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PROBING THE QUARK-GLUON PLASMA AT THE LHC WITH Z^0-TAGGED JETS IN CMS

CAMELIA MIRONOV*, MARIA CASTRO,
PAUL CONSTANTIN and GERD J. KUNDE

Los Alamos National Laboratory, P.O. Box 1663,
Los Alamos, NM 87545, USA
** cmironov@lanl.gov*

RAMONA VOGT

Laurence Berkeley National Laboratory, 1 Cyclotron Road 50R4049,
Berkeley, CA 94720, USA
UC Davis, One Shields Ave, Davis, CA 95616, USA
Lawrence Livermore National Laboratory, P.O. Box 808,
Livermore, CA 94550, USA
vogt@lbl.gov

An important tool in quark-gluon plasma studies at RHIC has been the measurement of dijets investigated via leading hadron correlations. With much higher rates for hard processes at the Large Hadron Collider, studies of Z^0-tagged jets become possible. A clear experimental signature is provided by the measurement of muon pairs from the Z^0 decays, for which CMS is an ideally suited detector. Instead of measuring back-to-back correlations of two strongly interacting particles, one side is replaced by an electromagnetic probe which propagates through the plasma undisturbed and provides a measurement of the energy of the initial hard scattering. We propose to use lepton-pair tagged jets to study medium-induced partonic energy loss and to measure in-medium parton fragmentation functions. The lepton pairs from semileptonic decays of heavy meson pairs ($B\overline{B}$ and $D\overline{D}$) are a background source for the tagged dilepton-jet signal. We present the calculated signal rates (using PYTHIA) and background rates (using HVQMNR). We also discuss strategies for maximizing the signal-to-background ratio.

1. Introduction

Measurements performed at RHIC indicate that a new state of matter is created in relativistic heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV.[1] The challenge and the motivation for the LHC heavy-ion program is to study the properties of this new form of matter. Dijet studies are an important tool for this purpose. In particular, two-hadron *angular* and *transverse momentum* correlations probe the back-to-back hard-scattered partons that propagate in the medium before fragmenting.[2]

We investigate a dijet channel energetically possible, for the first time, at the LHC: high transverse momentum Z^0-bosons in association with hadronic jets.[3,4] The production channels are $q\overline{q} \rightarrow Z^0 g$ ($q\overline{q}$ annihilation) and $gq \rightarrow Z^0 q$ (Compton scattering) with the subsequent Z^0 decay, $Z^0 \to l^+l^-$ ($l = e, \mu$), and parton fragmentation, $q/g \to$ jet. Because leptons interact weakly with the medium, their reconstructed momentum gives direct access to the initial momentum of the opposite-side jet, making it possible to infer information about the medium from the jet analysis.

2. Angular and Transverse Momentum Correlations

Our azimuthal analysis was performed in the plane perpendicular to the beam axis. The only cuts on the muons are those imposed by the CMS muon detector, $p^\mu > 3.5$ GeV/c and $|\eta^\mu| < 2.4$. On an event-by-event basis, dileptons (*trigger*) coming from Z^0 decays are identified and paired with all hadrons within different momentum ranges from the same event (*associated hadrons*). The overall azimuthal distribution per trigger particle is defined as

$$Y(\Delta\phi) = \frac{\sum N_{\text{pairs}}(\Delta\phi)}{\sum N_{\text{trig}}}$$

where $\Delta\phi = \phi^{\text{assoc}} - \phi^{\text{trig}}$ and the sum is over all events.

The $Y(\Delta\phi)$ distributions are generated for a fixed $p_{\text{T}}^{\text{trig}}$ interval and several $p_{\text{T}}^{\text{assoc}}$ intervals. After extracting the away-side ($\Delta\phi \sim \pi$) jet component, the dependence of its yield, Y_{away}, for a fixed $p_{\text{T}}^{\text{trig}}$ interval is analyzed as a function of the variable $z = p_{\text{T}}^{\text{assoc}}/p_{\text{T}}^{\text{trig}}$. The $D(z) = (1/N_{\text{trig}})(dY_{\text{away}}|_{p_{\text{T}}^{\text{trig}}}/dz)$ distribution contains all hadronic fragments of the initial parton, including the hadrons from the fragmentation of medium-induced gluon radiation of the parton. Thus $D(z)$ is not the vacuum fragmentation function as measured in e^+e^-, it is a medium-modified fragmentation function.

