Bachelor Thesis

Separation of Hard and Soft Production in High Multiplicity pp Collisions using Transverse Spherocity

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Abstract

A big question at LHC is if the Quark-Gluon Plasma is produced in small systems such as pp and p-Pb collisions. A general problem in small systems is that possible medium effects are small and can be obscured by hard collisions such as jet production. In this project the goal is to use a new method, the Transverse Spherocity, to subdivide proton-proton events into soft and hard classes. The hope is that one in this way can select soft pp collisions where the medium effects are enhanced and the hard processes are suppressed.

Acknowledgments

First of all I want to thank my supervisor Peter Christiansen for giving me this opportunity. I am so very thankful for all the help, support and inspiration. A big thank you to all the wonderful people at the office; Martin Ljunggren, Vytautas Vislavicius, Jonatan Adolfsson, Madeleine Burheim, Adam Johansson, Rickard Lydahl and Adrian Nassirpour, for the help with everything from fixing the resolution on my screen to answer my questions about physics, and of course for an amazing time! A special thanks to Vytautas for helping me with the programming!

Contents

1 Introduction

In this thesis the goal is to see if it is possible to separate high multiplicity proton-proton (pp) events into soft and hard classes using the transverse spherocity method (a new method still under development) on LHC data from the ALICE experiment. With this one hopes to see some effects of the medium of Quark Gluon Plasma (QGP). The ALICE experiment is one of the detectors on the Large Hadron Collider (LHC) ring at CERN, a research laboratory situated on the border between Switzerland and France close to Geneva.

The main focus of the ALICE experiment is to study the physics of strongly interacting matter at high energy densities that gives rise to a phase of matter called the QGP [1]. The QGP is believed to have existed a few microseconds after the Big Bang, where the fundamental particles, quarks and gluons, were no longer confined inside hadrons due to the high energy density but were instead free to move inside the QGP [2].

Evidence for this phase of matter has been observed for Pb-Pb (lead-lead) and there are some indications that it is also formed in p-Pb (proton-lead) collisions, but not yet for pp (proton-proton) collisions. It is therefore of great interest to study high multiplicity pp collisions to see if the QGP is created in small systems as well. Experimentally, it is hard to study soft effects, i.e. the effects of a possible QGP, since there is a large hard "foreground". Therefore, the transverse spherocity method will be used in this project to hopefully be able to separate the collisions into hard and soft classes.

This thesis will start with some background theory about the fundamental particles, their interaction and some effects of this, in order to understand concepts that will be discussed later. The accelerator and detector used in the ALICE experiment will be described in section 4. Thereafter, a description of the method and the results for how the transverse spherocity method is tested and improved, and the data analysis method of the real data is given. The results and the discussion are presented in section 6 with a following conclusion and outlook in section 7.

2 Theory

2.1 The Standard Model

The Standard Model (SM) is a quantum field theory which explains the current knowledge of fundamental particles and forces and how they are related. The fundamental particles are first divided into two groups decided by their intrinsic spin; fermions and bosons, which hold a half-integer and integer spin, respectively. It is the fermions that are the building blocks of all known matter, whereas the interactions between the fermions are mediated by bosons.

There are four known fundamental forces; the gravitational, the electromagnetic, the weak and the strong force. All, but the gravitational force, are explained by the SM. When fermions interact they transfer four-momentum by the exchange of bosons. The mediating boson of the electromagnetic force is the photon, a electrically neutral and massless boson. The $W^{\pm}$ and Z^0 bosons are the massive force mediators for the weak interaction, where the W bosons carry electric charge and the Z bosons are electrically neutral. The force mediator for the strong force is the massless and color charged gluon. Since no force mediator has yet been discovered for the gravitational force and therefore is just a theoretical prediction, it is not included in the SM.

The fermions are further divided into two subgroups; quarks and leptons, where each group consists of six particles. Note that each quark and lepton also has an anti-particle partner. The lightest and most stable particles belong to the first generation whereas the heavier and more unstable particles make up the second and third generation seen in Fig. 1.

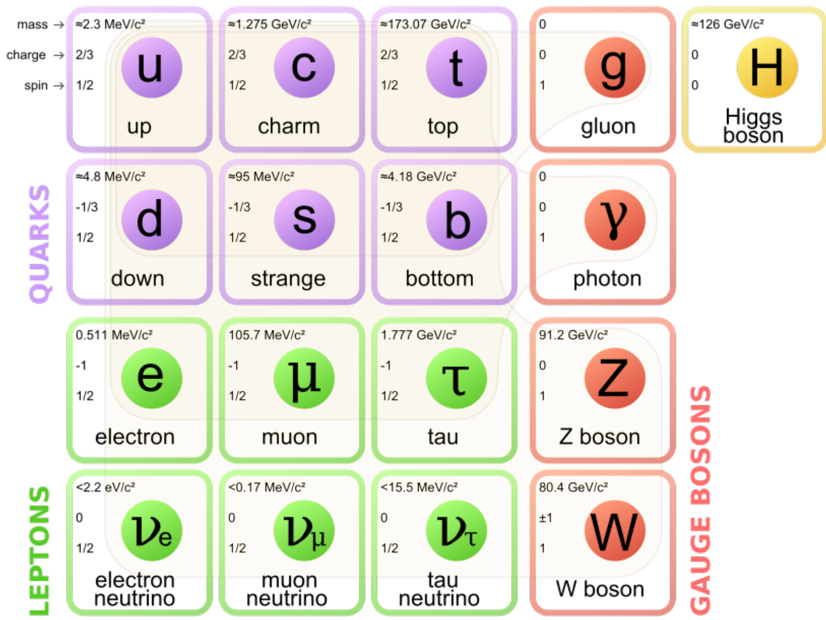

Figure 1: Schematic view of the SM. [3]

There are six different flavors of quarks: the up (u), down (d), charm (c), strange(s), top (t) and bottom (b) quarks, and all of these have both color and electric charge. It is the color charge that confines the quarks within color-neutral hadrons, meaning that they cannot be observed individually. Hadrons are particles made up of quarks and gluons. Those with a quark and an anti-quark are called mesons and hadrons with three quarks are called baryons.

The other group of fermions, the leptons, consists of the electron and the electron neutrino (first generation), the muon and the muon neutrino (second generation), and the tau and the tau neutrino (third generation), where the electron, muon and tau have electric charge and a sizeable mass. This is not the case for the three neutrinos that are electrically neutral and have a very small mass [4] [5].

