LIP-STUDENTS-20-16

B-jet interaction with the quark gluon plasma in Pb+Pb collisions with the ATLAS detector

Vicente Mendes[1,a]

[1] *Instituto Superior Técnico, Lisboa, Portugal*

Project supervisor: H. Santos

October 2020

Abstract. A study on the effects of the Quark Gluon Plasma (QGP) on b-jets formed in Pb+Pb collisions, compared with light (u, d, s) jets. The analysis was performed using data samples from Run 2 of the LHC recorded by the ATLAS detector, in 2018. The ATLAS detector and the theoretical predictions are briefly discussed. The strategies adopted to suppress background events are presented. The two observables studied were *Di-Jet Asymmetry* and R_{CP}. We show that the results suggest that b-jets interact less with the QGP than light jets. The shortfalls of the methods used are discussed, as well as the potential for new results in Run 3 of the LHC.

KEYWORDS: LHC, QGP, b-jets

1 Introduction

1.1 The ATLAS detector

ATLAS is a detector of the Large Hadron Collider (LHC), in CERN. It is the largest detector in volume and has a cylindrical shape (Figure 1). The detector is multi-layered and consists of six different detecting subsystems wrapped concentrically, recording the trajectory, energy and momentum of particles. The detector's large volume and symmetry make it ideal for the study of heavy ion collisions. A full description can be found in [1].

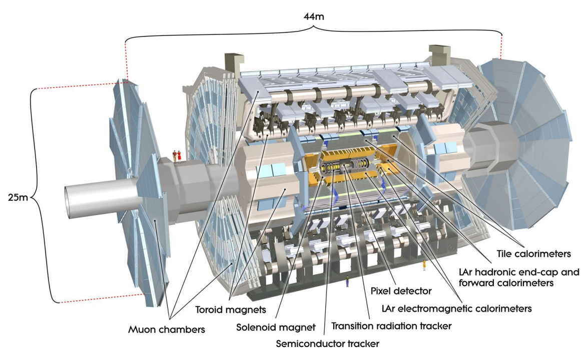

Figure 1. The ATLAS detector

1.2 Heavy Ion Collisions and the Quark Gluon Plasma

A few millionths of a second after the Big Bang, the universe was an extremely energy dense "soup" which we call the Quark Gluon Plasma (QGP). The energy density in the plasma is so high that the quarks are extremely close. The strong force, described by Quantum Chromodynamics (QCD), and that keeps quarks together, has little effect - we say that the quarks and gluons are "free" from confinement. The way these conditions are achieved in the lab, in a controlled environment, is by colliding heavy ions like lead, which contains 208 nucleons. By analysing data from these collisions, we can therefore infer properties of the QGP. (A full description of the heavy ion program can be found in [2]).

1.3 Jets as the "golden probes" of the QGP; Heavy-flavour jets

The so-called "golden probes" of the QGP are the jets formed in the collisions, as their interaction with the QGP generally makes them lose energy. Therefore, we can interpret the variables measured by the detector to understand what happened after the collision. In this study b-tagging was used to study specifically the effects of the QGP on b-jets, formed by the heavy quark bottom, which are expected to be less interacting [3].

1.4 Collision centrality, $FCal - E_T$ and the QGP

Two ions may collide in a multitude of ways. For instance, they may collide centrally, "head on", which means that most of their nucleons will be involved in collisions. On the other hand, they might collide more peripherally, in which case fewer nucleons collide and the others may continue unscathed. Collision centrality is therefore an important predictor of QGP formation, as the energy density will be higher the more central a collision is and thus the formation of the QGP is more likely to happen. Collision centrality can be estimated by the energy deposited by the particles in the ATLAS's forward calorimeters - $FCal{-}E_T$. As seen below in figure 2, the bigger $FCal - E_T$ is the more central the collision. We can also observe that peripheral collisions are more likely to happen then central collisions, which goes accordingly with the geometry of the collisions.