3. Signal

The following discussion considers Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV with nominal luminosity $L = 5 \times 10^{26}$ cm^{-2}s^{-1}. A runtime of 10^6 s is used, corresponding to one month of collisions at 50% efficiency, giving an integrated luminosity of 0.5 nb^{-1}. The $Z^0 +$jet rate in Pb+Pb collisions is obtained from the pp cross section, evaluated with PYTHIA 6.32 (default settings and CTEQ5M PDFs),[5] scaled so that $\sigma_{AA} = A^2\sigma_{pp}$. In order to reduce the MC generation time, all PYTHIA processes were turned off (`MSEL=0`) except $q\overline{q} \to Z^0(\gamma^*)g$ (`ISUB=15`) and $qg \to Z^0(\gamma^*)q$ (`ISUB=30`). The Z^0 (`MSTP(43)=2`) and $\gamma*$ (`MSTP(43)=1`) contributions were separated from each other. To obtain good statistics at high transverse momentum, 10 K events were simulated in 10 GeV $\widehat{p}_{\text{T}}$ bins, between 10 and 300 GeV/c. Each bin was afterwards scaled by its corresponding cross section and added to the others, to give the final signal spectra. We have only selected dimuons from $Z^0 \to \mu^+\mu^-$ decays (B. R. = 3.37%) and with momentum and pseudorapidity within the CMS acceptance $p_{\text{T}}^\mu > 3.5$ GeV/c and $|\eta^\mu| < 2.4$. The results of the PYTHIA simulations are presented in Fig. 1, which shows the total integrated yield above the corresponding p_T^{min} for Z^0 + jet. For comparison, the γ + jet yield is also shown.

In order to estimate the statistical significance of the year one measurement in $z = p_T^{assoc}/p_T^{trig}$, 1000 PYTHIA dimuon triggers were generated with $p_T^{\mu\mu} >$ 25 GeV/c. Figure 2, obtained using the recipe described in Sec. 2, shows the cor-

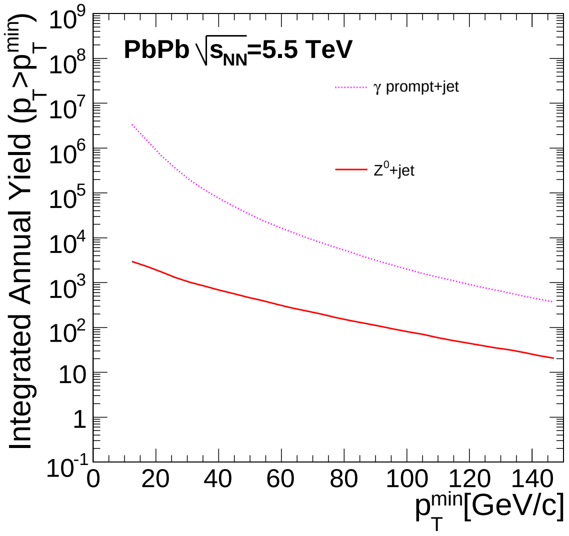

Fig. 1. The integrated yield of tagged jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV with a luminosity of 0.5 nb^{-1}, as a function of the lower bound p_T^{min}. The lines depict γ tags and $Z^0 \rightarrow \mu^+\mu^-$ tags. The dimuon channel was restricted to $p_T^\mu > 3.5$ GeV/c and $|\eta^\mu| < 2.4$.

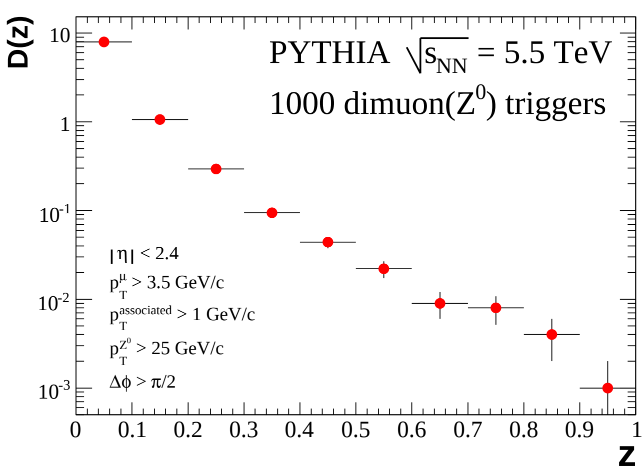

Fig. 2. The number of associated charged hadrons with $\Delta\phi > \pi/2$ per trigger dimuon as a function of z, for $p_T^{\mu\mu} > 25$ GeV/c, $p_T^{assoc} > 1$ GeV/c, $p_T^\mu > 3.5$ GeV/c and $|\eta^\mu| < 2.4$. The statistical error bars reflect the sample size.

