Azimuthal anisotropy of jets in heavy ion collisions observed in ALICE at the LHC

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dedication...

Acknowledgments

I would like to thank...

Abstract

This comprehensive outlines a measurement of the azimuthal anisotropy (also known as jet v_n) of jets emerging from heavy ion collisions observed by ALICE (A Large Ion Collider Experiment) at the LHC (Large Hadron Collider). Analysis is conducted on 5 TeV lead-lead collisions. Jet azimuthal anisotropy is measured up to the third [or perhaps fourth] harmonic.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Theory

The Standard Model of particle physics describes the behavior of the fundamental particles which compose our universe. All matter is made up of spin-1/2 massive particles, called $fermions$, which interact through the exchange of integer spin particles, called *bosons*, giving rise to the fundamental forces: electromagnetism, the weak nuclear force, and the strong nuclear force. Gravity is absent from this list, as its behavior cannot yet be described in terms of boson exchange.

Among these three forces, the most familiar to everyday life is electromagnetism, which can serve as a useful analogy for understanding the others. The electromagnetic force describes the interactions between all electrically charged particles, such as electrons, via the exchange of photons, electrically neutral, spin-1 bosons. This interaction leads to a Coulomb potential, of the form:

$$V(r) = -\frac{\alpha_{EM}}{r}$$

At low energies, at which the charged is screened by virtual particle production, α_{EM} is the fine structure constant, $\alpha_{EM} = \frac{e^2}{\hbar c} \approx \frac{1}{137}$. This low value enables the use of perturbation theory in electromagnetic calculations. However, at higher energies, the electromagnetic coupling does not remain constant, and in fact asymptotically approaches infinity.

The weak force describes interactions between particles possessing weak hypercharge (e.g. quarks, leptons, and higgs) through the exchange of $W^{\pm}$ and Z^0 bosons. Since these bosons are massive, the potential for the weak force takes the form of a Yukawa potential, meaning its magnitude drops off exponentially with radius.

$$V(r) = -\frac{g^2 e^{-kmr}}{r}$$

At low energies, the electromagnetic and weak forces appear very different. This is due to spontaneous symmetry breaking of the $SU(2) \times U(1)$ gauge group via the Higgs mechanism. However, at energies above 100 GeV, the Higgs boson acquires an expectation value, and the electromagnetic and weak interactions become unified into a single $electro-weak$ force. The behavior of these forces is well explained by theory: Quantum Electrodynamics (QED) at low energies, and Electro-weak Theory (EWT) above the unification energy. In both cases, the coupling constants remain conveniently low, allowing the use of perturbation theory to make predictions.

The strong force governs the interactions between quarks, massive fermions possesing both a fractional electric charge and a color charge. They come in red, green, or blue (or antired, antigreen, or antiblue for antiquarks). The strong force operates on these color charges through the exchange of gluons, massless spin-1 bosons, which have a color charge of their own. Quarks and gluons are collectively known as $partons$.

Because gluons are charged under the strong force, they are capable of self interaction. This leads to an anti-screening of color charges, which results in a potential that resembles that of the electromagnetic force, but with an additional linear term.

$$V(r) = -\frac{\alpha_S}{r} + \kappa r$$

Here α_S is the strong coupling constant. Just like in QED and EWT, the strong coupling constant is not a constant at all, but depends on the energy level of the interaction in question. Unlike the other two forces, however, the strong coupling constant rises asymptotically at low energies, and goes to zero for high energies. This scaling is known as $asymptotic freedom$, and it leads to many interesting effects in Quantum Chromodynamics (QCD), the theory of the strong force.

At low energy, when α_S is high, the strong potential between partons increases with radius without limit. As a consequence, individual color charged particles are not found in isolated states under normal circumstances. Instead, quarks and gluons exist in bound states known as hadrons, which have no net color. Attempting to liberate a parton from a hadron requires supplying the field with enough energy to form new quark antiquark pairs, which then bind with the pre-existing partons, forming new colorless hadrons.

Hadrons are divided into two types: mesons, composed of a bound quark antiquark pair, and baryons, which are composed of three quarks (or antiquarks). Baryons include the familiar protons and neutrons found within the nucleus of all atoms, as well as many more exotic species.

1.2 Quark Gluon Plasma

Because the coupling between partons is not constant, quarks and gluons can come unbound under very high color charge densities, where α_S has a low value. Under such conditions, hadrons melt away into a new phase of matter composed of deconfined quarks and gluons. This new phase of matter has been dubbed *quark gluon plasma* (QGP) in an analogy to a normal plasma, which is composed of unbound electrons and atomic nuclei.

