

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

by

Zhaozhong Shi

B.A., University of California, Berkeley (2016)

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Physics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2021

© Massachusetts Institute of Technology 2021. All rights reserved.

Author
Department of Physics
September 5, 2021

Certified by
Yen-Jie Lee
Associate Professor
Thesis Supervisor

Accepted by
Nergis Mavalvala
Associate Department Head of Physics

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

by

Zhaozhong Shi

Submitted to the Department of Physics
on September 5, 2021, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy in Physics

Abstract

A novel analysis of fully reconstructed B_s^0 , B^0 , and B^+ mesons decay into J/ψ and strange hadrons using Compact Muon Solenoid (CMS) Experiment 2017 pp dataset and 2018 PbPb data at the center of mass energy per nucleon $\sqrt{s_{NN}} = 5.02$ TeV at the Large Hadron Collider (LHC) is presented in this thesis. We apply machine learning techniques along with multivariate analysis to obtain significant B-meson signals and extend the kinematic regime of B-meson measurements. In our analysis, B_s^0 signal of greater than 5σ significance is first confirmed in heavy-ion collisions. The inclusive beauty production cross section in pp collisions from the B^+ exclusive decay cross section down to zero transverse momentum is measured. The precise measurement of B-meson nuclear modification factor and B_s^0/B^+ ratio and the comparisons with theoretical model predictions will also be discussed. Our results will help elucidate the beauty production and hadronizaton mechanisms in vacuum and quark-gluon plasma at the LHC energy.

Thesis Supervisor: Yen-Jie Lee
Title: Associate Professor

Acknowledgments

This is the acknowledgements section. You should replace this with your own acknowledgements.

Contents

1	Introduction	25
1.1	The Standard Model of Particle Physics	25
1.2	Quantum Chromodynamics	26
1.2.1	QCD Lagrangian	26
1.2.2	Asymptotic Freedom	27
1.2.3	Perturbative QCD	28
1.2.4	Non-perturbative QCD	29
1.2.5	QCD Factorization Theorem	29
1.2.6	Color Confinement	30
1.2.7	Hadronization	30
1.3	QCD In Extreme Conditions	31
1.3.1	QCD at Finite Temperature	31
1.3.2	Melting of QCD Vacuum	32
1.3.3	Chiral Symmetry Restoration	32
1.3.4	Temperature Dependence of QCD Static Potential	34
1.3.5	Hadron Mass Spectrum and Hagedorn Temperature	35
1.3.6	Color Deconfinement	36
1.3.7	QCD at High Parton Density	36
1.3.8	Color Glass Condensate	37
1.3.9	Gluon Saturation	37
1.3.10	Nuclear Shadowing	38
1.4	QCD Matter	38

1.4.1	QCD Phase Diagram	38
1.4.2	Hadron Resonance Gas	40
1.4.3	Quark-Gluon Plasma	41
1.4.4	Color Superconductor	42
1.4.5	Phase Transition	43
1.4.6	Critical Point	44
1.5	High Energy Nuclear Physics	44
1.5.1	Laboratories	44
1.5.2	Relativistic Heavy Ion Collider (RHIC)	45
1.5.3	Large Hadron Collider (LHC)	47
1.5.4	High Energy Physics Coordinates	49
1.5.5	Stages of Heavy-Ion Collisions	52
1.5.6	Global Event Observables	53
1.5.7	Glauber Model	56
1.6	Characterization of Quark-Gluon Plasma	60
1.6.1	Signatures	60
1.6.2	J/ψ and Υ suppression	60
1.6.3	Jet Quenching	62
1.6.4	Elliptic Flow	65
1.6.5	Strangeness Enhancement	70
1.6.6	Discovery	71
1.6.7	Macroscopic Properties	73
1.6.8	Open Questions	74
1.7	Hard Probes	74
1.7.1	Jets	76
1.7.2	Electroweak Bosons	76
1.7.3	Heavy Quarks	78
1.8	Open Heavy Flavor Physics	79
1.8.1	Heavy Flavor Physics in Vacuum	79
1.8.2	Heavy Quark Diffusion	83

1.8.3	Heavy Quark Energy Loss	86
1.8.4	Heavy Quark Hadronization	89
1.8.5	Experimental Observables	91
2	The CMS Detector	95
2.1	Overview	95
2.2	Triggers	97
2.2.1	L1 Trigger	97
2.2.2	MB Trigger	98
2.2.3	Centrality Efficiency with MB Trigger	100
2.2.4	HLT Trigger	100
2.2.5	DiMuon Trigger	101
2.3	Tracking System	102
2.3.1	Silicon Detectors	102
2.4	Muon System	104
2.5	Calorimeter System	105
2.5.1	ECAL	107
2.5.2	HCAL	107
2.5.3	HF	108
2.6	Relevant Detector Components	108
3	Reconstructed Objects	111
3.1	Event	111
3.2	Hit	113
3.3	Cluster	114
3.4	Track	115
3.4.1	Overview of Basic Principles	115
3.4.2	CMS Tracking Algorithm	118
3.5	Muon	124
3.6	Vertex	125
3.6.1	Primary Vertex	125

3.6.2	Secondary Vertex	125
4	Data Analysis	127
4.1	Tools	127
4.2	Analysis Strategies	128
4.2.1	Physics Goals	128
4.2.2	General Workflow	128
4.2.3	Technical Challenges	128
4.3	Global Event Observables	128
4.3.1	Datasets	128
4.3.2	Total Number of Events	128
4.3.3	Centrality Definition	128
4.3.4	Number of Participants Nucleons	128
4.3.5	Number of Binary Collisions	128
4.3.6	Event Multiplicity	128
4.4	Monte Carlo Simulations	128
4.4.1	PYTHIA	128
4.4.2	Hydjet Embedding	128
4.4.3	EvtGen Package	128
4.4.4	Reweighting	128
4.5	B meson Reconstruction	128
4.5.1	Decay Channels	128
4.5.2	Event Selections	128
4.5.3	Track and Muon Selections	128
4.5.4	Results	128
4.6	Cut Optimization	128
4.6.1	Topological Variables	128
4.6.2	Multivariate Analysis	128
4.6.3	Machine Learning Techniques	128
4.6.4	Training Performance	128

4.6.5	Working Point Determination	128
4.7	Signal Extraction	128
4.7.1	B-meson Invariant Mass Distributions	128
4.7.2	Fitting Models	128
4.7.3	Raw Yield Extraction	128
4.7.4	Signal Significance Estimation	128
4.8	Acceptance and Efficiency Correction	128
4.8.1	Analysis Challenges	128
4.8.2	Fiducial Measurement	128
4.8.3	Fine 2D Efficiency Map	128
4.8.4	Data-Drive Efficiency Correction	128
4.8.5	Tag & Probe Techniques	128
4.8.6	Nominal Results	128
4.9	Cross Section Results	128
4.10	Validation Tests	128
4.10.1	Mass Scraping Test	128
4.10.2	Raw Yield Closure	128
4.10.3	Efficiency Closure	128
4.10.4	sPlot Closure	128
4.11	Statistical Uncertainties Determination	128
4.11.1	Data Bootstrapping	128
4.11.2	Statistical Uncertainties Interpretation	128
4.12	Systematic Uncertainties Estimation	128
4.12.1	Global Observables	128
4.12.2	Branching Ratios	128
4.12.3	Tracking Efficiency	128
4.12.4	Muon Efficiency	128
4.12.5	Selection Efficiency	128
4.12.6	Signal Extraction	128
4.12.7	Summary	128

4.13 Final Results	128
4.13.1 B_s^0 and B^+ Cross Section	128
4.13.2 B_s^0/B^+ Ratio	128
4.13.3 B_s^0 and B^+ Nuclear Modification Factor	128
5 Conclusions	129
5.1 Comparison with Other Experiments and Theoretical Models	129
5.2 Physics Messages Discussion	129
5.3 Conclusions	129
5.4 Future Outlooks	129
6 Other Studies	131
6.1 sPHENIX Heavy Flavor Physics Simulations	131
6.2 sPHENIX Electromagnetic Calorimeter Studies	131
6.3 EIC Electromagnetic Calorimeter R&D	131
A Tables	133
B Figures	135
List of Symbols	139
Abbreviations	141

List of Figures

1-1	The 17 elementary particles, including leptons, quarks, gauge bosons, and Higgs boson, and their basic properties, such as mass, electric charge, spin, in the Standard Model of Particles Physics are shown above.	26
1-2	The running of the strong coupling constant α_s in different experiments at different energy scale Q and the comparison with QCD calculations are shown above.	28
1-3	The QCD factorization theorem applied to a pp collision event involving in soft and hard processes are shown above.	29
1-4	The fragmentation process of charms quarks hadronize into D^\pm (left) and the coalescence process of beauty quark with a strange quark nearby to form a B_s^0 are shown above.	31
1-5	Many-body dynamics of QCD in different physics limits is shown above.	31
1-6	The Feynman diagram of a triangular quark loop under external magnetic field B describe the generation of chiral magnetic current via chiral anomaly is shown above.	33
1-7	The schematics of charge separation due chirality imbalance of quarks under a strong magnetic field in heavy-ion collisions, know as Chiral Magnetic Effect, is shown above.	34
1-8	The QCD potential $V(r)$ from at zero and at finite temperatures as a function of distance r is shown above. Here, the critical temperature $T_c = 192$ MeV. We can see that the QCD saturates at a finite value at finite temperature.	35

1-9	The double-log scale of energy landscape $\ln x$ and the virtuality $\ln Q^2$ diagram picturing the different regimes of the hadron wave function, the saturation line separates the dilute (DGLAP) regime from the dense (saturation) regime is shown above.	38
1-10	The P-T diagram of water in gas, liquid, solid phases is shown above.	39
1-11	The theoretical QCD phase diagram of different QCD matter, including hadron resonance gas, quark-gluon plasma, neutron star, and color superconductor, as function of temperature and baryon chemical potential is shown above. The solid line indicates the conjecture of first order phase transition between quark-gluon plasma and hadron gas while the dash line is a smooth crossover.	39
1-12	The schematic plot of potential energy between two nucleon via pion exchange as a function of distance is shown above [53]. This potential with a well minimizing near 100 MeV allow nucleons to bind together and form atomic nuclei and nuclear matter.	40
1-13	The pressure and energy density from lattice simulation compared with ideal hadron resonance gas and Van der Waas interaction at different $\frac{\mu_B}{T}$ are shown above.	41
1-14	Predictions the normalized pressure to the stefan Boltzmann pressure $P_{SB} = \sigma T^4$ as a function of temperature T for three-flavor QGP obtained from lattice QCD, the MIT bag model and perturbative QCD including their uncertainties bands are shown.	43
1-15	The overview of RHIC at BNL from the sky view is shown above. The actual locations of other accelerator facilities at BNL, including Linac, Booster, EBIS, NSRL, AGS, and the experiments at RHIC,STAR and PHENIX, are also labelled.	46
1-16	The acceleration of gold ions for RHIC is shown above.	47
1-17	The overview of LHC at CERN from the sky view is shown above. The actual locations of the experiments at the LHC, ATLAS, CMS, ALICE and LHCb, as well as the French-Swiss border, are also labelled.	48

1-18 The schematic overview of CERN accelerator complex with the accelerators labelled is shown above. Proton and lead ion are accelerated using these facilities to boost to the energy scale of TeV.	49
1-19 The cylindrical coordinate system in the position space (left) and the space time diagram (right) for relativistic heavy-ion physics analysis are shown above.	50
1-20 An event of a typical heavy-ion collisions event with different stages as time evolves is shown above.	52
1-21 The space-time evolution of heavy-ion collisions is shown above. It consists of four stages: initial state before the collision, the creation of quark-gluon plasma right after of the collision, hadronization after quark-gluon plasma expands and cools down, and the freeze-out stage, first chemical freeze out when the particle species no longer change, and then kinetic freeze out when the inelastic scattering process ceases.	53
1-22 The definition of impact parameter b in heavy-ion collision and the overlapping interaction region and the break up remnants of the two nuclei, which is called spectator, moving in the z-direction are shown above. We can also see that heavy-ion collisions have an almond shape interaction region, which results in the azimuthal anisotropic emission of final state particles.	54
1-23 The plot showing relationship among number of charged particle, N_{ch} , related to the number of participating nucleon N_{part} , the differential cross section $\frac{d\sigma}{dN_{ch}}$, and the centrality, according to the Glauber Model calculations, is shown above.	56
1-24 Two gold ions collide head-on in the STAR detector. The event with reconstructed tracks of final state particles are display by STAR TPC shown above.	57

1-25 The A-B collision with the definition of the impact parameter vector \vec{b} and the distance of nucleon to the center of projectile B \vec{s} are shown above. The distance of the nucleon in B to center of the target A is $\vec{s} - \vec{b}$ according to vector subtraction rule. Here we assume both nuclei A and B are perfect spheres.	58
1-26 The N_{part} and N_{coll} as a function impact parameter calculated from the Glauber Model with optical approximation (lines) and from MC simulations (circles) are shown above. We can see they have almost perfect agreement with each other.	60
1-27 The nuclear modifications factor R_{AA} of fully reconstructed J/ψ as a function of p_T (left) and N_{part} (right) measured by the STAR experiment (red data points) at RHIC and CMS (blue diamond data points) and the ALICE (blue circle data points) experiment at the LHC are shown above. We can see that the $J/\psi R_{AA}$ is below 1 for both p_T and N_{part} . There is no significant p_T dependence of $J/\psi R_{AA}$. The $J/\psi R_{AA}$ decreases as N_{part} increases, consistent to the increasing creation probability of QGP with larger N_{part}	62
1-28 The nuclear modifications factor R_{AA} of fully reconstructed Υ as a function of N_{part} measured by the STAR experiment (left) at RHIC and CMS experiment (right) at the LHC are shown above. We can see that R_{AA} of the three Υ states is below 1 for both $N_{part} > 3$. The $J/\psi R_{AA}$ decreases as N_{part} increases, consistent to the increasing creation probability of QGP with larger N_{part} . In addition, a sequential suppression of ΥR_{AA} is observed by the CMS experiment: $R_{AA}^{\Upsilon(1S)} > R_{AA}^{\Upsilon(2S)} > R_{AA}^{\Upsilon(3S)}$, which agrees with the expectation QGP color screening effect.	63

1-34 The yield ratio of ϕ/π as a function N_{part} in p + p, p + Au, and Au + Au from the STAR experiment at RHIC (left) and strange hadrons $K_s^0, \Lambda^+, \Xi^0, \Omega^-$ as a function of $\langle dN_{ch}/d\eta \rangle$ from the ALICE experiment at LHC are shown above. We can see a clear trend of the increase of the strange hadron to pion ratio as the event multiplicity increases. In addition, we also see that the ϕ/π ratio increases as $\sqrt{s_{NN}}$ increases, which suggests the strangeness content enhances as the temperature of the system increase.	71
1-35 The announcement of discover of QGP in a special seminar at CERN on February 10 2000 is shown above.	72
1-36 The schematic view of Rutherford scattering (left) and Deep Inelastic Scattering (right) experimental setups are shown above.	75
1-37 The schematic plot illustrating dijet imbalance (left) compared to the display of original event (right) are shown above. Image from [137]. . .	76
1-38 The R_{AA} vs p_T of direct photon (left) and Z boson (right) measured with the CMS experiment at LHC are shown above. We could see that the R_{AA} of both photon and Z boson are consistent with unity within their uncertainties.	77
1-39 The schematic plot of a Z + jet event with the creation of QGP and the invariant mass of fully reconstructed Z boson via the decay channel $Z \rightarrow \mu^+ \mu^-$ in the front cover of Physics Review Letter (Volume 119, Issue 8) is shown above. We could see that the Z boson is essentially unmodified by the QGP medium.	77
1-40 The four lowest order tree level Feynman diagrams of heavy quark pair production are shown above.	78
1-41 The schematic plots of heavy quark production and hadronization in vacuum (left) and QGP (right) are shown above.	79
1-42 The charm quark (left) and beauty quark (right) transverse momentum p_T distribution at $\frac{d\sigma}{dp_T}$ at $ y < 1$ from FONLL calculations are shown above.	80

1-43 Single-inclusive hadron production process, where fragmentation function are involved, in (a) electron-positron annihilation, (b) deep-inelastic lepton-nucleon scattering, (c) proton-proton scattering are shown above.	80
1-44 R , the corrected yield ratio of B_s^0/B^+ , as a function the pp collision energy \sqrt{s} (top), the f_s/f_d ratio as a function p_T (middle), and the f_s/f_d ratio as a function η_B (bottom), from the LHCb experiment are shown above.	84
1-45 The charm quark fragmentation fraction to different charm hadrons species in e^+e^- , ep , and pp collisions are presented above. From the ALICE experiment, we can clearly see that the fragmentation fraction of D^0 has drop by about 40% while the Λ_c^+ has enhanced by about a factor of 4. Therefore, the hadronization universality is clear broken at the LHC energy in the charm sector.	85
1-46 The schematic demonstration of the pQCD picture: collisional energy loss (left) and radiative energy loss (right) of heavy quarks in the QGP medium are shown above.	87
1-47 The schematic demonstration of ADS/CFT picture: the energy loss of a quark in the QGP medium holographically due ADS/CFT drag force.	87
1-48 The schematic demonstration of a charm quark radiate and suppression in small angle due to the dead cone effect in the QGP medium is shown above.	88
1-49 The ladder diagram used by the TAMU model to describe heavy quark diffusion in the QGP medium is shown schematically above.	89
1-50 The NCQ scaled $D^0 v2/n_q$ vs K_T/n_q and the comparison light hardons measured by the STAR experiment at RHIC (left) and the CMS experiment at LHC (right) are shown above.	92
1-51 The $D^0 R_{AA}$ vs p_T with the STAR experiment in 0 - 10%, 10 - 40%, and 40 - 80% centrality at RHIC and the D^0 , B^+ , non-prompt J/ψ and charged hadrons R_{AA} vs p_T at at 0 - 100% centrality with the CMS experiment at LHC are shown above.	92

1-52 The fully reconstructed Λ_C^+/D^0 ratio in pp and heavy-ion collisions measured by the STAR experiment at RHIC (left) and the CMS experiment at LHC (right) are shown above.	93
2-1 The front view of the CMS detector at the underground collision hall is shown above.	96
2-2 The schematic view of the CMS detector with brief descriptions of all its components is shown above. Image from [182]	96
2-3 The figure above demonstrates how the CMS L1 hardware trigger function schematically.	98
2-4 In the CMS 2018 PbPb Run 326791, the ZB data (red), Empty Bunches (blue), and MB data (green) ADC distributions (left), and the HF energy according to the charge collected as a function of ADC (right) are shown above. We can see that the HF energy is about (0.5 - 1) conversion factor to the ADC.	99
2-5 In the CMS 2018 PbPb Run 326791, the ZB data (red), Empty Bunches (blue), and MB data (green) maximum ADC distributions (left) and the efficiencies of MB OR (blue) and MB AND (red) as a function ADC threshold (right) are shown above.	99
2-6 The figure above shows the total number of 20 PbPb MB events from and corresponding luminosity how the as a function Run ID from November 15 to December 2 2018.	100
2-7 The efficiency vs centrality with $ADC > 16$ for MB OR (blue) and MB AND (green) are shown above.	101
2-8 The dimuon invariant spectrum $m_{\mu\mu}$ reconstructed by CMS HLT trigger in the 2018 pp dataset is shown above. We can identify the neutral vector boson resonances shown above.	102
2-9 The schematic view of the CMS tracking system is shown above.	103
2-10 The schematic plot explaining how a silicon tracker detector charged particles is shown above.	104

2-11 The particle flow of long life particles, such as electrons, muons, photons, charged hadrons: π , K , p , and neutral hadrons: neutrons, in the CMS detector are shown above.	105
2-12 A visualization of Townsend Avalanche (top) and schematic plot of the CMS drift tube detecting a muon (bottom) are shown above.	106
2-13 The schematic view of the CMS forward region including HF, CASTOR, and ZDC (left) and the physical view of the HF (right) are shown above.	108
2-14 The distribution of sum of HF energy using Minimum Biased Trigger and Jet Trigger with the classification of centrality binning is shown above. As we can see, the energy of the HF increase as the collision events become more central, which is within our expectation.	109
2-15 The picture of the CASTOR (left) at the CMS underground collision hall and ZDC (right) at 140 m away from the CMS beam interacting point are shown above.	109
3-1 The bubble chamber picture of the an Ω^- baryon reconstructed from an event: $K^- p \rightarrow K^0 K^+ \Omega^- \rightarrow \Xi^0 \pi^- \rightarrow \Lambda^0 \gamma\gamma \rightarrow \pi^- p$ taken from the group led by Nicholas Samios at BNL is shown above.	112
3-2 The schematic plot of a CMS silicon chip with pixel sensor is shown above.	113
3-3 The schematic views of a charged particle (blue line) entering the silicon pixel layer (black) at a normal angle (left) and a small tilting angle (right) with the pixels fired (red) are shown above. The left cluster has 1 hit and the right cluster has 4 hits.	114
3-4 The helix motion of a charged particle under a constant and uniform magnetic field \vec{B} pointing in the $+z$ direction (left) and the fit to 3 points to determine the center and the radius of a circle (right) are shown above.	116

3-5 A track (blue) initiated from the beam spot (orange) passing through 3 layers of pixel detectors (black) with 3 clusters (red) is shown on the left and the circular fit to the 3 clusters with the definition of R , L , and θ is shown on the right.	117
3-6 The transverse momentum resolution $\frac{\sigma_{p_T}}{p_T}$ of a track as a function of transverse momentum p_T is shown above.	118
3-7 The Data (blue) and MC (red) of the number of primary vertex distribution (left) and event multiplicity (right) are shown above. We can see that an event could be more than 1 vertices with more than 100 tracks, which make it very challenging to perform tracking.	119
3-8 The schematic block diagram of CMS tracking workflow is shown above.	120
3-9 The four steps of CMS track finding workflow (left) and the schematic demonstration of each step (right) are shown above.	121
3-10 The four schematic plots demonstrating each of the four steps for track finding are shown respectfully above.	122
3-11 The schematic demonstration Kalman filter along with Rugga-Katta propagator to improve the tracks fitting is shown above.	123
3-12 The CMS tracking efficiency (left) and fake rate (right) as a function of p_T from simulations of $t\bar{t}$ events at 13 TeV with different pileup conditions are shown above.	124
B-1 Armadillo slaying lawyer.	135
B-2 Armadillo eradicating national debt.	136

List of Tables

A.1 Armadillos	133
--------------------------	-----

Chapter 1

Introduction

1.1 The Standard Model of Particle Physics

Physics is the research of relationship between space and time and energy and matter. Physicists enjoy searching for symmetries and consideration laws in nature. They develop elegant mathematical formulations to describe the beauty of the nature and predict or explain the experimental results and observed phenomena.

There are four known fundamental forces in nature: gravitational force, electromagnetic force, strong force, and weak force. The gravitation force describes the interaction between two massive objects. The electromagnetic force describes the interaction between electrically charged objects. The strong force describes the interaction between nucleons. The weak force describes the radioactive decay of particles. The Standard Model (SM) of Particle Physics is based on theoretical of relativistic quantum field theory with a gauge symmetry of $SU(3) \times SU(2) \times U(1)$ [1]. It unifies the strong, weak, and electromagnetic into a single theory and describes all particles participating in these interactions. The ingredient of the standard model are lepton, quarks, gauge boson, and Higgs boson shown in Figure 1-1.

There are 19 parameters in the Standard Model: 6 quark masses, 3 lepton masses, 3 coupling strengths, 4 CKM angles, Higgs mass, vacuum expectation value, and QCD vacuum angle. These parameters are determined from the experiments. Physicists perform calculations based on the Standard Model and predict the cross section

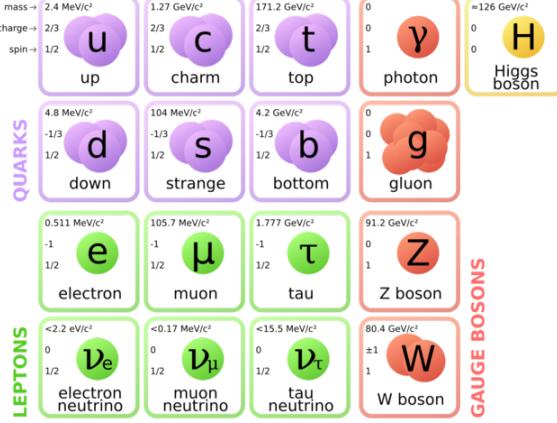


Figure 1-1: The 17 elementary particles, including leptons, quarks, gauge bosons, and Higgs boson, and their basic properties, such as mass, electric charge, spin, in the Standard Model of Particles Physics are shown above.

of different processes in high energy physics experiments. Since it is proposed in the 1970s, the Standard Model has been tested extensively in countless high-energy physics experiments. Its prediction holds for all of them with very few exceptions. The Standard Model consists of two sectors: the Electroweak theory (EW) and Quantum Chromodynamics (QCD). The Lagrangian of the Standard Model can be written as the sum of EW and QCD: $\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD}$

1.2 Quantum Chromodynamics

1.2.1 QCD Lagrangian

QCD, a non-abelian gauge theory with $SU(3)$ symmetry, is the theory for the strong interaction between quarks and gluons. The QCD Lagrangian is as follows:

$$\mathcal{L}_{QCD} = \bar{\Psi}^i i(\not{D})_{ij} \Psi^j - m \bar{\Psi}^i \Psi_i - \frac{1}{16\pi^2} G_a^{\mu\nu} G_a^{\mu\nu} \quad (1.1)$$

Where

$$\not{D} = \gamma^\mu \partial_\mu - ig_s \frac{\lambda}{2} \gamma^\mu A_\mu \quad (1.2)$$

$$G_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial_\nu A_a^\mu + g_s f_{abc} A_b^\mu A_c^\nu \quad (1.3)$$

Here, λ are the Gell-Mann Matrices. f_{abc} is the structure of constant of $SU(3)$. A^μ is the eight gluon field. g_s is the strong coupling constant. The color indices i and j run from 1 to 3, which stands for 3 colors: red, blue, and green. The gluon field indices a , b , and c run from 1 to 8, standing for the 8 gluon state (Gluon octet as the combination of 3 color and 3 anticolor: $3 \times \bar{3} = 1 \oplus 8$) living in the adjoint representation of $SU(3)$ of color.

1.2.2 Asymptotic Freedom

The running of the strong coupling constant $\alpha_s = \frac{g_s^2}{4\pi}$ according to the 1-loop calculations in the renormalization theory [2] is shown as follows

$$\alpha_s(Q^2) = \frac{12\pi}{(11N_c - 2N_f) \ln(\frac{Q^2}{\Lambda_{QCD}^2})} \quad (1.4)$$

We can see that as the energy scale increases, the coupling strength of the strong interaction decreases. This is in contrast to QED where the electromagnetic coupling strength increases as the energy scale increases. In the ultra-violate limit $Q^2 \rightarrow \infty$ and $\alpha_s \rightarrow 0$, quarks and gluons behave like free particles. This feature in QCD is call Asymptotic Freedom [4]. Meanwhile, in the infrared limit, the strong coupling constant increases. Near the $\Lambda_{QCD} \simeq 100$ MeV, the coupling is greater than 1, where the perturbative expansion of QCD breaks down. Experimentally, physicists measure the strong coupling constant at different energy scales from different experiments at different colliders. Figure 1-2 [3] show the running of strong coupling constant in experiment and comparison with the theoretical calculations

An excellent agreement between the theoretical predictions and experimental results of the strong coupling constant is observed in Figure 1-2.

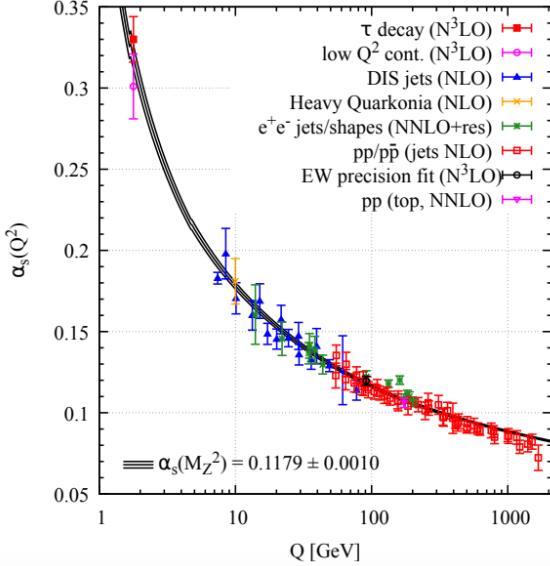


Figure 1-2: The running of the strong coupling constant α_s in different experiments at different energy scale Q and the comparison with QCD calculations are shown above.

1.2.3 Perturbative QCD

It is mathematically proven that there is in general no closed form expression for the Standard Model Lagrangian under the Quantum Field Theory framework. Therefore, physicist develop perturbation theory in Quantum Field Theory and apply it to the Standard Model. Physicist obtain asymptotic expansions as power series of the coupling constants and approximately calculate the expectation values of the observables to prediction experimental results.

For QCD, in high energy and hard scattering processes, since the coupling constant is much less than 1, perturbation theory is applicable to QCD. Feynman rules and diagrams are applicable in the matrix element to evaluate the cross section of hard parton-parton scattering. Perturbative QCD (pQCD) calculations have been tested various experiments such as electron positron annihilation, deep inelastic electron proton scattering, and high energy proton-proton collisions.

1.2.4 Non-perturbative QCD

At low energy and soft scattering processes, the coupling constant is greater than 1, perturbation theory of QCD breaks down. Many low-energy QCD processes such as hadronization and hadron-hadron interactions are non-perturbative. Historically, physicists developed Lattice gauge theory such as Lattice QCD to calculate the mass [5] of the proton and effective theory such as Chiral Perturbation Theory to study pion-nucleon scattering [6]. Non-perturbative QCD have achieved many successes. Currently, many novel developments applying non-perturbative QCD to understand nuclear structure and nucleon spin structure are being carried by physicists.

1.2.5 QCD Factorization Theorem

The QCD factorization theorem states that in events involving both hard and soft QCD processes, hard and soft process are mathematically factorized in the cross section computation as follows [7]:

$$\sigma_X = \sum \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij \rightarrow X}(p_1, p_2, \mu_R^2, \mu_F^2) \quad (1.5)$$

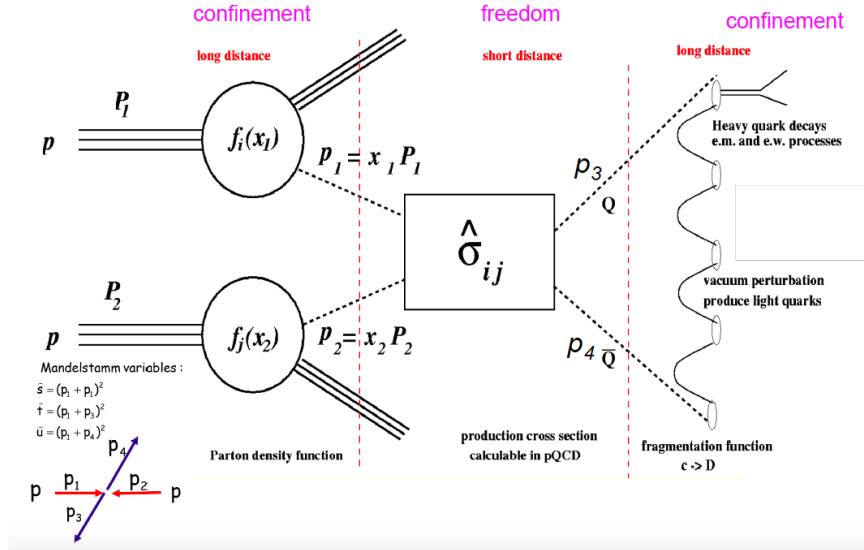


Figure 1-3: The QCD factorization theorem applied to a $p\bar{p}$ collision event involving in soft and hard processes are shown above.

The hard processes are encoded in the factor of partonic cross sections while the soft processes are measured in experiments. Physicists developed parton distribution function to describe initial kinematic of partons inside hadrons and fragmentation function to describe the parton hadronization process. Both parton distribution function and fragmentation function are measured in experiments.

Physicists apply QCD factorization theorem to perform pQCD calculation of hard scattering processes and use the measurement from the to understand the hadron spectroscopy in electron-positron, electron-proton, and proton-proton collisions.

1.2.6 Color Confinement

Another feature of QCD as a non-abelian gauge theory is color confinement. The strong force carrier gluon itself is also color charged. Color charged partons, namely quarks and gluons, are never detected in isolation. In experiments, only color neutral hadrons are detected. Currently, the analytic explanation of color confinement is still not yet rigorously proven. The theoretical explanation of color confinement in QCD remains one of the unsolved problem in physics.

1.2.7 Hadronization

The formation process hadrons from partons is called hadronization. Because in experiments we only measure final state hadrons, in order to study the interactions and dynamics of quarks and gluons during partonic stage from hadron spectra, we also need to understand hadronization mechanisms. However, hadronization is in general non-perturbative and cannot yet be described by first principle QCD calculations. Therefore, physicists make phenomenological models such as the Statistical Hadronization Model [8], Lund String Model [9], Quark Coalescence Model [10] to study hadronization. Figure 1-4 shows the schematics of hadronization of a beauty quark via fragmentation and coalescence process.

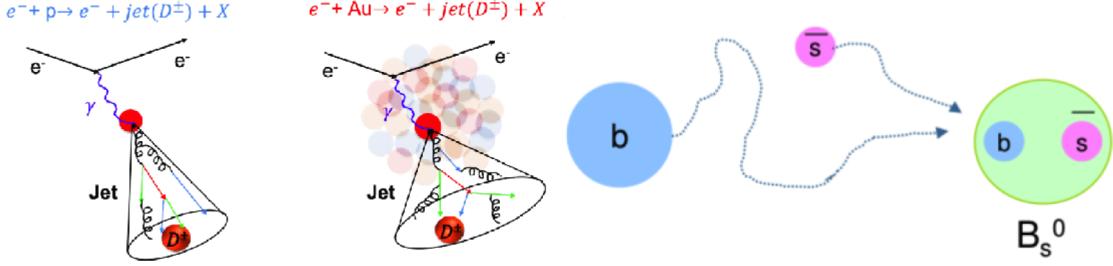


Figure 1-4: The fragmentation process of charms quarks hadronize into D^\pm (left) and the coalescence process of beauty quark with a strange quark nearby to form a B_s^0 are shown above.

