Probing the Dead Cone using the Lund Jet Plane

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Abstract. The Lund Jet Plane (LJP), mapping the momentum and angular orientation of radiation from a parton, aids in studying jet substructure. Here, we use the LJP to investigate the Dead Cone effect, where gluon radiation around a massive quark is suppressed in heavy-flavour jets. We develop a method to observe this phenomenon using simulated collider events. Although the emission density within the resulting LJP for bottom-tagged jets shows a hint of a suppression, further refinement to the analysis is required for a more conclusive observation.

1 Introduction

In high-energy colliders, we study the fundamental constituents of matter, which include quarks and gluons (collectively known as partons). The goal is to better understand and validate predictions made by Quantum Chromodynamics (QCD), a theory that describes the strong force or the interaction of quarks by the exchange of gluons. At such high energies, new quark pairs can be created. As a quark/antiquark moves away from the collision point, it loses energy by emitting soft gluons in a cascading process called a parton shower [1]. Eventually, the low-energy quark combines with other quarks to form particles called hadrons. When many hadrons are produced in the same direction, they form a spray of particles collected in a reconstructed object called a jet, which can be detected in experiments.

The probability of soft-gluon radiation from a quark depends on the quark mass. A suppression was predicted [2] around the forward axis of a radiating massive quark, an effect known as the Dead Cone. The Dead Cone is more pronounced in parton showers of heavy quarks than in those of light quarks. This is a result of the relationship;

$$\theta_{DC} \geq \frac{m_Q}{E_Q} \, , \tag{1}$$

where θ_{DC} is the size of the suppressed region, m_Q is the mass of the quark, and E_Q is the energy of the quark. According to this relation, gluon radiation is suppressed at angular scales smaller than m_Q/E_Q, making the effect more significant for heavier quarks at lower energies. There are challenges to observing the Dead Cone experimentally. The direction of the quark changes as it radiates (see Fig. 1), making it difficult to precisely define the quark direction in analysis. Additionally, the Dead Cone region can be contaminated by contributions from other processes in the collision, such as pile-up and underlying event (UE).

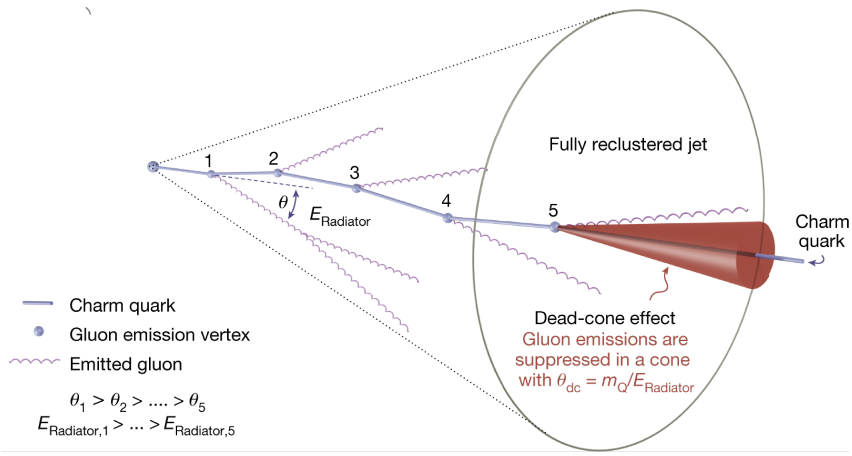

Figure 1: Schematic of branchings inside a charm-quark jet, showing the Dead Cone effect [3]

In this study, the Lund Jet Plane (LJP) is used to investigate the Dead Cone effect in the parton shower of a bottom quark (mass $\sim$ 4.2 GeV). The LJP is a two-dimensional plot which provides a theoretical representation of the phase space within jets [4]. It typically plots the momentum fraction of an emission against its angle relative to the emitting core, though other splittings properties can also be visualized. This representation allows us to probe different physical processes occurring at various energy scales within a jet [4].

2 Analysis

To simulate the production of bottom quark pairs from a high-energy proton-proton collision, we use a Monte Carlo based event generator called PYTHIA8 [5]. This outputs a list of particles that would result from such collisions/events. The RIVET analysis toolkit [6] is then used to analyze the events. Because individual quarks cannot be directly detected, we rely on jets to study their behaviour. The commonly used jet clustering algorithm is the anti-k_T [7], mainly because it aligns with particle detection through their energy deposits in calorimeters at the LHC. The anti-k_T algorithm clusters particles in momentum space, starting from the one with the highest momentum and sequentially adding nearby particles within a defined radius that sets the jet size.

