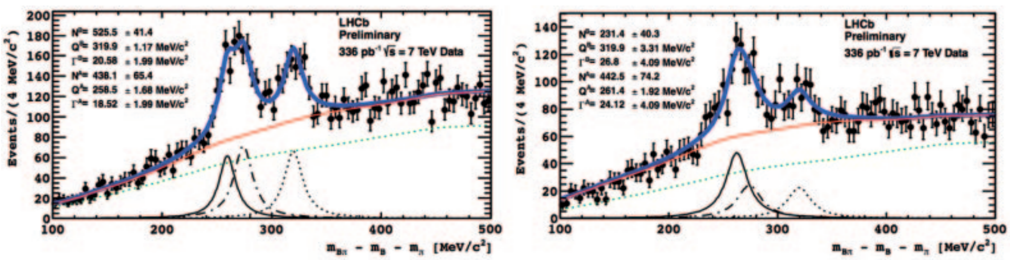

Fig. 4. – Invariant-mass distribution of $M(B^-\pi^+) - M(B^-) - M(\pi^+)$ (left) and $M(B^0\pi^+) - M(B^0) - M(\pi^+)$ (right). The black points show the data distribution. The green dotted curve gives wrong sign combination. The solid blue line shows the fitted distribution with the solid red curve as background distribution including combinatorial background and associated production. The three breit-wigner distributions at the bottom of each plot correspond to $B_1^{0(+)} \to B^{*-(0)}\pi^+$, $B_2^{0(+)} \to B^{*-(0)}\pi^+$ and $B_2^{0(+)} \to B^{-(0)}\pi^+$ from left to right.

TABLE I. – *Measured masses and significances of orbital excited $B_{(s)}$ mesons.*

Decay channels	Mass (MeV/c^2)	Significance
$B_{s1}^0 \to B^{*+} + K^-$	$5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B{\rm mass}}_{\rm syst}$	12.5σ
$B_{s2}^{*0} \to B^+ + K^-$	$5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.5^{B{\rm mass}}_{\rm syst}$	22σ
$B_1^0 \to B^{*+} + \pi^-$	$5724.1 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst} \pm 0.45^{B{\rm mass}}_{\rm syst}$	13.5σ
$B_2^0 \to B^{(*)+} + \pi^-$	$5738.6 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst} \pm 0.3^{B{\rm mass}}_{\rm syst}$	$8.0(2.6)\sigma$
$B_1^+ \to B^{*0} + \pi^-$	$5726.3 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst} \pm 0.5^{B{\rm mass}}_{\rm syst}$	9.9σ
$B_2^+ \to B^{(*)0} + \pi^-$	$5739.0 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst} \pm 0.3^{B{\rm mass}}_{\rm syst}$	$4.0(0.0)\sigma$

the right plot of fig. 4. Two new B^{**+} excited states are observed with 9.9 (4.0)σ, respectively with their masses and significances in table I using similar fit procedure as for B^{**0}.

4. – B_c^+ meson

The B_c mesons are the unique double heavy-flavoured mesons in the standard model. Precise calculations could be done in the B_c system due to large b and c quark masses. It is thus very interesting to measure its properties and compare them with theoretical predictions. The LHCb has a program to measure B_c properties such as the B_c^+ mass and lifetime, B_c^+ production and decay modes etc. Current results on B_c^+ mass, B_c^+ production and a new observed decay channel $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ are shown here.

Using $35\,{\rm pb}^{-1}$ data, 28 ± 7 $B_c^+ \to J/\psi\pi^+$ events are reconstructed and the measured

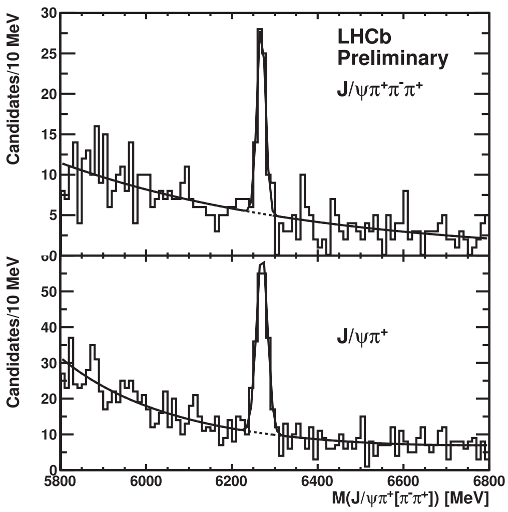

Fig. 5. – Invariant-mass distribution of $J/\psi\pi^+\pi^-\pi^+$ (top) and $J/\psi\pi^+$ (bottom) with fit function superimposed.

mass is found to be

$$M(B_c^+) = 6268.0 \pm 4.0_{\rm stat} \pm 0.6_{\rm syst}\,{\rm MeV}/c^2. \tag{5}$$

The measured mass agrees with previous measurement from CDF [28] and D0 [29]. The B_c^+ production is measured with the same dataset in the range $p_T > 4\,{\rm GeV}/c$ and $\eta \in [2.5, 4.5]$. The relative branching fraction gives

$$\frac{\sigma(B_c^\pm)\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm)\mathcal{B}(B^\pm \to J/\psi\pi^\pm)} = 2.2 \pm 0.8_{\rm stat} \pm 0.2_{\rm syst}\%. \tag{6}$$

With more dataset collected in 2011 ($0.3\,{\rm fb}^{-1}$), the LHCb is able to discover more "rare" decays, *i.e.* $B_c^+ \to J/\psi\pi^-\pi^+\pi^+$. In fact, its branching fraction is predicted to be $1.5 \sim 2.3$ times larger than $B_c^+ \to J/\psi\pi^+$, but due to lower detection efficiency (~ 10 times less), more data is needed to observe it than $B_c^+ \to J/\psi\pi^+$. The invariant mass distribution for $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$ and $B_c^+ \to J/\psi\pi^+$ are shown in fig. 5. The observed number of $B_c^+ \to J/\psi\pi^+\pi^+\pi^-$ ($B_c^+ \to J/\psi\pi^+$) is 58.2 ± 9.6 (163.1 ± 15.7) corresponding to 6.8 (11)σ significance. Together with the relative efficiencies between the two decay channels (0.119 ± 0.006), we determine the branching fraction ratio to be $3.0 \pm 0.6_{\rm stat} \pm 0.4_{\rm syst}$. Our result favours the prediction of the ratio to be 2.3 [30]. Further look of the invariant mass distributions of $\pi^+\pi^-$ and $\pi^+\pi^+\pi^-$ shows that the dominated contribution of this channel comes from $B_c^+ \to J/\psi a_1^+(1260)$ with $a_1^+(1260) \to \rho^0\pi^+$.

5. – Conclusion

The LHCb experiment has a rich program on the search of heavy-quark spectrum. First studies of $X(3872)$ and $X(4140)$ demonstrate its potential to explore exotic meson sector. Future results with larger dataset will be built on this. It has also access to the poorly explored $B_{(s)}^{**}$ and B_c sectors, and will significantly improve the knowledge of their properties and decays.

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