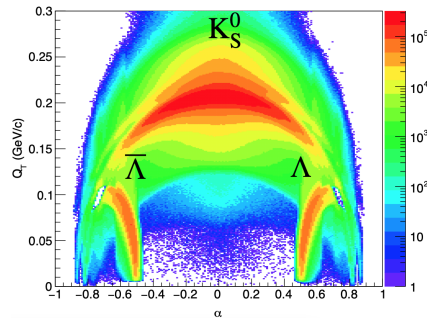




DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY MADRAS
CHENNAI – 600036

Strange particles femtosopic correlation in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector at the LHC



A Thesis

Submitted by

RAGHUNATH PRADHAN

For the award of the degree

Of

DOCTOR OF PHILOSOPHY

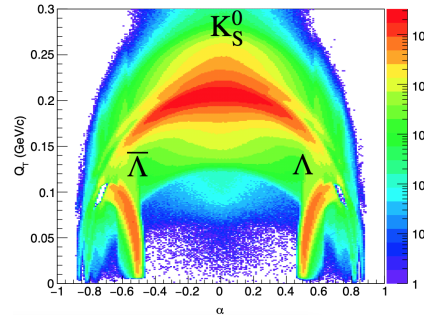
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Dedicated to my parents and my family.

THESIS CERTIFICATE

This is to undertake that the Thesis titled **Strange particles femtoscopic correlation in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector at the LHC**, submitted by me to the Indian Institute of Technology Madras, for the award of **Doctor of Philosophy**, is a bona fide record of the research work done by me under the supervision of **Dr. Prabhat R. Pujahari**. The contents of this Thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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LIST OF PUBLICATIONS

I. REFEREED JOURNALS BASED ON THESIS

- K_S^0 and Λ ($\bar{\Lambda}$) two-particle femtoscopic correlations in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, [arXiv:2301.05290](https://arxiv.org/abs/2301.05290), Submitted to Phys. Lett. B.
- Strange hadron collectivity in pPb and PbPb collisions, J. High Energ. Phys. 2023, 7 (2023).

II. REFEREED JOURNALS (OTHERS)

- Inspire HEP website: <https://inspirehep.net/authors/1704473>

III. PRESENTATIONS IN CONFERENCES

International:

- Oral presentation: *Results of femtoscopic correlations at CMS*
“8th International Conference On Physics and Astrophysics Of Quark-Gluon Plasma (ICPAQGP-2023)”, February 7th–10th, 2023, Blue lily beach resort, Puri, Odisha, India.
Link: <https://events.vecc.gov.in/event/19/contributions/782/>
- Oral presentation: *Results of femtoscopic correlations at CMS*
“The 20th International Conference On Strangeness in Quark Matter (SQM 2022)”, June 13th–17th, 2022, Busan, Republic Of Korea.
Link: <https://indico.cern.ch/event/854124/contributions/4134807/>
- Oral presentation: *Strange, charm, and bottom hadron flow in pPb and PbPb collisions*
“The 22nd Particles and Nuclei International Conference (PANIC 2021)”, September 5th–10th, 2021, Lisbon, Portugal.
Link: <https://indico.lip.pt/event/592/contributions/3250/>
- Oral presentation: *Collectivity of strange, charm, and bottom hadrons in pPb and PbPb with CMS*
“The VIth International Conference On the Initial Stages (IS 2021)”, January 10th–15th, 2021, Weizmann Institute of Science, Israel.
Link: <https://indico.cern.ch/event/854124/contributions/4134807/>
Public video: <https://cds.cern.ch/record/2749455>

National:

- Oral presentation: ***Strange particles femtoscopy in PbPb collisions with CMS detector***
“DAE-BRNS symposium on Contemporary and Emerging Topics in High Energy Nuclear Physics (CETHENP 2022)”, November 15th–17th, 2022, Variable Energy Cyclotron Center, Kolkata, India.
Link: <https://events.vecc.gov.in/event/18/contributions/706/>
- Oral presentation: ***Strange particle femtosopic correlation in PbPb collisions at 5.02 TeV***
“The 1st National Conference On Hot QCD Matter”, May 12th–14th, 2022, Goa University and IIT Goa, Goa, India.
Link: <https://iitgoa.ac.in/QCDMatter2022/timetable.html>
- Oral presentation: ***Measurement of two-particle femtosopic correlations in PbPb collisions with CMS***
“The 6th Physics In-House Symposium”, April 22nd–23rd, 2022, Department Of Physics, IIT Madras, Chennai, India.
Link: <https://physics.iitm.ac.in/pihs/programme.html>
- Oral presentation: ***Femtoscopic Correlation and Search for Exotic H-Dibaryon***
“India-CMS Collaboration Meeting”, January 24th–25th, 2020, Department Of Physics, Panjab University, India.
Link: <https://indico.cern.ch/event/869890/contributions/3718734/>
- Poster presentation: ***CMS heavy-Ion physics***
“The 5th Physics In-House Symposium”, November 8th–9th, 2019, Department Of Physics, IIT Madras, Chennai, India.
Link: <https://physics.iitm.ac.in/pihs19/poster.html>
- Oral presentation: ***Lambda - Lambda correlation and search for exotic particles***
“India-CMS Collaboration Meeting”, August 22nd–24th, 2019, Department Of Physics and Astrophysics, Delhi University, India.
Link: <https://indico.cern.ch/event/822985/contributions/3528878/>

IV. PUBLICATIONS IN CONFERENCE PROCEEDINGS

- ***Results of femtosopic correlations at CMS***
The 20th International Conference On Strangeness in Quark Matter (SQM 2022)
[EPJ Web of Conferences 276, 03003 \(2023\)](#)
- ***Dynamics of Hot QCD Matter – Current Status and Developments***

The 1st National Conference On Hot QCD Matter
[Int. J. Mod. Phys. E 31, 2250097 \(2022\)](#)

- ***Strange, charm, and bottom hadron flow in pp, pPb, and PbPb collisions***
The 22nd Particles and Nuclei International Conference (PANIC 2021)
[PoS PANIC2021, 262 \(2022\)](#)

ACKNOWLEDGEMENTS

I would like to acknowledge the invaluable support and guidance I received throughout my Ph.D. journey, without which this accomplishment would not have been possible. I am deeply grateful to the following individuals and entities:

First and foremost, I would like to express my profound gratitude to the Almighty for providing me with the strength, resilience, and inspiration to overcome the challenges and obstacles along the way. Your divine presence has been a constant source of solace and motivation, filling my heart with unwavering hope and faith.

I am immensely grateful to my parents, Chandra Sekhar Pradhan and Ashalata Pradhan, for their unconditional love, support, and sacrifices they have made to provide me with the best possible opportunities. Their unwavering faith in my potential has been the driving force behind my achievements, and I am eternally grateful for their presence in my life.

My deepest appreciation goes to my esteemed guide, Dr. Prabhat Ranjan Pujahari, whose guidance, expertise, and mentorship have been instrumental in shaping my research and academic development. Their vast knowledge, commitment, and ability to challenge and inspire me have pushed the boundaries of my intellectual capabilities. I am truly fortunate to have had the privilege of working under their guidance.

I would like to pay my sincere thank to Prof. Jim Libby for his kind help and support throughout my Ph.D. and for his suggestions in my analysis.

I would extend my thank to Dr. Quan wang for his help in V^0 particle reconstruction and technical discussion.

I would like to thank all the conveners of the flow/correlation group and the heavy-ion

Physics Analysis Group (HIN PAG), as well as the members of the Analysis Review Committee (ARC), Language Editor (LE), Publication Committee (Pub Com), and Journal Submission Expert (JSE) of CMS collaboration for their insightful suggestions, help and support on the data analysis, during pre-approval and approval sessions of my analysis, during ARC review, during Community Wide Review (CWR) and Final Reading (FR) stages as well as writing paper and submitted it to the journal.

I would also like to thank all the Doctoral committee (DC) members of the physics department at IIT Madras for reviewing my progress every six months and for their valuable feedback/remarks.

I would like to dedicate a special acknowledgement to my beloved friend Lopamudra Mohanty. Your presence in my life has been a constant source of strength and inspiration. Thank you for being there for me through the ups and downs, the triumphs and challenges of this academic pursuit. Your unwavering belief in me, even during my moments of self-doubt, has given me the strength to persevere and overcome obstacles.

I would like to express my gratitude to my labmates Subash Behera, Nihar Ranjan Saha, Sayan Chatterjee, Rohit Kumar Singh, Pranjal Verma, Arya Dattamunsi, Akash Kumar Jena, Vaivabi Gawas, and Srisendu Roy. Your friendship, camaraderie, and intellectual discussions have been a constant source of inspiration and motivation. Your support, encouragement, and belief in my abilities have been instrumental in my personal and academic growth. I am grateful for the laughter, shared moments, and support we have experienced together. I would like to thank Hareram Swain, Bubunu Biswal, Subash Behera, Nihar Ranjan Saha, and Sayan Chatterjee for their friendship, with whom I have shared numerous cooking adventures, especially the joy of preparing mutton dishes.

I would also like to express my gratitude to Dr. Baidyanath Sahoo and Dr. Nirbhaya Behera for their assistance in helping me learn the C++ code in the initial days of my PhD journey and for the physics discussion. Furthermore, I would like to thank Dr. Ravindra

Verma for helping me learn the CMS environment and validation work.

I would like to thank the entire staff of IIT Madras, especially the physics department and academics, for their support and assistance with all the academic and administrative formalities throughout my journey. I would like to express my heartfelt appreciation to the dedicated cleaning staff of IIT Madras, who played a crucial role in maintaining a clean and conducive environment throughout my PhD journey. In addition, I would like to acknowledge the contributions of all the individuals who have directly or indirectly supported me during my research journey.

Lastly, I would like to express my gratitude to the institution, department, and funding organizations that have provided me with the necessary resources, research facilities, and opportunities to pursue my Ph.D. studies.

ABSTRACT

KEYWORDS Heavy-ion; Strange hadrons; Strong interaction; Femtoscopy; Correlations; Source size; Scattering parameters

The relativistic heavy-ion collider at BNL and the large hadron collider at CERN have created an extraordinary phase of nuclear matter known as Quark Gluon Plasma (QGP) at extremely high temperatures and energy densities. The correlation measurements among the produced particles from the ultra-relativistic heavy-ion collisions provide a unique tool to understand the dynamics of particle production mechanisms and the evolution of the systems produced in these collisions. Such correlations help study the produced medium's collective behaviour, revealing the initial overlapping region and its fluctuations between the colliding nuclei. Two-particle correlations in relative momentum, so-called femtoscopic correlations, arising from relativistic heavy-ion collisions, provide a powerful technique for studying the space-time dimensions of the particle emitting sources produced in the collisions and the subsequent interactions of the emitted particles. These correlations are sensitive to quantum statistics and final-state interactions between the particles. Two-particle femtoscopic correlations are presented for K_S^0 , Λ , and $\bar{\Lambda}$ strange hadrons in lead-lead collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The dataset corresponds to an integrated luminosity of 0.607 nb^{-1} and was collected using the CMS detector at the CERN LHC. This is the first femtoscopic correlation measurement of $\Lambda\Lambda$ in lead-lead collisions at the LHC. The source size is extracted from the $K_S^0 K_S^0$ correlations in different centrality bins and found to decrease central to peripheral collisions. A comparison of source size with the other experiments is also presented. Along with source size, the strong interaction scattering parameters (i.e., scattering length and effective range) are determined from the ΛK_S^0 and $\Lambda\Lambda$ (including their charge conjugates) correlations using the Lednický–Lyuboshitz model and are compared to theoretical and other experimental results.

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CHAPTER 1

INTRODUCTION

The contribution of relativistic heavy-ion physics to gain insight into the origins of our universe is outstanding. Understanding the strong force, which describes the interaction between quarks and gluons, and the theory governed by the strong force, quantum chromodynamics (QCD), are the main objectives of relativistic heavy-ion physics. The heavy-ion collisions enable one to study the strongly interacting matter of quarks and gluons at very high energy density and high temperature, known as Quark Gluon Plasma (QGP). QGP is a deconfined state of quarks and gluons believed to have been present in the early universe. Such a novel state of matter is created in the laboratories¹ by colliding two heavy nuclei at ultra-relativistic speed. By studying the properties of QGP, we can gain insight into the universe's origin and the characteristic of the strong force, which is challenging to obtain theoretically. The heavy-ion physicist continued to study the properties of the QGP over the last two decades by smashing the heavy nuclei at ultra-relativistic speed in the laboratory.

Unfortunately, the QGP state exists for a short period of time, and we cannot observe directly. Therefore, various indirect probes have been proposed, which are the signature of the presence of QGP. Femtoscopic correlation is one of the important probes used by physicists to study high-energy heavy-ion collisions.

Two-particle correlations in relative momentum, called femtoscopic correlations, arising from relativistic heavy-ion collisions provide a powerful tool for studying the properties of the quark-gluon plasma (QGP) that is created in the collisions and the subsequent interactions of the emitted particles [1]. All two-particle correlations involving hadrons

¹The Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN)

are affected by final-state interaction (FSI) effects, and correlations of identical particles are also sensitive to the constraints of quantum statistics (QS). The correlations among the neutral K_S^0 , Λ , and $\bar{\Lambda}$ particles, collectively referred to as V^0 particles, are of special interest. First, they can be used to determine the space-time characteristics of the particle emitting source region at kinetic freeze-out. In addition, information can be extracted about the strong-interaction scattering parameters, i.e., the scattering length and the effective range, that is impossible to obtain from currently achievable scattering experiments [2–6]. Because of their relatively large mass and the absence of a Coulomb interaction, femtoscopy based on K_S^0 particles supplements the more commonly studied pion and charged kaon pairs [7]. The results from $\Lambda\Lambda$ correlation studies can help constrain baryon-baryon and, more specifically, hyperon-hyperon interaction models that are used, for example, in modeling the composition of neutron stars [8–10].

Regarding the scattering parameters, of particular interest is establishing whether the interaction between two Λ particles allows for the existence of the H-dibaryon, a bound state with quantum numbers $I = 0, J^P = 0^+, S = -2$. In 1977, Jaffe predicted the existence of such a six-quark (uuddss) state having a mass about 81 MeV below the threshold of twice the Λ mass by considering the strong attraction resulting from color magnetic interactions [11]. Although a double hypernucleus, ${}_{\Lambda\Lambda}^6\text{He}$, was subsequently observed in the NAGARA event from the E313 hybrid emulsion experiment at KEK [12, 13], the observed $\Lambda\Lambda$ binding energy was not consistent with the conjectured H-dibaryon [14]. A study of $\Lambda\Lambda$ correlations may provide additional information on whether the baryon-baryon interaction can lead to the formation of the conjectured H-dibaryon.

Recently, the ALICE Collaboration reported on ΛK correlations in lead-lead (PbPb) collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 2.76$ TeV [15]. According to their findings, the strong force is repulsive in ΛK^+ interactions, yet attractive in ΛK^- interactions. For the ΛK_S^0 pairs, the uncertainty of the ALICE results does not permit a definite conclusion on whether the associated strong interaction is repulsive or attractive.

A more precise measurement of ΛK_S^0 correlations would improve our understanding of the strong interaction in baryon-meson systems.

This thesis presents the reconstruction of K_S^0 and Λ ($\bar{\Lambda}$) particles and their femtoscopic correlations as a function of relative momentum in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using data recorded by the CMS experiment during the 2018 LHC run. Also, the elliptic azimuthal anisotropy coefficient (v_2) of these particles obtained in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are discussed in this thesis. The $K_S^0 K_S^0$ femtoscopic correlations are measured in six centrality intervals within the 0–60% range, where centrality refers to the percentage of the total inelastic hadronic nucleus-nucleus cross section [16], and 0% corresponds to the maximum overlap of the colliding nuclei. The $K_S^0 K_S^0$, ΛK_S^0 , and $\Lambda\Lambda$ correlations are measured in an integrated centrality range (0–80%), with the $\Lambda\Lambda$ femtoscopic correlation measured in PbPb collisions at the LHC for the first time. The source size and strong interaction parameters are determined using the Lednický–Lyuboshitz (LL) model [17]. Unless otherwise indicated, all measurements include the charge conjugate states, so ΛK_S^0 and $\Lambda\Lambda$ include $\bar{\Lambda} K_S^0$ and $\bar{\Lambda}\bar{\Lambda}$, respectively.

The work in this thesis is organized as follows. Chapter 2 discusses the strong interaction, the Quark-Gluon Plasma, heavy-ion collisions, and a few signatures of the Quark-Gluon Plasma. Chapter 3 discusses the history of femtoscopy and the theoretical framework of femtoscopic correlation. The experimental setup of the LHC accelerator and the CMS detector and the future plan of the LHC are discussed in Chapter 4. In Chapter 5, the complete data analysis procedure is discussed. Chapter 6 discusses the experimental results and the comparison with other theoretical and experimental results. Chapter 7 summarizes this thesis. In addition, two appendices are included in this thesis. Appendix A shows data and MC comparison of control plots and other $K_S^0 K_S^0$ correlation plots. Appendix B describes the collaborative responsibility and service task.

The work presented in this thesis is divided into two parts. The first part contains the

reconstruction of K_S^0 and Λ ($\bar{\Lambda}$) particles, described in the paper accepted by JHEP [18]. This paper also contains the results of elliptic azimuthal anisotropy coefficient (v_2) of these particles. The second part contains the K_S^0 and Λ ($\bar{\Lambda}$) two-particle femtoscopic correlation, described in the paper submitted in Phys. Lett. B [19].

CHAPTER 2

STRONG INTERACTION AND THE QUARK-GLUON PLASMA

The Big Bang theory states that our universe began approximately 14 billion years ago from a point of infinitesimally small volume with an extremely high temperature and energy density. Since its birth, it has undergone several stages of evolution [20] shown in Fig. 2.1. According to the Big Bang theory, in the early universe (when our universe was $\sim 10^{-44}$ seconds (s) old), the temperature was the order of $T \sim 10^{19}$ GeV, and all four fundamental forces of nature (the gravitational force, the electromagnetic force, the weak force, and the strong force) were unified to a single force. As the universe continued to expand, it cooled, and after $\sim 10^{-43}$ s, when the temperature was about $\sim 10^{16}$ GeV, the grand unification occurred. Here the gravitational force is separated, and the electromagnetic, weak, and strong forces are unified. As the universe further expanded and cooled, the strong and electroweak forces were separated. Finally, the electromagnetic and weak forces were separated after $\sim 10^{-11}$ s ($T \sim 100$ GeV). At this time, the universe was so hot and existed as a deconfined state of quarks and gluons called Quark Gluon Plasma (QGP). After $\sim 10^{-6}$ s of the universe's birth when the temperature was around $T \sim 200$ MeV, the phase transition from the deconfined state (QGP) to confined state occurred, and hadrons (e.g., proton, neutron, etc.) were formed. After that, protons and neutrons are bound together to form nuclei, and atoms, molecules, and matter are gradually formed. Finally, we are here today after 14 billion years. A similar condition, like a few microseconds after the birth of our universe, is believed to be produced in the laboratory by colliding two heavy nuclei at RHIC and LHC, which is called Little Bang. The heavy-ion programs at RHIC and LHC helped the scientific community understand the properties of a novel state of matter known as QGP. [21].

To understand the formation of matter, it is necessary to study the properties of fundamental forces, their carriers, and the building block of matter, described in the next section.

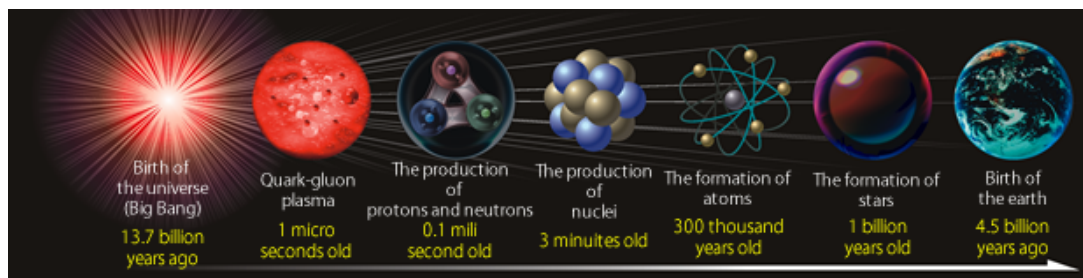


Figure 2.1: Evolution of the universe after its birth. This figure is taken from <https://j-parc.jp/c/en/facilities/nuclear-and-particle-physics/hadron.html>.

2.1 THE STANDARD MODEL

The Standard Model (SM) is a theory that explains the properties of three of the four fundamental forces of nature (except gravitational force) and the building blocks of all known matter (elementary particles) in the universe and their interactions. According to the SM, the elementary particles are classified as fermions and bosons, shown in Fig. 2.2. Fermions are half integral spin and are further classified as leptons and quarks. These fermions have certain quantum numbers. For example, the leptons have a lepton number, electric charge, etc., and the quarks have an electric charge, color charge, etc. There are six leptons correspond to three generations: the electron (e^-) and the electron neutrino (ν_e), the muon (μ^-) and the muon neutrino (ν_μ), and the tau (τ^-) and the tau neutrino (ν_τ). The neutrinos (ν_e , ν_μ , and ν_τ) are massless and electrically neutral, while the other leptons (e^- , μ^- , and τ^-) have sizeable mass and negative electric charge (-1). Similar to leptons, there are six flavors of quarks arranged in three generations: the up (u) and down (d) quarks, the charm (c) and strange (s) quarks, and the top (t) and bottom (b) quarks. The first quarks of each generation (u, c, and t) have a positive electric charge ($+2/3$), and the others (d, s, and b quarks) have a negative electric charge ($-1/3$). Each quark also carries a color charge, which can take one of three different red (r), green (g), or blue

(b) values. Moreover, the SM requires the existence of an antiparticle for each fermion listed above. The antiparticles of the charged leptons have an opposite electric charge and lepton number. Similarly, for the neutrinos, the antineutrinos have opposite lepton numbers. In the case of quarks, the corresponding antiquarks have opposite electric and color charges.

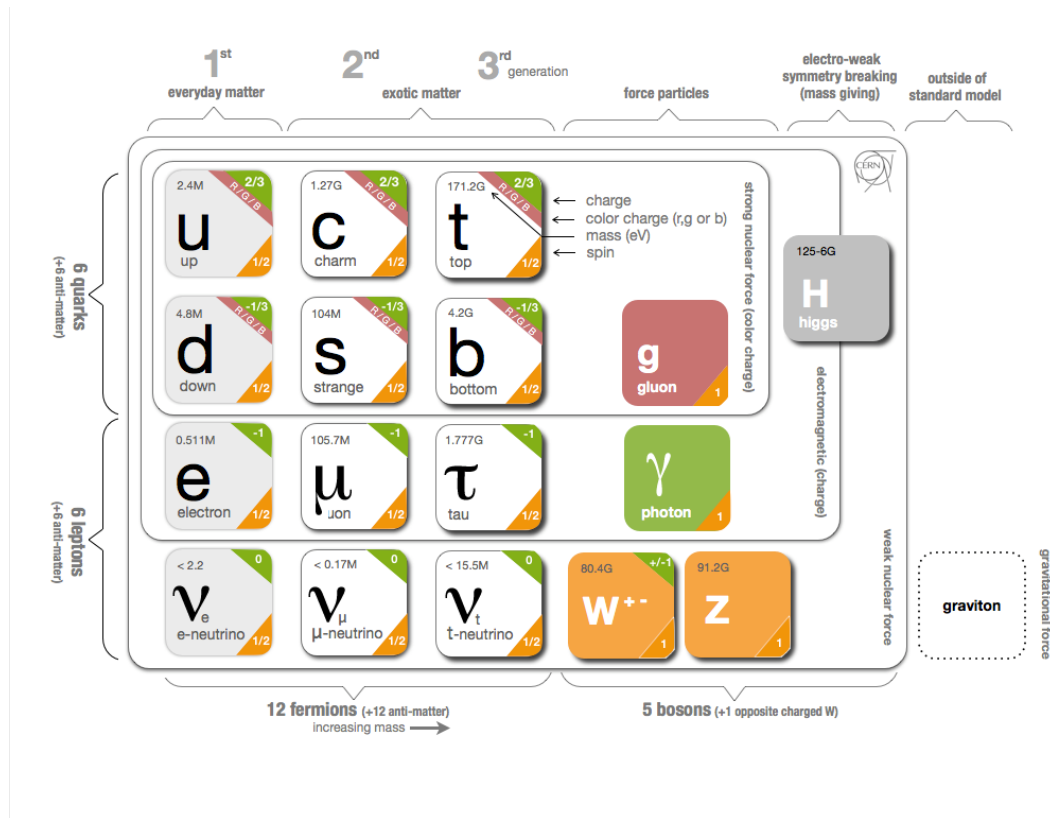


Figure 2.2: Fundamental particles that make up the Standard Model of particle physics. This figure is taken from <https://cds.cern.ch/record/1473657>.

In the SM, the other fundamental particles are called bosons. There are a total of 4 vector bosons¹ (photon (γ), gluon (g), W[±], and Z) with spin-1 and one scalar (Higgs (H)) boson with spin-0. The three fundamental forces describe the interaction between fermions by exchanging vector bosons (force carriers). Gluon (g) is the force carrier of the strong force, photon (γ) is the force carrier of the electromagnetic force, and W[±] and Z bosons are the force carriers of the weak force. The photon and gluon are massless,

¹Also called gauge bosons

whereas the $W^\pm$ and Z bosons are massive. All vector bosons except $W^\pm$ are chargeless. All the fundamental charged fermions can interact through the electromagnetic force by exchanging photons, described by the Quantum Electrodynamics theory (QED). The weak force can act on all the fundamental fermions, and they can interact by exchanging $W^\pm$ and Z bosons. The interaction between the colored charged particles is caused by the strong force, which is mediated by gluons, and it is described by the theory of Quantum Chromodynamics (QCD). Unlike photons, gluons can interact with each other via the strong interaction. The electromagnetic and strong forces are 10^4 and 10^6 times stronger than the weak force, respectively.

The Brout-Englert-Higgs (BEH) mechanism [22, 23] explains how elementary particle mass is generated in the SM. Due to the interaction with the Higgs field, all the fundamental fermions and weak bosons ($W^\pm$ and Z) acquire their mass. The stronger a particle interacts with the Higgs field, the more massive it becomes. This mechanism predicted the existence of the Higgs boson, which is the quantum excitation of the Higgs field. The BEH mechanism was confirmed experimentally in 2012 after the CMS [24] and ATLAS [25] collaboration announced the discovery of the Higgs boson.

The work in the thesis is focused on the strong interaction described by the QCD theory.

2.2 QUANTUM CHROMODYNAMICS (QCD)

QCD is the theory of strong force which describes the interaction between quarks and gluons. One can compare the QCD with QED, where the quarks and antiquarks are analogous to the electrons and positrons, and the gluons are identical to the photons. Despite this analogy, there are some differences between QCD and QED. Unlike electrons (positrons), quarks (antiquarks) carry one unit of color (anticolor) charge (e.g., $r(\bar{r})$). One crucial difference is that in QED, the photons are electrically neutral, but in QCD, the gluons carry color charges and interact with each other. The gluons are the bicolored object (e.g., $(r\bar{b}+b\bar{r})/\sqrt{2}$). Due to the self-interacting nature of gluons, unlike photons,

QCD theory is much more complicated than QED.

QCD is a non-abelian gauge theory² based on the color SU(3) symmetry group with eight generators corresponding to eight gluons. The QCD lagrangian density is given by

$$\mathcal{L}_{\text{QCD}} = \sum_{\text{flavors}(f)} \bar{\psi}_{f,i} (i\gamma^\mu D_\mu - m_f) \psi_{f,j} - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a, \quad (2.1)$$

where γ^μ are the Dirac γ matrices, m_f is the mass of quark with flavor f , and $\psi_{f,i}$ is the Dirac spinor of a quark with flavor f with color index i running from $i = 1$ to 3. The gauge covariant derivative D_μ and the gluon field strength tensor $F_{\mu\nu}^a$ are given by

$$D_\mu = \partial_\mu - i\frac{g_s}{2} \lambda^a A_\mu^a \text{ and} \quad (2.2)$$

$$F_{\mu\nu}^a = \partial^\mu A_\nu^a - \partial^\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c, \text{ respectively,}$$

where g_s is the coupling of the strong interactions, λ^a are the Gell-Mann matrices, f^{abc} are the SU(3) structure constants, and A_μ^a corresponds to eight vector field of the gluons.

The strong coupling constant α_s defines the strong interaction's strength and is written as $\alpha_s = g_s^2/4\pi$. In QCD theory, the anti-screening effect due to the gluon-gluon interaction leads to the quantum correction to the strong coupling constant α_s and suggests that the α_s is not a constant; instead, it depends on the momentum transfer Q and can be approximated as

$$\alpha_s(Q^2) = \frac{g_s^2(Q^2)}{4\pi} \propto \frac{1}{\ln\left(\frac{Q^2}{\Lambda_{\text{QCD}}^2}\right)}, \quad (2.3)$$

where $\Lambda_{\text{QCD}} (\approx 255 \text{ MeV [26]})$ is the QCD scale parameter at which the coupling becomes infinite (called QCD Landau pole).

The running coupling constant α_s (also called effective coupling constant) exhibits a logarithmic decrease with increasing Q^2 that can be seen in Fig. 2.3. Therefore, at large momentum (corresponding to a short distance according to the de Broglie hypothesis), the

²Gauge theories are called non-abelian as the generators associated with the symmetry group do not commute with each other.

coupling becomes small, while for small momentum (corresponding to a large distance), the coupling is large. The latest average value of α_s obtained experimentally at the mass of Z boson is $\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$.

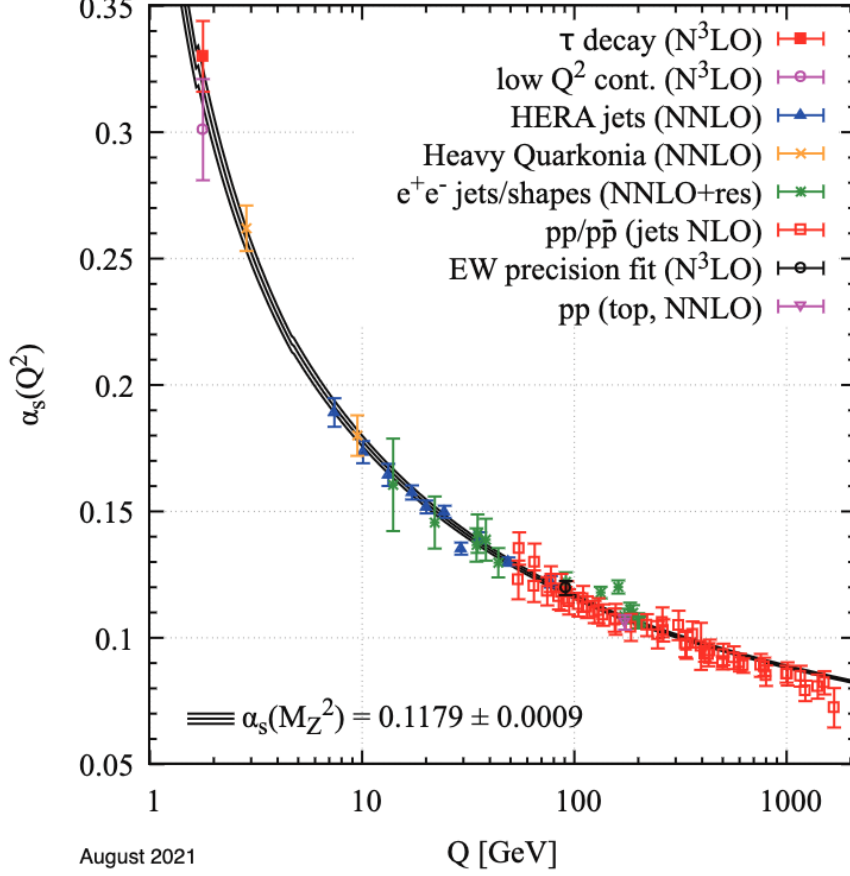


Figure 2.3: α_s measurements as a function of the energy scale Q . This figure is taken from Ref. [27].

Two exciting phenomena of QCD, color confinement and asymptotic freedom, can be identified using running coupling constant. At low Q^2 ($Q^2 \leq \Lambda_{\text{QCD}}^2$) or at a large distance between color charged particles (quarks and gluons), QCD coupling increases as seen in Fig. 2.3. The large coupling between color charged particles causes them to be confined in hadrons. Due to this, quarks and gluons have never been found isolated in nature. This phenomenon is called color confinement. Because of this confinement, the strong force is a short range force. As the existence of individual quarks and gluons is forbidden, only

the color neutral bound states (hadrons) of quarks and gluons can exist freely in nature.

At high Q^2 ($Q^2 \gg \Lambda_{\text{QCD}}^2$) or at a small distance between color charged particles, QCD coupling decreases asymptotically ($Q^2 \rightarrow \infty, \alpha_s \rightarrow 0$). That means, at high Q^2 , or at short distances, the quarks and gluons behave as asymptotically free particles. This is called asymptotic freedom. This feature was discovered in 1973 by Gross and Wilczek [28], and also by Politzer [29]. This feature of QCD gives rise to the hypothesis of the presence of a novel state of matter known as quark-gluon plasma, which is covered in the following section.

2.3 QUARK-GLUON PLASMA (QGP)

The running coupling constant and the concept of asymptotic freedom allow the quarks and gluons to behave freely at high momentum transfer or very small distances. Thus, it was hypothesized that at very high energy density, quarks and gluons are no longer confined into hadronic bound states; instead, they are allowed to act freely³ within the boundaries of such an energetically dense region and behaves like weakly interacting gas. This deconfined state of quarks and gluons is called Quark-Gluon Plasma⁴ (QGP). But surprisingly, in the high-energy heavy-ion collisions at Relativistic Heavy-Ion Collider (RHIC)⁵ [31] and the Large Hadron Collider (LHC)⁶, it has been found that the QGP phase did not act as a weakly interacting gas but as a strongly-coupled hydrodynamic system, behaving like a near-perfect liquid with extremely low viscosity [32].

According to the lattice QCD calculation, the QGP phase of matter may be produced from a hadronic phase at an exceptionally high temperature of 150-200 MeV (order of 10^6 times more than the sun temperature at its core) and an energy density of $\geq 1 \text{ GeV/fm}^3$ [33]. theorists anticipated that this high energy density and temperature conditions might

³They are not truly free but “quasi free” particles

⁴The name given by Shuryak [30]

⁵A particle accelerator and collider at Brookhaven National Laboratory (BNL)

⁶A particle accelerator and collider at European Council for Nuclear Research (CERN)

be attained. using ultra-relativistic nucleus-nucleus (AA) collisions [34, 35]. And for the first time, in 2000, the QGP was discovered experimentally in the Super Proton Synchrotron (SPS) at CERN by projecting lead (Pb) ion beams on Pb or gold (Au) targets [36]. Interestingly, the QGP state is believed to have been present in the early universe, as discussed earlier in this chapter. Thus, studying the properties of this state will give us insight into the physics of the early universe. The heavy-ion physics program runs at the RHIC and LHC to study the properties of QGP. Currently, LHC is the most powerful particle accelerator in the world.

2.3.1 Ultra-relativistic heavy-ion Collisions and its Evolution

LHC, the world's most powerful particle accelerator, accelerates the two oppositely traveling $^{208}_{82}\text{Pb}$ ions beams at ultra-relativistic speed (velocity $v \sim 0.99999997 c$ at a center-of-mass energy per nucleon-nucleon pair of $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$), and collide them together. A schematic view of a heavy-ion collision can be seen in Fig. 2.4. In the lab frame of reference, two incoming heavy nuclei are shown as thin “pancakes” due to relativistic Lorentz contraction. The impact parameter b is defined as the distance between the center of two nuclei. Depending on the impact parameter values, we characterize the collisions. When $b \approx 0$, we call it a central collision, where two nuclei entirely overlap with each other, and as b increases ($b \gg 0$), the collisions become peripheral. When $b \geq 2R_{\text{nucleus}}$, we call it a ultra-peripheral collision. A single nucleus-nucleus collision can be considered as a series of nucleon-nucleon collisions. Participants (N_{part}) are those nucleons who participate in the collision, and those who do not participate, we call spectators (N_{spec}). N_{part} and b are inversely proportional to each other but N_{spec} and b are directly proportional. Using this simple geometry, one can calculate b and N_{part} from the Glauber model [37]. However, experimentally, it is impossible to calculate the b and N_{part} . Therefore, the characterization of a collision (an event) is done using the final state charged particle multiplicity (N_{ch}) of that event (larger multiplicity means small b and large N_{part}) or the sum of transverse energy (E_T) deposited in the calorimeter (larger transverse energy means small b and large N_{part}). These final state quantities

are directly related to the b and N_{part} . Generally, we classified the heavy-ion events as centrality classes and expressed them as a percentage (%), where 0% corresponds to the maximum overlap of the colliding nuclei. The smaller centrality percentage means central collisions, and the higher centrality percentage means peripheral collisions. Left panel of Fig. 2.5 shows an example of how the mapping between centrality, N_{ch} , N_{part} , and b . According to this plot, the events with N_{ch} values between 1350 to 1850 refer to 0–5% centrality, and so on. The right panel shows the centrality determination in the CMS experiment using the sum of E_T deposited in the Hadron Forward (HF) calorimeter. In this plot, events with the sum of E_T in the HF between 3.4 to 4.5 TeV refer to 0–5% centrality and so on.

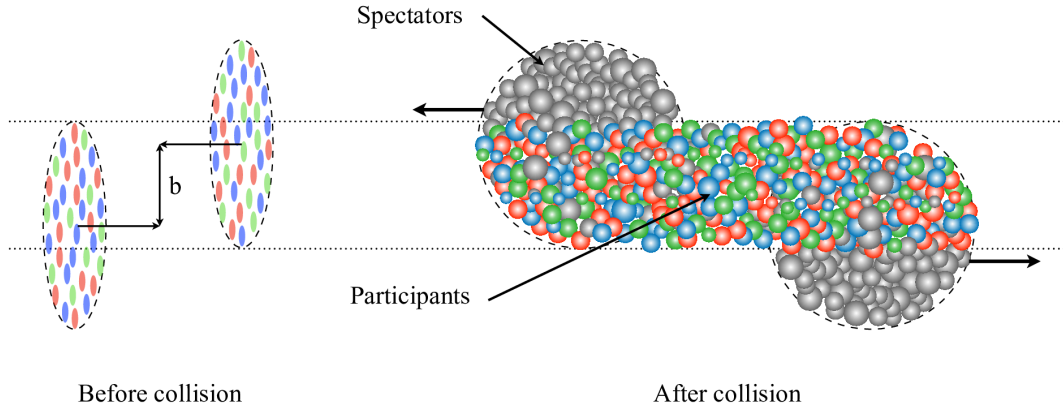


Figure 2.4: Schematic view of the collisions of two heavy-ion. The impact parameter b is shown, as well as the spectator and participant nucleons. This figure is taken from <https://cds.cern.ch/record/2789548>.

Space-time evolution of heavy-ion collision

When two relativistic heavy nuclei collide head-on, a fireball is produced, which then expands and cools. Bjorken [39] suggested that the expansion of the fireball occurs through various stages in space-time and can be described in terms of light cone variables

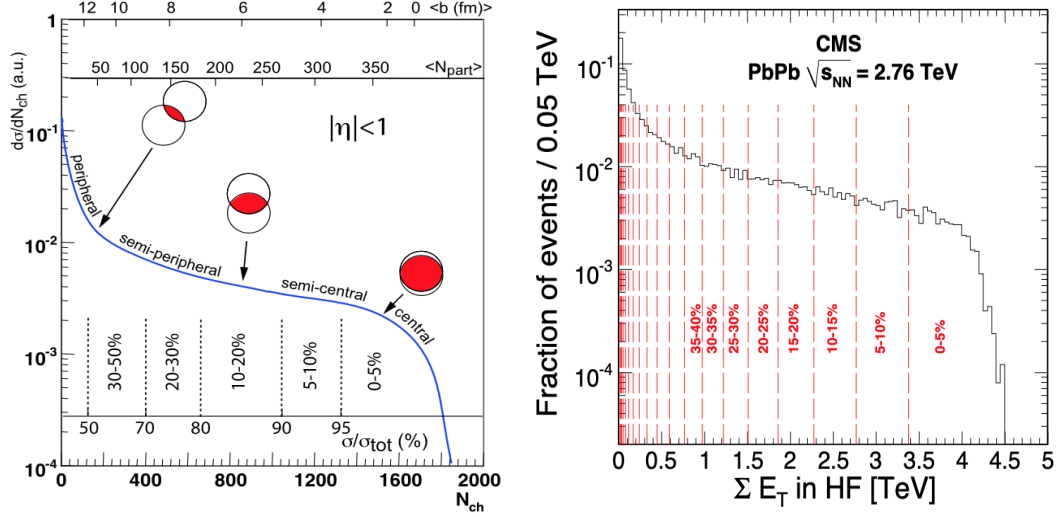


Figure 2.5: Left: mapping between N_{ch} , centrality, N_{part} , and b . Right: centrality determination in the CMS using the sum of E_T deposited in the HF calorimeter in $\sqrt{s_{NN}} = 2.76$ TeV [38]. The black solid line represents the data, and the dashed vertical red lines are centrality classes.

(time t and the direction of the incoming beams of particles z), shown in Fig. 2.6. The proper time is defined as $\tau = \sqrt{t^2 - z^2}$, situated on space-time hyperbolas of the diagram. Various stages [40] of the space-time evolution of a collision with QGP are discussed below and shown in the right part of Fig. 2.6.

- **Pre-equilibrium ($\tau \leq 1$ fm/c):** Interaction between participant nucleons of two heavy nuclei produces partons (quarks and gluons), which interact further. The results of hard scattering between the partons with high momentum transfer lead to the production of jets, heavy quarks, etc. Also, a large number of prompt photons are produced in this stage.
- **Thermal equilibrium ($\tau \approx 1$ fm/c):** Due to the interaction between the partons, the fireball approaches the local thermal equilibrium. This leads to the production of a hot and dense thermally equilibrated state of matter known as QGP, which acts as a strongly-coupled hydrodynamic system that behaves as an almost perfect fluid. At this stage, the mean free path among the interacting partons is smaller than the size of the fireball and can be described by the hydrodynamics [41]. The fireball eventually expands to the surrounding vacuum and cools down.
- **Hadronization ($\tau \approx 10$ fm/c):** The system cools down to its critical temperature T_c , and the quarks and gluons are confined inside hadrons. As a result, a mixed phase that contains both QGP and hadrons is produced. At RHIC and LHC energies, the transition from the QGP phase to the hadronic phase is a smooth crossover.

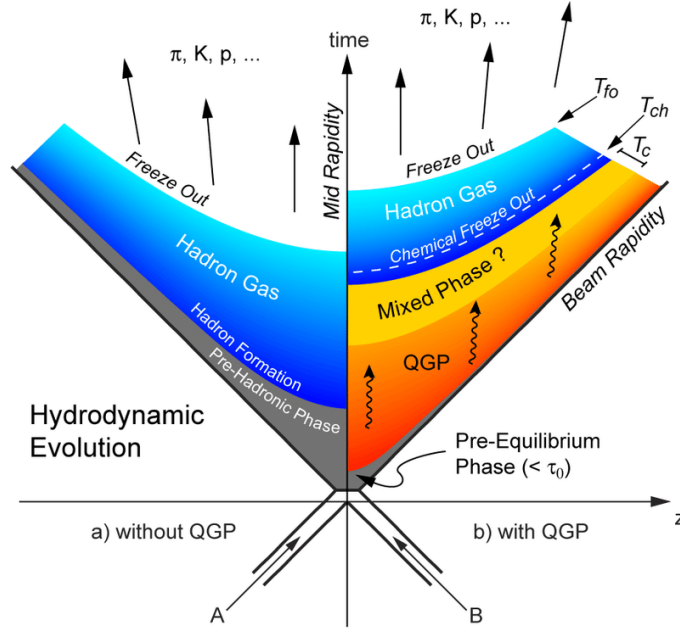


Figure 2.6: Space-time evolution of a heavy-ion collision with (right) and without (left) QGP. This figure is taken from <https://cds.cern.ch/record/2745520/>.

- **Chemical freeze-out** ($\tau \geq 10 \text{ fm/c}$): The produced hadrons then interact with each other, and due to this interaction, the system continues to expand and cool down until the Chemical freeze-out occurs. In this stage, all the inelastic processes stop (i.e., no new hadrons are produced), and the chemical composition of the system remains unchanged (i.e., the composition of hadrons).
- **Kinetic freeze-out** ($\tau \approx 20 \text{ fm/c}$): Hadrons can interact elastically until kinetic freeze-out because inelastic interaction ends at the chemical freeze-out stage. At this stage, the elastic interaction between the hadrons stops, and the particles freely travel in the vacuum. Finally, the produced particles are then detected by the detector.

Space-time evolution of a collision without QGP (e.g., proton-proton (pp) collision) is also shown in the left part of Fig. 2.6. Without QGP, the system goes through a pre-hadronic phase, hadron formation, and finally, freeze-out occurs.

2.4 SIGNATURES OF THE QGP

The QGP phase lasts in heavy-ion collisions for a very short period ($\leq 10 \text{ fm/c}$ or 10^{-23} s), after which hadronization occurs, and the final state particles are detected in

the detector. Therefore, it is impossible to directly observe the QGP in the laboratory. However, several signatures of QGP can be measured using the final state particles. The following subsections provide descriptions of a few of these signatures.

2.4.1 Direct photons

As discussed in the previous section, the deconfined state of quarks and gluons, called QGP, is expected to form when the energy density $\geq 1 \text{ GeV/fm}^3$ and the temperature $\approx 150\text{--}200 \text{ MeV}$. By measuring the direct photons, one can extract the temperature of the QGP phase. These photons are produced very early in the collisions and interact electromagnetically; therefore, they contain undistorted properties of the medium. In p-p collisions, where we do not expect QGP formation, the direct photons come from quark-gluon Compton scattering, quark-antiquark annihilation, and jet fragmentation. However, in the case of heavy-ion collisions (PbPb, AuAu, etc.), where we expect the formation of QGP, additional photons are formed due to the scattering of thermalized partons [42, 43]. As a result, the spectra measurement of direct photons contains information about the initial temperature of the thermalized medium (QGP) produced in heavy-ion collisions.

Figure 2.7 shows the ALICE results of direct photon spectra distribution as a function of transverse momentum p_T [44]. The black circle represents the PbPb data in 0–40% centrality and the blue line is the calculation for pp collisions. One can see an excess amount of photon production in PbPb collisions compared to pp at low p_T ($1 \leq p_T \leq 4 \text{ GeV}$), suggesting the existence of a thermalized medium. By fitting the spectra distribution using the exponential function $\sim e^{p_T/T}$, one can extract the temperature (T) of the thermalized system which emitted the photons. The red line in Fig. 2.7 represents the fit to the data using the above equation. ALICE extracted the temperature $T = 304 \pm 51 \text{ MeV}$, which is above the predicted value, which signifies the QGP formation. It should be noted that this temperature is an effective temperature, and its value can be significantly enhanced above the actual temperature due to other phenomena (e.g., radial flow [45]).

Therefore, this temperature alone is not sufficient evidence of the presence of QGP.

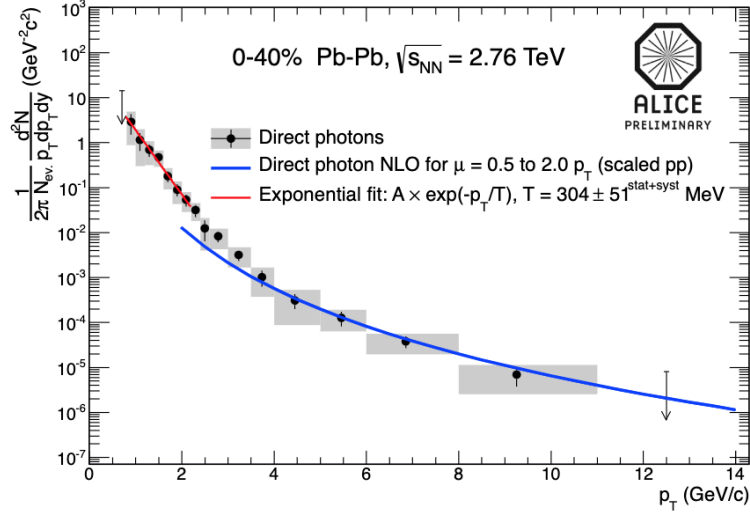


Figure 2.7: Spectra measurement of the direct photons [44]. The black circle represents the PbPb data in 0–40% centrality, the blue line is the calculation for pp collisions, and the red line represents the fit to the data.

2.4.2 Jet quenching

In high energy collisions, jets are produced by the fragmentation of hard scattered partons. Hard scattered partons are formed due to the hard scattering between quarks or gluons. The fragmentation process occurs in the vacuum in pp collisions as there is no medium. But in heavy-ion collisions, these partons travel through the thermalized hot and dense medium and lose their energy by interacting with that medium. Hard scattering between two quarks produces two quarks in the $2 \rightarrow 2$ QCD process. After that, they hadronized and produced a collimated spray of particles. Bjorken [46] in 1982 proposed that if two jets are produced back-to-back in heavy-ion collisions, there is a possibility that one jet will be quenched due to the interaction with the dense medium and the other will be measured with high energy. A sketch of the back-to-back dijet production in heavy-ion (right) and pp (left) collisions can be seen in Fig. 2.8.

Experimentally, this effect was first observed by STAR collaboration at RHIC by measuring the di-hadron azimuthal correlations as a function of $\Delta\phi$ in central AuAu

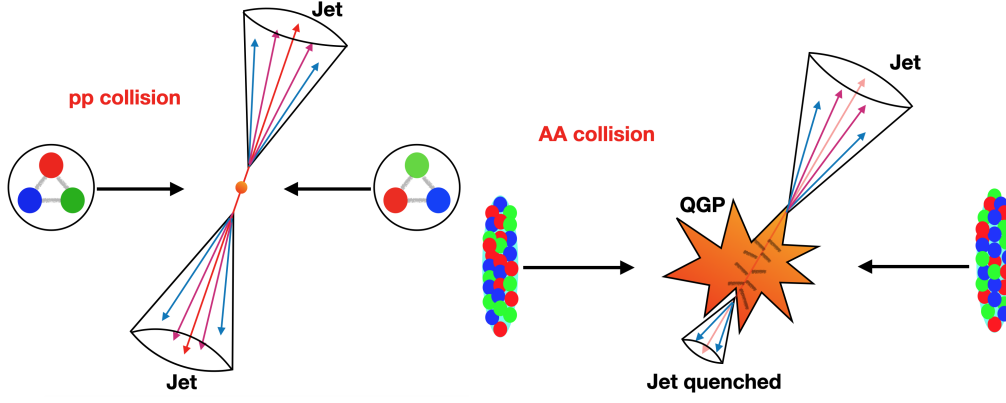


Figure 2.8: Schematic view of the back-to-back dijet production in heavy-ion (right) and pp (left) collision (right).

collisions at $\sqrt{s_{NN}} = 200$ GeV [47], where ϕ is the azimuthal angle of the hadron and $\Delta\phi$ is the difference of azimuthal angle of two hadrons, shown in Fig. 2.9. The AuAu results (blue star) are compared with pp (black line) and dAu (red circle) collisions results. In this plot, one can see two peaks around $\Delta\phi \approx 0$ and $\Delta\phi \approx \pi$ because of two back-to-back jets in pp and dAu collisions. But, in the case of the AuAu collision, the peak around $\Delta\phi \approx \pi$ disappeared because of the jet quenching effect. This result strongly supports the presence of QGP in heavy-ion collisions. Later, this jet quenching effect is also studied at the LHC [48, 49].

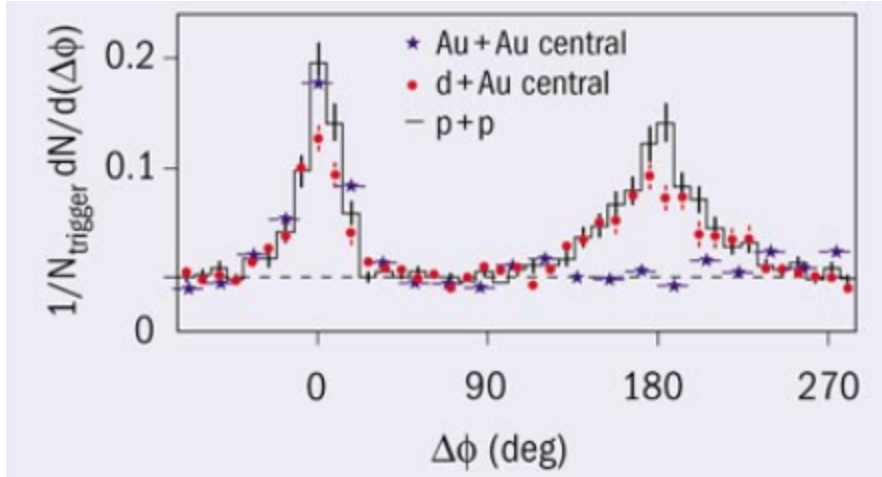


Figure 2.9: Di-hadron correlation as a function $\Delta\phi$ in central AuAu, dAu, and pp collisions. This figure is taken from <https://cerncourier.com/a/deuteron-gold-collisions-clarify-jet-quenching-results/>.

2.4.3 Quarkonium suppression

Quarkonium is a bound state of a heavy quark (charm (c) or bottom (b)) and its antiquark. These come in two flavors: charmonium, a bound state of $c\bar{c}$ (e.g., J/ψ), and bottomonium, a bound state of $b\bar{b}$ (e.g., $\Upsilon(1S)$). Matsui and Satz first proposed the suppression of quarkonium states in the QGP in 1986 [50]. The presence of color charge carriers (quarks and gluons) in the QGP causes color screening, which is analogous to Debye screening in electromagnetism. If the color screening length is smaller than the binding radius of quarkonium states, the quark-antiquark pairs of the quarkonium states will dilute in the QGP, i.e., the probability of the formation of quarkonium will be suppressed in the presence of QGP. The formation of quarkonium states also depends on the QGP temperature. If the QGP temperature is higher than the binding energy of the quarkonium states, the bound states of heavy quark-antiquark pairs dissociate; therefore, the formation of quarkonium is suppressed. The excited quarkonium states, $\psi(2S)$ is the excited state of J/ψ and $\Upsilon(2S)$ and $\Upsilon(3S)$ are excited states of $\Upsilon(1S)$, are further suppressed because they are loosely bound than their ground states. Thus, one should expect a sequential suppression in the quarkonium yield measured in heavy-ion collisions.

The experimental method involved to measure this suppression is called nuclear modification factor (R_{AA}) [51]. This is the measurement of the yield of the quarkonium states in AA collisions to that from pp collisions. The measured yield in the pp collisions needs to be scaled to match the number of colliding nucleons in the AA collisions. If $R_{AA} = 1$, then there is no suppression in the AA system compared to the pp system, i.e., there is no QGP. Fig. 2.10 shows the recent R_{AA} measurement of $\Upsilon(nS)$ states as a function of N_{part} (left panel) and p_T (right panel) in the CMS experiment at $\sqrt{s_{NN}} = 5.02$ TeV. One can clearly see that the R_{AA} values are below 1 in all the p_T bins and after $N_{part} \geq 50$. The comparison between all the bottomonium states ($\Upsilon(1S)$ (red), $\Upsilon(2S)$ (blue), and $\Upsilon(3S)$ (green)) shows the clear sequential suppression in PbPb collisions.

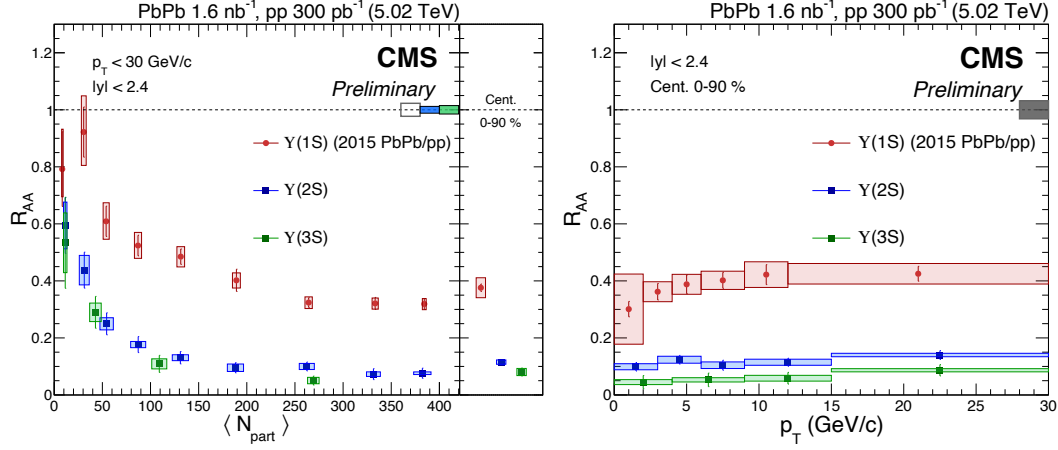


Figure 2.10: R_{AA} measurement for $Y(nS)$ states as a function of N_{part} (left panel) and p_T (right panel) [51]. The vertical lines and boxes are statistical and systematic uncertainties, respectively.

2.4.4 Strangeness enhancement

Generally, the s quarks are produced in the hard collision as the colliding nuclei consist of only u and d quarks. Therefore, in comparison to u and d quarks, the s quarks production is suppressed because of its heavy mass. In the QGP medium, s quarks are produced by the lowest order QCD processes: gluon fusion ($gg \rightarrow s\bar{s}$) and quark-antiquark annihilation ($q\bar{q} \rightarrow s\bar{s}$). Because of the gluon-rich medium (QGP), the gluon fusion process dominates over the quark-antiquark annihilation, and a large number of $s\bar{s}$ pairs are produced. As a result, final-state strange hadron production increases. Therefore, strangeness enhancement is believed to be a strong signal of the QGP formation.

Figure 2.11 shows the strange hadron (Ω^- , Ξ^- , and Λ) yield in PbPb collisions relative to those from pp collisions measured by ALICE at $\sqrt{s_{NN}} = 2.76$ TeV [52]. A clear enhancement is seen for all the strange hadrons, which increases with N_{part} . Also, the enhancement increases with the constituent strange quarks, i.e., $\Omega^- (sss) > \Xi^- (dss) > \Lambda (uds)$.

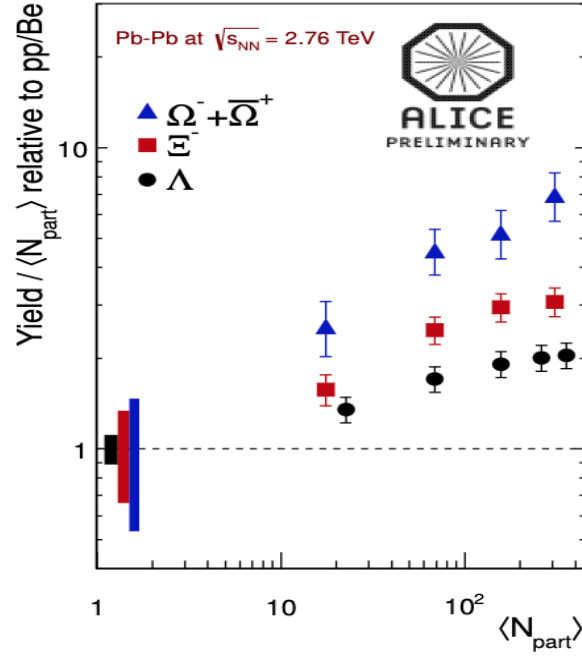


Figure 2.11: Yield of Ω^- (blue triangle), Ξ^- (red square), and Λ (black circle) in PbPb collisions relative to those from pp collisions measured by ALICE at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [52].

2.4.5 Anisotropic flow

Anisotropic flow (collective flow) measurement is one of the most substantial evidence of QGP formation. The initial overlapping region of colliding nuclei in a non-central heavy-ion collision (shown in the left panel of Fig. 2.12) bears the shape of an almond and is spatially anisotropic. Thus, the initial state of the system exhibits spatial anisotropy in the azimuthal plane. Due to frequent interaction between the initial state particles with adequate strength, the system approaches local thermal equilibrium. Once it reaches the equilibrium, one can explain the system using thermodynamic quantities, such as pressure, temperature, etc. The initial spatial anisotropy of the almond-shaped overlap zone generates the anisotropic pressure gradient in the transverse plane, which is more in the x-direction than the y-direction. The anisotropic pressure gradient causes the system expansion and production of the particles more in the x-direction, which leads to the anisotropy in the final state particles distribution in momentum space. This azimuthal

anisotropy can be expanded by using a Fourier expansion as [53]

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \psi_{\text{RP}})] , \quad (2.4)$$

where ϕ is the azimuthal angle of the particles, ψ_{RP} is the reaction plane angle, and v_n are the Fourier coefficients of n^{th} harmonics. The Fourier coefficients are called anisotropy flow coefficients, where v_1 is directed flow, v_2 is the elliptic flow, v_3 is the triangular flow, etc. The higher order flow coefficients ($v_3, v_4, \dots$) come from the fluctuations in the initial state positions of the partons in the colliding nuclei.

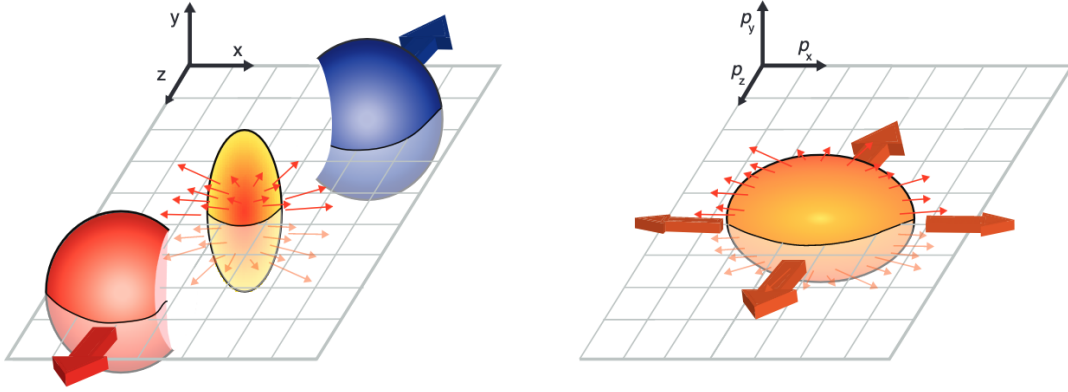


Figure 2.12: Left: schematic view of two colliding nuclei and the almond shape overlapping region (spatial anisotropy). Right: momentum anisotropy. These figures are taken from <https://cds.cern.ch/record/2826205>.

If there is no anisotropy in the final state particle distributions, then $v_n = 0$. To generate non-zero flow coefficients, two ingredients must be needed, which are: initial state spatial anisotropy and sufficient interaction. There won't be any flow if one or both of the components are missing. Thus, v_n is the measure of the degree of thermalization of the hot and dense matter⁷ produced in the heavy-ion collisions.

Figure. 2.13 shows the different order flow coefficients (v_2-v_5) of charged hadron as a function N_{part} in three different p_T range measured by the CMS experiment in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [54]. The magnitude of the flow coefficients increases

⁷Remeber, QGP is a hot and dense thermally equilibrated state of matter.

with the decrease in harmonic order, and larger values are obtained for v_2 than the other coefficients because of the initial elliptic geometry. The v_2 values (black circle) are smaller in the very large and very small N_{part} . This is because at very large N_{part} (i.e., central collisions), there will be less anisotropy, and at very small N_{part} (i.e., peripheral collisions), although the anisotropy is present, adequate interaction is missing. Also, the values of flow coefficients decrease with increasing the p_T range.