1.3 QCD In Extreme Conditions

Historically, many efforts to understand QCD in extreme conditions have been made [11]. There are mainly two directions: temperature and parton density. Figure 1-5 shows the different studies of QCD in different conditions [12]:

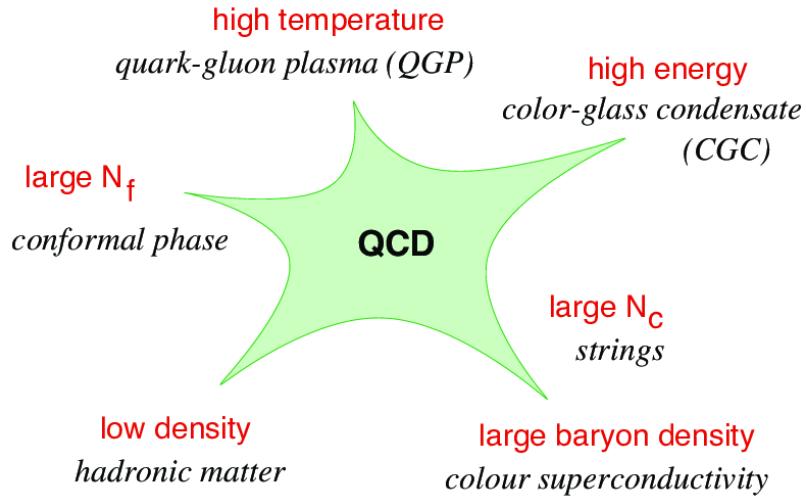


Figure 1-5: Many-body dynamics of QCD in different physics limits is shown above.

1.3.1 QCD at Finite Temperature

In QCD, under extremely high energy density, the degree of freedom of the system increases via particle production. Many-body dynamics become relevant. In the

limit of large number of quarks and gluons, after a sufficiently long period of time, the system reach thermal equilibrium via the strong interaction [13–15]. Therefore, a description based on thermodynamics can be formulated to study such systems [17]. We call this thermalized and strongly interacting many-body system of quarks and gluons to be QCD matter.

Therefore, an additional variable temperature (\mathbf{T}) can be introduced to study such QCD systems. There are some interesting QCD phenomenologies involving temperature as listed in the following subsections.

1.3.2 Melting of QCD Vacuum

The QCD vacuum is filled with various condensates of quarks-antiquark pair and gluon fields [16]. In the QCD vacuum, the three flavor of light quarks: u , d , s form a flavor symmetry group of $SU(3)_f$. However, for quark-quark pair, the $SU(3)_f \times SU(3)_f$ chiral symmetry is spontaneously broken. For example, in the vacuum, a quark-antiquark pair field has a non-vanishing expectation value of $\langle 0 | \bar{\psi}(x)\psi(x) | 0 \rangle \simeq (250 \text{ MeV})^3$ [1]. Therefore, in the physical QCD vacuum, all color field are confined in hadrons. In 1974 T.D. Lee formulated the idea that the non-perturbative vacuum condensates could be “melted down ... by distributing high energy or high nucleon density over a relatively large volume” [18, 19]. As the energy density in space increases, the color field start to permeate all space. This is effective melting the QCD Vacuum as the temperature of the system increases. Therefore, the temperature of the system will affect the QCD vacuum structure.

1.3.3 Chiral Symmetry Restoration

At a finite critical temperature $T_c > 0$, the quark-antiquark pair field will have a vanishing expectation value. In this scenario, massive quarks behave as if massless [20]. Thus, the chiral symmetry of quarks is restored [21]. Therefore, under a strong magnetic field, due to the restored chiral symmetry, the quarks generate anomalous chiral current j_5^μ described by $U(1)_A$ chiral anomaly, calculated by the famous “Triangle

Feynman diagram” in Figure 1-6 shown below:

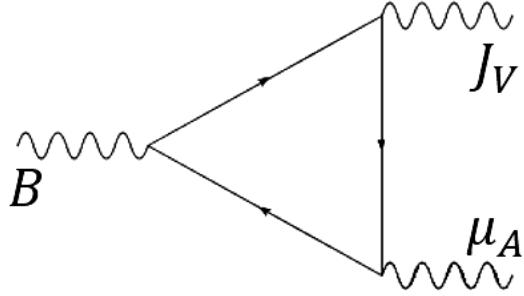


Figure 1-6: The Feynman diagram of a triangular quark loop under external magnetic field B describe the generation of chiral magnetic current via chiral anomaly is shown above.

The anomalous chiral current $j^{\mu 5}$ is given by [22]

$$\partial_\mu j_5^\mu = -\frac{N_f g^2}{16\pi^2} G_a^{\mu\nu} \widetilde{G}_{\mu\nu}^a \quad (1.6)$$

Here $G_a^{\mu\nu}$ is defined as

$$\widetilde{G}_{\mu\nu}^a = \frac{1}{2} \epsilon_{\mu\nu\lambda\sigma} G^{\lambda\sigma a} \quad (1.7)$$

According to the continuity equation of chiral current

$$\frac{\partial \rho_5}{\partial t} + \nabla \vec{j}_5 = 0 \quad (1.8)$$

By definition, the chiral current ρ_5 is the difference of the right-handed charge ρ_L and left-handed charge ρ_R .

In terms of number of particles $N_5 = \frac{Q_5}{e} = \int \rho_5 e d^3x$, integrating both sides by the spatial volume and divide by the volume, we have

$$\frac{dN_5}{dt} = \int d^3x \nabla \vec{j}_5 = \int -\frac{N_f g^2}{16e\pi^2} G_a^{\mu\nu} \widetilde{G}_{\mu\nu}^a d^3x \quad (1.9)$$

The chiral chemical potential μ_5 is proportional to the number of particle N_5 : $j_5 \propto N_5$. This non-vanishing anomalous chiral current implies non-zero chiral magnetic

dipole moment density $\mu_5 \neq 0$. Finally, under an external magnetic field, the induced electric current j_V^μ is given by

$$\vec{J}_V = \frac{N_c e}{2\pi^2} \mu_A \vec{B} \neq 0 \quad (1.10)$$

In experiments, we should expect to see the separation of left-handed and right-handed quarks Q_V due to this electric current \vec{J}_V where charge imbalance between the positive and negative direction along the magnetic field [23] as $\Delta Q = \int_0^\tau \vec{J}_V \cdot \vec{A} dt \neq 0$. We call this chirality imbalance effect due to the restored chiral symmetry of quarks at finite temperature as **Chiral Magnetic Effect** [24]. Figure 1-7 illustrates the schematics of Chiral Magnetic Effect in Heavy-Ion Collisions [25]

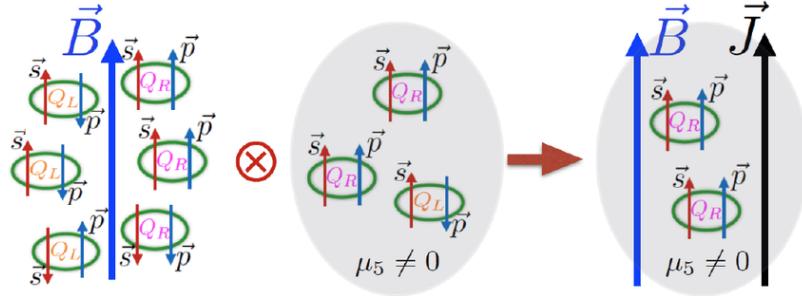


Figure 1-7: The schematics of charge separation due chirality imbalance of quarks under a strong magnetic field in heavy-ion collisions, know as Chiral Magnetic Effect, is shown above.

Currently, physicists are actively looking for evidences of Chiral Magnetic Effect in experiments but have not yet reported any conclusive results so far [26].

1.3.4 Temperature Dependence of QCD Static Potential

If we consider two color charged quarks in the limit of infinite mass and are essentially at rest in the lab frame, we can define a QCD static potential between these two quarks due to the strong interaction. In vacuum, such a potential is called “Cornell Potential” [27]. The potential as a function of the distance between two quarks is shown as follows:

$$V(r) = -\frac{\alpha_{eff}}{r} + \sigma r \quad (1.11)$$

Here, α_{eff} is the effective strong coupling coupling between the two quarks and $\sigma \simeq 0.184 \text{ GeV}/c$ is the string coupling constant [28].

Now if we consider at finite temperature T with a thermalized system between the two quarks, the QCD static potential becomes:

$$V(r) = -\frac{\alpha_{eff}}{r} e^{-m_D r} + \frac{\sigma}{m_D} (1 - e^{-m_D r}) \quad (1.12)$$

Here, $m_D \sim g_s T$ is the Debye mass due to Debye color screening effect [29], which essentially modifies the gluon propagator by inserting a finite mass term: $-i \frac{g^{\mu\nu}}{q^2} \rightarrow -i \frac{g^{\mu\nu}}{q^2 - m_D^2}$. In fact, Equation (2) reduces to the Cornell potential when $T = 0$. The QCD static potential is shown below in Figure 1-8 [30]

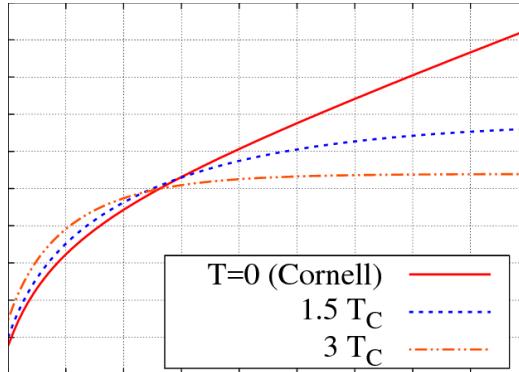


Figure 1-8: The QCD potential $V(r)$ from at zero and at finite temperatures as a function of distance r is shown above. Here, the critical temperature $T_c = 192 \text{ MeV}$. We can see that the QCD saturates at a finite value at finite temperature.

Many interesting physics implications can be derived from QCD at finite temperature.

1.3.5 Hadron Mass Spectrum and Hagedorn Temperature

In 1965, Hagedorn proposed a statistical thermodynamically bootstrap model, giving the temperature dependence of hadron spectra [31]. According to the principle of

asymptotic bootstrap, in the limit of high mass resonance $m \rightarrow \infty$ the mass spectrum of hadrons $\rho(m)$ grows exponentially

$$\rho(m) \propto m^{-\frac{5}{2}} e^{\frac{m}{T_0}} \quad (1.13)$$

Here, $\rho(m) dm$ stands for the number of excited hadron with mass between m and $m + dm$. $T_0 \simeq 158$ MeV is the temperature parameter extract from experiments. As $T \rightarrow T_0^-$, $\rho(m) \rightarrow \infty$. The mass spectrum of hadrons diverges. Therefore, it stands for the highest possible temperature achievable for the strong interaction between hadrons. Hence, T_0 is also called the “Hagedorn Temperature”. For $T > T_0$, the description of color-neutral hadrons mass spectrum will break down, indicating a new type of matter with deconfined degree of freedom in the interaction [32].

1.3.6 Color Deconfinement

As mentioned in the sections above, we see that, at finite temperature, the QCD static potential is screened and color degree of freedom become relevant in the system. As the temperature of the system increase, the quarks and gluon inside color-neutral hadrons will have more available space to move around and start to deconfine [33]. At some critical temperature T_c , quarks and gluons will form a new type color deconfined QCD matter, which is called Quark-Gluon Plasma (QGP). The typical temperature of QGP is in the order of a few hundred MeV or about 10^{12} K, which is about hundreds of thousands times hotter than the core of the Sun.

1.3.7 QCD at High Parton Density

In the other direction, while keeping zero temperature, by increasing density of the color fields of the system, another form of QCD matter will also emerge [34]. Due to confinement, a single quark or gluon cannot exit in vacuum. Therefore, the simplest form of QCD system will be a meson, which consist of one quark and one antiquark. The next more complex system will be baryon, for instances, nucleons, which consistent of three quarks. We can then use nucleons to form atomic nuclei and even

neutron stars. As the number of nucleons in the system increases, the nucleon density also increases, which increase the color field density. Below, we will discuss the consequence of increasing color field density by increasing the color field lines and decreasing the volume of the system. In general, we can study QCD at High Parton Density by probing small- x physics [35]

1.3.8 Color Glass Condensate

One way to increase the color field density is by decreasing its volume. The radius of a hadron will shrink due to the Lorentz contraction effect as it moves with respect to the spectator. However, since the number of color charges inside the does not change, the color field density will increase. According to the parton distribution function (pdf), at small x , the gluon pdf will dominate. Hence, at very high energy, which is equivalent to small x , the hadrons will turn into “gluon walls” [36] and form a dense color field of matter [37] named Color Glass Condensate (CGC) is formed [38].

1.3.9 Gluon Saturation

However, it is believed that color density of a hadron will not increase indefinitely due to gluon splitting process: $g \rightarrow gg$. At very small x , recombination of gluons: $gg \rightarrow g$ also occurs. These two processes compete and eventually balance. They result in a equilibrium color density or, equivalently, a saturation scale Q_s^2 [39]. We call this phenomenon as gluon saturation. Gluon saturation can be described by QCD evolution equations [40–44]. Figure 1-9 below shows schematically the different state of a hadron in the double-log scale plot of energy landscape $\ln x$ and the virtuality $\ln Q^2$ [45]

At the EIC, experiments will also be capable of precisely investigating gluon saturation effects through dihadron correlations analysis [46].

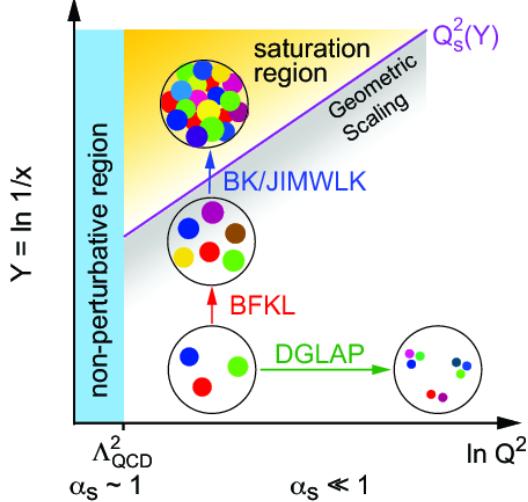


Figure 1-9: The double-log scale of energy landscape $\ln x$ and the virtuality $\ln Q^2$ diagram picturing the different regimes of the hadron wave function, the saturation line separates the dilute (DGLAP) regime from the dense (saturation) regime is shown above.

1.3.10 Nuclear Shadowing

At high energy, or equivalently, small x , according to the QCD evolution equation, the gluons inside the nucleon of the nuclei will “create shadows” on each other [47]. The high density effects results in the modification of the nuclear structure function and the gluon nucleon parton distribution [48]. Therefore, in high energy hadron-nucleus collision, we expect to see the decrease of cross section per participant nucleons at small- x region compared other x region [49]. We call this effect as “nuclear shadowing (of gluons)” [52].

1.4 QCD Matter

1.4.1 QCD Phase Diagram

Similar to form everyday matters such as metal, water, wood, glass, and plastic, which are formed by electromagnetic interaction and could all be described macroscopically by equations of states that are parameterized by thermodynamic variables. Figure 1-10 shows the phase diagram of water (H_2O) at different temperature and pressure:

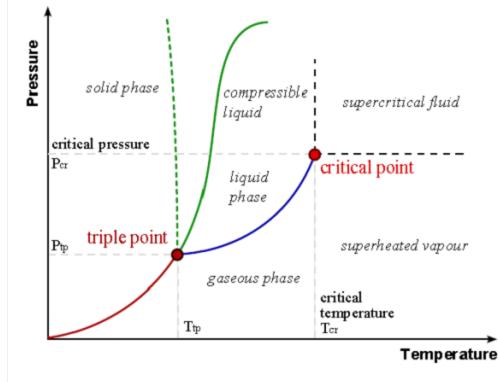


Figure 1-10: The P-T diagram of water in gas, liquid, solid phases is shown above.

Similarly, QCD matter is the matter formed by numerous quarks and gluons via the strong interaction and can also be described by equations of states. Like our everyday matter which has gas, liquid, and solid phases at different pressure and temperature, QCD matter also has different phases at different temperature and baryon chemical potential. and can be described by QCD phase diagrams. Figure 1-11 shows the QCD phase diagram at different temperature and baryon chemical potential:

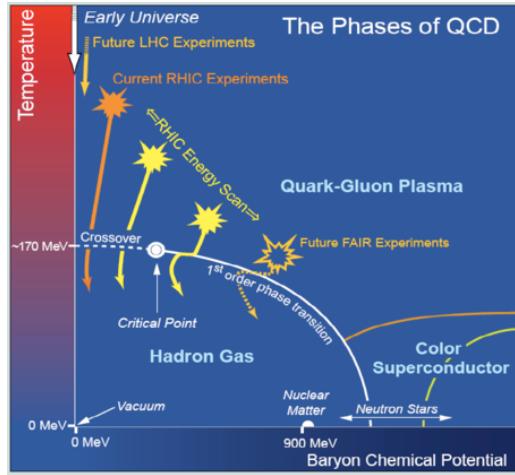


Figure 1-11: The theoretical QCD phase diagram of different QCD matter, including hadron resonance gas, quark-gluon plasma, neutron star, and color superconductor, as function of temperature and baryon chemical potential is shown above. The solid line indicates the conjecture of first order phase transition between quark-gluon plasma and hadron gas while the dash line is a smooth crossover.

1.4.2 Hadron Resonance Gas

One of the most familiar type of QCD matter is hadron resonance gas, which lies at the left bottom corner of the QCD phase diagram. Hadron resonance gas is a system of color neutral hadrons at relative low temperature. The interaction between hadrons are the Van der Waals like strong nuclear force as the residue of the color force via exchange of mesons. The strong nuclear force between two nucleons shown below Figure 1-12.

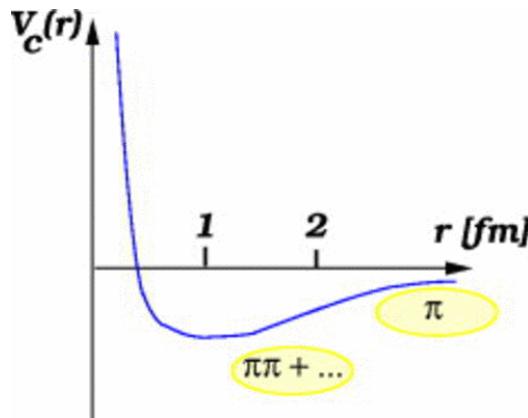


Figure 1-12: The schematic plot of potential energy between two nucleon via pion exchange as a function of distance is shown above [53]. This potential with a well minimizing near 100 MeV allow nucleons to bind together and form atomic nuclei and nuclear matter.

The equation of state of non-interacting hadron resonance gas could be described by grand canonical ensemble of bosons (mesons) and fermions (baryons) [50]. We should note that pions dominates the hadron gas at low temperature. The realistic equation of state of hadron resonance gas should also consider the interaction. An example of the equation of state of hadron resonance gas consider the Van der Waals interaction comparing with lattice QCD simulation is given in Figure 1-13 below [51]:

Nuclear matter is considered as part of the hadron resonance gas in the QCD phase diagram. Examples of typical hadron gas will be atomic nuclei at a famous nuclear matter saturation density $n_S = 0.16 \text{ fm}^{-3}$ (baryon density $n_B = 3n_S$) and nuclear matter like neutron star at large baryon density.

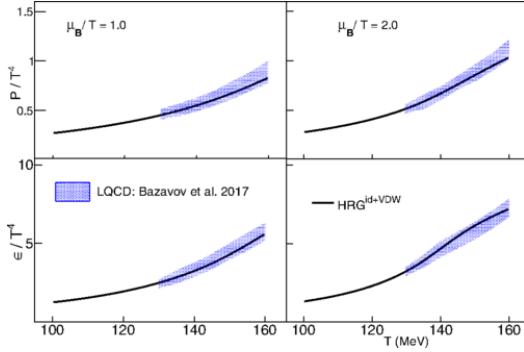


Figure 1-13: The pressure and energy density from lattice simulation compared with ideal hadron resonance gas and Van der Waas interaction at different $\frac{\mu_B}{T}$ are shown above.

1.4.3 Quark-Gluon Plasma

At very high temperature, quarks and gluons inside the color neutral hadron resonance gas will deconfine and form a new type of matter called quark-gluon plasma (QGP). In cosmology, it is believed that QGP exists in the early universe just several microseconds after the Big Bang during the quark epoch after electroweak phase transition and before nucleosynthesis [54].

The temperature of QGP is in order of hundreds of MeV, which is about hundreds of thousands times hotter than the core of the Sun. Moreover, according to extensive experimental and theoretical studies, QGP demonstrates strongly coupled ideal liquid behavior, which directly contracts to the prediction from asymptotic freedom which predict such matter should behavior like a gas of weakly interacting quarks and gluons. Therefore, the inner workings and proper degrees of freedom of QGP must be somewhere in between weakly coupled quarks and gluons and color neutral hadrons because it still demonstrate significant color freedom due to deconfinement. However, the microscopic structure of QGP is still unknown. Currently, both experimental and theoretical efforts have been conducted to actively investigate the internal structure of QGP.

Based on its ideal liquid feature, QGP could be described by relativistic viscous hydrodynamics. In fact, the quantum limit predicted by the Anti-de-Sitter Space Conform Field Theory (AdS/CFT). It is about a factor of larger than water.

The accurate equation of state of QGP is currently unknown. However, it is safe to assume that the strong interaction dominates in the QGP phase because its large coupling results in large cross section compared to the electroweak interaction cross section. Therefore, one can consider only strong interaction between quarks and gluons in the QGP. According to MIT Bag Model, the energy density ϵ and pressure p of a plasma of free quarks and gluons as a function of temperature T is as follows [55]:

$$\epsilon = \frac{37\pi^2}{30}T^4 + \mathcal{B} \quad (1.14)$$

$$p = \frac{37\pi^2}{90}T^4 - \mathcal{B} \quad (1.15)$$

Here, \mathcal{B} is the Bag Constant, which can be understood as the pressure of the vacuum on the quarks and gluons to make them form hadrons with finite size.

If we represent p in terms of ϵ , we get

$$p = \frac{1}{3}(\epsilon - 4\mathcal{B}) \quad (1.16)$$

Figure 1-14 below shows the equation of state of QGP of three flavor quarks of different model at $\mu_B = 0$ [56].

We can clearly see that a gradual rise of the pressure from near 0 to 1 as the temperature increases, indicating an smooth increase the total degree of freedom of the system due to the color deconfinement.

1.4.4 Color Superconductor

Under extremely high net baryon density, there is another hypothetical state of QCD matter named Color Superconductor where the color charges can move freely [57]. Similar to the Cooper Pair formation mechanism of electrons in metals, quarks, as fermions, pair up and bosonized into diquark, and undergo Bose-Einstein condensation [57]. The diquark condensate, carrying color charges, can move without resistance and thus demonstrate color superconductivity. It is believed that the color supercon-

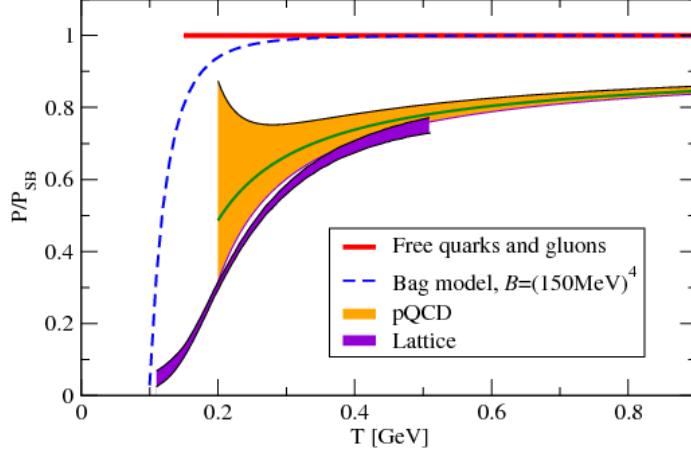


Figure 1-14: Predictions the normalized pressure to the stefan Boltzmann pressure $P_{SB} = \sigma T^4$ as a function of temperature T for three-flavor QGP obtained from lattice QCD, the MIT bag model and perturbative QCD including their uncertainties bands are shown.

ductor exists in the core of neutron stars where the net baryon chemical potential is high [58]. However, so far no color superconductor has been discovered in laboratory or astrophysical observations.

1.4.5 Phase Transition

As we increase the temperature, hadron resonance gas will undergo a phase transition into QGP. The chiral symmetry is restored from the phase transition of hadron resonance gas to QGP. However, the order of the phase transition from resonance hadron to QGP is still unknown. According to lattice QCD calculations, near zero baryon chemical potential ($\mu_B = 0$), the phase transition is a smooth cross over. According to lattice QCD calculations, at $\mu_B = 0$, the degree of freedom transition drastically increases near the critical temperature T_c .

However, at finite baryon chemical, it is believe that the phase is a first order phase transition according to different model calculations [59]. The hint of first order phase transition can be found in the softening equation of state in the cross over region [60]. However, currently, the order of phase transition from hadron resonance gas to QGP at high baryon chemical potential is still an open question.

1.4.6 Critical Point

If the theoretical predictions are correct, according to thermodynamics, there must be a critical point between the first order phase transition and the smooth crossover. Theoretical calculations predict that the critical point is $\mu_B = 350 - 700$ and $T_c \approx 160$ MeV [61]. Experimentally, the scale of the critical temperature may occur at $T_c \approx 175$ MeV from high moment analyses [62]. The research on critical point, a landmark in the QCD phase diagram, and the phase transition between QGP and hadron resonance gas are very important topics for physicists to understand the nature of QCD matters. The STAR Collaboration has carried out a Beam Energy Scan, both Phase I and II, at RHIC and plan to extend it to higher baryon chemical potential and lower temperature in the future Fixed Target Mode to search the critical point in the QCD phase diagram. However, so far efforts to search the precise locations of the critical point is still ongoing. The results are still inconclusive [?].

1.5 High Energy Nuclear Physics

Nuclear Physics is a study of atomic nuclei and their structures and interactions, which a typical energy scale ranging from MeV to GeV. High Energy Nuclear Physics is a subfield of Nuclear Physics at an energy scale on the order of GeV using heavy nuclei ($A > 56$). Its main goal is to understand the physics of QCD matter from various approaches such as collider experiments, astrophysical observations, lattice QCD computation, and theoretical modeling. In this thesis, I will focus on the research of QGP physics from the experimental approach using high energy heavy-ion colliders.

1.5.1 Laboratories

In laboratories, high energy nuclear physicists accelerate and collide heavy ions ($A > 56$) at center of mass high energy per nucleon at greater than 1 GeV to create extremely hot and dense condition and study QGP. Relativistic heavy-ion collision is also known as “The Little Bang” compared to “The Big Bang” in cosmology [].

Historically, many colliders, such as the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL), in Upton, Long Island, New York and Super Proton Synchrotron (SPS) at European Center for Nuclear Research (CERN) in Meyrin, Switzerland, and GSI at Helmholtz Centre for Heavy Ion Research with both proton-proton and relativistic heavy-ion collision capabilities, have been built and established high energy nuclear physics research programs. Today, two active colliders, the RHIC at BNL and LHC at CERN, are running at different energy with various nuclei species at a wide range of impact parameters. In the future, another one collider Facility for Antiproton and Ion Research (FAIR) running at a relatively low energy and high baryon chemical potential is being constructed at Darmstadt, Germany to map the location of critical point in the QCD Phase Diagram.

In addition to collider facilities, QGP might also be studied from astrophysical observations. For instance, strange stars, a quark star made of strange quark matter, may be form from stable strangelet according to Bodmer–Witten conjecture [64] or exist in the core of neutron stars under extreme pressure and temperature. It is believed there are several potential strange stars candidates according to telescope observations and gamma ray burst analysis [65–67].

1.5.2 Relativistic Heavy Ion Collider (RHIC)

Located at BNL in Upton, Long Island, New York, United States of America, RHIC is one of the major high energy accelerator facilities and currently the highest energy collider in America. It is a circular collider with a circumference of 3.843 kilometers and can provide proton energy up to 500 GeV and gold energy up to 200 GeV [68]. It was built in 2000 in order to search for a strongly interacting hot and dense state of matter created under ultra-relativistic heavy-ion collisions, currently known as QGP, with hints from the measurement at AGS. Moreover, RHIC provides physicists with a wide range of energies and a variety of ion species from proton to deuteron and copper to uranium create different sizes of system at different temperature and baryon chemicals. In addition, taking the advantage from its highly polarization beam with high luminosity, it has a great machine capabilities for cold QCD physics. Figure 1-15

below shows a sky view of RHIC at BNL:

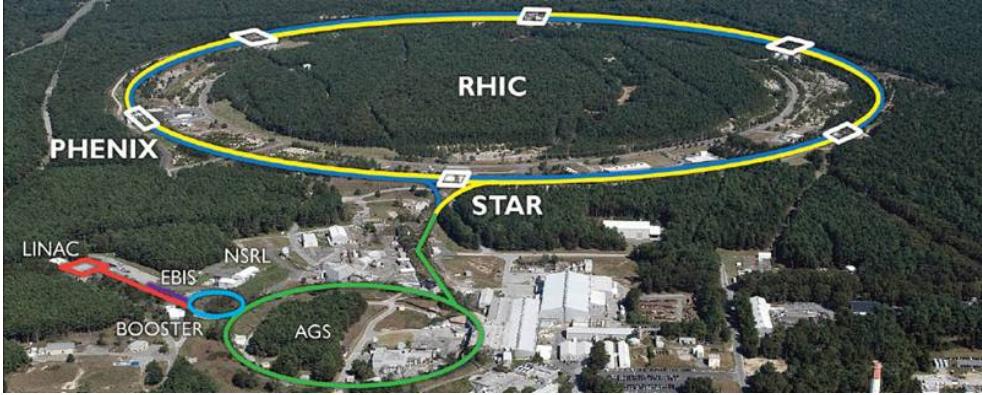


Figure 1-15: The overview of RHIC from the sky view is shown above. The actual locations of other accelerator facilities at BNL, including Linac, Booster, EBIS, NSRL, AGS, and the experiments at RHIC, STAR and PHENIX, are also labelled.

Here is how RHIC accelerates charged particles to the energy scale of GeV per nucleon. For instance, if we consider the acceleration of a typical ion source gold ($^{197}_{79}Au$) ion, we first use a cesium sputter ion source operated in the pulsed beam mode point to the gold metal and produce the Au^- ion [70]. Then, the Au^- will undergo a series of electron stripping process to reach the Au^{79+} ion [71]. First, 13 electrons are stripped by the carbon foil in the Terminal Stripping (S1) after the acceleration of tandem Van der Gaaf generator to turn Au^- to Au^{12+} . Then, the Au^{12+} ion will go through the Object Foil (S2) at the second stripping stage and becomes Au^{31+} . Next, the Au^{31+} will go through the third stripping station BTA foil (S3) made of aluminum and vitreous carbon between the Booster Synchrotron and AGS and becomes Au^{77+} . Finally, two more electrons of the gold ion Au^{77+} are removed at the fourth stripping station ATF foil (S4) made of thin tungsten, located between the AGS and RHIC. The fully stripped gold ion Au^{79+} inject to the blue and yellow rings at RHIC. For polarized protons, H^- pass a single stripping stage called located in the Booster Synchrotron. The stripping station is called Linac-to-Booster (LTB) stripper made of carbon foils with special geometry and converts polarized H^- to H^+ . Figure 1-16 schematically shows the accelerating process of gold ions at RHIC [72]

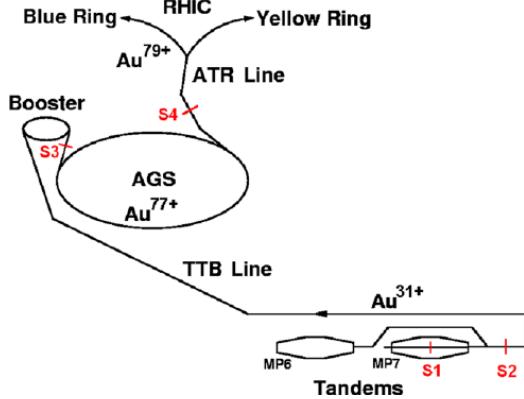


Figure 1-16: The acceleration of gold ions for RHIC is shown above.

At RHIC, we will accelerate the Au^{79+} ions in the superconducting Radio Frequency (RF) cavity under perpendicular electric and magnetic fields and increase their energies to about 100 GeV/c per nucleon. Then, we collider them via bunch crossing at interaction points of the experiments to perform relativistic heavy-ion collisions to study high energy nuclear physics. The RHIC collider usually operates in the first six months of a calendar year. At RHIC, the energy can also be lower where the ion beam collides with ions at a lower energy in the laboratory frame. STAR beam energy scan even fixed target mode.

1.5.3 Large Hadron Collider (LHC)

Located at the border between Switzerland and France, LHC is one of the major high energy accelerator facilities in Europe and currently the highest energy collider in the world. It is a circular collider with a circumference of 26.7 kilometers and can provide proton energy up to 14.0 TeV and lead ion energy up to 5.02 TeV [73]. It was built in 2008 with the main purpose to discover the Higgs Boson, perform precision measurements on SM, and search for Physics beyond SM. Due to its high energy and ion capabilities, high energy nuclear physicists also use the existing general purpose detectors for high energy particle experiment at the LHC to conduct research on relativistic heavy-ion physics. LHC ion physics runs usually starts at the end of the year and lasts for about a month. The photo taken from the sky to picture LHC is

shown in Figure 1-17:

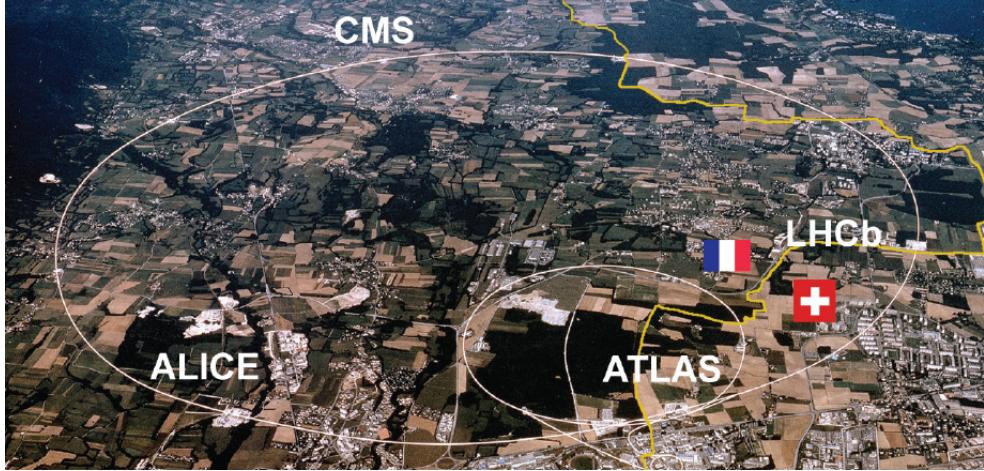


Figure 1-17: The overview of LHC at CERN from the sky view is shown above. The actual locations of the experiments at the LHC, ATLAS, CMS, ALICE and LHCb, as well as the French-Swiss border, are also labelled.

