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Probing the Quark-Gluon Plasma with Jets in CMS at the LHC

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At the Large Hadron Collider energies, unprecedented high rates for hard probes will be available. We present the Compact Muon Solenoid Detector's capabilities for measuring some of these probes and how they are used for high-density QCD phenomenology studies.

High-pT physics at LHC
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1. The Large Hadron Collider Challenges

The Large Hadron Collider (LHC) opens a new era for our understanding of matter at extreme conditions. With more than a 25-fold increase in center-of-mass energy compared with the Relativistic Heavy Ion Collider (RHIC), it is hard to believe that nothing novel will be revealed. But even if this will not happen, the LHC scientists will have to face a few challenges, some physics-related but also some technical and machine-related challenges.

With regards to the *physics*, 'old' questions will have to be asked: 'Is there proof for deconfinement?', 'Has thermalization been achieved?', 'Are the used observables enough to claim a deconfined system of quarks and gluons?'. Of course, new questions (e.g. "What is x in x-*QGP*?") will be faced by both theorists and experimentalists. The answers to all these questions will be given by using old probes (e.g. high-$p_{\rm T}$ hadrons, heavy mesons, etc) and methods (e.g. multi-particle correlations) that proved their power at RHIC and at the Super Proton Synchroton (SPS). However, due to the increased energy, higher rates for all the existing probes will be achieved (which will increase the transverse momentum reach), and more importantly, new probes (e.g. Z^0, Υ states) will become available. In these conditions, new methods to investigate the medium will also become possible (e.g. full jet reconstruction) [1].

From the *technical* point of view, the challenges are related to the unprecedented high multiplicity that will be created when colliding Pb beams at $\sqrt{s_{NN}} = 5.5$ TeV (see Table 1). This requires, in order to have a successful physics program, performant tracking, detectors with good momentum resolution, and also a smart trigger scheme.

Machine	AGS	SPS	RHIC	LHC
$\sqrt{s_{NN}}$(GeV/A)	4	17	200	5500
N_{ch}	700	3000	5000	15000

Table 1: The evolution in center-of-mass collision energy and multiplicity at the heavy-ion accelerators.

2. CMS Detector Capabilities and Performances

In Figure 1 the geometrical acceptance of the CMS detector subcomponents is sketched. Some of its characteristics will be laid out in the following.

Large acceptance tracking and calorimetry. With 2π calorimetric coverage in azimuth, full jet reconstruction is possible. The Si-tracker spans 5 units in pseudorapidity ($|\eta| < 2.5$), making possible a detailed study of b and c quark physics. Among the LHC experiments, CMS has a uniquely large range in rapidity for charged and neutral hadrons in the barrel region, $|\eta| < 6.6$, and also in the forward region, $|\eta| > 8$, for neutral hadrons.

CMS has the detector coverage to address the physics.

High resolution. The fine granularity of the Si-pixel layers combined with the strong (4T) magnetic field assures, for $p_{\rm T} < 50$ GeV/c, a momentum resolution better than 1.5% (Figure 2 left [2]). For jet finding, the calorimeters have $\sigma_\eta = 0.028$ and $\sigma_\phi = 0.032$.

CMS has the technical design performance needed to resolve the physics.

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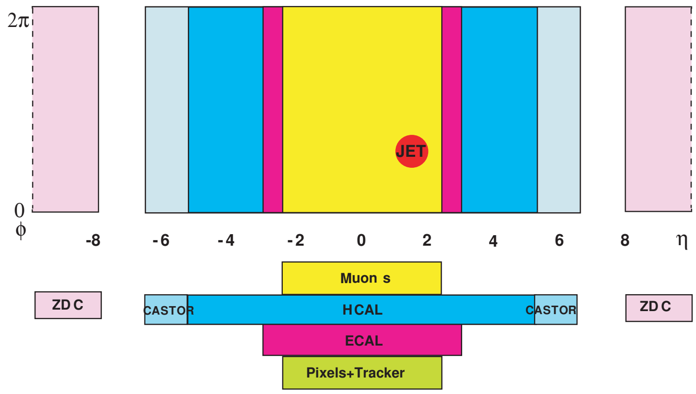

Figure 1: CMS detector acceptance in pseudorapidity η and azimuth ϕ.