[a]e-mail: vicente.mendes@tecnico.ulisboa.pt

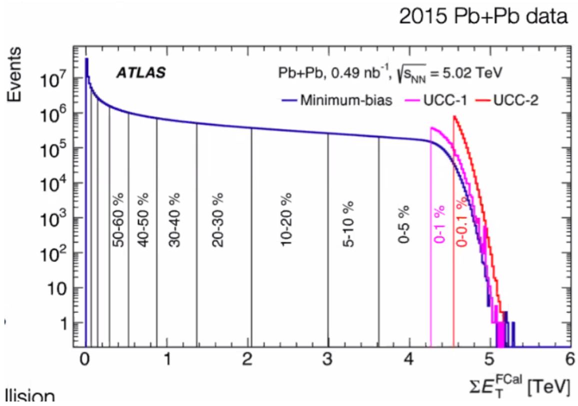

Figure 2. Collision centrality from $FCal - E_T$ [4]

2 Sample Preparation

A sample from the 2015 Pb+Pb collisions data was prepared prior to this study. Only events with at least two jets were selected. From these, only the kinematic variables from the two jets with higher transverse momentum p_T were selected, being the "Leading" and "sub-leading" jets, as well as the $FCal - E_T$ from each of these events. The variable $\Delta\phi$, the difference in ϕ between the two leading jets, was computed, and only events with $\Delta\phi$ above $\pi/2$ remained in the sample, thus requiring jets in opposing hemispheres. The initial state of the sample in the beginning of this study can be visualized in Figure 3.

2.1 Relevant variables

Here we present a list of the main variables which can be measured with the detector and are used in this analysis.

- p_T : transverse momentum;
- $\eta = -\ln(\tan\theta/2)$: pseudorapidity;
- ϕ : angle of the trajectory of the object in the plane transverse to the direction of the proton beams;
- $FCal - E_T$: transverse energy deposited at the forward calorimeters;

3 Background suppression strategy

From the initial sample, several cuts were employed to eliminate as much fake jets as possible.

Transverse Momentum, p_T, cuts

Both leading jet p_T and sub-leading jet p_T were cut in order to eliminate fake jets, most probably originating in fluctuations of the underlying event and secondaries produced in passive material of the detector. This latter fake jet production is associated with the clear spikes in the initial η graph, and one can confirm that hypothesis by observing the η graph after the p_T cuts, in Figure 4, where the spikes are clearly reduced after a 50 GeV cut to sub-leading jet p_T. From here on now, all the analysis are performed with a 50GeV cut to sub-leading jet p_T and a 100 GeV cut to Leading jet p_T.

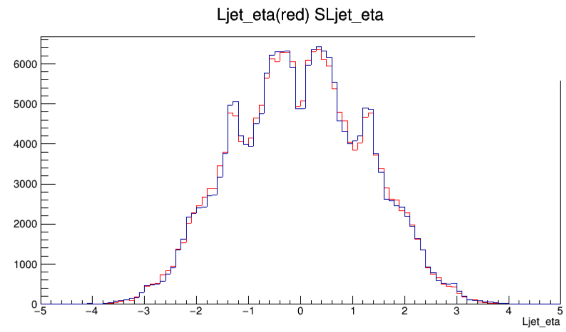

Figure 4. η after p_T cut

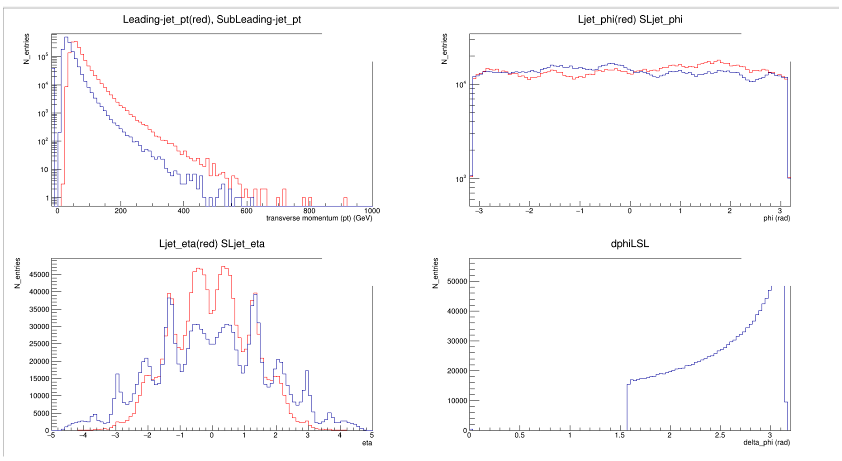

Figure 3. Sample used - all variables uncut

$\Delta\phi$ and η cuts

The $\Delta\phi$ variable was further cut in values closer to π in order to increase the number of clear back-to-back events. The exact value used was 2.1 radians. Furthermore, the absolute value of η was required to be less then 2.8 units to guarantee the jets were in a well understood region of the detector.

