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Study of Λ – Hadron Correlations in Pb–Pb Collisions at $\sqrt{s_{NN}} = 5.36$ TeV Using the ALICE Detector

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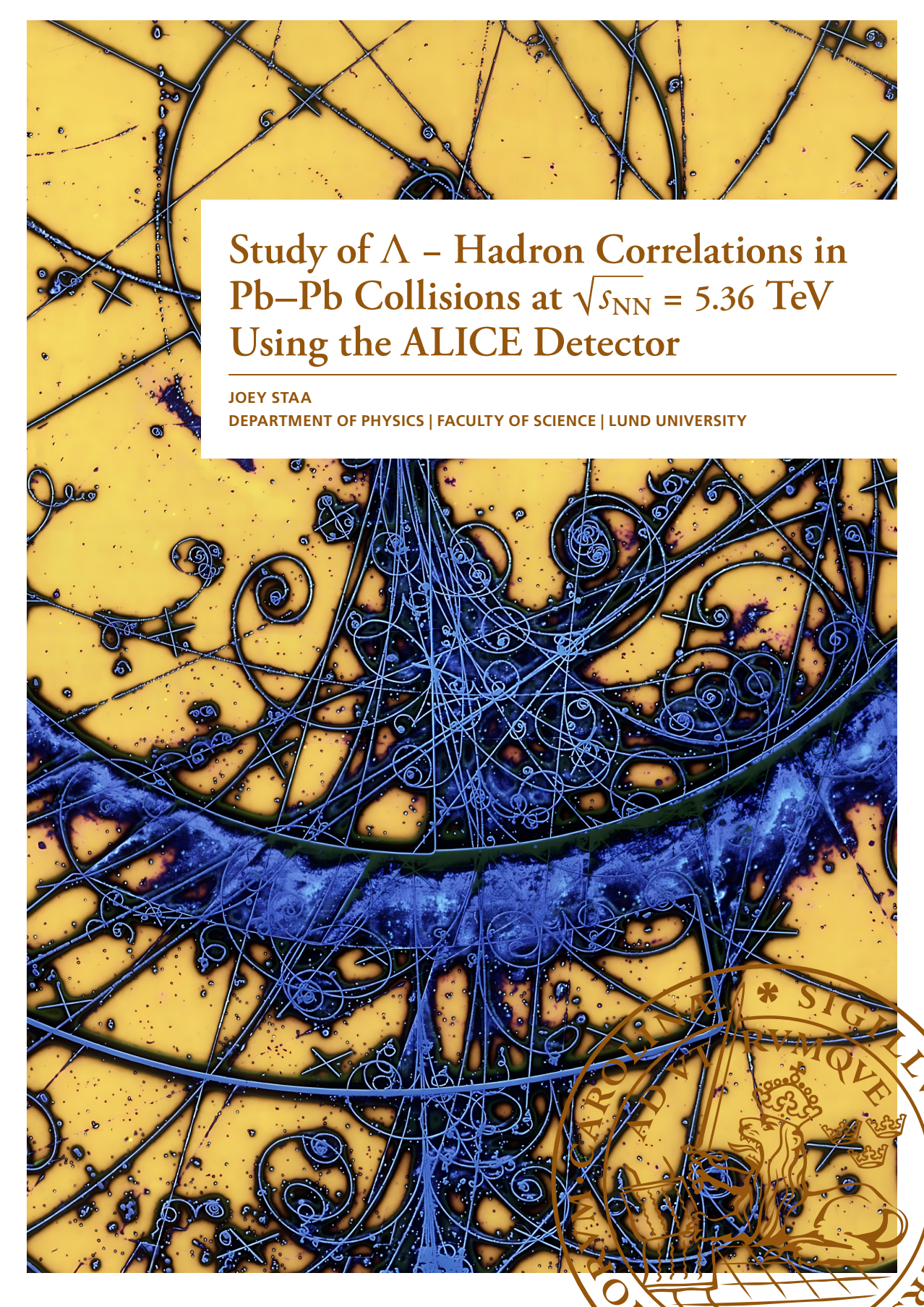
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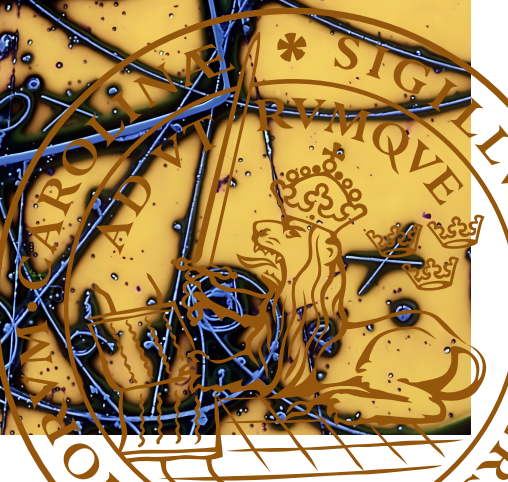
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Study of Λ – Hadron Correlations in Pb–Pb Collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV Using the ALICE Detector

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DEPARTMENT OF PHYSICS | FACULTY OF SCIENCE | LUND UNIVERSITY



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Study of Λ – Hadron Correlations in Pb–Pb Collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV Using the ALICE Detector

by Joey Staa



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Thesis for the degree of Doctor of Philosophy

Thesis advisors: Dr. Alice Ohlson, Prof. Peter Christiansen,
Prof. David Silvermyr

Faculty opponent: Prof. Rosi Reed

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Abstract Ultrarelativistic heavy-ion collisions, which take place at particle accelerators like the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), are known to produce a strongly-interacting, fluid-like state of matter referred to as the Quark-Gluon Plasma (QGP). Despite the medium's short lifetime of approximately 10^{-23} s, its presence is known to influence particle production in a collision event. This is expected to include the production of particles carrying strangeness and baryon number, two quantum numbers that are conserved in interactions. If the QGP does affect the production of conserved quantities, this will be reflected in the distribution of the final-state particles that carry the corresponding conserved quantum numbers. Furthermore, it will be worthwhile to study the dependence of these final-state distributions on the collision centrality, as this concept is closely related to the size of the QGP medium. The analysis presented in this thesis aims to gain an understanding of the QGP's influence on the production mechanisms of strangeness and baryon number. To this end, data from the ALICE detector of Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV is used to construct $\Lambda - h$ angular correlation functions, where h is either of π, K or p. Separating the correlation functions into the four possible (electric) charge configurations ($\Lambda - h^+$, $\Lambda - h^-$, $\bar{\Lambda} - h^+$, $\bar{\Lambda} - h^-$) allows one to produce opposite- and same-sign correlations, where the sign refers to the relative sign between the quantum numbers of the Λ baryon and the chosen hadron. By subtracting the same-sign correlations from the opposite-sign correlations, a distribution known as the balance function is obtained. This distribution is expected to be free of any correlations apart from those arising due to opposite-sign quantum numbers, allowing one to study the evolution of quantum number balancing. The results show that the opposite-sign $\Lambda - K$ and $\Lambda - p$ correlations are greater on the near-side ($-\frac{\pi}{2} < \Delta\varphi \leq \frac{\pi}{2}$) and almost identical on the away-side ($\frac{\pi}{2} < \Delta\varphi < \frac{3\pi}{2}$) compared to their same-sign counterparts. This leads to a prominent near-side peak in the $\Lambda - K$ and $\Lambda - p$ balance functions, indicating that strangeness and baryon number are conserved locally between particles in close proximity to each other. This is an unexpected outcome, as the presence of a thermal, deconfined QGP in Pb–Pb collisions should “wash out” correlations between balancing quantum numbers. Furthermore, comparing the balance functions to predictions from the Lund string model reveals that the widths (σ) of the balance functions are considerably greater in Pb–Pb collisions than in pp collisions. This seems to suggest that the mechanisms governing strangeness and baryon number conservation in Pb–Pb occur over a wider range compared to pp, being neither entirely local nor completely global. For $\Lambda - \pi$, the opposite- and same-sign correlations show no discernible differences, leading to a flat balance function. Since the $\Lambda - \pi$ correlations are free from strangeness and baryon number balancing, this is to be expected.			
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Cover illustration front: Bubble chamber with colour enhanced tracks. Original image credits: CERN.

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*In remembrance of my sanity,
which has been missing for 27 years.*

Abstract

Ultrarelativistic heavy-ion collisions, which take place at particle accelerators like the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), are known to produce a strongly-interacting, fluid-like state of matter referred to as the Quark-Gluon Plasma (QGP). Despite the medium's short lifetime of approximately 10^{-23} s, its presence is known to influence particle production in a collision event. This is expected to include the production of particles carrying strangeness and baryon number, two quantum numbers that are conserved in interactions. If the QGP does affect the production of conserved quantities, this will be reflected in the distribution of the final-state particles that carry the corresponding conserved quantum numbers. Furthermore, it will be worthwhile to study the dependence of these final-state distributions on the collision centrality, as this concept is closely related to the size of the QGP medium.

The analysis presented in this thesis aims to gain an understanding of the QGP's influence on the production mechanisms of strangeness and baryon number. To this end, data from the ALICE detector of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV is used to construct $\Lambda - h$ angular correlation functions, where h is either of π , K or p. Separating the correlation functions into the four possible (electric) charge configurations ($\Lambda - h^+$, $\Lambda - h^-$, $\bar{\Lambda} - h^+$, $\bar{\Lambda} - h^-$) allows one to produce opposite- and same-sign correlations, where the sign refers to the relative sign between the quantum numbers of the Λ baryon and the chosen hadron. By subtracting the same-sign correlations from the opposite-sign correlations, a distribution known as the balance function is obtained. This distribution is expected to be free of any correlations apart from those arising due to opposite-sign quantum numbers, allowing one to study the evolution of quantum number balancing.

The results show that the opposite-sign $\Lambda - \text{K}$ and $\Lambda - \text{p}$ correlations are greater on the near-side ($-\frac{\pi}{2} < \Delta\varphi \leq \frac{\pi}{2}$) and almost identical on the away-side ($\frac{\pi}{2} < \Delta\varphi < \frac{3\pi}{2}$) compared to their same-sign counterparts. This leads to a prominent near-side peak in the $\Lambda - \text{K}$ and $\Lambda - \text{p}$ balance functions, indicating that strangeness and baryon number are conserved locally between particles in close proximity to each other. This is an unexpected outcome, as the presence of a thermal, deconfined QGP in Pb–Pb collisions should “wash out” correlations between balancing quantum numbers. Furthermore, comparing the balance functions to predictions from the Lund string model reveals that the widths (σ) of the balance functions are considerably greater in Pb–Pb collisions than in pp collisions. This seems to suggest that the mechanisms governing strangeness and baryon number conservation in Pb–Pb occur over a wider range compared to pp, being neither entirely local nor completely global.

For $\Lambda - \pi$, the opposite- and same-sign correlations show no discernible differences, leading to a flat balance function. Since the $\Lambda - \pi$ correlations are free from strangeness and baryon number balancing, this is to be expected.

Populärvetenskaplig Sammanfattning på svenska

Det är allmänt känt att ämnen eller material kan genomgå en fasövergång när mediets temperatur passerar kok- eller fryspunkten. Ämnet eller materialet omvandlas sedan till ett nytt materietillstånd och blir antingen fast, flytande eller gasformigt. Emellertid finns det också mer exotiska materietillstånd, inklusive ett som uppnås när temperaturen, densiteten och trycket hos vanlig materia pressas till sina fysiska extremer. Detta tillstånd kännetecknas av att kvarkar, materiens grundläggande byggstenar, kan frias från sitt bundna tillstånd inuti protoner och neutroner. Tillsammans med gluoner – partiklarna som ansvarar för att bära den starka kärnkraften – bildar de ett nytt materietillstånd som kallas Quark-Gluon Plasma (QGP). Inom detta nya materietillstånd beter sig kvarkar och gluoner som om de vore fria partiklar. Eftersom temperaturen, densiteten och trycket hos QGP är högre än hos något annat känt medium, antas det att universum en gång bestod av ett enda QGP, flera mikrosekunder efter Big Bang. Genom att studera QGP och få en förståelse för dess egenskaper kan vi kanske lära oss mer om hur universum utvecklades till den form vi ser idag.

För att uppnå de temperatur- och tryckförhållanden som krävs för att producera QGP i en experimentell miljö använder forskare kollisioner mellan tunga joner, såsom bly eller guld. Dessa joner ges en enorm mängd kinetisk energi, vilket får deras hastigheter nära ljusets hastighet. Atomkärnorna tillåts sedan krocka med varandra och bildar ett litet, lokaliserat område med enorm energitäthet, temperatur och tryck. Det är här som materietillståndet som kallas QGP förväntas bildas. Tyvärr orsakar QGP:s höga temperatur att mediet avdunstar nästan omedelbart, vilket gör direkt observation omöjlig. Istället måste dess egenskaper uppskattas från de slutliga hadroner som skapas i kollisionen och observeras i våra detektorer. Dessa kollisioner äger rum i storskaliga partikkelkolliderare runt om i världen, såsom "Relativistic Heavy-Ion Collider (RHIC)" vid Brookhaven och "Large Hadron Collider (LHC)" nära Genève. Med hjälp av dessa kolliderare har några anmärkningsvärda egenskaper hos QGP redan fastställts, inklusive upptäckten att QGP beter sig som en nästan friktionsfri vätska, där transporten av partiklar kan beskrivas med hjälp av relativistisk hydrodynamik.

Förutom partikeltransport förväntas även QGP påverka produktionen av olika partikelsorter i kollisionen. Bland dem finns partiklar som innehåller en sär(anti)kvark – en speciell typ av kvark som kan ses som en tyngre version av nedkvarken – eller partiklar som är uppbyggda av tre (anti)kvarkar, kallade baryoner. Partiklar som dessa bär det som kallas ett kvanttal, en egenskap som kännetecknar en partikels kvanttillstånd. Kvantantalen för särkvarkar och baryoner kallas särantal respektive baryontal. Dessutom är dessa två kvanttal bevarade, vilket innebär att deras nettovärden inte förändras i olika växelverkan. Eftersom bevarade kvantiteter är bland de viktigaste begreppen inom fysiken är det värdefullt att avgöra om och hur QGP påverkar produktionen av partiklar som bär särantal och baryontal, eftersom det också kan belysa andra egenskaper hos mediet.

För att få en uppfattning om hur närvaron av QGP påverkar produktionsmekanismerna för särantal och baryontal, syftar denna analys till att studera röreselsemängdskorrelationerna mellan olika partikelarter. Analysen fokuserar särskilt på korrelationer mellan Λ baryoner

(uttalas "lambda") – partiklar som består av en upp-, ned- och särkvark – och tre vanligt observerade hadroner (h): pionen, kaonen och protonen. Genom att identifiera alla möjliga $\Lambda - h$ partikelpar i en kollisionshändelse, beräkna avståndet mellan dem och lagra det avståndet i ett histogram, erhålls en fördelning som kallas korrelationsfunktionen. Denna fördelning visar det genomsnittliga antalet pioner, kaoner eller protoner per Λ baryon, och ger en tydlig indikation på var partiklar sannolikt produceras i en händelse i förhållande till varandra. Dessutom möjliggör noggrann separering av $\Lambda - h$ -par baserat på den elektriska laddningen och (anti)kvarksammansättningen hos båda partiklarna att en annan typ av fördelning, känd som balansfunktionen, kan tas fram. Konstruktionen av denna fördelning innehåller endast korrelationer som härrör från kvanttal med motsatt tecken, vilket gör det möjligt att undersöka bevarandet av särtal och baryontal.

Korrelations- och balansfunktionerna indikerar att särtal och baryontal verkar bevaras lokalt i kollisioner med tunga joner. Detta skiljer sig från den ursprungliga förväntningen att, i närvaro av QGP, skulle särtal och baryontal endast bevaras globalt. En jämförelse av balansfunktionerna i kollisioner med tunga joner med resultat från modeller som exkluderar QGP-bildning visar dock att de förstnämnda är betydligt mindre lokala än de sistnämnda. Därför verkar produktionsmekanismen för särkvarkar och baryoner ligga någonstans mellan lokalt och globalt bevarande.

Popular Scientific Summary in English

It is commonly understood that substances or materials can undergo a phase transition when the medium temperature passes its boiling or freezing point. The substance or material will then transform into a new state of matter, becoming either a solid, a liquid or a gas. However, more exotic states of matter also exist, including one that is reached when the temperature, density and pressure of ordinary matter are pushed to their physical extremes. This state is characterized by the fact that quarks, the fundamental building blocks of matter, are able to escape their confined state inside protons and neutrons. Together with gluons – the particles responsible for carrying the strong nuclear force – they form a new state of matter referred to as the Quark-Gluon Plasma (QGP). Within this new state of matter, quarks and gluons behave as if they were free particles. Because the temperature, density and pressure of the QGP are higher than those of any other medium known to exist, it is hypothesized that the Universe once consisted of a single QGP, several microseconds after the Big Bang. By studying the QGP and gaining an understanding of its properties, we may be able to learn more about how the Universe evolved into the form we observe today.

In order to reach the temperature and pressure conditions necessary to produce the QGP in an experimental environment, scientists make use of collisions between heavy ions, such as lead or gold. These ions are given a tremendous amount of kinetic energy, bringing their velocities to close to the speed of light. The atomic nuclei are then allowed to smash into each other, forming a small, localised region of enormous energy density, temperature and pressure. It is here that the state of matter known as the QGP is expected to be formed. Unfortunately, the high temperature of the QGP causes the medium to evaporate almost immediately, making direct observation impossible. Instead, its properties must be inferred from the final-state hadrons that are created in the collision and observed in our detectors. These collisions take place in large-scale particle colliders located around the world, such as the “Relativistic Heavy-Ion Collider (RHIC)” in Brookhaven and the “Large Hadron Collider (LHC)” near Geneva. Using these colliders, some remarkable properties of the QGP have already been determined, including the discovery that the QGP behaves like a nearly frictionless fluid, where the transport of particles can be described using relativistic hydrodynamics.

In addition to particle transport, the QGP is also expected to affect the production of different particle species in the collision. Among them are particles that contain a strange (anti)quark – a special type of quark that can be seen as a heavier version of the down quark – or particles that are built up from three (anti)quarks, referred to as baryons. Particles such as these carry what is known as a quantum number, a property that characterizes a particle’s quantum state. The quantum numbers of strange quarks and baryons are known as strangeness and baryon number, respectively. In addition, these two quantum numbers are conserved, meaning that their net values do not change in different interactions. Since conserved quantities are among the most important concepts in physics, determining whether and how the QGP influences the production of particles carrying strangeness and baryon number is a worthwhile endeavour, as it may also shed light on other properties of the medium.

To get an idea of how the presence of the QGP affects the production mechanisms of strangeness and baryon number, this analysis aims to study the momentum correlations between different particle species. In particular, the analysis focuses on correlations between Λ baryons (pronounced “lambda”) – particles consisting of an up, down and strange quark – and three commonly observed hadrons (h): the pion, the kaon and the proton. By identifying all possible $\Lambda - h$ particle pairs in a collision event, calculating the distance between them and storing that distance in a histogram, a distribution known as the correlation function is obtained. This distribution shows the average number of pions, kaons or protons per Λ baryon, and provides a clear indication of where particles are most likely to be produced in an event relative to each other. In addition, carefully separating $\Lambda - h$ pairs based on the electric charge and (anti)quark composition of both particles allows for another type of distribution, known as the balance function, to be assembled. By construction, this distribution contains only correlations arising from opposite-sign quantum numbers, allowing for the conservation of strangeness and baryon number to be examined.

The correlation and balance functions indicate that strangeness and baryon number appear to be conserved locally in heavy-ion collisions. This differs from the original expectation that, in the presence of the QGP, strangeness and baryon number would be conserved only globally. However, comparing the balance functions in heavy-ion collisions with results from models that exclude QGP formation reveals that the former are significantly less local than the latter. Therefore, the production mechanism of strangeness and baryon appear to lie somewhere between local and global conservation.

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Chapter 1

Introduction

1.1 General Background

Within the scientific field of particle physics, few concepts are as remarkable or as intriguing as the Quark-Gluon Plasma (QGP). This fascinating substance is expected to occur when the temperature, density and pressure of ordinary matter are pushed to their extremes, resulting in a phase transition and the subsequent creation of a novel, fluid-like state of matter. This novel state, comprised entirely of Standard Model quarks and gluons, is theorised to have filled the Universe microseconds after it came into existence following the Big Bang (see Fig. 1.1), and as such is one of the most interesting systems to study from a cosmological point of view. In addition, the QGP possesses thermodynamic and hydrodynamic properties that are unlike those of ordinary matter, such as having the highest temperature and the lowest viscosity of any medium known to exist. Furthermore, the quarks and gluons that make up the QGP are no longer confined inside hadrons, which makes the system ideal for studying phenomena in the Quantum Chromodynamics (QCD) sector of particle physics.

The conditions necessary for achieving the phase transition from ordinary matter to a QGP state may be realised in ultrarelativistic heavy-ion collisions, which take place at particle accelerators like the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Here, the overlapping area between the colliding nuclei forms a small, localised environment with an energy density several times larger than the inside of a hadron and a temperature five orders of magnitude greater than the core temperature of the Sun. This will cause the nucleons in the colliding nuclei to break apart, forming a medium consisting of strongly-coupled quarks and gluons, which is thereafter referred to as the QGP. Although the system is predicted to be extremely short-lived (with a lifetime of approximately $10 \text{ fm}/c \approx 10^{-23} \text{ s}$), signatures of its existence may be inferred from measurements of the final-state particles produced in the collision. By using large-scale particle detectors, like the ALICE (A Large Ion Collider Experiment) detector at the LHC, the final-state par-

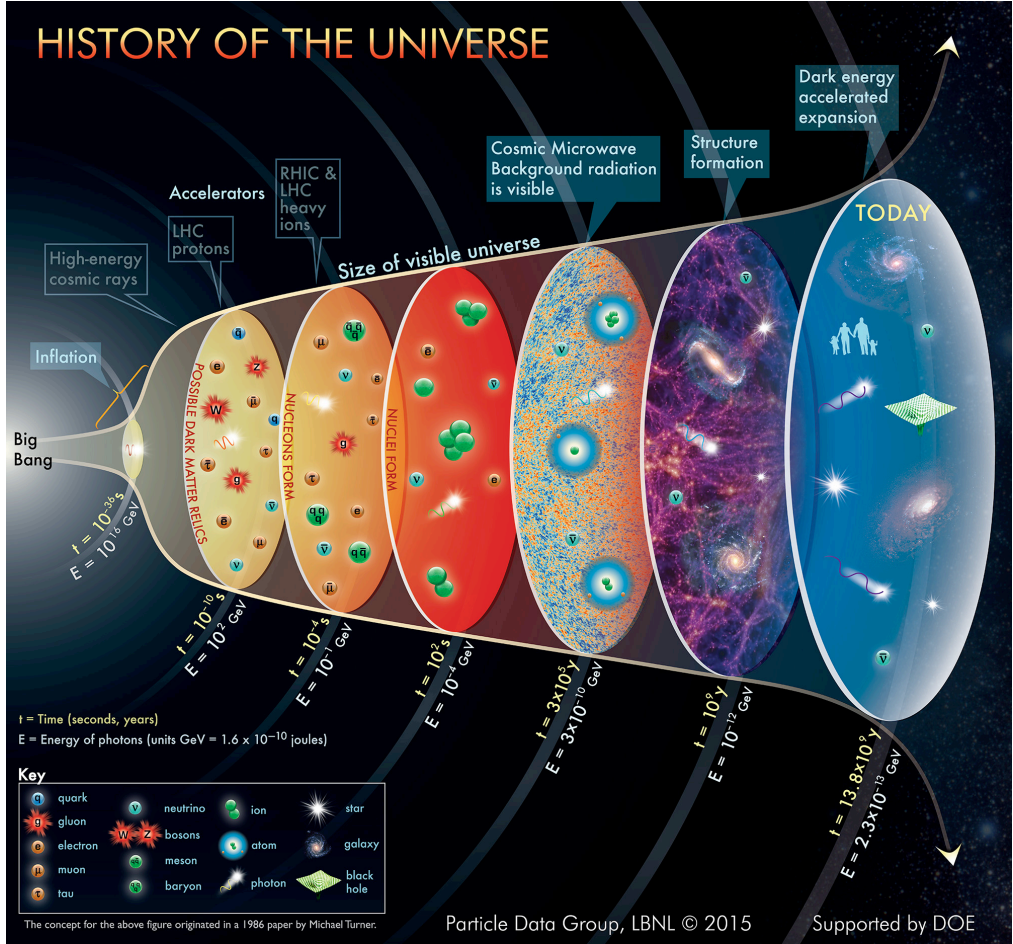


Figure 1.1 – Illustration showing the various stages of the history of the Universe. Figure is taken from [5].

ticles may be identified and their dynamics, which would be affected by the presence of the QGP, may be evaluated, thereby providing an indirect link for studying and understanding the medium.

The presence of the QGP in a heavy-ion collision may not only affect the dynamics, but also the production of the final-state particles. Notably, the medium is expected to have an influence on hadrons containing a strange quark, baryons, and their production mechanisms, which themselves are closely related to the conservation of strangeness and baryon number¹. Indeed, measurements of hadrons produced in particle collisions have revealed that large collision systems, like Pb–Pb, see an increase in the multiplicity of particles con-

¹Here, strangeness (S) and baryon number (B) are defined according to the net number of (strange) quarks over antiquarks, i.e. $S \equiv -(n_s - n_{\bar{s}})$ and $B \equiv \frac{1}{3}(n_q - n_{\bar{q}})$.

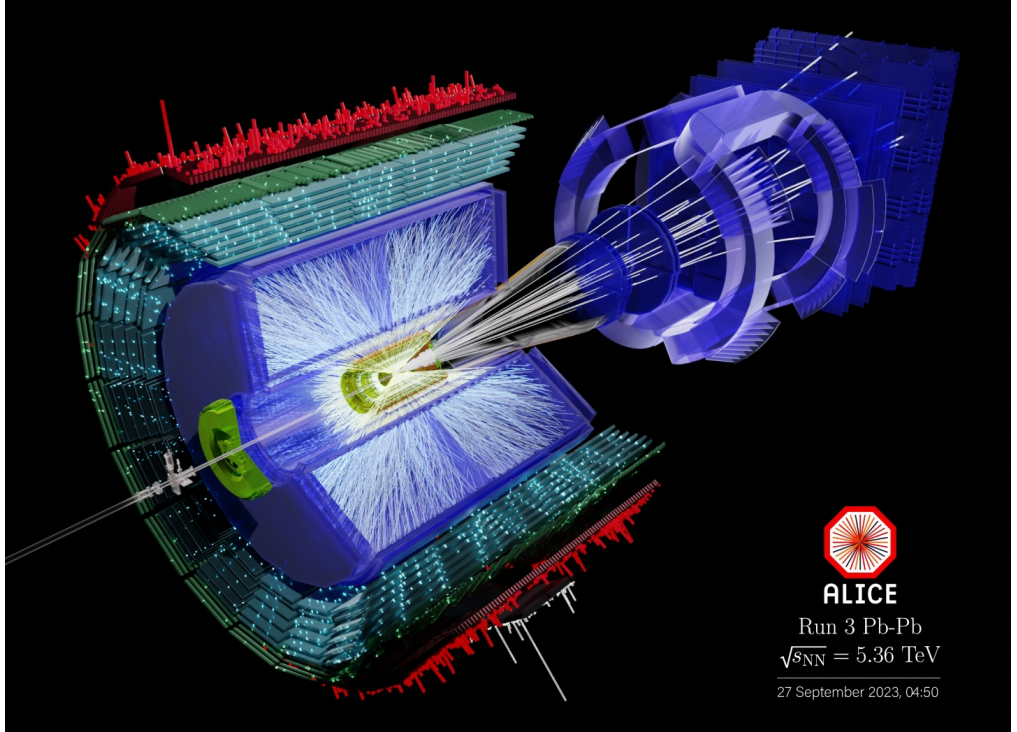


Figure 1.2 – Depiction of a Pb–Pb collision event at a center-of-mass energy of $\sqrt{s_{NN}} = 5.36$ TeV. Figure is taken from [6].

taining a strange quark compared to smaller collision systems like pp and p–Pb, which is thought to be attributable to the formation of the QGP in heavy-ion collisions (see Chapter 3 and Section 3.3.1 on strangeness enhancement). Furthermore, baryon number fluctuations are predicted to be considerably smaller in heavy-ion collisions as opposed to smaller collision systems [7], an effect that is considered to be a signature of QGP formation. The research presented in this thesis is dedicated to these two conserved quantum numbers, as is explained below.

1.2 Research Goal

The goal of this analysis is to study the production mechanisms of strangeness and baryon number in ultrarelativistic heavy-ion collisions. In particular, the influence of the Quark-Gluon Plasma on these production mechanisms is of interest, and needs to be quantified. To achieve this, the analysis employs the use of angular correlation functions to map the relative angular separation between particles carrying quantum numbers of opposite sign. These correlation functions are constructed from Pb–Pb collision data at a center-of-mass energy of $\sqrt{s_{NN}} = 5.36$ TeV, collected using the ALICE detector during the LHC’s Run 3 as

shown in Fig. 1.2. As strangeness and baryon number are conserved quantities, the angular correlation function allows one to see where quantum numbers that are correlated and conserved, such as an antistrange quark to a strange quark or an antibaryon to a baryon, end up after they are produced in the collision. The particles chosen for this purpose include the Λ and $\bar{\Lambda}$ baryons, since they are the lightest particles that carry both strangeness and baryon number, as well as the kaon and the proton (and their antiparticles) which represent just one conserved charge, these being strangeness and baryon number respectively. Additionally, the pion is included in the selection of particles as it carries neither of the conserved charges, and can therefore serve as a baseline.

1.3 Thesis Outline

This thesis is divided into three parts, with each part containing two chapters. Part I, titled “Elemental Theory & Heavy-Ion Physics”, offers an introduction to the fundamental theoretical framework that underlies the analysis. Starting with Chapter 2, the Standard Model of Particle Physics is introduced and several of its most important concepts are discussed. These include elementary particles, the theory of QED & QCD as well as the properties of the QGP. This is then followed up by Chapter 3, which details the unique physics involved in the process of colliding two heavy nuclei in a particle accelerator to form the QGP. Furthermore, several well-known physics results related to the QGP are presented, including strangeness enhancement, anisotropic flow and jet quenching. These results are considered signatures of the QGP and are regarded by many as evidence of QGP formation in heavy-ion collisions.

Next, Part II, titled “Experimental Setup & Methodology”, provides an overview of the experimental apparatus and analysis procedures that are central to the acquisition and processing of the Pb–Pb collision data. Chapter 4 covers the CERN LHC and its four main detectors, before describing the ALICE detector in greater detail. In particular, the detector subsystems that have been the most relevant for this analysis are highlighted. These include the FIT-FT0, the ITS, the TPC and the TOF detectors. Afterwards, Chapter 5 goes over the methodology used to process and analyse the experimental data recorded by ALICE. This involves defining the $\Lambda - h$ angular correlation function, establishing the necessary event selections, identifying and selecting trigger and associate particles, applying the necessary corrections to the data and calculating the systematic uncertainties on the measurements.

Finally, Part III, titled “Author’s Measurements”, delivers the primary findings of the analysis as well as an interpretation of the results. Starting with Chapter 6, the $\Lambda - h$ angular correlation and balance functions are shown in two dimensions ($\Delta\varphi, \Delta\eta$) and as projections in one dimension ($\Delta\varphi$ or $\Delta\eta$). Furthermore, a series of fits is applied to the projected balance functions in order to quantify their dependence on the event centrality. Lastly, Chapter 7 wraps up the thesis by presenting the main conclusions from the analysis, as well as an outlook on how this analysis might be continued in the future.

1.4 Author's Contributions

The vast majority of my time as a PhD has been dedicated to developing and refining the analysis, as described in this thesis. However, I have also contributed to the data taking and managing of the ALICE apparatus in several detector shifts during the LHC Run 3 period. Furthermore, during my ALICE service task, I contributed to the Run 4 upgrade of the ALICE detector by working on the calibration and pixel sensor characterization of the Inner Tracking System upgrade (ITS3). This work was concluded in 2025 and was published in an ALICE paper, which is listed below.

- O. Abdelrahman *et al.*, “Characterisation of the first wafer-scale prototype for the ALICE ITS3 upgrade: The monolithic stitched sensor (MOSS),” *Nucl. Instrum. Meth. A*, vol. 1086, p. 171297, 2026.
Paper summarizing the results from the testing of the babyMOSS beam telescope, used for characterizing the babyMOSS pixel sensors that are to be applied in the ITS3 upgrade of the ALICE detector. The beam telescope was tested using a series of test beams at the CERN Proton Synchrotron (PS), which I participated in.

Part I

Elemental Theory & Heavy-Ion Physics

Chapter 2

The Standard Model of Particle Physics

This chapter offers a summary of several aspects of theoretical particle physics, which is necessary for understanding and interpreting the analysis. The currently prevailing theory of particle physics is known as the Standard Model and provides a description of nature in terms of both its fundamental constituents and interactions. While the Standard Model is still an incomplete theory, it has proven to be incredibly successful, and remains the most widely accepted theory for describing the dynamics of particles and their interactions with each other. The chapter will begin with an overview of the Standard Model, the theory of Quantum Electrodynamics (QED) and the use of Feynman diagrams. Afterwards, the theory of Quantum Chromodynamics (QCD) and its prediction of the Quark-Gluon Plasma are introduced, the latter of which is discussed in more detail in the next chapter.

2.1 The Standard Model

As was mentioned earlier, the Standard Model operates in terms of fundamental constituents and interactions. These constituents, known as *elementary particles*, form the basis for all other particles in particle physics which, in turn, make up all matter¹. In addition, several elementary particles act as force carriers of the fundamental interactions (or forces) of nature. Figure 2.1 shows a chart listing the currently known elementary particles, along with some of their properties like their mass and electric charge. It should be noted that every elementary particle possesses a corresponding *antiparticle*, which has equivalent mass but opposite (electric) charge. The figure also indicates that elementary particles are grouped together depending on whether their spin is a multiple of an integer or a half-integer. The former are known as *bosons* while the latter are referred to as *fermions*.

¹For the remainder of this thesis, “matter” refers to visible, non-dark matter unless explicitly stated otherwise.

Standard Model of Elementary Particles

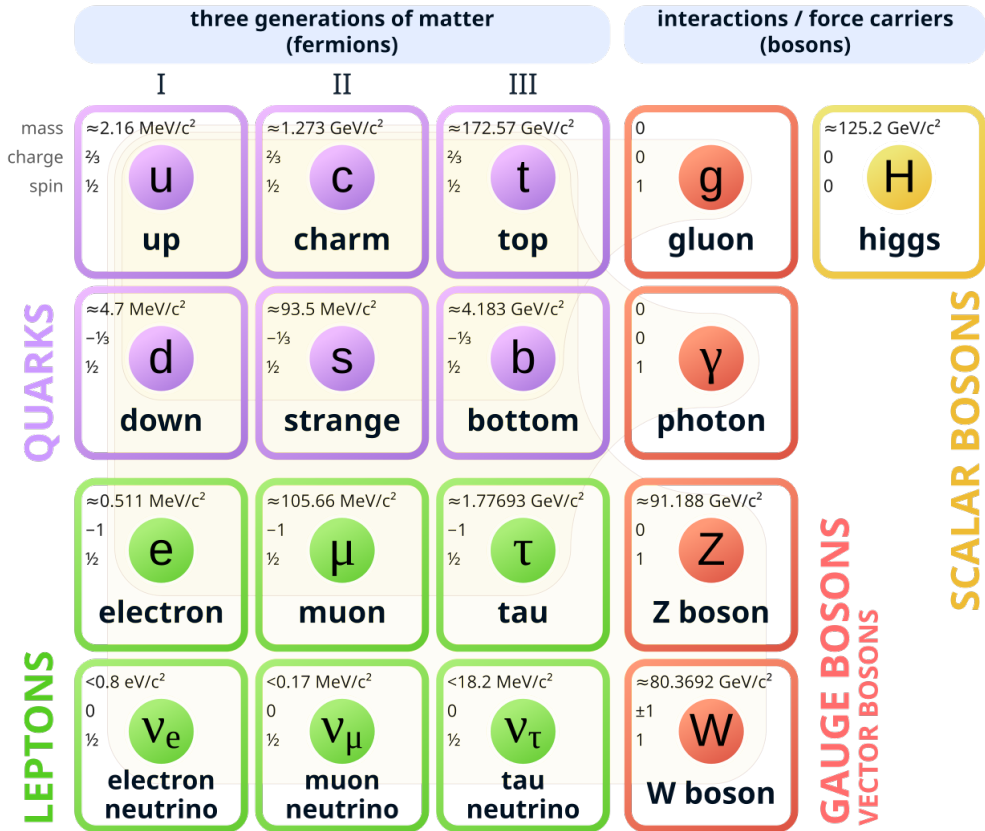


Figure 2.1 – Graphical overview of the elementary particles of the Standard Model. The chart indicates by colour whether an elementary particle is a quark, a lepton, a gauge boson or a scalar boson. In addition, the mass, charge and spin for each particle are shown. Figure is taken from [8].

The group of bosons with a spin of 1 are referred to as *gauge bosons*, named so because they naturally arise within the framework of gauge theories in the Standard Model [9, ch. 3-4]. The gauge bosons act as force carriers or mediators of the fundamental forces between particles that the Standard Model is able to describe. The fundamental forces are the strong interaction, electromagnetism, the weak interaction and gravity. The Standard Model correctly predicts three of the four forces, with the exception being gravity due to its relative strength being much lower in magnitude compared to the others and being practically negligible at the subatomic level [10, p. 6]. Conversely, the strong interaction has, as the name suggests, the highest relative strength at the subatomic level compared to

the other three forces. It is mediated by the massless gluon (g) and is responsible for keeping elementary particles that carry the colour charge in bound states. Next, the electromagnetic force (or electromagnetism) interacts with all particles that carry electric charge, and is mediated by the massless photon (γ). Like the strong interaction, the electromagnetic force keeps atoms in bound states consisting of a positive nucleus surrounded by negative electrons. Finally, the weak interaction acts on all elementary particles with the exception of the force carriers, and is mediated by the massive $W^\pm$ and Z^0 bosons. The weak interaction is primarily responsible for the radioactive β -decay of nuclei, and is the only fundamental force to violate the conservation of certain quantum numbers, unlike the electromagnetic and strong interaction.

The first group of fermions are the *quarks*, which come in the varieties (or flavours) “up” (u), “down” (d), “strange” (s), “charm” (c), “top” (t) and “bottom” (b), along with their antiparticles. Quarks are a unique set of fermions that carry both electric charge and colour charge. Similarly to how electric charge can be positive, negative or zero, the colour charge can be “red” (r), “green” (g) or “blue” (b). Colour determines how quarks interact with gluons of the strong interaction, which themselves carry both a colour and an anti-colour. Due to the nature of the strong interaction², quarks cannot exist in isolation, and must instead combine with other “coloured” particles to form an object that is colour neutral, called a *hadron*. Colour neutrality can be achieved by either pairing a colour with its anti-colour (for example, $r\bar{r}$ or $b\bar{b}$), or by combining the three colours together (for example, rgb). These combinations are referred to as *mesons* and *baryons*, respectively.

The second group of fermions are the *leptons*. Like the quarks, there are six flavours of leptons, these being the electron (e), the muon (μ) and the tau (τ) as well as the electron, muon, and tau neutrinos (ν_e, ν_μ, ν_τ). However unlike the quarks, leptons do not carry the colour charge, meaning that they don’t experience the strong interaction and can exist on their own. Instead, they interact electromagnetically (except for the neutrinos, since they are electrically neutral) and through the weak interaction. An additional curiosity of the leptons involves the three neutrinos. According to theory, the Standard Model predicts that the electron, muon, and tau neutrinos should be massless [10, p. 183]. However, as can be seen in Fig. 2.1, the neutrinos have masses that are non-zero, albeit exceedingly small. The neutrino mass discrepancy between theory and experiment is one of several indications that the Standard Model remains an incomplete theory [11].

An interesting feature of the Standard Model is that the up quark, the down quark, the electron and the electron neutrino act almost as “templates” for the remaining heavier fermions in the Standard Model. For example, the charm quark and the muon can be viewed as heavier versions of the up quark and the electron respectively, and similarly for the strange quark or the tau neutrino with respect to the down quark and the electron neutrino. For this reason, fermions are often placed in *generations* consisting of two quarks (of type up and down) and two leptons (of type electron and neutrino), where all three generations can be treated in much the same way. While not only convenient, it offers significant predictive power, such as how the top quark was predicted to exist years before its discovery in 1995 [12] due to the presence of other fermions within its generation. The reason why the Standard Model appears to contain precisely three generations of fermions remains an important open question in particle physics [11].

²This is explained in more detail in Section 2.3.

Finally, the Standard Model contains one additional boson, called the Higgs boson (H) or simply the Higgs. Unlike the vector bosons, the Higgs boson has a spin of zero and is therefore referred to as a *scalar boson*. The Higgs was discovered in 2012 [13, 14], and is the most recent addition to the list of Standard Model elementary particles. Despite this, the existence of the Higgs boson was theorised much earlier as arising from the Higgs mechanism [15], which explains the masses of the $W^\pm$ and Z^0 bosons in addition to those of all other massive fermions.

2.2 Quantum Electrodynamics and Feynman Diagrams

In the Standard Model, the propagation of particles and the interactions between particles are mathematically formulated using Quantum Field Theory (QFT). Here, the elementary particles are treated as physical fields which follow field equations that are derived from the theory. In practice, the theory is often represented using the Lagrangian formalism, where a quantity known as the Lagrangian ($\mathcal{L}$) captures all dynamics of the individual fields. The field equation for a particular field $\varphi(t, \vec{x})$ is then obtained by solving the Euler-Lagrange equation

$$\frac{\partial \mathcal{L}}{\partial \varphi} = \partial_\mu \left(\frac{\partial \mathcal{L}}{\partial (\partial_\mu \varphi)} \right), \quad (2.2.1)$$

where ∂_μ is the four-vector derivative $(\partial_t, \vec{\nabla})$. The three fundamental forces of the Standard Model each have their own QFT for describing the propagation of their gauge boson(s) and their participating fermions. In addition, the QFTs for the fundamental forces are gauge theories, meaning that their gauge bosons and, in turn, their interactions naturally arise within the theory as a consequence of requiring that the Lagrangian obeys certain local symmetries. In the Standard Model, the Lagrangian remains invariant under local $U(1) \times SU(2) \times SU(3)$ transformations, giving rise to the electromagnetic, weak, and strong interaction respectively [9, ch. 6-7].

The QFT for electromagnetism is called Quantum Electrodynamics (QED), which is a quantum-mechanical description of the theory of electricity and magnetism. QED is the most well-tested theory in physics [16] and acts as a template for nearly all other QFTs developed afterwards, including the ones for the strong and weak interaction. The Lagrangian of QED has the following form [17]

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - q\bar{\psi}\gamma^\mu A_\mu\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}. \quad (2.2.2)$$

Here, ψ is the field of a fermionic particle with mass m and charge q , γ^μ are the Dirac matrices, A_μ is a spin-1 field associated with the photon and $F^{\mu\nu}$ is the electromagnetic field strength tensor, defined as $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$. The first and third term in Eq. 2.2.2 represent the free motion of the fermion and the photon respectively, while the second term indicates that interactions between photons and (charged) fermions are possible.

The three terms in the QED Lagrangian define the behaviour of participating particles in isolation as well as in their mutual vicinity. These terms are sometimes represented graphically using lines and vertices, resulting in two propagation diagrams and one interaction diagram.



The straight and wiggly line indicate the free propagation of a fermion and a photon field respectively, while the point where two straight lines and one wiggly line come together is called an *interaction vertex*, corresponding to the term $q\bar{\psi}\gamma^\mu A_\mu\psi$ in Eq. 2.2.2. These graphical representations can be used for constructing *Feynman diagrams*, which are a way of visualising interactions between particles. In addition, applying a set of rules, called Feynman rules [10, p. 124], to the diagrams allows physicists to greatly simplify the calculation of the scattering amplitude $\mathcal{M}$. When multiplied with its complex conjugate, this quantity gives the probability amplitude for the corresponding process. Figure 2.2 shows two examples of Feynman diagrams for electron-electron scattering, the first containing two vertices and the second containing four.

The diagrams show that electrons “feel” each other through the exchange of a photon. The number of interaction vertices determines the order of the diagram, with the minimum order being 2. Each vertex contributes a factor $q \sim e \sim \sqrt{\alpha}$, where $\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$ is called the *fine-structure constant*³, which determines the strength of the electromagnetic interaction. The scattering amplitudes of the two Feynman diagrams are then proportional to α and α^2 respectively. The full calculation of the probability amplitude for a physical process requires that all possible Feynman diagrams, including ones of higher-order, are summed together before multiplying with the complex conjugate. However, since higher-order diagrams contribute powers of $\alpha \ll 1$, the value of the scattering amplitude is largely determined by the leading-order diagram, with higher-order diagrams acting as perturbative corrections.

Despite this, higher-order diagrams remain important. As the distance between particles decreases, equivalent to an increase in the momentum transfer [9, p. 152], loop corrections like the one in Fig. 2.2 will contribute more to the total scattering amplitude. This effectively makes the strength of the electromagnetic interaction dependent on the momentum transfer involved, and leads to effects such as “screening”. Here, charged particles become surrounded by an increasing number of virtual particle-antiparticle pairs at greater and greater distances, as shown in Fig. 2.3. To an outside observer, the electric charge of the central particle will appear smaller, effectively reducing the value of α . Likewise, a high-energy probe will observe a charge closer to the true value, effectively increasing the value of α .

³In SI units, $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$. Since α is a dimensionless quantity, it has the same value in any unit system.

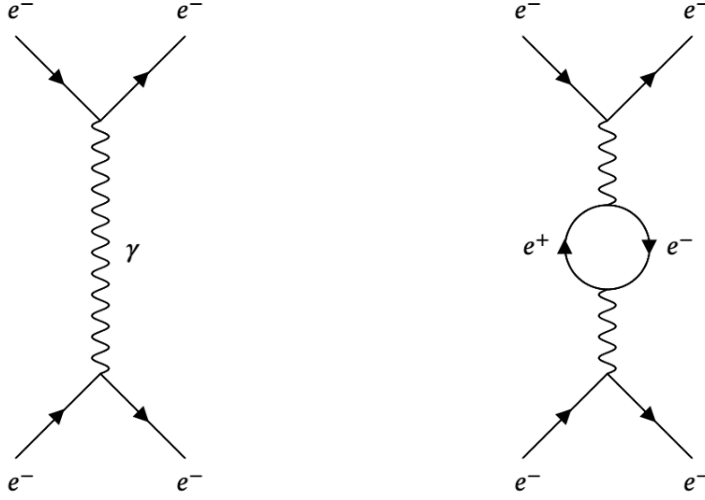


Figure 2.2 – Possible QED Feynman diagrams for electron-electron scattering. The right diagram contains two more interaction vertices due to the addition of an internal electron-positron loop.

A full derivation of the momentum dependence of α is beyond the scope of this thesis, but the end result is an expression of the form [10, p. 256]

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi} \ln\left(\frac{Q^2}{\mu^2}\right)}. \quad (2.2.3)$$

Thus, the value of α at an energy scale Q^2 is calculated as a correction to the known value of α at an energy scale μ^2 . Most importantly, Eq. 2.2.3 shows that the value of the fine-structure constant increases as the energy scale increases.

2.3 Quantum Chromodynamics

The QFT for the strong interaction is called Quantum Chromodynamics (QCD), where “chromo” refers to the colour charge carried by some particles of the Standard Model, namely quarks and gluons. As was mentioned earlier, the theory of QCD is derived in an analogous way to QED. As such, the Lagrangian has a similar form [18]

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi + g_s \bar{\psi} \gamma^\mu \frac{\lambda^a}{2} G_\mu^a \psi - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a. \quad (2.3.1)$$

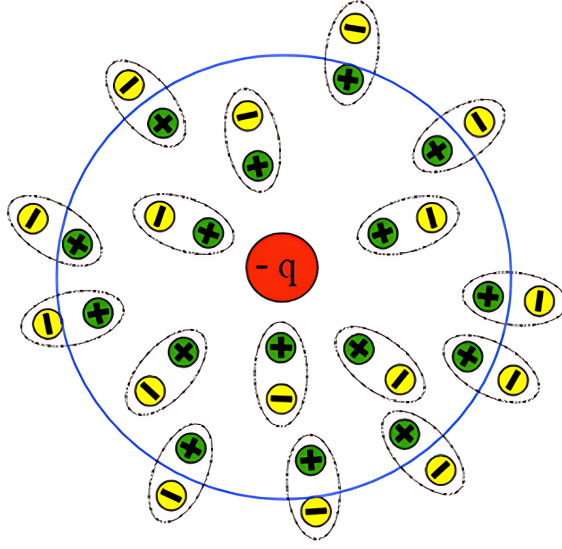
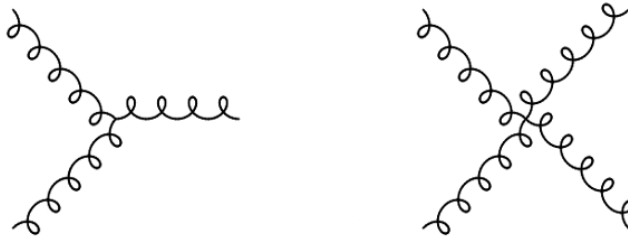


Figure 2.3 – “Screening” of a charge $-q$ by virtual particle-antiparticle pairs. Due to the polarization of the virtual particle pairs, the central charge will appear smaller in magnitude to an outside observer. By contrast, a high-energy probe is able to approach the central charge more closely and will observe a value closer to q . Figure is taken from [19].

Equation 2.3.1 still contains a term corresponding to the propagation of a fermion field. However, the interaction term is now proportional to a coupling strength factor g_s . Furthermore, the term involves the gluon field G_μ^a multiplied by the Gell-Mann matrices λ^a [10, p. 266], which are the eight generator matrices of the SU(3) group with a running from 1 to 8. Finally, $G_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu + g_s f_{abc} G_b^\mu G_c^\nu$ is the gluon field strength tensor which contains an additional term proportional to a factor f_{abc} , which is known as the structure constant of the SU(3) group.

A crucial aspect of QCD is that the generator matrices of SU(3) don’t commute, making the theory non-Abelian. Unlike QED, this leads to a non-vanishing structure constant and to the QCD Lagrangian containing terms involving three and four gluon fields. This means that the gluon is self-interacting, leading to two additional Feynman diagram interaction vertices compared to QED.



It is possible to define a coupling constant of QCD analogously to the fine-structure constant of QED, giving $\alpha_s = \frac{g_s^2}{4\pi}$. Like in QED, the value of α_s can change depending on the momentum transfer involved due to the presence of loop corrections. However, an additional type of loop correction can now be created compared to QED, namely one that consists purely of gluons as shown in Fig. 2.4. The addition of the gluon loop has a significant impact on the momentum dependence of α_s , which takes the form [9, p. 258]

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (33 - 2N_f) \ln(\frac{Q^2}{\mu^2})}. \quad (2.3.2)$$

Here, $N_f \leq 6$ is the number of quark flavours that can participate in loop corrections at the energy scale Q (the requirement being that $m_f \leq Q$). The behaviour of α_s , according to Eq. 2.3.2, has been confirmed by experiment, as is shown in Fig. 2.5. Here, two important observations can be made. Firstly, α_s becomes very large as Q decreases, indicating that the strength of the strong interaction grows between quarks as they become more separated. This phenomenon is called *colour confinement* and ensures that quarks cannot exist in isolation and are confined to colour-neutral objects. Secondly, at larger and larger values of Q , α_s tends to zero. This leads to the strong interaction vanishing over short distances and quarks, when struck by a high-energy probe, will behave as if they were free particles, a phenomenon that has been dubbed *asymptotic freedom*.