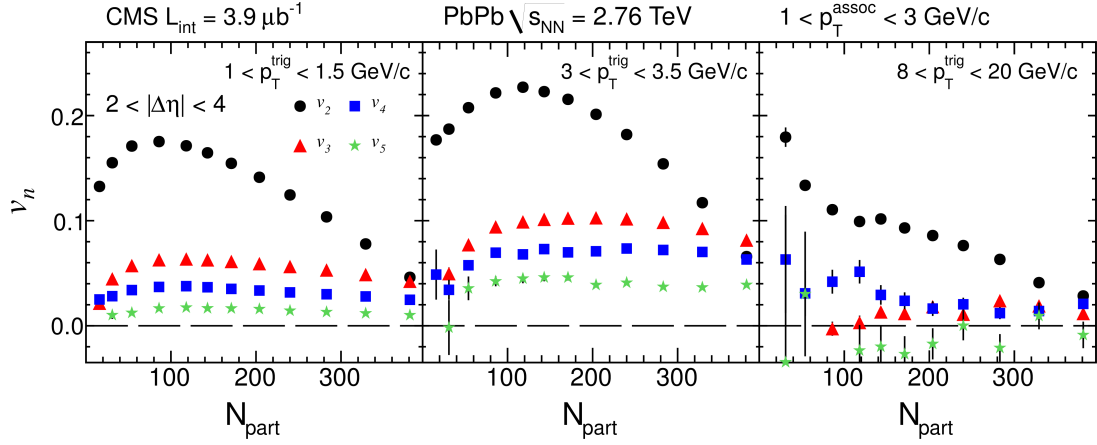


Figure 2.13: Different order flow coefficients of charged hadron as a function N_{part} measured by the CMS experiment in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [54]. The black circle represents the v_2 , the red triangle represents the v_3 , the blue square represents the v_4 , and the green star represents the v_5 .

Figure 2.14 shows the elliptic flow coefficient (v_2) as a function p_T for different particles measured by the ALICE experiments for 10-20% centrality in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [55]. A clear mass ordering can be seen at low p_T ($p_T \lesssim 2$ GeV) with low mass particles having larger v_2 value, and this behaviour is reproduced by the hydrodynamic model [55]. The discovery of this hydrodynamic flow exhibits the properties of the QGP as an almost perfect fluid.

Traditionally, the anisotropic flow is believed to be present only in heavy-ion collisions because, as stated above, to generate non-zero flow coefficients, two ingredients must be needed: initial state spatial anisotropy and sufficient interaction. In small systems (e.g., pp and pPb), it is believed that these ingredients are not present. Therefore, there is no

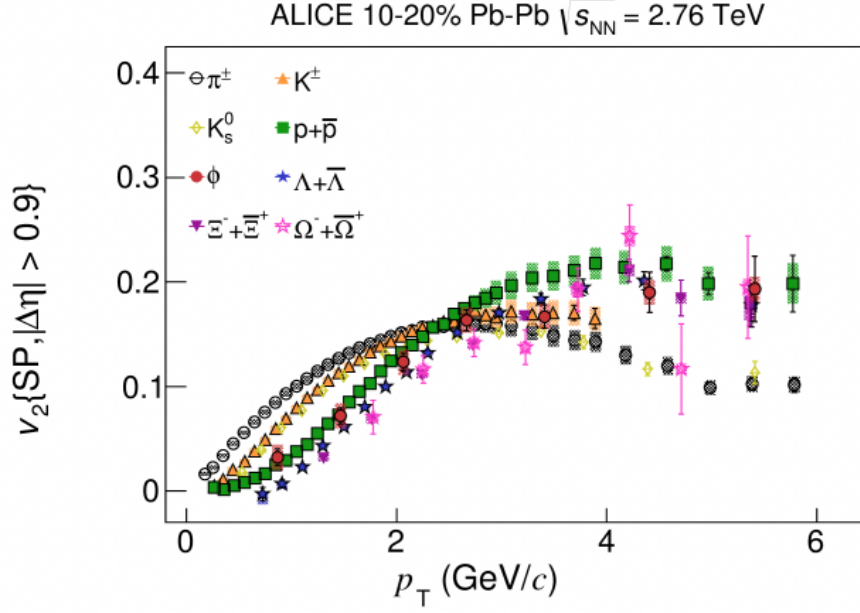


Figure 2.14: Elliptic flow coefficient (v_2) as a function p_T for different particles measured by the ALICE experiments for 10-20% centrality in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [55]. Different color markers represent different particle species.

anisotropic flow in the small colliding systems, which suggests that the probability of forming a thermalized medium is zero in the small systems. Surprisingly, in 2010, the CMS collaboration observed the long-range near-side ridge structure in high multiplicity pp collisions at $\sqrt{s} = 7$ TeV in the two-particle correlation measurement [56]. This ridge structure is directly related to the anisotropic flow coefficients. The observation of long-range near-side ridge structure and non-zero v_2 (shown in Fig. 2.15) values by the CMS collaboration in pp and pPb collisions [57] triggered the heavy-ion community to investigate the reasons of such interesting behaviour in small systems and understand the dynamics of particle production mechanism in small systems.

Recently, The CMS collaboration measured the elliptic flow harmonic, v_2 , using scalar-product ($v_2\{SP\}$) and multiparticle Q-cumulant ($v_2\{2k\}$, $k=1,\dots,4$) methods [59, 60] of identified strange hadrons (K_S^0 and Λ ($\bar{\Lambda}$) in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [18]. Figure 2.16 shows the v_2 values measured in pPb collisions for different multiplicities, and Fig. 2.17 shows the v_2 values measured in

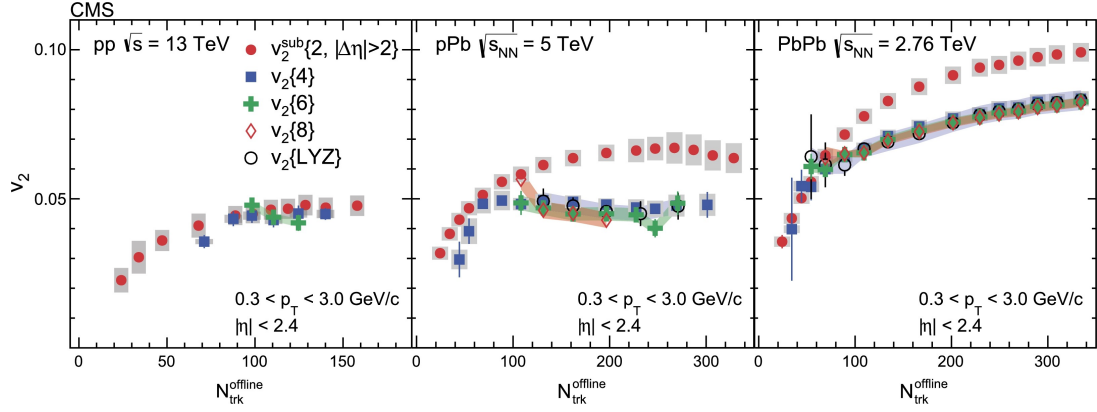


Figure 2.15: v_2 values measured in pp at $\sqrt{s} = 7$ TeV (left panel), pPb at $\sqrt{s_{NN}} = 5$ TeV (middle) panel, and PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (right panel) collisions [57] using two-particle correlation $v_2^{\text{sub}}\{2\}$ [58], multiparticle Q-cumulant ($v_2\{2k\}$, $k=1,\dots,4$) [59], and LYZ [57] methods. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

PbPb collisions for different centralities. The predictions of the event-by-event viscous hydrodynamic model with AMPT initial conditions [61] for PbPb collisions are compared with data, and a qualitative consistency has been found. In pPb collisions, the $v_2\{\text{SP}\}$ was measured separately with respect to the Pb-going and p-going side of the event planes. The results show that the v_2 with the p-going side event plane is systematically larger than the Pb-going side event plane v_2 , at higher transverse momenta (p_T), which suggests that the nonflow contribution has a larger effect on the higher p_T . The results $v_2\{4\} \approx v_2\{6\}$ in Fig. 2.16 for pPb collisions with $185 \leq N_{\text{trk}}^{\text{offline}} \leq 250$ support the interpretation of a collective nature in high-multiplicity pPb collisions as in PbPb collisions. Such collective behaviour could indicate the formation of the QGP in small systems.

2.4.6 Femtoscopy

Femtoscopy is an experimental technique used to study the space-time dimension of particle emitting “sources” created in ultra-relativistic particle collisions. Studying the source regions through femtoscopy provides valuable insights into the dynamics and evolution of the system produced in the collisions. This is the main topic of this thesis. Details theory of femtoscopy, as well as the experimental technique and results, are

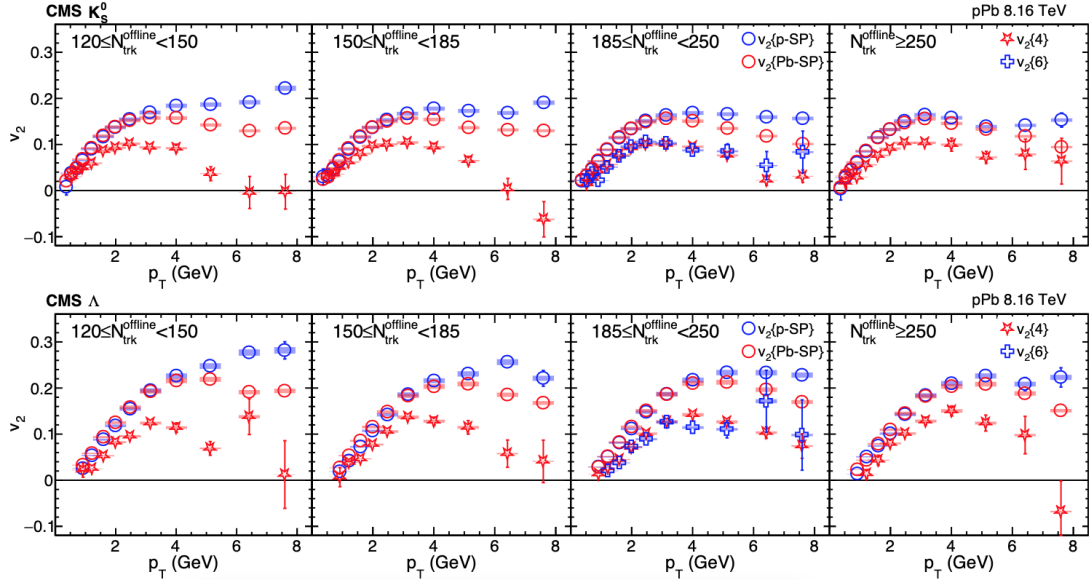


Figure 2.16: Scalar-product and multiparticle cumulant v_2 results in PPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV for K_S^0 (top panel) and Λ (bottom panel) in different multiplicity intervals [18]. The scalar-product results $v_2\{\text{SP}\}$ are based on Q-vectors that are determined in either the p-going (p-SP) or Pb-going (Pb-SP) side. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

briefly described in chapters 3, 5, and 6, respectively.

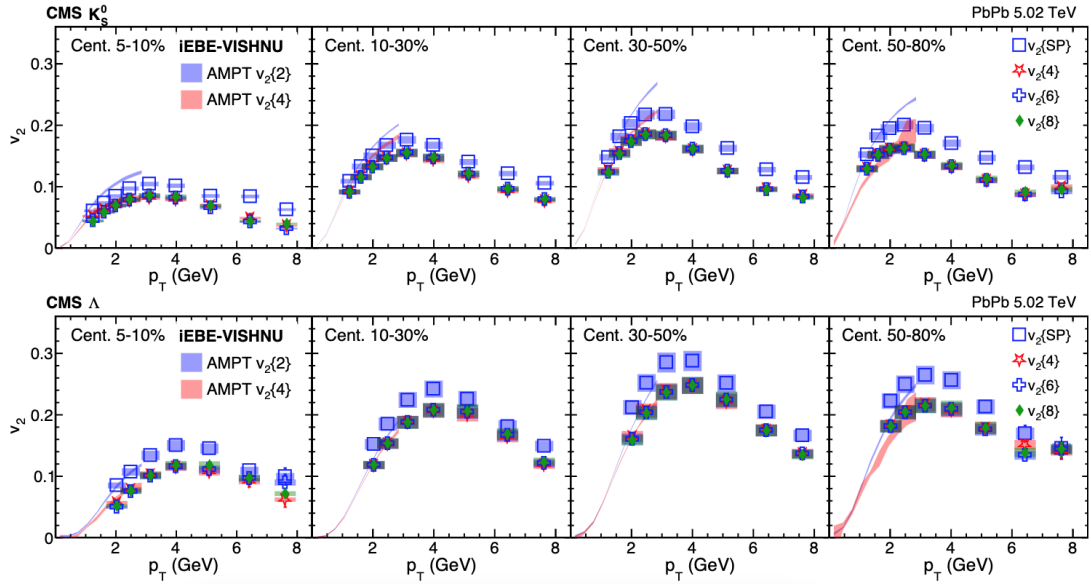


Figure 2.17: Scalar-product and multiparticle cumulant v_2 results in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for K_S^0 (top panel) and Λ (bottom panel) in different centrality intervals [18]. The shaded bands are hydrodynamic calculations of v_2 (blue) and v_4 (rubber radish) values with AMPT initial conditions. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

CHAPTER 3

FEMTOSCOPY

Femtoscopia is an interferometric technique that uses the final state particle correlation to study the spatio-temporal characteristics of the particle emitting “sources” created in ultra-relativistic particle collisions. Two-particle correlations in relative momentum, called femtoscopic correlations, arising from relativistic heavy-ion collisions provide a powerful tool for studying the properties of the quark-gluon plasma (QGP) created in the collisions and the subsequent interactions of the emitted particles [1]. This method allows us to measure the size, shape, and lifetime of the particle emitting sources created in the heavy-ion collisions at kinetic freeze-out. Studying these source regions enables us to investigate the system’s dynamics as it evolves from the hot and dense state of matter known as QGP. These characteristics are sensitive to various factors related to the presence of the QGP, such as collective flow and lifetime of the system. All two-particle correlations involving hadrons are affected by final-state interaction (FSI) effects, and correlations of identical particles are also sensitive to the constraints of quantum statistics (QS). Using the femtoscopic correlation distributions, one can extract the strong interaction scattering parameters, such as complex scattering length and effective range, that are impossible to obtain from currently achievable scattering experiments [2–6].

This chapter describes the origin of femtoscopia and the mathematical derivation of the femtoscopic correlation in the presence of QS and strong FSI.

3.1 ORIGIN OF FEMTOSCOPY

Femtoscopia, popularly known as HBT interferometry, started with the work of Hanbury Brown and Twiss, who developed the theory and built the experiment to measure the

angular size of stars and other astronomical objects using two photons correlation [62, 63]. In 1956, they performed an experiment to measure the angular size of the star Sirius using intensity interferometry [64]. In that experiment, they measured the correlation coefficient $\Gamma^2(d)$ (probability of detecting two photons simultaneously) as a function of baseline d (distance between the two detectors, shown in Fig. 3.1) and fitted by a function

$$\Gamma^2(d) = \left[\frac{2J_1(\pi\theta_{ij}\lambda/d)}{\pi\theta_{ij}\lambda/d} \right]^2, \quad (3.1)$$

where θ_{ij} is the angular size of the star Sirius, λ is the wavelength of the photon emitted from the star, and J_1 is the Bessel function. A schematic diagram of HBT interferometry used to measure the angular size of the star Sirius can be seen in Fig. 3.1.

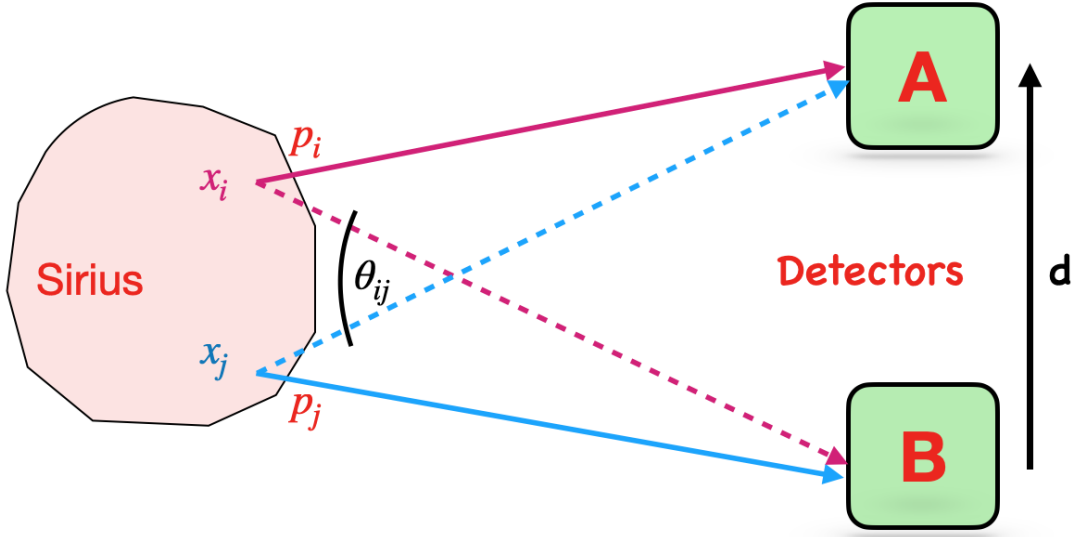


Figure 3.1: Schematic diagram of HBT interferometry used to measure the angular size of the star Sirius. Two photons with wave vector p_i and p_j are emitted from the positions x_i and x_j of the star Sirius with angular separation θ_{ij} and detected by two detectors (A and B) situated on earth and separated by a distance d .

In the field of particle physics, the femtoscopic correlation between identical pions was first observed in 1960 by Goldhaber et al. [65]. At that time, authors were not aware of the work by Hanbury Brown and Twiss. They performed an experiment in 1959 at the Bevalac, LBNL¹, aiming to look for the ρ^0 meson from opposite-charged pions in $p\bar{p}$

¹Lawrence Berkeley National Laboratory, USA

collisions at $\sqrt{s} = 2.1$ GeV. In that experiment, they found that the angular distribution of like sign pions differs from the unlike sign pions. In 1960, they reproduced the angular distributions by considering the symmetrized wave function in the statistical model and concluded that Bose-Einstein statistics for like sign pions influenced the effect. Then they measured the correlation between them and found that like sign pion pairs show enhancement compared to unlike sign pairs. Then they fitted the like sign correlation distribution with the Gaussian $1 + e^{-(|p_1 - p_2|)^2 \rho^2}$, where p_1 and p_2 are the four momentum of pions, and ρ refer to the radius of the interaction volume of $p\bar{p}$ collisions. Thus, this experiment shows that the size of the particle emitting source region can be determined by measuring the correlation as a function of relative momentum ($|p_1 - p_2|$).

In the 1970s and 1980s, the theoretical method was refined and developed in order to study such correlation [1, 17, 66–68]. Now, one can study multi-dimensional analysis, the effect of strong and Coulomb final state interaction, multiparticle femtoscopic correlation, etc. Nowadays, femtoscopic correlation is vastly used in high-energy physics experiments to study the particle emitting source region and explore the final state interaction between them using the different types of particles in different collision systems. The theoretical description of the two-particle femtoscopic correlation is discussed briefly in the next section.

3.2 FEMTOSCOPIC CORRELATION FUNCTION

The general theoretical description of the two-particle femtoscopic correlation is the ratio between the joint probability of detecting two particles, $\mathcal{P}_2(p_1^\mu, p_2^\mu)$, and the probability of detecting individual particles, $\mathcal{P}_1(p_i^\mu)$, and, can be written as [67, 69]

$$C(p_1^\mu, p_2^\mu) = \frac{\mathcal{P}_2(p_1^\mu, p_2^\mu)}{\mathcal{P}_1(p_1^\mu)\mathcal{P}_1(p_2^\mu)}, \quad (3.2)$$

where p_1^μ and p_2^μ are the four momenta of the two particles. From now on, we will not use four-vector indices ($\mu, \nu, \dots$) to simplify the notation.

This correlation function is affected by quantum statistical effect (QS) and final-state interaction (FSI), which are briefly described below.

3.3 QUANTUM STATISTICS (QS)

The quantum statistical effect (Bose-Einstein or Fermi-Dirac) is presents in the correlation of identical particles and can be described by their wave function symmetrization (Bose-Einstein) or antisymmetrization (Fermi-Dirac). We can understand these phenomena by considering a simple diagram shown in Fig. 3.2. Consider a static source from which two identical particles (bosons or fermions) are emitted from positions x_1 and x_2 , respectively, and are detected by detectors A and B. As the detected particles are indistinguishable, two scenarios are possible, as shown in Fig. 3.2. In the first scenario (solid lines), a particle emitted from position x_1 was detected in detector A with momentum p_1 , and another particle emitted from position x_2 was detected in detector B with momentum p_2 . In the second scenario (dotted lines), the particle coming out from x_1 was detected in detector B with momentum p_2 , and the particle coming out from x_2 was detected in detector A with momentum p_1 . Neglecting FSI, the probability amplitude for these two cases can be written using plane waves. The amplitude for the first case where two detector at x_A and x_B simultaneously detect two particles with momenta k_1 and k_2 can be written as [67, 69]

$$A_2^I(p_1, p_2) = e^{-ip_1 \cdot (x_A - x_1)} e^{i\phi_1} e^{-ip_2 \cdot (x_B - x_2)} e^{i\phi_2}, \quad (3.3)$$

where ϕ_i is the random phase associated with each independent emission.

For the second case, the amplitude can be written as [67, 69]

$$A_2^{II}(p_1, p_2) = e^{-ip_1 \cdot (x_A - x_2)} e^{i\phi_2} e^{-ip_2 \cdot (x_B - x_1)} e^{i\phi_1}. \quad (3.4)$$

Now, the total amplitude for the process that two detectors at x_A and x_B simultaneously

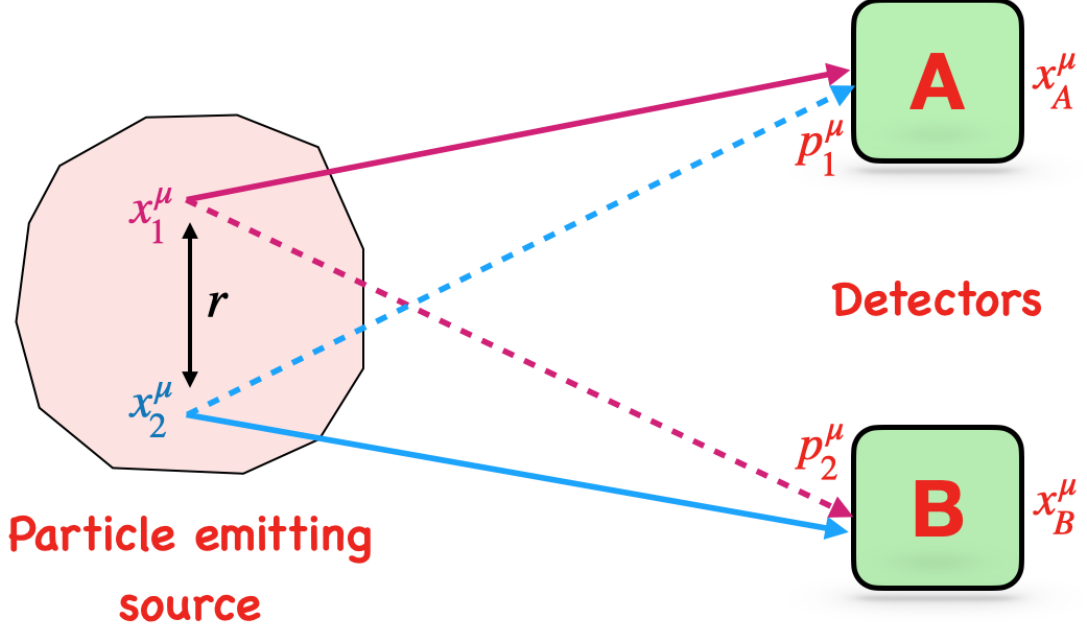


Figure 3.2: Simplified schematic diagram of a particle emitting source which emits particles that are detected by detectors A and B. Details are described in the text.

detect two particles with momenta k_1 and k_2 can be written as

$$A_2(p_1, p_2) = \frac{1}{\sqrt{2}} [A_2^I(p_1, p_2) \pm A_2^{II}(p_1, p_2)], \quad (3.5)$$

where the “+” sign corresponds to wave function symmetrization due to the two-boson exchange and the “-” sign corresponds to wave function antisymmetrization due to the two-fermion exchange.

Now, the joint probability of detecting two identical particles, $\mathcal{P}_2(p_1, p_2)$, will be

$$\begin{aligned} \mathcal{P}_2(p_1, p_2) &= \langle |A_2(p_1, p_2)|^2 \rangle \\ &= \frac{1}{2} \left[2 \pm \left(e^{i(p_1 - p_2) \cdot (x_1 - x_2)} \langle e^{i(\phi_1 + \phi_2 - \phi_1 - \phi_2)} \rangle \right. \right. \\ &\quad \left. \left. + e^{-i(p_1 - p_2) \cdot (x_1 - x_2)} \langle e^{-i(\phi_1 + \phi_2 - \phi_1 - \phi_2)} \rangle \right) \right] \\ &= 1 \pm \cos [(p_1 - p_2) \cdot (x_1 - x_2)]. \end{aligned} \quad (3.6)$$

The amplitude for the process that the detector x_A detects the particle from either of the

point sources with momentum p_i is

$$A_1(p_i) = \frac{1}{\sqrt{2}} \left[e^{-ip_i \cdot (x_A - x_1)} e^{i\phi_1} \pm e^{-ip_i \cdot (x_A - x_2)} e^{i\phi_2} \right]. \quad (3.7)$$

Then, the probability of detecting one particle with momentum p_i , $\mathcal{P}_1(p_i)$, will be

$$\begin{aligned} \mathcal{P}_1(p_i) &= \langle |A_1(p_i)|^2 \rangle \\ &= \frac{1}{2} \left[2 \pm (e^{ip_i \cdot (x_1 - x_2)} \langle e^{i(\phi_1 - \phi_2)} \rangle + e^{-ip_i \cdot (x_1 - x_2)} \langle e^{-i(\phi_1 - \phi_2)} \rangle) \right]. \end{aligned} \quad (3.8)$$

As we considered the incoherent or chaotic sources, i.e., the random phase associated with each independent emission, $\langle e^{\pm i(\phi_1 - \phi_2)} \rangle = 0$ and we obtain

$$\mathcal{P}_1(p_i) = 1. \quad (3.9)$$

In presence of only the QS effect, the correlation function can be obtained using Eq. (3.6) and (3.9) as

$$\begin{aligned} C(p_1, p_2) &= \frac{\mathcal{P}_2(p_1, p_2)}{\mathcal{P}_1(p_1)\mathcal{P}_1(p_2)} \\ &= 1 \pm \cos(q \cdot r), \end{aligned} \quad (3.10)$$

where $q = p_1 - p_2$ and $r = x_1 - x_2$ are the relative momentum and separation, respectively. The correlation function depends on the relative momentum of the two particles and the relative separation of two point sources.

In a more realistic case, e.g., in heavy-ion collisions, the particle emitting sources are not static. It evolves with space-time. Also, the particles can be emitted from any other position of the source. Therefore, assuming particles are emitted independently, $\mathcal{P}_2(p_1, p_2)$ can be written as [1]

$$\begin{aligned} \mathcal{P}_2(p_1, p_2) &= \int S(x_1, p_1) S(x_2, p_2) [1 \pm \cos(q \cdot r)] d^4x_1 d^4x_2 \\ &= \mathcal{P}_1(p_1)\mathcal{P}_1(p_2) \pm \int S(x_1, p_1) S(x_2, p_2) \cos(q \cdot r) d^4x_1 d^4x_2, \end{aligned} \quad (3.11)$$

where $S(x_i, p_i)$ is the source function, also called the single-particle Wigner function,

which gives the probability of emitting a particle with momentum p_i from position x_i and

$$\mathcal{P}_1(p_i) = \int S(x_i, p_i) d^4x_i. \quad (3.12)$$

Using Eq. (3.11) and (3.12), the correlation function $C(p_1, p_2)$ can be written as

$$C_2(p_1, p_2) = 1 \pm \frac{\int S(x_1, p_1) S(x_2, p_2) \cos(q \cdot r) d^4x_1 d^4x_2}{\int S(x_1, p_1) d^4x_1 \int S(x_2, p_2) d^4x_2}. \quad (3.13)$$

It is convenient to express $S(x_i, p_i)$ and $C(p_1, p_2)$ in terms of the average pair momentum $K = (p_1 + p_2)/2$ and the relative momentum $q = p_1 - p_2$. Using the relations $p_1 = K + q/2$ and $p_2 = K - q/2$, we can write the Eq. (3.13) as

$$C_2(q, K) = 1 \pm \frac{\int S(x_1, K + q/2) S(x_2, K - q/2) \cos(q \cdot r) d^4x_1 d^4x_2}{\int S(x_1, K + q/2) d^4x_1 \int S(x_2, K - q/2) d^4x_2}. \quad (3.14)$$

As our interest at the low q region (i.e., $p_1 \approx p_2$), we can make the smoothness approximation by assuming that the source function has a weak dependence on q [68, 70]. Therefore, $S(x_i, K \pm q/2) \approx S(x_i, K)$. Using this approximation, we can write the Eq. (3.14) as

$$\begin{aligned} C_2(q, K) &\approx 1 \pm \frac{\int S(x_1, K) S(x_2, K) \cos(q \cdot r) d^4x_1 d^4x_2}{\int S(x_1, K) d^4x_1 \int S(x_2, K) d^4x_2}, \\ &= 1 \pm \frac{\int S(x_1, K) S(x_2, K) \left[\frac{1}{2} e^{iq \cdot x_1} e^{-iq \cdot x_2} + \frac{1}{2} e^{-iq \cdot x_1} e^{iq \cdot x_2} \right] d^4x_1 d^4x_2}{\int S(x_1, K) d^4x_1 \int S(x_2, K) d^4x_2}, \\ &= 1 \pm \left[\frac{1}{2} \frac{\int S(x_1, K) e^{iq \cdot x_1} d^4x_1 \int S(x_2, K) e^{-iq \cdot x_2} d^4x_2}{\int S(x_1, K) d^4x_1 \int S(x_2, K) d^4x_2} \right. \\ &\quad \left. + \frac{1}{2} \frac{\int S(x_1, K) e^{-iq \cdot x_1} d^4x_1 \int S(x_2, K) e^{iq \cdot x_2} d^4x_2}{\int S(x_1, K) d^4x_1 \int S(x_2, K) d^4x_2} \right] \\ &= 1 \pm \left| \frac{\int S(x, K) e^{iq \cdot x} d^4x}{\int S(x, K) d^4x} \right|^2. \end{aligned} \quad (3.15)$$

The above equation shows that the correlation function is related to the source function by a Fourier transformation, and one can easily evaluate the Eq. (3.12) by reconstructing the source function $S(x, p)$ from the measured correlation function using inverse Fourier transformation. Generally, the source function $S(x, p)$ must be evaluated on-shell, i.e., $p^0 = E_{\vec{p}} = \sqrt{m^2 + \vec{p}^2}$. As the measured particles in the detector are

on-shell, the momentum combination q and K are off-shell, $K^0 \neq E_{\vec{K}}$ (i.e., $E_1 + E_2 \neq \sqrt{(m_1 + m_2)^2 + \vec{K}^2}$), and they satisfy the orthogonality relation²

$$q \cdot K = 0. \quad (3.16)$$

Therefore, the source function $S(x, K)$ present in the Eq. (3.15) cannot be evaluated on-shell, which means we need to know its off-shell behaviour. However, the interesting part of the correlation function is at low q . Expanding K^0 at low q one can find $K^0 \approx E_{\vec{K}}$, and this is on-shell approximation [66]. Using this approximation, we can evaluate the source function $S(x, K)$ on-shell.

Using the Eq. (3.16), we can calculate

$$q^0 = \frac{\vec{q} \cdot \vec{K}}{K^0} = \vec{q} \cdot \vec{\beta}, \quad \vec{\beta} = \frac{\vec{K}}{K^0} \approx \frac{\vec{K}}{E_{\vec{K}}}. \quad (3.17)$$

From Eq. (3.17), we can see that q^0 is not an independent variable, it is dependent on $\vec{q}$ and the velocity $\vec{\beta}$ of the pair. With only three independent q -components, we cannot reconstruct four-dimensional $S(x, K)$ using inverse Fourier transformation of Eq. (3.15). Inserting Eq. (3.17) into Eq. (3.15)

$$\begin{aligned} C_2(\vec{q}, \vec{K}) &\approx 1 \pm \left| \frac{\int S(x, K) e^{i\vec{q} \cdot (\vec{x} - \vec{\beta}t)} d^4x}{\int S(x, K) d^4x} \right|^2 \\ &= 1 \pm \frac{\int S(x_1, K) S(x_2, K) \cos[\vec{q} \cdot (\vec{x}_1 - \vec{x}_2 - \vec{\beta}(t_1 - t_2))] d^4x_1 d^4x_2}{\int S(x_1, K) d^4x_1 \int S(x_2, K) d^4x_2}. \end{aligned} \quad (3.18)$$

The above equation shows that both spatial and temporal information are present in the source function. If we rewrite the Eq. (3.18) in the pair rest frame (PRF), we can separate

²The orthogonality relation also holds for non-identical particles with different mass by defining $q = (p_1 - p_2) - \frac{(p_1 - p_2) \cdot K}{K^2} K = (p_1 - p_2) - \frac{m_1^2 - m_2^2}{K^2} K$ [71]. Note that for two particles with the same mass ($m_1 = m_2$), the second term of q is zero, and $q = p_1 - p_2$.

the spatial and temporal characteristics of the source function. In the PRF,

$$\begin{aligned}
\vec{K} &= 0 \\
\Rightarrow \vec{\beta} &= 0 \\
\Rightarrow q^0 &= 0.
\end{aligned} \tag{3.19}$$

Using Eq. (3.19) and (3.18), we can write the correlation function in a convenient way using PRF as [68, 72]

$$C_2(\vec{q}, \vec{K}) = \int S_{\vec{K}}(\vec{r}) [1 \pm \cos(\vec{q} \cdot \vec{r})] d^3\vec{r}, \tag{3.20}$$

where

$$S_{\vec{K}}(\vec{r}) = \frac{\int S(x_1, p_1) S(x_2, p_2) \delta(\vec{r} - \vec{x}_1 + \vec{x}_2) d^4x_1 d^4x_2}{\int S(x_1, p_1) d^4x_1 \int S(x_2, p_2) d^4x_2}. \tag{3.21}$$

Here $S_{\vec{K}}(\vec{r})$ is the time integrated pair source distribution and normalized to unity ($\int S_{\vec{K}}(\vec{r}) d^3\vec{r} = 1$) and $S_{\vec{K}}(\vec{r})$ gives the emission probability density for two particles of pair momentum $\vec{K}$ at relative distance $\vec{r}$ in the PRF. We can gain information about the particles emitting source region using Eq. (3.21). Since Eq. (3.21) depends on $\vec{K}$, we can probe the region of the particle emitting source for a specific pair momentum $\vec{K}$ and not the entire source. This region is called the “region of homogeneity”. In this thesis, we do not study the $\vec{K}$ dependence correlation due to limited statistics, and it is common to assume the source function is independent of $\vec{K}$.

One can find the bracketed term $[1 \pm \cos(\vec{q} \cdot \vec{r})]$ in Eq. (3.20) as $|\Psi(\vec{q} \cdot \vec{r})|^2$ using the equal time approximation in the PRF, which assumes that both particles are emitted at the same time [1]. Here $\Psi(\vec{q} \cdot \vec{r})$ is the two-particle (anti)symmetrized wave function

(without FSI), given by

$$\begin{aligned}
\Psi(\vec{q}, \vec{r}) &= \frac{1}{\sqrt{2}} [\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) \pm \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)] \\
&= \frac{1}{\sqrt{2}} \left[e^{-i\vec{p}_1 \cdot \vec{x}_1} e^{-i\vec{p}_2 \cdot \vec{x}_2} \pm e^{-i\vec{p}_1 \cdot \vec{x}_2} e^{-i\vec{p}_2 \cdot \vec{x}_1} \right] \\
&= \frac{1}{\sqrt{2}} e^{i\vec{K} \cdot (\vec{x}_1 + \vec{x}_2)} \left(e^{i\frac{\vec{q}}{2} \cdot \vec{r}} \pm e^{-i\frac{\vec{q}}{2} \cdot \vec{r}} \right).
\end{aligned} \tag{3.22}$$

With this, we obtain

$$C_2(\vec{q}) = \int S(\vec{r}) |\Psi(\vec{q} \cdot \vec{r})|^2 d^3\vec{r}. \tag{3.23}$$

This equation is called *Koonin-Pratt equation* [73, 74]. This is the general formalism where the correlation function is described by the source function and two-particle wave function. To explain the experimentally measured correlation and extract the information about the source, we need to insert the source function into the theoretical correlation function (Eq. (3.23)) and calculate the integral together with the two-particle wave function. The parametrization of the source function is described in the next section.

3.3.1 Source function

As discussed in sec. 3.3, the general formalism of correlation depends on the source function. One of the simplest approaches is to assume that the source is described by a spherically symmetric function in the PRF, such as a Gaussian. As a result, the source function can be expressed by a single, invariant, one-dimensional parameter R_{inv} , often called the “homogeneity length” or the source size at freeze-out. However, in most heavy-ion collisions, the source may not be spherically symmetric since the interaction zone between two ions resembles a pancake or an almond in shape. Furthermore, the best approximation might not necessarily be a Gaussian. Sometimes a Cauchy-Lorentz function or Lévy type source [75] works better observed in the experiments [76, 77]. Assuming the normalized Gaussian source

$$S(\vec{r}) = \frac{e^{-\vec{r}^2/4R_{\text{inv}}^2}}{(4\pi R_{\text{inv}}^2)^{3/2}}, \tag{3.24}$$

the correlation function for identical particles (without FSI)³ can be obtained using Eq. (3.23) as a function of the single variable in the PRF⁴ $q_{\text{inv}} = \sqrt{-q_\mu q^\mu} = 2k = |\vec{q}|$, which takes the shape of a one-dimensional Gaussian,

$$\begin{aligned} C(q_{\text{inv}}) &= \int \frac{e^{-\vec{r}^2/4R_{\text{inv}}^2}}{(4\pi R_{\text{inv}}^2)^{3/2}} [1 \pm \cos(\vec{q} \cdot \vec{r})] d^3\vec{r} \\ &= 1 \pm e^{-q_{\text{inv}}^2 R_{\text{inv}}^2} \\ &= 1 + C_{\text{QS}}(q_{\text{inv}}). \end{aligned} \quad (3.25)$$

Here $C_{\text{QS}}(q_{\text{inv}}) = \pm e^{-q_{\text{inv}}^2 R_{\text{inv}}^2}$ represents the correlation due to the QS effect only. The “+” sign is for identical bosons and the “-” sign is for identical fermions. Figure. 3.3 shows the example of a theoretical correlation function and its behavior considering the QS effect for different values of R_{inv} using Eq. (3.25) for identical bosons (left) and fermions (right). In these plots, the green line is for $R_{\text{inv}} = 6$ fm, the red line is for $R_{\text{inv}} = 3$ fm, and the blue line is for $R_{\text{inv}} = 1$ fm. The correlation function is going up at a lower q_{inv} as the two bosons follow the Bose–Einstein quantum statistics (left panel) and down at a lower q_{inv} as the two fermions follow the Fermi–Dirac quantum statistics (right panel). When we increase the R_{inv} , the width of the correlation function decreases.

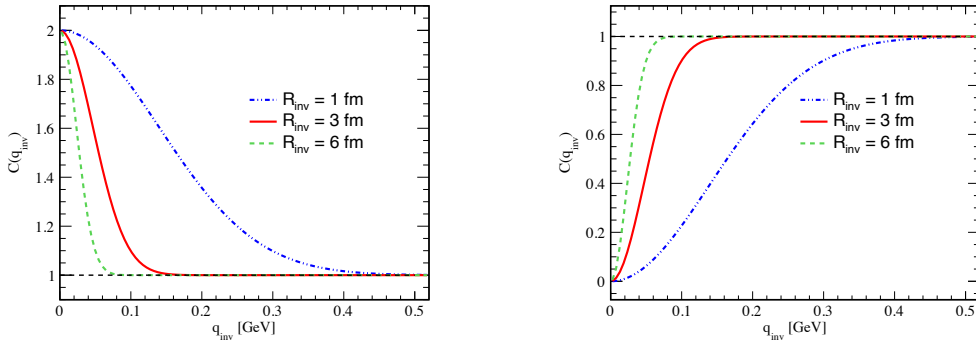


Figure 3.3: Theoretical correlation function (only QS) for identical spin zero bosons (left) and spin half fermions (right) using Eq. (3.25). The different lines are for different values of R_{inv} .

³In case of non-identical particles, $|\Psi(\vec{q} \cdot \vec{r})|^2 = 1$. Therefore, $C(q_{\text{inv}}) = \int S(\vec{r}) d^3\vec{r} = 1$.

⁴In experimental analyses, the correlation function is always measured as a function of invariant quantity q_{inv} .

3.3.2 Spin dependence

The correlation function of identical and non-identical particles are theoretically calculated in sec. 3.3 and 3.3.1 while considering the QS effect. However, the associated particle's spin also has a significant impact and needs to be considered. The correlation function depends on total spin S of the pair, which takes the values $S = |s_1 - s_2|, |s_1 - s_2 + 1|, \dots, |s_1 + s_2|$, where s_i is the spin of individual particle. When the spin effect is taken into account, the modulus squared of the two-particle wave function, $|\Psi|^2$, will have both spin and spatial components. For two identical boson pairs, the total wave function should be symmetric. Therefore, both spin and spatial states either should be symmetric or antisymmetric. If we take the example of identical spin zero boson pairs (e.g., $K_S^0 K_S^0$), the spin state is symmetric as $S = 0$, which implies that the spatial state should also be symmetric. In this case, the symmetrized two-particle wave function and correlation function can be written as

$$\begin{aligned} |\Psi|^2 &= \sum_S \rho_S |\Psi^S|^2 = \frac{1}{2} \sum_{S=0} \rho_S |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \\ &= \frac{1}{2} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \end{aligned} \quad (3.26)$$

and

$$C(q_{\text{inv}}) = 1 + e^{-q_{\text{inv}}^2 R_{\text{inv}}^2}, \text{ respectively.}$$

Where ρ_S is the normalized probability for a state with total spin S ($\sum_S \rho_S = 1$), given by $\rho_S = \frac{(2S+1)}{(2s_1+1)(2s_2+1)}$.

In the case of identical spin half fermion pairs (e.g., $\Lambda \Lambda (\bar{\Lambda} \bar{\Lambda})$), both symmetric ($S = 1$) and antisymmetric ($S = 0$) spin states will contribute, and the total wave function must be antisymmetric. Therefore, if the spin state is symmetric, the spatial state should be antisymmetric, and vice versa. The symmetrized two-particle wave function and

correlation function, in this case, can be written as

$$\begin{aligned}
|\Psi|^2 &= \sum_S \rho_S |\Psi^S|^2 = \frac{1}{2} \sum_{S=0} \rho_S |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \\
&\quad + \frac{1}{2} \sum_{S=1} \rho_S |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) - \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \\
&= \frac{1}{2} \left[\frac{1}{4} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 + \frac{3}{4} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) - \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \right] \text{ and} \\
C(q_{\text{inv}}) &= 1 + \frac{1}{4} e^{-q_{\text{inv}}^2 R_{\text{inv}}^2} - \frac{3}{4} e^{-q_{\text{inv}}^2 R_{\text{inv}}^2} = 1 - \frac{1}{2} e^{-q_{\text{inv}}^2 R_{\text{inv}}^2}, \text{ respectively.}
\end{aligned} \tag{3.27}$$

In general, we can write the correlation function by considering only the QS effect with spin dependence as

$$C(q_{\text{inv}}) = 1 + C_{\text{QS}}(q_{\text{inv}}) = 1 + \alpha e^{-q_{\text{inv}}^2 R_{\text{inv}}^2}, \tag{3.28}$$

where $\alpha = 1$ for identical spin zero bosons, $\alpha = -\frac{1}{2}$ for identical spin half baryons, and $\alpha = 0$ for non-identical particle correlations. From the Eq. (3.28), at $q_{\text{inv}} = 0$, one can calculate the $C(q_{\text{inv}}) = 2$ for identical spin zero bosons, $1/2$ for identical spin half baryons, and 1 for non-identical particles. Figure 3.4 illustrates the behavior of identical spin zero bosons, identical spin half baryons, and non-identical particle correlations in the presence of the QS effect with spin dependence.

3.3.3 λ parameter

The λ parameter was introduced by Deutschmann et al. [78] to reduce the systematic errors in the experimental fits of the correlation function. Fitting without λ leads to discrepancies and large systematic errors which were associated with the Gaussian fit function described in sec 3.3.1. In the case of identical bosons, the correlation function reaches the maximum at 2 for $q_{\text{inv}} = 0$ GeV. But this behavior was not observed in the experimental data. They found the value less than 2 for $q_{\text{inv}} = 0$ GeV. The easiest way to circumvent this apparent inconsistency was to add a fit parameter, thus reducing the systematic errors by the introduction of this extra degree of freedom in the fit function. Later they described this effect may be due to resonance decays, q_{inv} bin width resolution,

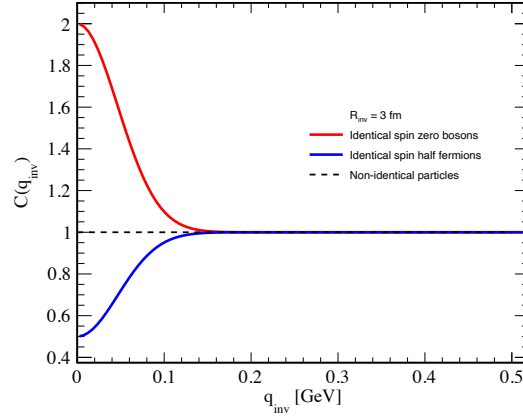


Figure 3.4: Spin dependence theoretical correlation function (only QS) for identical spin half fermions (blue line) and spin zero bosons (red line), and for non-identical particles (black line) using Eq. (3.25).

particle misidentification, etc. Using the λ parameter, the correlation can be written as

$$C(q_{\text{inv}}) = 1 + \lambda C_{\text{QS}}(q_{\text{inv}}) = 1 + \lambda (\alpha e^{-q_{\text{inv}}^2 R_{\text{inv}}^2}). \quad (3.29)$$

The parameter λ is referred to as the incoherence parameter. In the absence of FSI effects, λ equals to unity for a perfectly incoherent Gaussian source. Effects such as resonance decay violate the incoherent source assumption and can lead to deviations of the λ parameter from the unity. Its value can also be affected by non-Gaussian components of the correlations function and by the FSI between particles.

Figure 3.5 shows the correlation function's behavior in the presence of QS effects for different values of λ . The left plot is for identical spin zero bosons and the right plot is for identical spin half fermions. In these plots, the R_{inv} value is fixed to 3 fm.

3.4 FINAL-STATE INTERACTION (FSI) [STRONG INTERACTION ONLY]

The femtoscopic correlation is not only sensitive to the QS effect but also to the FSI effects such as strong and Coulomb. This thesis presents the result of V^0 particles (K_S^0 ,

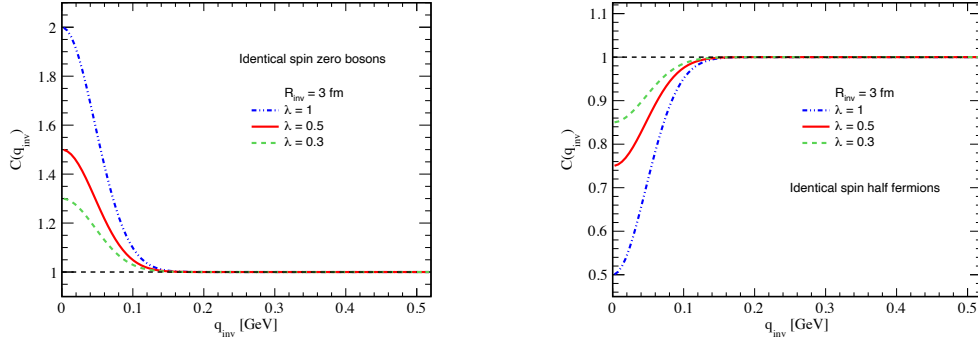


Figure 3.5: Theoretical correlation function (only QS) for identical spin half fermions (right) and spin zero bosons (left) using Eq. (3.29). The different line is for different values of λ .

Λ , and $\bar{\Lambda}$). These particles are neutral, and therefore, we will not discuss the Coulomb interaction. We only discuss the strong FSI in this section.

The theoretical formalism that we discussed so far is for non-interacting particles, where the correlation function contains only the QS effect. In this case, the non-symmetrized wave function takes the form

$$\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) = e^{-i\vec{p}_1 \cdot \vec{x}_1} e^{-i\vec{p}_2 \cdot \vec{x}_2} = e^{-i\vec{K} \cdot (\vec{x}_1 + \vec{x}_2)} e^{-i\frac{\vec{q}}{2} \cdot \vec{r}}. \quad (3.30)$$

For the case of interacting particles, the non-symmetrized wave function can be written as [17]

$$\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) = e^{-i\vec{K} \cdot (\vec{x}_1 + \vec{x}_2)} \left(e^{-i\frac{\vec{q}}{2} \cdot \vec{r}} + \phi_{p_1 p_2}(r) \right), \quad (3.31)$$

where $\phi_{p_1 p_2}(r)$ describes the FSI between the particles and can be written as

$$\phi_{p_1 p_2}(r) = f(k) \Phi_{p_1 p_2}(r) = f(k) \frac{e^{ikr}}{r}, \quad (3.32)$$

assuming the range of the interaction potential is smaller than the distance between emission points r and the magnitude of the relative momentum is much smaller than the mass of the particles (i.e., $k \ll m$). Here, $f(k)$ is the s-wave scattering amplitude in the

effective range approximation, defined as [17]

$$f(k) = \left[\frac{1}{f_0} + \frac{1}{2}d_0k^2 - ik \right]^{-1}, \quad (3.33)$$

where $k = |\vec{q}|/2 = q_{\text{inv}}/2$, f_0 is the complex scattering length, and d_0 is the effective range. Due to the interaction being dominated by near-threshold resonances, the scattering amplitude is expressed differently for neutral kaons (K_S^0) (see sec. 3.5).

Then, the symmetrized wave function involving strong FSI along with the QS can be written using Eq. (3.31) for the case of identical spin zero bosons as

$$|\Psi|^2 = \frac{1}{2} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \quad (3.34)$$

and for identical spin half fermions as

$$|\Psi|^2 = \frac{1}{2} \left[\frac{1}{4} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) + \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 + \frac{3}{4} |\psi_{\vec{p}_1, \vec{p}_2}(\vec{x}_1, \vec{x}_2) - \psi_{\vec{p}_2, \vec{p}_1}(\vec{x}_1, \vec{x}_2)|^2 \right] \quad (3.35)$$

Using the symmetrized wave function (Eq. (3.34) for identical spin zero bosons and Eq. (3.35) for identical spin half fermions), the source function (Eq. (3.24)), and the “Koonin-Pratt equation” (Eq. (3.23)), one can calculate the correlation function involving strong FSI along with the QS for identical spin zero bosons and spin half fermions.

This thesis presents the results of $K_S^0 K_S^0$, $\Lambda\Lambda$ ($\bar{\Lambda}\bar{\Lambda}$), $\Lambda\bar{\Lambda}$, and ΛK_S^0 ($\bar{\Lambda} K_S^0$) femtoscopic correlations. Details about their correlation function involving strong FSI along with the QS are described below. The FSI function is derived in the Lednický–Lyuboshitz (LL) analytical model [17].

3.5 $K_S^0 K_S^0$ CORRELATION FUNCTION

Neglecting CP violation, the K_S^0 state can be written as

$$|K_S^0\rangle = \frac{|K^0\rangle + |\bar{K}^0\rangle}{\sqrt{2}} = \frac{|d\bar{s}\rangle + |\bar{d}s\rangle}{\sqrt{2}} \quad (3.36)$$

Then, $K_S^0 K_S^0$ state can be written as using Eq. (3.36)

$$|K_S^0 K_S^0\rangle = \frac{1}{2} \left(|K^0 K^0\rangle + |K^0 \bar{K}^0\rangle + |\bar{K}^0 K^0\rangle + |\bar{K}^0 \bar{K}^0\rangle \right). \quad (3.37)$$

The QS (Bose–Einstein in the case of $K_S^0 K_S^0$ pairs) and FSI effects for the $K_S^0 K_S^0$ correlation mainly come from identical ($|K^0 K^0\rangle$ and $|\bar{K}^0 \bar{K}^0\rangle$) and non-identical⁵ ($|K^0 \bar{K}^0\rangle$ and $|\bar{K}^0 K^0\rangle$) pairs, respectively. In addition, it is mentioned in the paper [79] that only the symmetric part of the $K^0 \bar{K}^0$ amplitude will also lead to a Bose–Einstein enhancement at small q_{inv} .

Therefore, the $K_S^0 K_S^0$ correlation function can be calculated analytically using the LL model [17, 79] as

$$C(q_{\text{inv}}) = 1 + \lambda \left[C_{\text{QS}}(q_{\text{inv}}) + C_{\text{FSI}}(q_{\text{inv}}) \right]. \quad (3.38)$$

The $C_{\text{QS}}(q_{\text{inv}})$ follow Bose–Einstein quantum statistics, with

$$C_{\text{QS}}(q_{\text{inv}}) = \alpha e^{(-q_{\text{inv}}^2 R_{\text{inv}}^2)}, \quad (3.39)$$

where $\alpha = 1$ due identical spin zero bosons.

The FSI for the $K_S^0 K_S^0$ correlations is modeled by

$$C_{\text{FSI}}(q_{\text{inv}}) = \frac{1}{2} \left[\left| \frac{f(k)}{R_{\text{inv}}} \right|^2 + \frac{4\Re f(k)}{\sqrt{\pi} R_{\text{inv}}} F_1(q_{\text{inv}} R_{\text{inv}}) - \frac{2\Im f(k)}{R_{\text{inv}}} F_2(q_{\text{inv}} R_{\text{inv}}) \right], \quad (3.40)$$

where

$$F_1(z) = \frac{1}{z} e^{-z^2} \int_0^z e^{x^2} dx \text{ and} \quad (3.41)$$

$$F_2(z) = \frac{1 - e^{-z^2}}{z}.$$

The function $f(k)$ is the $K^0 \bar{K}^0$ s-wave scattering amplitude, with real and imaginary parts $\Re f(k)$ and $\Im f(k)$, respectively. This amplitude is dominated by the near-threshold s-wave isoscalar resonance $f_0(980)$ and the s-wave isovector resonance $a_0(980)$, with the

⁵In the case of non-identical pairs, the QS effect is absent.

total scattering amplitude given by an average of these contributions: $f(k) = (f_{f_0(980)}(k) + f_{a_0(980)}(k))/2$. The individual resonance amplitudes depend on the resonance mass m_r , with $r = f_0(980)$ or $a_0(980)$, the kaon mass m_{K^0} , and the resonance couplings γ_r (γ'_r) to the $K^0\bar{K}^0$ ($\pi\pi$ for $f_0(980)$ and $\pi^0\eta$ for $a_0(980)$) channels. Then, $f_r(k) = \gamma_r / [m_r^2 - \zeta - i\gamma_r k - i\gamma'_r k']$, where $\zeta = 4(m_{K^0}^2 + k^2)$ and k' denotes the momentum in the second ($\pi\pi$ or $\pi^0\eta$) decay channel⁶ with the corresponding partial width $\Gamma' = \gamma'_r k' / m_r$ (more details can be found in Ref. [79]). The scattering amplitude is calculated using the resonance mass and the coupling parameters from Refs. [80–83], taken from row C of the below Table.

Table 3.1: The $f_0(980)$ and $a_0(980)$ masses and coupling parameters, all are in GeV, from (a) [80], (b) [81], (c) [82, 83], and (d) [82, 83]

Ref.	$m_{f_0(980)}$	$\gamma_{f_0 \rightarrow K^0\bar{K}^0}$	$\gamma'_{f_0 \rightarrow \pi\pi}$	$m_{a_0(980)}$	$\gamma_{a_0 \rightarrow K^0\bar{K}^0}$	$\gamma'_{a_0 \rightarrow \pi^0\eta}$
a	0.978	0.792	0.199	0.974	0.333	0.222
b	0.973	2.763	0.5283	0.985	0.4038	0.3711
c	0.996	1.305	0.2684	0.992	0.5555	0.4401
d	0.996	1.305	0.2684	1.003	0.8365	0.4580

An example of the theoretical correlation function using Eq. (3.38) for $K_S^0 K_S^0$ pair can be seen in Fig. 3.6. In this figure, the blue dotted line represents the QS effect, the solid violate line represents the FSI effect, and the solid red line represents the QS plus FSI effect. The QS line is going up at a lower q_{inv} due to Bose–Einstein quantum statistics. The FSI line is going down at lower q_{inv} ($q_{\text{inv}} \approx 0.07$ GeV), which signifies the repulsive character of strong FSI originates from $\bar{K}^0 K^0$ and $K^0 \bar{K}^0$, similar to an annihilation process. In all these plots, the R_{inv} and λ values are fixed to 3 fm and 1, respectively, and the mass and coupling parameters are taken from Table 3.1.

⁶ k'_{f_0, a_0} defined as $k'_{f_0, a_0} = \sqrt{(m_{f_0, a_0} - (m_{\pi^0, \eta} - m_{\pi, \pi})^2)(m_{f_0, a_0} - (m_{\pi^0, \eta} + m_{\pi, \pi})^2)} / 2m_{f_0, a_0}$

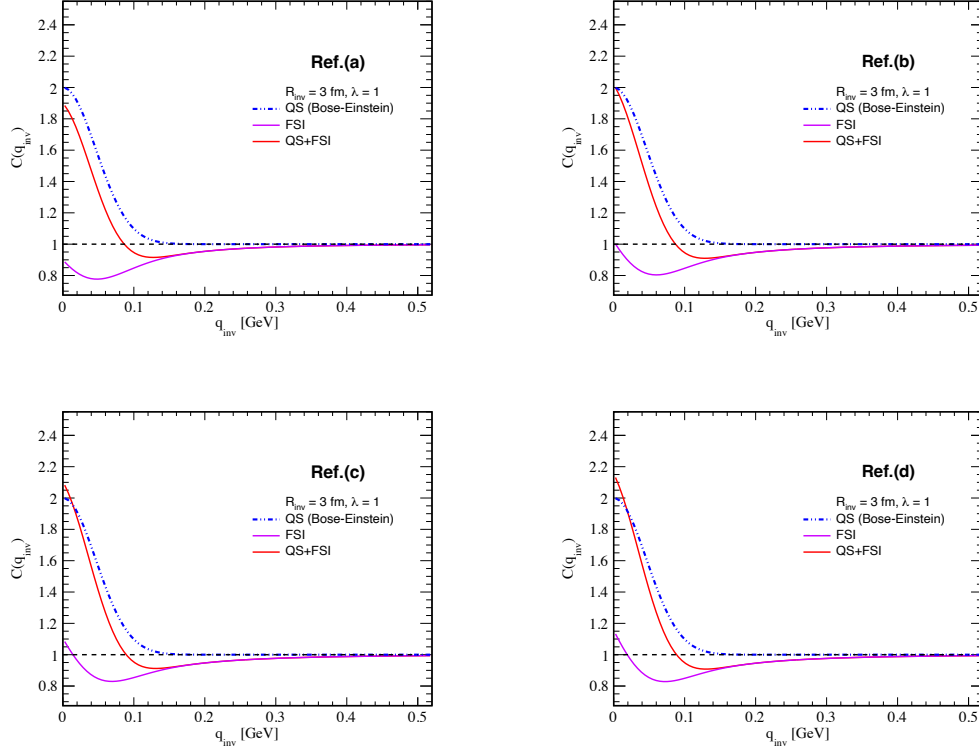


Figure 3.6: Theoretical correlation functions involving both QS and FSI for the $K_S^0 K_S^0$ pair using Eq. (3.38). The mass and coupling parameters are taken from Ref.(a) for the top left plot, Ref.(b) for the top right plot, Ref.(c) for the bottom left plot, and Ref.(d) for the bottom right plot of the Table 3.1. The QS line is drawn using $1 + \lambda(C_{QS}(q_{inv}))$, the FSI line is drawn using $1 + \lambda(C_{FSI}(q_{inv}))$, and the QS+FSI line is drawn using Eq. (3.38).

3.6 CORRELATION FUNCTIONS INVOLVING Λ ($\bar{\Lambda}$) BARYONS (ΛK_S^0 , $\bar{\Lambda} K_S^0$, $\Lambda\Lambda$, $\bar{\Lambda}\bar{\Lambda}$, AND $\Lambda\bar{\Lambda}$)

For the correlations involving Λ baryons, the correlation function can be written the same as $K_S^0 K_S^0$ in Eq. (3.38), but the $C_{QS}(q_{\text{inv}})$ and $C_{\text{FSI}}(q_{\text{inv}})$ functions are [17]

$$C_{QS}(q_{\text{inv}}) = \alpha e^{(-q_{\text{inv}}^2 R_{\text{inv}}^2)}, \quad \text{and} \quad (3.42)$$

$$C_{\text{FSI}}(q_{\text{inv}}) = (1 + \alpha) \left[\frac{1}{2} \frac{|f(k)|^2}{R_{\text{inv}}^2} \left(1 - \frac{1}{2\sqrt{\pi}} \frac{d_0}{R_{\text{inv}}} \right) + \frac{2\Re f(k)}{\sqrt{\pi} R_{\text{inv}}} F_1(q_{\text{inv}} R_{\text{inv}}) - \frac{\Im f(k)}{R_{\text{inv}}} F_2(q_{\text{inv}} R_{\text{inv}}) \right],$$

where $\alpha = -1/2$ for $\Lambda\Lambda$ ($\bar{\Lambda}\bar{\Lambda}$) correlations for two identical fermions and $\alpha = 0$ for ΛK_S^0 ($\bar{\Lambda} K_S^0$) and $\Lambda\bar{\Lambda}$ correlations as there are no QS effects for non-identical particles [17]. The scattering amplitude $f(k)$ is parameterized by a complex scattering length (f_0) and an effective range (d_0) with $f(k) = \left[\frac{1}{f_0} + \frac{1}{2} d_0 k^2 - ik \right]^{-1}$ [17]. The imaginary part of f_0 is responsible for inelastic processes (annihilation). For an attractive interaction that is not strong enough to produce a bound state, the real part of f_0 is positive, while a repulsive interaction corresponds to a negative $\Re f_0$ of the order of the range of the repulsive potential. In the presence of a bound state, $\Re f_0$ is also negative, but with a much larger magnitude. The femtoscopic sign convention and notation for the scattering length differ from those used in nuclear physics, where the corresponding scattering length $a_0 = -f_0$. As the ΛK_S^0 ($\bar{\Lambda} K_S^0$) and $\Lambda\Lambda$ ($\bar{\Lambda}\bar{\Lambda}$) correlations, each has only one spin state that contributes to the s -wave scattering, Eq. (3.42) suffices to describe the FSI effects.

An example of a theoretical correlation function for $\Lambda\Lambda$ ($\bar{\Lambda}\bar{\Lambda}$) pair can be seen in Fig. 3.7. In this figure, the blue dotted line represents the QS effect (Fermi–Dirac), the solid violet line represents the repulsive FSI effect, the green solid line represents attractive FSI, the red solid line represents the QS plus repulsive FSI effect, and the azure solid line represents the QS plus attractive FSI effect. All these plots, the R_{inv} , $\Im f_0$, and λ values are fixed to 2 fm, 0 fm and 1, respectively, and the values of $\Re f_0$ and d_0 parameters were

changed to see the behaviour of the correlation function.

