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Heavy-Flavor production and spectroscopy at CMS

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Summary. — A representative sample of recent CMS measurements in Heavy-Flavor physics, based on proton-proton collision data collected in 2011 at a center-of-mass energy of 7 TeV, are reviewed. Particular emphasis is given to exotic quarkonia, properties of b-hadrons and observation of new hadrons.

PACS `14.20.Mr` – Bottom baryons ($|B| > 0$).
PACS `14.40.Nd` – Bottom mesons ($|B| > 0$).
PACS `14.40.Pq` – Heavy quarkonia.

1. – Introduction

The mission of the Compact Muon Solenoid experiment at the CERN Large Hadron Collider (LHC) includes a wide program of Heavy-Flavor (HF) physics [1]. The importance of precision measurements of production and properties of b-hadrons is due to multiple reasons. Measurements of HF production provide a testing ground for Quantum Chromodynamics (QCD) calculations: while next-to-leading order (NLO) contributions dominate at the LHC energies, large theoretical uncertainties remain due to factorization and renormalization scales. Moreover, b-jet identification is crucial in searches for New Physics, as many SM processes are known to have b-hadrons in their final state, and several scenarios beyond the SM foresee predominant couplings to the heaviest known quarks and leptons. Therefore, measurements of b-hadron properties provide important tests of the SM and any deviation from the predicted values would be an indirect indication of New Physics.

A representative sample of recent results in HF physics, obtained with the CMS experiment housed at the CERN LHC, and based on proton-proton collision data collected in 2011 at a center-of-mass energy of 7 TeV, and made public since the previous edition of the "Réncontres de Physique de la Vallée d'Aoste", is reviewed herein.

The CMS apparatus is described in detail in ref. [2]. It is designed around a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. At its core, a silicon pixel detector and a silicon microstrip tracker are immersed in the magnetic field. Together, they allow the measurement of charged particle momenta over the whole 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. Electromagnetic and hadronic calorimeters are housed inside the superconducting solenoid too. Muon detectors, based on drift tubes and resistive plate chambers, are embedded in the steel return yoke of the magnet, up to $|\eta| < 2.4$. The resolution in transverse momentum (p_T) measurement of the combined tracking making use of both the silicon tracker and the muon detectors is better than 1% [3, 4].

All the events used in the analyses presented herein were collected using the two-level trigger system of CMS. The first level is based on custom hardware processors and relies on information from muon detectors [5]. The "high-level trigger" is a processor farm which further reduces the event rate before data storage [6]. All the online selection criteria in the analyses presented herein require the presence of two muons with an invariant mass compatible with the J/ψ mass. Occasionally, the additional request of a displaced dimuon vertex is made.

2. – Measurement of the $X(3872)$ production cross section via decays to $J/\psi\pi\pi$ in pp collisions at $\sqrt{s} = 7$ TeV

The $X(3872)$ state was first observed in 2003 at Belle [7], it is an unexpected charmonium state and, until present day, its nature is unclear. The $X(3872)$ was observed in several decay channels also at BaBar [8], at the Tevatron [9, 10] and at the LHC [11]. The $X(3872)$ is produced both promptly and in B-decays, and angular analysis favors $J^{PC} = 1^{++}$. Recent updates were presented at this edition of the "Réncontres de Physique de la Vallée d'Aoste". Quantitative prediction of its production cross section are calculated in the framework of non-relativistic QCD (NRQCD), in the hypothesis that $X(3872)$ is standard charmonium.

The measurement [12] is based on $4.8\,\text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV collected in 2011 with prompt J/ψ dimuon triggers. The candidate $X(3872)$ is selected via its decay to $J/\psi\pi^+\pi^-$. An opposite-sign muon-pair with central rapidity, consistent with J/ψ mass, is selected applying stringent criteria on track selection, and it is combined to two additional opposite-sign tracks, assumed to be pions. The candidate is selected in a $p_T(J/\psi\pi^+\pi^-)$ range from 10 to 50 GeV and with a pseudorapidity $|\eta(J/\psi\pi^+\pi^-)| < 1.2$. The vertex of the four-tracks system is refit at the end of the selection procedure.

The production cross section is measured relative to the $\psi(2\text{S})$ one, in the same final state. The signal yield is extracted with an unbinned maximum-likelihood fit to the four-track invariant mass. The fit is performed in five different bins of $p_T(J/\psi\pi^+\pi^-)$. The ratio between the two cross sections is calculated as

$$R = \frac{N_{X(3872)} \times A_{\psi(2\text{S})} \times \epsilon_{\psi(2\text{S})}}{N_{\psi(2\text{S})} \times A_{X(3872)} \times \epsilon_{X(3872)}}\,,$$

where A is the acceptance and ϵ the selection efficiency. Corrections and efficiency factors are calculated from simulations assuming the $X(3872)$ is unpolarized and quantum numbers $J^{PC} = 1^{++}$. The main background is due to the random combination of tracks and it is reduced with a requirement on the distance in $\phi \times \eta$ space between the candidate J/ψ and additional pions. The result is not sensitive to the number of multiple interactions per bunch crossing thanks to the good selection of primary vertices. The major sources of systematic uncertainties are due to the pion-pair efficiency and to the p_T spectrum of candidate $X(3872)$ and $\psi(2\text{S})$.

