Measurements of high-$p_T$ probes in heavy ion collisions at CMS

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Abstract

The capabilities of the CMS detector at the LHC will be described for measuring high-$p_T$ hadrons, photons and jets in heavy ion collisions. Detailed simulations of various studies planned with the CMS apparatus, including charged particle tracking, jet reconstruction using calorimetry, dimuon and isolated photon detection and the measurement of in-medium fragmentation functions using high-$p_T$ photon-jet correlations will be discussed.

High-$p_T$ processes have proven to be an important tool in investigating the hot, dense matter created in the collision of relativistic heavy ions. The large suppression observed for high-$p_T$ hadronic yields in central heavy ion collisions relative to the binary scaling of p+p collisions is evidence of large partonic energy loss in the medium. At RHIC energies, several complications have arisen in the interpretation of the high-$p_T$ phenomena. The high-$p_T$ hadrons (and jets) are surface-biased if the created medium is opaque, masking the real amount of medium-induced parton energy loss [1]. Fragility of some observables (like nuclear modification factors) hinders their discriminative power between models and model parameters [2].

In the new energy frontier at the LHC a larger $p_T$ region, fully developed jets, and several new observables will be accessible. New ways that will be available to study energy loss include $\gamma$-jet, $Z^0$-jet, dijet correlations, and jet fragmentation function measurements. Since the photon (or $Z^0$) escapes from the medium with little interaction, it gives a calibrated probe of the original parton energy. The first heavy ion run at the LHC is scheduled for late 2010 at $\sqrt{s_{NN}} \approx 4$ TeV.

The CMS apparatus [3] is equipped with various subsystems that make it a powerful tool to study high-$p_T$ phenomena in heavy ion collisions. The highly segmented electromagnetic and hadronic calorimeters have a large longitudinal coverage up to $|\eta| < 6.6$, including the CASTOR calorimeter [4], and the Zero Degree Calorimeter will detect spectator neutrons at $|\eta| > 8.3$. The muon detectors will be used to reconstruct $Z^0$, $J/\psi$, $\Upsilon$ particles, with coverage of $|\eta| < 2.4$. The silicon tracker system can reconstruct charged tracks with good efficiency and purity. The silicon pixel layers have less than 2% hit occupancy even in heavy ion collisions. The high level trigger will be able to inspect each event before the trigger decision, including complicated on-line reconstruction algorithms [5]. Some more details on these capabilities will be given below.

The tracking performance of the CMS detector was studied under a conservative assumption on the charged particle multiplicity for central Pb+Pb events, at $dN_{ch}/dy|_{y=0} = 3500$ [6]. The simulation results show 75% reconstruction efficiency and less than 5% fake rate in the $1 < p_T < 30$ GeV/$c$ range for charged particles. The $p_T$ resolution was found to be 1-3% depending on $\eta$ and $p_T$. The left panel of Fig. shows the expected transverse impact parameter resolution of charged tracks that will become relevant for displaced vertex reconstruction [6]. The $p_T$ reach of the tracking in CMS was extended down to $p_T \approx 200$ MeV/$c$, and particle identification capability based on the specific energy loss (dE/dx) in the silicon tracker was demonstrated [7].
The reconstructed and simulated $p_T$ spectra of identified hadrons are also shown in Fig. 1(right).

The CMS detector features excellent dimuon reconstruction capabilities, due to the high, 4 Tesla magnetic field and accurate tracking and muon detectors. Figure 2 shows the reconstructed dimuon mass spectra in the $J/\Psi$ (left) and $\Upsilon$ (right) dimuon mass regions for simulated central Pb+Pb events with $dN_{ch}/d\eta|_{|\eta|=0}=2500$. The statistics correspond to $0.5nb^{-1}$ integrated luminosity. The signal to background ratio is about 5 for the $J/\Psi$ and 1 for the $\Upsilon$ where both muons have $|\eta|<0.8$. A mass resolution of 54 MeV/c$^2$ can be achieved for the $\Upsilon$ states [7].

High energy jets can be reconstructed in the CMS calorimeters using the iterative cone algorithm with event-by-event background subtraction. Although the determination of the absolute jet energy scale is difficult, the jet finding efficiency is more than 50% at $E_T=50$ GeV and close to 100% above 70 GeV [8].

The $E_T$ resolution is about 16% at $E_T=100$ GeV with a background of $dN_{ch}/dy|_{y=0}=5000$. 

Figure 2: Reconstructed invariant mass spectra of opposite-sign and like-sign muon pairs from simulated central Pb+Pb events with $dN_{ch}/d\eta|_{|\eta|=0}=2500$, in the $J/\Psi$ (left) and $\Upsilon$ (right) mass regions, where both muons have $|\eta|<0.8$. 
The typical angular resolution of the jet axis obtained is $\sigma_\phi = 0.03$ and $\sigma_\eta = 0.02$. By applying a series of jet triggers in a nominal 0.5nb$^{-1}$ run, the statistical $p_T$ reach of the jet and charged hadron spectrum measurement is 500 and 300 GeV/c, respectively [5, 9]. The high statistics of reconstructible jets opens the way to more detailed jet quenching studies.

The high resolution electromagnetic calorimeter with large coverage and segmentation makes it possible to analyze $\gamma$-jet events, and use the measured $\gamma$ energy to calibrate the jet energy scale, coincidentally measuring the properties of the quenched away side jet. Figure [3] shows a simulated $\gamma$-jet event as seen by the calorimeters, and the relatively tight correlation between the $E_T$ of the $\gamma$ and that of the away side parton at the event generator level [10]. Isolated photons are selected for this analysis using an isolation cut based on a combination of various cluster shape variables, suppressing $\pi^0$s produced in jets usually associated with large hadronic activity.

A signal to background ratio of 4.5 for isolated photons is achieved, as shown on the left
As a next step, the away-side jet was reconstructed, on the opposite side of the γ, requiring $E_T > 30$ GeV. The fragmentation function, $dN/d\xi$ where $\xi = \ln(E_T/p_T)$, was obtained from the charged particle tracks that were reconstructed within the jet cone of radius $R=0.5$. Finally, the contribution from the underlying event with soft hadrons, shown on the right panel of Fig. 4 was subtracted. The expected statistics for a $0.5 \text{nb}^{-1}$ heavy ion run at $\sqrt{s_{NN}} = 5.5$ TeV is 4300 events with $E_T^\gamma > 70$ GeV and 1200 events with $E_T^\gamma > 100$ GeV.

An example for the reconstructed fragmentation function of quenched jets after subtraction of the underlying event is shown on the left panel of Fig. 5, for the sample where the minimum $E_T$ of the photon candidate ECAL cluster was 70 GeV. Also shown in Fig. 5 the ratio of quenched and non-quenched fragmentation function after reconstruction (symbols) and the simulated truth (histogram). The estimated systematic errors (gray band) are small enough to allow the quantitative measurement of the medium modification of the jet fragmentation function [10].

To summarize, some of the capabilities of CMS for high-$p_T$ studies were presented. In particular, an overview of the tracking, jet, photon and dimuon reconstruction and triggering was given. Using $\gamma$-jet events, the expected strong modification of jet fragmentation function can be measured. With the above capabilities, a whole list of new observables will become available to CMS at the LHC, like dijet correlations, $Z^0$-jet events, $b$-tagged jets, forward jets, among others.

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