Production rates and branching fractions of heavy hadrons & quarkonia at LHC experiments

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Measurements of production cross-sections of inclusive b-hadrons pairs, bottom mesons and baryons, and quarkonia at LHC will be shown. Recent measurements of branching fractions of bottom baryons, bottom mesons with baryons in the final state, and a new result about look for intermediate states in meson decay will also be shown.

I. INTRODUCTION

Measurements of heavy hadrons and quarkonia cross sections at LHC allow probing QCD processes; they are also reference or ingredient for searches and measurements of rarer or new processes, as well as the baseline for associated production of heavy floavour and other objects.

The study of decay properties and branching fractions does allow a test of form-factor models as well as the search for new and exotic states that can be produced in the decay.

Results from ATLAS [1], CMS [2] and LHCb [3] will be shown in the following.

II. PRODUCTION CROSS-SECTIONS

A. Inclusive b-hadrons

An inclusive b-hadron pair production cross section measurement was obtained by ATLAS [4] at an energy $\sqrt{s} = 8$ TeV; final states were selected looking for a J/ψ coming from the first hadron and decaying to $\mu^+\mu^-$, and a muon coming from the second hadron. The fiducial volume was defined requiring the two muons from the J/ψ to have $|\eta_{\mu,J/\psi}| < 2.3$ and the third muon to have $|\eta_\mu| < 2.5$; a minimum transverse momentum was also required: $p_{T,\mu} > 6$GeV. The total cross section in the fiducial volume was found:

$$\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X))) = (17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst}))\ \text{nb}\ .$$

B. Bottom mesons and baryons

1. B^+ production

The differential $pp \to B^+X$ cross-section versus transverse momentum or rapidity was measured by CMS [5] at an energy $\sqrt{s} = 13$ TeV in the region $|y_B| < 1.45$ or $|y_B| < 2.1$ and 10 GeV $< p_{T,B} <$ 100 GeV or 17 GeV $< p_{T,B} <$ 100 GeV; the ratio with the corresponding cross-section at $\sqrt{s} = 7$ TeV was measured and compared with FONLL [7–9] and PYTHIA [10] predictions. Results are shown in Fig. 1.

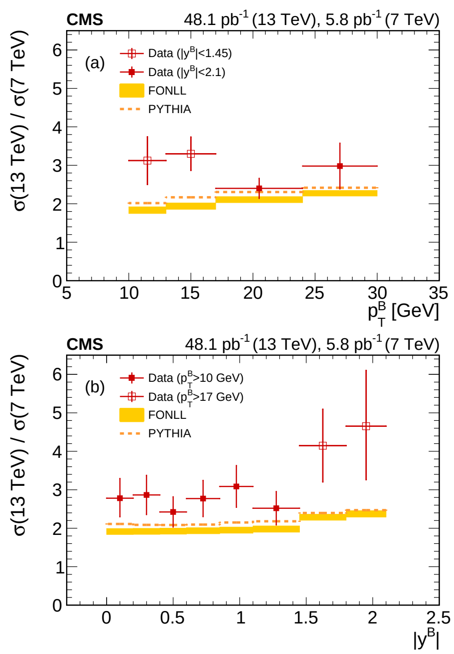

FIG. 1: Ratios of B^+ differential production cross sections at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV measured by CMS [5].

An analogous study was done by LHCb [11], that measured the double differential cross-section versus transverse momentum and rapidity in the region $2.0 < |y_B| < 4.5$, $p_{T,B} < 40$ GeV. Again the ratio with the corresponding cross-section at $\sqrt{s} = 7$ TeV was measured and compared with FONLL [12] predictions. Differential cross-sections are shown in Fig. 2; the integrated cross sections were found:

$$\sigma(pp \to B^\pm X\ (\sqrt{s} = 7\ \text{TeV}) = (43.0 \pm 0.2(\text{stat}) \pm 2.5(\text{syst}) \pm 1.7(\text{b.r.}))\ \mu\text{b}$$
$$\sigma(pp \to B^\pm X\ (\sqrt{s} = 13\ \text{TeV}) = (86.6 \pm 0.5(\text{stat}) \pm 5.4(\text{syst}) \pm 3.4(\text{b.r.}))\ \mu\text{b}$$

where the last uncertainty comes from the $B^\pm \to J/\psi K^\pm$ branching fraction.