2.2 Quantum Chromodynamics

The theory describing the strong force in the SM is called Quantum Chromodynamics (QCD). In Quantum Electrodynamics (QED), the photon works as the force mediator and couples to electric charge, while in QCD the gluon is the force mediator and couples to color charge.

Quarks carry color charge that can be either red, green or blue, while the color charge for anti-quarks can be anti-red, anti-green or anti-blue. Although gluons also carries color charge, they carry a color and an anti-color which allows them to self-interact. This self-interaction makes it possible for the gluons to emit and absorb gluon pairs that leads to an anti-screening of the original charge, meaning that the strong coupling constant increases at long ranges and the force remains constant there.

Due to what was previously mentioned there are two crucial properties of the QCD and the strong force, namely *confinement* and *asymptotic freedom*. Confinement means that one can not observe free color charged particles but they have to be confined inside color neutral hadrons. Asymptotic freedom means that the interacting force gets weaker when the distance between the quarks reaches 0.1 fm or less, which means that the quarks act as if they are free inside hadrons. The potential between two quarks is distance dependent and includes the running coupling constant, α_s, that characterizes the two properties confinement and asymptotic freedom. For confinement, $\alpha_s \sim 1$, and for asymptotic freedom, $\alpha_s \ll 1$.

The two and three quarks making up mesons and baryons respectively, are referred to as the valence quarks and carry the largest part of the hadron four-momentum. Also confined in hadrons are sea quarks, gluons and virtual quark-antiquark pairs carrying a smaller fraction of the hadron four-momentum [6] [7].

2.3 Quark Gluon Plasma

As mentioned before, quarks and gluons are confined within hadrons due to the color confinement. However, since the strong interaction weakens at short distances, a phase transition of matter can occur when the density or temperature increases. When the density or temperature of strongly interacting matter has increased to an order of 1 GeVfm^{-3}, a state forms where the quarks and gluons no longer will be able to identify their partners but are free to move inside a volume that is much larger than a hadron [4]. It is this state of matter that is called the Quark Gluon Plasma (QGP).

It is believed that a few microseconds after the Big Bang, when the universe was extremely hot and dense and therefore could not form hadrons, it was in a QGP state. For that reason, studying the structure and dynamics of the QGP provides a greater understanding of the evolution of the universe. Today it is possible to briefly create QGP by colliding heavy ions with large enough collision energy, e.g., at the LHC [4]. However, the QGP has not yet been observed in pp collisions, that according to Ref. [8] is due to that there are too few particles produced to fulfill the conditions for QGP.

3 High-Energy Collisions

3.1 Heavy-Ion Collisions

The reason for colliding heavy ions is to gain a better understanding of how nuclear matter behaves at high energies [7]. Ions that are stable and consist of many nucleons, such as gold and lead ions, are the most commonly used ions. Before the collision, the nuclei get Lorentz contracted due to relativistic effects, which only affect the shape of the nuclei in the directions of motion. The interacting nucleons in a collision are called participants and those nucleons that do not interact are called spectators. The dominating process of the participants is the inelastic nucleon-nucleon collisions, and these collisions can be classified as soft or hard interactions [9]. In a hard collision a large fraction of momentum is transferred by interacting partons, i.e., particles that are part of hadrons which gives rise to jets, highly energetic hadrons and heavy quarks [7]. In a soft collision, on the other hand, just a small fraction of momentum is transferred and it is the transfer of color that results in the formation of quarks, antiquarks and gluon pairs [10]. It is these soft collisions that form the QGP.

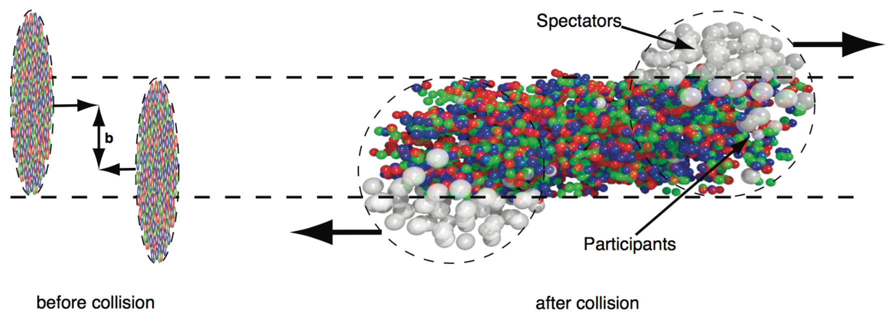

Figure 2: To the left, the two Lorentz contracted ions are shown before the collision with an impact parameter b. To the right, the system is shown after the collision where the spectators are unaffected and the participants are involved in the particle production [11].

In a collision the nuclei collide with an impact parameter b, which is the distance between the centers in the plane that is perpendicular to the direction of the beam line. This length corresponds to the shortest distance between the centers of the colliding nuclei, see Fig 2. A smaller value of b means that more nucleons interact and the collision is more central. A larger value of b corresponds to less participants and the collision is called peripheral. Due to the larger number of interacting nucleons in a central collision do the high particle multiplicity events (high number of particle events) come from these collisions.

3.2 Azimuthal and Polar angles

Since one expects collisions to have no preferred direction in the azimuthal plane a cylindrical coordinate-system is of good use. It gives each particle track two angles; the polar angle, θ, that lies between the track and the beam line, and the azimuthal angle, ϕ that is the angle in the transverse plane.

3.3 Transverse momentum

The transverse momentum, p_T, of a particle is the fraction of momentum in the plane perpendicular to the beam line direction (usually defined as the z-axis). The perpendicular plane is defined with the horizontal x-axis and vertical y-axis, and p_T is defined as,

$$p_T = \sqrt{p_x^2 - p_y^2}. \tag{1}$$

To look at p_T is of interest since, initially it is 0, when observed it can give information about the dynamics of the collision. The hard collisions produce higher p_T particles while the soft produce lower p_T particles [7].