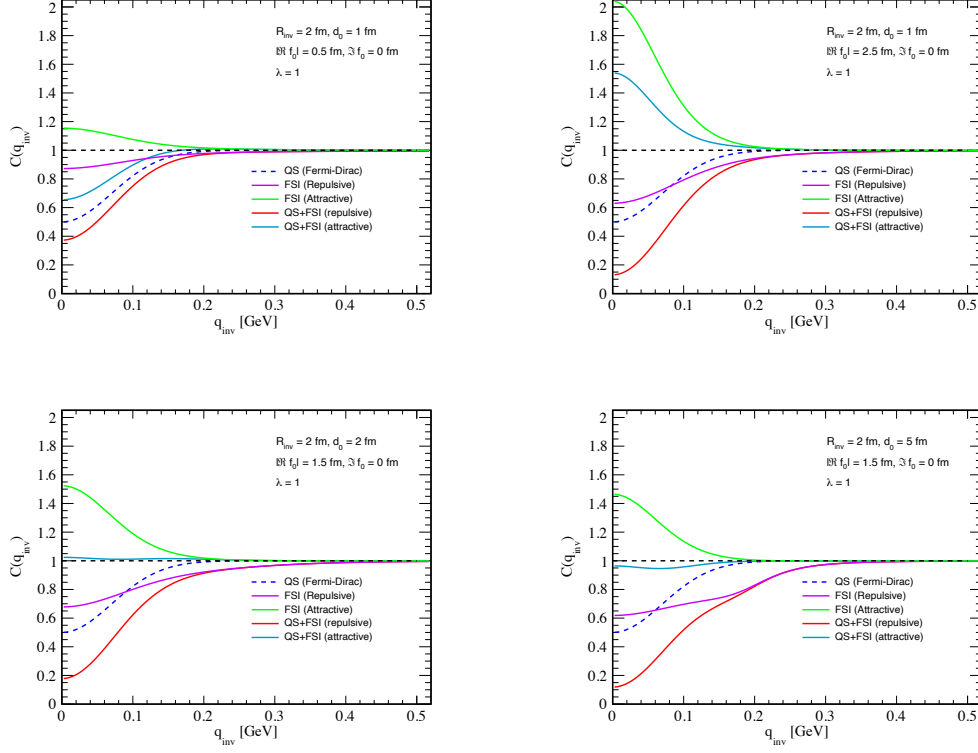


Figure 3.7: Theoretical correlation functions involving both QS and FSI for the $\Lambda\Lambda$ ($\bar{\Lambda}\bar{\Lambda}$) pair using Eq. (3.38) where the $C_{\text{QS}}(q_{\text{inv}})$ and $C_{\text{FSI}}(q_{\text{inv}})$ function are taken from Eq. (3.42). The QS line is drawn using $1 + \lambda(C_{\text{QS}}(q_{\text{inv}}))$, the FSI line is drawn using $1 + \lambda(C_{\text{FSI}}(q_{\text{inv}}))$, and the QS+FSI line is drawn using Eq. (3.38).

CHAPTER 4

EXPERIMENTAL SETUP

This chapter will discuss the experimental setup that produced the lead-lead (PbPb) data used for this analysis. This chapter will begin with an overview of the Large Hadron Collider (LHC), a particle accelerator and collider located at CERN¹, Geneva. After that, a detailed description of the CMS (Compact Muon Solenoid) detector/experiment, which was used to collect the data for this analysis, is provided.

4.1 THE LARGE HADRON COLLIDER

The LHC is currently the world's biggest and most powerful particle accelerator and collider [84]. It is an apparently circular ring with 27 km of circumference situated about 45–170 m underground at the France-Switzerland border. The tunnel, where the CERN LEP experiment [85] ran from 1989 to 2000, was used to build this collider. It is originally designed to be a 14 TeV center-of-mass energy proton-proton collider with a luminosity² of about $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ which would also be able to accelerate heavy-ions, e.g., Pb and xenon (Xe). CERN approved the LHC project in 1994, and it took almost a decade, from 1998 to 2008, to finish the construction work.

The LHC ring consists of two beam pipes through which two high-energy particle beams³ travel anticlockwise at nearly the speed of light ($\sim 99.99999991\%$ of c). Inside the beam pipe, an ultrahigh vacuum (vacuum pressure is about 10^{-7} Pa in the beam pipes and 10^{-9} Pa close to the interaction points) is maintained to avoid collisions between the beam and gas molecules. The LHC ring is not a perfect circle. Each beam pipe is made up of eight arcs and eight straight sections. The two beam pipes cross each other at four of

¹European Council for Nuclear Research or Conseil Européen pour la Recherche Nucléaire

²It is a measurement of the number of collisions produced in a detector per cm^2 and per second.

³Beam is composed of bunches of particles.

these straight sections where the four primary detectors⁴ of the LHC are situated. The radio frequency cavities, which help to accelerate the beams to achieve desired energy, are installed in another straight section. In LHC, there are eight superconducting RF cavities per beam whose primary role is to keep the bunches tightly bunched to ensure high luminosity at the interaction points and hence maximize the number of collisions. The LHC placed 1232 superconducting dipole magnets along the beam path, producing magnetic fields greater than 8 T to bend the beam trajectory and maintain alignment inside the beam pipes. Superfluid helium is used to cool these magnets to temperatures below 2 K. The LHC also uses the superconducting quadrupoles, sextupoles, and octupoles to focus the beam. A total of ~ 9300 magnets are used in the LHC. Some of the LHC parameters and their values can be found here [86]. A layout of LHC can be seen in Fig. 4.1.

4.1.1 CERN accelerator complex

In the LHC ring, the proton or ion beams do not directly travel in the desired collision energy. The LHC is the last part of the CERN accelerator complex (see Fig. 4.2), which consists of several low-energy accelerators that accelerate the protons and ions.

The proton beams are created by extracting the protons from hydrogen gas in a duoplasmatron [89], a metal cylinder surrounded by an electrical field to break down the hydrogen gas into its constituent protons and electrons. Then the protons are accelerated by the linear accelerator LINAC 2 [90] to reach energies up to 50 MeV. The accelerated protons are then injected into Proton Synchrotron Booster (PSB) [91], where the protons are grouped into bunches and accelerated to 1.4 GeV. They are then sent to the Proton Synchrotron (PS) where the bunches are split with 25 ns of bunch spacing and accelerated again to reach the energy of 25 GeV. Before transferring to the LHC, these bunches are sent to the Super Proton Synchrotron (SPS) [92], which boosts the proton beams to 450 GeV. Finally, the SPS injects the proton beams into the LHC, where the

⁴A Toroidal LHC ApparatuS (ATLAS), A Large Ion Collider Experiment (ALICE), Compact Muon Solenoid (CMS), and LHC beauty (LHCb)

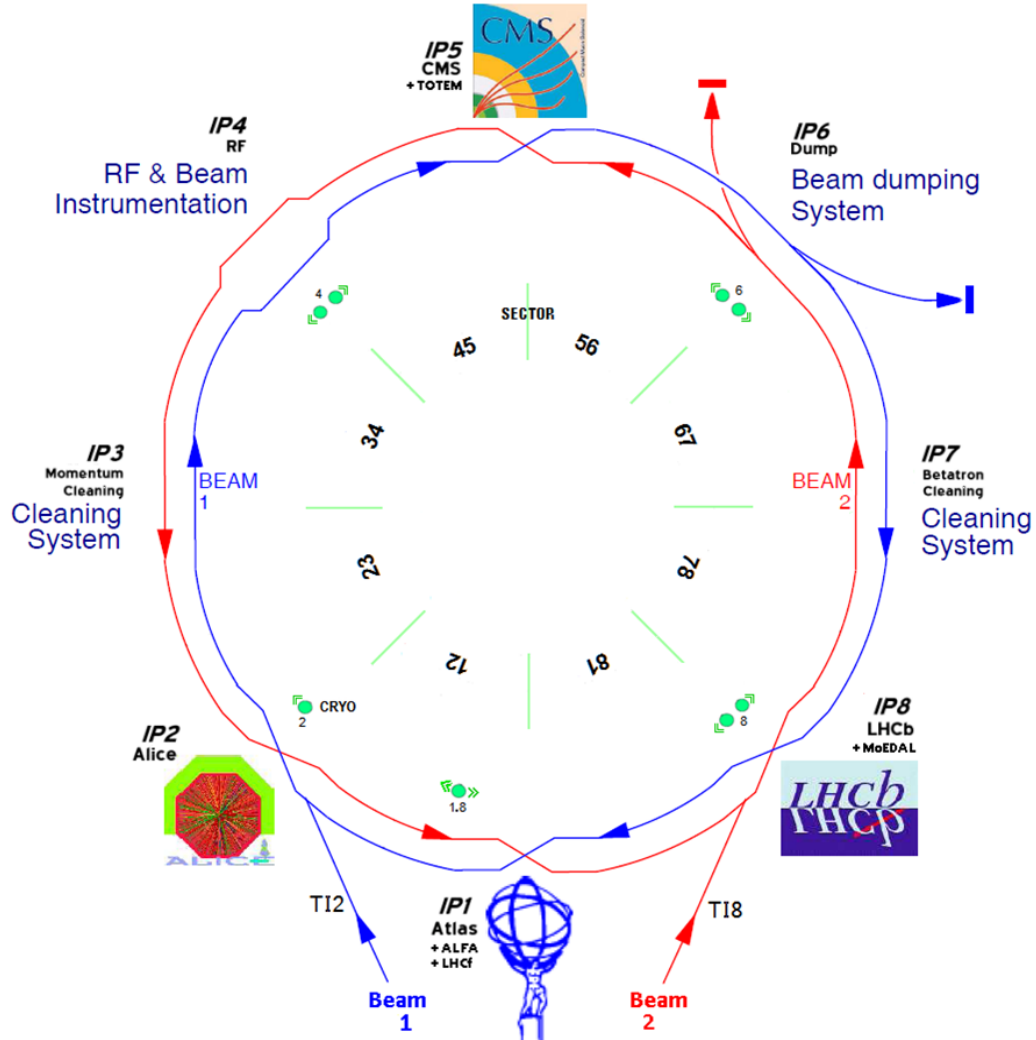


Figure 4.1: Schematic diagram of the LHC layout with the eight interaction points labeled IP1 to IP8. The figure is taken from Ref. [87]. The experiments ATLAS, ALICE, CMS, and LHCb are installed in IP1, IP2, IP5, and IP8, respectively. The RF cavities are installed at IP4. Beam 1 is injected close to IP2 and circulates clockwise, and Beam 2 is injected close to IP8 and circulates counterclockwise.

The CERN accelerator complex *Complexe des accélérateurs du CERN*

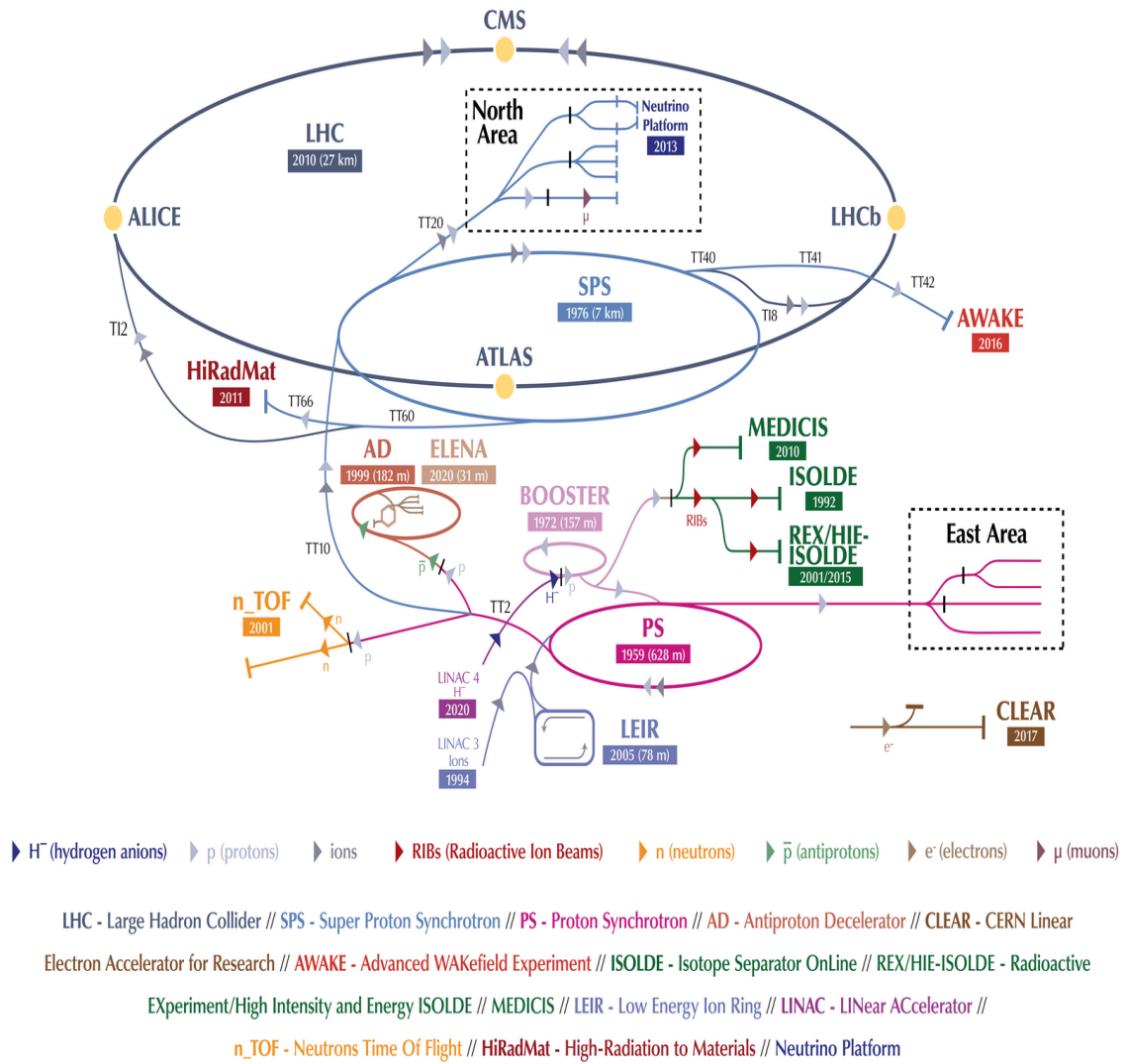


Figure 4.2: Schematic diagram of the CERN accelerator complex. The Figure is taken from Ref. [88].

final acceleration occurs, and the beams achieve the nominal energy and collide.

In the case of Pb ion beams, Pb^{+27} ions are first produced in the Electron Cyclotron Resonance Ion Source (ECRIS) [93]. Then LINAC 3 [94] accelerates those Pb ions to 4.2 MeV per nucleon and sends them into the Low Energy Ion Ring (LEIR) [95]. Before entering the LEIR, the Pb ions are passed through a thin carbon foil with a thickness of about $0.3 \mu\text{m}$, which strips 27 more electrons making them Pb^{+54} . Inside the LEIR, the Pb ions are accelerated to 72.2 MeV per nucleon. Before moving to the PS, the ions are grouped into bunches. In the PS, bunch splitting occurs with 100 ns of bunch spacing, and they are accelerated to 5.9 GeV per nucleon. After that, the Pb ion beams pass through the aluminum foil with a thickness of about 0.88 mm to get fully ionized Pb^{+82} ion beams. Then the fully ionized Pb ion beams are sent to the SPS for further acceleration to reach the energy of 176.4 GeV per nucleon. Finally, the SPS injects the ion beams into the LHC, where the final acceleration takes place to achieve the desired energy.

The LHC is designed to hold ~ 2800 proton bunches and ~ 700 Pb ion bunches per beam with $\sim 10^{11}$ no. of protons and $\sim 10^{7-8}$ no. of ions per bunches, respectively.

4.1.2 Detectors at the LHC

There are four main detectors installed in the LHC ring are:

1. A Toroidal LHC ApparatuS (ATLAS) [96]: a general-purpose particle detector located at IP1 (Meyrin, Switzerland), weighing ~ 7000 tons, with a dimensional length of 46 m, a height of 25 m, and a width of 25 m. This is the largest detector at the LHC. The ATLAS collaboration is involved in several fields of physics, including the Higgs boson discovery, searches for physics beyond the Standard Model, precision measurements of top-quark and electroweak properties, and heavy-ion physics.
2. A Large Ion Collider Experiment (ALICE) [97]: a particle detector located at IP2 (France), weighing ~ 10000 tones, with a dimensional length of 26 m, a height of 16 m, and a width of 16 m. This detector is specially designed to measure and analyze heavy-ion collisions. The ALICE collaboration is primarily interested in studying the QGP and many facets of heavy-ion physics.

3. Compact Muon Solenoid (CMS) [98]: a multi-purpose particle detector located at IP5 (Cessy, France), weighing ~ 14000 tons, with a dimensional length of 28 m, a height of 15 m, and a width of 15 m. It has a similar design and the same physics motivation as the ATLAS detector. Details about the CMS detector and its inner components are described in sec. 4.2.
4. Large Hadron Collider beauty (LHCb) [99]: a single-arm forward spectrometer located at IP8 (Ferney-Voltaire, France), weighing ~ 5600 tons, with a dimensional length of 21 m, a height of 10 m, and a width of 13 m. Its purpose is to investigate CP violation and other rare phenomena in the decay of hadrons with heavy flavours, particularly B mesons. Nowadays, LHCb collaboration covers different research areas, including heavy-ion physics and electroweak. By introducing a small quantity of noble gas (such as helium) within the beam pipe close to the collision location, LHCb can also run in fixed-target mode.

In addition to these detectors, LHC houses three small experiments, which are TOTal cross section, Elastic scattering and Diffraction Dissociation Measurement (TOTEM) [100], Large Hadron Collider forward (LHCf) [101] and Monopole and Exotics Detector at the LHC (MoEDAL)[102]. The TOTEM is installed near the point where protons collide in the center of the CMS detector and measures the total pp cross-section and studies elastic and diffractive scattering at the LHC. The LHCf detector is placed on either side of the ATLAS experiment. The aim is to study the neutral-particle production cross sections in the very forward region of proton-proton and nucleus-nucleus interactions. The MoEDAL detector is deployed at the intersection region at IP8 on the LHC ring around the Vertex Locator detector (VELO) of the LHCb detector and the motivation is to search for the magnetic monopole and search for very specific exotic particles. The locations of these detectors can be seen in Fig. 4.1.

4.1.3 Luminosity

Luminosity is one of the most important parameters of any collider and based on its value, the performance of a collider can be characterized. The higher the luminosity of a collider, the ability to produce the required number of interactions of that collider is higher. It is a measurement of the number of collisions that can be produced in a detector per cm^2 and per second. The number of interactions per unit time dN/dt

produced in a reaction is proportional to the cross-section σ and defined as

$$\begin{aligned} \frac{dN}{dt} &\propto \sigma \\ \Rightarrow \frac{dN}{dt} &= \mathcal{L}\sigma, \end{aligned} \quad (4.1)$$

where $\mathcal{L}$ is the instantaneous luminosity. In the case of a circular collider, the instantaneous luminosity can be expressed as

$$\mathcal{L} = \frac{k_b N_b^1 N_b^2 f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \quad (4.2)$$

where k_b is the number of bunches that collided, N_b^1 and N_b^2 are the number of particles per bunch in the two beams, f_{rev} is the revolution frequency which is 11245 Hz in the LHC, γ is the Lorentz gamma factor, ϵ_n is the normalized transverse beam emittance, β^* is the amplitude function at the interaction point which is related to the width of the beams, and F is the geometric luminosity reduction factor due to the angle at which the two beams collide. The integrated luminosity is obtained by integrating the instantaneous luminosity over a given time period, defined as

$$L_{\text{int}} = \int \mathcal{L} dt \quad (4.3)$$

where L_{int} is the integrated luminosity. An example of total integrated luminosity measured during the 2018 PbPb run can be seen in Fig. 4.3. The goal of LHC to achieve the integrated luminosity during Run-3 can be seen in Fig. 4.4.

Therefore, the total number of interactions in that period will be $N_{\text{tot}} = L_{\text{int}} \sigma$.

4.1.4 LHC schedule

After almost a decade of construction work (1998-2008), LHC finally began operating in September 2008. Due to some technical issues with the magnet, LHC stopped its operation and started again in 2009 after being repaired and calibrated. It continued to deliver collision data until 2013 in the first data taking period (Run-1). During this period, the LHC performed pp collisions at a center-of-mass energy of $\sqrt{s} = 0.9$ TeV and

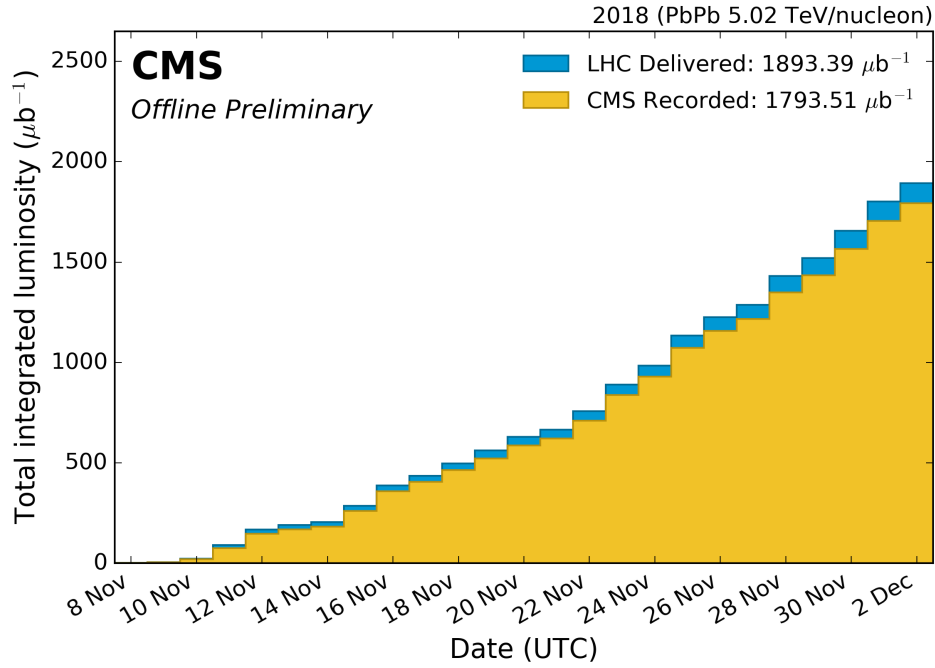


Figure 4.3: Measured luminosity delivered by the LHC to CMS (blue) and recorded by CMS (orange) for the 2018 PbPb run at a 5.02 TeV center-of-mass energy per nucleon. The Figure is taken from <https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>.

Mode	GPDs	LHCb	ALICE
p-p	250/fb	25 - 30/fb (~50/fb by LS4)	200/pb
Pb-Pb	7/nb (13/nb by LS4)	1/nb (2/nb by LS4)	7/nb (13/nb by LS4)
p-Pb	0.5/pb (~1/pb by LS4)	0.1/pb (~0.2/pb by LS4)	0.25/pb (~0.5/pb by LS4)
O-O	0.5/nb	0.5/nb	0.5/nb
p-O	LHCf 1.5/nb	2/nb	

Figure 4.4: Integrated luminosity goal of LHC for Run-3. Here GPDs stands for General Purpose Detectors (e.g., CMS and ATLAS). The table is taken from <https://lhc-commissioning.web.cern.ch/performance/Run-3-targets.htm>.

2.36 TeV in 2009, pp collisions at $\sqrt{s} = 7$ TeV and PbPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV between 2010 and 2011. In 2012 and 2013, LHC collides pp at $\sqrt{s} = 8$ TeV and ppb at $\sqrt{s_{NN}} = 5.02$ TeV, respectively. In December 2013, LHC stopped its operation for two years to upgrade the machine. This period is called long shutdown 1 (LS1). In 2015, LHC started its second operation (Run-2) and delivered collision data until 2018. In this period, LHC collided pp at $\sqrt{s} = 13$ TeV in 2015, ppb at $\sqrt{s_{NN}} = 8.16$ TeV in 2016, pp at $\sqrt{s} = 5.02$ TeV and Xe-Xe at $\sqrt{s_{NN}} = 5.16$ TeV in 2017, and PbPb at $\sqrt{s_{NN}} = 5.02$ TeV in 2018. The LS2 started in December 2018 and ended in July 2022. In July 2022, LHC began its operation to deliver the third round of collision data (Run-3) with pp collisions at $\sqrt{s} = 13.6$ TeV and its plan is to continue until 2025, including oxygen-oxygen (O-O), p-O, and PbPb collisions.

The long-term plan of the LHC until 2038 can be seen in Fig. 4.5. The LHC is scheduled to run until 2038, followed by LS3 and LS4.

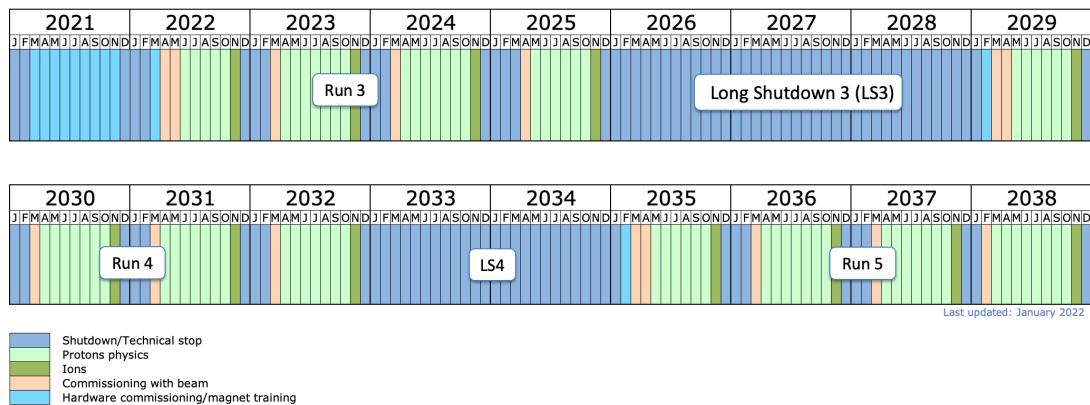


Figure 4.5: Long-term plan of the LHC. The figure is taken from <https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm>.

4.2 THE CMS DETECTOR

The CMS is a multi-purpose particle detector designed to meet several physics goals of the LHC [103]. Over 4000 particle physicists, engineers, computer scientists, technicians, and students from over 240 universities and institutes across more than 50 nations work

at CMS. In 1995, the CMS project received approval, and in 1998 work on the surface building began. The first beams circulated in the LHC ring in September 2008, and CMS began to collect data. The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there is a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). The tracker detector measures the trajectory of the charged particles. The calorimeters measure the energy of charged and neutral particles. The steel flux-return yoke outside the solenoid contains gas-ionization detectors that are used to measure muons. Details about these subdetectors and the superconducting solenoid are briefly described below. Besides these main subdetectors, the CMS also has two very forward subdetectors, Centauro and Strange Object Research (CASTOR) [104] and Zero Degree Calorimeter (ZDC) [105]. A cutaway view of the CMS detector, including all the subdetectors, is shown in Fig. 4.6.

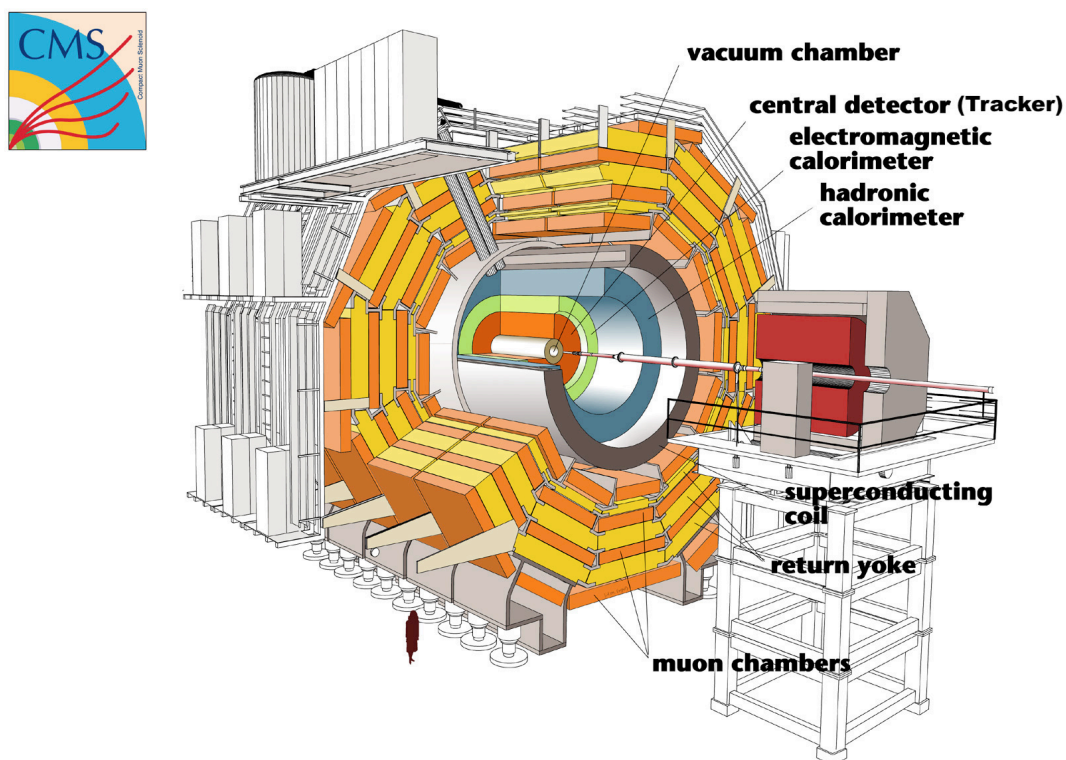


Figure 4.6: Cutaway view of the CMS detector. The figure is adapted from <https://cds.cern.ch/record/39040>.

A transverse layout of the CMS detector with its subdetectors and particle interaction with them is shown in Fig. 4.7. All the charged particles leave their curved trajectory in the tracker. The neutral particles trajectory is not observed in the tracker. The electron (red solid line) and photon (blue dashed line) are stopped by ECAL and deposit all their energy. As the energy deposition of electrons and photons are similar, the identification between them is done using the information from the tracker. The charged (green solid line) and neutral (green dashed line) hadrons are stopped by HCAL and deposit all their energy. The neutral and charged hadrons identification is done using the information from the tracker. Muons interact weakly, and therefore, they are not stopped by any of the calorimeters. Dedicated muon chambers are placed in the outer part of the detector to detect muons.

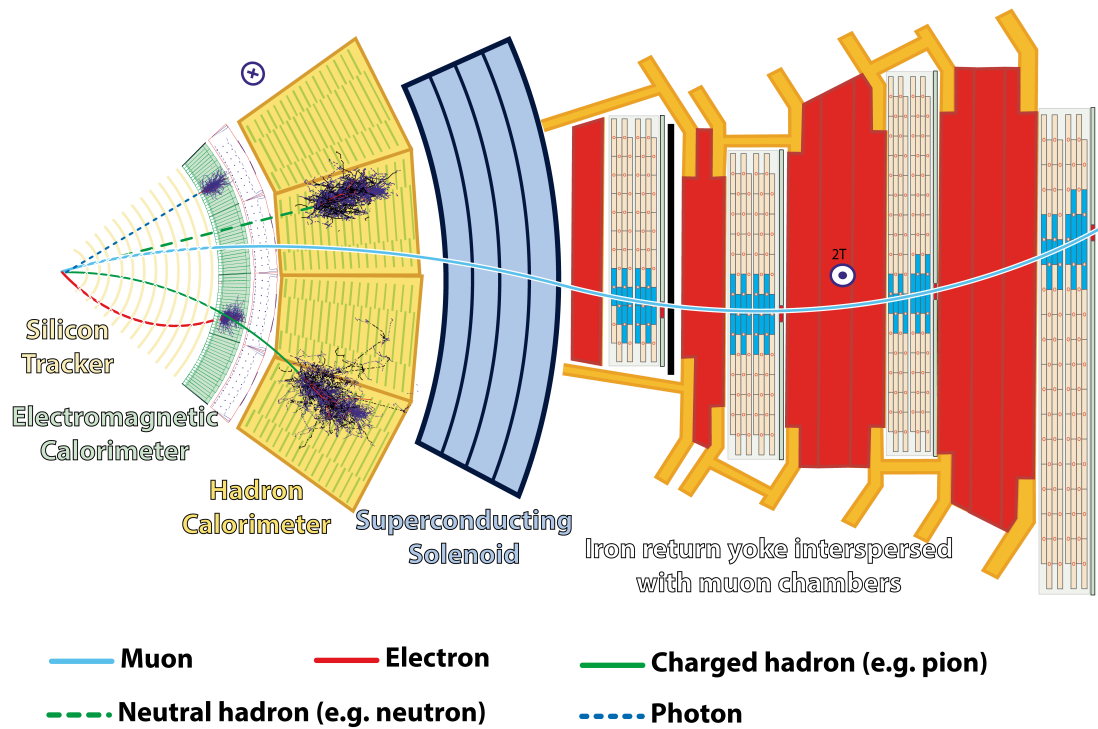


Figure 4.7: Transverse layout of the CMS detector. It also shows how the particle interacts with different subdetectors. The figure is taken from <https://cds.cern.ch/record/2120661>.

4.2.1 CMS coordinate system

The coordinate system of the CMS is oriented in such a way that it has the origin at the nominal interaction point (IP), the x -axis points radially inward to the center of the LHC ring, the y -axis points upward perpendicular to the LHC plane, and the z -axis is parallel to the beam pipe with its positive direction specified along the anticlockwise direction of the beam. The schematic diagrams of the coordinate system used in the CMS experiment can be seen in Fig. 4.8 and 4.9.

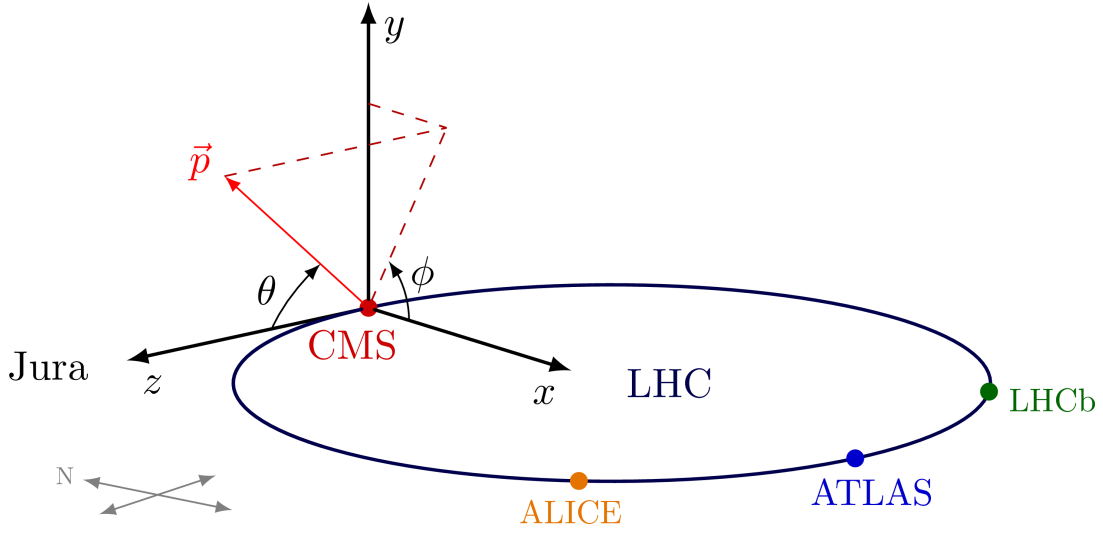


Figure 4.8: Schematic diagram of the CMS coordinate system. The Figure is taken from https://tikz.net/axis3d_cms/.

Since our detector is cylindrical, using the cylindrical coordinate system (see the bottom plot of Fig. 4.8), the radial distance $r = \sqrt{x^2 + y^2}$ and the azimuthal angle $\phi = \tan^{-1} \left(\frac{y}{x} \right)$, which is the angle measured from the x -axis, are measured in the x - y plane, called the transverse plane. The polar angle θ is measured from the z -axis in the r - z plane.

In experimental particle physics, we often use the variables transverse momentum p_T ,

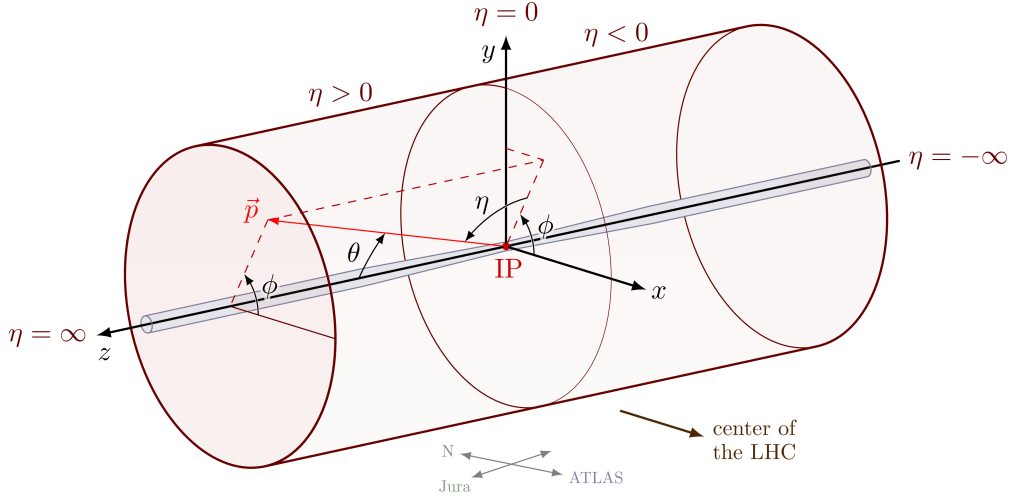


Figure 4.9: Cylindrical coordinate system of the CMS detector. The Figure is taken from https://tikz.net/axis3d_cms/.

pseudorapidity η , and ϕ in momentum space, defined as

$$\begin{aligned}
 p_T &= \sqrt{|\vec{p}_x|^2 + |\vec{p}_y|^2} \\
 \eta &= \frac{1}{2} \ln \left(\frac{|\vec{p}| + |\vec{p}_z|}{|\vec{p}| - |\vec{p}_z|} \right) = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \text{ and} \\
 \phi &= \tan^{-1} \left(\frac{|\vec{p}_y|}{|\vec{p}_x|} \right) \text{ respectively,}
 \end{aligned} \tag{4.4}$$

where, the $\vec{p}_x$ and $\vec{p}_y$ are the momenta in x and y directions, $|\vec{p}|$ is the total momentum, and E is the total energy of the particle. The η is zero in the transverse plane and approaches $(+\infty)$ toward the $+z$ -axis. For the massive particles, we used the rapidity y in place of η , which is defined as

$$y = \frac{1}{2} \ln \left(\frac{E + |\vec{p}_z|}{E - |\vec{p}_z|} \right). \tag{4.5}$$

For the massless particles or the relativistic particles ($E \gg m$), $E \approx |\vec{p}|$, and therefore, $y \approx \eta$. The advantage of using η or y in accelerator physics is that it follows the simple addition, unlike velocity, simple shape invariance nature, and the difference between these quantities for two particles (e.g., $\Delta\eta = \eta_1 - \eta_2$ or $\Delta y = y_1 - y_2$, where η_1 (y_1) and η_2 (y_2) are the pseudorapidities (rapidities) of the first and second particles, respectively.) are Lorentz invariant under longitudinal boosts. The variables p_T and ϕ are also Lorentz

invariant under longitudinal boosts as these are measured in the x - y plane while the boost is along the z direction.

4.2.2 CMS magnet

The CMS magnet system consists of the superconducting coil, the vacuum tank, and the magnet yoke. The central feature of the CMS detector [103] is a superconducting solenoid of 12.5 m long and 6 m internal diameter, providing a uniform magnetic field of 3.8 T that is 10^5 times stronger than the Earth's magnetic field. It is the world's largest superconducting solenoid. The solenoid consists of four layers. Each layer is made up of a "Rutherford-type Cable" comprising Niobium-Titanium (NbTi) superconducting strands coated with copper, which are extruded with pure aluminum and mechanically reinforced with an aluminum alloy. Each cable has 16×2 strands, and each strand can carry more than ~ 2000 A current when cooled to 4.4 K using liquid helium. The superconducting coils work in a vacuum vessel and are thermally insulated, allowing electric currents to flow without resistance. An artistic view of the CMS solenoid can be seen in Fig. 4.10.

To control the magnetic field outside the solenoid and maintain the homogeneous field inside the solenoid, it is necessary to use a return yoke. The main role of the CMS dodecagon return yoke is to increase the field homogeneity in the tracker volume and to reduce the stray field by returning the magnetic flux of the solenoid. The field strength in the return yoke is around 2 T. The superconducting solenoid is enclosed inside an 11000 tons return yoke made of common structural steel. Due to its heavy weight, the return yoke is segmented into 5 barrel rings and two endcaps. The central barrel rings are four layered structures, while others are three layered. Each of the endcaps contains three disks. The return yoke allows the insertion and mechanical support of the muon chambers. The central barrel supports the vacuum chamber of the superconducting coil. The barrel rings and endcap disks are supported by steel feet and carts, respectively. A view of 3 and 4 layers of barrel return yoke enclosing vacuum vessel can be seen in

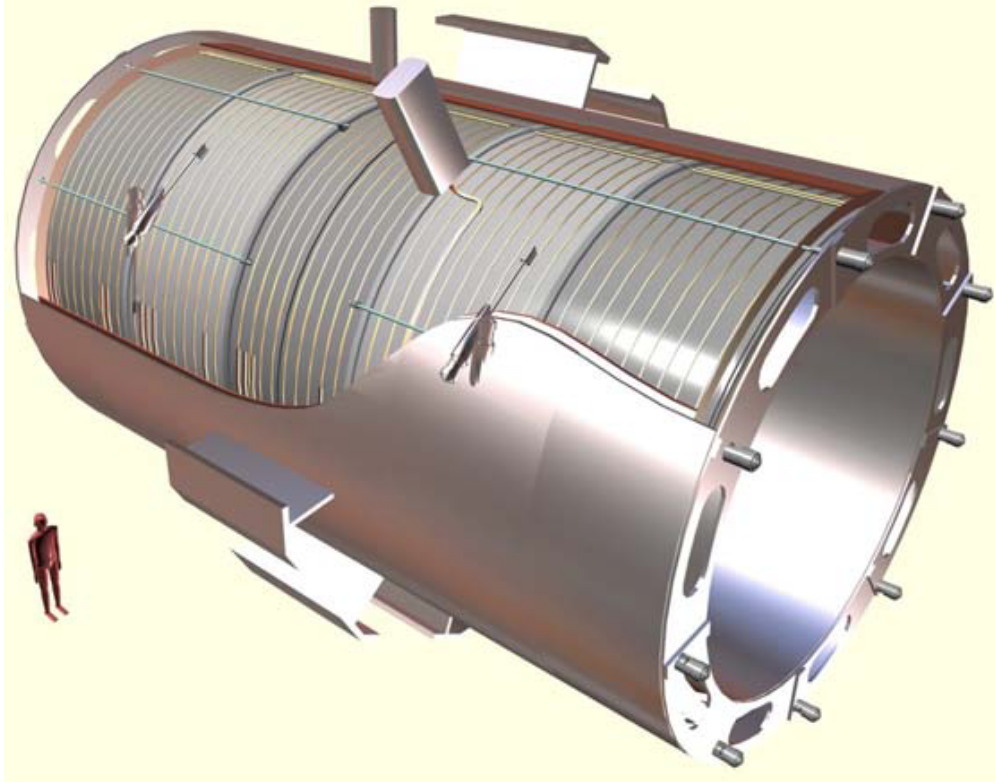


Figure 4.10: Artistic view of the CMS solenoid [103].

Fig. 4.11.

The CMS magnet weighs 12000 tons and uses almost twice as much iron as the Eiffel Tower. A nominal current of 19.14 kA is provided to generate the magnetic field of 3.8 T. This magnetic field helps in the charge identification and momentum estimation of the charged particles produced in the collisions. The predicted magnetic flux density $|B|$ and the directions of the field lines at the CMS detector can be shown in Fig. 4.12. The different colors represent the values of $|B|$. The magnetic flux density inside the solenoid (mainly in the barrel part) is ≈ 3.8 T. The directions of the field lines are shown in black and white.

4.2.3 Tracker System

The CMS tracking detector, called the tracker [103], is designed to provide a precise and efficient measurement of the trajectories of charged particles produced in the collisions and

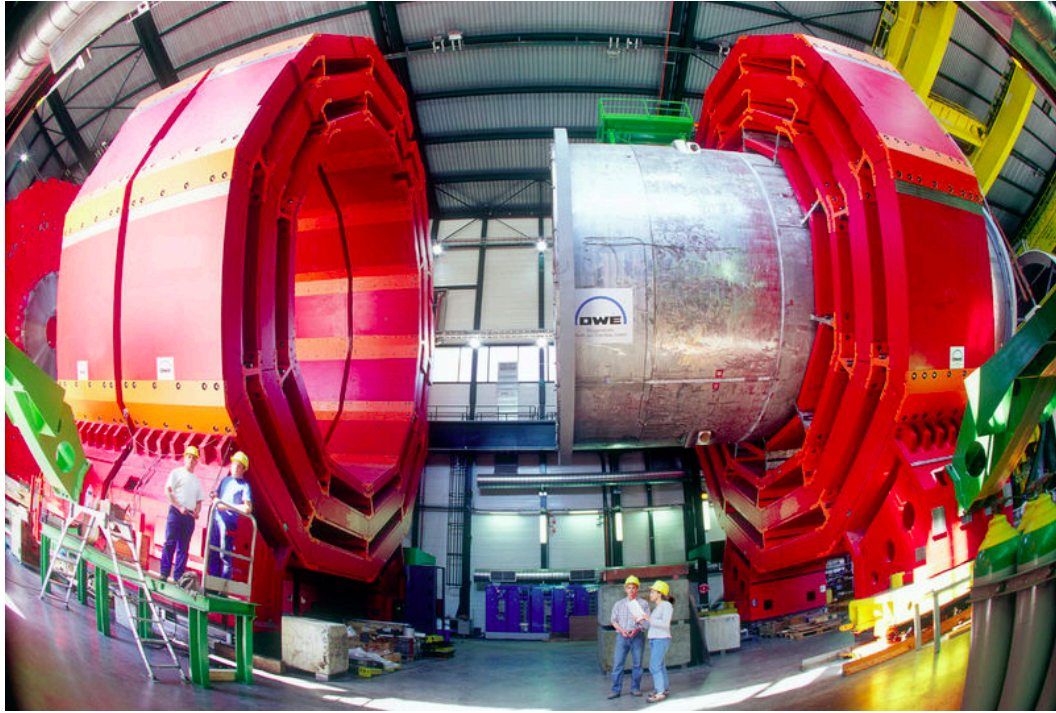


Figure 4.11: A view of 3 and 4 layers of barrel return yoke (red color) enclosing vacuum vessel. The figure is taken from <https://pdg.lbl.gov/pom/cms/ring.html>.

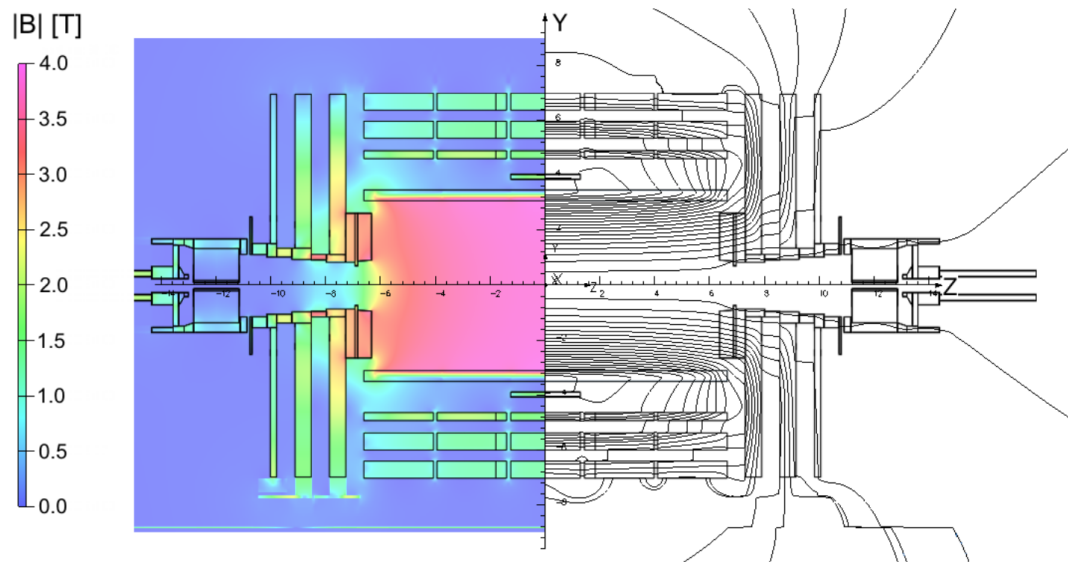


Figure 4.12: Predicted magnetic flux density (left) and field lines (right) of the CMS detector [106].

to reconstruct the 3-dimensional vertices, both the primary vertices⁵ and the secondary vertices formed due to unstable particle decay. The tracker is the innermost detector of the CMS and surrounds the interaction points. It has a length of 5.8 m and a diameter of 2.5 m and is completely surrounded by the volume of the solenoid magnet in the barrel region. The CMS tracker comprises of a pixel detector and a silicon strip tracker. A schematic view of the CMS tracker can be seen in Fig. 4.13.

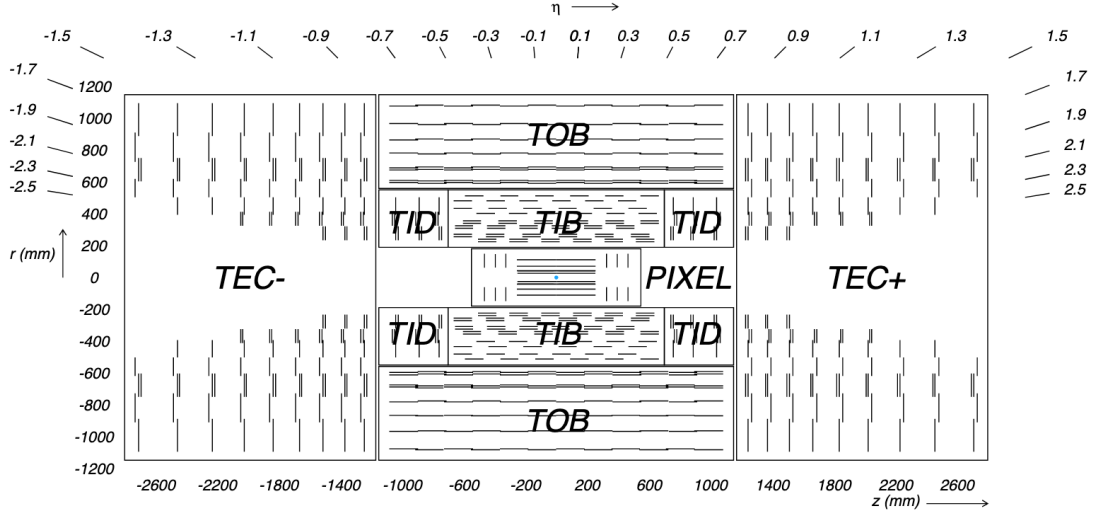


Figure 4.13: Schematic view of the CMS tracker in r - z plane [103].

The pixel detector is the closest detector to the interaction points and consists of four Barrel Pixel (BPIX) layers at radii of 2.9, 6.8, 10.9, and 16 cm, and three Forward Pixel (FPix) disks on each end at distances of 29.1, 39.6, and 51.6 cm from the center of the detector. Each BPIX layer is divided into two half-barrels and each has a total length of 54 cm. Similarly, each FPix disk is divided into two half-disks with a radial coverage from 4.5 to 16.1 cm. 1856 segmented silicon sensor modules are used (1184 modules are used in the BPIX and 672 modules are used in the FPix) to build the pixel detector. Each module has a size of $1.86 \times 6.66 \text{ cm}^2$ and consists of a sensor with 160×416 pixels. The size of one pixel is $150 \times 100 \mu\text{m}^2$. The total silicon area of the pixel detector is 1.9 m^2 and contains 124 million pixels. The pixel detector covers the pseudorapidity range

⁵The initial interaction points between protons or heavy-ions where the particles are emitted.

$|\eta| < 2.5$, and it has the spatial resolution of $\sim 9.5 \mu\text{m}$ and $\sim 22.5 \mu\text{m}$ in the transverse and longitudinal directions [107], respectively. A layout of the pixel detector can be seen in Fig. 4.14.

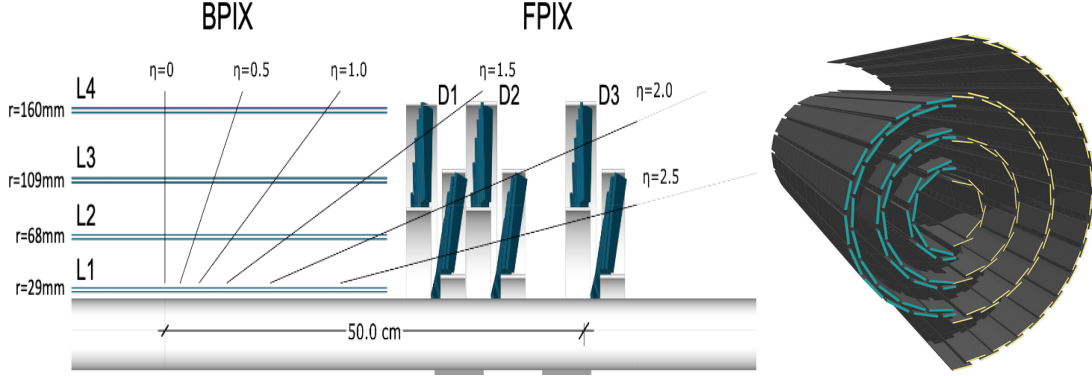


Figure 4.14: Left: layout of the CMS pixel detector. Right: transverse-oblique view of four pixel barrel layer (yellow color bands at the cross-sectional area). The three barrel layer with cyan color bands at the cross-sectional area was before the upgrade in 2016-2017. The Figure is taken from Ref. [107].

The silicon strip tracker occupies the outer region of the tracker with a total active silicon area of 198 m^2 which contains 9.3 million strips distributed in 24244 silicon sensors [103]. The silicon tracker is divided into four parts: Tracker Inner Barrel (TIB), Tracker Inner Disk (TID), tracker outer barrel (TOB), and tracker endcaps (TEC). The radial region (between 20 cm and 116 cm) is occupied by TIB, TID, and TOB. The TIB and TID extended to a radial distance of 55 cm. The TIB comprises of four cylindrical barrel layers and the TID comprises of three disks on each side. The TOB is made of six cylindrical barrel layers and extended to a radial distance of 116 cm. The TOB surrounds the TIB and TOB. The TIB covers the longitudinal distance of $z = \pm 60 \text{ cm}$ from the center of the detector, which is extended by TOB up to 118 cm. The TID is installed between the longitudinal distances of $z = \pm 80 \text{ cm}$ and $z = \pm 90 \text{ cm}$ with a radial coverage from 22.5 cm to 113.5 cm. The TEC, composed of nine discs containing up to seven rings, is positioned at each end of the tracker between the longitudinal distances of $z = \pm 124 \text{ cm}$ and $z = \pm 282 \text{ cm}$, and it covers a radial distance of 20 cm to 50 cm. The

sensors used in the TIB, TID, and the first four rings of TEC are made of $320\text{ }\mu\text{m}$ thick silicon micro-strips with their strips parallel to the beam axis in the barrel and radial on the disks. The TOB and the rest two rings of TEC are made of $500\text{ }\mu\text{m}$ thick silicon micro-strips. The average strip pitch varies between $80\text{--}120\text{ }\mu\text{m}$, $100\text{--}141\text{ }\mu\text{m}$, $122\text{--}183\text{ }\mu\text{m}$, and $97\text{--}184\text{ }\mu\text{m}$, in the TIB, TID, TOB, and TEC, respectively. The silicon strip detector extends the pseudorapidity range up to $|\eta| = 2.5$. The TIB and TID can obtain a spatial resolution of $\sim 23\text{--}35\text{ }\mu\text{m}$. In the longitudinal direction, the TIB and TID can achieve the spatial resolution of $\sim 230\text{ }\mu\text{m}$, and the TOB and TEC can achieve the spatial resolution of $\sim 530\text{ }\mu\text{m}$. A sketch of the Silicon strip tracker can be seen in Fig. 4.15.

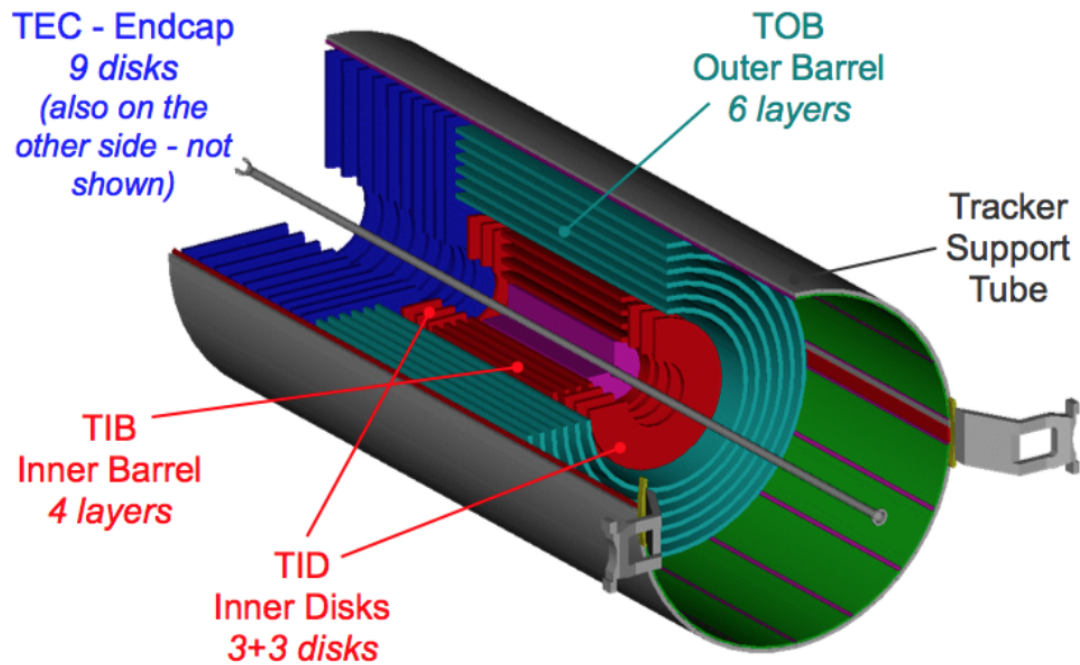


Figure 4.15: A sketch of the CMS Silicon strip tracker [108]. The pink color part represents the pixel detector.

The silicon pixel and silicon strip detectors are kept at $-20\text{ }^{\circ}\text{C}$ to reduce the damage by the continuous stream of particles. The working principle is the same for both these detectors. When a charged particle passes through the tracker, it interacts electromagnetically with silicon atoms in different layers of the tracker and produces electron-hole pairs. The electron signals from different layers are then collected and detected. The track

of a particle is reconstructed by combining the information from the different layers. Due to the magnetic field of 3.8 T, the trajectory of the charged particle bends, which helps to identify the electric charge of the particle. Using the information of electric charge, bending radius, and the magnetic field, it is possible to calculate the particle momentum. Once we reconstruct the track of the particles produced in the collisions or from secondary decays, 3-dimensional vertex positions can be determined.

4.2.4 Electromagnetic calorimeter (ECAL)

The CMS ECAL [103] is a compact, hermetic, and homogeneous calorimeter designed to fully absorb and measure the energy of electrons, positrons, and photons. It is made of 75848 lead tungstate (PbWO_4) scintillating crystals, with 61200 crystals in the barrel part and 14648 crystals in the two endcaps. These crystals are 98% metal but are completely transparent. The PbWO_4 crystal is chosen because of its radiation tolerance, small Molière radius⁶ (2.19 cm), small radiation length (0.89 cm), and high density (8.28 g cm^{-3}). It is also designed to have a fast response (25 ns) to match LHC running conditions. When a high-energy electron/positron or photon passes through the ECAL, it interacts with the nuclei of the crystal, loses energy mainly by bremsstrahlung or pair production, and generates a cascade of electromagnetic particles (photons, electrons, and positrons). This causes the crystals to emit blue scintillation light, which photodetectors measure. The energy that the incident particle deposits in the crystals directly relates to the overall amount of light that is generated.

The ECAL surrounds the tracker and has two parts, ECAL barrel (EB) and ECAL endcaps (EE). The cylindrical shape EB is made of 61200 crystals and covers the pseudorapidity range $|\eta| = 1.48$. Each barrel crystal is 23 cm long and has a front-face cross-section of $2.2 \times 2.2 \text{ cm}^2$. The crystals are grouped into 36 supermodules, each containing 1700 crystals. Each supermodule is composed of 4 modules, each containing 400 to 500 crystals. Silicon avalanche photodiodes (APDs) with an amplification factor of about 50

⁶It is a characteristic constant of material gives the transverse dimension of electromagnetic showers generated by incident electron/positrons or photons.

are used as photodetectors to measure the scintillation light. The operating voltage of APD is 340–430 V. A schematic layout and geometrical view of the CMS ECAL can be seen in Fig. 4.16. An artistic view of an electromagnetic shower in the single ECAL crystal can be seen in Fig. 4.16.

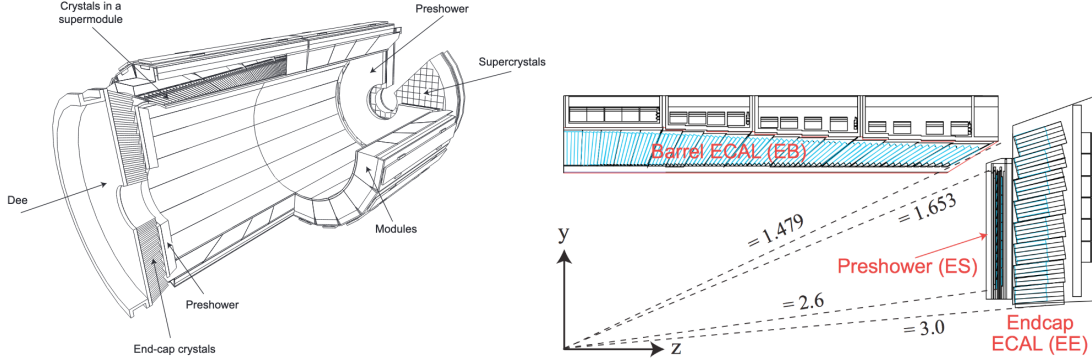


Figure 4.16: A schematic layout [103] (left) and a quarter-section [109] (right) of the CMS ECAL.

The two EE installed at $z = \pm 3.15$ m contains 14648 crystals (each EE contains 7324 crystals). The EE crystals are grouped in units of 5×5 crystal, called supercrystals. Each EE is divided into two halves called *Dees*, and each *Dees* contains 3662 crystals. The two EE extended the coverage of the ECAL to $|\eta| = 3$. The EE crystals are 22 cm long with a front-face cross-section 2.86×2.86 cm². To measure the scintillation light, vacuum phototriodes (VPTs) with an amplification factor of about ten are used as photodetectors in the EE. The VPTs are operated with the photocathode at ground potential and the dynode and anode biased at +600 V and +800 V, respectively. An artistic view of an electromagnetic shower generated in the single ECAL crystal can be seen in Fig. 4.17.

In addition to the EB and EE, there is an additional detector called the preshower (ES) detector (shown in Fig. 4.16) installed in the endcap between the tracker and EE with a total thickness of 20 cm. It is a sampling calorimeter with two layers: two lead absorbers that initiate electromagnetic showers, and silicon strip sensors are placed after each absorber to measure the deposited energy and the transverse shower profiles. A total of

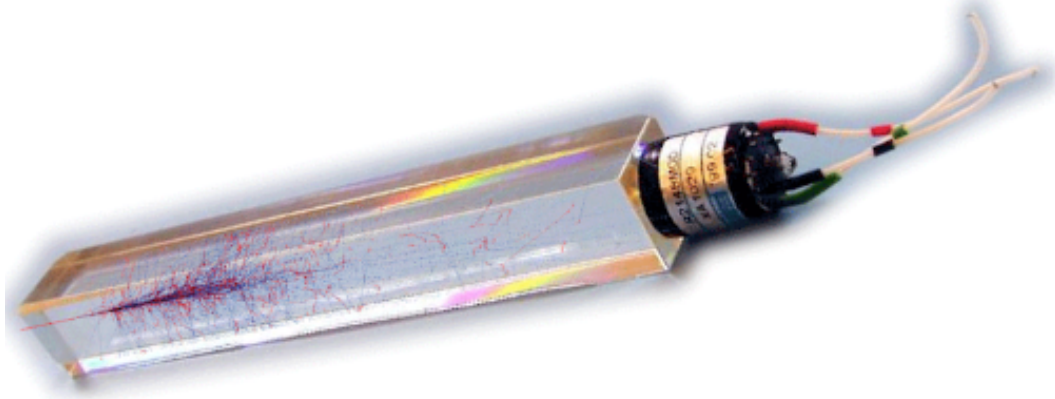


Figure 4.17: Artistic view of an electromagnetic shower generated in the single ECAL crystal. This figure is taken from https://thesis.fangmeier.tech/03_lhc_and_cms_detector.html.