Trigger architecture. The CMS trigger scheme consists of only two layers of triggers. Level-1 uses custom electronics and inspects events at the full bunch crossing rate, making full min-bias event information available. The High Level Trigger (HLT) runs off line reconstruction algorithms on every full PbPb event [3]. Using the HLT makes possible the reconstruction of jets up to $E_{\mathrm{T}} \approx 500\,\mathrm{GeV}$ (Figure 2 right).

3. High-p$_T$ Physics

To quantify the hadron production in AA with respect to baseline pp collisions, the nuclear modification factor R_{AA} is normally used. It represents the ratio of the yields in the two collision systems, properly scaled to take out geometrical effects present in AA but not in pp. Figure 3 left shows the R_{AA} factor as a function of p_{T} for one month of PbPb running (0.5 nb^{-1}). In order to obtain high statistics for the charged particles in AA at large transverse momentum, a jet trigger

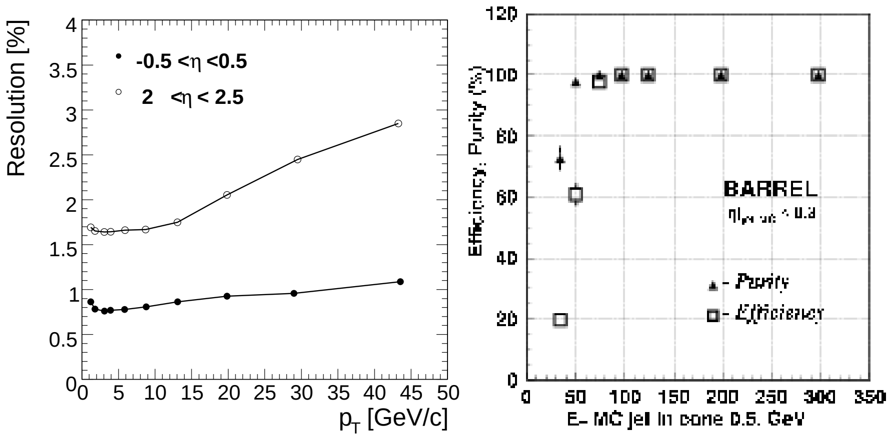

Figure 2: Left: p_{T} dependence of the track transverse momentum resolution achieved in heavy-ion events with $dN/dy = 3200$ in the barrel (full symbols) and in the forward (open symbols) regions. **Right:** Transverse energy dependence of the reconstruction efficiency (open squares) and purity (closed triangles) of the jet reconstruction, in central PbPb events in the central barrel ($|\eta| < 0.3$).