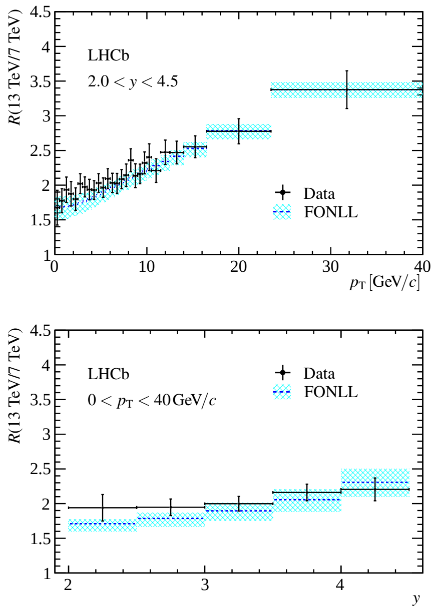

FIG. 2: Ratios of B^+ differential production cross sections at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 7$ TeV measured by LHCb [11].

2. Ξ_b^- production

Recently LHCb measured the ratio $f_{\Xi_b^-}/f_{\Lambda_b^0}$ of the fragmentation fractions to Ξ_b^- and Λ_b^0 [13]. The decay of the Ξ_b^- baryon has been studied since some time and a measurement of a branching fraction was done [14], but its absolute determination requires knowing the fragmentation ratio.

The quantity that's directly accessible is the ratio R of the number of reconstructed decays in the channel $\Xi_b^- \to J/\psi \Xi^-$, and a normalization one, with $\Lambda_b^0 \to J/\psi \Lambda^0$, but the ratio R can be expressed also as the ratio of the products of fragmentation and branching fractions; the latter can be expressed as the products of the ratios of partial widths and lifetimes:

$$R = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \cdot \frac{\Gamma(\Xi_b^- \to J/\psi \Xi^-)}{\Gamma(\Lambda_b^0 \to J/\psi \Lambda^0)} \cdot \frac{\tau_{\Xi_b^-}}{\tau_{\Lambda_b^0}} = \frac{N(\Xi_b^- \to J/\psi \Xi^-)}{N(\Lambda_b^0 \to J/\psi \Lambda^0)} \cdot \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}} .$$

The ratio of widths can be assumed to be 2/3 from $SU(3)$ flavor symmetry [15–17] and the ratio of lifetimes can be taken from PDG [18] so that the fragmentation ratio can be obtained. The decay has been reconstructed pairing a $J/\psi \to \mu^+\mu^-$ with a $\Lambda^0 \to p\pi^-$ or a $\Xi^- \to \Lambda^0\pi^-$. For the reconstruction of the Ξ^- or Λ^0 tracks have been classified as "long" or "downstream", depending on the track originating before or after the vertex detector. For Λ^0 downstream tracks have been used, due to the long lifetime, while a long track was used as candidate for the pion coming from the Ξ^- decay. The signal yields were estimated from fits to the mass distributions, as shown in Fig. 3.

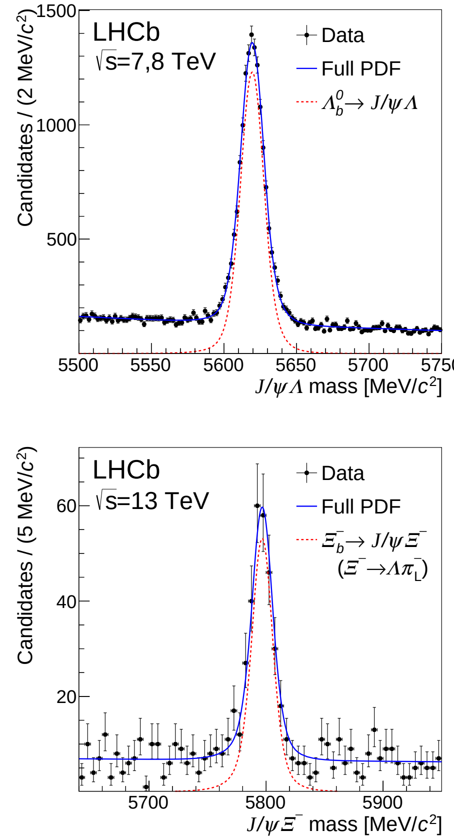

FIG. 3: Mass distributions for Ξ_b^- and Λ_b^0 reconstructed by LHCb [13].

