Performance Studies on Beauty and Charm Jets

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1 Introduction

The Standard Model of particle physics (SM) [1] describes how elementary particles interact with each other. One crucial aspect of understanding the SM from an experimental perspective involves the identification and classification of particles with different flavours. Heavy flavour (HF) quarks are characterised to have larger masses resulting in them playing a pivotal role in unraveling the mysteries of the subatomic world and enhancing our comprehension of the SM of particle physics in particular Quantum Chromodynamics (QCD) [2] which describes the strong interaction.

The SM is a theoretical model, constructed from observations [3] which includes hard scattering events. Hard scattering refers to a fundamental process that occurs during particle collisions at high energies. It involves the interaction between two high-energy particles, typically protons or other particles, where the constituents of these particles (quarks and gluons) collide with significant momentum transfer. The quarks and gluons from the hard scattering initiate a partonic shower in which many different types of particles are emitted in various directions. The resulting spray of collimated particles produced in a partonic shower is called a jet. Jets are reconstructed using a specific algorithm and resolution parameter as an input. The jet reconstruction algorithms were created as a strategy to better collect and analyse the vast amount of particles observed. Jet themselves are constructed using a specific algorithm and resolution parameter as an input. They are cone-like structures which collect the hadrons produced when quarks fragment and hadronise as seen in Figure 1. HF jets are characterised to be initiated by heavy quarks such as beauty or charm quark.

HF-jet tagging is a powerful technique employed by A Large Ion Collider Experiment(ALICE) [4] experiments to discern and isolate HF jets amidst the myriad of other particles produced during collisions. The ALICE experiment is specifically designed to study a state of matter known as the quark-gluon plasma, which is believed to have existed in the early universe [5]. The quark-gluon plasma is a state of matter where quarks and gluons, which are typically confined within particles like protons and neutrons, become deconfined due to the extremely high energy densities [4]. HF-jet tagging is an indispensable tool enabling ALICE to study the properties and behaviors of these elusive particles and providing a deeper understanding of fundamental interactions. There a number of reasons as to why HF-jet tagging is important, one of them being that, HF processes provide an important testing ground for QCD. It allows us to gain more insight in the differences between quark and gluon showers, as jets originating from a quark or gluon will have a different parton showering pattern. By using HF-jet tagging we can isolate a high purity of quark-initiated showers. It also supports the study of

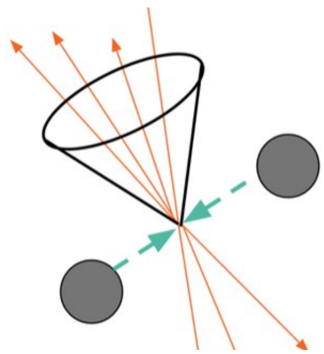

Figure 1: Schematic diagram of a collision between two highly-energetic particles with a jet collecting the emitted particles.

the production, showering and hadronization mechanisms of heavy quarks in different environments, either in proton-proton (pp) or heavy-ion collisions.

The incentive for tagging these jets is that the ALICE experiment will be able differentiate if a jet originates from a gluon or quark which is usually difficult due to low branching fractions, low reconstruction efficiency and low purity. In the next sections I will be expanding on the aim of the project and the tasks that I carried out, followed by some results that were obtained.

2 Methodology

The aim of the project was to develop HF-jet tagging in ALICE. HF-jet tagging in the ALICE experiment involves identifying jets that originate from the hadronization of HF quarks, specifically charm and beauty quarks, as previously mentioned. These HF jets are crucial for studying the properties of heavy quarks and their interactions with the quark-gluon plasma produced in high-energy heavy-ion collisions. Majority of the work has been developing a Monte Carlo (MC) matching criteria for detector and particle-level HF-jet tagging in O2 [6] framework. These developments are a good starting point for Run 3 analyses and ALICE 3 projections. The two methods used in HF-jet tagging include: secondary vertex reconstruction and particle identification. Secondary vertex reconstruction is usually done by reconstructing the HF hadron and its displaced secondary vertex. Since they have longer lifetimes they will have displaced vertices as seen in Figure 2, making them easier to tag. Reconstructing the HF hadron is an ineffective method due to low reconstruction efficiency and in the project we plan to tag the HF jets by identifying the displaced secondary vertex. Particle identification searches for specific particles that are known to decay from a B hadron but this is also an ineffective strategy as a result of low branching ratios.