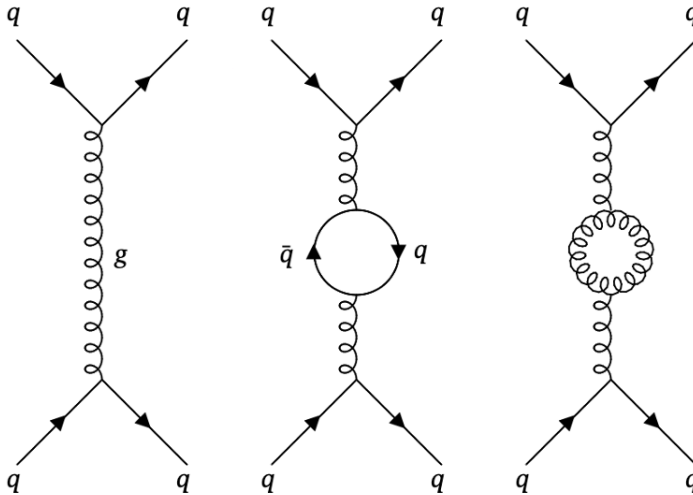


Figure 2.4 – Possible QCD Feynman diagrams for quark-quark scattering. The left and center diagrams are nearly identical to their QED counterparts in Fig. 2.2, while the right-most diagram, containing an internal boson loop, is unique to non-abelian gauge theories.

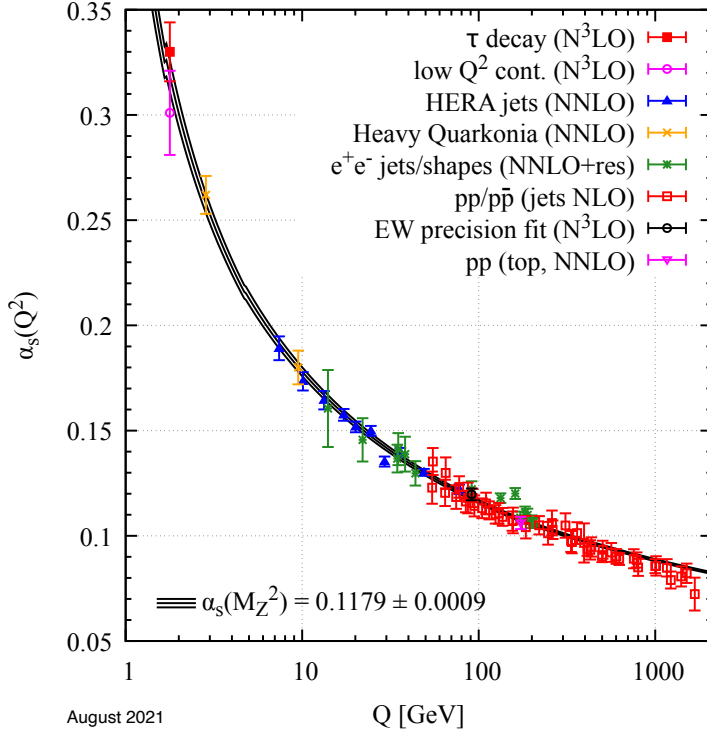


Figure 2.5 – Diagram showing the behaviour of α_s as a function of Q . The datapoints come from various experimental measurements of QCD, and demonstrate the validity of the predicted Q -dependence. Figure is taken from [20].

Lattice QCD

As was explained in Section 2.2, the fine-structure constant's low order of magnitude enables the use of perturbation theory, such that tree-level Feynman diagrams are already able to provide reasonably accurate predictions of QED. For the strong interaction however, this is generally not the case, since the strength of the interaction is much higher in comparison. In fact, α_s gets to be of order 1 at lower values of the energy scale Q , and perturbation theory breaks down. Despite this, it remains possible to make predictions concerning the behaviour of strongly-interacting matter, although a new theoretical procedure is required. This procedure is known as *lattice QCD*, whereby non-perturbative QCD processes are computed numerically on a quantized lattice [21]. By using a lattice spacing a , a momentum cut-off of order $1/a$ is introduced naturally, allowing the theory to be regularized. If a is then taken to be infinitesimally small, a continuum approximation of QCD is recovered. While lattice QCD is computationally demanding, the approach has led to a number of striking results. Most notably, the method predicts the existence of a QCD phase transition to a new state of matter, which is explained in the next section.

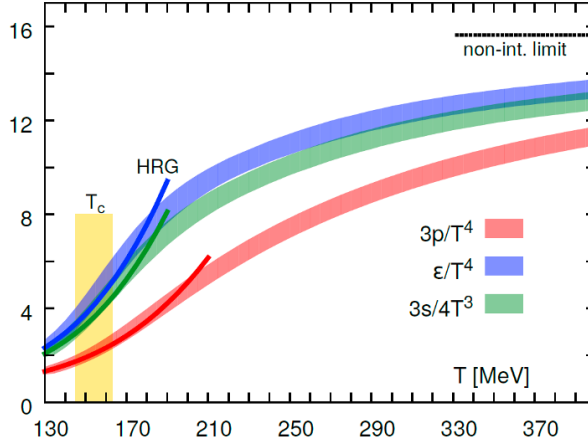


Figure 2.6 – Graph showing the pressure, energy density and entropy density (scaled by inverse powers of the temperature) of hot QCD matter in thermal equilibrium, as a function of the medium temperature. At $T \approx T_c$, a continuous shift is observed, leading to a flattening of the thermodynamic quantities that is not reproduced in QGP-less models like the *Hadron Resonance Gas* (HRG) model (solid lines). Figure is taken from [22].

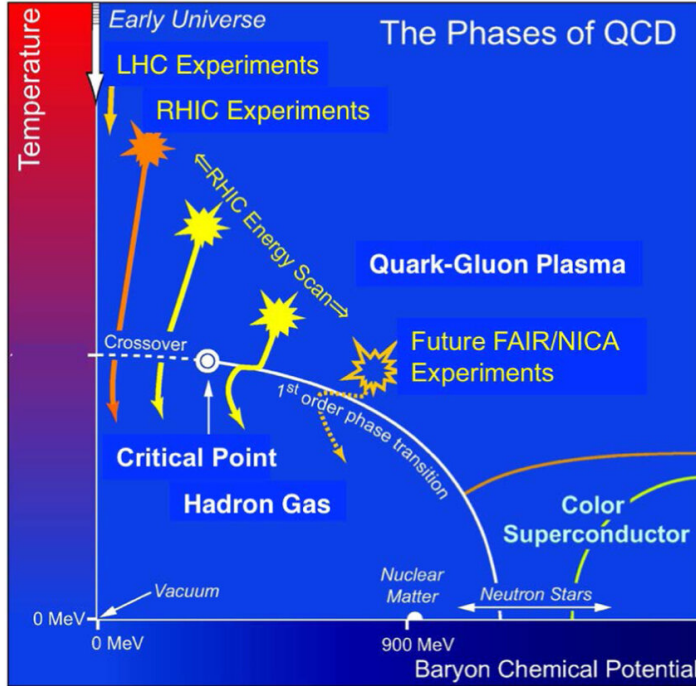


Figure 2.7 – Illustration of the QCD phase diagram in terms of the medium temperature and baryon chemical potential. The diagram shows the different phases of QCD matter, the order of the phase transition between a hadron gas and the QGP and several experiments which aim to probe the relevant regions of the diagram. Figure is taken from [23].

2.4 QCD Phase Transitions and the Phase Diagram

The dependence of α_s on the energy scale Q , as is highlighted in Eq. 2.3.2 and Fig. 2.5, has profound implications on the behaviour of hadronic matter, particularly when Q is taken to the extreme. As the energy scale increases, α_s tends to zero and the strength of the strong interaction becomes negligible over greater and greater distances. Eventually, the strong interaction will have become so weak that quarks, usually confined inside colourless hadrons, are able to escape their bound state, causing the hadrons to “melt”. This is a phase transition from a system of highly thermal hadrons to a new state of QCD matter, composed entirely of strongly-interacting quarks and gluons which are able to roam free inside a volume considerably larger than that of a nucleon (~ 1 fm). This new state of strongly-interacting, highly deconfined QCD matter has been given the name *Quark-Gluon Plasma* (QGP) [24], and is thought to be the same state of matter that filled the Universe shortly after the Big Bang.

Evidence for a phase transition from a hadron gas to a deconfined state of QCD matter has been found using lattice QCD calculations. Figure 2.6 shows the pressure, energy density and entropy density of hot QCD matter in thermal equilibrium at a temperature T . The graph indicates that at a certain critical temperature $T_c \approx 155$ MeV, a continuous shift is observed for all three thermodynamic quantities. This behaviour is taken as an indication of a phase transition, as the shift from a hadron gas to a deconfined state of QCD matter is accompanied by an increase in the number of thermodynamic degrees of freedom. Furthermore, the phase transition appears to be either a *crossover* or a second-order transition, as the slopes are continuous.

It should be noted that the results from lattice QCD correspond to a net baryon density⁴ of zero, as the theory breaks down at finite values of μ_B due to the well-known sign problem [25]. By combining lattice QCD calculations with other theoretical models, a rough approximation of the QCD phase diagram may be obtained, as is shown in Fig. 2.7. For $\mu_B \approx 0$, the transition from a hadron gas to a QGP is a smooth crossover, as described by lattice QCD. However, when the chemical potential is increased through compression of the nuclear matter⁵, a first-order transition is expected to occur instead. If this is indeed the case, there needs to exist a critical point in the diagram where the smooth crossover and the discontinuous first-order transition meet. While a precise measurement of the critical point is still an active area of theoretical and experimental investigation, it is generally agreed that close to the critical point, several QGP observables are expected to exhibit large fluctuations [27], which may be investigated to constrain its value.

⁴The net baryon density of QCD matter is usually expressed in terms of the baryon chemical potential μ_B .

⁵At sufficiently high baryon densities, the nuclear matter is expected to behave like the QCD equivalent of an electric superconductor, called a colour superconductor. This is predicted to occur naturally in neutron stars [26].

2.5 Properties of the Quark-Gluon Plasma

In the previous section, the onset of the QGP was motivated by the idea of asymptotic freedom, where α_s tends to zero and the strong interaction “vanishes”. This is not entirely true, as the quarks and gluons inside the QGP are still able to interact with each other. Instead, the use of the term *deconfinement* is preferred, as was done earlier. The term refers to the fact that the quarks and gluons are no longer restricted to a confined state inside a hadron, and are able to traverse the entire QGP volume. In fact, the quarks and gluons that make up the QGP will act as a collective medium, and its evolution is governed by relativistic hydrodynamics. This is explained in more detail in the next chapter.

Some properties of the QGP may be derived from theory. Firstly, Fig. 2.6 already showed that lattice QCD predicts a phase transition at $T \approx T_c$, meaning that the temperature of the QGP must be around or above this value. Secondly, it is possible to obtain an estimate of the medium’s transport properties by making use of a duality called the Anti-de Sitter/Conformal Field Theory (AdS/CFT) conjecture [28]. The duality, which is considered to be one of the most important breakthroughs in string theory, shows that there exists a correspondence between 5-dimensional Anti-de Sitter (AdS) space-time and conformal field theories in $3 + 1$ physical space-time. When applied to QCD, several problems may be solved perturbatively or even analytically, albeit under very idealised conditions. For example, the conjecture has revealed that the QGP is predicted to behave like an almost-ideal fluid, with a shear viscosity to entropy ratio lower than any other fluid known to exist [29]:

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi k_B} = 6.1 \times 10^{13} \text{ s K} \quad (2.5.1)$$

For reference, this is about a 12 orders of magnitude difference with the viscosity to entropy ratio of water and about 9 times smaller than that of superfluid helium. Furthermore, recent studies [30] have revealed that this value is not only a theoretical prediction, but also seems borne out by experimental measurements. This is why the QGP is sometimes referred to as “the most perfect liquid” in the Universe.

Chapter 3

Heavy-Ion Physics and Signatures of the Quark-Gluon Plasma

This chapter aims to provide a basic overview of the physics of high-energy, heavy-ion collisions. Massive ionised nuclei are accelerated, using large-scale particle colliders, to relativistic velocities before smashing into each other, resulting in the creation of vast amounts of lighter particles (see Fig. 3.1). In comparison to electron-positron or proton-proton collisions, the atoms used in heavy-ion collisions have a finite¹, non-negligible extension in space. This leads to several unique results and phenomena, which are not present in smaller collision systems. Furthermore, this chapter will go into more detail regarding aspects of the Quark-Gluon Plasma (QGP) that weren't discussed in the previous chapter. Most notably, a number of phenomena have been discovered in heavy-ion collisions which are regarded as characteristic signatures of the QGP, and are seen by many as evidence of the QGP's existence. The main results presented in this analysis may be connected to several of these signatures.

As this analysis is associated with the ALICE detector at the CERN Large Hadron Collider (see Chapter 4), most of the information and results discussed in this chapter focuses on Pb–Pb collisions. However, many of the key principles of heavy-ion collisions remain applicable to other collision systems such as Au–Au or Xe–Xe.

3.1 Timeline of a Heavy-Ion Collision

In heavy-ion physics, only the initial and final state of a heavy-ion collision, corresponding to the original ultrarelativistic nuclei and to the many hadrons and leptons seen in the detector, are observable. Any processes that take place in between these two states occur

¹Although protons too have a finite radius at $r_p \approx 0.8$ fm [31], this is considerably smaller than the radius of a typical lead nucleus ($r_{Pb} \approx 5.5$ fm [32]) in a heavy-ion collision.

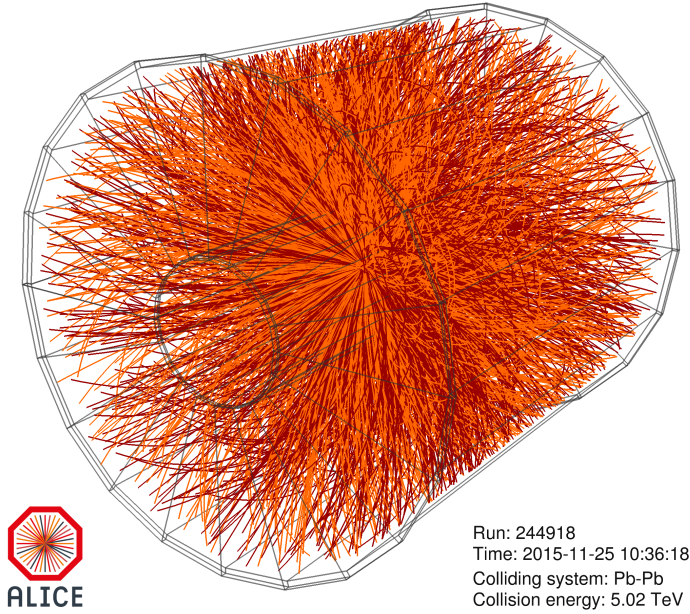


Figure 3.1 – Event display of a Pb–Pb collision at 5.02 TeV inside the ALICE detector. All coloured lines belong to individual tracks, giving an indication of the vast number of particles created in a heavy-ion collision. Figure is taken from [33].

over a timescale of order 10^{-23} s, making it impossible to observe them directly. Despite this, the evolution of the colliding medium may be predicted from theory to establish the “timeline” of a heavy-ion collision [34, 35], which can be divided into several stages. Each stage is marked by the proper time elapsed after impact ($\tau \equiv \sqrt{t^2 - z^2}$, expressed in fm/c) and their dynamics are largely determined by the system size and energy density at that point in time. In total, four distinct stages in the timeline of a heavy-ion collision can be identified which, in addition to the collision’s initial and final state, are summarized below and are presented graphically as a diagram in Fig. 3.2.

1. *Initial state*: Two ultrarelativistic nuclei approach each other at velocities $v \approx c$. The nuclei are heavily Lorentz-contracted, and resemble flattened “pancakes” with a diameter of about 14 fm and a thickness $\ll 1$ fm.
2. *Pre-equilibrium stage* ($\tau \leq 1$ fm/c): The two nuclei collide and their overlapping area (defined by the impact parameter b) forms a region of space with a tremendous energy density of approximately 12 GeV/fm³ [35], about 24 times the energy density inside a typical hadron. As such, the hadrons inside the overlapping area will break apart to form a state of matter consisting purely of quarks and gluons, which are so strongly coupled that they act as a collective medium. As the medium expands and cools, it will settle into an equilibrium phase, at which point it is identified as the Quark-Gluon Plasma.

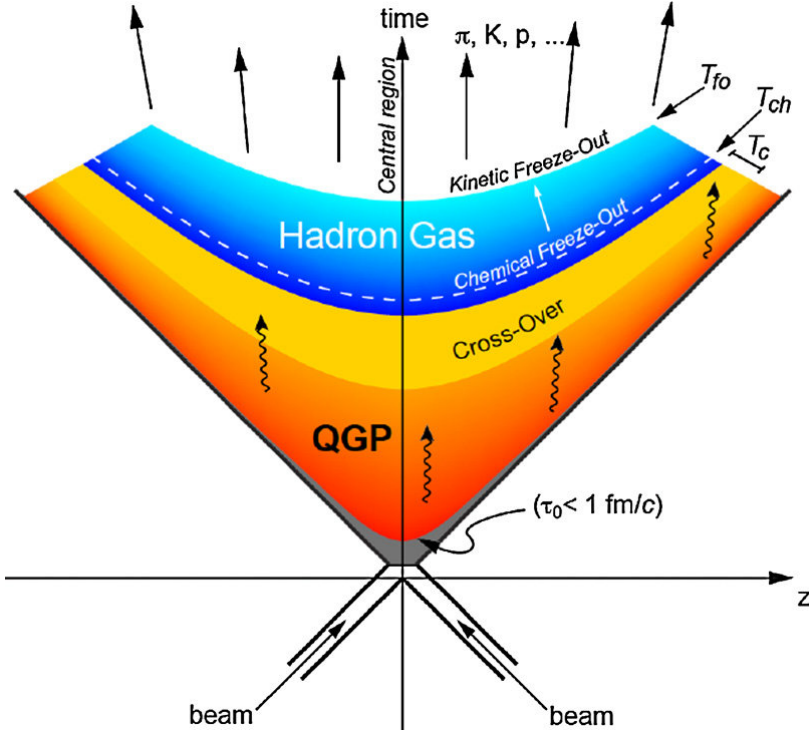


Figure 3.2 – Space-time diagram of a heavy-ion collision, showing the incoming beams and the stages of the collision timeline. The stages are coloured according to the temperature of their respective medium with exception of the pre-equilibrium stage, which is marked in grey. These temperatures are also listed in the top-right corner. The straight and wavy lines represent hadrons and thermal photons respectively, with the latter being radiated away by the hot QGP. Figure is courtesy of Boris Hippolyte and was taken from [36].

3. **Hydrodynamics stage** ($1 \leq \tau \leq 10 \text{ fm}/c$): As was mentioned in Section 2.5, the QGP acts as a near-perfect fluid with shear viscosity to entropy ratio $\eta/s \approx 1/4\pi$. Its evolution, therefore, is governed by relativistic hydrodynamics. A pressure gradient between the center and the outskirts of the QGP causes radial flow, leading to an initial isotropic expansion of the medium. However, additional pressure gradients in the QGP contain a directional dependence, resulting in flow that is not isotropic. Such anisotropic flow is caused by spatial anisotropies in the initial state, which occur when the collision is not head-on ($b > 0$). These spatial anisotropies are converted to momentum anisotropies via the hydrodynamic response (see Section 3.3.2).
4. **Chemical Freeze-Out** ($\tau \sim 10 \text{ fm}/c$): As the QGP flows and expands, its temperature will continue to decrease until it reaches $\sim 155 \text{ MeV}^2$. Around this temperature, known as the critical temperature T_c , a phase transition (crossover) will occur, transforming the QGP into a Hadron Resonance Gas (HRG). At this stage, the temper-

²Equivalent to $1.8 \times 10^{12} \text{ K}$, about 115 000 times the core temperature of the Sun.

ature is low enough to allow hadrons to be formed, but still high enough such that their internal composition may change through inelastic interactions. Shortly afterwards, the HRG reaches the temperature for *Chemical Freeze-Out* (T_{chem}), at which point the hadrons no longer interact inelastically and their composition is fixed.

5. **Kinetic Freeze-out** ($\tau \sim 20 \text{ fm}/c$): After chemical freeze-out, the hadrons are still able to interact, exchanging energy and momentum through elastic collisions. All the while, the HRG continues to expand and cool, becoming more and more diffuse in the process until the medium reaches the temperature for *Kinetic Freeze-Out* (T_{kin}). At last, the HRG has become so diluted that the hadrons are unable to interact with each other, at which point their kinetics are fixed.
6. *Final state*: The hadrons and leptons produced in the collision have ceased interacting with each other, and will continue to propagate outwards. Their energy and momentum, which were fixed during kinetic freeze-out, are recorded by the particle detector, along with a number of their other properties.

3.2 Geometry of a Heavy-Ion Collision

As was mentioned at the beginning of this chapter, the nuclei involved in heavy-ion collisions are composite objects consisting of many nucleons, and are far from point-like. Unlike electron-positron or proton-proton systems, the collisions between two heavy ions can be non-central or glancing, requiring the collision's geometry to be taken into account. In a glancing collision, only a select number of nucleons will actively participate in the event, namely those that fall within the overlap region between the two colliding nuclei. These nucleons are appropriately called the *participants* of the collision. Likewise, the nucleons that don't participate are known as *spectators*, with $N_{\text{part}} + N_{\text{spec}} = A_1 + A_2$. An example of the geometry of a heavy-ion collision is shown in Fig. 3.3.

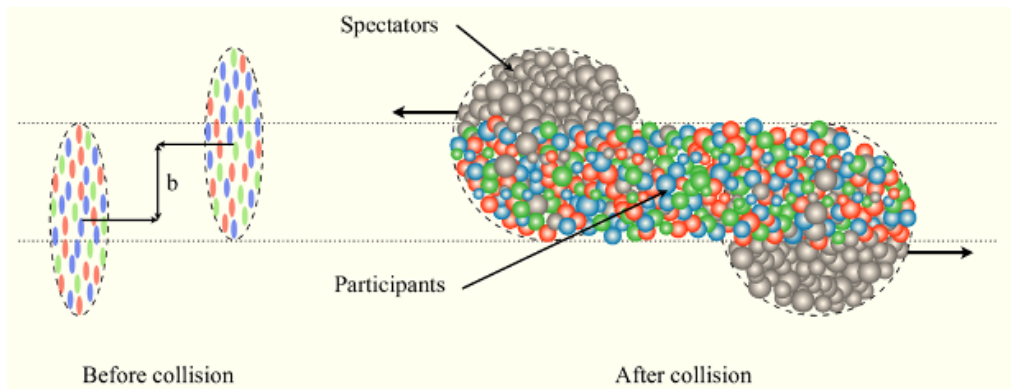


Figure 3.3 – Geometry of a heavy-ion collision, showing the impact parameter b between the two Lorentz-contracted disks as well as the participants and spectators moments after the collision has taken place. Figure is taken from [37].

The geometry of a collision between two spherical objects is determined by the impact parameter b , which is defined as the distance between the centers of both objects³. For spheres of radius R , the impact parameter can be $0 < b < 2R$. In practice, a collision's geometry is often defined in terms of the *event centrality*, which can be viewed as the ratio between the cross-sections belonging to the impact parameter and the radius of the sphere ($0\% < \frac{b^2}{4R^2} < 100\%$, with the lower and upper bounds referred to as central and peripheral⁴ events, respectively). In heavy-ion analyses, events are often grouped together according to their centrality (which itself is usually divided into several centrality classes) to study the dependence of physical observables on the system size and shape. However, the impact parameter and nuclear radius can't be measured directly, and the event centrality must instead be inferred from the event multiplicity through a process known as Monte-Carlo Glauber modelling, which is described below.

Monte-Carlo Glauber Modelling

Glauber modelling is a technique whereby the event centrality is estimated from measurements of the charged-particle multiplicity, using a Monte-Carlo (MC) approach to establish the relationship between the latter and the event geometry. The main idea behind MC Glauber modelling is simple, yet powerful. Namely, the model simulates the colliding nuclei in terms of the individual nucleons, where the position of each nucleon within the nucleus is randomly generated according to a nuclear density profile [39]. For nuclei consisting of many nucleons, like Pb and Au, the nucleus can be approximated as spherical, and the density profile follows the Woods-Saxon distribution

$$\rho(r) = \rho_0 \left(\frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)} \right). \quad (3.2.1)$$

Here, ρ_0 represents the nucleon density at the center of the nucleus, R corresponds to the nuclear radius, w characterizes any deviations from a spherical shape and a indicates the thickness of the nucleon skin. For Pb and Au nuclei, $R \approx A^{1/3}$ fm and $w \approx 0$.

Figure 3.4a shows an example of a MC Glauber simulation, highlighting the participant and spectator nucleons. In addition, the simulation keeps track of the total number of binary⁵ collisions that occur between nucleons (N_{coll}). In order to relate N_{part} and N_{coll} to the charged-particle multiplicity of an event (N_{ch}), the model assumes that the number of “ancestor” particles, which will decay to lighter particles to form N_{ch} , is given by [40]

$$N_{\text{ancestors}} = fN_{\text{part}} + (1 - f)N_{\text{coll}}, \quad (3.2.2)$$

³The nuclei in a heavy-ion collision are far from spherical, as they are heavily Lorentz-contracted along the beam axis. Nevertheless, their area perpendicular to the beam direction remains circular, and the impact parameter can be defined accordingly.

⁴For more information about the fascinating dynamics of *Ultra-Peripheral Collisions* (UPCs), where $b > 2R$, please refer to [38].

⁵A binary collision refers to a single encounter between a left- and right-moving nucleon.

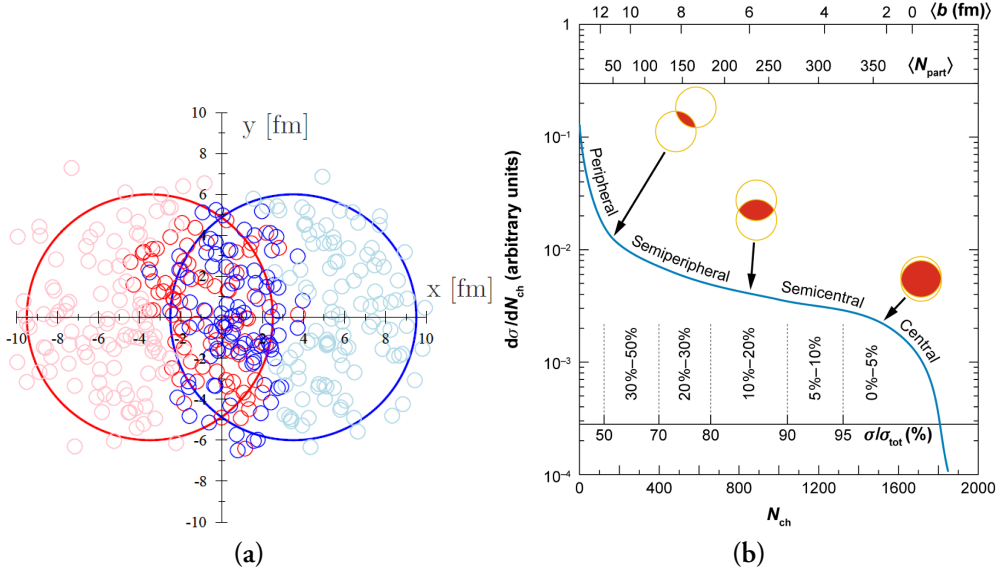


Figure 3.4 – Example of MC Glauber modelling. (a) shows a Glauber simulation of two colliding nuclei in the transverse plane. The participant and spectator nucleons are represented by dark and light circles, respectively. (b) shows a graph of the differential cross-section as a function of the charged-particle multiplicity. The distribution allows for a Glauber + NBD fit to be applied, indicating how the centrality classes are defined as fractions of the integrated area. Furthermore, the graph shows the geometry of the collision as well as $\langle b \text{ (fm)} \rangle$ and $\langle N_{part} \rangle$ for a given multiplicity. Figures are taken from [41] and [39].

where f is a fit parameter used to control the fractional contribution from processes that scale with N_{part} and N_{coll} . Furthermore, the number of particles that each ancestor is expected to decay to is governed by the Negative Binomial Distribution (NBD)

$$P_{\mu,\kappa}(N_{ch}) = \frac{\Gamma(N_{ch} + \kappa)}{\Gamma(N_{ch} + 1)\Gamma(\kappa)} \cdot \frac{(\mu/\kappa)^{N_{ch}}}{(\mu/\kappa + 1)^{N_{ch} + \kappa}}, \quad (3.2.3)$$

where μ is the mean multiplicity per ancestor and κ is a parameter that defines the width of the distribution, thereby controlling fluctuations to large multiplicity. Equations 3.2.2 and 3.2.3 are multiplied to yield the Glauber + NBD fit function, which can be applied to the charged-particle multiplicity distribution obtained from data. A cartoon example is presented in Fig. 3.4b, which also highlights the connection between initial-state quantities (b, N_{part}) and final-state observables (N_{ch}). Finally, the centrality classes are defined such that the centrality intervals (in percent) match the fractions of the integrated area (in percent) underneath the fit. For example, the 0–5% centrality class corresponds to the first 5% of the fit area, integrated from the right. Likewise, the 5–10% and the 10–20% classes indicate the next 5% and 10% of the fit area, and similarly for the other centrality classes.

3.3 Signatures of the Quark-Gluon Plasma

After the pre-equilibrium stage of a heavy-ion collision, the system settles into the QGP as the hydrodynamics stage takes over. While hot and dense, the medium will expand and cool rapidly, making the QGP very short-lived ($\sim 10 \text{ fm}/c$). Nevertheless, its presence in a heavy-ion collision is expected to have an influence on the final-state particles that are observed. Indeed, when compared to smaller collision systems⁶ such as pp or p-A, heavy-ion collisions have shown that a number of results behave differently in a way that can't easily be explained without requiring the QGP to play a major part. Below, three important results, which are seen as characteristic signatures of the QGP, are discussed in more detail.

3.3.1 Strangeness Enhancement

One of the earliest [43] proposed signatures of the QGP concerns the production of strange quarks inside the medium. Unlike the lighter quarks (up & down) and the gluons, there is no net strangeness brought into the reaction by the colliding nuclei, meaning that any strange hadron observed in the final state must have been “freshly” produced in the collision event. The production of quarks in a thermal medium predominantly occurs through gluon fusion, which is shown in Fig. 3.5.

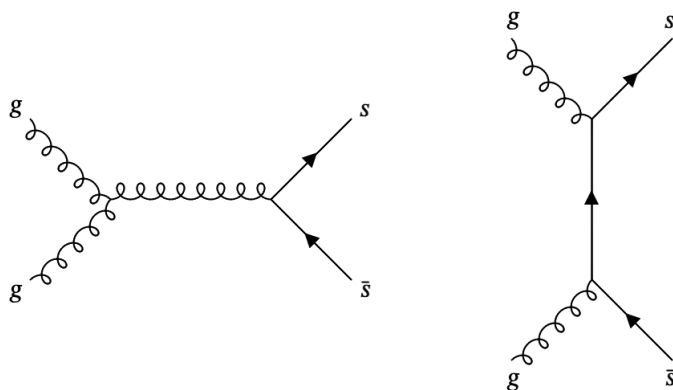
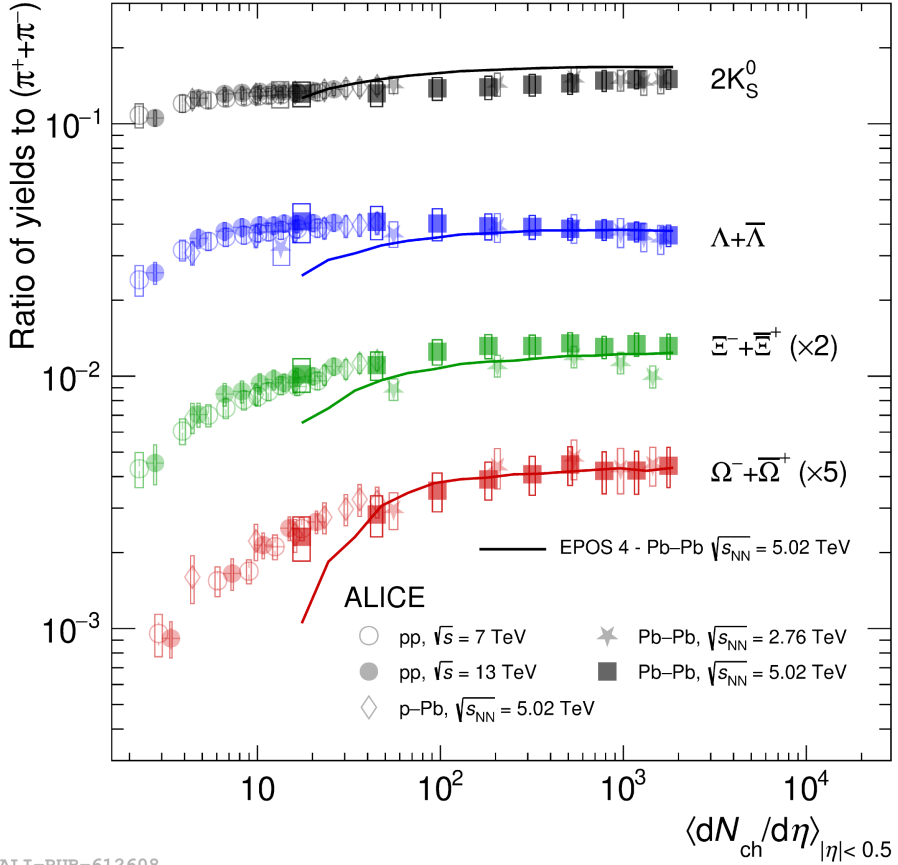


Figure 3.5 – Examples of tree-level Feynman diagrams showing gluon fusion, resulting in a strange quark-antiquark pair being produced.

In a hadron gas, the production of strange quarks would be suppressed in part due to its higher mass compared to the up and down quarks ($m_s = 93.5 \text{ MeV}/c^2$ versus $m_d = 4.7 \text{ MeV}/c^2$), but mostly because of the the high confinement energy required to form strange hadrons ($\sim 420 \text{ MeV}/c^2$ for charged kaons). For the QGP however, the decon-

⁶Experimental results [42] have indicated that the QGP may also be formed in smaller collision systems, which raises interesting questions about the minimum system size for which a droplet of QGP can still exist.



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Figure 3.6 – Graph showing the ratio of strange-hadron yields to the pion yield for various collision systems in ALICE, as a function of the average multiplicity density. The increase in the strange-to-pion ratio for Pb–Pb collisions compared to smaller collision systems is clearly visible. The solid lines correspond to predictions from EPOS 4. Figure is taken from [44].

finer nature of the medium eliminates the confinement energy requirement, allowing heavier quarks to be formed through gluon fusion so long as the temperature of the medium remains higher than the quark mass. As the QGP is an extremely thermal and gluon-dense medium, with a temperature $T_{\text{QGP}} \sim T_c \sim 155$ MeV, the production of strange quarks and antiquarks is expected to be enhanced, resulting in an increased number of strange hadrons and antihadrons being observed. Furthermore, for multi-strange hadrons (containing two or three strange quarks), the enhancement factor is expected to be even larger than for single-strange hadrons. This phenomenon, where an enhancement in the number of strange hadrons is observed, has appropriately been dubbed *strangeness enhancement*, and is thought to be an indication of the QGP's existence.

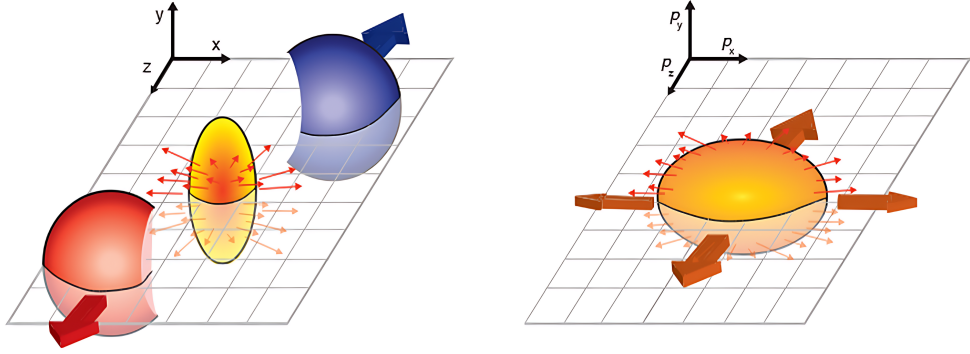


Figure 3.7 – Illustration showing anisotropic flow in a heavy-ion collision. The pressure gradient parallel to the reaction plane (defined by the two shortest symmetry axes of the overlap region) is the highest, causing the medium to expand the fastest in this direction. Figure is courtesy of Masashi Kaneta and Boris Hippolyte.

The increase in the strange content of the final-state particles has been confirmed by experiment. Figure 3.6 shows the ratio of strange hadron yields to pion yields in pp, p–Pb and Pb–Pb collision systems, recorded by the ALICE detector. The enhancement effect is clearly visible as the average multiplicity density moves from pp and p–Pb collisions to Pb–Pb collision systems. In addition, the enhancement factor is proportional to the strange content of the hadron, being much larger for Ξ (dss) and Ω (sss) compared to Λ (uds). Finally, the saturation of the strange-to-pion ratios at high multiplicities indicate that the medium formed in Pb–Pb collisions is in thermal and chemical equilibrium, as is the case for the QGP.

3.3.2 Anisotropic Flow

As was described in Section 3.1, the QGP evolves according to relativistic hydrodynamics once the system settles into equilibrium. The pressure inside the collision overlap region is immense, particularly compared to the vacuum outside, and the QGP will expand as a collective medium. If the collision between the nuclei was head-on ($b \approx 0$), the collision geometry would be close to spherical, and the medium would expand radially outward in an isotropic manner. This type of expansion is known as *radial flow*. However, it is far more likely for the nuclei to collide non-centrally, causing the overlap region to be elliptical or “almond”-like in shape as is shown in Fig. 3.7. Here, the overlap region is shorter along one symmetry axis than it is along the other, resulting in the pressure gradient along the shorter axis being much larger. The system will therefore expand faster in the direction of the short symmetry axis, leading to collective motion that is not isotropic and is thus named *anisotropic flow*.

The presence of (an)isotropic flow in the collision environment will be reflected in the azimuthal distribution of the final-state particles. By utilising a Fourier decomposition, the azimuthal distribution may be broken down into flow harmonics, allowing the effects of (an)isotropic flow to be quantified [45]:

$$\frac{dN}{d\varphi} \propto \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_n)) \right), \quad (3.3.1)$$

where Ψ_n is the symmetry plane angle for the n -th order flow harmonic and v_n are the flow coefficients, defined as $v_n = \langle \cos(n(\varphi - \Psi_n)) \rangle$. The first- and second-order flow harmonics correspond to *directed* and *elliptic flow* respectively, with the latter being closely related to the ellipticity of the overlap region in a non-central collision. Furthermore, higher-order flow harmonics like *triangular flow* (v_3) are generated by fluctuations in the positions of the nucleons inside the colliding nuclei, ensuring that anisotropic flow remains present even as collisions become more central.

Determining the flow coefficients directly from the particles' azimuthal distribution is impractical, as the symmetry plane angle Ψ_n is difficult to calculate on an event-by-event basis and may introduce a measurement bias [46]. Instead, the flow coefficients are usually obtained through the use of *multi-particle cumulants*, where azimuthal correlations are used to eliminate the dependence on the orientation of the symmetry plane. To demonstrate, the two-particle cumulant is defined as

$$\begin{aligned} \langle 2 \rangle &\equiv \langle e^{in(\varphi_1 - \varphi_2)} \rangle \\ &= \langle e^{in(\varphi_1 - \Psi_n - \varphi_2 + \Psi_n)} \rangle \\ &= \langle e^{in(\varphi_1 - \Psi_n)} e^{-in(\varphi_2 - \Psi_n)} \rangle \\ &\approx \langle e^{in(\varphi_1 - \Psi_n)} \rangle \langle e^{-in(\varphi_2 - \Psi_n)} \rangle \\ &= \langle \cos(n(\varphi_1 - \Psi_n)) \rangle \langle \cos(n(\varphi_2 - \Psi_n)) \rangle = v_n^2, \end{aligned} \quad (3.3.2)$$

Then,

$$c_n\{2\} = \langle \langle 2 \rangle \rangle \text{ and } v_n\{2\} = \sqrt{c_n\{2\}} = \sqrt{\langle v_n^2 \rangle}. \quad (3.3.3)$$

Here, single angular brackets indicate an averaging over all particles in a given event and double angular brackets correspond to an additional averaging over all events. In practice, Eqs. 3.3.2 and 3.3.3 are not entirely complete, as the correlators will be contaminated by short-range correlations originating from sources such as resonance decays and jet fragmentation. These *non-flow* effects will affect the value of $\langle v_n^2 \rangle$, and need to be suppressed in order to obtain an accurate estimate of the flow coefficients. This typically involves correlations between more than two particles, which are used to calculate additional higher-order cumulants. Further detail regarding the removal of non-flow can be found in [47].

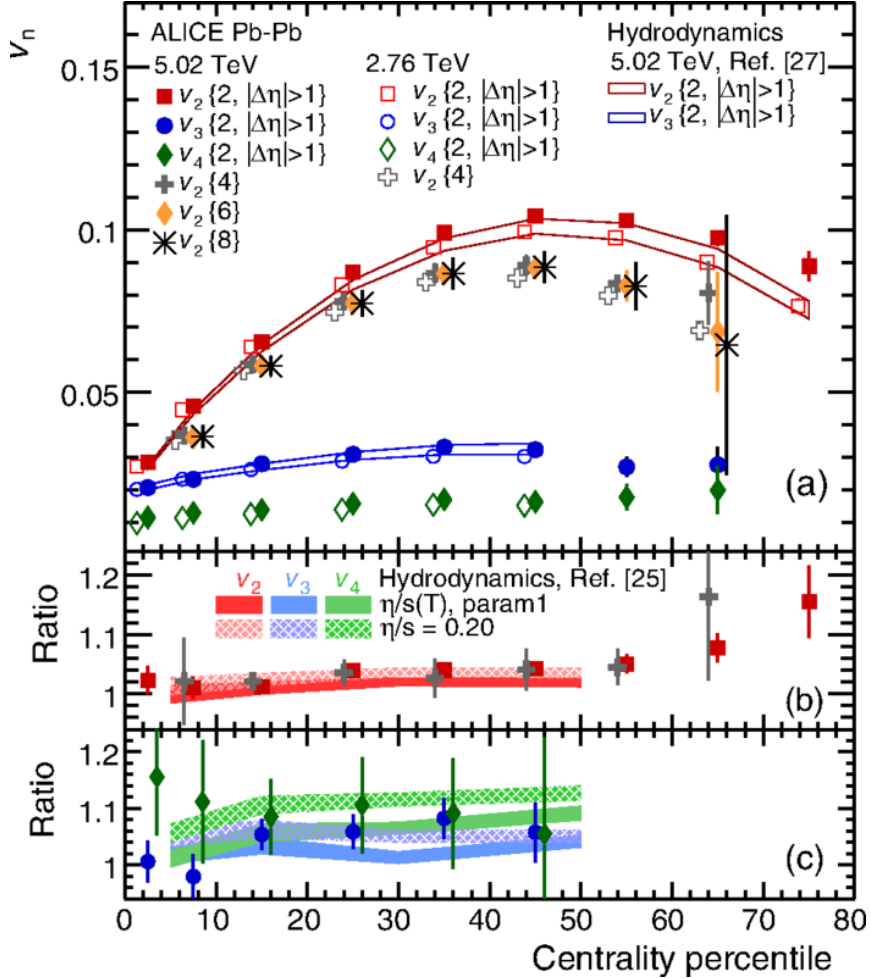


Figure 3.8 – Graph showing flow coefficients for Pb–Pb collisions in ALICE, as a function of centrality. Results from a hydrodynamical model are indicated by solid lines, which correctly predict the centrality dependence of $v_2\{2\}$ and $v_3\{2\}$. Figure is taken from [45].

Figure 3.8 shows the flow coefficients for elliptic (v_2), triangular (v_3) and quadrangular (v_4) flow recorded by ALICE, as a function of the collision centrality. All three flow coefficients are non-zero, indicating that anisotropic flow plays a considerable part in the evolution of the medium. Furthermore, $v_2\{2\}$ and $v_3\{2\}$ are well described by hydrodynamic calculations, strengthening the case for QGP formation in Pb–Pb collisions. The behaviour of $v_2\{2\}$ mirrors the expected shape of the overlap region, growing larger as the collision geometry becomes more elliptical until it reaches a maximum at around 50% centrality. At this point, the size of the medium becomes too small to effectively translate the geometric anisotropy into collective flow, and $v_2\{2\}$ starts to decrease. The values of $v_3\{2\}$ and $v_4\{2\}$ are much smaller in comparison and the centrality dependence is considerably weaker.

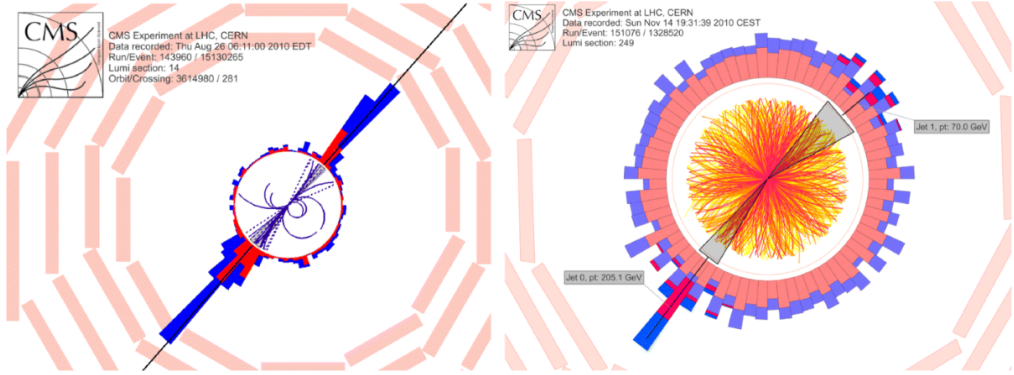


Figure 3.9 – CMS event display of a dijet event for pp (left) and Pb–Pb (right) collisions. In Pb–Pb, the energy of one of the jets is significantly lower than the other, despite the two appearing to have been emitted back-to-back. Figure is taken from [48].

3.3.3 Jet Quenching

In the context of high-energy physics, “jets” are among the most striking phenomena in the field, and have led to a domain of research that is entirely dedicated to understanding their properties. A jet is a collimated spray of hadrons that is produced in high-energy collisions when scattering occurs between partons (quarks & gluons) with high momentum. As the partons scatter, they will propagate away from the center of the collision while carrying the colour charge. Since coloured particles cannot exist in isolation due to colour confinement, the partons will quickly create other coloured objects around themselves to form a narrow cone of colourless hadrons.

What makes jets so interesting is that they act as internally-generated probes of the medium created in an event, as the scattered partons will have travelled through the collision environment before the system hadronises. For the QGP, this means that jets will lose energy and momentum due to the jet partons interacting with the QCD-dominated environment, an effect that is referred to as *jet quenching*. The energy and momentum loss can be seen very clearly in a dijet event, where two jets emerge from an event back-to-back due to momentum conservation. Figure 3.9 shows the comparison of a dijet event display between a pp and Pb–Pb collision in the CMS detector. The jets in the pp event have roughly equal but opposite momentum, whereas the Pb–Pb event displays a significant momentum asymmetry, indicating that the jet with lower momentum was quenched.

A relatively easy way of establishing if jet quenching occurred involves looking at the differential particle yields in a heavy-ion collision and comparing them to a known baseline. To this end, an observable called the *nuclear modification factor* is defined as [49]

$$R_{AA}(p_T) = \frac{1}{N_{\text{coll}}(\epsilon)} \frac{d^2 N^{AA}/dp_T dy}{d^2 N^{pp}/dp_T dy}, \quad (3.3.4)$$

where $N_{\text{coll}}(\epsilon)$ is the number of binary collisions for a given centrality ϵ , and $d^2 N^{AA}/dp_T dy$ and $d^2 N^{pp}/dp_T dy$ are the differential particle yields for nucleus-nucleus and proton-proton collisions, respectively. Since jets originate from a hard scattering event, they are the primary source of hadrons falling within the high- p_T range of the particle spectra. If no jet quenching occurred due to a lack of QGP formation, the spectrum of a nucleus-nucleus collision is expected to be comparable to that of a proton-proton collision after a trivial scaling by N_{coll} , and $R_{AA} \approx 1$. However, any non-trivial modification of the collision environment will be reflected in the high- p_T tail of $d^2 N^{AA}/dp_T dy$, such that $R_{AA} \neq 1$. The latter result can clearly be seen in Fig. 3.10, implying a non-trivial modification of the collision environment compared to proton-proton collisions.

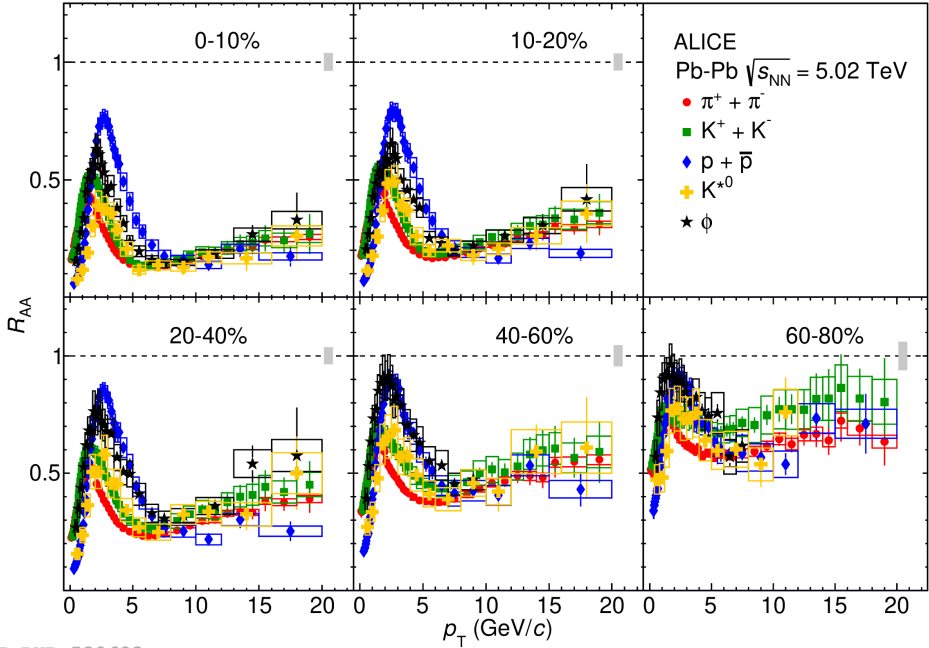


Figure 3.10 – Graph showing the nuclear modification factor R_{AA} belonging to different particle species at various centrality classes for Pb–Pb collisions in ALICE, as a function of p_T . Figure is taken from [50].