3.4 Rapidity and pseudorapidity

Rapidity, y, is an alternative to the standard velocity but is used at relativistic energies. It is defined as

$$y = \frac{1}{2} ln \left(\frac{E + p_z}{E - p_z} \right) \tag{2}$$

where $E = \sqrt{m^2 + p^2}$ is the total energy of the particle, m the mass of the particle, p its momentum and p_z is the momentum of the particle in z-direction. The rapidity is additive for Lorentz boosts along the beam-line. Considering that the masses of the produced particles are hard to measure, it complicates the calculations of the mass-dependent rapidity. Therefore one often uses the mass-independent pseudorapidity that is almost equal to rapidity for p_T much greater than the mass. The pseudorapidity, η, is defined as

$$\eta = \frac{1}{2} ln \left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right) = -ln \left(tan \frac{\theta}{2} \right) \tag{3}$$

where θ is the polar angle.

An expression that will be used when explaining and discussing transverse spherocity is mid-rapidity. The mid-rapidity region (also called central rapidity region) is the region the center-of-mass frame where $y \approx \eta \approx 0$ [7].

3.5 Proton-proton collisions

The focus of this thesis is on high multiplicity pp collisions since it is of interest to check if the QGP is created there just as in heavy-ion collisions. Because of the large hard "foreground" it is challenging to study the soft effects, i.e the effects of a possible QGP.

3.6 Transverse Spherocity

The mid-rapidity charged hadron transverse spherocity, S_0, is used as a selection to extract more information from data by looking at event shapes. More specifically it is used to categorize the events through the geometrical distribution of the p_T's of the charged hadrons. It is restricted to the transverse plane in order to avoid the bias from the boost along the beam axis. The S_0 is defined as

$$S_0 = \frac{\pi^2}{4} \left(\frac{\sum_i |\vec{p_{T_i}} \times \hat{n}|}{\sum_i p_{T_i}} \right)^2 \tag{4}$$

where $\vec{n}$ is the transverse unit vector that minimizes the ratio. The value of S_0 gives an indication of whether an event is hard or soft.

$$S_0 = \begin{cases} 0 & \text{"pencil-like" limit (hard events)} \\ 1 & \text{"isotropic" limit (soft events)} \end{cases} \tag{5}$$

It is expected that by implementing the transverse spherocity selection, the soft and hard spectra to be more exponential and power-law like, respectively [12].

4 Experiment

Data used and analyzed in this thesis comes from LHC and the ALICE detector at CERN. These facilities will be described in this chapter.

4.1 The Large Hadron Collider

The world's largest and most powerful particle accelerator today is the Large Hadron Collider (LHC) at CERN outside of Geneva, Switzerland. The 27 km LHC ring consists of superconducting magnets that accelerate the particles along the way. The two high-energy particle beams inside the accelerator have a velocity that is close to that of the speed of light (0.999999991 times the speed of light [13]) just before they collide. It is the superconducting magnets that focus the particle-beams in the accelerating ring and bring them to collide [14].

4.2 The ALICE Experiment

ALICE is one of the seven detectors at LHC and is an acronym for A Large Ion Collider. It is designed to mainly measure the particles that are produced in collisions at mid-rapidity. The main aim is to study the physics of strongly interacting matter at extreme energy densities made from head-on heavy-ion collisions, where a QGP forms. ALICE is optimized for a low transverse momentum threshold of $p_T^{min} \approx 0.15$ GeV/c and particle identification capabilities up to 20 GeV/c [15].

The dimensions of ALICE is $16 \times 16 \times 26$ m^3 and it weighs approximately 10000 tons. It consists of 17 different detection systems, which is shown schematically in Fig.3. The 17 different detector systems are divided up into three different categories; central barrel detectors, forward detectors and MUON spectrometer. Detectors that belong to the central barrel are the Inner Tracking System (ITS), Time Projection Chamber (TPC), Transition Radiation Detector (TRD), Photon Spectrometer (PHOS), Electromagnetic Calorimeter (EMCal) and the High Momentum Particle Identification Detector (HMPID), and all of these detectors are enclosed in a solenoid magnet that generates a magnetic field of up to $B = 0.5$ T [15].

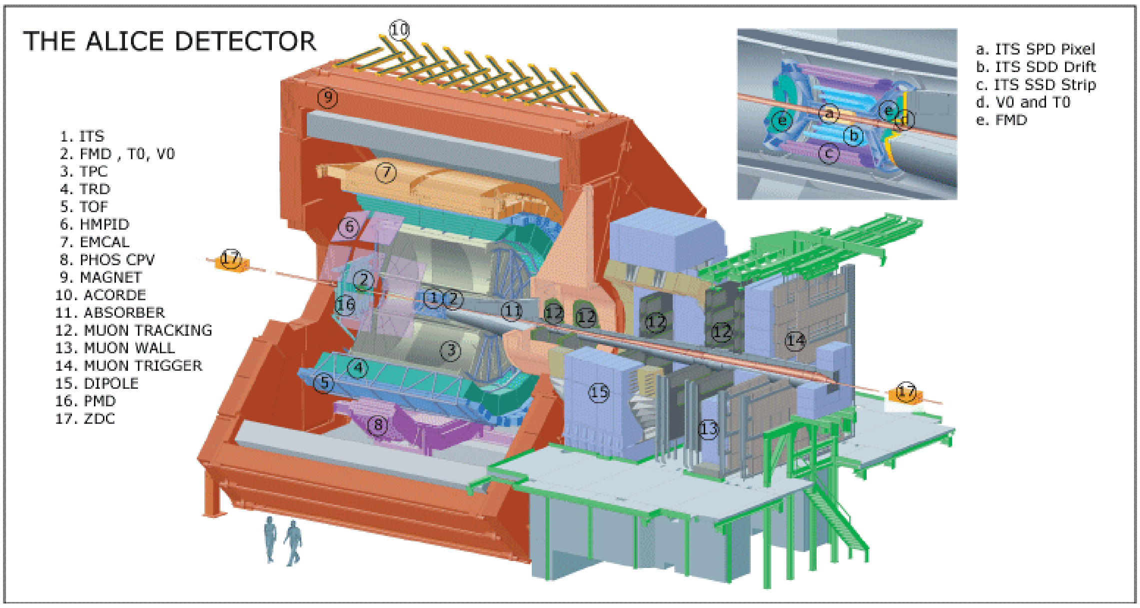

Figure 3: A schematic picture of the ALICE detector. [16]

It is the ITS and TPC that are the main tracking detectors in ALICE [17]. Due to the magnetic field in the central barrel, the trajectories of the charged particles bend and from the curvature of the tracks it is possible to determine the momentum. Inside the TPC is the ITS (the detector closest to the beam line) which is very precise and can identify particles that result from decays of other particles with short life times such as charm quarks, by seeing that they originate a small distance from the vertex (the point where the collision took place). The ITS also improves the resolution of the momentum for the tracks measured by the TPC [16].