The ion source CERN usually uses is lead $^{208}_{82}Pb$, which is stable and approximately spherical. In the 2017 ion run, it also used the xenon $^{131}_{52}Xe$. Currently, there is also a discussion of potential future lighter ions such as oxygen $^{32}_{16}O$ [74]. Similar to RHIC, the lead ion at the LHC also undergoes a series of stripping processes using stripping foils in to order to become partially ionized Pb^{81+} [75]. Also, the lead ions pass a series of energy boosting before reaching to the desired energy at the LHC. Lead ions starts from a source of vaporized lead and enter Linac 3 before being collected and accelerated in the Low Energy Ion Ring (LEIR) at the energy from 4.2 MeV to 72 MeV. Then, the lead ion will inject to Proton Synchrotron (PS) to boost its energy. Then, they are sent to the Super Proton Synchrotron (SPS). Finally, the lead ion are injected to the LHC and increase their energy to TeV scale two LHC rings with the RF cavity with 400 MeV and an electric field strength of 5 MV/m [73]. The energetic lead ions beams from two LHC rings will collide heads on with a small crossing angle at the interaction points of the LHC experiments. The CERN accelerator complex is shown schematically in 1-21

After Run III, LHC will upgrade to High Luminosity (HL) LHC and allow physicists to collect huge datasets, which is crucial for the precision measurements to study

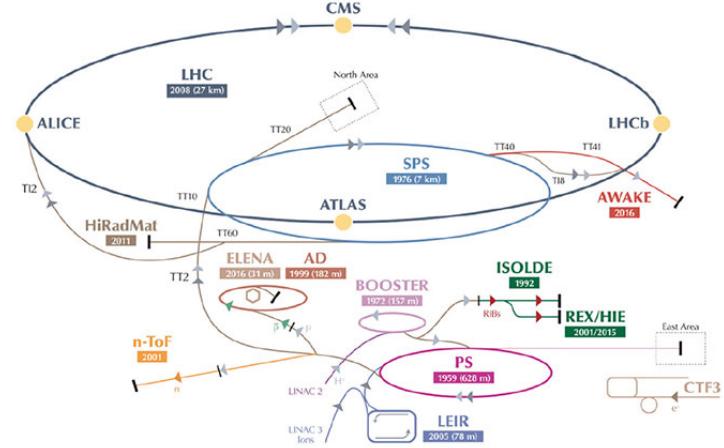


Figure 1-18: The schematic overview of CERN accelerator complex with the accelerators labelled is shown above. Proton and lead ion are accelerated using these facilities to boost to the energy scale of TeV.

QGP in the heavy-ion physics program. Due to its far higher energy than RHIC, the QGP created at LHC has a higher temperature and a smaller baryon chemical potential than the one created at RHIC.

1.5.4 High Energy Physics Coordinates

As mentioned in the previous section, the collision system of heavy-ion is in general highly relativistic. Therefore, Lorentz transformation will be relevant in our studies. In Cartesian coordinates $x^\mu = (t, x, y, z)$, under Lorentz transformation, if we boost the system by a speed β in the $+z$ direction. The Lorentz gamma factor will be given by $\gamma = \frac{1}{\sqrt{1-\beta^2}}$. The four vector $x^\mu \rightarrow x'^\mu$ transforms as follows

$$\begin{bmatrix} t' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & 0 & 0 & -\gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\gamma\beta & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} t \\ x \\ y \\ z \end{bmatrix} \quad (1.17)$$

The equation above is called the Lorentz Transformation. It is an orthogonal

transformation preserving the Minkowski metric tensor $\text{diag}(1, -1, -1, -1)$ using particle physicists conventions.

Experimentally, nowadays, heavy-ion detectors usually have 2π angular coverage in the transverse direction with some finite longitudinal acceptance along the beam line. They look cylindrically symmetric. Hence, it is convenient and wise to choose a cylindrical coordinate system and use kinematic variables with Lorentz invariance, including boosting and rotation. In standard cylindrical coordinates in the position space, Lorentz four-vectors is used $(t, x, y, z) \rightarrow (t, r, \phi, z)$.

The relativistic coordinate system for our analysis are shown below in Figure 1-19.

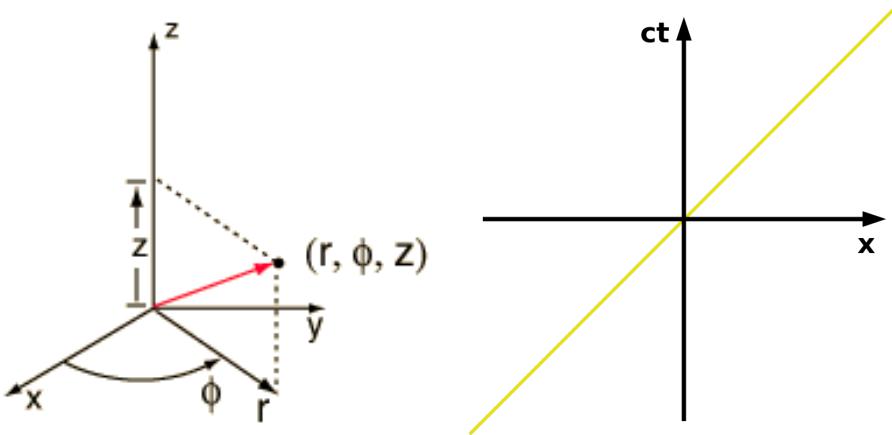


Figure 1-19: The cylindrical coordinate system in the position space (left) and the space time diagram (right) for relativistic heavy-ion physics analysis are shown above.

Thus, for the momentum space, we can use $p^\mu = (E, p_x, p_y, p_z) \rightarrow (E, p_T, \phi, p_z)$

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (1.18)$$

$$\phi = \arctan\left(\frac{p_y}{p_x}\right) \quad (1.19)$$

We also define rapidity y , a relativistic version of velocity that can be convenient add to the boost.

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (1.20)$$

Experimentally, we also use pseudo-rapidity η , which is more directly connected to the detector measurement assuming ultra-relativistic limit kinematics ($E \rightarrow p$). The definition of pseudo-rapidity η is shown as follows:

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right) \quad (1.21)$$

Here θ is the angle labelled in the left of Figure 1-19. Particularly, $y = 0$ and $\eta = 0$ when $p_z = 0$. In addition, boosting by a speed β in the longitudinal z-direction, we found that the rapidity simply shift by a const number $y' = y + \tanh \beta$. We should note that the cylindrical coordinates (p_T, ϕ, p_z) are perfectly orthogonal while (p_T, ϕ, y) or (p_T, ϕ, η) are not.

For general collider experiments, two particles are moving toward each other with four-momenta p_1^μ and p_2^μ and interact with each other. It is also very convenient to use the Mandelstam variables s, t, u in our studies. They are defined as follows

$$s \equiv (p_1 + p_2)^2 \quad (1.22)$$

$$t \equiv (p_1 - p_2)^2 \quad (1.23)$$

$$u \equiv (p_1 - p_3)^2 \quad (1.24)$$

Here the center of mass frame, since we know the tree vector $\vec{p}_1 = -\vec{p}_2 = \vec{p}$ energy is the Mandelstam variable $s \equiv (p_1 + p_2)^2$ where p_1 and p_2 are the four-momenta of the incident beam particles. Therefore, we can see that $p_1^\mu = (E, \vec{p})$ and $p_2^\mu = (E, -\vec{p})$. Hence, $s \equiv (p_1 + p_2)^2 = 4E^2 = E_{CM}^2$. Hence, the center of mass energy of the collision system could be represented by the Mandelstam variable \sqrt{s} : $E_{CM} = \sqrt{s}$.

1.5.5 Stages of Heavy-Ion Collisions

In high energy heavy-ion collisions, both Electroweak and QCD processes occur in each event and contribute to the total cross section. We classify the events with elastic and inelastic reaction processes. For elastic processes, two nuclei scatter mainly electromagnetically with each via photon exchange without breaking themselves up or losing energy. For inelastic scattering, we classify diffractive and non-diffractive disassociation processes. In diffractive dissociation processes, the two nuclei may be slightly excited and lose a relatively small fraction of energy, producing relatively small number of particles. On the other hand, in non-diffractive dissociation processes, the nuclei lose a substantial fraction of their energies and produce a large number of particles [76].

Therefore, in events with significant contribution from non-diffractive dissociation, the interaction between two nuclei is indeed a multi-stage process including both perturbative and non-perturbative QCD processes. We can define stages of heavy collisions and understand the details of each stage. It consists of five stages: initial state of two high Lorentz contracted nuclei before the collision, the very early pre-equilibrium stage where hard scattering between partons inside nuclei starts, the rapid expansion of the fireball begins when the thermally and chemically equilibrated QGP, the hadronization stage after QGP expands and cools down, and the freeze-out stage when the inelastic scattering process ceases.

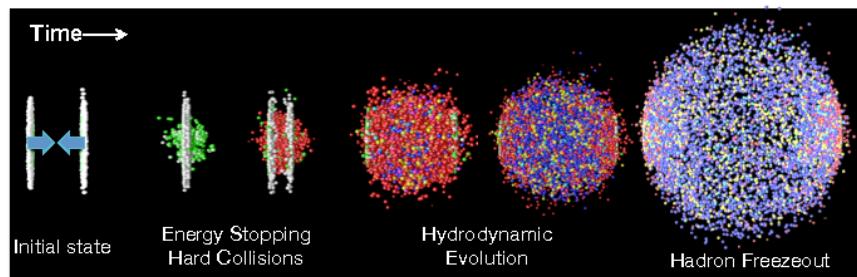


Figure 1-20: An event of a typical heavy-ion collisions event with different stages as time evolves is shown above.

Theoretically, many phenomenological models such as Ultra-Relativistic Quantum

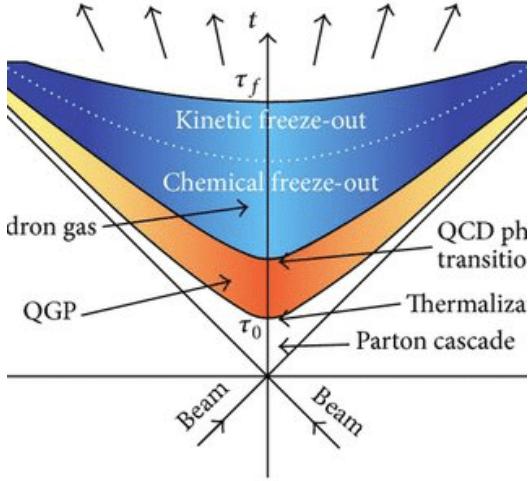


Figure 1-21: The space-time evolution of heavy-ion collisions is shown above. It consists of four stages: initial state before the collision, the creation of quark-gluon plasma right after of the collision, hadronization after quark-gluon plasma expands and cools down, and the freeze-out stage, first chemical freeze out when the particle species no longer change, and then kinetic freeze out when the inelastic scattering process ceases.

Molecular Dynamics (UrQMD) and A Multi-Phase Transport Model (AMPT) are developed to describe relativistic heavy-ion collisions.

1.5.6 Global Event Observables

Globally, we can define some physics quantities to describe heavy-ion collisions to generally characterize each event. Heavy-ion Physicists defined the impact parameter, centrality, number of participants, We will discuss all of them below.

Impact Parameter: Prior to heavy-ion collisions, similar to other collider experiments, each event are prepared with the same unpolarized incoming particles with the same center of mass energy. Therefore, the incoming state $|i\rangle$ is used for each event. However, different from e^+e^- and pp collision, in heavy-ion physics, we introduce another parameter called the impact parameter denoted b to the transverse distance between center of two nuclei to classify the events. Therefore, the incoming state can be rewritten as $|i(b)\rangle$. Figure 1-22 shows the definition of impact parameter

in heavy-ion collision [77].

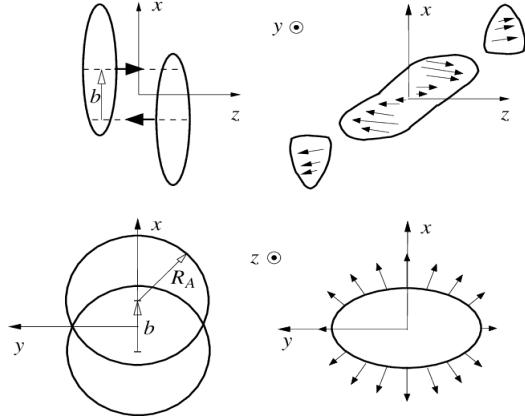


Figure 1-22: The definition of impact parameter b in heavy-ion collision and the of overlapping interaction region and the break up remnants of the two nuclei, which is called spectator, moving in the z -direction are shown above. We can also see that heavy-ion collisions have an almond shape interaction region, which results in the azimuthal anisotropic emission of final state particles.

Number of Participating Nucleons: Right at the end of heavy-ion collisions after two nuclei pass through with each other, we can define the number of participating nucleon denoted N_{part} . The smaller the impact parameter, the more overlap volume between two nuclei, leading to a larger number of number of participating nucleon in the collision. The nuclear interaction system size is determined by the number of participating nucleons. However, due to event-by-event nuclei geometry fluctuations caused by the motion of nucleons inside nuclei [78], it is more proper to say that the average number of participating nucleon is related to the impact parameter.

Number of Binary Nucleon-Nucleon Collisions: In addition to N_{part} , we can also define another quantity that characterize details interaction of the events at the rather hard scale. The number of binary nucleon-nucleon collisions, denoted N_{coll} , is also related to the impact parameter. At higher energy, nucleons inside nuclei become a relevant degree of freedom to the cross section. We could treat the collisions of two nuclei as the superposition of the collisions between nucleons inside the nuclei. Since binary nucleon-nucleon collision has a rather small cross section, it dominates the

total nucleon-nucleon cross section according to binomial principle. Glauber model is developed to study the relationship between b , N_{part} , and N_{coll} in nuclei collisions and will be discussed in the following subsection.

Centrality: Experimentally, it is difficult to directly measure the impact parameter of each collision. Therefore, we define another physical quantity called centrality to characterize the impact parameter. The centrality (C) is defined fraction of the total nuclear interaction cross section: $C = \int_0^b \frac{d\sigma}{dx} dx$. Centrality is expressed in terms of percentage [79]. It is proportional to the quantity: $\frac{\pi b^2}{4\pi R_A^2}$ where R_A is the radius of a nuclei defined above in Figure 1-22. When the impact parameter between two nuclei is 0, the centrality is at 0%. When the impact parameter between two nuclei is $2R_A$, the centrality is 100%. There is a relationship between the centrality and the average number of participant nucleons. Heavy-ion experimental measurements are in general presented in terms of centrality or average number of participating nucleon. Experimentally, we look at the number of tracks and activities of calorimeters at the very forward direction (Zero Degree Calorimeters) to estimate the centrality [80–82].

Virtuality: Similar to deep inelastic scattering, we can also define the virtuality Q^2 , which is the momentum transfer between the two nucleons in nucleon-nucleon collisions. To generate nucleon-nucleon collision event, we used \hat{p}_T , defined as the transverse momentum of the hard subprocess, which is a quantity related to Q^2 , developed by the high energy theory group of Lund University.

Event Multiplicity: We can also define the event multiplicity by counting the number of final state charged particles to quantify the activity of the event. Event multiplicity can be denoted as N_{trk} , number of tracks in the event, which is proportional to the number of charged particle denoted as N_{ch} . Figure 1-23 shows the correlation between the number of participating nucleons in a heavy-ion collision, their cross section and the impact parameter, defining the centrality classes [83].

The initial global parameters such as the collisions energy, impact parameter, and polarization can be treated the knobs for high energy nuclear physicists to play with in order to study relativistic heavy-ion collisions and create the strongly interacting system at different sizes with different chemical potentials and temperatures in the

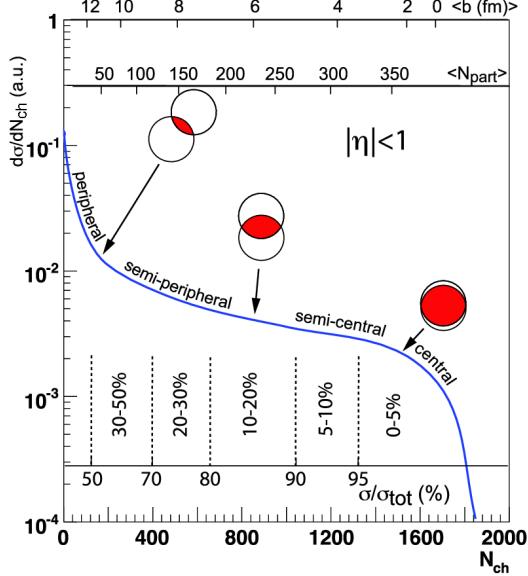


Figure 1-23: The plot showing relationship among number of charged particle, N_{ch} , related to the number of participating nucleon N_{part} , the differential cross section $\frac{d\sigma}{dN_{ch}}$, and the centrality, according to the Glauber Model calculations, is shown above.

QCP phase diagram. Figure 1-24 shows an event display of thousands of tracks from a central Au + Au collision event at 200 GeV recorded by the Time Projection Chamber (TPC) of the STAR experiment at RHIC.

1.5.7 Glauber Model

The Glauber Model, named after Physicist Roy Glauber [84], is originally developed to address high energy scattering problem with composite particles in the optical limit where optical theorem is applicable [85, 86]. It is a model describing two composite objects collider inelastically with each other and relate the cross section to the cross section of collision between two point objects. The Glauber Model can be applied to study nucleon-nucleus (N-A) and nucleus-nucleus (A-B) collisions with nucleon-nucleon (N-N) collisions and determine relationship between the global observables mentioned in the previous subsection.

If we consider a spherically symmetric nucleus, the nuclear charge density can be parameterize $\rho(r)$ by the Fermi distribution with three parameters below

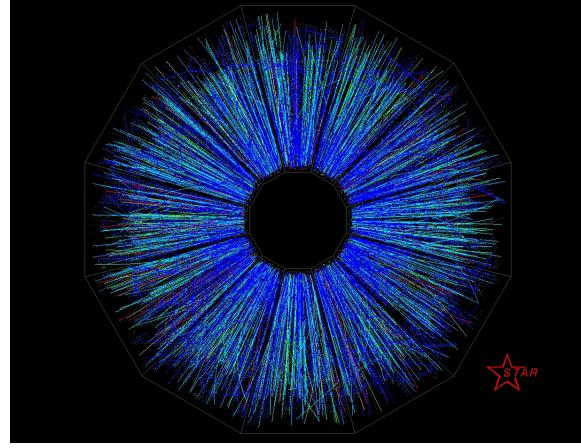


Figure 1-24: Two gold ions collide head-on in the STAR detector. The event with reconstructed tracks of final state particles are display by STAR TPC shown above.

$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp(\frac{r-R}{a})} \quad (1.25)$$

According to the Glauber Model [84], the N-N inelastic cross section is denoted as σ_{in}^{NN} and the effective thickness function of a nucleon is defined as a function of impact parameter in the transverse direction: $T(\vec{b})$. It is defined as follow

$$T(\vec{b}) = \int \rho(\vec{b}, z) dz \quad (1.26)$$

It is normalized to unity: $\int_0^{R_A} T(\vec{b}) d^2 b = 1$. $T(\vec{b})$ essentially depends on density of the nucleus $r(b)$. If the nucleus has a uniform cylinder and the collide on its circular face along its height, then $T(\vec{b})$ will be a constant. Therefore, the probability that a nucleon collides with a nucleon inside the nucleus is given by $\sigma_{in} T(\vec{b})$. Therefore, the probability of n nucleon collision is given by

$$P_n = \binom{A}{n} \sigma_{in}^{NN} T(\vec{b})^n [1 - \sigma_{in} T(\vec{b})]^{A-n} \quad (1.27)$$

Hence, if we consider a constant fraction of μ ($0 \leq \mu \leq 1$) of particle produced after each collisions, we can calculation the average multiplicity $\langle N(\mu) \rangle$:

$$\langle N(\mu) \rangle = \sum_n P_n \sum_0^{n-1} \mu^m = \sum_{n-1} P_n \frac{1-\mu^n}{1-\mu} = \frac{1}{1-\mu} \{ 1 - [1 - (1-\mu)\sigma_{in} T(\vec{b})]^A \} \quad (1.28)$$

It turns out that we have the following relationship between N_{part} and N_{coll} with $\langle N(\mu) \rangle$ [84]

$$N_{part} = \langle N(\mu = 0) \rangle \quad (1.29)$$

$$N_{coll} = \frac{1}{2} \langle N(\mu = 1) \rangle = AT(\vec{b}) \sigma_{in}^{NN} \quad (1.30)$$

In a more generalized case: A-B collisions, Figure 1-25 shows sides view and beam-line view of heavy-ion collision of projectile B on target A

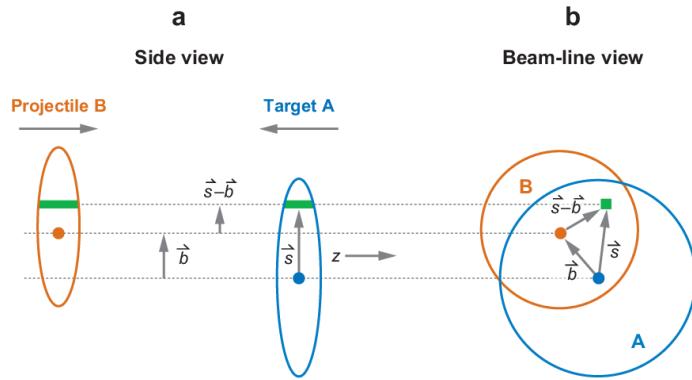


Figure 1-25: The A-B collision with the definition of the impact parameter vector \vec{b} and the distance of nucleon to the center of projectile B \vec{s} are shown above. The distance of the nucleon in B to center of the target A is $\vec{s} - \vec{b}$ according to vector subtraction rule. Here we assume both nuclei A and B are perfect spheres.

Using similar ideas [83], we could first calculate the effective thickness function T_{AB} as follows:

$$T_{AB}(\vec{b}) = \int T_A(\vec{s}) T_B(\vec{b} - \vec{s}) d^2s \quad (1.31)$$

Now replacing $T(\vec{b})$ in N-A by $T_{AB}(\vec{b})$ in A-B, we can obtain

$$\langle N(\mu) \rangle = \frac{A}{1-\mu} \int_0^b T_A(\vec{s}) \{1 - [1 - (1-\mu)T_B(\vec{b}-\vec{s})\sigma_{in}^{NN}]^A\} d^2s + \frac{B}{1-\mu} \int_0^b T_B(\vec{s}) \{1 - [1 - (1-\mu)T_A(\vec{b}-\vec{s})\sigma_{in}^{NN}]^B\} d^2s \quad (1.32)$$

To obtain N_{part} , evaluate at $\mu = 0$, we get

$$N_{part} = A \int_0^b T_A(\vec{s}) \{1 - [1 - T_B(\vec{b}-\vec{s})\sigma_{in}^{NN}]^A\} d^2s + B \int_0^b T_B(\vec{s}) \{1 - [1 - T_A(\vec{b}-\vec{s})\sigma_{in}^{NN}]^B\} d^2s \quad (1.33)$$

To obtain N_{coll} , evaluate at $\mu = 1$, we get

$$N_{coll} = AB T_{AB}(\vec{b}) \sigma_{in}^{NN} \quad (1.34)$$

In a very special case, assume the nucleon are simply perfect rigid sphere with the same radius and head-on collide with each other (impact parameter is $b = 0$). That is $T_A \sigma_{in}^{NN} = T_B \sigma_{in}^{NN} = T_{AB} \sigma_{in}^{NN} = 1$, we get

$$N_{part} = A + B \quad (1.35)$$

$$N_{coll} = AB \quad (1.36)$$

The results above of N_{part} and N_{coll} agree to our expectation.

The comparison of the Glauber Model with simulations of the N_{part} and N_{coll} as a function of impact parameter b . Figure 1-26 from the [83]

Therefore, we can apply the Glauber model to determine N_{part} and N_{coll} for a given centrality range of AA collision ($T_{AB} \rightarrow T_{AA}$), which will be used in our analysis to obtain the corrected yield. It is believed that the production of light hadrons, such as pions and kaons, are scaled as N_{part} [87] while electroweak bosons, such as W and Z boson, are scaled as N_{coll} [88].

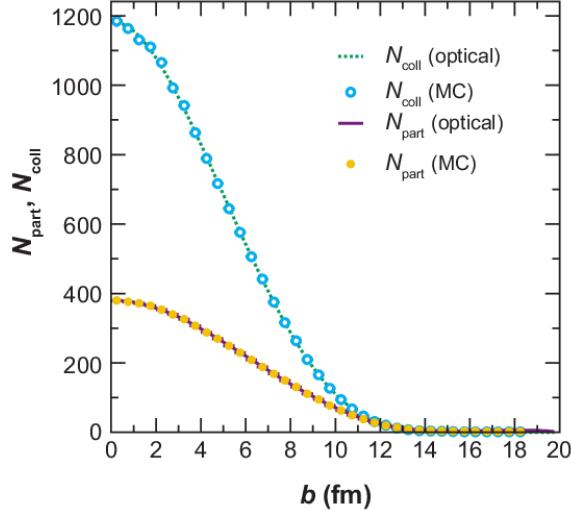


Figure 1-26: The N_{part} and N_{coll} as a function impact parameter calculated from the Glauber Model with optical approximation (lines) and from MC simulations (circles) are shown above. We can see they have almost perfect agreement with each other.

1.6 Characterization of Quark-Gluon Plasma

Equipped with the knowledge and collider technologies of heavy-ion collisions, we are ready to apply them to conduct scientific research on QGP in laboratories. The following subsections will describe the characterization of QGP from its predicted signature to open questions today, which leads to my thesis research.

1.6.1 Signatures

QGP has been hypothesize long before its discovery as a color deconfined phase of quark matter named “quark gluon plasma” [89] and will demonstrate some specific benchmarks in experiments to prove the creation of QGP [90]. Here, four classic signatures of QGP will be discussed: J/ψ suppression, jet quenching, elliptic flow, strangeness enhancement.

1.6.2 J/ψ and Υ suppression

J/ψ meson, as a type of heavy quarkonia, is bound state of $c\bar{c}$, made of charm quark and an anti-charm quark, whose mass is heavier than the Λ_{QCD} . Therefore, we could

approximately treat the interaction between charm and the anti-charm quark a static the Cornell potential $V(r)$ in the non-relativistic quantum mechanical hamiltonian system [91]:

$$\hat{H} = \hat{T} + \hat{V} \quad (1.37)$$

$$\hat{H} |\psi\rangle = i\frac{\partial}{\partial t} |\psi\rangle \quad (1.38)$$

and solve Schrodinger equation the to describe J/ψ mesons in vacuum []. As we have seen in Section 1.3.4, with the QGP medium, at a finite temperature T , the potential is modified due to color screen effect. As the distance between two charm quarks $V(r) \rightarrow \frac{\sigma}{m_D}$, which does not diverge, as $r \rightarrow \infty$. Therefore, the $c\bar{c}$ system could be unbounded if they have sufficient energy. In the field theory picture, this could be understood as the color string breaking between charm and anti-charm quark [93], also known as quarkonia melting [94]. Hence, with the influence of QGP at $T > 0$, the production cross section of J/ψ will decrease compared to the vacuum at $T = 0$. Experimentally, we define an observable to quantify the modification of particle production cross section in AA collision compared to the reference pp collisions normalized by the number of binary nucleon-nucleon collisions N_{coll} , which is defined in the previous subsection. We called this observable as nuclear modification factor denoted R_{AA} . Mathematically, R_{AA} is defined as follows:

$$R_{AA} = \frac{1}{N_{coll}} \frac{\frac{d^2N_{AA}}{dp_T dy}}{\frac{d^2N_{pp}}{dp_T dy}} = \frac{1}{T_{AA}} \frac{\frac{d^2N_{AA}}{dp_T dy}}{\frac{d^2\sigma_{pp}}{dp_T dy}} \quad (1.39)$$

Therefore, $R_{AA} < 1$ means suppression. $R_{AA} = 1$ means no modification. $R_{AA} > 1$ means enhancement. Hence, in experiments, we should observe the $R_{AA} < 1$ a suppression of J/ψ production. Figure 1-27 shows the measurement of fully reconstructed J/ψ at RHIC and LHC [95]

In fact, we could see that $R_{AA} < 1$ for every data point, which indicates a clear suppression of J/ψ production from experiments at both RHIC and the LHC. How-

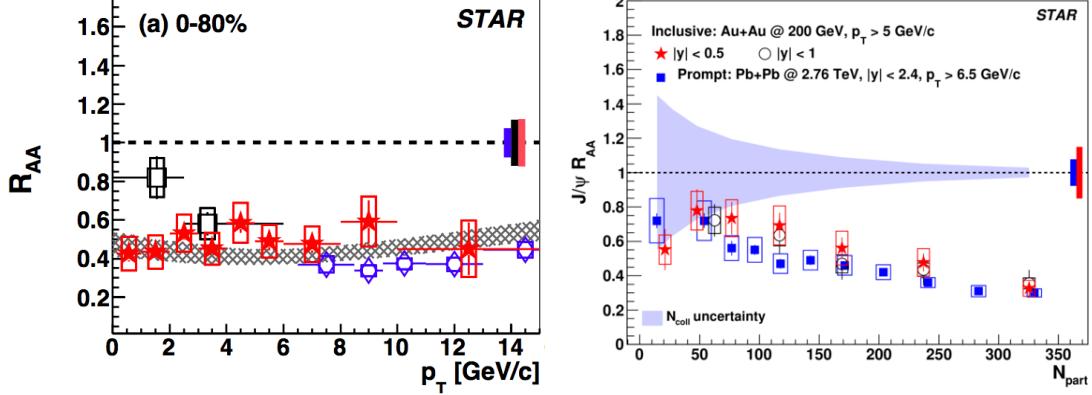


Figure 1-27: The nuclear modifications factor R_{AA} of fully reconstructed J/ψ as a function of p_T (left) and N_{part} (right) measured by the STAR experiment (red data points) at RHIC and CMS (blue diamond data points) and the ALICE (blue circle data points) experiment at the LHC are shown above. We can see that the $J/\psi R_{AA}$ is below 1 for both p_T and N_{part} . There is no significant p_T dependence of $J/\psi R_{AA}$. The $J/\psi R_{AA}$ decreases as N_{part} increases, consistent to the increasing creation probability of QGP with larger N_{part} .

ever, we should note that the larger $J/\psi R_{AA}$ observed at the LHC compared to RHIC could be explained by regeneration mechanism [96]. The observation of J/ψ suppression is one of the earliest evidence of the discovery of QGP.

Similarly, we expect to see this in Υ , which is made of $b\bar{b}$. Indeed, they expect to have sequential suppression since we have 3 Υ states: $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ could be observed in experiments. Because the energy of the $b\bar{b}$ system or equivalently the rest mass: $m_{\Upsilon(3S)} > m_{\Upsilon(2S)} > m_{\Upsilon(1S)}$, a sequential suppression: $R_{AA}^{\Upsilon(1S)} > R_{AA}^{\Upsilon(2S)} > R_{AA}^{\Upsilon(3S)}$ should be observed if QGP is created. Figure 1-28 shows the measurement of fully reconstructed Υ states at RHIC and LHC [97, 98]

1.6.3 Jet Quenching

Experimentally, due to color confinement, it is impossible to directly detect and track the energetic parton. Therefore, physicists define jet as a spray of collimated hadrons within a narrow cone initiated from the color charged parton. In nuclear and particle physics, jets are used to study the dynamics of partons before hadronization [99] and understand the properties of QGP [100]. A schematic view of a di-jet production from

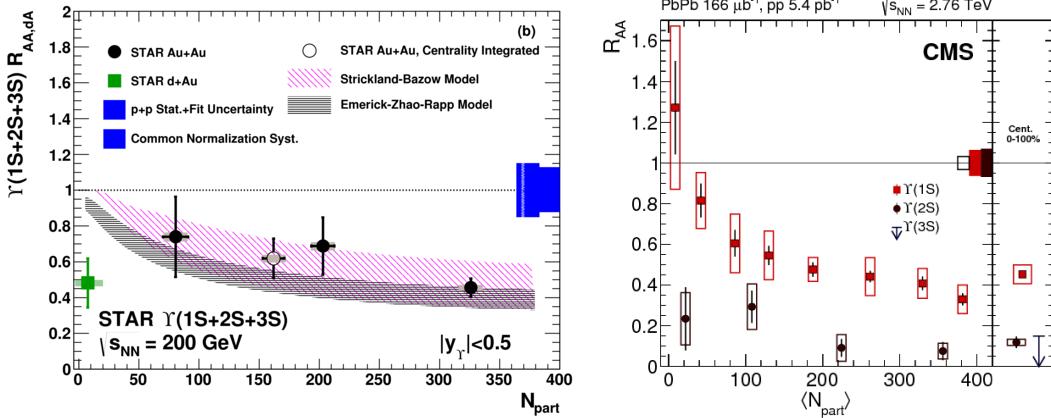


Figure 1-28: The nuclear modifications factor R_{AA} of fully reconstructed Υ as a function of N_{part} measured by the STAR experiment (left) at RHIC and CMS experiment (right) at the LHC are shown above. We can see that R_{AA} of the three Υ states is below 1 for both $N_{part} > 3$. The J/ψ R_{AA} decreases as N_{part} increases, consistent to the increasing creation probability of QGP with larger N_{part} . In addition, a sequential suppression of Υ R_{AA} is observed by the CMS experiment: $R_{AA}^{\Upsilon(1S)} > R_{AA}^{\Upsilon(2S)} > R_{AA}^{\Upsilon(3S)}$, which agrees with the expectation QGP color screening effect.

di-quark event in electron-positron collider $e^+e^- \rightarrow q\bar{q}$ is shown below in Figure 1-29

Since we know QGP a color deconfined phase of matter, an energetic parton carrying color charge traveling through the QGP medium is expected to lose a substantial amount its energy to the medium. This is similar the effect that an electron beam losing energy in the electron-ion plasma via electromagnetic interaction [1]. We call this effect as jet quenching. Figure 1-30 shows jet quenching in QGP in AA collisions compared to pp collisions

Experimentally, compared to pp collision where QGP is not expected to be created, the jet spectra is modified by the QGP medium. The angular distributions would be broaden due to interaction with the medium and the p_T spectra will be shifted to the left due to energy loss. This can be quantified by jet nuclear modification factor R_{AA} similar to the R_{AA} for quarkonium suppression mentioned in the previously. Figure 1-31 Shows the hadron angular correlation with the STAR experiment at RHIC and jet R_{AA} as a function of p_T with the ALICE experiments at LHC [100, 101]:

The jet R_{AA} are all below 1 at RHIC and LHC, which suggest jet quenching in AA collisions, supporting existence of QGP.

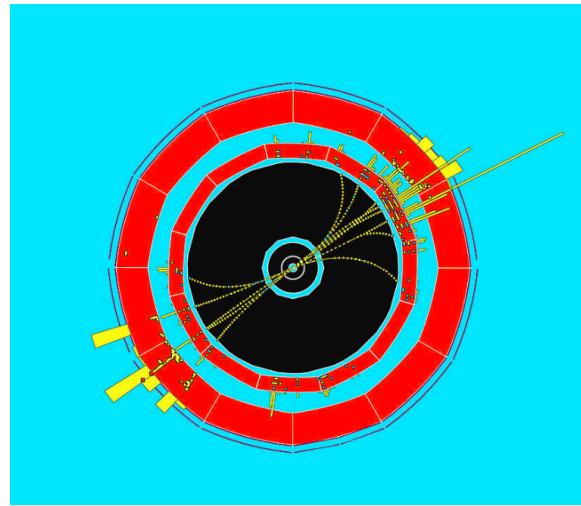


Figure 1-29: The schematic display of a di-jet event from the ALEPH (a particle detector at the Large Electron-Positron collider) Experiment at the Large Electron-Positron Collider (LEP) is shown above. We can see two sprays of back to back particles within narrow cone, representing a di-jet event.