Part II

Experimental Setup & Methodology

Chapter 4

The Large Hadron Collider & the ALICE Detector

This chapter will cover the central experimental apparatus of the analysis. The apparatus in question is the ALICE detector, which is a part of the Large Hadron Collider (LHC) located at CERN. ALICE is one of the four main experiments at the LHC, and is specifically designed to study high-energy, heavy-ion collisions. These collisions form an environment of extremely high temperature, density and pressure, mimicking the state of the universe seconds after the Big Bang. It is in this environment that the Quark-Gluon Plasma, discussed in the previous chapter, is expected to be formed. The chapter will start with a brief introduction to the LHC and its main experiments before covering the ALICE detector and describing, in further detail, several of its detector subsystems.

4.1 The CERN Large Hadron Collider

The European Organization for Nuclear Research, abbreviated as CERN¹, is the world's leading institute in particle and nuclear physics. The organization was founded in 1954 by twelve European countries, and marked a collaborative effort to establish a laboratory dedicated to the study of high-energy physics and atomic nuclei. Over the years, the collaboration has allowed for a research infrastructure far greater than could be achieved by a single country. Research performed at CERN has proven to be instrumental in both particle and computer science, examples of which are the discovery of the $W^\pm$, Z^0 and H bosons, the creation of antimatter atoms and the invention of the World Wide Web for sharing information on a global scale. Today, CERN is made up of 24 member states and allows for international collaboration between more than 12 000 scientists from institutes in over 70 countries.

¹The abbreviation comes from the French translation: *Conseil Européen pour la Recherche Nucléaire*.

The CERN accelerator complex *Complexe des accélérateurs du CERN*

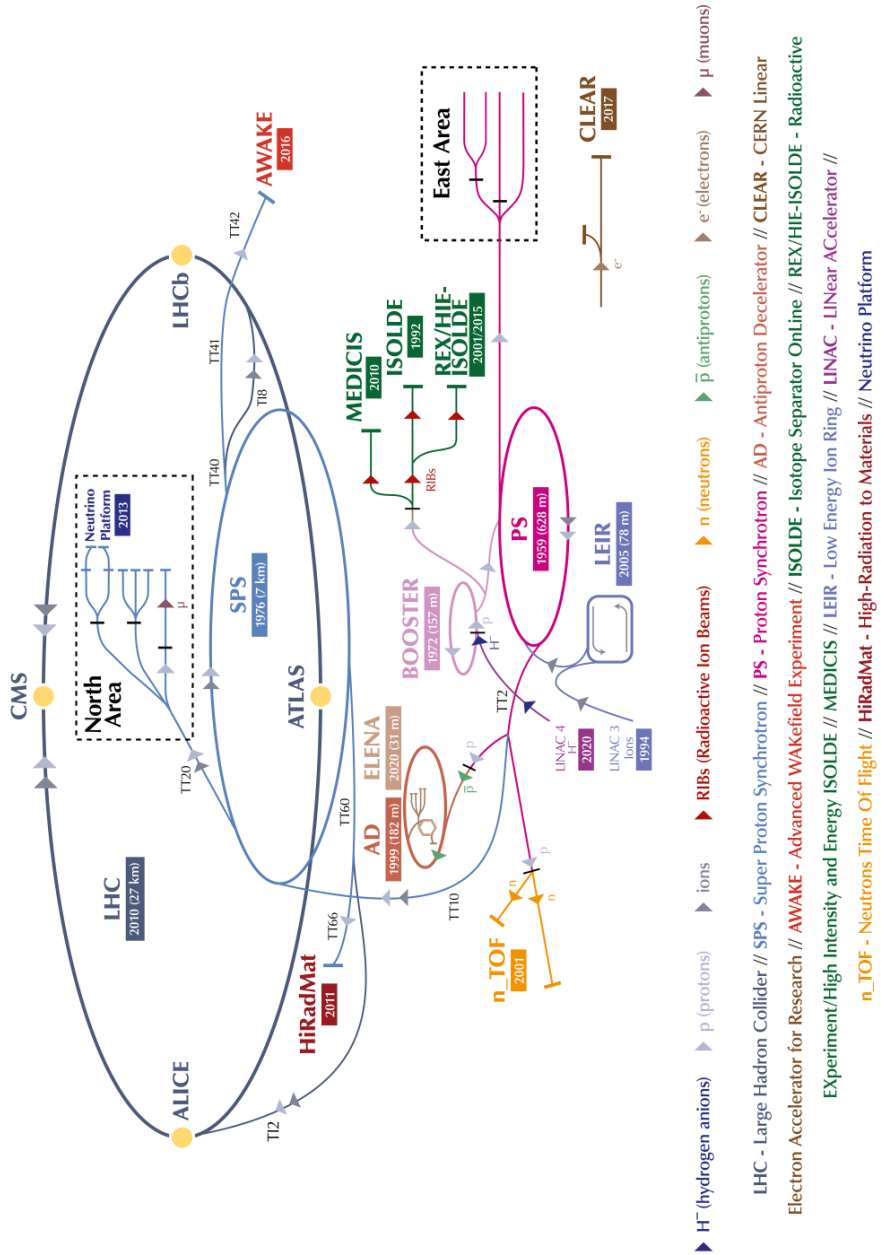


Figure 4.1 – Diagram showing the full CERN accelerator network, along with the four main LHC experiments. Figure is taken from [51].

The Large Hadron Collider (LHC) is currently² the highlight of CERN’s long list of achievements, and holds the distinction of being both the most powerful particle accelerator and the largest single machine in the world [52]. The LHC is a circular accelerator with a circumference of approximately 27 km, placed inside an underground tunnel located about 100 m below the region near the CERN site. The collider itself consists of two beam pipes, surrounded by a total of 1232 superconducting dipole magnets that provide a uniform magnetic field along the ring. Particles with equal but opposite charge can then travel in opposite directions through each beam pipe. In addition to the dipole magnets, quadrupole and higher multipole magnets are employed for focusing the particles together into narrow bunches, as well as providing minute corrections to the beam trajectories.

The acceleration of charged particles in the LHC to relativistic velocities occurs in several stages, where smaller linear and circular accelerators are used at each stage to form an accelerator network. A schematic overview of this network is shown in Fig. 4.1. After being stripped of their electrons, the ionised particles are accelerated to an energy of 2 GeV using the *LI*Near *AC*celerator 4 (LINAC 4) and the *Proton Synchrotron Booster*. Afterwards, the particles pass through the *Proton Synchrotron* (PS) and the *Super Proton Synchrotron* (SPS), reaching a total energy of 450 GeV before being injected into the main collider. For most of the year, the LHC runs collisions in pp systems, reaching a total center-of-mass energy of $\sqrt{s} = 13.6$ TeV. Occasionally, heavier collision systems, such as p–Pb at $\sqrt{s_{\text{NN}}} = 8.16$ TeV or Pb–Pb at $\sqrt{s_{\text{NN}}} = 5.36$ TeV, are studied instead.

At four locations in the accelerator ring, the two beam pipes are joined together into a junction point, allowing the particle beams travelling in the clockwise and counter-clockwise directions to collide. It is at these junction points where large-scale particle detectors, corresponding to the main experiments of the LHC, are stationed. In addition to ALICE, the LHC has three other large-scale particle detectors:

- **ATLAS** (*A Toroidal LHC ApparatuS*) [53]: the first of two general-purpose detectors and the largest experiment at the LHC. ATLAS is used for studying a wide range of physics, including the Higgs boson and dark matter.
- **CMS** (*Compact Muon Solenoid*) [54]: the second general-purpose detector, albeit with a different technical design compared to ATLAS. CMS focuses on much the same physics as its “brother”, including the discovery of the Higgs boson, which was made independently at the same time as ATLAS.
- **LHCb** (*Large Hadron Collider beauty*) [55]: the smallest of the four experiments. LHCb aims to perform precise measurements on the “bottom” (*b*) quark to find evidence for CP violation, which may have led to the large matter-antimatter asymmetry that is observed in the universe.

²Construction of the successor to the LHC, currently named the *Future Circular Collider* (FCC), is planned to begin in 2030.

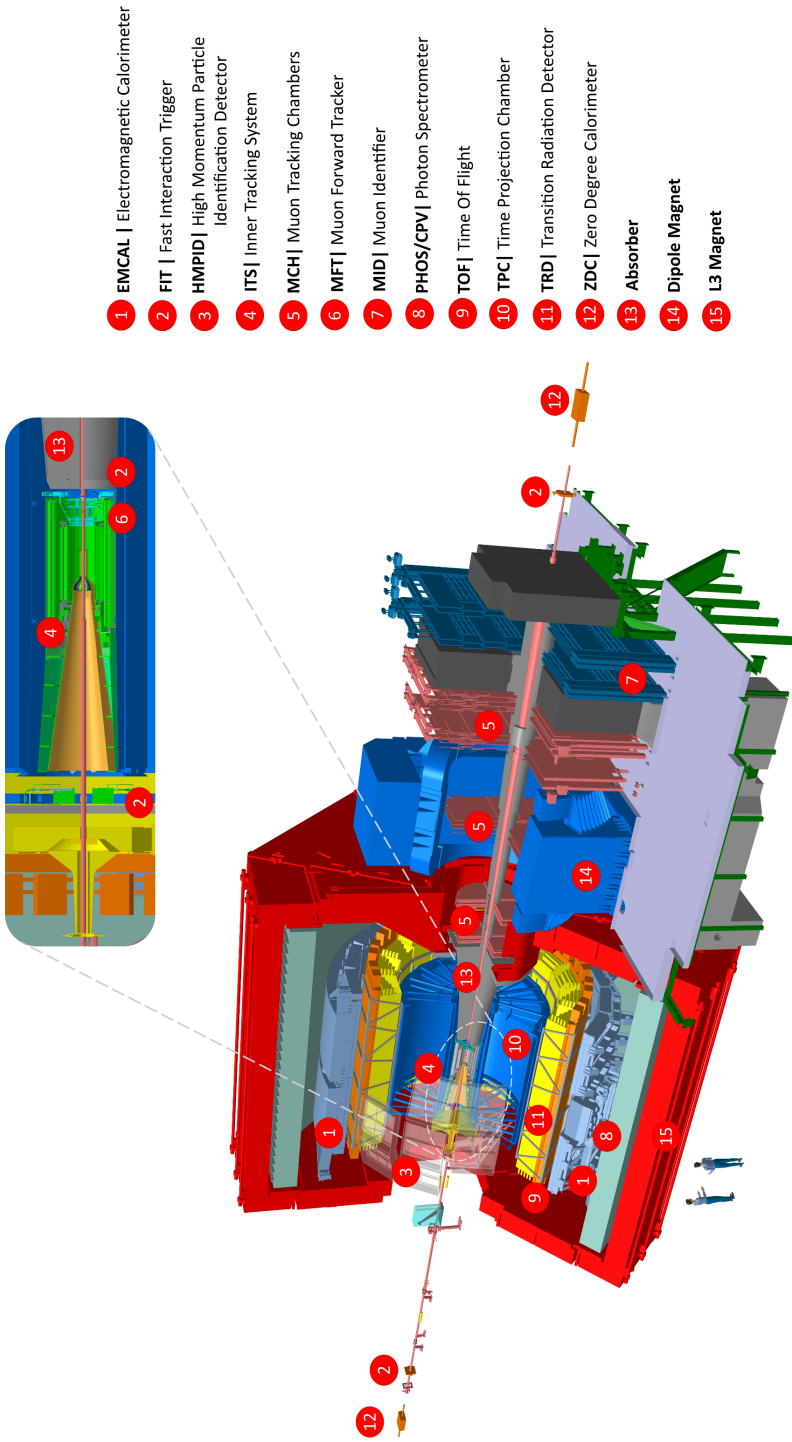


Figure 4.2 – Illustration of the full ALICE detector, showing a cross-section of the apparatus. Figure is taken from [56].

4.2 The ALICE Detector

ALICE (*A Large Ion Collider Experiment*) [57] is the fourth detector at the LHC, with its primary goal being the study of the QGP state of matter. Whereas ATLAS, CMS and LHCb were built with the intention of recording pp collisions, ALICE instead focuses on studying high-energy, heavy-ion collisions where the QGP is expected to be formed. The presence of the QGP will influence the dynamics of the particles produced in such collisions, which carries over to ALICE's measurements of the final-state hadrons and leptons. The focus on heavy-ion collisions over pp collisions places strong constraints on the design of the detector. A Pb–Pb collision at $\sqrt{s_{NN}} = 5.36$ TeV will have an average charged-particle multiplicity density of $\langle dN_{ch}/d\eta \rangle \approx 2000$ for central collisions, which is significantly larger than for a pp collision ($\langle dN_{ch}/d\eta \rangle \approx 10$ for $\sqrt{s} = 13.6$ TeV) [58]. As the characteristics of the QGP are reflected in the final-state position and momentum of each particle, the identification and characterization of each particle track needs to be as accurate as possible. As such, the ALICE detector is capable of achieving a very high spatial resolution and tracking efficiency, particularly for particles at low p_T .

A detailed cross-section of the ALICE detector is shown in Fig. 4.2. The entire detector has dimensions of $16 \times 16 \times 26$ m³ and weighs approximately 10 000 tonnes. It consists of a central barrel, covering a polar angle from 45° to 135° , combined with forward muon spectrometers for detecting outgoing muons at angles between 2° and 9° from the beam-line. The central barrel is embedded in a large solenoid magnet that was previously used in the L3 experiment, providing a uniform magnetic field of $B = 0.5$ T. The forward spectrometers are positioned to the right³ of the central barrel, and employ a dipole magnet with $B = 0.67$ T for bending the muons away from the interaction point. Both the barrel and the forward spectrometers house a number of smaller detector systems, which can be grouped together based on the function that they perform:

- **Tracking:** The central barrel includes a number of tracking detectors, which are placed in close proximity to the interaction point. The first is the *Inner Tracking System* (ITS), which is primarily used to localize the collision vertex and to track particles with a momentum lower than 200 MeV/c. It also assists in the tracking performed by the *Time Projection Chamber* (TPC), which is ALICE's main tracking detector and is capable of tracking particles with p_T ranging between 0.1 GeV/c to 100 GeV/c. Finally, the central barrel includes the *Transition Radiation Detector* (TRD), which assists in the tracking of electrons and positrons above 1 GeV/c by measuring their transition radiation.
- **Particle identification:** In addition to tracking, the ITS, TPC and TRD also provide a means of particle identification by measuring the specific energy loss of a particle as it travels through each detector. These measurements are complemented by ALICE's other dedicated identification detectors, these being the *Time-of-Flight* (TOF) detector and the *High-Momentum Particle Identification Detector* (HMPID). The former works in tandem with the ITS and TPC to identify particles up to about 1 GeV/c, while the latter covers the momentum range above this threshold.

³As seen from Fig. 4.2. The left and right sides of the detector are known as “A” and “C”, respectively.

- **Calorimetry:** As the environment created in heavy-ion collisions has an extremely high temperature, it will radiate away part of its energy in the form of photons. Furthermore, particle jets created in the collision will traverse the environment before fragmenting into hadrons. Both of these processes retain information about the QGP, and can be used to ascertain its thermal and dynamical properties. For this reason, the ALICE detector employs the *PHoton Spectrometer* (PHOS) and the *ElectroMagnetic CALorimeter* (EMCAL) for recording the energy carried by electromagnetic particles as well as jets.
- **Forward detectors:** The ALICE detector makes use of a number of detectors that are placed parallel, rather than perpendicular, to the beam direction. The forward FV0 and FT0 detectors, part of the *Fast Interaction Trigger* (FIT), are positioned closest to the interaction point, and are used for multiplicity estimation and generating a reference time (T0) for the TOF. By contrast, the *Zero Degree Calorimeter* (ZDC) is placed outside the central barrel, and measures the energy carried by spectators in a collision to provide a reference for the number of participating nucleons. Finally, a large muon spectrometer is placed on the C-side of the detector for recording muons, mainly coming from the decay of heavy vector mesons produced in the collision.

For the remainder of this chapter, the detector subsystems that have been the most relevant for this analysis will be discussed in more detail. For a dedicated description of all detector subsystems, please refer to [57].

4.3 The FIT Detector and the FT0 System

The Fast Interaction Trigger (FIT) is one of ALICE's aforementioned forward detectors, designed to detect collision products with large longitudinal momentum. As its name implies, the FIT is an event-trigger system whose primary purpose is to provide triggers for selecting minimum-bias events in ALICE collisions. In addition, the FIT is able to determine the background and luminosity of the particle beam in real time. Finally, the FIT is used for characterizing events by measuring their multiplicity and their collision time, as well as by providing an initial indicator for the collision vertex position. A schematic overview of the FIT detector is shown in Fig. 4.3. The figure indicates that the FIT detector actually consists of three subdetector systems, these being the FV0, the FT0 and the FDD. Furthermore, the FT0 and the FDD come in pairs, such that one of each detector is present at both the A-side and the C-side of ALICE.

While all three FIT subdetectors have been relevant for the data-taking of Pb–Pb collisions in ALICE, the FT0 system has been of particular importance for this analysis, and will be discussed in further detail. The FT0 consists of a pair of Cherenkov arrays which, as was mentioned earlier, are placed on both sides of the central barrel (FT0-A & FT0-C). The arrays themselves are made up of individual modules, which in turn consist of four quartz Cherenkov radiators that are each connected to a photomultiplier tube. As is shown in Fig. 4.3, the FT0-A and FT0-C contain $24 + 28 = 52$ modules, amounting to a total of 208 quartz radiators. The Cherenkov-based design of the FT0 allows for measurements

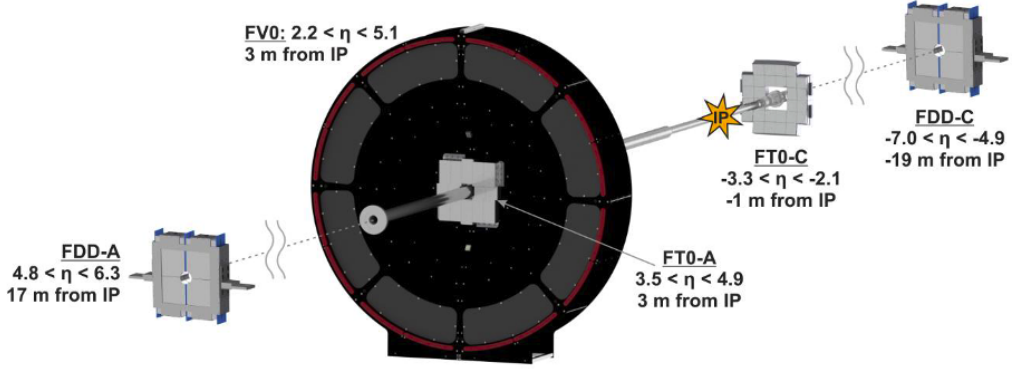


Figure 4.3 – Schematic overview of the FIT system. The figure shows the three detector systems that make up the FIT, together with their pseudorapidity coverage and their distance from the interaction point (IP). Figure is taken from [59].

of an event's collision time (T_0) to an outstanding accuracy, reaching a time resolution of ~ 4.4 ps in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV [60]. The T_0 parameter is of critical importance for the functioning of the Time-of-Flight (TOF) detector. Furthermore, it can be used for determining the location of the primary vertex, the results of which have been found to be in good agreement with measurements made by the Inner Tracking System (ITS) [59].

Another important function of the FT0 is determining the centrality of an event, which is achieved by measuring the forward charged-particle multiplicity. This measurement is then compared to the results from a MC Glauber + NBD fit, which relates the signal amplitude of the FT0 to the corresponding centrality class. This process was described in Chapter 3 and is illustrated again in Fig. 4.4, which shows the Glauber + NBD fit applied to the FT0-C amplitude distribution. It should be noted that both the FT0-A and FT0-C contribute to the determination of the event centrality, and the final result is typically calculated by taking the sum of both measurements⁴. For this analysis however, only the centrality determination made by the FT0-C was used, as the FT0-A has been known to become saturated in Pb–Pb collisions [61]. As such, all centrality-dependent results shown in this thesis were obtained using the centrality determination belonging to FT0-C.

4.4 The Inner Tracking System

The Inner Tracking System (ITS) is ALICE's innermost detector, making it the first detector that particles pass through as they move outwards from the collision. As was mentioned earlier, the ITS serves a number of purposes. These include tracking and identification of particles with low momentum, determining the location of the primary vertex, reconstructing any secondary decay vertices and improving the tracking resolution of the Time

⁴The combination of FT0-A and FT0-C is referred to as FT0-M.

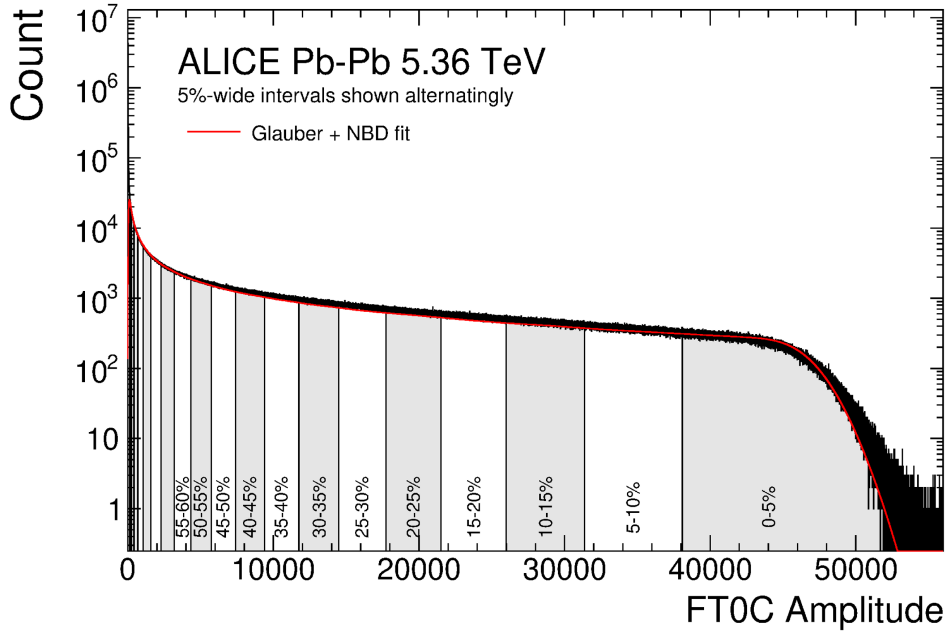


Figure 4.4 – Distribution of the FT0C signal amplitude in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV. The intervals showing the different centrality classes are indicated, and are determined by the Glauber + NBD fit. Figure is taken from [60].

Projection Chamber. The current version of the ITS, known as ITS2 [62], replaced the previous version of ITS during the LHC’s Long Shutdown 2 (LS2), and is the version discussed below.

A schematic overview of the ITS2 is shown in Fig. 4.5. The detector [63] makes use of 192 silicon staves, amounting to a total of 12.5×10^9 pixels, that run parallel to the beam direction. The staves are placed such that they form seven cylindrical layers of silicon-based sensors, which are positioned concentrically around the beam pipe at radii ranging from 23 mm to 400 mm. The seven layers are broken up into three Inner Layers (IL), two Middle Layers (ML) and two Outer Layers (OL), containing 48, 54 and 90 staves of length 27 cm, 84 cm and 150 cm, respectively. In total, the seven layers provide a total measurement area of 10 m² and allow for a pseudorapidity coverage of $|\eta| < 1.22$.

Unlike the original ITS, where each layer used a different design for its silicon sensors, the ITS2 uses a single type of silicon chip, called the ALPIDE (ALICE Pixel Detector) chip, for all its layers. ALPIDE is a Monolithic Active Pixel Sensor (MAPS), meaning that the chip’s sensor and readout electronics are placed on the same silicon substrate. Several of ALPIDE’s characteristics are summarized in Table 4.1. Compared to the sensors used in the original ITS, the ALPIDE chip offers a significant improvement in power consumption, radiation tolerance, material budget and position reconstruction, with the latter reaching an impressive 5 μm in spatial resolution [62].

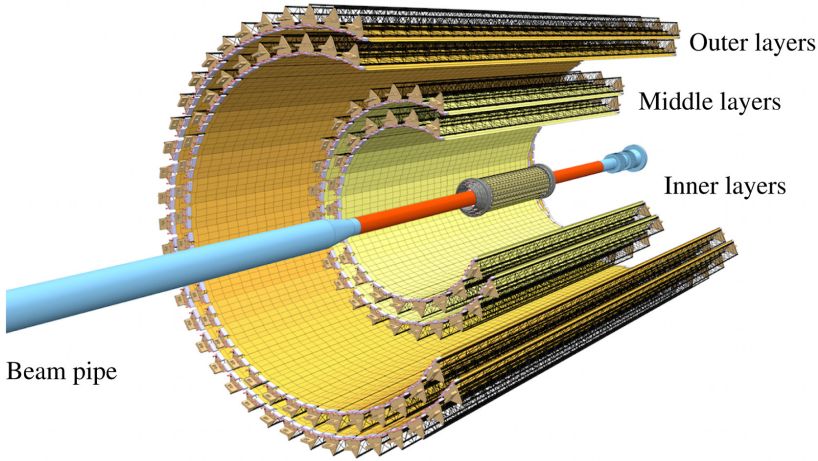


Figure 4.5 – Illustration of the ITS2, showing the silicon staves which make up the seven layers of the detector. Figure is taken from [63].

Table 4.1 – ALPIDE pixel-chip characteristics. Here, TID and NIEL stand for Total Ionising Dose and Non-Ionising Energy Loss, respectively. Table is taken from [63].

Parameter	Value
Chip dimensions	15 mm $\times$ 30 mm ($r\varphi \times z$)
Spatial resolution	5 μ m
Detection efficiency	> 99%
Fake-hit rate	$\ll 1 \times 10^{-6}$ /event /pixel
Power density	< 40 mW/cm ²
TID radiation hardness	> 270 krad
NIEL radiation hardness	> 1.7×10^{12} 1 MeV n_{eq} /cm ²

ITS Upgrade

During the LHC’s fourth run, which is slated to begin in 2030, the ALICE detector is planned to make use of an upgraded version of ITS2, appropriately named ITS3 [64]. The upgrade, which is planned to be installed during Long Shutdown 3 (LS3), is currently in active development, and features a unique and innovative new design for the detector based on wafer-scale silicon sensors. Here, the sensors that make up the layers are just 50 μ m thick, and are curved in such a way that together, they form a truly cylindrical layer of silicon material. This results in a significant (80%) reduction of the material budget, as no supporting staves or circuit boards will be necessary within the active measurement area. In addition, the lack of mechanical support allows the layers to be moved closer to the interaction point at just 2 mm from the beam pipe. Thanks to these changes, the ITS3 is expected to have its spatial resolution improved by a factor of 2, as well as higher efficiency for tracking particles with low-momentum [65].

4.5 The Time Projection Chamber

Following the ITS, the next detector that particles pass through as they move outwards is the Time Projection Chamber (TPC). This is ALICE's main detector for resolving the trajectories of charged particles created in a collision. Furthermore, the TPC provides the means of discerning a tracked particle's species by measuring its average specific energy loss $\langle dE/dx \rangle$, which is characteristic for particles of the same type at a given momentum. Since ALICE was built with the intention of studying heavy-ion collisions, the TPC was designed to cope with the high charged particle multiplicities that are expected to be present. Even at multiplicity densities of $dN_{\text{ch}}/d\eta = 8000$, corresponding to roughly 20 000 tracks in a single Pb–Pb interaction, the momentum and dE/dx resolution of the TPC remain good, which contributes to ALICE having the best tracking ability of the experiments at the LHC [66, 67]. Similarly to the ITS, the TPC underwent an upgrade during LS2, and is the version of the TPC discussed in this section.

Figure 4.6 shows a schematic overview of the TPC. The detector [68] takes the form of a hollow cylinder with an inner radius of 0.8 m, an outer radius of 2.5 m and a length of 5 m. The inner and outer radii correspond to the inner and outer field cages, respectively. The empty space inside the cylinder is filled with a Ne–CO₂–N₂ gas mixture, which is referred to as the *drift gas*. In addition, a large central electrode is placed inside the cylinder, splitting the detector in two halves which, like the FT0, are labelled by their respective sides of the detector (“A” and “C”). When operated at a voltage of 100 kV, the central electrode produces an electric field of strength 400 V/cm, which points away from the center of the detector along the beam pipe and is restricted to the inside of the cylinder thanks to the inner and outer field cages.

When a charged particle passes through the TPC, it will ionise the drift gas inside the detector. The liberated electrons are accelerated by the longitudinal electric field provided by the central electrode, and will drift towards the A-side and C-side of the TPC. Here, each endcap of the cylinder is divided into 18 trapezoidal sectors, which themselves consist of one Inner Readout Chamber (IROC) and one Outer Readout Chamber (OROC). Additionally, the latter is segmented into three stacks, labelled OROC1, OROC2 and OROC3. As the electrons are liberated in the vicinity of the traversing charged particle, they will drift in a straight line towards the end of the detector, creating a two-dimensional (r, φ) projection of the traversing particle's trajectory onto the ROCs. This can then be extended to a full three-dimensional (r, φ, z) reconstruction by combining the arrival time and the known drift velocity of the liberated electrons to calculate the path of the traversing particle along the z -axis. The three-dimensional track reconstruction, along with the total amount of charge deposited onto the ROCs, allows the TPC to determine a particle's momentum and $\langle dE/dx \rangle$, which gives insight into the particle's identity.

A crucial aspect of the TPC, particularly of the ROCs, is the conversion from individual drift electrons to a readable electronic signal. For this reason, the ROCs consist of Gas Electron Multipliers (GEM), which replaced the original Multi-Wire Proportional Chamber (MWPC) design during the LS2 upgrade. Near the GEM stacks, which act as the anode to the central electrode's cathode, the magnitude of the electric field is the highest, result-

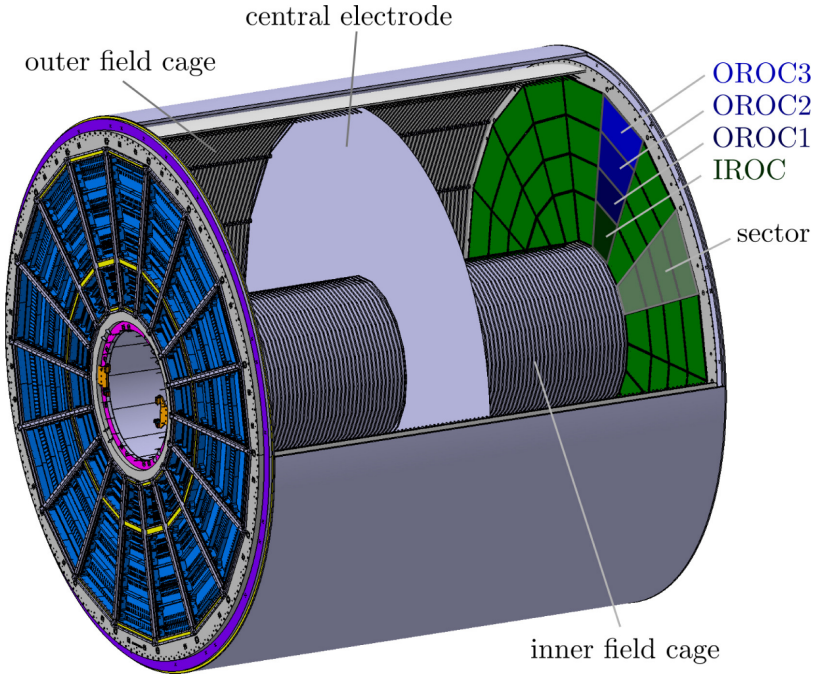


Figure 4.6 – Schematic overview of the TPC, showing the central electrode, the inner and outer field cages and the Readout Chambers (ROCs) on the circular surface of the detector. Figure is taken from [67].

ing in the liberated electrons gaining enough energy to liberate other electrons in the drift gas. This gives rise to a chain reaction of secondary ionisations, a phenomenon known as *avalanche multiplication*. The biggest advantage of using GEM stacks over a MWPC based system is the absence of a gating grid, which was necessary for minimising distortions in the readout signal caused by ion backflow from the amplification system [67]. Without the grid, the TPC is able to operate continuously, increasing the detector's previous readout rate from a few kHz during Run 2 to 50 kHz during Run 3, matching the expected interaction rate of Pb–Pb collisions in the LHC.

4.6 The Time-of-Flight Detector

After the ITS, the TPC and the TRD, the final-state products of the collision arrive at the Time-of-Flight (TOF) detector. Unlike the ITS and TPC, which were designed primarily as tracking detectors, the TOF is a fully dedicated Particle Identification (PID) device. As its name suggests, the detector aims to perform highly accurate [69] measurements of a particle's time of flight, from the interaction point where it is created to the TOF layer inside the central barrel where it is measured. The time of flight can be used to

derive a particle's velocity which, when plotted against the particle's momentum⁵, gives a characteristic distribution for identical particles, similar to the TPC's measurement of the specific energy loss. Together with the TPC, the TOF forms the core of this analysis' PID strategy for long-lived particles, which will be described in Chapter 5.

Located inside the central barrel, the TOF [70, 71] possesses a pseudorapidity coverage of $|\eta| < 0.9$ and is positioned at a distance of approximately 3.8 m from the interaction point. The detector is made up of trapezoidal arrays placed concentrically around the beam pipe, with each array covering $1/18^{\text{th}}$ of the full azimuth. Along the z-axis, five layers of arrays are placed back-to-back for a total of $18 \times 5 = 60$ trapezoidal arrays, amounting to a total measurement area of 141 m^2 . Each array consists of between 15 and 19 strips of Multigap Resistive Plate Chambers (MRPCs), which are gaseous detectors known for their high detection efficiency and excellent time resolution. In total, the TOF makes use of 1593 MRPCs distributed across the 60 arrays that form the detector. A cross-section of an MRPC strip used in the TOF is shown in Fig. 4.7.

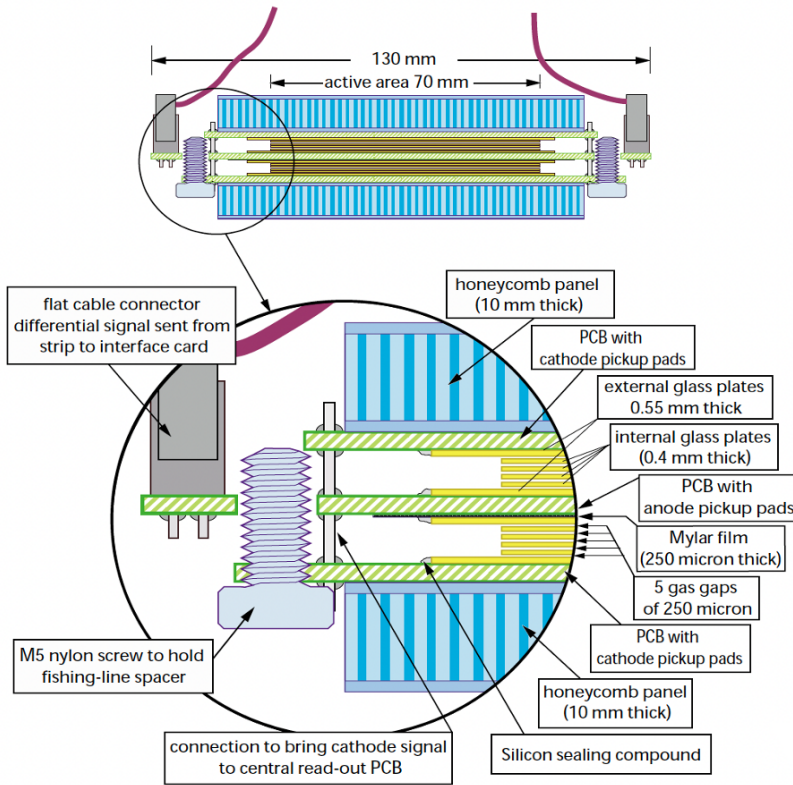


Figure 4.7 – Cross-section of a single MRPC detector strip, which make up the trapezoidal arrays that together form the ALICE TOF. Figure is taken from [72].

⁵Obtained from the track reconstruction performed by the TPC

Each strip consists of two stacks of five resistive plates, which take the form of commercially available soda-lime glass sheets. The stacks are placed between two cathodes positioned at the top and bottom of the MRPC, and are separated by an anode running down the center of the strip. Between each plate, fishing line is stretched across the glass sheets to create gaps of width $250\text{ }\mu\text{m}$, which are filled with a gas mixture containing $\text{C}_2\text{H}_4\text{F}_4$, $\text{i-C}_4\text{H}_{10}$ and SF_6 . The field applied between the anode and the cathodes is strong enough to induce avalanche multiplication when a charged particle passes through and ionises the gas. The electrons are then picked up by the anode to produce a signal. The purpose of the glass plates is to act as blockades for the electron avalanches to reduce the time jitter, which scales with the propagation distance. Using the MRPC design, the TOF is able to achieve a time resolution of less than 50 ps [69].

Chapter 5

Λ - Hadron Correlations and Conserved-Charge Balance Functions

5.1 Overview of the Analysis

This chapter details my own work & research project, which is dedicated to probing and understanding the production of particles inside the Quark-Gluon Plasma (QGP) created in heavy-ion collisions. Specifically, this analysis focuses on the production mechanisms of two quantum numbers, strangeness and baryon number. These quantum numbers (sometimes called charges) are conserved in physical processes, making understanding them an important and worthwhile endeavour. Furthermore, the presence of the QGP in heavy-ion collisions is known to affect the distribution of the final-state hadrons measured in detector experiments. Therefore, studying the production of conserved charges may allow for QGP effects to be discerned, improving our knowledge of this unusual medium. Finally, the results of this analysis may be used as input for theorists for the sake of explaining and predicting the physics of the Standard Model (SM).

In order to study the production mechanisms of strangeness and baryon number, this analysis makes use of *angular correlations* between Λ baryons and three light SM hadrons, these being the pion (π), the kaon (K) and the proton (p). As the Λ is a baryon, consisting of three quarks (uds) with one of them being the strange quark, it contains both strangeness and baryon number, making it perfectly suited for this analysis. Furthermore, the kaon and the proton each represent just one conserved charge, with the former containing a strange quark and the latter being a baryon. Finally, the pion contains neither strangeness nor baryon number, making correlations between it and the Λ ideal for acting as a baseline that $\Lambda - K$ and $\Lambda - p$ correlations may be compared to.

Depending on the quantum number content of the Λ baryons and the light hadrons, the particles are paired up such that they either form $Q - \bar{Q}$ ($\bar{Q} - Q$) correlations or $Q - Q$ ($\bar{Q} - \bar{Q}$) correlations, where Q denotes the particle's strangeness or baryon number. For example, the combination $\Lambda - K^+$ ($\bar{\Lambda} - K^-$) probes strange–antistrange quark correlations while $\Lambda - \bar{p}$ ($\bar{\Lambda} - p$) probes baryon–antibaryon correlations, with the other possible charge combinations relating to correlations between $Q - Q$ ($\bar{Q} - \bar{Q}$) instead. As the pion does not contain strangeness or baryon number, it is paired up with the Λ using the same (electric) charge combination as its fellow $K^\pm$ meson.

Since strangeness and baryon number are conserved, the production of a strange quark or a baryon is necessarily balanced by the simultaneous production of an antistrange quark or an antibaryon. Thus, one would expect $Q - \bar{Q}$ ($\bar{Q} - Q$) correlations to be noticeably stronger than $Q - Q$ ($\bar{Q} - \bar{Q}$). By comparing the two types of correlations and calculating their difference to obtain what is known as the *balance function*, the properties of charge balancing (conservation of quantum numbers) may be studied in greater detail.

5.2 Rapidity and Pseudorapidity

As the correlations discussed in this thesis exist in angular space, it is important to consider how the angular components of the detector coordinate system are defined. Despite the ALICE detector having a cylindrical design, a point inside the detector is usually represented in terms of either Cartesian or spherical coordinates. However, these coordinate systems are less natural for tracking the motion of particles produced in a collision, since their velocities are relativistic. In the spherical coordinate system, the azimuthal angle (φ) remains Lorentz-boost invariant, as it is defined perpendicular to the direction of motion (the z -axis). However, the polar angle (θ) contains a component parallel to the beam axis and is therefore not a boost-invariant quantity. Instead, a variable called the *rapidity* is used as a measure of a particle's longitudinal trajectory

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (5.2.1)$$

Here, E is the particle's total energy ($= \sqrt{|\vec{p}|^2 + m^2}$) and p_z is the momentum component along the z -axis. Although rapidity itself is also not a Lorentz-invariant quantity, differences in rapidity remain the same in any frame of reference and are additive under Lorentz boosts. Furthermore, particle yields tend to be roughly uniform in rapidity (especially near mid-rapidity), as opposed to a distribution in polar angle. While determining the total energy of a particle may be experimentally challenging, there is a trick that can be used for particles that are highly relativistic. As the velocity of a particle approaches the speed of light, $p_z \approx E \cos \theta$ and Eq. 5.2.1 becomes

$$\frac{1}{2} \ln \left(\frac{1 + \cos \theta}{1 - \cos \theta} \right) = \frac{1}{2} \ln \left(\cot^2 \frac{\theta}{2} \right) = -\ln \left(\tan \frac{\theta}{2} \right) = \eta, \quad (5.2.2)$$

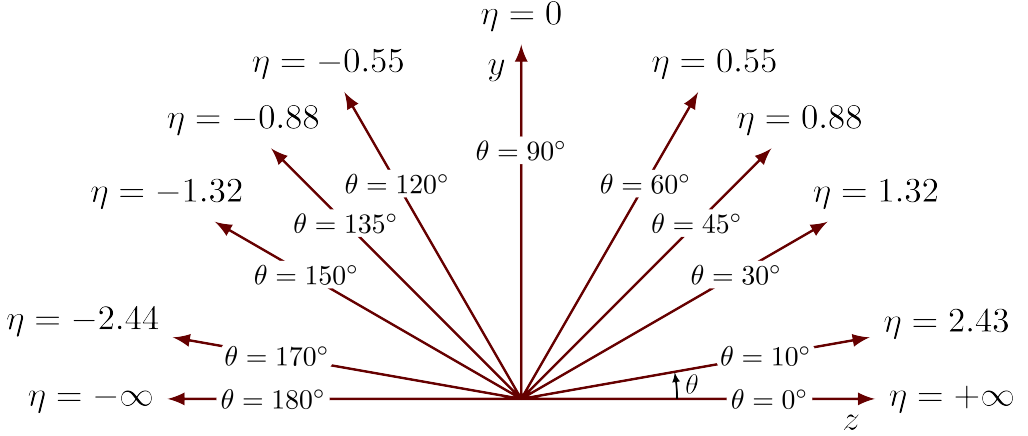


Figure 5.1 – Illustration of the correspondence between the polar angle θ and the pseudorapidity η . The value of η changes sign for $\theta > 90^\circ$. Figure is taken from [73].

where η is known as the *pseudorapidity*. In the massless limit, rapidity and pseudorapidity are equivalent and may be used interchangeably. Figure 5.1 shows an illustration of the pseudorapidity and how it relates to the polar angle measured in the lab frame. While pseudorapidity is not strictly Lorentz invariant, it has been used throughout this analysis in place of rapidity for a number of reasons. Firstly, all particles considered in this analysis (π , K, p, Λ) travel at relativistic velocities, making rapidity and pseudorapidity equally viable. In addition, using pseudorapidity over rapidity eliminates the need to determine the particle's mass and subsequently, its total energy, which greatly simplifies the analysis procedure.

5.3 The Angular Correlation Function

The angular correlation function is a distribution of the average angular separation between two or more particles. For a given event, particles that are to be correlated are first separated into two categories, known as triggers and associates. In this analysis, the triggers are the Λ baryons and the associates are the light hadrons (π , K, p). Then, for every trigger-associate pair in that event, the difference in azimuthal angle ($\Delta\varphi$) and pseudorapidity ($\Delta\eta$) is calculated as

$$\Delta\varphi = \varphi_{\text{trigg}} - \varphi_{\text{assoc}},$$

$$\Delta\eta = \eta_{\text{trigg}} - \eta_{\text{assoc}},$$

where $\Delta\varphi$ is rotated to fall within $(-\frac{\pi}{2}, \frac{3\pi}{2})$. Storing the angular separations in a two-dimensional histogram with axes $\Delta\varphi$ and $\Delta\eta$, averaging over the number of pairs and dividing by the width of the $\Delta\varphi$ and $\Delta\eta$ bins gives the angular correlation function, which can be written as

$$\mathbb{C}(\Delta\varphi, \Delta\eta) = \frac{1}{N_{\text{pairs}}} \frac{d^2 N_{\text{pairs}}}{d\Delta\varphi d\Delta\eta}. \quad (5.3.1)$$

Here, N_{pairs} is the number of trigger-associate particle pairs. This distribution can instead be normalised to the number of trigger particles to give the per-trigger yields

$$\mathbb{Y}(\Delta\varphi, \Delta\eta) = \frac{1}{N_{\text{trigg}}} \frac{d^2 N_{\text{pairs}}}{d\Delta\varphi d\Delta\eta}, \quad (5.3.2)$$

where N_{trigg} is the number of trigger particles. Choosing this normalisation has the advantage of making the correlation function easy to interpret, as the per-trigger yields¹ is simply a distribution of the average number of associate particles per trigger, as a function of their angular separation.

For a real detector however, the available phase space is limited and the acceptance is non-uniform. As a result, the correlation function will become convoluted with the detector acceptance. Correcting for this requires a distribution that exclusively captures the effect of limited detector acceptance. This is commonly done through event mixing, where the trigger particle and the associate particle come from *different* events such that the resulting correlation function is free from any physics. The acceptance-corrected per-trigger yields is then given by

$$\mathbb{Y}(\Delta\varphi, \Delta\eta) = \frac{\text{SE}(\Delta\varphi, \Delta\eta)}{\text{ME}(\Delta\varphi, \Delta\eta)}, \quad (5.3.3)$$

where $\text{SE}(\Delta\varphi, \Delta\eta)$ follows Eq. 5.3.2, using triggers and associates coming from the same event, and $\text{ME}(\Delta\varphi, \Delta\eta)$ has the form

$$\text{ME}(\Delta\varphi, \Delta\eta) = \frac{1}{\mathcal{C}} \frac{d^2 N_{\text{pairs}}^{\text{mixed}}}{d\Delta\varphi d\Delta\eta}, \quad (5.3.4)$$

where $\mathcal{C}$ is a constant chosen such that $\text{ME}(\pi, 0)^2 = 1$ and $N_{\text{pairs}}^{\text{mixed}}$ indicates that the trigger-associate pairs are from mixed events.

For mixed-event correlations, events that are to be mixed must have roughly the same detector acceptance. This was ensured by creating mixing pools based on the event centrality and z-coordinate of the primary vertex. An event in a pool would only be mixed with other events in that same pool. For the mixing pools, the following binnings were used

$$\begin{aligned} \text{Centrality (\%)} &: [0, 10, 20, 30, 40, 50, 60, 70, 80, 90], \\ z_{\text{vtx}} \text{ (cm)} &: [-10.0, -8.0, -6.0, -4.0, -2.0, 0.0, 2.0, 4.0, 6.0, 8.0, 10.0]. \end{aligned}$$

¹Strictly speaking, the per-trigger yields is not a correlation function, as the latter is a distribution in probability. However, the former is referred to as a correlation function for the remainder of this thesis.

²The mixed-event correlations are normalised here to avoid interference with the Radial Distance method, which is explained in Section 5.7.

For the acceptance correction, the same-event correlations were placed in pools similar to the mixed-event correlations, using the same binning in centrality and z_{vtx} . Finally, Eq. 5.3.3 was then applied for every bin and averaged over the z_{vtx} to give the acceptance-corrected yields as a function of centrality. An example of how the acceptance correction is performed is shown in Fig. 5.2.

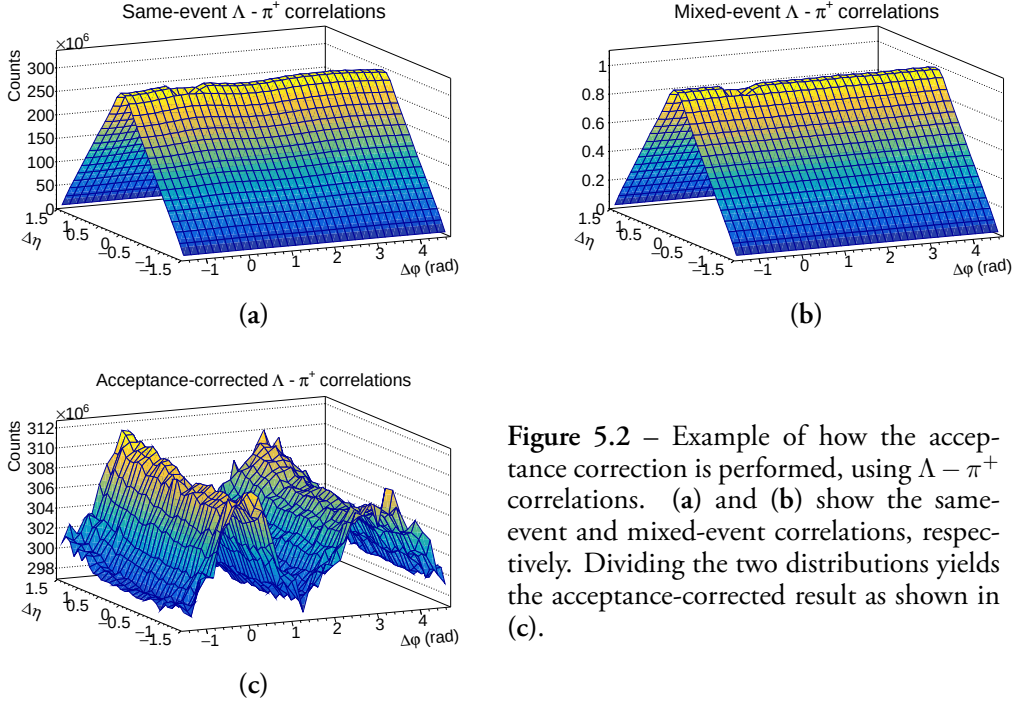


Figure 5.2 – Example of how the acceptance correction is performed, using $\Lambda - \pi^+$ correlations. (a) and (b) show the same-event and mixed-event correlations, respectively. Dividing the two distributions yields the acceptance-corrected result as shown in (c).

5.4 Event Selection

The results presented in this thesis were made using data from Pb–Pb collisions collected in 2023 during Run 3 at the LHC, corresponding to approximately 12 billion events. This dataset was the first heavy-ion dataset to be recorded by the ALICE detector after Long Shutdown 2 (LS2), which made it the natural choice to use for this project. In addition, the Pb–Pb data was complemented by an associated Monte-Carlo (MC) dataset consisting of approximately 86 million events. This was obtained from simulations by the PYTHIA8 event generator [74] and all tracks were propagated through the detector using the GEANT4 simulation [75]. The MC dataset was used for several aspects of the analysis, including efficiency calculation, track cut validation and closure tests.

Before the data could be analysed, several event selections were applied to remove low-quality events from the dataset. For a number of these selections, the `aod::evsel` module available in the O2Physics analysis framework was used to filter out any events that didn't pass the selection criteria. The following event selections were applied:

- Events must satisfy the standard physics selection using the minimum-bias trigger. For Run 3, this means that a hit in both the FT0-A and FT0-C detectors is required (`evsel::Sel8`).
- Events must be free of pile-up, meaning that there is no contamination by data from a different bunch crossing (`evsel::kNoSameBunchPileup`).
- Events must have a primary vertex where the z-coordinate was reconstructed using both global tracks and timing information from the FT0. Furthermore, the difference between the two methods must be below 1 cm (`evsel::kIsGoodZvtxFT0vsPV`).
- Events must contain little to no occupancy effects, referring to the deterioration of TPC clusters in an event by signals from other nearby collisions. The event occupancy was restricted to fall between 0–500 and a standard occupancy cut was applied (`evsel::kNoCollInTimeRangeStandard`).
- The event centrality must be within 0% – 90%. At higher centralities, the event multiplicity gets to be too low to obtain reliable results.
- The z-coordinate of the primary vertex must be $|\text{vtx}_z| < 10.0$ cm from the detector center. This ensures uniform efficiency within the detector.

