Formation of Quark Gluon Plasma and Enhancement of Strangeness in Proton-Proton Collisions

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Abstract

Quark Gluon Plasma (QGP) is the state of matter created in labs to study the first few moments after the big bang. It is characterized by its high energy density and the deconfinement of the quarks within it. Among the markers of QGP is the production of strange quarks, produced by processes such as flavour creation and gluon splitting. Such production of strange quarks is observed in proton-proton collisions at the Large Hadron Collider (LHC), indicating that QGP is indeed produced. However other markers such as jet quenching and charmonia suppression are still in question. Though some QGP formation markers are absent, the production of strangeness in pp collisions makes a strong case that QGP was indeed produced.

Introduction

The beginning of the universe is characterized by its extreme conditions . Shortly after the big bang, the entirety of the observable universe was confined to a very small and extremely energy dense state, the nature of which has been a subject of study within the field of high energy physics for decades. Understanding this initial state of the universe is vital to explain many of the phenomena that still interest physicists today including that of matter-antimatter asymmetry, the nature of the strong force, the composition of dark matter, and many more. Recently, observations have been made supporting the formation of such a state in proton to proton collisions, which was initially considered to be physically improbable. The purpose behind this paper is to detail this state of matter and discuss the experimental production of such matter in proton collisions as well as the properties of it that we have observed thus far.

Quarks and The Strong Force

The fundamental constituents of matter and their properties lead to several emergent phenomena in extreme conditions, the understanding of which is integral to understanding the beginning of the universe. Visible matter as we know it consists of quarks and leptons. For this exploration, however, leptons will not be relevant and for this reason, will not be discussed in much depth. Quarks, which we will see are of utmost relevance in this exploration, are categorized into various flavours and make up the majority of the matter we see, most notably neutrons and protons. Flavours define different types of quarks. They include up, down, charm, strange, top and bottom quarks as well as their antimatter counterparts. Most of the mass in the universe consists of up and down quarks which are the lightest. Heavier quarks, such as strange quarks, are produced in high energy interactions and generally decay over time into up or down quarks. Such quarks, when they interact with each other, can create bound states called hadrons which form due to a fundamental force, known as strong force, which is roughly 100x stronger than the electromagnetic force(*Four Forces*, 2024). This force has its own boson, or force carrying particle, called a gluon that carries the strong force between quarks in the same way a photon carries the electromagnetic force between two electromagnetically charged particles.(Brodsky et al., 2024).

The strong force exclusively acts over small distances, such as the diameter of a proton or neutron and its magnitude is proportional to the distance that it is acted over, similar to how a rubber band pulls harder the more you stretch it (Brodsky et al., 2024).

Formation and Evolution of QGP

This correlation between strong force and distance leads to a paradoxical phenomenon between quarks: it is extremely difficult to isolate individual quarks since increasing the distance would only increase the attraction between quarks. However, when the same quarks are moved very close together, the strong force diminishes significantly to the extent that the quarks achieve a near unbound state: this behavior of the strong force is called asymptotic freedom (Stritto, 2024). At such energy densities, heavier quarks, such as strange quarks, are produced due to energy-mass equivalence. In this state, hadronic boundaries will diffuse to create a soup of quarks and gluons –a state of matter is referred to as Quark Gluon Plasma (QGP) or Quark Matter (Sahoo, 2019). For QGP to form, the temperature of the nuclei has to be raised and/or the quarks have to be compressed together to very high densities, both of which take place during particle collisions at accelerators such as The Large Hadron Collider (LHC) at CERN and The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (Sahoo, 2019).

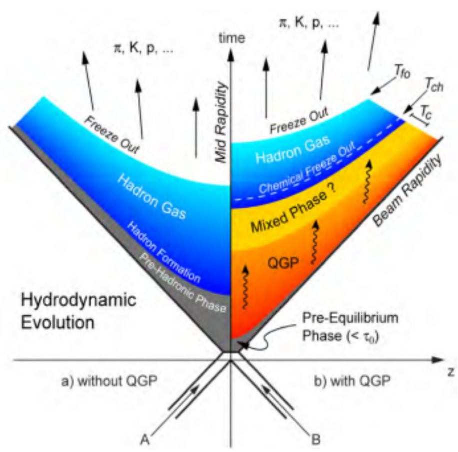

Figure 1: The diagram above compares stages after the collisions if QGP is not formed (left) and if it is formed (right) in a Minkowski space-time diagram. Only the right part is relevant to our discussion here (Sahoo, 2019).

