Measurement of charged hadron production in $Z$-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV

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Abstract

The production of charged hadrons within jets recoiling against a $Z$ boson is measured in proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by the LHCb experiment. The charged-hadron structure of the jet is studied longitudinally and transverse to the jet axis for jets with transverse momentum $p_T > 20$ GeV and in the pseudorapidity range $2.5 < \eta < 4$. These are the first measurements of jet hadronization at forward rapidities and also the first where the jet is produced in association with a $Z$ boson. In contrast to previous hadronization measurements at the Large Hadron Collider, which are dominated by gluon jets, this measurement probes predominantly light-quark jets. Therefore, these results can provide valuable information on differences between quarks and gluons regarding nonperturbative hadronization dynamics.


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Quantum chromodynamics (QCD), the theory of the strong interaction, is unique amongst the fundamental forces due to the nonperturbative processes that confine quarks and gluons, collectively referred to as partons, within bound-state hadrons. The parton structure of protons has been the focus of intense research efforts. However, the understanding of how hadrons arise from scattered partons is limited compared to that of the partonic structure of hadrons. Perturbative QCD calculations utilize fragmentation functions to determine cross-sections of hadron production from scattered partons. Fragmentation functions are nonperturbative distributions that, at leading order, describe the probability for a particular parton to fragment into a particular hadron \[1,2\]. Several global fits to experimental data have parameterized fragmentation functions (see e.g. Ref. \[3\] and references therein); however, there is a significant lack of understanding in the mechanisms through which hadrons are formed from partons in the nonperturbative hadronization process. Therefore, additional data are required to further understand the nonperturbative processes that form hadrons from scattered partons.

Fragmentation function studies have been performed using inclusive hadron production in the simpler environment of $e^+e^-$ colliders \[4–10\]. Semi-inclusive deep-inelastic-scattering measurements have also been used to constrain fragmentation functions at smaller values of $Q^2$, the hard scale of the partonic interaction \[11,12\]. Additionally, inclusive hadron production measurements have been used to study fragmentation functions in the more complex environment of proton-proton ($pp$) collisions \[13–15\]. However, such measurements are limited by the lack of an explicit way to relate the scattered parton to the final-state hadron. Measuring fragmentation functions with respect to a high transverse momentum ($p_T$) jet offers a unique opportunity to study hadron production relative to an object that is correlated to the scattered parton. For example, the transverse profile, in addition to the longitudinal dynamics of hadrons within jets, can be used to study fragmentation functions in multiple dimensions. Such multidimensional measurements that go beyond inclusive hadrons, or those that consider correlations between particles, have the potential to answer unique questions within QCD related to universality, factorization, and the importance of color-charge flow \[16,17\].

This Letter reports a study of charged hadrons produced in jets recoiling against a $Z$ boson, also referred to as $Z$-tagged jets, in the forward region of $pp$ collisions. The longitudinal momentum fraction, $z$, the momentum transverse to the jet axis, $j_T$, and the radial distribution, $r$, of charged hadrons are measured with respect to the jet axis in the laboratory frame, defined as

\[ z \equiv \frac{p_{\text{jet}} \cdot p_{\text{hadron}}}{|p_{\text{jet}}|^2}, \]
\[ j_T \equiv \frac{|p_{\text{jet}} \times p_{\text{hadron}}|}{|p_{\text{jet}}|}, \]

and

\[ r \equiv \sqrt{(\phi_{\text{jet}} - \phi_{\text{hadron}})^2 + (y_{\text{jet}} - y_{\text{hadron}})^2}. \]

Here, $p$ is the 3-momentum vector, $\phi$ is the azimuthal angle, and $y$ is the rapidity. The data sample is selected from an integrated luminosity of approximately 2 fb$^{-1}$ collected at a center-of-mass energy $\sqrt{s} = 8$ TeV with the LHCb detector in 2012. Events with only one reconstructed primary vertex are analyzed to better identify signatures of a

\[ ^1 \text{Throughout this Letter the notation Z includes both the } Z^0 \text{ and virtual } \gamma^* \text{ contributions.} \]
hard two-to-two partonic scattering. Jets are clustered with the anti-\(k_T\) algorithm \(^{18}\) using a distance parameter \(R = 0.5\) and are measured differentially in \(p_T\) for \(p_T > 20\) GeV, and in the pseudorapidity range \(2.5 < \eta < 4\).\(^2\) Charged hadrons within the jet are required to have \(p_T > 0.25\) GeV, momentum \(p > 4\) GeV, and to lie within the jet cone such that \(\Delta R < 0.5\), where \(\Delta R \equiv \sqrt{(\phi_{\text{jet}} - \phi_{\text{hadron}})^2 + (\eta_{\text{jet}} - \eta_{\text{hadron}})^2}\). The distributions are unfolded to account for the detector response and to facilitate comparisons with theoretical and numerical predictions. This is the first measurement of charged hadrons within jets produced in association with a \(Z\) boson, as well as the first measurement of charged hadrons in jets at forward pseudorapidity. This process is primarily sensitive to light quark jets \(^{19,20}\). Thus, these data provide new and complementary information to previous jet substructure measurements in the inclusive jet channel at midrapidity in hadronic collisions, which are sensitive to primarily gluon jets \(^{21-26}\). Recent results at midrapidity in the isolated photon-jet channel can also probe fragmentation differences when a photon, rather than a massive vector boson, is measured opposite the jet \(^{27}\).