In the analysis, a tagging procedure that identifies jets containing B-hadrons (particles that contain a bottom quark) is applied, then such jets are isolated as heavy-flavour jets. After tagging, the jet with the highest transverse momentum (p_T) is selected in each event. To reconstruct the internal cascade, the jets are reclustered using the Cambridge/Aachen (C/A) algorithm. The C/A algorithm mimics the angular-ordered structure of a QCD parton shower. As its inputs, charged particle tracks in the central part of a detector are used because they offer better resolution than calorimeter deposits in the detector. Unlike anti-k_T, the C/A algorithm clusters particles in angular space, starting with the closest pair [8]. Once the jet is reclustered, the branching history can be retrieved by undoing the C/A clustering procedure. Each declustering step returns a splitting into two prongs, and the soft prong is taken to represent the emission , which is then recorded as a point on the LJP.

Recording points from following both prongs at each step would construct the full Lund plane (see Fig. 2), recording all emissions within the jet. However, the interest is in the primary Lund Plane (pLP), which captures only the emissions from the jet-initiating quark. It is constructed by following the harder prong. Each emission is then plotted on the plane, with the angular separation from the quark on the $x - axis$, and the quark's energy at the time of emission on the $y - axis$ (see Fig. 2). To reduce contamination from hadron decays which add low-momentum splittings, a selection on the relative transverse momentum of each emission (k_T) is necessary. Specifically, we require $k_T > 0.2$ GeV, in line with the hadronization scale, $\Lambda_{QCD} \sim 200$ MeV.

The above choice of coordinates allows a clearer investigation of the Dead Cone effect, with the suppression expected to occur in the soft-collinear region of the LJP (bottom right region). This follows from the relationship given in equation 1; the effect becomes more significant for heavier quarks at lower energies. To identify the suppression, we compare the radiation pattern of b-jets to that of light-quark jets, where the Dead Cone is not expected. Therefore the same analysis is repeated in light-quark events for reference.

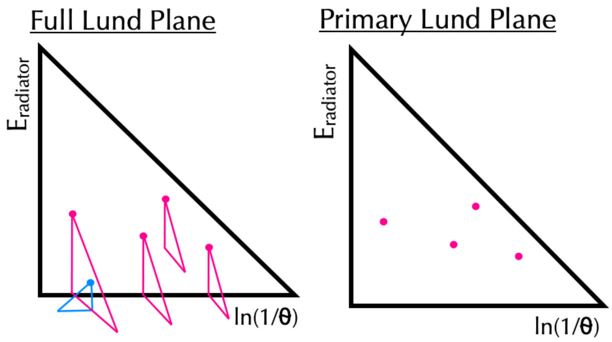

Figure 2: (*left*) Schematic of a Full Lund Plane, depicting all splittings inside a jet. The pink points represent primary emissions, while the blue points represent secondary emissions. (*right*) Schematic of a primary Lund plane, depicting only primary splittings inside a jet.

3 Results and Discussions

Figure 3 shows the LJP for jets containing one B-Hadron. The red curve serves as a visual guide to indicate the expected region of the suppression for different quark energies. Figures 4 and 5, show horizontal slices through the LJP in different energy bins. They show the jet emission density, Q, spanning the entire angular scale. Q is decribed by equation 2. For a direct comparison, each slice is overlaid with the corresponding slice from light-quark jets at the same energy bins. The overlaid plots are labeled A, B, and C, matching the reference keys in Figure 3.

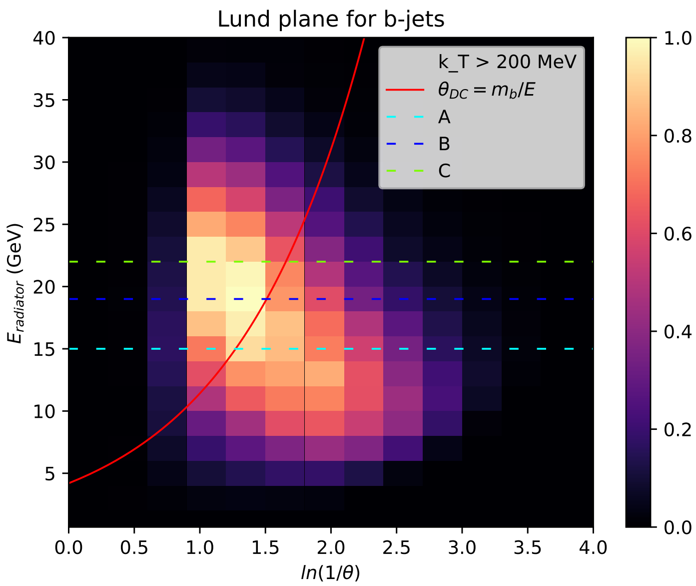

Figure 3: The average emission density, for R = 0.4 and $30\ GeV < Jet\ p_T < 40\ GeV$ b-tagged jets reclustered with the C/A algorithm.