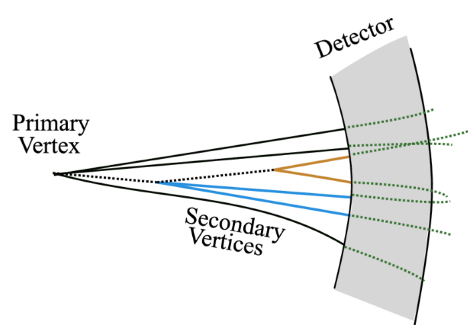

Figure 2: Diagram showing the primary vertex where the hard scattering of two protons or heavy-ions takes place and the secondary vertex is a result of the longer lifetime of HF hadrons. They travel a small distance before they decay into other particles

Jets were reconstructed using tracks from charged particles with transverse momenta (p_{T}), from 0.15

GeV/c to 1000 GeV/c, reconstructed in the central tracking detectors within the pseudorapidity range $|\eta| < 0.9$ and φ range of 0 to 2π. The jets were assembled using the anti-k_t algorithm [7] with $R = 0.4$. Using the tracks, we worked backwards to find the particle associated with the track then proceeded to investigate if the mother is a beauty hadron. The reason for doing is, when we run on simulated data samples it allows us to assess the tagging performance. The logic behind this approach is that beauty quarks will fragment and hadronise into different variations of B hadrons, so if the mother is either a B meson or B baryon there is a chance the jet originated from a beauty quark. Beauty quarks can come from the hard-scattered subprocess, subsequent subprocess, initial state radiation (ISR), beam remnants or gluon splitting. This meant that we needed to, not only, identify the first mother but also check the PDG code [8] and the status code of the mother [9]. The PDG code would assist in isolating only the B hadrons and the status code would ensure that we only work with beauty quarks from the hard-scattered subprocess, subsequent subprocess, ISR, beam remnants.

We employed two requirements for detector-level HF-jet tagging. Firstly, once we found the associated particle from the track, we isolated particles from the hard-scattered subprocess, subsequent subprocess, ISR, beam remnants using the relevant status code: 23, 33, 43 and 63. Secondly, what I was specifically tasked to do was, from the isolated events I further required them to have a specific PDG code which corresponds to B mesons and B baryons. We then proceeded to run our code through beauty-enriched simulated data for Run 3, then I plotted a series of histograms using ROOT to gain a better understanding of the kinematic properties of the mother particle and the resulting jet.

3 Results

I ran the HF-tagger task through beauty-enriched simulated data for Run 3 pp collisions, with a jet p_T min cut of 10 GeV/c. I proceeded to plotted a series of histograms as previously mentioned. In the first histogram Figure 3, the entries in this plot are b-jets and it shows the various status codes of their mothers. Close to half of the b-jets that were tagged originated from outgoing particles produced by final-state-showers produced by parton branching (51). This is unexpected as beauty-enriched simulated data was used. The different status codes and their descriptions can be found in Ref. [9].

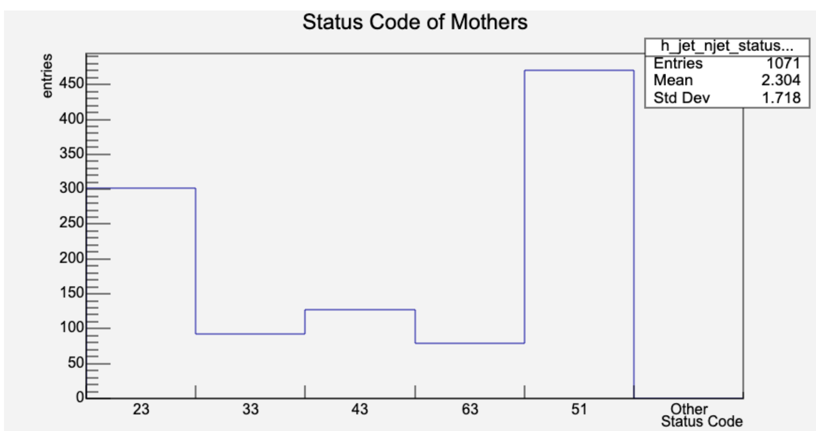

Figure 3: Histogram showing the varies status codes of the mothers. The value 23 represents beauty jets whose mothers is an outgoing particle of the hardest subprocess, 43 are outgoing mothers produced by initial-state-showers through branching, 33 are outgoing mothers of subsequent subprocesses, 63 are outgoing mothers produced by beam-remnant treatment and lastly 51 are outgoing mothers produced by final-state showers produced by parton branching

In Figure 4, the histograms show the number of jets and b-jets in each collision. When comparing the plots, both peak at 0, this means that in each collision there are mostly no b-jets and jets. In Figure 5, the histograms show the transverse momentum, p_T of jets and b-jets with a cut applied of 10 GeV. When comparing the plots, both exhibit a similar trend with a peak at 10 GeV followed by a steeply falling spectrum. Figure 6, displays the ratio of the p_T of the jet and the p_T of mother. This plot allows us to understand and analyse how much of the p_T was reconstructed. The plot peaks between