QCD calculations predict this phase transition to occur at a temperature of 155 MeV, or an energy density of 1 GeV/fm^3. Such extreme conditions are thought to have only occurred naturally for a few microseconds after the Big Bang, when the universe was much more hot and dense than its current state. These conditions can be recreated artificially with modern particle accelerators capable of conducting relativistic heavy ion collisions, such as the Relativistic Heavy Ion Collider (RHIC) in Brookhaven, New York, or the Large Hadron Collider (LHC) at CERN.

In a relativistic heavy ion collision, two beams of atomic nuclei with high atomic mass (e.g. lead nuclei) are accelerated in opposite directions to near the speed of light. Where these beams cross, the nuclei collide with a center of mass energy on the order of TeV per nucleon. The energy density achieved in these collisions is sufficient to create a QGP phase in which quarks and gluons move about freely, interacting with each other enough to come to a local thermal equilibrium. Here it should be pointed out that the name ”quark gluon plasma” is somewhat of a misnomer, as it is more similar to a low viscosity fluid, whose flow is describable under relativistic hydrodynamics.

CUT

This QGP is incredibly short-lived, on the order of [blank] femtoseconds. It rapidly expands and cools, condensing into a gas of hadrons, which then freeze out into a collection of final state particles which can be observed by detectors surrounding the beam crossing point. Since the QGP exists for such a short period of time in a very small region of space, its properties cannot be directly measured from an outside probe. Instead, a probe internal to the heavy ion collision must be used.

1.3 Jets

When two nuclei collide relativistically, two of their constituent partons may undergo a hard scattering event, i.e. a scattering with a large momentum transfer Q. In the center of mass rest frame of the parton pair, they fly apart with equal and opposite momentum. As discussed previously, this leads to the creation of new quark antiquark pairs. The momentum of the new particles is small in comparison to Q, so their trajectories closely follow the initial scattered partons. The end result is two back-to-back columnated sprays of particles known as *jets*, which are observable as angular clusters of final state particles. Because they originate early in the collision and pass through the medium, jets serve as an excellent probe of the QGP.

Partons traversing the QGP medium lose energy through both collisional and radiative processes. ~~Collisional energy loss takes the form of elastic scatterings~~ $\cancel{qq \to qq}$, $\cancel{qq \to gg}$, ~~or~~ $\cancel{gg \to gg}$. Energy loss per unit length due to scattering is given by:

[scattering energy loss equation]

Color charged particles traveling through the QGP also lose energy through radiation of gluons. This process is analogous to Bremsstralung, the phenomenon in which photons are radiated by electrically charged particles moving through a medium faster than the speed of light in that medium. The energy loss due to radiation is given by the equation:

[radiative equation]

Unlike collisional energy loss, energy loss due to radiation scales quadratically with distance traveled, and does not depend on the energy of the initial parton. This means that at low energy, the radiative process dominates, while at high energy, the collision process dominates.

In either case, a jet's energy is reduced on its journey through the QGP. This effect, referred to as *jetquenching*, is the key to using jets to probe the QGP. The degree to which a jet is quenched is dependent on the path length it travels through the QGP. Because a pair of jets begins with a pair of hard scattered partons with equal and opposite momentum, the final state jets should have the equal and opposite momentum in the absence of a QGP. This is shown to be the case in proton proton collisions, in which no QGP is formed. However, in heavy ion collisions, the jet which travels a longer path through the medium will experience more quenching, leading to a broader, weaker final jet. Asymmetry in back-to-back jets is an important signal that a QGP has formed in a heavy ion collision. Furthermore, comparison of the two jets can reveal information about the QGP's properties.

Chapter 2

Experiment

[Here I describe the LHC, ALICE, its sub-detectors, and what we're measuring]

2.1 The Large Hadron Collider

2.2 ALICE

[ALICE, TPC, EMCAL]

2.3 Measuring Jets

Chapter 3

Analysis

[This is where I will describe the measurement taking place and the data that will be collected and analyzed. Also, need to introduce terminology]

3.1 Terminology

[reaction plane, centrality, RAA, eta, phi, etc.]

3.2 Azimuthal Anisotropy

[vn (include equation)] [what detectors am I getting data from?] [include pics of circular harmonics]

Chapter 4

Conclusions

Bibliography

Appendices

A Summary of Equations

some text here

A.1 Cartesian

some equations here

A.2 Cylindrical

some equations also here

B Summary of Stuff

some text here

B.1 More Things

some equations here

B.2 Other Aspects

some equations also here

Vita

Vita goes here. The vita should be a brief biography about the author written in third person and paragraph format. It should not be the author's resume or CV.