For information about the particles identity, additional detectors are needed. The TOF measures the time it takes for the particles to travel from the vertex to the detector, with a high precision. With this information the speed of the particles can be measured. The HMPID also can determine the speed due to the resulting Cherenkov radiation, the TRD identifies the electrons and the muons are measured by the muon spectrometer. In order to tell anything about the temperature of the system it is necessary to measure the energy of the photons and electrons, this is done in a limited area with PHOS and over a wider area by EMCal by seeing how they interact with different layers of matter [16].

The forward detectors of ALICE include the PMD, the FMD and the T0 detector where the photons, charged particles and time and longitudinal position of the interaction are measured respectively. V0 is also one of the forward detectors in ALICE, it is a silicon detector that measures charged particles and is mainly used to determine the centrality of a collision [15]. In this project the V0 detector provides information of the multiplicity.

5 Methods

This section will be divided up into two parts. The first part will describe the method used in order to hopefully improve the the transverse spherocity selection. The second part will describe how the transverse spherocity is used to analyze ALICE data. For both methods new software was written in the programming language C++, with the data analysis framework of ROOT [18].

5.1 Determining the Transverse Spherocity

At the start of the project, the task was to reproduce a toy generator [19] in order to gain a better feeling regarding the discriminating power of transverse spherocity to isolate real jet-like and isotropic events. This was done by following instructions from Ref. [19] and was then compared with an already made and working transverse spherocity class. The aim was to write a code that gave the same results as shown in Fig.4, which is from Ref. [19], in order to validate that the code is correct.

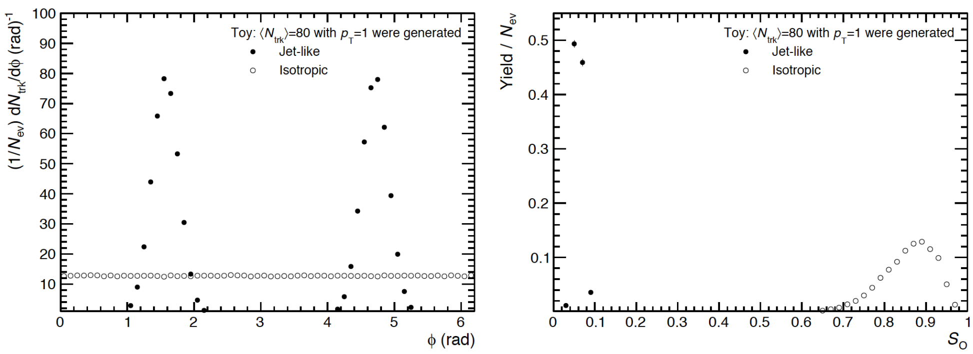

Figure 4: Left: The ϕ distribution for jet-like and isotropic events. Right: The black dots correspond to a S_0-distribution with only jet-like events and the white dots correspond to a S_0-distribution with only isotropic events. [19]

In the code given, the unit vector, $\vec{n}$, that minimizes the S_0 distribution, was found by checking each unit vector in steps of two degrees around in a circle in the transverse plane. However, it was proposed in Ref. [20] that the smallest $\vec{n}$ should coincide with one of the track vectors. The next task was therefore to check if this is true. So instead of going step by step in the transverse plane to find the smallest $\vec{n}$ one finds the unit vector by looking at the tracks. Fig.5 is an attempt to visualize the two methods.

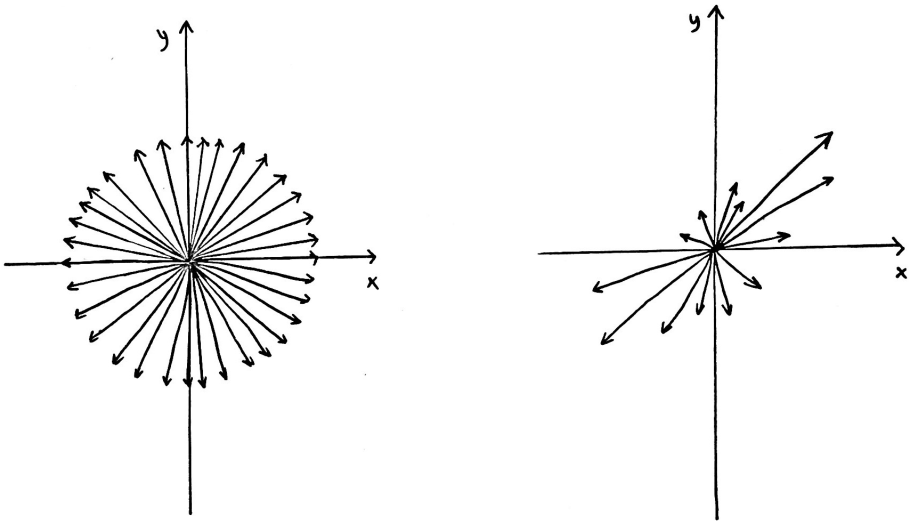

Figure 5: To the left, $\vec{n}$ is found by looking at all the angles in steps of 2°. To the right, $\vec{n}$ is found by looking at the actual tracks.

To do this a new method was written. The code is shown below.

```
Double_t TransvSpherocity::GetTransvSpherocityTracks()
{
  if(fNtracks < fMinMulti)
    return -1;

  Double_t RetTransvSpherocity = 1000;
  Double_t sumpt = 0;
  Double_t pt;
  for(Int_t i = 0; i < fNtracks; i++) {

    pt = TMath::Sqrt(TMath::Power(fPx[i], 2) + TMath::Power(fPy[i], 2));
    Double_t nx =fPx[i] / pt; // x component of a unitary vector n
    Double_t ny =fPy[i] / pt; // y component of a unitary vector n

    Double_t num = 0;
    for(Int_t j = 0; j < fNtracks; j++) {
      num += TMath::Abs(ny*fPx[j] - nx*fPy[j]);

      if(i==0)
sumpt += TMath::Sqrt(fPx[j]*fPx[j] + fPy[j]*fPy[j]);
    }

    Double_t pFull = TMath::Power((num/sumpt), 2); //Projection of sp.
    on the segment
```

```
    if(pFull < RetTransvSpherocity)  //Select the lowest projection
      RetTransvSpherocity = pFull;
  };

  RetTransvSpherocity *= TMath::Pi()*TMath::Pi()/4.0;
  fHistSpher->Fill(RetTransvSpherocity);

  return RetTransvSpherocity;
};
```

The toy generator was used as a debugger when writing the new code to check that the distribution still had the same shape. Before one could determine which method gives the best results, a comparison was made by taking the difference between them. If the difference is always less then zero or always bigger than zero, this means that one of the methods always gives a smaller value and it is this method that one wants to use.

