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Production and spectroscopy of open-flavoured hadrons at hadron colliders

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Studies on the production and spectroscopy of heavy hadrons provide important inputs to test the reliability of several models and techniques. Recent results on the production of the charmed and beauty mesons and baryons at hadron colliders are summarized. The observations of new excited heavy hadrons and new B_c^+ decays are also presented.

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1. Production of open-flavoured hadrons

Measurement of charm and beauty production in multi-TeV proton-proton collisions at the LHC provide important tests of quantum chromodynamics. State of the art theoretical predictions are given by the fixed-order plus next-to-leading logarithm (FONLL) approach [1]. Despite the substantial progress achieved in the understanding of heavy-quark production at Tevatron energies, large theoretical uncertainties still remain due to the choice of the renormalisation and factorisation scales, and the assumed heavy quark mass.

The LHC experiments can study in great detail the open-flavoured hadron production due to their high performance detectors which cover different and complementary regions in rapidity (y) and transverse momentum ($p_{\rm T}$). The production studies of the c- (D^0, D^+, D_s^+, Λ_c^+) and b-hadrons (B^0, B^+, B_s^0, Λ_b^0) are carried out by reconstructing either part of the decay chain (*e.g.* J/ψ, $\psi(2S)$, χ_c) or the entire final state. When studying the inclusive production of a state (*e.g.* J/ψ), one has to take into account a prompt contribution, produced directly in the proton-proton collision and indirectly through the decay of heavier states (*e.g.* $\chi_{c1} \to J/\psi\gamma$), and a non-prompt contribution from long-lived hadrons (e.g. $B^+ \to J/\psi K^+$). These two contributions are discerned by using the impact parameter or the pseudo-proper time as discriminator variable. The differential cross-section of a reaction, measured in bins of the transverse momentum and rapidity, is computed as

$$\frac{{\rm d}^2\sigma}{{\rm d}y{\rm d}p_{\rm T}} = \frac{N}{\mathscr{L} \times \varepsilon \times \mathscr{B} \times \Delta y \times \Delta p_{\rm T}},$$

where N is the number of events observed in the $\Delta y \times \Delta p_{\rm T}$ bin, $\mathscr{L}$ is the integrated luminosity, ε is the total efficiency (which takes in account acceptance, trigger, and reconstruction effects), and $\mathscr{B}$ is the branching fraction of the reaction.

1.1 Production of charmed hadrons

The production of the charmed mesons at $\sqrt{s} = 7$ TeV is studied by fully reconstructing the $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $D_s^+ \to \phi(K^+K^-)\pi^+$, and $\Lambda_c^+ \to pK^-\pi^+$ decay chains [2, 3]. The impact parameter of the charmed candidate is used to account for charmed hadrons produced in b-hadron decays. The measured differential cross-sections are in agreement with theoretical predictions within uncertainties. Figure 1a shows the cross-section of the D^0 meson as a function of the transverse momentum [2]. The ALICE collaboration has also measured the production of the charmed hadrons by studying the transverse impact parameter of the electrons from D and B semileptonic decays (Fig. 1b) [4].

1.2 Production of beauty hadrons

All the LHC experiments are active into studying the bottom production at $\sqrt{s} = 7$ TeV by a partial [5, 6, 7, 8] or full [9, 10, 11] reconstruction of the final states. In the latter case the measurements of differential cross-sections are carried out by studying the $B^+ \to J/\psi(\mu^+\mu^-)K^+$, $B^0 \to J/\psi(\mu^+\mu^-)K^{*0}(\to K^+\pi^-)$, and $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays.