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range \(2 < \eta < 5\), described in detail in Refs. \(^{28,29}\). Simulations are used to evaluate the detector performance with regard to the jet reconstruction, track-in-jet reconstruction, and to validate the analysis methods. The simulated \(pp \rightarrow Z + \text{jet} + X\) events are generated using \(\text{Pythia 8}\) \(^{20}\) with a specific LHCb configuration \(^{30}\). Decays of hadronic particles are described by \(\text{EvtGen}\) \(^{31}\), and final-state radiation in the simulation is generated using \(\text{Photos}\) \(^{32}\). Finally, the \(\text{Geant4}\) toolkit \(^{33}\) is used to simulate the interactions of the particles with the detector, as described in Ref. \(^{34}\).

This analysis uses the same data set as that in the \(Z+\text{jet}\) cross section, where events are selected and \(Z\) bosons are measured via their dimuon decay as described in Ref. \(^{35}\). Candidate events are required to pass a trigger \(^{36}\) which selects muons with \(p_T > 10\) GeV. Only events that contain two high-\(p_T\) muons are retained. The muons are required to satisfy track-reconstruction and muon-identification criteria, as in Refs. \(^{35,37}\), and are also required to fall within the fiducial region of \(2 < \eta < 4.5\), where the detector performance is well understood. Finally, the dimuon system must have an invariant mass, \(M_{\mu\mu}\), within the range \(60 < M_{\mu\mu} < 120\) GeV.

Jet reconstruction is performed using a particle flow algorithm \(^{38}\), where the charged and neutral particles are clustered using the anti-\(k_T\) algorithm as implemented in Ref. \(^{39}\). Reconstructed jets with \(p_T > 15\) GeV that lie within \(2.5 < \eta < 4\) are analyzed, where the range of \(15 < p_T < 20\) GeV is included to unfold the detector response. The pseudorapidity requirement ensures that the full jet cone lies within the fiducial area of the LHCb detector, and thus provides a constant \(p_T\) resolution. Selection requirements are placed on the jets to reduce the rate of jets not associated with a hard scattered parton, which is already suppressed by the requirement of a single reconstructed primary vertex in the event. Additionally, the decay muons from the \(Z\) boson must not be contained within the jet cone. Only jets that are on the azimuthal away-side of the \(Z\) boson, defined by \(\Delta \phi_{Z-\text{jet}} \equiv |\phi_Z - \phi_{\text{jet}}| > 7\pi/8\), are analyzed. This requirement selects the highest-\(p_T\) jet in all events in the data sample, and thus better identifies signatures of a two-to-two partonic scattering. The jet energy calibrations are the same as those used in Ref. \(^{35}\). Charged hadrons within the jet are identified by the particle flow algorithm utilizing the particle-identification systems and several track-quality criteria \(^{29}\). The charged hadrons

\(^2\)In this Letter, natural units \((c = \hbar = 1)\) are used.
must also satisfy $\Delta R < 0.5$, which ensures that the corresponding tracks fall within the tracking acceptance.

The methods used to determine the charged-hadron fragmentation distributions are as described in Refs. [21,24,40]. The fragmentation distributions are corrected for tracking inefficiencies and then unfolded for resolution effects, which primarily occur due to the jet energy resolution. The unfolded distributions are then normalized by the total number of $Z+$jet events in a given jet $p_T$ bin, which is determined separately from the hadron-in-jet unfolding procedure and is described below. In this analysis, the $Z$-boson $p_T$ is integrated to provide the statistical precision to measure the fragmentation as a function of jet $p_T$. The integral of the fragmentation distributions then corresponds to the multiplicity of charged hadrons within the jet.

The number of $Z+$jet pairs in each jet $p_T$ bin is corrected to account for reconstruction and selection inefficiencies. The muon detection efficiencies are determined in data using the technique employed in the inclusive $W$ and $Z$ boson cross-section measurements of LHCb [37, 41]. The jet reconstruction efficiency is evaluated from simulation, and is greater than 90% for the jet $p_T$ range studied. A correction is also applied to account for differences between the number of events produced and measured in a given $p_T$ bin due to the jet $p_T$ resolution. This correction is determined from simulation, and is less than 10%. The method described above is cross checked by comparing the results to a full Bayesian unfolding [42] as implemented in Ref. [43]. The two methods give the same jet $p_T$ distribution to within 1%.

