Revealing the medium-recoil effect with high-p_T Z boson tagged underlying event distribution in PbPb collisions at CMS

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Abstract. The utilization of Z bosons, which are insensitive to the strong interaction, can constrain the initial energy, direction, and flavor of recoiling partons prior to their interaction with the quark-gluon plasma. This investigation focuses on charged particle yields in Z boson events, enabling a detailed exploration of in-medium modifications in both the recoiling parton showers and soft particles resulting from medium response. This presentation shows measurements of azimuthal angle distributions and fragmentation functions for charged particles associated with Z bosons in both lead-lead and proton-proton collisions at $\sqrt{s_{NN}} = 5.02$ TeV, utilizing data collected by the CMS detector.

1 Introduction

When heavy ions collide at high energies, a quark-gluon plasma (QGP) is formed. As energetic partons traverse this medium, they deposit energy and recoil effects can be generated [1–3]. The energy deposited could give rise to a Mach cone accompanied by a diffusion wake [4–6]. These modifications provide insight into the QGP properties such as transport coefficients and the equation of state. At CMS, we employ Z bosons, which are insensitive to the strong interaction, to tag the initial momentum of partons propagating through the medium. The subsequent charged hadron distributions, compared to the distributions in pp collisions which we use as a reference, are sensitive to medium modifications of the parton shower and induced medium excitations.

2 Analysis Method

The CMS detector [7] provides charged particle reconstruction and electron/muon identification capabilities well-suited for Z boson measurements. The PbPb collision data analyzed in this result has an integrated luminosity of 1.67 ± 0.03 nb^{-1}, taken in 2018, while the pp reference data has an integrated luminosity of 301 ± 6 pb^{-1}, taken in 2017. Candidate Z bosons are reconstructed from opposite-sign, same-flavor lepton pairs with invariant mass $60 < M_Z < 120$ GeV and transverse momentum $p_T > 30$ GeV. Each Z boson is paired with charged tracks having $p_T > 1$ GeV and pseudorapidity $|\eta| < 2.4$ from the same event. Combinatorial background is estimated using a mixing technique that accounts for extra event

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activity that accompanies the Z bosons, where each Z candidate is paired with tracks in random events from minimum-bias samples matched with similar forward energy deposited in the forward hadron (HF) calorimeters: $E^{\mathrm{HF,MB}} = E^{\mathrm{HF}} - E^{\mathrm{HF},Z}$, where $E^{\mathrm{HF},Z}$ is estimated from Z events in pp data samples. Since the minimum-bias events contain the average background level, which in data includes contributions from flow modulation, this procedure inherently accounts for flow modulation found in data.

The key observables are:

1) $\Delta\phi_{\mathrm{trk},Z} = |\phi^{\mathrm{trk}} - \phi^{Z}|$, the azimuthal angle between tracks and the Z boson;

2) $\xi_{\mathrm{T}}^{\mathrm{trk},Z} = \ln \frac{-|\vec{p}_{\mathrm{T}}^{Z}|^2}{\vec{p}_{\mathrm{T}}^{\mathrm{trk}} \cdot \vec{p}_{\mathrm{T}}^{Z}}$, the "fragmentation function" of tracks in Z events, which characterizes the relative projected momentum of a track in the direction of the Z boson.

3 Results

Medium modifications of partons arising from initial multiple parton interactions (MPI) may lead to a uniform soft hadron enhancement in $\Delta\phi$, which has been studied with underlying events using Z events in pp data [8]. Figures 1 and 2 show the $\Delta\phi_{\mathrm{trk},Z}$ and $\xi_{\mathrm{T}}^{\mathrm{trk},Z}$ distributions in PbPb events compared to pp collisions in different centrality ranges, respectively. For $\Delta\phi_{\mathrm{trk},Z}$, we observe an overall enhancement in the most central events (centrality 0-30%), especially at $\Delta\phi \sim \pi$, indicating an excess of soft hadron production. This is consistent with constant enhancement with a hint of wake-like structure around 2.5. In addition to MPI, medium excitation could also lead to constant enhancement. The $\xi_{\mathrm{T}}^{\mathrm{trk},Z}$ distribution is depleted of high p_{T} particles and enhancement of low p_{T} particles in the most central events (centrality 0-30%), which can be explained by initial parton energy loss and medium modified parton shower. These features are described by phenomenological models like CoLBT and Hybrid+wake that include energy loss mechanisms in the QGP [9]. For the most peripheral events (centrality 70-90%), the $\Delta\phi_{\mathrm{trk},Z}$ and $\xi^{\mathrm{trk},Z}$ distributions in PbPb events are consistent with the pp ones.

