The Lund jet plane in light and heavy quarks at LHCb

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Heavy Quark Showering and Fragmentation

1. The Dead Cone Effect

2. The Leading Particle Effect

Lund Jet Plane
The Dead Cone Effect
Bremsstrahlung off moving charges

- The relativistic and massless splitting probability in pQCD is given by

\[ dP_{i\rightarrow ig} = \frac{\alpha_s C_i}{\pi} \frac{d\theta^2}{\theta^2} \frac{dz}{z} \]

\[ z : \text{Energy Fraction} \]
\[ \theta : \text{Splitting angle} \]
\[ C_i : \text{Color factor} \]

- For heavy quarks (HQ), a characteristic angle appears in the equation

\[ dP_{i\rightarrow ig} = \frac{\alpha_s C_i}{\pi} \frac{\theta^2 d\theta^2}{(\theta^2 + \theta_{HQ}^2)^2} \frac{dz}{z} \]

\[ \theta_{HQ} = \frac{m_{HQ}}{E} \]
Heavy Quark Fragmentation

Heavy quarks maintain most of their energy

- Light partons lose most of their energy in hard collinear radiation
- The dead cone effect in heavy quarks prevents collinear radiation → very few hard and collinear bremsstrahlung!
- Thus, the heavy quark maintains most of its energy

Energy fraction of the jet carried by the b-hadron

(SLD), Phys. Rev. D65
(Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
Single partons are inaccessible! Only access to collimated cone of hadrons a.k.a *Jets.*
Jet Clustering Algorithms

Anti-$k_T$

- Infrared and Collinear safe
- Conical jets
- Standard jet clustering algorithm

Cambridge/Aachen

- Respects angular ordering
- Reconstructs splitting history
- *Not* infrared safe
Angular Ordering

Accessing the splitting history

• Gluon radiation is ordered from larger to smaller angles throughout the showering

\[ \theta_1 > \theta_2 > \ldots > \theta_n \]

• The C/A algorithm clusters jets based on smallest angles first = respects angular ordering!

C/A gives us access to the splitting history of the jet

Image: Mangano-Lect3
Iterative Declustering

1. Using the FastJet algorithm, cluster jets with the anti-$k_T$ algorithm (“AK5” for $R = 0.5$)

2. Recluster jets passing the selection criteria using C/A

3. Following the hardest/heavy-flavor branch, at each splitting point record the variables of interest:
   $k_T, z, \Delta R, \theta, E_{rad}$

References:
- The European Physical Journal C 72 (2012): 1-54
Splitting Variables

- We adopt the following definitions for the Lund jet plane variables:
  - \( \theta_{ij} \): the angle between the soft daughter and radiator
  - \( E_{rad} \): the energy of the radiator
  - \( \Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \): angular distance
  - \( k_T = p_T^{soft} \sin(\Delta R) \): relative transverse momentum
  - \( z = \frac{p_T^{soft}}{p_T^{hard} + p_T^{soft}} \): transverse momentum fraction
Splitting Variables

\[ \rho(E_{rad}, \theta) = \frac{1}{N_{emissions}} \frac{d^2n}{dE_{rad} d \ln(1/\theta)} \]

- Focusing on these variables:
  - \( \theta_{ij} \): the angle between the soft daughter and radiator
  - \( E_{rad} \): the energy of the radiator

Hard: \( p_{Ti} > p_{Tj} \)

Dead cone plane in \( E_{rad} \) and \( \theta \)

\[ \theta_{HQ} = \frac{m_{HQ}}{E} \]
Splitting Variables

- Focusing on these variables:
  
  \[ \Delta R = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \]
  
  \[ k_T = p_T^{\text{soft}} \sin(\Delta R) \]
  
  \[ z = \frac{p_T^{\text{soft}}}{p_T^{\text{hard}} + p_T^{\text{soft}}} \]

\[
\rho(\Delta R, k_T) = \frac{1}{N_{\text{emissions}}} \frac{d^2 n}{d \ln(R/\Delta R) d \ln(k_T)}
\]

\[
\rho(\Delta R, z) = \frac{1}{N_{\text{emissions}}} \frac{d^2 n}{d \ln(R/\Delta R) d \ln(1/z)}
\]

**Lund jet plane**

\[ \rho(R, z) = \frac{1}{N_{\text{emissions}}} \frac{d^2 n}{d \ln(R/\Delta R) d \ln(1/z)} \]

**Hard:** $p_T^i > p_T^j$
The Lund jet plane

• The Lund jet plane (LJP) is a 2D “image” of parton emissions in jets

• Different representations of the LJP are possible, e.g. \([\ln(1/z), \ln(R/\Delta R)]\) or \([\ln(k_t), \ln(R/\Delta R)]\)

• The LJP separates various types of emissions into different regions

• The plane is populated uniformly for soft and collinear emissions

\[
dP_{i\rightarrow ig} = \frac{\alpha_s C_i}{\pi} \frac{d\theta^2}{\theta^2} \frac{dz}{z}
\]

F. A. Dreyer, G. P. Salam, and G. Soyez,
Studying the Lund jet plane gives us access to many interesting phenomena in QCD such as the parton shower, hadronization, the dead cone effect, and jet flavor discrimination all in one!
Previous measurements of the Lund plane

ALICE and ATLAS

**Figure 3:** Fully corrected primary Lund plane density.

**Figure 2.** The LJP measured using jets in 13 TeV \( pp \) collision data, corrected to particle level. The inner set of axes indicates the coordinates of the LJP itself, while the outer set indicates corresponding values of \( z \) and \( \Delta R \).
Prospects for the LJP at LHCb
The LHCb Detector
Forward-arm spectrometer

- Forward rapidities: $2 < \eta < 5$
- Excellent vertex resolution
- Tracking and particle identification
- Hadronic and electromagnetic calorimetry
- Muon system
Large Heavy Flavor Cross-sections

Lots of HF jets!