The event selection resulted in a reduction of the total number of analysed events, to approximately 2 billion in data and 56 million in MC.

5.5 Particle Identification

As mentioned in Section 5.3, the relevant particles in this analysis are the Λ baryon (triggers), as well as the pion, kaon and proton (associates). Separating particles into triggers and associates (and associates into π , K, p) requires a form of particle identification that can robustly perform this separation while also rejecting any other particles not listed above. This is achieved through a combination of trigger- and associate-specific cuts and identification methods. As the associate particles are charged and have a relatively long lifetime, they will leave a track in the detector that can be used to distinguish charged particles from each other. Meanwhile, the trigger particles are neutral and must instead be identified from the decay topology and the invariant mass of their daughter particles. Both procedures will be described in detail in the following sections.

5.5.1 Identification of Associate Particles (π , K, p)

The pion, kaon and proton are among the few particles that can be observed directly in the detector, along with others such as the electron and the muon. Unlike heavier hadrons and leptons, these particles are either stable or live long enough such that they can travel a significant distance inside the ALICE central barrel, reaching the subdetectors dedicated to

direct particle identification. As the associate particles are charged, they will leave a track inside the TPC & TOF detectors (see Chapter 4) which may be used to discern some of their properties like their momentum and charge sign. In addition, measurements of both the specific energy loss inside the TPC and the relativistic velocity $\beta = v/c$ inside the TOF provide the means of determining the identity of charged particles, as they are both fundamentally dependent on the particle's mass.

For the TPC, the charged particles will ionise the drift gas inside the detector, leading to a deposition of electric charge as the liberated electrons drift towards the circular surfaces of the cylindrical barrel. The amount of charge recorded by the Readout Chambers (ROCs) is directly proportional to the average energy loss due to ionisation that a particle experiences as it travels through the drift gas. The average energy loss $\langle dE/dx \rangle$ for a charged particle traversing a (gaseous) medium is given by the Bethe-Bloch formula, which takes the form

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi\alpha^2 h^2 Z^2 n_e}{m_e \beta^2} \left(\ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I} \right) - \beta^2 - \frac{\delta(\gamma)}{2} \right). \quad (5.5.1)$$

Here, α and h are the fine-structure constant and Planck's constant respectively, m_e and n_e are the electron mass and electron density inside the medium, Z is the charge of the particle, I is the ionisation potential and $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor for a particle moving at relativistic velocity β . Finally, δ is a factor which accounts for energy loss due to dielectric screening. Equation 5.5.1 shows that if the traversed medium is homogeneous, i.e. the medium properties remain constant, the particle's energy loss depends entirely on its charge and velocity, with the latter expressed in terms of the relativistic factors β and γ . These factors may additionally be written in terms of the particle's mass and momentum, giving

$$\beta = \frac{p}{\sqrt{p^2 + m^2}}, \quad \gamma = \sqrt{1 + \left(\frac{p}{m} \right)^2},$$

where natural units have been used such that $c = 1$. As the momentum may be obtained from the track's radius of curvature inside the magnetic field, measurements of $\langle dE/dx \rangle$ and β inside the TPC and TOF may be related back to the particle's mass, thereby providing unique identifiers for the associate particles.

Figure 5.3 shows the performance of the TPC and TOF for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Within the distributions displayed in both graphs, clearly distinguishable particle bands appear, corresponding to particles that share the same mass. Additionally, the particle bands recorded by the TPC have been fitted with a parametrisation proposed by the ALEPH collaboration, which takes the form [76]

$$\frac{dE}{dx} = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right), \quad (5.5.2)$$

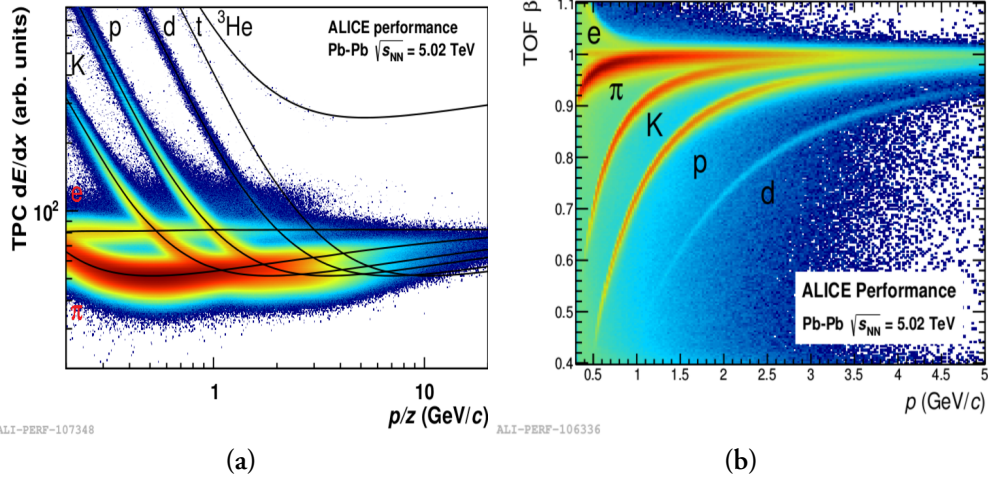


Figure 5.3 – Recording of the TPC signal (specific energy loss) and the TOF signal (relativistic velocity) for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The distributions in (a) have been fitted using the ALEPH parametrisation, highlighting the identified particle species. For (b), the distributions show a clear mass ordering, in accordance with β being inversely proportional to m . Figures are taken from [77].

where $P_1 - P_5$ are fit parameters. In order to provide a reliable means of particle identification, a track's deviation from the expected response, as indicated by the particle bands, is quantified to provide a “likelihood” of the track being a particle of a given type. Finally, the performance plots indicate a notable difficulty when identifying particles at high momentum. Past the 1 – 2 GeV/c momentum range, the particle bands start to mix together and the identification of tracks will become contaminated by interference from different particle species. Furthermore, the particle bands display a smearing of the distribution that is attributable to the detector resolution, leading to a considerable spread around the expected average. The mixing of the particle bands is accounted for in the particle identification procedure, which will be described shortly.

For this analysis, the tracks recorded in the Pb–Pb dataset were subjected to a number of track selection cuts, which are listed in Table 5.1. Many of these cuts, indicated with (*), were implemented using the `requireGlobalTrackInFilter()` function, which is defined in [78]. The default values for these cuts can be found in [79]. The cuts were applied before particle identification was performed, and can roughly be broken down into three categories. The cuts on the transverse momentum and pseudorapidity limit the available tracks to a region of phase space where identification can reliably be performed. They are complemented by a number of ITS and TPC parameter cuts to ensure good identification quality and detector resolution. Finally, two cuts on the Distance-of-Closest-Approach (DCA) between the track and the primary vertex were implemented to remove any contamination from secondary particles and to eliminate out-of-bunch pileup effects.

Table 5.1 – Track cuts used for associated particles

Transverse momentum	$0.2 < p_T < 3.0 \text{ GeV}/c$
Pseudorapidity	$ \eta < 0.8$
TPC and ITS refits (*)	required
Golden χ^2 (*)	required
Number of TPC crossed rows (*)	$N_{rs} \geq 70$
Ratio of TPC crossed rows to findable clusters (*)	$N_{rs}/N_{cl}^f > 0.8$
TPC goodness-of-fit χ^2 per cluster (*)	$\chi^2/N_{cl} < 4$
Number of associated SPD hits (*)	≥ 1
ITS goodness-of-fit χ^2 per cluster (*)	$\chi^2/N_{cl} < 36$
Transverse DCA (*)	$DCA_{xy} < 0.0105 + 0.035p_T^{-1.1} \text{ cm}$
Longitudinal DCA (*)	$DCA_z \leq 2 \text{ cm}$

As was mentioned earlier, the deviation of a track's PID response from the expected average is used for identification. In the central processing of ALICE data, the spread measured in the TPC is approximated using a Gaussian distribution, allowing the track's detector response to be converted to a number of standard deviations $n\sigma$ from the expected response. A similar approach is used for the TOF response, although the wider tail of the distribution is not captured properly by a Gaussian, falling off as $\exp(-\beta)$ instead. Nevertheless, this means that every track is assigned a series of numbers $n\sigma_{\text{TPC/TOF}}^i$, where $i = \pi, K, p$, representing the inverse likelihood for the track to be a pion, a kaon or a proton. Naturally, whichever i returns the smallest number of standard deviations is used as an initial guess for the particle's identity. Next, the smallest $n\sigma$ was subjected to a number of p_T -dependent cuts, which were chosen to avoid contamination from other particle species. These cuts are listed in Table 5.2 and were based on the full $n\sigma^i$ distributions (see Appendix A.28 through A.36), with the cut values determined through visual inspection by checking at how many standard deviations the Gaussians from different particle species would intersect. Figure 5.4 shows two examples of the $n\sigma_{\text{TOF}}^K$ distribution, highlighting how contamination occurs as p_T increases.

Table 5.2 – p_T -dependent $n\sigma$ cuts for pions, kaons and protons

p_T -range	PID cut (π)	p_T -range	PID cut (K)
0.2 - 0.3 GeV	Reject	0.2 - 0.5 GeV	Reject
0.3 - 1.6 GeV	$ n\sigma_{\text{TOF}} \leq 4.0$	0.5 - 1.5 GeV	$ n\sigma_{\text{TOF}} \leq 4.0$
1.6 - 2.0 GeV	$-4.0 \leq n\sigma_{\text{TOF}} \leq 2.0$	1.5 - 2.0 GeV	$-1.0 \leq n\sigma_{\text{TOF}} \leq 4.0$
2.0 - 2.3 GeV	$-4.0 \leq n\sigma_{\text{TOF}} \leq 0.0$	2.0 - 2.3 GeV	$0.0 \leq n\sigma_{\text{TOF}} \leq 4.0$
> 2.3 GeV	Reject	> 2.3 GeV	Reject
$ n\sigma_{\text{TPC}} \leq 4.0$		$ n\sigma_{\text{TPC}} \leq 4.0$	

p_T -range	PID cut (p)
0.2 - 0.6 GeV	Reject
0.6 - 2.3 GeV	$ n\sigma_{\text{TOF}} \leq 4.0$
2.3 - 3.0 GeV	$-2.0 \leq n\sigma_{\text{TOF}} \leq 4.0$
$ n\sigma_{\text{TPC}} \leq 4.0$	

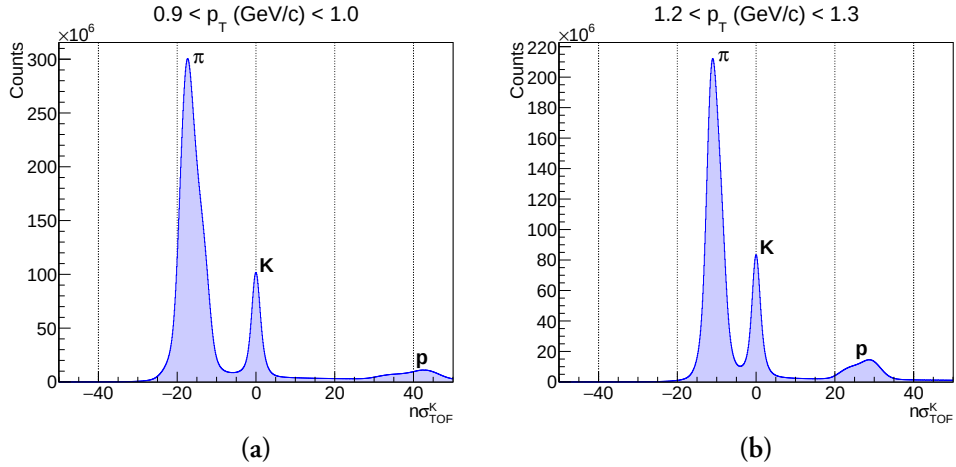


Figure 5.4 – Example of $n\sigma_{\text{TOF}}$ distribution for kaons at (a) $0.9 < p_T < 1.0$ GeV/ c and (b) $1.2 < p_T < 1.3$ GeV/ c . The peaks in the distribution correspond to the $n\sigma_{\text{TOF}}^K$ values for different particle species, with the one centered at zero naturally belonging to kaons. The graphs further demonstrate how the different peaks move closer together as p_T increases, requiring the cuts listed in Table 5.2 to be applied to avoid contamination.

During the analysis, it was found that the detector response from the TPC was somewhat unreliable. This was observed by looking at the distribution of $n\sigma_{\text{TPC}}^i$ for different values of p_T . Given how the deviation from the expected response was quantified, one would expect to see a (Gaussian) peak centered at $n\sigma^i = 0$, corresponding to particles of type i . This turned out not to be the case, as the peak would often appear shifted away from $n\sigma^i = 0$. Furthermore, contamination by other particle species began to occur at much lower p_T ranges compared to the TOF detector. Because of this, the choice was made to rely primarily on the TOF detector for this analysis, identifying tracks and applying p_T -dependent cuts using only the smallest $n\sigma_{\text{TOF}}^i$. Despite this, a global cut of $|n\sigma_{\text{TPC}}| \leq 4.0$ was applied for all particle species to act as a consistency check for the TOF detector.

A disadvantage of this particle identification procedure is that the application of a “hard” cut on the $n\sigma$ distribution is likely to result in a loss of statistics. When the intersection between Gaussians is identified by eye, tracks that are correctly identified by the smallest $n\sigma$ may be more likely to fall just outside the cut window, resulting in “good” associates being rejected from the analysis. While this is true, it does mean that the purity of the final track sample, meaning the fraction of tracks that are correctly identified, is very high. This can be verified in MC by comparing the number of tracks that are identified using the particle’s MC identity and the $n\sigma$ method listed above (true selected) to the number of tracks that are identified using only the $n\sigma$ method (selected). Figure 5.5 shows this comparison, confirming the validity of the method. As a high purity of associate particles is very important for this analysis, and the loss of “good” associates is expected to be compensated through the efficiency correction, the choice was made to continue using this identification procedure.

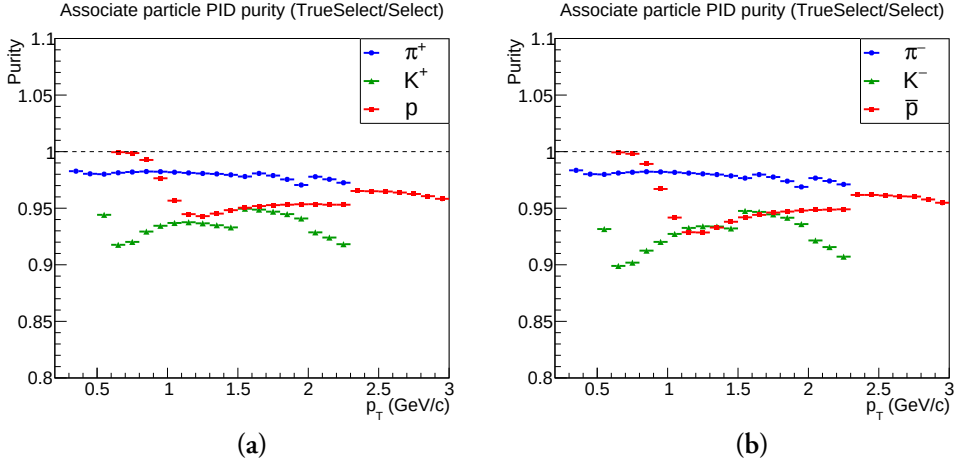


Figure 5.5 – Purity of associates for (a) positive particles and (b) negative particles, defined as the ratio of true selected particles over selected particles.

5.5.2 Identification of Trigger Particles (Λ)

The central particle of this analysis is the Λ baryon, as it is involved in all correlation functions discussed in this thesis. While the Λ is an unstable hadron, its mean lifetime is still long enough to allow it to travel several centimeters before decaying, meaning it should, in principle, be directly observable in a collision event. Unlike the associate particles however, the Λ baryon is neutral and doesn't leave a trace behind in ALICE's tracking detectors. This renders the particle effectively invisible and makes direct detection impossible. Despite this, the Λ may still be observed and identified, albeit indirectly, through its characteristic decay topology. The Λ and $\bar{\Lambda}$ will decay primarily as

$$\Lambda^0 \longrightarrow \pi^- + p \quad \text{BR} = 64.1\%,$$

$$\bar{\Lambda}^0 \longrightarrow \pi^+ + \bar{p} \quad \text{BR} = 64.1\%.$$

Here, the daughter pion and proton are charged, causing them to leave a track inside the TPC & TOF detectors. Furthermore, their opposite charge sign means that they will curve away from each other in the detector's magnetic field, resulting in the tracks forming a characteristic “V”-shaped pattern. Unstable particles that leave behind such patterns have been dubbed V^0 s, as the original particle must have been electrically neutral. While this decay topology is not unique to Λ baryons, it allows for neutral, unstable particles that feature this topology to be reconstructed and identified. A schematic overview of the V^0 decay topology is shown in Fig. 5.6.

In order to identify V^0 s in a collision event, tracks that reproduce the expected decay topology of a V^0 particle are grouped together, which is done already in the central processing

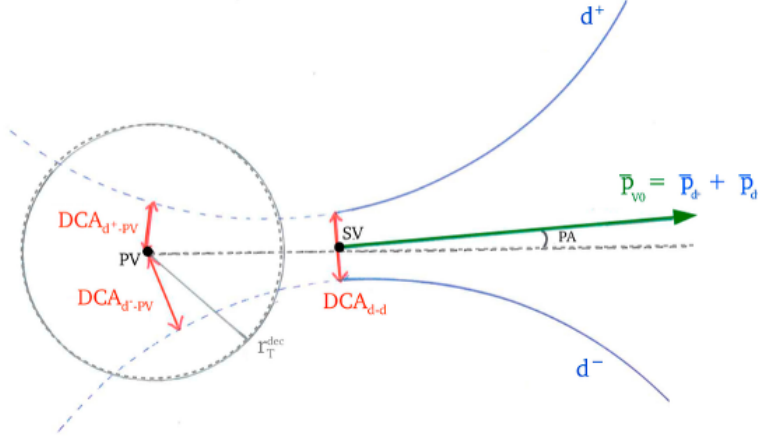


Figure 5.6 – Schematic overview of the V^0 decay topology. Several parameters that quantify the topology are highlighted, including the transverse decay radius r_T^{dec} , the pointing angle (PA) between the V^0 momentum and the V^0 trajectory, the DCA from the daughter particles to the primary vertex (PV) and the DCA between daughters measured at the secondary vertex (SV). Figure is taken from [80].

of ALICE data. In addition, the tracks are required to satisfy a series of (loose) topological cuts to increase the likelihood that the two oppositely charged tracks have the same origin. These same cuts can be tightened to not only determine which tracks belong to V^0 particles, but also to narrow down which V^0 s are the Λ baryons relevant to this analysis. The list of topological and quality cuts is presented in Table 5.3. The majority of these cuts, indicated with (*), are taken from a separate analysis focusing on strange particle production in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV [81]. The exceptions are the p_T and η cuts for the V^0 s, with the former made to capture as many V^0 particles as possible and the latter chosen to be slightly lower than the $|\eta| < 0.8$ cut for tracks, such that daughter particles are still likely to fall within this pseudorapidity window.

The topological cuts listed in Table 5.3 are based on the parameters shown in Fig. 5.6 which quantify the topology, and were chosen specifically to separate Λ baryons from other V^0 particles. A cut was placed on the *decay radius* and *proper lifetime* of the V^0 , with the former corresponding to the distance between the primary and secondary vertex in the transverse plane, and the latter representing the proper length of the path traversed by the V^0 (defined as mL/p) before decaying. Furthermore, the pointing angle of the V^0 , defined as the angle between the V^0 's trajectory and direction of total momentum, should be close to zero. As such, only V^0 s where the cosine of θ_{PA} was close to unity were accepted. As for the V^0 daughter tracks, they were each required to have a hit in the TPC detector, and cuts were placed on the DCA between the daughters and the primary vertex as well as on the DCA between daughters measured at the secondary vertex. Since the daughters are supposed to originate from the latter, an upper limit was set on $\text{DCA}_{\text{d-d}}$ and lower limits were set on $\text{DCA}_{\text{d-PV}}$.

Table 5.3 – V^0 and daughter track cuts used for trigger particles

V^0 cuts	
Transverse momentum	$1.6 < p_T < 12.0 \text{ GeV}/c$
Pseudorapidity	$ \eta < 0.72$
Decay radius (*)	$r_T^{\text{dec}} > 1.2 \text{ cm}$
Proper lifetime (*)	$mL/p < 30 \text{ cm}$
Cosine of pointing angle (*)	$\cos \theta_{PA} > 0.995$
DCA between V^0 daughters (*)	$\text{DCA}_{d-d} < 1\sigma$
Daughter track cuts	
Pseudorapidity (*)	$ \eta < 0.8$
Number of TPC crossed rows (*)	$N_{rs} > 70$
PID selection (*)	$ n\sigma_{\text{TPC}} < 5$
Pion daughter DCA (*)	$\text{DCA}_{\pi-PV} > 0.2 \text{ cm}$
Proton daughter DCA (*)	$\text{DCA}_p-PV > 0.05 \text{ cm}$
Other constraints	Correlations between V^0 s and their daughter tracks are avoided

Finally, a constraint was placed on the daughter tracks belonging to triggers. Namely, when pairing trigger and associate particles, the associate tracks could not be daughters of the trigger. Otherwise, the correlation and balance functions would be contaminated by autocorrelations. The constraint was enforced by checking if the associate track's global index matched one of the trigger daughter indices.

Despite these topological and quality cuts, the selected group of trigger particles was still found to contain misidentified V^0 s, which didn't correspond to Λ baryons. While some of them may have corresponded to neutral hadrons other than Λ s, the majority of V^0 particles consisted of combinatorial background, where two random, oppositely charged tracks were incorrectly identified as having the same origin due to them appearing to exhibit the characteristic decay topology. In order to prevent misidentified triggers from contaminating the correlation functions, an additional selection variable was employed based on the *invariant mass* of the daughter particles, which is defined as

$$M_{\text{inv}} = \sqrt{\left(\sum_i E_i\right)^2 - \left|\sum_i \vec{p}_i\right|^2}. \quad (5.5.3)$$

Here, E_i and $\vec{p}_i$ are the energy and momentum of the daughter particles, with the former calculated as

$$E_i = \sqrt{p_i^2 + m_i^2}, \quad (5.5.4)$$

where m_i is the daughter particle's rest mass under the proton and pion mass hypothesis³.

³As it cannot be said *a priori* if a V^0 daughter track of a given charge belongs to a proton or a pion from a Λ^0

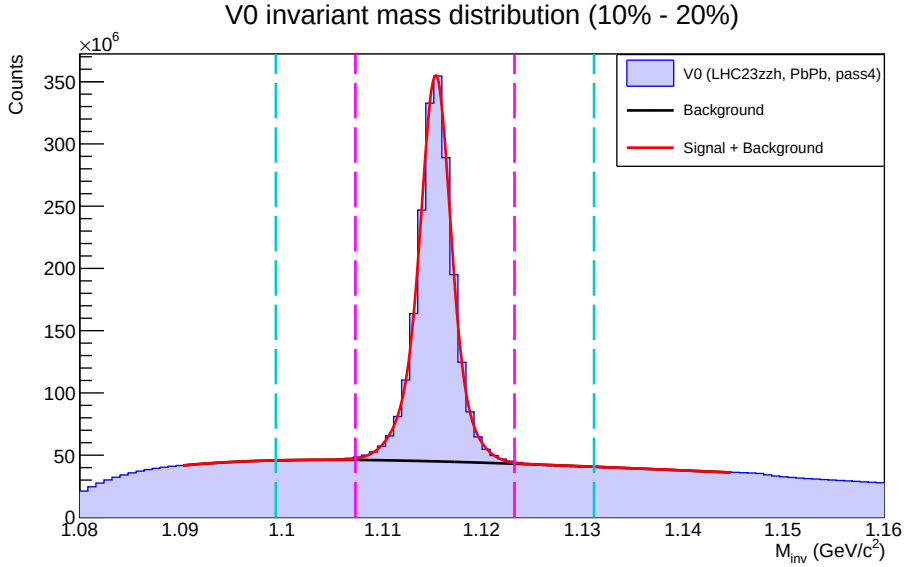


Figure 5.7 – Invariant mass distribution of V^0 particles in the 10% – 20% centrality interval, showing a peak at $m_\Lambda = 1.115683 \text{ GeV}/c^2$ [31]. The solid red and black lines belong to the signal and background fits, while the dashed purple and cyan lines indicate the SGNL and SB regions.

The invariant mass of the trigger particles is employed in a procedure known as *sideband subtraction*. Here, the contribution from misidentified triggers is subtracted from the full correlation function, making use of the fact that the latter is additive. The subtraction is performed using the V^0 invariant mass distribution, displayed in Fig. 5.7 for the 10% – 20% centrality interval. For every centrality class, a fit was applied to the distribution consisting of a double Gaussian to describe the Λ peak and a background function of the form

$$\text{Background}(x) = Ax^n + Bx + C, \quad (5.5.5)$$

where $x = M_{\text{inv}}$. Using the standard deviation of the double Gaussian, two invariant mass windows were defined; a SGNL region ($-4\sigma \leq M_{\text{inv}} \leq 4\sigma$) and a SB region ($-8\sigma \leq M_{\text{inv}} < -4\sigma$ & $4\sigma < M_{\text{inv}} \leq 8\sigma$), shown in Fig. 5.7 as the area between the purple lines and the area between the purple and cyan lines, respectively. In turn, trigger-associate pairs would be placed in separate SGNL and SB correlations depending on the invariant mass of the trigger. Finally, the SB correlations were scaled to the background underneath the Λ peak (the area between the purple and black lines) before being subtracted from the SGNL correlations. This should result in a correlation function containing only contribu-

or $\bar{\Lambda}^0$ decay, the V^0 grouping algorithm calculates the invariant mass for both the $p\pi^-$ and $\bar{p}\pi^+$ assumptions simultaneously. In this analysis, whichever mass is closest to the true m_Λ is used to distinguish between them.

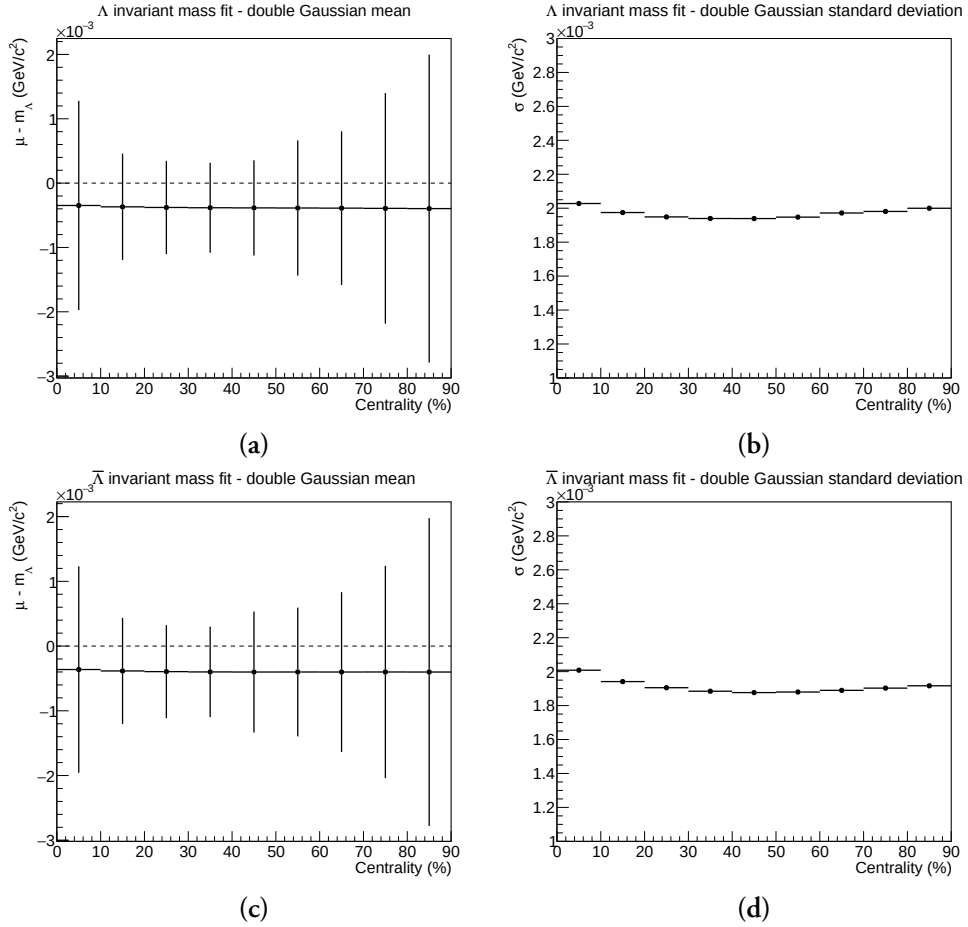


Figure 5.8 – Centrality evolution of the mean (a) and standard deviation (b) for Λ baryons, with (c) and (d) corresponding to the same quantities for $\bar{\Lambda}$ s. For (a) and (c), the difference $\mu - m_\Lambda$ is shown, which is expected to be close to zero.

tions from “true” Λ baryons. Additionally, the invariant mass distribution and background fit were used for determining the number of triggers in each centrality interval, which was necessary for normalising the correlation functions in accordance with Eq. 5.3.2. The full set of invariant mass fits for Λ and $\bar{\Lambda}$ candidates can be found in Appendix A.37 and A.38.

Figure 5.8 illustrates the invariant mass fitting procedure, showing the mean and standard deviation of the double Gaussian distribution as a function of the event centrality. The difference $\mu - m_\Lambda$ is very close to zero, and remains approximately constant. The same holds true for σ , retaining a near-constant value as the centrality increases. Using the standard deviation, the SGNL and SB correlation functions are established. Examples of both, along with the sideband-subtracted correlations, are shown in Fig. 5.9.

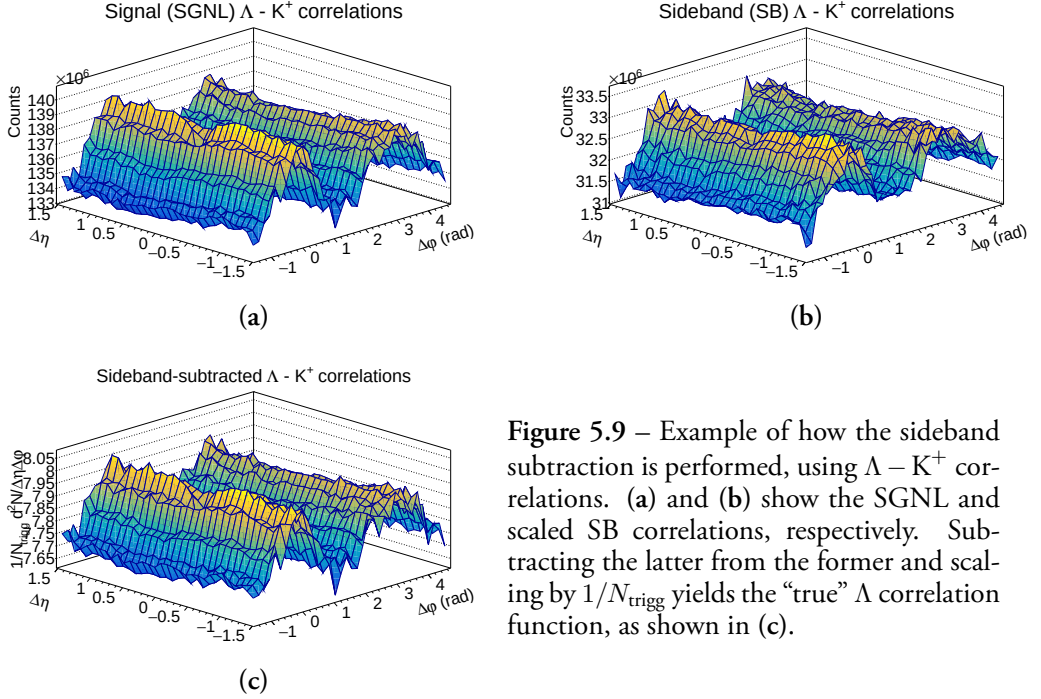


Figure 5.9 – Example of how the sideband subtraction is performed, using $\Lambda - K^+$ correlations. (a) and (b) show the SGNL and scaled SB correlations, respectively. Subtracting the latter from the former and scaling by $1/N_{\text{trigg}}$ yields the “true” Λ correlation function, as shown in (c).

5.6 Efficiency & Spectra Correction

When a trigger and an associate particle are found, each satisfying their respective selection criteria, their angular separation (in terms of $\Delta\varphi$ and $\Delta\eta$) is stored in a two-dimensional histogram. The angular correlation function then emerges naturally by summing over all possible trigger-associate pairs, as was explained in Section 5.3. However, for correlation functions constructed in data, one needs to take into account the efficiency loss in the detector due to tracking inefficiencies. Furthermore, the efficiencies of the particle identification procedures are limited, and need to be corrected for. As such, the analysis makes use of MC simulations of the collision environment in order to calculate an efficiency correction factor, which can be applied when filling the correlation histograms. Doing so returns the correlation functions to their original underlying distributions.

For both the triggers and the associates, the efficiency is calculated in a similar way, by taking the MC reconstructed yields of particles propagated through the detector and dividing by the original MC generated yields. Then, when filling the correlation histogram⁴, each entry is weighted by a factor $1/\epsilon(p_T, \eta)$, where $\epsilon(p_T, \eta) = \epsilon_{\text{trigg}}(p_T, \eta) \times \epsilon_{\text{assoc}}(p_T, \eta)$ is the combined efficiency for triggers and associates, as a function of their p_T and η . For the generated yields, the particles were distinguished according to their MC identity, while the reconstructed yields made use of the particle identification procedures outlined in the

⁴As the correlation functions are constructed in centrality intervals, the efficiency is calculated separately for each interval as well.

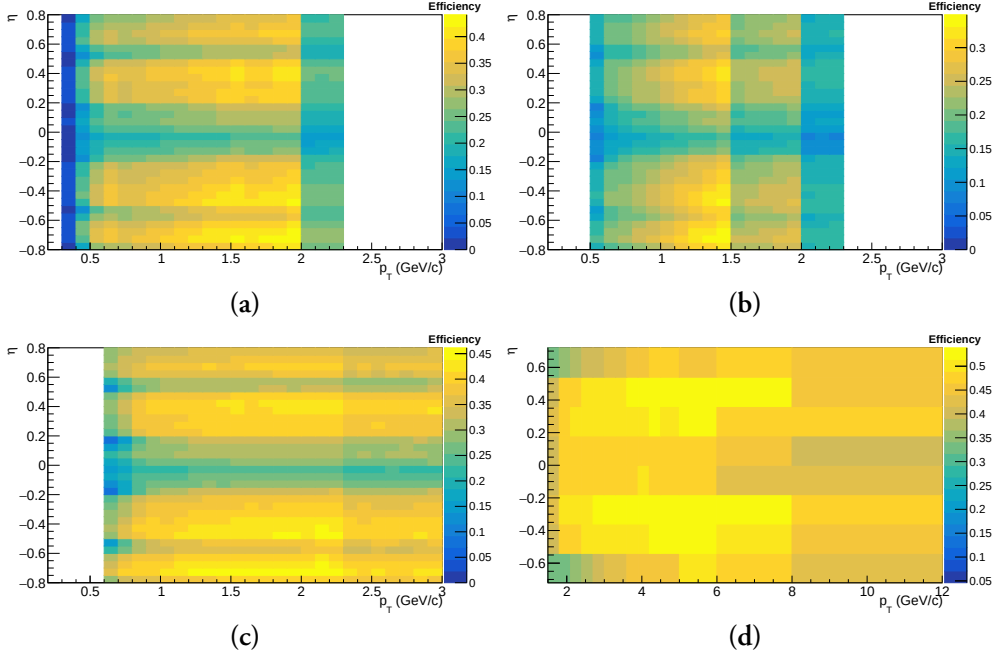


Figure 5.10 – Efficiency distributions of (a) π^+ , (b) K^+ , (c) p and (d) Λ for the 10% – 20% centrality class, as a function of p_T and η . The white areas in (a), (b) and (c) reflect the $n\sigma$ cuts listed in Table 5.2.

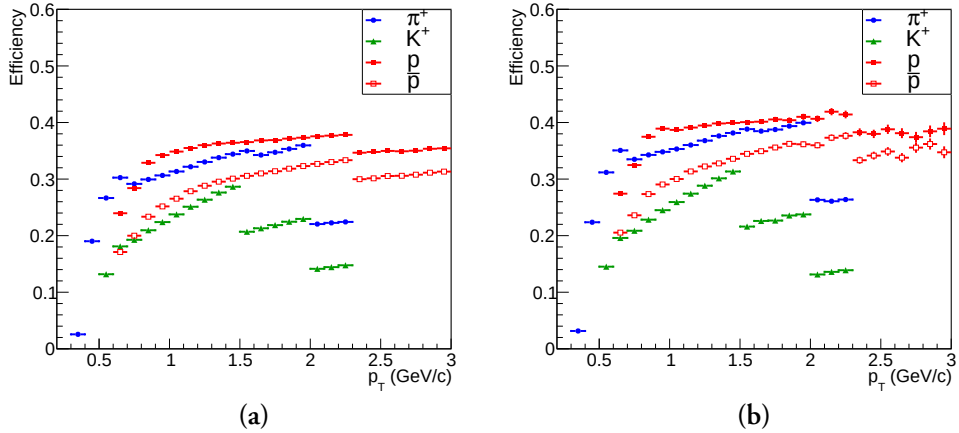


Figure 5.11 – p_T -projections of the π^+ , K^+ , p and $\bar{p}$ efficiency distributions in (a) central (10% – 20%) and (b) peripheral (70% – 80%) collisions. The distributions for π^- and K^- are not shown as they overlap with those of their charge conjugates.

previous two sections. Furthermore, the triggers and associates of the reconstructed yields were required to satisfy their respective V^0 and track selections listed in Tables 5.1, 5.2 and 5.3. Finally, the generated yields consisted only of particles originating directly from the primary vertex, as opposed to the reconstructed yields. This way, the contamination of the correlation functions by secondary particles, an effect known as feed-down, could effectively be corrected for. Figure 5.10 shows the efficiency distributions of (positive) pions, kaons, protons and Λ baryons for the 10% – 20% centrality class, as a function of their p_T and η . In addition, the efficiencies of associate particles are compared directly in Fig. 5.11, which displays p_T -projections of the efficiency distributions in central and peripheral collisions.

By applying the efficiency correction factor, the particle yields recorded in data are corrected back to a generator-level state, before any loss due to material interactions or particle identification could occur. In doing so, one would expect that the yields of positive particles match those of negative particles [82], as both charge states are equally likely to be produced. However, this was found not to be the case, with positive and negative particles displaying a considerable disparity even after efficiency correction. This can be seen in Fig. 5.12a, which shows a comparison between the spectra of protons and antiprotons after efficiency correction has been applied. The ratio of positive to negative varies considerably with p_T , at times getting to be as high as 10%. Given that correlation functions of different trigger-associate charge combinations are to be compared to each other, this is an effect that needs to be corrected for.

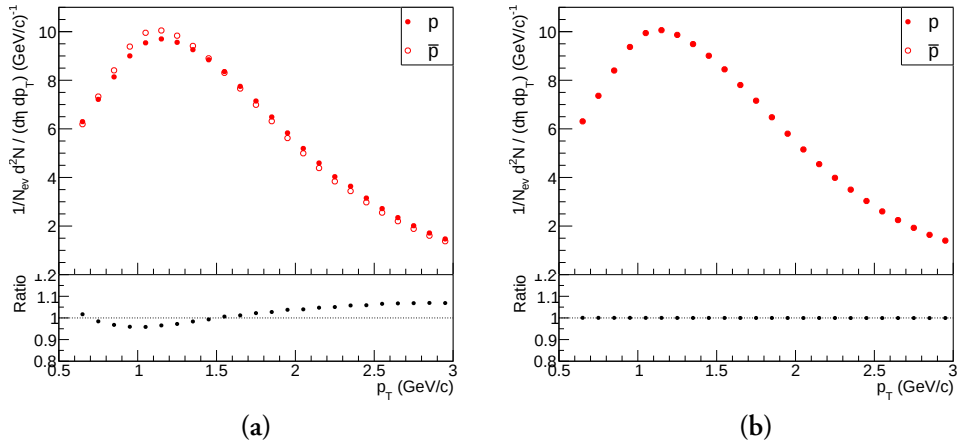


Figure 5.12 – Spectra of protons and antiprotons (a) before and (b) after applying the spectra correction factor. The ratio N_+/N_- is shown below.

Since the correlation functions are more sensitive to the number of associates than to the number of triggers (due to the scaling by $1/N_{\text{trigg}}$), it was decided to focus on applying an additional, data-driven correction to the associate particles. For pions, kaons and protons, the spectra ratios like the one shown in Fig. 5.12a were used to calculate a spectra correction factor, defined as

$$\rho_{\pm}(p_T) = \left(N_{+}(p_T) + N_{-}(p_T) \right) / 2N_{\pm}(p_T), \quad (5.6.1)$$

where the appropriate sign is used for positive and negative particles. The efficiency weighting that was discussed previously is then changed to $\rho_{\pm}(p_T)/\epsilon(p_T, \eta)$ such that the yields of both charge signs are brought to a common average. Figure 5.12b shows the spectra of protons and antiprotons after the spectra correction has been applied, indicated by a ratio of unity across p_T .

5.7 Eliminating Contamination From Track Merging: the Radial Distance Method

In previous examples of the acceptance-corrected correlation function, like the ones shown in Figs. 5.2c and 5.9, one may have noticed that the distributions display a sharp “dip” at $(\Delta\varphi, \Delta\eta) = (0, 0)$. This indicates a significant loss of trigger-associate pairs, which seemingly occurs when both particles are found close to each other in angular space. Moreover, the presence of a dip at $(0, 0)$ has been observed in other correlation studies focusing on Pb–Pb collision data collected during Run 3 [83], with the exact cause remaining unknown at the time of writing this thesis. Initially, it was assumed that the trigger-associate pair loss came about due to *track merging*, where the trajectories of an associate particle and of a trigger daughter particle end up overlapping, causing the detector to see one “merged” track rather than two individual tracks. This would then naturally lead to a loss of pairs, as either the trigger or the associate would be unable to be identified. In order to eliminate the effects of track merging, a method known as the *Radial Distance* method (also known as the $\Delta\varphi^*$ method) was employed, which is described below. While the method was ultimately unable to explain or remove the dip in its entirety, it did end up reducing the magnitude of the dip. Therefore, the decision was made to keep the method in place for the remainder of the analysis.

The Radial Distance method is a technique whereby the trajectory of a charged particle, moving through the detector, is tracked manually. As the particle traverses the detector barrel, its trajectory will follow a circular arc in the transverse plane when exposed to the detector’s magnetic field. This arc is defined in terms of a parameter known as the radius of curvature R_T , which depends on the magnetic field strength (B) as well as on the particle’s charge (z) and transverse momentum (p_T). Using the radius of curvature, one is able to determine the position of a particle at a given radius r inside the detector. This involves making an adjustment to the azimuthal angle φ to calculate a new angle called $\varphi^*(r)$, which is defined as

$$\begin{aligned} \varphi^*(r) &= \varphi + \Omega(r) = \varphi + \arcsin\left(-\frac{r}{2R_T}\right) \\ &= \varphi + \arcsin\left(-\frac{0.3Bzr}{2p_T}\right), \end{aligned} \quad (5.7.1)$$

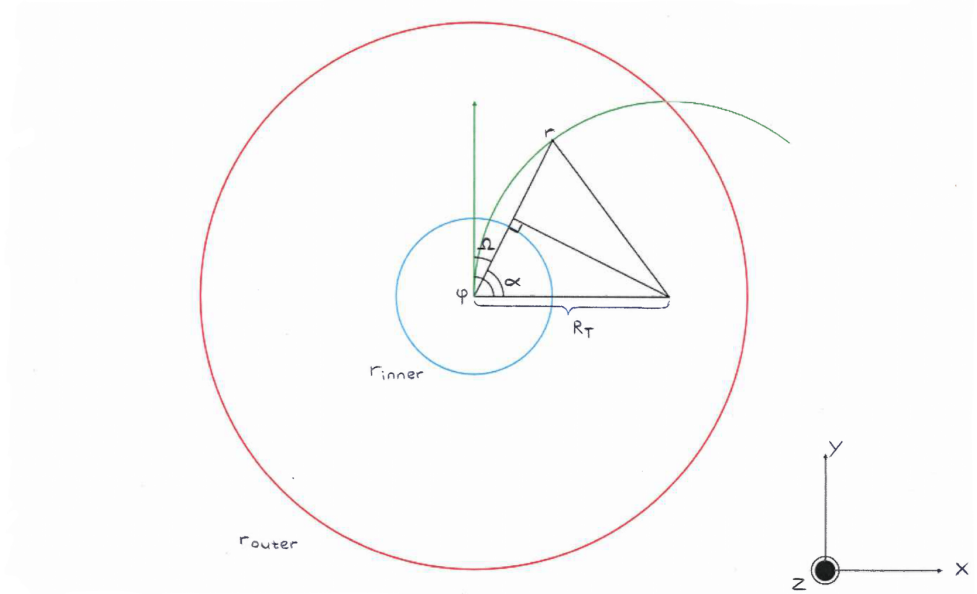


Figure 5.13 – Drawing of the principle behind the Radial Distance method. A positive particle (green arc) curves in a positively oriented magnetic field (along the z -axis) as it traverses the tracking detector (TPC), represented by an inner and outer radius (blue & red circles). Here, $\frac{r}{2R_T} = \cos(\alpha(r)) = \sin(\Omega(r))$, allowing for the original φ angle (green arrow) to be corrected such that it points to r (requiring an additional minus sign such that the angle becomes more acute).

where the formula $p_T = 0.3BzR_T$ has been used, which holds for p_T in GeV/ c , B in tesla (T), R_T in meters (m) and $|z| = e$ [84]. Here, the angle $\Omega(r) = \arcsin(-\frac{r}{2R_T})$ provides a correction to the original azimuthal angle φ , such that a point along the trajectory of the particle can be represented using coordinates $(r, \varphi^*(r))$. The exact derivation of $\Omega(r)$ is shown in Fig. 5.13. Consequently, the difference in azimuthal angle between two particles at a given distance from the center follows

$$\Delta\varphi^* = \varphi_1 + \arcsin\left(\frac{-0.3Bz_1r}{2p_{T1}}\right) - \varphi_2 - \arcsin\left(\frac{-0.3Bz_2r}{2p_{T2}}\right), \quad (5.7.2)$$

where the particles are labelled 1 and 2 respectively. Similarly to $\Delta\varphi$, the angular difference is restricted to the range $(-\frac{\pi}{2}, \frac{3\pi}{2})$. Using the Radial Distance method, the angular separation between a trigger daughter track and an associate track can be calculated at any radius within the tracking detector. This then allows for track merging effects to be reduced by establishing a cut on both $|\Delta\varphi^*|$ and $|\Delta\eta|$, ensuring that the two tracks do not overlap and remain identifiable.

To determine the cut values, the $\Delta\varphi^*$ for daughter-associate pairs was calculated at various radii within the TPC, starting from $r = 0.8$ m (inner radius) and increasing in steps of 0.01 m to $r = 2.5$ m (outer radius). Together with the daughter-associate $\Delta\eta$, their $\Delta\varphi^*(r = 0.8 \text{ m})$ and $\langle\Delta\varphi^*\rangle$ were stored in separate histograms to map their distribution. These histograms were then divided by their mixed-event counterparts to eliminate any detector acceptance effects, similarly to the correlation functions discussed in Section 5.3. Finally, the acceptance-corrected distributions were normalised to an arbitrary point far away from $(\Delta\varphi^*, \Delta\eta) = (0, 0)$, where track merging should not occur. Figure 5.14 shows these normalised histograms for the Λ proton daughter, which have been separated into opposite- (OS) and same-sign (SS) combinations of electric charge between the proton and the associate particle. As OS and SS combinations will cause the particles to either curve away from each other or travel in the same direction within the detector, different angular cuts may be necessary.

The histograms display pronounced dips when the angular separation is close to zero, corresponding to a loss of daughter-associate pairs (in turn, leading to a loss of trigger-associate pairs) due to track merging. While Figs. 5.14a and 5.14d each contain a single dip at the center of the distribution, Figs. 5.14b and 5.14c instead show two dips at positive and negative values of $\Delta\varphi^*(r = 0.8 \text{ m})$ and $\langle\Delta\varphi^*\rangle$ respectively. For the former, the positive

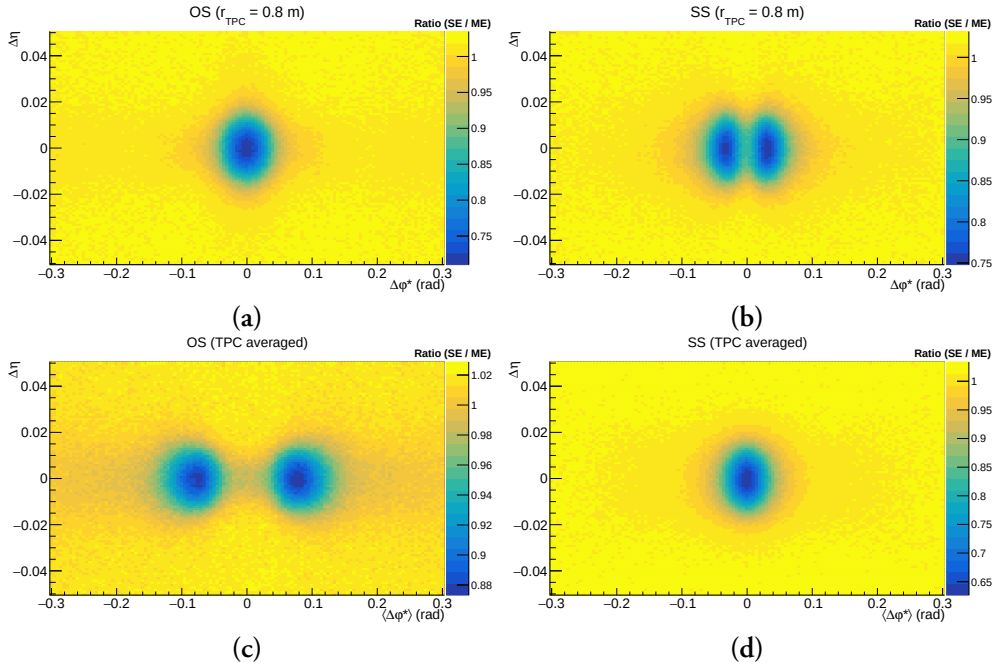


Figure 5.14 – Distribution of the angular separation between Λ proton daughters and associate particles, expressed in terms of (a, b) $\Delta\varphi^*$ at the inner radius of the TPC and (c, d) $\langle\Delta\varphi^*\rangle$ averaged over the full TPC radius, for OS and SS pairs. Several dips can be seen in the distributions, indicating a loss of pairs due to track merging effects.

and negative dips correspond to the positive and negative SS pairs while for the latter, the dips belong to positive and negative values of the angular separation. It should be noted that the magnitude of the dips in Fig. 5.14c is considerably lower than for the other three distributions, which is unsurprising given that OS pairs will curve away from each other.