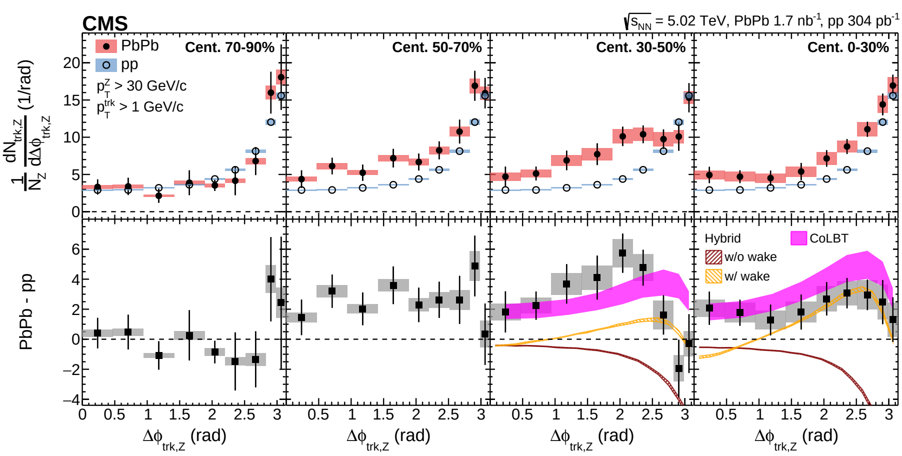

Figure 1. Upper: the $\Delta\phi_{\mathrm{trk},Z}$ distribution in pp collisions compared to PbPb collision events with different centrality regions: 70-90 (left), 50-70, 30-50, and 0-30% (right). Lower: ratios of the PbPb to pp distributions. The vertical bars depict the statistical uncertainties, while the shaded boxes represent the systematic uncertainties [9].

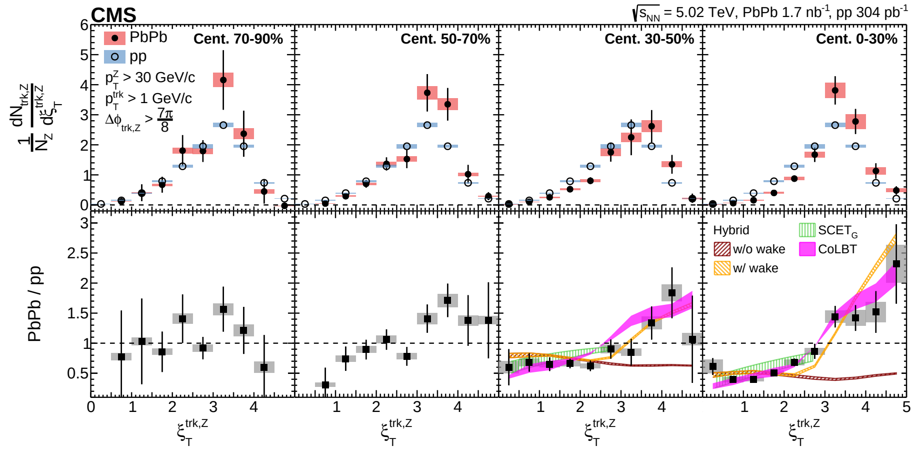

Figure 2. Upper: the $\xi_T^{trk,Z}$ (right) distributions in pp collisions compared to PbPb collision events with different centrality regions: 70-90 (left), 50-70, 30-50, and 0-30% (right). Lower: ratios of the PbPb to pp distributions. The vertical bars depict the statistical uncertainties, while the shaded boxes represent the systematic uncertainties [9].

4 Future Prospects

It is necessary to constrain the MPI effects to observe the diffusion wake. In a recent paper [10], a valley-like structure is predicted in the $\Delta\eta_{jet,trk}$ with a low track p_T region below 2 GeV due to the diffusion-wake effect. To see such a valley, we need a 2-dimensional $\Delta\eta$ vs. $\Delta\phi$ correlation, and it is in the region far away from the jet peak. Consequently, both $\Delta\eta_{jet,trk}$ and $\Delta\eta_{Z,trk}$ may be useful in extracting the diffusion wake effect and the MPI ridge. Such measurements will additionally benefit from the increased statistics collected in Run 3 (2022–2025) of the LHC.

5 Conclusions

The angular distributions of charged tracks relative to Z bosons provide sensitivity to modifications in both in-medium parton showers and medium recoils. In contrast, fragmentation functions offer insights into modifications in the longitudinal structure of the parton shower within the medium. These observables offers insights into the interaction between propagating partons and the quark-gluon plasma. A comparison between PbPb and pp results reveals modifications in angular correlation functions, indicating substantial modifications of the fragmentation functions originating from recoiled partons. These findings complement measurements conducted using inclusive jets, dijet, and photon-tagged jet events. With more data expected and additional studies with different observables possible, this technique will lead to deeper understanding of quark-gluon plasma properties.

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