Searching for the dead cone effects with iterative declustering of heavy-flavor jets

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We present a new method to expose the dead cone effect at colliders using iterative declustering techniques. Iterative declustering allows to unwind the jet clustering and to access the subjets or branches at different depths of the jet tree. Our method consists on declustering the heavy flavour-tagged jet using Cambridge-Achen algorithm following the branch containing the heavy flavour at each step and registering the kinematics of the complementary untaged prong. The kinematics of the complementary untaged prong fill a Lund map representing the gluon radiation off the heavy flavour quark at each step of the vacuum shower.

Using Pythia8 MC, we show that a simple cut on the Lund plane introduced by \( \log(k_T) > 0 \), suppresses hadronisation effects and the angular separation between the jet prongs becomes very sensitive to flavour effects. A clear suppression for heavy flavour jets relative to inclusive jets in the region of splitting angles delimited by the relation \( \theta < m_Q/E \) is observed, where \( m_Q \) is the mass of the heavy quark and \( E \) is the energy of the radiator or splitting prong.

I. INTRODUCTION

The dead cone effect is a fundamental prediction of QCD (and gauge theories in general) according to which the radiation from a charged particle of mass \( m \) and energy \( E \) is suppressed at angular scales given by \( m/E \) [1].

To experimentally uncover the dead cone is a difficult task. The decays of the heavy flavor particles happen at similar angular scales and fill the deadcone. The irresolution of the axis chosen as proxy for the heavy flavor direction can also obscure its measurement. In [2] the first direct measurement in \( e^+e^- \) collisions of the depletion of fragmentation particles not coming from the heavy flavor decay vertex in heavy-flavor tagged jets was presented. The main limiting element was the choice of the reference axis, which was estimated using the thrust direction, the jet axis and the vertex direction.

Recently new ideas were proposed to measure the dead cone using Soft Drop grooming techniques and boosted top quarks at the Large Hadron Collider [3].

In this paper we discuss the use of new iterative declustering techniques [4, 5] that allow to penetrate the jet shower and access the deepest levels of the clustering history which correspond to the splittings at the smallest angles. This may allow to unveil the dead cone even for low mass heavy flavors such as charm and beauty, provided they can be fully reconstructed in the experiment and that the angular resolution of the detector is good enough to separate subjets at distances of order 0.1 radians, which is typically the case with a tracking device.

II. ITERATIVE DECLUSTERING OF HEAVY FLAVOR-TAGGED JETS

We have generated Pythia 8.226 Tune 4C [6] hard events leading to charm and beauty quark-initiated jets and we have inhibited the decay of the D and B mesons. We reconstruct the jets with anti-\( k_T \) algorithm [7] and tag the jets when a D\(^0\) or B\(^0\) meson is found as one of its constituents.

The tagged jets are then declustered using the Cambridge/Aachen (C/A) algorithm [8]. Since the C/A metric is such that particles at small angles are combined first, the first steps of the declustering process find the prongs at the largest relative angles.

When moving backwards through the jet history, we always follow the branch containing the heavy flavor and we register the relative transverse momentum \( k_T \) and angle \( \theta \) of the complementary untaged prong onto the Lund map. The cases where the heavy-flavor tagged prong is not the hardest are of the order of 1% and 0.001% in the explored kinematic regime for c and b-jets respectively and their exclusion from the Lund map has no quantitative impact on the results, so there are no ambiguities in the comparison to the inclusive jets, in which case we follow the hardest prong.

Figure 1 left column, shows the Lund maps for b and c-tagged jets together with inclusive jets, at parton level. The \( y \) and \( x \) axes are \( \log(k_T) \) and \( \log(1/\theta) \) respectively. The 2D maps are normalized to the total number of entries, so they represent a splitting density. The underlying event was switched off.

Already visually, without further analysis, one can note that the small angle region is less filled for heavy quarks jets than for inclusive jets.
The Lund diagrams for charm and beauty and inclusive jets at parton level and UE switched off, for low momentum jets of $10 < p_T \text{jet} < 40$. Right column: Same plots but at hadron level.

Figure 1 right column shows the Lund maps for b and c-tagged jets together with inclusive jets at hadron level. The hadronisation effects pollute the low $\log(k_T)$ part of the diagram, which corresponds to non-perturbative scales. The UE pollutes the large-angle sector, where catchment area is maximal. In order to suppress non-perturbative effects a simple cut on the splitting scale is possible: $\log(k_T) > 0$, which selects splittings governed by scales of at least 1 GeV/c.
III. THE DEAD CONE

A different representation of the Lund diagram which exposes the dead cone effect more clearly is that where the horizontal axis corresponds to the energy of the radiating daughter prong and the vertical axis corresponds to the splitting angle $\theta$. We construct this 2D map and we consider the relative difference between heavy quark-tagged jets and inclusive jets as a way to study the relative enhancement/suppression in the different areas of interest:

$$Q = \frac{P^Q(\log(1/\theta), E_{radiator}) - P^{inc}(\log(1/\theta), E_{radiator})}{P^{inc}(\log(1/\theta), E_{radiator})}$$

(1)

where $P(\log(1/\theta), E_{radiator})$ represents the probability for a a radiator prong with energy $E_{radiator}$ to split with an aperture angle $\theta$. This is illustrated in Figure 2a. The cut $\log(k_T) > 0$ translates into $E_{radiator} > 1/(z\theta)$, where $z$ is the energy fraction carried by the daughter prong. The kinematic limit $z = 0.5$ imposes the sharp threshold in the curve above which there are no entries in the inclusive reference.