Since the Λ baryon decays to both a pion and a proton, similar histograms like the ones shown in Fig. 5.14 were produced for the pion daughters. However, the pair loss was found to be significantly lower compared to protons, and no cuts were deemed necessary. Instead, Figs. 5.14a and 5.14d were used to establish a cut on the angular separation between proton daughters and associates to remove track merging effects from the correlation functions. The cut values were selected as the region where the SE/ME ratio would fall below 97%, leading to $|\Delta\varphi^*(r = 0.8 \text{ m})| > 0.09 \text{ rad}$ for opposite-sign pairs and $|\langle\Delta\varphi^*\rangle| > 0.095 \text{ rad}$ for same-sign pairs, in addition to $|\Delta\eta| > 0.023$ for all daughter-associate pairs⁵. The impact of these cuts can be observed in Fig. 5.15, showing the $(\Lambda\bar{p} + \bar{\Lambda}p)/2$ correlation function before and after the cuts are applied. While the central dip remains present, its magnitude has clearly decreased.

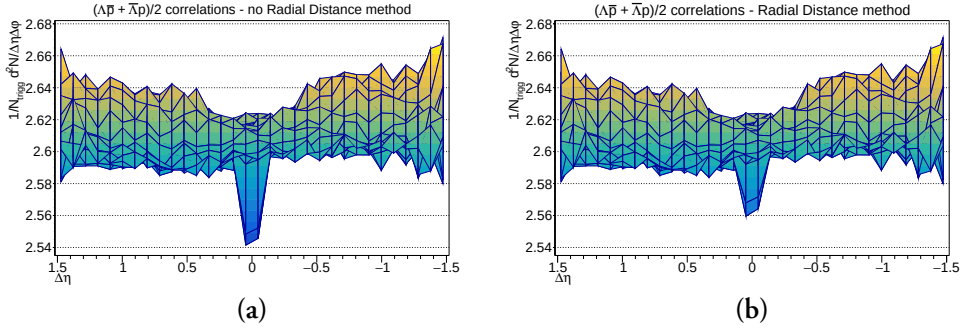


Figure 5.15 – Frontal view ($\Delta\varphi = -\frac{\pi}{2}$) of $(\Lambda\bar{p} + \bar{\Lambda}p)/2$ correlations (a) before and (b) after the Radial Distance method cuts are applied. The decrease in the dip’s magnitude is clearly visible.

5.8 Systematic Uncertainties

As in any experiment, a measurement of some physical quantity must always be accompanied by an associated uncertainty, giving insight into the measurement’s reliability. In general, uncertainties can be broken down into statistical and systematic components, each having a different origin. The former appears due to limitations in the statistical power of the sample, and can be reduced by increasing the sample size or by repeating the experiment multiple times and combining the results. Systematic uncertainties, on the other hand, remain the same regardless of how many times an experiment is repeated, as they arise due to imperfections or uncertainties in the experimental setup or in the method itself.

⁵These cuts are responsible for the dip at $(0, 0)$ in the same-event and mixed-event correlations shown in Figs. 5.2a and 5.2b, and require that the latter is normalised at $(\pi, 0)$.

While the practice of calculating a measurement's statistical uncertainty is well-established, this is not the case for the systematic component. Ideally, one would estimate the systematic uncertainty by repeating the measurement using a different experimental setup and comparing the new results with those from the original experiment. This is often not possible in practice however, as large-scale experimental setups (like the LHC and the ALICE detector) are unique in the world and cannot be replicated. Instead, the recommended procedure involves repeating the analysis while applying small variations to the cuts and input parameters used throughout the method. This will then be reflected in the final results, and the systematic uncertainty may be estimated by comparing the output from the altered configuration with the one from the default configuration.

For this thesis, the following variations to the analysis parameters⁶ were studied for determining the systematic uncertainties:

- Use a looser and tighter set of V^0 and daughter track cuts for the trigger particles. These sets of cuts are listed in Table 5.4.
- Use a tighter set of track cuts for the associate particles. These sets of cuts are listed in Table 5.5. Due to the implementation of the original track cuts via the `requireGlobalTrackInFilter()` function, a looser set of track cuts could not be used.
- Use a tighter PID selection for the associated particles by reducing the upper and lower limits of the $n\sigma$ cuts in Table 5.2 by 0.5 (for a total reduction of 1.0). This is done independently for the TPC and TOF cuts.
- Use a more narrow range for the z-coordinate of the primary vertex when selecting events, $|vtx_z| < 8.0$ cm.
- Change the definition of the SGNL and SB invariant mass windows to $(-4.5\sigma \leq M_{inv} \leq 4.5\sigma)$ and $(-9\sigma \leq M_{inv} < -4.5\sigma \ \& \ 4.5\sigma < M_{inv} \leq 9\sigma)$, respectively.

Table 5.4 – Variations on the V^0 and daughter track cuts used for trigger particles, separated into loose and tight selections. If an entry in the table is empty, only one type of variation was considered.

Cut	Loose	Tight
Proper lifetime	$mL/p < 33$ cm	$mL/p < 27$ cm
Cosine of pointing angle	$\cos \theta_{PA} > 0.994$	$\cos \theta_{PA} > 0.996$
DCA between V^0 daughters		$DCA_{d-d} < 0.8\sigma$
Number of TPC crossed rows		$N_{TS} > 75$
Pion daughter DCA	$DCA_{\pi-PV} > 0.25$ cm	$DCA_{\pi-PV} > 0.17$ cm
Proton daughter DCA	$DCA_{p-PV} > 0.07$ cm	

⁶The cuts and input parameters were varied independently from each other.

Table 5.5 – Variations on the track cuts used for associate particles. Due to the implementation of the default track cuts via the `requireGlobalTrackInFilter()` function, only tighter cuts were considered.

Cut	Default value	Systematic variation
TPC goodness-of-fit χ^2 per cluster	$\chi^2/N_{cl} < 4$	$\chi^2/N_{cl} < 3$
ITS goodness-of-fit χ^2 per cluster	$\chi^2/N_{cl} < 36$	$\chi^2/N_{cl} < 34$
Longitudinal DCA	$DCA_z \leq 2$ cm	$DCA_z \leq 1$ cm

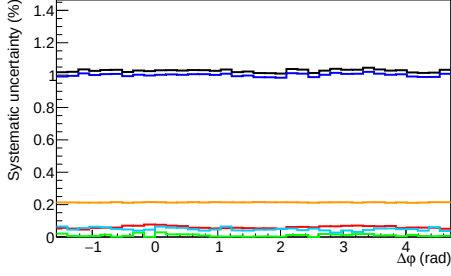
Since each configuration still uses the same binning for the correlation and balance function histograms as the default configuration, the systematic uncertainty can be calculated and applied to each bin individually. The systematic uncertainty is defined as

$$\sigma_{syst}^i = \frac{|\text{Var}^i - \text{Def}^i|}{\text{Def}^i}, \quad (5.8.1)$$

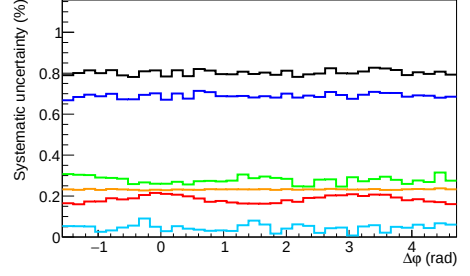
where Var^i and Def^i are the values of the i -th bin for the variation and default configurations. If an analysis parameter has both a loose and tight cut, the average between their respective systematic uncertainties is taken. It should be noted that for the balance functions, the absolute uncertainty ($\sigma_{syst}^i = |\text{Var}^i - \text{Def}^i|$) was used rather than the fractional uncertainty. This is a purely stylistic choice, since the balance functions will be quite close to zero and relatively small variations may display a disproportionally large fractional uncertainty. Finally, the total systematic uncertainty for each bin was obtained by summing the contributions from all variations in quadrature.

Summary of Systematic Uncertainties

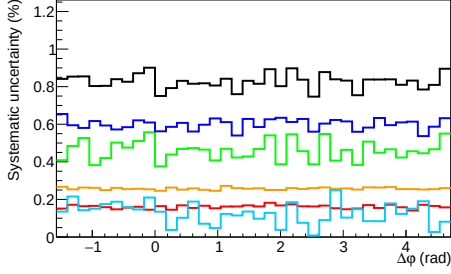
A summary of the systematic uncertainties for the correlation and balance functions at different centrality classes is presented below. Summaries of the systematic uncertainties for opposite-sign correlations, and differences between opposite- and same-sign correlations are shown in Fig. 5.16 for $\Lambda - \pi$ correlations, Fig. 5.17 for $\Lambda - K$ correlations and Fig. 5.18 for $\Lambda - p$ correlations. The same-sign correlations have been omitted from this chapter, as they are qualitatively and quantitatively similar to the opposite-sign correlations. However, summaries of the opposite-sign correlations, same-sign correlations and balance functions for all centrality classes are displayed in Appendix A.39 through A.50. Only results for projections in $\Delta\varphi$ are shown in the figures. The systematic uncertainties for projections in $\Delta\eta$ were calculated separately. The full range of variations of projections in $\Delta\varphi$, near-side $\Delta\eta$ and away-side $\Delta\eta$ is summarized in Table 5.6.



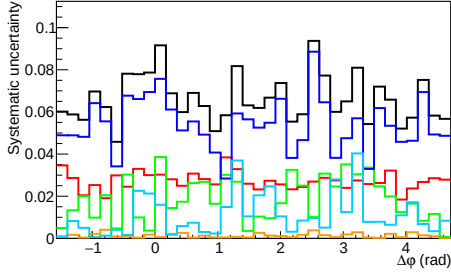
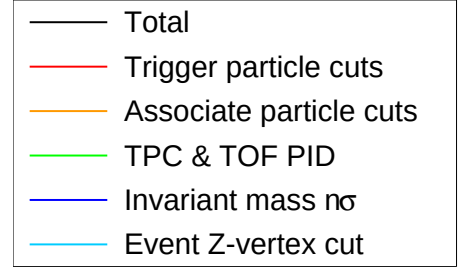
(a)



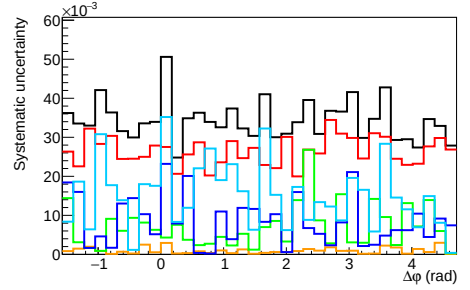
(b)



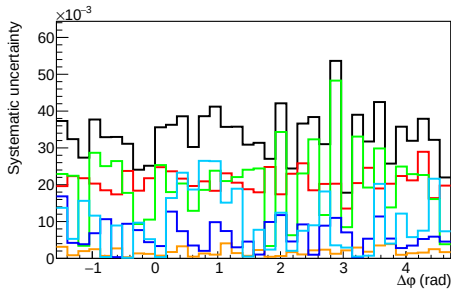
(c)



(d)

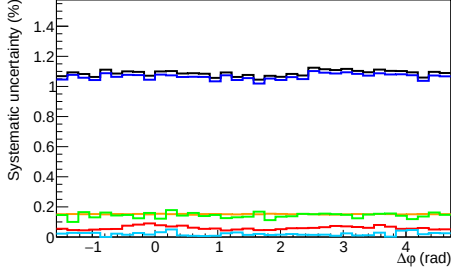


(e)

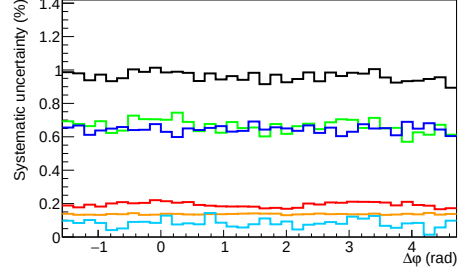


(f)

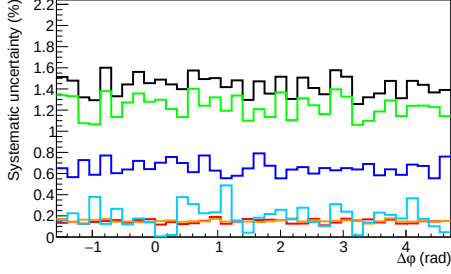
Figure 5.16 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, b, c) opposite-sign $\Lambda - \pi$ correlations and (d, e, f) $\Lambda - \pi$ balance functions. Centrality classes are (a, d) 20% – 30%, (b, e) 40% – 50% and (c, f) 60% – 70%.



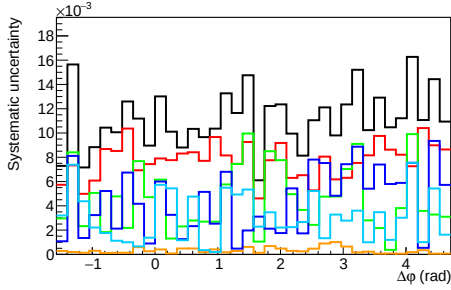
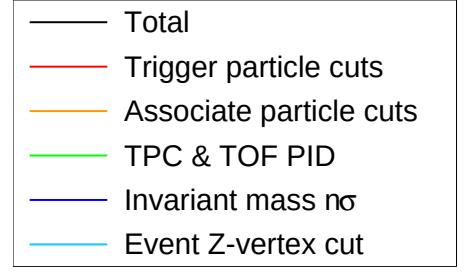
(a)



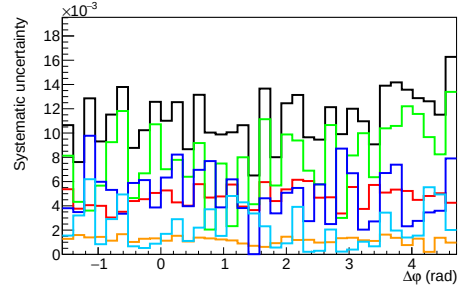
(b)



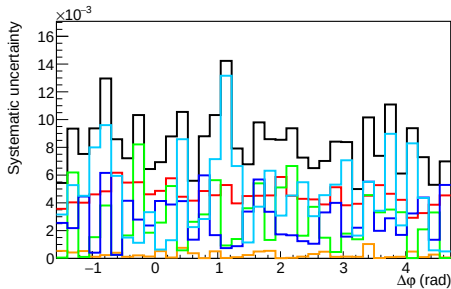
(c)



(d)

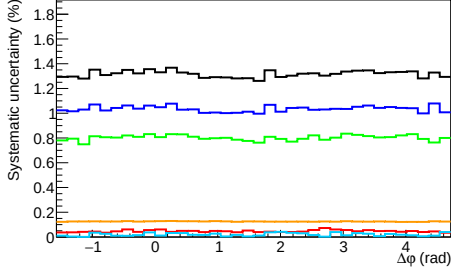


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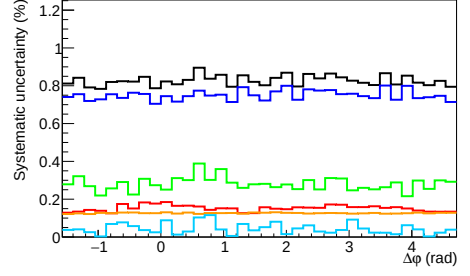


(f)

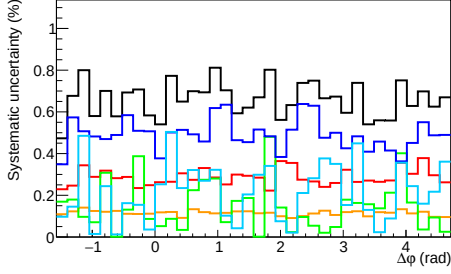
Figure 5.17 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, b, c) opposite-sign $\Lambda - K$ correlations and (d, e, f) $\Lambda - K$ balance functions. Centrality classes are (a, d) 20% – 30%, (b, e) 40% – 50% and (c, f) 60% – 70%.



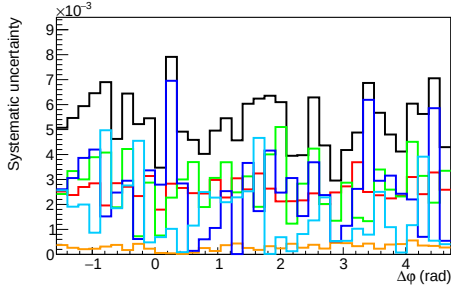
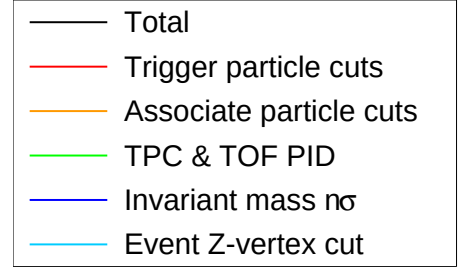
(a)



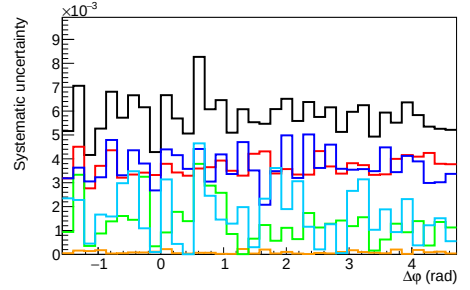
(b)



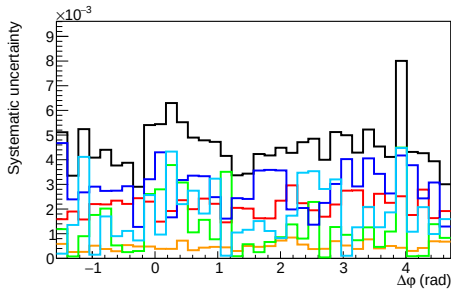
(c)



(d)



(e)



(f)

Figure 5.18 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, b, c) opposite-sign $\Lambda - p$ correlations and (d, e, f) $\Lambda - p$ balance functions. Centrality classes are (a, d) 20% – 30%, (b, e) 40% – 50% and (c, f) 60% – 70%.

Table 5.6 – Summary of all systematic uncertainties. The ranges are the minimum and maximum values of each quantity across all centrality classes. For the balance functions, absolute uncertainties are given. Legend: OS = opposite sign, SS = same sign.

Systematic effect	OS π	SS π	OS K
V^0 topological cuts	0.02 – 1.62%	0.03 – 1.26%	0.04 – 3.62%
π , K, p track cuts	0.01 – 0.32%	0.14 – 0.58%	0.01 – 0.81%
PID cuts	0 – 4.45%	0 – 2.16%	0.02 – 8.44%
vtx_z range	0.01 – 2.09%	0.18 – 2.20%	0 – 2.24%
Invariant mass windows	0 – 3.53%	0 – 4.57%	0 – 7.23%
Total	0.44 – 4.81%	0.75 – 4.66%	0.87 – 11.30%

Systematic effect	SS K	OS p	SS p
V^0 topological cuts	0.04 – 2.77%	0.03 – 5.77%	0.04 – 3.37%
π , K, p track cuts	0 – 0.24%	0 – 0.38%	0.01% – 0.85%
PID cuts	0 – 11.37%	0 – 4.36%	0 – 5.49%
vtx_z range	0 – 2.28%	0 – 2.23%	0.01 – 3.05%
Invariant mass windows	0 – 8.48%	0 – 7.27%	0 – 7.80%
Total	0.71 – 13.29%	0.47 – 9.30%	0.57 – 9.05%

Systematic effect	OS - SS π ($\times 10^{-2}$)	OS - SS K ($\times 10^{-2}$)	OS - SS p ($\times 10^{-2}$)
V^0 topological cuts	1.0 – 20	0.2 – 5.6	0.1 – 2.3
π , K, p track cuts	0 – 4.0	0 – 0.8	0 – 0.2
PID cuts	0 – 23	0 – 9.0	0 – 1.8
vtx_z range	0 – 36	0 – 4.2	0 – 2.6
Invariant mass windows	0 – 18	0 – 4.3	0 – 1.3
Total	1.8 – 39	0.4 – 11	0.2 – 3.4

Part III

Author's Measurements

Chapter 6

Correlation & Balance Results

6.1 Λ -Hadron Correlation Functions

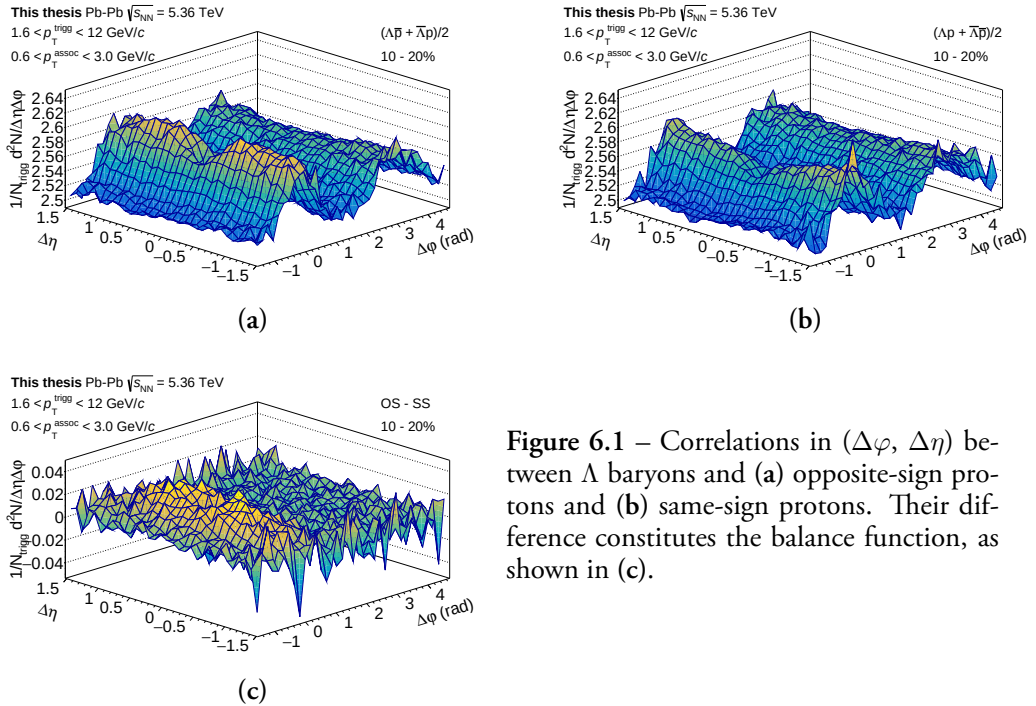


Figure 6.1 – Correlations in $(\Delta\phi, \Delta\eta)$ between Λ baryons and (a) opposite-sign protons and (b) same-sign protons. Their difference constitutes the balance function, as shown in (c).

Angular correlation functions between $\Lambda - p$, $\Lambda - K$ and $\Lambda - \pi$ in $(\Delta\phi, \Delta\eta)$ space in the 10% – 20% centrality class, measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.36$ TeV in ALICE, are presented in Figs. 6.1, 6.2 and 6.3. In addition, the balance function, defined as the difference between opposite- and same-sign correlations, is shown. Comparing the

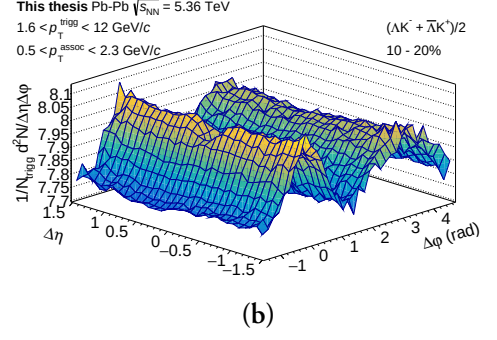
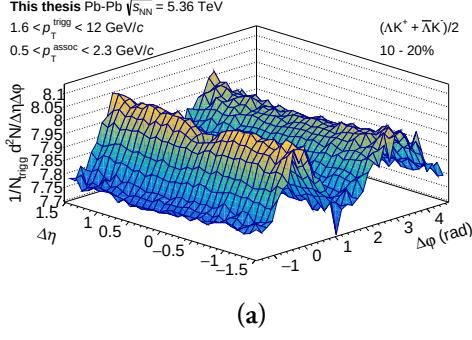


Figure 6.2 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a) opposite-sign kaons and (b) same-sign kaons. Their difference constitutes the balance function, as shown in (c).

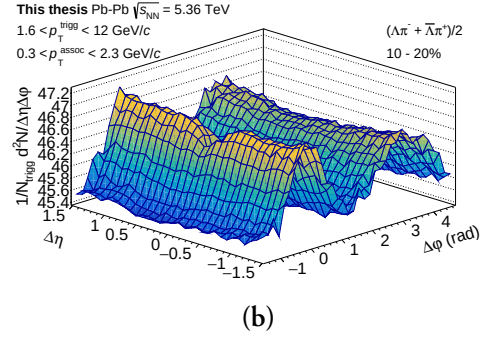
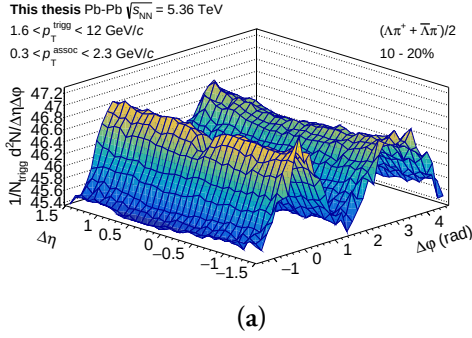
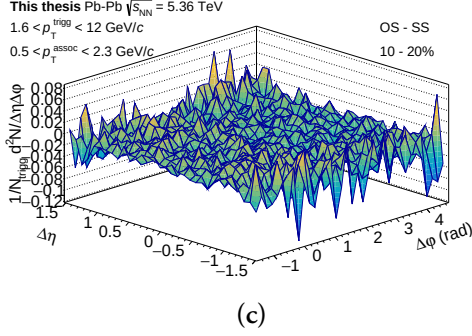
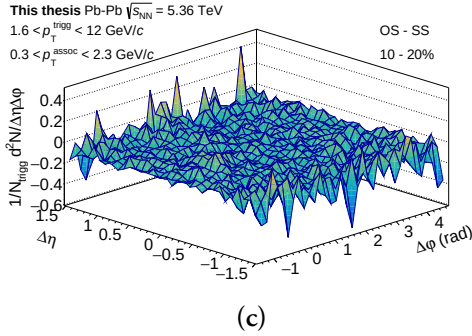


Figure 6.3 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a) opposite-sign pions and (b) same-sign pions. Their difference constitutes the balance function, as shown in (c).



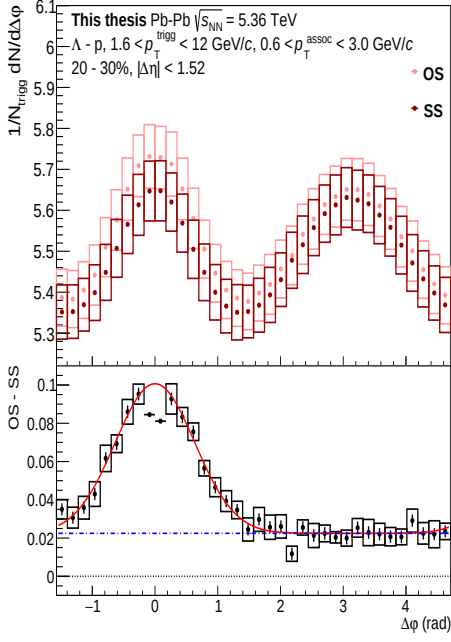
correlation functions for the three associates, some common features can be identified. These include two ridges that extend out into $\Delta\eta$ within the distribution's *near-side* and *away-side*, corresponding to the regions with $-\frac{\pi}{2} < \Delta\varphi \leq \frac{\pi}{2}$ and $\frac{\pi}{2} < \Delta\varphi < \frac{3\pi}{2}$, respectively. These regions are shown on the left- and right-hand side of each figure, with the ridges arising due to the presence of elliptic flow within the medium. Furthermore, the slight difference in magnitude between the near- and away-side ridges is caused by interference between elliptic and triangular flow, which will be constructive at $\Delta\varphi = 0$ and destructive at $\Delta\varphi = \pi$. Since the amplitude of v_3 is considerably smaller than that of v_2 , this results in a slight reduction of the away-side ridge compared to the near-side ridge. Finally, all distributions display the track merging dip at $(\Delta\varphi, \Delta\eta) = (0, 0)$ that was discussed in Section 5.7. Despite the implementation of the Radial Distance method, the phenomenon remains present in the distributions. The full set of opposite- and same-sign correlation functions for all centrality classes, as well as the corresponding balance functions, can be found in Appendix A.1 through A.9.

For $\Lambda - p$, the difference between the opposite-sign correlations and same-sign correlations is the most apparent, with the near-side of the former being considerably greater in magnitude compared to the latter. This is reflected in the balance function, which shows a peak at the near-side indicating strong correlations between triggers and associates produced in close proximity to each other. Meanwhile, the away-side region appears nearly identical between opposite- and same-sign correlations, with the corresponding region in the balance function thus being mostly flat. This indicates that little to no charge balancing is present, and balancing trigger-associate pairs are more likely to travel in the same direction than in the opposite direction. For $\Lambda - K$, the opposite- and same-sign correlations are more comparable, and appear almost identical. Furthermore, the resulting balance function is almost entirely flat in both $\Delta\varphi$ and $\Delta\eta$. This seems unusual, as it implies little to no balancing effects for strangeness, despite its status as a conserved quantity. However, the next section will reveal that the balance function does exhibit a sign of quantum number balancing, albeit at a much lower magnitude compared to $\Lambda - p$ correlations.

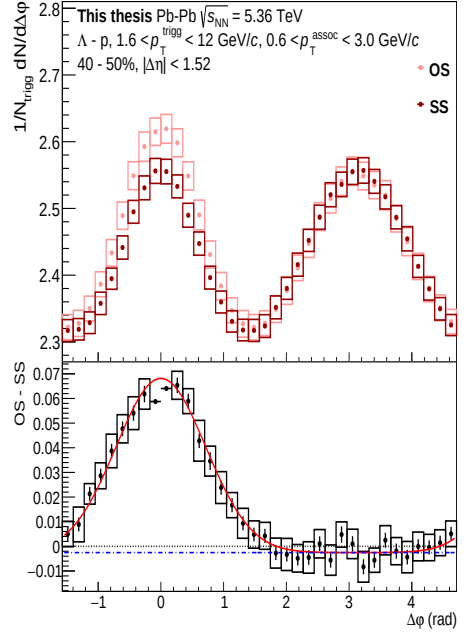
For $\Lambda - \pi$, a similar situation to the $\Lambda - K$ correlations is observed, with nearly identical correlation functions and a balance function that is essentially flat. Unlike the kaons however, this is the expected behaviour for pions as they are free from strangeness and baryon number balancing. Furthermore, the next section will reveal that the balance function exhibits no observable pattern, as opposed to the $\Lambda - K$ correlations.

6.2 $\Delta\varphi$ & $\Delta\eta$ Projections

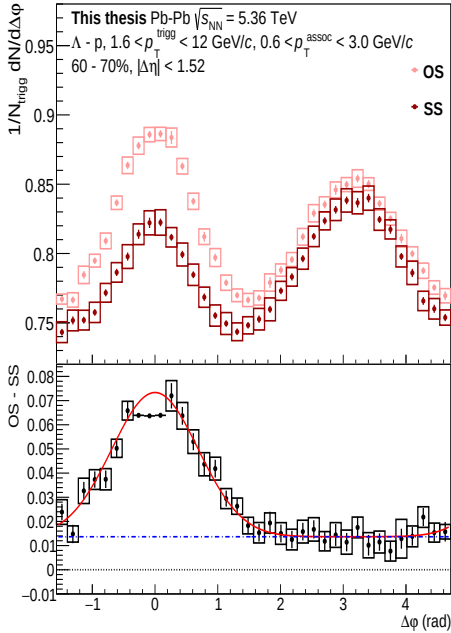
In order to study the evolution of the correlation and balance functions from central to peripheral events, the $(\Delta\varphi, \Delta\eta)$ distributions are projected in $\Delta\varphi$ and $\Delta\eta$. Examples of such projections for $\Lambda - p$, $\Lambda - K$ and $\Lambda - \pi$ correlations in three different centrality classes are shown in Figs. 6.4, 6.5, 6.6, 6.7, 6.8, 6.9. For each projection, the top panel contains the opposite- and same-sign correlation functions and the bottom panel depicts the resulting balance function including, if applicable, a fit function. The full set of projections in $\Delta\varphi$ and in $\Delta\eta$ on the near- and away-side can be found in Appendix A.10 through A.27.



(a)

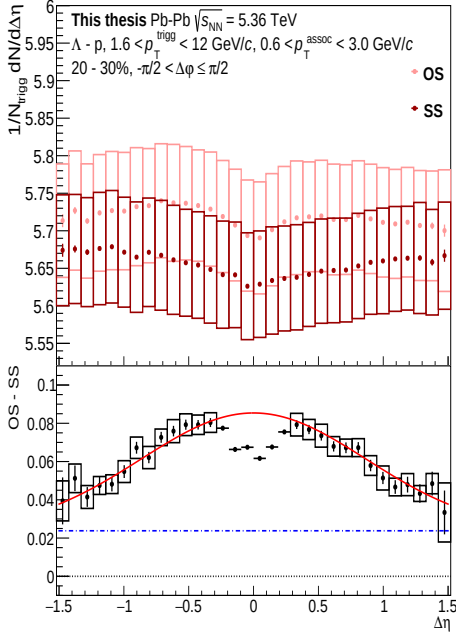


(b)

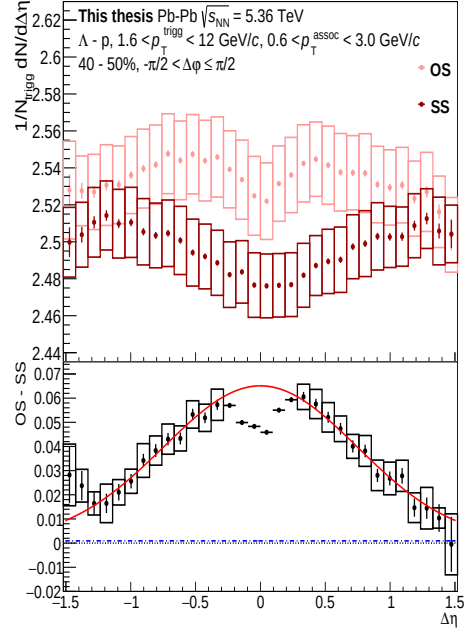


(c)

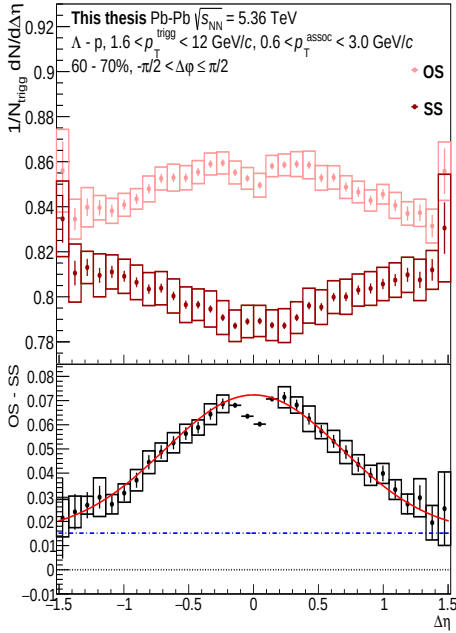
Figure 6.4 – $\Delta\phi$ projection of correlations between Λ baryons and protons for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations, together with the fit to a Gaussian (solid red line) on a pedestal (dashed & dotted blue line). Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.



(a)

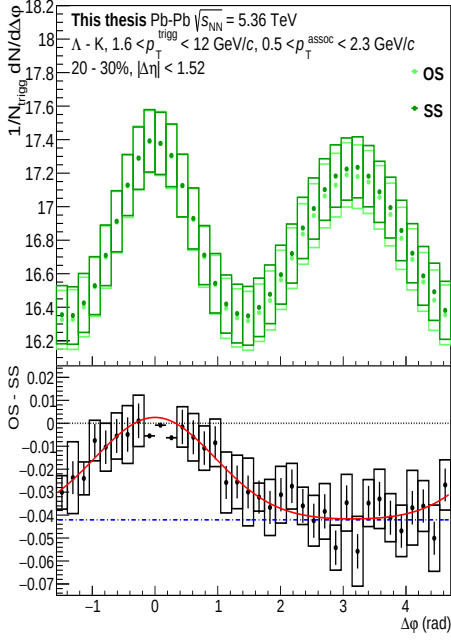


(b)

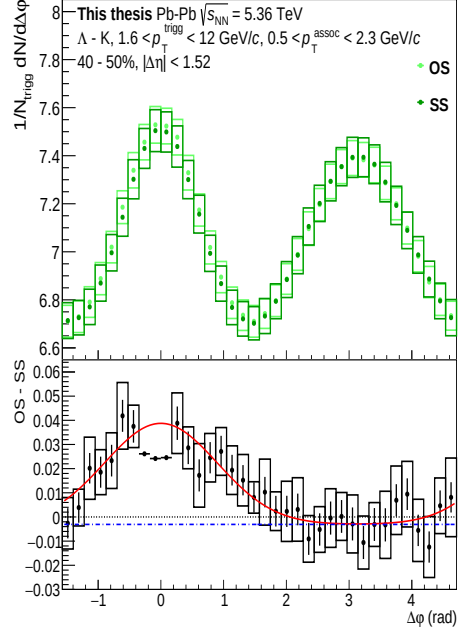


(c)

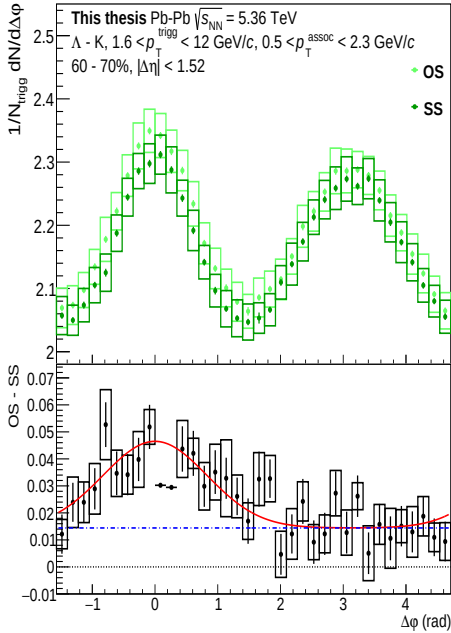
Figure 6.5 – $\Delta\eta$ near-side projection of correlations between Λ baryons and protons for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations, together with the fit to a Gaussian (solid red line) on a pedestal (dashed & dotted blue line). Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.



(a)



(b)



(c)

Figure 6.6 – $\Delta\phi$ projection of correlations between Λ baryons and kaons for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations, together with the fit to a Gaussian (solid red line) on a pedestal (dashed & dotted blue line). Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.

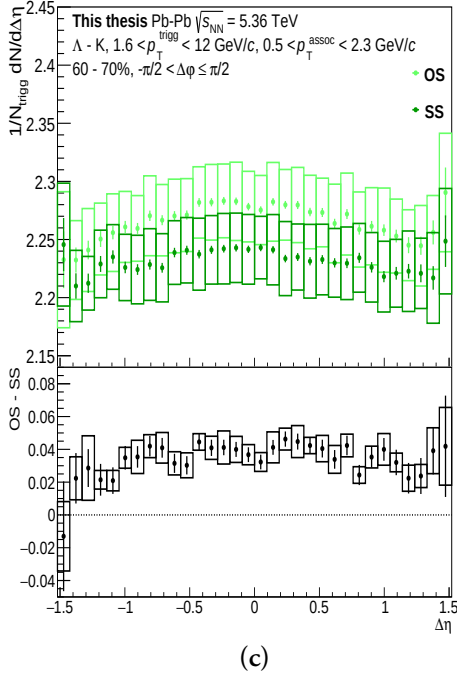
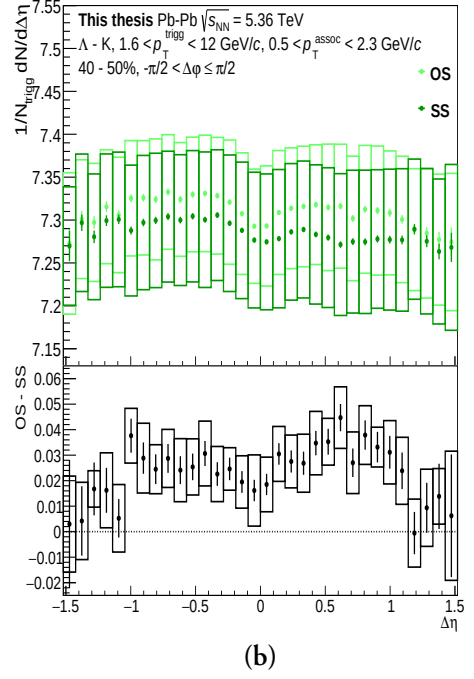
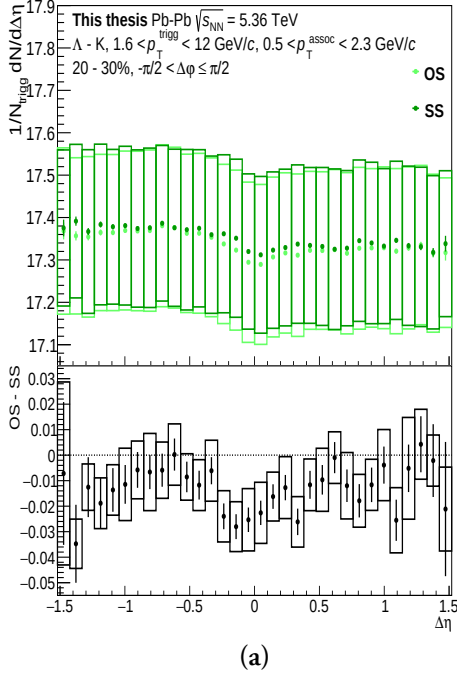
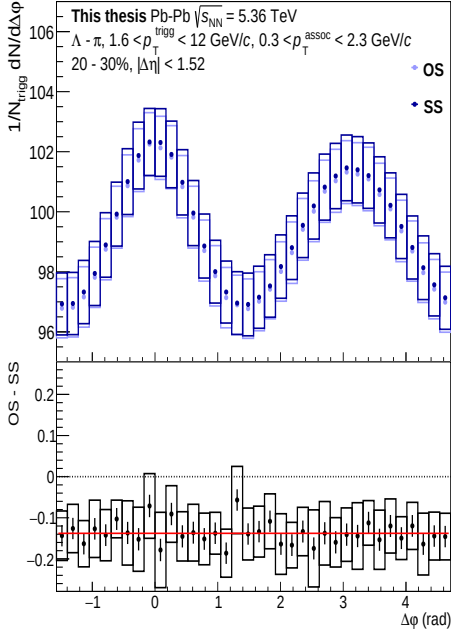
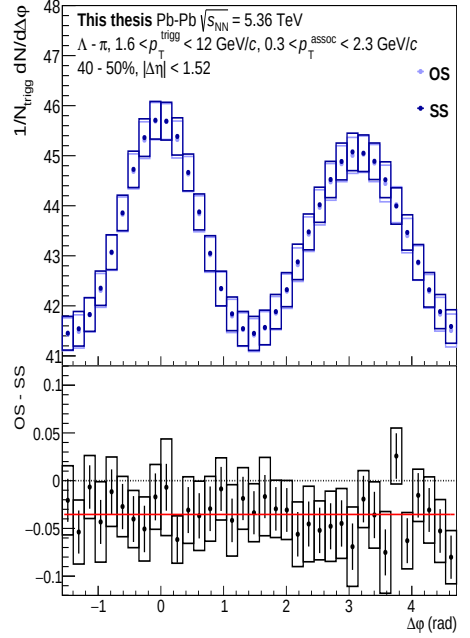


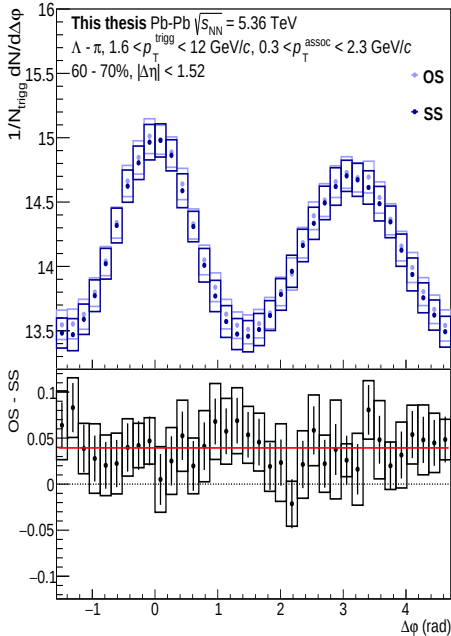
Figure 6.7 – $\Delta\eta$ near-side projection of correlations between Λ baryons and kaons for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations. Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.



(a)



(b)



(c)

Figure 6.8 – $\Delta\phi$ projection of correlations between Λ baryons and pions for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations, together with the fit to a constant parameter (solid red line). Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.

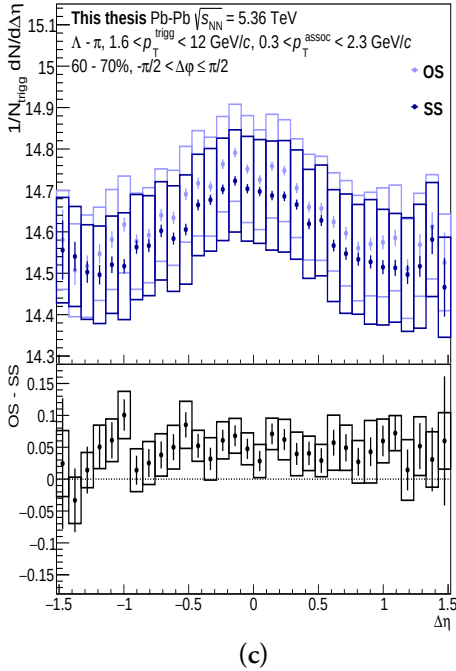
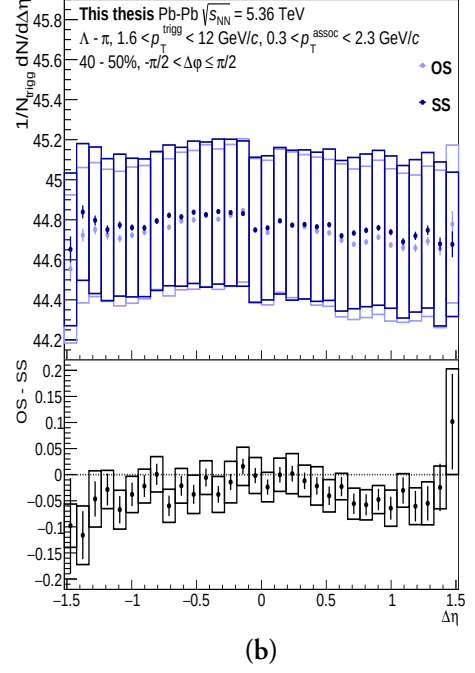
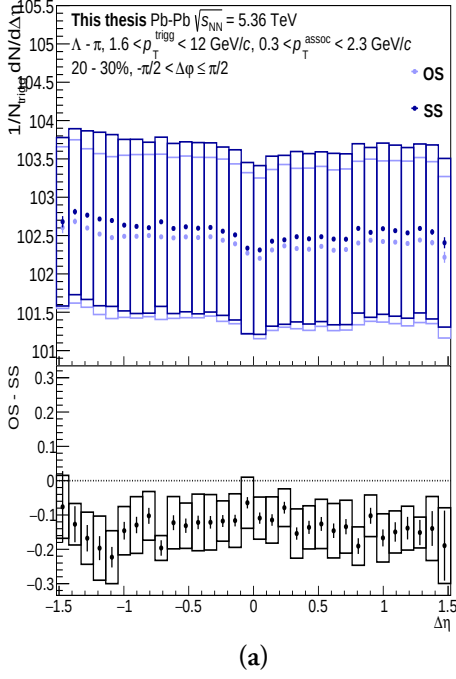


Figure 6.9 – $\Delta\eta$ near-side projection of correlations between Λ baryons and pions for different centrality classes. The bottom panel shows the balance function, defined as the difference between opposite-sign (OS) and same-sign (SS) correlations. Statistical and systematic errors are marked with bars and boxes, respectively. Centrality classes are (a) 20% – 30%, (b) 40% – 50% and (c) 60% – 70%.

For the $\Lambda - p$ correlations displayed in Figs. 6.4 and 6.5, the difference between the opposite- and same-sign correlations that was pointed out earlier is clear to see. Within the $\Delta\varphi$ projections in Fig. 6.4, the opposite-sign correlations show an increase in magnitude on the near-side compared to the same-sign correlations, with the difference on the away-side being much smaller. However, there is a stark difference between the two correlation functions in the $\Delta\eta$ projections shown in Fig. 6.5. Here, the same-sign correlations depict a large overall dip, which spans the entire $\Delta\eta$ -axis range. By contrast, the opposite-sign correlations show a general increase in magnitude as $\Delta\eta$ gets closer to zero, apart from the smaller track merging dip that was pointed out and discussed earlier in Section 6.1. The large overall dip in the same-sign correlations will be discussed in the next chapter. Nevertheless, taking the difference between the opposite- and same-sign correlations yields the balance functions, which show a peak at $\Delta\varphi = 0$ and $\Delta\eta = 0$ in each projection. This peak is modelled using a Gaussian distribution on a constant (flat) background¹, making it possible to determine the width and integrated yields of the balance functions. It should be mentioned that during the fitting procedure, several datapoints within the balance functions were excluded from the fit. These datapoints, shown in the graphs without error bars, correspond to the track merging dip near $(\Delta\varphi, \Delta\eta) = (0, 0)$, and are considered unphysical.

For the $\Lambda - K$ correlations shown in Figs. 6.6 and 6.7, the difference between the opposite- and same-sign correlations is far less apparent, particularly when compared to $\Lambda - p$. Furthermore, the behaviour of the two correlation functions remains similar in both the $\Delta\varphi$ and $\Delta\eta$ projections, unlike what was observed for protons. However, one major difference between $\Lambda - K$ and $\Lambda - p$ is that, for some centrality classes, the former's same-sign correlations are actually greater in magnitude than its opposite-sign correlations. As was mentioned earlier, this is an unexpected outcome, and results in some centrality classes having a negatively-valued balance function (discussed in Section 7.4). Despite this, the $\Delta\varphi$ projections in Fig. 6.6 still show a peak at $\Delta\varphi = 0$, with the balance functions able to be fitted with the same function that was used for protons. The same does not hold true for the $\Delta\eta$ projections in Fig. 6.7, where a successful fit could not be applied.

For the $\Lambda - \pi$ correlations shown in Figs. 6.8 and 6.9, very slight differences between the opposite- and same-sign correlations are observed, similarly to the $\Lambda - K$ correlations. In addition, the two correlation functions continue to behave in the same way across $\Delta\varphi$ and $\Delta\eta$. Unlike the $\Lambda - p$ and $\Lambda - K$ correlations however, the balance functions depict no observable pattern, and remain approximately constant. This can be seen in Fig. 6.8, where the balance functions have been fitted with a constant parameter.

