Hadronization Studies in Z-tagged Jets at LHCb

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Jets as systems for studying hadronization

- Hadronization remains poorly understood despite being a fundamental component of QCD
- Jets contain the final state particles produced during the high-energy hadronization process - measuring hadron distributions in jets can help us learn about hadronization!

Jets can probe:
- Hadronization dynamics
- Flavor dependence of hadronization
  - u/d/s
  - b/c
- Color neutralization mechanisms
This talk: **Forward Z-tagged jets** as systems for studying **light-quark** hadronization

I) Light quark jet tagging at LHCb with Z-tagged jets

II) LHCb results of charged hadron distributions in Z-tagged jets

III) Comparison to ATLAS inclusive jet results, which are gluon-jet dominated
The Large Hadron Collider beauty (LHCb) Detector

Forward spectrometer designed to study the production and decay of heavy flavor hadrons

The Large Hadron Collider beauty (LHCb) Detector

Full hadronic and electromagnetic calorimetry, tracking, particle identification, and muon ID in $2 < \eta < 5$
• Quark-gluon LO process dominates at LHC energies, selecting quark-initiated Z-tagged jets

• Most forward Z-tagged jets are quark-initiated, with the majority being light-quark-initiated due to the large-x quark needed for forward production

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P_T^Z [GeV]

Partonic Fraction

PYTHIA 8.235

qg→Zq

sq = 8 TeV

qg→Zg

2<η_Z<4.5

2.5<η_j<4

LO Z+jet processes:
Z-tagged Jets at LHCb

- LHCb has measured the Z+jet cross section at √s = 7 and 8 TeV
- Jet reconstruction is performed with a particle flow algorithm and anti-k_T clustering with a distance parameter R = 0.5
- Z bosons are reconstructed in the Z->μμ decay channel
- For charged hadron measurements, an additional cut requiring Δφ(Z, jet) > 7π/8 is applied to enhance 2->2 partonic scattering events
Charged Hadron Observables

Longitudinal momentum fraction $z$

$$z = \frac{P_{\text{jet}} \cdot P_{\text{hadron}}}{|P_{\text{jet}}|^2}$$

Transverse momentum with respect to the jet axis $j_T$

$$j_T = \frac{|P_{\text{jet}} \times P_{\text{hadron}}|}{|P_{\text{jet}}|}$$

Radial distribution $r$

$$r = \sqrt{(\phi_{\text{jet}} - \phi_{\text{hadron}})^2 + (y_{\text{jet}} - y_{\text{hadron}})^2}$$

$p_{\text{hadron}} > 4 \text{ GeV}$

$p_{T,\text{hadron}} > 0.25 \text{ GeV}$
Distributions are approximately constant as a function of jet $p_T$ at high $z$

Higher $p_T$ jets probe lower $z$ values
Results: Transverse Momentum $j_T$

- Transition from a nonperturbative shape at small $j_T$ to a perturbative tail at large $j_T$ indicates sensitivity to both small and large transverse momentum scales
- Needed to constrain transverse momentum dependent (TMD) jet fragmentation functions

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Results: Radial distribution $r$

- Strong dependence on jet $p_T$ at very small $r$, with more hadrons produced close to the jet axis in high-$p_T$ jets.

- Reduced jet $p_T$ dependence at larger values of $r$ could indicate that nonperturbative contributions away from the jet axis do not depend strongly on jet $p_T$.