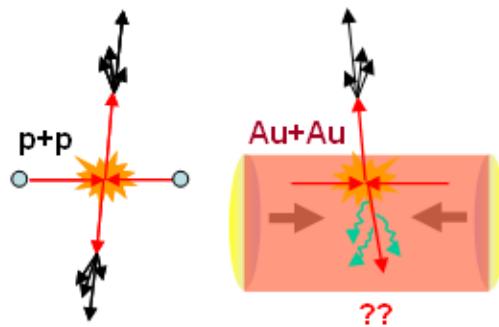


Figure 1-30: The schematic picture explaining jet quenching is shown above. Hard scatterings in pp collisions produce back-to-back "jets" of particles, but in $AuAu$ collisions, the presence QGP modifies the jets' properties.

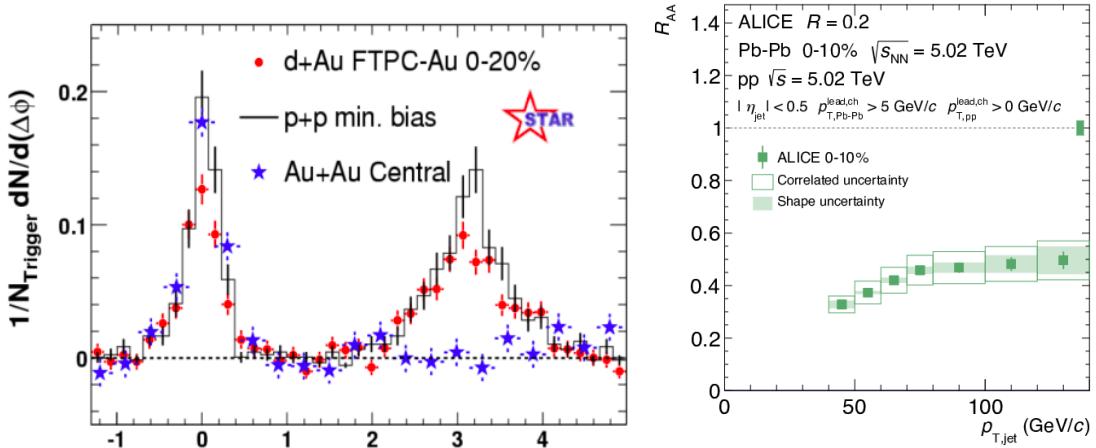


Figure 1-31: Comparison of two-particle azimuthal distributions for central dAu collisions to those seen in pp and central AuAu collisions measured with the STAR experiment jet R_{AA} as a function p_T measured by the ALICE experiment at LHC (right). From the STAR result, in central AuAu collisions, the back-to-back peak has disappeared due to the transfer of jet energy to the slow expanding medium constituents. The jet R_{AA} from ALICE measurement is clearly below 1, suggesting jet losing a significant fragment of its energy in AA collision compared to pp.

1.6.4 Elliptic Flow

The reaction region in heavy-ion collisions, where the two nuclei overlap with each other, has an almond shape, which is azimuthally asymmetric. If a color deconfined matter QGP is created, particles emitted from the almond shape fire ball are expected to be anisotropic due to differences of the pressure gradient of the QGP in the and their path length through QGP in the x and y direction. Experimentally, physicists Dr. Arthur Poskanzer who sadly just passed away in June 30 2021, and Dr. Sergey Voloshin developed the event plane method to analyze the azimuthal anisotropy of particle emission in heavy-ion collisions [104]. The reaction plane is defined as the plane of the impact parameter and the x-axis. Figure 1-32 schematically shows the definition of reaction plane in heavy-ion collisions.

The particle spectra in heavy-ion collisions can be factorized as

$$E \frac{d^3 N}{d^3 p} = E \frac{1}{2\pi p_T} \frac{d^3 N}{dp_T dy d\phi} = E \frac{1}{2\pi p_T} \frac{d^2 N_1}{dp_T dy} \frac{dN_2}{d\phi} \quad (1.40)$$

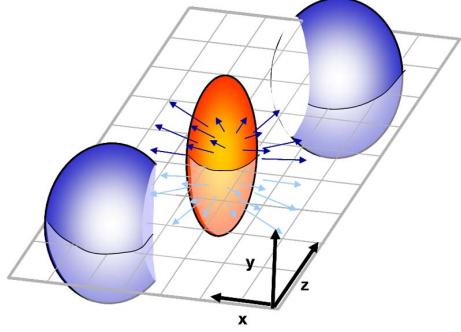


Figure 1-32: The figure above shows the ellipsoid of the overlapping nuclear reaction region of two nuclei in heavy-ion collisions. The reaction plane, which is the x-z plane shown as above, is constructed by the beam direction and the impact parameter vector. The emissions of particles are azimuthally anisotropic in the x-y plane.

Since the particle emission is azimuthally anisotropic, we can expand the $F(p_T, \phi, y) = \frac{dN_2}{d\phi}$ into a Fourier series [104]:

$$F(p_T, \phi, y) = \frac{x_0(p_T, y)}{2\pi} + \sum_{n=1}^{\infty} [x_n(p_T, y) \cos(n\phi) + y_n(p_T, y) \sin(n\phi)] \quad (1.41)$$

According to trigonometry, we get

$$F(p_T, \phi, y) = \frac{x_0(p_T, y)}{2\pi} + \sum_{n=1}^{\infty} 2v_n(p_T, y) \cos[n(\phi - \Psi_n)] \quad (1.42)$$

Here, $v_n = \frac{1}{2} \sqrt{x_n^2 + y_n^2}$ and $\Psi_n = \frac{1}{n} \arctan(\frac{y_n}{x_n})$.

To find the Fourier coefficients v_n , we can apply the Fourier tricks to find x_n and y_n .

Theoretically, because the function $\frac{dN_2(\phi)}{d\phi}$ is continuously analytical, we can use integral to find the Fourier coefficients [18]

$$x_n = 2 \int_0^{2\pi} \frac{dN_2(\phi)}{d\phi} \cos(n\phi) d\phi \quad (1.43)$$

$$y_n = 2 \int_0^{2\pi} \frac{dN_2(\phi)}{d\phi} \sin(n\phi) d\phi \quad (1.44)$$

Experimentally, because our data take on discrete values, we can convert the integral into a sum

$$x_n = \frac{2}{N} \sum_{n=1}^N \cos(n\phi) d\phi = 2\langle \cos n\phi \rangle \quad (1.45)$$

$$y_n = \frac{2}{N} \sum_{n=1}^N \sin(n\phi) d\phi = 2\langle \sin n\phi \rangle \quad (1.46)$$

Here, we sum up all tracks in the experiment to get the x_n and y_n . Then, we will be able to find

$$v_n = \frac{1}{2} \sqrt{x_n^2 + y_n^2} = \sqrt{(\langle \cos n\phi \rangle)^2 + (\langle \sin n\phi \rangle)^2}. \quad (1.47)$$

In heavy-ion physics, the first order Fourier coefficient v_1 is called the directed flow.

$$v_1 = \sqrt{(\langle \cos \phi \rangle)^2 + (\langle \sin \phi \rangle)^2}. \quad (1.48)$$

It can be connected to the initial tilting source of the colliding nuclei [102] and can be used to study Chiral Magnetic Effect [103].

The second order Fourier coefficient v_2 is called elliptic flow.

$$v_2 = \sqrt{(\langle \cos 2\phi \rangle)^2 + (\langle \sin 2\phi \rangle)^2} = \sqrt{(\langle \cos^2 \phi \rangle - \langle \sin^2 \phi \rangle)^2 + (2\langle \sin \phi \rangle \langle \cos \phi \rangle)^2}. \quad (1.49)$$

Assuming in initial stage before the collision, the sum of the momentum of two colliding nuclei \vec{p}_1 and \vec{p}_2 is exactly 0 without any fluctuation. That is

$$\vec{p}_1 + \vec{p}_2 = 0 \quad (1.50)$$

According to momentum conservation, for the final state particles, we have

$$\sum_i^N p_x^i = 0 \quad (1.51)$$

$$\sum_i^N p_y^i = 0 \quad (1.52)$$

Therefore, we have

$$\langle p_T \cos \phi \rangle = \langle p_x \rangle = \frac{1}{N} \sum_i^N p_x^i = 0 \quad (1.53)$$

$$\langle p_T \sin \phi \rangle = \langle p_y \rangle = \frac{1}{N} \sum_i^N p_y^i = 0 \quad (1.54)$$

But since the p_T and ϕ are completely orthogonal, the random variable p_T is uncorrected to ϕ . Therefore, we have

$$\langle p_T \cos \phi \rangle = \langle p_T \rangle \langle \cos \phi \rangle = 0 \quad (1.55)$$

$$\langle p_T \sin \phi \rangle = \langle p_T \rangle \langle \sin \phi \rangle = 0 \quad (1.56)$$

Finally, we know that $p_T > 0$, thus

$$\langle p_T \rangle > 0 \quad (1.57)$$

Hence,

$$\langle \cos \phi \rangle = 0 \quad (1.58)$$

$$\langle \sin \phi \rangle = 0 \quad (1.59)$$

Therefore, we have

$$v_2 = \sqrt{(\langle \cos^2 \phi \rangle - \langle \sin^2 \phi \rangle)^2 + (2\langle \sin \phi \rangle \langle \cos \phi \rangle)^2} = \langle \cos^2 \phi \rangle - \langle \sin^2 \phi \rangle. \quad (1.60)$$

In terms of momentum p_x and p_y , we can rewrite v_2 as

$$v_2 = \langle \cos^2 \phi \rangle - \langle \sin^2 \phi \rangle = \left\langle \frac{p_x^2}{p_T^2} \right\rangle - \left\langle \frac{p_y^2}{p_T^2} \right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle. \quad (1.61)$$

Classically, we know that the momentum is proportional to the pressure gradient. Schematically, we could write

$$p_x \simeq \frac{m\tau}{\rho} \frac{\partial P}{\partial x} \simeq \frac{m\tau}{\rho} \frac{P}{L_x} \quad (1.62)$$

Where m is the mass of the particle, τ is the life time of the QGP, ρ is the density of the QGP, and L_x is the minor axis of the ellipse in the x direction according to the geometry of Figure 1-32.

Likewise, we have the same relation for p_y

$$p_y \simeq \frac{m\tau}{\rho} \frac{\partial P}{\partial y} \simeq \frac{m\tau}{\rho} \frac{P}{L_y} \quad (1.63)$$

Here, L_y is the major axis of the ellipse in the y direction according to the geometry of Figure 1-32. Apparently, $L_y > L_x$.

Hence, we can write v_2 as

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \frac{\frac{1}{L_x^2} - \frac{1}{L_y^2}}{\frac{1}{L_x^2} + \frac{1}{L_y^2}} = \frac{L_y^2 - L_x^2}{L_x^2 + L_y^2} > 0 \quad (1.64)$$

In heavy ion collision, we define the eccentricity ϵ_s of an ellipse is defined as [105]

$$\epsilon_s \equiv \frac{L_y^2 - L_x^2}{L_x^2 + L_y^2} \quad (1.65)$$

Hence, we have

$$v_2 \simeq \epsilon_s \quad (1.66)$$

Therefore, we can see that v_2 is essentially proportional to the eccentricity simply

based on ellipse geometry of reaction region. Historically, v_2 has extensively studied experimentally and theoretically. It turns out light hadrons demonstrate collectivity. Their elliptic flow v_2 could be calculated using relativistic viscous hydrodynamics, which we will describe in the next section. If QGP is created, we expect v_2 of the light flavor hadrons created direction from the QGP to be positive as we derive above. Figure 1-33 show the v_2 as a function of p_T of charged light flavor hadrons in heavy-ion collisions at mid-rapidity measured by RHIC and LHC experiment [106, 107]

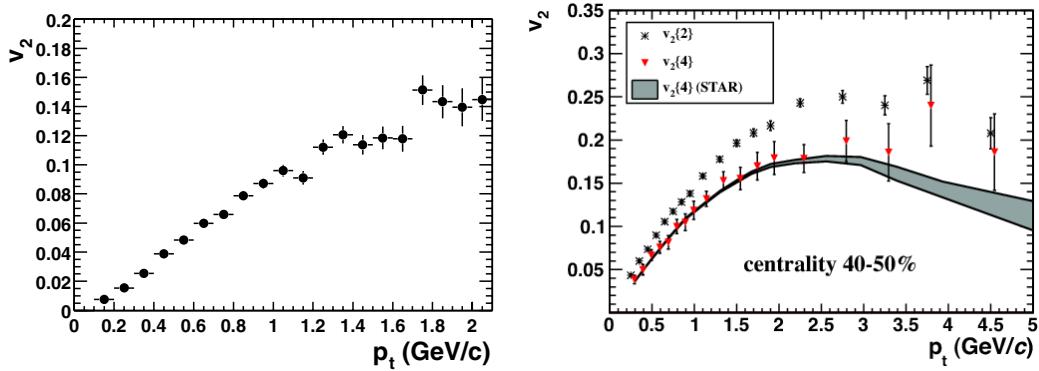


Figure 1-33: The elliptic flow of charged particles v_2 as a function of p_T in AuAu collision measured by the STAR experiments at RHIC (left) and in PbPb collisions by the ALICE experiments at LHC (right) are shown above. Clearly, $v_2 > 0$ is observed in both experiments.

We can clearly see positive v_2 of charged particles at both RHIC and LHC, which also supports the creation of QGP in high energy heavy-ion collisions.

1.6.5 Strangeness Enhancement

As described in Section 1.4.6, the temperature of QGP is well above 100 MeV, which is much larger than the strange quark mass (about 95 MeV). Therefore, since $T_{QGP} > m_s$, in thermally and chemically equilibrated QGP, strange quarks could be produced thermally via the pair production process $u\bar{u}, d\bar{d} \rightarrow s\bar{s}$, and $gg \rightarrow s\bar{s}$, creating the chemical abundance equilibrium [109]. Therefore, the strangeness content in the QGP is enhanced, which could be experimentally observed from enhancement of strange particle yields in AA collisions compared to pp collisions. A direct experimental

observable is the ratio of strange hadron yield to pions in AA and pp collisions. Figure 1-34 shows measurements on strange meson and baryons to pion ratios in AA and pp at RHIC and LHC

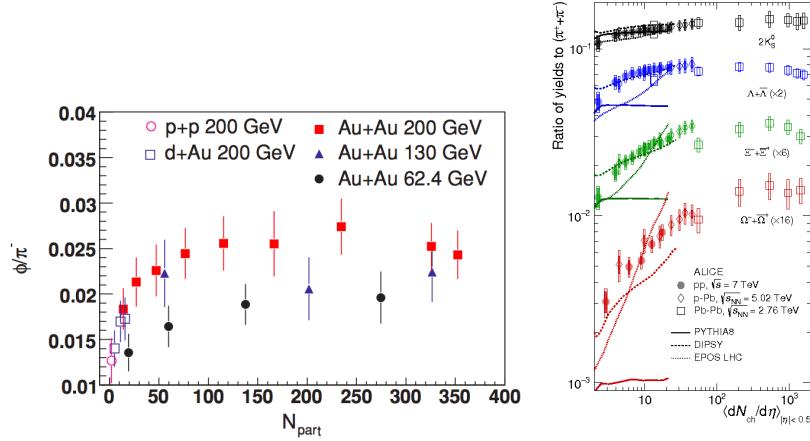


Figure 1-34: The yield ratio of ϕ/π as a function N_{part} in $p + p$, $p + Au$, and $Au + Au$ from the STAR experiment at RHIC (left) and strange hadrons $K_s^0, \Lambda^+, \Xi^0, \Omega^-$ as a function of $\langle dN_{ch}/d\eta \rangle$ from the ALICE experiment at LHC are shown above. We can see a clear trend of the increase of the strange hadron to pion ratio as the event multiplicity increases. In addition, we also see that the ϕ/π ratio increases as $\sqrt{s_{NN}}$ increases, which suggests the strangeness content enhances as the temperature of the system increase.

We can see that ϕ/π ratio increases as N_{part} and $\sqrt{s_{NN}}$ increases, which indicates strangeness enhancement in AA collisions compare to pp collisions. This again can be served as an evidence for the formation of QGP in heavy-ion collisions at RHIC and LHC.

1.6.6 Discovery

Knowing signatures of QGP, physicists build experiments in heavy-ion colliders to search for QGP. Historically, in a special seminar at CERN February 2000, the discovery of QGP was announced [112]. Figure 1-35 shows the announcement

The four typical QGP signatures: quarkonia suppression, jet quenching, elliptic flow, and strangeness enhancement, mentioned previous subsection was also verified

C

SPECIAL SEMINAR

TITLE : A New State of Matter:
Results from the CERN Lead-Beam Programme
TIME : Thursday 10 February at 09.30 hrs
PLACE : Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN²P³)
The J/ ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General, CERN)
Summary.

Figure 1-35: The announcement of discover of QGP in a special seminar at CERN on February 10 2000 is shown above.

by RHIC [113–116] and LHC [117] later.

1.6.7 Macroscopic Properties

Since the discovery of QGP in laboratories, physicists have conducted extensive studies to pin down its macroscopic properties.

Transient Lifetime: According to experimental results at RHIC and LHC, QGP has a very short lifetime. It is on the order of 10 fm/c [118]. It is generally assumed that QGP reaches thermal [119] and near chemical equilibrium [120] via the strong interaction. So far, there is not sufficient experimental evidence to directly support this assumption.

Strong Interacting System: Moreover, QGP, as a deconfined phase of matter, demonstrates a strongly interacting behavior, which contradicts to the prediction weak coupling according to the asymptotic freedom of quarks and gluons in QCD [4]. At $T \sim 1 - 3 T_c$, the coupling strength of QGP is still strong: $g_s \sim O(1)$ [121]. Therefore, strong interaction between the QGP constituents is in general non-perturbative. The equation of state of strong interacting QGP, as an input for hydrodynamic calculations, could be reasonably non-perturbative models such as MIT Bag Model or Lattice QCD [122].

Perfect Liquid Behavior: Finally, QGP demonstrates a near-perfect liquid properties. The expansion of QGP in the fireball stage is approximately isentropic and could be well described by hydrodynamics [126]. More specially, due to the relativistic nature of the strongly coupled near-perfect liquid system, assuming QGP reaches thermal [119] and near chemical equilibrium [120], relativistic viscous hydrodynamics [125] is the correct theoretical formalism for the dynamics of QGP. QGP is almost a perfect liquid. Its shear viscosity to entropy density ratio is very small: $\frac{\eta}{s} \sim (1 - 2.5) \frac{1}{4\pi}$ [123], approaching the quantum limit $\frac{\eta}{s} = \frac{1}{4\pi}$ predicted by the strongly coupled N=4 supersymmetric Yang-Mills plasma in Anti-de-Sitter Space/Conform Field Theory (AdS/CFT) correspondence [124].

Color Opaque Plasma: It is also interesting that QGP is a color opaque plasma [127]. This means that gluons propagating through the QGP will be absorbed by the

plasma medium. Experimentally, the suppression of hadrons is a measure of the color opacity of the QGP [127]. Physicists found that QGP is indeed highly color opaque [128].

1.6.8 Open Questions

Today, it has been more than 20 years since the discovery of QGP. However, there are still many outstanding conundrums, most of which are derived from the mysterious macroscopic behavior of QGP. Below is the list of selected open questions and are currently under active investigation by the heavy-ion physics community [129]:

- 1) **Thermalization of QGP:** How can QGP reach thermal equilibrium within such a short time, which is on the order $1 \text{ fm}/c$, from the non-equilibrium stage?
- 2) **Inner Workings of QGP:** What is the correct degree of freedom to describe QGP? The inner workings of QGP, as a deconfined phase of matter, must lie between asymptotically free quarks and gluons and color neutral hadrons. That is also why the sPHENIX experiment at RHIC, as the next generation DOE flagship Heavy Ion Physics program in the U.S., is going to be built at BNL and collect data to probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.
- 3) **Smallest Droplet of QGP:** What is the smallest droplet of QGP that can be created? Can QGP be created in pPb, pp, or even e^+e^- collision systems? What are the limits of the applicability of hydrodynamics?

1.7 Hard Probes

Traditionally, in Nuclear Physics, when we discover a new state of unknown matter, we use prepared, clean, known, and controllable probes to scatter off of it and look into the scattering patterns of the probes to study its internal structure. Historically, there are many examples. For instance, the Rutherford Scattering using alpha particle to probe the internal structure of atoms [130] and Deep Inelastic scatter using energetic electrons to probe the internal structure of nucleons [131–133]. Figure 1-36 shows the schematic pictures of Rutherford Scattering and Deep Inelastic Scattering

Experiments:

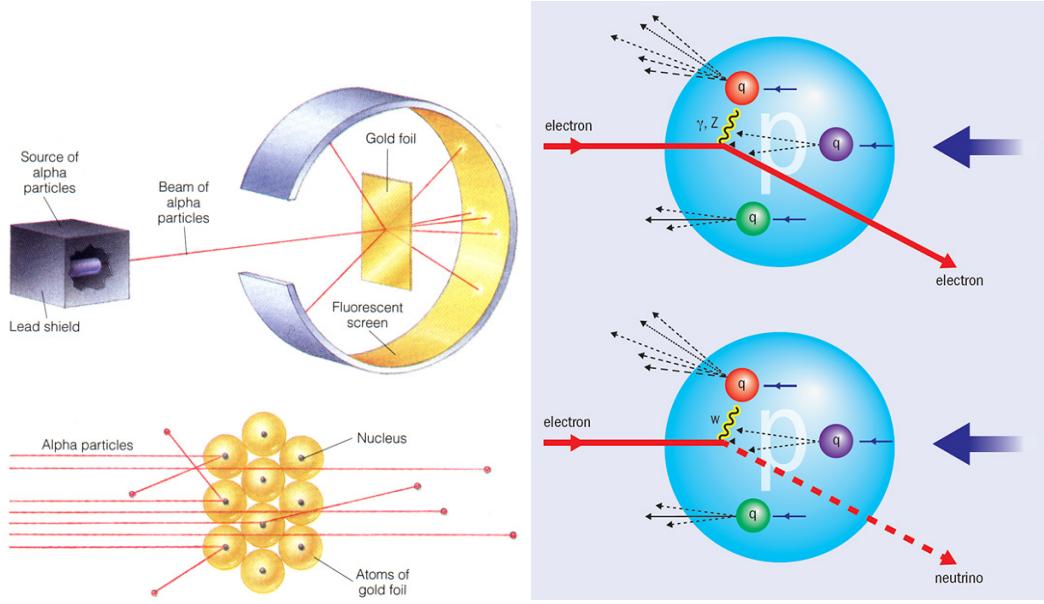


Figure 1-36: The schematic view of Rutherford scattering (left) and Deep Inelastic Scattering (right) experimental setups are shown above.

Unlike atoms, atomic nuclei, and nucleons, QGP is much more unstable with a transient lifetime. It is in principle impossible to use an external probe to scatter off the QGP and study its microscopic structure. Moreover, since QGP is a color deconfined state of matter, to understand its internal structure, the probe should also be color charged, which is not possible to be prepared externally due to color confinement. Fortunately, in experiments, we could use the other particles produced along with the QGP in heavy-ion collisions and probe the inner workings of the QGP through their interaction with the QGP medium. Particularly, hard probes, such as jets, electroweak bosons, and heavy quarks, are accessible and relatively clean [134]. In the last two decades, they have been extensively used in the heavy-ion physics community to study QGP [135]. In the follow subsections, I will briefly introduce the mechanisms of jets, electroweak bosons, and heavy quarks to probe the microscopic structure of QGP in heavy-ion experiments.

1.7.1 Jets

Jet is a relatively hard probe compared to other physics objects. Jets can be used to probe the length scale resolution ability of QGP to resolve the jet internal structure. The study of jet can reveal path length dependence of energy loss dE/dx in the QGP medium. It is essentially a calorimetry of the QCD matter, which is an analog to the energy loss dE/dx of electrically charged particles passing through QED matter used in particle radiation detection [3]. From the modification of the jet shape and jet substructure studies in heavy-ion collisions [138], we can understand how jet energy is redistributed to the QGP medium [139, 140]. Experimentally, the observables are di-jet angular correlation, jet R_{AA} , and jet fragmentation function. Figure 1-37 shows schematically how jets are used to probe the QGP

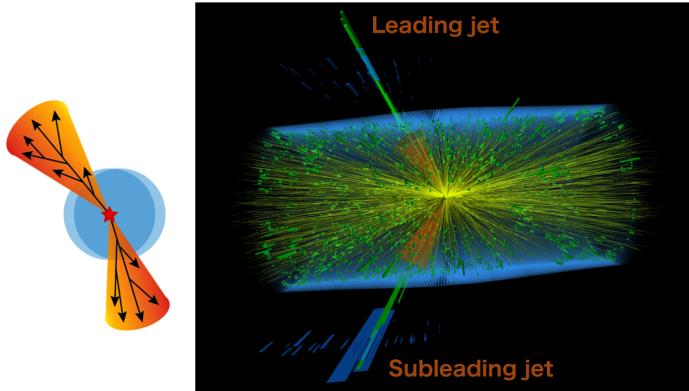


Figure 1-37: The schematic plot illustrating dijet imbalance (left) compared to the display of original event (right) are shown above. Image from [137].

1.7.2 Electroweak Bosons

Electroweak bosons, including photon, W, and Z bosons, due to their color neutrality, are relatively clean probes to tag the initial parton dynamics in the QGP. It has shown that they are essentially unmodified as they traverse through the QGP medium. No significant deviation of R_{AA} from unity is observed isolated photon and Z boson measurements in heavy-ion collisions [141, 142] as shown in Figure 1-38

Experimentally, we can study the angular correlation between photon-tagged and

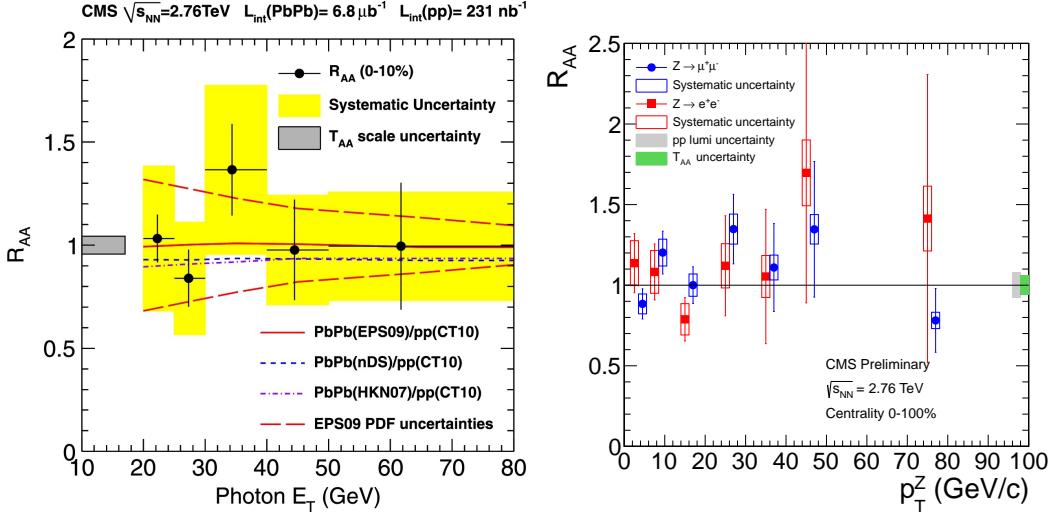


Figure 1-38: The R_{AA} vs p_T of direct photon (left) and Z boson (right) measured with the CMS experiment at LHC are shown above. We could see that the R_{AA} of both photon and Z boson are consistent with unity within their uncertainties.

Z-tag jets to understand the medium effect to the jet and probe the internal structure of QGP. Figure 1-39 show schematically an event with a electroweak boson and a jet produced in and propagate through the QGP medium from the Cover in one of the issues of Physical Review Letter [143].

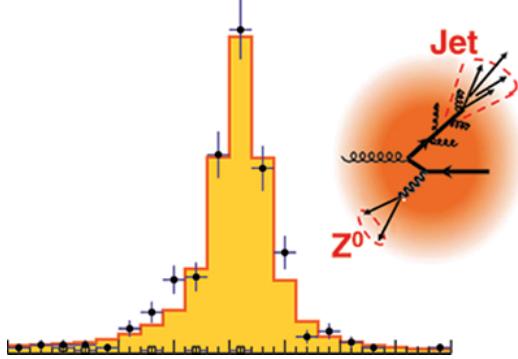


Figure 1-39: The schematic plot of a $Z +$ jet event with the creation of QGP and the invariant mass of fully reconstructed Z boson via the decay channel $Z \rightarrow \mu^+\mu^-$ in the front cover of Physics Review Letter (Volume 119, Issue 8) is shown above. We could see that the Z boson is essentially unmodified by the QGP medium.

1.7.3 Heavy Quarks

Heavy quarks, such as charm and beauty quarks, have large mass compared to the Λ_{QCD} and T_{QGP} . Therefore, they are predominantly produced in early stage of heavy-ion collisions where hard scattering processes occur. Their production could be calculated by perturbation QCD. Figure 1-40 show the lowest order Feynman diagrams of heavy quark pair production in QCD.

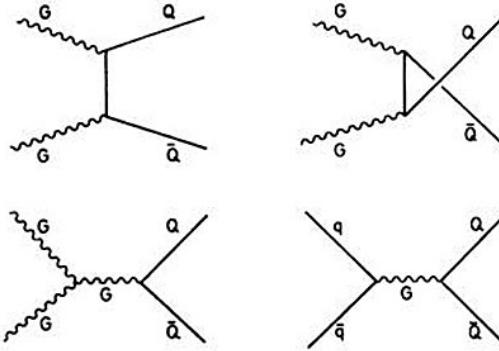


Figure 1-40: The four lowest order tree level Feynman diagrams of heavy quark pair production are shown above.

In general, due to their relatively momentum transfer to the medium constituents compared to mass [], they do not reach complete thermalization via multiple scattering as they traverse through the QGP. In addition, since their lifetime is much longer than the QGP lifetime, they retain their identities and record the evolution of the QGP, which makes them excellent probes. Then, they travel through the medium, hadronize into heavy flavor hadrons, and decay weakly. Their decay products are detected and identified by particles detectors.

Experimentally, from the final stage decay products, we can fully reconstruct open heavy flavor hadrons where heavy quark dynamics is encoded with different transverse momenta to study their diffusion coefficients, hadronizaton mechanism, and energy loss to probe the microscopic structure of QGP via their scattering patterns with the QGP constituents at different wavelengths. Figure 1-41 below shows respectfully an event of beauty heavy quark production and hadronization in vacuum and QGP.

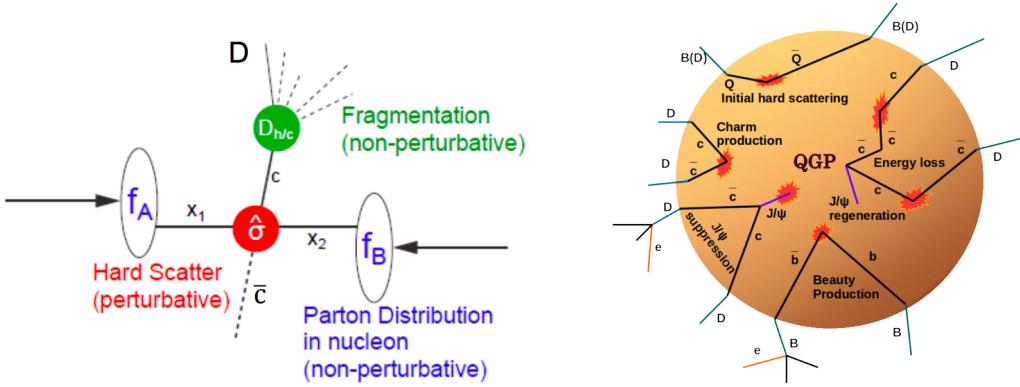


Figure 1-41: The schematic plots of heavy quark production and hadronization in vacuum (left) and QGP (right) are shown above.

1.8 Open Heavy Flavor Physics

My graduate research focuses on answering the second question through the data analysis of fully reconstructed heavy flavor hadrons with the CMS experiment to understand transport properties and probe the microscopic structure of QGP. In this section, we will focus on discussing open heavy flavor physics where the only one heavy quark Q is in hadron. Open heavy flavor hadrons have ± 1 heavy flavor number. Quarkonia states $Q\bar{Q}$ are considered as hidden heavy flavor with a zero net heavy flavor quantum number. Their properties are different from open heavy flavor hadrons. We will not be discussed them in the follow subsections.

1.8.1 Heavy Flavor Physics in Vacuum

To use heavy quark to probe the QGP created in heavy-ion collisions, we first need to understand heavy quark physics in vacuum from pp collisions. In the process $pp \rightarrow Q\bar{Q}$, QCD factorization theorem could be applied to study the using perturbative QCD (pQCD). Fixed-to-Next-to-the-Leading (FONLL) is pQCD model calculating the spectra of charm and beauty quarks, schematically denoted as: $\frac{d^2\sigma^Q}{p_T dp_T dy}$, in $pp \rightarrow Q\bar{Q}$ at different energies [144]. Figure 1-42 shows the FONLL calculations of charm and beauty quarks spectra produced at the LHC energy for pp collisions at $\sqrt{s} = 5.02$

TeV.

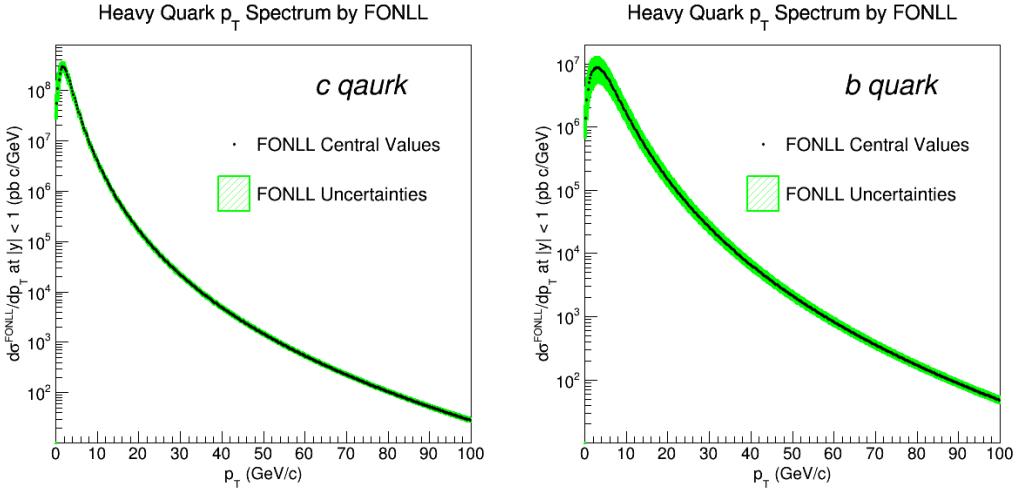


Figure 1-42: The charm quark (left) and beauty quark (right) transverse momentum p_T distribution at $\frac{d\sigma}{dp_T}$ at $|y| < 1$ from FONLL calculations are shown above.