4 Di-Jet Asymmetry Analysis

The Di-Jet Asymmetry observable is based on the simple idea that, of the two jets produced in the collision, generally one will have to cross more plasma than the other, thus interacting more with it, and consequently losing more energy [5]. That jet should then be the sub-leading jet. Concretely, we will define asymmetry in this study as:

$$A = \frac{LJetp_T - SLJetp_T}{LJetp_T + SLJetp_T} \tag{1}$$

This way, the bigger the asymmetry, the bigger the difference between leading and sub-leading jets. Therefore, we expect higher values of asymmetry in collisions where the QGP is formed.

4.1 General Case

Using $FCal - E_T$ to separate collisions by centrality [6], one can observe the way the asymmetry changes with centrality.

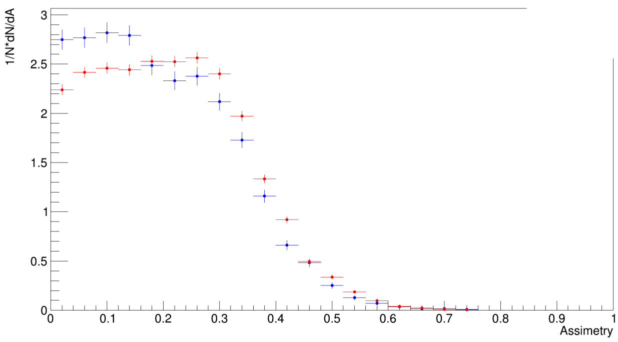

Figure 5. Asymmetry by centrality (red - central (0-10%), blue - peripheral (40-80%)

Here we can verify that central collisions have indeed a higher transverse momentum asymmetry. Therefore, we confirm that the QGP, most likely formed in central collisions, does interact with jets making them lose energy and momentum.

4.2 b-jets asymmetry

After verifying the asymmetry for inclusive jet flavour, we used b-tagging algorithms [7] to select b-jets and check if, as predicted theoretically [3], they were less interactive with the QGP. This would lead to the observation of a lower difference in asymmetry when comparing central and peripheral collisions between b-jets and light jets*[1].

Firstly, a thorough look on the results of two different b-tagging algorithms [7] (mv2c10 and dl1) was taken, in order to correctly choose the best values for the b-tagging cuts. Both algorithms had similar results, which increases our confidence in the accuracy of the b-tagging.

As asymmetry results from the difference between leading and sub-leading jets in the same collision event, both leading and sub-leading jets had to be required to be b-jets in order to observe any meaningful result. Therefore, a b-tagging cut was performed on both leading and sub-leading jets, separately. However, events with both b-jets are only 0.7% ([8]) of the inclusive jet sample, which renders the statistic too small. To increase the statistic, the transverse momentum cuts were lowered ($SLJetp_T < 40GeV$ and $LJetp_T < 75GeV$). Furthermore, the ideal events for this study are back-to-back b-jets which led us to increase the $\Delta\phi$ cut to 2.8 radians.

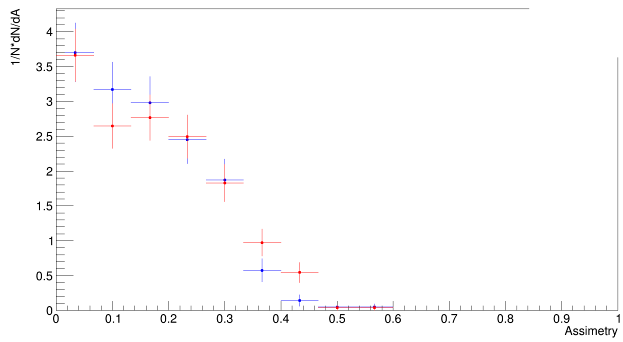

Figure 6. b-jet asymmetry by centrality (red - central (0-10%), blue - peripheral (40-80%)

There appears to be less difference in the asymmetry of b-jets. The central collisions red line does not have the same flattened aspect at the beginning, as there are relatively more symmetric events. Finally, both central and peripheral collisions have lower values of asymmetry (the normalized value of the first bin is bewteen 3.5 and 4, whereas in 5 the value was between 2.5 and 3). However, with only about 300 entries, the statistic was still too small to make any meaningful conclusions, which is the perfect motivation to move on to the next observable: the R_{CP}, which allows a similar analysis while using considerably more statistic, which is explained further in the following section.