Concerning the partially reconstructed analyses, inclusive samples of $J/\psi \to \mu^+\mu^-$ (Fig. 1c), $\psi(2S) \to \mu^+\mu^-$, $J/\psi\pi^+\pi^-$ (Fig. 1d) and $\chi_{c1,2} \to J/\psi(\mu^+\mu^-)\gamma(e^+e^-)$ (Fig. 1e) candidates are selected in order to study the prompt and the non-prompt productions. The two components are

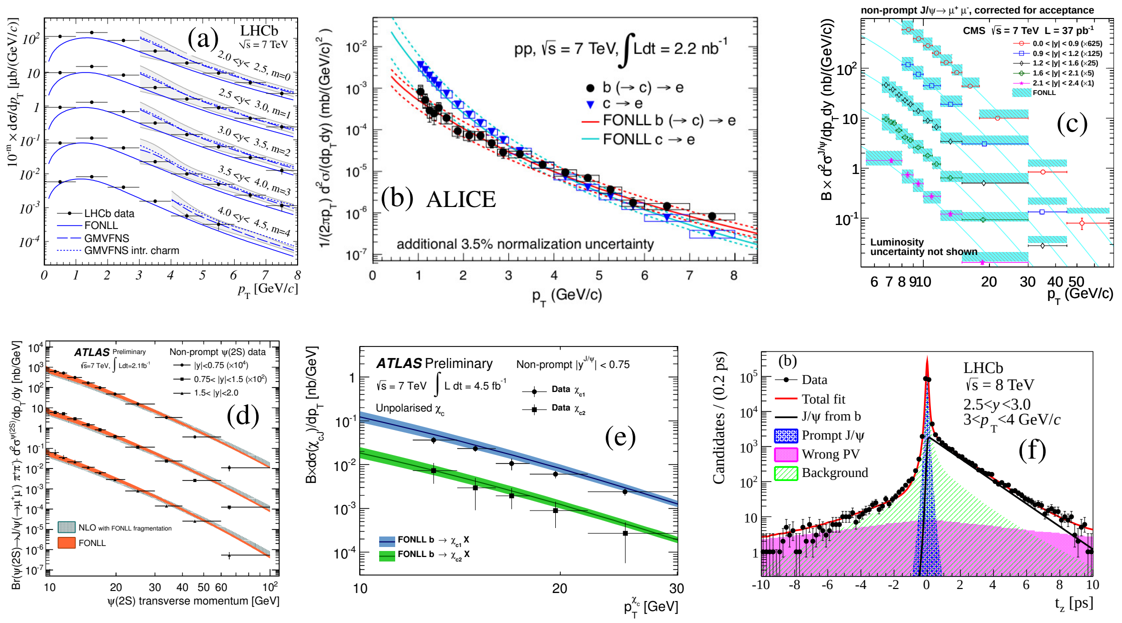

Figure 1: Differential invariant cross sections of *(a)* the D^0 meson, *(b)* electrons from beauty and from charmed hadron decays, *(c)* the J/ψ, *(d)* the $\psi(2S)$ and *(e)* the $\chi_{c1,2}$ mesons from beauty hadrons measured at $\sqrt{s} = 7$ TeV as a function of the transverse momentum. *(f)* Distribution of the J/ψ pseudo proper-time in a given bin of $p_{\rm T}$ and y.

discriminated by a two dimensional fit of the invariant mass and the pseudo-proper time of the charmonium state. The pseudo-proper time is defined as $t_z = \frac{L_z \times M}{p_z}$ or $t_{xy} = \frac{L_{xy} \times M}{p_T}$ where $L_z(L_{xy})$ is the projection along the z axis (xy plane) of the vector from the primary vertex to the decay vertex, M is the invariant mass, and p_z ($p_{\rm T}$) is the projection along the z axis (xy plane) of the momentum vector of the charmonium state. The distribution of the pseudo-proper time is expected to peak at zero and to decrease exponentially for prompt and non-prompt components respectively (Fig. 1f). In general experimental data are in good agreement with theoretical predictions. However some discrepancies are observed at large values of the transverse momentum in the $\psi(2S)$ inclusive analysis (Fig. 1d). Moreover theory tends to overestimate the cross-sections of the bottom hadrons in the $\chi_{c1,2}$ inclusive analysis (Fig. 1e).

Measurements of the differential cross-section of the beauty hadrons by studying an inclusive J/ψ are also performed at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 8$ TeV by the LHCb collaboration [12]. The behaviour of the cross-section for J/ψ from b-hadrons as a function of the centre-of-mass energy is in good agreement with the prediction. This provides confidence on the reliability of predictions for the b-hadron cross-sections at the higher energies expected at the LHC in a near future.