4300 sensors are used. Each sensor has $61 \times 61 \text{ mm}^2$ active area and contains 36 strips with $320 \text{ }\mu\text{m}$ thickness and 1.9 mm pitch. The principal aim of the ES is to identify the single incident photons from the two closely spaced photons decaying from neutral pion π^0 in the endcaps.

The operating temperature influences the sensitivity of the crystals and the signal amplification of the APDs. A water flow cooling system is therefore put in place to maintain the crystals and sensors at a constant temperature of $18.00 \pm 0.05 \text{ }^\circ\text{C}$.

The energy resolution of the ECAL can be parameterized by [103]

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2, \quad (4.6)$$

where E is the deposited energy, σ_E is the error of E , S is the stochastic term, N is the noise term, and C is the constant term. Event-to-event fluctuations in the shower, fluctuation in the energy deposited in the preshower absorber, and fluctuation in the photodetector gain contribute to the stochastic term. There are three contributions to the noise term: noise due to electronics and signal digitization and pileup noise. Pileup noise occurs when additional particles reaching the calorimeter cause signal overlap.

The most important contributions to the constant term come from the non-uniformity of the longitudinal light collection, intercalibration errors, and leakage of energy from the back of the crystal [103]. By fitting the above equation to the energy resolution (σ_E/E) distribution as a function of E measured from a beam test found that $S = 2.8\%$ ($\text{GeV}^{1/2}$), $N = 12\%$ (GeV), and $C = 0.3\%$ [103].

4.2.5 Hadronic calorimeter (HCAL)

The HCAL [103] is a hermetic sampling calorimeter designed to completely absorb and measure the energy of charged and neutral hadrons. The ECAL and the HCAL complete the CMS calorimeter system and are combined to measure jets and missing transverse energy. The HCAL comprises of 70000 plastic-scintillator tiles interleaved with layers of absorber plate. The scintillator tile is used as an active material in the HCAL. When a charged hadron interacts with the absorber plate, it produces a shower of secondary particles, which pass through scintillator tiles located in between the absorbers. This leads to the emission of scintillator lights, which are collected by WaveLength-Shifting (WLS) fibres. The WLS fibre shifts the scintillator light to the green spectrum and passes it to fibre-optic waveguides. Finally, the lights are measured by photodetectors. The amount of light measured by photodetectors is proportional to the energy of the incident hadron. The HCAL surrounds the ECAL and is divided into four parts: HCAL Barrel (HB), HCAL Endcap (HE), HCAL Outer (HO), and HCAL Forward (HF). A geometrical view of the CMS HCAL can be seen in Fig. 4.18.

The central region of HCAL is divided into HB and HO. The HB is placed between the ECAL and the magnet coil and covers the pseudorapidity range $|\eta| < 1.3$. The HB is divided into two half barrels made from 36 identical azimuthal wedges. The wedges are made of flat brass absorber plates aligned parallel to the z -axis. The first eight brass absorber plates are 50.5 mm thick and the last six are 56.5 mm thick. For structural strength, the innermost and outermost plates are constructed from 40 mm and 75 mm thick stainless steel, respectively. The plastic scintillator tiles are divided into 16 η sectors

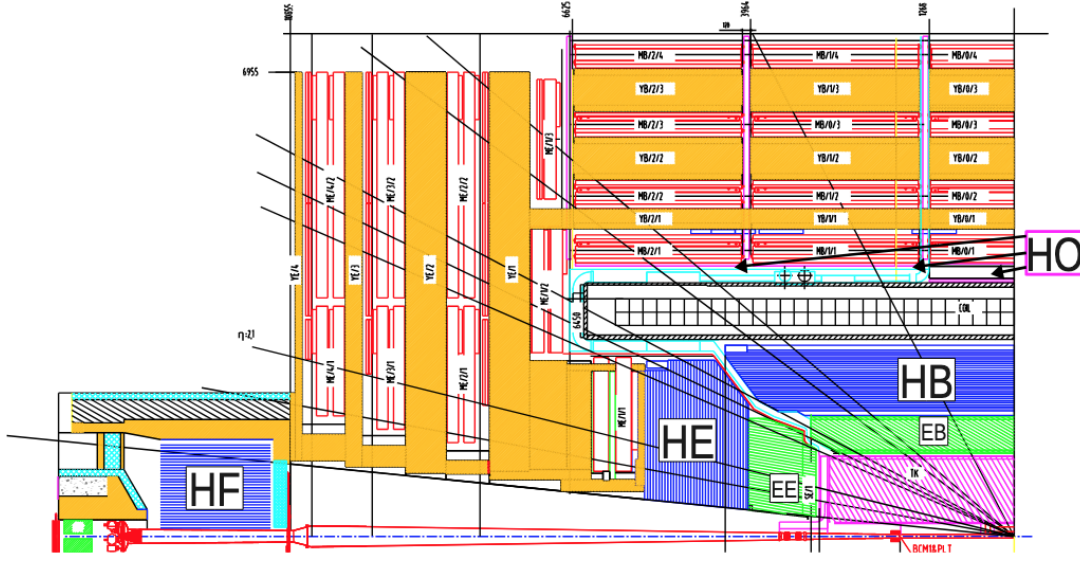


Figure 4.18: Geometrical view of one quadrant of the CMS detector showing the locations of the HB, HE, HO, and HF calorimeters [110].

and segmented into multiple $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ towers. The HB uses Hybrid PhotoDiode (HPD) transducers to measure the light.

The HO is placed between the solenoid and steel return yoke and covers the pseudorapidity range $|\eta| < 1.4$. The HO functions as a tail-catcher for hadronic showers and is useful for muon identification. The HO uses the same active material as HB, but for the absorber, HO uses the steel return yoke and magnet material of CMS. The HO has 2730 scintillator tiles providing roughly the same towers of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ as the HB. The HO uses Silicon PhotoMultiplier (SiPM) to measure the scintillation light.

The HE functions the same way as the HB and is placed in the endcap covering the pseudorapidity range $1.3 < |\eta| < 3$. The HE comprises of 79 mm thick brass plates with a 9 mm thick gape to accommodate the scintillators. It contains 20916 plastic scintillator tiles and provides the towers of granularity $\Delta\eta \times \Delta\phi = 0.17 \times 0.17$. The HE also uses HPDs to measure the scintillator light.

The pseudorapidity range of the HCAL is extended to $|\eta| < 5$ by installing the HF located

at $z = \pm 11.2$ m. Due to the high energy deposition at the forward side, it is designed to handle high radiation levels. The HF uses steel as an absorber and radiation hard quartz fibre as active material. The steel absorbers are made of 5 mm thick grooved plates, and the fibres are inserted in these grooves. The HF is a cylindrical steel structure with an outer radius of 130 cm. The fibres are placed parallel to the beamline and are bundled to form 0.175×0.175 ($\Delta\eta \times \Delta\phi$) towers. The HF is a Cherenkov calorimeter. When energetically charged particles from the shower pass through the quartz fibres, Cherenkov light is generated and collected by multi-anode PhotoMultiplier Tubes (PMT).

The approximate energy resolution of HCAL was obtained from the test beam as [111]

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{120\%}{\sqrt{E}}\right)^2 + (5\%)^2 \quad (4.7)$$

4.2.6 Muon system

The muon system [103] is designed and installed in the outer part of the detector with detection area $\sim 25000 \text{ m}^2$ to measure the momentum and charge of the muons in the pseudorapidity range $|\eta| < 2.4$. It also provides the trigger for the muons [103]. It is composed of a cylindrical barrel section and two planar endcap regions. CMS muon system uses three types of chambers for muon identification, which are Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC). These are gaseous particle detectors and are placed inside the return yoke. Most of the electrons/positrons, photons, and hadrons lose their energy and are stopped by the calorimeters, whereas the muons can reach the muon system losing only a tiny portion of their energy. When a muon passes through these gaseous detectors, it ionizes the gas atoms and produces electron-ion pairs. Then the free electrons and ions accelerate toward the anode and the cathode, respectively, due to the electric field produced by the applied potential difference between them. While accelerating toward the respective electrode (anode and cathode), the electron and ions can also ionize the gas atoms, creating an avalanche effect. The electronic system collects these electron-ion pairs, which allows for measuring the

muons.

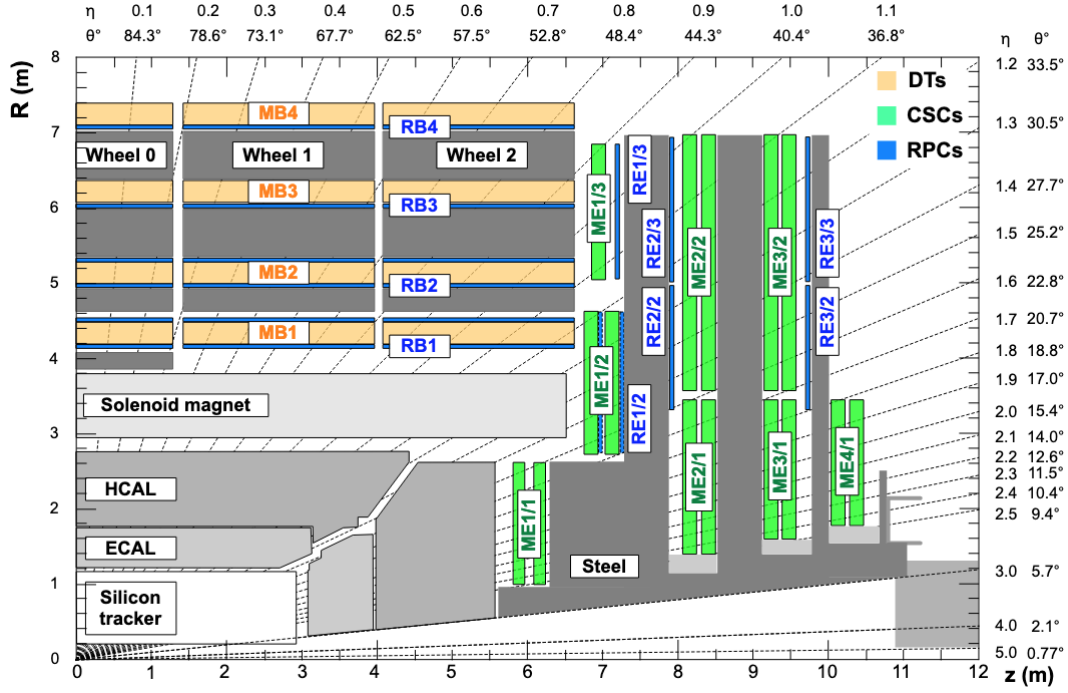


Figure 4.19: Longitudinal view of a quadrant of the CMS detector in r - z plane [112]. The chambers are shown in orange (DT), green (CSC), and blue (RPC).

In the barrel regions, DT detectors are arranged into four stations between the layers of the flux return yoke and cover the pseudorapidity range $|\eta| < 1.2$. The four stations correspond to four concentric cylinders. The first three cylinders contain 60 DT chambers each, while the fourth cylinder includes 70. The transverse dimension of the drift cell is 21 mm and filled with a gas mixture of 85% argon (Ar) and 15% carbon dioxide (CO₂). The DT contains 172000 sensitive anode wires of 2.4 m length and 50 μ m diameter to collect the charge of the drift electrons.

The 486 CSCs are installed in the endcap region and cover the pseudorapidity range $0.9 < |\eta| < 2.4$. The CSC system is built to handle the larger non-uniform magnetic field and the higher particle rate in the forward region. The CSCs are trapezoidal shaped multiwire proportional chambers with six anode wire planes arranged between seven copper cathode panels. The gap between the cathode panels is filled with a gas mixture

of 40% Ar, 50% CO₂, and 10% carbon tetrafluoride (CF₄). There are about 180000 anode wires to collect the electron charges.

The barrel and endcap sections complement RPC detectors with good time resolutions to enable fast muon triggering and cover the pseudorapidity range $|\eta| < 1.6$. The RPC signal directly provides the time and position of a muon hit with the desired accuracy. An RPC is a double-plate gaseous detector with two gaps filled with a gas mixture of 96.2% freon (C₂H₂F₄), 3.5% isobutane (*i*C₄H₁₀), and 0.3% sulfur hexafluoride (SF₆). In the barrel section, 480 rectangular RPC chambers form six coaxial cylinders around the beam axis and are arranged into four stations.

4.2.7 Trigger system and data acquisition

LHC is designed to collide two proton beams with the luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. With this luminosity, the expected bunch crossing is 40 million per second (40 MHz) with 25 ns bunch spacing, and each bunch crossing (one event) results in about 1 Megabyte (MB) of data. With these LHC conditions, the CMS experiment collects ~ 0.5 Picobyte (PB) of data per second and stores it in the CERN main computing farm (Tier-0) for further processing with the CMS SoftWare (CMSSW). But, the Tier-0 input and processing rate is limited by its storage capacity and CPU performance. The input data rate should be reduced to around or less than 1 GB/s. Also, not all events contain the physics of interest in the CMS physics program. Only a small fraction of events have interesting physics and are stored for later offline analysis. Therefore, a trigger system [113] is required to reduce the event rate and store the events of potential physics interest. The CMS trigger system utilizes two-level triggers: the Level-1 (L1) Trigger and the High-Level Trigger (HLT).

Level-1 (L1) trigger

The L1 trigger system [114] is an extremely fast and hardware based trigger that uses the information from the calorimeters (ECAL and HCAL) and the muon system to decide whether the event will be stored or not within $4 \mu\text{s}$ of a collision. With the

help of this trigger, the event rate can be lowered from 40 MHz to under 100 kHz. The selection is performed using a list of algorithms (called “seeds”) that check events against predetermined criteria, collectively called “menu”. Any event that meets the requirements of at least one seed in the menu is accepted for further processing in the trigger chain. Trigger algorithm consists of criteria applied to one or more objects such as muons, hadronic jets, tau leptons, photons or electrons, etc. Standard criteria include thresholds on the transverse component of the object’s energy E_T (or momentum) and its η [114].

High-Level trigger (HLT)

It is a software based trigger that further reduces the event rate to less than 1 kHz before data storage [113]. After the HLT trigger, the data storage rate is reduced to ~ 100 MB/s. The HLT is executed on a processor farm composed of multi-core computers which run scientific Linux. The HLT software consists of filter-builder units. The builder units assembled the individual event fragments from the detector to form complete events. Then these events are subsequently sent to the filter unit. The filter unit then reconstructs these events and selects them for data analysis. The event selection at the HLT is performed similarly to that used in the offline analysis (e.g., jets with energy higher than 20 GeV).

After L1 and HLT trigger selections, the events are stored in the RAW data format. The RAW data contains all the information from the detector with the size of ~ 0.75 MB per event, and generally, it is not used directly for analysis. An offline reconstruction is performed over RAW data using CMSSW and saved in a new data format called RECO⁷ with the size of ~ 1.5 MB per event. The RECO data contains reconstructed physics objects (e.g., tracks, vertices, jets, electrons, muons, etc.) and reconstructed hits. The RECO data can be used for analysis, but it is too big to be used frequently once the CMS has gathered a sizable data sample. A distilled version of data called AOD⁸ is derived

⁷RECOⁿstructed data

⁸Analysis Object Data

from the RECO to provide data for physics analysis in a convenient and compact format. AOD data format is a subset of RECO and usable directly by physics analyses with the size of ~ 0.1 MB per event. It contains the physics objects (e.g., tracks, vertices, jets, electrons, muons, etc.) and possibly small quantities of very localized hit information.

This thesis uses the AOD data to produce the results. But nowadays, people further reduce the event size and create new data formats, MiniAOD and NanoAOD, with the typical size of ~ 35 Kilobyte (KB) and ~ 2 KB per event, respectively. During Run-1 and 2, the CMS heavy-ion data are stored in AOD data format. But the pp collisions data are stored in AOD data format during Run-1 and in MiniAOD and NanoAOD data formats during Run-2. For Run-3, the heavy-ion data will be stored in MiniAOD data format.

4.2.8 computing resources

The CMS computing environment has been constructed as a distributed system of computing services and resources that interact with each other as Grid services. The set of services and their behaviour comprise the computing, storage, and connectivity resources that CMS uses for data processing, data archiving, Monte Carlo event generation, and all kinds of computing-related activities. More than 170 computing centers in 42 countries share their resources in the grid. This structure is called Worldwide LHC Computing Grid (WLCG). The computational infrastructure is meant to be accessible to the CMS collaborators equitably, regardless of their physical locations. The computing centers available to CMS worldwide are distributed and configured in a tiered architecture. Each of the four tier levels provides different resources and services.

Tier-0 (T0)

The first tier is Tier-0 (T0), for which only one site is located at CERN. It stores RAW data coming from the detector, repacks the RAW data into primary datasets based on trigger information, and distributes RAW datasets among the next tier stage resources

(Tier-1) so that two copies of every piece of RAW data are saved for safety. It also performs first pass reconstruction (called Prompt), which writes the RECO, AOD, and MiniAOD datasets and distributes them among Tier-1 centers. The T0 does not provide analysis resources.

Tier-1 (T1)

The second stage of resources are called Tier-1 (T1). There are 14 T1 sites, which are large centers in CMS collaborating countries (large national labs, e.g., Fermilab). The T1 sites provide substantial computing power for the re-reconstruction of RAW data after any modifications in the reconstruction algorithms, dataset skimming, calibration, and AOD extraction. Each T1 site stores a full copy of the AOD and a subset of RAW data received from T0 (safety copy) and distributes the RECO, skim, and AOD dataset to the other T1 centers and the associated group of Tier-2 centers. It also provides secure storage for Monte Carlo (MC) events generated by the Tier-2 sites.

Tier-2 (T2)

There are a total of 155 smaller Tier-2 (T2) sites, mostly in universities and specific institutes (e.g., Tata Institute Of Fundamental Research (TIFR), India), which store sufficient data and provide adequate computing power for the physics analysis, calibration, and MC production for the whole experiment. Each Tier-2 is associated with a specific Tier-1 site.

Tier-3 (T3)

The final stage resources are called Tier-3 (T3). The T3 resources are much smaller and consist of local clusters in a university department or even an individual PC, providing local grid access. There is no formal engagement between T3 resources and WLCG. Compared to a Tier-2 site, Tier-3 facilities give physicists more freedom to test and debug their code and the freedom and flexibility to do the studies they want.

CHAPTER 5

DATA ANALYSIS

5.1 ANALYSIS TOOLS

The analysis tools used in this thesis include a MacBook laptop, HP and iMac desktops, the high-performance computing resources at TIFR and CERN, the C++ programming language, and the ROOT analysis software for high-energy physics investigations. The CERN lxplus system processes the CMS data files using the crab task submission framework and saves them in tree format root files at the TIFR Tier-2 computing center. CMSSW release version 10_3_1_patch2 and a dedicated C++ macro were used to process the CMS data files. Finally, the analysis is performed using the CERN lxplus system by writing the C++ macro that takes the input of tree format root files.

5.2 DATA AND MONTE CARLO SAMPLES

The analysis of V^0 particles (K_S^0 , Λ , and $\bar{\Lambda}$) femtoscopic correlations in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is performed using data recorded by the CMS experiment during the 2018 LHC run, corresponding to a total integrated luminosity¹ of about 0.61 nb^{-1} . Official golden json² file has been applied to select good runs³ certified by the CMS data certification team. The official data samples used in this analysis are listed in Table 5.1 below. This analysis uses 4.27×10^9 minimum bias (MB) events that are triggered by requiring signals above the readout threshold of 3 GeV in each of the HF calorimeters [113].

The Monte Carlo (MC) samples for PbPb collisions are generated based on HYDJET 1.9 [41] in this analysis to determine the performance of track reconstruction, event

¹<https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>

²json: JavaScript Object Notation

³A run refers to the data taken during a continuous recording session of the CMS detector.

Table 5.1: Official data samples for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Run Range	Dataset
326381–327564	/HIMinimumBias[0-19]/HIRun2018A-04Apr2019-v1/AOD

selection efficiency, and cross-check of other potential detector effects. The sample is produced with the “data-taking” detector conditions and listed in Table 5.2.

Table 5.2: HYDJET MC samples for $\sqrt{s_{\text{NN}}} = 5.02$ TeV in PbPb collisions

Generator	Dataset
HYDJET	/MinBias_Hydjet_Drum5F_2018_5p02TeV/HINPbPbAutumn18GS-103X_upgrade2018_realistic_HI_v11-v1/GEN-SIM
HYDJET	/MinBias_Hydjet_Drum5F_2018_5p02TeV/clindsey-RECODEBUG_20190625-5db5dfa073297cb96791f14c622e83e2/USER

5.3 EVENT SELECTIONS

The MB data sample contains several background events which are not coming from hadronic collisions, such as beam-gas collisions⁴, electromagnetic interactions (ultra-peripheral collisions (UPC)⁵), and beam scraping events⁶. Therefore, the events for 2018 PbPb collisions are further selected offline following the recipes from the Global Observable group in CMS⁷: a primary vertex filter (*pprimaryVertexFilter*), an HF coincidence of two towers activated with at least 4 GeV (*phfCoincFilter2Th4*), and a cluster compatibility filter (*pclusterCompatibilityFilter*) are used. These filters help to remove beam-gas collisions, beam scraping events, and UPC events. Details about these filters are described below.

- **pprimaryVertexFilter:** This filter requires an event with at least one primary interaction vertex determined using two or more tracks with z-positions of the vertex (v_z) should be lies between ± 25 cm, and the transverse positions of vertex

⁴Collisions of the beam with remaining gas inside the beam pipe.

⁵No physical interaction between two lead (Pb) nuclei. Interaction happens between γ and Pb.

⁶Events with a very large number of tracks in the tracker without any sign of a common origin within the CMS detector.

⁷Section “Event Selection (PbPb Data 2018)” from <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideHeavyIonCentrality>.

$\rho = \sqrt{v_x^2 + v_y^2} < 2$ cm. This requirement of accepted vertex removes non-inelastic collision events (e.g., beam-gas collisions and UPC events) with large HF energy deposits but very few pixel hits.

- **phfCoincFilter2Th4:** This filter requires at least 2 towers on each side of the interaction point in the HF with a tower above the 4 GeV threshold. This requirement removes approximately 99% of UPC events.
- **pclusterCompatibilityFilter:** A particle traversing a pixel module at some angle leaves a cluster with a width proportional to its angle of incidence. The particle pseudorapidity and z-position of the collision vertex can determine the expected width of the cluster. For a given z-position, one can determine the number of clusters in the event that have a width compatible with the hypothesis that the collision vertex was at the z-position. One can scan the z-axis to determine how many clusters are compatible with a vertex at each position. This technique can be used to locate the z-position of a collision vertex or determine if a collision likely occurred outside the interaction region (i.e., beam scraping events).

In addition, the primary vertex position in the z direction (v_z) is required to be within 15 cm. These requirements help to remove beam-gas collision events, beam scraping events, and UPC events from the data sample and provide pure hadronic events for the analysis.

5.4 CENTRALITY DETERMINATION

Heavy-ion events are classified as centrality classes, where centrality refers to the percentage of the total inelastic hadronic nucleus-nucleus cross section, and 0% corresponds to the maximum overlap of the colliding nuclei. The centrality classes for 2018 PbPb collisions are determined using an event variable called HF transverse energy (E_T). It is the total transverse energy (E_T) deposited in the HF calorimeters per event. The events are divided into 200 centrality bins, each of which corresponds to a centrality class that makes up 0.5% of the total inelastic hadronic cross-section. The bin boundaries are a simple list of HF E_T after passing through the MB trigger and the event selection criteria described in sec. 5.2 and 5.3. The HF E_T values for each event are sorted and divided into 200 parts. Figure 5.1 shows the HF E_T distribution and the centrality bin boundaries in data.

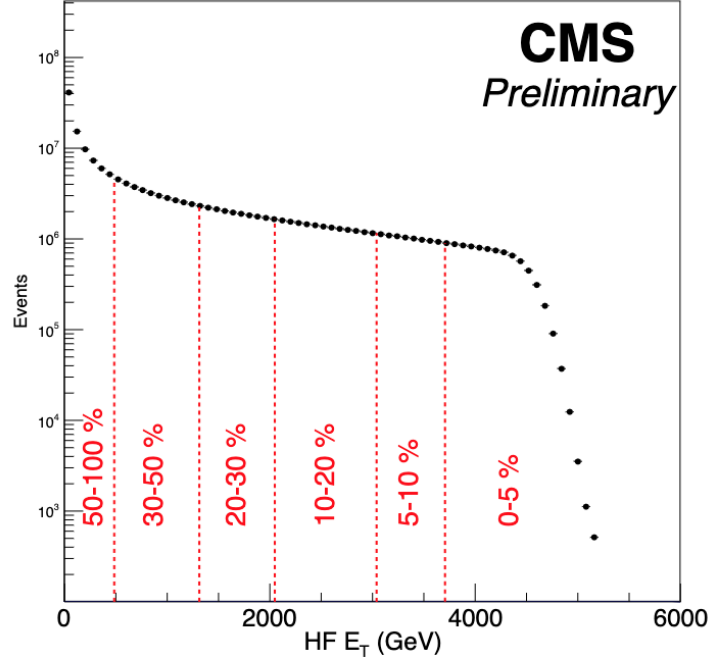


Figure 5.1: Distribution of the sum of E_T deposited in the HF calorimeters for MB events. The centrality classes are shown in red.

HYDJET MC sample with HF E_T less than a chosen threshold was used to account for the event selection efficiency and contamination that affect the peripheral events. The HF E_T distribution from HYDJET MC sample is scaled along the x-axis by a scale factor called “MC X scale” to match the data in the central region with best χ^2 value. The χ^2 values are computed by fitting HYDJET distribution to the data for the different scale factors. The MC X scale = 0.86 had the best χ^2 and was used to calculate the efficiency and contamination. The data/MC ratio is interpreted as efficiency and contamination and found to be $\sim 97\%$. The HF E_T threshold was also determined in the same way as done for the MC X scale. The left panel of Fig. 5.2 shows the HF E_T distributions in HYDJET MC (solid line) and data (circles). The nominal HF E_T threshold was chosen to be 100 GeV. The right panel shows the centrality bin distributions for the 2018 PbPb data using three HF E_T thresholds. The nominal HF E_T threshold was chosen to be 100 GeV, and the other two values are used as systematic variations. The excess of events in the peripheral regions (hiBin $\approx [160-200]$) indicates remaining electromagnetic

contamination after event selection. Each hiBin corresponds to a centrality value of 0.5%, i.e., 5% corresponds to hiBin 10, 50% corresponds to hiBin 100, and so on. To avoid electromagnetic contamination, we performed the analysis up to 80% centrality.

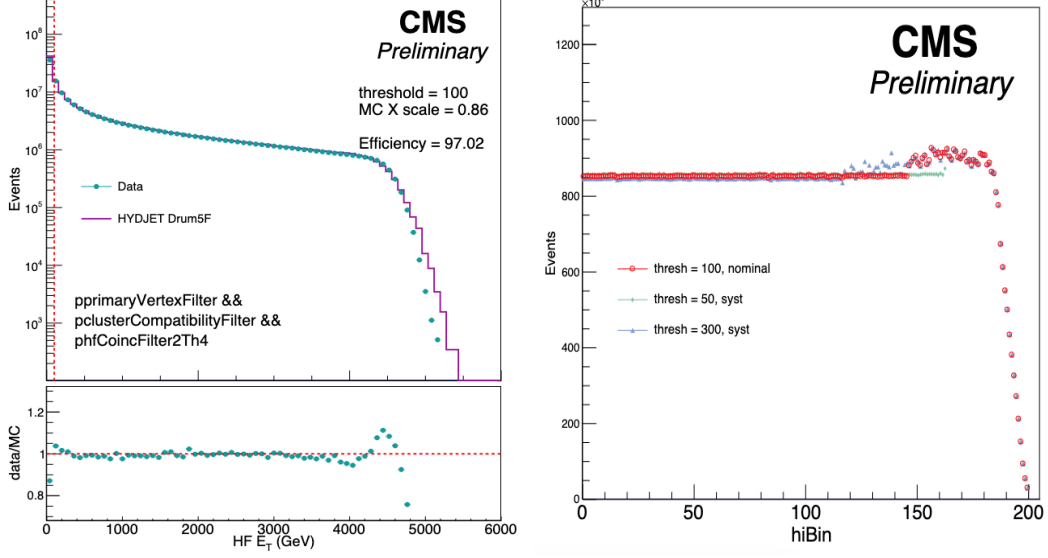


Figure 5.2: Distribution of the sum of transverse energy deposited in the HF calorimeters for MB events. The centrality classes are shown in red.

5.5 RECONSTRUCTION OF K_S^0 AND Λ CANDIDATES

The K_S^0 and $\Lambda(\bar{\Lambda})$ candidates, denoted as V^0 candidates, used in this study are reconstructed as in previous CMS analyses [18, 115, 116]. The V^0 candidates are generally reconstructed from their decay products because they decay after traveling a certain distance (e.g., $c\tau \approx 2.6844$ cm for K_S^0 and $c\tau \approx 7.89$ cm for $\Lambda/\bar{\Lambda}$). A typical V^0 decay topology can be seen in Fig. 5.3. The V^0 candidates are found by combining oppositely charged tracks that pass criteria based on the “loose” selection discussed in Ref. [117]. The charged tracks are assumed to be $\pi^+\pi^-$ in K_S^0 reconstruction and π^-p in Λ reconstruction. For the latter, the higher momentum track is assumed to be a proton since the proton carries nearly all of the momentum in the Λ decay. Each oppositely charged track must have hits in at least three layers of the silicon tracker, and both tracks must have transverse and longitudinal impact parameter significances (defined as the

parameter value divided by its uncertainty) with respect to the primary vertex greater than 1. The two tracks are fitted to a common vertex and the χ^2 per degree of freedom (dof) from the fit must be less than 7. The distance of the closest approach between the two tracks is required to be less than 1 cm. As a consequence of the long lifetime of K_S^0 and Λ particles, the significance of the V^0 decay length, which is the three-dimensional distance between the primary and V^0 vertices divided by its uncertainty, is required to be greater than 2.5 to reduce combinatorial backgrounds contributions. To remove K_S^0 candidates misidentified as Λ particles and vice versa, the $\Lambda(K_S^0)$ candidates must have a corresponding $\pi\pi$ ($p\pi$) mass more than 14 (7) MeV (corresponding to approximately three times the average resolution) away from the world-average value [27] of the $K_S^0(\Lambda)$ mass. Details about the removal of misidentified V^0 candidates can be seen in sec. 5.5.2. The angle θ between the V^0 momentum vector and the vector connecting the primary and V^0 vertices is required to satisfy $\cos \theta > 0.999$. This reduces the contribution from nuclear interactions, random combinations of tracks, and Λ particles originating from weak decays of Ξ and Ω particles. Further selection of V^0 candidates is performed with a boosted decision tree (BDT) method [118], described in the next section.

5.5.1 BDT selection

To maximize the V^0 selection efficiency and minimize the combinatorial background, the BDT method is used, which has been implemented in the ROOT [119] Toolkit for Multivariate Data Analysis (TMVA)⁸ [118]. The BDT training is performed using the simulated MB sample (HYDJET) separated into the signal and background subsamples using the generator-level information. Those reconstructed V^0 candidates are matched with the generator-level candidates, we label them as signals, and for those that are not matched, we label them as backgrounds. The training variables include: the collision centrality, the V^0 candidate p_T and rapidity (y), the distance of closest approach of the track pair, the three-dimensional decay length and significance, $\cos \theta$, and the V^0 vertex

⁸TMVA is specially designed for machine learning application of high energy physics which provides the environment for the processing, parallel evaluation, and application of multivariate classification and multivariate regression techniques.

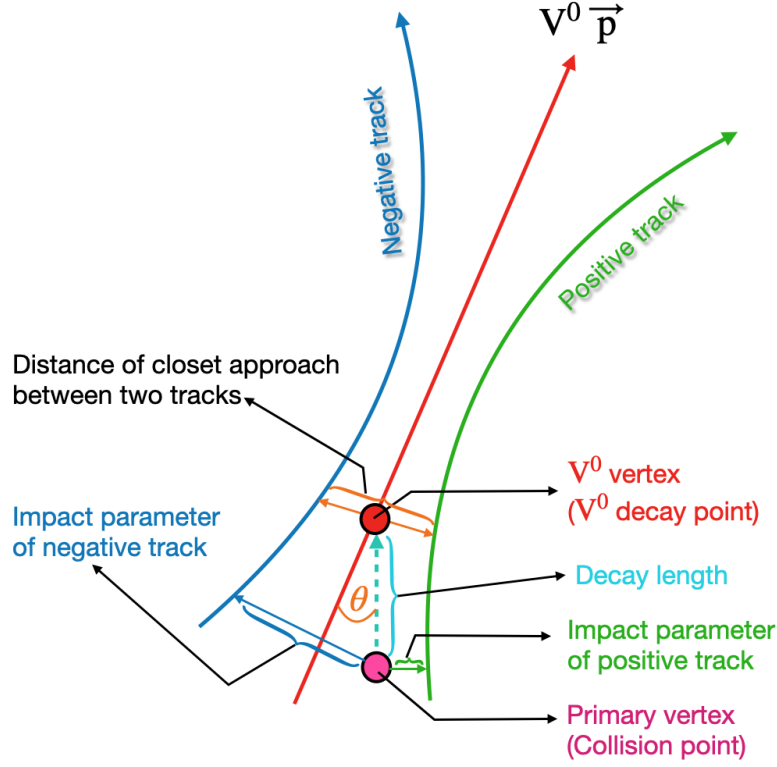


Figure 5.3: Schematic view of the V^0 decay.

fit χ^2 . The included variables related to the V^0 daughters are p_T , uncertainty in p_T , η , the number of hits in the silicon tracker, the number of pixel detector layers with hits, and the transverse and longitudinal impact parameter significances with respect to the primary vertex. The BDT training is performed using the simulated minimum bias sample separated into the signal and background subsamples using the generator-level information. The variables used in the training process are listed in Table 5.3. There are also spectator variables listed in Table 5.4. The comparison between signal and background samples for each training variable is shown in Fig. 5.5 for K_S^0 and Fig. 5.7 for Λ . Also, the correlation matrix of input variables is shown in Fig. 5.8 for K_S^0 and Fig. 5.9 for Λ . A data and MC comparison of all the variables used in training can be seen in sec. A.1. There is a very good agreement for the variables between data and MC.

The ROC (receiver operating characteristic) curves of the MVA selection based on the MC are shown in Fig. 5.10. The training was done by taking 250 and 850 decision

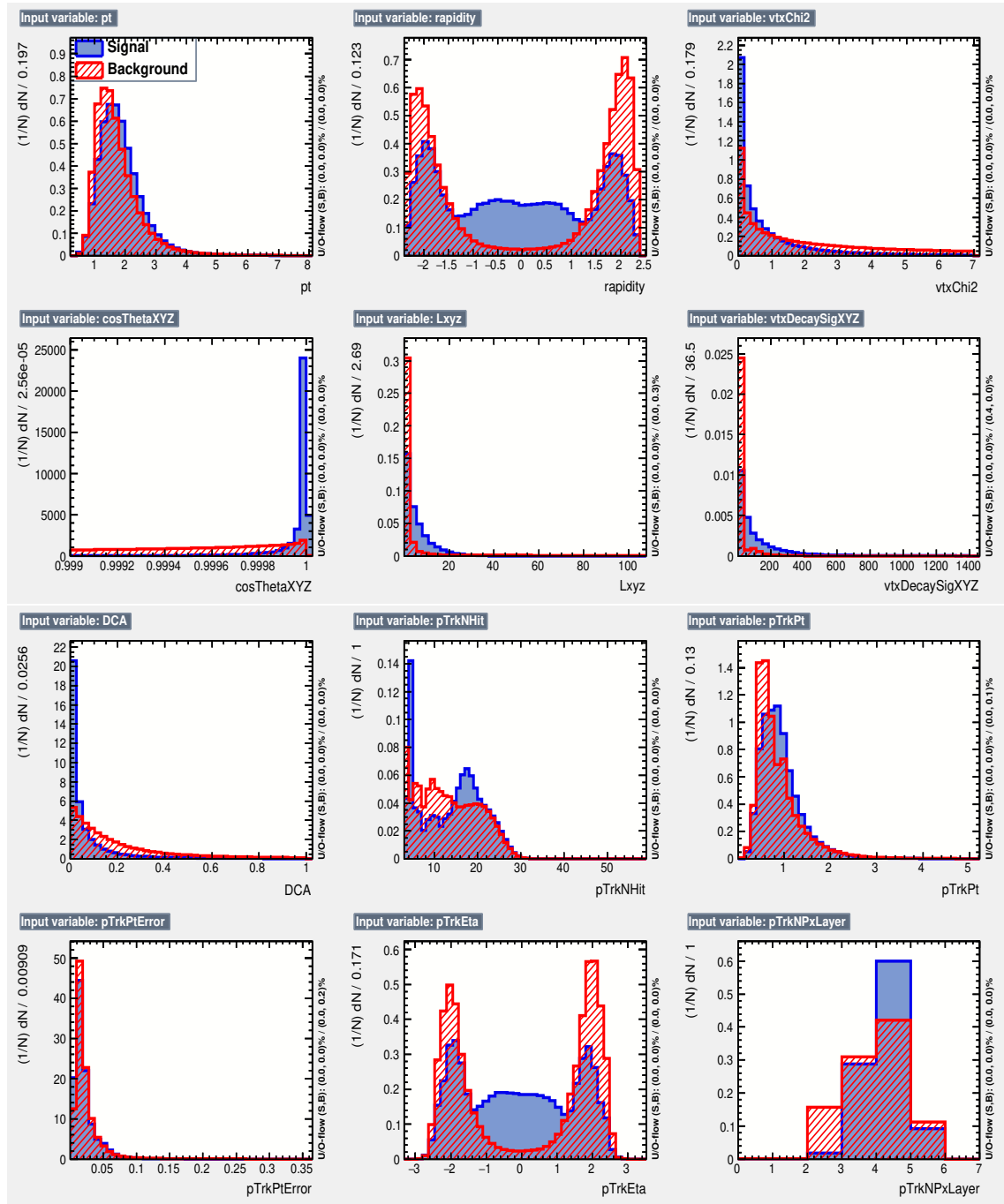


Figure 5.4: Comparison of K_S^0 training variables between signal and background samples from MC.

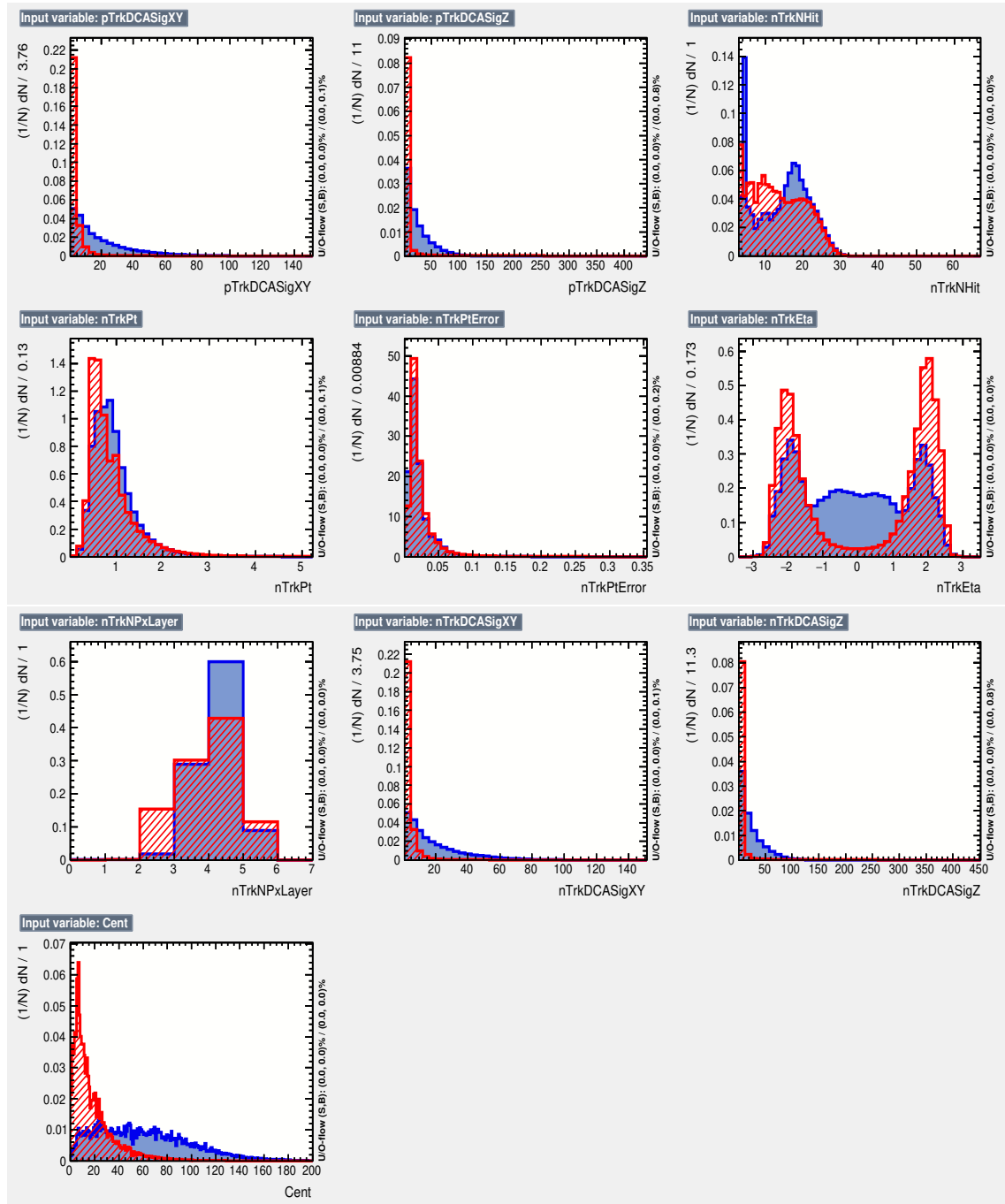


Figure 5.5: Comparison of K_S^0 training variables between signal and background samples from MC.

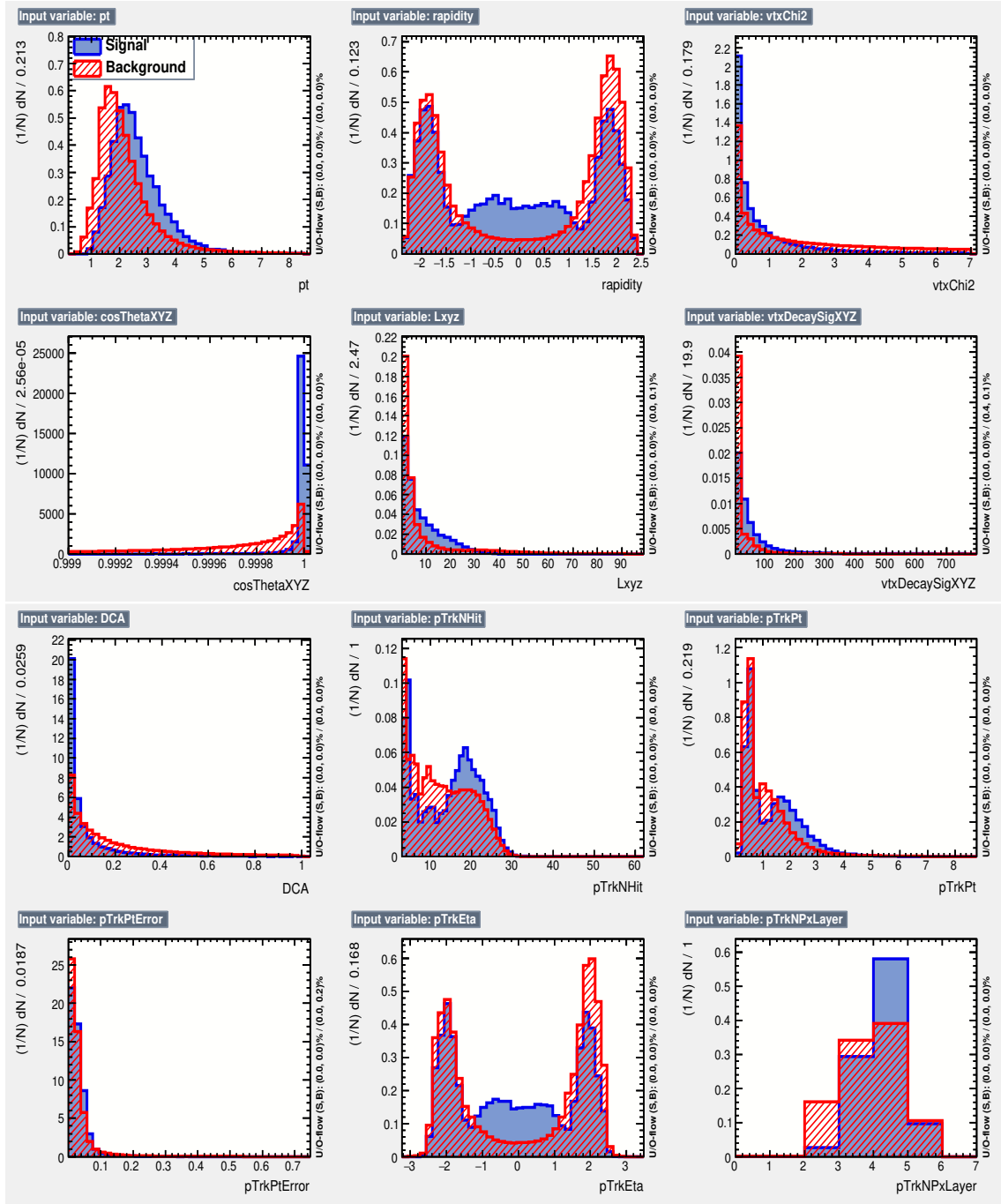


Figure 5.6: Comparison of Λ training variables between signal and background samples from MC.

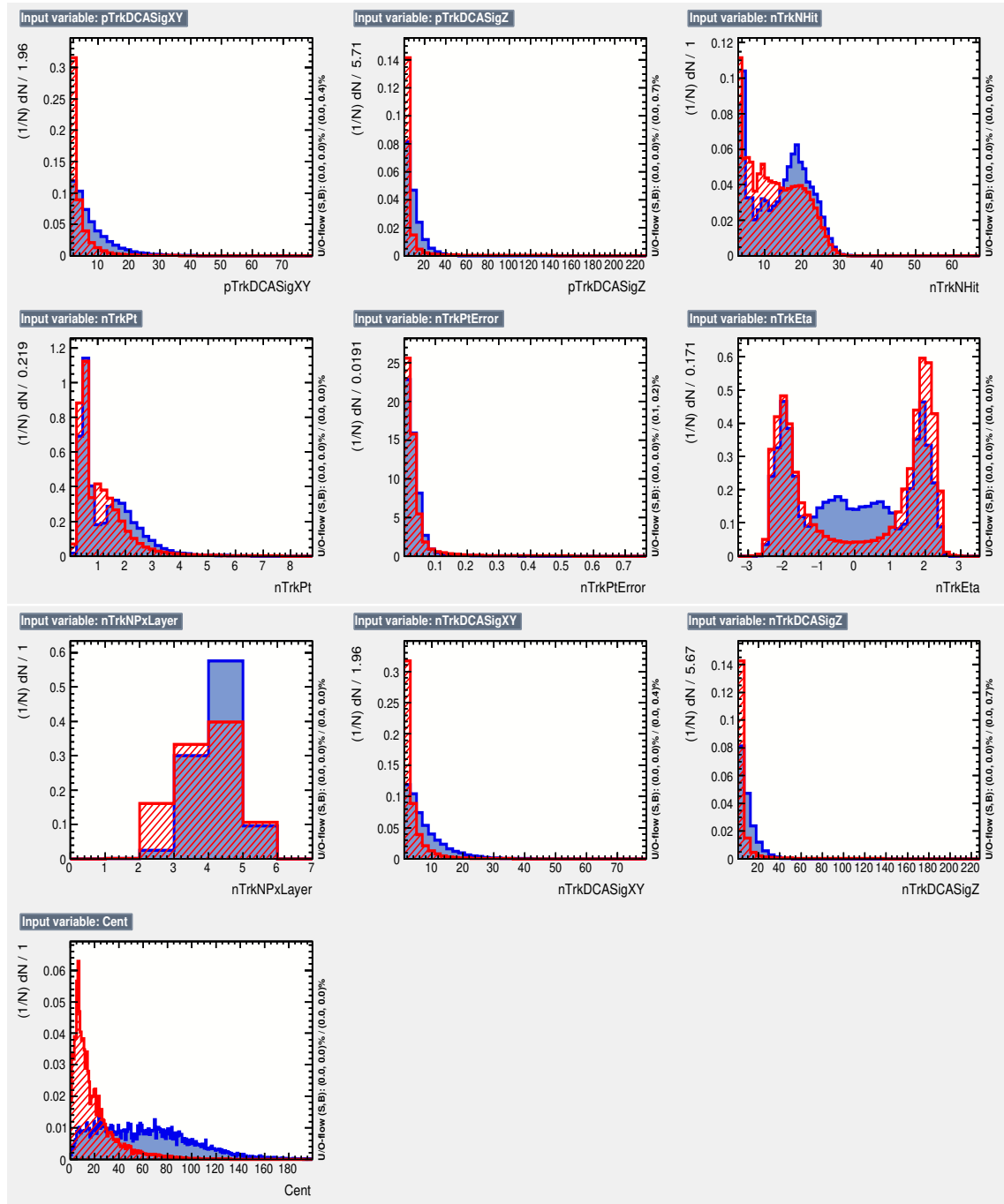


Figure 5.7: Comparison of Λ training variables between signal and background samples from MC.

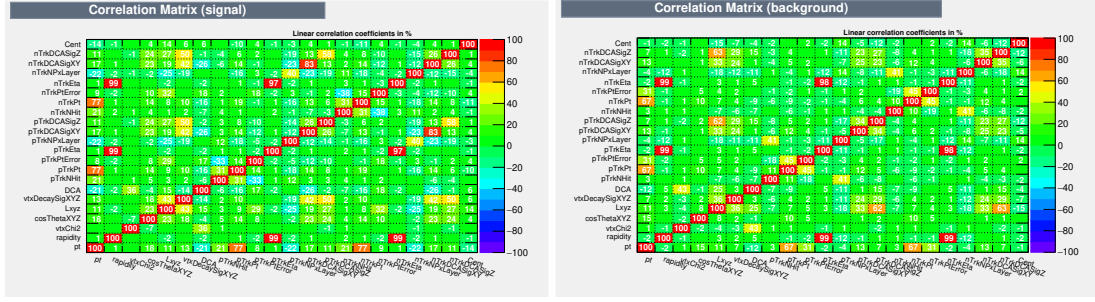


Figure 5.8: Correlation matrix of K_S^0 input variables. The values are linear correlation coefficients between the input variables for signal (left panel) and background (right panel) training samples.

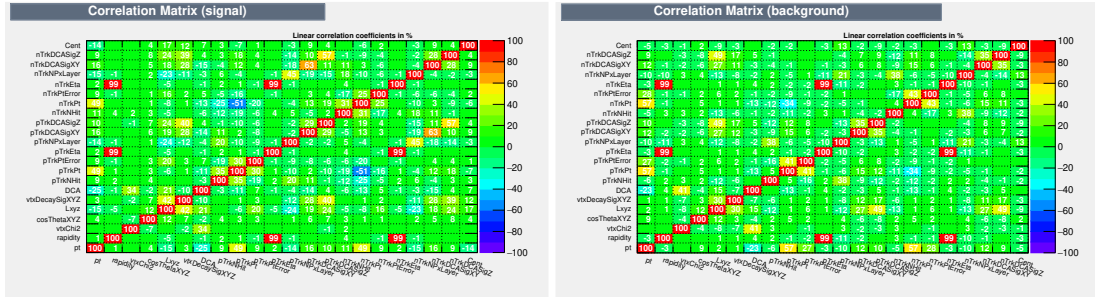


Figure 5.9: Correlation matrix of Λ input variables. The values are linear correlation coefficients between the input variables for signal (left panel) and background (right panel) training samples.

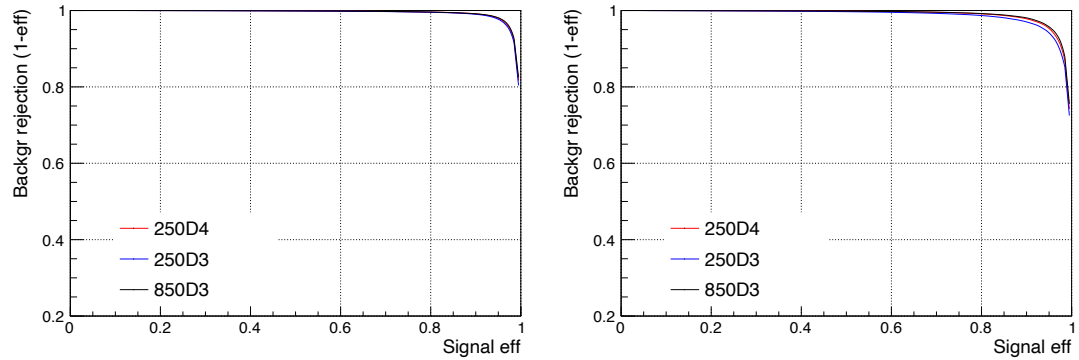


Figure 5.10: ROC curves (background rejection vs signal efficiency) for K_S^0 (left) and Λ (right) using the BDT method with the different number of decision trees and depth. The red line is for 250 decision trees with depths of 4, the blue line is for 250 decision trees with depths of 3, and the black line is for 850 decision trees with depths of 3.

Table 5.3: List of BDT V^0 training variables.

cosThetaXYZ	Cosine 3D pointing angle θ
Cent	centrality bin
Lxyz	3D decay length
pt	p_T
rapidity	y
DCA	Distance of closest approach between the two tracks
pTrkNHit	NHit of the positive daughter track
nTrkNHit	NHit of the negative daughter track
vtxChi2	vertex Chi2
pTrkPt	p_T of the positive daughter track
nTrkPt	p_T of the negative daughter track
pTrkEta	η of the positive daughter track
nTrkEta	η of the negative daughter track
pTrkDCASigXY	transverse DCA significance of the positive daughter track
nTrkDCASigXY	transverse DCA significance of the negative daughter track
pTrkDCASigZ	longitudinal DCA significance of the positive daughter track
nTrkDCASigZ	longitudinal DCA significance of the negative daughter track
vtxDecaySigXYZ	3D vertex significance
pTrkPtError	p_T error of the positive daughter track
pTrkNPxLayer	NPixel layer with hits of the positive daughter track
nTrkPtError	p_T error of the negative daughter track
nTrkNPxLayer	NPixel layer with hits of the negative daughter track

trees with depths of 3 and 4. For K_S^0 , the performance is similar for both 250 and 850 decision trees with depths of 3 and 4. But for Λ , the performance is slightly down when we consider 250 decision trees with a depth of 3, whereas, the training performance is very similar for 250 decision trees with a depth of 4 and 850 decision trees with a depth of 3. Considering the memory usage and timing, we decided to use 250 decision trees with a depth of 4 as our nominal setup for the BDT.

Overtraining checks

BDT distributions obtained with the training samples can be considerably different than the BDT distributions when applying the resulting classification to other events due to

Table 5.4: List of BDT V^0 spectator variables.

mass	V^0 particle mass
eta	V^0 particle η
phi	V^0 particle ϕ
pdgId	V^0 particle ID

overtraining. In order to check if there is overtraining with the set of variables employed in the training, the BDT distributions for training and the test samples are compared in both cases signal and background, as shown in Fig. 5.11. For K_S^0 , the BDT distributions obtained using the test sample and the training sample are matched for both signal and background. But for Λ , there is a small mismatch between the signal test sample and the training sample, which is because of low statistics in the MC sample for Λ particles. A Kolmogorov-Smirnov (KS) test⁹ is used to determine whether the training sample and test sample are compatible. In general, it is shown that the probability values are far from zero (see Fig. 5.11), indicating that the test and training samples are compatible.

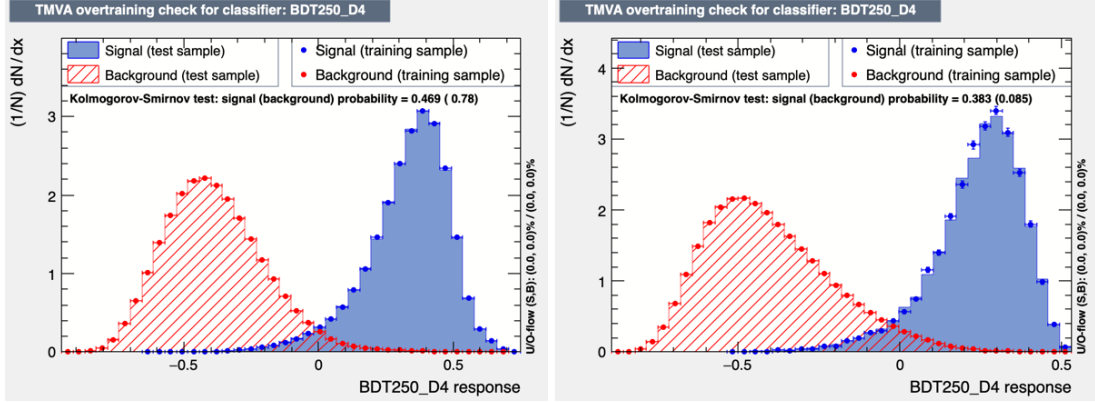


Figure 5.11: Comparison of BDT training (closed circle) and testing (continuous line) distributions for both signal (blue) and background (red) samples using the Kolmogorov-Smirnov test for K_S^0 (left panel) and Λ (right panel).

⁹It is used to compare and determine if two samples are significantly different from each other.

BDT Optimization

The working BDT cut value is optimized to have the maximum significance, putting emphasis on the high p_T in the most central collisions. The significance is defined as $S/\sqrt{S+B}$ from data within the peak region, where S is the number of true V^0 particles, and B is the combinatorial background from the fit.

The significance as a function of the BDT cut is shown in Fig. 5.13 at 5–10% centrality and Fig. 5.15 at 10–30% centrality for K_S^0 , and in Fig. 5.12 at 5–10% centrality and Fig. 5.14 at 10–30% centrality for Λ . The figure shown on the left is for the high p_T $7.0 < p_T < 8.5$ GeV, and on the right is for the low p_T $1.8 < p_T < 2.2$ GeV. Based on the high p_T significance plots, the BDT cut is set at 0.15 for K_S^0 and 0.20 for Λ . For the low p_T significance plots, the peak is relatively flat, and for simplicity, we decided to use the same BDT cut as high p_T , meaning no p_T dependence of BDT cut. Considering the low p_T significance, we introduce a systematic check on BDT cut. Finally, the K_S^0 mesons are selected with $1 < p_T < 8.5$ GeV and $|y| < 1$, while the Λ baryons are required to have $1.8 < p_T < 8.5$ GeV and $|y| < 1$. The minimum p_T and maximum y requirements are used to reduce background while the maximum p_T requirement is to reduce contributions from jets.

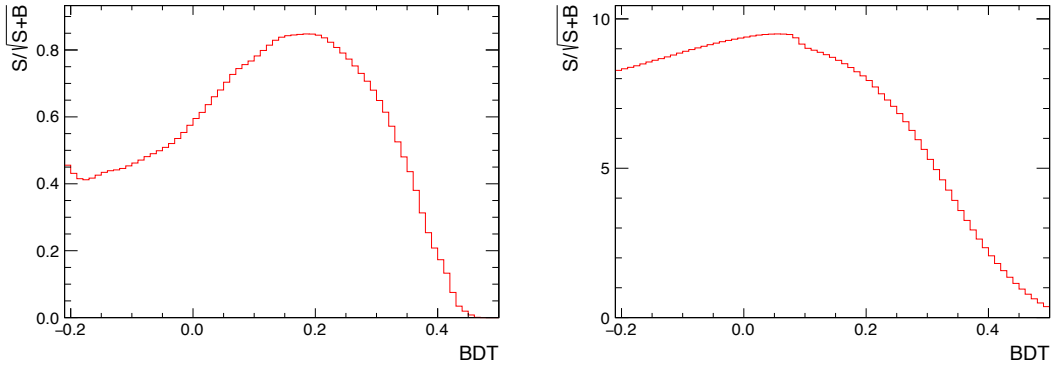


Figure 5.12: The significance ($S/\sqrt{S+B}$) as a function of BDT cut value for Λ of $7.0 < p_T < 8.5$ GeV (left) and $1.8 < p_T < 2.2$ GeV (right) in PbPb collisions at 5–10% centrality.

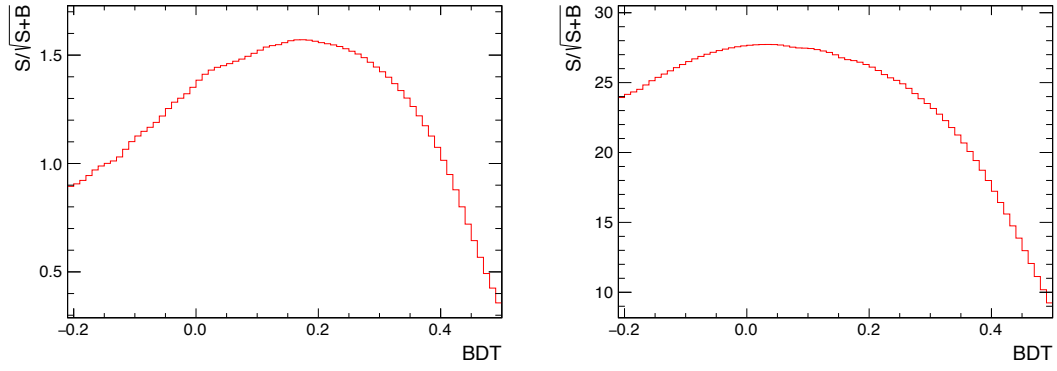


Figure 5.13: The significance ($S/\sqrt{S+B}$) as a function of BDT cut value for K_S^0 of $7.0 < p_T < 8.5$ GeV (left) and $1.8 < p_T < 2.2$ GeV (right) in PbPb collisions at 5–10% centrality.

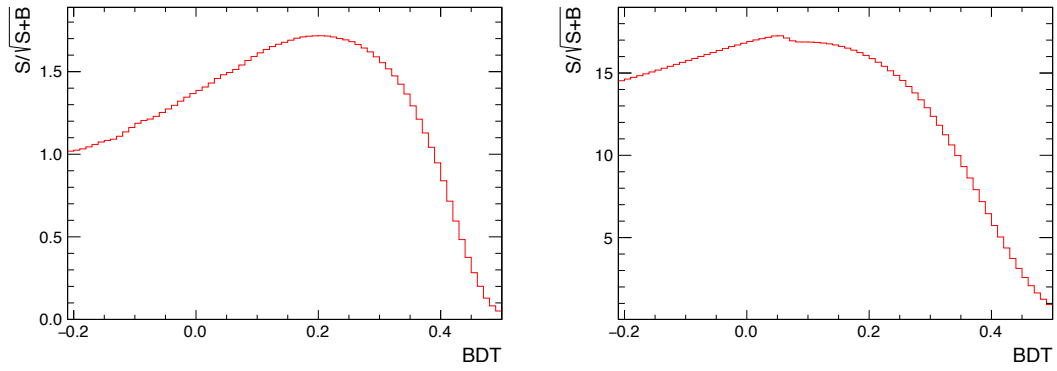


Figure 5.14: The significance ($S/\sqrt{S+B}$) as a function of BDT cut value for Λ of $7.0 < p_T < 8.5$ GeV (left) and $1.8 < p_T < 2.2$ GeV (right) in PbPb collisions at 10–30% centrality.

