Heavy quark probes of QCD

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Large heavy flavor enriched data sets are being accumulated by the CMS experiment in different collision environments and energies provided by the LHC. These offer robust probes for testing the standard model and potentially reaching beyond it. In this report I concentrate on recent production measurements in proton-proton, ion-ion and proton-ion collisions. These allow to probe the underlying QCD mechanisms of hadron formation and the properties of QCD matter under extreme temperatures.

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CMS is a general purpose detector at the LHC [1]. In addition to collecting data at the highest energies, which allow for probing the electroweak and symmetry breaking sector and searching for new heavy particles directly, exploring the energy frontier, the experiment also accumulates sizeable datasets at lower energies, exploring the luminosity frontier. In this regard, and in addition to joining ATLAS in the high-p_T front, CMS complements the experiments dedicated to the study of b hadrons, LHCb, and of heavy-ion collisions, ALICE. Owing to robust and flexible tracking, muon, and trigger systems and the ability to efficiently explore the highest LHC luminosities and the different collision systems, CMS is making significant and unique contributions to the heavy flavor (HF) realm. We report briefly on recent HF production results in pp, pPb and PbPb collisions.

Hadronic systems involving heavy quarks, b and c, provide a suitable laboratory in which to study Quantum Chromodynamics (QCD). Measurements of differential production cross sections have been performed for S-wave quarkonia [2] and B^+ mesons [3] with initial Run2 data at 13 TeV, which extend similar measurements that had been performed at 7 TeV. The smaller pp dataset collected at 5 TeV has allowed corresponding measurements of J/ψ [4], ψ(2S) [5], D^0 [6], B^+ [7], B_s^0 [8] and $\Upsilon(nS)$ [9]. Similar results having been performed for the quarkonium states also at 2.76 TeV, these allow a study of the $\sqrt{s}$ dependence of the production cross sections. The heavier B_c meson has also been probed [10]. Polarization measurements have been performed for the S-wave quarkonium states at 7 TeV, and also for the Λ_b baryon [11]. Associated production of heavy flavor with other states provide a complementary view that is also explored, e.g. double quarkonia $J/\psi + J/\psi$ [12] and $\Upsilon(1S) + \Upsilon(1S)$ [13], ψ+jets [14], and W+ charm [15].

The bottomonium system plays a special role for an improved understanding of underlying production mechanisms that has been extensively explored in Run1 [16]. With the Run2 data an higher p_T region has been probed for S-wave states and enough yields also exist to study P-wave states. The $\chi_{b,J}(3P)$ triplet ($J = 0, 1, 2$) is interesting in particular for allowing to infer how its properties are affected by the proximity to the open beauty ($B\bar{B}$) threshold. The merged states had been observed by ATLAS [17] earlier in Run1 (the first newly observed state at the LHC). Using an integrated luminosity of $80\,fb^{-1}$ collected during Run2, CMS has reported the observation of the resolved $\chi_{b,1}(3P)$ and $\chi_{b,2}(3P)$ states, along with a measurement of their masses [18]. Studies of P-wave B_s^0 mesons have been also pursued, leading to the observation of the $B_{s2}^* \to B^0 K_S$ and evidence of the $B_{s1} \to B^{*0} K_S$ decays [19].

Heavy quarks provide sensitive and novel hard probes of the hot QCD medium created in heavy ion collisions. Important properties of the medium such as its temperature and the mechanisms of energy loss and their flavor dependence are probed. These are inferred by comparing cross sections across various systems (in addition to PbPb and pp, also pPb for quantifying so-called cold nuclear matter effects) as well as particle distributions and correlations. The exploration of the bottomonium family of states resulted in the flagship Run1 observation of sequential quarkonium suppression [20], which has more recently been confirmed at the higher Run2 energies [21]. The charmonium states have been similarly explored [4, 5], which in addition to melting (via Debye screening) are sensitive to recombination effects. In addition to quarkonia also open-flavor states are being actively investigated. These include the D^0 meson that is successfully reconstructed in its fully hadronic final state also in PbPb collisions [6]. B mesons are traditionally accessed in the heavy-ion environment in an inclusive fashion, via their leptonic decays, or more effectively via displaced charm, i.e. non-prompt ψ [4] and D [22]. In addition, however, CMS has directly
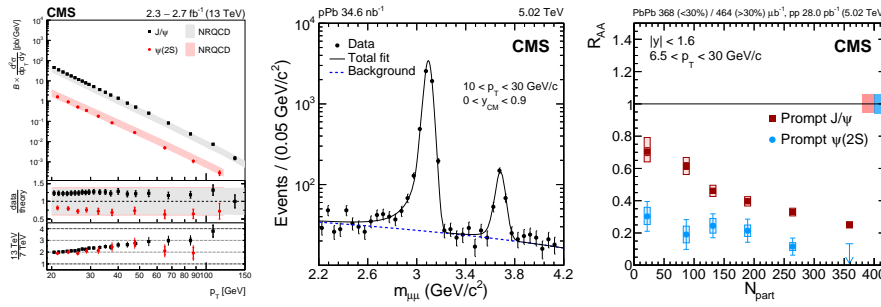
Figure 1: The charmonium system. Left: Differential cross section in pp collisions at 13 TeV [2]. Middle: Reconstruction in pPb collisions at 5 TeV [5]. Right: Suppression factor in PbPb collisions at 5 TeV [4].
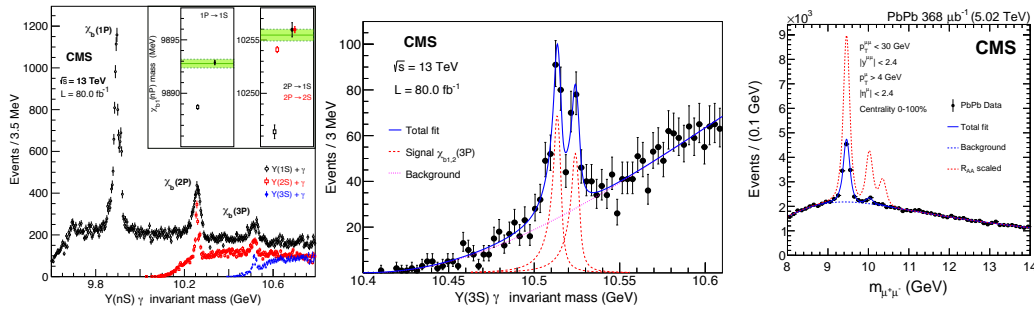