Using the mass difference $m_{\Xi_b^-} - m_{\Lambda_b^0}$ as free parameter in the fit and using the Λ_b^0 mass from the PDG [18] the most precise measurement of Ξ_b^- mass was obtained:

$$m_{\Xi_b^-} = (5796.70 \pm 0.39(\text{stat}) \pm 0.15(\text{syst}) \pm 0.17(m_{\Lambda_b^0}))\ \text{MeV}$$

where the last uncertainty comes from the Λ_b^0 mass.

With the signal yields from the fits and the efficiencies from simulation the ratio R was obtained, and in the end the fragmentation fraction was extracted:

$$\frac{f_{\Xi_b^-}}{f_{\Lambda^0}} = (6.7 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \pm 2.0(\text{f.s.})) \times 10^{-2} \quad [\sqrt{s} = 7,8\ \text{TeV}]$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda^0}} = (8.2 \pm 0.7(\text{stat}) \pm 0.6(\text{syst}) \pm 2.5(\text{f.s.})) \times 10^{-2} \quad [\sqrt{s} = 13\ \text{TeV}]$$

where the last uncertainty is due to the flavor symmetry assumption and taken to be 30%.

C. Quarkonia

Several measurements of the cross-section production for quarkonia have been done at LHC experiments; a special interest can be found in the production of quarkonia pairs. Quarkonia pairs can be produced in single parton scattering (SPS), that's assumed to dominate and lead to strongly correlated pairs with small rapidity differences, but, in the high parton densities in proton-proton collisions, also double parton scattering (DPS) can occur producing multiple heavy flavour particles with large Δy [19, 20].

A measurement of the DPS contribution in double J/ψ production was done by ATLAS [21] at $\sqrt{s} = 8$ TeV. In the analysis J/ψ pairs coming from different pp interactions were removed with a cut on the distance along the beam direction between the reconstructed vertices, while the residual pile-up contamination was estimated looking at the kinematic variables distributions in sidebands. In double parton scattering J/ψ candidates are assumed to be produced independently, so a template $\Delta y \Delta \phi$ distribution has been built with J/ψ pairs from different events and has been normalized to data at large rapidity difference. Then event weights in each $\Delta y \Delta \phi$ bin have been computed from the ratio of the normalized template and full data; this weight can be used as an estimate of the DPS fraction, that can be compared to prediction from NLO versus rapidity difference and transverse momentum as shown in Fig. 4.

The total cross-section, in two fiducial regions $|y_{J/\psi}| < 1.05$, $1.05 < |y_{J/\psi}| < 2.1$ with $p_{T,J/\psi} > 8.5$ GeV, $p_{T,\mu} > 2.5$ GeV and $|\eta_\mu| < 2.3$, were found to be:

$$\sigma_{\rm Fid}(\quad |y_{J/\psi}| < 1.05) = (15.6 \pm 1.3({\rm stat}) \pm 1.2({\rm syst}) \pm 0.2({\rm b.r.}) \pm 0.3({\rm lum}))\ {\rm pb}$$

$$\sigma_{\rm Fid}(1.05 < |y_{J/\psi}| < 2.1\ ) = (13.5 \pm 1.3({\rm stat}) \pm 1.1({\rm syst}) \pm 0.2({\rm b.r.}) \pm 0.3({\rm lum}))\ {\rm pb}$$

with a DPS fraction

$$f_{\rm DPS} = (9.2 \pm 2.1({\rm stat}) \pm 0.5({\rm syst}))\%\ .$$

A similar measurement at $\sqrt{s} = 13$ TeV has been done from LHCb [25, 26]; the measured total cross-section for the production in the region $2.0 < |y| < 4.5$, $p_T < 10$ GeV was:

$$\sigma = (15.2 \pm 1.0({\rm stat}) \pm 0.9({\rm syst}))\ {\rm nb}\ .$$

The DPS component prediction was obtained from a large number of pseudoexperiments, where two uncorrelated J/ψ mesons were produced according to

