Study of correlations between neutral bosons and jets in lead-lead collisions at 2.76 TeV with the ATLAS detector

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Abstract

The correlations of jets with neutral bosons is a particularly powerful tool to probe the underlying physics of jet quenching. To gain insight into the physics of this process, we can study Z boson + jet and photon + jet correlations. Because the Z and photons do not directly couple to the strong force, in a jet+boson event the unmodified bosons allow us to access the modification of the opposite side jet; unlike dijet events, where both jets potentially lose energy, these bosons provide an excellent calibration of the energy of the recoil jet. The ATLAS experiment has measured jet correlations with direct photons as well as with Z bosons via dilepton channels in Pb+Pb collisions at √s_{NN} = 2.76 TeV in a data sample of nearly 0.15 nb^{-1} of integrated luminosity. Both boson + jet analyses show modification of the jet momentum relative to the boson momentum qualitatively consistent with jet quenching.

One of the earliest observations in relativistic heavy-ion collisions at RHIC was the strong suppression of high transverse momentum hadrons [1, 2], and one of the first results in the LHC era was a significant energy imbalance observed in di-jet pairs [3]. By contrast, the production of color neutral objects such as photons and Z bosons appear to be unaffected [4, 5, 6, 7]. The detailed mechanism by which color sensitive objects are modified in the hot dense medium of heavy ion collisions remains unknown, however the boson + jet system allows insight into this mechanism by providing a jet calibrated to the neutral boson. Photon + jet measurements have recently been made in Pb+Pb collisions at √s_{NN} = 2.76 TeV by the CMS collaboration [8], and this analysis presents photon + jet [9] and Z boson + jet [10] measurements made by the ATLAS experiment [11]. The measurements were made from a data sample of nearly 0.15 nb^{-1} of integrated luminosity collected in the 2011 LHC Pb+Pb run at √s_{NN} = 2.76 TeV.

Prompt isolated photons candidates were identified using calorimeter shower shape cuts and isolation energy from a photon triggered data sample [12]. In this analysis, only leading photons with 60 < p_T < 90 GeV and |η| < 1.3 are considered. Each event containing such a candidate was then scanned for a reconstructed jet. Jets were reconstructed from Δφ×Δφ = 0.1×0.1 calorimeter towers using the anti-k_t algorithm with several distance parameters, R, and the underlying event energy subtracted from the jet energy [13]. In order to reject fake jets in addition to the calorimeter reconstruction of the jet, a corroborating signal was required either as a jet reconstructed from charged tracks with p_T > 4 GeV or a high energy electromagnetic cluster with p_T > 7 GeV. Only the leading jet in the event was considered, and to ensure robust jet reconstruction, jets were limited to p_T > 25 GeV and |η| < 2.1.

1 A list of members of the ALTAS Collaboration and acknowledgements can be found at the end of this issue.
To measure the correlation between the photon and jet, two quantities were considered: the jet energy fraction, $x_J = p_T^J/p_T^\gamma$, and the opening angle, $\Delta \phi_J = |\phi^J - \phi^\gamma|$. To select events in which both photon and jet came from the same initial scattering only photon-jet pairs with $\Delta \phi_J > 7/8 \pi$ were used for $x_J$. In addition, in order to fill the photon-jet kinematic phase space evenly $x_J > 25/60$ (the minimal $p_T$ of the jet and photon, respectively) is required. To account for background in the photon sample, an $x_J$ distribution is formed using photons that do not pass the photon identification cuts. This distribution is normalized using the “double sideband” method [9] and subtracted. The $x_J$ distributions were then unfolded using the singular-value decomposition approach and corrected for efficiency. The unfolded and fully corrected distributions may then be compared to PYTHIA [14] events at the generator level. The $x_J$ and $\Delta \phi_J$ distributions are shown in Figure 1.