6.3 Centrality Dependent Results

Applying the Gaussian fits to the $\Delta\varphi$ and $\Delta\eta$ projections in Figs. 6.4, 6.5 and 6.6 provides insight into the behaviour of the correlation and balance functions when moving from central to peripheral events. In particular, measuring the widths and integrated yields of the distributions allows for the centrality evolution of quantum number balancing in Pb–Pb collisions to be quantified. This evolution is shown in Fig. 6.10, where the widths (standard deviation) and integrated yields are presented as a function of centrality.

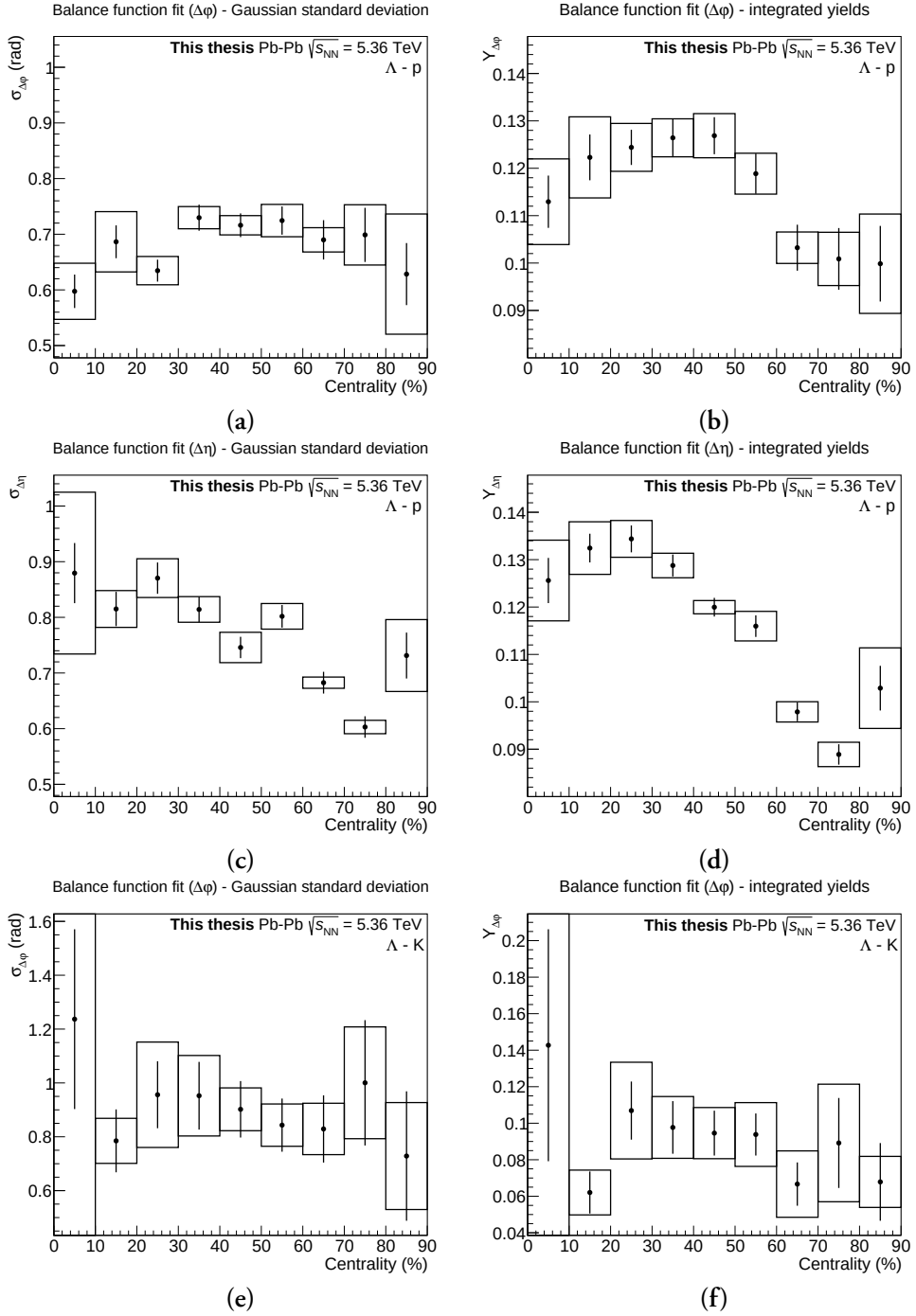


Figure 6.10 – Balance function width (standard deviation) and integrated yields for (a, b) $\Lambda - p$ in $\Delta\phi$, (c, d) $\Lambda - p$ in $\Delta\eta$ and (e, f) $\Lambda - K$ in $\Delta\phi$, as a function of centrality. Statistical and systematic errors are marked with bars and boxes, respectively.

Here, the width of the balance function provides a measure of the average angular separation between balancing pairs, with the integrated yields representing the fractional number of balancing pairs observed in the detector. In the ideal scenario where all particles with balancing quantum numbers are observed and detected, the integral would be unity. However, the number of particles that can be detected is limited by both the detector and the analysis. For example, the detector is unable to directly observe particles that are neutral, despite some of them carrying strangeness or baryon number. Furthermore, the events and particles in this analysis must satisfy several cuts and restrictions before being used in the correlation and balance functions. As a result, the integral will generally be less than one.

For the $\Delta\varphi$ projections of the $\Lambda - p$ balance functions shown in Figs. 6.10a and 6.10b, the widths and integrated yields of the distributions exhibit an observable dependence on the event centrality. This is to be expected, as the available phase space in $\Delta\varphi$ depends on the size of the overlapping area between colliding nuclei. Starting from central events, both graphs display an increase in their respective quantities before reaching a peak at around the 40% – 50% centrality interval. Afterwards, a slight discrepancy in their behaviour is observed, with Fig. 6.10b showing a sizeable decrease when moving to peripheral events as opposed to Fig. 6.10a, where the decrease is much less steep. As for the $\Delta\eta$ projections of the $\Lambda - p$ balance functions shown in Figs. 6.10c and 6.10d, the behaviour is slightly different. Here, both the width and integrated yields of the balance function decrease almost uniformly with increasing event centrality. This result appears unusual since the available phase space in $\Delta\eta$ should not depend on the size of the collision area, as opposed to $\Delta\varphi$. An interpretation of these results will be given in the next chapter.

For the $\Delta\varphi$ projections of the $\Lambda - K$ balance functions shown in Figs. 6.10e and 6.10f, the overall behaviour is considerably different compared to protons. Here, both the width and integrated yields appear to be largely independent of the event centrality, with both graphs displaying little to no evolution when moving from central to peripheral events. This seems very surprising, considering the earlier argument that the $\Delta\varphi$ projections are expected to depend strongly on the event centrality. The next chapter will discuss these results in more detail.

¹For $\Delta\eta$, the shift parameter was obtained by fitting the balance function on the away-side with a constant parameter. This constant would then be used in the near-side fit.

Chapter 7

Discussion of Results, Conclusions and Outlook

7.1 Summary of the Results & Research Goals

This chapter is dedicated to discussing and interpreting the results presented in this thesis, as well as to offering suggestions on how future analyses may build upon this project. The previous chapter presented the centrality-dependent $\Lambda - p$, $\Lambda - K$ and $\Lambda - \pi$ angular correlation functions, measured in Pb–Pb collisions at the LHC at a center-of-mass energy of $\sqrt{s_{NN}} = 5.36$ TeV by the ALICE detector. As was discussed at the beginning of Chapter 5, the $\Lambda - h$ correlation functions were separated into $Q - \bar{Q}$, $\bar{Q} - Q$, $Q - Q$ and $\bar{Q} - \bar{Q}$ correlations, where Q corresponds to the particle’s quantum number of interest (strangeness for $\Lambda - K$ correlations and baryon number for $\Lambda - p$ correlations, with $\Lambda - \pi$ correlations using the same electric charge pairing as $\Lambda - K$). Taking the average between charge conjugates for opposite- and same-sign quantum number pairings yields the opposite- and same-sign correlation functions.

Due to the additive nature of the correlation functions, the balance function may be obtained by taking the difference between the two. As any form of underlying correlation apart from those originating from quantum number balancing is expected to be identical between opposite- and same-sign correlations, the resulting balance function is predicted to be a distribution consisting purely of correlations arising due to the conservation of quantum numbers. The correlation and balance functions were displayed in $(\Delta\varphi, \Delta\eta)$ space, as well as projected in $\Delta\varphi$ and in $\Delta\eta$ on the near-side. Furthermore, the centrality evolution of the balance function width (standard deviation) and integrated yields were shown for the $\Lambda - p$ balance function in $\Delta\varphi$ and $\Delta\eta$, as well as for the $\Lambda - K$ balance function in $\Delta\varphi$. The main purpose of these results, and of this research project as a whole, has been to study the production mechanisms of strangeness and baryon number in an environment where QGP formation is expected to occur.

The chapter will examine the $\Lambda - p$, $\Lambda - K$ and $\Lambda - \pi$ correlation and balance functions individually, including the results from the fit to the balance functions wherever applicable. Moreover, they will be discussed in the context of both theoretical expectations and previous results in the field. Afterwards, the conclusion and outlook of this thesis will be presented.

7.2 $\Lambda - p$ Correlations

Of all the $\Lambda - h$ correlation functions presented in this thesis, the results from $\Lambda - p$ correlations appear the most striking. Within each centrality interval, the opposite-sign correlations are considerably greater in magnitude compared to the same-sign correlations, particularly on the near-side. As was explained earlier, the sinusoidal shape of the correlation functions in $\Delta\varphi$ (see Fig. 6.4) arises due to the presence of elliptic flow in the medium. Furthermore, the opposite-sign correlations show a slight discrepancy between the peaks, which is attributable to the constructive and destructive interference between elliptic and triangular flow at $\Delta\varphi = 0$ and $\Delta\varphi = \pi$, respectively. However, this behaviour is seemingly reversed for the same-sign correlations, with the away-side peak being slightly larger than the near-side peak. This mirrors what was seen in the $\Delta\eta$ near-side projections in Fig. 6.5, where a significant depression in the same-sign correlation functions is observed. The depression, which covers the entire $\Delta\eta$ range, matches closely with results obtained from $\Lambda - p$ correlations in pp collisions at $\sqrt{s} = 7$ TeV, as seen in Fig. 7.1.

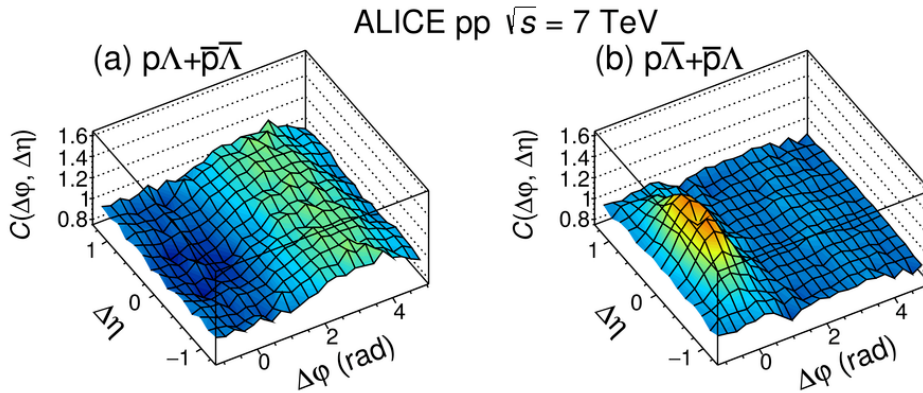


Figure 7.1 – Correlation functions for combined pairs of (left) $\Lambda p + \bar{\Lambda}\bar{p}$ and (right) $\Lambda\bar{p} + \bar{\Lambda}p$ for ALICE pp collisions at $\sqrt{s} = 7$ TeV. Figure is taken from [85].

The authors of [85] offer several possible explanations for the observed depletion in the same-sign baryon number correlations. One such possibility frames the depression as a manifestation of local baryon number conservation, which will influence the hadronization process. In models employing string hadronization, the local conservation of baryon number requires that two baryons produced in a single fragmentation are separated by

at least one particle with a different baryon number [86]. Therefore, same-sign baryon pairs will be kinematically suppressed, as opposed to the opposite-sign baryon pairs. To verify this, the authors of [85] compared the correlation functions of same-sign baryon pairs to predictions from several MC models, including the string-fragmentation based PYTHIA6 and PYTHIA8 Monash models. However, none of the models were able to even qualitatively describe the observed depletion. As such, the authors concluded that some additional, unidentified mechanism could be at play. At the time of writing this thesis, the nature of this unidentified mechanism remains unknown. However, given the differences between pp and Pb–Pb collisions, it is quite remarkable that the same effect is observed in both collision systems.

The large difference between opposite- and same-sign correlations leads to a prominent near-side peak in the balance functions, as displayed in the bottom panels of Figs. 6.4 and 6.5. As was mentioned earlier, the balance function is constructed to be a pure product of quantum number balancing correlations. Therefore, the prominent peak, along with the flatness of the distribution on the away-side seems to indicate that baryon number conservation is not distributed isotropically, and occurs almost exclusively between particles in close proximity to each other. This seems somewhat surprising, as the presence of a deconfined QGP in thermal equilibrium is expected to “wash out” correlations between balancing quantum numbers, leading to baryon number being only globally conserved. However, the near-side peak in the balance functions demonstrate that baryon number is conserved locally as well.

The idea of local baryon number conservation aligns strongly with predictions from the Lund string model, where quarks and antiquarks are created in pairs as part of a QCD string. The net baryon number of the string is zero, ensuring that baryon number is conserved locally. Since the quark and antiquark occupy the same string, they retain a degree of correlation when the string breaks and hadrons are formed, which is reflected in the increased magnitude of the opposite-sign correlations over the same-sign correlations.

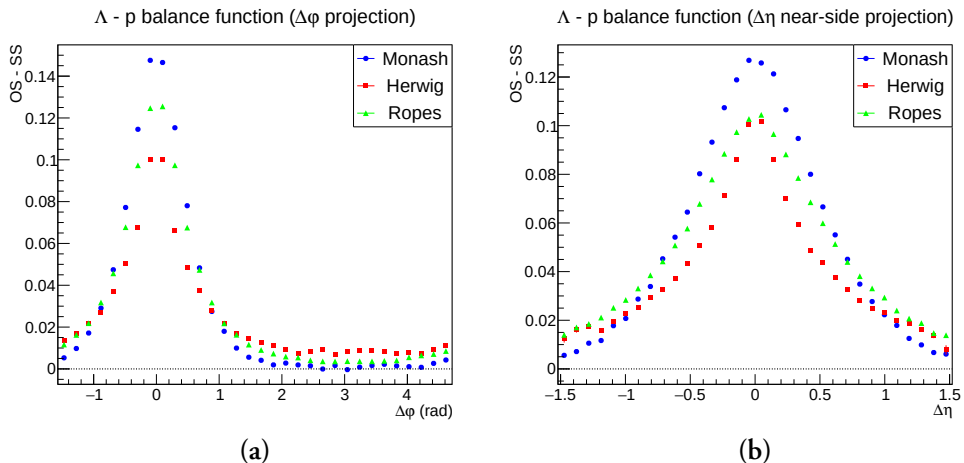


Figure 7.2 – Λ - p balance functions in (a) $\Delta\phi$ and (b) $\Delta\eta$ produced using the PYTHIA8 Monash, Herwig and PYTHIA8 ropes models. Figures were obtained through [87].

The results pertaining to $\Lambda - p$ correlations presented in this thesis may be compared to the $\Lambda - p$ balance functions from simulated pp collisions at $\sqrt{s} = 13$ TeV, produced using several Lund string-based MC models (PYTHIA8 Monash [74], Herwig [88], PYTHIA8.3 ropes [89]) and shown in Fig. 7.2. Doing so reveals some similarities, the most notable being the same prominent peak in $\Delta\varphi$ and $\Delta\eta$ in the near-side region. However, the widths of the peaks differ greatly from their experimental counterparts, being much more narrow than the peaks shown in the bottom panels of Figs. 6.4 and 6.5. This seems to suggest that baryon number conservation in Pb–Pb occurs over a wider range compared to pp, being neither entirely local (Lund string) nor completely global (“pure” deconfined QGP) in accordance with predictions from net-baryon fluctuations in Pb–Pb collisions [90].

Finally, the centrality-dependent evolution of the $\Lambda - p$ balance function width and integrated yields display a slight difference in behaviour between the $\Delta\varphi$ and $\Delta\eta$ projections, as shown in Figs. 6.10a–d. Whereas $\sigma_{\Delta\eta}$ and $Y_{\Delta\eta}$ appear to scale linearly with the collision centrality, $\sigma_{\Delta\varphi}$ and $Y_{\Delta\varphi}$ display a non-trivial dependence (although the yields have similar magnitudes within uncertainties). While there have not yet been any publications on the $\Lambda - p$ balance function in heavy-ion collisions at the time of writing this thesis, there have been measurements of balance functions between pairs of particles of the same type, including p – p. One such example focuses on balance functions between identified particles (π , K, p) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [91], and includes a centrality-dependent study of the balance function width and integrated yields as shown in Fig. 7.3.

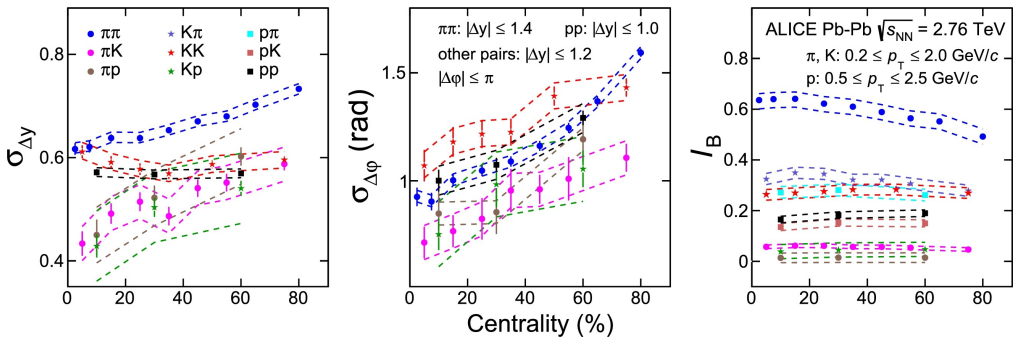


Figure 7.3 – Longitudinal (Δy) widths (left), azimuthal ($\Delta\varphi$) widths (center) and integral (right) of balance functions between pairs of identified (π , K, p) particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as a function of centrality. Figure is taken from [91].

It should be noted that the balance functions of $\Lambda - p$ and p – p may not be quantitatively comparable, owing to the difference in trigger particle, the usage of Δy over $\Delta\eta$, the unique kinematic selections applied in each analysis and the difference in center-of-mass energies. Nevertheless, comparing the results from $\Lambda - p$ with p – p reveals some interesting differences. Firstly, $\sigma_{\Delta y}$ in Fig. 7.3 is of the same order of magnitude as $\sigma_{\Delta\eta}$ in Fig. 6.10c, although the latter depends far more strongly on centrality. By contrast, $\sigma_{\Delta\varphi}$ in Fig. 7.3 scales quickly with the event centrality, as opposed to Fig. 6.10a which changes very little. Finally, both the yields in Figs. 6.10b and 6.10d decrease when going from central to peripheral events, whereas I_B in Fig. 7.3 remains approximately constant. These discrepancies are quite surprising, as both the $\Lambda - p$ and p – p balance functions share the same purpose of probing the conservation of baryon number.

7.3 $\Lambda - K$ Correlations

The $\Lambda - K$ correlation and balance functions allow for the conservation of strangeness to be probed, similarly to the results from $\Lambda - p$ for baryon number. Unlike $\Lambda - p$ however, the differences between the opposite- and same-sign correlations for $\Lambda - K$ are relatively small compared to the overall magnitude of the correlation functions, although their shapes remain similar. Moreover, the large depression across $\Delta\eta$ that was observed in $\Lambda - p$ appears in neither the opposite- nor the same-sign correlation functions shown in Fig. 6.7. This behaviour again matches with the results from [85], where the authors observed no depletion for $(K^+ - K^+ + K^- - K^-)$ or $K^+ - K^-$ correlations. The fact that the dip doesn't appear in $\Lambda - K$ correlations either, despite the presence of at least one baryon, suggests that the mechanisms responsible for the large $\Delta\eta$ depression involves some form of (anti)correlation between baryon-baryon pairs.

The small differences between opposite- and same-sign correlations are reflected in the balance functions, which display a relatively small peak on the near-side of the distributions as shown in the bottom panels of Figs. 6.6 and 6.7. While the magnitudes of the $\Lambda - K$ balance functions are much lower than their $\Lambda - p$ counterparts, the distributions themselves remain qualitatively similar, particularly in $\Delta\varphi$. Like the case for baryon number, the $\Lambda - K$ balance functions indicate that strangeness too is conserved locally, in spite of the presence of the thermal, deconfined QGP. Furthermore, comparing the $\Lambda - K$ balance functions to predictions from Lund string-based models (see Fig. 7.4) reveals the same discrepancy in the width of the distribution, indicating that strangeness production in Pb-Pb collisions similarly fits somewhere in between local conservation and global conservation. Again, this result aligns with predictions from net-strangeness fluctuations [92].

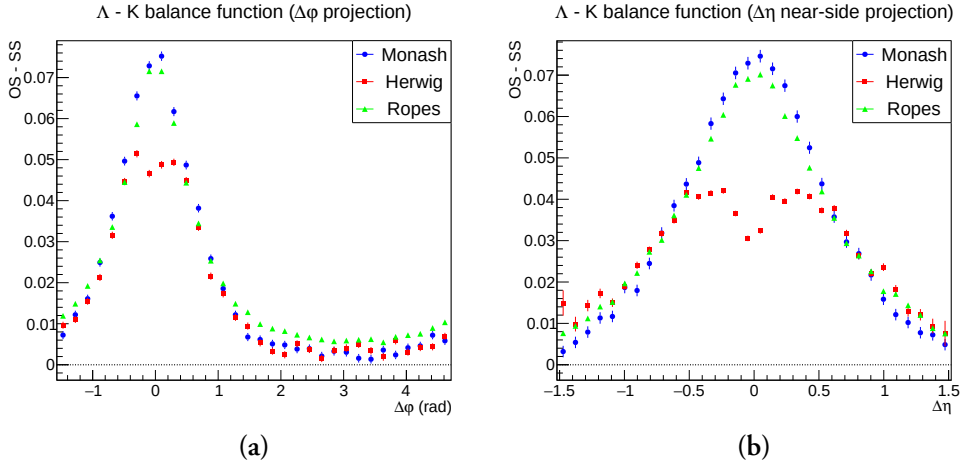


Figure 7.4 – $\Lambda - K$ balance functions in (a) $\Delta\varphi$ and (b) $\Delta\eta$ produced using the PYTHIA8 Monash, Herwig and PYTHIA8 ropes models. The dip near $\Delta\varphi = 0$ and $\Delta\eta = 0$ in Herwig is a known feature of the way strangeness enhancement is implemented in the model. Figures were obtained through [87].

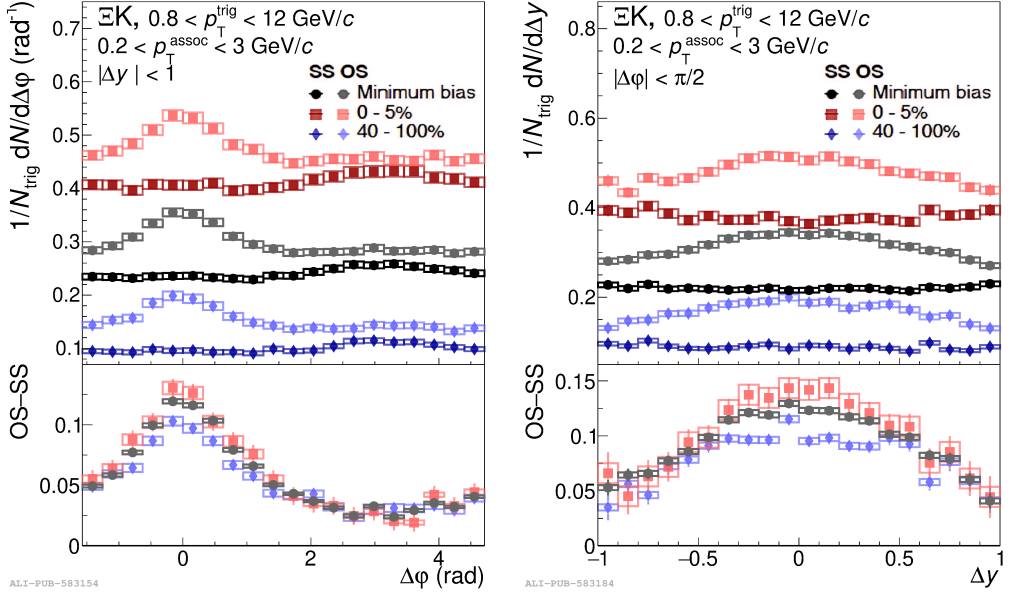


Figure 7.5 – Correlations between Ξ baryons and kaons for different multiplicity classes in (left) $\Delta\phi$ and (right) $\Delta\eta$ on the near-side for ALICE pp collisions at $\sqrt{s} = 13$ TeV. The bottom panels show differences between opposite- and same-sign correlations for each selection. Statistical and systematic errors are marked with bars and boxes, respectively. Figures are taken from [93].

Looking at the quark content of the triggers and associates involved in the opposite- and same-sign $\Lambda - K$ correlations reveals that the former involves strange-antistrange quark balancing, while the latter contains a contribution from up-antiup quark balancing. Since the latter is subtracted from the former, this may explain why the magnitudes of the $\Lambda - K$ balance functions are quite low. To verify this, the results from $\Lambda - K$ may be compared to balance functions obtained from $\Xi - K$ correlations, where only strange-antistrange quark balancing plays a role. As shown in Fig. 7.5, the magnitude of the $\Xi - K$ balance function is significantly higher, indicating that the up-antiup quark balancing may be responsible for the low magnitude in $\Lambda - K$. It should be noted that this interpretation does not take the differences between pp and Pb-Pb collisions into account, and warrants further investigation before it can be validated (see Section 7.6).

Similarly to $\Lambda - p$, the centrality-dependent evolution of the $\Lambda - K$ balance function width and integrated yields may be compared to the results from [91] shown in Fig. 7.3. Again, one should keep in mind that the balance functions of $\Lambda - K$ and $K - K$ may not be quantitatively comparable. Despite this, both $\sigma_{\Delta\phi}$ and $Y_{\Delta\phi}$ in Figs. 6.10e and 6.10f are of similar magnitude to their counterparts in $K - K$, displayed in Fig. 7.3. Furthermore, the behaviour of $Y_{\Delta\phi}$ in Fig. 6.10f matches what is shown in Fig. 7.3, remaining approximately constant as centrality increases. On the other hand, $\sigma_{\Delta\phi}$ behaves vastly different between $K - K$ and $\Lambda - K$, with the former showing a clear increase with centrality while the latter remains approximately constant within uncertainties.

7.4 $\Lambda - \pi$ Correlations

As was mentioned at the beginning of Chapter 5, the $\Lambda - \pi$ correlations probe neither strangeness nor baryon number, and their aim is to serve as a baseline that the results from $\Lambda - p$ and $\Lambda - K$ may be compared to. As such, the opposite- and same-sign correlations shown in Figs. 6.8 and 6.9 appear almost identical, and the balance functions in the bottom panels display no observable structure. Furthermore, the fit of a constant parameter to the balance functions matches the data quite well, and indicates that no quantum number balancing is observed. For some centrality classes, the balance functions display the negative baseline that was also observed for the $\Lambda - K$ correlations. However, its presence in a system that contains no quantum number balancing indicates that the effect is likely of an unphysical nature. It is important to keep in mind that constructing the balance function involves the subtraction of two large numbers, meaning that small imperfections in e.g. the MC model used for efficiency calculation can result in inexact cancellation.

While the $\Lambda - \pi$ correlations involve neither strangeness nor baryon number conservation, the system does contain a degree of charge balancing between the trigger and the associate particle. When written in terms of the quark content, the opposite- and same-sign correlations become

$$\begin{aligned} \text{OS: } \Lambda - \pi^+ + c.c. &= (uds) - (u\bar{d}) + c.c., \\ \text{SS: } \Lambda - \pi^- + c.c. &= (uds) - (\bar{u}d) + c.c., \end{aligned}$$

where *c.c.* stands for *charge conjugate*. The quark content reveals that the opposite- and same-sign correlations involve down-antidown and up-antiup quark balancing, respectively. The high degree of symmetry that exists between up and down quarks would explain why, when the opposite- and same-sign correlations are subtracted from each other, the resulting balance function remains flat.

7.5 Conclusions

The results from the $\Lambda - h$ correlation and balance functions indicate that the conservation of strangeness and baryon number occurs locally between particles in close proximity to each other. This is an unforeseen phenomenon, as the Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV that were used throughout this thesis constitute an environment where the Quark-Gluon Plasma (QGP) is expected to be formed. Since the QGP is a deconfined and highly thermal state of matter, correlations between particles originating from quantum number balancing should vanish. As has been demonstrated in this thesis, this is not the case. However, the size of the region in which local quantum number balancing occurs is considerably larger in Pb–Pb collisions compared to predictions from pp collisions using models that exclude QGP formation. Therefore, the presence of the QGP in Pb–Pb collisions is expected to influence the production of strangeness and baryon number, leading to conservation mechanisms that are neither entirely local nor completely global.

7.6 Outlook

The following studies are proposed as an extension of this analysis:

- Three-particle correlations between the Λ baryons and two of π , K, p. These were originally planned to be included in this analysis, although the idea was prevented from coming to fruition due to time constraints. The three-particle correlations would complement the two-particle correlations for strangeness and baryon number, and test whether there exists any interplay between their respective production mechanisms.
- Different trigger and associate particles for probing quark balancing correlations. As was mentioned in Section 7.3, a disadvantage of the $\Lambda - K$ system is that the balance function is contaminated by correlations arising due to up-antiup quark balancing. In future studies, the trigger and associate particles should be chosen such that only one form of quark-antiquark balancing is probed when the balance function is constructed from the opposite- and same-sign correlations. As an example, the Λ baryon could be replaced with the Ξ^- (dss) baryon, such that $\Xi - K$ correlations would exclusively probe strange-antistrange quark balancing. In addition, this allows for direct comparison with the results from [93], providing a way of quantifying the differences between pp and Pb–Pb collisions.
- Correlation functions for other conserved quantum numbers. The analysis framework used in this thesis can be applied to conserved quantum numbers other than strangeness and baryon number, allowing for their production mechanisms to be probed. An obvious candidate would be charm ($C \equiv n_c - n_{\bar{c}}$), pertaining to hadrons carrying charm quarks and antiquarks. Similarly to the $\Lambda - K$ correlations, a combination of trigger and associate particles could be found that probe charm-anticharm quark correlations, giving insight into the associated production mechanism.
- Thorough analysis of $\Lambda - h$ correlation and balance functions in MC. Sections 7.2 and 7.3 included a small comparison between the $\Lambda - p$ and $\Lambda - K$ balance functions in data and in several Lund string-based models. It would be worthwhile to study the correlation and balance functions in MC in more detail¹, and investigate if other MC models that don't necessarily rely on the Lund string model succeed or fail in reproducing the data.
- Measurements of the p_T -dependent $\Lambda - h$ correlation and balance functions. This would reveal whether the behaviour of the $\Lambda - h$ correlations is different between hard and soft scattering processes. Furthermore, a p_T -dependent study might reveal whether the correlation functions are subject to radial flow.

¹It should be noted that many MC models designed with heavy-ion physics in mind don't include local charge conservation mechanisms.

- Future ALICE upgrades. Before the start of the LHC's Run 5 (scheduled to commence in 2036), the ALICE detector is planned to receive a series of upgrades to several of its subdetectors. These upgrades (collectively referred to as ALICE 3) will not only improve the detector resolution and particle identification capabilities, but also increase the available window of acceptance. This would be a significant improvement for correlation studies, allowing for correlations between particles to be probed over a wider $\Delta\eta$ range.

Appendix A

Complementary Figures

This appendix contains a number of complementary figures which were relevant to the analysis, but couldn't easily be placed in the main body of the thesis. Appendix A.1 through A.9 displays the $\Lambda - p$, $\Lambda - K$ and $\Lambda - \pi$ opposite-sign correlations, same-sign correlations and balance functions in $(\Delta\varphi, \Delta\eta)$ space at all centrality intervals. Appendix A.10 through A.27 then shows the same correlation and balance functions, but projected in $\Delta\varphi$ and in $\Delta\eta$ on the near- and away-side. Next, Appendix A.28 through A.36 lists the TOF $n\sigma^i$ distributions – where $i = \pi, K, p$ – for $0.2 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$, and Appendix A.37 and A.38 highlight the Λ and $\bar{\Lambda}$ invariant mass fits at all centrality intervals. Finally, Appendix A.39 through A.50 contains the summary of the systematic uncertainties for the $\Delta\varphi$ and $\Delta\eta$ projections at all centrality intervals.

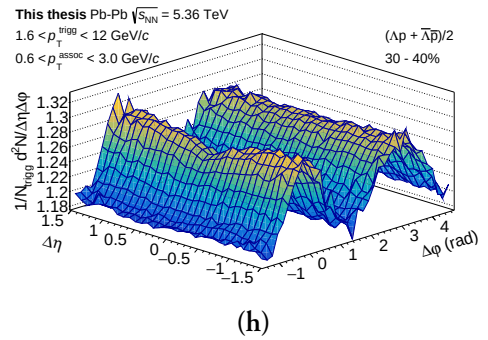
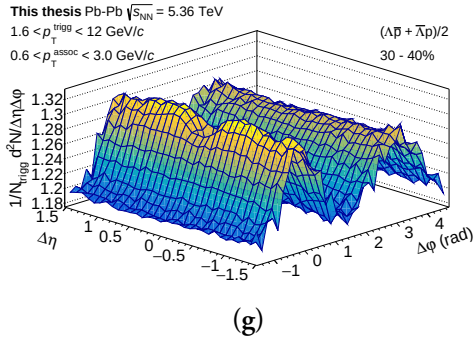
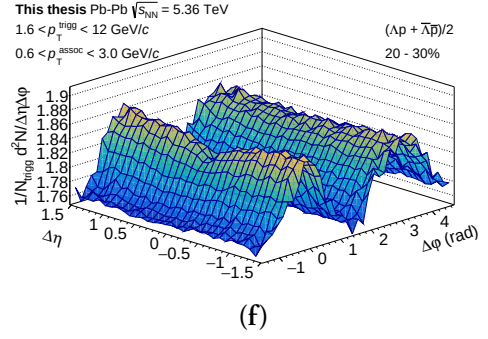
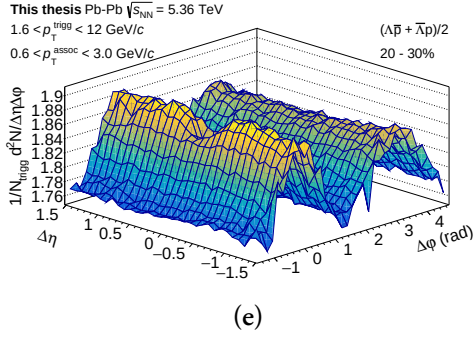
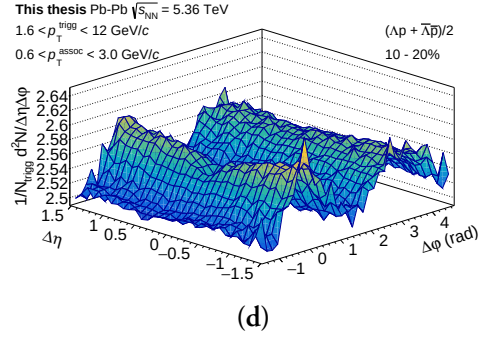
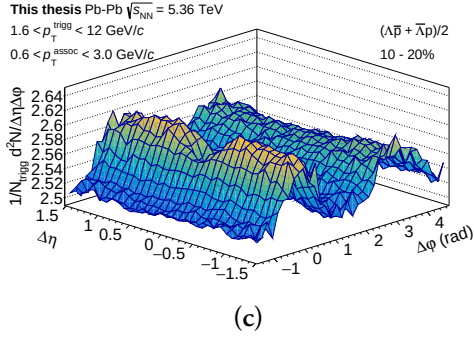
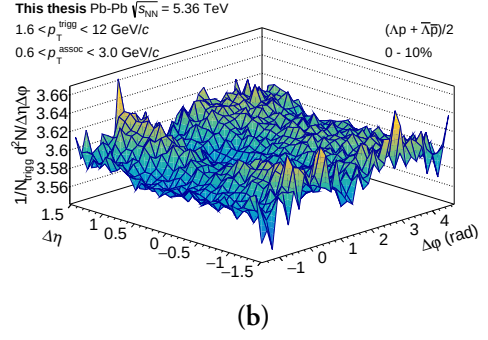
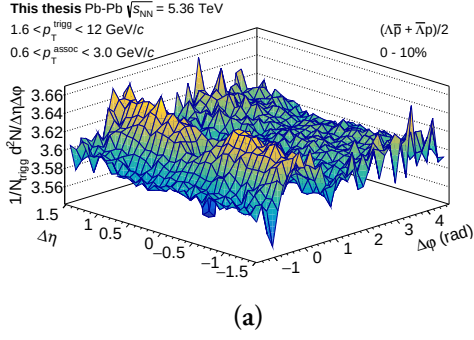


Figure A.1 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign protons and (b, d, f, h) same-sign protons at various centrality classes (0% – 40%).

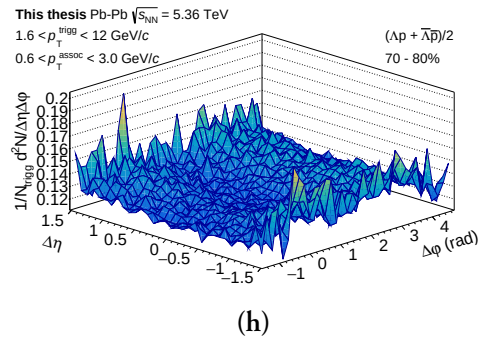
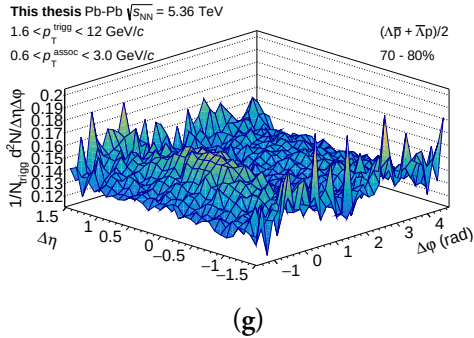
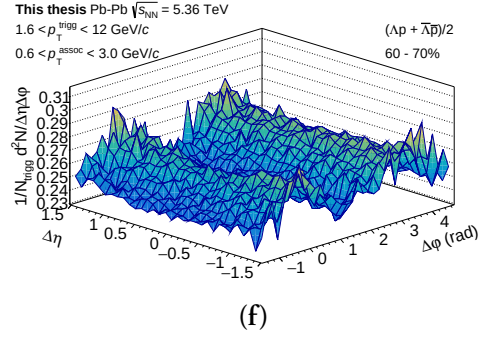
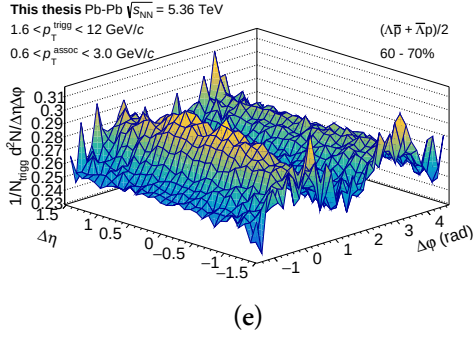
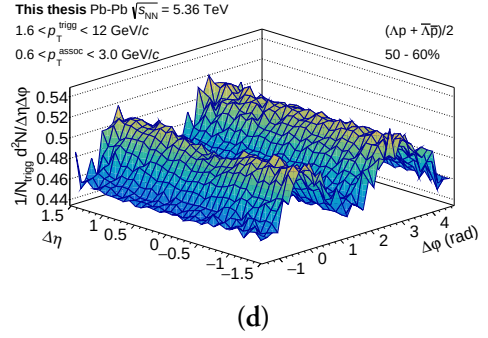
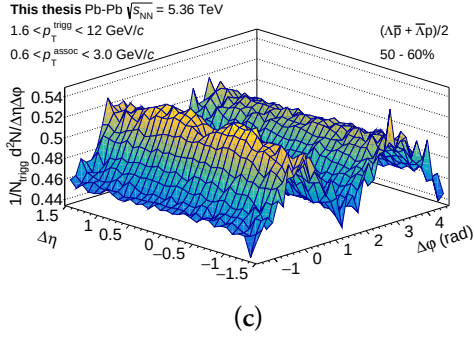
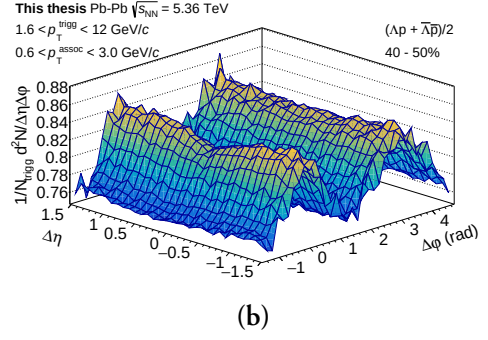
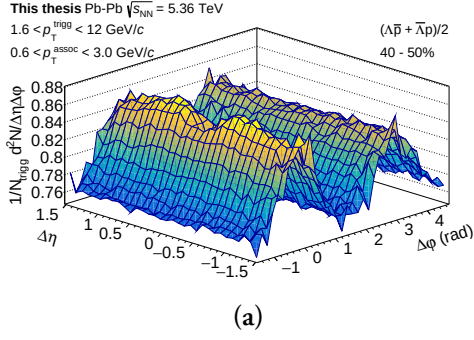
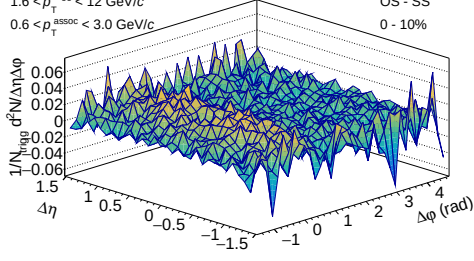


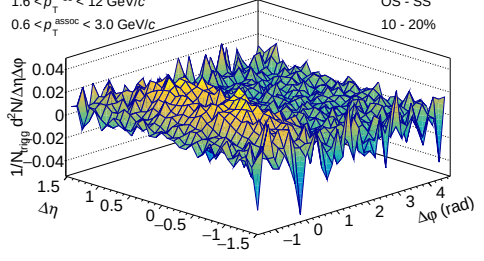
Figure A.2 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign protons and (b, d, f, h) same-sign protons at various centrality classes (40% – 80%).

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
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 $0.6 < p_T^{\text{assoc}} < 3.0$ GeV/c



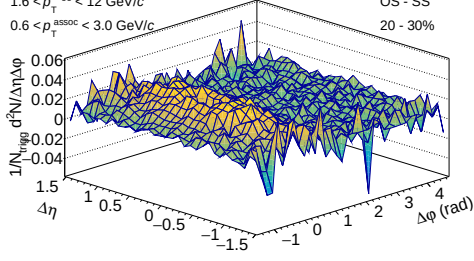
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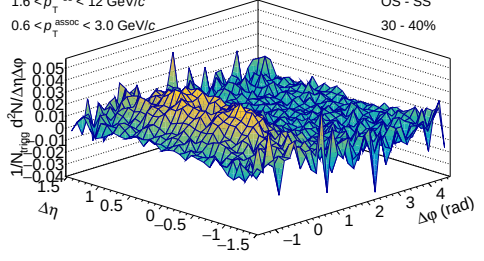
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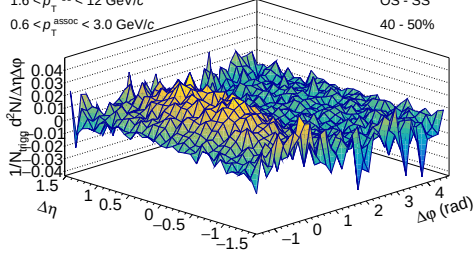
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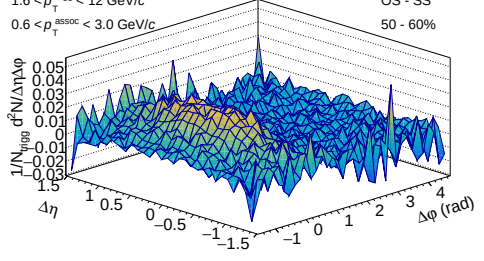
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This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
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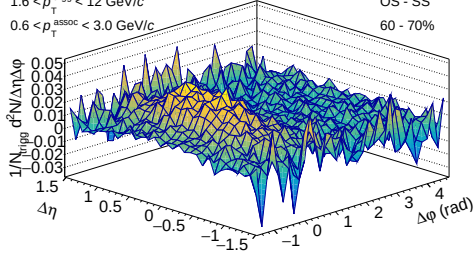
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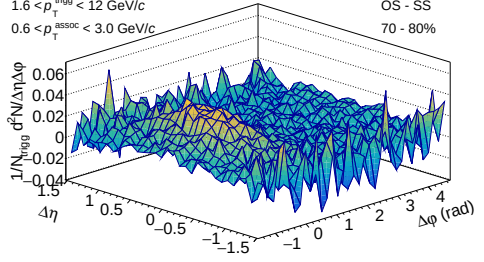
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(g)

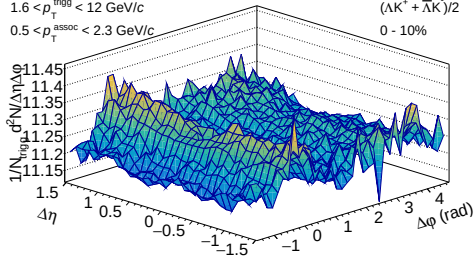
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(h)

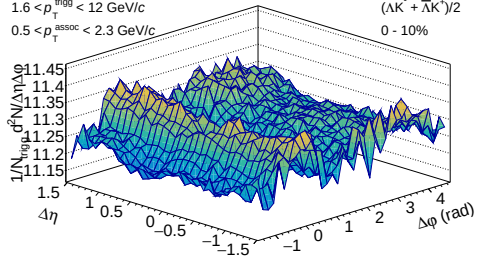
Figure A.3 – Balance functions for $\Lambda - p$ correlations in $(\Delta\varphi, \Delta\eta)$ at various centrality classes (0% – 80%). Here, the balance function is defined as the difference between opposite- and same-sign correlations.

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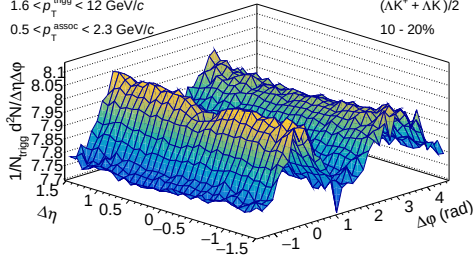
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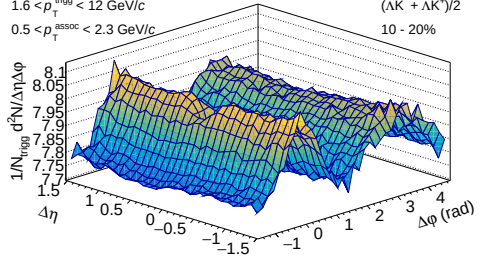
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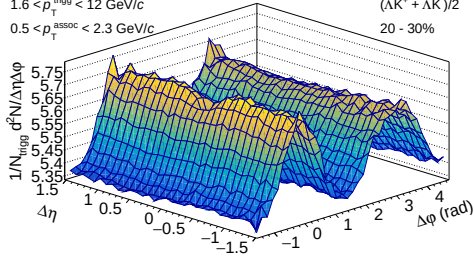
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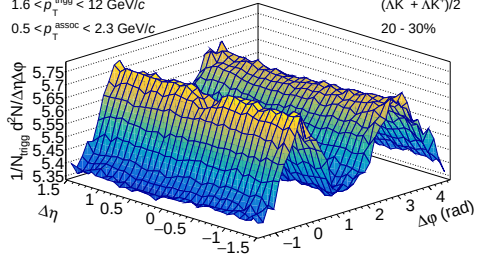
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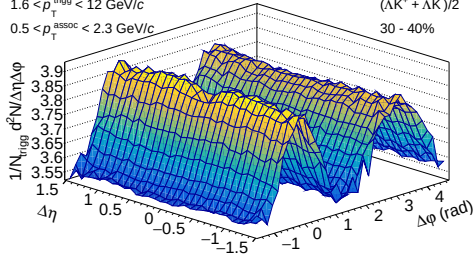
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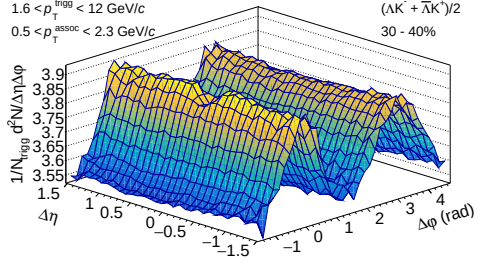
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(g)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
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 $0.5 < p_T^{\text{assoc}} < 2.3$ GeV/c



(h)

Figure A.4 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign kaons and (b, d, f, h) same-sign kaons at various centrality classes (0% – 40%).