QGP goes through several stages in a particle collision as its energy density decreases over time, a diagram of which is shown in Figure 1. Upon the formation of QGP, quarks are unbound and so there is no formation of hadrons, known as hadronization. After some time, the quarks and energy diffuse leading to too low of an energy density to sustain QGP which initiates hadronization where the quarks are no longer deconfined. Following this, chemical freeze-out, characterized by an absence of inelastic collisions, occurs, indicating that no more hadrons are being broken or formed leading to fixed ratios of different types of hadrons which happens around 1GeV/fm^3. After chemical freeze-out, no QGP is left since the state of matter has transitioned into a hadron gas. This is when detectors in the colliders detect the composition of the resulting matter (Pradeep & Stephanov, 2023). As a result, detectors detect hadrons, not individual quarks, even though it is known that at some point the quarks were unbounded. Consequently, the yield of strange quarks is determined from the yield of hadrons containing strange quarks, also known as hyperons.

As time passes and energy diffuses further, kinetic freeze out occurs, characterized by the absence of elastic collisions. At this point in the QGP evolution all collisions between hadrons have ceased (Sahoo, 2019). Many markers are used to prove that QGP has formed. The ridge property, a graphical pattern observed originally in heavy ion collisions, is among these properties. This graphical marker, shown in Figure 2, is a characteristic of known QGP forming collisions and serves as strong evidence for the production of QGP in proton to proton collisions as well (Lopes, 2023).

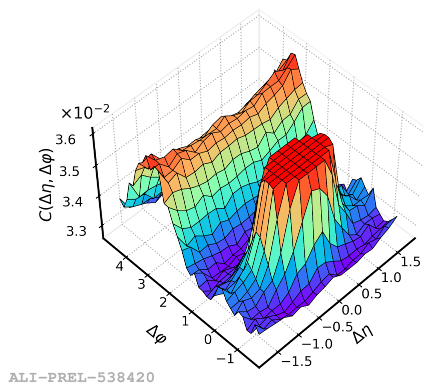

Figure 2: The graphical “ridge” observed in pp collisions (Lopes, 2023)

The formation of charmonia, a hadron consisting of a charm (c) and anti-charm ($\bar{c}$) quark, is known to be suppressed in the formation of QGP. Due to the presence of other quarks and gluons as well as the lack of string tension between c and $\bar{c}$ at very extreme temperatures, the formation of this bound state is suppressed which allows for the charm quarks to combine with light flavored quarks in its proximity. As a result, yields of lighter charm possessing baryons, such as D baryons, are enhanced, serving as a marker for QGP formations (Sahoo, 2019).

Furthermore, the production of particles with significant transverse momentum are also notable markers for QGP. Jets, a conical volume of high transverse momentum particles, are produced as a result of interactions within QGP. However, such high transverse momentum particles lose energy as they travel through the high density region, in which case the loss of energy is proportional to the distance travelled by the particle. As a result, jets formed near the peripheral of the QGP medium will lose less energy as compared to those formed deeper within the medium. Suppression of high transverse momentum particles is seen in heavy ion collisions where QGP is expected to form, and not observed in other types of experiments This is due to the energy loss within the high energy medium, leading it to be another signature for QGP (Sahoo, n.d). The only major signature is the production of Strangeness, the focus of this exploration.

Strangeness

Recall that strange quarks (s), along with anti-strange quarks ($\bar{s}$) are a specific quark flavour. Strangeness is a property in physics related to these quarks, though its definition varies across different usages of the term.

First, Strangeness, can be a numerical value used to quantify the imbalance in the presence of strange and anti-strange quarks, likened to baryon number, a numerical value comparing matter and anti-matter number densities. Similarly, just like baryon number, the importance of this strangeness value is its conservation across various quark interactions, however, the relevance of this specific definition lies in other fields such as antimatter-matter symmetry, weak decay of quarks, etc. (Fitch, 1981). Since neither of these are in any way relevant to this investigation, this definition will be dismissed in lieu of another.