5 R_{CP} Analysis

R_{CP} presents, in principle, a good solution to the problem of low statistic. It is defined as([9]):

$$R_{CP}(p_T) = \frac{1}{R_{Coll}^{cent}}\left(\frac{\frac{N_{jet}^{cent}(p_T)}{N_{evt}^{cent}}}{\frac{N_{jet}^{60-80}(p_T)}{N_{evt}^{60-80}}}\right) \tag{2}$$

[1]The presented analysis consider "light" as u-, d-, s-, and c-jets

This is the ratio between two histograms: the histogram with jets produced in a given centrality range divided by the histogram with jets produced in peripheral collisions, here defined as the 60–80% centrality interval (Figure 1). In this ratio we can include b-jets from events that had only one b-jet formed, thus increasing the amount of statistic to about 7% of the total sample. The numerator is the sample of jets produced in 0–10% centrality range.

As for the meaning of the numerical result, the lower the R_{CP} value, the more energy was lost in central collisions - the more the QGP had an impact. This way, we can compare the R_{CP} of b-jets and the R_{CP} of light jets in the same graph (Figure 7).

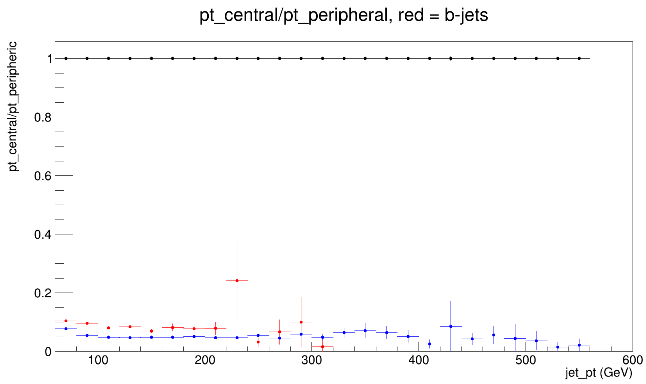

Figure 7. division of centralp_T over peripheralp_T of b-jets (red) vs light jets (blue)

There is plenty to take from this graph. To begin with, we can observe that both lines are essentially flat, meaning that the R_{CP} does not vary with respect to transverse momentum. Secondly, the results suggest that the R_{CP} for b-jets in red is higher than for light jets in blue, which would mean less energy was lost by b-jets. However, we reiterate that correct pT spectra for detector effects is needed before drawing conclusions. Finally, the numerical values of the R_{CP} are quite considerably lower than previously obtained ones in the literature [10]. This is most likely the result of the bias introduced in the sample when only events with at least two jets were taken, and from those only the information regarding the two leading jets. However, since we are concerned with the comparison between b-jets and light jets the comparison is still valid as the bias affects both equally, most likely. Still, the same analysis should be performed on a less biased sample to increase confidence in the result.

Besides, the R_{CP} for b-jets, in red, stops at about 300 GeV and starts having high uncertainties at about 220 GeV. Therefore, there is still a whole range of GeV to discover in what concerns b-jets R_{CP}, in order to see if the comparison keeps up for higher values of transverse momentum. Once again, more statistic would be of great value here.

In figures 5, 6 and 7, the vertical bars on the points represent the statistical uncertainties, while the horizontal bars stand for bin width. In figure 7, a 100% correlated error associated with RColl is not included in the error bars, and is included on the flat black line at the top.

6 Conclusions and Next Steps

From the limited amount of data available from Run 2, results suggest that b-jets interact less with the QGP than light-jets. Following this study, it would be of interest to make the same analysis with a more broad and less biased sample from Run 2. It will also be of interest to look at both asymmetry and R_{CP} with Run 3 data, to have more accuracy and to reach higher transverse momentum values in the R_{CP} analysis.

Acknowledgements

Thanks Prof. Helena Santos for the patience to answer all my questions during the summer internship and LIP for the opportunity to do this kind of research!

References

[1] T.A.C. et al, JINST 3 S08003 (2008)

[2] H.S. behalf of the ATLAS Collaboration, ATL-PHYS-PROC-2019-026 (2019)

[3] Y.L. Dokshitzer, Kharzeev, Phys. Lett. B519 (2001) 199-20 (2001)

[4] A. Collaboration, Eur. Phys. J. C 78 (2018) 997 (2018)

[5] J.D. Bjorken, FERMILAB-PUB-82-059-THY (1982)

[6] A. Collaboration, Phys.Lett. B707 (2012) 330-348 (2012)

[7] A. Collaboration, ATL-PHYS-PUB-2017-013 (2017)

[8] T.A. Collaboration, Eur. Phys. J. C (2013) 73:2301 (2012)

[9] T.A. Collaboration, CERN-PH-EP-2012-134 (2013)

[10] A. Collaboration, Phys. Rev. Lett. 114 (2015) 072302 (2015)