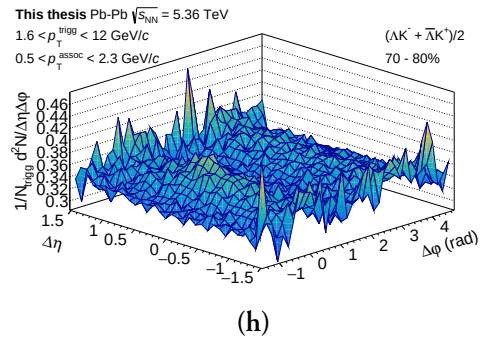
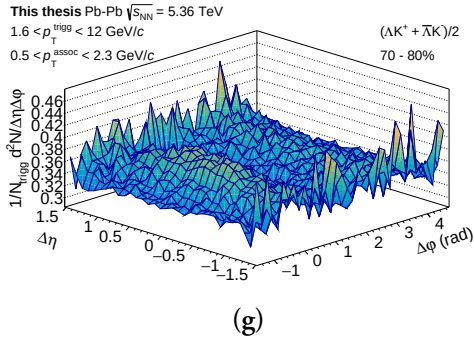
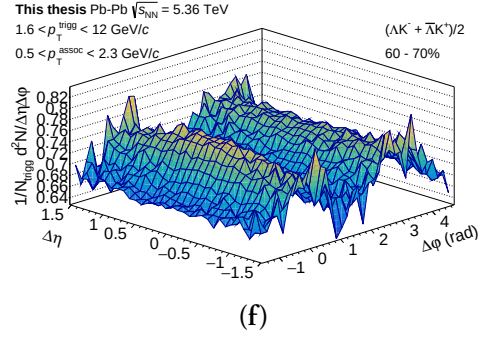
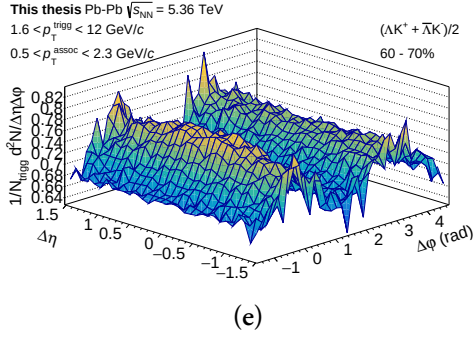
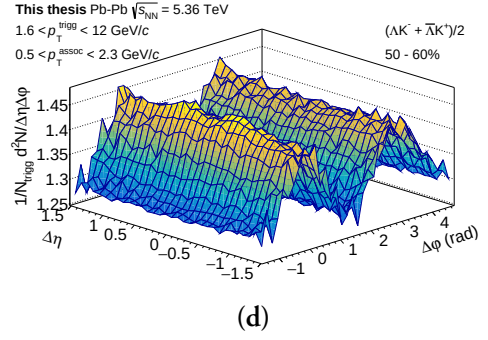
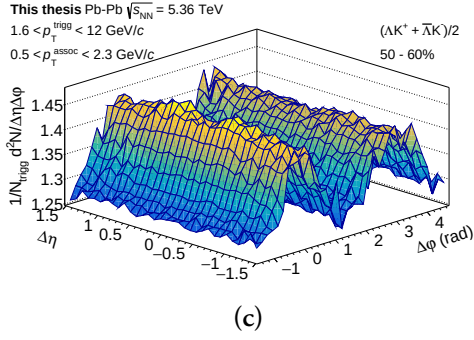
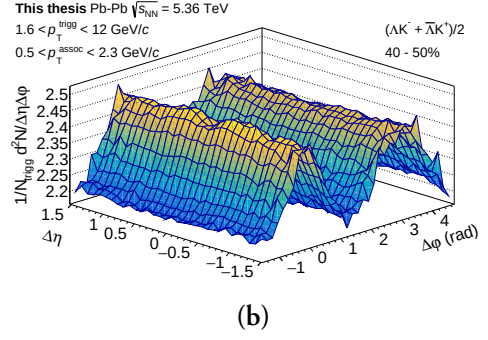
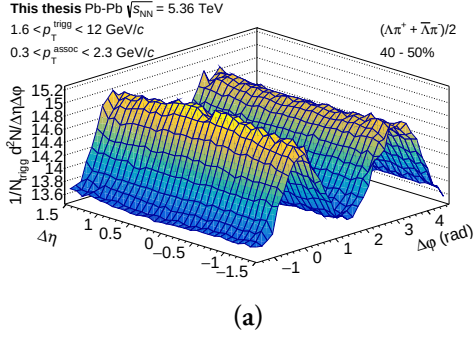


Figure A.5 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign kaons and (b, d, f, h) same-sign kaons at various centrality classes (40% – 80%).

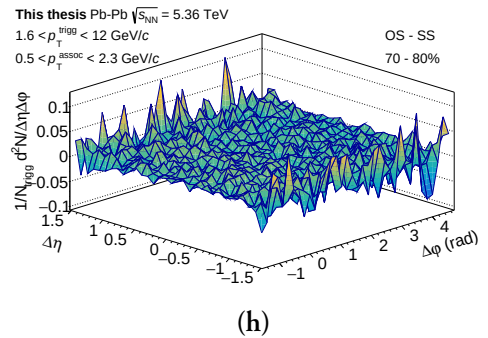
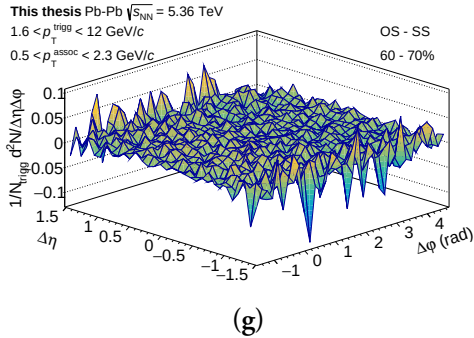
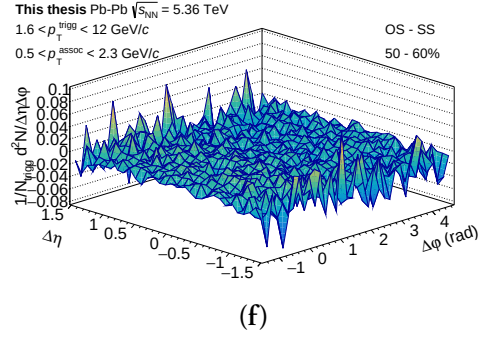
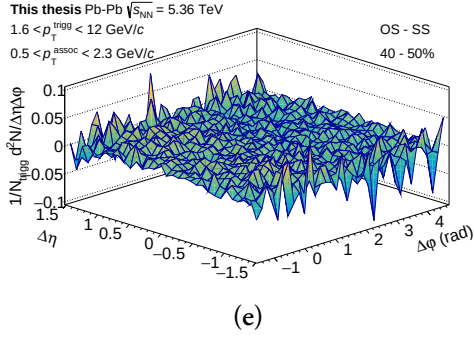
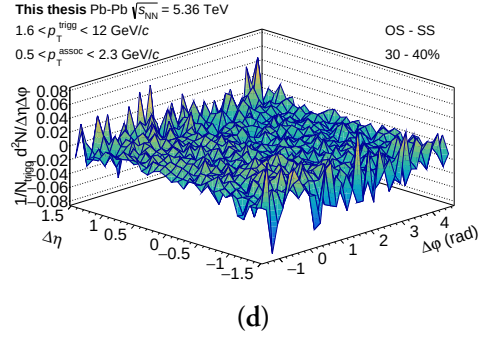
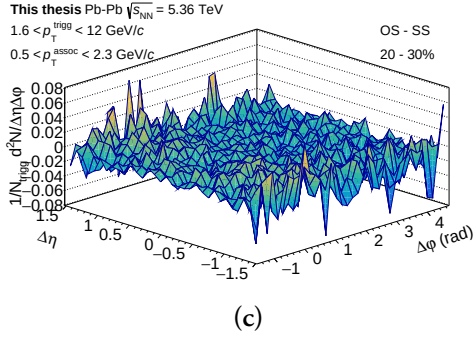
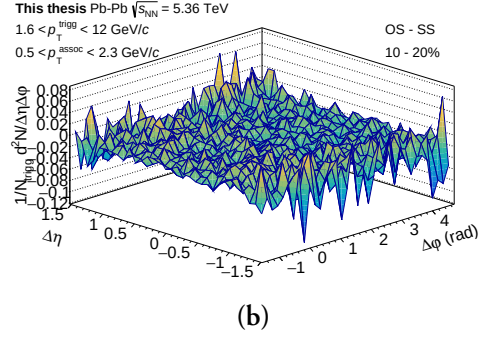
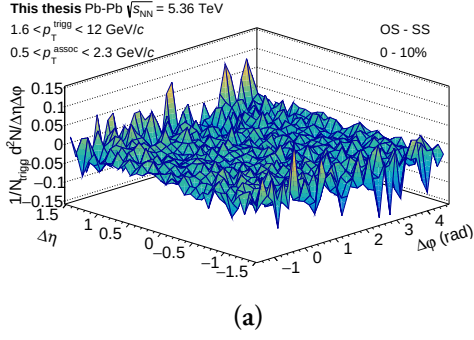
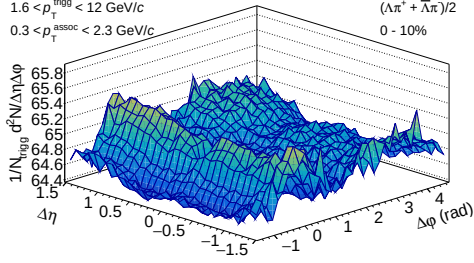


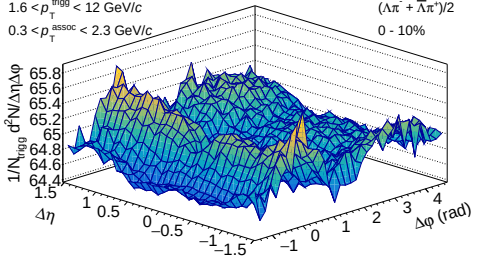
Figure A.6 – Balance functions for $\Lambda - K$ correlations in $(\Delta\varphi, \Delta\eta)$ at various centrality classes (0% – 80%). Here, the balance function is defined as the difference between opposite- and same-sign correlations.

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 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



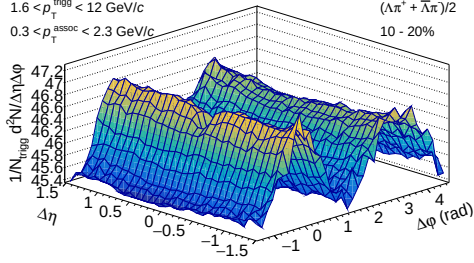
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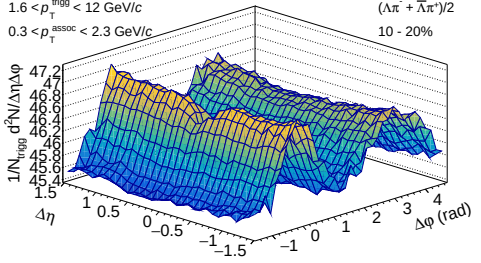
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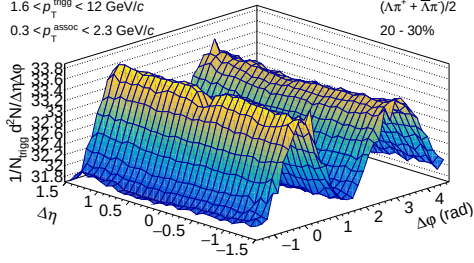
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This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
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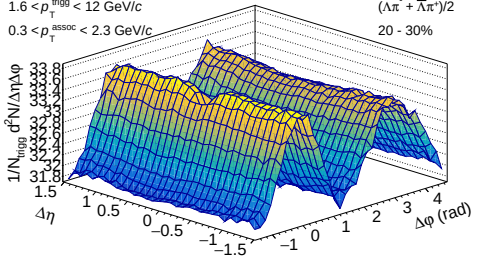
(d)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
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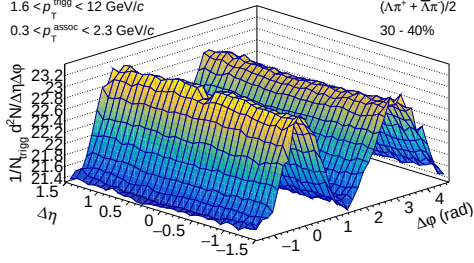
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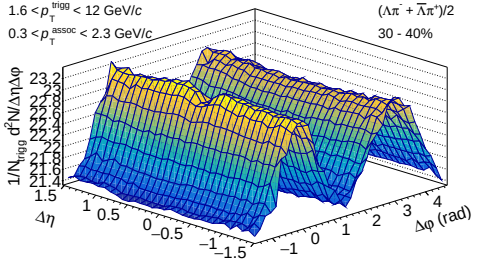
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(g)

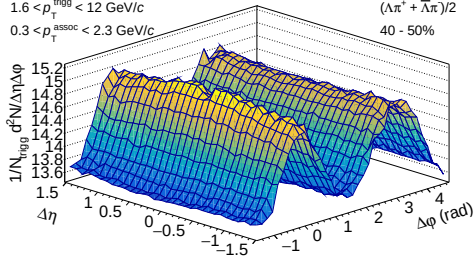
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(h)

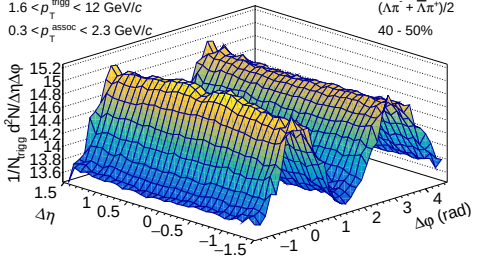
Figure A.7 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign pions and (b, d, f, h) same-sign pions at various centrality classes (0% – 40%).

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



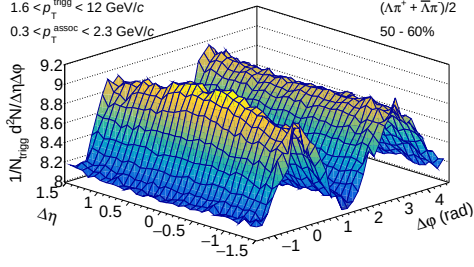
(a)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



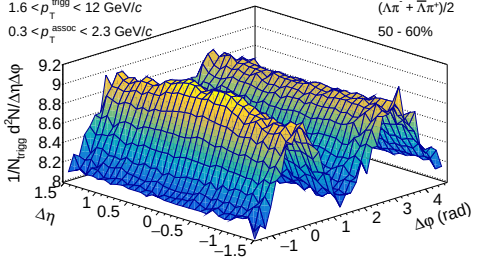
(b)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



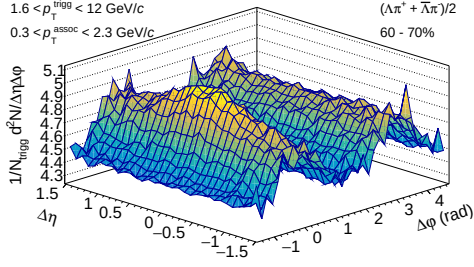
(c)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



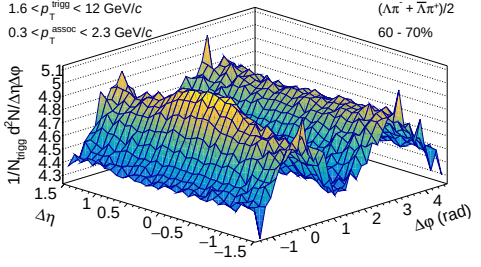
(d)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



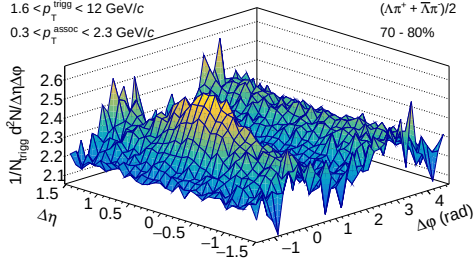
(e)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



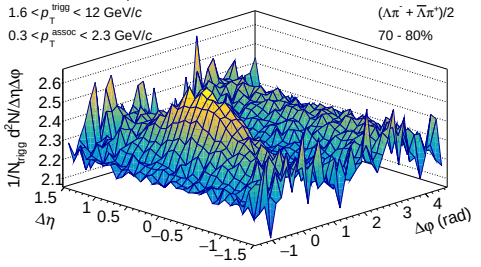
(f)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



(g)

This thesis Pb-Pb $\sqrt{s_{NN}} = 5.36$ TeV
 $1.6 < p_T^{\text{trigg}} < 12$ GeV/c
 $0.3 < p_T^{\text{assoc}} < 2.3$ GeV/c



(h)

Figure A.8 – Correlations in $(\Delta\varphi, \Delta\eta)$ between Λ baryons and (a, c, e, g) opposite-sign pions and (b, d, f, h) same-sign pions at various centrality classes (40% – 80%).

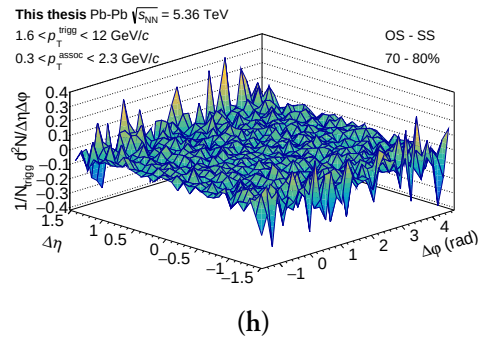
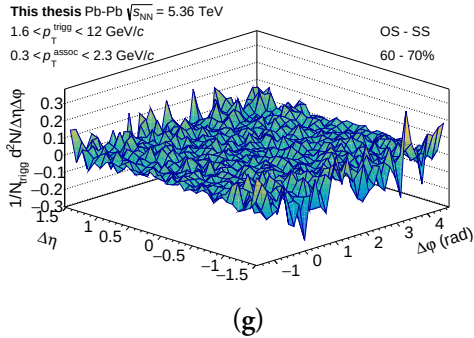
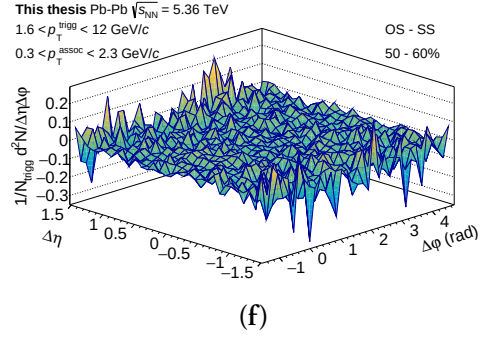
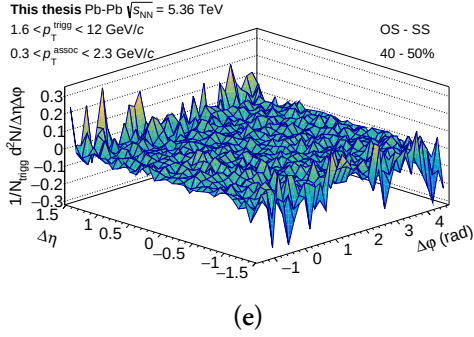
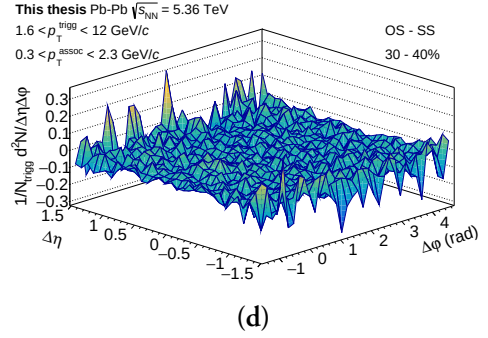
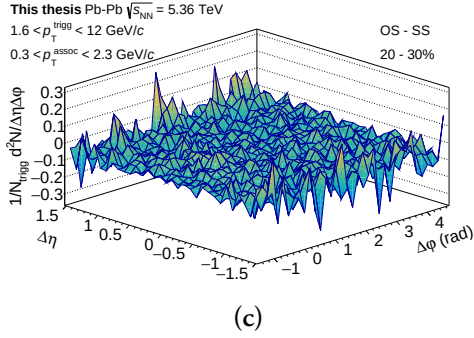
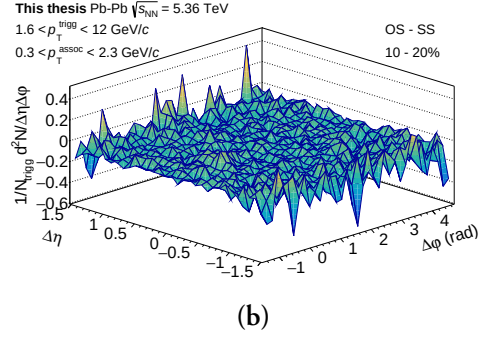
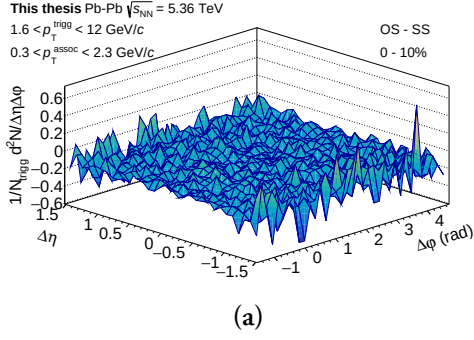
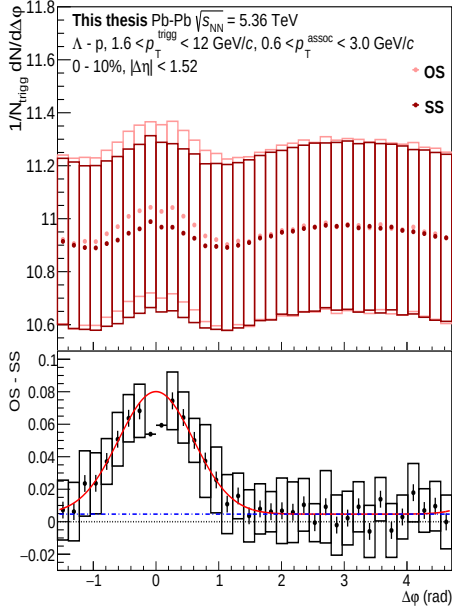
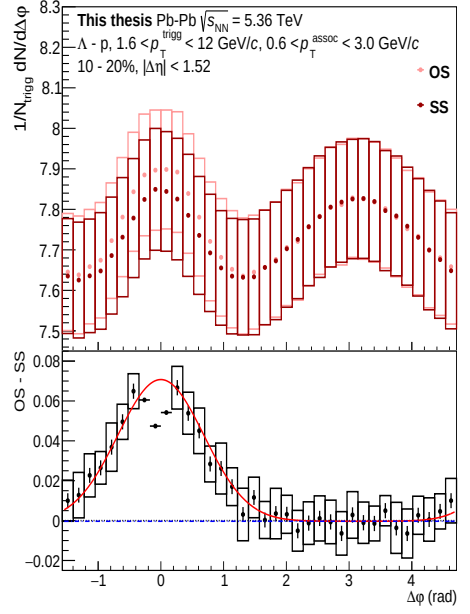


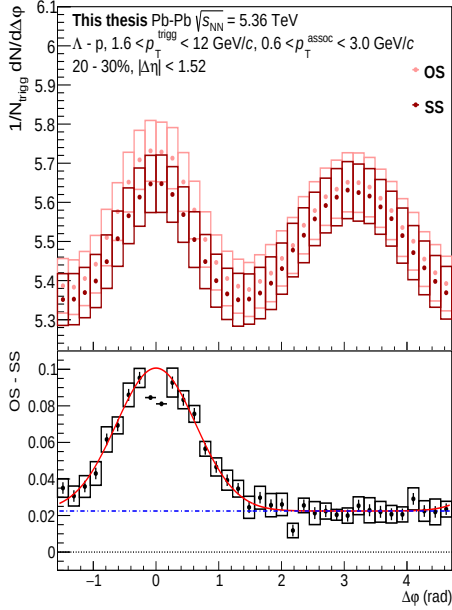
Figure A.9 – Balance functions for $\Lambda - \pi$ correlations in $(\Delta\varphi, \Delta\eta)$ at various centrality classes (0% – 80%). Here, the balance function is defined as the difference between opposite- and same-sign correlations.



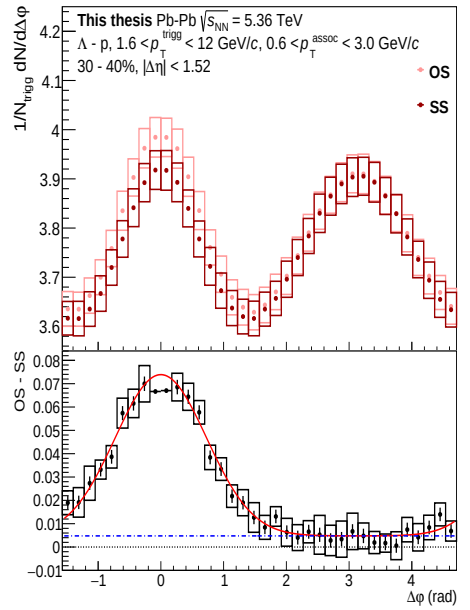
(a)



(b)

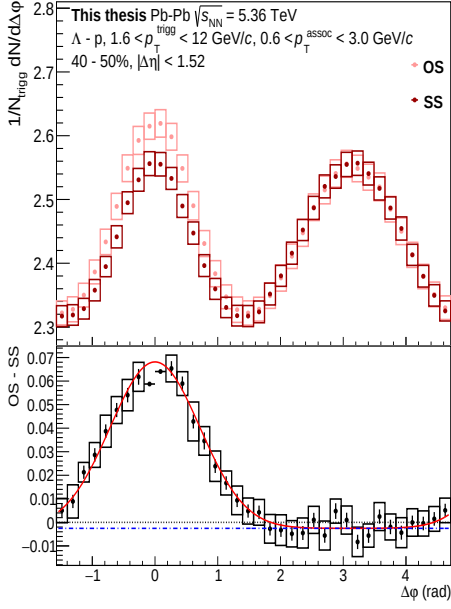


(c)

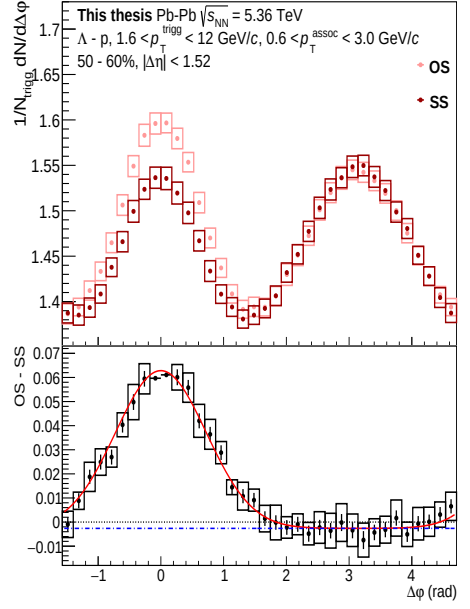


(d)

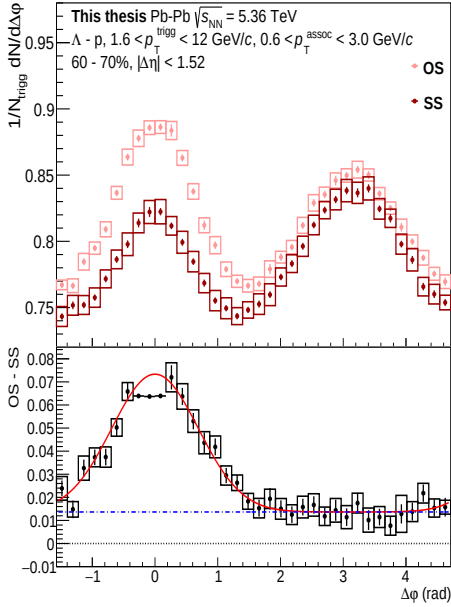
Figure A.10 – $\Delta\phi$ projection of correlations between Λ baryons and protons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



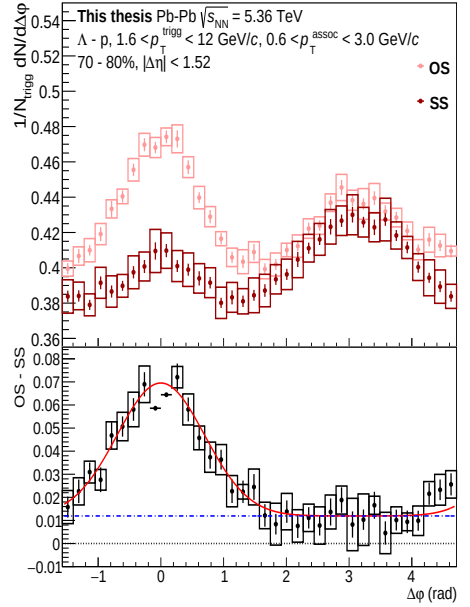
(a)



(b)

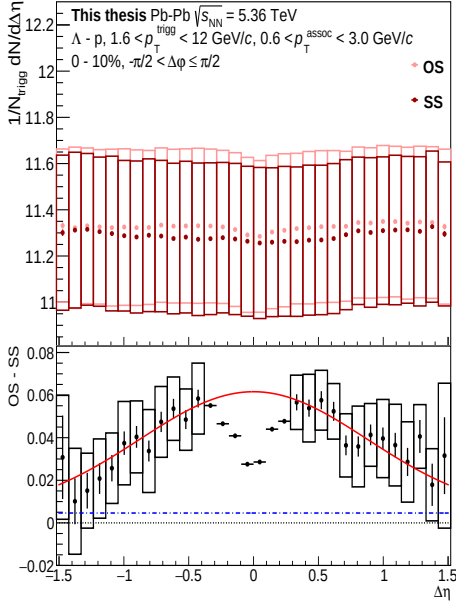


(c)

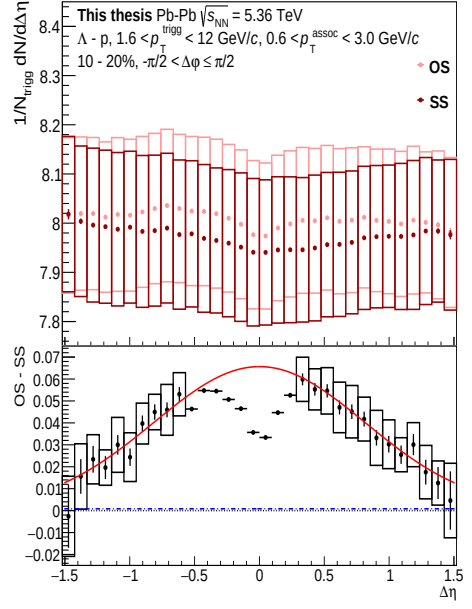


(d)

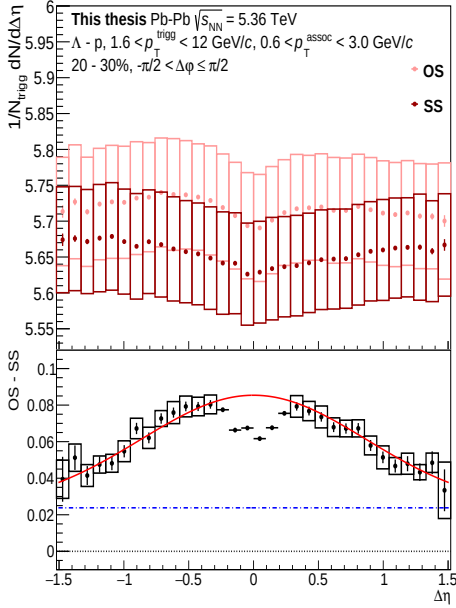
Figure A.11 – $\Delta\phi$ projection of correlations between Λ baryons and protons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



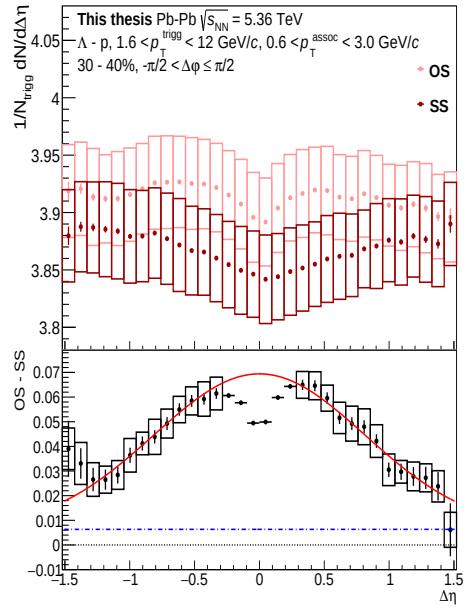
(a)



(b)

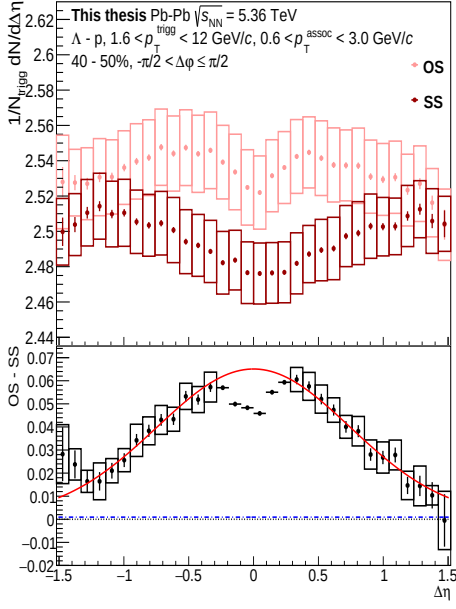


(c)

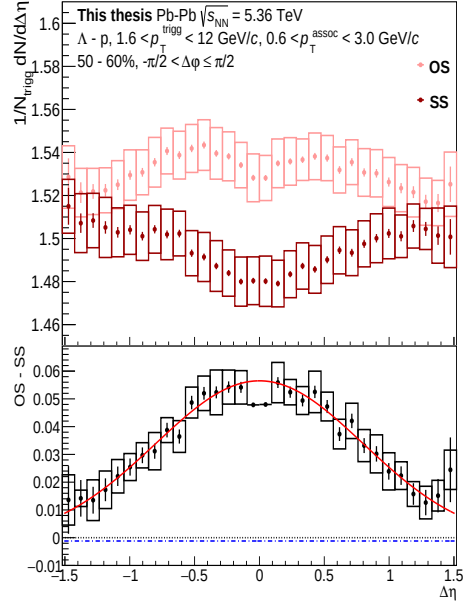


(d)

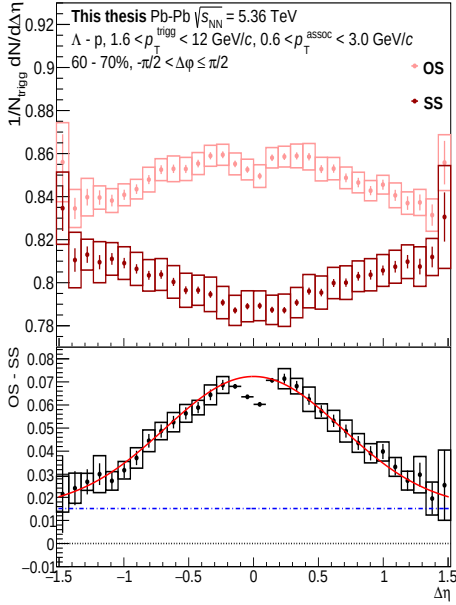
Figure A.12 – $\Delta\eta$ near-side projection of correlations between Λ baryons and protons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



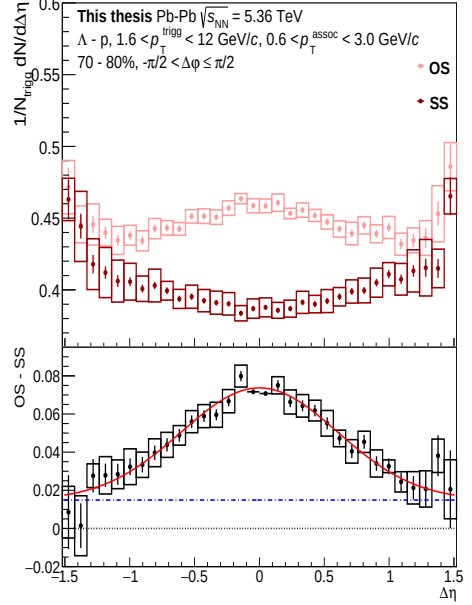
(a)



(b)

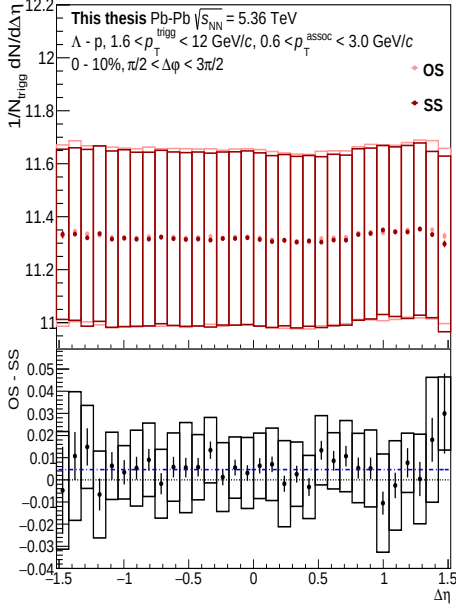


(c)

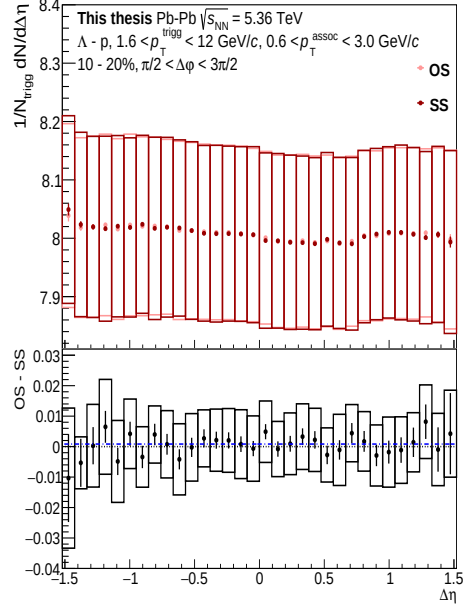


(d)

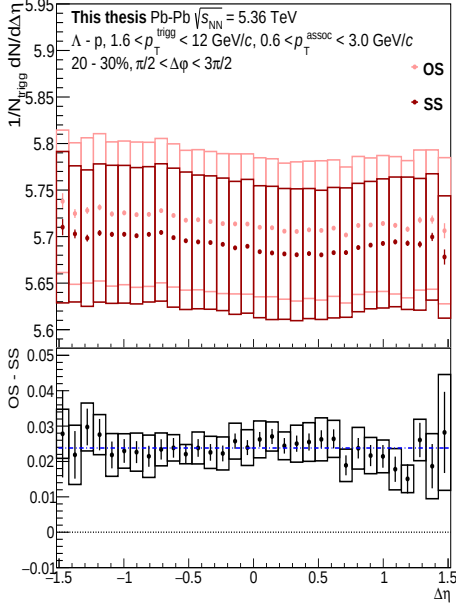
Figure A.13 – $\Delta\eta$ near-side projection of correlations between Λ baryons and protons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



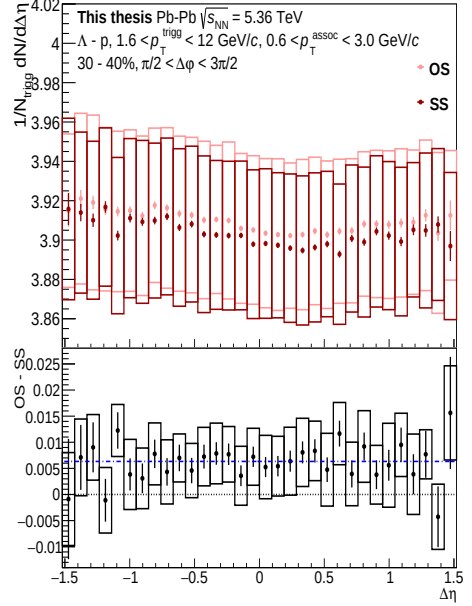
(a)



(b)

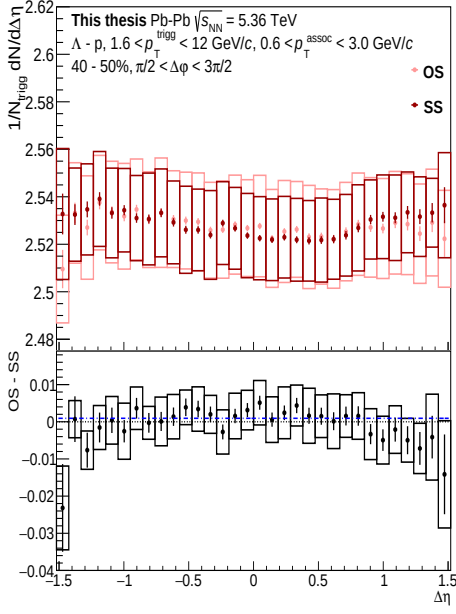


(c)

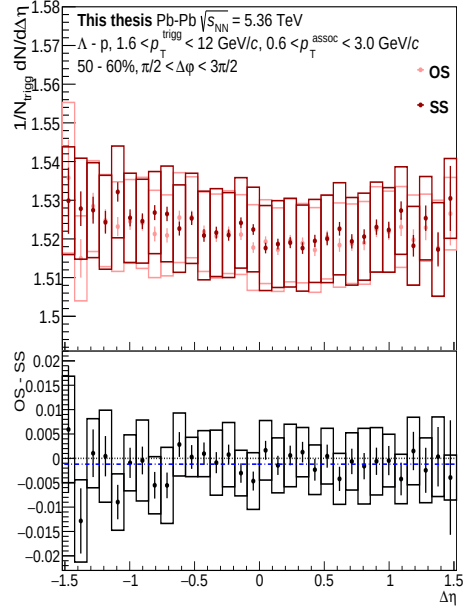


(d)

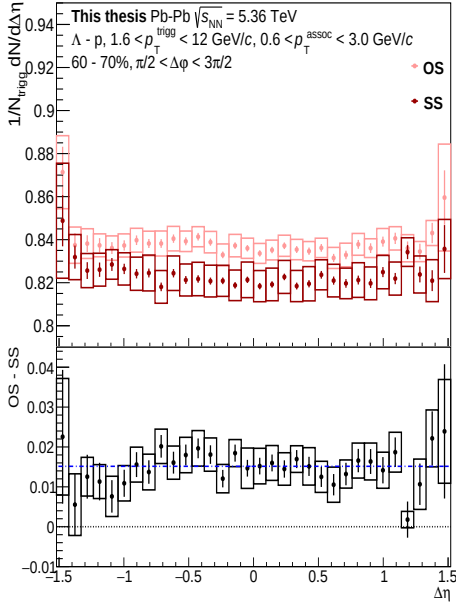
Figure A.14 – $\Delta\eta$ away-side projection of correlations between Λ baryons and protons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



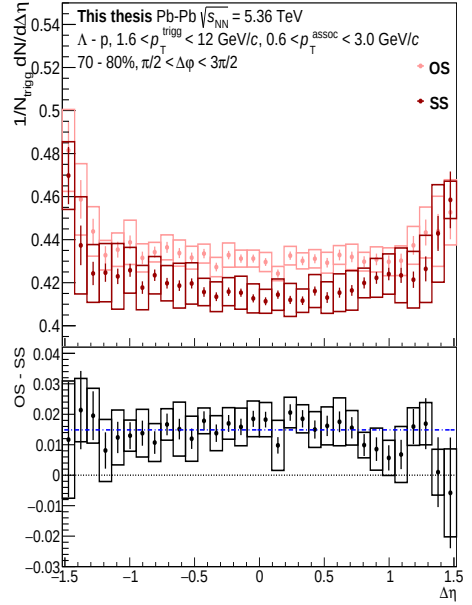
(a)



(b)

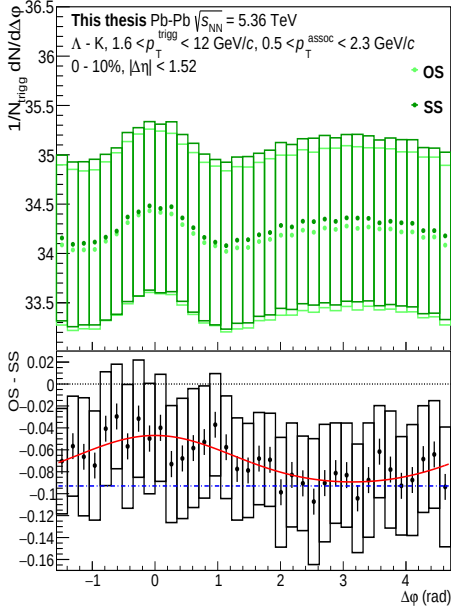


(c)

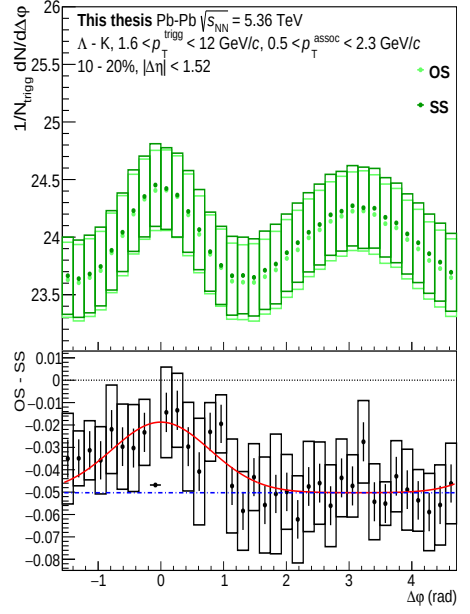


(d)

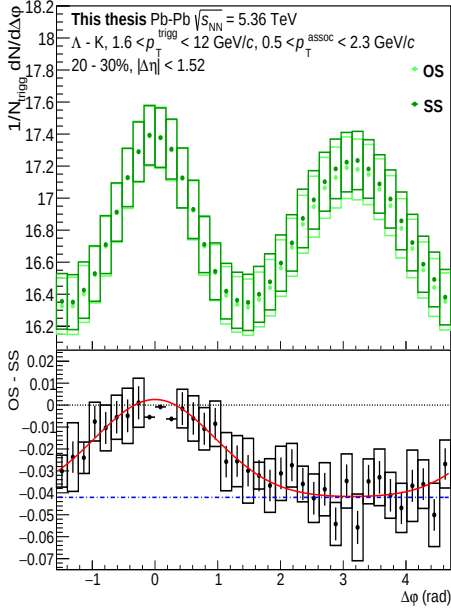
Figure A.15 – $\Delta\eta$ away-side projection of correlations between Λ baryons and protons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



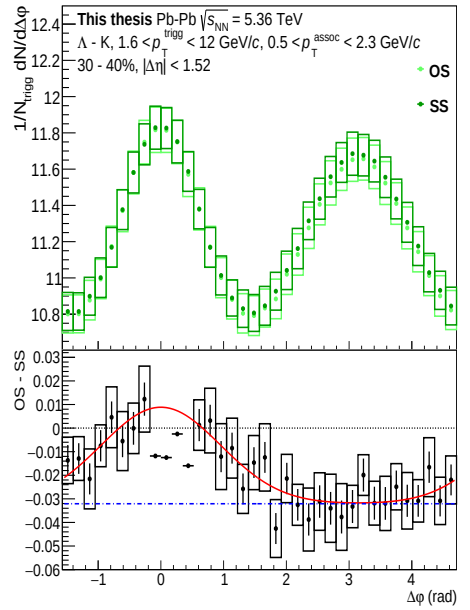
(a)



(b)

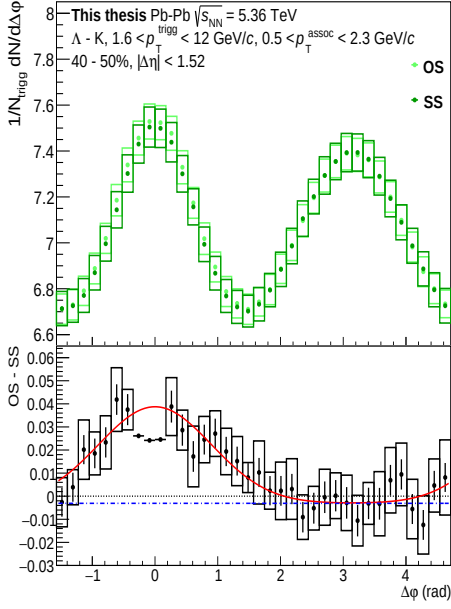


(c)

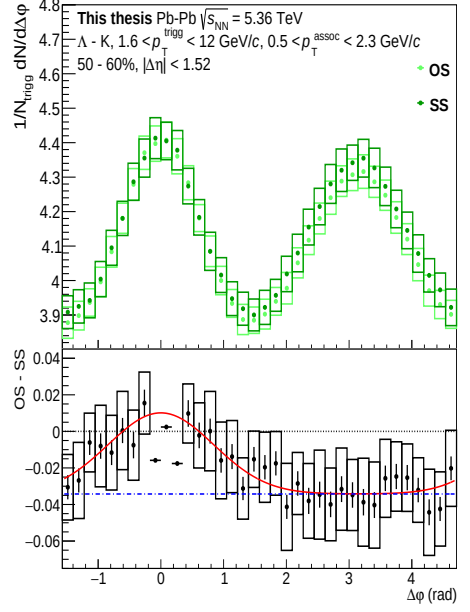


(d)

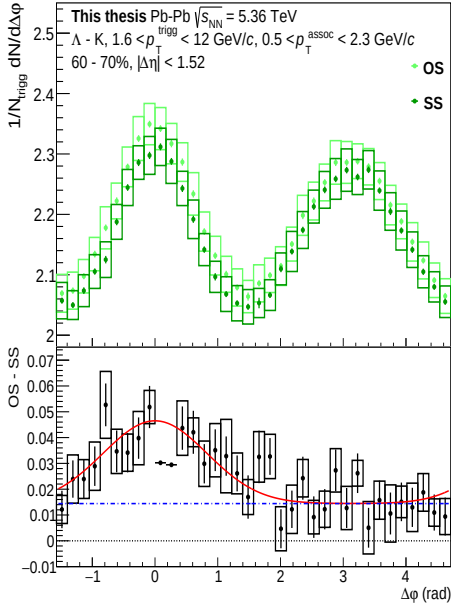
Figure A.16 – $\Delta\phi$ projection of correlations between Λ baryons and kaons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



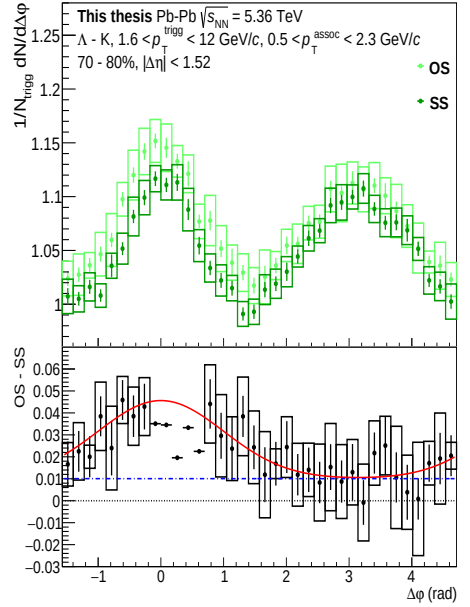
(a)



(b)

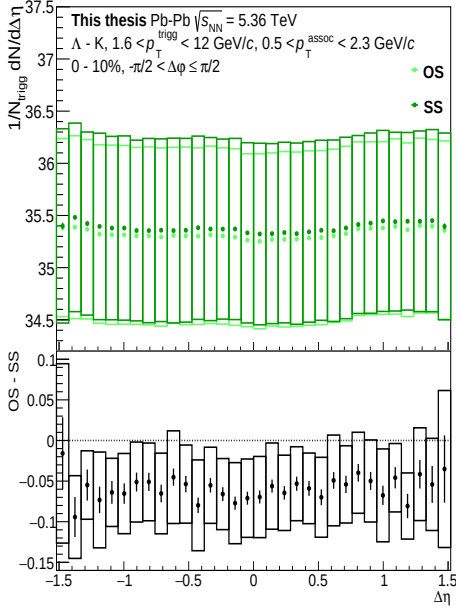


(c)

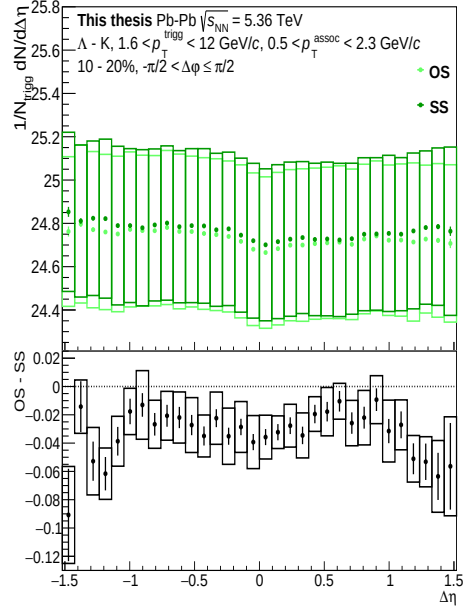


(d)