Strangeness can also be defined as a general, non-quantitative measure of the prevalence of strange and anti-strange quarks in a system. This definition, unlike the previous, has to do with the production of both strange and anti-strange quarks . Moreover, it is not numerically specific, meaning that it is used as a qualitative generalization. Strangeness enhancement and strangeness production are various ways to refer to an overall increase in the number of strange quarks and anti-quarks. This use of the term “strangeness” will be the one employed in the rest of this study. (Hanafy et al., 2021)

Strangeness in relation to QGP

The collisions used to form QGP include collisions between two lead nuclei (Pb-Pb) or between a proton and a lead nucleus (Pb-p). The strangeness production in Pb-Pb collisions is generally significantly higher than in Pb-p collisions, which is attributed to the larger amount of mass that is present in Pb-Pb collisions. Einstein’s mass energy equivalence principle shows that even a small change in mass coincides with a large change in energy. As a result, in experiments with the same or similar initial velocities of particles, the higher mass in Pb-Pb compared to Pb-p allows for a much higher energy density after the collision allowing for more QGP to form (ALICE COLLABORATION, n.d.).

This relationship between mass and energy is also the reason that strange quark production is of such importance to the study of QGP. When it comes to quark flavours, up and down quarks, which make up protons and neutrons, are of the lowest mass. Strange quarks are comparatively of much higher mass, and, consequently, the amount of energy density required to produce them is also higher by the same equivalence principle (Rafelski, 1981).

Dr. Johann Rafelski authored a paper before QGP was first experimentally produced in which he argued that the significance of strangeness enhancement lay in the question of whether it can “tell the difference between different phases of hadronic matter [Hadronic Gas and QGP]” (Rafelski, 1981). In this paper, he proved that production of strange quarks was a marker that QGP had been created, as opposed to just a very energy dense hadron gas. This was very significant due to the fact that it is not possible to directly measure energy distribution in environments as extreme as those required to form QGP, and so it is necessary that we use markers, such as strangeness enhancement, to indirectly probe that QGP has indeed been formed (Rafelski, 1981).

Due to this same correlation between mass and energy, many physicists believed at the time that small system collisions, such as proton to proton (pp) would not yield quark gluon plasma, because there simply wasn’t enough mass to achieve sufficiently high energy density (ALICE COLLABORATION, 2017). However, pp collisions were conducted at the LHC at energies of 7 and 13 TeV that showed signs of QGP production (Sahoo, 2023).

Processes of Strange and Anti-strange Quark Production

Processes by which strange and anti-strange quarks are produced are generally divided into three categories: flavour creation, gluon splitting and flavour excitation (Sahoo, 2019).

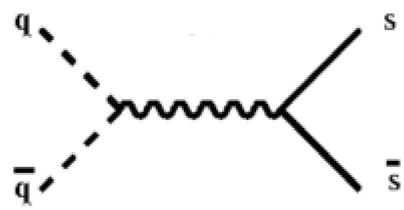

Figure 3: This Feynman diagram shows the lowest order quark-antiquark interaction that results in production of strange and antistrange quarks. (Rafelski,1981)

Flavour creation, the feynman diagram of which is shown in Figure 3, is the process in which a quark (q) and it's antiquark ($\bar{q}$) counterpart annihilate to produce high amounts of energy that is then converted into the formation of a strange and antistrange quark ($q\bar{q} \rightarrow s\bar{s}$) (Rafelski, 1981). Another process under the category of flavour creation is gluon fusion ($gg \rightarrow s\bar{s}$). In this process, two gluons fuse which then form a strange and an anti-strange quark. This process is the most important when it comes to strangeness enhancement since it is the main process to which the majority of the strangeness enhancement is attributed (Rafelski, 1981).

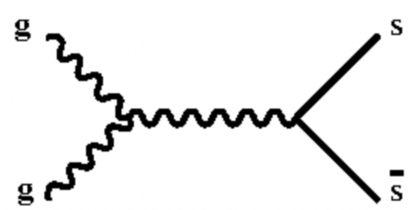

Figure 4: Lowest order Feynman Diagram of Gluon Fusion to Produce Strange Antistrange quark pair. (Rafelski 1981)

Gluon splitting is a process explained by Quantum Chromodynamics, a theory explaining the behavior of the strong force, with *color charge* acting similar to electric charge in the Electro-Magnetic force (*DOE Explains...Quarks and Gluons*, n.d.), its feynman diagram can be seen in Figure 4. Every quark has a color charge, which can be one of three types: red, blue or green (*DOE Explains...Quarks and Gluons*, n.d.). Subsequently, there is also anti-red, anti-blue and anti-green (Gross et al, 2022). It is necessary that quarks remain in bound states that are color neutral. In order to be color neutral, a hadron has to have red, green and blue charge; having any color and its anti-color counterpart also cancels out making a meson neutral (Gross et al, 2022). Unlike photons, which don't inherently carry electromagnetic charge, gluons do carry color charge. Gluons carry both a color and an anti-color charge (Gross et al, 2022), and this gives the gluon the ability to “split” and create a strange and antistrange quark, each one inheriting one of the color charges of the gluon. This process, however, is mostly relevant to the production of bottom and charm quarks, though it is acknowledged as a possible way to produce strangeness as well (Brodsky et al., 2024).