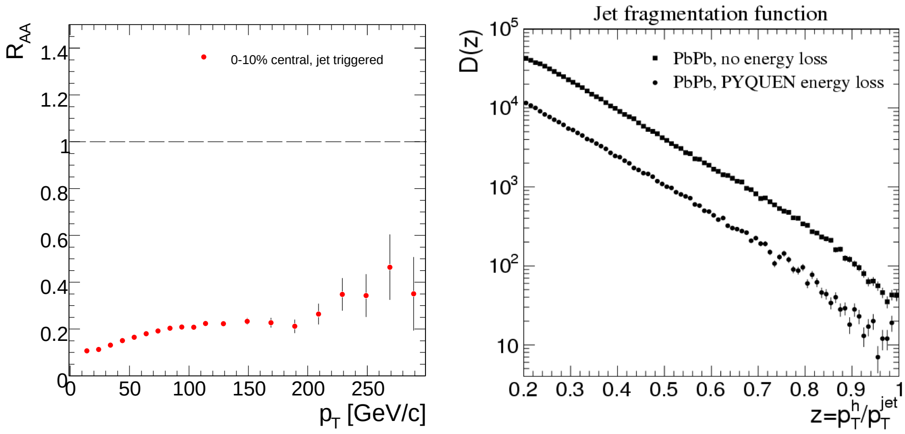

Figure 3: Left: Illustration of the statistical reach for the nuclear modification factor, $R_{AA}(p_T)$, for charged hadrons in central PbPb collisions generated with HYDJET for a nominal integrated luminosity of 0.5 nb^{-1} and data triggered on high-E_T jets. **Right:** Jet fragmentation function for leading hadrons with $|\eta^h| < 2.4$, $|\eta^{jet}| < 3$ and $E_T > 100\,\mathrm{GeV}$ in central PbPb collisions for the cases without (squares) and with (circles) partonic energy loss. The histogram entries and statistical errors correspond to the estimated jet rate in most central PbPb collision for one month of a LHC run.

scheme with three different thresholds was applied [1]. By these means, values of $p_T \approx 200$ GeV/c could be reached. The PbPb data set was generated with the HYDJET [4] event generator. The PYTHIA [5] proton-proton spectrum has been used here as denominator for the ratio. The actual value $R_{AA} \approx 0.3$ reflects the specific implementation of the jet energy loss model in the HYDJET event generator.

The possible measurement of jets up to $E_T \approx 500\,\mathrm{GeV}$ and of leading hadrons up to $p_T \approx 300$ GeV/c makes possible the detailed study of the properties of the effects of parton energy loss on the "jet fragmentation function" (JFF), $D(z)$, defined as the probability for a given product of the jet fragmentation to carry a fraction z of the jet transverse energy, E_T. Comparison of the JFF in nuclear and pp collisions (or in central and peripheral nuclear interactions) yields information about the in-medium modification of the JFF. Figure 3 right shows JFFs with and without partonic energy loss simulated with PYTHIA. The one with energy loss has been computed for central PbPb collisions using the PYQUEN energy loss model [6]. The jet energy was determined as the total transverse energy of the final particles collected around the direction of the leading particle inside a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$. Extra cuts of $|\eta^h| < 2.4$, $|\eta^{jet}| < 3$ and $E_T^{jet} > 100$ GeV were applied.

3.1 Two particle correlations

An important tool in the study of the medium created in high energy collisions is the measurement of dijets via hadron correlations. In particular, two hadron azimuthal correlations allow the study of back-to-back hard scattered partons that propagate in the medium before fragmenting into jets of hadrons. While traversing the medium, the hard-scattered partons lose energy through collisions and radiation, and thus the properties of the final jet is modified. By measuring these modifications, information about the properties of the medium is obtained. However, in AA collisions, both jets are affected by the medium. This means the *initial* energy of the jets is unknown.

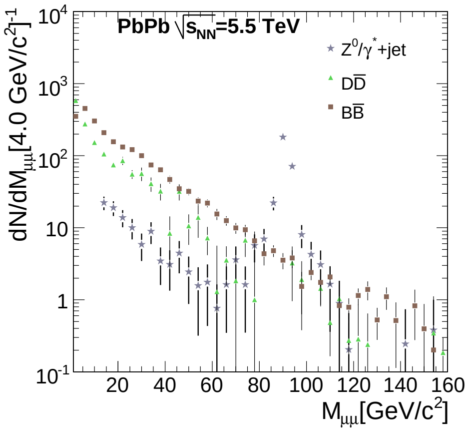

Figure 4: Invariant mass distribution for Z^0/γ^* and $\mathrm{D\overline{D}/B\overline{B}}$ dimuon decays in PbPb collisions at 5.5 TeV. An integrated luminosity of $0.5\,\mathrm{nb}^{-1}$ is assumed.

From this point of view, the measurement of $Z^0/\gamma^*(\rightarrow \mu^+\mu^-)$+jet presents an advantage. Replacing on one side the hadronic probe by an electromagnetic probe, which propagates through the medium undisturbed, a measurement of the p_T of the initial hard scattering is possible since $\overrightarrow{p}_T^{jet} \approx -\overrightarrow{p}_T^{Z^0/\gamma^*}$. The relation is valid up to k_T effects, where k_T is the intrinsic transverse momentum of the partons that enter the hard scattering.