5.2 Analyzing pp-collisions

The second part of this thesis work was to apply the transverse spherocity method when analyzing data from pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV produced at the ALICE experiment at CERN.

The goal is to use the new transverse spherocity selection to separate the jet-like and isotropic events, looking at all the charged particles. Some event selections was recommended and the ones used here were the following: a pile up rejection, a vertex selection and a minimum multiplicity. Pile up happens when two interactions take place in the same bunch crossing and can give rise to what appears to be a single very high multiplicity event. For this reason pile up events are rejected. An event was rejected when a second primary vertex was reconstructed. For the vertex selection, the vertex was required to be within ± 10 cm along the z-coordinate, vertexes longer than 10 cm were rejected. Transverse spherocity is defined for a minimum multiplicity, the events have to have more than two tracks with transverse momentum larger than 0.15 Gev/c [19]. A minimum multiplicity cut was made at 10 tracks since this was recommended in Ref. [19].

To validate the analysis it is useful to reproduce published results. For this reason a minimum bias spectrum of the used data was also measured. It was then compared to the published results by making a ratio. Since it is the collisions with a high multiplicity that this analysis aims to analyze, and the fact that transverse spherocity is defined only for mid-rapidity, further cuts in the data had to be made. A high multiplicity collision means a more central collision, hence the usage of collisions with a centrality of $0 - 10\%$ where the centrality interval is provided by the V0-detector. The mid-rapidity cut was made for $|\eta| < 0.8$.

With all of these cuts, a new top 10% centrality p_T spectrum was created and the transverse spherocity was applied to the data and filled in a histogram to visualize the S_0 distribution (This distribution is shown in Fig.6). From this distribution a selection of two values was made, one value closer to 0 and the other one closer to 1 representing the limits for jet-like and isotropic events respectively. The tracks with an S_0-value of 0.47 or less correspond to jet-like events and tracks with an S_0-value of 0.76 or higher to isotropic events.

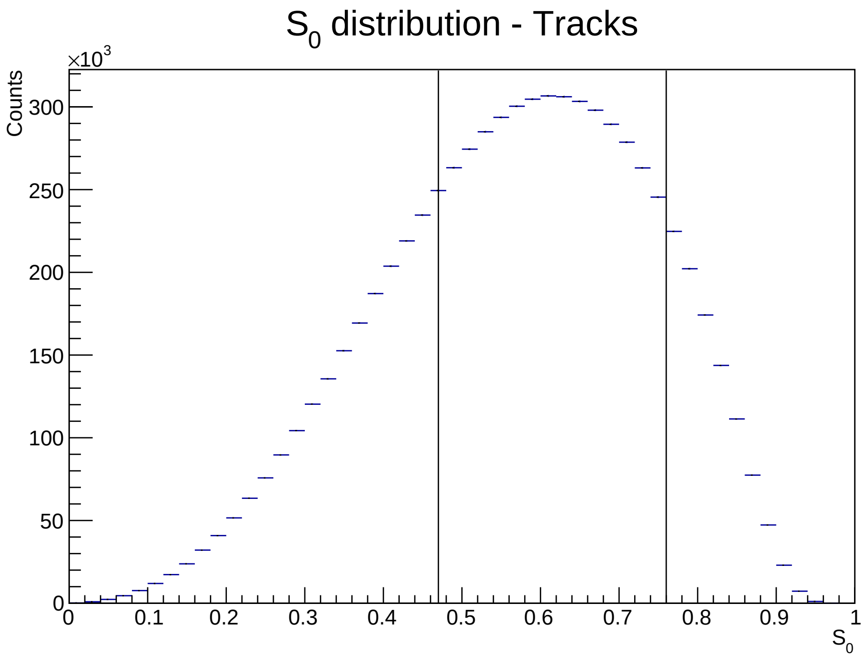

Figure 6: Spherocity distribution for high multiplicity pp collisions with cuts. Tracks with $S_0 < 0.47$ corresponds to jet-like and tracks with $S_0 > 0.76$ to isotropic.

Two p_T spectra were filled for each type of events and were then compared to the p_T spectra without the transverse spherocity selection in order to see if there is a separation and if this separation agrees with expectations from simulated data.

6 Results and Discussion

In this section, the results from the method used in the previous section are presented together with some discussion.

6.1 Determining the Transverse Spherocity

The ϕ distribution in Fig. 8 of generated tracks using the new transverse spherocity class (where the smallest unit vector $\vec{n}$ coincides with one of the tracks) agrees with published results. It looks almost exactly the same as for the ϕ-distribution using the old class (shown in Fig.7).

When comparing the two classes' S_0-distribution in Fig. 9 it is possible to see that they agree with small differences. These two figures indicate that the new class is correct in the sense that it can calculate the transverse spherocity but in order to decide if the new class has improved the measurements one has to look at the difference between the values of S_0 for each event for both of the classes which is done in Fig. 10 below.

It is of interest to look at the difference, due to the fact that the smallest $\vec{n}$ is wanted in order to minimize the S_0 ratio, and since the old class is subtracted from the new tracks-class the difference for all the events has to be less than zero for the tracks-class to be improved, which is what Fig. 10 presents.

