Hard Physics with Heavy Ions in CMS

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Abstract. The LHC will collide protons at $\sqrt{s}=14$ TeV and lead beams at $\sqrt{s_{NN}}=5.5$ TeV as well as possibly other AA and pA combinations. The physics program of the Compact Muon Solenoid (CMS) includes the study of heavy-ion collisions, where the collision energy, higher than at RHIC, will allow the study of the dense partonic system with hard probes. A broad palette of these probes is within the reach of CMS. Some are likely to be modified, relative to p-p collisions, by the presence of the hot medium, like quarkonia ($J/\psi$ and $\Upsilon$) or high-$p_T$ jets. Others, like heavy quarks, $Z^0$ bosons and photons, will act as reference candles. This article overviews the hard physics reach and unique abilities of CMS in studying the medium produced in heavy-ion collisions at the LHC.

1. Introduction
The CMS detector is very well equipped to carry out a wide range of physics measurements with ultra-relativistic heavy-ion collisions. It was designed to provide tracking and calorimetry with high resolution and granularity, with full azimuthal coverage over a large range of rapidities. A detailed description of the detector elements is given in the Technical Design Report [1] recently prepared; here we only provide a brief description of the components.

The central part of the detector consists of a 22 m long solenoid capable of providing a magnetic field of 4 T. The collision region is surrounded by a silicon tracker composed of pixel and strip layers, and by two calorimeters, one electromagnetic (ECAL) and one hadronic (HCAL). The silicon system, with the outer layers covering $\pm 2.5$ units of pseudorapidity, provides tracking and the means for primary vertex reconstruction. The inner pixel detectors have individual energy read-outs for each of their $100 \times 150 \mu m^2$ pads. The occupancy for the pixel detectors is expected to be at the level of 1–3%, even in the heavy-ion environment. The extensive coverage of both electromagnetic and hadronic calorimetry is one of the distinguishing features of CMS. The electromagnetic and hadronic calorimeters cover $\pm 3$ and $\pm 5.2$ units of pseudorapidity, respectively. This set of detectors is complemented by the muon chambers residing outside of the central field region. The muon system covers a total of $\pm 2.4$ units of pseudorapidity, with the barrel detectors covering $\pm 1.3$ and the endcaps the window $0.9 < |\eta| < 2.4$. Enhanced coverage in the forward region is provided by additional detectors: the CASTOR calorimeter ($5.3 < |\eta| < 6.6$), TOTEM ($7 < |\eta| < 10$), and the Zero Degree Calorimeter (ZDC) ($|\eta| > 8.3$).

With this set of detectors CMS has the ability to study particle production in heavy-ion collisions up to the limits of the LHC phase space. It has excellent abilities for complete jet reconstruction, dimuon measurements with unprecedented mass resolution, and very good tracking capabilities, essential for global event characterization. The expected detector performance has shaped the initial expectations for the physics studies at the LHC, including...
high $p_T$ particle spectra and correlations, jet quenching and fragmentation measurements, heavy quark identification and Equation-of-State studies. In addition, CMS has a sophisticated trigger system, which is crucial for the heavy-ion program. The combination of the fast hardware-based Level-1 Trigger and the massive computing power of the Higher Level Trigger (HLT) will be used to fully reconstruct specific portions of the individual events and to provide statistically significant information on rare probes. In addition, HLT algorithms specifically tuned for the heavy-ion program are being designed to trigger on centrality, reaction plane, etc.

In the following, the capabilities of this detector for hard physics with heavy-ion collisions are reviewed. For soft and forward physics and further details, the reader is referred to Ref. [2], an extensive and comprehensive review of the abilities of CMS to study QCD at the LHC.

2. Hard physics

Interesting events are first selected by the level-1 trigger. Fully implemented in hardware, fast decisions are made within about 3 $\mu$s after the collision, essentially using signals from the muon chambers and calorimeters. After that, the event rate is still high so that the efficient observation of rare hard probes requires a high level trigger (HLT). The HLT uses about ten thousand CPUs working with the full event information, including data from the silicon tracker. A detailed study has been done with running offline algorithms by parameterising their performance. Trigger tables are produced considering various channels and luminosity scenarios (Fig. 1).

![Figure 1](image)

**Figure 1.** Minimum bias and high level trigger $J/\psi$, $\Upsilon$, and jet trigger rates for design luminosity in central Pb-Pb collisions.

### 2.1. Quarkonia

Melting of the charmonia and bottomonia resonances can convey the thermodynamical state of the QCD medium. It is an open question whether these states can be regenerated or are fully suppressed at LHC energies. They can be reconstructed in the dimuon decay channel with the help of precise tracking and matching between the silicon tracker and the muon chambers. Acceptances are 25% ($\Upsilon$) and 1.2% ($J/\psi$) for an 80% efficiency and 90% purity. The mass resolution is 86 MeV/$c^2$ at the $\Upsilon$ and 35 MeV/$c^2$ at the $J/\psi$, in the full acceptance, and even better in the barrel (Fig. 2), the best dimuon mass resolutions achieved at the LHC. With the help of the HLT, up to 35 times more $J/\psi$ and $\Upsilon$ can be collected.
2.2. Jets

Finding jets on top of a large background is a challenge for Pb-Pb collisions at the LHC. Jets are reconstructed using a pile-up subtraction algorithm. It consists of an iterative jet cone finder and an event-by-event background subtraction. The directional resolutions for 100 GeV jets are $\sigma_\eta \approx 2.8\%$ and $\sigma_\phi \approx 3.2\%$, while the energy resolution is $\sigma_{E_T} \approx 16\%$. Thanks to the HLT, the jet $E_T$ measurement can be extended to about 0.5 TeV (Fig. 3-left). The data sets, triggered with 50, 75 and 100 GeV, are merged using a simple scaling procedure.

Figure 2. Invariant mass spectra of opposite-sign and like-sign muon pairs with $dN_{ch}/d|\eta|_{|\eta|=0} = 2500$ in the $J/\psi$ (left) and $\Upsilon$ (right) mass regions.

Figure 3. Left: Expected inclusive jet $E_T$ distributions in 10 centrality bins. Right: Expected statistical reach for the nuclear modification factor for inclusive charged hadrons. Central Pb-Pb collisions at 5.5 TeV have been generated by Hydjet [3] for an integrated luminosity of 0.5 nb$^{-1}$. 

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2.3. High $p_T$ hadrons

Parton energy loss in the hot and dense medium created in Pb-Pb collisions can be studied by measuring the nuclear modification factors $R_{AA}$ and $R_{CP}$. High $p_T$ charged particles can be tracked with about 75% efficiency, only a few percent fake track rate for $p_T > 1$ GeV/c and excellent momentum resolution. Using the HLT, the $p_T$ reach of the measurement is extended from 90 to 300 GeV/c (Fig. 3-right).

Summary

The CMS detector should perform superbly in physics studies requiring hard probes, taking advantage of the high level trigger for increased $p_T$ reach. CMS will also study soft and forward physics where the detector performance is expected to be equally good.

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References

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[3] “HYDJET fast event generator”, located at http://cern.ch/lokhtin/hydro/hydjet.html.