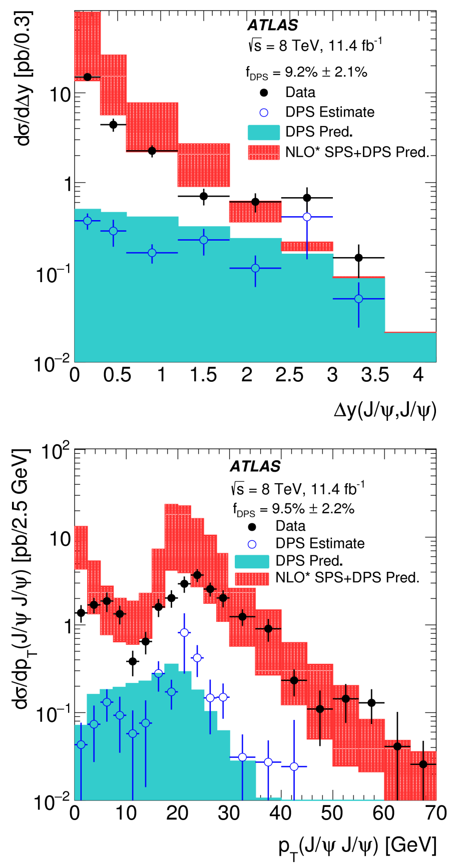

FIG. 4: The DPS and total differential cross-sections as a function of difference in rapidity and the transverse momentum of the di-J/ψ measured by ATLAS [21], compared with LO DPS [22] and NLO* SPS [23, 24] predictions.

the measured differential cross-sections, and SPS predictions from theoretical calculations using several approaches (LO, NLO, color singlet or color octet). Several data distributions were fitted with a two-component model to obtain the DPS fraction giving results in the range:

$$f_{\rm DPS} = ((42 \pm 25) \div (86 \pm 55))\%\ .$$

As an example, the comparison between the measured and predicted differential cross-section vs. $p_{T,J/\psi J/\psi}$ is shown in Fig. 5.

III. BRANCHING FRACTIONS

A. Bottom baryon decay

Ratios of branching fractions of b-hadrons with a J/ψ or a $\psi(2S)$ in the final state allow testing the factorization of amplitudes; some recent result of such ratios involve baryons. A measurement of the ratio

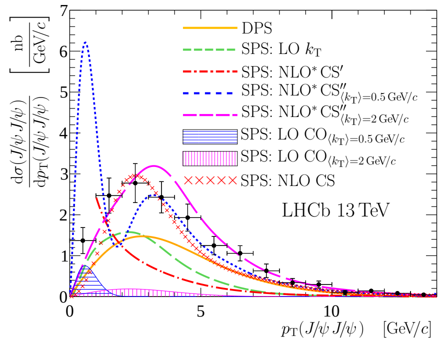

FIG. 5: Comparisons between the measured and predicted differential cross-section vs. $p_{T,J/\psi J/\psi}$ from LHCB [25, 26].

of branching fractions of $\Lambda_b^0 \to \psi(2S)\Lambda^0$ and $\Lambda_b^0 \to J/\psi\Lambda^0$ was done by ATLAS [27] a few years ago giving a result that shows a discrepancy from covariant quark model prediction [28, 29]. Another measurement has just been done by LHCb [30] that reconstructed ψ from non-prompt muons, a Λ^0 with two tracks of the same type, "long" or "downstream", built a common vertex and applied a constrained fit with the masses of the ψ and the Λ^0.

Events have been weighted with the inverse of efficiency; the latter was estimated in the simulation as well as the background from decays of $B^0 \to \psi(K_S^0 \to \pi^+\pi^-)$ or $\Xi_b^- \to \psi(\Xi^- \to \Lambda^0\pi^-)$: the invariant mass distributions are shown in Fig. 6.

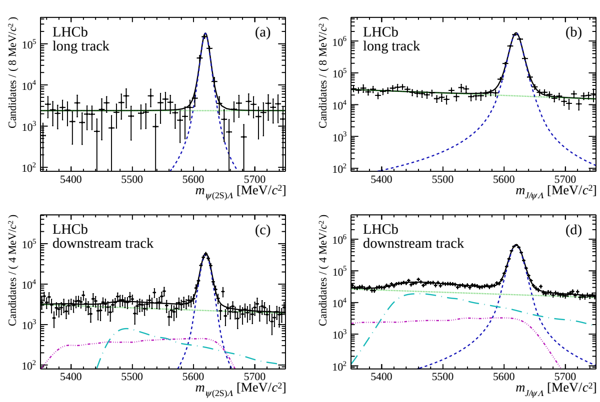

FIG. 6: Fits to the invariant-mass distributions for $\Lambda_b^0 \to \psi(2S)\Lambda^0$ (a,c) and $\Lambda_b^0 \to J/\psi\Lambda^0$ (b,d) obtained by LHCb [30]. The signal (blue, dashed), the combinatorial background (green, dotted), the $B^0 \to \psi K_S^0$ background (cyan, long-dash-dotted) and the $\Xi_b^- \to \psi\Xi^-$ background (violet, dash-triple-dotted) are indicated.