![Figure 1](image-url)

**Figure 1:** Top: Fully unfolded and corrected $x_J$ distributions ($x_J > 25/60$) from lead-lead data (closed symbols) compared with PYTHIA truth jet/true photon distributions (filled histogram), for simulated events (with data overlay) with a reconstructed photon passing analysis selections and $|\Delta \phi_J| > 7/8 \pi$. Bottom: Reconstructed $\Delta \phi_J$ distributions from lead-lead data (closed symbols) compared with reconstructed PYTHIA data events, selected in the same way as data (filled histogram). No jet efficiency corrections are applied to the $\Delta \phi_J$ distributions, but each event is weighted by the inverse of the total photon efficiency. The columns represent different centralities. The kinematic cuts here are photon $60 < p_T^\gamma < 90 \text{ GeV}$, $|\eta_J| < 1.3$, $p_T^J > 25 \text{ GeV}$, $|\phi^\gamma| < 2.1$. The error bars represent statistical errors, while the bands indicate the systematic uncertainties. The figures are from reference [9].

The $\Delta \phi_J$ distribution is largely consistent between PYTHIA and the data for all centrality, although the data shows some signal at $\Delta \phi_J < 2$ likely due to jets not truly correlated with the photon. However, in central events the $x_J$ distribution of the data is significantly modified compared to PYTHIA. To quantify this the mean energy fraction $\langle x_J \rangle$ is plotted in Figure 2. The integral of the normalized $x_J$ distributions, $R_J$, which measures the yield of leading jets per photon and expresses the suppression of associated jet production, is also plotted.

The Z boson + jet analysis is performed similarly to the photon + jet analysis. Z bosons are reconstructed via both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ decay channels from electron and muon triggered data, respectively [15]. Events with a Z boson reconstructed with $p_T > 60 \text{ GeV}$, are scanned for...
a jet reconstructed identically to the jets in the photon+jet analysis. Because the $Z \rightarrow \ell \ell$ cross-section is significantly lower than the photon cross-section, the requirement on the opening angle between the $Z$ boson and jet is loosened to $\Delta \phi_{zJ} > \pi/2$. The $Z \rightarrow \ell \ell$ sample used has background contamination of less than 3% and is therefore not subtracted. Due to the low number of $Z$ boson + jet pairs, rather than using singular value decomposition unfolding a bin-by-bin unfolding in $p_T^Z$ and $p_T^J$ is used. As in the photon + jet analysis, the fully corrected data are compared to generated level PYTHIA events. Figures 3 and 4 are analogous to Figures 1 and 2 but for $Z$ boson + jet pairs. As in the photon + jet case, there is clear qualitative evidence of jet quenching relative to the boson with hints of a centrality dependence, without any evidence of modification of the $\Delta \phi_{zJ}$ distribution within the experimental precision.

Figure 2: Left: The mean energy fraction ($s_{zj}$) from fully corrected and unfolded distributions calculated as a function of jet radius ($R = 0.2$ and $R = 0.3$), and for each radius as a function of $N_{part}$. Right: The integrated yield of jets per photon $R_{zJ}$. The kinematic cuts are photon $60 < p_T^Z < 90$ GeV, $p_T^{jet} > 25$ GeV and $\Delta \phi_{zJ} > 7 \pi/8$. The error bars represent statistical errors, while the grey bands indicate the systematic uncertainties. The data is compared to PYTHIA+Data events, calculated for true jets and photons, for simulated events (with data overlay) with a reconstructed photon passing analysis selections. The figures are from reference [9].

Figure 3: The ratio $p_T^{Z} / p_T^{J}$ normalized per $Z$ boson unfolded and efficiency corrected from Pb+Pb data. The same quantity from PYTHIA with no jet energy quenching is also shown. The $\Delta \phi$ distribution (folded around $\pi$), normalized to unity, is inset in the plot. Bars represent statistical uncertainties, and shaded boxes systematic uncertainties. The mean uncertainties listed are statistical for PYTHIA, and statistical followed by systematic for the data. The left plot is 20–80% centrality, and the right plot is 0–20% centrality. Jets are reconstructed with a cone size of $R=0.3$. The figures are from reference [10].
Taken together the boson + jet measurements qualitatively confirm expectations that color sensitive jets are modified relative to the color neutral electroweak bosons they are correlated with. This is observed by a downward trend in the energy fraction $p_T^{\text{boson}}/p_T^{\text{jet}}$, as well as the mean number of leading jets associated with a high energy boson (with a clear centrality dependence in the photon case). These analyses present a limited part of the relevant kinematic phase-space due to the fairly limited number of measured events, however the strength of the photon + jet results is already clear and both studies show great promise for a detailed exploration of the mechanisms of the energy loss of color sensitive objects in the hot dense medium of heavy ion collisions.

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References