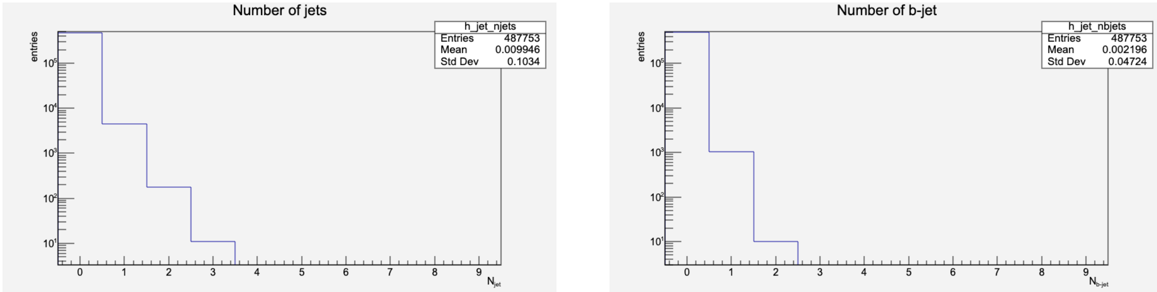

Figure 4: The histogram (a) on the left corresponds to the number of jets in each collision. The entries in this plot corresponds to the number of collisions. Histogram (b) on the right displays the number of b-jets in each collision

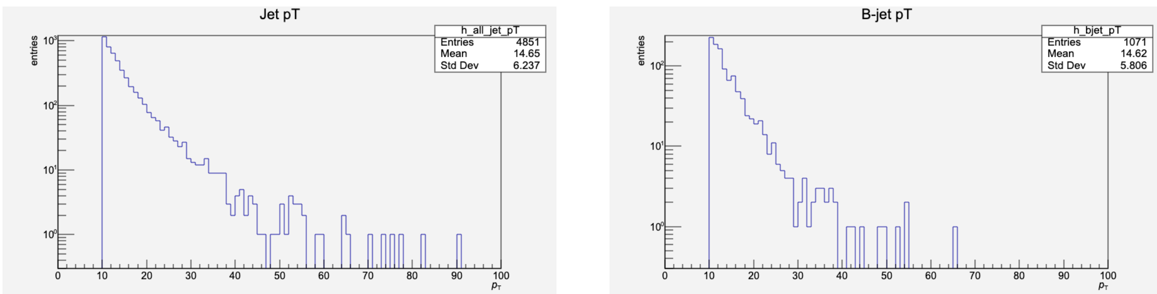

Figure 5: The histogram (a) on the left corresponds to the transverse momentum of all jets. Histogram (b) on the right also depicts the transverse momentum but of only b-jets.

0 and 1, followed by a steeply falling spectrum. For jets reconstructed from tracks it is expected to reconstruct about 2/3 of the initial parton momentum because most of the tracks are charged pions, and all pions are produced with the same probability.

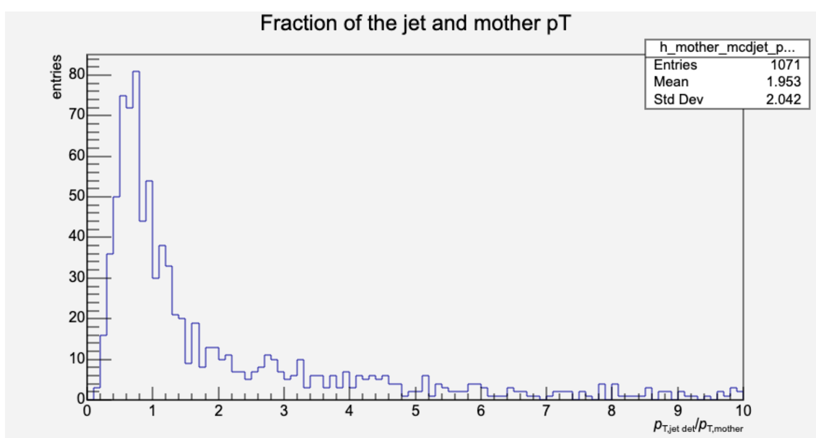

Figure 6: Histogram displaying the fraction between the p_{T} of the jet and the p_{T} of mother.

In Figure 7, we plotted the absolute value of the difference between the p_{T} of the jet and mother divided by the p_{T} of the jet. The distribution peaks at around 1, as we are working with charged jets. In Figure 8, we plotted the absolute value of the difference between the η of the jet and the η of the mother. The distribution peaks at the value of 0.5, followed by a tail of values that extend to the value of 8.5. This was an unexpected, as we expected the η values to correspond to smaller values. In Figure 9, we plotted the absolute value of the difference between the φ of the jet and the φ of mother. The distribution peaks at 0 followed by a tail of values.

