Characterizing the QCD Matter at the Large Hadron Collider: Present and Future

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Introduction

The discovery of the primordial matter composed of quarks and gluons as the quanta of the system, that filled our early Universe made a landmark in the high-energy nuclear physics landscape at the Relativistic Heavy-Ion Collider, BNL, USA. This extreme state of subnucleonic matter behaves like a perfect fluid with the lowest shear viscosity-to-entropy ratio found in nature. The Large Hadron Collider (LHC) at CERN, Geneva, opened a new domain with its energy and luminosity frontier, which unraveled new multihadron production dynamics and emerging phenomena in the study of quark-gluon plasma (QGP), including small collision systems showing heavy-ion-like QGP signatures [1]. In this overview, I plan to cover some of the important findings from the LHC experiments with a focus on ALICE, which is the dedicated experiment for QGP studies. These results will be compared with the latest theory/phenomenological developments. The results comprise global properties of QCD matter produced in TeV hadronic and nuclear collisions, multiparticle production dynamics, freeze-out properties, charmonia suppression, enhanced strangeness production, quenching of jets, speed of sound as a probe of the equation of state, and some other important findings at the LHC including the double slit experiment at the femtoscale. We shall also explore the ALICE future upgrades and the associated physics program.

Results and Discussion

The study of the global properties of the produced QCD matter in hadronic and heavy-ion (AA) collisions– like the initial energy density and temperature from the hadronic transverse momentum spectra along with the charged particle phase space density is the day one measurement to ensure if an extreme condition of energy density and temperature to form a deconfined plasma is produced in the laboratory. One compares the obtained values with the lattice QCD estimated ones to ensure that such a condition has been achieved. Identified particle spectra obtained through the excellent PID capabilities of ALICE are a very useful tool to understand the hadrochemistry of the QCD matter as it evolves in time and reveals the plasma's freeze-out properties.

Strangeness enhancement has been considered a smoking gun signature of the formation of a deconfined medium as the enhanced production of strangeness is a QCD-based partonic process. With the temperature of the plasma being higher than the mass of a strange quark, strangeness is thermally produced in the system. Recent measurements in ALICE show the kinetic freeze-out temperatures in high-multiplicity pp collisions at $\sqrt{s}$ = 7 and 13 TeV are comparable with the corresponding values one obtains in AA collisions and approach the pseudocritical QCD temperature $T_c = 156 \pm 1.5$ MeV for a deconfinement transition [2]. Putting all collision systems and energies available at the LHC on a similar footing by taking the final state charged particle multiplicity, one observes a smooth evolution of strangeness production with a strangeness hierarchy– hadrons with higher strangeness show higher yield enhancement. Further, a strong increase of strange

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baryon production with effective energy (collision energy minus the forward energy) is observed for fixed charged-particle multiplicity at midrapidity [3]. These observations, along with the CMS experiment's observation of long-range and near-side ridge-like structures in the two-particle azimuthal correlation in high-multiplicity pp collisions have brought up a new dimension of looking at QGP-like signals in these collisions, which has so far been used as a baseline measurement for characterizing the QCD medium in AA collisions. However, suppression of quarkonia and jet quenching are not yet observed in high-multiplicity pp collisions, which has made the search for QGP droplets elusive. To have a better understanding of multiparticle production dynamics in these hadronic collisions, event topological studies are emerging areas connecting to AA collisions [4].

Compared to RHIC energies the observed degree of charmonia suppression at the LHC AA collisions is lower, which has made the QCD medium effect a dynamic one with suppression/dissociation competing with regeneration of charm quarks because of the higher energy phase space available at the LHC. Further, new and interesting measurements like the speed of sound from mean transverse momentum and the final state charged particle multiplicity by the CMS and ALICE experiments to probe the equation of state of the QCD matter produced in Pb-Pb collisions, have been the most talked about observation recently [5, 6]. ALICE has observed a femtometer scale interference pattern similar to the double-slit experiment using ultra-peripheral Pb-Pb collisions. The measured $\cos(2\phi)$ modulation of the ρ^0 photoproduction yield for different values of the impact parameter, with a strong impact parameter dependence when confronted with theoretical estimations, reveals that it is a result of a quantum interference effect at the femtometre scale [7].

The ALICE upgrade for RUN 4 is planned to have an ITS with a novel vertex detector consisting of curved wafer-scale ultra-thin silicon sensors arranged in perfectly cylindrical layers, which will improve impact parameter resolution and significantly extend the physics capability in heavy-flavor and low-mass dielectron sectors. Additionally, a Forward Calorimeter consisting of a Si-W electromagnetic calorimeter with pad and pixel readout will help ALICE with unique capabilities to measure small-x gluon distributions via prompt photon production. Further, new analysis methods using decay topologies and machine learning techniques can efficiently be used to extract useful physics information like separating prompt and non-prompt charmonia and studying their production dynamics and in-medium properties [8, 9]. For a summary of important RUN 1 and RUN 2 results of ALICE, one can see Ref. [10].

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