The last process, flavour excitation, describes a process where a virtual particle becomes non-virtual due to the scattering of particles called partons. However, since the contribution of flavour excitation to strangeness enhancement is negligible, it will not be explored to much depth here.

Comparison of Strangeness Yield in Small and Large System Collision

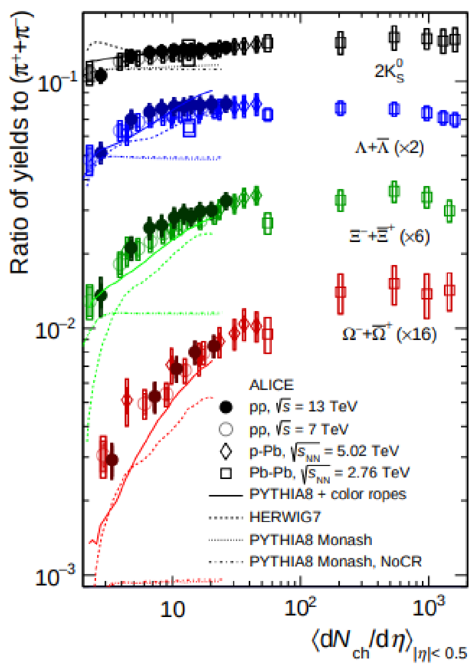

Figure 5: Production of Hyperons in pp, Pb-Pb and Pb-Pb collisions (Sahoo, 2019)

As the data in Figure 5 comparing strange quark possessing hadrons in different collision systems shows, the production of strange quarks in pp, Pb-Pb and Pb-p collisions all generally follow a very similar trend (WA97 Collaboration, 2000). There is an increase in the yield of these hadrons as the energy density of the medium increases, with the production of baryons such as Ω baryons and Ξ, which contain 3 and 2 strange quarks respectively, being much lower than Λ baryons and K mesons that contain 1 strange quark each. This trend is followed by all collision sizes in the ALICE experiments and data acquired from collision simulators such as PYTHIA8.

However, Figure 5 also shows that beyond a specific threshold of charged particle density, enhancement of strangeness is only found in Pb-Pb collisions. As $(dN_{ch}/d\eta)_{|\eta|<0.5}$ approaches 10^3, strange quark possessing hadrons are only produced in Pb-Pb collisions. This can be attributed to the lower particle density that Pb-p and pp collisions reach because of their lower center of mass energies. Despite disparity in particle density, the yield of strange quarks detected are very similar, which is why it is assumed that QGP is formed in pp collisions, because the strangeness enhancement in pp collisions is the same in Pb-Pb collisions which are known to produce QGP (WA97 Collaboration, 2000).

Conclusion

Quark Gluon Plasma, or Quark matter, is a state of matter mimicking the state of the universe shortly after the big bang. This is due to the extremely high energy density in QGP that allows quarks to reach a near unbound state. This is created in particle accelerators by colliding heavy ions that briefly reach the extreme conditions necessary for QGP. Dr. Johann Rafelski proved that the strangeness production is a way to prove that QGP, as opposed to a hadron gas, has been formed, and this same marker served as a proof for QGP production in proton to proton collisions at LHC.

Production of strange and antistrange quarks can be attributed to 3 noted processes: flavour creations, gluon splitting and flavour excitation; the most important of which is the gluon fusion process since it is responsible for the greatest degree of strangeness production. The yield of strangeness in pp collisions is lower than that of large system collisions such as Pb-Pb, and this can be attributed to the lower mass not allowing for as high of an energy density in small system collisions.

The production of QGP in pp collisions, however, is still in question despite the ridge property and enhancement of strangeness since other markers such as jet quenching and suppression of charmonia is not observed in pp collisions (Sahoo, 2023).

As of the writing of this paper, the last run of the RHIC is commencing which will utilise the 25 years of the colliders research and experience to measure QGP properties in gold ion collisions with “unprecedented precisions”. This greater degree of precision within heavy ion collisions can serve to provide a more accurate understanding of QGP production to supplement research in small ion collisions (Brookhaven National Laboratory, 2025).

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