Taking the signal yields from the mass distributions fit and branching fractions of the ψ from PDG [18] the branching fractions ratio was obtained:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda^0)} = 0.513 \pm 0.023(\text{stat}) \pm 0.016(\text{syst}) \pm 0.011(\text{b.r.})$$

where the last uncertainty comes from the ψ branching fraction.

B. Baryon production in meson decays

1. $B^0_{d,s}$ decay

Some special interest related to baryons can be found in heavy hadron decays not only when baryon themselves are decaying, but also when they're present in the final state. Their presence can be used to look for possible pentaquark intermediate states; an evidence was claimed by LHCb [31, 32] in the decay of $\Lambda_b^0 \to J/\psi pK^-$. The presence of a baryon and an antibaryon can also test possible glueball states [33, 34]. LHCb then studied the decays $B^0_{d,s} \to J/\psi p\bar{p}$ [35]; both the decays are suppressed: the B_d^0 decay in this channel is suppressed by Cabibbo while the B_s^0 decay in the same channel is suppressed by OZI. A branching ratio at the level of 10^{-9} would be expected, with some enhancement via a resonant contribution from $f_J(2220) \to p\bar{p}$.

The branching fraction is measured by a comparison with a normalization channel, so that the ratio of branching fractions is measured, using the well known $B_s^0 \to J/\psi\phi$ decay as reference. The branching fraction of the studied channel is given by the ratio of reconstructed decays, multiplied by the branching fractions of $B_s^0 \to J/\psi\phi$, $\phi \to K^+K^-$ and, only for B_d^0, the ratio of fragmentation fractions:

$$\mathcal{B}(B_d^0 \to J/\psi p\bar{p}) = \frac{N_{B_d^0\to J/\psi p\bar{p}}}{N_{B_s^0\to J/\psi\phi}} \cdot \mathcal{B}(B_s^0 \to J/\psi\phi) \cdot \mathcal{B}(\phi \to K^+K^-) \cdot \frac{f_s}{f_d}$$

$$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) = \frac{N_{B_s^0\to J/\psi p\bar{p}}}{N_{B_s^0\to J/\psi\phi}} \cdot \mathcal{B}(B_s^0 \to J/\psi\phi) \cdot \mathcal{B}(\phi \to K^+K^-) \; .$$

The number of events was obtained by an extended maximum likelihood fit to the mass distributions, as shown in Fig. 7; the product $\mathcal{B}(B_s^0 \to J/\psi\phi) \cdot \mathcal{B}(\phi \to K^+K^-) \cdot f_s/f_d$ was measured [36] at $\sqrt{s} = 7$ TeV as well as the fragmentation ratio f_s/f_d [37, 38] and scaled to $\sqrt{s} = 13$ TeV [39].

The $B^0_{d,s} \to J/\psi p\bar{p}$ decays branching ratios have finally been extracted:

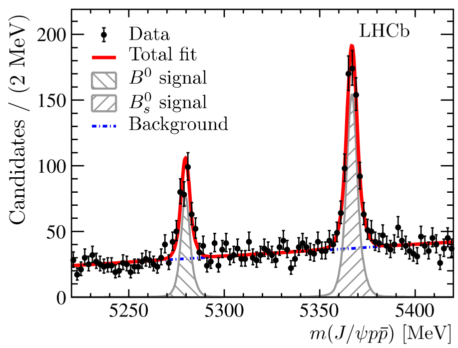

FIG. 7: Fit to invariant mass distribution of $B^0_{d,s} \to J/\psi p\bar{p}$ from LHCB [35].

$$\mathcal{B}(B^0_d \to J/\psi p\bar{p}) =$$
$$(4.51 \pm 0.40(\text{stat}) \pm 0.44(\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) =$$
$$(3.58 \pm 0.19(\text{stat}) \pm 0.33(\text{syst})) \times 10^{-6} \ .$$

Due to the very low phase space available the momentum uncertainty is negligible; that does allow as a side results the most precise single measurements of B^0_d and B^0_s masses:

$$m_{B^0_d} = (5279.74 \pm 0.30(\text{stat}) \pm 0.10(\text{syst}))\ \text{MeV}$$
$$m_{B^0_s} = (5366.85 \pm 0.19(\text{stat}) \pm 0.13(\text{syst}))\ \text{MeV} \ .$$

2. B^+ decay

Another study including the look for intermediate states has been done by CMS about the decay $B^+ \to J/\psi\bar{\Lambda}^0 p$ [40]: that decay was first seen at B-factories [41, 42]; in this new study new exotic states were searched in the $J/\psi\bar{\Lambda}^0$ or $J/\psi p$ systems.