responding per trigger distribution for $\sqrt{\langle k_{\rm T}^2\rangle} = 3$ GeV/c and $p_{\rm T}^{\rm assoc} > 1$ GeV/c. Redoing the calculations with $\sqrt{\langle k_{\rm T}^2\rangle} = 0$ and 5 GeV/c, the shape of the z distribution remains essentially unaffected, showing that $p_{\rm T}^{\mu\mu} > 25$ GeV/c region is insensitive to $k_{\rm T}$ effects.

4. Background

There are several background sources contributing to the opposite-sign dimuon sample. The main source is due to simultaneous semileptonic D and $\overline{D}$ (charm) or B and $\overline{B}$ (bottom) decays. Dijets can also contribute through hadrons that punch through the absorber materials (calorimeters and magnet) and are misidentified as muons in the muon chambers as well as through kaon and pion decays to muons. Here we only discuss the heavy flavor background. The other background sources are the subject of further studies.

The semileptonic branching ratio of heavy mesons, $D/B \to lX$, is ~10.5%. A heavy meson pair can thus produce a dilepton through $D\overline{D}/B\overline{B} \to l^+l^- + X$, creating a background to the real dilepton signal from Z^0 decays. In order to estimate the effect of this background, we have used, as in previous studies,[6] the NLO HVQMNR[7] code with the CTEQ6M parton distribution functions.[8] The Peterson fragmentation function is used.[9] The azimuthal distributions of the heavy quark pairs (and corresponding decay dileptons) are peaked at $\Delta\phi = \pi$, with a more pronounced peak for bottom than for charm. The HVQMNR input parameters are listed in Table 1.

Figure 3 shows the dimuon invariant mass distribution. The continuum dimuons are dominated by the bottom and charm decays but the Z^0 peak is perfectly visible above the background.

Figure 4 shows the dimuon $p_{\rm T}^{\mu\mu}$ distribution in the mass window where the Z^0 peak dominates: 81–101 GeV/c^2. Naturally, the Z^0 signal is well above the $D\overline{D}$ and $B\overline{B}$ background for the entire $p_{\rm T}^{\mu\mu}$ range.

The signal dileptons from Z^0 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. We studied the influence of a DCA cut consisting of two separate "point-to-line" DCA cuts, requesting that *at least one* of the DCAs must be bigger than a 3σ

Table 1. The HVQMNR parameters: $\langle k_{\rm T}\rangle$ is the mean intrinsic momentum, ϵ is the parameter in the Peterson fragmentation function, and ξ_F and ξ_R are the factorization and renormalization scale factors, describing the proportionality to the $m_{\rm T}$ of the $Q\overline{Q}$ pair.

	m_Q (GeV/c^2)	$\langle k_{\rm T}\rangle$ (GeV/c)	ϵ	$\xi_{\rm F}$	$\xi_{\rm R}$
Charm	1.5	1.0	0.06	1.0	1.0
Bottom	4.75	1.0	0.006	1.0	1.0

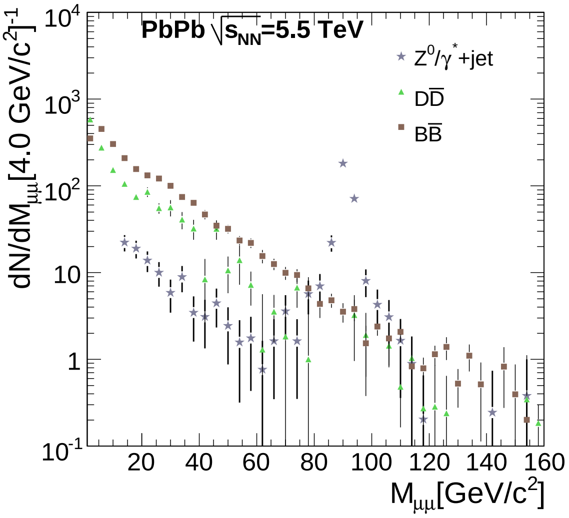

Fig. 3. The invariant mass distribution for Z^0/γ^* and $D\overline{D}/B\overline{B}$ dimuons with $p_T^{\mu\mu} > 25$ GeV/c, $p^\mu > 3.5$ GeV/c and $|\eta^\mu| < 2.4$. An integrated luminosity of 0.5 nb^{-1} is assumed. Statistical error bars only.