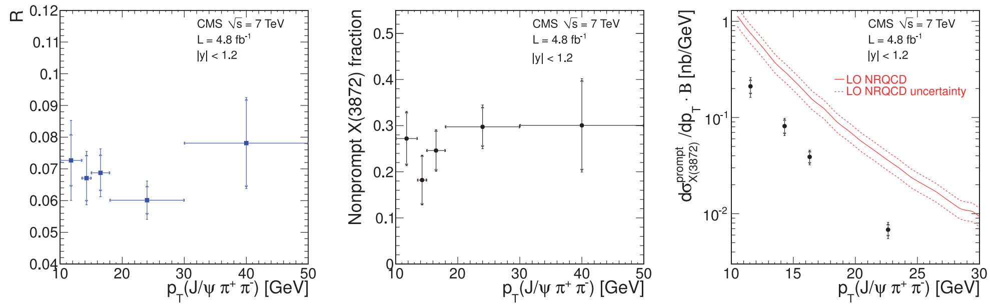

Fig. 1. – Left: measured value of the production cross section ratio between $X(3872)$ and $\psi(2S)$, differential in $p_T(J/\psi\pi^+\pi^-)$. Middle: measured fraction of non-prompt $X(3872)$. Right: measured differential production cross section of promptly produced $X(3872)$.

Figure 1 shows, from left to right, the cross section ratio R, the non-prompt fraction of produced $X(3872)$, and the production cross section of prompt $X(3872)$, computed for each bin of $p_T(J/\psi\pi^+\pi^-)$. The non-prompt fraction is measured selecting only candidate $X(3872)$ with a pseudo-proper decay length larger than 0.1 mm. This selection retains about the 80% of non-prompt $X(3872)$'s while the contamination from promptly produced $X(3872)$ candidates is less than 0.1%. The prompt $X(3872)$ production cross section is obtained from the measured values of the non-prompt fraction, R, and the $\psi(2S)$ production cross section of 3.53 ± 0.26 (stat.) $\pm\, 0.32$ (syst.) $\pm\, 0.14$ (lumi.) nb [13]. The measured differential cross section is remarkably lower than the one predicted by NRQCD, not consistently with the standard charmonium hypothesis. The integrated prompt $X(3872)$ production cross section has been measured in the same final state where the kinematic range is restricted to $10 < p_T < 30$ GeV and $|y| < 1.2$. In such a region, the average value of R is 0.0682 ± 0.0032 (stat.) $\pm\, 0.0065$ (syst.) while the average non-prompt fraction of produced $X(3872)$ is 0.260 ± 0.024 (stat.)± 0.016 (syst.). The resulting prompt cross section times branching ratio for the production of $X(3872) \to J/\psi\pi^+\pi^-$ is 1.06 ± 0.11 (stat.) $\pm\, 0.15$ (syst.) nb.

3. – Observation of the decays $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ in pp collisions at $\sqrt{s} = 7$ TeV

The B_c^+ meson is a unique probe for heavy-quark dynamics which is not accessible to $b\bar{b}$ or $c\bar{c}$ bound states. It is the ground state of two different bound heavy quarks with competing decay modes. The measurement of its properties would help in understanding such dynamics. The $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ decay was first observed at LHCb [14] and this measurement by CMS is the only experimental confirmation so far.

The measurement [15] is based on 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV collected in 2011 with displaced J/ψ dimuon triggers. Both the decays are identified from an opposite-sign muon-pair, consistent with the J/ψ mass, selected applying stringent quality criteria on the selected muon tracks. One or three additional tracks are selected and assumed to be pions (conjugate states are implicit). The largest-p_T B_c^+ candidate is retained and required to have $p_T(B_c^+) > 10$ GeV and $|\eta(B_c^+)| < 1.6$. Additional requirements on 3D secondary-vertex significance are made specifically for each decay channel.