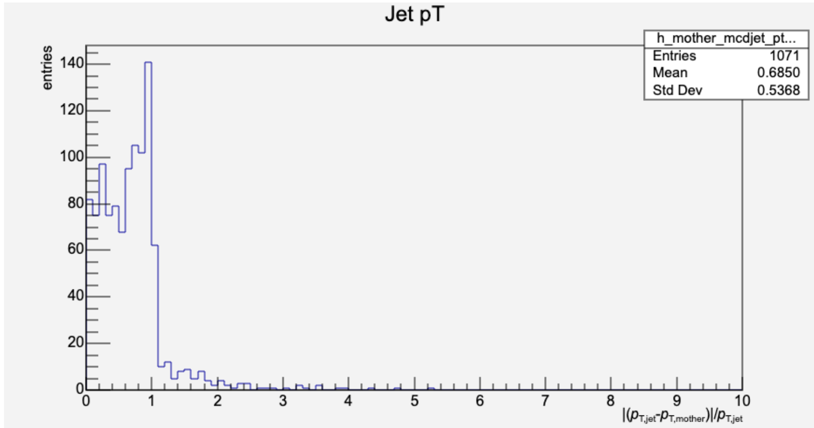

Figure 7: Histogram displaying the absolute value of the difference between the p_{T} of the jet and mother divided by the p_{T} of the jet.

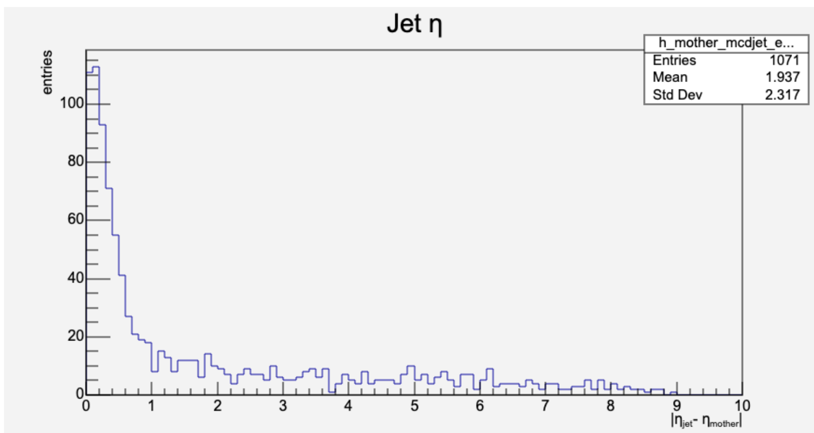

Figure 8: Histogram displaying the absolute value of the difference between the η of the jet and the η of the mother.

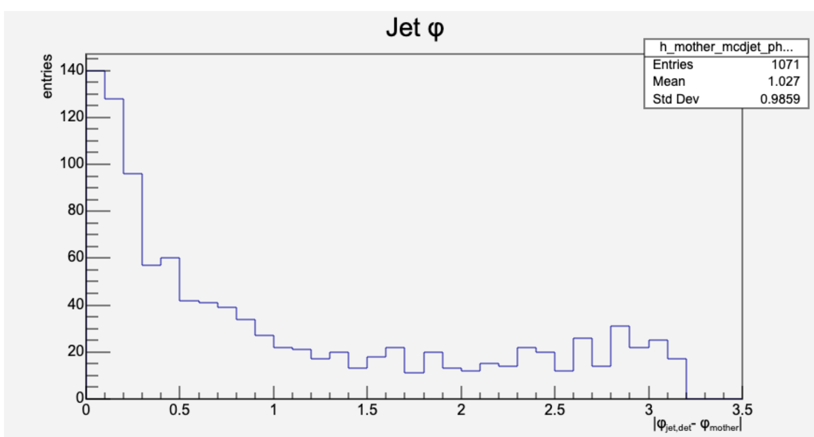

Figure 9: Histogram displaying the absolute value of the difference between the φ of the jet and the φ of the mother

4 Conclusion and prospects

The aim of the project was to work on HF-jet tagging for ALICE for Run 3 analyses and ALICE 3 projections. The project was motivated by the difficulty of differentiating between a gluon and quark-initiated jet due to low branching fractions and low efficiency. In a broader aspect, HF-jet tagging will also assist in studying the production, showering and hadronization mechanisms of heavy quarks in different environments, such as proton-proton or heavy-ion collisions. What I have achieved thus far is working on the first steps in developing a MC criteria for detector level HF-jet tagging in O2 for b-jets. In the results that were obtained there were a few unexpected trends, related to the kinematics properties such as the difference in η and why some of the mothers were outgoing particles produced by final-state showers produced by parton branching. This is unexpected based on the simulated data was used. The next steps in this project would be developing a better understanding of the results obtained and modifying the HF-jet tagging task accordingly and extending the MC matching criteria to charm jets.

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