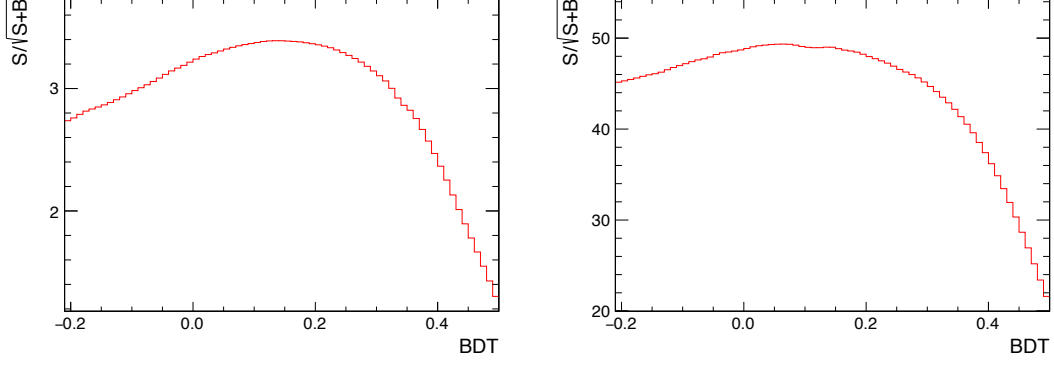


Figure 5.15: The significance ($S/\sqrt{S+B}$) as a function of BDT cut value for K_S^0 of $7.0 < p_T < 8.5$ GeV (left) and $1.8 < p_T < 2.2$ GeV (right) in PbPb collisions at 10–30% centrality.

5.5.2 Misidentified V^0 removal using Armenteros-Podolanski Plot

As the identity of each track cannot be determined in the CMS experiment, the mass of each track has to be assumed depending on the identity of V^0 candidate. It is possible that $K_S^0(\Lambda)$ candidates are misidentified as $\Lambda(K_S^0)$ candidates. Especially, there is a high probability that a track assumed to be a proton in a Λ candidate is actually a pion. To select clean samples of K_S^0 and Λ , the Armenteros-Podolanski (A-P) plot is investigated. By looking at the A-P plot, one can check what type of V^0 particles is reconstructed.

A-P plot is a two-dimensional plot between Q_T and α , where $Q_T = |\vec{p}_1 \times \vec{p}_2|/|\vec{p}_{V^0}|$ is the transverse momentum of the daughters with respect to the V^0 candidate and $\alpha = (p_{1L} - p_{2L})/(p_{1L} + p_{2L})$ is the longitudinal momentum asymmetry. Here, $\vec{p}_i$ is the momentum of V^0 daughters, $\vec{p}_{V^0} = \vec{p}_1 + \vec{p}_2$ is the momentum of V^0 , and $p_{iL} = (\vec{p}_{V^0} \cdot \vec{p}_i)/|\vec{p}_{V^0}|$ is the longitudinal momentum with respect to the V^0 candidate. An example of an A-P plot can be seen in Fig. 5.16. The obtained distribution can be understood as the pair of pions from K_S^0 decay having the same mass, their momenta are distributed symmetrically on average (top band). For the $\Lambda(\bar{\Lambda})$ case, the proton (antiproton) takes a large part of the momentum compared to pions, which results in an asymmetric distribution (two lower bands). Sometimes we have written Q_t instead of original notation Q_T (e.g., in Fig. 5.17 and 5.20). Please ignore the notation here.

Fig. 5.17 shows the A-P plot for Λ candidates. We have checked this in two mass regions. The left plot is for $1.08 < M < 1.16$ GeV and the right plot is for the peak region. As one can see, misidentified candidates can be clearly observed in $1.08 < M < 1.16$ GeV. The V^0 candidates above $Q_T \approx 0.11$ are misidentified K_S^0 which needs to be removed. To remove the misidentified K_S^0 , we apply the $\pi\text{--}\pi$ hypothesis to Λ candidates. The hypothesis assumes that the daughter tracks from the Λ decay are pions and recalculate the invariant mass of the mother particle. The re-calculated mass distributions for Λ candidates are shown in Fig. 5.18 (left: in $1.08 < M < 1.16$ GeV, right: in peak region). Clear peaks at standard K_S^0 invariant mass is observed in $1.08 < M < 1.16$ GeV, which indicates some of the candidates are misidentified K_S^0 . A veto of range 0.497614 ± 0.014 GeV is applied to the re-calculated mass distribution to remove the misidentified K_S^0 . But, in the peak region (right plot of Fig. 5.18), the misidentified K_S^0 contribution is almost negligible. There is also a chance that both of the daughter tracks are in fact

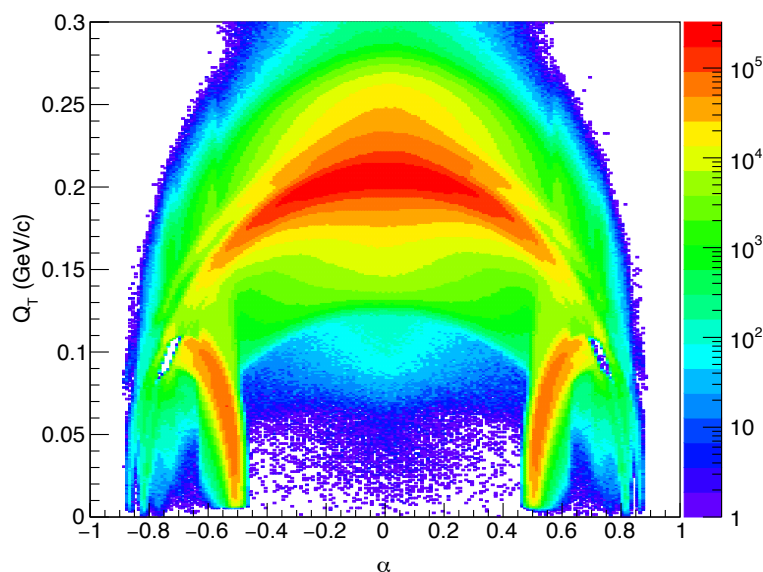


Figure 5.16: An example of the A-P plot.

electrons from photon conversion. Peaks can be seen in the e-e hypothesis re-calculated mass distributions in Fig. 5.19 (left: in $1.08 < M < 1.16$ GeV, right: in peak region).

Therefore, a veto of invariant mass less than 0.015 GeV is also applied to remove misidentified photons. The A-P plots after the removal of misidentified candidates for the Λ candidates in the peak region are shown in Fig. 5.23 (left). Although a small part Λ candidates are removed, the K_S^0 band is completely removed by our cuts. Moreover, a small number of candidates with extremely low Q_T have been removed as misidentified conversion photons, which has very little impact on our Λ candidates.

Similarly to remove the misidentified Λ while reconstructing K_S^0 candidates, we have applied the $p\pi$ hypothesis which is, the K_S^0 candidates must have a corresponding $p\pi$ mass more than 7 MeV away from the PDG value of the K_S^0 mass [120]. Fig. 5.20 shows the A-P plot for K_S^0 before applying the misidentified candidates cut. Fig. 5.21 and 5.22 show the recalculated mass distributions for K_S^0 candidates assuming $p-\pi$ and e-e hypothesis. The A-P plots after the removal of misidentified candidates for the K_S^0 candidates in the peak region are shown in Fig. 5.23 (right).

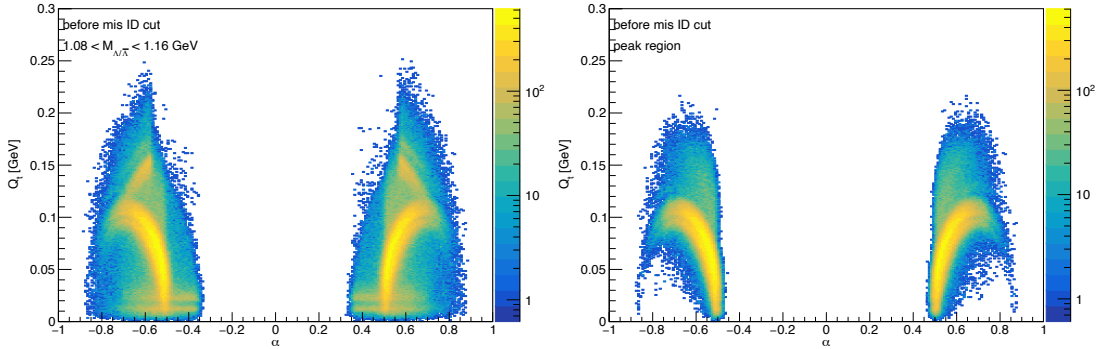


Figure 5.17: Armenteros-Podolanski (A-P) plots for Λ candidates in $1.08 < M < 1.16$ GeV (left) and in peak region (right) before applying the misidentified candidate mass cuts.

5.5.3 V^0 Selection efficiency

Using the MC sample, the total efficiency (reconstruction efficiency $\times$ acceptance) and fake rate are calculated as a function of p_T and rapidity. The 2D efficiency and fake rate plots as a function of p_T and rapidity are shown in Fig. 5.24–5.27 for K_S^0 and Fig. 5.28–5.31 for Λ in 0–10%, 10–30%, 30–50%, and 50–80%. The 1D efficiency as a

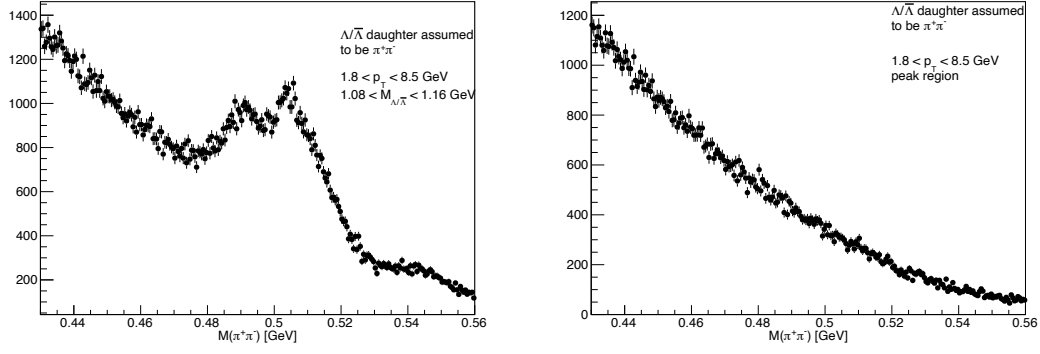


Figure 5.18: π - π hypothesis recalculated mass distributions for Λ candidates in $1.08 < M < 1.16$ GeV (left) and in peak region (right).

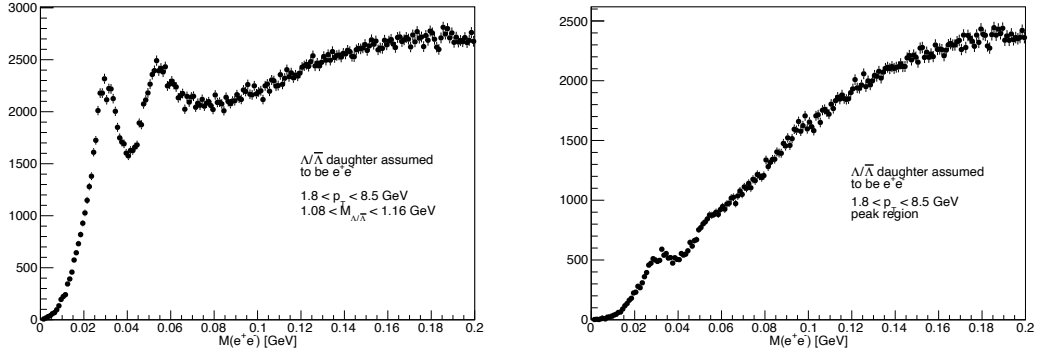


Figure 5.19: e - e hypothesis re-calculated mass distributions for Λ candidates in $1.08 < M < 1.16$ GeV (left) and in peak region (right).

function of p_T (left) and rapidity (right) are shown in Fig. 5.32 for K_S^0 , and Fig. 5.33 for Λ in the mentioned centrality ranges. The combined V^0 reconstruction and selection efficiencies are strongly dependent on the centrality of the event and the p_T of the V^0 . Integrating over the selected p_T ranges, the combined efficiencies from the most central to peripheral PbPb collisions are 1–3% for K_S^0 and 1–2% for Λ .

5.5.4 Duplicate V^0 removal

The V^0 reconstruction algorithm does not prevent a track from being used for more than one V^0 . While this is normally an infrequent occurrence, selecting pairs of V^0 particles close together in phase space makes it a significant contribution. An example

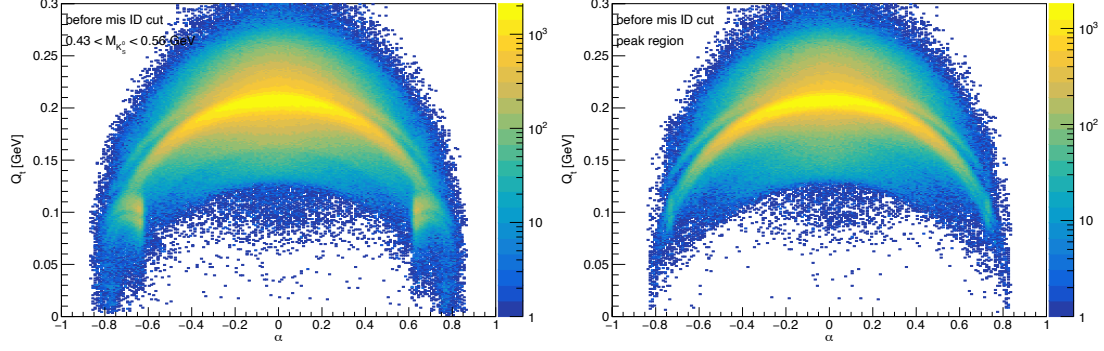


Figure 5.20: Armenteros-Podolanski (A-P) plots for K_S^0 candidates in $0.43 < M < 0.56$ GeV (left) and in peak region (right) before applying the misidentified candidate mass cuts.

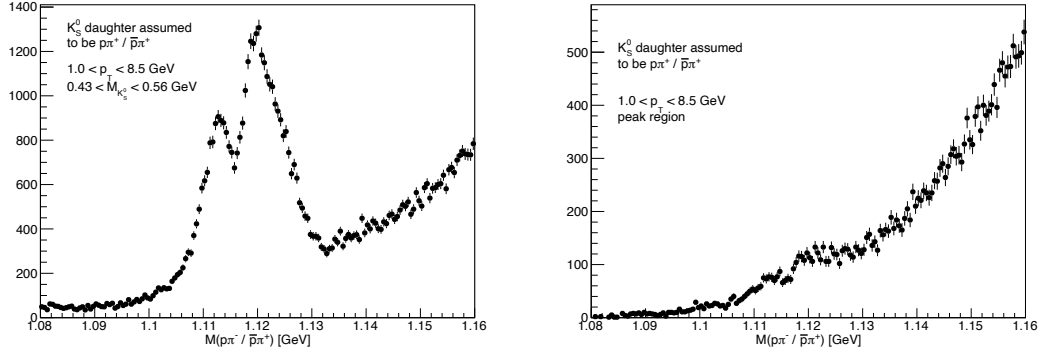


Figure 5.21: p - π hypothesis re-calculated mass distributions for K_S^0 candidates in $0.43 < M < 0.56$ GeV (left) and in peak region (right).

of this situation can be seen in Fig. 5.34. We observed that some duplicate V^0 's polluted our sample and their effect can be seen in Fig. 5.35. A bump in the lower q_{inv} part of the signal distributions¹⁰ (red circle), which are constructed from the same event, was observed in the identical V^0 pairs (ΛK_S^0 and $\Lambda \Lambda$). But in the reference distributions¹¹ (blue triangle), which are constructed from the different events, the bump was not found.

To confirm the problem in the V^0 reconstruction, we checked the signal distribution of $K_S^0 K_S^0$ pair in the simulated events by taking reconstructed (RECO) K_S^0 and generated (GEN) K_S^0 . We found a similar bump in the RECO $K_S^0 K_S^0$ pair (Fig. 5.36), as seen in

¹⁰The definition of signal distribution is described in the sec. 5.6

¹¹The definition of reference distribution is described in the sec. 5.6

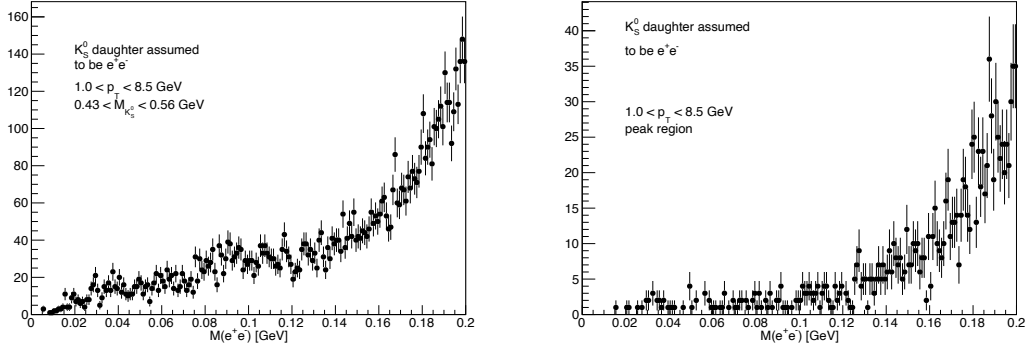


Figure 5.22: e-e hypothesis re-calculated mass distributions for K_S^0 candidates in $0.43 < M < 0.56$ GeV (left) and in peak region (right).

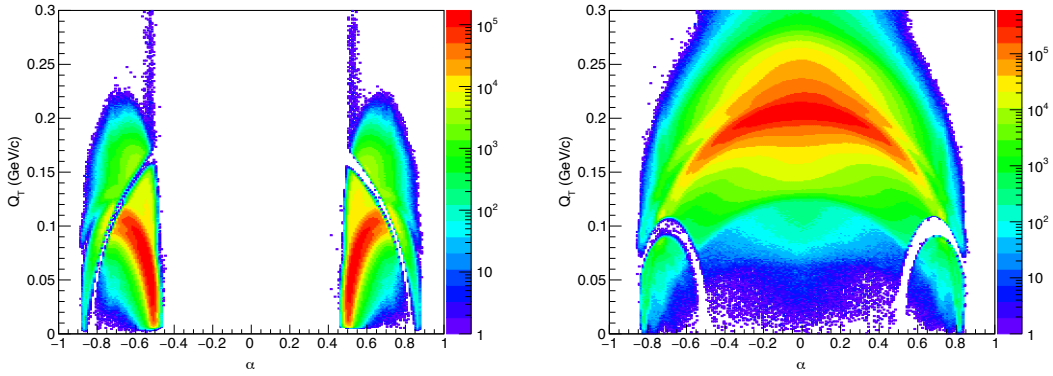


Figure 5.23: The A-P plot in the peak region of Λ (left), K_S^0 (right) after the misidentified cut.

the data (Fig. 5.35), but not in the GEN $K_S^0 K_S^0$ pair, which confirms that the problem is in the reconstruction. As the problem is in the reconstruction, it is good to study the properties of the tracks used to reconstruct V^0 particles. We plotted the $|\Delta\eta|$ vs $|\Delta\phi|$, $|\cos\theta_{ij}|$ vs $|\Delta p_T|$ and $|\Delta\chi^2/\text{ndf}|$ distributions between the daughters of V^0 pairs in data, and found that a sharp peak at around $[|\Delta\eta|, |\Delta\phi| \simeq (0, 0)]$, $[|\cos\theta_{ij}|, |\Delta p_T| \simeq (1, 0)]$, and $[|\Delta\chi^2/\text{ndf}| \simeq (0)]$ in the same charge daughter distributions in the Fig. 5.37 for $K_S^0 K_S^0$ pair and Fig. 5.38 for $\Lambda\Lambda$ pair. Here θ_{ij} is the angle between the momentum vector of two daughters. Additionally, we found that the track properties (e.g. $\eta, \phi...$) are exactly the same between the same charge daughters. A similar problem was found for

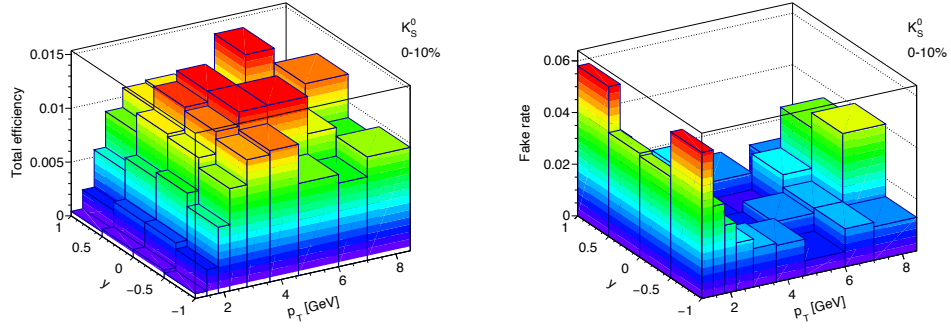


Figure 5.24: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for K_S^0 in 0–10%.

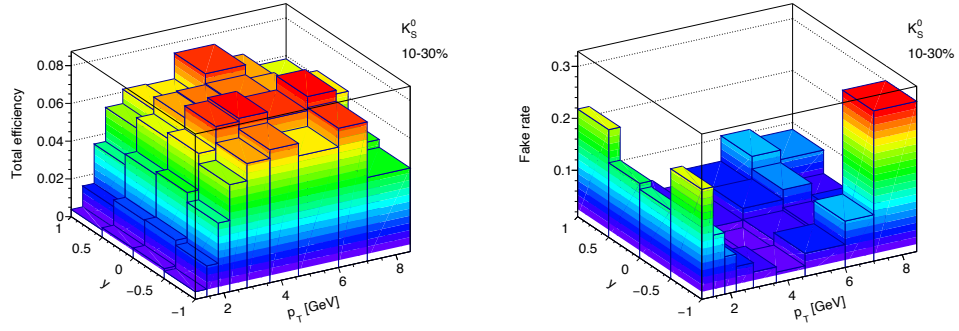


Figure 5.25: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for K_S^0 in 10–30%.

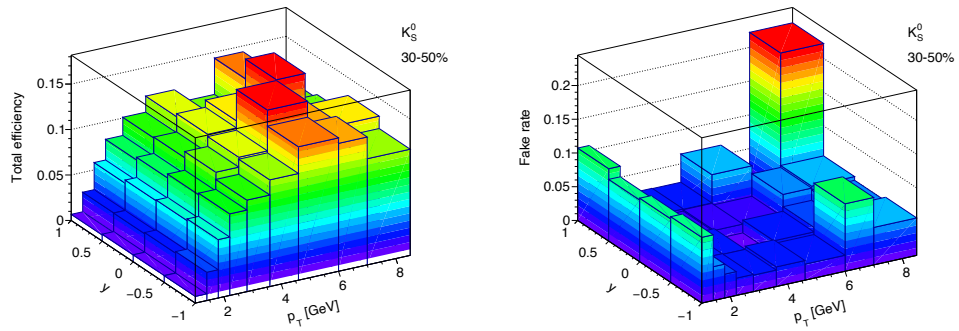


Figure 5.26: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for K_S^0 in 30–50%.

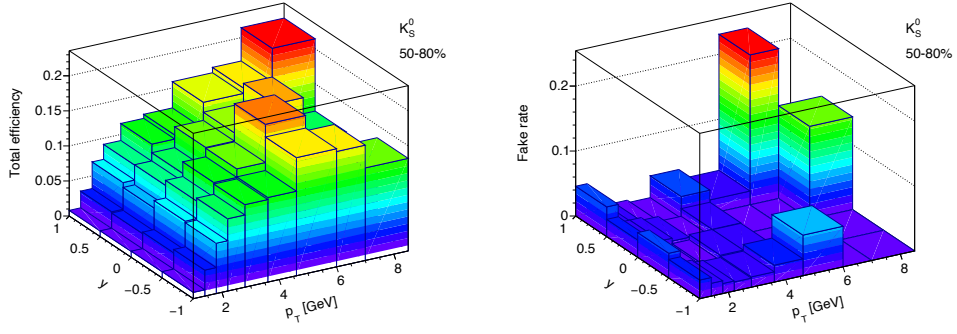


Figure 5.27: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for K_S^0 in 50–80%.

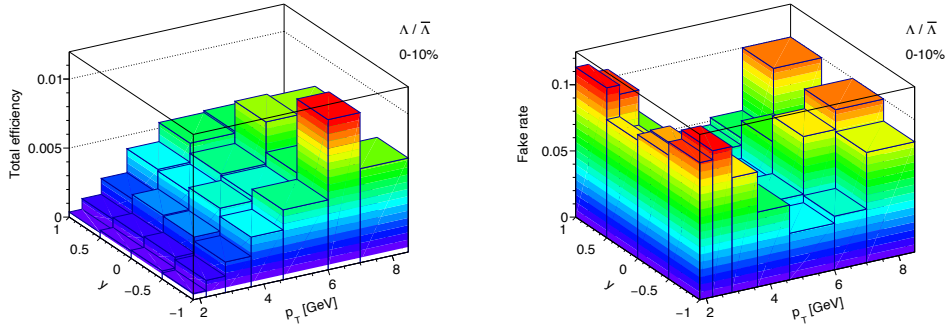


Figure 5.28: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for Λ in 0–10%.

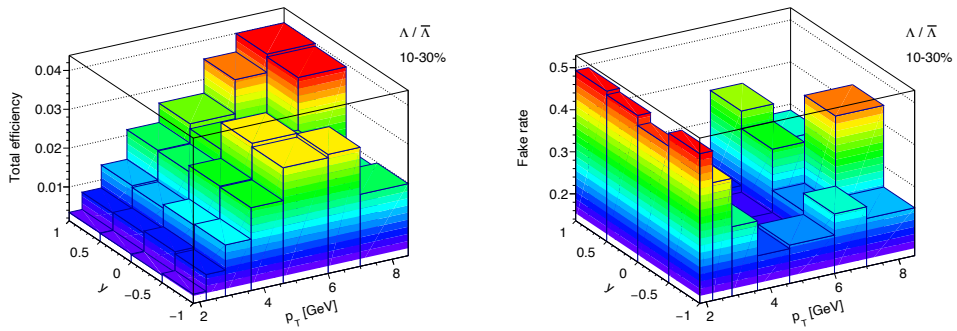


Figure 5.29: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for Λ in 10–30%.

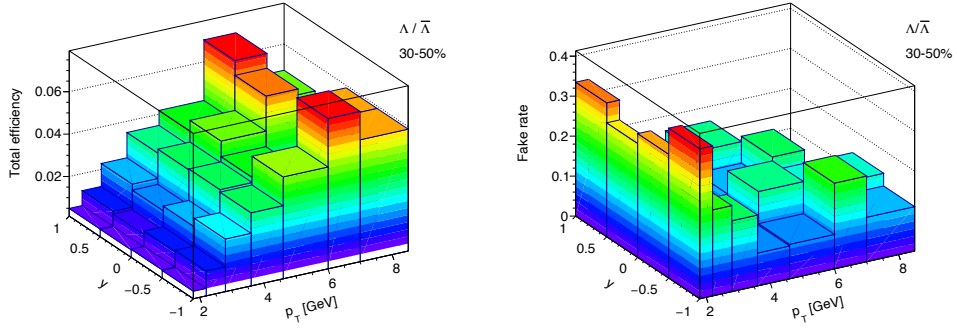


Figure 5.30: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for Λ in 30–50%.

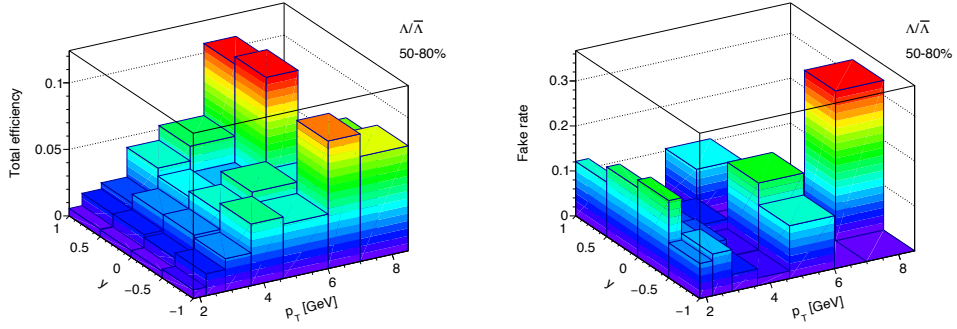


Figure 5.31: The 2D efficiency (left) and fake rate (right) as a function of rapidity and p_T for Λ in 50–80%.

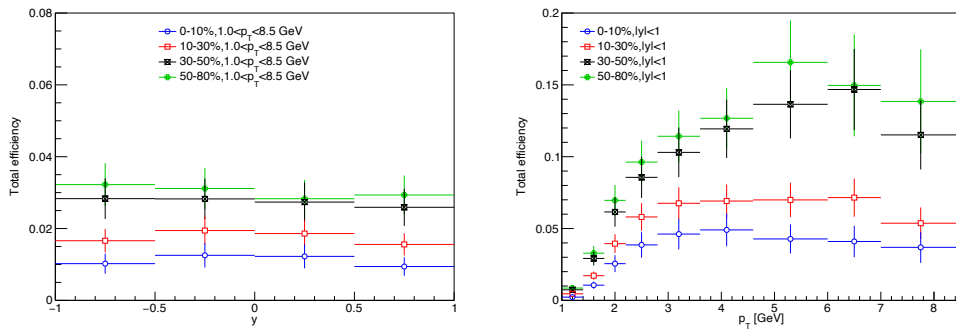


Figure 5.32: The 1D efficiency as a function of rapidity (left) and p_T (right) for K_S^0 in 0–10% (blue marker), 10–30% (red marker), 30–50% (black marker), and 50–80% (green marker).

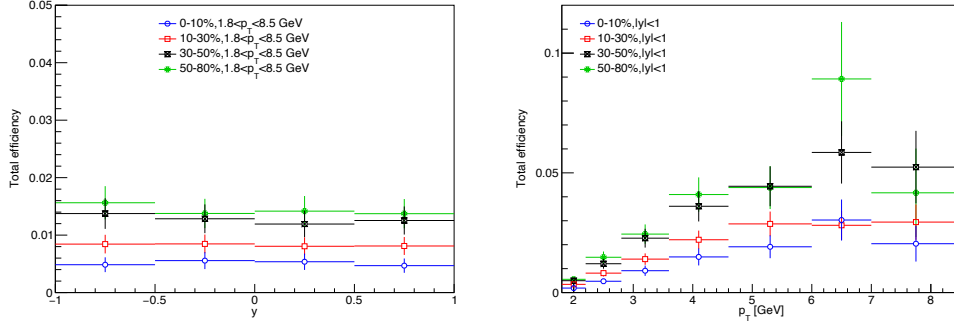


Figure 5.33: The 1D efficiency as a function of rapidity (left) and p_T (right) for Λ in 0–10% (blue marker), 10–30% (red marker), 30–50% (black marker), and 50–80% (green marker).

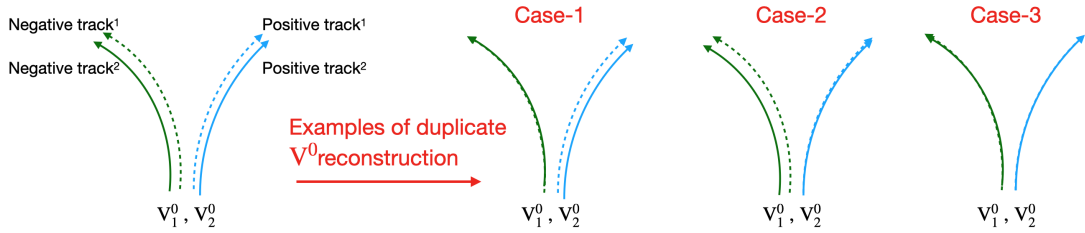


Figure 5.34: Figures show the illustration of how two V^0 share their daughters. The left-most figure shows the two V^0 does not share their daughters and all other three cartoons on the right-hand side show the two V^0 share their daughters. The two V^0 's share only their positive daughters and negative daughters are shown in cases 1 and 2, and share both positive and negative daughters in case 3.

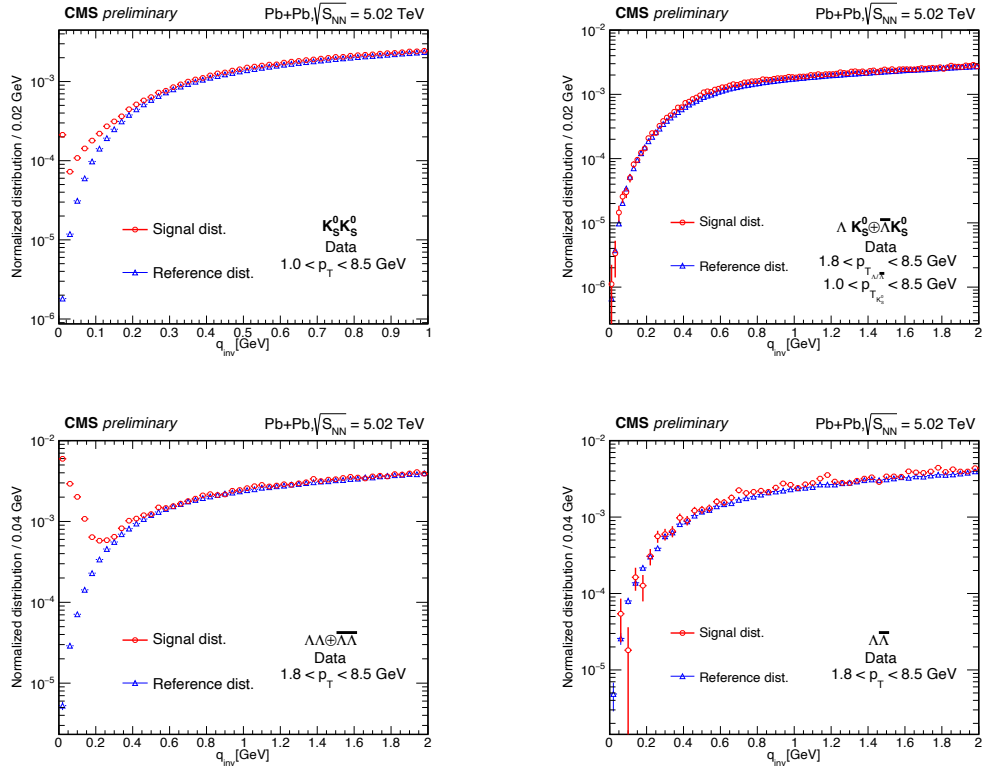


Figure 5.35: Normalized signal (open circle) and reference distributions (open triangle) as a function of q_{inv} for $K_S^0 K_S^0$ (top left), ΛK_S^0 (top right), $\Lambda\Lambda$ (bottom left) and $\Lambda\bar{\Lambda}$ (bottom right) pairs.

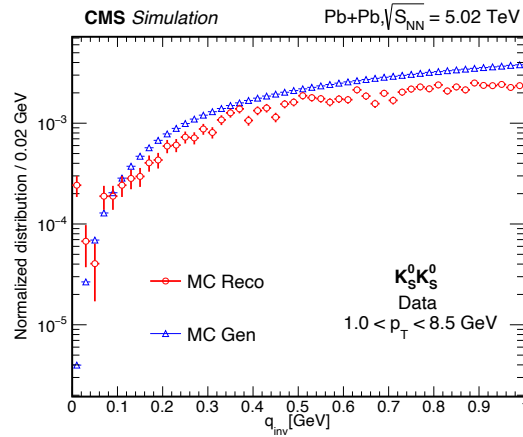


Figure 5.36: Figure shows the normalized signal distribution for $K_S^0 K_S^0$ pair from MC reco (open circle) and MC gen (open triangle).

the ΛK_S^0 pair daughters (Fig. 5.39) even though we did not see any bump in the signal distribution (Fig. 5.35), but for $\Lambda \bar{\Lambda}$ pair, we do not find such problems (Fig. 5.39).

This study suggests that we have exactly the same daughters with at least two V^0 candidates in some cases (not all V^0 has the same daughters). This problem occurs because we combine all positive tracks with all negative tracks to increase the statistics, and we may have reconstructed some V^0 candidates with the same tracks which caused the bump at lower q_{inv} in the signal distributions (Fig. 5.35) (because we are constructing pair with two duplicate V^0 's which has exactly the same daughters). To resolve this problem, we have adopted two cuts, which are

$$|\Delta\eta \ \& \ \Delta\phi| = 0 \quad \text{and} \quad \left| \frac{\Delta\chi^2}{ndf} \right| = 0. \quad (5.1)$$

Where $\Delta\eta$, $\Delta\phi$ & $\Delta\chi^2$ is the pseudorapidity, azimuthal angle, and χ^2 difference between two daughters of the same charge, respectively. We can apply either of these two above cuts. Both give exactly the same results. In this analysis/thesis, we are applying the $|\Delta\chi^2/ndf|$ cut because χ^2/ndf is the track reconstruction quantity. We measured $|\Delta\chi^2/ndf|$ between each daughter pair of the same charge and compared it with the above condition. If the above condition is satisfied, then one of the V^0 is a duplicate. As we cannot distinguish which V^0 is a duplicate and which V^0 is real, we removed one V^0 randomly. We applied this cut for all pairs. We have separate macros for each pair. While removing one duplicate K_S^0 in the case of $K_S^0 K_S^0$ pair that does not mean we removed that K_S^0 for ΛK_S^0 pair. This is because maybe that K_S^0 not shared the daughters with Λ ($\bar{\Lambda}$) while making ΛK_S^0 pair. Similarly, while removing one Λ ($\bar{\Lambda}$) for $\Lambda \Lambda$ pair that does not mean we removed that Λ ($\bar{\Lambda}$) for ΛK_S^0 or $\Lambda \bar{\Lambda}$ correlations. We are running separate macros for each pair, and if we found the duplicate V^0 's for the corresponding pair, we removed one V^0 randomly. For the systematic, two alternative approaches are used. One in which both V^0 candidates are removed and another in which, for events with multiple V^0 candidates pair combinations, only the pairs in which the two V^0 share a daughter are

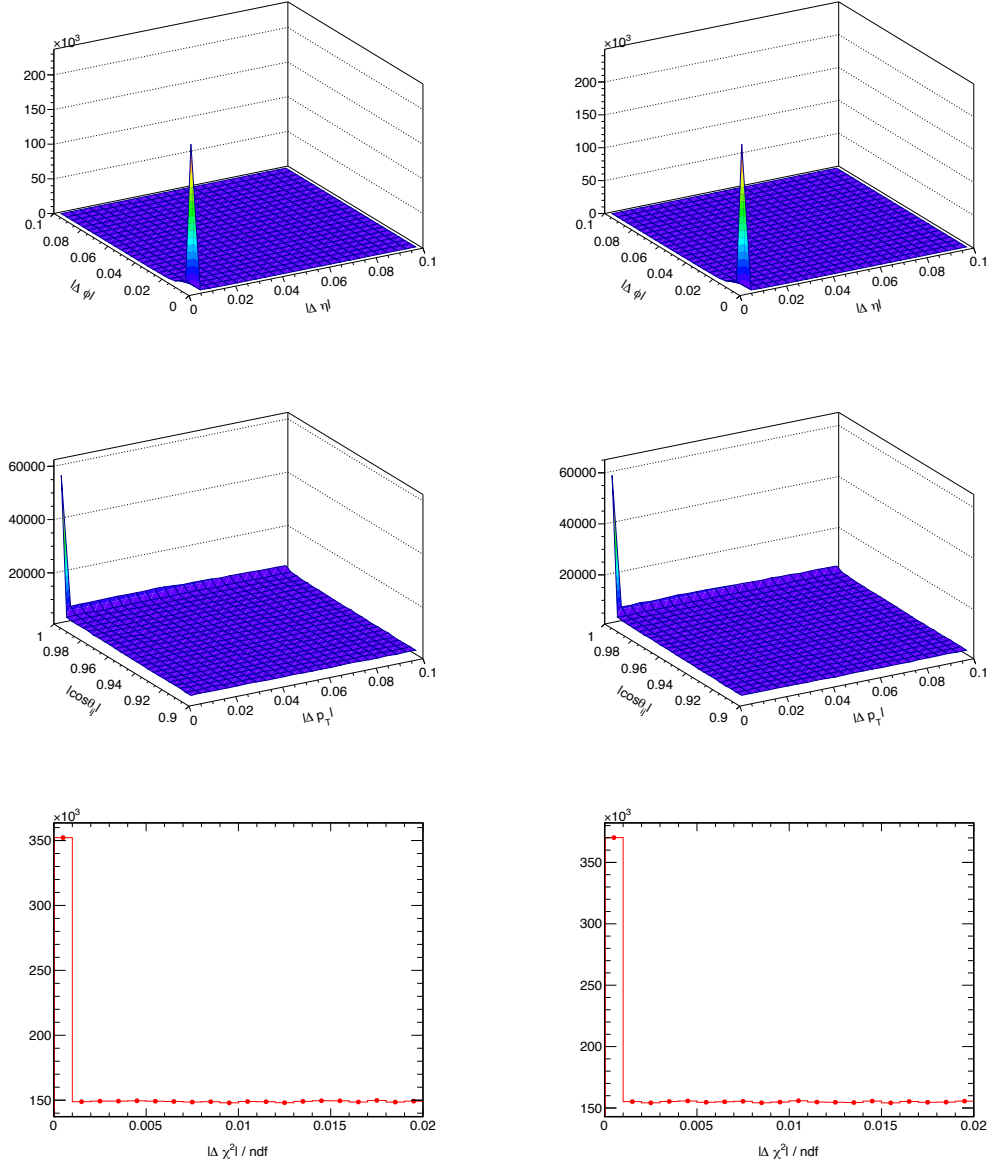


Figure 5.37: $|\Delta\eta|$ vs $|\Delta\phi|$ (upper panels), $|\cos\theta_{ij}|$ vs $|\Delta p_T|$ (middle panels), and $|\Delta\chi^2|/\text{ndf}$ (bottom panels) distribution between two positive daughters (left) and two negative daughters (right) of $K_S^0 K_S^0$ pair.

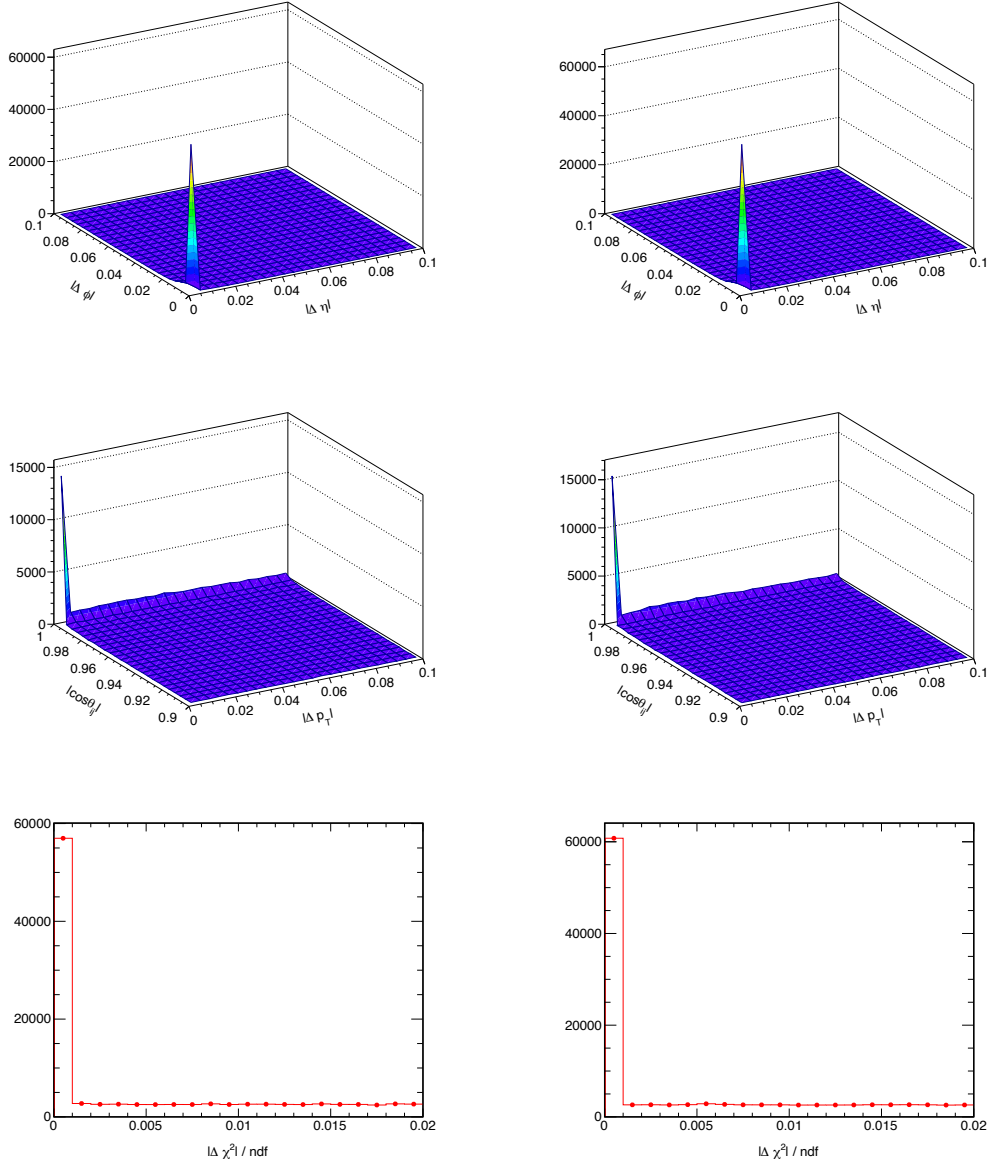


Figure 5.38: $|\Delta\eta|$ vs $|\Delta\phi|$ (upper panels), $|\cos\theta_{ij}|$ vs $|\Delta p_T|$ (middle panels), and $|\Delta\chi^2|/\text{ndf}$ (bottom panels) distribution between two positive daughters (left) and two negative daughters (right) of $\Lambda\bar{\Lambda}$ pair.

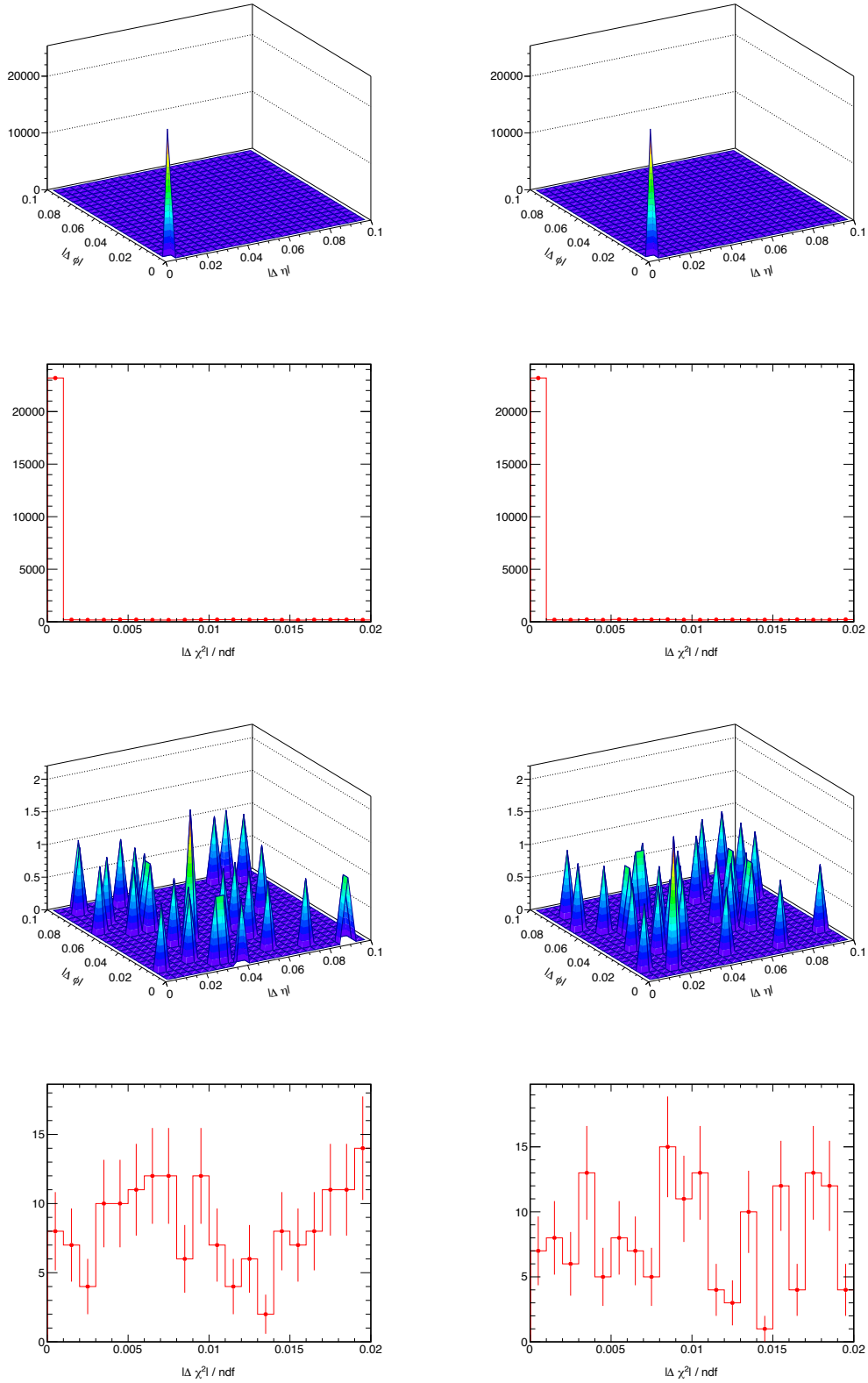


Figure 5.39: $|\Delta\eta|$ vs $|\Delta\phi|$ and $|\Delta\chi^2/\text{ndf}|$ distribution between two positive daughters (left) and two negative daughters (right) of ΛK_S^0 (two upper panels) and $\Lambda \bar{\Lambda}$ (two bottom panels) pairs.

removed. Examples of signal distributions after applying the duplicate V^0 removal cuts (discussed above) can be seen in Fig. 5.40. The red marker shows the signal distribution before applying the duplicate V^0 removal cut. The green and blue markers show the signal distribution after applying the duplicate V^0 removal cuts. We checked the $|\cos \theta_{ij}|$

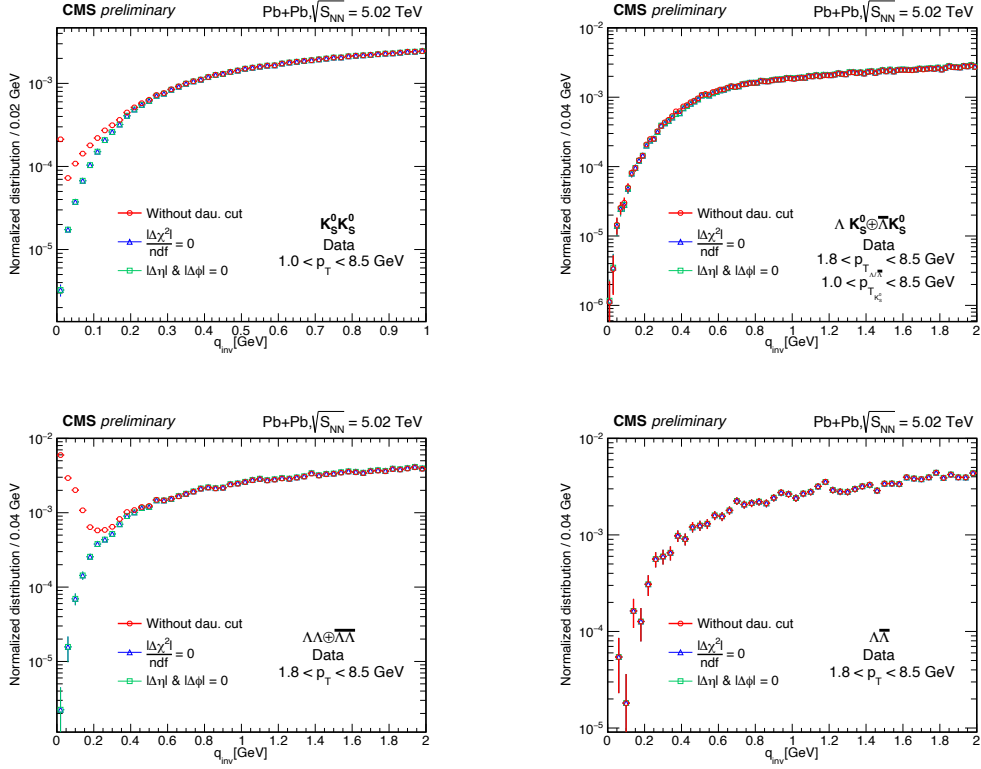


Figure 5.40: Normalized signal distribution before and after applying the duplicate V^0 removal cut as a function of q_{inv} for $K_S^0 K_S^0$ (left), ΛK_S^0 (top right), $\Lambda \Lambda$ (bottom left) and $\Lambda \bar{\Lambda}$ (bottom right) pairs. The red marker shows the signal distribution before applying the duplicate V^0 removal cut. The green and blue markers show the signal distribution after applying the duplicate V^0 removal cuts.

vs $|\Delta p_T|$ distribution between the daughters of the same charge for $K_S^0 K_S^0$ pair (Fig. 5.41) and $\Lambda \Lambda$ pair (Fig. 5.42) after applying the duplicate V^0 removal cut to check if there are still any effects from the duplicate V^0 's. But we see that our distribution is flat, which means, the duplicate V^0 's are completely removed after applying the cut.

However, this requirement may introduce some bias in our results, because we are

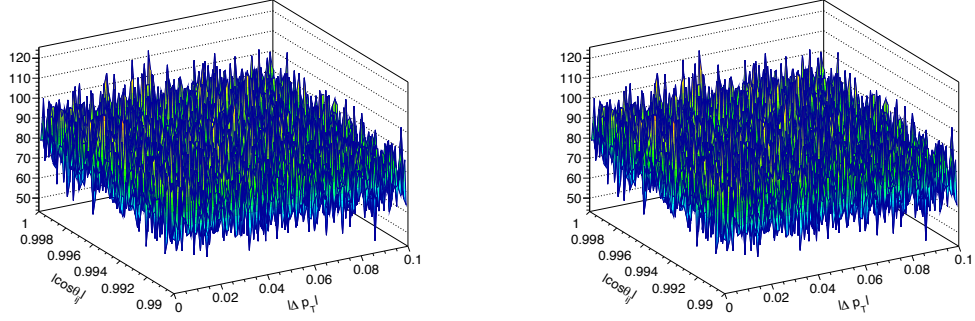


Figure 5.41: $|\cos \theta_{ij}|$ vs $|\Delta p_T|$ distribution between two positive daughters (left) and two negative daughters (right) of $K_S^0 K_S^0$ pair.

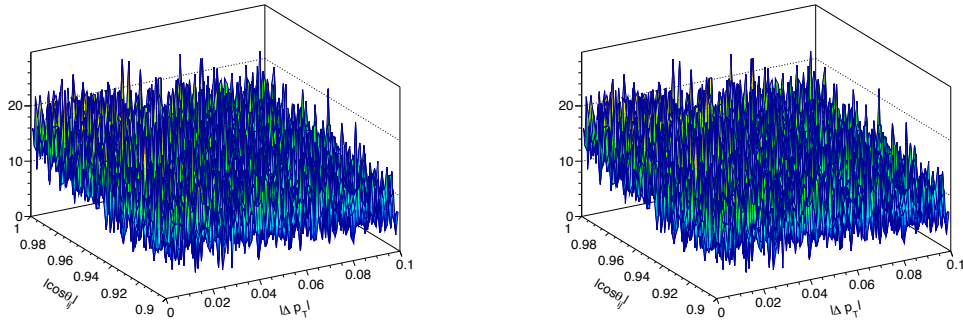


Figure 5.42: $|\cos \theta_{ij}|$ vs $|\Delta p_T|$ distribution between two positive daughters (left) and two negative daughters (right) of $\Lambda\Lambda$ pair.

removing the correlated pair from the low q_{inv} region, which is the region of interest, by applying the duplicate V^0 removal cut. To check that, we did some study using the HYDJET MC sample that is discussed in sec. 5.5.4.

Bias test

The duplicate V^0 removal cut helps us to eliminate the contamination from signal distribution in the lower q_{inv} part, but this may introduce some bias in our correlation measurement¹², which is the ratio of signal distribution and reference distribution. As in this analysis, the interest is in the low q_{inv} region ($0 < q_{\text{inv}} < 0.4$ GeV), we need to investigate up to which q_{inv} value we introduce bias or in which q_{inv} ranges we removed the contaminated pair in the signal distributions. In the previous CMS charged hadron analysis, this investigation was done by looking at the q_{inv} distribution produced by pairing one particle which is removed by the cut¹³ with another particle that is not removed by this cut. They found that the value of q_{inv} is affected by the requirement is extremely narrow, $q_{\text{inv}} < 0.02$. That means the contaminated pairs are removed in the range $0 < q_{\text{inv}} < 0.02$ GeV. Then they excluded this range to extract the physical parameters by fitting the theoretical correlation functions to the experimental correlations. Details about the correlation measurement and fitting can be seen in sec.sec. 5.6 and 5.7.

A similar technique we used to check the bias in this analysis. In the previous CMS charged hadron analysis, they used data to check bias, but in this analysis, we used the HYDJET MC sample to check the effect of bias because of the combinatorial background. In the data, we cannot separate combinatorial background, but in MC, we can separate the pure V^0 and combinatorial background using MC reco and gen level information. A q_{inv} distribution was plotted by pairing one V^0 which is removed by the duplicate V^0 removal cut with another V^0 which is not removed by that cut which can be seen in Fig. 5.43 (red circle). One can see that the contaminated pairs are ranging towards a higher q_{inv} range ($q_{\text{inv}} \approx 0.2$ GeV for $K_S^0 K_S^0$ and $q_{\text{inv}} \approx 0.5$ GeV for $\Lambda\Lambda$). But here, the contaminated pairs include

¹²details about the correlation measurement described in sec. 5.6

¹³they applied the cut on Δp_T and $\cos \theta_{ij}$

the contributions from both pure V^0 's correlation (signal contributions) and background V^0 's correlations (background contributions). To check how much signal contributions we removed by this cut, we did the matching of reco V^0 with gen V^0 using the HYDJET MC sample. For the matching we used $\sqrt{(\eta_{V^0}(g) - \eta_{V^0}(r))^2 + (\phi_{V^0}(g) - \phi_{V^0}(r))^2} < 0.03$ and $|p_{TV^0}(g) - p_{TV^0}(r)|/p_{TV^0}(g) < 0.03$ conditions. Here “g” stands for gen and “r” stands for reco. The matched V^0 's are pure V^0 and the unmatched V^0 's are basically background. After that, we construct pairs of the matched V^0 's which are removed by the duplicate V^0 removal cut with the other matched V^0 's which are not removed by the cut. Similarly, we measured this for matched-unmatched, unmatched-matched, and unmatched-unmatched V^0 's particles. The matched-matched pair gives us an idea of how much signal contributions we removed or about up to which q_{inv} range we introduce bias and all other cases (matched-unmatched, unmatched-matched, and unmatched-unmatched) give us the idea about how much background contributions we removed which can be seen in Fig. 5.43. The blue marker represents how much signal contributions we removed by the duplicate V^0 removal cut or up to which q_{inv} range we introduce bias.

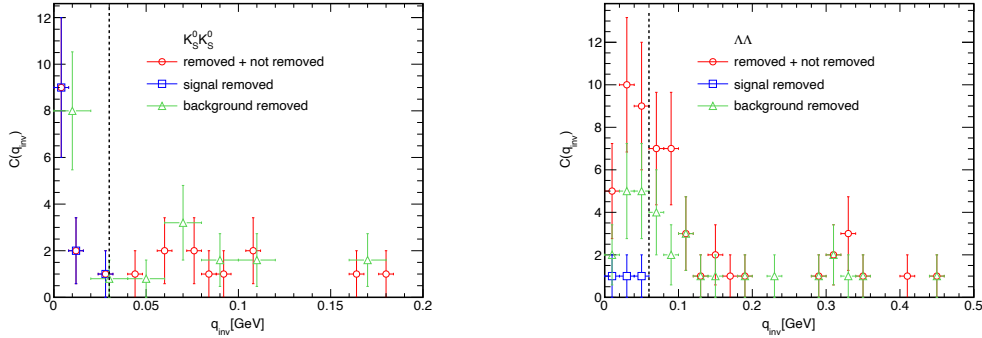


Figure 5.43: The q_{inv} distribution of $K_S^0 K_S^0$ pairs (left) and $\Lambda\Lambda$ pair (right), where one of the K_S^0 or Λ is removed by the duplicate V^0 removal cuts described in the sec. 5.5.4. The red marker represents how much signal plus background we removed by the duplicate V^0 removal cut and the blue marker represents how much signal we removed by the duplicate V^0 removal cut.

From Fig. 5.43, we can see that the range of q_{inv} value affected by the duplicate V^0

removal cut is very narrow, $q_{inv} < 0.03$ GeV for $K_S^0 K_S^0$ pair and $q_{inv} < 0.06$ GeV for $\Lambda\Lambda$ pair. The effect is in the very first bin of q_{inv} . So while fitting, we will exclude the first bin for all possible pairs to extract the physical parameters.

5.5.5 Invariant mass distributions

After all these selections described in sec. 5.5, finally, we plotted the invariant mass distributions from all the PbPb events which can be seen in Fig. 5.44–5.46. Figure 5.44 shows the invariant mass distributions of reconstructed $K_S^0 (\pi^+\pi^-)$ used in $K_S^0 K_S^0$ correlation in different centrality regions, Fig. 5.45 shows the invariant mass distributions of reconstructed $K_S^0 (\pi^+\pi^-)$ (left panel) and $\Lambda + \bar{\Lambda} (p\pi^- + \bar{p}\pi^+)$ (right panel) used in ΛK_S^0 correlations, and Fig. 5.46 shows the invariant mass distributions of reconstructed $\Lambda + \bar{\Lambda} (p\pi^- + \bar{p}\pi^-)$ used in $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) correlations. In all these plots, the V^0 peaks can be clearly identified. Fits to the invariant mass distributions are performed using a sum of three Gaussian functions with a common mean to describe the signal distribution and a fourth-order polynomial to describe the background. These empirical functions were chosen to provide a good description of the data. Peak and sideband invariant mass regions are defined to select events dominated by signal and background, respectively. Defining σ ¹⁴ as the average resolution based on the Gaussian sum, the peak regions are selected to be within $\pm 2\sigma$ from the nominal V^0 mass and are given by $486 < M(\pi^+\pi^-) < 509\text{MeV}$ and $1111.5 < M(p\pi^- + \bar{p}\pi^+) < 1120.4\text{MeV}$ for K_S^0 and $\Lambda + \bar{\Lambda}$ candidates, respectively. The sideband regions are selected to be more than 4σ from the nominal V^0 mass and are given by $23.5 < |M(\pi^+\pi^-) - 497.5| < 62.5\text{MeV}$ for K_S^0 candidates and $1080 < M(p\pi^- + \bar{p}\pi^+) < 1107.5\text{MeV}$ together with $1124.2 < M(p\pi^- + \bar{p}\pi^+) < 1160\text{MeV}$ for $\Lambda + \bar{\Lambda}$ candidates. The invariant mass distributions, their fitting, the ratio between data and fit, and the pull distributions¹⁵ for K_S^0 and $\Lambda + \bar{\Lambda}$ are

¹⁴ σ represents the root mean square of the three standard deviations (σ_1 from the first Gaussian, σ_2 from the second Gaussian and σ_3 from the third Gaussian) of the triple Gaussian functions weighted by the yields (Y_1 from the first Gaussian, Y_2 from the second Gaussian and Y_3 from the third Gaussian), given

$$\text{by } \sigma = \sqrt{\frac{Y_1}{Y_1+Y_2+Y_3}\sigma_1^2 + \frac{Y_2}{Y_1+Y_2+Y_3}\sigma_2^2 + \frac{Y_3}{Y_1+Y_2+Y_3}\sigma_3^2}.$$

¹⁵ $\text{pull} = \frac{\text{data}_i - \text{fit}_i}{\text{data error}_i}$, where “i” represents the number of bins.

shown in Fig. 5.44–5.46. In these plots, the circles are the data, and the fit is shown with a solid (red) line for the total fit and a solid (green) line for the background fit. The three dashed lines represent the three Gaussian. The vertical dashed-dotted (azure) lines indicate the peak regions. In each plot, the middle panel shows the ratio between data and fit and the bottom panel shows the pull distribution. The signal significance ($S/\sqrt{S+B}$), purity ($S/(S+B)$), χ^2/ndf , signal yields, mean, and σ are also shown in each plot. For the systematic study, we have considered double and quadruple Gaussian for signal, and 2nd order polynomial, 3rd order, polynomial and exponential function for background. We also varied the peak region by $\pm 1.5\sigma$ and $\pm 2.5\sigma$ and sideband regions by $\pm 4.5\sigma$ and $\pm 3.5\sigma$ for the systematic study.

