Charged hadron distributions in \( Z \)-tagged jets

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A proton + proton collision

- (Initial state) Parton shower
- (Final state) Parton shower
- Hadronization
- Hadron decays
- Beam remnant
- Underlying event

Monte Carlo generator representation

Jet substructure/event shape

• Motivated mostly by search for new particles and BSM physics

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  • Splitting functions,
  • Constraining $\alpha_s$

• Theory revolutionized & experimental techniques developed in past decade, e.g.
  • Soft Collinear Effective Field Theory,
  • Sophisticated jet grooming algorithms

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Fragmentation functions (FF)

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- Also, STAR measured TSSA of hadrons within a jet that enables access to Collins (polarized TMD) FF’s; new approach.

- We can access **collinear FF’s** as well as **unpolarized TMD FF’s** by measuring hadron distributions within Z tagged jets at LHCb!
The LHCb Detector

Detector design:

- Forward geometry to optimize acceptance for $c\bar{c}$ and $b\bar{b}$ pairs: $2 < \eta < 5$
- VERtex LOcator (VELO): vertex position, lifetime and impact parameter.
- Tracking stations TT, T1-T3 and dipole magnet: momentum of charged particles.
- PID system (RICH, calorimeters): $\pi/K/\rho$ separation, triggering on high $p_T$ hadrons and $e^\pm$, $\gamma$ energy.
- Muon stations M1-M5: triggering on muons, tracking stations for muon identification.

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Features attractive for hadronization studies:

- Full jet reconstruction with tracking, ECAL and HCAL
- Tagging of jets from light-quark, c- and b-quark
- Charged hadron identification from 2 < p < 100 GeV/c
- Large pp datasets available from Run I (3.23/fb at √s = 7-8 TeV) and Run II (5.9 /fb at √s = 13 TeV)

Can study identified hadron distributions within jets!

~40% of all produced c̅c and b̅b pairs are in LHCb acceptance.
Studying hadronization in jets: Z$^0$ tagged jets at LHCb

- Z boson + jet production is predominantly sensitive to quark initiated jets.
- Forward kinematics further increases fraction of light quark jets, in particular up and down flavored quarks
- Events are selected such that there is a back-to-back ($\Delta\varphi > 7/8 \pi$) Z + leading jet pair present per event.
Studying hadronization in jets: Z\(^0\) tagged jets at LHCb

- LHCb previously measured Z\(^0\) + jet cross section
  - *JHEP 05, 131 (2016)*
- Now have measured unidentified charged hadron distributions within the jet in the same dataset.
  - PRL 123, 232001 (2019)
- First measurement at the LHC of charged hadrons within Z\(^0\)-tagged jets and also at forward rapidity.
- Measurement of identified hadron distributions within the jet under way.

![Graph showing the ratio of measured data to theoretical predictions for the Z\(^0\) + jet cross section at LHCb, with data points and error bars indicating statistical and systematic uncertainties. The graph compares measured data with predictions from POWHEG and aMC@NLO calculations.](image)

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Charged hadrons in jets: Observables

- Longitudinal momentum fraction $z$
- Transverse momentum with respect to jet axis $j_T$
- Radial profile $r$

Lays the foundation for a broader hadronization program at LHCb utilizing
- Full particle identification
- Charm- and beauty-initiated jets
- Multiparticle correlations within jets
- Hadron distributions in correlated jet pairs

$$Z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

$$j_T = \frac{|p_{jet} \times p_h|}{|p_{jet}|}$$

$$r = \sqrt{(\phi_{jet} - \phi_h)^2 + (\gamma_{jet} - \gamma_h)^2}$$
Analysis

- Follow similar analysis strategy to previous ATLAS and LHCb papers
  - LHCb: PRL 118, 192001 (2017)
Results: Radial profile

- Observe that the greater energy available in higher transverse momentum jets leads to more hadrons produced.
- Almost all of the additional particles are produced close to the jet axis, and go from a depletion to an excess.

\[ 1 \frac{dN}{dr} \]

LHCb \( \sqrt{s} = 8 \text{ TeV} \)

- \( 20 < p_T^{\text{jet}} < 30 \text{ GeV} \)
- \( 30 < p_T^{\text{jet}} < 50 \text{ GeV} \)
- \( 50 < p_T^{\text{jet}} < 100 \text{ GeV} \)
Quark- vs. gluon-initiated jets: Radial profile

- Quark-initiated jets narrower (more collimated) than gluon-initiated jets measured by ATLAS.
  - i.e. more charged hadrons at small radii, fewer at large radii.
  - Qualitatively agrees with conventional expectations, but this shows clear and quantitative evidence from data.
Quark- vs. gluon-initiated jets: Longitudinal profile

• Quark-initiated jets have relatively more hadrons produced at higher longitudinal momentum fractions than gluon-initiated jets.

• Measuring identified charged hadron distributions will be sensitive to the quark flavor transition between hard scattering and formation of a hadron at high $z$. 

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Quark- vs. gluon-initiated jets: Longitudinal profile

- ATLAS midrapidity $\gamma$+jet and LHCb Z+jet longitudinal momentum distributions are more similar
  - $\gamma$+ jet, like Z+jet, enhances quark jet fraction
  - Further evidence that differences observed between LHCb and ATLAS results are due to differences in quark and gluon hadronization
Future work

Two-dimensional analysis of hadron distributions

- \( j_\perp \) vs z: Access to unpolarized Transverse-momentum-dependent Fragmentation Functions (TMD FF)

Identified charged hadron distributions in jets & charge ratio thereof

- Statistical sensitivity to flavor of quarks that initiate jets
Conclusion

• Jet substructure/event shape research advanced in past decade improved our knowledge of QCD.

• TMD observables have gained much interest in nuclear physics community and unpolarized TMD fragmentation functions are poorly constrained.

• LHCb has full potential of measuring identified hadron distributions within a jet in order to access unpolarized TMD fragmentation functions.

• First measurement of unidentified hadron distributions within a jet has been recently published, showing results that are
  • in contrast to inclusive jets results from ATLAS.
  • similar to photon+jet results from ATLAS.

• Lays the foundation for a variety of future measurements related to hadronization in jets.