1.3 Measurements of the fragmentation fraction ratios

The fragmentation fractions f_u, f_d, f_s and f_{Λ_b} describe the probability that a b-quark will hadronize into a $B_q(q = u,d,s)$ meson or into a Λ_b baryon. The knowledge of the fragmentation fraction ratios are crucial at the LHC when determining the absolute branching fraction for B_s^0 and Λ_b^0 decays (*e.g.* $B_s^0 \to \mu^+\mu^-$). Precise measurements of the f_s/f_d [13] and $f_{\Lambda_b}/(f_u + f_d)$ [14] ratios

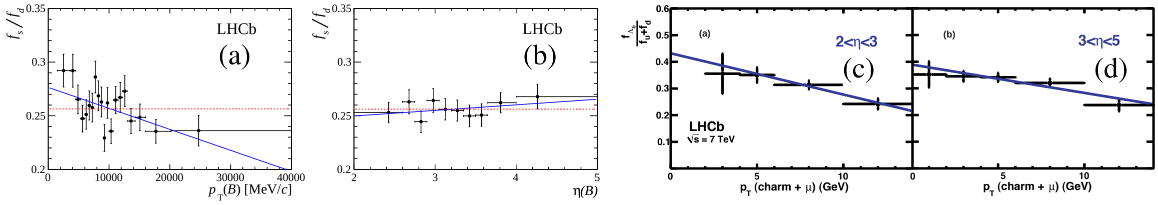

Figure 2: Fragmentation ratio f_s/f_d dependence upon *(a)* the B transverse momentum and *(b)* the B pseudo-rapidity. *(c)*, *(d)* Fragmentation ratio $f_{\Lambda_b}/(f_u+f_d)$ dependence upon the transverse momentum in two pseudo-rapidity intervals.

are performed by the LHCb collaboration as functions of the transverse momentum and pseudo-rapidity (η) (Fig. 2). The f_s/f_d is measured using the decay modes $B^0 \to D^- K^+$ and $B_s^0 \to D_s^- \pi^+$ while the measurements of the $f_{\Lambda_b}/(f_u+f_d)$ ratio is carried out by studying semileptonic decays $B \to D\mu\nu X$ and $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu} X$. A dependence upon the transverse momentum is observed while there is no indication of a dependence on the pseudo-rapidity (Fig. 2).

1.4 Λ_b^0 polarization at $\sqrt{s} = 7$ TeV

The longitudinal polarization of the Λ_b^0 baryons in the pp collisions vanishes due to parity conservation of the strong interactions while transverse polarization is predicted to be as large as 20%. However the polarization is expected much smaller by extrapolating the Λ polarization measured by the fixed-target experiments. An angular analysis of the $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ decay is carried out by the LHCb [15] and ATLAS [16] collaborations in order to measure the Λ_b^0 polarization and the decay helicity amplitudes. The Λ_b^0 polarization is found in agreement with the Λ extrapolation while a value of 20% is disfavoured at the level of 2.7 standard deviations.

2. Spectroscopy of open-flavoured hadrons

2.1 Charmed mesons

The quark model predicts many excited states in limited mass regions. Recently LHCb has performed [17] an inclusive study of the $D^+(\to K^-\pi^+\pi^+)\pi^-$, $D^0(\to K^-\pi^+)\pi^+$ and $D^{*+}(\to D^0\pi^+)\pi^-$ (Fig. 3a) final states. The natural spin-parity states ($J^P = 0^+, 1^-, 2^+, 3^- ...$) can decay to $D\pi$ and $D^*\pi$ final states, while the unnatural spin-parity states ($J^P = 0^-, 1^+, 2^-, 3^+ ...$) can decay to $D^*\pi$ final state only. As a consequence both natural and unnatural states can appear in the $D^*\pi$ mass spectrum but they are characterized by a different angular distribution of the helicity angle. Such feature is used to enhance the natural or the unnatural component and to measure the masses and widths of the involved resonances. Three unnatural states and four natural states are claimed. Future studies of the $D^{(*)}\pi$ spectrum in the B decays are needed to unravel the associated spin-parity.

