Studying Jet Fragmentation and Hadronization at LHCb

Christine A. Aidala
University of Michigan
On behalf of the LHCb Collaboration

International Conference on New Frontiers in Physics
Kolymbari, Greece
August 22-29, 2019
Jet hadronization

- Jets are a proxy for partons, thus providing sensitivity to the underlying partonic dynamics
- Robust comparison between experiment and theory enabled by e.g. anti-$k_T$ jet algorithm has made jets powerful tools at the LHC
Jet hadronization

- Jets are a proxy for partons, thus providing sensitivity to the underlying partonic dynamics
- Robust comparison between experiment and theory enabled by e.g. anti-$k_T$ jet algorithm has made jets powerful tools at the LHC

- But jets are formed from final-state hadrons!
- Nonperturbative elements of QCD still important in understanding perturbative jet formation
- We can study a perturbative object to learn also about nonperturbative physics
Parton shower: in theory....

First splitting

direction of shower

direction of clustering
Parton shower: in practice

First splitting

direction of shower

direction of clustering
Parton shower: in theory...

First splitting

Direction of shower

Fragmentation
Hadronization

Direction of clustering
Fragmentation vs. Hadronization

- Use jet grooming algorithms to identify “prongs” of jet, as proxy for partonic splittings
- Study correlations of individual hadrons with jet axis and each other

Christine Aidala, ICNFP, Aug 2019
Understanding hadronization: A wish list

1. A way to connect the initial-state parton to the final-state hadrons
   - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

2. A way to connect the flavor of the initial-state parton to the final-state hadrons
   - Would allow for complete characterization of parton → hadron

Courtesy Joe Osborn
Understanding hadronization: A wish list

1. A way to connect the initial-state parton to the final-state hadrons
   - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

2. A way to connect the flavor of the initial-state parton to the final-state hadrons
   - Would allow for complete characterization of parton $\rightarrow$ hadron

Courtesy Joe Osborn
Understanding hadronization:
A wish list

1. A way to connect the initial-state parton to the final-state hadrons
   - Jets, as a proxy for a parton, are a tool to connect the perturbative to nonperturbative

2. A way to connect the flavor of the initial-state parton to the final-state hadrons
   - Would allow for complete characterization of parton $\rightarrow$ hadron

- Baryon vs. meson
- Correlations (e.g. strangeness, heavy flavor)
- Resonance production ($\phi$, $J/\psi$, $Y$)
- Increase projectile/target size (hadronization in medium)

...
The LHCb experiment

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

• Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$

• Tracking: Momentum resolution <1% for $p < 200$ GeV/c

• Particle ID: Excellent capabilities to select exclusive decays
The LHCb experiment

LHCb is the experiment devoted to heavy flavor at the LHC

Detector design:

- Forward geometry to optimize acceptance for $b\bar{b}$ pairs: $2 < \eta < 5$
- Tracking: Momentum resolution <1% for $p < 200$ GeV/c
- Particle ID: Excellent capabilities to select exclusive decays

Some features specifically attractive for hadronization:
- Full jet reconstruction with tracking, ECAL, HCAL
- Heavy flavor tagging of jets
- Charged hadron PID from $2 < p < 100$ GeV
Can study identified particle distributions within jets!
**x-Q^2 coverage affects parton mix**

- LHCb also has unique x-Q^2 coverage
  - Enhanced light quark jet fraction in forward region
$J/\psi$ production in jets at LHCb

- First LHCb jet substructure measurement was $J/\psi$-in-jet production
  - $J/\psi$ from b decay well described by PYTHIA
  - Prompt $J/\psi$-in-jet not! Can shed light on prompt $J/\psi$ production mechanism(s). How is a prompt $J/\psi$ produced within a jet??

Christine Aidala, ICNFP, Aug 2019
**Forward Z+jet**

- Z+jet is predominantly sensitive to quark jets.
- Forward kinematics increases fraction of light quark jets.

![Graph showing partonic fraction vs. $p_T$ for Z+jet production](image)

*PYTHIA 8.2, $\sqrt{s} = 8$ TeV*
**Forward Z+jet**

- In contrast to midrapidity inclusive jets, dominated by gluons
- Opportunity to study light quark vs. gluon jets
  - Hadronization dynamics
  - Jet properties

![Graph showing partonic fraction vs. jet transverse momentum](image-url)

**PYTHIA 8.2**
\[ \sqrt{s} = 8 \text{ TeV} \]
Midrapidity inclusive jet

Christine Aidala, ICNFP, Aug 2019
Forward $Z+$jet

- LHCb previously measured the forward $Z+$jet cross section
  - JHEP 05, 131 (2016)

- Now have measured charged hadron distributions within the jet, in the same data set
  - arXiv:1904.08878

- First LHC measurement of charged hadrons within $Z$-tagged jets
- First LHC measurement of charged hadrons-in-jets at forward rapidity
**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:

- Particle ID
- Heavy flavor jet tagging
- Resonance production within jets
- Correlations with flavor ID

\[
    z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}
\]

\[
    j_T = \frac{|p_h \times p_{jet}|}{|p_{jet}|}
\]

\[
    r = \sqrt{(\phi_h - \phi_{jet})^2 + (y_h - y_{jet})^2}
\]

Christine Aidala, ICNFP, Aug 2019
Analysis details

• Follow similar analysis strategy to ATLAS and previous LHCb papers

• \( Z \to \mu^+ \mu^- \) identified with \( 60 < M_{\mu\mu} < 120 \text{ GeV} \), in \( 2 < \eta < 4.5 \)
• Anti-\( k_T \) jets are measured with \( R = 0.5, \ p_T^{\text{jet}} > 20 \text{ GeV} \), in \( 2 < \eta < 4.5 \)
• \( |\Delta \phi_{Z+\text{jet}}| > 7\pi/8 \) selects \( 2\to2 \) event topology
• Charged hadrons selected with \( p_T > 0.25 \text{ GeV}, \ p > 4 \text{ GeV}, \Delta R < 0.5 \)
• Results efficiency corrected and 2D Bayesian unfolded
Results: Longitudinal momentum distributions

- Measurements in three $p_T^{\text{jet}}$ bins, integrated over $Z$ kinematics
- Longitudinal hadron-in-jet distributions independent of jet $p_T$ at high $z$
- Distributions diverge at low $z$ due to kinematic phase space available

$N/p_\text{Z-jet}$

$LHCb \quad 20 < p_T^{\text{jet}} < 30 \text{ GeV}$

$LHCb \quad 30 < p_T^{\text{jet}} < 50 \text{ GeV}$

$LHCb \quad 50 < p_T^{\text{jet}} < 100 \text{ GeV}$

arXiv:1904.08878
LHCb-PAPER-2019-012
Longitudinal momentum distributions: Comparison to ATLAS inclusive jets

- Comparing ATLAS midrapidity inclusive jets to LHCb forward Z+jet shows longitudinal distributions in Z+jet “flatter” as a function of z

- Caveats – ATLAS/LHCb measurements can only be compared qualitatively due to different kinematics
Longitudinal momentum distributions: Comparison to ATLAS $\gamma$+jet

- ATLAS midrapidity $\gamma$+jet and LHCb Z+jet longitudinal distributions are instead very similar in the comparable jet $p_T$ bin
  - $\gamma$+jet, like Z+jet, enhances quark jet fraction!

- Kinematic fiducial space similar but not exactly the same

arXiv:1904.08878
LHCb-PAPER-2019-012
**Results: Transverse momentum distributions**

- Transverse momentum of hadron with respect to jet axis shows nonperturbative to perturbative transition

- Shapes very similar as function of $p_T^{\text{jet}}$ – slight increase of $\langle j_T \rangle$ with $p_T^{\text{jet}}$
Transverse momentum distributions: Comparison to ATLAS inclusive jets

- Transverse momentum distributions show smaller $<j_T>$ in $Z$+jet vs. inclusive jet at small $j_T$

arXiv:1904.08878
LHCb-PAPER-2019-012
Results: Radial profiles

- Radial profiles largely independent of jet $p_T$ away from the jet axis
- Multiplicity of hadrons along jet axis rises sharply with jet $p_T$
Radial profiles: Comparison to ATLAS inclusive jets

- Forward Z-tagged jets more collimated than midrapidity inclusive jets
  - I.e. more charged hadrons at small radii, fewer at large radii
PYTHIA generally underpredicts the number of high-momentum charged hadrons within Z-tagged jets, correlated with low radii.

arXiv:1904.08878
LHCb-PAPER-2019-012
Hadronization in jets at LHCb—More in progress!

• Charged hadron distributions in b- and c-tagged jets
• Identified hadron ($\pi^{+/−}, \, K^{+/−}$) distributions in light quark, b- and c-tagged jets
• Beauty and charm hadron distributions in b- and c-tagged jets
• Baryon and meson distributions in jets
• More quarkonia in jets: Y, $\phi$, J/$\psi$ polarization in jets
Summary

- LHCb has unique capabilities to study hadronization within jets, complementary to other LHC experiments
  - Forward acceptance
  - Particle ID
- Recent measurements of charged hadron distributions in forward Z+jet, in particular when compared with midrapidity inclusive jets and γ+jet, can provide information on quark vs. gluon hadronization
  - For full details, see


- Stay tuned for more jet hadronization results in the near future!
Extra
LHCb jet measurements

• W/Z+jet cross sections
  – JHEP 05, 131 (2016)
  – JHEP 01, 064 (2015)
  – JHEP 01, 33 (2014)

• Heavy flavor jets
  – PRL 118, 192001 (2017)
  – JINST 10, P06013 (2015)
The LHCb detector – Particle ID

Reconstructed Cherenkov angle for Isolated Tracks

Pion Mis-ID vs Kaon ID efficiencies for events with many tracks


Kara Mattioli, University of Michigan