Simulation is used to determine the tracking efficiency and to account for effects from misreconstructed tracks moving into and out of the jet cone. The efficiency is evaluated as a function of momentum and pseudorapidity and applied on a per-track basis. The efficiency decreases for $p > 150$ GeV due to a requirement placed within the particle flow algorithm on the uncertainty of the track bending radius, which has a larger effect at high momentum. To test the determination of these effects, the simulation sample is split in half and the efficiencies are determined with one half and applied to the other. Good recovery of the generated charged hadron distributions in $p$ and $\eta$ is observed. Within the statistical precision of the sample the track efficiency is not dependent on the jet $p_T$.

The effects of bin migration in jet $p_T$ and in the fragmentation observables, primarily due to the jet energy and momentum resolutions, are corrected using the two-dimensional Bayesian unfolding method. Response matrices are constructed for each fragmentation observable using simulated samples that study the correlations between the generated and reconstructed yields in bins of $[z, p_T^{\text{jet}}]$, $[r, p_T^{\text{jet}}]$, and $[r, p_T^{\text{jet}}]$. Typically the bin migration is less than 5%; however, it can be larger in more extreme values of the distributions, for example at large $z$. The number of iterations in the Bayesian unfolding procedure is selected to be the minimum number for which the relative change in the fragmentation functions at $z \approx 0.05$ is smaller than 0.2% per additional iteration in all of the jet $p_T$ bins. Based on this criterion, the unfolding is iterated seven times for each observable.

Systematic uncertainties that arise from the uncertainties on the various efficiencies in the muon reconstruction efficiency is negligible. Systematic uncertainties on the jet reconstruction are evaluated as in Ref. [35] by comparing the jet reconstruction quality requirements in simulation and data. Similarly to the muon efficiencies, the precision with which the uncertainty of the jet reconstruction efficiencies are determined is also evaluated; however, this is found to be negligible compared to the jet reconstruction
efficiency uncertainty of 1.9%. The normalization is not corrected for $Z$+jet background
events, and thus a systematic uncertainty of 1.7% is assigned for the impurity of both
$Z$ bosons and jets in the measurement, as determined in Refs. [35,37]. Effects from pile
up are also studied and found to be negligible. The total normalization uncertainty is
determined by adding these components in quadrature, which gives 2.7%.

The jet-energy scale and resolution are also considered as sources of systematic
uncertainty. The jet-energy scale and its uncertainty have been studied in previous
measurements of the $Z$+jet cross-section [35,38]. To estimate the effects of the jet-energy
scale, the scale is varied by one standard deviation of its uncertainty. New unfolding
matrices are constructed with this modification, and the difference in the charged hadron-
in-jet fragmentation distributions determined with the modified and nominal response
matrices is taken as a systematic uncertainty. Similarly, the systematic uncertainty due to
the jet-energy resolution is evaluated by smearing each component of the jet momentum by
an additional term corresponding to the uncertainty on the jet resolution and constructing
new response matrices. The difference between the nominal and smeared unfolded charged
hadron-in-jet distributions is taken as the uncertainty on the jet-energy resolution.

Uncertainties on the unfolding procedure are validated with two different tests. The
first test is performed by splitting the simulated sample in two and using one half to
generate the response matrices with which the other half is unfolded. Recovery of the
generator-level fragmentation distributions is observed and average deviations from perfect
agreement are 2%, which is assigned as an uncertainty on the unfolding procedure. A
second test is performed by splitting the simulated sample in half by $Z$-boson $p_T$, and
performing a similar test to the previous one to check for any uncertainty associated with
the assumed prior. The results again deviate from perfect agreement by about 2%, which
confirms that the 2% systematic uncertainty on the unfolding procedure is appropriate.

The track selection requirements, track efficiency, and charged-hadron identification
are also studied as sources of systematic uncertainty. The track selection uncertainty is
assigned by requiring a tight fake-track removal criterion and repeating the analysis. The
differences in the final fragmentation distributions with and without this requirement are
taken as systematic uncertainties. The track selection uncertainty is typically less than
5%; however, it reaches a maximum of approximately 8% at some values of $z$, $j_T$, and $r$
in the highest jet $p_T$ bin studied. The systematic uncertainty on the tracking efficiency is
determined by smoothing the two-dimensional efficiency and repeating the analysis. The
resulting distributions are compared to the nominal distributions and the differences are
taken as uncertainties on the tracking efficiency; these are generally less than 3% but can
rise to up to 10% in some bins. Uncertainties associated to misidentifying charged hadrons
are also considered by comparing the nominal fragmentation functions to those obtained
when hadron-to-lepton (and vice versa) misidentification probabilities are considered.
These uncertainties are less than 5%, except at large $z$ where the charged pion-to-electron
misidentification probability becomes larger due to the high momentum of the charged
hadrons [29].