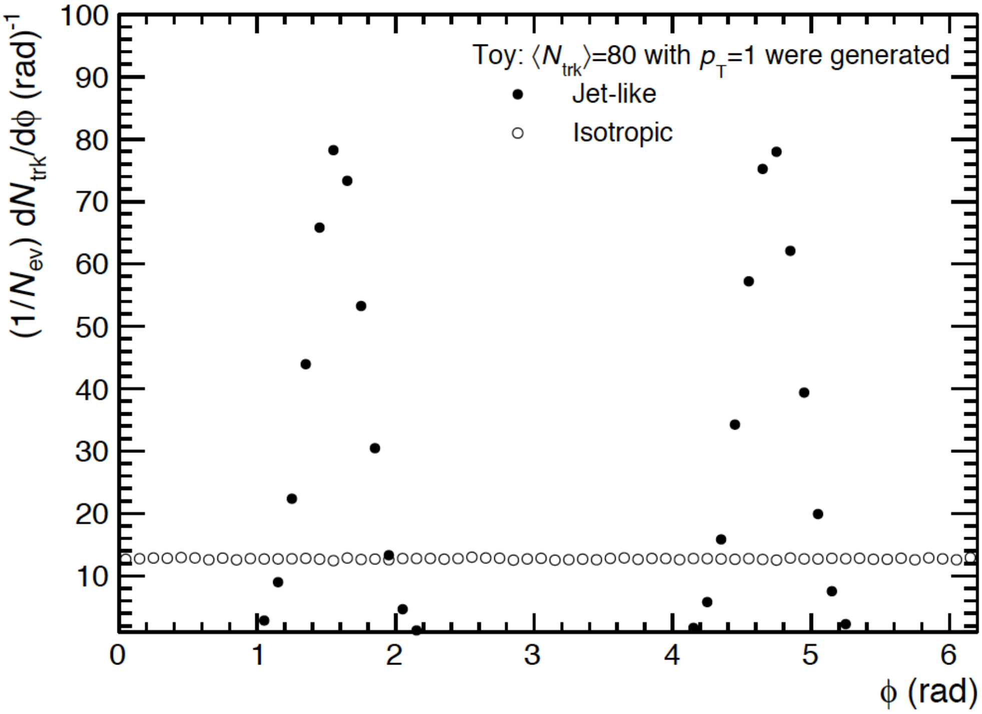

Figure 7: The ϕ distribution using the old class.

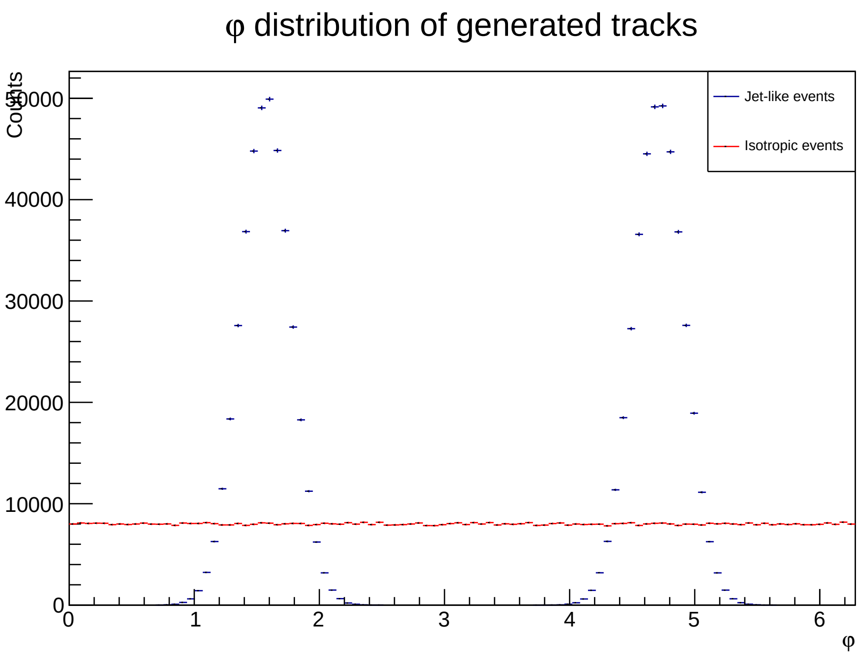

Figure 8: The azimuthal distribution for jet-like(blue) and isotropic(red) events when using the track-class.

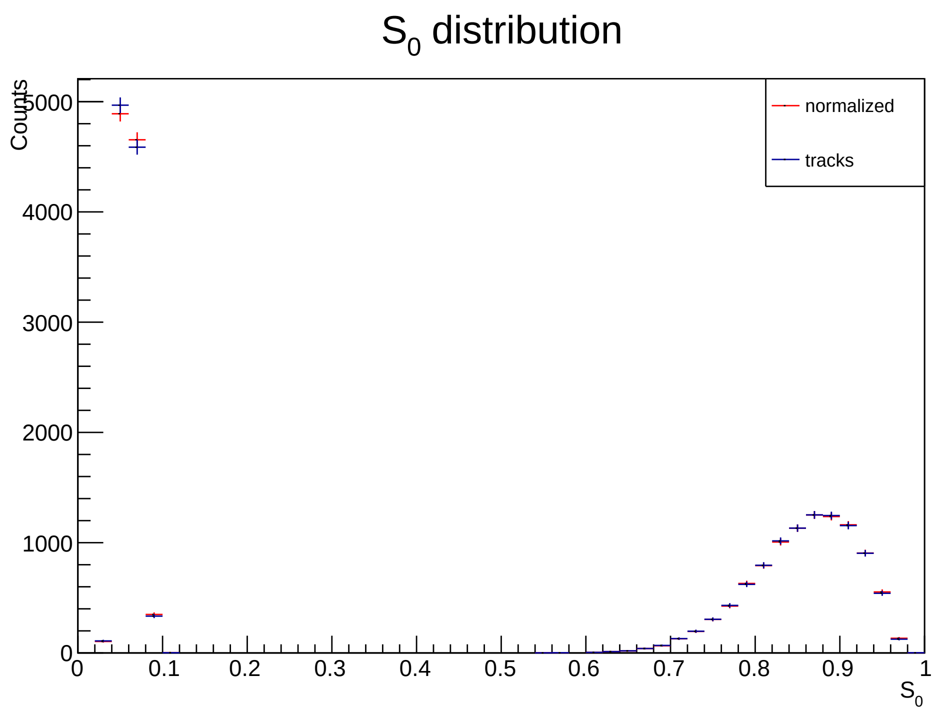

Figure 9: Comparing the spherocity distributions given by the old and new class. The jet-like events to the left and isotropic to the right.