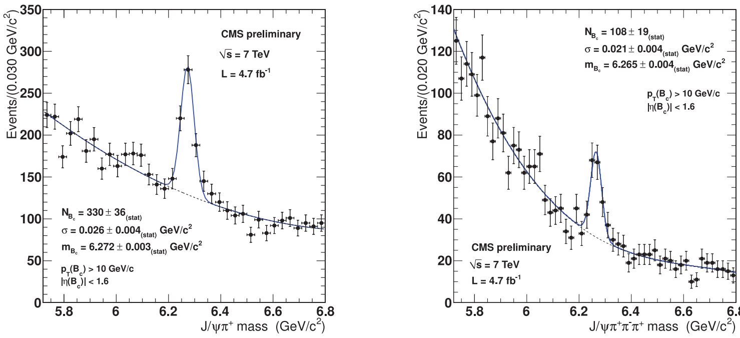

Fig. 2. – Left: signal yield from fit to invariant mass for the $B_c^+ \to J/\psi\pi^+$ decay channel. Right: signal yield from fit to invariant mass for the $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ decay channel.

Figure 2 shows the signal yield for each decay channel, obtained from fit to the invariant mass distribution of the candidate B_c^+ meson. The number of observed events is 330 ± 36 (stat.) $\pm\, 23$ (syst.) in the $B_c^+ \to J/\psi\pi^+$ decay channel, with a significance $S/\sqrt{S+B} = 10.5$. The number of observed events is 108 ± 19 (stat.) $\pm\, 14$ (syst.) in the $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ decay channel, with a significance $S/\sqrt{S+B} = 6.1$.

4. – Observation of a new Ξ_b baryon

There are several predicted baryons with beauty and strange valence quarks according to the SM. These include the Ξ_b^0 ground state, with $J^P = \frac{1}{2}^+$, the Ξ_b^{0*} excited state, with with $J^P = \frac{3}{2}^+$, and two states with negative parity. Ξ_b^0 candidates were observed at the Tevatron, but their quantum numbers still have to be probed.

The measurement [16] is based on $5.3\,\text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 7\,\text{TeV}$ collected in 2011 with displaced J/ψ dimuon triggers. The search for the Ξ_b^{0*} excited state requires the full reconstruction of a complex decay chain with three secondary vertices (conjugate states are implicit): $\Xi_b^{0*} \to \Xi_b^-\pi^+$, $\Xi_b^- \to J/\psi\Xi^-$, with $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, and $\Lambda \to p\pi^-$. Contamination from K_S^0 is removed with invariant mass constraints. The reconstruction of each track and of each intermediate step is analogous to those described in other measurements reported in this contribution.

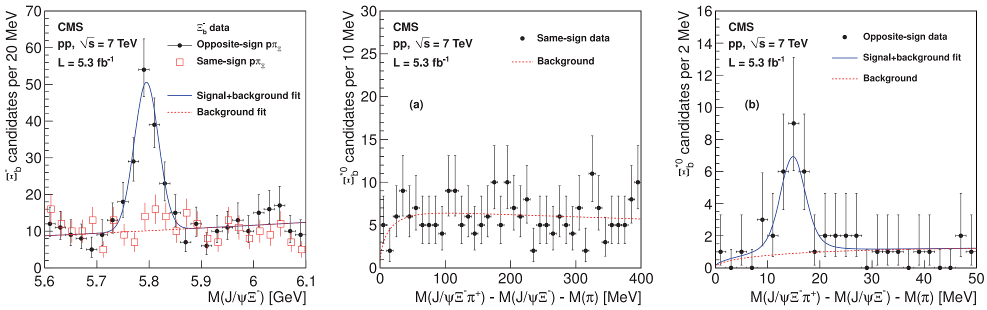

Fig. 3. – Left: reconstruction of the Ξ_b^- candidate. Middle: parametrization of Q for combinatorial background using uncorrelated momenta of like-charge candidates. Right: fit to data of signal plus background for opposite-charge candidates.

The signal yield is extracted from an unbinned maximum-likelihood fit to the difference Q between the mass of the candidate Ξ_b^{0*} and the masses of its decay products: $Q = m(J/\psi\Xi^-\pi^+) - m(J/\psi\Xi^-) - m(\pi^+)$. The combinatorial background is modeled with Ξ_b^- candidates combined with like-charge pions. Measured distributions are used to generate uncorrelated momenta of like-charge candidates to calculate Q.

Figure 3 shows, from left to right, the invariant mass distribution for $J/\psi\Xi^-$ pairs, which is used to calculate Q, the parameterization of Q for the combinatorial background in an extended range, and the distribution of Q for candidate Ξ_b^{0*}'s together with the result of the fit procedure. This is the first observation, with a 6.9 σ significance, of a state fitting the Ξ_b^{0*} hypothesis. The measured mass is $m = 5945.0 \pm 0.7$ (stat.) $\pm$ 0.3 (syst.) $\pm$ 2.7 (PDG Ξ_b^- mass) MeV.

5. – Concluding remarks

The excellent performance of the LHC and CMS allowed our collaboration to perform high-quality studies in HF physics. In particular, the excellent performance of the tracker and of muon detectors was crucial in studying fully-reconstructed decays of b-hadrons. We reviewed some of the most recent results in exotic quarkonia, measurements of properties of b-hadrons, and observation of new hadrons.

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