2.2 Beauty mesons

While the orbitally ($L=1$) excited charmed states are well established, the corresponding excited B mesons are affected by large uncertainties. The charged B_1^+ and B_2^{*+} mesons have not been discovered yet and the observation of the B_{s1}^0 meson needs to be confirmed. Studies of the $B^+\pi^-$ (Fig. 3b),

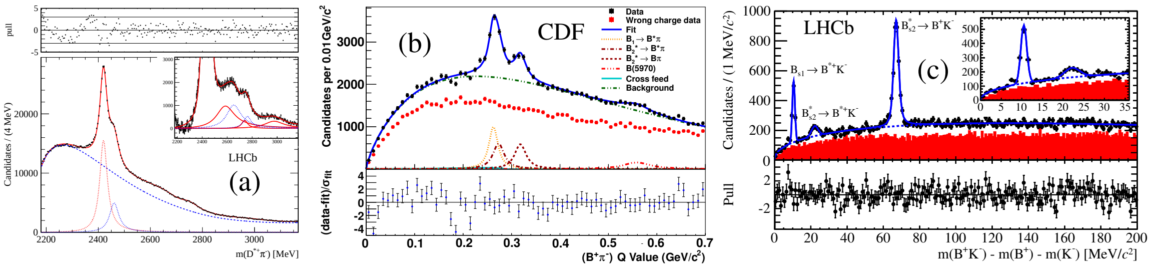

Figure 3: Invariant mass distributions for *(a)* $D^{*+}\pi^-$, *(b)* $B^+\pi^-$ and *(c)* B^+K^- candidates.

$B^0\pi^+$, and B^+K^- (Fig. 3c) mass spectra are carried out at the LHCb and CDF experiments [18]. The masses and widths of the $B_{(s)1}$ and $B^*_{(s)2}$ are measured with great precision. The decay of the B^{*0}_{s2} into the $B^{*+}K^-$ final state is observed for the first time as a feed-down into the B^+K^- mass spectrum (Fig. 3c), where the photon from the B^{*+} decay is not reconstructed. This favours the spin-parity assignment of $J^P = 2^+$ to the B^{*0}_{s2} meson, since only the natural states (except $J^P = 0^+$) can decay to both B^+K^- and $B^{*+}K^-$ final states. CDF collaboration has claimed the evidence (4.4σ) of a new excited B state at the mass of the 5970 MeV/c^2. Based on comparison of the measured mass to the theoretical prediction, such a state is interpreted as a $B^{(*)}$ radial or an orbitally ($L = 2$) excitation.

2.3 Doubly charmed baryons

All of the ground states with charm quantum number $C = 0$ or $C = 1$, expected according to the quark model, have been discovered. Three weakly decaying $C = 2$ states are expected: a Ξ_{cc} isodoublet (ccu, ccd) and an Ω_{cc} isosinglet (ccs), each with $J^P = 1/2^+$. Signals for the Ξ^+_{cc} baryon were reported in the $\Lambda^+_c K^-\pi^+$ and pD^+K^- final states by SELEX collaboration [19], with a production much larger than expected, but they are not yet confirmed by any other experiments. LHCb collaboration has performed a search for Ξ^+_{cc} into the $\Lambda^+_c K^-\pi^+$ final state with an integrated luminosity of 0.65 fb^{-1} [20]. No significant signal is found. Upper limits on the Ξ^+_{cc} cross-section times branching ratio relative to the Λ^+_c cross-section $\left(\frac{\sigma(\Xi^+_{cc})\mathscr{B}(\Xi^+_{cc}\to\Lambda^+_c K^-\pi^+)}{\sigma(\Lambda^+_c)}\right)$ are obtained for a range of mass ($3300 < M < 3700$ MeV) and lifetime hypotheses ($100 < \tau < 400$ fs). The upper limits depend strongly on the lifetime, varying from 1.5×10^{-2} for 100 fs to 3.9×10^{-4} for 400 fs.

