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# What have hard probes taught us about the quark–gluon plasma as measured in CMS?

Julia Velkovska (for the CMS Collaboration)

*Department of Physics and Astronomy, Vanderbilt University, Station B 1807, Nashville, TN 37235, USA*

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**Abstract**

This paper reviews recent CMS measurements from hard probes and their implications in assessing the properties of the QGP. Results from pPb collisions are compared and contrasted to measurements in PbPb collisions. The role of pPb collisions as a "control experiment" separating initial from final state effects is discussed.


*Keywords:* Heavy-ion collisions; Quark–gluon plasma; Jets; Charged hadrons; Electroweak bosons; Quarkonia

## 1. Introduction

The study of the high energy density phase of nuclear matter (the quark–gluon plasma) usually relies on one of two approaches: studies of the bulk medium produced in the collisions via measurements of low momentum particles and correlations between them, or using "probes" that propagate through the medium and sense its properties. It is imperative that the particles that would be used as probes are not part of the thermalized medium itself. It has long been recognized that jets and high-momentum particles that are produced in scatterings with large momentum transfer can serve as tomographic probes of the medium. The majority of the produced jets originate in the hard scatterings of gluons or light quarks. In more rare instances, the outgoing parton is a heavy (c or b) quark, or the jet partner may be an electroweak boson. Particles that interact via

*E-mail address:* julia.velkovska@vanderbilt.edu (J. Velkovska).

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the strong interaction are expected to lose a significant fraction of their energy, while propagating through the quark–gluon plasma (QGP) and this energy loss may depend on the parton flavor, while particles that only participate in electroweak interactions are not expected to experience energy loss. Hard scattering processes may also produce bound states of heavy-quark–antiquark pairs. The production rate of these quarkonium states in different collisions systems is of particular interest, since in the presence of deconfined quarks and gluons the force that binds the pair together is reduced; the modification of the yield of the different quarkonium states is sensitive to the temperature of the QGP. In addition to the measurements in nucleus–nucleus (AA) collisions, the study of the QGP requires reference measurements from systems in which the QGP is not expected to be formed, such as pp and pA collisions. The long-standing paradigm in the heavy-ion community has been that in pA collisions due to the absence of a produced medium one can isolate the nuclear effects from the initial state of the hard-scattering process; the effects from the final state in AA collisions can then be assessed more reliably. Some of these assumption are now tested more carefully both in LHC and in RHIC data.

Equipped with high-resolution tracking and muon systems, along with highly segmented calorimetry and a sophisticated two-level trigger system, the CMS detector is ideally suited for studies involving hard probes. A full description of the CMS detector can be found in Ref. [1]. This paper gives a brief overview of the measurements performed by CMS in PbPb and pp collisions at a nucleon–nucleon center-of-mass energy of 2.76 TeV, and in pPb collisions at 5.02 TeV. The results are based on integrated luminosity of 150 $\mu b^{-1}$ for PbPb collisions, 5.3 $pb^{-1}$ of pp collisions collected in 2013, and 35 $nb^{-1}$ of pPb collisions. More information on all of the CMS heavy-ion physics results can be found on the Public Physics Results web page [2].

## 2. Evidence for QGP in PbPb collisions

The studies of jets in heavy-ion collisions using CMS began in 2010 with the observation that the momentum imbalance between pairs of back-to-back jets was much larger in central PbPb collisions than in either pp or peripheral PbPb collisions [3]. Despite this evidence for significant parton energy loss, there was no sign of any medium-induced acomplanarity, the two jets still emerged essentially back to back. By studying charged particles in events with unbalanced jets, the missing energy was found to emerge predominantly in low momentum particles at large angles with respect to the jet axis. A more detailed study of the jet energy loss was performed using the high-statistic data from 2011. In Ref. [4], the ratio of the transverse momenta of the two jets is studied as a function of centrality and the transverse momentum of the leading jet (for leading jet $p_T > 120$ GeV$/c$ and sub-leading jet $p_T > 30$ GeV$/c$). The jet energy loss is found to increase as the collisions become more central, but for any given centrality the dijet imbalance is found to be independent of jet $p_T$ up to the highest momentum studied.

CMS has conducted a comprehensive set of measurements aiming to understand how the medium interacts with particles of different nature. The jet-quenching phenomenon is investigated using a variety of rare probes and fully reconstructed jets. The quenching of the heavy b-quarks is studied via their decays into $J/\psi$ mesons [5] and with fully reconstructed b jets [6]. Fig. 1 presents a collection of results [5–11] for the nuclear modification factors ($R_{AA}$) of various single particles (left panel) and fully reconstructed jets (right panel). Electroweak bosons ($\gamma$, W, Z) remain unmodified by the medium and their production serves as a reference process. A similar suppression is observed for all other probes, including the heavy b jets, indicating that the medium is extremely opaque. Some indication of parton flavor dependence is seen at low $p_T$ where the non-prompt $J/\psi$ appear to be less suppressed than the charged hadrons, but the