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Abstract

Doctoral thesis in Physics

The B_c^+ meson and high-energy partons in the quark-gluon plasma of heavy-ion collisions in the CMS detector at the LHC.

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This thesis addresses how heavy-quark hadronisation, and parton interactions in general, are affected by the quark-gluon plasma (QGP), a hot and dense medium created in heavy-ion collisions at the LHC. Data from the CMS detector are analysed to achieve the first observation of B_c^+ mesons in heavy-ion collisions. Two scaling laws are also brought to light from a model of radiative energy loss in the QGP.

The analysis of CMS data from 2017 proton-proton and 2018 lead-lead (PbPb) collisions at a centre-of-mass energy of 5.02 TeV per nucleon pair leads to the observation of $B_c^+ \to (J/\psi \to \mu^+\mu^-)\,\mu^+\,\nu_\mu$ decays, and to the measurement of the B_c^+ nuclear modification factor in two bins of the trimuon transverse momentum ($p_T^{\mu\mu\mu}$) or of the PbPb collision centrality. Three main backgrounds are described with simulation or with specifically-designed data-driven samples. A Boosted Decision Tree (BDT) is trained on the selected background and simulated signal candidates. A likelihood fit is run on signal and background templates, binned in BDT, trimuon invariant mass, and $p_T^{\mu\mu\mu}$ or centrality. The acceptance and efficiency of the selection chain are evaluated iteratively in each $p_T^{\mu\mu\mu}$ or centrality bin with the simulated signal, whose $p_T^{\mu\mu\mu}$ spectrum is first corrected with the one measured in a preliminary analysis. The B_c^+ meson is found to be less suppressed than all measured open and hidden heavy flavour mesons, except the B_s^0 meson. The results also hint at a softening of the p_T spectrum in PbPb collisions. These may indicate that heavy-quark recombination is a significant B_c^+ production mechanism. As an amuse-gueule for this analysis, Fig. 1 shows a PbPb collision in CMS that has a very high probability of containing a B_c meson.

At high-p_T ($\gtrsim 10-15\,\text{GeV}$), radiative energy loss should be the dominant source of suppression of hadrons in the QGP. An existing model for the radiative energy loss of partons, based on the BDMPS medium-induced gluon spectrum, predicts a universal p_T-dependence of the nuclear modification factor. This is proved to fit collected measurements in systems of various geometric configurations and energies, from which the corresponding mean energy losses are determined. A new scaling law is also found consistent with the gathered measurements: it links the extracted mean energy loss with the average path length in the medium and the charged particle multiplicity. This can lead to an extraction of medium expansion and diffusion properties, and to a prediction of the elliptic flow coefficient.

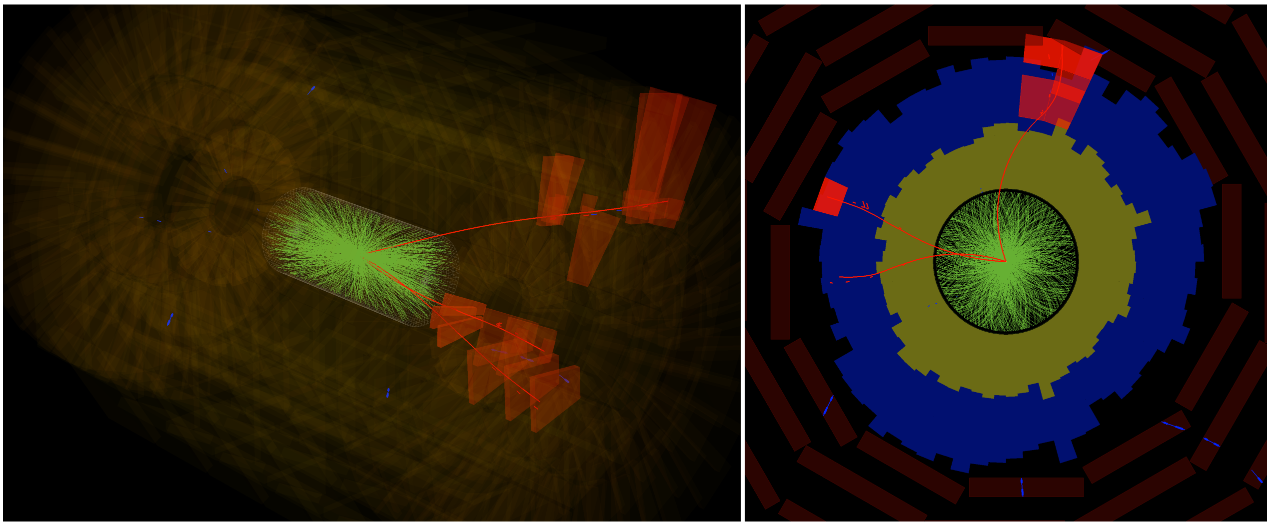

FIGURE 1: Display of the PbPb 2018 collision event #209030061 (run #327004, LS #497) in the CMS detector. This PbPb collision (at 5% centrality) has a very high probability to contain a B_c decaying to three muons, shown in red. Only 4 selected PbPb events have BDT values as high as this event, to be compared to less than 0.1 background events expected in this BDT range. The 3D (*left*) and transverse to the beam (*right*) views are shown. The trimuon from this B_c decay has $(m^{\mu\mu\mu}, p_T^{\mu\mu\mu}, y^{\mu\mu\mu}) = (5.5\,\text{GeV}, 9.8\,\text{GeV}, 1.7)$; the high trimuon mass means the energy taken by the neutrino of the decay is small. One opposite-sign dimuon has a mass of 3.07 GeV, close to the J/ψ mass. The trimuon vertex is displaced by about 1 mm from the primary vertex, to which most of the charged tracks point (tracks with $p_T > 1.2\,\text{GeV}$ are shown in green). The yellow and blue histograms show the transverse energy deposition in the calorimeters. The S-shape trajectory of the muons, inspiring the CMS logo, is due to the magnetic field changing sign in the return yoke embedded in the muon detectors.

This thesis is structured with an introduction (chapter 1) travelling from general considerations about (particle) physics to concepts needed in the following, then a first part concerning the B_c analysis, and a second part concerning my work on the phenomenology of energy loss. Ch. 2 motivates the experimental search for B_c mesons in heavy ion collisions. Ch. 3 presents the LHC and the CMS detector and the overall analysis strategy (section 3.3). Ch. 4 deals with the backgrounds blurring the B_c signal, and ch. 5 details the candidate selection established to discriminate against them. Ch. 6 shows the extraction of the signal yields from a template fit of trimuon mass distributions. Ch. 7 computes the correction of the observed yields for the acceptance and efficiency of the signal reconstruction and selection. Ch. 8 summarises the sources of uncertainties and how they are estimated. Ch. 9 shows the results, including the B_c nuclear modification factor, and their interpretation. In the phenomenology part, ch. 10 describes the energy loss model I start from, and ch. 11 shows two scaling laws it results in. Ch. 12 shows some improvements and additions to the model. Lists of abbreviations and acronyms, and of the values of some constants, can be found at the end of the document.