- HF dijet cross-section is large at forward rapidities!
- For an integrated luminosity of 1.6 fb$^{-1}$, millions of heavy flavor jets are created!
Tracking and PID

Excellent momentum resolution and particle identification

Resolution <1% up to 200 GeV

Capability of selecting exclusive decays!

Powerful reconstruction of exclusive decays

\[ B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+ \]

\[ B^+ \rightarrow [\mu^+\mu^-]_{J/\psi}K^+ \]

LHCb

\[ D^0 \rightarrow K^-\pi^+ \]

PRD 95, 052005 (2017)

Phys. Rev. D 104 (2021) 072010
Lund plane at LHCb

• We plan on:
  • measuring the LJP for light, charm, and beauty jets,
  • measuring the LJP for tracks as well as tracks + neutrals,
  • and measuring the dead-cone and leading-particle effects from the various LJP parametrization.
Planning ahead: Jet Samples

Z-tagged jets, jets around $D^0$, jets around $B^\pm$

- We use Run 2 p+p collisions at $\sqrt{s} = 13$ TeV data during the years 2016-2018.

- For light partons (u/d/s/g), jets recoiling off a Z-boson are used to obtain a quark-enriched jet sample. $pp \rightarrow Z(\rightarrow \mu\mu) + q(g)$

- For charm-initiated jets, we reconstruct $D^0 \rightarrow K^-\pi^+$ candidates and find jets that contain the $D^0/\bar{D}^0$ within the jet radius.

- For beauty-initiated jets, we reconstruct $B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+$ candidates and find jets that contain the $B^\pm$ within the jet radius.
LJP at forward rapidities

Pythia8 Simulations

$\sqrt{s} = 13$ TeV

$2.5 < \eta_j < 4$

$p_{T,jet} > 20$ GeV

$z = \frac{p_{T,soft}}{p_{T,hard} + p_{T,soft}}$

Light quark jets
LJP at forward rapidities

Pythia8 Simulations

Light quark jets

Soft and wide

Hard and collinear

pp collisions

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ 2.5 < \eta_j < 4 \]

\[ p_{T,jet} > 20 \text{ GeV} \]
LJP at forward rapidities
Pythia8 Simulations

pp collisions

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ 2.5 < \eta_j < 4 \]
\[ p_{T,jet} > 20 \text{ GeV} \]
LJP at forward rapidities
Pythia8 Simulations

$pp$ collisions

$\sqrt{s} = 13$ TeV

$2.5 < \eta_j < 4$

$p_{T,\text{jet}} > 20$ GeV

Suppression of hard collinear radiation = Heavy quarks maintain most of their energy!
LJP at forward rapidities

Pythia8 Simulations

$\sqrt{s} = 13$ TeV
$2.5 < \eta_j < 4$
$p_{T,jet} > 20$ GeV

Suppressed collinear radiation = dead cone effect!
Dead cone at forward rapidities
Pythia8 Simulations

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ 2.5 < \eta_j < 4 \]
\[ p_{T,jet} > 20 \text{ GeV} \]
Dead cone at forward rapidities

Pythia8 Simulations

Charm/Light

Beauty/Charm

Beauty/Light

\[
\ln \left( \frac{1}{\theta} \right)
\]

Red line: Dead cone angle as a function of Eradiator

\[
\theta_{HQ} = \frac{m_{HQ}}{E}
\]

pp collisions

\[
\sqrt{s} = 13 \text{ TeV}
\]

\[
2.5 < \eta_j < 4
\]

\[
p_{T,jet} > 20 \text{ GeV}
\]
Dead cone at forward rapidities
Pythia8 Simulations

pp collisions

\( \sqrt{s} = 13 \text{ TeV} \)

\( 2.5 < \eta_j < 4 \)

\( p_{T,jet} > 20 \text{ GeV} \)

Dead cone effect is most prominent for Beauty/Light ratio
Dead cone measurement by ALICE

Ratio of charm to inclusive jets

- ALICE has observed the dead cone in charm jets relative to inclusive jets
- We would like to make a measurement of beauty/light, charm/light, and beauty/charm

Nature 605, no. 7910 (2022): 440-446
Recap: Lund plane at LHCb

• We plan on:
  • measuring the LJP for light, charm, and beauty jets,
  • measuring the LJP for tracks as well as tracks + neutrals,
  • and measuring the dead-cone and leading-particle effects from the various LJP parametrization.
Backup slides
Jets and Clustering Algorithms

**Anti-$$k_T$$, Cambridge/Aachen**

- Given a collection of particles, define a distance between two particles as:
  \[ d_{ij} = \min \left( \frac{p_{T_i}^2}{p_{T_j}^2}, \frac{p_{T_j}^2}{p_{T_i}^2} \right) \Delta R_{ij}^2 / R^2 \]

  \[ p = 1: k_T \]

  \[ p = 0: \text{Cambridge Aachen (C/A)} \]

  \[ p = -1: \text{Anti-}k_T \]

- Merge the two particles with the lowest distance first, repeat until all particles have been merged/clustered

- **Anti-$$k_T$$ is infrared and collinear safe (IRC), and produces conical jets!**
Partonic fractions at forward rapidity

Low-x enhances the light-quark jet fraction

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