$LHCb$ $\sqrt{s} = 8$ TeV

$\frac{1}{N_{Z+jet}} \frac{dN}{dr}$

$r = \sqrt{(\phi_{jet} - \phi_{hadron})^2 + (y_{jet} - y_{hadron})^2}$

$20 < p_T^{jet} < 30$ GeV

$30 < p_T^{jet} < 50$ GeV

$50 < p_T^{jet} < 100$ GeV

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Theoretical comparisons

- Perturbative QCD calculations agree well with measured $z$ distributions for intermediate $z$ values

- 2D $j_T$ vs. $z$ distribution measurements in progress - will allow for jet TMD FF extraction

Kang, Lee, Terry, Xing PLB **798**, 134978 (2019)
Comparing **gluon-dominated** and **light-quark-dominated** jets

Comparisons between midrapidity inclusive jets and forward Z-tagged jets can probe differences between light-quark and gluon hadronization.
Controlling for $\eta$ dependence: $z$

$\gamma$-tagged jets have same LO diagrams as Z-tagged jets:

- Similar $z$ distributions between forward Z-tagged jets and midrapidity $\gamma$-tagged jets
- Differences between inclusive midrapidity jets and forward Z-tagged jets should be due to quark vs. gluon hadronization

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$\frac{1}{N_{\text{jet}}} \frac{dN}{dz}$

**ATLAS inclusive jet**

- EPJ C71, 1795 (2011)
- $\sqrt{s} = 7$ TeV
- $|\eta^{\text{jet}}| < 1.2$, $R = 0.6$
- $p_T^{\text{track}} > 0.5$ GeV
- $25 < p_T^{\text{jet}} < 40$ GeV
- $40 < p_T^{\text{jet}} < 60$ GeV (x10)

**LHCb $Z$+jet**

- $\sqrt{s} = 8$ TeV
- $60 < M_{\mu\mu} < 120$ GeV, $2 < \eta^{Z} < 4.5$
- $2.5 < \eta^{\text{jet}} < 4$, $R = 0.5$
- $p_T^{\text{hadron}} > 0.25$ GeV, $p_T^{\text{hadron}} > 4$ GeV
- $20 < p_T^{\text{jet}} < 30$ GeV
- $30 < p_T^{\text{jet}} < 50$ GeV (x10)

- **ATLAS inclusive jets: gluon-dominated**
- **LHCb $Z$-tagged jets: light-quark-dominated**

- **Gluon-initiated jets have a more steeply falling $z$ distribution than light-quark-initiated jets**

- **Light-quark-initiated jets have slightly more hadrons produced at higher $z$ values**
Comparison to gluon-dominated jets: $j_T$

- Light-quark-initiated jets and gluon-initiated jets have similar $j_T$ distributions
Comparison to gluon-dominated jets: 

- Light-quark-initiated jets are more collimated than gluon-initiated jets
More to come from LHCb’s hadronization program!

- **Identified** charged hadron distributions in Z-tagged jets, utilizing LHCb’s excellent particle ID capabilities

- Charged hadron distributions in **beauty and charm-tagged** jets utilizing LHCb’s heavy flavor jet tagging

- **Quarkonia in jets** - $J/\psi$ polarization, $\Upsilon$, $\phi$

- **Strange hadron correlations in jets**, to test ideas about string breaking models of hadronization
Summary

• Jets are ideal systems in which to study high-energy hadronization.

• LHCb has measured the longitudinal momentum fraction $z$, transverse momentum with respect to the jet axis $j_T$, and radial distribution $r$ of charged hadrons in Z-tagged jets.

• Comparisons between light-quark-dominated forward Z-tagged jets and gluon-dominated midrapidity inclusive jets show that light-quark-initiated jets are more collimated and have more charged hadrons at high $z$ values than gluon-initiated jets.

• Many more hadronization measurements are still to come from LHCb, including identified charged hadron distributions in Z-tagged jets and charged hadron distributions in b- and c-tagged jets.

Thanks for your attention!
backup
LHCb phase space at $\sqrt{s} = 8$ TeV

- Forward kinematics of LHCb provide access to low- and high-x PDFs
- Complementary to phase space of midrapidity LHC experiments
η dependence of Z-tagged jet cross section

LHCb, $\sqrt{s} = 8$ TeV

Data
d
Data
POWHEG
aMC@NLO

JHEP 05, 131 (2016)