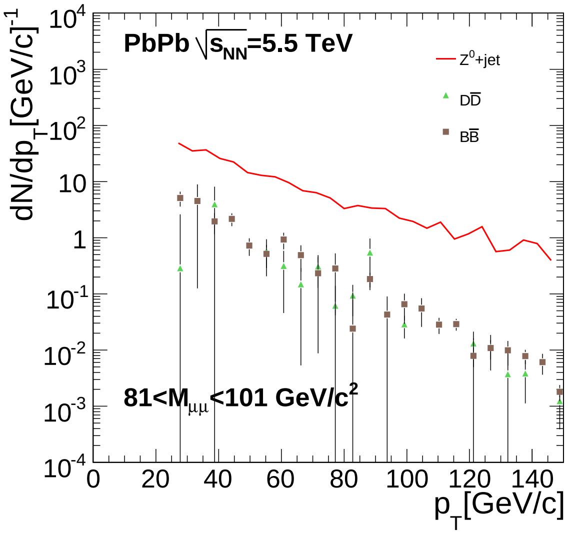

Fig. 4. The dimuon p_{T} distribution for signal and background dimuons in the mass interval $M_{Z^0} \pm 10$ GeV/c^2 with an integrated luminosity of 0.5 nb^{-1}.

cut. The dilepton rejection factor for heavy meson pair decays has been estimated with a typical DCA cut for the CMS silicon vertex tracker. The DCA resolution in a heavy-ion environment[10] is $\sigma_{r\phi} \approx 20\ \mu$m in the transverse plane and $\sigma_{rz} \approx 50\ \mu$m in the longitudinal plane. Figure 5 shows the rejection factor achieved with a 3σ

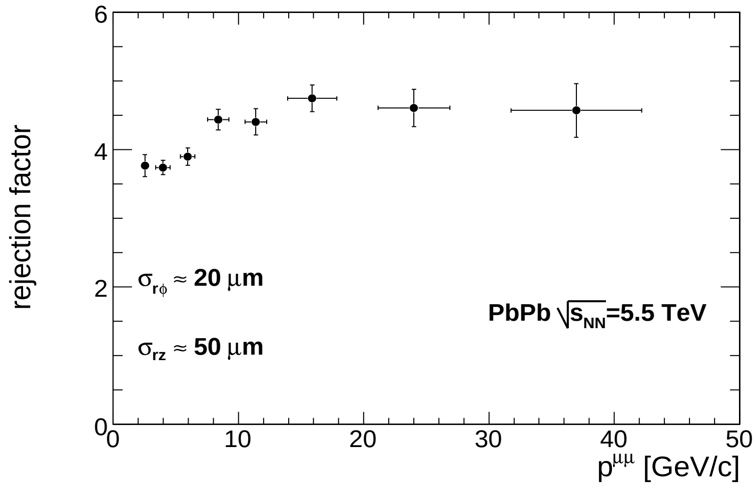

Fig. 5. The DCA rejection factor assuming resolutions of $\sigma_{r\phi} \approx 20$ μm in the transverse plane and $\sigma_{rz} \approx 50$ μm in the beam direction. A 3σ DCA cut is applied on the individual muons. The vertical bars are statistical errors while the horizontal bars are momentum rms.

cut. We see that a rejection factor of about 5 can be obtained by two simple DCA cuts between each lepton trajectory and the primary vertex OR'ed together.

5. Conclusion

We have presented a case study for measuring dilepton-tagged jets via angular correlations in heavy-ion collisions at the LHC. The signal rates, $Z^0(\rightarrow \mu\mu) + \text{jet}$ were computed with PYTHIA. The heavy meson semileptonic background, $D\overline{D}/B\overline{B} \rightarrow \mu\mu$, was calculated at NLO with the HVQMNR code. Kinematical studies of both signal and background show that the study of dimuon-tagged jets at the LHC is feasible in Pb+Pb collisions.

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