The fluctuation in the pull distributions with high χ^2/ndf value is because of integrated p_T and centrality ranges where the different detector resolutions are merged. Here ndf ¹⁶ represents the number of degrees of freedom.

5.6 EXPERIMENTAL CORRELATION

The theoretical framework of femtoscopic correlation is covered in chapter 3. The correlation function is explained by the source function and the two-particle wave function. However, in high-energy experiments, one cannot directly access these quantities. Experimentally, the correlation function is constructed as

$$C^{\text{obs}}(q_{\text{inv}}) = \mathcal{N} \frac{A^{\text{obs}}(q_{\text{inv}})}{B^{\text{obs}}(q_{\text{inv}})}, \quad (5.2)$$

where $C^{\text{obs}}(q_{\text{inv}})$ is the observed normalized pair yield, corrected for detector effects, as a function of the invariant relative momentum q_{inv} , defined as [1]

$$q_{\text{inv}} = \sqrt{-q^\mu q_\mu},$$

$$q^\mu = (k_1 - k_2)^\mu - \frac{(k_1 - k_2)^\mu P_\mu}{P^\mu P_\mu} P^\mu, \quad (5.3)$$

¹⁶In this thesis, sometimes we used NDF or dof (degrees of freedom).

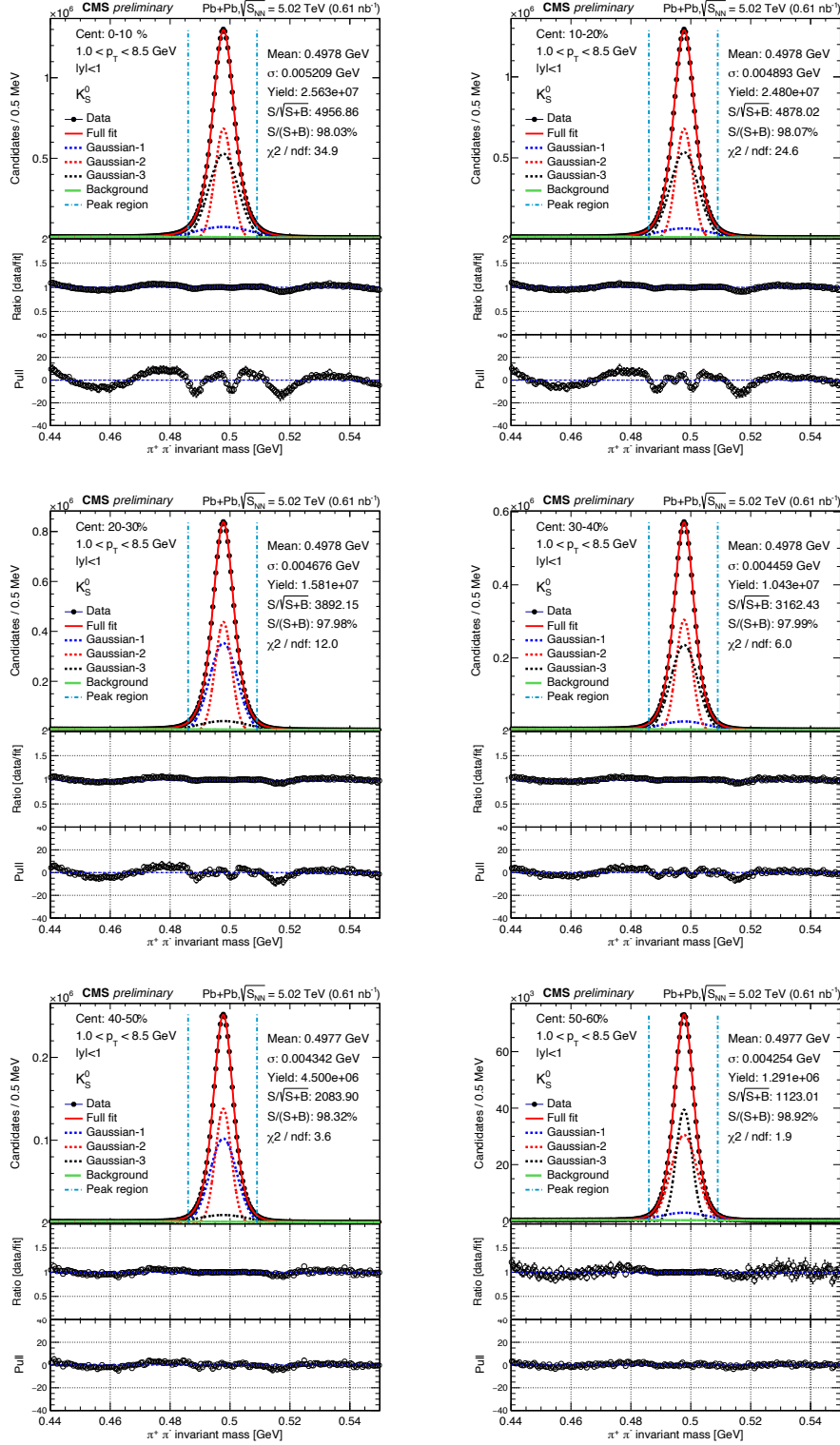


Figure 5.44: The invariant mass, fitting, ratio, and pull distributions of reconstructed $K_S^0 K_S^0$ used in $K_S^0 K_S^0$ correlation with $1.0 < p_T < 8.5$ GeV at mid-rapidity $|y| < 1$ for different centrality bins after the selection.

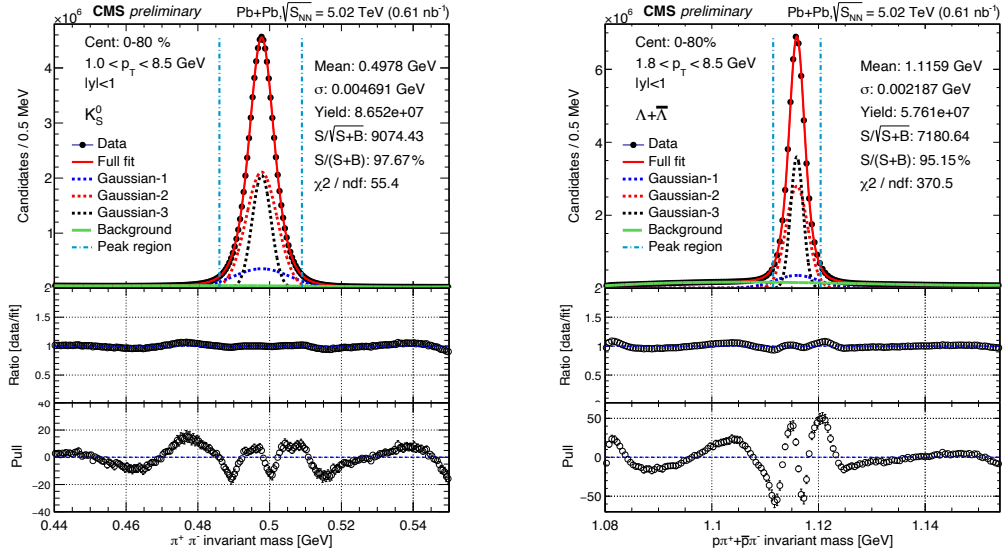


Figure 5.45: The invariant mass, fitting, ratio, and pull distributions of reconstructed K_S^0 (left) and $\Lambda + \bar{\Lambda}$ (right) used in ΛK_S^0 correlation with $1.0 < p_{T_{K_S^0}} < 8.5$ GeV and $1.8 < p_{T_{\Lambda(\bar{\Lambda})}} < 8.5$ GeV at mid-rapidity $|y| < 1$ for 0–80% centrality after the selection.

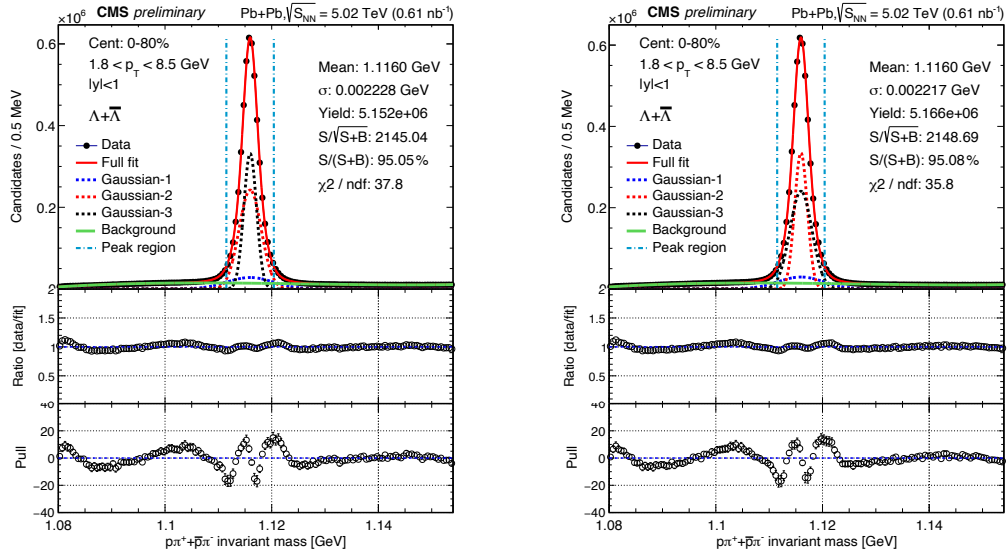


Figure 5.46: The invariant mass, fitting, ratio, and pull distributions of reconstructed $\Lambda + \bar{\Lambda}$ used in $\Lambda\Lambda$ correlation (left) and in $\Lambda\bar{\Lambda}$ correlation with $1.8 < p_T < 8.5$ GeV at mid-rapidity $|y| < 1$ for 0–80% centrality after the selection.

where $P = k_1 + k_2$, and k_1 and k_2 are the four momenta of the V^0 particles. Note that for two particles of the same mass, the second term of q^μ is zero.

The distribution $A^{\text{obs}}(q_{\text{inv}})$ is the signal distribution that contains femtoscopic correlations formed by pairing the selected V^0 particles from a given event. The reference distribution $B^{\text{obs}}(q_{\text{inv}})$ is used to correct for phase space effects, largely removing artifacts due to detector non-uniformities in the $A^{\text{obs}}(q_{\text{inv}})$ distribution. The $B^{\text{obs}}(q_{\text{inv}})$ distribution is constructed by mixing the V^0 particles from different events [121]. In this procedure, the V^0 particle from one event is paired with V^0 particles from 30 different events to minimize the statistical fluctuation in the correlation from the reference sample. To ensure that the 30 events used in the mixing are similar to the signal events, the centrality and primary vertex of each mixed event must be within 5% and 2 cm, respectively, of those in the corresponding signal event. The normalization factor $\mathcal{N}$ is the ratio of the number of pairs in the reference distribution to that in the signal distribution.

Figure 5.47 shows the normalized signal (red markers) and reference (blue markers) distributions for $K_S^0 K_S^0$ pair in six centrality bins (0–10% (top left), 10–20% (top right), 20–30% (middle left), 30–40% (middle right), 40–50% (bottom left), and 50–60% (bottom right)) with $0 < k_T < 2.5$ GeV, where $k_T \equiv |\vec{p}_{T,1} + \vec{p}_{T,2}|/2$ is the average transverse momentum of the particle pair. The normalized signal and reference distributions for ΛK_S^0 pair are shown in Fig. 5.48 in 0–80% centrality with no restriction on k_T . Figure 5.49 shows the normalized signal (red markers) and reference (blue markers) distributions for $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs in 0–80% centrality with no restriction on k_T . The corresponding correlation distributions using Eq. (5.2) are shown in Fig. 5.50 for $K_S^0 K_S^0$, Fig. 5.51 for ΛK_S^0 , and Fig. 5.52 for $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs. Histograms of the correlation distributions are generated in the range $0 < q_{\text{inv}} < 6$ GeV with 0.02 GeV wide bins for the $K_S^0 K_S^0$ and ΛK_S^0 correlations and 0.04 GeV wide bins for the $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ correlations.

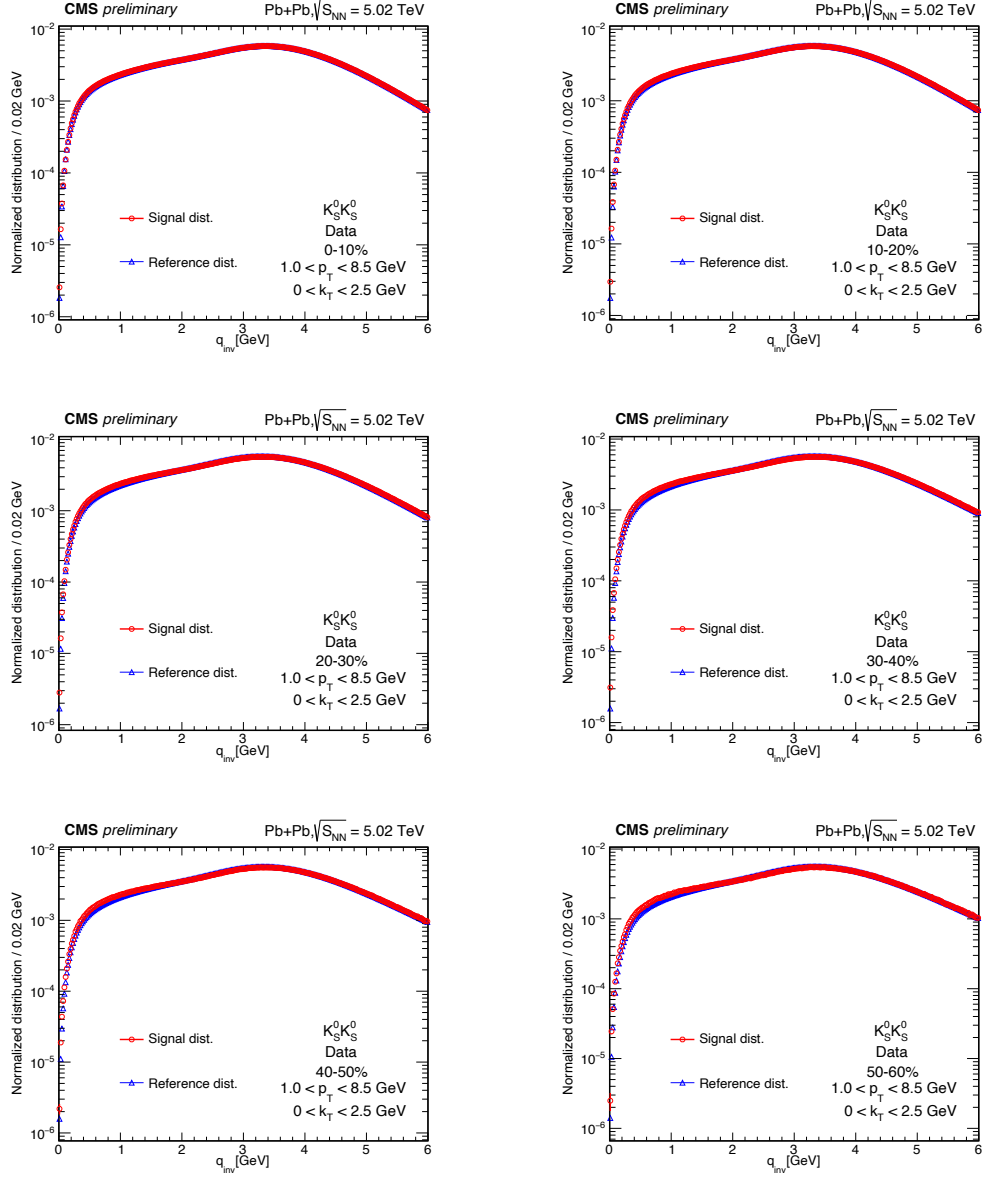


Figure 5.47: Normalized signal (red markers) and reference (blue markers) distributions of $K_S^0 K_S^0$ pair in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV.

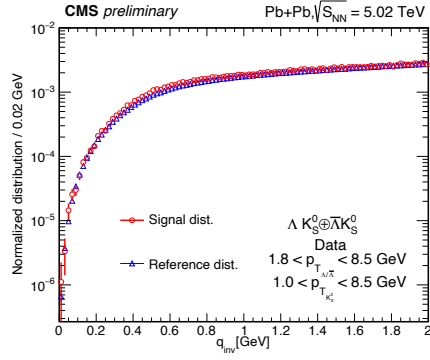


Figure 5.48: Normalized signal (red markers) and reference (blue markers) distributions of ΛK_S^0 pair in 0–80% centrality with no restriction on k_T .

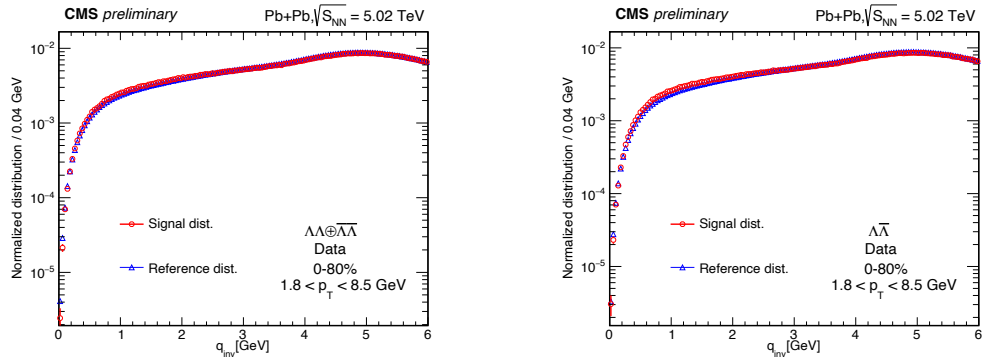


Figure 5.49: Normalized signal (red markers) and reference (blue markers) distributions of $\Lambda\Lambda$ (left) and $\Lambda\bar{\Lambda}$ (right) in 0–80% centrality with no restriction on k_T .

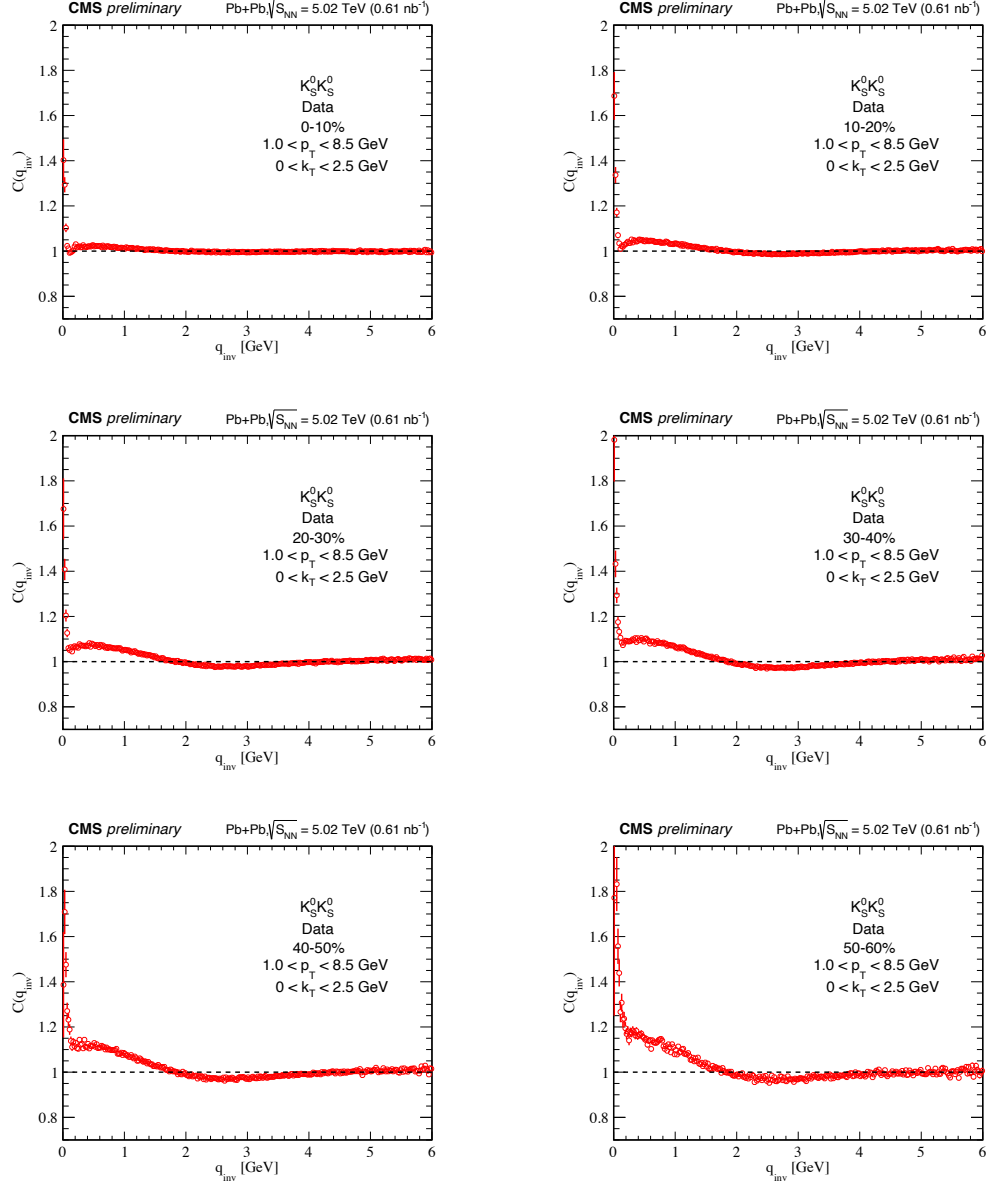


Figure 5.50: Correlation distributions of $K_S^0 K_S^0$ pair in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV.

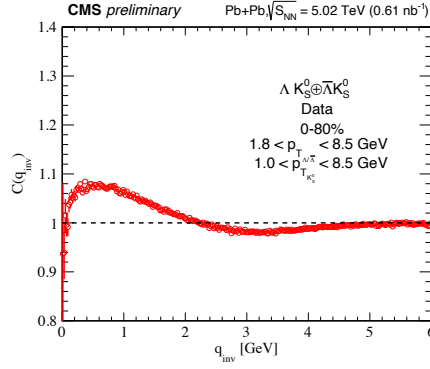


Figure 5.51: Correlation distribution of ΛK_S^0 pair in 0–80% centrality with no restriction on k_T .

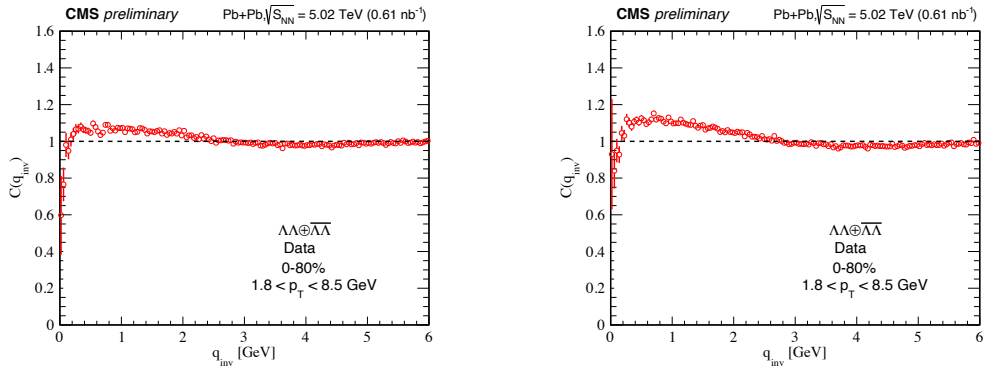


Figure 5.52: Correlation distributions of $\Lambda\Lambda$ (left) and $\Lambda\bar{\Lambda}$ (right) in 0-80% centrality with no restriction on k_T .

5.6.1 Purity correction

While constructing signal distribution, we correlate two V^0 's within the peak region. But in the peak region, we have the pure signal (s) as well as combinatorial background (b). Therefore, the measured signal distribution ($A^{\text{obs}}(q_{\text{inv}})$) contains contributions from signal-signal ($A^{\text{ss}}(q_{\text{inv}})$), signal-background ($A^{\text{sb}}(q_{\text{inv}})$), and background-background ($A^{\text{bb}}(q_{\text{inv}})$) correlations. But our motive is to take only ($A^{\text{ss}}(q_{\text{inv}})$), which means we need to subtract ($A^{\text{sb}}(q_{\text{inv}})$) and $A^{\text{bb}}(q_{\text{inv}})$ from $A^{\text{obs}}(q_{\text{inv}})$. The measured $A^{\text{obs}}(q_{\text{inv}})$ distribution can be written as

$$A^{\text{obs}}(q_{\text{inv}}) = f^{\text{ss}} A^{\text{ss}}(q_{\text{inv}}) + f^{\text{sb}} A^{\text{sb}}(q_{\text{inv}}) + f^{\text{bb}} A^{\text{bb}}(q_{\text{inv}}). \quad (5.4)$$

The distributions $A^{\text{sb}}(q_{\text{inv}})$ and $A^{\text{bb}}(q_{\text{inv}})$ are obtained from the peak-sideband and sideband-sideband combinations, respectively. The small amount of background (signal) contamination in the signal (sideband) region has a negligible effect on the shape of $A^{\text{sb}}(q_{\text{inv}})$ ($A^{\text{bb}}(q_{\text{inv}})$). All distributions, $A^{\text{obs}}(q_{\text{inv}})$, $A^{\text{ss}}(q_{\text{inv}})$, and $A^{\text{bb}}(q_{\text{inv}})$ are normalized to unity. The parameters, f^{ss} , f^{sb} , and f^{bb} are the signal-signal, signal-background, and background-background fractions, extracted using an invariant mass fit based on combinatorial analyses with

$$\begin{aligned} f^{\text{ss}} &= \frac{\binom{s}{2}}{\binom{s+b}{2}}, \\ f^{\text{bb}} &= \frac{\binom{b}{2}}{\binom{s+b}{2}}, \text{ and} \\ f^{\text{sb}} &= 1 - f^{\text{ss}} - f^{\text{bb}}, \end{aligned} \quad (5.5)$$

where $\binom{n}{2} = \frac{n(n-1)}{2}$ is the binomial coefficient, which returns the number of ways that a pair can be chosen from n objects. The quantities s and b in the binomial coefficients are the number of signal and background particles, respectively, obtained by integrating the appropriate function from the fit to the invariant mass distribution.

The extracted fractions, f^{ss} , f^{sb} , and f^{bb} as a function of q_{inv} from the invariant mass fit are shown in the Fig. 5.53 for $K_S^0 K_S^0$, Fig. 5.54 for ΛK_S^0 , and Fig. 5.55 for $\Lambda \Lambda$ (left

panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs. From these plots, one can observe that the factors, f^{ss} , f^{sb} , and f^{bb} are independent of q_{inv} or have very small dependence on q_{inv} ($< 2\%$ for all the pairs), and are extracted using constant fit. The fluctuations at very low q_{inv} bins come from the invariant mass fit due to the small number of pairs. The obtained signal-signal fractions f^{ss} for $K_S^0 K_S^0$ pairs are $\approx 95\%$, for ΛK_S^0 pair is $\approx 93\%$, and for $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs are $\approx 90\%$. Due to high signal-signal fractions in all the pairs, the signal-background and background-background fractions are very small. The obtained f^{sb} and f^{bb} for $K_S^0 K_S^0$ pairs are $< 5\%$ and $< 0.1\%$, respectively, for ΛK_S^0 pair is $< 6.5\%$ and $< 0.2\%$, respectively, and for $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs are $< 10\%$ and $< 0.3\%$, respectively. One can also observed that, $f_{K_S^0 K_S^0}^{ss} > f_{\Lambda K_S^0}^{ss} > f_{\Lambda\Lambda(\Lambda\bar{\Lambda})}^{ss}$ as expected because the purity of K_S^0 is larger than the Λ ($\bar{\Lambda}$).

Once we have all the distributions ($A^{\text{obs}}(q_{\text{inv}})$, $A^{\text{sb}}(q_{\text{inv}})$, and $A^{\text{bb}}(q_{\text{inv}})$) and the parameters (f^{ss} , f^{sb} , and f^{bb}), the $A^{ss}(q_{\text{inv}})$ distribution can be extracted using Eq. (5.4), with

$$A^{ss}(q_{\text{inv}}) = \left[A^{\text{obs}}(q_{\text{inv}}) - f^{sb}(A^{\text{sb}}(q_{\text{inv}})) - f^{bb}(A^{\text{bb}}(q_{\text{inv}})) \right] / f^{ss}. \quad (5.6)$$

Figures 5.59–5.61 shows the $A^{\text{obs}}(q_{\text{inv}})$ (red marker), $A^{ss}(q_{\text{inv}})$ (blue marker), $A^{\text{sb}}(q_{\text{inv}})$ (green marker), and $A^{\text{bb}}(q_{\text{inv}})$ (azure marker) distributions with multiplying respective fractions as in Eq. (5.4) for all the pairs. One can see that the purity correction is very small as the $A^{\text{obs}}(q_{\text{inv}})$ and $f^{ss}A^{ss}(q_{\text{inv}})$ distributions are very close to each other. This is expected because f^{ss} is $> 90\%$ for all the pairs.

The same procedure is followed for the reference distribution. After extracting the $A^{ss}(q_{\text{inv}})$ and $B^{ss}(q_{\text{inv}})$ distributions, the correlation distribution is calculated as

$$C^{ss}(q_{\text{inv}}) = \mathcal{N} \frac{A^{ss}(q_{\text{inv}})}{B^{ss}(q_{\text{inv}})}. \quad (5.7)$$

The effect of purity correction on the correlation measurements is also shown for all the pairs in Fig. 5.56–5.58. The red full circles are showing the purity corrected correlation

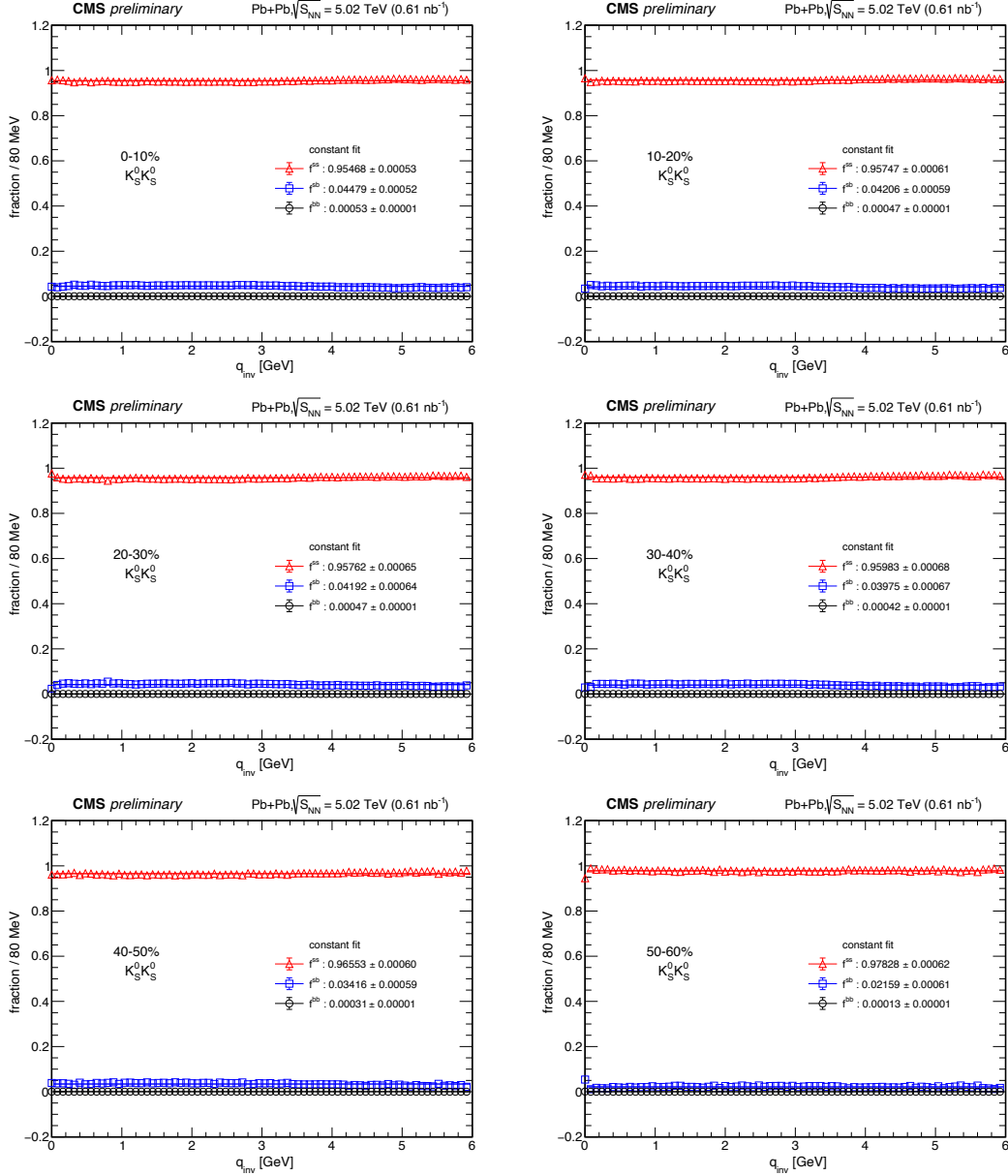


Figure 5.53: Fractions f^{ss} (red marker), f^{sb} (blue marker), and f^{bb} (black marker) are extracted from invariant mass fit as a function of q_{inv} for $K_S^0 K_S^0$ pairs in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV. The solid lines represent the constant fit to these factors.

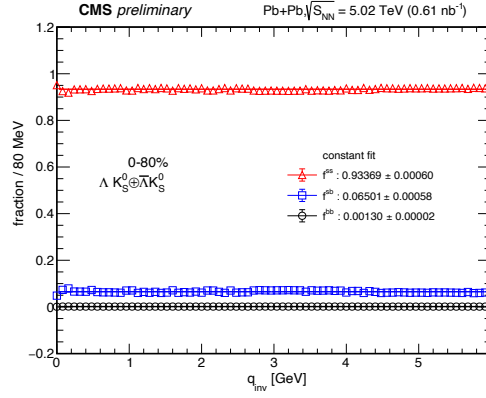


Figure 5.54: Fractions f^{ss} (red marker), f^{sb} (blue marker) and f^{bb} (black marker) are obtained from invariant mass fit as a function of q_{inv} for ΛK_S^0 pair in 0–80% centrality with no restriction on k_T . The solid lines represent the constant fit to these factors.

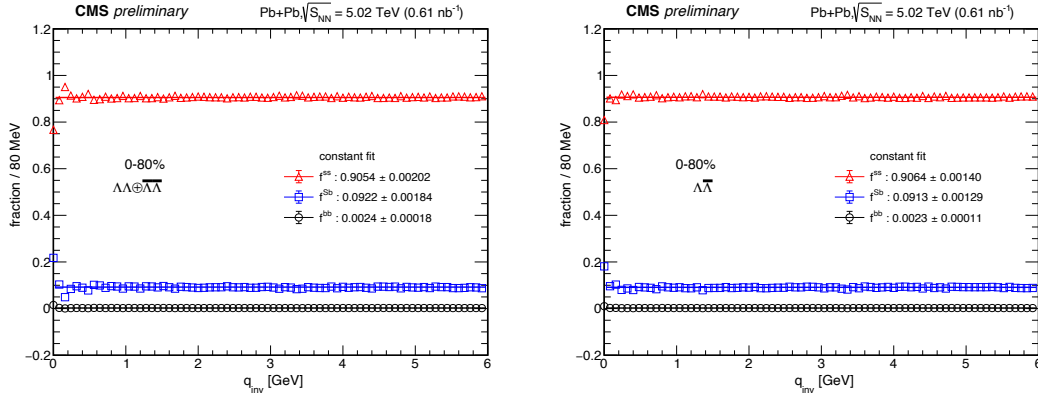


Figure 5.55: Fractions f^{ss} (red marker), f^{sb} (blue marker) and f^{bb} (black marker) are extracted from invariant mass fit as a function of q_{inv} for $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs in 0–80% centrality with no restriction on k_T . The solid lines represent the constant fit to these factors.

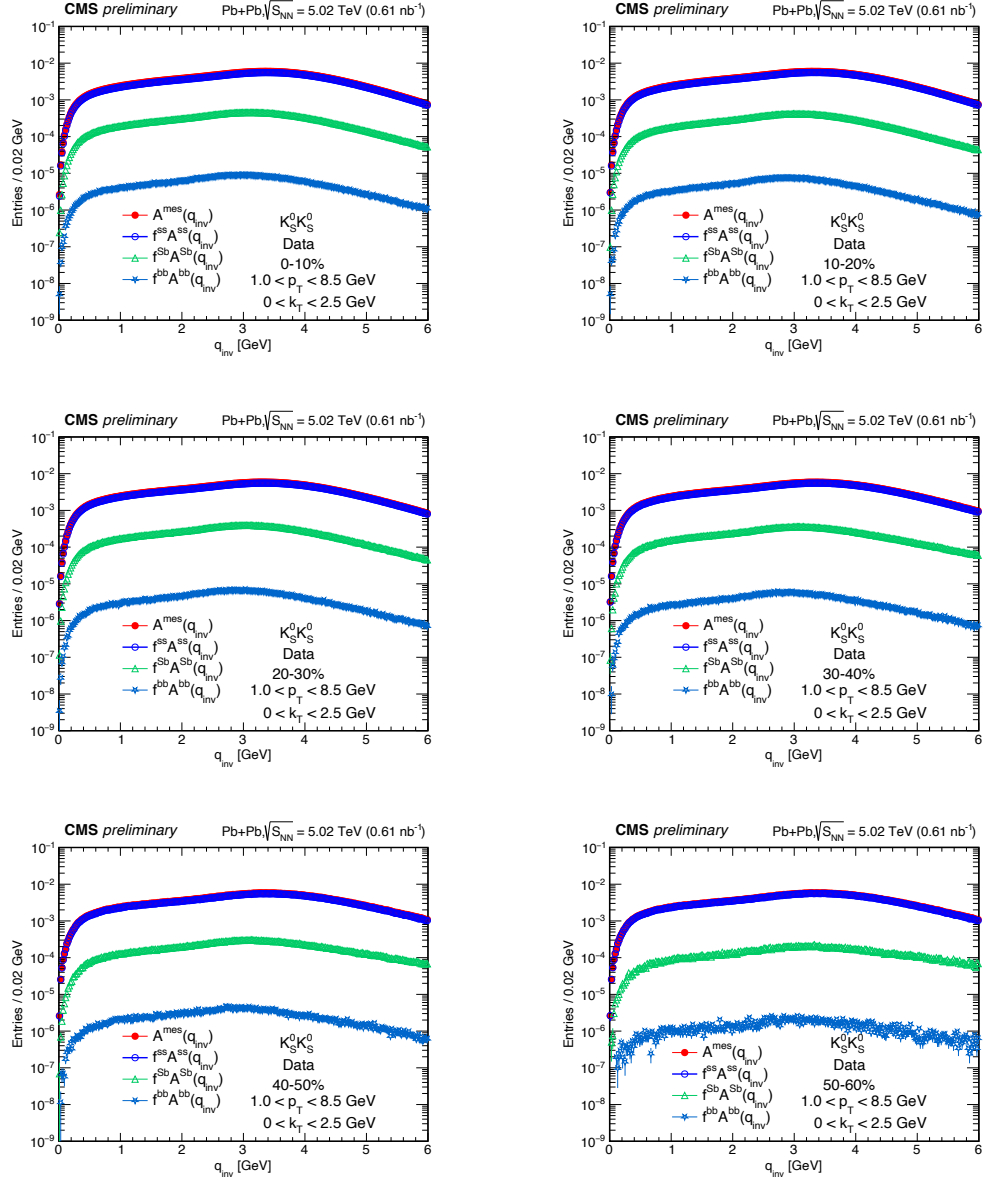


Figure 5.56: Normalized $A^{obs}(q_{inv})$ (red marker), $f^{ss}A^{ss}(q_{inv})$ (blue marker), $f^{sb}A^{sb}(q_{inv})$ (green marker), and $f^{bb}A^{bb}(q_{inv})$ (azure marker) distributions of $K_S^0 K_S^0$ pairs in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV.

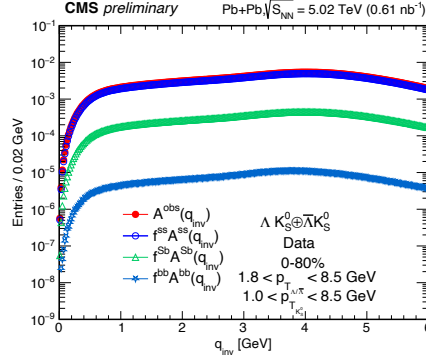


Figure 5.57: Normalized $A^{\text{obs}}(q_{\text{inv}})$ (red marker), $f^{\text{ss}}A^{\text{ss}}(q_{\text{inv}})$ (blue marker), $f^{\text{sb}}A^{\text{sb}}(q_{\text{inv}})$ (green marker), and $f^{\text{bb}}A^{\text{bb}}(q_{\text{inv}})$ (azure marker) distributions of ΛK_S^0 pair in 0–80% centrality with no restriction on k_T .

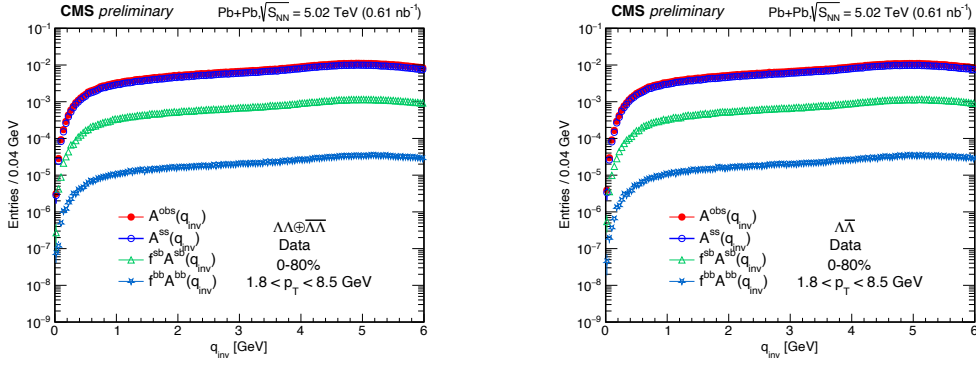


Figure 5.58: Normalized $A^{\text{obs}}(q_{\text{inv}})$ (red marker), $f^{\text{ss}}A^{\text{ss}}(q_{\text{inv}})$ (blue marker), $f^{\text{sb}}A^{\text{sb}}(q_{\text{inv}})$ (green marker), and $f^{\text{bb}}A^{\text{bb}}(q_{\text{inv}})$ (azure marker) distributions of $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs in 0–80% centrality with no restriction on k_T .

$C^{\text{ss}}(q_{\text{inv}})$ and the blue open circles are showing the correlation measurement $C^{\text{obs}}(q_{\text{inv}})$ without purity correction. We can observe that the effect of purity correction on the correlation measurement is very small and in the very low q_{inv} bins.

5.6.2 Non-femtoscopic background

A significant non-femtoscopic background is observed in the correlation distribution $C^{\text{ss}}(q_{\text{inv}})$ of all the pairs after correcting for detector effects and non- V^0 backgrounds. Our correlation distributions are not flat at 1 after the signal regions ($q_{\text{inv}} < 0.4$ GeV). It is above 1 at lower q_{inv} bins and below 1 at intermediate q_{inv} bins. At very high q_{inv} ($q_{\text{inv}} \geq 5$ GeV), the correlation distributions are flat at 1. These are the sign of non-femtoscopic backgrounds. The non-femtoscopic backgrounds are primarily due to the elliptic flow [122], minijets [7], resonance decays [7], and energy-momentum conservation [123]. The effect of flow produces suppression at intermediate q_{inv} and enhancement at low q_{inv} . The effect such as minijets and resonances decay enhances the lower q_{inv} and this effect increases significantly with increases of k_T and centrality. The energy-momentum conservation effect can enhance the correlation distributions and this effect is more in small colliding systems (e.g., pp and pPb). To best describe the experimental data, an understanding of the non-femtoscopic background is needed.

In MC, we do not have femtoscopic correlation, therefore we should expect that the correlation distribution should be flat at 1. But, similar non-femtoscopic behaviour is observed in the MC gen level correlation distributions. The correlation distributions in MC generated level can be seen in Fig. 5.62 for $K_S^0 K_S^0$, Fig. 5.63 for ΛK_S^0 , and Fig. 5.64 for $\Lambda\Lambda$ (left) and $\Lambda\bar{\Lambda}$ (right) pairs. Several methods are used by the CMS, ALICE, and ATLAS experiments to correct these non-femtoscopic effects, which are double ratio technique [76, 124], cluster subtraction technique [7], hybrid-cluster subtraction technique [76, 125] etc. The methods mentioned above mostly depend on MC and the opposite charge pair. Due to the limitations of the methods and MC sample, in this analysis, we have applied a technique that is fully data-driven. The non-femtoscopic

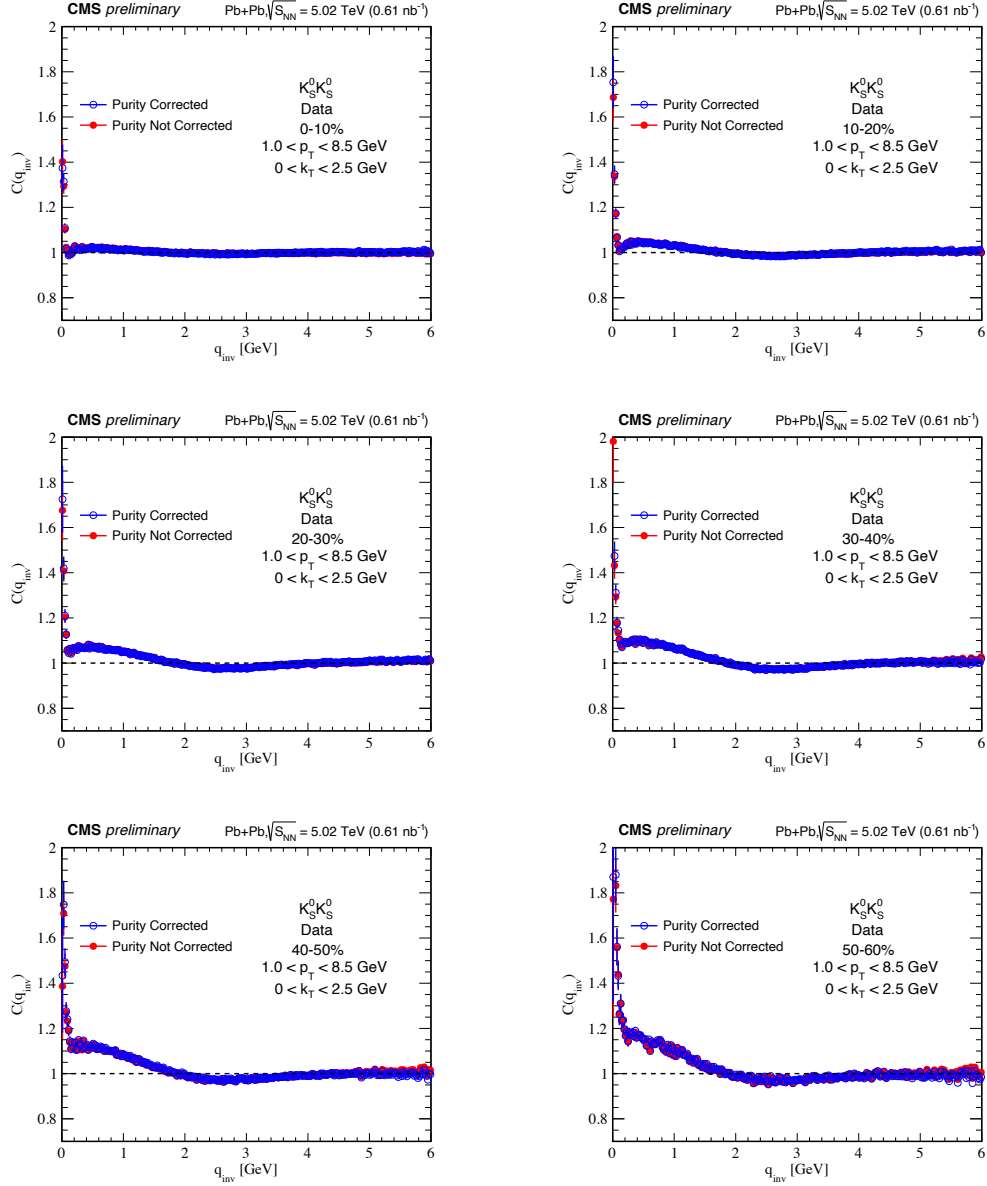


Figure 5.59: Correlation measurements of $K_S^0 K_S^0$ before purity correction (red full circle) and after purity correction (blue open circle) in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV.

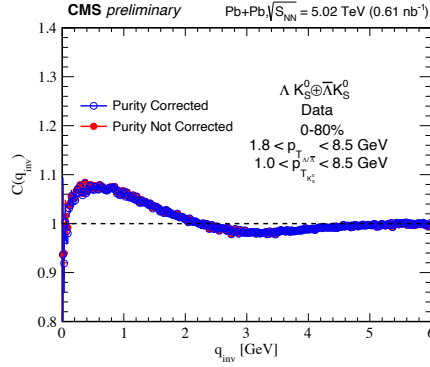


Figure 5.60: Correlation measurement of ΛK_S^0 before purity correction (red full circle) and after purity correction (blue open circle) in 0–80% centrality with no restriction on k_T .

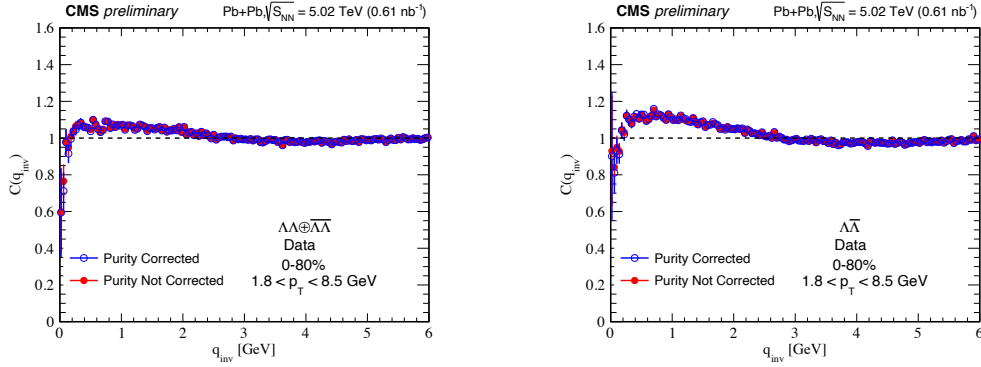


Figure 5.61: Correlation measurement of $\Lambda\Lambda$ (left) and $\Lambda\bar{\Lambda}$ (right) before purity correction (red full circle) and after purity correction (blue open circle) in 0–80% centrality with no restriction on k_T .

background contribution is modeled using an empirically determined double Gaussian function

$$\Omega(q_{\text{inv}}) = N \left(1 + \alpha_1 e^{-q_{\text{inv}}^2 R_1^2} \right) \left(1 - \alpha_2 e^{-q_{\text{inv}}^2 R_2^2} \right), \quad (5.8)$$

where N , α_1 , α_2 , R_1 , and R_2 are fit parameters.

As in both data and MC gen levels correlations distributions, the behaviour of non-femtoscopic backgrounds is similar, we first fitted this function in MC gen level correlation distributions (we do not have the femtoscopic correlation in this case), which can be seen in Fig. 5.62 for $K_S^0 K_S^0$, Fig. 5.63 for ΛK_S^0 , and Fig. 5.64 for $\Lambda \Lambda$ (left panel) and $\Lambda \bar{\Lambda}$ (right panel) pairs. It can be seen that the non-femtoscopic background function perfectly describes the MC gen level correlation distributions for all the pairs. We will use the same function to account for the non-femtoscopic background in data which is discussed in the next section.

5.7 FITTING FUNCTION

To extract the source size and strong interaction scattering parameters, we need to fit the theoretical correlation function (described in sec. 3) to the measured experimental correlation distribution $C^{\text{ss}}(q_{\text{inv}})$. As the V^0 particles are neutral, the Coulomb interaction is absent. However, the correlations are sensitive to QS and FSI effects, with s -wave interactions assumed to dominate for the small relative momenta of the particle pairs analyzed. The correlation distribution for all pairs ($K_S^0 K_S^0$, ΛK_S^0 , $\Lambda \Lambda$, and $\Lambda \bar{\Lambda}$) is interpreted in the LL model and also described in sec. 3. The theoretical formalism relates the two-particle correlation function to the source size and also takes into account FSI effects [17]. Along with QS and FSI, we need to consider the non-femtoscopic background effect discussed in sec. 5.6.2. The general correlation function is

$$C_{\text{total}}(q_{\text{inv}}) = \left[1 + \lambda \left(C_{\text{QS}}(q_{\text{inv}}) + C_{\text{FSI}}(q_{\text{inv}}) \right) \right] \Omega(q_{\text{inv}}), \quad (5.9)$$

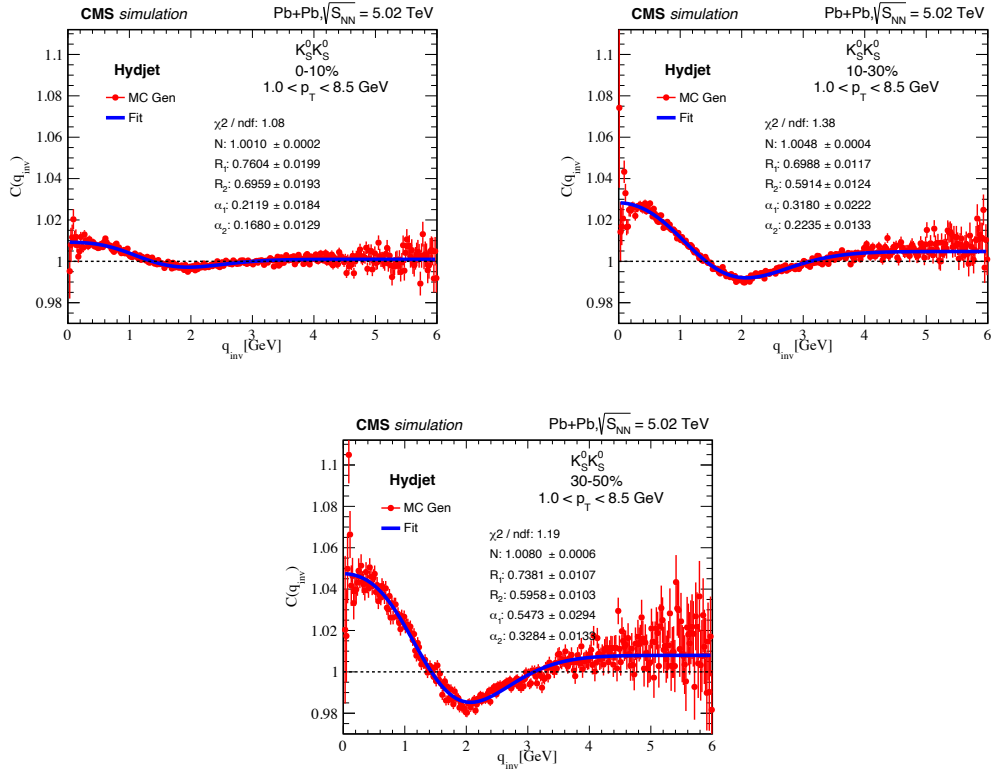


Figure 5.62: MC generated level correlation distributions (red circle) and fit (blue line) using Eq. (5.8) for $K_S^0 K_S^0$ pairs in 0–10% (top left), 10–30% (top right), 30–50% (bottom) centrality.

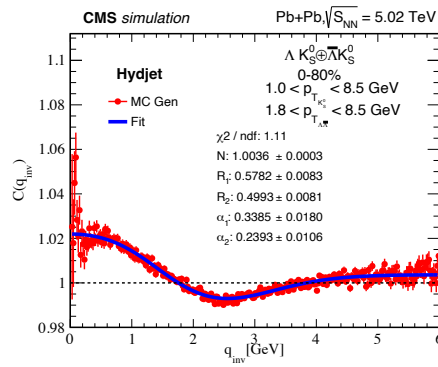


Figure 5.63: MC generated level correlation distribution (red circle) and fit (blue line) using Eq. (5.8) for ΛK_S^0 pair in 0–80% centrality.

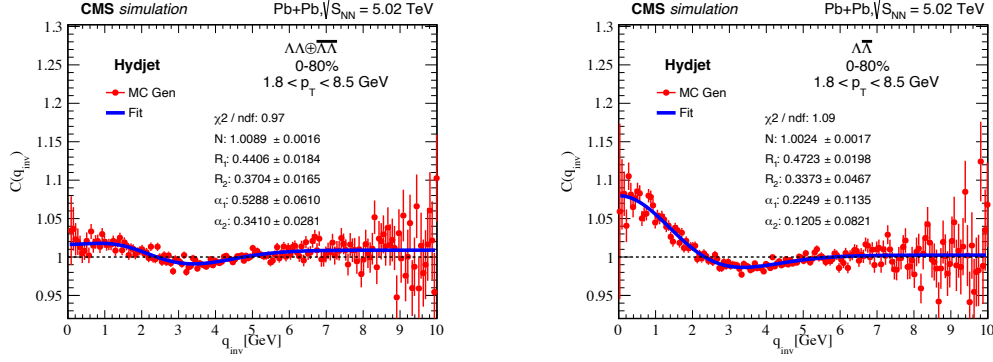


Figure 5.64: MC generated level correlation distributions (red circle) and fit (blue line) using Eq. (5.8) for $\Lambda\Lambda$ (left panel) and $\Lambda\bar{\Lambda}$ (right panel) pairs in 0–80% centrality.

where $C_{QS}(q_{inv})$ is the QS function, $C_{FSI}(q_{inv})$ is the strong FSI function, and $\Omega(q_{inv})$ is the non-femtoscopic background function. Details about $C_{QS}(q_{inv})$ and $C_{FSI}(q_{inv})$ functions are described in sec. 3. For non-identical particle correlations (ΛK_S^0 and $\Lambda\bar{\Lambda}$), $C_{QS}(q_{inv}) = 0$ (see details in sec. 3.3.1).

Fits to the correlation distribution of all the pairs were performed using Eq. (5.9) with the non-femtoscopic background parameters (N , α_1 , α_2 , R_1 , and R_2) treated as free parameters. For $K_S^0 K_S^0$ correlations, the parameters of interest are R_{inv} and λ , with the scattering amplitude based on previous measurements [80–83]. The ΛK_S^0 , $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ correlations include additional parameters: d_0 , $\Re f_0$, and $\Im f_0$. The $\Im f_0$ term for $\Lambda\Lambda$ correlations is set to zero since there are no baryon-baryon annihilation processes. The fits exclude the first q_{inv} bin to avoid a potential bias from the method used to address cases where V^0 candidates share daughter tracks. Studies using simulated events indicate that only this first bin is affected by this remediation (see details in sec. 5.5.4). Least-square fits are performed to the experimental data with the uncertainties in the fit parameters calculated using the MINOS technique [126]. Examples of correlation measurements and their fits for all the pairs are presented in Fig. 5.65. In all the plots, extracted fit parameters are mentioned with the values of χ^2 , NDF, and fit probability

(prob.). Details about these plots and extracted fit parameters are briefly discussed in chapter 6.

Due to the limited statistics and low signal compared to the non-femtoscopic background at low q_{inv} for the $\Lambda\bar{\Lambda}$ pair, we are not able to fit the $\Lambda\bar{\Lambda}$ correlation with all the non-femtoscopic background parameters treated as free parameters. The fit parameters are not stable and fluctuate rapidly with changing the fit ranges, which signifies that the statistics available for $\Lambda\bar{\Lambda}$ correlation are not enough for the fitting and demand further studies with high statistics. However, by fixing the non-femtoscopic background parameters in the full fit by extracting them using a different fit at higher q_{inv} ($0.5 < q_{\text{inv}} < 6$ GeV) using Eq. (5.8), we are able to stabilize the fit. But we cannot trust the obtained fitting parameters from this fit. Therefore, we will not discuss the results extracted from the $\Lambda\bar{\Lambda}$ pair.

5.8 MC CLOSURE TEST

MC closure test has been studied using HYDJET MC sample to check if there is any effect in our measurement due to detector inefficiency. Generally, this test performs on the correlation measurements. But as we have low statistics for V^0 pairs, we perform this test for signal, reference, and correlation distributions of all the pairs. In this test, we have compared the signal, reference, and correlations distributions of all the pairs between the MC reco level, MC reco level with efficiency correction, and MC gen level. The efficiency correction is performed by applying a p_T and rapidity dependent weight (extracted from the 2D plot of sec. 5.5.3) defined as $(1-\text{fake})/\text{efficiency}$. For two-particle correlations, this weight is $[(1-\text{fake1})/\text{efficiency1}] \times [(1-\text{fake2})/\text{efficiency2}]$. Here the $(1-\text{fake1})/\text{efficiency1}$ is the weight of 1st particle and $(1-\text{fake2})/\text{efficiency2}$ is the weight of 2nd particle. If we have accounted for the detector inefficiency correctly, then efficiency corrected MC reco level distributions should match with MC gen level distributions. Fig. 5.66–5.69 shows the comparison of signal (left panel) and reference (right panel) distributions

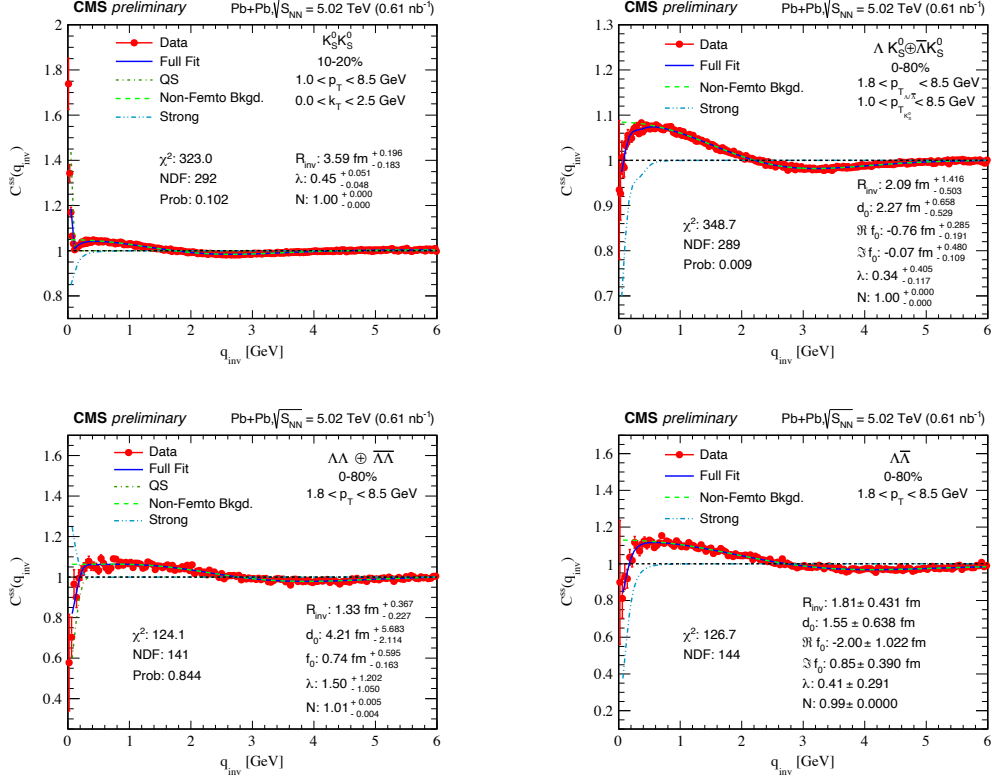


Figure 5.65: Figures show the correlation measurement and fits for $K_S^0 K_S^0$ pair in 10–20% centrality with $0 < k_T < 2.5$ GeV (top left) and ΛK_S^0 (top right), $\Lambda\Lambda$ (bottom left), and $\Lambda\bar{\Lambda}$ (bottom right) pairs in 0–80% centrality with no restriction on k_T . In these plots the red filled circle represents the data, the blue solid line is fit using Eq. (5.9), the green dashed line is the non-femtoscopic background (Eq. (5.8)), the dashed double dotted line is the strong FSI function, and the dash dotted line is the QS function. QS line drawn using the equation $1 \pm e^{-q_{inv}^2 R_{inv}^2}$, where the R_{inv} is taken from the LL fit.

between MC gen level (red circle), MC reco level (blue square), and MC reco level with efficiency correction (black square) for all the pairs ($K_S^0 K_S^0$ (Fig. 5.66), ΛK_S^0 (Fig. 5.67), $\Lambda\Lambda$ (Fig. 5.68), and $\Lambda\bar{\Lambda}$ (Fig. 5.69)). The ratio distributions between MC gen level and efficiency corrected MC reco level distributions are also shown for these plots. Due to low statistics in the MC sample, all the distributions are shown in integrated centrality 0–80% with q_{inv} bin width 0.12 GeV for $K_S^0 K_S^0$, 0.2 GeV for ΛK_S^0 , and 0.6 GeV for $\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ pairs. From these distributions, we can see that efficiency corrected MC reco level distributions (black square) are very close with MC gen level distributions (red circle) within their uncertainty, while the MC reco level without efficiency correction distribution is not matching with MC gen level distributions. From the ratio plots, one can observe that the shape in both signal and reference distributions are similar, and the remaining effect due to detector inefficiency should be canceled out when we measured the correlation by taking the ratio between signal and reference distributions using (see the Eq. (5.2)). Fig. 5.70 shows the correlation distributions for all the pairs ($K_S^0 K_S^0$ (top left), ΛK_S^0 (top right), $\Lambda\Lambda$ (bottom left), and $\Lambda\bar{\Lambda}$ (bottom right)) between MC gen level (red circle), MC reco level (blue square), and MC reco level with efficiency correction (black square). Due to low statistics for V^0 particles in the MC sample, the statistical uncertainty is very high and many fluctuations are observed for all the pairs. However, for the $K_S^0 K_S^0$ pair, it can be seen that the good agreement between MC gen level and efficiency corrected the MC reco level within the large uncertainties. Additionally, one can observe that the correlation distributions in MC reco level with and without efficiency correction is matching within their uncertainties. This suggested that there is no effect of efficiency correction on the correlation measurement. The detector inefficiency is canceled out when we take the ratio between signal and reference distribution to measure the correlation.