In vacuum, heavy quarks fragment into heavy flavor hadrons $Q \rightarrow H_Q$. We can defined the parton fragmentation function $D_i^{H_Q}(z, \mu^2)$ where is the probability for a quark q with energy E fragment into a hadron with energy zE ($0 < z < 1$) at the factorization scale of μ^2 [145]. According to pQCD, $D_i^{H_Q}(z, \mu^2)$ is universal in vacuum from e^+e^- , ep , and pp collisions. Figure 1-43 shows the scattering processes which fragmentation fraction is involved:

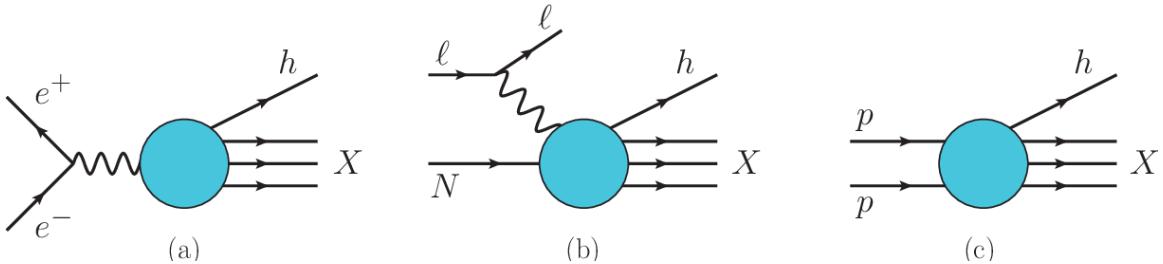


Figure 1-43: Single-inclusive hadron production process, where fragmentation function are involved, in (a) electron-positron annihilation, (b) deep-inelastic lepton-nucleon scattering, (c) proton-proton scattering are shown above.

Next, we are ready to define heavy quark fragmentation fraction $f(Q \rightarrow H_Q)$. First we know, the energy

$$E = \sqrt{m^2 + p_T^2 \cosh^2 y} \quad (1.67)$$

Ignoring the mass, we have

$$E \simeq p_T \cosh y \quad (1.68)$$

So energy of hadron E^h that the quark with E^Q fragmented to will be

$$E^h = z E^Q \quad (1.69)$$

So we have the transverse momentum of the hadron p_T^h

$$p_T^{H_Q} = z p_T^Q \quad (1.70)$$

With heavy quark spectra $\frac{d^2\sigma^Q}{p_T dp_T dy}$ and parton fragmentation function $D_i^{H_Q}(z, \mu^2)$, we let

$$\frac{d^2\sigma^Q}{p_T dp_T dy} = F^Q(p_T, y) \quad (1.71)$$

Hence, for a hadron with p_T , the heavy quark will have p_T/z with probability $D_i^{H_Q}(z)$ to fragment into this hadron. Therefore, the heavy flavor hadron spectra is given by:

$$\frac{d^2\sigma^{H_Q}}{p_T dp_T dy} = \int_{x_T}^1 F^Q(p_T/z, y) D_i^{H_Q}(z, \mu^2) dz \quad (1.72)$$

Here $x_T = \frac{2p_T}{\sqrt{s}}$ [146].

Now if we consider a factorization scaling near the heavy quark mass $\mu^2 \rightarrow m_Q^2$, according to PDG reference [3], solving the leading evolution equation, heavy quark fragmentation function $D_Q^{H_Q}(z)$ is in a form of delta function and light quark q and gluons g ($i = g, q$) will not contribute to produce heavy flavor hadrons. Hence, we could right

$$D_{q,g}^{H_Q}(z, \mu^2)|_{\mu^2=m_Q^2} = 0 \quad (1.73)$$

$$D_Q^{H_Q}(z, \mu^2)|_{\mu^2=m_Q^2} = f(Q \rightarrow H_Q) \delta(1-z) \quad (1.74)$$

Here $f(Q \rightarrow H_Q)$ is the heavy quark fragmentation fraction and stands for the probability of a heavy quark Q hadronize into an open heavy flavor hadron H_Q . Indeed, according to the momentum sum rule constraint of the parton fragmentation function [145]

$$\sum_{H_Q} \int_0^1 z D_Q^{H_Q}(z, \mu^2) dz = 1 \quad (1.75)$$

$$\sum_{H_Q} \int_0^1 z f(Q \rightarrow H_Q) \delta(1-z) dz = 1 \quad (1.76)$$

$$\sum_{H_Q} f(Q \rightarrow H_Q) = 1 \quad (1.77)$$

This verifies that the sum of heavy quark fragmentation fraction over all heavy flavor hadrons is equal to 1. Next, we have

$$\frac{d^2\sigma^{H_Q}}{p_T dp_T dy} = \int_{x_T}^1 F^Q(p_T/z, y) D_i^{H_Q}(z, \mu^2) dz = \int_{x_T}^1 F^Q(p_T/z, y) D_Q^{H_Q}(z, m_Q^2) dz \quad (1.78)$$

Thus,

$$\frac{d^2\sigma^{H_Q}}{p_T dp_T dy} = \int_{x_T}^1 F^Q(p_T/z, y) f(Q \rightarrow H_Q) \delta(1-z) dz = f(Q \rightarrow H_Q) F^Q(p_T, y) \quad (1.79)$$

Hence, we have

$$\frac{d^2\sigma^{H_Q}}{p_T dp_T dy} = f(Q \rightarrow H_Q) \frac{d^2\sigma^Q}{p_T dp_T dy} \quad (1.80)$$

This means that the open heavy flavor hadron spectra $\frac{d^2\sigma^{HQ}}{p_T dp_T dy}$ is essentially proportional to the heavy quark spectra $\frac{d^2\sigma^Q}{p_T dp_T dy}$ with heavy quark fragmentation fraction $f(Q \rightarrow H_Q)$ the as the coefficient of proportionality. Experimentally, charm and beauty fragmentation fractions have been measured at LEP, HERA, and the LHC and documented in PDG [3]. The fragmentation fraction is often treated roughly a constant independent to p_T , y , and \sqrt{s} and is assumed to be universal in e^+e^- , ep , and pp collisions systems [3].

In terms of being a constant, according LHCb pp results [147], it appears that the fragmentation fraction has significant \sqrt{s} and p_T dependence while no significant y_B (or η_B) dependence is observed. Figure 1-44 shows the beauty quark fragmentation fraction: $f_u = f(b \rightarrow B^+)$, $f_d = f(b \rightarrow B^0)$, and $f_s = f(b \rightarrow B_s^0)$

In terms of universality, according to Strangeness Quark Matter Conference (SQM) in 2021, a hadronization universality breaking is observed from the ALICE experiment at the LHC [148]. Figure 1-45 shows the hadronization universality breaking reported by the ALICE experiment in SQM 2021

Further investigations of these results are currently ongoing. However, we will not expand the discussions here. Now, equipped with the understanding of heavy flavor physics in vacuum from pp collisions as a reference, we are ready to use heavy quarks to probe the inner workings of QGP created in heavy-ion collisions.

1.8.2 Heavy Quark Diffusion

In the limit of low p_T or equivalently long wavelength, for heavy quarks inside the QGP medium, their elastic collision cross section dominates. In elastic $Qq \rightarrow Qq$ process in the thermally equilibrated QGP medium, heavy quarks has the relatively small momentum transfers of the order of the temperature compared to the heavy quark mass: $m_Q > |k| \simeq T$. Considering the mean free time of HQ in the QGP medium is about $\tau \sim 0.44 fm/c$ [150]. Therefore, the number of scattering of heavy quarks in the QGP medium is about $n \sim \frac{\tau_{QGP}}{\tau_{HQ}} \simeq 23 \sim O(10)$.

Now, we can consider a simple binomial process to model the diffusion of heavy

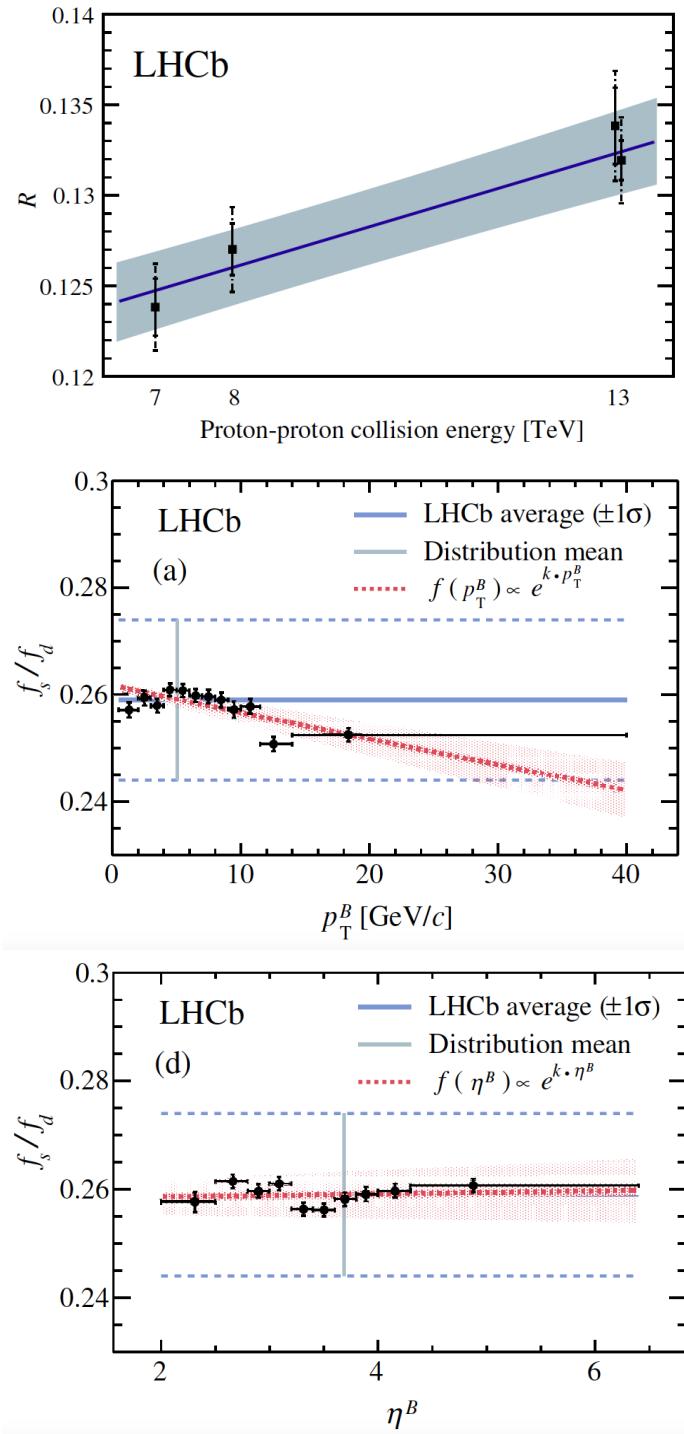


Figure 1-44: R , the corrected yield ratio of B_s^0/B^+ , as a function the pp collision energy \sqrt{s} (top), the f_s/f_d ratio as a function p_T (middle), and the f_s/f_d ratio as a function η_B (bottom), from the LHCb experiment are shown above.

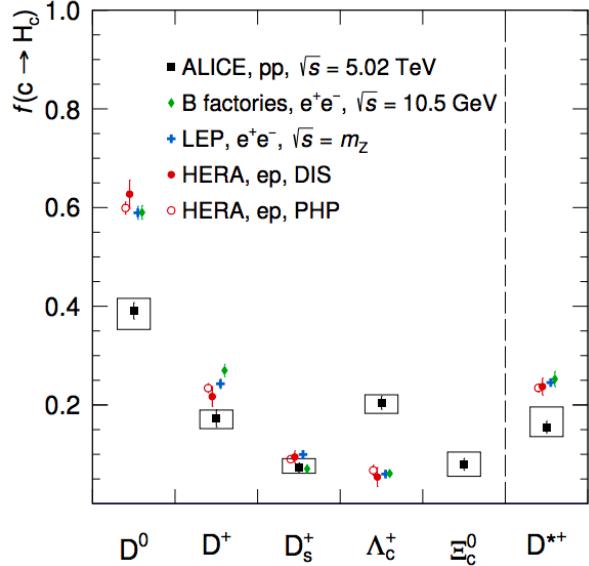


Figure 1-45: The charm quark fragmentation fraction to different charm hadrons species in e^+e^- , ep , and pp collisions are presented above. From the ALICE experiment, we can clearly see that the fragmentation fraction of D^0 has drop by about 40% while the Λ_c^+ has enhanced by about a factor of 4. Therefore, the hadronization universality is clear broken at the LHC energy in the charm sector.

quark in the QGP medium. Therefore, assuming the momentum of the heavy quark at $t = 0$ is p , after the time τ_{HQ} , one scattering happens. The momentum of the heavy quark at $t = \tau_{HQ}$ either $p + k$ or $p - k$. Each has $1/2$ probability. Next, after another τ_{HQ} , another scattering happens. The momentum of the heavy quark at $t = 2\tau_{HQ}$ either $p + 2k$, p or $p - 2k$ with $1/4$, $1/2$, and $1/2$ probability respectfully. Therefore, the standard deviation of binomial process $\sigma_p = \frac{\sqrt{n}}{2}k$. If we take $n = 25$, $\sigma_p = 2.5k \simeq 2.5T_{QGP} = 0.4$ GeV. Experimentally, we consider a heavy quark with momentum about $p > 1.5$ GeV/c $\gg \sigma_p$.

We could see that the heavy quark transverse momentum is well above 1 GeV/c. Hence, such heavy quarks still retain a lot of memory about its initial conditions after multiple small scattering with QGP medium. Hence, in these conditions, heavy quark undergoes Brownian-like motion in the QGP medium [149]. Their motion in the QGP medium could be characterized by the Planck-Fokker Equation, which could be schematically written as follows [151]:

$$\frac{\partial}{\partial t} f_q(t, \vec{p}) = \frac{\partial}{\partial p_i} \{ A_i(\vec{p}) f_q(t, \vec{p}) + \frac{\partial}{\partial p_j} [B_{ij}(\vec{p}) f_q(t, \vec{p})] \} \quad (1.81)$$

Here, $f_q(t, \vec{p})$ is the heavy quark phase space distribution function. If we ignore modification of the cold nuclear matter effect on the heavy quark initial production spectra, then in heavy-ion collision:

$$F^Q(t = 0, p_T) \propto \frac{d\sigma_{FONLL}}{p_T dp_T} \quad (1.82)$$

The transport parameters $A_i(\vec{p})$ is related to the thermal relaxation rate and $B_{ij}(\vec{p})$ is related to the momentum diffusion of heavy quark [149]. The heavy quark special diffusion coefficient D_s is related to the transport parameter as follows:

$$D_s = \frac{T}{m_Q A(p = 0)} \quad (1.83)$$

D_s characters the fundamental property of the QGP $\frac{\eta}{s}$ via the relationship

$$2\pi T D_s \simeq \frac{\eta}{s} \quad (1.84)$$

More detailed studies has been carried out to examine heavy quark coupling strength and quantify the information heavy quarks carry as they traverse through the QGP medium [152].

1.8.3 Heavy Quark Energy Loss

In the limit of high p_T or equivalently short wavelength, inelastic cross section starts to dominate [1]. Heavy quarks lose a substantial amount of energy as they travel fast through the QGP medium [157]. In a simplified schematization, there are two different pictures that describe the energy loss mechanism of heavy quark in the QGP medium. In the pQCD picture, the coupling of the constituents of the QGP is assumed to be weak. Therefore, 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 [151]. The collisional energy loss is given by $-\frac{dE}{dx} = \kappa_{coll} T^2$ and the radiative energy loss is given by $-\frac{dE}{dx} = \kappa_{rad} T^3 x$ [153, 154]. Figure 1-46 shows schematically heavy quark energy loss mechanism in the QGP medium

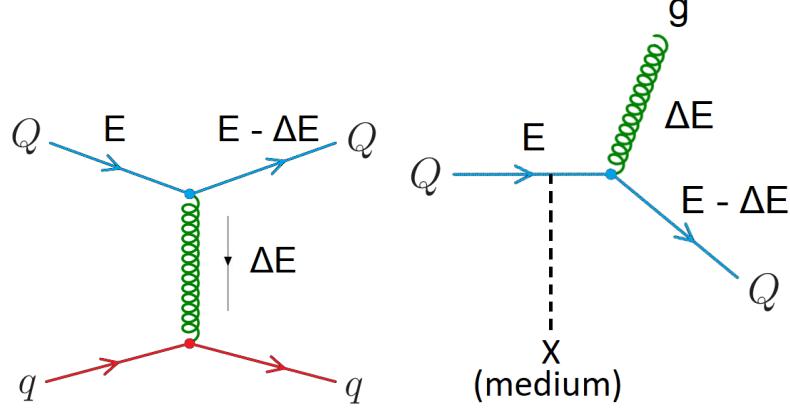


Figure 1-46: The schematic demonstration of the pQCD picture: collisional energy loss (left) and radiative energy loss (right) of heavy quarks in the QGP medium are shown above.

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 [155] to calculate the energy loss of heavy quark [156] in the QGP medium

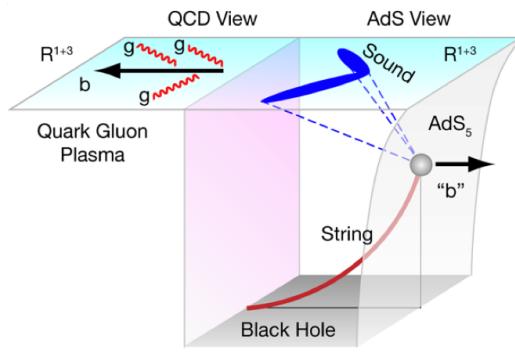


Figure 1-47: The schematic demonstration of ADS/CFT picture: the energy loss of a quark in the QGP medium holographically due ADS/CFT drag force.

In pQCD picture, in the limit of $p_T \rightarrow \infty$, similar to electron Bremsstrahlung via QED radiation in the matter [158], for a heavy quark traveling through the QGP

medium, its radiative energy loss via soft gluon radiation will dominate. The soft gluon radiation spectrum by a parton in the QGP medium is given by [159]

$$dP = \frac{\alpha_S C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 dk_\perp^2}{(k_\perp^2 + \omega^2 \theta_0^2)^2} \quad (1.85)$$

Where

$$\theta_0 \equiv \frac{m}{E} \quad (1.86)$$

Here, ω is the energy of the gluon and k_\perp is the transverse momentum of the gluon, C_F is color factor (Casimir) which is 3 for gluons with one color and one anti-color charges and $4/3$ for quarks with one color charge. From Eq 1.84 above, a suppression of radiation at a small angle $0 - \theta_0$ is observed. This effect is known as the dead cone phenomenon [159]. We also know that from Eq 1.85, that as m increases, the dead cone angle $\theta_0 = \frac{m}{E}$ will decrease. Figure 1-48 schematically shows a charm quark radiate gluon in the medium with a dead cone in the small angle:

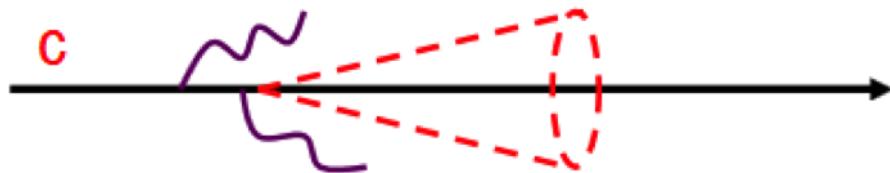


Figure 1-48: The schematic demonstration of a charm quark radiate and suppression in small angle due to the dead cone effect in the QGP medium is shown above.

Since we have the follow mass hierarchy for quarks and gluons:

$$m_g < m_q < m_c < m_b \quad (1.87)$$

We should expect the energy loss to follow

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b \quad (1.88)$$

We call the inequality above to be the flavor dependence of energy loss, which is an important feature of heavy quark energy loss mechanism in the QGP medium. The studies of heavy quark energy loss mechanism in QGP will help us determine the fundamental jet transport coefficient \hat{q} that characterizes the scattering power of the medium [149], which relates to the mean free path and the momentum diffusion coefficient of heavy quarks [160]. The determination of \hat{q} will be crucial for us decipher the inner workings of the QGP [161].

1.8.4 Heavy Quark Hadronization

After heavy quarks traverse through the medium, it will hadronize into heavy flavor hadrons, which could be fully reconstructed from their final state decay products in experiments. As described in section 1.2.7, in general, hadronization is non-perturbative. Considering heavy quark dynamics and apply hadronization models, physicists develop theoretical models to describe heavy quark hadrochemistry. Below, I will present two model candidates, the Texas A&M University (TAMU) Model [162] and the Model developed from Cao et. al. [165], to describe beauty quark production and hadronization in vacuum:

TAMU Model

The TAMU Model uses a thermodynamic T-matrix formulism in terms of “ladder diagrams” to compute the heavy quark in-medium scattering amplitude and determine the non-perturbative transport parameters A_i and B_{ij} in the Planck-Fokker equation shown in Eq 1.81 [162]. Figure 1-49 shows schematically the “ladder diagram” describing the dynamic evolution of a heavy quark in the QGP medium

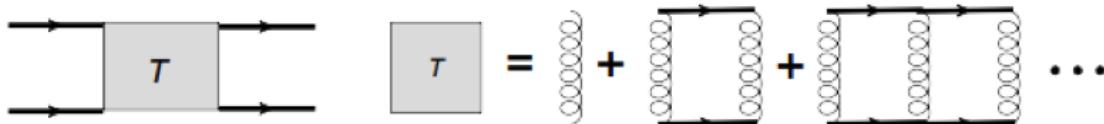


Figure 1-49: The ladder diagram used by the TAMU model to describe heavy quark diffusion in the QGP medium is shown schematically above.

The input of T-matrix uses a lattice QCD potential [163] corrected with relativistic effects to model the non-perturbative interaction between heavy quarks and partons in the medium and make it consistent with HF spectroscopy in vacuum to determine the thermal relaxation rate coefficient $A_i(p, T)$. Only elastic collisional energy loss is included in the calculation. Resonance recombination model of heavy quark with a light quark nearby is applied to describe heavy quark hadronization [164]. Finally, effective hadronic scattering amplitudes is used to heavy flavor hadronic rescattering with other hadrons before kinetic freezout stage. The background parton composition and kinematics are modeled by the standard hydrodynamic simulations of the bulk medium in nuclear collisions

Cao, Sun, Ko Model

The Cao, Sun, Ko Model use an advanced Langevin-hydrodynamics approach [166, 167] incorporating both elastic and inelastic energy loss of heavy quarks inside the dynamical QGP medium. The equation below schematically shows relativistic Langevin equation to simulate heavy quark dynamics in the QGP medium

$$\Delta \vec{p} = -\gamma \frac{T^2}{M} \vec{p} \Delta t + \vec{\xi}(t) \quad (1.89)$$

And

$$\Delta \vec{x} = -\frac{\vec{p}}{E} \Delta t \quad (1.90)$$

The noise is modeled by the Gaussian diffusion function

$$P(\vec{\xi}) \propto \exp\left[\frac{\vec{\xi}^2}{2D_p \Delta t}\right] \quad (1.91)$$

The dimensionless γ factor is defined as

$$\gamma = \frac{M}{\tau_{HQ} T^2} \quad (1.92)$$

A comprehensive coalescence model with strict energy-momentum conservation and PYTHIA fragmentation simulation [169] with the default Peter fragmentation

function, where the coalescence probability is determined from resonant scattering rate of heavy quarks in the QGP according to the resonant recombination model [164, 168], are applied to model heavy quark hadronization.

In addition to TAMU Model and Cao, Sun, Ko Models, there are many other theoretical models that describe heavy quark hydrochemistry in heavy-ion collisions. Nevertheless, due to the large discrepancies between hadronization models, which significant limits the heavy-ion community to interpret the heavy flavor data. Therefore, experimentalists precisely measure heavy flavor observables and provide constrains for theoretical models.

1.8.5 Experimental Observables

Therefore, physicists propose many experimental observables to study open heavy flavor physics and test theoretical models in heavy ion collisions. Traditionally, heavy flavor hadron v_2 , R_{AA} , and yield ratio are extensively studied.

Heavy Quark Diffusion: v_2

In the QGP medium, heavy quark diffused by the color force and multiple scatter with medium constituents, which could generate sizable azimuthal anisotropy v_2 [149]. Experimentally, we scale the v_2 and the hadron kinetic energy $K_T = \sqrt{m^2 + p_T^2} - m^2$ of heavy quarks with n_q according to the Number of Constituent Quark (NCQ) Scaling in quark coalescence model [172]. Figure 1-50 shows the comparison of the v_2/n_q as a function of K_T/n_q of D^0 ($c\bar{u}$) meson with light flavor hadrons with STAR experiments at RHIC [173] and the CMS experiment at LHC [174].

We could see a reasonably good NCQ scaling behavior of D^0 meson with other light flavor hadrons, which suggests sizable collectivity of charm quarks in the QGP medium.

Heavy Quark Energy Loss Mechanism: R_{AA}

As we mentioned previously, the nuclear modification factor R_{AA} of heavy flavor hadrons as a function of p_T could quantify the energy loss of quarks via the shift of the p_T spectra to the left in AA collisions compared to pp collisions. Figure 1-51 R_{AA} heavy and flavor hadrons measured with experiments at RHIC and LHC.

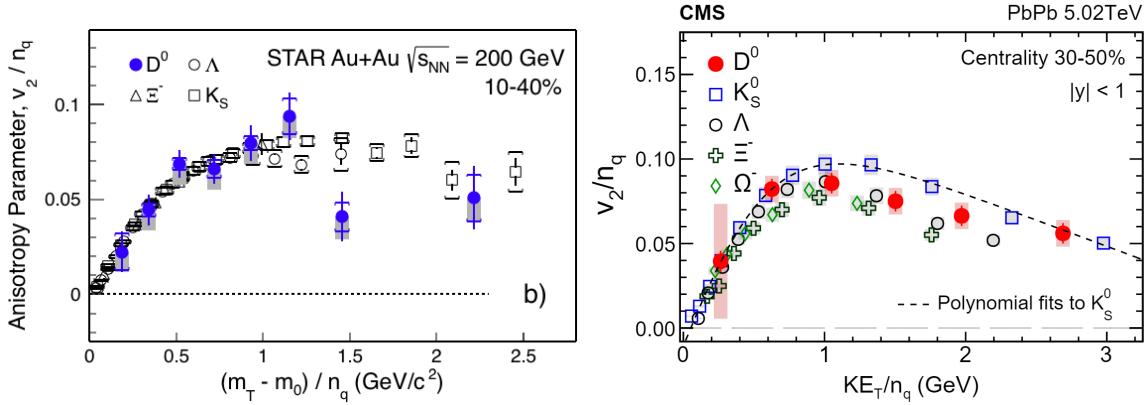


Figure 1-50: The NCQ scaled $D^0 v_2/n_q$ vs K_T/n_q and the comparison light hardons measured by the STAR experiment at RHIC (left) and the CMS experiment at LHC (right) are shown above.

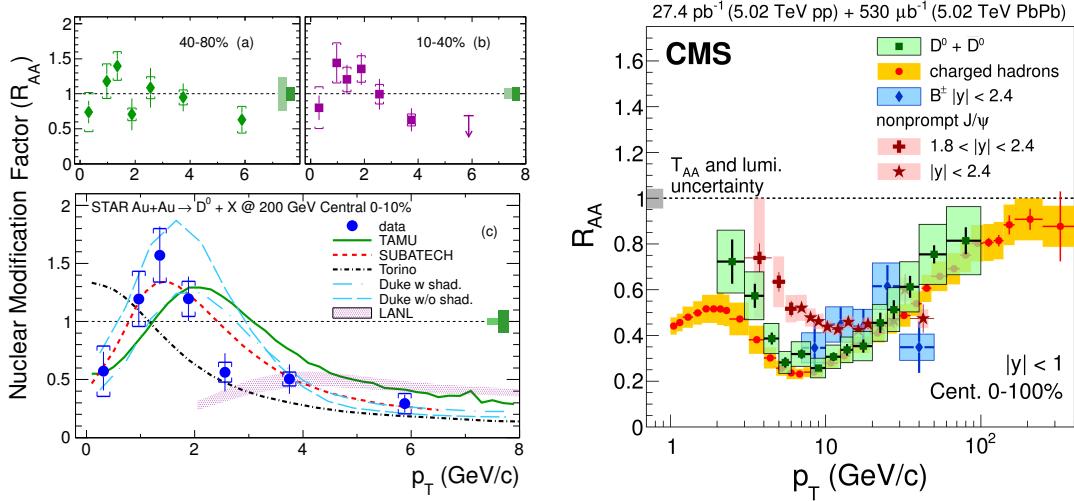


Figure 1-51: The $D^0 R_{AA}$ vs p_T with the STAR experiment in 0 - 10%, 10 - 40%, and 40 - 80% centrality at RHIC and the D^0 , B^+ , non-prompt J/ψ and charged hadrons R_{AA} vs p_T at 0 - 100% centrality with the CMS experiment at LHC are shown above.

We could see that R_{AA} of D^0 and B^+ are both below 1, which suggest charm and beauty quarks lose a significant fraction of energy to the QGP medium. As p_T increases, the R_{AA} of light and heavy flavor hadrons converge to the same value and approach 1, which Lorentz γ factor come into play where the mass of the hadron become irrelevant. In addition, the CMS results above indirectly agree with the expectation of the flavor dependence of energy loss: $R_{AA}^h < R_{AA}^D < R_{AA}^B < 1$. With both R_{AA} and v_2 , we can constrain theoretical models and understand the interaction mechanism of heavy quarks with the QGP medium.

Heavy Quark Hadronization: H_s/H^0 and Λ_Q/H^0

According to the theoretical reviews of heavy quarks hadrochemistry in heavy-ion collisions [170, 171], the strange-to-non-strange meson (H_s/H^0) and baryon-to-meson (Λ_Q/H^0) ratios are excellent observables to test hadronization models. Figure 1-52 shows the fully reconstructed Λ_C^+/D^0 ratio measured by the STAR and CMS experiments

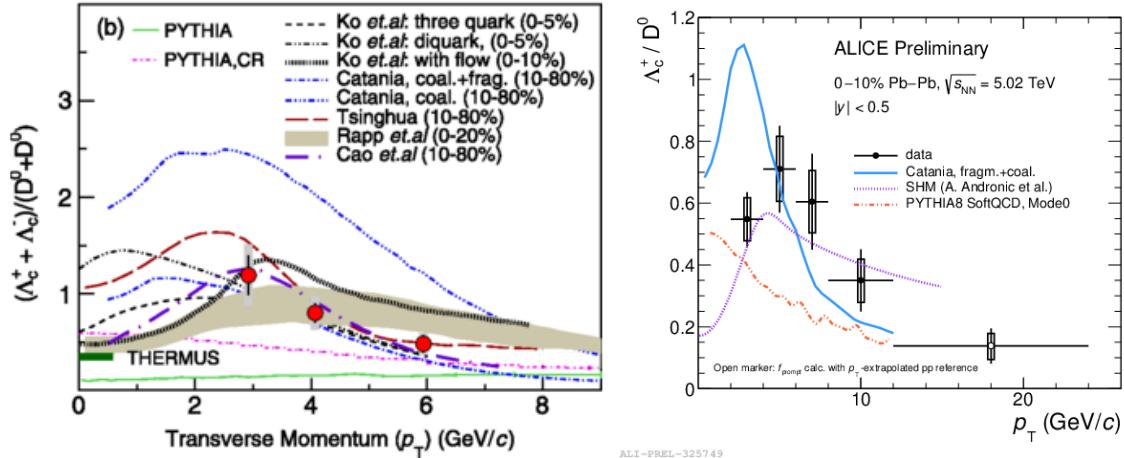


Figure 1-52: The fully reconstructed Λ_C^+/D^0 ratio in pp and heavy-ion collisions measured by the STAR experiment at RHIC (left) and the CMS experiment at LHC (right) are shown above.

We can see that in general, Λ_C^+/D^0 ratio in heavy-ion collisions lies above its ratio in pp collisions. Moreover, there are many different theoretical predictions agree reasonably well with the experiments due to the large uncertainties. More precise Λ_C^+/D^0 measurements will be desired in order to constrain theoretical models.

In addition to v_2 , R_{AA} , and Λ_Q/H^0 , some modern observables with more differentiation such as the hadron-hadron correlation and heavy flavor jet substructure measurements have been recently carried out [179, 180].

Hence, with the motivation to understand the hadronization mechanism of heavy quarks and investigate the inner workings of the QGP, I propose to carry out open heavy flavor physics measurements. In this thesis, I will focus on the measurement of the experimental observable B_s^0/B^+ ratio from fully reconstructed B_s^0 and B^+ mesons (and their anti-particles) via decay channels of $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ and $B_s^0 \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^-K^+$ in pp and PbPb collisions with the CMS experiment at the LHC to study the beauty production and hadronization mechanism in vacuum and QGP.

Chapter 2

The CMS Detector

2.1 Overview

The Compact Muon Solenoid (CMS) Detector is a general purpose high-energy physics detector located 100 meters underground on the French side of the LHC [181]. Overall, the complete detector is 21 m long, 15 m wide and 15 m high with a weight of 14 kiloton, heavier than the Eiffel Tower in Paris. It functions as a giant, high-speed camera, taking 3D “photograph” of particle collisions from all directions up to 40 million times each second. Figure 2-1 shows the photo taken for the CMS detector at the underground collision hall.

The CMS detector is made of sub-detectors including silicon strip and pixel trackers, the preshower made of silicon strips, the crystal electromagnetic calorimeter (ECAL), the superconducting solenoid with 3.8 T of magnetic field strength, the inner hadronic calorimeter (HCAL), the steel returning yoke to enhance the magnetic field strength, the outer hadronic calorimeter, the muon chambers, and the forward hadronic calorimeter [181]. Figure 2-2 shows schematic view of the CMS detector

The CMS detector is built, operated, and maintained by the CMS Collaboration. The CMS Collaboration consists of over 4000 members including scientists, engineers, technicians, students, and administrative assistants from 200 institutes and universities in 40 countries around the world. Physicists take data from the CMS detector and share data with each other with online system. The data are store in tapes and

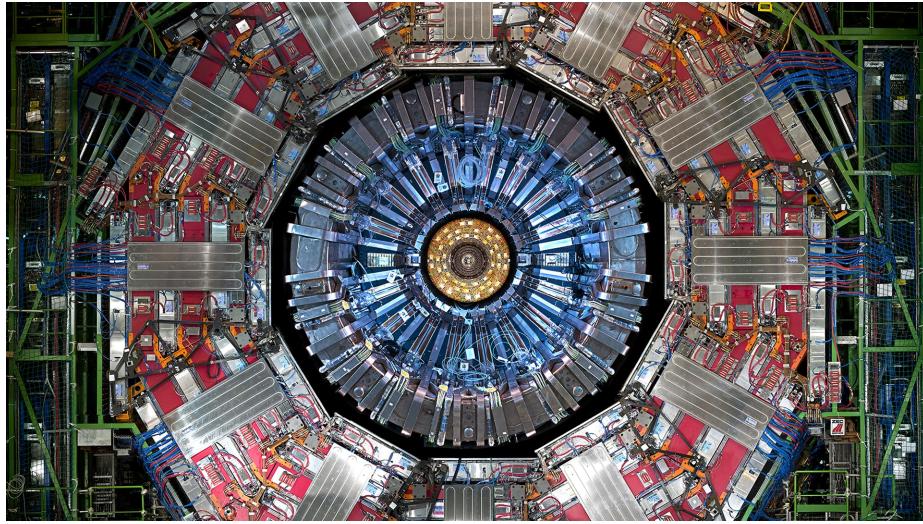


Figure 2-1: The front view of the CMS detector at the underground collision hall is shown above.