As in the previous study of $B^0_{d,s}$ decay branching fraction has been measured as ratio with the normalization channel $B^+ \to J/\psi K^{*+}$ ($K^{*+} \to K^0_S\pi^+$, $K^0_S \to \pi^+\pi^-$).

The ratio and the absolute vaule of branching fractions were measured as:

$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} =$$
$$1.054 \pm 0.057(\text{stat}) \pm 0.028(\text{syst}) \pm 0.011(\text{b.r.})$$
$$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}^0 p) =$$
$$(15.07 \pm 0.81(\text{stat}) \pm 0.40(\text{syst}) \pm 0.86(\text{b.r.})) \times 10^{-6}$$

where the last uncertainty comes from the involved cascade decays branching fractions.

The distributions of invariant masses of the $J/\psi\bar{\Lambda}^0$ and $J/\psi p$ systems have then been studied and compared with expectations, from pure phase space or phase space corrected for reflections from $K^{*+} \to \bar{\Lambda}^0 p$ resonances. To do that the event sample has been divided in $M(\bar{\Lambda}^0 p)$ invariant mass bins and in each bin the first 8 Legendre polynomials and momenta have been computed using the $\bar{\Lambda}^0 p$ helicity angle to describe the angular distributon. Simulated events have then be reweighted using the $\bar{\Lambda}^0 p$ mass distribution ratio as reference, or the weights given by Legendre polynomials and moments. The distributions obtained in this way have been fitted to data.

The $J/\psi p$ and $J/\psi\bar{\Lambda}^0$ invariant mass distributions are shown in Fig. 8, compared with the simulation using pure phase space, the simulation reweighted with the Legendre polynomials or a function fitted to the $\cos\theta_{K^*}$ distribution in data.

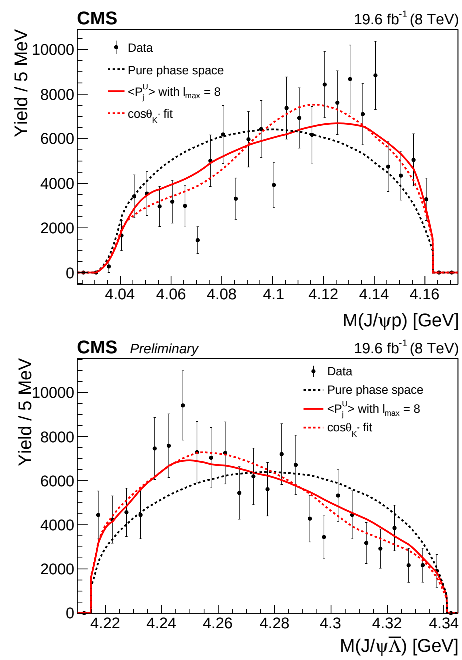

FIG. 8: Invariant mass distributions of $J/\psi p$ and $J/\psi\bar{\Lambda}^0$ obtaind by CMS [40] in the decay $B^+ \to J/\psi\bar{\Lambda}^0 p$, compared to the simulation using pure phase space (black), phase space corrected by the Legendre polynomials (red, solid) and a fit to the $\cos\theta_{K^*}$ distribution (red, dashed).

The quality of the data description from the different hypotheses has been estimated generating a large number of pseudoexperiments according to the PDF for the pure phase space or the reweighted angular distributions; a log-likelihood ratio has then been computed, to extract a compatibility, or incompatibility, significance. The significance of the incompatibility of data with the pure phase space was found to be much larger than the incompatibility with the phase space corrected by the Legendre polynomials:

	$J/\psi p$	$J/\psi\bar{\Lambda}^0$	$\bar{\Lambda}^0 p$
pure phase-space	$5.5 \div 7.4$	$6.1 \div 8.0$	$3.4 \div 4.6$
reweighted phase-space	$1.3 \div 2.8$	$1.3 \div 2.7$	$-$

IV. CONCLUSIONS

ATLAS, CMS and LHCb have produced many measurements of heavy hadrons production cross-section and decay branching fractions:

- cross-sections have been compared to predictions and simulations and are input for other measurements,
- branching fractions allow test model predictions,
- in the study of decays the possible presence of intermediate exotic states has been investigated.

All those measurements allow important tests of QCD.

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