Regarding the background, two of the main processes contributing to the dimuon signal are the semi-leptonic decays of the heavy charm and bottom mesons. A $D\overline{D}/B\overline{B} \rightarrow \mu^+\mu^-$ decay creates a muon pair that can fake the real dimuon signal from $Z^0/\gamma*$ decays.

Figure 4 shows the dimuon invariant mass distribution for both the signal (simulated with PYTHIA) and the background (simulated with HVQMNR [7]), obtained assuming an integrated luminosity of $0.5\,\mathrm{nb}^{-1}$. At low invariant mass, the continuum dimuons are overwhelmed by the heavy-meson decays, but in the Z^0 mass region, the Z^0 peak is well above the background.

The signal dileptons from Z^0/γ^* decays come directly from the collision vertex, while the background muons from $D\overline{D}$ and $B\overline{B}$ decays are usually produced a few hundred μm away. The distance of closest approach (DCA) between the primary vertex and the lepton trajectory can, therefore, be used to decrease the background level. The influence of a DCA cut was studied. It consisted of two separate "point-to-line" DCA cuts, requesting *at least one* of the DCAs is bigger than a 3σ cut. Figure 5 shows a rejection factor of about 5, achieved with a 3σ DCA cut and assuming, in a heavy-ion environment [2], detector resolutions of $\sigma_{r\phi} \approx 20\,\mu$m in the transverse plane and $\sigma_{rz} \approx 50\,\mu$m in the longitudinal plane.

4. Conclusions

The CMS detector is perfectly equipped for exploring perturbative phenomena in heavy-ion collisions at the LHC. With its 2π calorimetric coverage, combined with excellent tracking capabilities, high-p_T resolution and trigger architecture, reconstruction is achieved for charged hadrons up to 300 GeV/c in p_T and for jets up to $E_\mathrm{T} \sim 500$ GeV. A new control channel, Z^0+jet, is energetically accessible for the first time in heavy-ion collisions: a few thousands Z^0+jet signal events

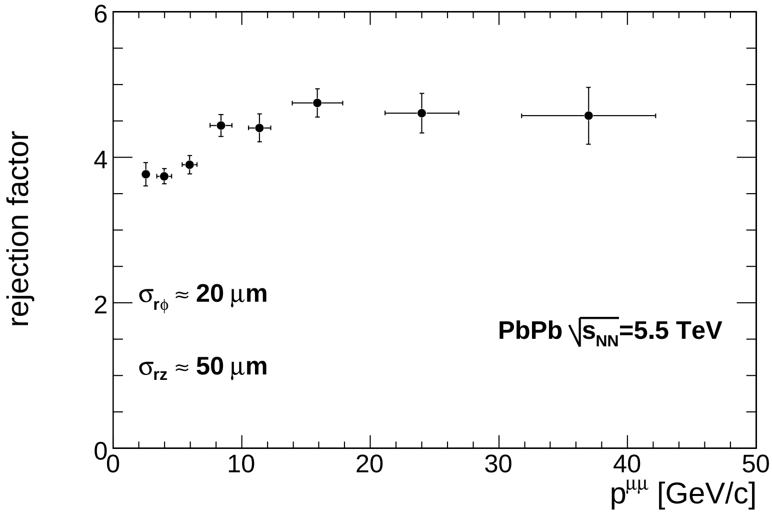

Figure 5: The rejection factor of *D* and *B* decay muon pairs obtained applying a 3σ DCA cut in the CMS silicon vertex tracker. The vertical bars are statistical errors while the horizontal are r.m.s. momentum.

can be collected, considering an integrated luminosity of $0.5\,\mathrm{nb}^{-1}$, sufficient for studies of the medium-induced modification of jet fragmentation functions.

References

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