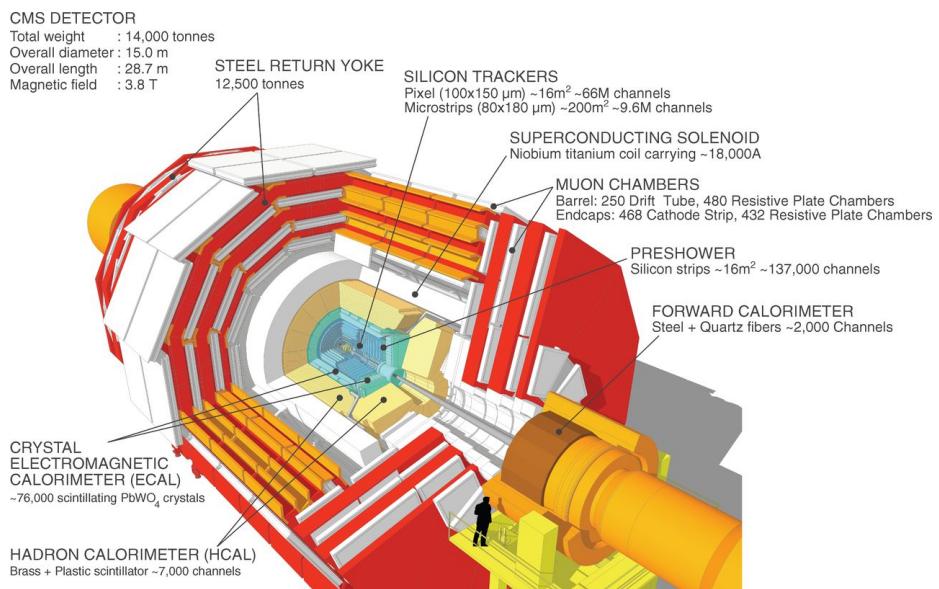


Figure 2-2: The schematic view of the CMS detector with brief descriptions of all its components is shown above. Image from [182]

kept at different institutions. Members of the CMS experiment collaborate with each other on detector studies and data analysis to produce important scientific results and have published in more than 1000 papers in internationally recognized journals.

In the following sections, I will describe in more details the CMS experiment including the trigger system for data acquisition, the tracking system to track charged particles, the muon system for muon detection, identification, and reconstruction, and the calorimeter system to measure the energy of the particles.

2.2 Triggers

The CMS experiment develops triggers to acquire experimental data [183]. Its main purpose is to select events of potential physics interests from approximately one billion events per second the particles collisions at the LHC. The CMS trigger system consists of two levels of triggers: hardware level 1 (L1) trigger and the software high level trigger (HLT). Different triggers encoded in the L1 and HLT are designed and fire to collect datasets for specific physics studies.

2.2.1 L1 Trigger

In the CMS experiment, an event is defined as a snapshot of one collision at the LHC. In the L1 trigger, physicists develop algorithms according to detector electronics response to decide if an event is accepted or rejected within the L1 trigger latency time. Figure 2-3 shows the schematic overview of L1 trigger making its decision online to select events based on the information from the calorimeter and muon systems.

In the interest of heavy-ion studies, physicists develop a set of dedicated triggers algorithms in the L1 trigger to build datasets. The minimum biased (MB) trigger is designed to collect minimum bias data for elliptic flow, D^0 meson, and charged particle multiplicity analyses while the single muon trigger is designed to select events muons for heavy flavor and electroweak physics analyses. We will describe the MB trigger since we will need to use it to determine the number of MB events in our analysis.

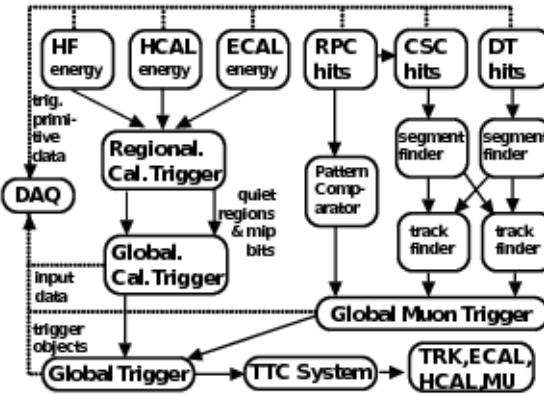


Figure 2-3: The figure above demonstrates how the CMS L1 hardware trigger function schematically.

2.2.2 MB Trigger

By definition, an MB event corresponds to a non-single diffractive inelastic interaction [184]. A totally inclusive trigger, or called zero bias (ZB) trigger, corresponds to a randomly reading out from the detector whenever a collision is possible. MB trigger is algorithm to determine interesting MB events based on the response from forward HCAL located at $3 < |\eta| < 5$. It is put a fixed analog to digital converter (ADC) threshold in the HCAL response to reject background noise and collect MB events from ZB trigger. There is also an essentially linear relation between the maximum ADC with the actual energy response of the forward HCAL. Figure 2-4 shows the ADC distribution and HF energy as a function of ADC in 2018 PbPb run.

The MB trigger consist “MB OR”, which requires the ADC threshold on either one of the forward HCAL (HF) out of both forward ECAL in both positive and negative sides, and “MB AND”, which requires the ADC threshold on both of HFs out of both forward ECAL in both positive and negative sides. Figure 2-5 shows the L1 MB trigger analysis of Run 326791 in the 2018 CMS PbPb data taking

In the 2018 CMS PbPb data taking, to reject the noisy background, the max ADC of each event is required to be greater than 15 with MB AND along with the HLT trigger of at least one pixel track are applied to select MB events, as seen above from Figure 2-5 in the max ADC distribution of MB events in green. A total number

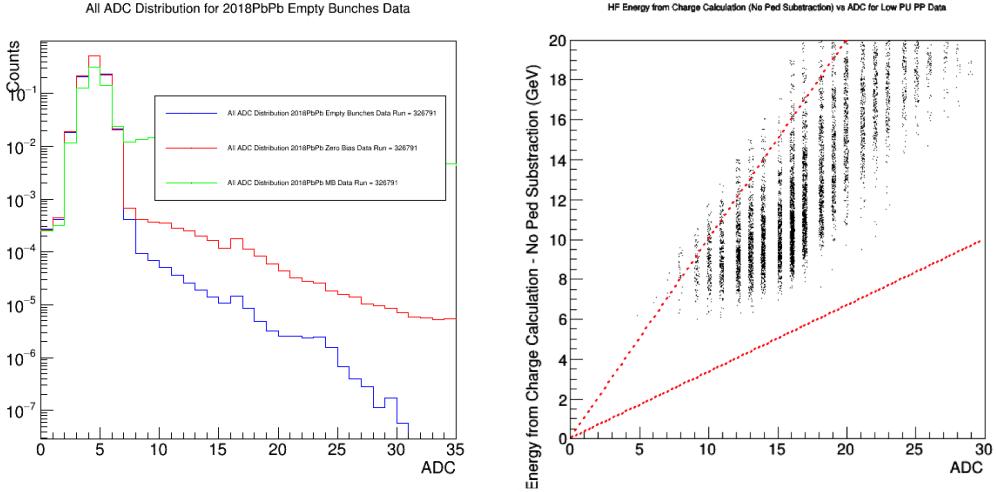


Figure 2-4: In the CMS 2018 PbPb Run 326791, the ZB data (red), Empty Bunches (blue), and MB data (green) ADC distributions (left), and the HF energy according to the charge collected as a function of ADC (right) are shown above. We can see that the HF energy is about (0.5 - 1) conversion factor to the ADC.

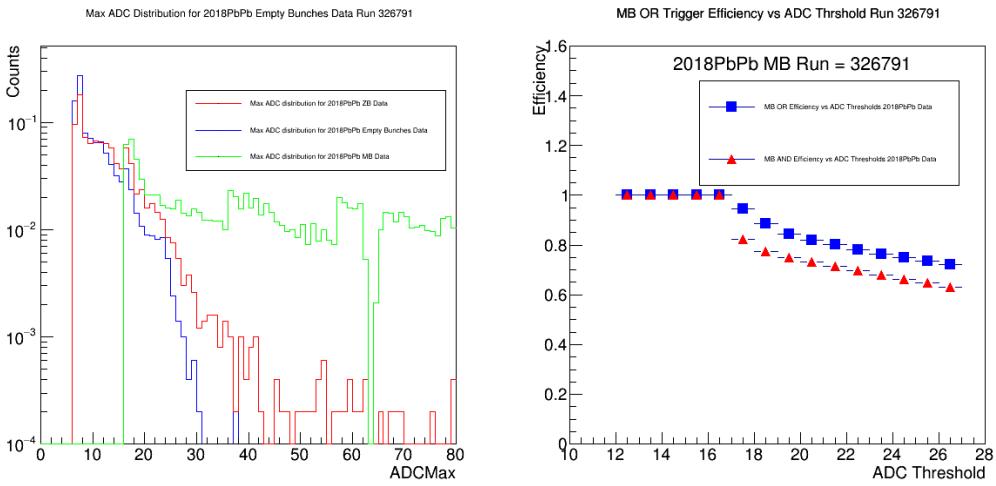


Figure 2-5: In the CMS 2018 PbPb Run 326791, the ZB data (red), Empty Bunches (blue), and MB data (green) maximum ADC distributions (left) and the efficiencies of MB OR (blue) and MB AND (red) as a function ADC threshold (right) are shown above.

of about 2.4 billion MB events corresponding to a luminosity about 1.7 nb^{-1} have been collected by CMS during the 2018 LHC PbPb run from November to December 2018. Figure 2-6 shows the MB events and corresponding luminosity as a function day throughout the 2018 CMS PbPb data taking period

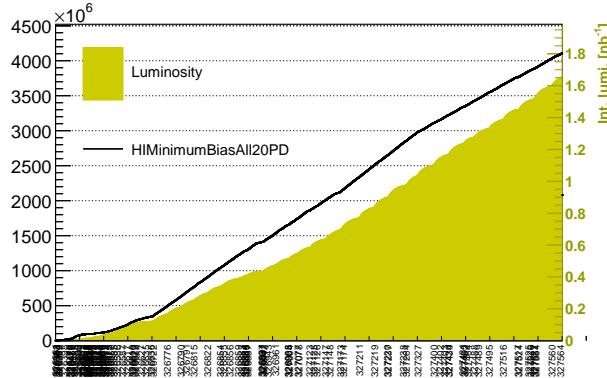


Figure 2-6: The figure above shows the total number of 20 PbPb MB events from and corresponding luminosity how the as a function Run ID from November 15 to December 2 2018.

2.2.3 Centrality Efficiency with MB Trigger

In addition to overall efficiency vs the ADC with the MB trigger, we also study the centrality efficiency with different ADC thresholds. Figure 2-7 shows the centrality as a function of efficiency using MB OR and MB AND with different thresholds

Because other physics trigger are mainly based on the MB datasets, in the physics analyses using 2018 CMS PbPb datasets, it is recommended to remove the ultra-peripheral centrality range from 80 - 100%, which is not fully efficient (efficiency < 100%). Therefore, the most of the CMS heavy-ion physics results using the 2018 PbPb dataset will be presented in the centrality range of 0 - 80%.

2.2.4 HLT Trigger

The HLT software trigger is an array of commercially available computers running high-level physics algorithms [183]. Unlike the online L1 hardware trigger which runs

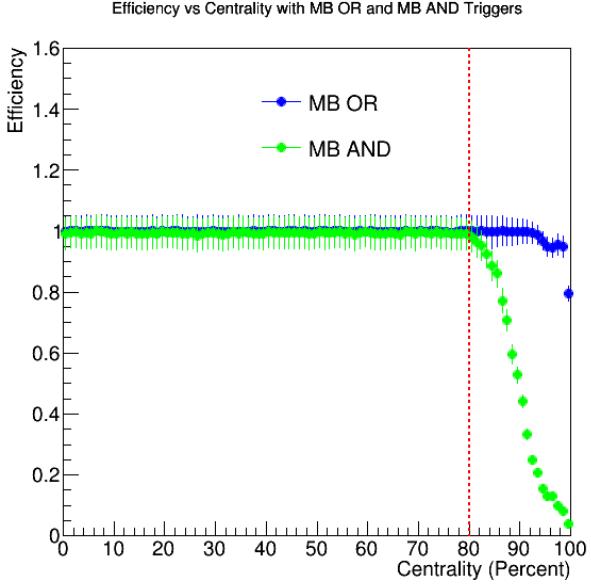


Figure 2-7: The efficiency vs centrality with $\text{ADC} > 16$ for MB OR (blue) and MB AND (green) are shown above.

on-the-go during the data taking process, HLT is an offline software trigger that runs after the data are acquired. In the HLT trigger, more sophisticated analyses are performed to determine if the event is accepted or rejected for a specific dataset. The event data are stored locally on disk and eventually transferred to downstream systems, the CMS Tier-0 computing center, for offline HLT processing and permanent storage [183]. There are many trigger paths in the HLT such as the high multiplicity trigger to specifically collect events with many tracks, the D meson trigger to select high p_T D mesons, and the dimuon trigger to enrich Drell-Yen events, are designed and encoded in the HLT trigger. In the following, we will describe the dimuon trigger in details because the dimuon dataset will be used to fully reconstruct B mesons in this thesis.

2.2.5 DiMuon Trigger

The dimuon trigger, as it is named, is a trigger based on the information of two muons tracks. HLT is able to quickly reconstruct the invariant mass of two oppositely charged muons $m_{\mu\mu}$. Figure 2-8 shows the $m_{\mu\mu}$ reconstructed by the CMS HLT with 2018 pp

dataset.

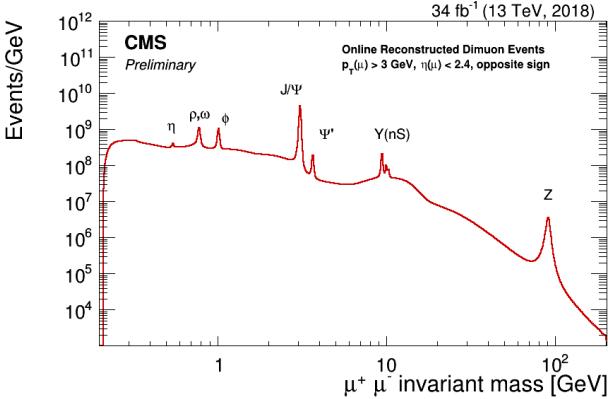


Figure 2-8: The dimuon invariant spectrum $m_{\mu\mu}$ reconstructed by CMS HLT trigger in the 2018 pp dataset is shown above. We can identify the neutral vector boson resonances shown above.

In the 2018 PbPb run, the dimuon trigger requires the presence of two muon candidates, with no explicit momentum threshold and with the HLT reconstructed dimuon invariant mass of $1.0 \text{ GeV}/c^2 < m_{\mu\mu} < 5.0 \text{ GeV}/c^2$, near the J/ψ PDG mass $m_{J/\psi} = 3.0969 \text{ GeV}/c^2$ [3], in coincidence with lead bunches crossing at the interaction point. Moreover, One of the trigger-level muons is reconstructed using information both from the muon detectors and the inner tracker with requirement of more than or equal to 10 hits (named as L3 muon), while for the other only information from the muon detectors is required (named as L2 muon) [185].

2.3 Tracking System

2.3.1 Silicon Detectors

The CMS tracking system applies solid state semiconductor technologies. It consists of the 3 layers of silicon pixel tracker and 10 layers of silicon strip detector including 4 inner barrel layers and 6 outer barrel layers [186]. It have a $\phi = 2\pi$ and $|\eta| < 2.4$ acceptance coverage. Figure 2-9 shows the CMS tracking system schematically

In nuclear and particle physics, a tracker is a detector that measures the trajectory of a particle as it passes through a series of sensitive layers, typically using the magnetic field of a magnet to bend the particle's path and measure its angle of deflection.

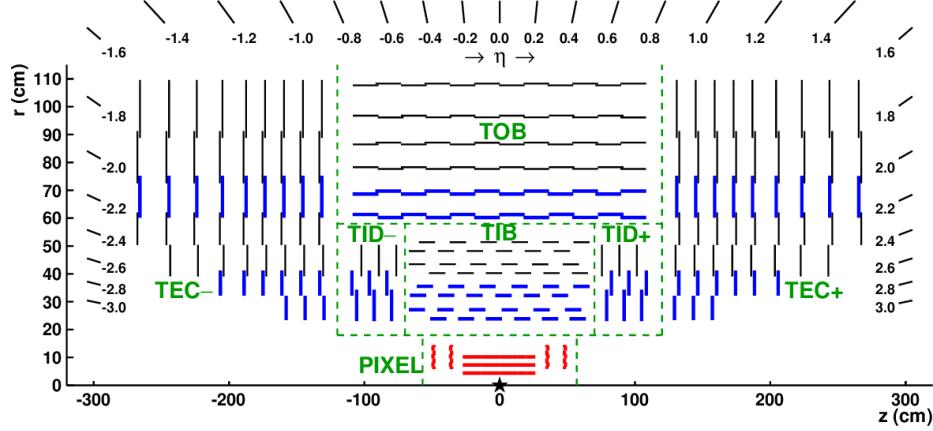


Figure 2-9: The schematic view of the CMS tracking system is shown above.

ries of charged particles via ionization. In general, it does not destroy or significantly change the energy of the particle. With the external magnetic field, the tracker can measure the momentum, the charge, and the mass of the particle by studying the electric charges collected from electron avalanche or electron-hole pair. The CMS tracking systems provides physicists with excellent tracking capabilities. The CMS silicon tracker is solid state detector employing semiconductor technologies. The silicon tracker is operated at a reverse bias mode with a depletion voltage of about 600V. High energy charged particles passing through the silicon tracker has an energy loss of $dE/dx \simeq 0.5 \text{ keV}/\mu\text{m}$ [3]. Therefore, for a $320 \mu\text{m}$ thick silicon sensor, the charged particle will lose about 160 keV. The electron-hole pair in silicon is about 3 eV per pair. Therefore, the charged particle will produce roughly on the order of 10^4 electrons. The hit resolution in $r\phi$ direction of the silicon strip is about $10 - 40 \mu\text{m}$ [187]. Figure 2-10 shows schematically how a high energy charged particle ionized an electron-hole pair in the depletion region of a silicon P-N junction diode operated at a reverse biased mode

However, in the CMS silicon tracker, due to the small number of electrons produced in the silicon sensor, the energy loss dE/dx vs momentum p of charged particle is not good enough resolution to separate and identify electron, pion, kaons and protons. Therefore, we generally do not perform particle identification (PID) for hadrons with CMS detector in physics analyses.

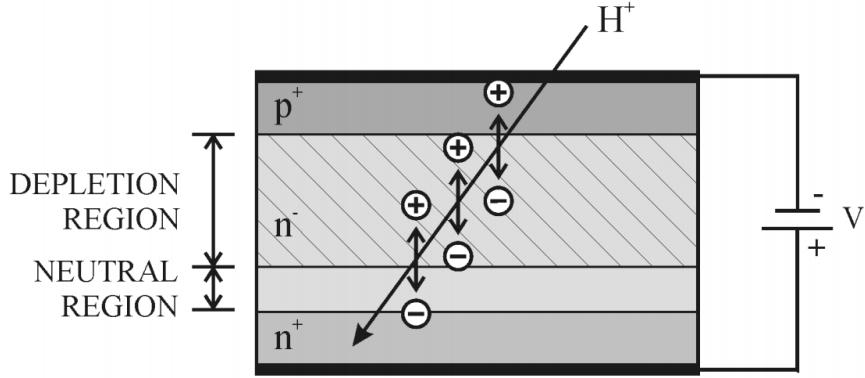


Figure 2-10: The schematic plot explaining how a silicon tracker detector charged particles is shown above.

2.4 Muon System

Named as “Compact **Muon** Solenoid”, the study on muon is one of the most important physics tasks of the CMS experiment. The CMS muon system has 1400 muon chambers including 250 drift tubes and 540 cathode strip chambers to track the positions of the muons and provide a trigger and 610 resistive plate chambers form a redundant trigger system with an acceptance coverage of $|\eta| < 2.4$. Due to the small energy loss of muon in ECAL and HCAL [3], the muon produced from the collisions usually penetrates through the trackers and calorimeters. Therefore, the muon system is located at the outer of the CMS detector. Figure 2-11 shows the particles produced at the interaction points and pass through the CMS detector

The muon system employ gaseous detector technology. Physical modules of drift tubes, cathode strip proportional planes, and resistive plates are called “chambers”. When a muon pass through the chambers, it will ionize electrons of the gas atom. Under a strong electric field, the avalanche electrons will be drifted to the anode and the gas ion will be drifted to the cathode. Electronic signal will be generated as this occurs. Figure 2-12 shows schematically how electron avalanches works in a gaseous detector to detect charged particles as well as the design of CMS drift tube to detect muons.

Therefore, with both the tracking system and the muon chambers, the CMS de-

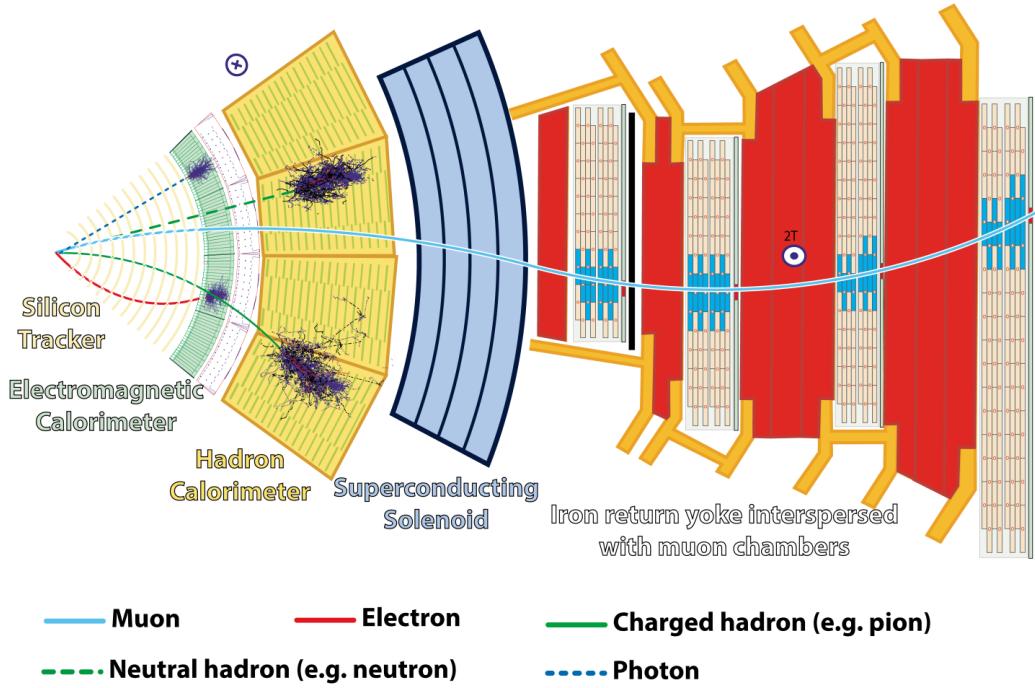


Figure 2-11: The particle flow of long life particles, such as electrons, muons, photons, charged hadrons: π, K, p , and neutral hadrons: neutrons, in the CMS detector are shown above.

tectors has excellent capabilities of detecting, identifying, and reconstructing muons, which is crucial for heavy flavor physics studies.

2.5 Calorimeter System

In nuclear and particle physics, a calorimeter is a detector that completely stops particles and measure the total energy deposited. According to the particles, calorimeter can be divided into electromagnetic calorimeter (ECAL or EMCAL) to measure the energy of electron and photons and hadronic calorimeter to measure the energy of charge and neutron hadrons. The CMS calorimeters system includes both ECAL and HCAL. It is located in between the tracker and the muon chambers as shown in Figure 2-2.

According to measurement of charged particle shower energy, calorimeter can typically be classified as sampling calorimeter and homogenous calorimeter. The

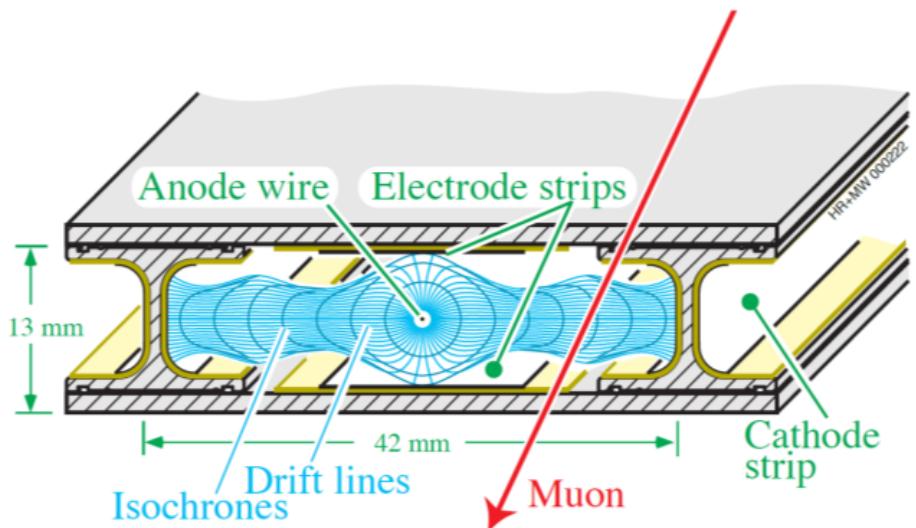
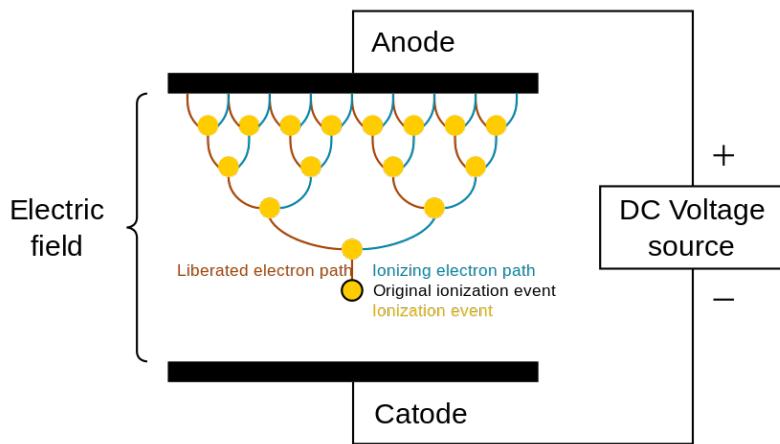


Figure 2-12: A visualization of Townsend Avalanche (top) and schematic plot of the CMS drift tube detecting a muon (bottom) are shown above.

sampling calorimeter has two components: absorber and scintillator. Absorber is generally made of metals and produces the shower. The scintillator collects a fraction of the total energy from the shower (visible energy) and then corrects the visible energy back to the total energy based on the light collection efficiency. On the other hand, the homogenous calorimeter collects all the energy deposited. Its material producing the particle shower also measures the energy deposition.

2.5.1 ECAL

The CMS ECAL is made of lead tungstate (PbWO_4) crystal and is a homogeneous type calorimeter. High energy electrons and photons interact with the CMS ECAL and undergo bremsstrahlung to produce electron, positron and photons and deposit energy to the ECAL. It has an acceptance coverage of $|\eta| < 1.48$ with a high granularity of $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ in the barrel region and $1.5 < |\eta| < 3.0$ in the endcap region. In addition, the ECAL has an excellent energy resolution of $\frac{\Delta E}{E} = \frac{2.83\%}{\sqrt{E}} \oplus \frac{12.0\%}{E} \oplus 0.26\%$ where E is in the unit of GeV [193] to precisely measure the energy of electrons and photons. It is capable of identifying electrons and detecting photons, which is crucial for heavy flavor physics studies and photon-jet analysis.

2.5.2 HCAL

The CMS HCAL is a sampling type calorimeter made of 926 tons of steel or brass. Over a million World War II brass shell casements are from the Russian Navy. Hadrons interact with the HCAL brass and steel nuclei and produce hadronic showers. A fraction of the shower energy is sampled by the tiles of plastic wavelength shifting scintillators and transferred readout boxes. Generally, all particles except muons and neutrinos will not be able to penetrate the HCAL. The CMS HCAL system consists of the inner HCAL with barrel (HB) and Endcap (HE), the outer HECAL (HO), and the forward HCAL (HF). The acceptance coverages of HB are $|\eta| < 1.39$, $|\eta| < 1.26$, $1.31 < |\eta| < 3.0$, and $2.85 < |\eta| < 5.19$ respectively. The HO and HB have a granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. The overall energy resolution of HCAL is

$\frac{\Delta E}{E} \approx \frac{100\%}{\sqrt{E}}$ [194], which is excellent for jet physics studies.

2.5.3 HF

The forward HCAL is a special component of the CMS HCAL system. It is segmented into 36×13 towers in the $\eta - \phi$ plane. Figure 2-13 shows schematic and physical views of the CMS HF detector [195]

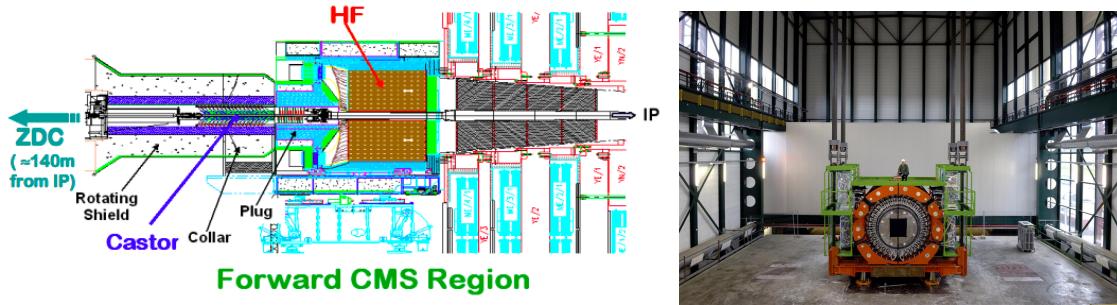


Figure 2-13: The schematic view of the CMS forward region including HF, CASTOR, and ZDC (left) and the physical view of the HF (right) are shown above.

As mentioned above, we have developed the L1 MB trigger based on HF response to select MB events. In addition, in CMS, centrality is defined based on the activities in the HF [196]. The more activity in the HF, the more remnants of colliding nuclei, the more central the collision event. Figure 2-14 shows the determination of centrality range from the HF response

In addition to HF, CASTOR ($-6.6 < \eta < -5.2$) and ZDC ($|\eta| > 8.1$) are also calorimeters which are located at the very forward region [197] as shown above on Figure 2-13. They can help select MB events and trigger ultra-peripheral collision (UPC) events. Figure 2-15 shows the pictures of CASTOR and the ZDC in the very forward direction of the CMS detector

2.6 Relevant Detector Components

In the data analysis of this thesis, the most relevant CMS sub-detectors are the silicon pixel and strip trackers and the muon chamber. We also use HF information to

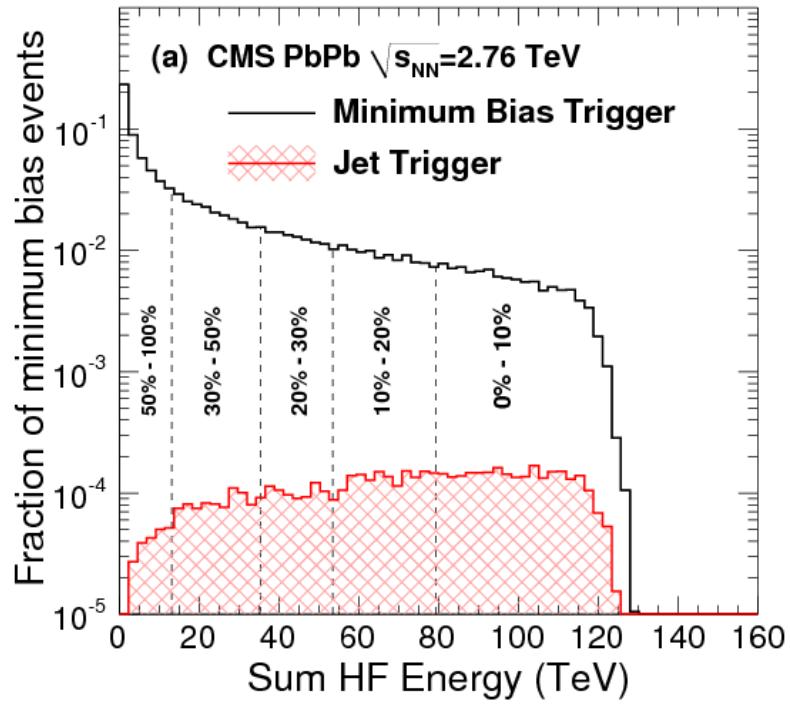


Figure 2-14: The distribution of sum of HF energy using Minimum Biased Trigger and Jet Trigger with the classification of centrality binning is shown above. As we can see, the energy of the HF increase as the collision events become more central, which is within our expectation.