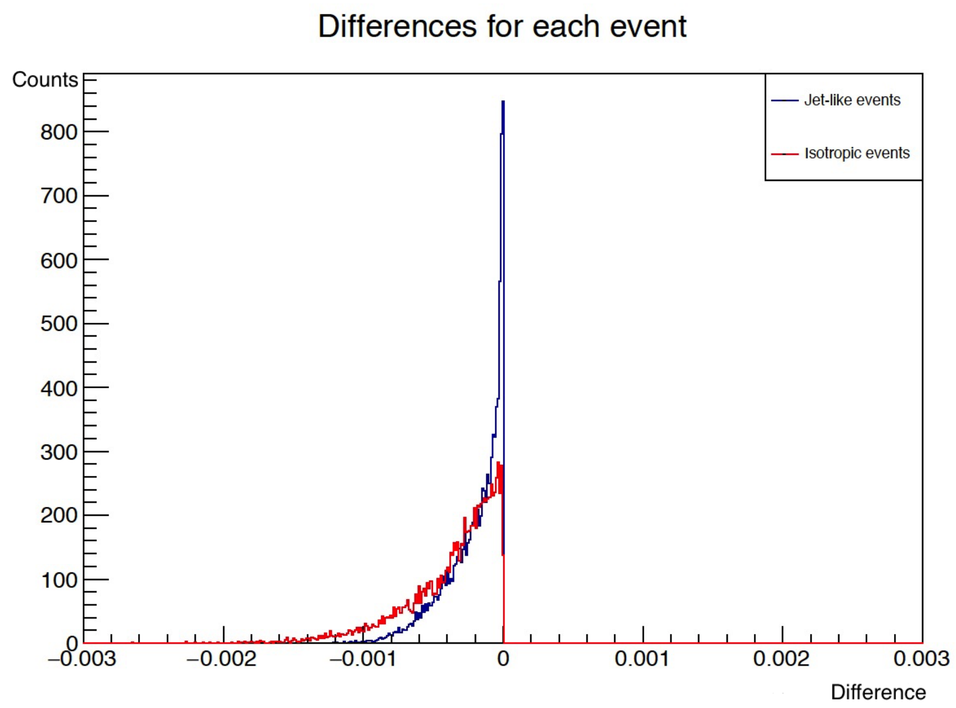

Figure 10: The difference between the two methods for jet-like and isotropic events.

6.2 Analyzing pp collisions

The calculated efficiency of the detector with Monte Carlo data shows a somewhat straight line in Fig. 11 and the value for this straight line lies slightly below the published value but still inside the systematic uncertainties (85.2% with a systematic uncertainty of +6.2 and -3.0) [21].

Looking at Fig. 12 where the reproduced spectrum is compared with the published spectrum, one can see that the ratio is a little high. Ideally the ratio should be precisely 1, whereas here it is ~ 1.06, which means that the reproduced spectrum lies a little above the published one. As the ratio is flat it means that there is some small difference in the overall normalization, could be due to the slightly low efficiency. But as the ratio is flat as a function of p_T we expect that the shape of the measured spectra is measured accurately and it is mainly the shape we are interested in for the transverse spherocity studies.

In Fig. 13 there is a clear separation of the soft (isotropic) and the hard (jet-like) events where the hard events goes above the unbiased inclusive distribution at high p_T while the soft events go quite far below the unbiased inclusive distribution. This agrees with the published simulated data. Hard scattering is supposed to have a power-law like p_T-spectrum, while for a thermal medium, such as the QGP, it is expected to have a more exponential p_T-spectrum which agrees with Fig. 13.

For the different ratios shown in Fig14, one can see that the isotropic events are enhanced for low p_T, while the jet-like events are suppressed, in other words are the effects of the medium enhanced for low p_T and the hard processes are suppressed.

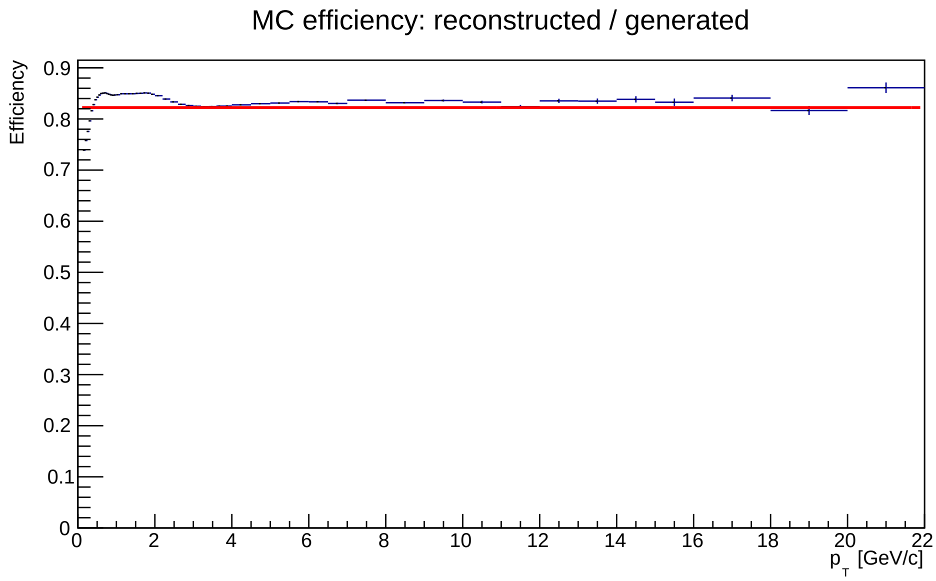

Figure 11: Calculated efficiency for 7 TeV pp-collisions using Monte Carlo simulations.