One can clearly see a region of the phase space where $Q$ becomes negative, indicating a suppression of the splittings for the heavy quarks compared to inclusive jets, both for c (left) and b jets (right). The angular suppression is coupled to a suppression of the high $z$ splittings.

The region of angles smaller than $\theta < \theta_C = m_Q/E$, corresponds to the area above the red curve. We note that the parametrical dead cone red line qualitatively coincides with the curve where $Q_{heavty}$ becomes $\sim 1$, when radiation of the heavy flavor prong is completely suppressed, though the relation is not exact. In the case of charm, the dead cone line is above the kinematic threshold for the given $k_T$ selection. More agressive cuts on the scale $k_T$ select more large angle radiation and reduce the range of observation of the dead cone related suppression.

At hadron level the effects are not washed out. A suppression of significant magnitude at angles smaller than the critical angle at all radiator energies for b and c jets is observed, see Figure 2b.

In Figure 2c we show the impact of considering a looser cut $\log(k_T) > -2$. Non-perturbative effects fill the dead cone and obscure the effect of the suppression of the radiation. In Figure 3 we show our proposed observable, which is the projection onto the vertical axis of the diagrams shown in Fig. 2b, for a range of low radiator energies, for instance $20 < E_{radiator} < 50$ GeV. The observable, denoted as $Q_0$, corresponds to the relative difference between the angular distribution of the splittings for heavy flavor jets and inclusive jets, at perturbative scales set by $\log(k_T) > 0$ and for low radiator energies for which the dead cone effects are maximal:

$$Q_0 = \frac{P^Q(1/\theta) - P^{inc}(1/\theta)}{P^{inc}(1/\theta)}, E_{radiator} \in (E_{min}, E_{max})$$

(2)

The suppression of the low angle emission probability for b-tagged radiators relative to inclusive ones is of order 80% at $\log(1/\theta) = 2$, which approximately corresponds 0.14 radians. The corresponding suppression for c-tagged radiators is of order 20%.

The ideal experiment would be able to fully reconstruct the heavy flavor hadrons and to tag prongs of very low momentum, and to separate subjets at angular scales of 0.1 and below.

We note that the inclusive jets are not the best reference since they are a mixture of $q \rightarrow gg$ and $q \rightarrow qg$ radiation with different fractions. The $g \rightarrow gg$ fill the phase space in a different way compared to $q \rightarrow qg$. We have checked that the magnitude of the suppression of $Q_0$ increases when light quark jets are considered as a reference instead of inclusive jets, see Fig. 4. Experimentally it is possible to enrich the quark fraction by using boson-jet correlations for instance. Or by statistically cutting on observables that are sensitive to differences between quark and gluon fragmentation such as the $p_T D$ or the jet angularity.

We have also tested that switching on/off the gluon splitting kernel $g \rightarrow qqbar$ has no impact on the results.

As a final remark we note that our method was tested only against Pythia8 and thus the exact magnitude of the dead-cone related effects and their onset rely on the specific Pythia8 implementation, which is done via matrix element corrections. However, parton shower generators feature the dead cone effect quite universally with better than 10% agreement wit NLO calculations [3].

IV. CONCLUSIONS

We have shown that iterative declustering is a tool that allows to access the deepest branches of the C/A jet trees which correspond to the smallest splitting angles and that can uncover quark mass differences related to the dead cone. We propose to build the Lund map for low $p_T$ jets tagged with a fully reconstructed heavy flavor hadron. Furthermore, we propose to expose the perturbative splittings within the shower with a selection of $\log(k_T) > 0$ and
Relative ratio to gluons and light flavor quarks

FIG. 2: Relative difference for heavy flavor and inclusive jets of the correlation of the splitting angle and the energy of the radiator. The red curves correspond to the critical angle \( \theta_C = m_Q / E \).

(a) Parton level c-jets (left) and b-jets (right).

(b) Hadron level c-jets (left) and b-jets (right).

(c) Hadron level with a relaxed cut on \( k_T \) - demonstration of the impact of non-perturbative effects
study the angular effects due to the deadcone at low radiator energies integrating over all declustering steps. At angles of order 0.1 radians, the Pythia8 simulations predict a suppression of approximately 20/80% for jets containing a fully reconstructed D/B meson relative to inclusive jets, for radiator energies above 20 GeV.
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