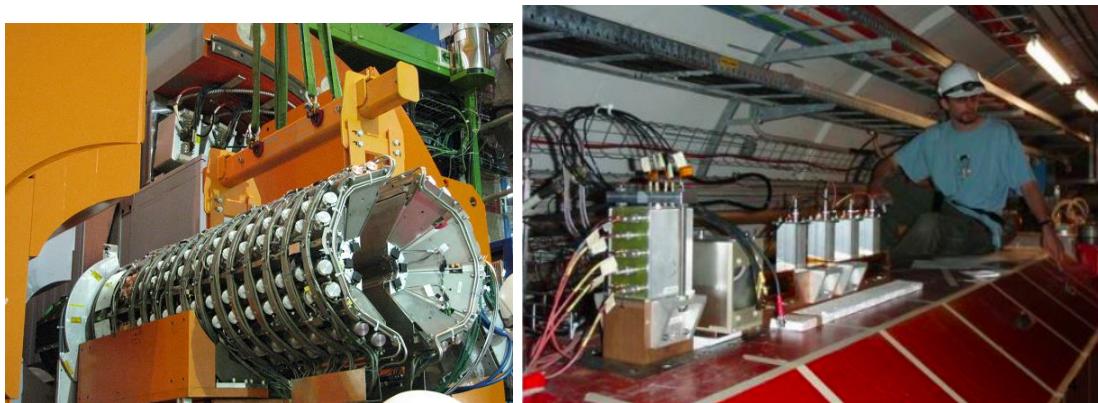


Figure 2-15: The picture of the CASTOR (left) at the CMS underground collision hall and ZDC (right) at 140 m away from the CMS beam interacting point are shown above.

select high quality events. The datasets we used in the analysis are dimuon triggered datasets. We also use the MB trigger samples to estimate the total number of MB events in order to determine the cross section in our analysis. In the next chapter, we will describe in details the physics objects obtained from the detectors and used in our analysis to fully reconstruct B mesons and measure theirs cross sections.

Chapter 3

Reconstructed Objects

The state-of-the-art CMS detector take a snapshot of each event and saves the detailed information of the collisions into datasets. In the datasets, we can access to event information with fully reconstructed objects including hits, tracks, muons, and vertex, which will be crucial for our data analysis to study B meson physics in heavy-ion collisions. Below, we will describe, in principle, how these objects with physical meaning are reconstructed from electronic signal in the CMS detector.

3.1 Event

As mentioned previously, an event is defined as a snapshot of one collision at the LHC. Many particles are produced in the collisions and then decay before they are detected in an event. Theoretically, to obtain the complete information of an event, we only need to know the position and momentum of each particle. Experimentally, we detect final state particles and record their kinematics. In high energy physics experiments, the particles reaching the detectors are e^\pm , μ^\pm , π^\pm , K^\pm , p , n , K_L^0 , γ . All other particles already decayed into these particles before they can be detected. In order to study them, they need to be reconstructed. Historically, this is used to be done by fast camera with high resolution. The Figure 3-1 shows a famous Ω^- baryon (Strangeness -3: sss) event reconstructed from one of picture taken in the bubble chamber [?].

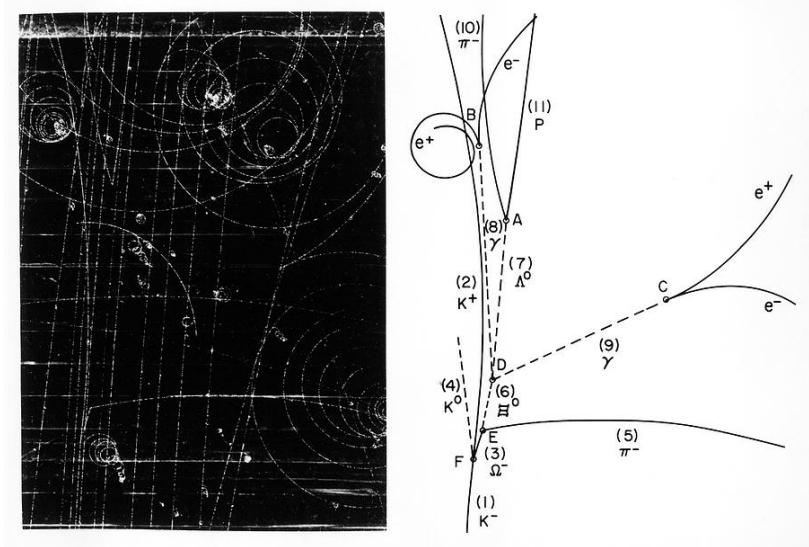


Figure 3-1: The bubble chamber picture of the an Ω^- baryon reconstructed from an event: $K^- p \rightarrow K^0 K^+ \Omega^- \rightarrow \Xi^0 \pi^- \rightarrow \Lambda^0 \gamma\gamma \rightarrow \pi^- p$ taken from the group led by Nicholas Samios at BNL is shown above.

Nowadays, the high speed electronics and semiconductor technologies have advanced. With the development of computing, detector hardware and readout electronics, high energy physics experiments are able to collect many events with higher precision of measurements. For instance, the CMS experiment has an event trigger rate of 100kHz, which corresponds to a rate of 100000 events per second with 100 GB/s information [198]. Experimental data have become more digital and abstract instead of pictorial and intuitive. All events information is stored at a file format instead of a photograph. Physicists use computer to read the experimental data and develop software to perform analysis of each event, extract the physics information from the analysis, and interpret the physics results.

In the following subsections, for simplicity, I will explain the reconstructed objects of events with only one charged particle.

3.2 Hit

All reconstructed objects start from hits as the energy deposition of particle passing through the detectors. Here I will explain the concept of hits based on CMS silicon pixel tracker. Figure 3-2, the schematic view of a chip with silicon pixels in the CMS tracker

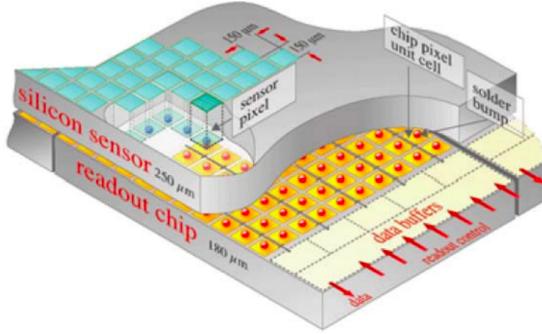


Figure 3-2: The schematic plot of a CMS silicon chip with pixel sensor is shown above.

When a charged particle pass through a layer of the CMS silicon pixel detector, we can look at the charges collected by each pixel on that layer due to the ionization of electron-hole pairs by the high energy charged particle. Ideally, if a particle enter the tracker at a normal angle, only one pixel is fired. However, in reality, its neighboring pixels may also have some response. When the particle enter the tracker with a small angle particularly when the part. Figure 3-3 schematically demonstrates the firing pixel when a particle passing the layer

Here we call each firing pixel as a hit, which is demonstrated above in Figure 3-3 in red. In CMS pixel tracker, the probability of a pixel firing when a charged particle passing through is greater than 99% [187], which means that it is very unlikely a hit is missing when a particle pass through the pixel.

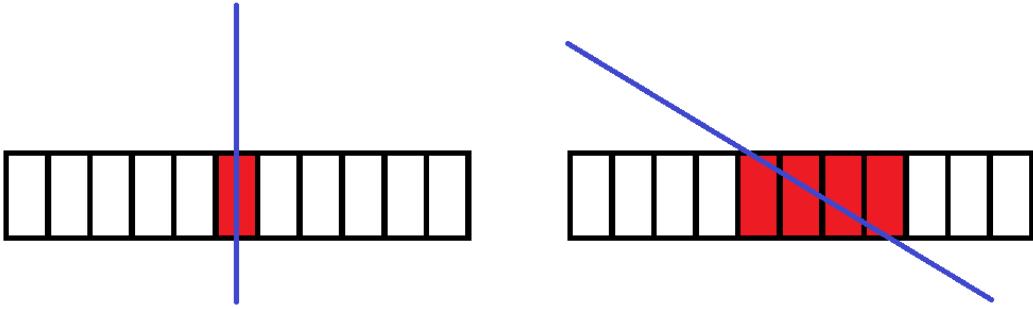


Figure 3-3: The schematic views of a charged particle (blue line) entering the silicon pixel layer (black) at a normal angle (left) and a small tilting angle (right) with the pixels fired (red) are shown above. The left cluster has 1 hit and the right cluster has 4 hits.

3.3 Cluster

Therefore, there should be at least one hit for each layer when a single particle pass through. We call the collection of the adjacent pixel hits in a layer due to one particle as a cluster [187]. Local hits reconstruction algorithm is implemented to obtain clusters. The number of electric charges Q is associated to each hit. We can design an algorithm determine the center of a cluster according to the charges of each hit. A simple algorithm is to calculate the center of gravity of the cluster taking the weighted averaging of the charge and the position of each hit. In this case, for a cluster with a single hit, its position is simply the center of the pixel. For clusters with many hits, we develop a dedicated algorithm to estimate its position [187]. The position of a cluster is a measurement of the particle trajectory.

However, in an event with many particles, the occupancy of each layer will be busy and the clusters will become complicated. The CMS collaboration develop In CMS terminology, the conversion of electronic signal of pixels to clusters is called DIGI.

3.4 Track

3.4.1 Overview of Basic Principles

In a uniform external magnetic field, the trajectory of a charged particle will be a helix in 3 dimensions. Geometrically, five parameters are needed to parametrize a helix. A parametric curve of a helix moving in the Cartesian coordinates moving in the z direction is written as follows

$$x(t) = R \cos(\omega t) + a \quad (3.1)$$

$$y(t) = R \sin(\omega t) + b \quad (3.2)$$

$$z(t) = vt + c \quad (3.3)$$

Therefore, we need at least 3 clusters to determine the all 5 parameters. 3 clusters can determine the radius R and the center of the circle (a,b) and also can determine the straight line in the z-direction. Figure 3-5 shows the helix path of a charged particle in a uniform magnetic field and the fit to determine the center and the radius of the helix.

Moreover, we can determine transverse momentum of the charged particle according to the R fitted from fit to the center of 3 clusters.

$$p_T = qRB \quad (3.4)$$

In general, the charges of the particles produced in the collision and pass through the tracker are $q = e$. Hence, $p_T = eRB$. For p_T in the unit of GeV, R in the unit of meter (m), and B in the unit of tesla (T), we have

$$p_T \simeq 0.3RB \quad (3.5)$$

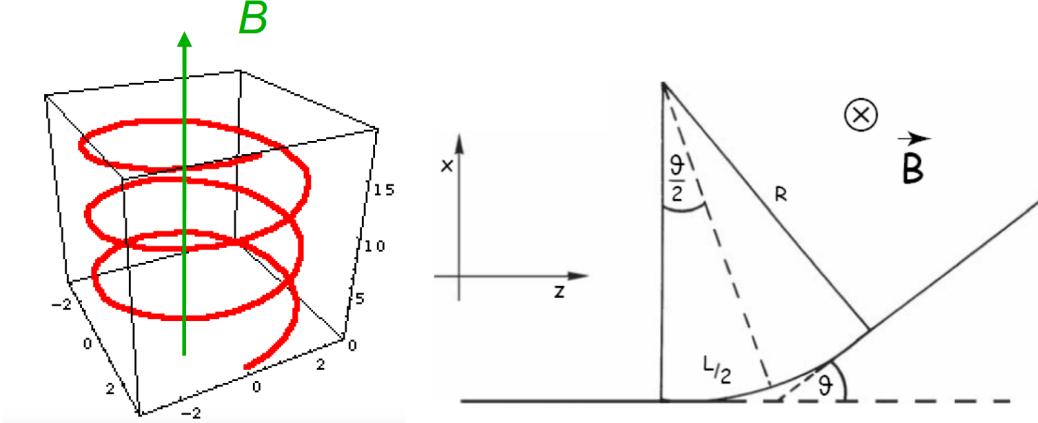


Figure 3-4: The helix motion of a charged particle under a constant and uniform magnetic field \vec{B} pointing in the $+z$ direction (left) and the fit to 3 points to determine the center and the radius of a circle (right) are shown above.

Therefore, as seen above from Figure 3-5, the transverse momentum resolution is driven by the determination of R assuming we have a perfect measurement on the magnetic field B .

According to Figure 3-5 on the right, at high p_T , essentially in parallel, for a 3 cluster fit. In addition, we know that the layers in the pixel track has equal spacing Δr between layers. For CMS pixel tracker, its inner most 3 layers has equal distance $\Delta r_{12} = \Delta_{23} = 2.9$ cm [199].

Hence, we can see that $L/2 = \Delta r$, which assume fixed with no uncertainties. Hence, we have

$$\frac{L}{2} = R \sin \frac{\theta}{2} \quad (3.6)$$

Again, at high p_T , the angle θ will be very small since the radius of the circle $R \gg \Delta r$, $\sin \theta \simeq \theta$ and $\cos \theta \simeq 1 - \frac{\theta^2}{2}$. Hence, we can use small angle approximation

$$L = 2R \sin \frac{\theta}{2} \simeq R\theta \quad (3.7)$$

Therefore,

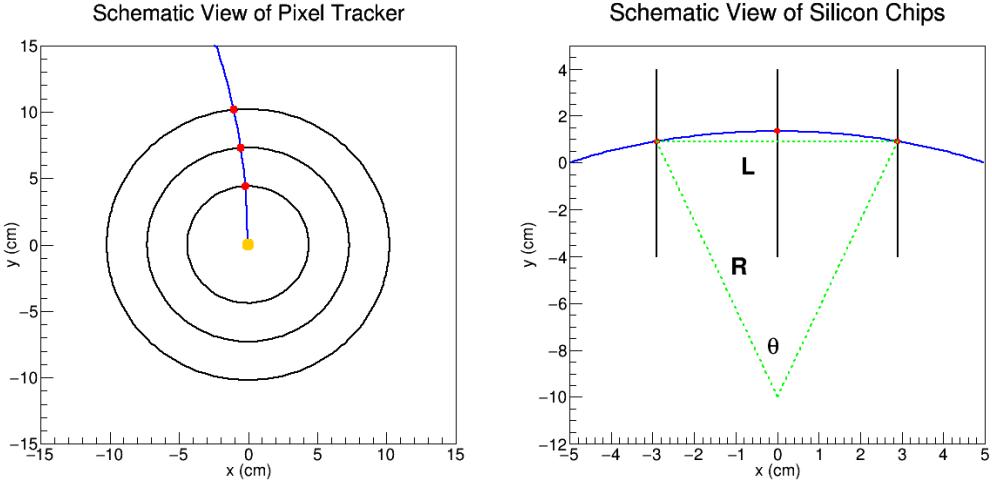


Figure 3-5: A track (blue) initiated from the beam spot (orange) passing through 3 layers of pixel detectors (black) with 3 clusters (red) is shown on the left and the circular fit to the 3 clusters with the definition of R , L , and θ is shown on the right.

$$p_T \simeq 0.3RB = 0.3 \frac{BL}{\theta} \quad (3.8)$$

Hence, geometrically, we have

$$s = R - R \cos \frac{\theta}{2} = R(1 - \cos \frac{\theta}{2}) = R(1 - \cos \frac{\theta}{2}) \simeq \frac{L}{\theta} \left\{ 1 - \left[1 - \frac{1}{2} \left(\frac{\theta}{2} \right)^2 \right] \right\} = \frac{L\theta}{8} = \frac{0.3BL^2}{8p_T} \quad (3.9)$$

Thus, the uncertainties on both sides go as

$$\sigma_s = \frac{0.3BL^2}{8p_T^2} \sigma_{p_T} \quad (3.10)$$

Hence, the transverse momentum resolution $\frac{\sigma_{p_T}}{p_T}$ is given by

$$\frac{\sigma_{p_T}}{p_T} = \frac{8\sigma_s}{0.3BL^2 p_T} \quad (3.11)$$

Here, σ_s is effective the position resolution of the silicon pixel detector. We can see that the transverse momentum resolution gets worse as p_T increases in the high p_T region. Figure 3-6 shows the $\frac{\sigma_{p_T}}{p_T}$ as a function p_T

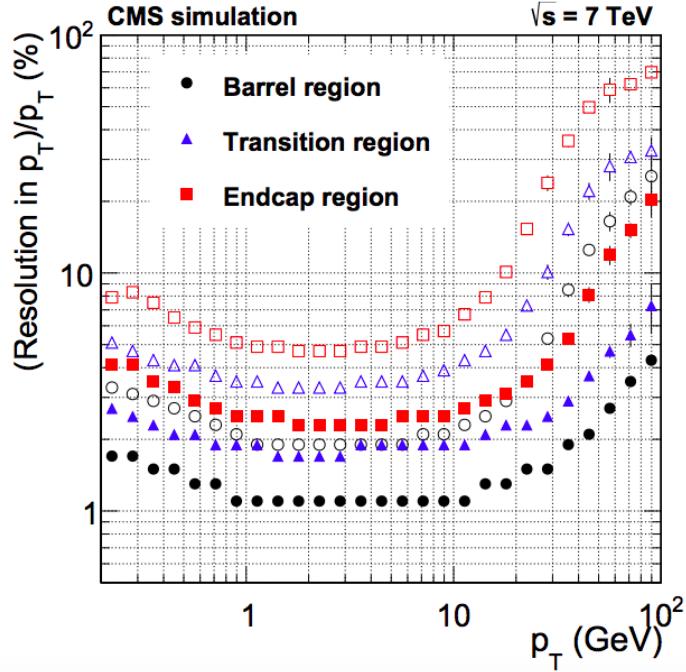


Figure 3-6: The transverse momentum resolution $\frac{\sigma_{pT}}{p_T}$ of a track as a function of transverse momentum p_T is shown above.

We can see that a good agreement with linear growth of $\frac{\sigma_{pT}}{p_T}$ for $p_T > 20 \text{ GeV}/c$ in the high p_T region.

Longitudinally, p_z can be determined by the p_T and the angle $\Delta\theta$ in the transverse direction

$$p_z = \frac{\Delta z}{\frac{R\Delta\theta}{p_T}} = 0.3B \frac{\Delta z}{\Delta\theta} \quad (3.12)$$

At this point, we have obtain the trajectory with the complete kinematic information about a particle except its mass which will require particle identification in order to determine.

3.4.2 CMS Tracking Algorithm

Because the CMS silicon tracker has 3 pixel and 10 strip layers, a charge particle passing through all 13 layers should leave 13 clusters, which is much more than required to determine the helix. Moreover, in real collision events at the LHC, many

tracks are produced at multiple vertices. Figure 3-7 shows the number of vertices and the number of tracks in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

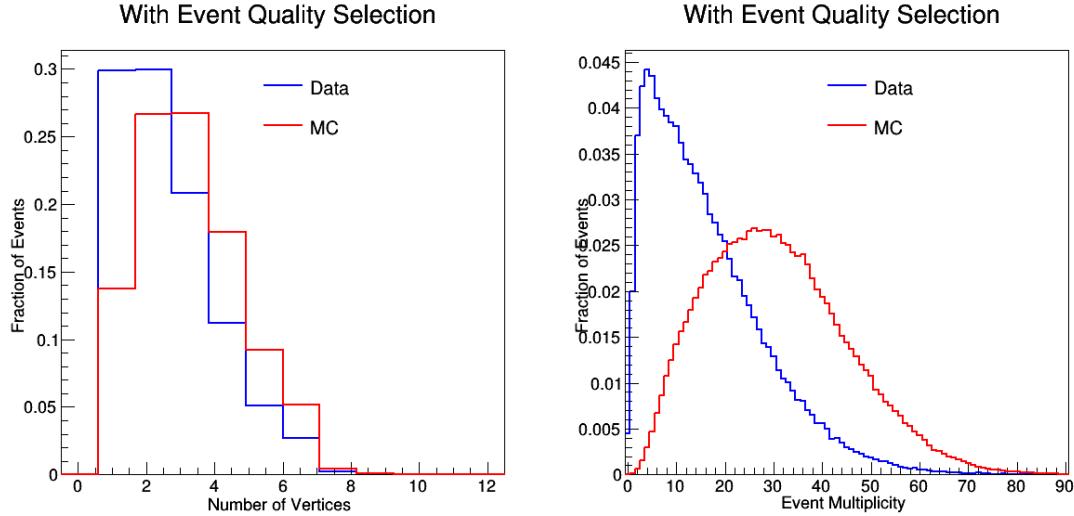


Figure 3-7: The Data (blue) and MC (red) of the number of primary vertex distribution (left) and event multiplicity (right) are shown above. We can see that an event could be more than 1 vertices with more than 100 tracks, which make it very challenging to perform tracking.

Hence, the CMS collaboration has developed the state-of-the-art tracking algorithm to reconstruct the paths and primary vertices of the collisions from the electronic readout signals. CMS tracking algorithm employs the Combinatorial Track Finder (CTF), an adaptation of the combinatorial Kalman filter [188–190], which in turn is an extension of the Kalman filter [191] to allow pattern recognition and track fitting to occur in the same framework. The collection of reconstructed tracks is produced by multiple passes (iterations) of the CTF track reconstruction sequence, in a process called iterative tracking [187]. The CMS tracking workflow and its performance are shown in Figure 3-8 and Figure 3-12

Track Seeding: After obtain the clusters and reconstruct the hits, the tracking is in the track seeding stage. A dedicated seeding algorithm is designed to select the clusters, either a triplet or a pair, from the pixel layers and other combinations of pixel and strip layers before fitting [187]. After these steps, preliminary fits to the seeds named trajectory seeds are created.

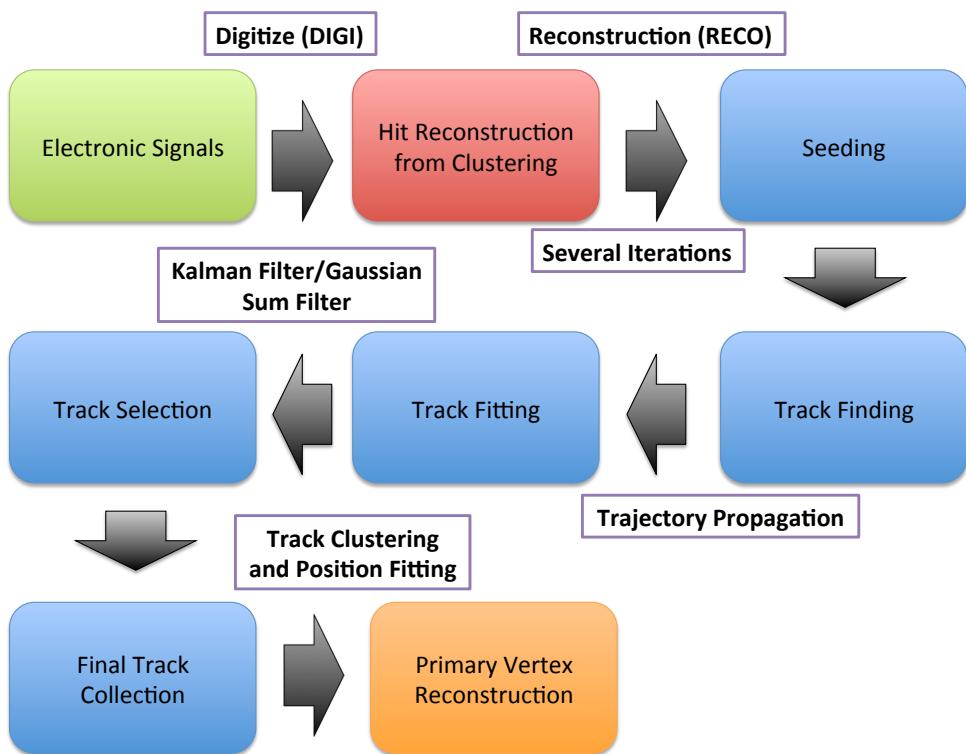


Figure 3-8: The schematic block diagram of CMS tracking workflow is shown above.

Track Finding: Then, it moves on to the track finding stage. A six-step iteration process, which includes navigation, hit search, hit grouping, and trajectory update, is implemented with the application of CFT algorithms based on Kalman Filter to build track candidates. A schematic overview of the track finding process is shown below Figure 3-10

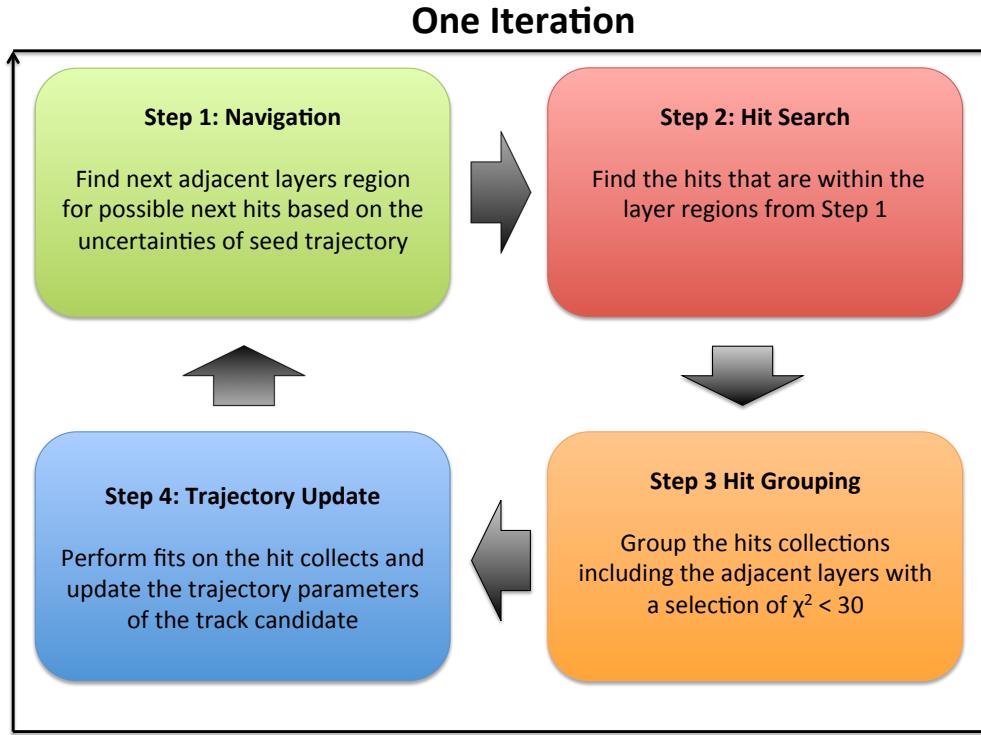


Figure 3-9: The four steps of CMS track finding workflow (left) and the schematic demonstration of each step (right) are shown above.

Track Fitting: Next, the tracking is in the stage of track fitting. Kalman filter [191] is applied to improve fitting performance. It starts from the innermost location with typically four hits [188–190]. When extrapolating the trajectory from one hit to the next, the filtering and smoothing procedure is carried out with a Rugga-Katta propagator to obtain the best precision. $\chi^2 < 20$ is required of each fit in order to improve its precision and reject fake tracks. Figure 3-11 schematically shows how the Kalman filter fit along with Rugga-Katta propagator is applied in the iterative fitting algorithm for CMS tracking

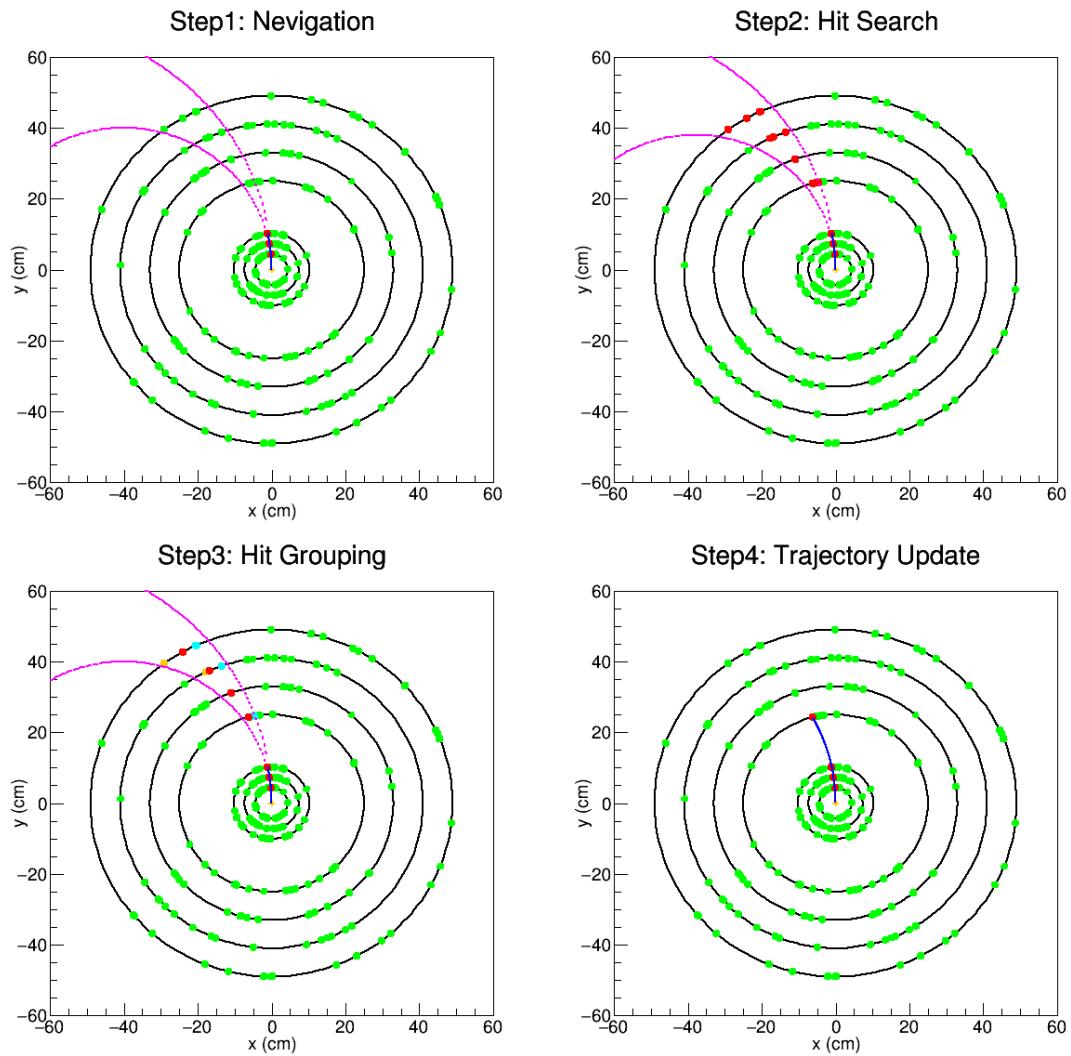


Figure 3-10: The four schematic plots demonstrating each of the four steps for track finding are shown respectfully above.

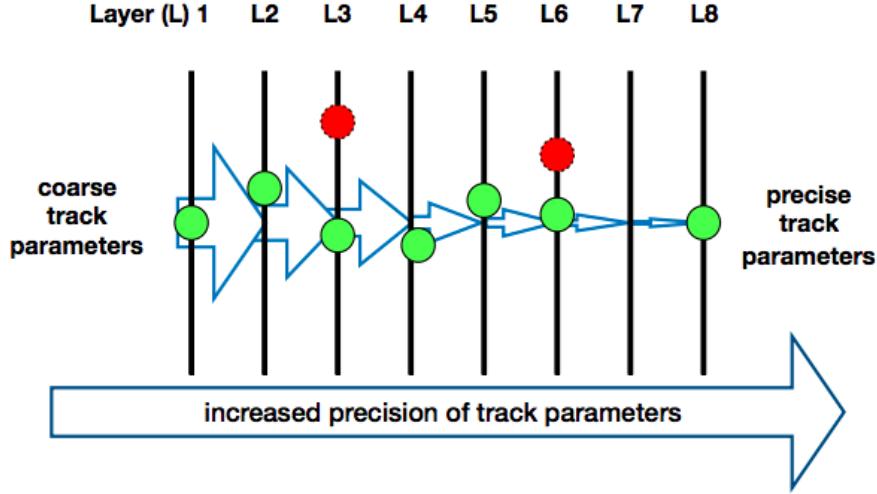


Figure 3-11: The schematic demonstration Kalman filter along with Rugga-Katta propagator to improve the tracks fitting is shown above.

Track Selection: Subsequently, the tracking is in the stage of track selection. At this point, we have already obtained a preliminary track collection of one event. To improve the track quality and reject fake tracks, further selection based on the track properties will be applied. The following selection criteria are applied to select high quality tracks [187]

- Minimum number of layers in which the track has at least one associated hit
- Minimum number of layers in which the track has an associated 3-D hit
- Maximum number of layers that has no associate hits
- $\chi^2/dof < \alpha_0 N_{layers}$
- $|d_0^{BS}|/\sigma_{d_0(p_T)} < (\alpha_1 N_{layers})^\beta$
- $|z_0^{PV}|/\sigma_{z_0(p_T, \eta)} < (\alpha_2 N_{layers})^\beta$
- $|d_0^{BS}|/\delta d_0 < (\alpha_3 N_{layers})^\beta$
- $|z_0^{PV}|/\delta z_0 < (\alpha_4 N_{layers})^\beta$

Here, α_n and β are configurable constant depend on the selection efficiency and purity requirements. d_0^{BS} is the closest transverse distance of the track to the beam spot and δd_0 is its associated error. z_0^{PV} is the distance along the beam-line from the closest pixel vertex and δz_0^{PV} is its associated error. Hence, $|d_0^{BS}|/\sigma_{d_0(p_T)}$ and $|z_0^{PV}|/\sigma_{z_0(p_T, \eta)}$ are expressed in terms of significance. $\sigma_{d_0(p_T)}$ and $\sigma_{z_0(p_T, \eta)}$ are essentially the associated errors of d_0^{BS} and z_0^{PV} parametrized by track p_T and η .

Final Track Collection: Finally, after we apply the selections, we have obtained a final track collection for one event. Figure 3-12 shows the general performance of CMS tracking algorithm

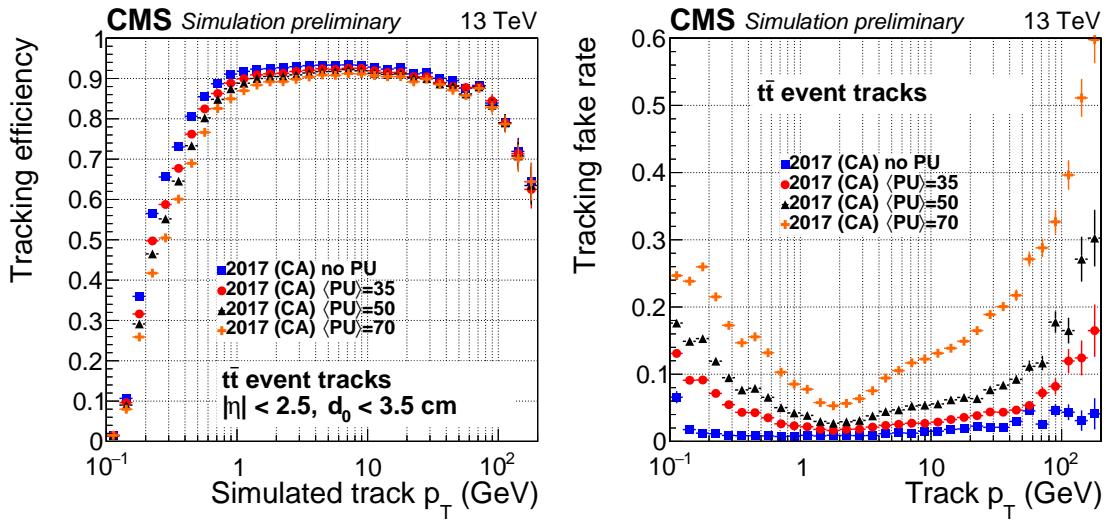


Figure 3-12: The CMS tracking efficiency (left) and fake rate (right) as a function of p_T from simulations of $t\bar{t}$ events at 13 TeV with different pileup conditions are shown above.