Figure 1 shows the distributions of $z$ in three jet $p_T$ bins. These illustrate that the
longitudinal momentum fraction is approximately constant as a function of jet $p_T$ at high
$z$. At low $z$ the fragmentation functions diverge, which is a kinematic effect due to the
requirement that the track momentum be greater than 4 GeV; therefore, higher $p_T$ jets can
probe smaller $z$. Comparing these measurements to inclusive jet measurements at central
rapidity from ATLAS [21] indicates that the fragmentation functions are not as steeply
falling at high $z$. This effect could originate from the different pseudorapidity regions measured. It may also reflect differences between light-quark and gluon fragmentation. For jet $p_T$ less than 100 GeV at the LHC, midrapidity inclusive jets are predominantly sensitive to gluon fragmentation while the forward rapidity $Z$+jet channel probes a high fraction of light-quark jets.

Figures 2 and 3 show the $j_T$ and $r$ fragmentation distributions of charged hadrons within jets. The $j_T$ profiles show a nonperturbative shape at small $j_T$ which turns over and transitions to a perturbative tail at larger $j_T$. This is indicative of an observable that can be treated in a so-called transverse-momentum-dependent framework, where sensitivity to both a large and small transverse momentum scale is necessary \[1,2,44\]. The radial profiles show that the number of charged hadrons at small $r$ is highly dependent on jet $p_T$; however, the values are relatively constant as a function of jet $p_T$ at nearly all other values of $r$. This may reflect that nonperturbative contributions to jets away from the jet axis are not strongly dependent on the jet $p_T$. Interestingly, the $j_T$ fragmentation distributions are similar to the central pseudorapidity inclusive jet results in Ref. \[21\]; however, these measurements are more collimated in $r$ than those in Ref. \[21\]. This behavior in $r$ is correlated to the flatter fragmentation in $z$ and may be a reflection of the different pseudorapidity region or differences in light-quark and gluon fragmentation.

The fragmentation functions are compared to predictions from PYTHIA $Z$+jet events, where the details of the PYTHIA configuration can be found in the Supplemental Material to this Letter \[45\]. An example of the comparison as a function of $z$ is shown in Fig. 4 in one jet $p_T$ bin; additional comparisons can be found in Ref. \[45\]. In general, PYTHIA underestimates the number of charged hadrons at high $z$; PYTHIA also underestimates the number of charged hadrons at small $r$ \[45\]. Comparisons of the data to predictions from PYTHIA as a function of $j_T$ show a consistent shape, but in general PYTHIA underestimates the number of charged hadrons in each bin by approximately 20% \[45\].

In summary, the production of charged hadrons in jets recoiling against a $Z$ boson is measured in $\sqrt{s} = 8$ TeV $pp$ collisions by the LHCb experiment. The jets are measured
Figure 2: Unfolded distributions of the transverse momentum of charged hadrons with respect to the jet axis in three bins of jet $p_T$. The bars (boxes) show the statistical (systematic) uncertainties.

Figure 3: Unfolded radial profile distributions of hadrons with respect to the jet axis in three bins of jet $p_T$. The bars (boxes) show the statistical (systematic) uncertainties.

in the fiducial region of $20 < p_T < 100 \text{ GeV}$ and $2.5 < \eta < 4$, while the hadrons are required to have $p_T > 0.25 \text{ GeV}$, $p > 4 \text{ GeV}$, and to be located within the jet cone of distance parameter $R = 0.5$. The longitudinal momentum fraction, momentum transverse to the jet axis, and radial profile of the charged hadrons are measured with respect to the jet axis. These results provide insight into hadronization mechanisms as they probe a new kinematic regime. They additionally probe a high fraction of light-quark jets versus gluon jets when compared to midrapidity inclusive jet measurements in the same jet $p_T$ range. The results are compared to predictions from the PYTHIA event generator with a specific LHCb configuration, and show that the simulation underestimates the number of high momentum hadrons within these jets. Additionally, comparisons with inclusive midrapidity jet measurements indicate that jets recoiling against a $Z$ boson at
forward rapidity are more collimated in both $z$ and $r$. This work lays the foundation for a broader hadronization research program at LHCb, utilizing the excellent tracking, particle identification, and heavy-flavor jet tagging capabilities already demonstrated by the LHCb detector [29][46].

**Acknowledgements**

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPEMP and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MSHE (Russia); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Aquitaine-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS; CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).
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