To confirm the efficiency correction is actually canceling out by taking the ratio between signal and reference distributions, we check the two-particle efficiency as a function of q_{inv} in MC. In this study, we checked the two-particle efficiency used for the signal

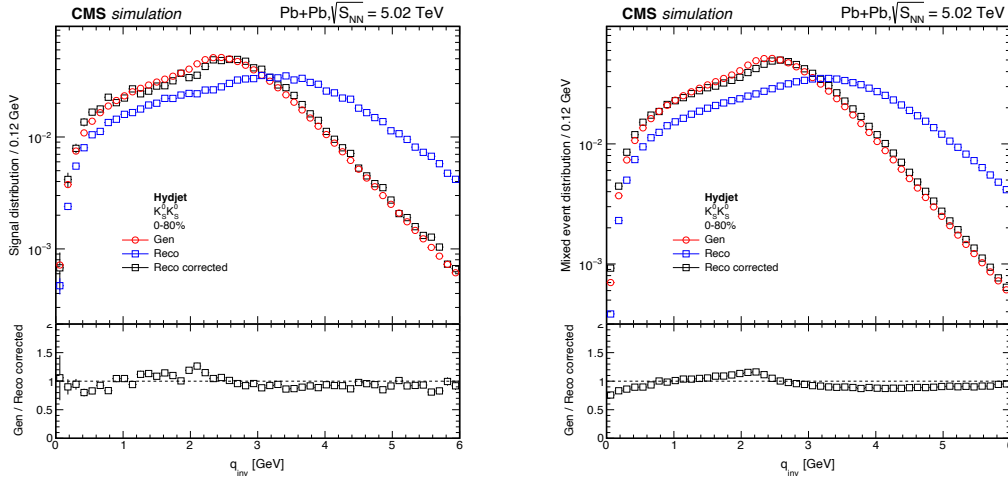


Figure 5.66: Normalized signal (left panel) and reference (right panel) distribution for $K_S^0 K_S^0$ pair in 0–80% centrality. In these plots, the red circle is for the MC gen level, the blue square is for the MC reco level, and the black square is for the efficiency corrected MC reco level. The ratio plot is between the MC gene level and the efficiency corrected MC reco level.

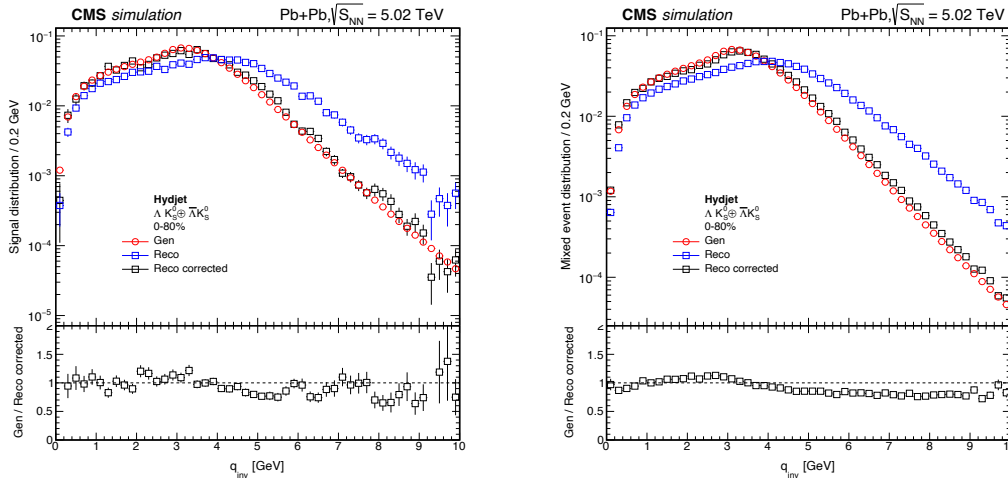


Figure 5.67: Normalized signal (left panel) and reference (right panel) distribution for ΛK_S^0 pair in 0–80% centrality. In these plots, the red circle is for the MC gen level, the blue square is for the MC reco level, and the black square is for the efficiency corrected MC reco level. The ratio plot is between the MC gene level and the efficiency corrected MC reco level.

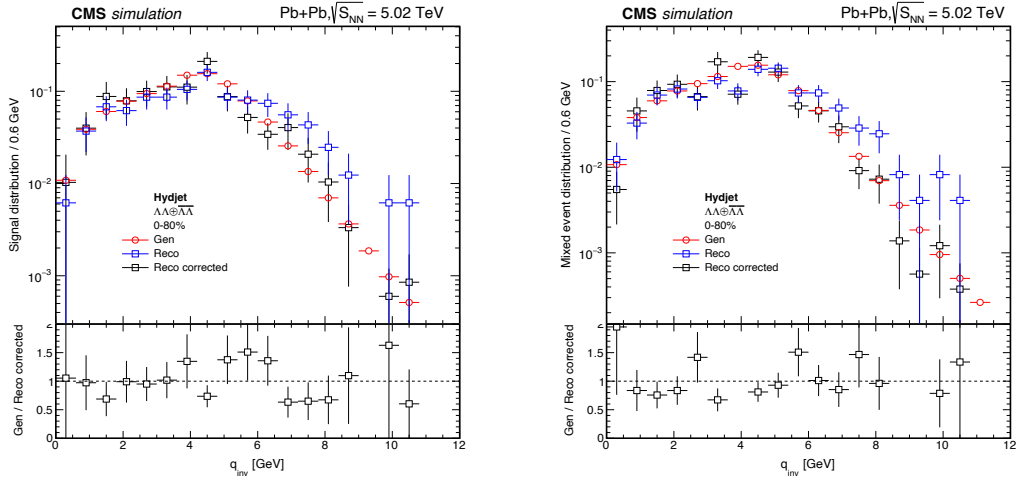


Figure 5.68: Normalized signal (left panel) and reference (right panel) distribution for $\Lambda\bar{\Lambda}$ pair in 0–80% centrality. In these plots, the red circle is for the MC gen level, the blue square is for the MC reco level, and the black square is for the efficiency corrected MC reco level. The ratio plot is between the MC gene level and the efficiency corrected MC reco level.

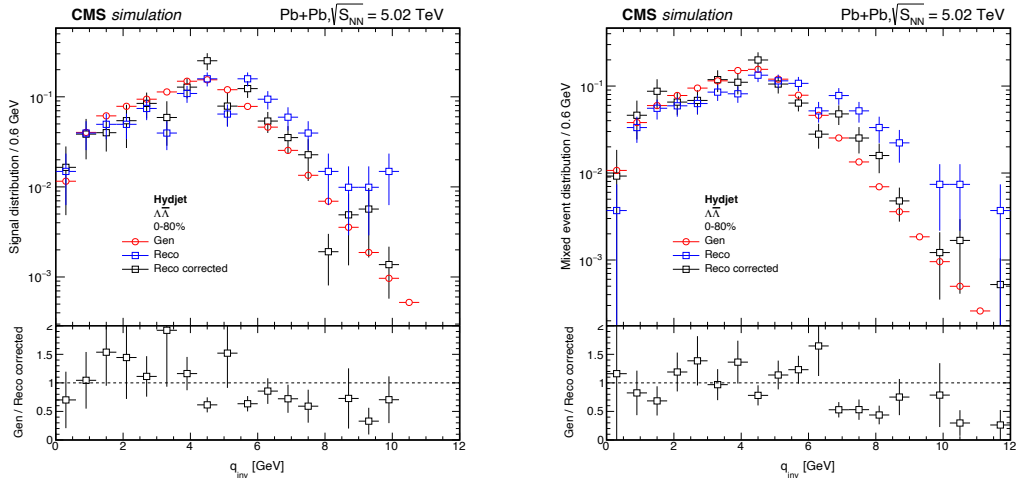


Figure 5.69: Normalized signal (left panel) and reference (right panel) distribution for $\Lambda\bar{\Lambda}$ pair in 0–80% centrality. In these plots, the red circle is for the MC gen level, the blue square is for the MC reco level, and the black square is for the efficiency corrected MC reco level. The ratio plot is between the MC gene level and the efficiency corrected MC reco level.

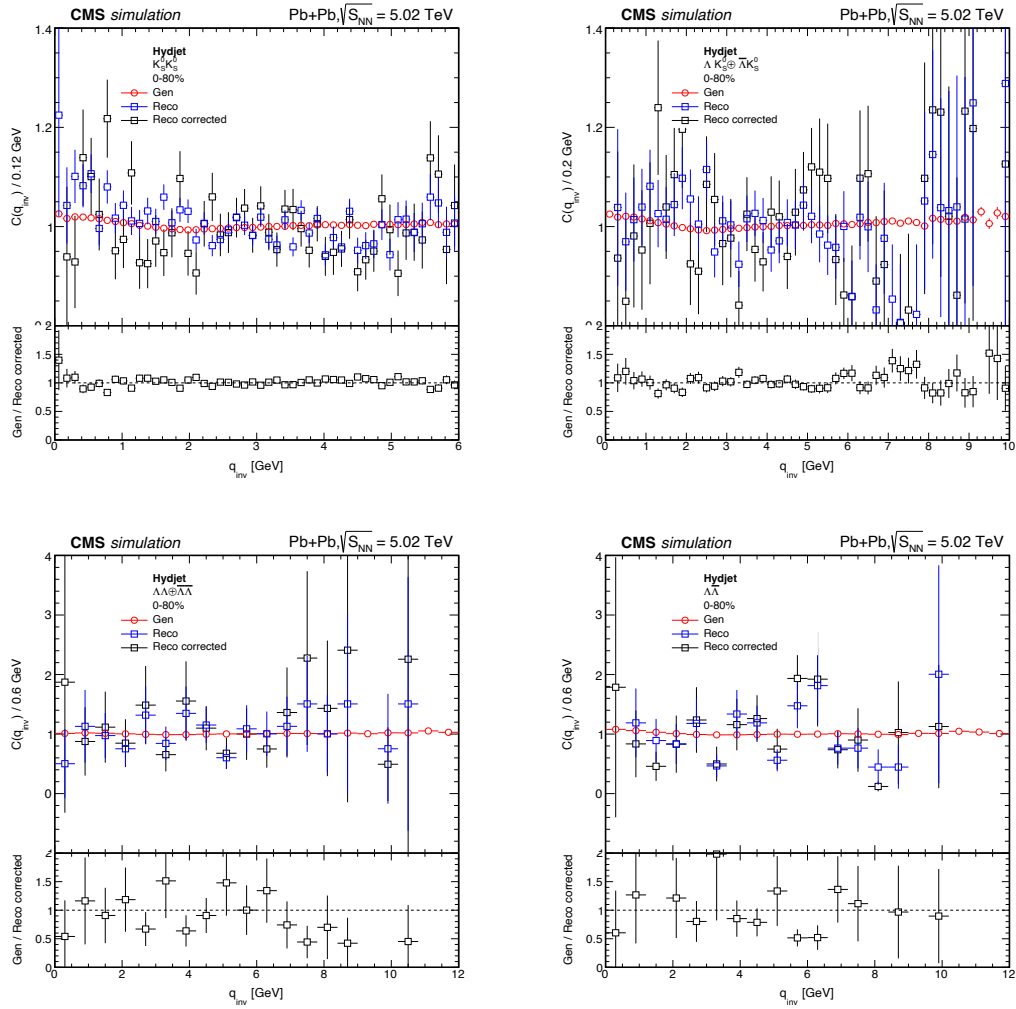


Figure 5.70: Correlation distributions of $K_S^0 K_S^0$ (top left), ΛK_S^0 (top right), $\Lambda\Lambda$ (bottom left) and $\Lambda\bar{\Lambda}$ (bottom right) pairs in 0–80% centrality. In these plots, the red circle is for the MC gen level, the blue square is for the MC reco level, and the black square is for the efficiency corrected MC reco level. The ratio plot is between the MC gene level and the efficiency corrected MC reco level.

and reference distributions as a function of q_{inv} . If the two-particle efficiency does not behave differently on the signal and reference distributions, both distributions will be matched after normalization and the effect of efficiency will cancel out in the ratio. But, if it behaves differently, then the effect of efficiency will not cancel out in the ratio and therefore, we need to apply efficiency correction to data. We perform this study only for $K_S^0 K_S^0$ (left panel) and ΛK_S^0 (right panel) pair in 0–80% with taking 0.2 GeV q_{inv} bin width due to limited statistics that can be seen in Fig. 5.71. One can see that the two-particle efficiency used in signal (red circle) and reference (blue square) distributions are perfectly matching and the ratio is very close to 1 in all the q_{inv} bins within their uncertainty. The fluctuation in the very 1st bin of q_{inv} is due to low statistics. From this study, one can confirm that the detector inefficiency is actually canceling out in the ratio and we do not need the efficiency correction for the correlation measurement. To study quantitatively, the ratio distributions are fitted with a linear function and extracted a factor using the fit parameters for each q_{inv} bin. Then we applied it as a correction factor to the correlation distributions for the corresponding q_{inv} bin in data. A comparison of correlation measurement for $K_S^0 K_S^0$ (left panel) and ΛK_S^0 (right panel) pair with (blue square) and without (red circle) this correction in data can be seen in Fig. 5.72. The correlation distributions with and without this correction are perfectly matching and there are no significant changes that can be seen from ratio distributions. We also checked the fit parameter by fitting the correlation distributions before and after this correction and found no changes in the fitting parameters which can be seen in Fig. 5.73. These studies suggested that this analysis does not need efficiency correction.

5.9 p_T REWEIGHT STUDY

In the previous section, we performed some studies using MC in order to justify that we do not need to apply the efficiency correction to the experimentally measured correlation distributions as it canceled out in the ratio of signal and reference samples. However, the V^0 efficiency strongly depends on low p_T , and differences in the MC and

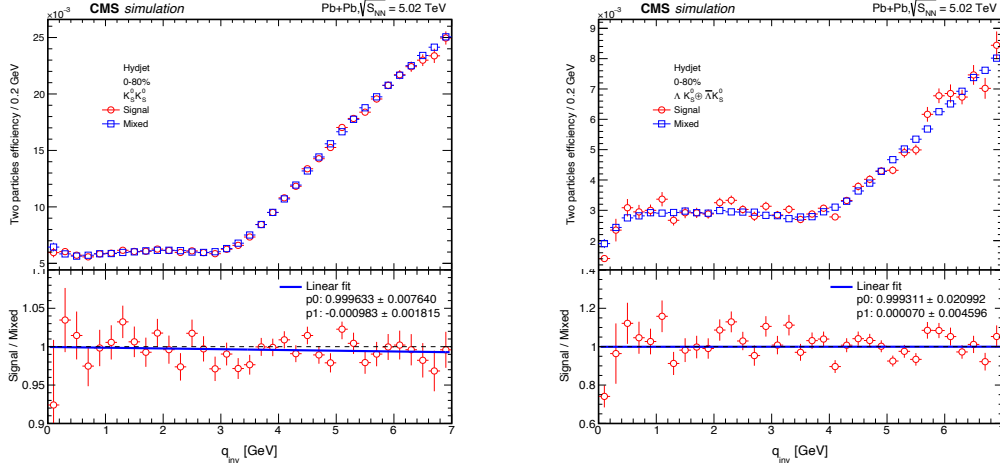


Figure 5.71: Two particles efficiency used for signal (red circle) and mixed event reference (blue square) distribution as a function of q_{inv} for $K_S^0 K_S^0$ (left panel) and ΛK_S^0 (right panel) pair in 0-80% centrality in MC. The bottom panel shows the ratio between these distributions.

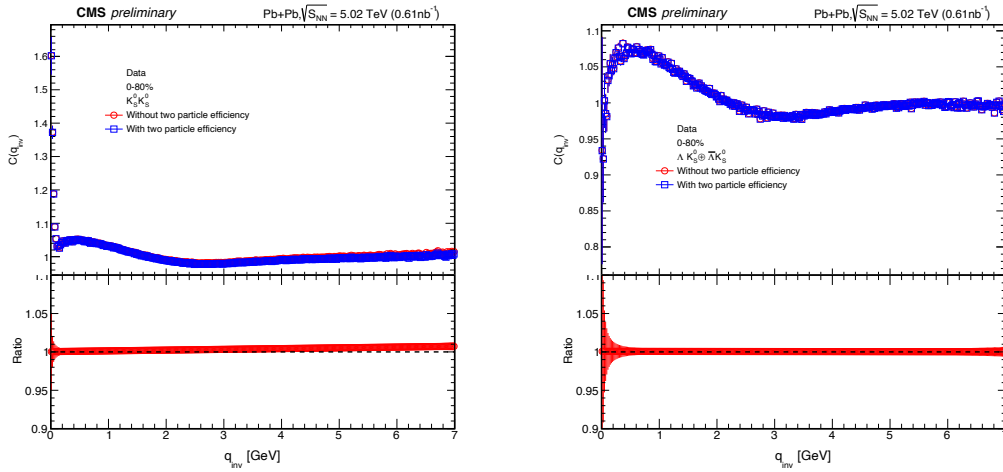


Figure 5.72: Figure shows the $K_S^0 K_S^0$ (left) and ΛK_S^0 (right) correlations measured in data with (blue square) and without (red circle) applying the correction factor extracted from Fig. 5.71 using linear fit in 0-80% centrality. The bottom panel shows the ratio between these distributions.

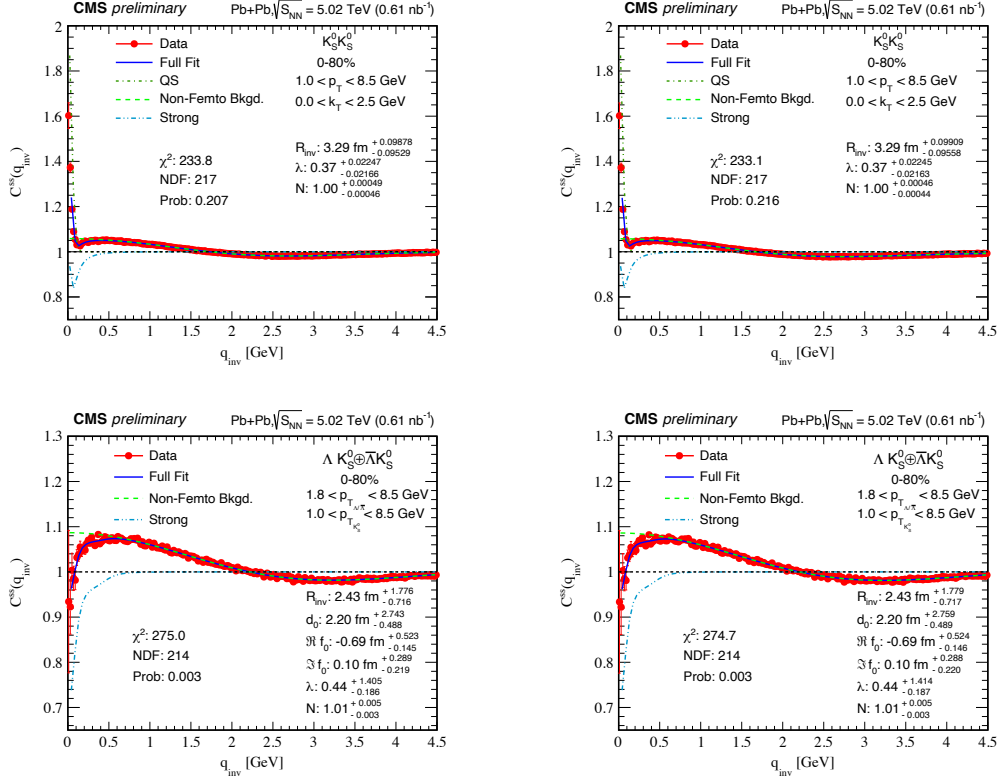


Figure 5.73: Correlation measurement and fitting for $K_S^0 K_S^0$ (top panel) and ΛK_S^0 (bottom panel) correlations in 0-80% centrality before (left) and after (after) the two particles efficiency correction extracted from the Fig. 5.71. In these plots, the red filled circle represents the data, the blue solid line is the fit using Eq. (5.9), the green dashed line is the non-femtoscopic background (Eq. (5.8)), the dashed double dotted line is the strong FSI function, and the dash dotted line is the QS function. QS line drawn using the equation $1 + e^{-q_{inv}^2 R_{inv}^2}$, where the R_{inv} is taken from the LL fit.

experimental p_T spectra could influence the cancellation of efficiency-dependent effects in the experimental correlation measurements. If we can show somehow the MC reco level pair distributions will match with data after applying some kind of weight, we can prove that there is no effect from the efficiency. Therefore, we perform a p_T reweight study.

In this study, a p_T weight is calculated using data and MC p_T spectra and applied in the MC reco level pair distributions (signal and reference distributions) to match with the data. If the p_T reweighted MC reco level pair distributions will be matched with data and behave similarly to the study conducted in sec. 5.8 after applying the two-particle efficiency, we will be confirmed that this analysis is robust and does not need the efficiency correction.

The p_T weight is calculated by dividing the V^0 p_T spectra from data and MC. The p_T spectra are measured in the peak ¹⁷ (i.e. $|\text{Mass}| < 2\sigma$) and sideband ¹⁸ regions (i.e. $4 < |\text{Mass}| < 6\sigma$), and then we subtract the sideband p_T spectra from the peak p_T spectra to have the contribution only from the signal. The weight factors as a function p_T can be seen in Fig. 5.74 for $K_S^0 K_S^0$ correlation, Fig. 5.75 for ΛK_S^0 correlation, and Fig. 5.76 for $\Lambda\Lambda$ correlation. For the ΛK_S^0 pair, as we have Λ and K_S^0 , we have calculated two different weights.

After that, we applied the p_T weight in MC reco level pair distributions to match with the data. After applying p_T weight, we found that the MC reco level signal and reference distributions are matching with data within their uncertainty that can be seen in Fig. 5.77 and 5.78 for $K_S^0 K_S^0$ pair and Fig. 5.79 and 5.80 for ΛK_S^0 pair. Figure 5.77 and 5.78 show the signal and reference distributions for $K_S^0 K_S^0$ pair in the data (red circle) and the MC (blue square) with p_T reweight (right panel) and without p_T reweight (left panel). One can clearly see that p_T reweighted MC distributions are matching with the data within

¹⁷In the peak region, we will have both signal and background components.

¹⁸In the sideband region, we will have only background component.

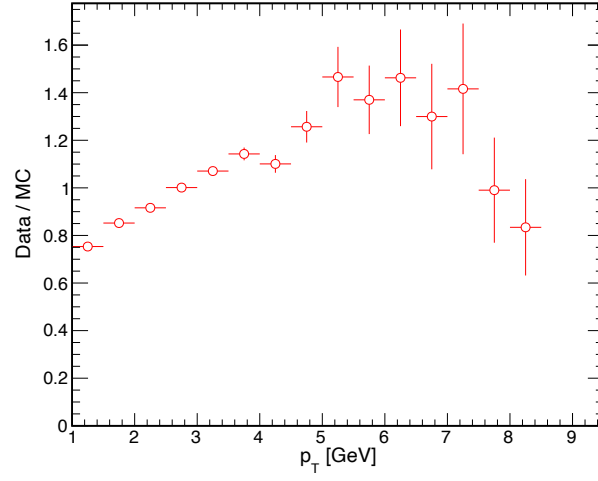


Figure 5.74: K_S^0 p_T weight for $K_S^0 K_S^0$ correlation in 0-80% centrality.

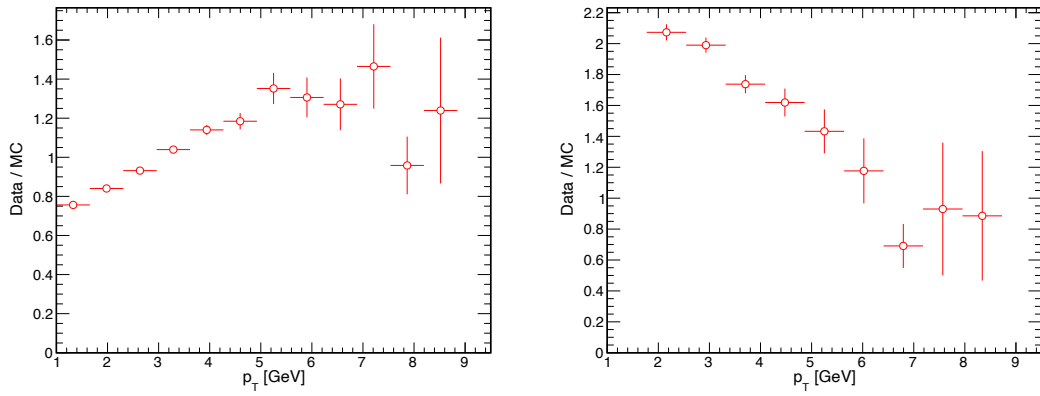


Figure 5.75: K_S^0 (left panel) and Λ (right panel) p_T weights for ΛK_S^0 correlation in 0-80% centrality.

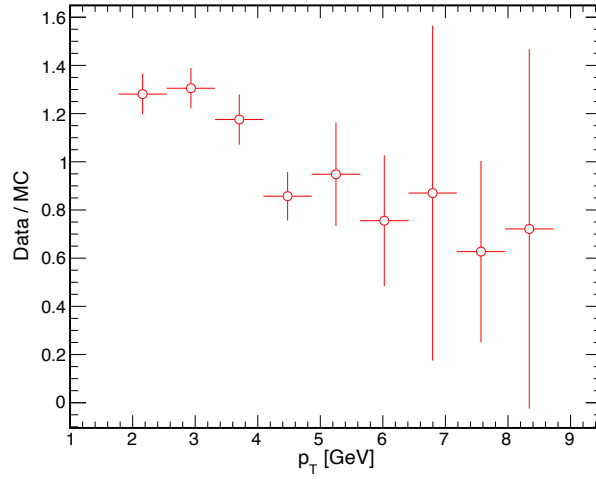


Figure 5.76: Λ p_T weight for $\Lambda\Lambda$ correlation in 0-80% centrality.

their uncertainty whereas, without p_T reweighted MC distributions are not matching with data. Similarly, one can check for ΛK_S^0 pair in Fig. 5.79 for signal distributions and Fig. 5.80 for reference distributions.

Then we do the same analysis as in sec. 5.8 to see if the efficiency corrected and p_T reweighted MC pair distributions behave similarly to the MC pair distributions without p_T reweighted but efficiency corrected. Figure. 5.81 shows the MC reco and gen level signal (top panel) and reference (bottom panel) distributions for $K_S^0 K_S^0$ pair with (left panel) and without (right panel) p_T reweight. The MC reco level correlations are corrected with two-particle efficiency. The MC reco and gen level correlations for $K_S^0 K_S^0$ pair with (left panel) and without (right panel) p_T reweight are shown in Fig. 5.82. From these plots, one can see that the efficiency corrected MC reco level distributions (left panel) behaves similarly to the MC reco level distributions with efficiency corrected and p_T reweighted (right panel). Also, the efficiency corrected and p_T reweighted MC reco level distribution are matching with gen level distribution within their uncertainty. A similar study one can be found for ΛK_S^0 pair in Fig. 5.83 for signal and reference distributions and in Fig. 5.84 for correlations distributions. All these studies were done in integrated centrality 0–80% for $K_S^0 K_S^0$ and ΛK_S^0 pairs due to limited statistics. These studies confirmed that we do not

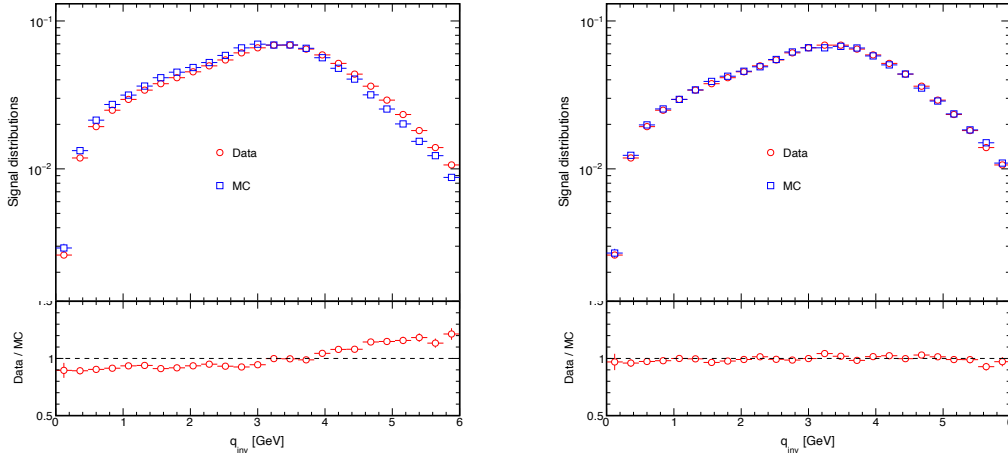


Figure 5.77: Comparison of signal distributions between the data (red circle) and the MC reco label (blue square) without (left panel) and with (right panel) p_T reweight for $K_S^0 K_S^0$ pair in 0-80% centrality. The bottom panels are the ratio between data and MC.

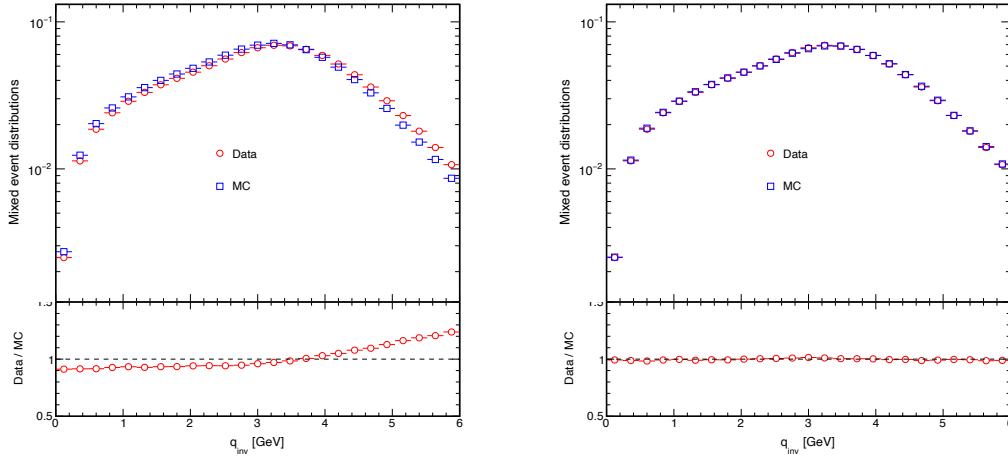


Figure 5.78: Comparison of reference distributions between the data (red circle) and the MC reco label (blue square) without (left panel) and with (right panel) p_T reweight for $K_S^0 K_S^0$ pair in 0-80% centrality. The bottom panels are the ratio between data and MC.

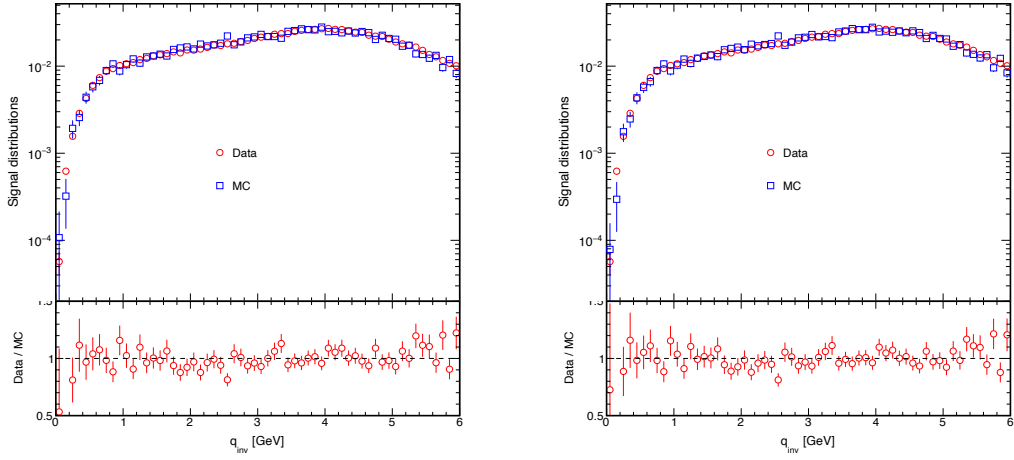


Figure 5.79: Comparison of signal distributions between the data (red circle) and the MC reco label (blue square) without (left panel) and with (right panel) p_T reweight for ΛK_S^0 pair in 0-80% centrality. The bottom panels are the ratio between data and MC.

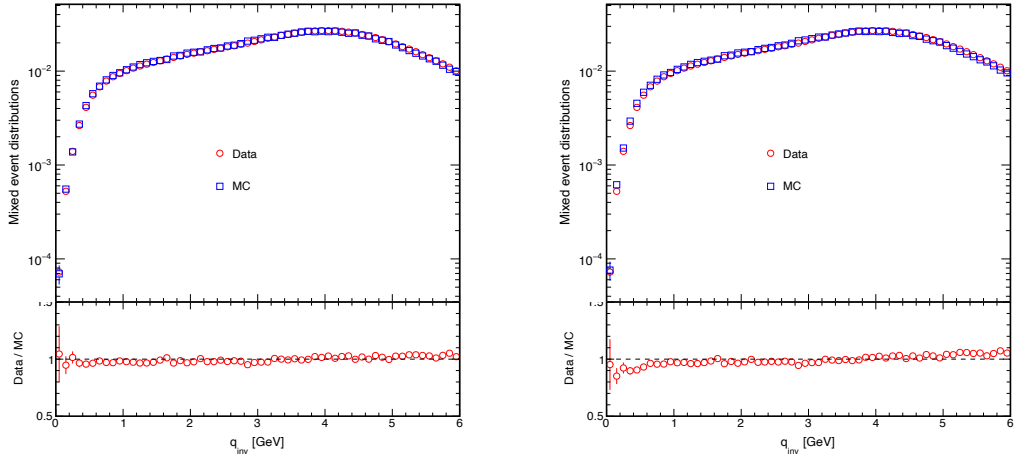


Figure 5.80: Comparison of reference distributions between the data (red circle) and the MC reco label (blue square) without (left panel) and with (right panel) p_T reweight for ΛK_S^0 pair in 0-80% centrality. The bottom panels are the ratio between data and MC.

need efficiency correction. However, we need to account for the difference observed in the MC and data p_T spectra (Fig. 5.74–5.76).

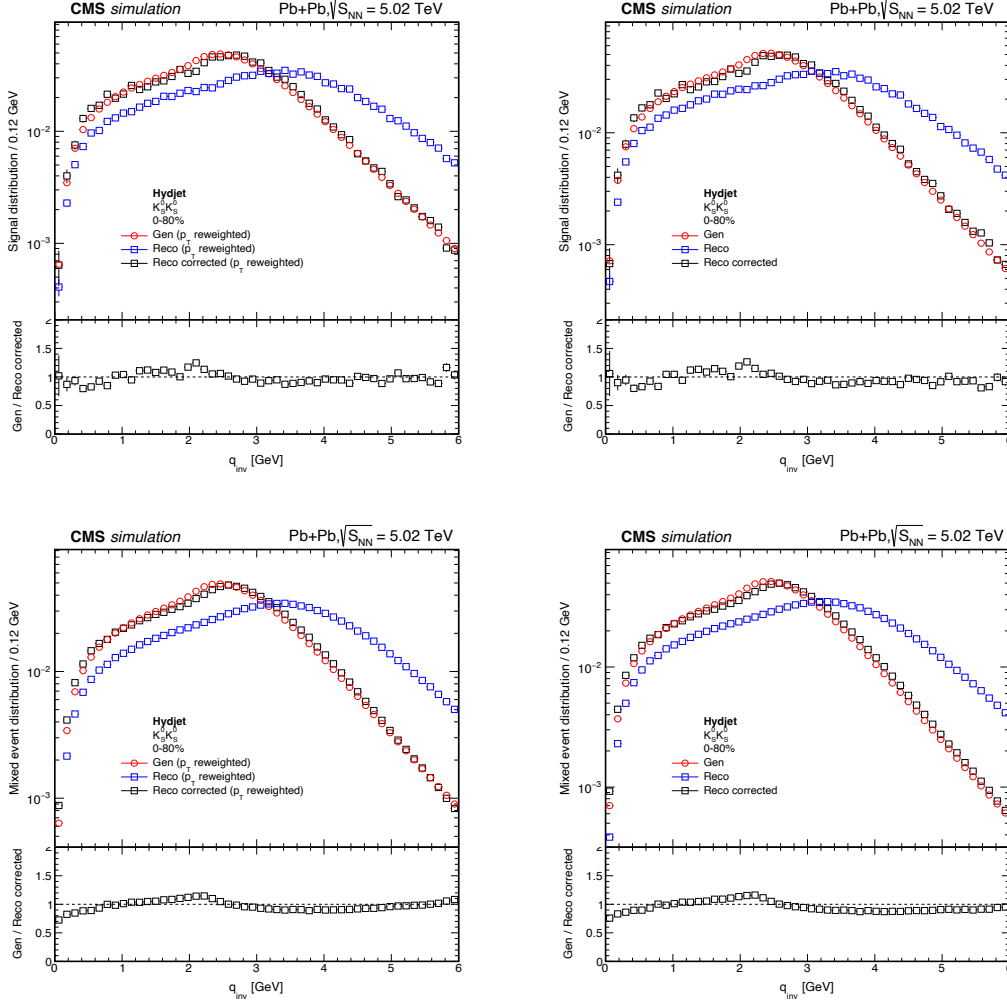


Figure 5.81: Top panel shows the signal distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the $K_S^0 K_S^0$ pair in 0-80% centrality. The bottom panel shows the reference distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the $K_S^0 K_S^0$ pair in 0-80% centrality

Finally, we applied the p_T weight to the correlation measurement in data to accounting for the difference observed between MC and experimental p_T spectra (see Fig. 5.85). The top panel is for $K_S^0 K_S^0$, the middle panel is for ΛK_S^0 , and the bottom panel is for $\Lambda\Lambda$

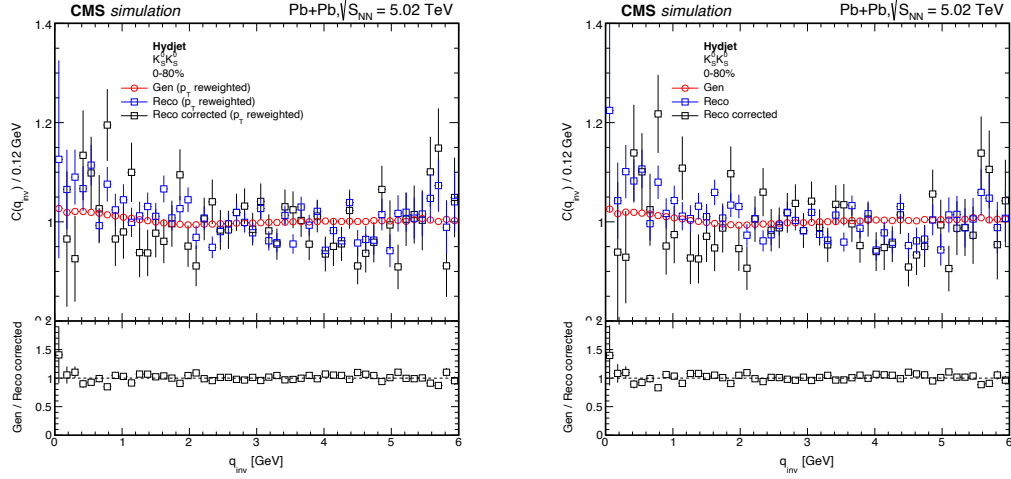


Figure 5.82: Correlation distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the $K_S^0 K_S^0$ pair in 0-80% centrality.

correlations. We compare the fit parameters with and without p_T weight and found that the fit parameters are varying slightly. The variations in the fit parameters are taken as a systematic uncertainty.

5.10 SYSTEMATIC UNCERTAINTIES

The systematic uncertainties for the fit parameters are based on the changes found in the parameter values after individually varying each of the analysis criteria, as discussed below. In cases with more than one variation for a single source, the maximum deviation from the nominal value is used. The total systematic uncertainty is obtained by adding the uncertainties from each source in quadrature. The BDT discriminant is varied so as to adjust the signal-to-background ratio, with the signal yield changing by $\pm 15\%$ in the process. The BDT variations also account for the low p_T significance discussed in sec. 5.5.1. The nominal method to account for V^0 candidates sharing daughter tracks is to remove one of the V^0 candidates at random, which is then not used by any pair. Two alternative approaches are used, one in which both V^0 candidates are removed and

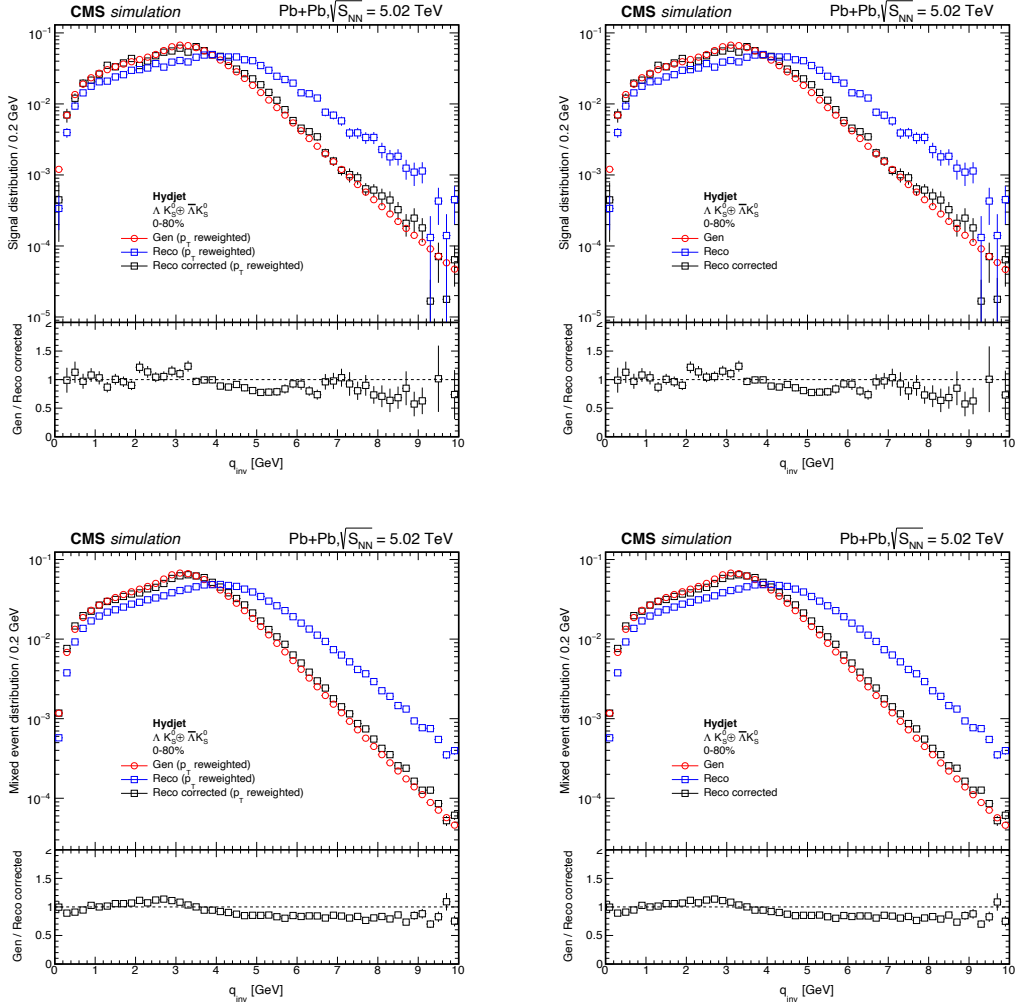


Figure 5.83: Top panel shows the signal distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the ΛK_S^0 pair in 0-80% centrality. The bottom panel shows the reference distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the ΛK_S^0 pair in 0-80% centrality

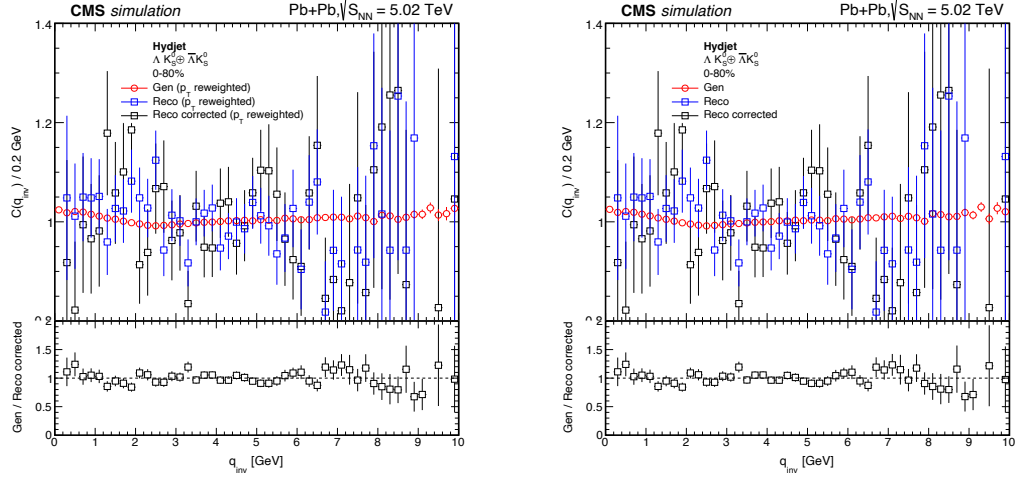


Figure 5.84: Correlation distributions with (left panel) and without (right panel) p_T reweight in the MC gen label (red circle), reco label (blue square), and efficiency corrected reco label (black square) for the ΛK_S^0 pair in 0-80% centrality.

another in which, for events with multiple V^0 candidate pair combinations, only the pairs in which the two particles share a daughter are removed. The systematic uncertainties related to V^0 signal and background modeling are investigated by varying the background shape from a fourth- to a third-order polynomial and the signal shape from a sum of three Gaussian functions to a sum of two or four Gaussian functions. An alternative non-femtoscopic background function $\Omega(q_{\text{inv}}) = N(1 + Be^{-|q_{\text{inv}}/\sigma|^2})(1 + \epsilon q_{\text{inv}})$ is used to assess the uncertainty associated with the choice of the non-femtoscopic background function. Here N , B , σ , and ϵ are the fit parameters. The selection requirements used to construct the mixed event sample are varied to require centrality matching of 3 and 7% instead of the nominal 5% and the primary vertex position matching with 1 and 3 cm instead of the nominal 2 cm. The effect of the centrality resolution has been checked and found to be negligible. The peak region requirement is changed from $<2.0\sigma$ to $<1.5\sigma$ and $<2.5\sigma$ and the sideband region selection from $>4.0\sigma$ to $>3.5\sigma$ and $>4.5\sigma$. The upper limit of the q_{inv} fit ranges is changed by ± 1 GeV and the lower limit is changed to include the first bin. At low p_T , the tracking efficiency is strongly dependent on p_T . Therefore, the simulated sample is used to explore the possible effects of tracking

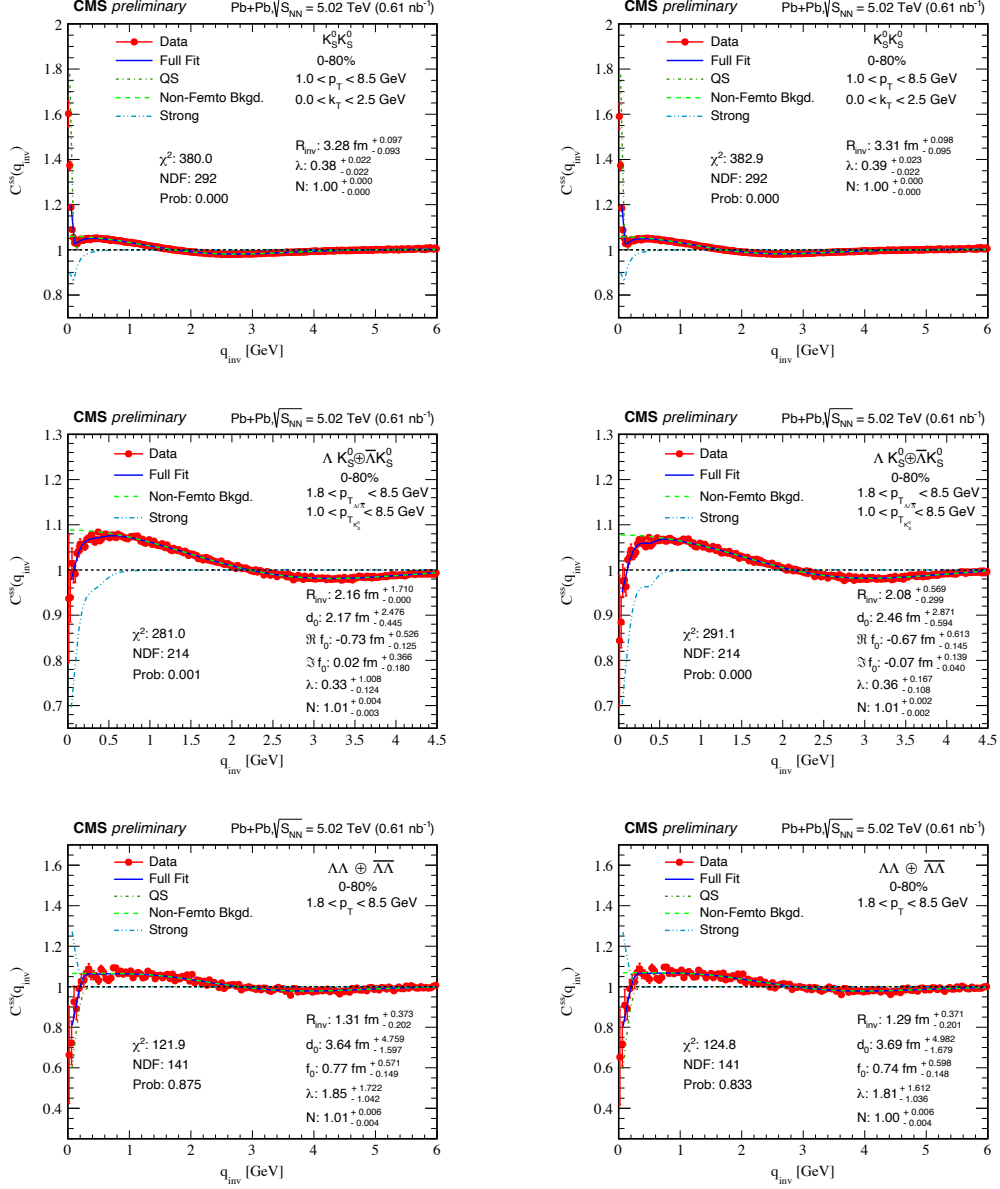


Figure 5.85: Correlation measurement and fitting in data for $K_S^0 K_S^0$ (top), ΛK_S^0 (middle), and $\Lambda\Lambda$ (bottom) pairs in 0-80% centrality before (left panel) and after (right panel) p_T reweight.

efficiency. Based on these studies, it is found that the V^0 reconstruction efficiency for the detection of two V^0 particles is well described by taking the product of the efficiency for each V^0 . It is also found that the fit results are only weakly affected by the V^0 reconstruction efficiency. This is understood as a consequence of the signal and reference samples being similarly affected by the V^0 efficiency. Differences in the Monte Carlo and experimental p_T spectra could influence the cancellation of efficiency-dependent effects in the signal and background correlations. Therefore, a systematic uncertainty for the efficiency is assessed by comparing the results for the default simulated sample to one in which the V^0 p_T distribution is reweighted to match the data. For the $K_S^0 K_S^0$ correlations, an additional systematic uncertainty is found from varying the mass and coupling parameters for the $f_0(980)$ and $a_0(980)$ resonances by using rows A, B, and D of Table 3.1. The systematic uncertainties are summarized in Table 5.5 for $K_S^0 K_S^0$ correlations, Table 5.6 for ΛK_S^0 correlation, and Table 5.7 for $\Lambda\Lambda$ correlation. We have not studied systematic uncertainty as the fit is not stable for the $\Lambda\bar{\Lambda}$ correlation.

Table 5.5: Summary of systematic uncertainties for $K_S^0 K_S^0$ correlations in different centrality bins. The values for R_{inv} are in fm.

Uncertainty sources	0 – 10%	10 – 20%	20 – 30%	30 – 40%	40 – 50%	50 – 60%
	R_{inv}	λ	R_{inv}	λ	R_{inv}	λ
BDT cut	0.14	0.03	0.18	0.04	0.04	0.01
Duplicate V^0 removal	0.28	0.05	0.21	0.05	0.40	0.08
Signal func.	0.01	0.01	0.00	0.00	0.00	0.00
Background func.	0.00	0.00	0.00	0.01	0.00	0.00
Non-femtoscopic func.	0.02	0.01	0.06	0.05	0.16	0.12
Reference sample	0.08	0.05	0.04	0.04	0.05	0.02
Peak region	0.02	0.01	0.03	0.01	0.07	0.02
Sideband region	0.03	0.01	0.02	0.00	0.02	0.01
Fitting range	0.07	0.02	0.10	0.04	0.09	0.04
Efficiency correction	0.03	0.01	0.03	0.01	0.03	0.01
$f_0(980)$ and $a_0(980)$ param.	0.11	0.04	0.14	0.04	0.09	0.03
					0.10	0.03
Total uncertainty	0.35	0.09	0.34	0.11	0.47	0.16
					0.31	0.10
					0.29	0.09
					0.41	0.08

Table 5.6: Summary of systematic uncertainties for ΛK_S^0 correlation in 0–80% centrality. The values for R_{inv} , d_0 , $\Re f_0$, and $\Im f_0$ are in fm.

Uncertainty sources	R_{inv}	d_0	$\Re f_0$	$\Im f_0$	λ
BDT cut	0.19	0.75	0.10	0.07	0.03
Duplicate V^0 removal	0.35	0.92	0.10	0.19	0.11
Signal func.	0.08	0.05	0.01	0.03	0.02
Background func.	0.04	0.01	0.01	0.01	0.02
Non-femtoscopic func.	0.02	0.17	0.05	0.07	0.03
Reference sample	0.22	0.48	0.12	0.12	0.03
Peak region	0.43	0.10	0.05	0.17	0.08
Sideband region	0.02	0.02	0.01	0.01	0.00
Fitting range	0.20	0.18	0.03	0.08	0.04
Efficiency correction	0.08	0.29	0.06	0.09	0.03
Total uncertainty	0.69	1.34	0.21	0.32	0.16

Table 5.7: Summary of systematic uncertainties for $\Lambda\Lambda$ correlation in 0–80% centrality. The values for R_{inv} , d_0 , and $\Re f_0$ are in fm.

Uncertainty sources	R_{inv}	d_0	$\Re f_0$	λ
BDT cut	0.06	0.43	0.05	0.31
Duplicate V^0 removal	0.01	1.14	0.05	0.14
Signal func.	0.00	0.03	0.00	0.02
Background func.	0.02	0.02	0.01	0.01
Non-femtoscopic func.	0.02	1.02	0.14	0.93
Reference sample	0.10	1.12	0.20	0.76
Peak region	0.22	1.21	0.08	0.35
Sideband region	0.01	0.03	0.01	0.04
Fitting range	0.04	1.79	0.20	0.60
Efficiency correction	0.02	0.05	0.03	0.04
Total uncertainty	0.25	2.91	0.34	1.43

CHAPTER 6

RESULTS AND DISCUSSION

This chapter presents the results for $K_S^0 K_S^0$, ΛK_S^0 , and $\Lambda\Lambda$ correlations. All the results are discussed based on the physics parameters (R_{inv} , λ , d_0 , $\Re f_0$, and $\Im f_0$) that we have extracted by fitting the correlation distributions discussed in sec. 5.7 and compared these results with the previous experimental and theoretical results. The R_{inv} and λ parameters extracted from $K_S^0 K_S^0$ correlation distributions for 6 different centrality bins (0–10%, 10–20%, 20–30%, 30–40%, 40–50%, and 50–60%) with $0 < k_T < 2.5$ GeV. For the comparison with the previous experimental results, we have extracted the R_{inv} from $K_S^0 K_S^0$ correlation distributions in 10–30%, and 30–50% centrality bins. A comparison of R_{inv} values for all these pairs ($K_S^0 K_S^0$, ΛK_S^0 , and $\Lambda\Lambda$) in 0–80% centrality is also discussed in this chapter. The correlation distributions and their fits of these centralities can be seen in appendix A.2.

The final correlation measurements and their fits and corresponding χ^2/dof values, are presented in Figs. 6.1 and 6.2. The $K_S^0 K_S^0$ correlations, shown in Fig. 6.1, are independently fitted for each of the six centrality bins with $0 < k_T < 2.5$ GeV. The ΛK_S^0 (top panel) and $\Lambda\Lambda$ (bottom panel) correlations, shown in Fig. 6.2, involve fewer events and, therefore, only a single fit is performed for each, with the data integrated over the centrality range 0–80% and with no restriction on k_T . The inset plots show the data and fit for the region of interest ($q_{\text{inv}} < 0.4$ GeV).

From the $K_S^0 K_S^0$ correlation distributions (Fig. 6.1), one can see that the fitting at low q_{inv} is poor after 40% centrality. This may be the consequence of the assumption about the source function discussed in sec. 3.3.1. The LL analytical model, which calculates the FSI functions for all the pairs also assumes the Gaussian source function. But, the

results from charged-particle correlations have demonstrated that this assumption breaks down for peripheral collisions [77, 127]. This is likely the cause of the poor fit at low q_{inv} for centralities above 40%. The magnitude of non-femtoscopic background function (green dashed line) increases from central (0–10%) to peripheral (50–60%) collisions as we discussed in sec. 5.6.2. It can be seen that the correlation function becomes narrower from peripheral (50–60%) to central (0–10%) collisions, resulting in the increase of R_{inv} presented in Fig. 6.3 from peripheral to central collisions as discussed in the sec. 3.3.1.

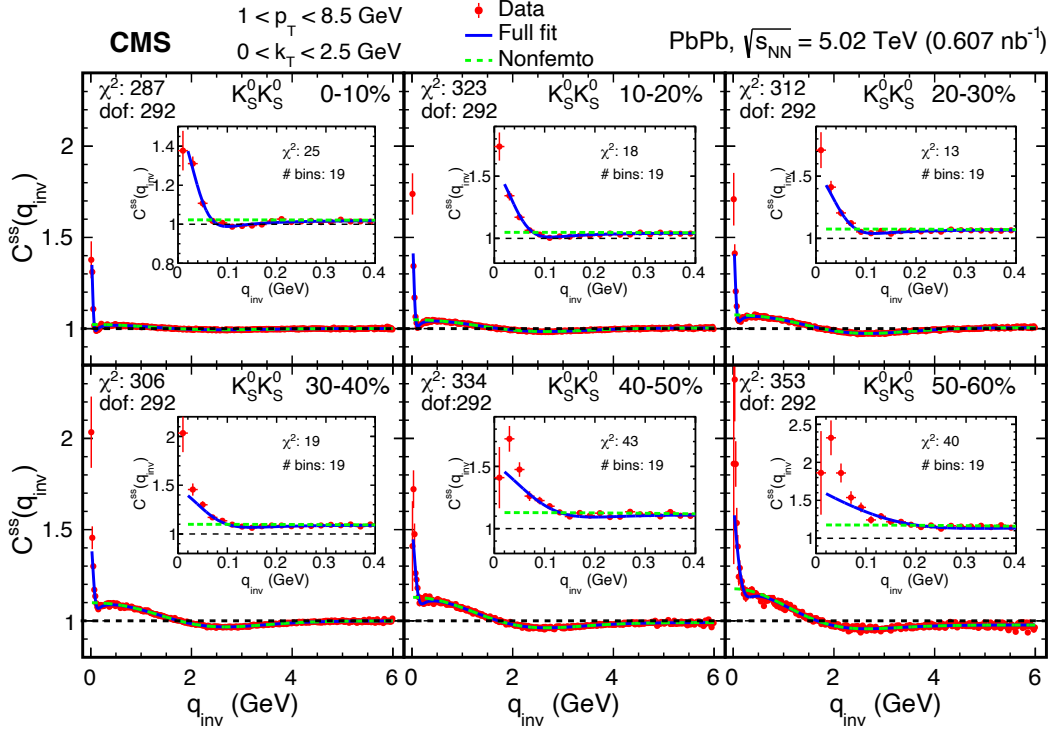


Figure 6.1: The correlation distributions and fits for $K_S^0 K_S^0$ pairs in different centrality ranges, starting from 0–10% centrality to 50–60% centrality, with $0 < k_T < 2.5$ GeV. In each plot, the red circles are the data, the blue solid line is the fit using Eq. (5.9), and the green dotted line is the non-femtoscopic background from Eq. (5.8). The χ^2 and dof values are for the full q_{inv} range. The inset plots show the data and the fit for the $q_{\text{inv}} < 0.4$ GeV region, with the χ^2 and number of bins evaluated in that region.