Figure 2: The bottomonium system. Left: The χ_b P-wave states, reconstructed in their decays to $\Upsilon\gamma$ [18]. Middle: Mass splitting of the $\chi_{b,1}(3P)$ and $\chi_{b,2}(3P)$ states, in the decays to $\Upsilon(3S)\gamma$ [18]. Right: The Υ S-wave states, in PbPb collisions (data points) and relative (R_{AA}-scaled) yields in pp collisions (dashed red line), at 5 TeV [21]. The $\Upsilon(nS)$ and γ particles are reconstructed resp. in the $\mu^+\mu^+$ and e^+e^- final states.

reconstructed *B* mesons for the first time in the ion collision environment [23, 7, 8], which allows to distinguish the mesons' flavor. The measured suppression for various meson species is collected in Fig. 3 (right), which reflects the flavor/mass dependence of energy loss with expected hierarchy. The B_s^0 meson has been reconstructed in the various collision systems [8, 23] (Fig. 4), hinting at a potential strangeness enhancement (relative to the lighter species); although here as elsewhere additional PbPb data will be crucial. Additional ion data will be no less precious for exploring even heavier, rarer heavy flavor probes. These include among others also the top quark, which was already observed in pPb [24] paving the way for its future investigation in PbPb collisions.

All CMS public results may be accessed via the Collaboration's publication portal [25]. The full Run2 dataset shall allow for improved precision but also for the exploration of additional heavy flavor processes and sensitive probes of the strong and electroweak sectors of the standard model as well as potentially the physics that lies beyond.

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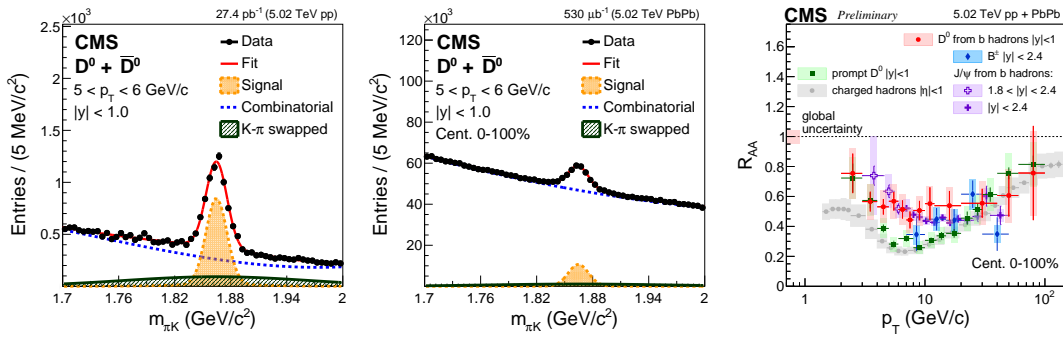
Figure 3: The D^0 system. Signal reconstructed in the $D^0 \to K^+\pi^-$ decay, in pp (Left) and PbPb (Middle) collisions at 5 TeV [6]. Right: Nuclear modification factor as function of p_T for various hadron species [22].
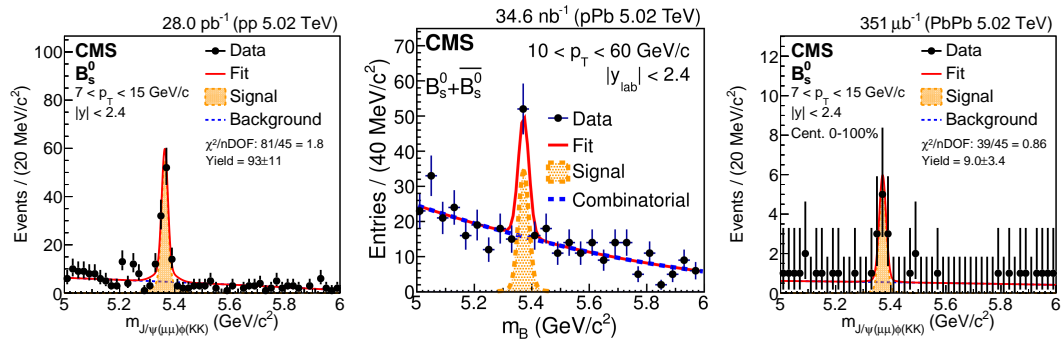
Figure 4: The B_s^0 system. The meson is reconstructed in the $B_s^0 \to J/\psi\phi$ decay, respectively in pp, pPb and PbPb collisions at 5 TeV [8, 23]. The J/ψ and ϕ mesons are reconstructed resp. as $\mu^+\mu^-$ and K^+K^-.

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