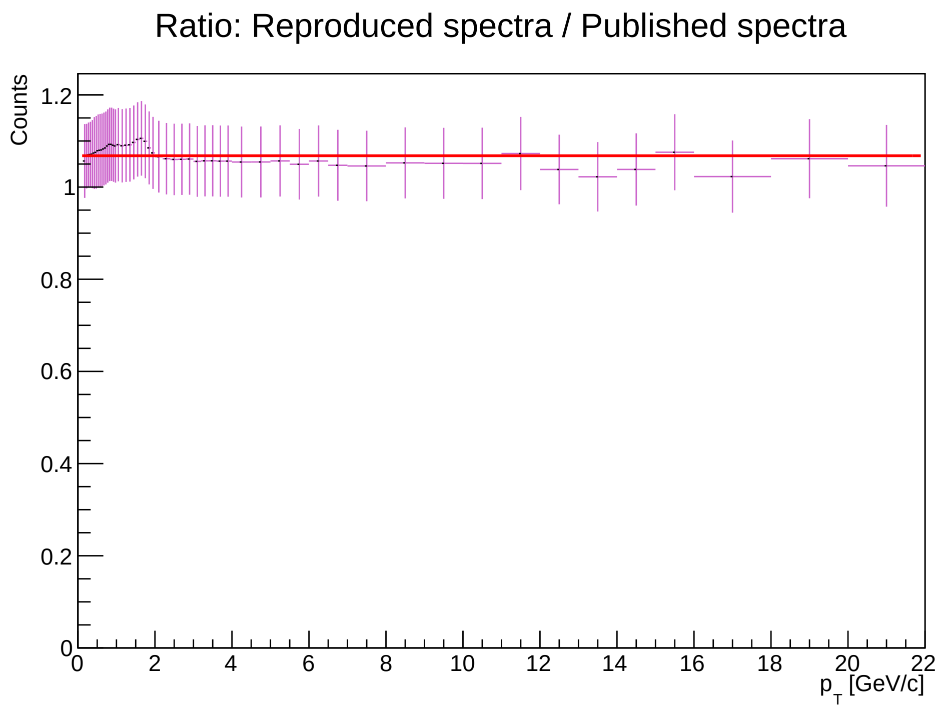

Figure 12: The ratio of the spectra produced in this thesis work compared with published spectra.

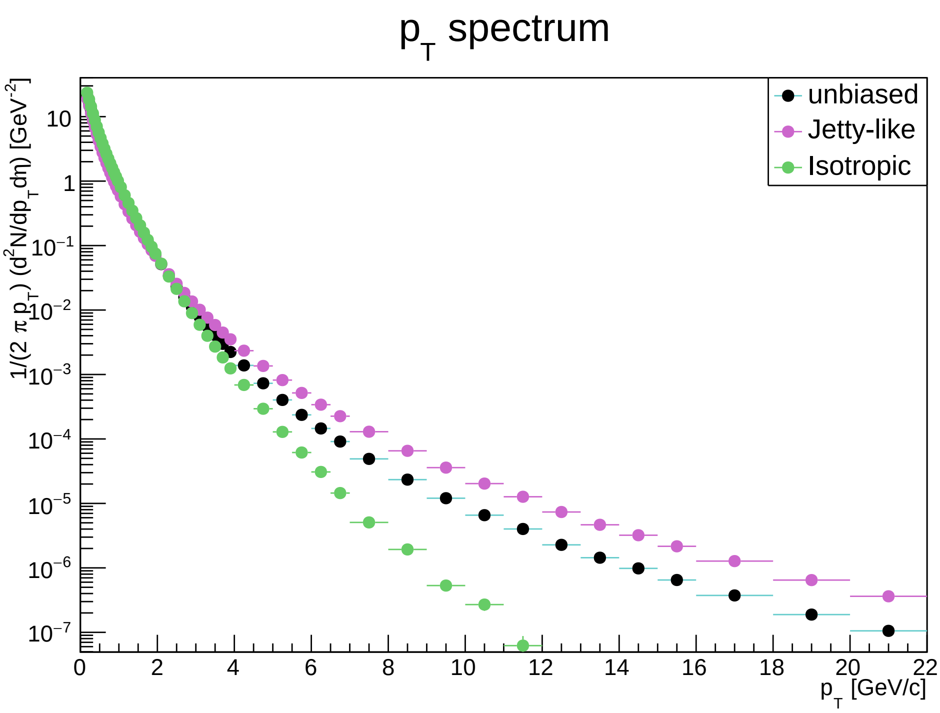

Figure 13: A p_T spectra with a clear separation of hard(jet-like) and soft(isotropic) production in high multiplicity pp collisions for all charged particles.

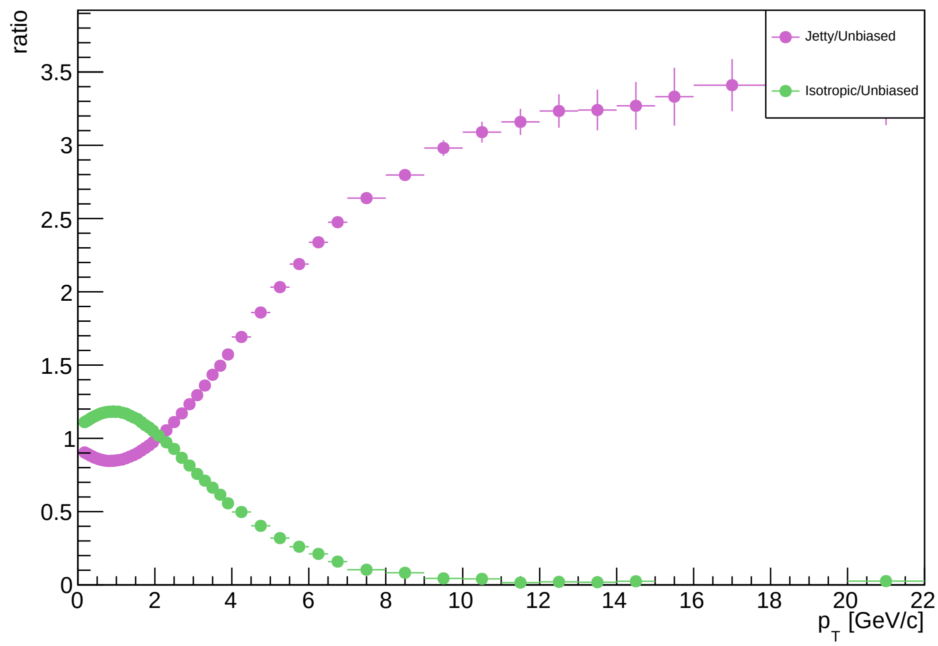

Figure 14: Two different ratios, jet/unbiased and isotropic/unbiased.

7 Conclusion and Outlook

In this project a new method to subdivide pp collisions into soft and hard events was tested. It was shown that with this method one can select soft events where there are more particles at low p_T, where one expects medium production to take place, and a lot less particle-production at high p_T, where one expects hard processes to occur. It therefore seems that the Transverse Spherocity method can indeed increase the sensitivity to QGP-like effects in small systems.

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