2.4 Beauty baryons

The system of baryons containing a b-quark remains largely unexplored, despite recent progress made at the experiments at the Tevatron. In particular the quark model predicts 15 bqq ($q = u,d,s$) ground state baryons but only 9 have been observed so far. Many excited states are foreseen as well. The CMS collaboration has reported the observation of a new baryon state decaying into $\Xi^-_b\pi^+$ [21], where the Ξ^-_b baryon is reconstructed via the decay chain $\Xi^-_b \to J/\psi(\mu^+\mu^-)\Xi^-(\Lambda\pi^-)$. The measured mass being close to the $\Xi^-_b\pi^+$ threshold, it is interpreted as the expected $J^P = 3/2^+$ ground state Ξ^{*0}_b. Two new beauty baryons have been also observed in the $\Lambda^0_b\pi^+\pi^-$ mass spectrum by the LHCb collaboration [22]. They are interpreted as the orbitally ($L = 1$) excited Λ^0_b states with quantum number $J^P = 1/2^+$ and $J^P = 3/2^+$. The observation of a Λ^0_b excited state has been confirmed by the CDF collaboration [23].

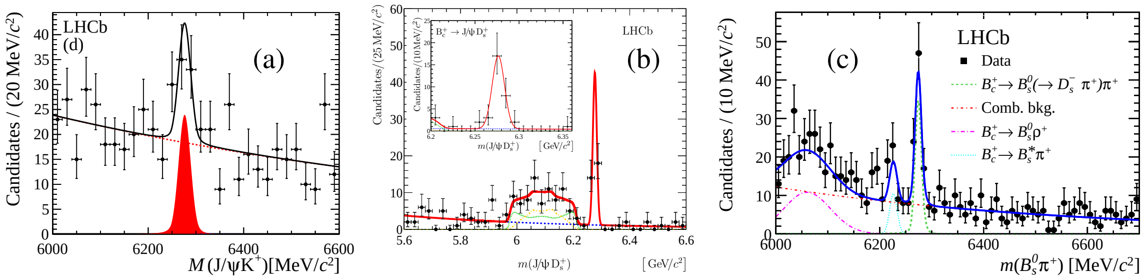

Figure 4: Mass distributions of the B_c^+ candidates decaying into the final states: *(a)* $J/\psi K^+$, *(b)* $J/\psi D_s^{(*)+}$, and *(c)* $B_s^0\pi^+$.

2.5 $\mathbf{B_c^+}$ meson

Before the LHC era, $B_c^+ \to J/\psi\pi^+$ was the only known hadronic decay mode of the B_c^+ meson. LHCb collaboration is largely increasing the knowledge about the B_c^+ meson by discovering new decay modes, such as $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to J/\psi K^+K^-\pi^+$ [24]. Recently the first Cabibbo suppressed decay has been discovered $B_c^+ \to J/\psi K^+$ (Fig.4a) [24]. Also decay modes with open charm mesons in the final state have been observed: $B_c^+ \to J/\psi D_s^{(*)+}$ (Fig.4b) [24]. The latter decay is suitable for the most precise measurement of the B_c^+ mass due to the small Q value of the reaction: $m_{B_c^+} = 6276.28 \pm 1.44(\text{stat}) \pm 0.36(\text{syst})$ MeV/c^2. Finally the observation of the decay $B_c^+ \to B_s^0\pi^+$ decay has been reported (Fig.4c) [24], where the B_c^+ meson decays to another B meson with the bottom quark acting as a spectator. Such decay opens the opportunity to flavour tag the B_s^0 meson using the accompanying pion once a larger amount of data is collected.

3. Conclusion

The experimental measurements of the charmed and beauty hadrons production at the LHC agree well with theoretical predictions. Since a few discrepancies are still observed, the study of the open-flavoured hadron production will be still part of the future research program at the LHC. In particular it will be interesting to test the models at higher center-of-mass energy.

On the spectroscopy side, highly excited D and B mesons have been observed in inclusive analyses and the list of the known B_c^+ decay modes is getting longer and longer. With the upcoming data taking, it is likely that the LHC experiments will be able to observe the first excited B_c^+ states and to discover some of the missing singly beauty baryons. In addition the sensitivity of the search for baryons with two heavy quarks will improve significantly.

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