We should note that a modified version of Kalman filter named Gaussian Sum Filter [200] is applied to improve the tracking performance of electrons [187].

3.5 Muon

The muon in the tracker uses a essentially the same tracking algorithms as other charged particles [187]. Tracking performance of muon is excellent. For isolated muons with $1 < p_T < 100$ GeV/c, the tracking efficiency is $> 99\%$ over the full η -

range of tracker acceptance and does not significantly depend on p_T while the fake rate is negligible [187]. We can require hits on the outer most muon chambers to identify muons because other charge particles will be stopped by the calorimeter and should not be able to enter the muon system as shown on Figure 2-11. Therefore, the CMS muon system has excellent capabilities of detecting, identifying, and reconstructing muons, which is crucial for heavy flavor physics studies.

In CMS terminology, there are three types of muons: global muons, soft muons, and standalone muons. They are defined as follows:

- **Global Muons:**
- **Soft Muons:**
- **Standalone Muons:**

3.6 Vertex

With the final track collection for each event, assuming all the tracks are promptly produced at a given interaction point, we can determine the primary vertex by selecting the tracks, performing track clustering, and fitting for the position of each vertex using its associated tracks [187]. The deterministic annealing algorithm [192] is track clustering algorithm that CMS is currently using. The track and vertex information of each event will be stored in datasets for physics analyses.

3.6.1 Primary Vertex

3.6.2 Secondary Vertex

Chapter 4

Data Analysis

4.1 Tools

The analysis tools we use is based on MAC and CMS high computing, linux shell script, C++ programing ROOT package for high energy physics experiments. Machine CERN lxplus, CMS submit Dataset contain events in ROOT files format. Sample are processed with CERN lxplus. job are submitted view condor.

4.2 Analysis Strategies

4.2.1 Physics Goals

4.2.2 General Workflow

4.2.3 Technical Challenges

4.3 Global Event Observables

4.3.1 Datasets

4.3.2 Total Number of Events

4.3.3 Centrality Definition

4.3.4 Number of Participants Nucleons

4.3.5 Number of Binary Collisions

4.3.6 Event Multiplicity

4.4 Monte Carlo Simulations

4.4.1 PYTHIA

4.4.2 Hydjet Embedding

4.4.3 EvtGen Package

4.4.4 Reweighting

4.5 B meson Reconstruction

4.5.1 Decay Channels

4.5.2 Event Selections

128

4.5.3 Track and Muon Selections

Chapter 5

Conclusions

5.1 Comparison with Other Experiments and Theoretical Models

5.2 Physics Messages Discussion

5.3 Conclusions

5.4 Future Outlooks

Chapter 6

Other Studies

6.1 sPHENIX Heavy Flavor Physics Simulations

6.2 sPHENIX Electromagnetic Calorimeter Studies

6.3 EIC Electromagnetic Calorimeter R&D

Appendix A

Tables

Table A.1: Armadillos

Armadillos	are
our	friends

Appendix B

Figures

Figure B-1: Armadillo slaying lawyer.

Figure B-2: Armadillo eradicating national debt.

List of Symbols

\hbar Reduced Planck constant

c Speed of light in a vacuum inertial frame

p_T Transverse momentum

R_{AA} Nuclear Modification Factor

CERN European Center for Nuclear Research

CMS Compact Muon Solenoid

LHC Large Hadron Collider

Abbreviations

\hbar Reduced Planck constant

c Speed of light in a vacuum inertial frame

p_T Transverse momentum

R_{AA} Nuclear Modification Factor

CERN European Center for Nuclear Research

CMS Compact Muon Solenoid

LHC Large Hadron Collider

References

- [1] M. K. Gaillard, P. D. Grannis, and F. J. Sciulli, “The Standard Model of Particle Physics”, Rev. Mod. Phys. 71 (1999)
- [2] C. D. Roberts, “Nonperturbative effects in QCD at Finite Temperature and Density”, Phys. Part. Nucl. 30 (1999)
- [3] P.A. Zyla et al. (Particle Data Group), “Review of Particle Physics”, Prog. Theor. Exp. Phys. 2020, 083 C01 (2020)
- [4] J. Gross and F. Wilczek, “Ultraviolet behavior of non-abelian gauge theories”, Phys. Rev. Lett. 30, 1343 (1973)
- [5] S. Dürr et al. “Ab Initio Determination of Light Hadron Masses”, Science. 322 (5905): 1224 7 (2008)
- [6] N. Fettes, U.-G. Meißner, and S. Steininger, “Pion-nucleon scattering in chiral perturbation theory I: Isospin-symmetric case”, Nucl. Phys. A 640 (1998)
- [7] J. C. Collins, D. E. Soper, and G. F. Sterman, “Factorization of Hard Processes in QCD”, Adv. Ser. Direct. High Energy Phys. 5 (1989)
- [8] Francesco Becattini, “What is the meaning of the statistical hadronization model?”, J. Phys. Conf. Ser. 5 (2005)
- [9] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, “Parton fragmentation and string dynamics”, Phys. Rep. 97 (1983)

- [10] R. J. Fries, V. Greco, and P. Sorensen “Coalescence Models For Hadron Formation From Quark Gluon Plasma”, Ann. Rev. Nucl. Part. Sci. 58 (2008)
- [11] F. Wilczek, “QCD In Extreme Conditions”, Contribution to: 9th CRM Summer School: Theoretical Physics at the End of the 20th Century, 567-636
- [12] E. d'Enterria, David G., et al., “CMS physics technical design report: Addendum on high density QCD with heavy ions”, J. Phys.G 34 (2007)
- [13] E. Altman, “Many-body localization and quantum thermalization”, Nat. Phys. 14, 979 - 983 (2018).
- [14] M. P. Heller, R. A. Janik, and P. Witaszczyk, “Characteristics of Thermalization of Boost-Invariant Plasma from Holography”, Phys. Rev. Lett. 108, 201602 (2012)
- [15] G. Parisi, “Some considerations on the Quark-Gluon Plasma”, Quark Matter 2018 Conference (2018)
- [16]
- [17] H.C. Chandola, G. Punetha, and H. Dehnen, “Dual QCD thermodynamics and quark-gluon plasma”, Nucl. Phys. A 945 (2016)
- [18] R. Stock, “Relativistic Nucleus-Nucleus Collisions and the QCD Matter Phase Diagram”, In *Landolt-Boernstein I 21A: Elementary particles* 7
- [19] T.D. Lee and G.C. Wick, “Vacuum stability and vacuum excitation in a spin-0 field theory”, Phys. Rev. D9 2291(1974)
- [20] J.O. Andersen and T. Brauner, “Linear sigma model at finite density in the 1/N expansion to next-to-leading order”, Phys .Rev. D 78:014030 (2008)
- [21] M. Asakawa and K. Yazaki, “Chiral Restoration at Finite Density and Temperature”, Nucl. Phys. A 504 (1989)
- [22] K. Fukushima, D.E. Kharzeev, and H.J. Warringa, “The Chiral Magnetic Effect”, Phys. Rev. D 78 074033 (2008)

- [23] S. Shi, H. Zhang, D. Hou, and J. Liao, “Signatures of Chiral Magnetic Effect in the Collisions of Isobars”, Phys. Rev. Lett. 125 (2020)
- [24] J. Zhao and F-Q. Wang, “Experimental searches for the chiral magnetic effect in heavy-ion collisions”, Prog. Part. Nucl. Phys. 107 (2019)
- [25] D.E. Kharzeev, J. Liao, S. A. Voloshin, and G. Wang, “Chiral Magnetic and Vortical Effects in High-Energy Nuclear Collisions — A Status Report”, Prog. Part. Nucl. Phys. 88 (2016)
- [26] S. Choudhury, G. Wang, W. He, Y. Hu, and H.Z. Huang, “Background evaluations for the chiral magnetic effect with normalized correlators using a multiphase transport model”, Eur. Phys. J. C 80 (2020)
- [27] H. S. Chung, J. Lee, and D. Kang, “Cornell potential parameters for S-wave heavy quarkonia”, J. Korean Phys. Soc. 52 (2018)
- [28]
- [29] J. Harris and B. Muller, “The Search for the quark-gluon plasma”, Ann. Rev. Nucl. Part. Sci. 46 (1996)
- [30] A. Dumitru, Y. Guo, A. Mócsy, and M. Strickland, “Quarkonium states in an anisotropic QCD plasma”, Phys. Rev. D 79 (2009)
- [31] R. Hagedorn, “Statistical thermodynamics of strong interactions at high energies”, Nuovo Cim. , Suppl. 3 (1965)
- [32] J. Rafelski, “Melting Hadrons, Boiling Quarks”, from Hagedorn Temperature to Ultra-Relativistic Heavy-Ion Collisions at CERN. Springer, Cham.
- [33] C.A. Dominguez, “Color Deconfinement in QCD at Finite Temperature”, Nucl. Phys. B Proc. Suppl.15 (1990)
- [34] K. Rajagopal and F. Wilczek, “The Condensed matter physics of QCD”, part of At the frontier of particle physics. Handbook of QCD. Vol. 1-3 (2000)

- [35] M.B. Gay Ducati, “High Density QCD”, *Braz. J. Phys.* 31 (2001)
- [36] D.E. Kharzeev, “Hot and dense matter: from RHIC to LHC: Theoretical overview”, *Nucl. Phys. A* 827 (2009)
- [37] L.D. McLerran, S. Schlichting, S. Sen, “Space-Time Picture of Baryon Stopping in the Color-Glass Condensate”, *Phys. Rev. D* 99, 074009 (2019)
- [38] F. Gelis, E. Iancu, and J. Jalilian-Marian, R. Venugopalan “The Color Glass Condensate”, *Ann. Rev. Nucl. Part. Sci.* 60 (2010)
- [39] A. Deshpande, Z.-E. Meziani, and J.-W. Qiu, “Towards the next QCD Frontier with the Electron Ion Collider”, *EPJ W of Conf.*, 113, 05019 (2016)
- [40] V.N. Gribov and L.N. Lipatov, *Sov. J. Nucl. Phys.* 15 (1972) 438.
- [41] G. Altarelli and G. Parisi, *Nucl. Phys.* B126 (1977) 298.
- [42] Yu. L. Dokshitzer, *Sov. Phys. JETP* 46 (1977) 641.
- [43] G.P. Salam, “An Introduction to leading and next-to-leading BFKL”, *Acta Phys. Polon. B* 30 (1999)
- [44] K. Rummukainen and H. Weigert, “Universal features of JIMWLK and BK evolution at small x”, *Nucl. Phys. A* 739 (2004)
- [45] C. Marquet, “Open questions in QCD at high parton density”, *Nucl. Phys. A* 904 - 905 (2013)
- [46] L. Zheng, E.C. Aschenauer, J.H. Lee, and B.-W. Xiao, “Probing Gluon Saturation through Dihadron Correlations at an Electron-Ion Collider”, *Phys. Rev. D* 89, 074037 (2014)
- [47] J Jalilian-Marian and X.N. Wang, “Small x gluons in nuclei and hadrons”, *Phys. Rev. D* 60, 054016 (1999)
- [48] V.P. Gonçalves “QCD at high parton density”, *Braz. J. Phys.* 34 (2004)

- [49] F. Arleo and T. Gousset, “Measuring gluon shadowing with prompt photons at RHIC and LHC”, Phys. Lett. B 660 (2008)
- [50] P. Huovinen and P. Petreczky , “QCD Equation of State and Hadron Resonance Gas”, Nucl. Phys. A 837 (2010)
- [51] N. Sarkar and P. Ghosh , “van der Waals hadron resonance gas and QCD phase diagram”, Phys. Rev. C 98, 014907 (2018)
- [52] Jamal. Jalilian-Marian and X.N. Wang, “Shadowing of gluons in perturbative QCD: A comparison of different models”, Phys. Rev. D63, 096001 (2001)
- [53] E. Epelbaum, H.-W. Hammer, and U.G. Meißner, “Modern theory of nuclear forces”, Rev. Mod. Phys. 81 (2009)
- [54] J. Rafelski, "Connecting QGP-Heavy Ion Physics to the Early Universe“, Nucl. Phys. B Proc. Suppl. 243-244 (2013)
- [55] S. M. Sanches Jr., F. S. Navarra, and D. A. Fogaça, “The quark gluon plasma equation of state and the expansion of the early Universe”, Nucl. Phys. A 937 (2015)
- [56] E.S. Fraga and A. Kurkela, “Interacting quark matter equation of state for compact stars”, Astrophys. J. Lett. 781, L25 (2014)
- [57] M. G. Alford, K. Rajagopal, T. Schaefer, A. Schmitt “Color superconductivity in dense quark matter”, Rev. Mod. Phys. 80 (2008)
- [58] M. G. Alford, “Color superconducting quark matter”, Ann. Rev. Nucl. Part. Sci. 51 (2001)
- [59] K. Rajagopal, “Mapping the QCD phase diagram”, Nucl. Phys. A 661 (1999)
- [60] G. Odyniec on behalf of STAR Collaboration, “Beam Energy Scan Program at RHIC (BES I and BES II) – Probing QCD Phase Diagram with Heavy-Ion Collisions”, PoS CORFU2018 (2019)

- [61] Z. Fodor and S.D. Katz, “Critical point of QCD at finite T and mu, lattice results for physical quark masses”, JHEP 04 050 (2004)
- [62] S. Gupta, X. Luo, B. Mohanty, H. G. Ritter, N. Xu, “Scale for the Phase Diagram of Quantum Chromodynamics”, Science 332 (2011)
- [63] U. Heinz, “The Little Bang: Searching for quark-gluon matter in relativistic heavy-ion collisions”, Nucl. Phys. A 685, 414-431, 2001
- [64] R.X. Xu, “Strange quark stars - A Review”, IAU Symp. 214 (2003)
- [65] Y.-Z. Fan, Y.-W. Yu, D. Xu, Z.-P. Jin, X.-F. Wu, D.-M. Wei, and B. Zhang, “A supra-massive magnetar central engine for short GRB 130603B”, Astrophys. J. Lett. 779 (2013)
- [66] Z. G. Dai, S. Q. Wang, J. S. Wang, L. J. Wang, and Y. W. Yu, “The Most Luminous Supernova ASASSN-15lh: Signature of a Newborn Rapidly-Rotating Strange Quark Star”, Astrophys. J. 817 (2016)
- [67]
- [68] D. Trbojevic and S. Peggs, “Required Accuracy of the RHIC Circumference”, United States: N. p., Web. doi:10.2172/1119398 (1993)
- [69] M. J. Rhoades-Brown, “The Heavy Ion Injection Scheme for RHIC”, Proc. of the Workshop on the RHIC Performance (1988)
- [70] D. B. Steski, J. Alessi, J. Benjamin, C. Carlson, M. Manni, P. Thieberger, and M. Wiplich, “Operation of the Relativistic Heavy Ion Collider Au^- ion source”, Review of Scientific Instruments 73, 797 (2002)
- [71] D.B. Steski and P. Thieberger, “Stripping foils at RHIC”, Nucl. Instrum. Meth. A 613 (2010)
- [72] P. Thieberger, L. Ahrens, J. Alessi, J. Benjamin, M. Blaskiewicz, J. M. Brennan, K. Brown, C. Carlson, C. Gardner, W. Fischer, D. Gassner, J. Glenn, W.

- Mac Kay, G. Marr, T. Roser, K. Smith, L. Snydstrup, D. Steski, D. Trbojevic, N. Tsoupas, V. Zajic, and K. Zeno, “Improved gold ion stripping at 0.1 and 10 GeV/nucleon for the Relativistic Heavy Ion Collider”, Phys. Rev. ST Accel. Beams 11, 011001 (2008)
- [73] L. Evans, “The Large Hadron Collider”, Phil. Trans. R. Soc. A 370 (2012)
- [74] J. Brewer, A. Mazeliauskas, and W. van der Schee, “Opportunities of OO and pO collisions at the LHC”, CERN Theory Report: CERN-TH-2021-028 (2021)
- [75] M. Schaumann, R. Alemany-Fernandez, H. Bartosik, T. Bohl, R. Bruce, G-H Hemelsoet, S. Hirlaender, J. Jowett, V. Kain, M. Krasny, J. Molson, G. Papotti, M.S. Camillocci, H. Timko, and J. Wenninger, “First partially stripped ions in the LHC ($^{208}Pb^{81+}$)” J. Phys. Conf. Ser. 1350, 012071 (2019)
- [76] C.Y. Wong, “Introduction to high-energy heavy ion collisions”, Singapore, Singapore: World Scientific (1994) 516 p
- [77] Z.-T. Liang and X.-N. Wang , “Globally Polarized Quark-Gluon Plasma in Non-central A + A Collisions”, Phys.Rev.Lett. 96, 039901 (2006)
- [78] B.Alver and G.Roland, “Collision geometry fluctuations and triangular flow in heavy-ion collisions”, Phys. Rev. C 81, 054905 (2010)
- [79] I. Altsybeev and V. Kovalenko, “Classifiers for centrality determination in proton-nucleus and nucleus-nucleus collisions”, EPJ Web Conf. 137, 11001
- [80] P. Cortese, “Performance of the ALICE Zero Degree Calorimeters and upgrade strategy”, J. Phys. Conf. Ser. 1162, 012006 (2019)
- [81] Oliver Suranyi, “Study of Very Forward Neutrons with the CMS Zero Degree Calorimeter”, Universe 5 10, 210 (2019)
- [82] P. Dmitrieva and I. Pshenichnov, “On the performance of Zero Degree Calorimeters in detecting multinucleon events”, Nucl. Instrum. Meth. A 906 (2018)

- [83] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, ?Glauber modeling in high energy nuclear collisions,? Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)
- [84] R. J. Glauber, “Quantum Optics and Heavy Ion Physics”, Nucl. Phys. A 774 (2006)
- [85] J. Chauvin, D. Bebrun, A. Lounis, and M. Buenerd, “Low and intermediate energy nucleus-nucleus elastic scattering and the optical limit of Glauber theory”, Phys. Rev. C. 28, 1970 (1983)
- [86] T. Wibig and D. Sobczynska, “Proton-nucleus cross section at high energies”, J. Phys. G: Nucl. Part. Phys. 24, 2037 (1998)
- [87] B. B. Back, “Studies of multiplicity in relativistic heavy-ion collisions”, J.Phys.Conf.Ser. 5 (2000)
- [88] A. Milov, “Electroweak probes with ATLAS”, PoS High-pT2017 016 (2019)
- [89] L. Van Hove, “Theoretical prediction of a new state of matter, the "quark-gluon plasma" (also called "quark matter")”, Part of Multiparticle Dynamics. Proceedings, 17th International Symposium, Seewinkel, Austria, June 16-20, 801-818 (1986)
- [90] S. A. Bass, M. Gyulassy, H. Stoecker, and W. Greiner, “Signatures of Quark-Gluon-Plasma formation in high energy heavy-ion collisions: A critical review”, J. Phys. G 25 R1-R57 (1999)
- [91] C. Quigg and J. L. Rosner, “Quantum Mechanics with Applications to Quarkonium”, Phys. Rept. 56 167-235 (1979)
- [92] P. Petreczky, “Quarkonium in Hot Medium”, J. Phys. G 37, 094009 (2010)
- [93] G. S. Bali, H. Neff, T. Duessel, T. Lippert, K. Schilling, “Observation of string breaking in QCD”, Phys. Rev. D 71, 114513 (2005)
- [94] P. Petreczky, “Quarkonium in Hot Medium”, J. Phys. G 37, 094009 (2010)

- [95] STAR Collaboration, “Measurement of inclusive J/ψ suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV through the dimuon channel at STAR”, Phys. Lett. B 797, 134917 (2019)
- [96] A. Andronic et. al., “Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions”, Eur.Phys.J.C 76, 107 (2016)
- [97] STAR Collaboration, “Suppression of Υ production in d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, Phys. Lett. B 735, 127-137 (2014)
- [98] CMS Collaboration, “Suppression of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production in PbPb collisions at $\sqrt{s_{NN}} = 200$ GeV”, Phys. Lett. B 770 357-379 (2017)
- [99] ZEUS Collaboration, “Forward jet production in deep inelastic ep scattering and low-x parton dynamics at HERA”, Phys. Lett. B 632 13-26 (2006)
- [100] STAR Collaboration, “Disappearance of back-to-back high p_T hadron correlations in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, Phys.Rev.Lett. 90, 082302 (2003)
- [101] ALICE Collaboration, “Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Rev. C 101, 034911 (2020)
- [102] P. Bozek and I. Wyskiel, “Directed flow in ultrarelativistic heavy-ion collisions”, Phys. Rev. C 81, 054902 (2010)
- [103] CMS Collaboration, “Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider”, Phys. Rev. C 97, 044912 (2018)
- [104] A. M. Poskanzer and S.A. Voloshin, “Methods for analyzing anisotropic flow in relativistic nuclear collisions”, Phys.Rev.C 58 1671-1678 (1998)
- [105] R. S. Bhalerao, J.-Y. Ollitrault, “Eccentricity fluctuations and elliptic flow at RHIC”, Phys. Lett. B 641, 260-264 (2006)

- [106] STAR Collaboration, “Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV”, Phys. Rev. Lett. 86, 402-407 (2001)
- [107] ALICE Collaboration, “Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV”, Phys. Rev. Lett. 105, 252302 (2010)
- [108]
- [109] J. Rafelski and B. Muller, “Strangeness Production in the Quark-Gluon Plasma”, Phys. Rev. Lett. 48, 1066 (1982)
- [110] STAR Collaboration, “Measurements of ϕ meson production in relativistic heavy-ion collisions at RHIC”, Phys. Rev. C 79, 064903 (2009)
- [111] ALICE Collaboration, “Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions”, Nature Phys. 13, 535-539 (2017)
- [112] U. W. Heinz and M. Jacob, “Evidence for a new state of matter: An Assessment of the results from the CERN lead beam program”, CERN Special Seminar Report, (2000)
- [113] “Quark Gluon Plasma an Color Glass Condensate at RHIC? The perspective from the BRAHMS experiment” , Nucl. Phys. A 757, 1-27 (2005)
- [114] PHOBOS Collaboration, “The PHOBOS Perspective on Discoveries at RHIC”, Nucl. Phys. A 757, 28-101 (2005)
- [115] STAR Collaboration, “Experimental and theoretical challenges in the search for the quark?gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions”, Nucl. Phys. A 757, 102-183 (2005)
- [116] PHENIX Collaboration, “Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration”, Nucl. Phys. A 757, 184-283 (2005)
- [117] J. Rafelski, “Discovery of Quark-Gluon-Plasma: Strangeness Diaries”, Eur. Phys. J. ST 229, 1-140 (2020)

- [118] C. Markert, R. Bellwied, and I. Vitev, “Formation and decay of hadronic resonances in the QGP”, Phys. Lett. B 669, 92-97 (2008)
- [119] T. Kodama, “Hunt for the quark-gluon plasma: 20 years later”, Braz. J. Phys. 34, 205-210 (2004)
- [120] A. Kurkela and A. Mazeliauskas, “Kinetic and Chemical Equilibration of Quark-Gluon Plasma”, Springer Proc. Phys. 250, 177-181 (2020)
- [121] J. L. Nagle, “The Letter S (and the sQGP)”, Eur. Phys. J. C 49, 275-279 (2007)
- [122] S.M. Sanches, F.S. Navarra, and D.A. Fogaca, “The quark gluon plasma equation of state and the expansion of the early Universe”, Nucl. Phys. A 937, 1-16 (2015)
- [123] U. Heinz, C. Shen, and H. Song, “The viscosity of quark-gluon plasma at RHIC and the LHC”, AIP Conf. Proc. 1441, 766-770 (2012)
- [124] G. Policastro, D.T. Son, and A.O. Starinets, “Shear viscosity of strongly coupled N=4 supersymmetric Yang-Mills plasma”, Phys. Rev. Lett. 87, 081601 (2001)
- [125] P. F. Kolb and U. Heinz, “Hydrodynamic description of ultra relativistic heavy-ion collisions”, Part of Quark-gluon plasma 4, 634-714 (2003)
- [126] J. Bjorken, “Highly Relativistic Nucleus-Nucleus Collisions: The Central Rapidity Region”, Phys.Rev.D 27 140-151 (1983)
- [127] B. V. Jacak and B. Müller, “The Exploration of Hot Nuclear Matter”, Science 337, 310-314 (2012)
- [128] A. Adil and M. Gyulassy, “Energy systematics of jet tomography at RHIC: $\sqrt{s_{NN}} = 62.4$ vs. 200 AGeV”,
- [129] Heavy Ion Collisions: The Big Picture, and the Big Questions, “Heavy Ion Collisions: The Big Picture, and the Big Questions”, Ann. Rev. Nucl. Part. Sci. 68, 339-376 (2018)

- [130] E. Rutherford, “The Scattering of α and β Particles by Matter and the Structure of the Atom”, *Philos. Mag.*, 6, 21 (1911)
- [131] H. W. Kendall, “Deep inelastic scattering: Experiments on the proton and the observation of scaling”, *Rev. Mod. Phys.* 63, 597-614 (1991)
- [132] R. E. Taylor, “Deep inelastic scattering: The Early years”, *Rev. Mod. Phys.* 63, 573-595 (1991)
- [133] J. I. Friedman, “Deep inelastic scattering: Comparisons with the quark model”, *Rev. Mod. Phys.* 63, 615-629 (1991)
- [134]
- [135] C. Lourenco and H. Satz, “Proceedings, 1st International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions (Hard Probes 2004) : Ericeira, Portugal, November 4-10, 2004”, *Eur. Phys. J. C* 43 1-4 (2005)
- [136] B. Betz and M. Gyulassy, “Constraints on the Path-Length Dependence of Jet Quenching in Nuclear Collisions at RHIC and LHC”, *JHEP* 08, 090 (2014)
- [137] CMS Collaboration, “Event displays and some infographics of jets in heavy ion collisions”, CMS-PHO-EVENTS-2021-007, <http://cds.cern.ch/record/2757389>
- [138] J. Casalderrey-Solana, G. Milhano, D. Pablos, and K. Rajagopal, “Modification of Jet Substructure in Heavy Ion Collisions as a Probe of the Resolution Length of Quark-Gluon Plasma”, *JHEP* 01, 044 (2020)
- [139] ALICE Collaboration, “Exploring jet substructure with jet shapes in ALICE”, *Nucl. Phys. A* 967 528-531(2017)
- [140] C. McGinn, “Mapping the redistribution of jet energy in PbPb collisions at the LHC with CMS”, MIT PHD Thesis (2019)
- [141] CMS Collaboration, “Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* 710, 256 (2012)

[142] CMS Collaboration, “Study of Z production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the dimuon and dielectron decay channels”, JHEP 03, 022 (2015)

[143] CMS Collaboration, “Study of Jet Quenching with $Z +$ jet Correlations in Pb-Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Rev. Lett. 119, 082301 (2017)

[144]

[145] A. Metz and A. Vossen, “Parton Fragmentation Functions”, Prog. Part. Nucl. Phys. 91, 136-202 (2016)

[146] S.J. Brodsky, H.J. Pirner, and J. Raufeisen “Scaling properties of high p_T inclusive hadron production”, Phys. Lett. B 637, 58-63 (2006)

[147] LHCb Collaboration, “Measurement of f_s/f_u variation with proton-proton collision energy and B-meson kinematics”, Phys. Rev. Lett. 124, 122002 (2020)

[148] ALICE Collaboration “Charm-quark fragmentation fractions and production cross section at midrapidity in pp collisions at the LHC”, CERN-EP-2021-088

[149] X. Dong, Y.-J. Lee, and R. Ralf, “Open Heavy-Flavor Production in Heavy-Ion Collisions”, Ann. Rev. Nucl. Part. Sci. 69, 417-445 (2019)

[150] Y. Liu, C. M. Ko, and F. Li, “Heavy quark correlations and the effective volume for quarkonia production”, Phys. Rev. C 93, 034901 (2016)

[151] F. Prino and R. Rapp, “Open Heavy Flavor in QCD Matter and in Nuclear Collisions”, J. Phys. G 43, 093002 (2016)

[152] A. M. Adare, M. P. McCumber, J. L. Nagle, and P. Romatschke, “Tests of the Quark-Gluon Plasma Coupling Strength at Early Times with Heavy Quarks”, Phys. Rev. C 90, 024911 (2014)

[153]

[154]

- [155] S. S. Gubser, “Drag force in AdS/CFT”, Phys. Rev. D 74, 126005 (2006)
- [156] A. Ficnar, J. Noronha, and M. Gyulassy, “Non-conformal Holography of Heavy Quark Quenching”, Nucl. Phys. A 855 (2011)
- [157] Y. Akiba, “Quest for the quark-gluon plasma - hard and electromagnetic probes” Prog. Theor. Exp. Phys. 2015, 03A105 (2015).
- [158] H. Bichsel and H. Schindler, “The Interaction of Radiation with Matter”, In: Fabjan C., Schopper H. (eds) Particle Physics Reference Library. Springer, Cham. (2020)
- [159] Y. L. Dokshitzer and D. E. Kharzeev, “Heavy quark colorimetry of QCD matter”, Phys. Lett. B 519, 199 (2001)
- [160] JET Collaboration, “Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions”, Phys. Rev. C 90, 014909 (2014)
- [161] S.-Q. Li, W.-J. Xing, F.-L. Liu, S. Cao, and C.-Y. Qin, “Heavy flavor quenching and flow: the roles of initial condition, pre-equilibrium evolution, and in-medium interaction”, Chin. Phys. C 44, 114101 (2020)
- [162] M. He, R. J. Fries, and R. Rapp, “Heavy flavor at the large hadron collider in a strong coupling approach”, Phys. Lett. B 735, 445 - 450 (2014)
- [163] F. Riek and R. Rapp, “Quarkonia and heavy-quark relaxation times in the quark-gluon plasma”, Phys. Rev. C 82, 035201 (2010).
- [164] Min He, Rainer J. Fries, and Ralf Rapp, “Heavy-quark diffusion and hadronization in quark-gluon plasma”, Phys. Rev. C 86, 014903 (2012)
- [165] S. Cao et. al., “Charmed hadron chemistry in relativistic heavy-ion collisions”, Phys. Lett. B 807, 135561 (2020)
- [166] S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C 88, 044907 (2013)
- [167] S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C 92, 024907 (2015)

- [168] Min He and Ralf Rapp, “Hadronization and Charm-Hadron Ratios in Heavy-Ion Collisions”, Phys. Rev. Lett. 124, 042301 (2020)
- [169] T. Sjostrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 Physics and Manual”, JHEP 0605, 026 (2006)
- [170] I. Kuznetsova and J. Rafelski, “Heavy flavor hadrons in statistical hadronization of strangeness-rich QGP”, Eur. Phys. J. C 51, 113-133 (2007)
- [171] Y. Oh, C. M. Ko, S. H. Lee, and S. Yasui, “Heavy baryon/meson ratios in relativistic heavy-ion collisions”, Phys. Rev. C 79, 044905 (2009)
- [172] Z. Tang, L. Yi, L. Ruan, M. Shao, H. Chen, C. Li, B. Mohanty, P. Sorensen, A. Tang, and Z. Xu, “Statistical Origin of Constituent-Quark Scaling in the QGP hadronization”, Chin. Phys. Lett. 30 031201(2013)
- [173] STAR Collaboration, “Measurement of D^0 Azimuthal Anisotropy at Midrapidity in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV’, Phys. Rev. Lett. 118, 212301 (2017)
- [174] CMS Collaboration, “Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity $p+Pb$ Collisions at $\sqrt{s_{NN}} = 8.16$ TeV”, Phys. Rev. Lett. 121, 082301 (2018)
- [175] STAR Collaboration, “Observation of D^0 Meson Nuclear Modifications in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV”, Phys. Rev. Lett. 113, 142301 (2014)
- [176] CMS Collaboration, “Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Lett. B 782, 474-496 (2018)
- [177] STAR Collaboration, “First measurement of Λ_C baryon production in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV”, Phys. Rev. Lett. 124, 172301 (2020)
- [178] ALICE Collaboration, “ Λ_C^+ production in Pb - Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys.Lett.B 793, 212-223 (2019)

- [179] ALICE Correlation, “Measurement of azimuthal correlations between D mesons and charged hadrons with ALICE at the LHC”, EPJ Web Conf. 80, 00034 (2014)
- [180] CMS Collaboration, “Studies of charm quark diffusion inside jets using PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Rev. Lett. 125, 102001 (2020)
- [181] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 S08004 (2008).
- [182] CMS Collaboration, “A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider”, Science 338, 1569-1575 (2012)
- [183] CMS Collaboration, “The CMS trigger system”, JINST 12 01, P01020 (2017)
- [184] Y. Chao, “Minimum-Bias and Underlying Event Studies at CMS”, Proceedings, 28th International Conference on Physics in Collision (PIC 2008) : Perugia, Italy, June 25-28, (2008)
- [185] Zhaozhong Shi, “Measurement of B_s^0 and B^+ meson yields in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, CMS-PAS-HIN-19-011
- [186] CMS Collaboration, “The Phase-2 Upgrade of the CMS Tracker”, CERN-LHCC-2017-009
- [187] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, JINST 9 10, P10009 (2014)
- [188] P. Billoir, “Progressive track recognition with a Kalman like fitting procedure”, Comput. Phys. Commun. 57, 390 (1989)
- [189] P. Billoir and S. Qian, “Simultaneous pattern recognition and track fitting by the Kalman filtering method”, Nucl. Instrum. Meth. A 294, 219 (1990)
- [190] R. Mankel, “A Concurrent track evolution algorithm for pattern recognition in the HERA-B main tracking system”, Nucl. Instrum. Meth. A 395, 169 (1997)

- [191] R. Fruhwirth, “Application of Kalman filtering to track and vertex fitting”, ? Nucl. Instrum. Meth. A 262, 444 (1987)
- [192] K. Rose, “Deterministic Annealing for Clustering, Compression, Classification, Regression and related Optimisation Problems”, Proceedings of the IEEE 86 (1998)
- [193] CMS Collaboration, “The CMS ECAL performance with examples”, JINST 9 C02008 (2014)
- [194] CMS Collaboration, “The CMS hadron calorimeter project : Technical Design Report”, CERN-LHCC-97-031 (1997)
- [195] A. Penzo and Y. Onel, “The CMS-HF quartz fiber calorimeters”, J.Phys.Conf.Ser. 160, 012014 (2009)
- [196] CMS Collaboration, “Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV”, Phys. Rev. C 84, 024906 (2011)
- [197] B. Roland, “Forward Physics Capabilities of CMS with the CASTOR and ZDC detectors”, Part of Proceedings, 17th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2019), Madrid, Spain, April 26-30 (2009)
- [198] T. Bawej el. at., “The New CMS DAQ System for Run-2 of the LHC”, IEEE Trans. Nucl. Sci. 62, 1099-1103 (2015)
- [199] CMS Collaboration, “Commissioning and performance of the CMS pixel tracker with cosmic ray muons”, JINST 5 T03007 (2010)
- [200] W. Adam, R. Fruhwirth, A. Strandlie, and T. Todorov, “Reconstruction of electrons with the Gaussian-sum filter in the CMS tracker at LHC”, J. Phys. G 31 N9 (2005)