Analysis of Beauty Production and Hadronization in Vacuum and Quark-Gluon Plasma with CMS

by

Zhaozhong Shi

Doctoral Thesis Proposal

Submitted for the degree of

Doctor of Philosophy

at

Department of Physics

Massachusetts Institute of Technology

Approved

by

4/09/2021

Thesis Supervisor Date

4/15/2021

Selected Thesis Reader Date

Assigned Thesis Reader Date

PhD Thesis Research Topics

To be trained to become an experimental nuclear physicist, I will carry out my PhD thesis research topics involving in physics measurements, Monte Carlo (MC) simulations, data analysis, software development, detector performance studies, and hardware instrumentation. The following CMS physics analysis will be the main topic of my PhD thesis.

PhD Thesis Research Main Topic

B^+ and B_s^0 Cross Section and Nuclear Modification Factor Measurements in pp and PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV with CMS at LHC

Methodology: Similar to traditional nuclear physics, such as Rutherford Scattering and Deep Inelastic Scattering, to study an unknown matter, physicists create quark-gluon plasma (QGP) in relativistic heavy-ion collisions and set up scattering experiments on QGP to understand its internal structure. However, due to color confinement and the short lifetime of QGP, it is impossible to conduct such scattering experiments using external probes.

Fortunately, we could use particles created along with the QGP from heavy-ion collisions to probe the QGP itself. Heavy quarks, such as bottom and charm quarks, are considered as golden probes because they are predominantly produced from hard scattering processes in the early stage in heavy-ion collisions. They traverse through the QGP medium and retain their identities before decaying. Moreover, due to their long thermal relaxation time, in general they do not fully thermalize. Because their thermal momentum is much larger than the momentum transverse with the QGP medium constituents, they undergo Brownian-like motion. They also lose a significant fraction of their energy through the QGP medium. Thus, they can record the evolution of the QGP. We can study their energy loss mechanism with QGP medium to probe the QGP internal structure and transport properties.

In a simplified schematization, there are two different pictures that describe the internal structure of QGP and the energy loss mechanism of heavy quark in the QGP medium. One, perturbative QCD (pQCD), assumes that the coupling of the constituents of the QGP is weak. Therefore, in the pQCD picture, the QGP is made of weakly coupled quasiparticles. Heavy quarks scatter off the constituents incoherently when propagating through the QGP medium. There are two energy loss mechanisms: collisional energy loss and radiative energy loss. The other picture, AdS/CFT, takes the strong coupling limit. In this picture, QGP behave like liquid and heavy quarks scatter off the constituents coherently in the QGP medium. The AdS/CFT model applies holographic drag force to calculate the energy loss of heavy quark in the QGP medium.

Because we cannot directly detect color charged particles but their final state color neutral hadrons, it is also important to understand the hadronization mechanism of heavy quarks in both vacuum and QGP medium. We can study the hadronization mechanism of heavy quarks in pp collisions, which can also be use as a reference for heavy-ion collisions. In the thermally and chemically equilibrated QGP medium, strange quarks could be produced via the $gg \to s\bar{s}$ process. According to parton coalescence mechanism, heavy quarks, particularly slow movings ones, can pick up nearby strange quarks in the QGP medium to form hadrons. Hence, strange heavy flavor hadrons are expected to enhance compared to the non-strange heavy flavor hadrons in relativistic heavy-ion collisions. Since hadronization is in general non-perturbative, at present, it is not yet feasible to describe hadronization process using first principle QCD calculations. Therefore, physicists developed phenomenological models for hadronizations such as Statistical Hadronization Model, Lung string Model, and Quark Coalescence Model to describe hadronization in vacuum and QGP.

Experimentally, the observables are production cross section, nuclear modification factor, anisotropic flow, and angular correlations of open heavy flavor hadrons. I will use the Compact Muon Solenoid (CMS) detector at the LHC to acquire data, perform data analysis, extract physics messages from my measurements, and compare my results with theory.

Technical Details: I plan to use the CMS Run II 2017 pp and 2018 PbPb datasets as well as the official Monte Carlo simulated samples to perform measurements of fully reconstructed B^+ and B_s^0 cross section in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The decay channels for our studies are $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$ and $B^+ \to J/\psi K^+ \to \mu^+\mu^-K^+$. I will apply Boosted Decision Tree, a machine learning algorithm that improves the signal statistical significance compared to traditional selection cut based method, to B-meson decay topological variables and obtain the optimal selections for the analysis. Our results will shed light on the beauty quark energy loss mechanism in the QGP medium and hadronization mechanism and test theoretical model predictions.

Timeline: Currently, I have completed the analysis of the PbPb dataset and am working to submit my paper for publication. I am also working on the pp dataset and will have analysis approved by the CMS Collaboration before graduation. I aim for late summer graduation and publication of paper by the end of 2021.

Other Research Projects

In addition, I have carried out research with sPHENIX, ALICE, and EIC EMCAL detector research and development. The follow projects will be summarized into one chapter in my PhD thesis:

sPHENIX EMCAL Characterization at Test Beam

Minimum Bias Trigger Development and Run Monitoring for CMS 2018 PbPb Data Taking

Software Developments of Quality Control System for ALICE ITS Upgrade

Simulation of B_s^0 and D_s^+ Cross Section Measurements in pp and AuAu at $\sqrt{s_{NN}}$ = 200 GeV with sPHENIX at RHIC

Development of Future EMCAL Technologies and Application for EIC Experiments