In plots B and C, there is a hint of a suppression, which may suggest the presence of the Dead Cone. However, we cannot conclusively attribute this suppression to the Dead Cone effect, as its location does not align with the expected onset indicated by the red curve in Figure 3. It is possible that a Dead Cone signature is present, but residual contamination from hadron decays may still be affecting the result, despite our efforts to mitigate this in the analysis. One observation that could support the presence of the Dead Cone is an expected shift of the suppression region to larger angles (leftward in the plots) as quark energy decreases. The observed suppression appears to shift as expected when comparing plots C and B in figure 5.

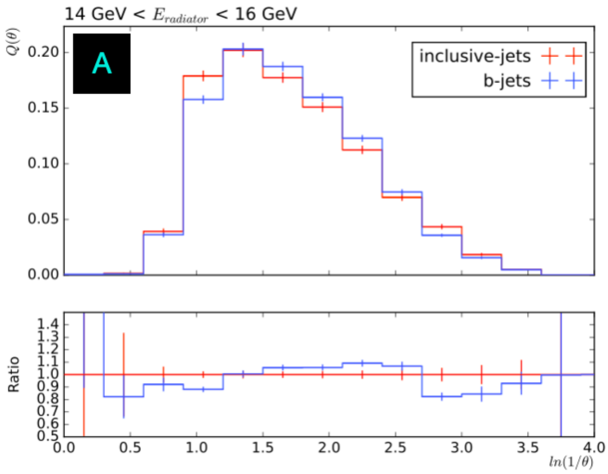

Figure 4: An example slice of the LPJ.

$$Q = \frac{dn_{jets}}{(N_{jets})(dln(\theta))} \tag{2}$$

$jets$ {b-jets or light-quark jets}.

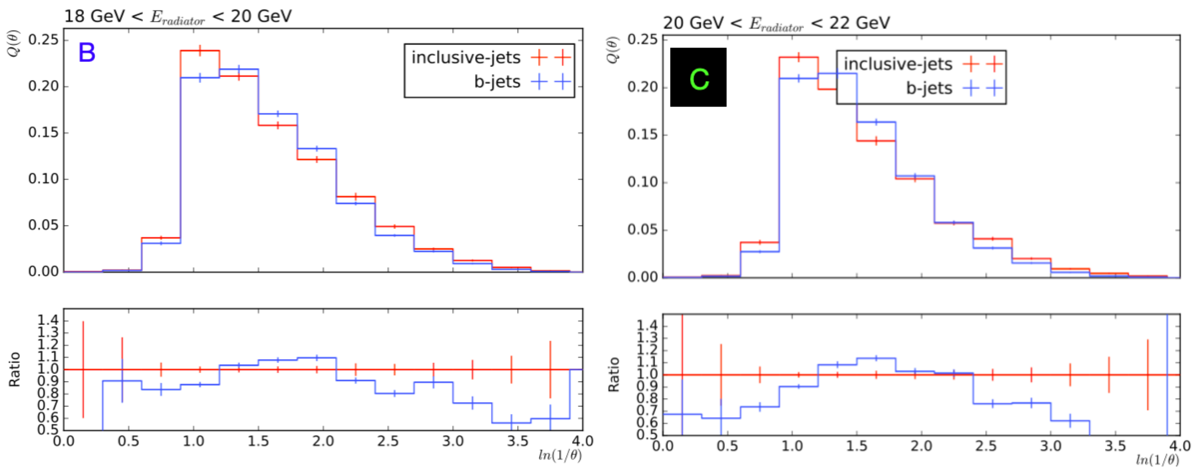

Figure 5: Example slices of the LPJ in different energy bins.

4 Conclusions

We used the Lund Jet Plane to study the Dead Cone effect in b-tagged jets. Signs of a suppression were observed, but contamination from hadron decays may still be present. We believe that imposing a stronger k_T threshold on emissions may further reduce contamination from these decays and better isolate the effect. Additionally, applying a jet grooming technique known as Soft Drop [9] may suppress contributions from pile-up and UE.

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