The R_{inv} and the λ parameter extracted from the $K_S^0 K_S^0$ correlations for $0 < k_T < 2.5$ GeV are shown as a function of centrality in Fig. 6.3. It is observed that the R_{inv} value decreases from central to peripheral events, as expected from a simple geometric picture of the

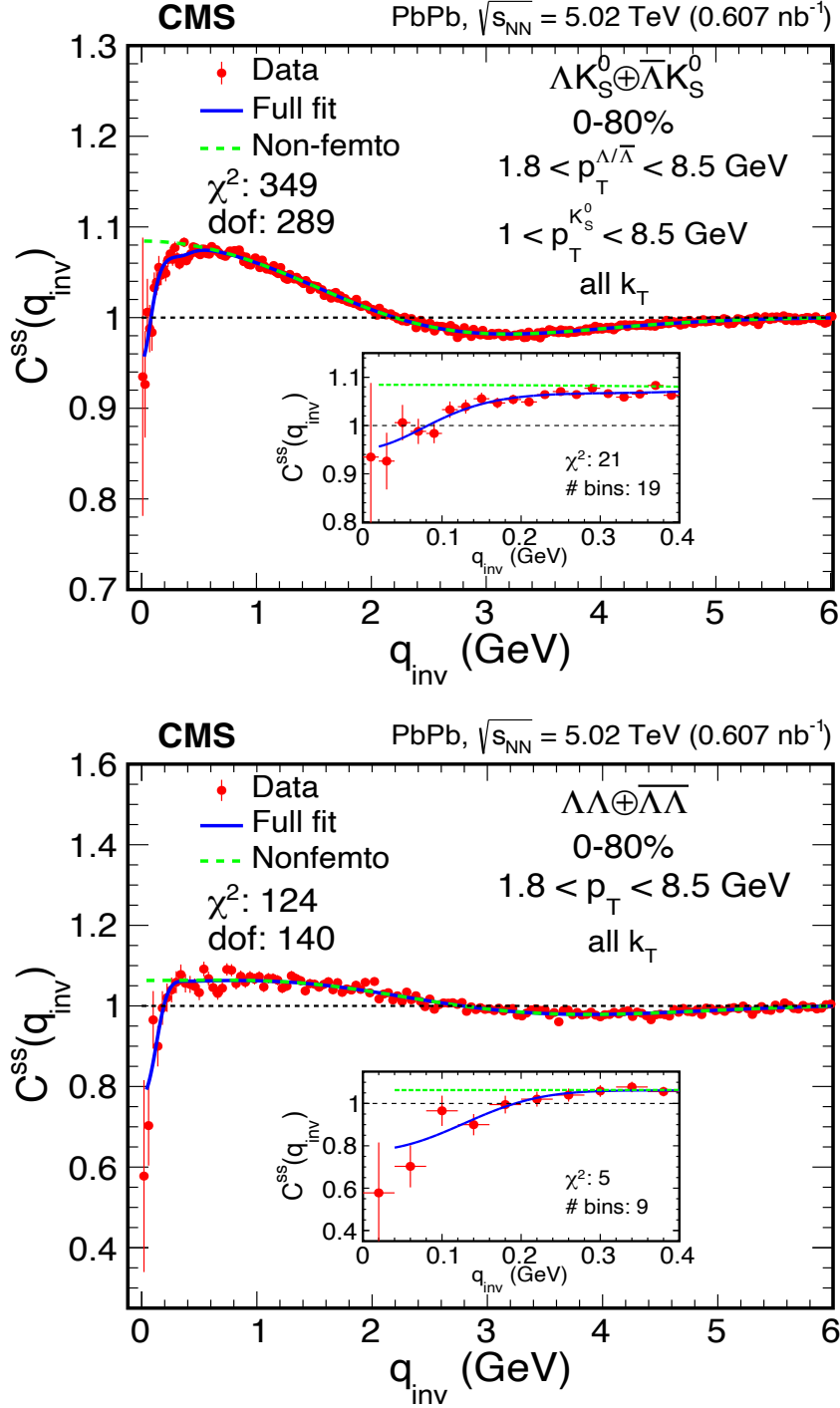


Figure 6.2: The correlation distributions and fits for ΛK_S^0 (top panel) and $\Lambda\Lambda$ (bottom panel) pairs with 0–80% centrality and no restriction on k_T . In each plot, the red circles are the data, the blue solid line is the fit using Eq. (5.9), and the green dotted line is the non-femtosopic background from Eq. (5.8). The χ^2 and dof values are for the full q_{inv} range. The inset plots show the data and the fit for the $q_{inv} < 0.4$ GeV region, with the χ^2 and number of bins evaluated in that region.

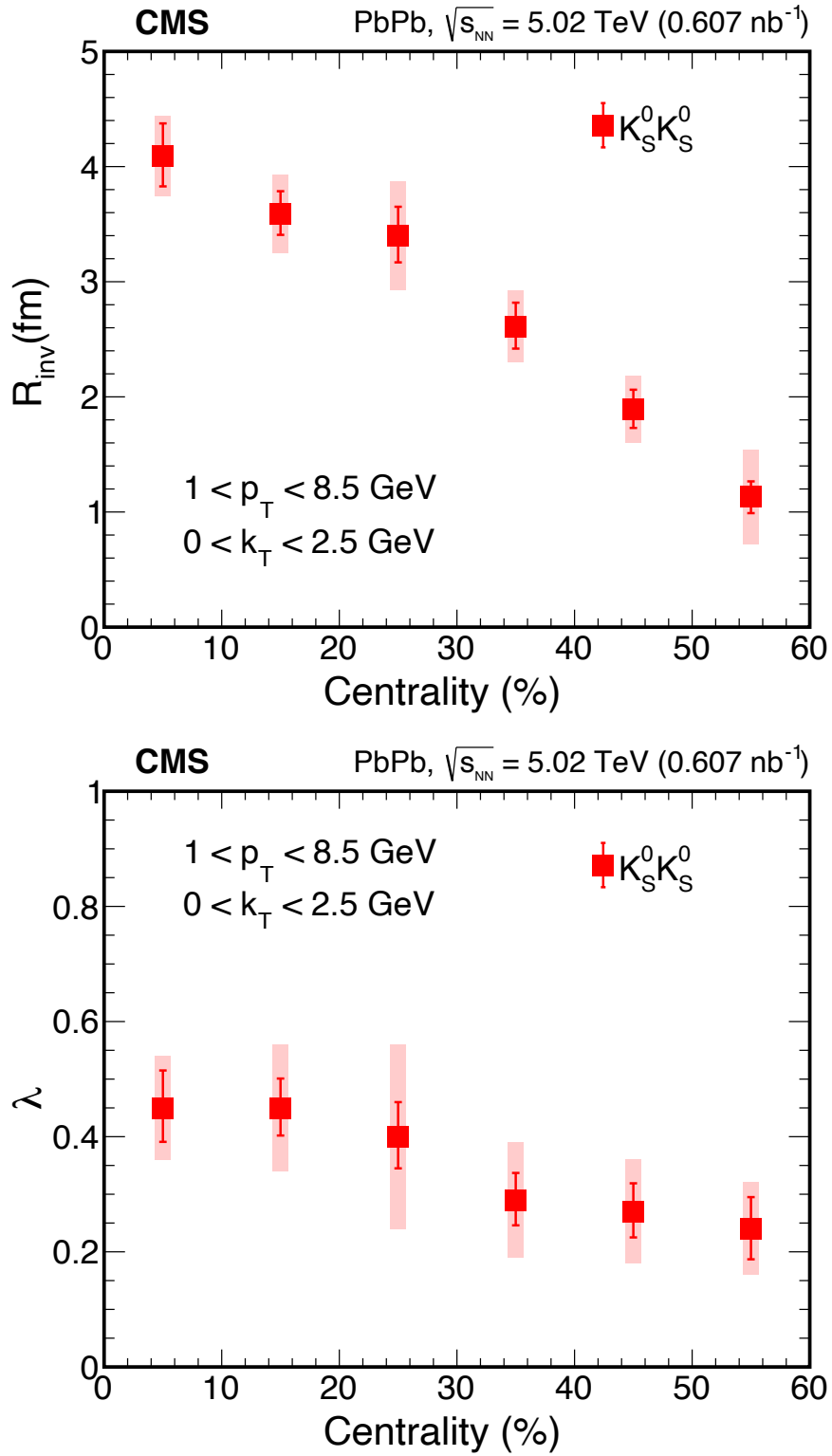


Figure 6.3: The R_{inv} (top panel) and λ parameter (bottom panel) as a function of centrality extracted from $K_S^0 K_S^0$ correlation distributions. For each data point, the line and shaded area indicate the statistical and systematic uncertainty, respectively.

collisions. Over the full centrality range of 0–80%, $R_{\text{inv}} = 3.30 \pm 0.10$ (stat) ± 0.37 (syst) fm. To compare our observed R_{inv} with the ALICE results, we extracted the R_{inv} values as a function of average transverse mass $\langle m_T \rangle$ in 0–10%, 10–30%, and 30–50% centrality. The transverse mass can be calculated as $m_T = \sqrt{(m_{\text{inv}}/2)^2 + k_T^2}$, where m_{inv} is the invariant mass of the two-particle system [15]. The average $\langle m_T \rangle$ is evaluated from the transverse mass distribution using two-particle pairs with $q_{\text{inv}} < 0.4$ GeV, accounting for background using the binomial analysis as done for the q_{inv} distributions. Our results for R_{inv} agree with the ALICE $K_S^0 K_S^0$ results from PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at a similar m_T value [128] which can be seen in Fig. 6.4.

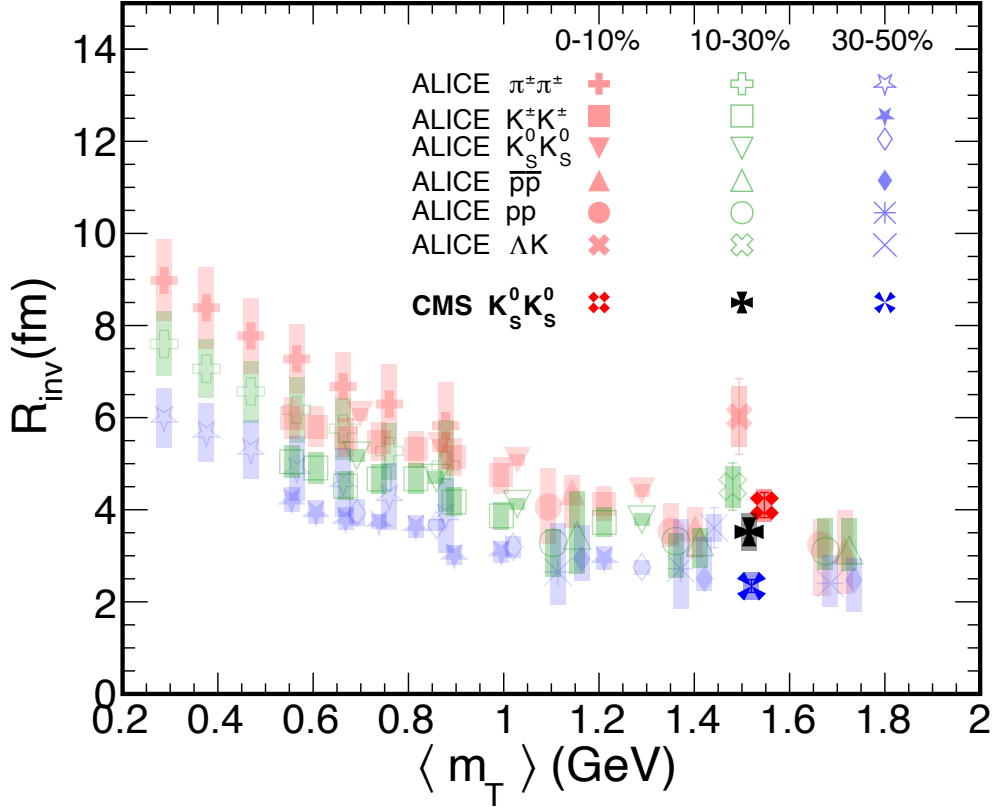


Figure 6.4: The R_{inv} as a function of m_T with the result from this experiment (dark color marker) at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and compared with ALICE results (light color marker) for PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [128] in 0–10%, 10–30%, and 30–50% centrality. The vertical solid line represents the statistical uncertainty and the vertical shaded rectangular area represents the systematic uncertainty.

The obtained λ parameter values are below unity, possibly due to the effect of resonance decay, non-Gaussian source function, and strong final state interaction. Also, it is seen to decrease from about 0.45 to 0.25 as the collisions become more peripheral. This decrease could arise due to increasingly non-Gaussian source function as the collisions become more peripheral. The LL analytical model that we use in the fitting assumes a Gaussian source function, and this assumption may also be responsible for the relatively poor fits at low q_{inv} for the most peripheral collisions, as seen in Fig. 6.1.

Table 6.1 includes the extracted R_{inv} and λ parameters as well as $\langle m_{\text{T}} \rangle$ for $\text{K}_{\text{S}}^0\text{K}_{\text{S}}^0$, $\Lambda\text{K}_{\text{S}}^0$, and $\Lambda\Lambda$ combinations in the 0–80% centrality range. A significant decrease is seen in R_{inv} as the $\langle m_{\text{T}} \rangle$ increases. Qualitatively similar results have been found, both for a given pair type in bins of m_{T} and when comparing multiple pair types [1]. Because of the different minimum p_{T} requirements for K_{S}^0 and Λ particles, the variation in $\langle m_{\text{T}} \rangle$ includes both $\langle p_{\text{T}} \rangle$ and particle mass differences. The anticorrelation of R_{inv} and $\langle m_{\text{T}} \rangle$ has been interpreted as indicating the presence of an expanding source [1].

Table 6.1 also includes the strong interaction scattering parameters d_0 , $\Re f_0$, and $\Im f_0$ obtained from the $\Lambda\text{K}_{\text{S}}^0$ and $\Lambda\Lambda$ correlations. Figure 6.5 shows d_0 and $\Im f_0$ versus $\Re f_0$ in the left and right panels, respectively, with the current results shown as red stars and squares for $\Lambda\text{K}_{\text{S}}^0$ and $\Lambda\Lambda$, respectively. The displayed uncertainties are one-dimensional and are not based on a two-dimensional contour.

The negative value of $\Re f_0$ observed for the $\Lambda\text{K}_{\text{S}}^0$ correlations, combined with its relatively small magnitude, suggests a repulsive $\Lambda\text{K}_{\text{S}}^0$ interaction. The uncertainty associated with the $\Im f_0$ value for the $\Lambda\text{K}_{\text{S}}^0$ correlations prevents any claim concerning possible inelastic processes. The value of $\Re f_0$ found for $\Lambda\text{K}_{\text{S}}^0$ correlations differs from that reported by the ALICE Collaboration (teal diamonds) [15], which is also for PbPb collisions but at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The uncertainties are too large to determine if d_0 and $\Im f_0$ also differ between the two results.

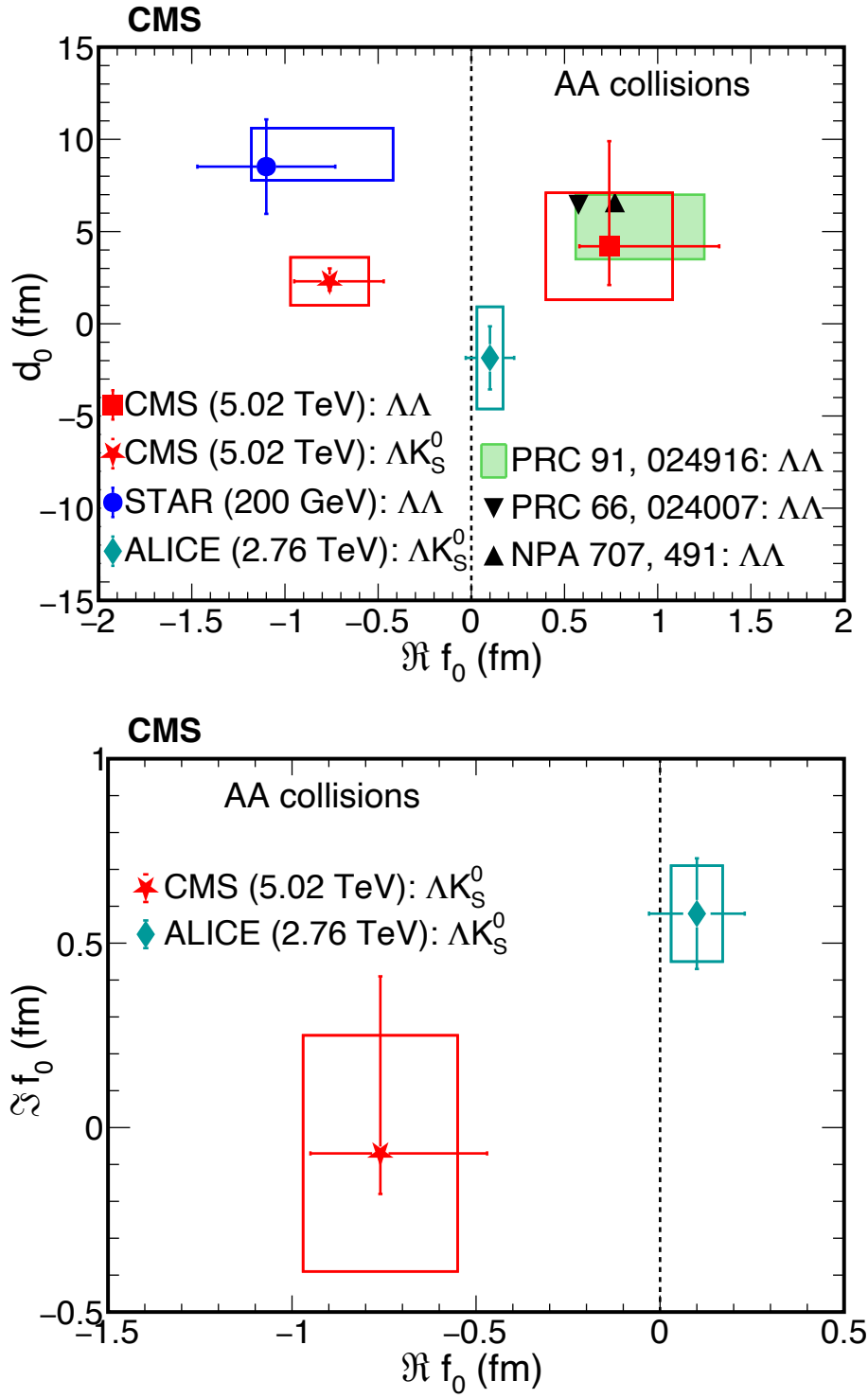


Figure 6.5: The measured values of d_0 versus $\Re f_0$ (top panel) and $\Im f_0$ versus $\Re f_0$ (bottom panel) from this analysis along with other measurements and predictions as described in the text. For each data point, the lines and the boxes indicate the (one-dimensional) statistical and systematic uncertainties, respectively.

Table 6.1: Extracted values of the R_{inv} , $\Re f_0$, $\Im f_0$, d_0 , λ , and $\langle m_T \rangle$ parameters from the $K_S^0 K_S^0$, ΛK_S^0 , and $\Lambda\Lambda$ combinations in the 0–80% centrality range. The first and second uncertainties are statistical and systematic, respectively.

Parameter	$K_S^0 K_S^0$	ΛK_S^0	$\Lambda\Lambda$
R_{inv} (fm)	$3.30 \pm 0.10 \pm 0.37$	$2.1^{+1.4}_{-0.5} \pm 0.7$	$1.3^{+0.4}_{-0.2} \pm 0.3$
$\Re f_0$ (fm)	—	$-0.76^{+0.29}_{-0.19} \pm 0.21$	$0.74^{+0.59}_{-0.16} \pm 0.34$
$\Im f_0$ (fm)	—	$-0.07^{+0.48}_{-0.11} \pm 0.32$	—
d_0 (fm)	—	$2.3^{+0.7}_{-0.5} \pm 1.3$	$4.2^{+5.7}_{-2.1} \pm 2.9$
λ	$0.38 \pm 0.02 \pm 0.08$	$0.34^{+0.41}_{-0.12} \pm 0.16$	$1.5^{+1.2}_{-1.1} \pm 1.4$
$\langle m_T \rangle$ (GeV)	1.53	2.09	2.60

The positive $\Re f_0$ value obtained for the $\Lambda\Lambda$ correlations suggests an attractive interaction that is not strong enough to produce a bound state such as the H-dibaryon [9, 129]. This result disagrees with the finding from the STAR Collaboration in gold-gold (AuAu) collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV (blue circle). The negative $\Re f_0$ value of $-1.10 \pm 0.37 \text{ stat}^{+0.68}_{-0.08} \text{ syst fm}$ found by STAR, combined with its magnitude, imply a repulsive interaction. It is noted, however, that a theoretical study of the STAR data which considers collective flow and feed-down effects (shown as a shaded region at $d_0 \approx 5$ fm, $\Re f_0 \approx 0.9$ fm) suggests that these data are consistent with the $\Lambda\Lambda$ interaction being attractive [9]. An exclusion plot by the ALICE Collaboration for the $\Lambda\Lambda$ scattering parameters obtained using the $\Lambda\Lambda$ correlations from pp collisions at $\sqrt{s} = 7$ and 13 TeV, as well as pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, also suggests an attractive interaction [10]. In addition, our results are consistent with two theoretical calculations (black triangles) that reproduce the $\Lambda\Lambda$ binding energy of ${}_{\Lambda\Lambda}^6\text{He}$, as extracted from the NAGARA event [130, 131].

CHAPTER 7

SUMMARY AND OUTLOOK

This thesis presents the femtoscopic correlation of all pair combinations of V^0 (K_S^0 , Λ , $\bar{\Lambda}$) particles in lead-lead (PbPb) collision data at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV, collected by the CMS Collaboration. For the first time, the results of $\Lambda\Lambda$ femtoscopic correlations were presented in this thesis in PbPb collisions at the CERN LHC. All the pairs ($K_S^0 K_S^0$, ΛK_S^0 , and $\Lambda\Lambda$) show significant femtoscopic correlations, except $\Lambda\bar{\Lambda}$. The identical pairs ($K_S^0 K_S^0$ and $\Lambda\Lambda$) are sensitive to quantum statistics and strong final state interaction, whereas the non-identical pairs (ΛK_S^0 and $\Lambda\bar{\Lambda}$), are sensitive to only strong final state interaction. A significant non-femtoscopic correlation is present in all the pairs in addition to the femtoscopic correlation. The non-femtoscopic correlation arises primarily from minijets and flow. A double Gaussian function is used to account for the non-femtoscopic correlation. All the correlations were corrected for pair purity. Finally, the Lednický–Lyuboshitz model was applied together with the non-femtoscopic background function to extract the physics parameters, such as source size R_{inv} , incoherence parameter λ , complex scattering length ($\Re f_0$ and $\Im f_0$), and scattering length d_0 , and compared to the other experimental and theoretical results. Due to limited statistics and low femtoscopic signal, the $\Lambda\bar{\Lambda}$ correlation fit was not stable, and therefore, the $\Lambda\bar{\Lambda}$ result was not discussed in this thesis.

The $K_S^0 K_S^0$ correlations were measured in six equal centrality bins covering the 0–60%. For the comparison with other experimental results and with the results presented in this thesis, $K_S^0 K_S^0$ correlations were also measured in 0–30%, 30–50%, and 0–80% centrality bins. The source size R_{inv} and the incoherence parameter λ were extracted from $K_S^0 K_S^0$ correlation in each centrality bin. The value of R_{inv} decreases from 4 to 1 fm going from central to peripheral collisions and agrees with results from the ALICE Collaboration at

a similar transverse mass. The obtained λ parameter values are below unity, possibly due to the effect of resonance decay, non-Gaussian source function, and strong final state interaction. Also, it decreases from about 0.45 to 0.25 as the collisions become more peripheral. The decrease could arise due to increasingly non-Gaussian source function as the collisions become more peripheral.

The ΛK_S^0 correlation is measured in 0–80% centrality bin, and along with the R_{inv} and λ parameters, the strong interaction scattering parameters, i.e., $\Re f_0$, $\Im f_0$, and d_0 , were extracted. The extracted R_{inv} and λ values are $2.1^{+1.4}_{-0.5} \pm 0.7$ fm and $0.34^{+0.41}_{-0.12} \pm 0.16$, respectively. The obtained values for $\Re f_0$, $\Im f_0$, and d_0 are $-0.76^{+0.29}_{-0.19} \pm 0.21$ fm, $-0.07^{+0.48}_{-0.11} \pm 0.32$ fm, and $2.3^{+0.7}_{-0.5} \pm 1.3$ fm, respectively. The negative $\Re f_0$ value indicates that the ΛK_S^0 interaction is repulsive.

The $\Lambda\Lambda$ correlation is measured in 0–80% centrality bin, and the extracted R_{inv} and λ parameters are $1.3^{+0.4}_{-0.2} \pm 0.3$ fm and $1.5^{+1.1}_{-1.2} \pm 1.4$, respectively. The extracted values for scattering parameters are $\Re f_0 = 0.74^{+0.59}_{-0.16} \pm 0.34$ fm and $d_0 = 4.2^{+5.7}_{-2.1} \pm 2.9$ fm. The positive $\Re f_0$ value obtained for the $\Lambda\Lambda$ correlations suggests an attractive interaction that is not strong enough to produce a bound state such as the H-dibaryon. The $\Lambda\Lambda$ scattering parameters help to constrain baryon-baryon and, more specifically, hyperon-hyperon interaction models.

These measurements provide additional input to understand the nature of the strong interaction between pairs of strange hadrons. One can use these results in modelling the composition of neutron stars. The obtained scattering parameters can constrain the baryon (hyperon)-baryon (hyperon) and baryon-meson interaction models and provide additional input to understand the strong interaction better. In particular, the $\Lambda\Lambda$ interaction is crucial as it helps understand the hyperon appearance in dense neutron-rich materials, such as neutron stars.

This work can be extended further by gathering large data samples. For instance,

transverse mass dependence source size can be extracted; multidimensional analysis can be performed using neutral kaons; $\Lambda\bar{\Lambda}$ scattering parameters can be obtained, etc. In addition, it is possible to extend the femtoscopic correlation measurements to multi-strange particles, e.g., Ξ and Ω , to better understand the strong interaction. Further, Λ -hyperon spin correlation one can provide novel insight into intrinsically quantum features of many-body parton dynamics. $\Lambda\bar{\Lambda}$ correlation can be used to understand the quantum dynamics of QCD strings.

APPENDIX A

ADDITIONAL PLOTS

A.1 DATA AND MC COMPARISON OF CONTROL PLOTS

We have checked all the control plots between data and MC, which are used as training variables in the BDT method (see sec. 5.5). The left side plots are for K_S^0 , and the right side plots are for Λ . We checked all these plots in 0–80% centrality. The red open circle is for data, and the black open square is for MC. We have a very good agreement between the data and MC within the uncertainty.

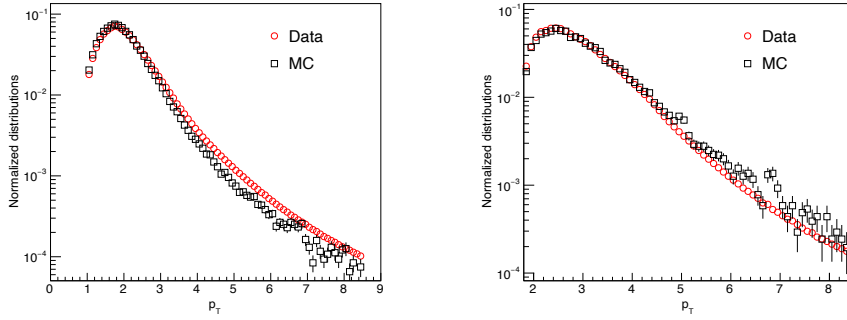


Figure A.1: Data and MC comparison of the transverse momentum distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

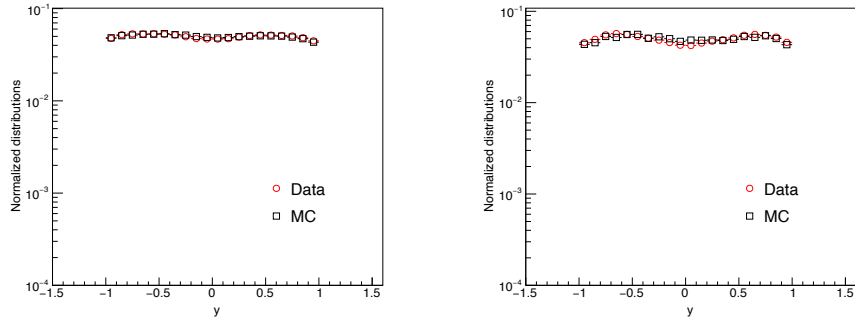


Figure A.2: Data and MC comparison of the rapidity distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

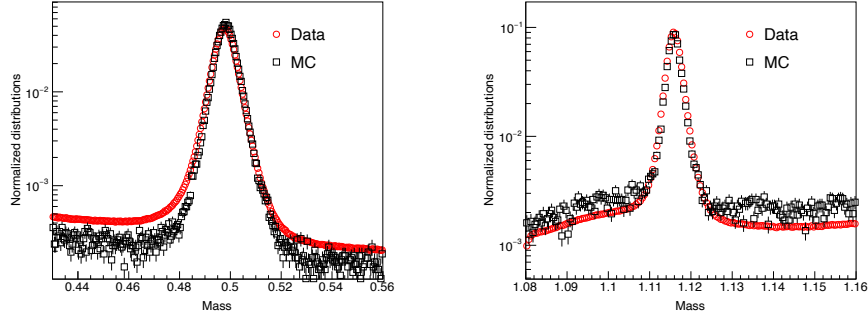


Figure A.3: Data and MC comparison of the invariant mass distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

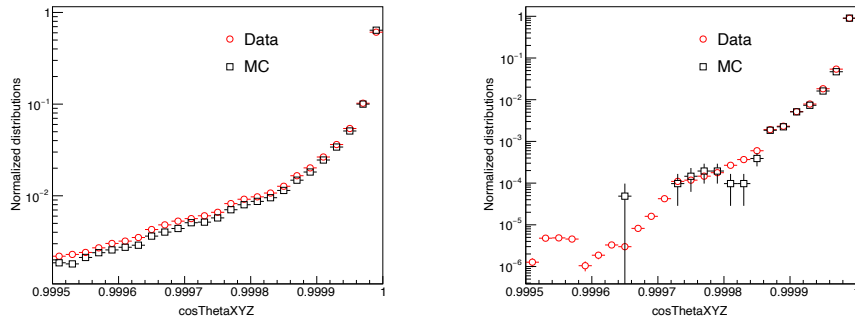


Figure A.4: Data and MC comparison of the Cosine 3D pointing angle θ distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

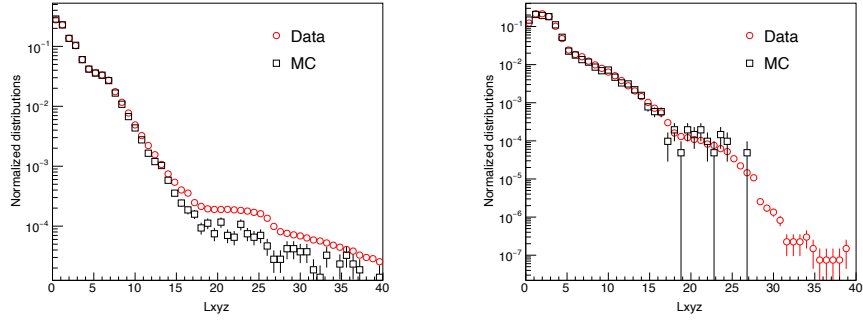


Figure A.5: Data and MC comparison of the 3D decay length distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

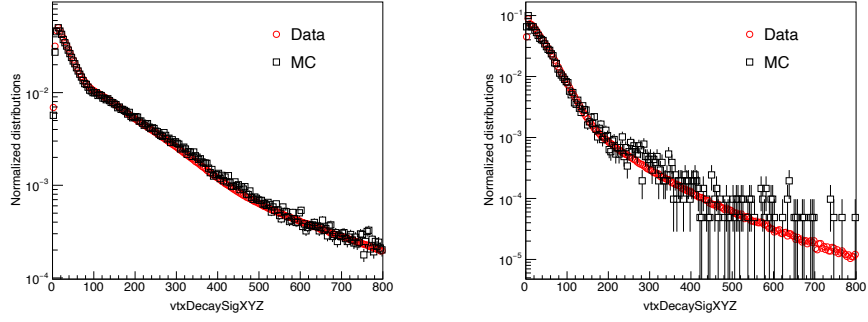


Figure A.6: Data and MC comparison of the 3D vertex significance distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

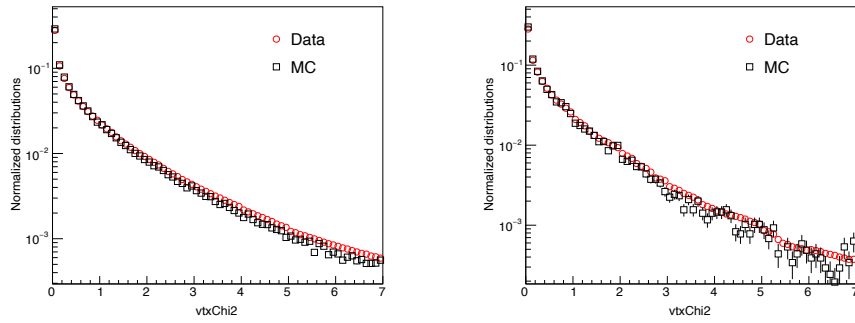


Figure A.7: Data and MC comparison of the vertex Chi2 distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

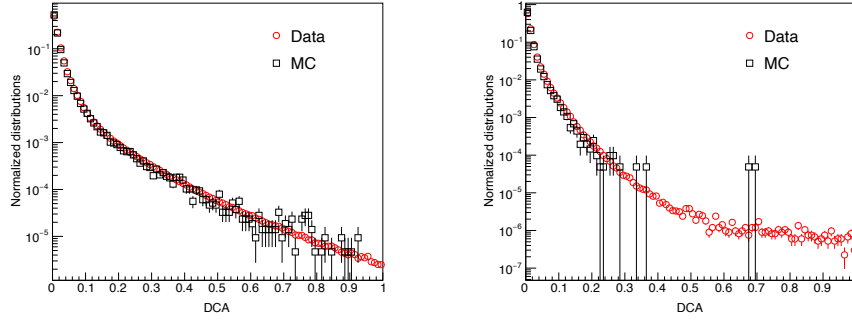


Figure A.8: Data and MC comparison of the distance of the closest approach distributions of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

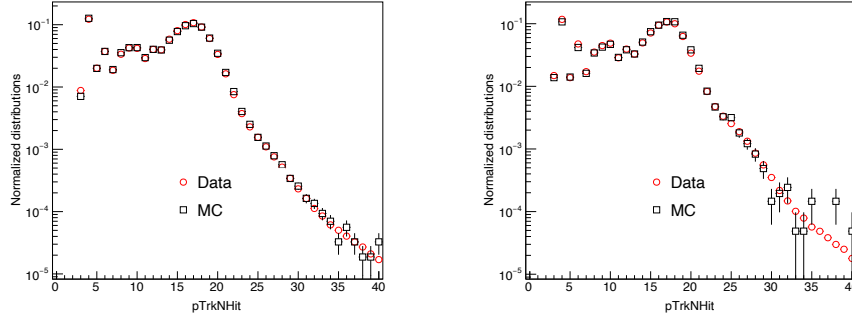


Figure A.9: Data and MC comparison of the nhit distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

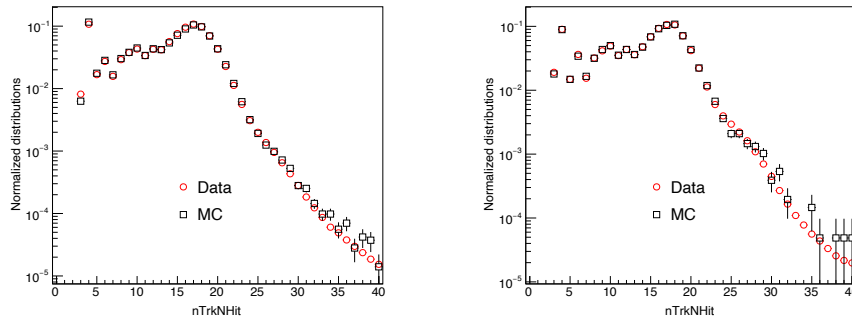


Figure A.10: Data and MC comparison of the nhit distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

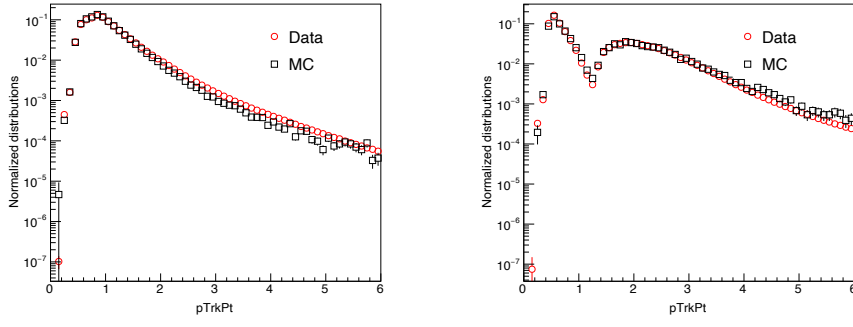


Figure A.11: Data and MC comparison of the transverse momentum distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

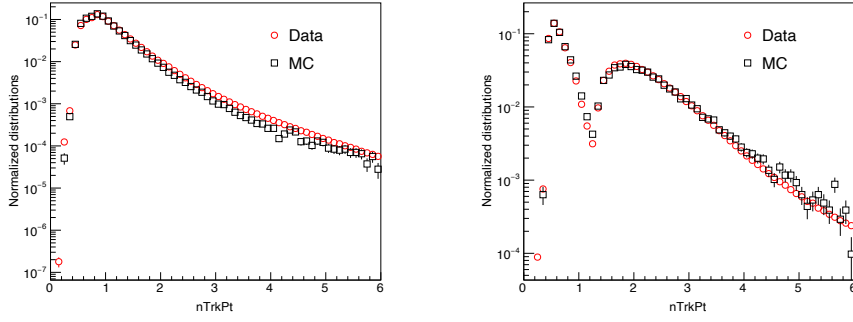


Figure A.12: Data and MC comparison of the transverse momentum distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

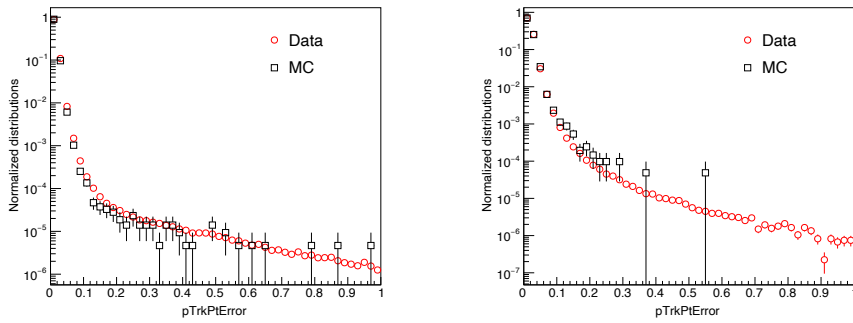


Figure A.13: Data and MC comparison of the transverse momentum error distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

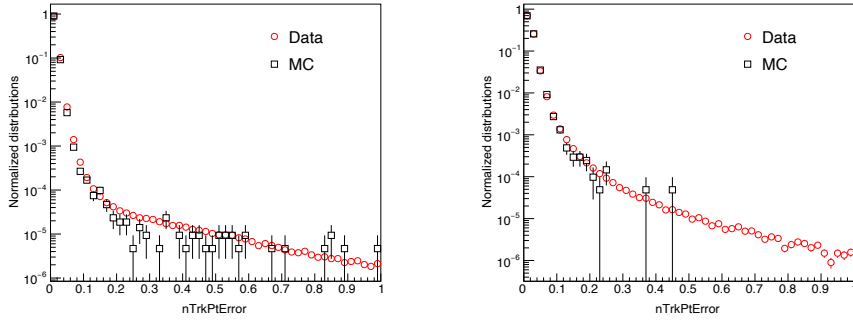


Figure A.14: Data and MC comparison of the transverse momentum error distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

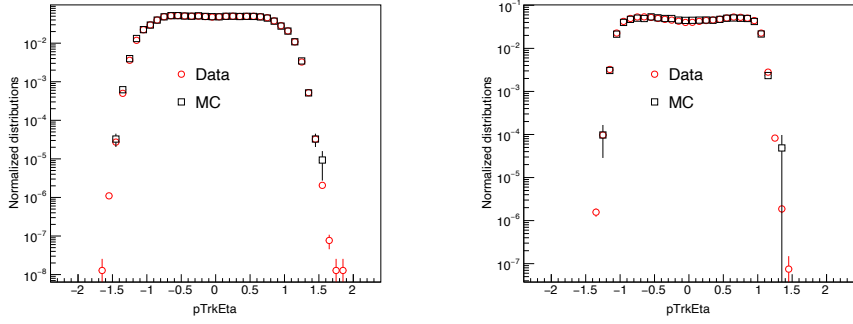


Figure A.15: Data and MC comparison of the pseudorapidity distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

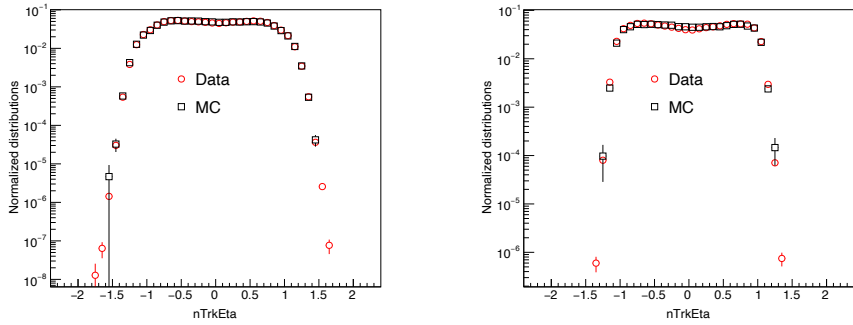


Figure A.16: Data and MC comparison of the pseudorapidity distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

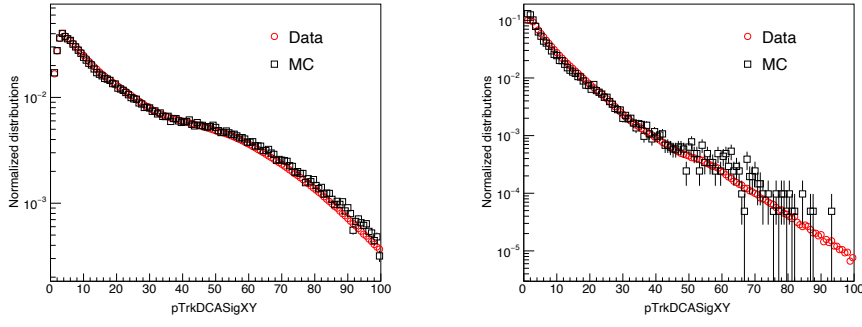


Figure A.17: Data and MC comparison of the transverse DCA significance distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

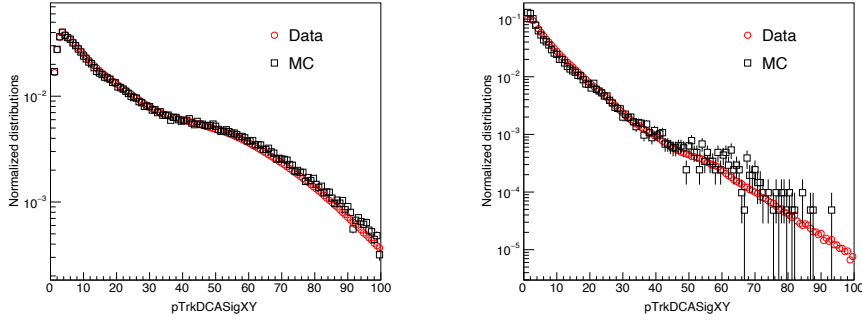


Figure A.18: Data and MC comparison of the transverse DCA significance distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

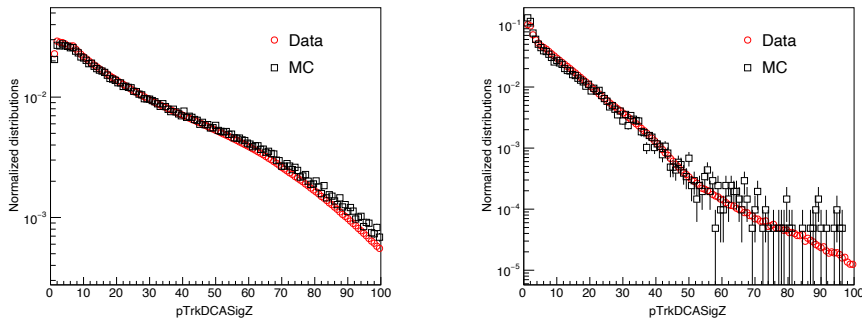


Figure A.19: Data and MC comparison of the longitudinal DCA significance distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

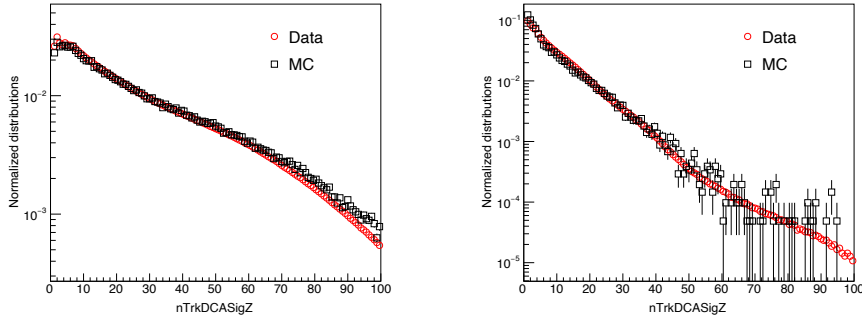


Figure A.20: Data and MC comparison of the longitudinal DCA significance distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

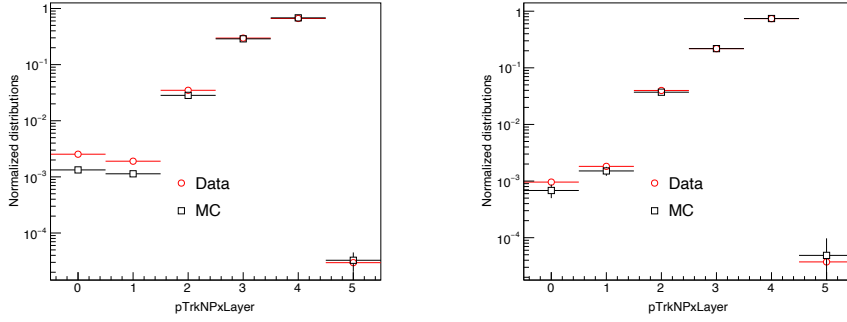


Figure A.21: Data and MC comparison of the pixel layer with hits distributions for the positive daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

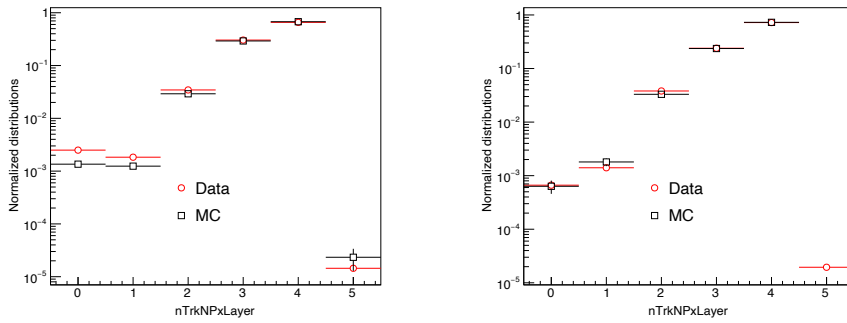


Figure A.22: Data and MC comparison of the pixel layer with hits distributions for the negative daughter track of K_S^0 (left) and Λ (right) in PbPb collisions for 0–80% centrality.

A.2 $K_S^0 K_S^0$ CORRELATION PLOTS

The below two plots are $K_S^0 K_S^0$ correlation measurement and their fit in 10–30% (left panel) and 30–50% (right panel) centrality bins.

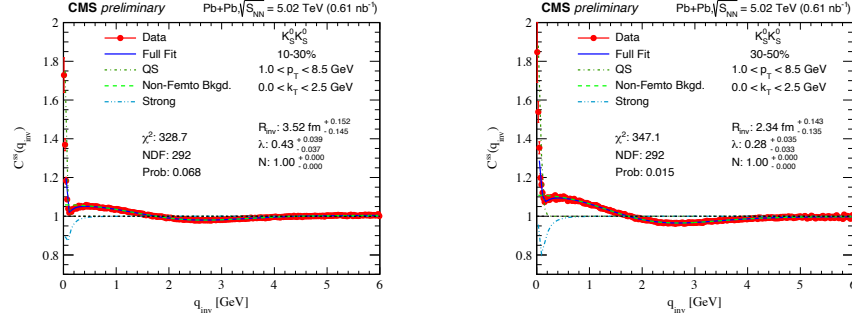


Figure A.23: $K_S^0 K_S^0$ correlation measurement and fit in 10–30% (left panel) and 30–50% (right panel) centrality bins. In these plots, the red filled circle represents the data, the blue solid line is fit using Eq. 5.9, the green dashed line is the non-femtoscopic background (Eq. 5.8), the dashed double dotted line is the strong FSI function, and the dash dotted line is the QS function. QS line drawn using the equation $1 + e^{-q_{inv}^2 R_{inv}^2}$, where the R_{inv} is taken from the LL fit.

APPENDIX B

COLLABORATIVE RESPONSIBILITY AND SERVICE TASK

All the CMS members are required to perform some collaboration work called Experimental Physics Responsibilities (EPR). The work involves improvement in software, hardware and detector upgrades, Monte Carlo (MC) production, data certification, etc. These works help us learn more about the detector and how collaboration functions. Based on the number of months we work, we receive some EPR credit. The EPR credit helps us to become an author of collaboration papers. Six credits are needed to become an author, and after that, four credits are required yearly to keep that authorship. Generally, collaboration informed each institution that you must complete a certain number of credits each year. These required credits depend on the number of members working in the collaboration. Afterwards, each member is responsible for earning that much credit by contributing to the collaboration. The following is the description of my collaborative work from 2018 to 2022.

B.1 MONTE CARLO REQUEST MANAGER (LEVEL-3 CONVENER)

[2019-2022]

The Monte Carlo (MC) samples are essential to perform any analysis. The CMS experiment offers a central production mechanism for the MC samples production to the analyzers. The PdmV¹ group of the PPD² group is responsible for MC production. Under the PdmV group, four subgroups are working in different fields. These subgroups are the validation team, development of PdmV tools team, MC request management team, and Data definition team. A certain number of people are working for each subgroup,

¹Physics Data And Monte Carlo Validation

²Physics Performance and Dataset

and we call them Level-3 conveners. All the subgroups manage by Level-2 conveners. I was a Level-3 convener in the MC request management team from 2019 to 2022. The job of the MC request managers is very crucial in MC production. The PdmV organization chart for the year 2022 can be seen in Fig. B.1.

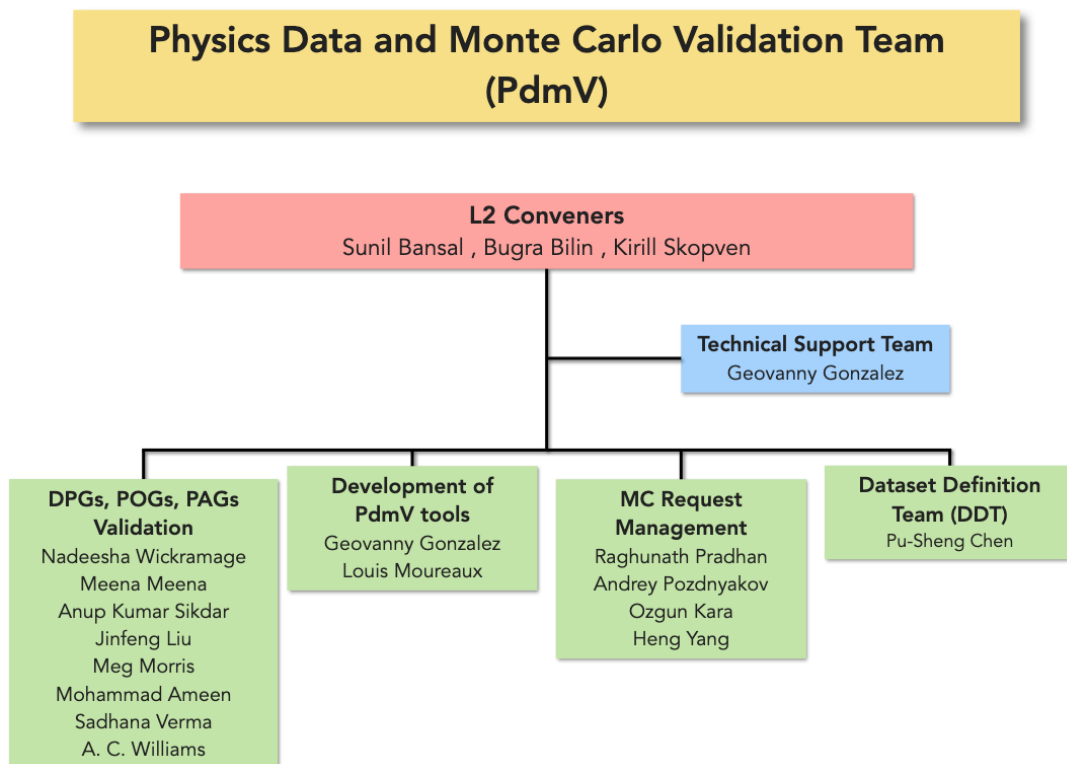


Figure B.1: PdmV organization chart

The following are the tools used for MC samples production and monitoring:

- **McM (Monte Carlo Management):** a central database that compiles all Monte Carlo requests that have previously been made or are planned for production.
- **pMp (Production Monitoring Platform):** a monitoring tool that displays the produced events for a given request or series of requests in a user-friendly manner.

The general work structures for the MC samples production are the following:

- **Analyzers/CMS users:** they request MC samples according to their needs for their own analysis or any detector performance studies.
- **MC contacts:** they set up the requests in McM once they acquire the requests

from the analyzers. Each POG³/PAG⁴/DPG⁵ group has its own MC connections for this job.

- **MC request managers (Level-3 convener):** We review the requests set up by the MC contacts, and if everything is OK, we submit them for production. After the submissions, we need to announce the batch. It is a kind of command for the computing side to start production. If we forget to announce the batch, even if the request has been submitted, official production will not start. So, every day we check whether we announce the submitted request batches. We are also responsible for setting up the campaigns under which the requests are created. But the Request manager's job does not end here. We have to monitor the submitted requests to see if everything goes smoothly until production. If any problem is found during production, we coordinate with Level-2 conveners and solve them. Every Wednesday, we arrange the McM meeting, where all the MC contacts from different groups present their requests. In this meeting, we mainly discussed the problem faced by the MC contacts while making and validating the request in McM. Each request is created under a specific campaign. The campaign is the central platform in McM used to produce a set of requests sharing the same physics goal, CMSSW software release, center-of-mass energy, event processing configuration, etc. We are responsible for setting up the campaigns, flows, and chained campaigns. Flows are the connector between the campaigns, starting from GEN-SIM to NanoAOD. Chained campaigns are constructed from campaigns that are connected together with flows. The request manager's job is crucial because the whole production will be wrong if we make a mistake while setting up the campaigns and flows. Also, if we do not adequately monitor the request, there is a chance of delay in production because sometimes we face problems in McM and from the computing side due to a large number of production. The number of CPUs used for the MC production from 17th – 23rd March 2023 and the number of running and pending MC requests can be seen in Fig. B.2 and B.3.

B.2 SILICON PIXEL AND STRIP RELEASE MC VALIDATOR

[2018-PRESENT]

The information on the configuration of the CMS detector is installed in the CMSSW software. But the CMSSW version is continuously upgraded, and a new version comes whenever any changes are made in the detector configuration. We then used the latest CMSSW version for our analysis or any detector performance study. But before the upgradation in the physical detector, we check the detector performances using a virtual detector created using GEANT4 with the new changes. A simulated MC sample with

³Physics Objective Group

⁴Physics Analysis Group

⁵Detector performance Group

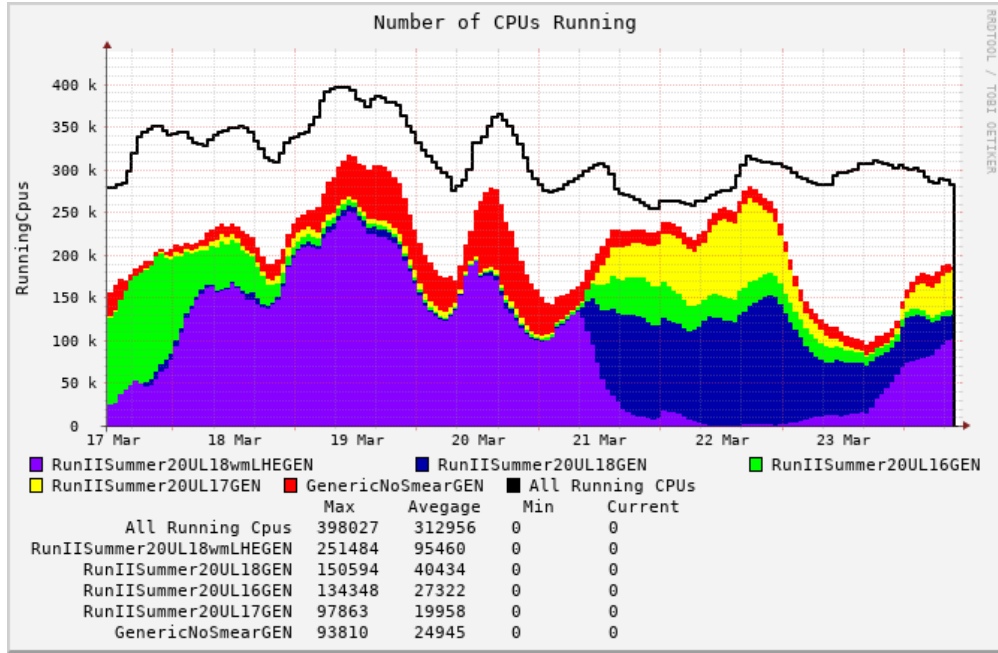


Figure B.2: Number of CPUs running for the MC production. The different color graphs show the CPUs used for the requests created from the different campaigns. The black solid lines show the total number of CPUs used for MC production from 17th – 23rd March 2023.

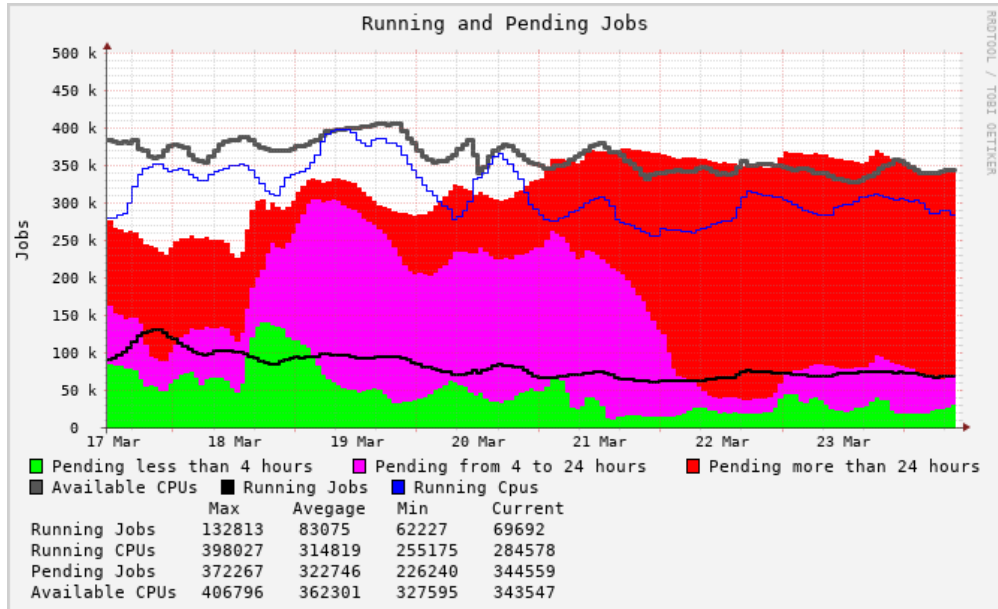


Figure B.3: Number of running and pending requests. The different color graphs show the pending request and running requests. Also, it shows the number of CPU running and available during 17th – 23rd March 2023.

fewer events is produced using the new CMSSW version, where the latest changes were installed and compared with the previous sample to check the performance. This process is called validation. I am a validator of silicon pixel phase-1 and strip detectors. Usually, I compare the plots of pixel phase-1 and strip detectors in the MC samples produced using new and old CMSSW versions and report to the tracker validation team. If any changes are found, I need to write the cause of the difference observed between the new and old samples. Many validators validate the different components of the detectors, e.g., ECAL, HCAL, etc. If no differences are found between these samples, all the validators give the green signal to the new CMSSW software. An example of the comparison plots between CMSSW_13_0_0_pre3_LTOG4VECGEOM and CMSSW_13_0_0_pre3 can be seen in Fig. B.4 and B.5. In these figures, significant differences were observed between the new (black solid line) and old (blue star) samples that can be seen in the ratio plot (lower panels).

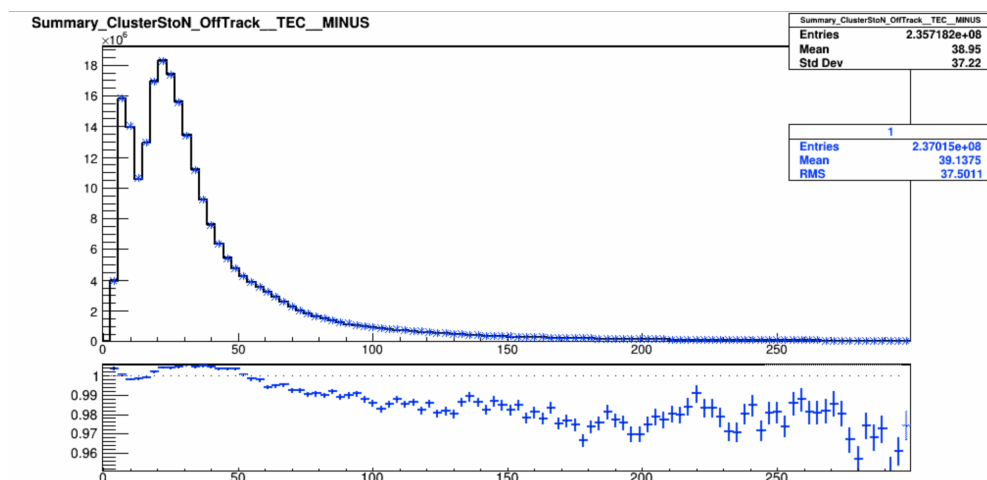


Figure B.4: Signal-to-noise ratio distribution from the -ve side of TEC. The black solid line is from CMSSW_13_0_0_pre3_LTOG4VECGEOM, and the blue star marker is for CMSSW_13_0_0_pre3.

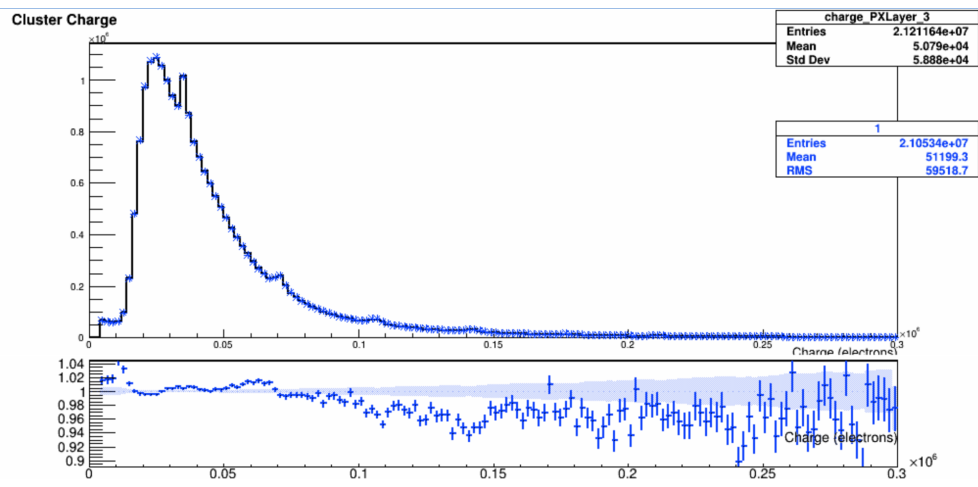


Figure B.5: Cluster charge distribution from the pixel barrel. The black solid line is from CMSSW_13_0_0_pre3_LTOG4VECGEOM, and the blue star marker is for CMSSW_13_0_0_pre3.

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