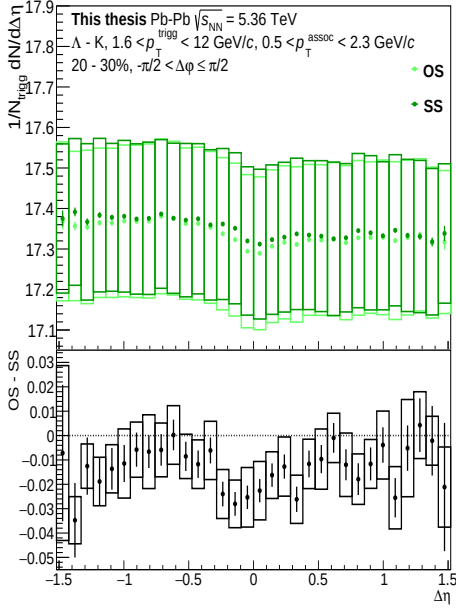
Figure A.17 – $\Delta\phi$ projection of correlations between Λ baryons and kaons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



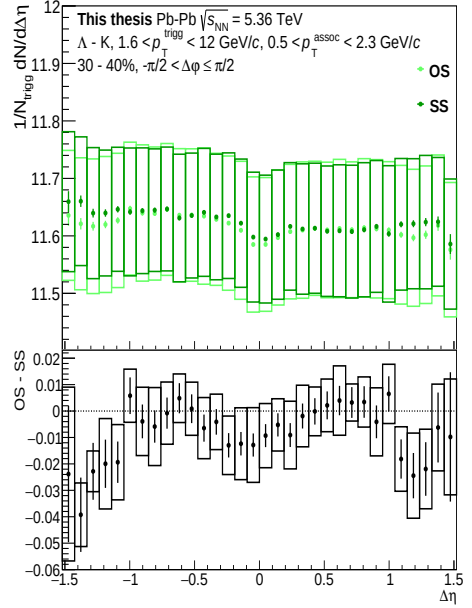
(a)



(b)

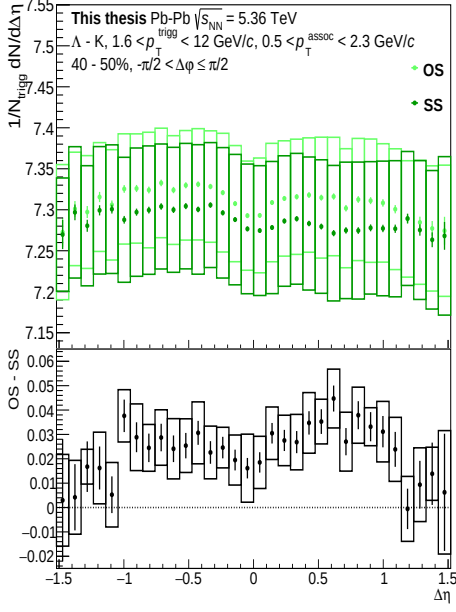


(c)

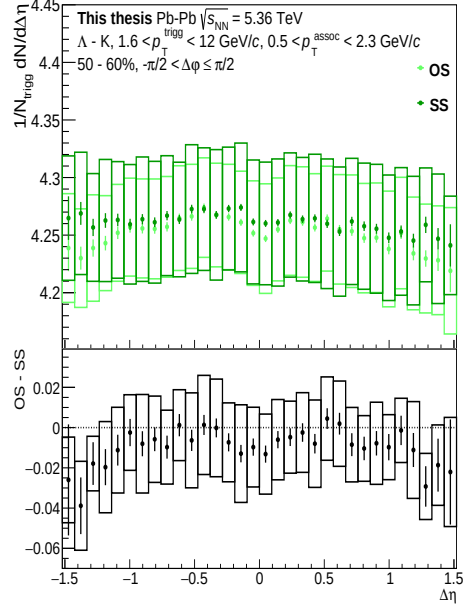


(d)

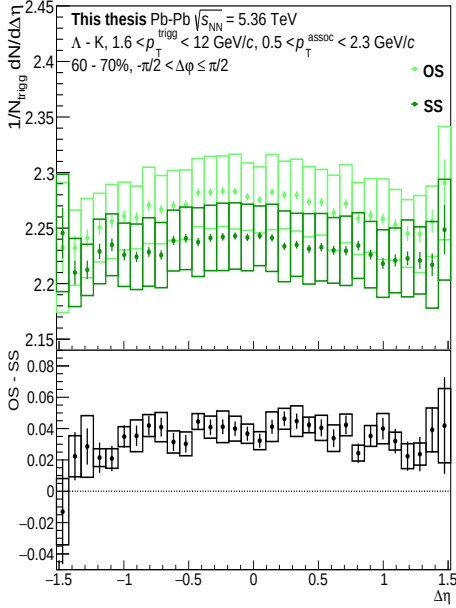
Figure A.18 – $\Delta\eta$ near-side projection of correlations between Λ baryons and kaons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



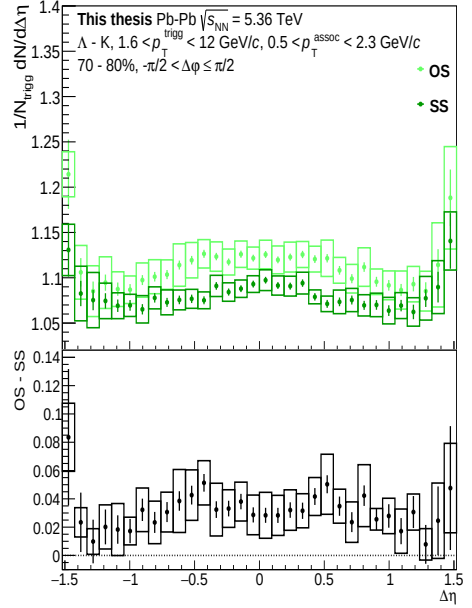
(a)



(b)

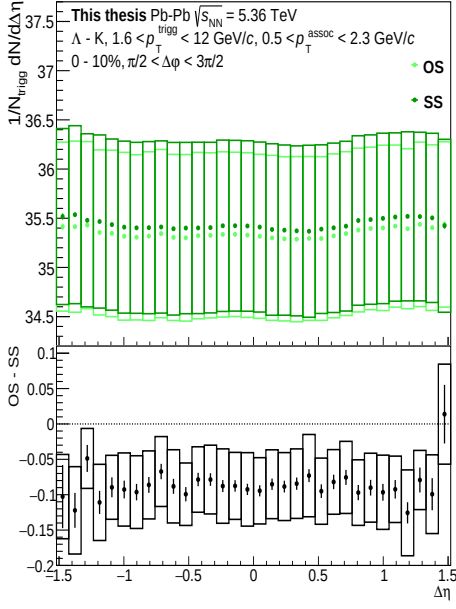


(c)

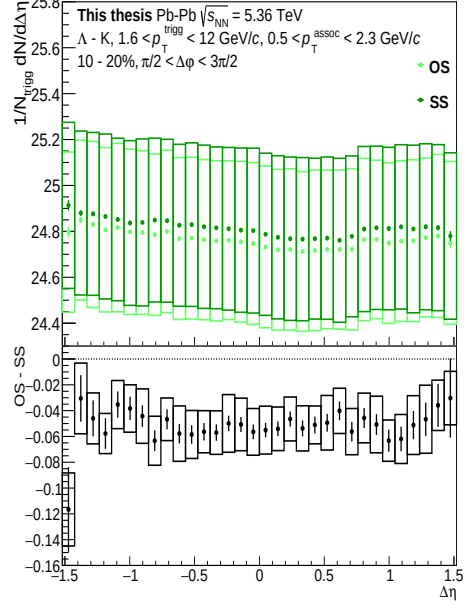


(d)

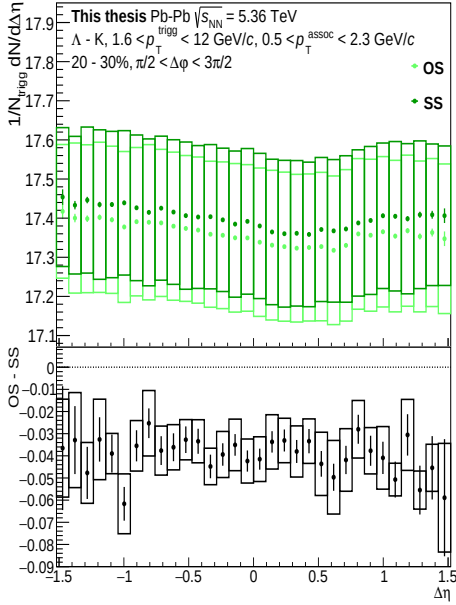
Figure A.19 – $\Delta\eta$ near-side projection of correlations between Λ baryons and kaons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



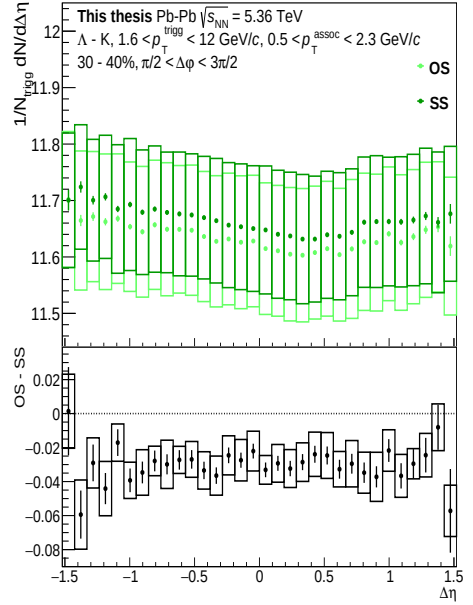
(a)



(b)

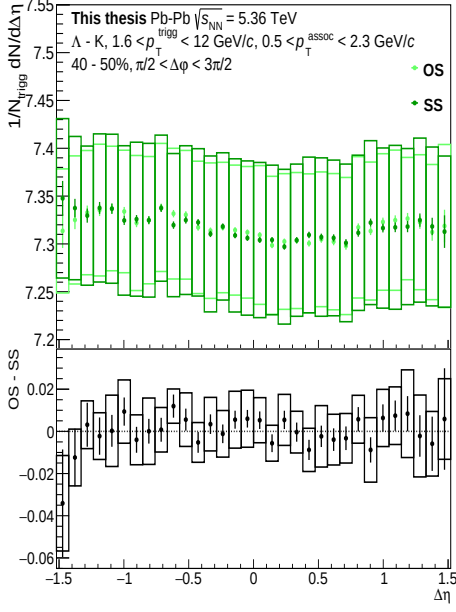


(c)

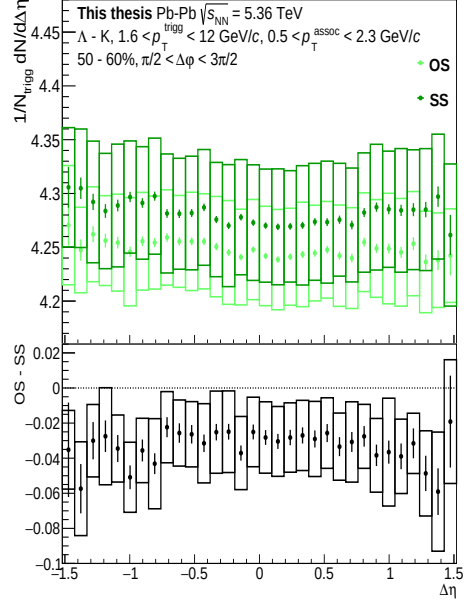


(d)

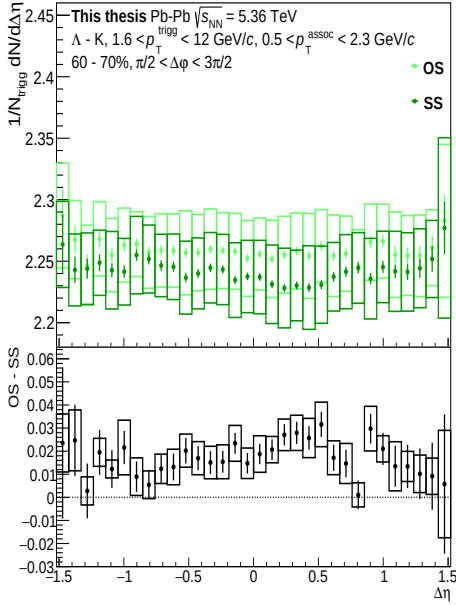
Figure A.20 – $\Delta\eta$ away-side projection of correlations between Λ baryons and kaons at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



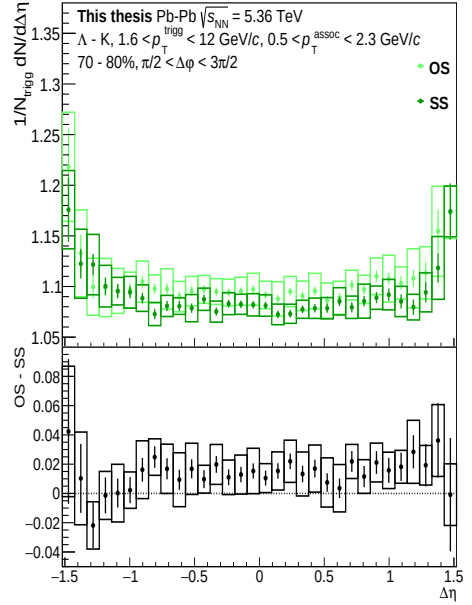
(a)



(b)

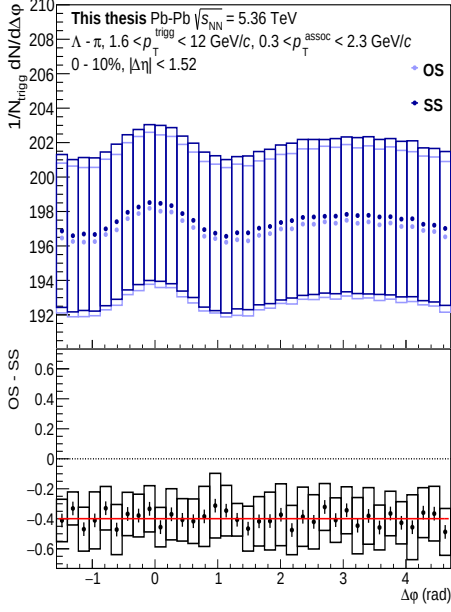


(c)

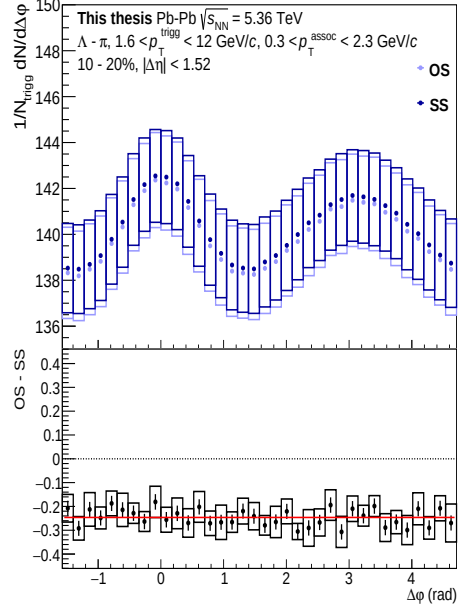


(d)

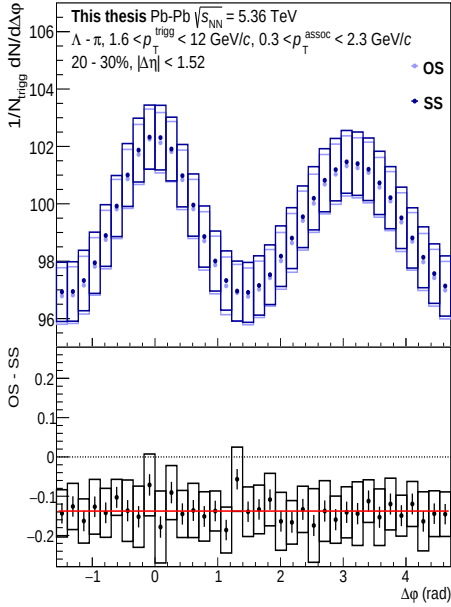
Figure A.21 – $\Delta\eta$ away-side projection of correlations between Λ baryons and kaons at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



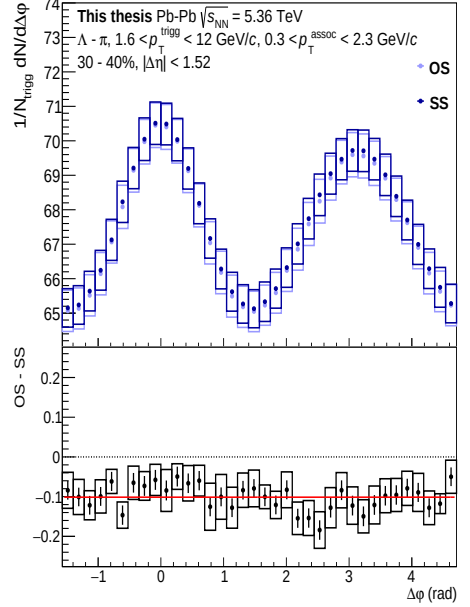
(a)



(b)

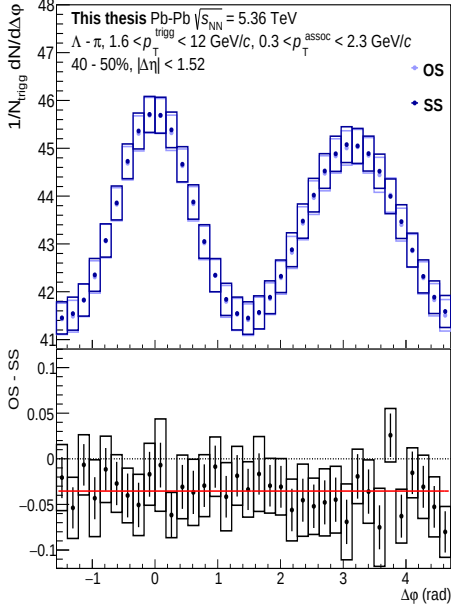


(c)

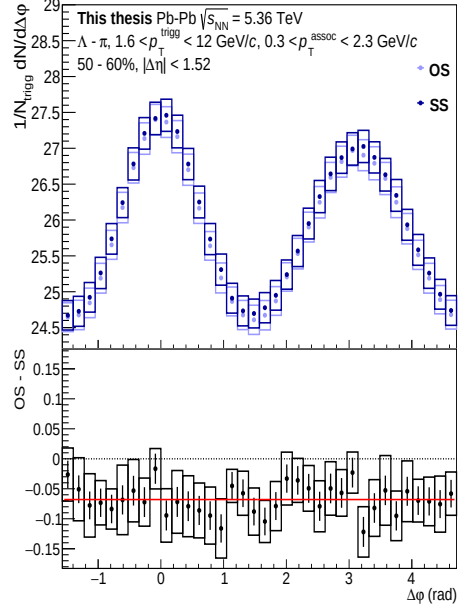


(d)

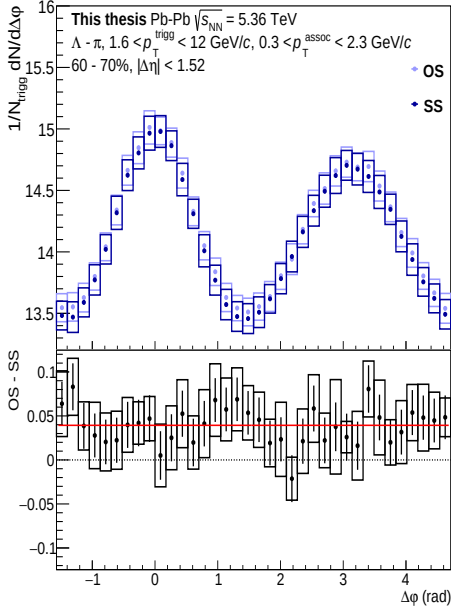
Figure A.22 – $\Delta\phi$ projection of correlations between Λ baryons and pions at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



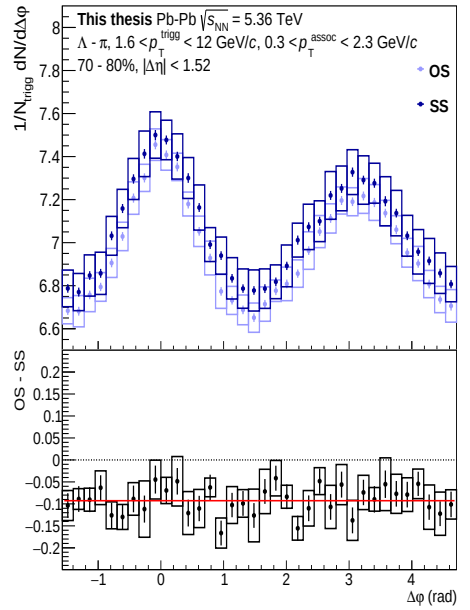
(a)



(b)

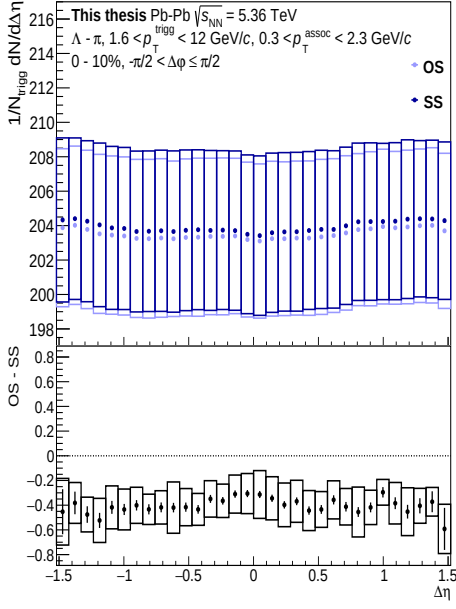


(c)

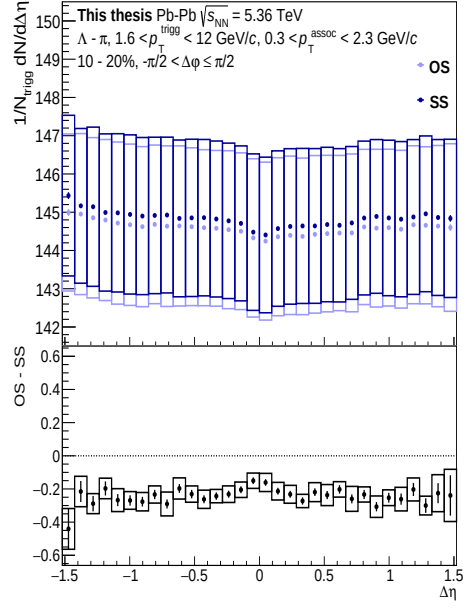


(d)

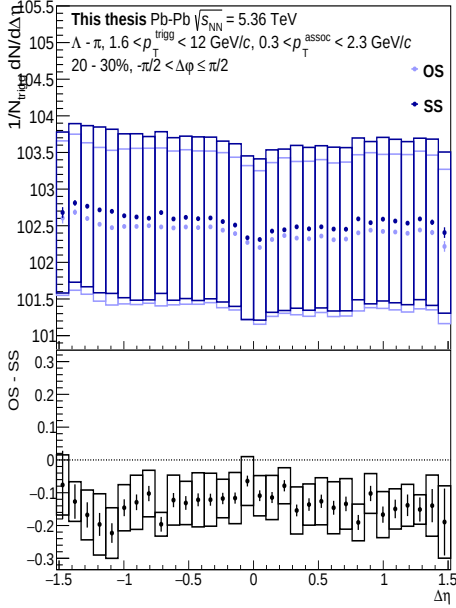
Figure A.23 – $\Delta\phi$ projection of correlations between Λ baryons and pions at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



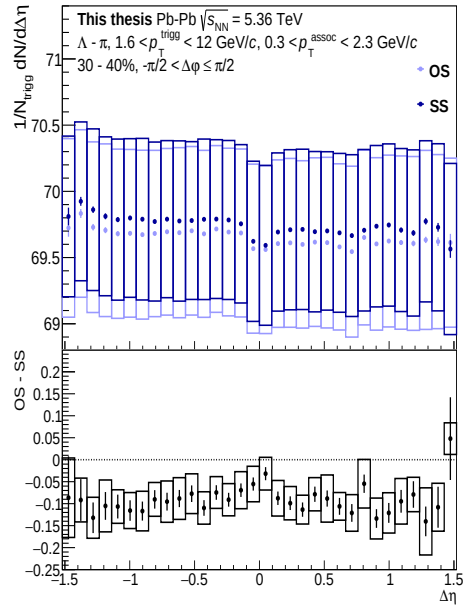
(a)



(b)

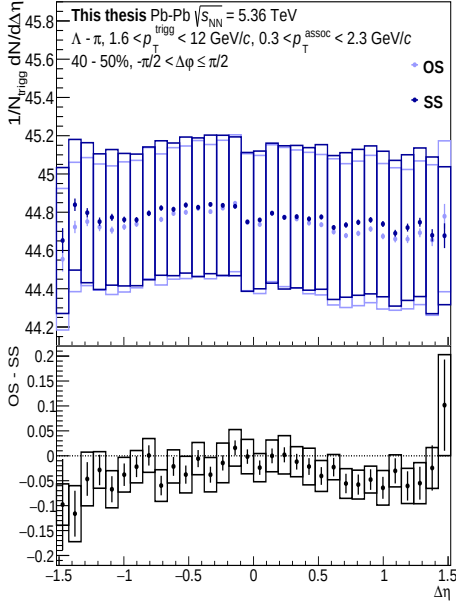


(c)

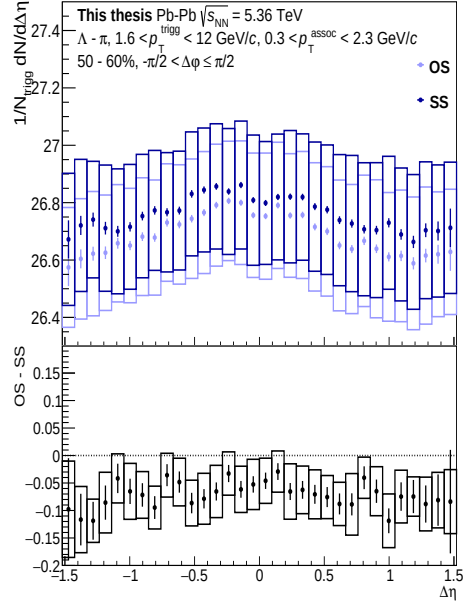


(d)

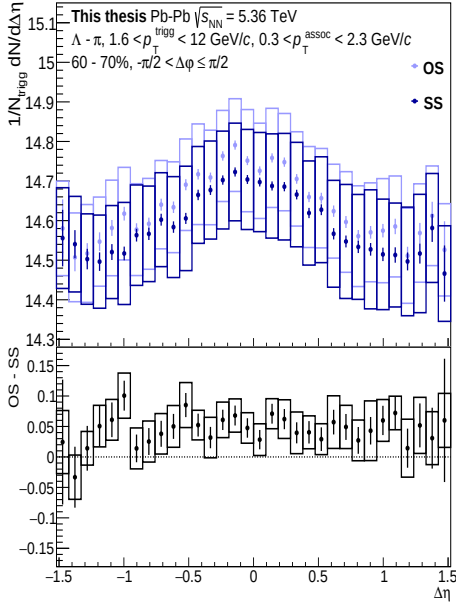
Figure A.24 – $\Delta\eta$ near-side projection of correlations between Λ baryons and pions at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



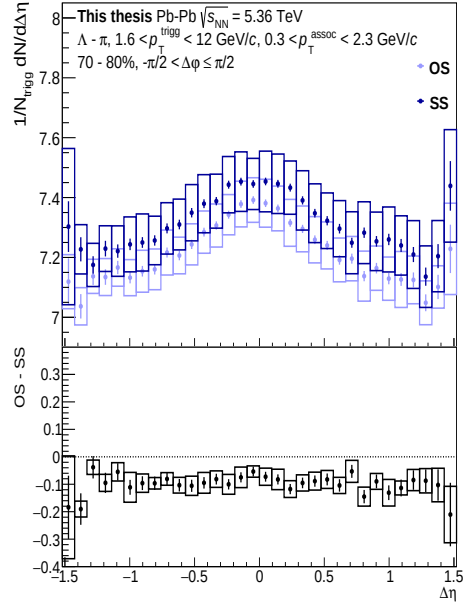
(a)



(b)

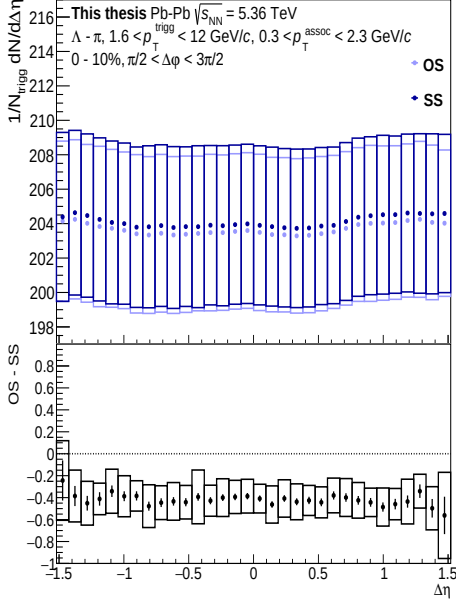


(c)

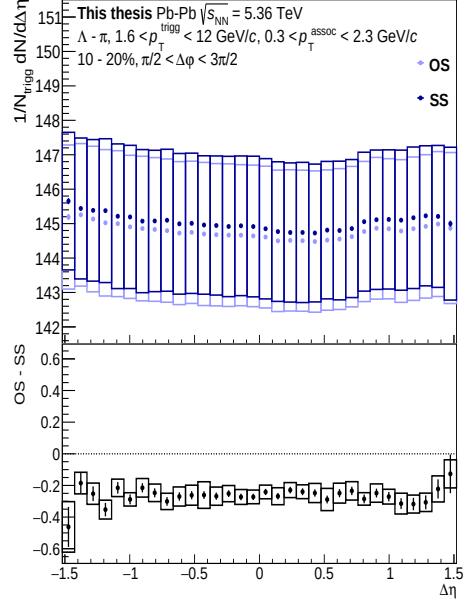


(d)

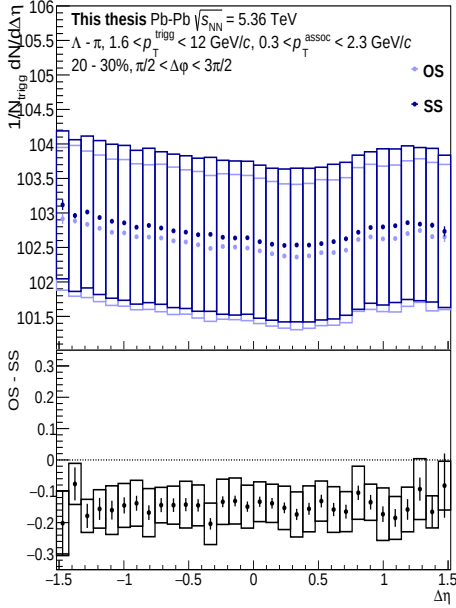
Figure A.25 $\Delta\eta$ near-side projection of correlations between Λ baryons and pions at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.



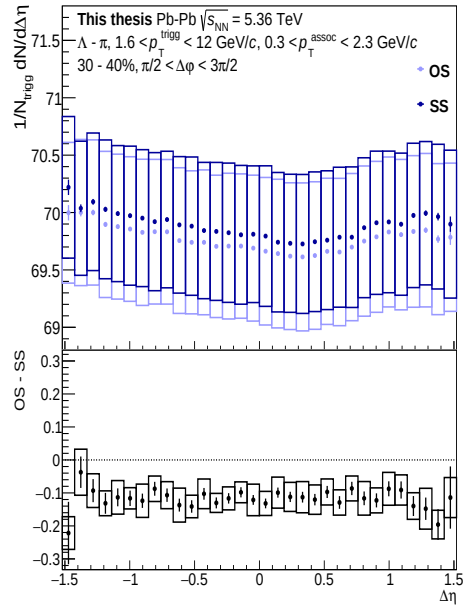
(a)



(b)

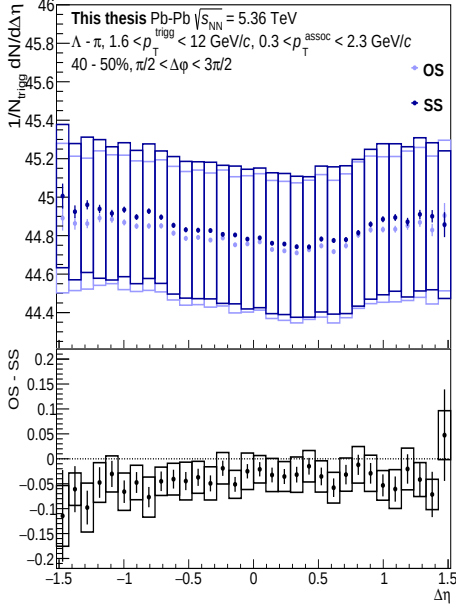


(c)

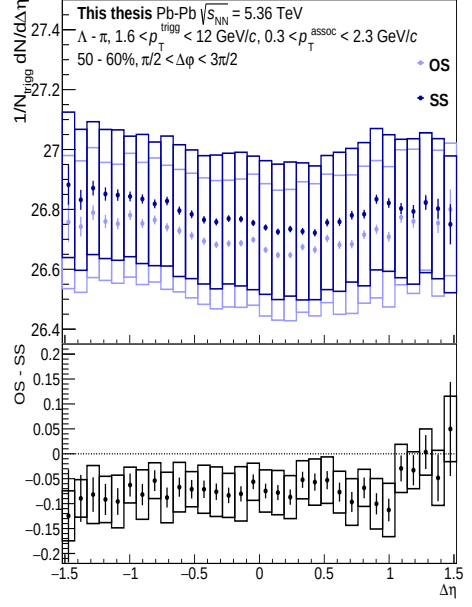


(d)

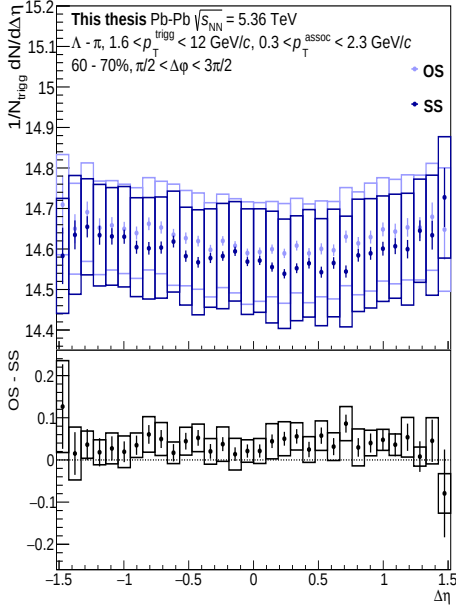
Figure A.26 – $\Delta\eta$ away-side projection of correlations between Λ baryons and pions at centrality (a) 0% – 10%, (b) 10% – 20%, (c) 20% – 30% and (d) 30% – 40%.



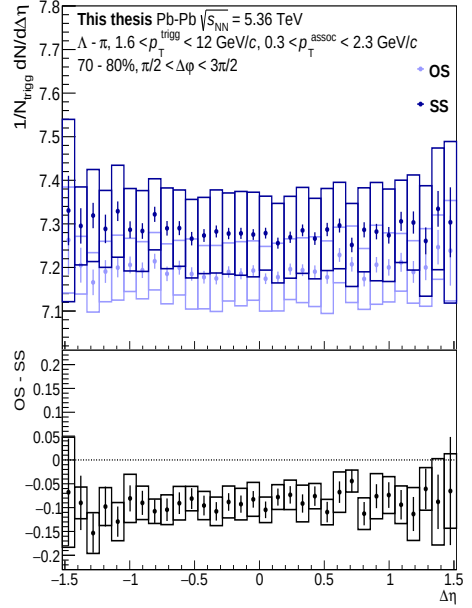
(a)



(b)



(c)



(d)

Figure A.27 – $\Delta\eta$ away-side projection of correlations between Λ baryons and pions at centrality (a) 40% – 50%, (b) 50% – 60%, (c) 60% – 70% and (d) 70% – 80%.

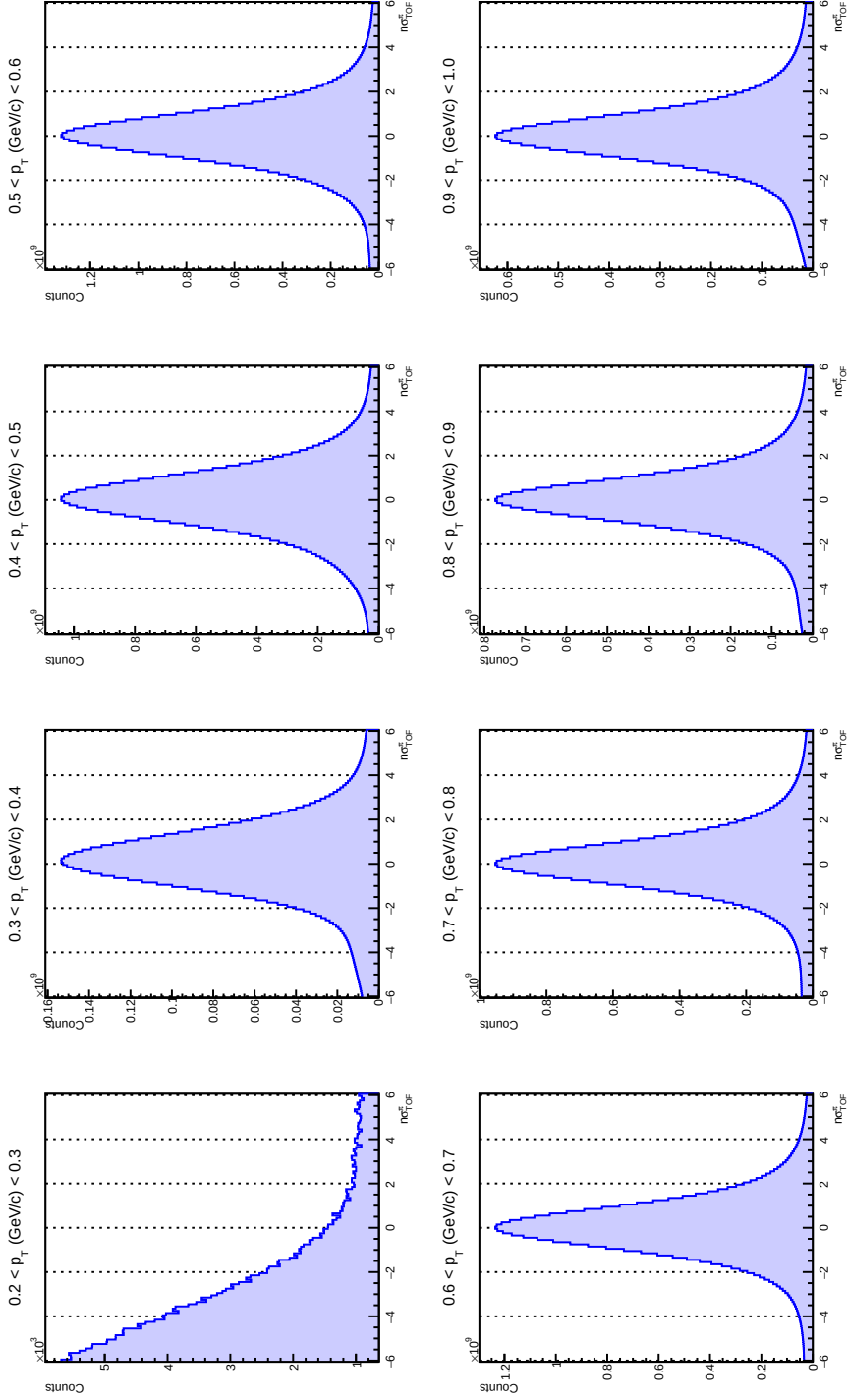


Figure A.28 – Distribution of TOF $n\sigma^\pi$ response for $0.2 \text{ GeV}/c < p_T < 1.0 \text{ GeV}/c$.

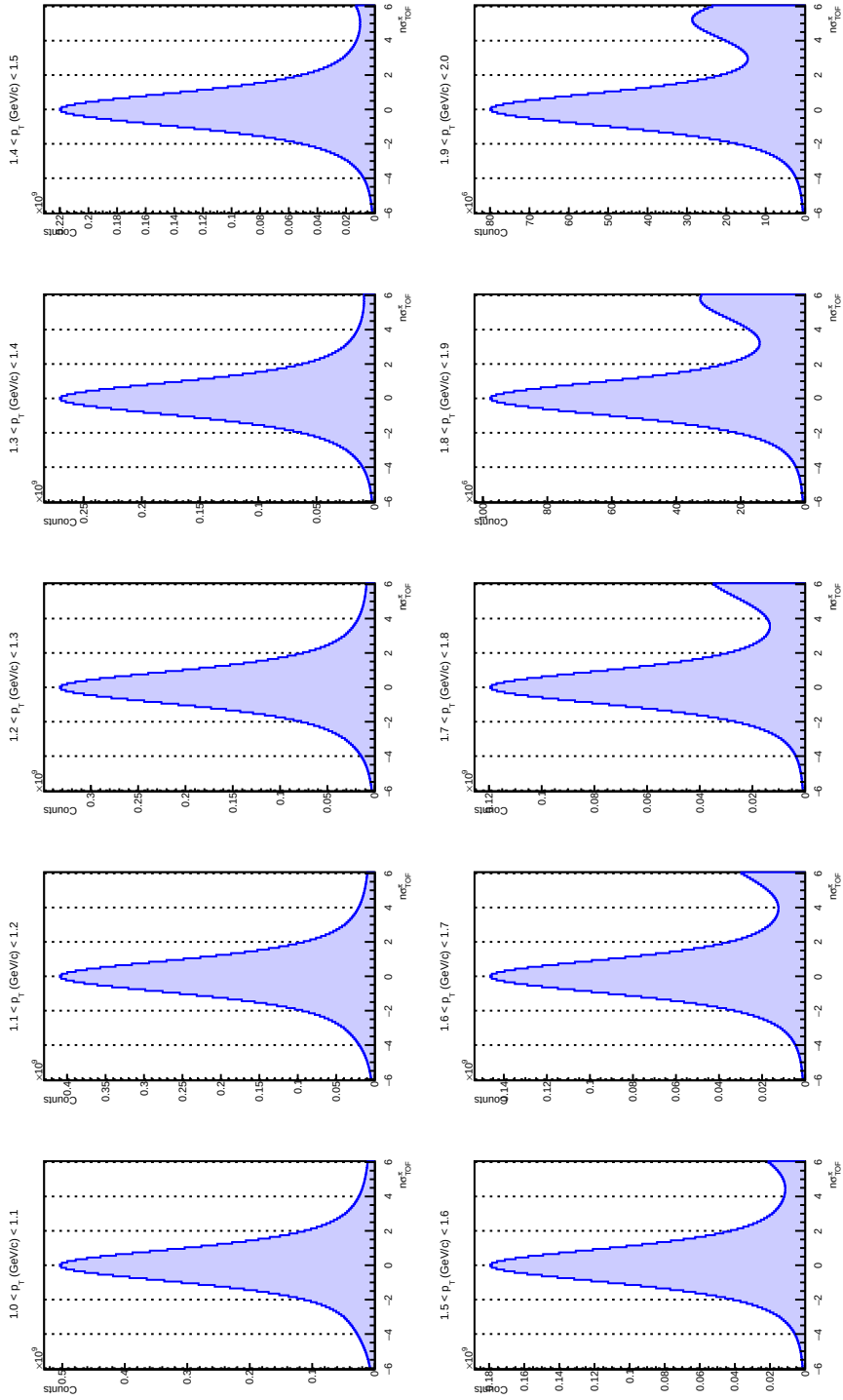


Figure A.29 – Distribution of TOF $n\sigma^\pi$ response for $1.0 \text{ GeV}/c < p_T < 2.0 \text{ GeV}/c$.

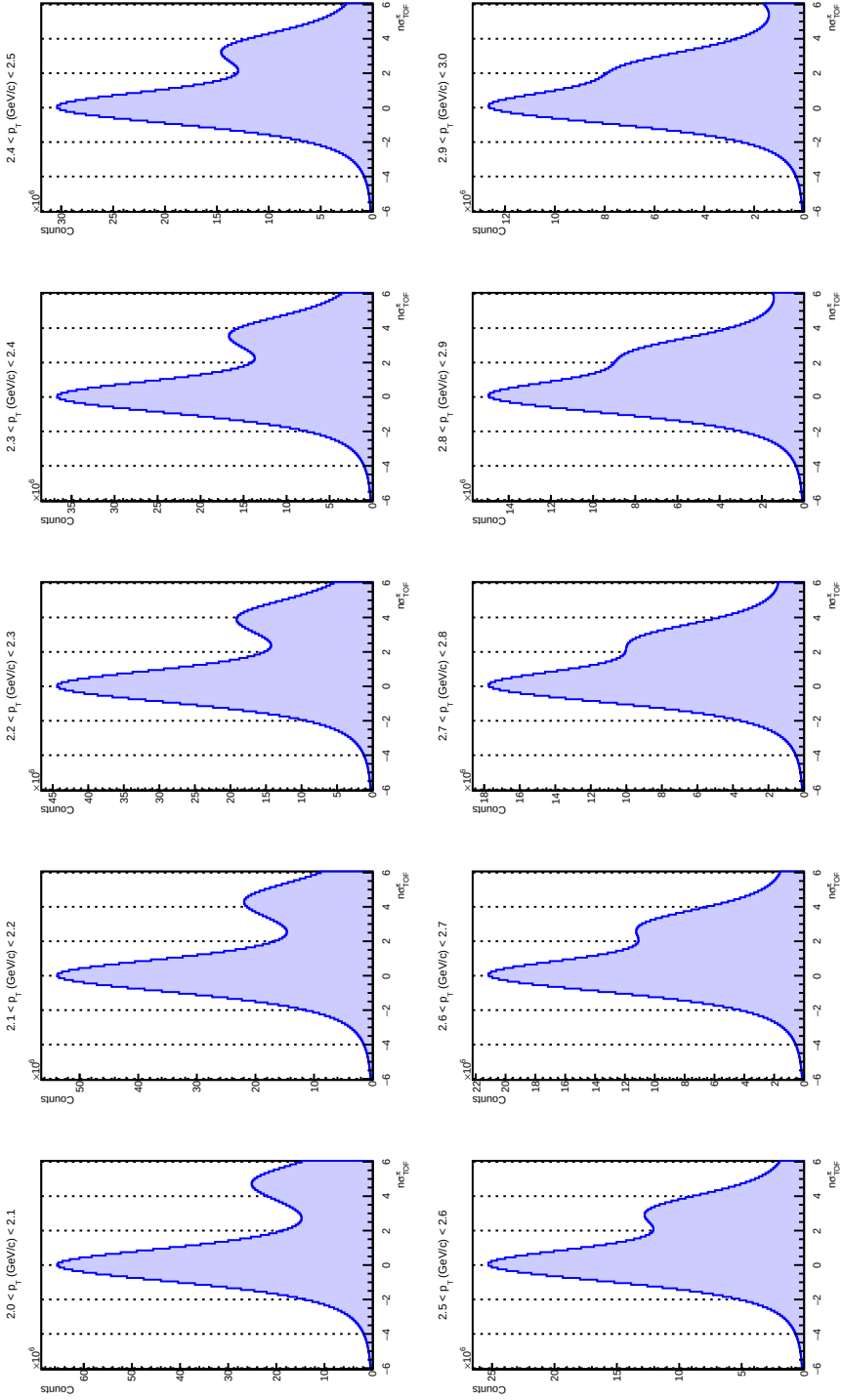


Figure A.30 – Distribution of TOF $n\sigma^\pi$ response for $2.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$.

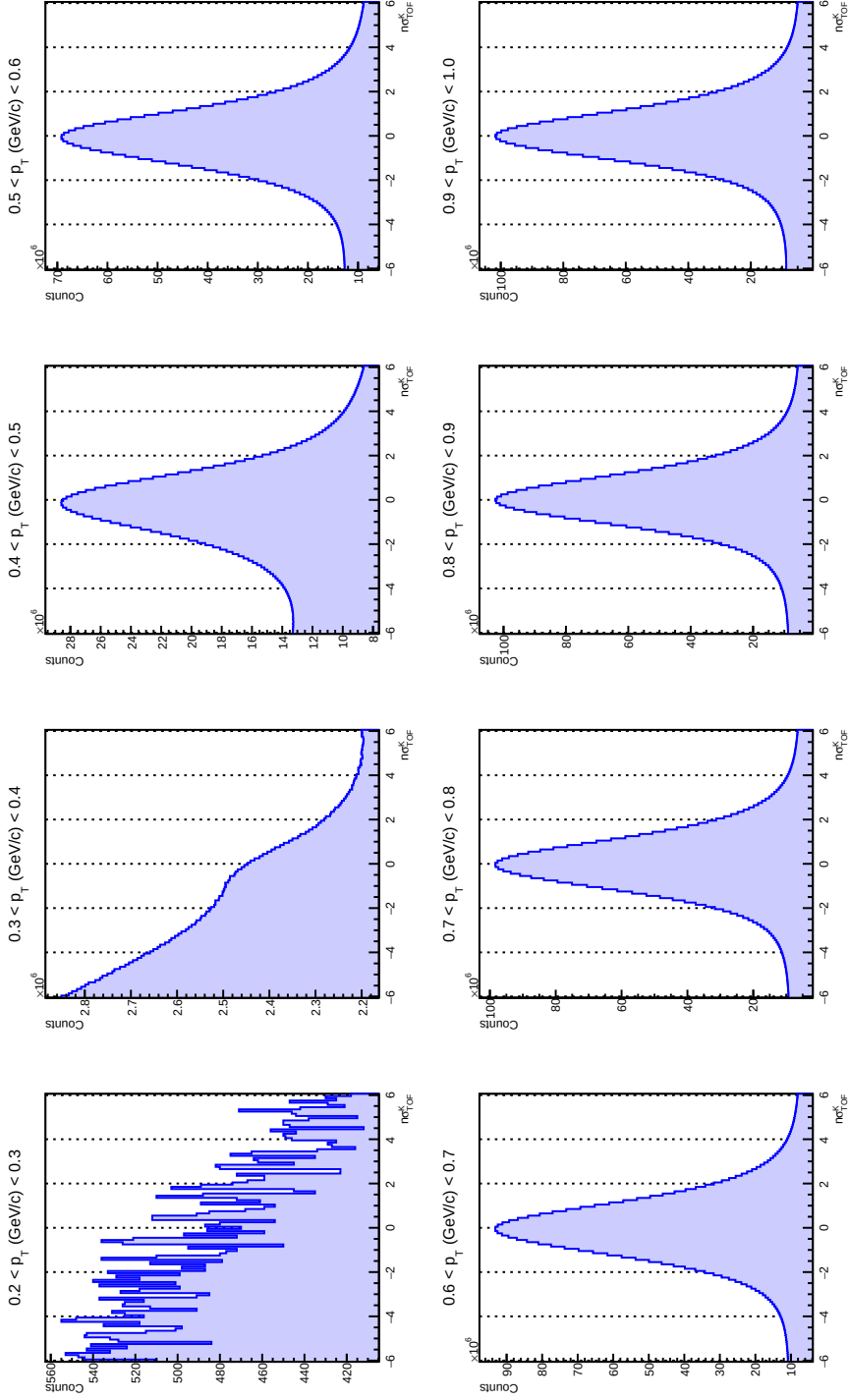


Figure A.31 – Distribution of TOF $n\sigma^K$ response for $0.2 \text{ GeV}/c < p_T < 1.0 \text{ GeV}/c$.

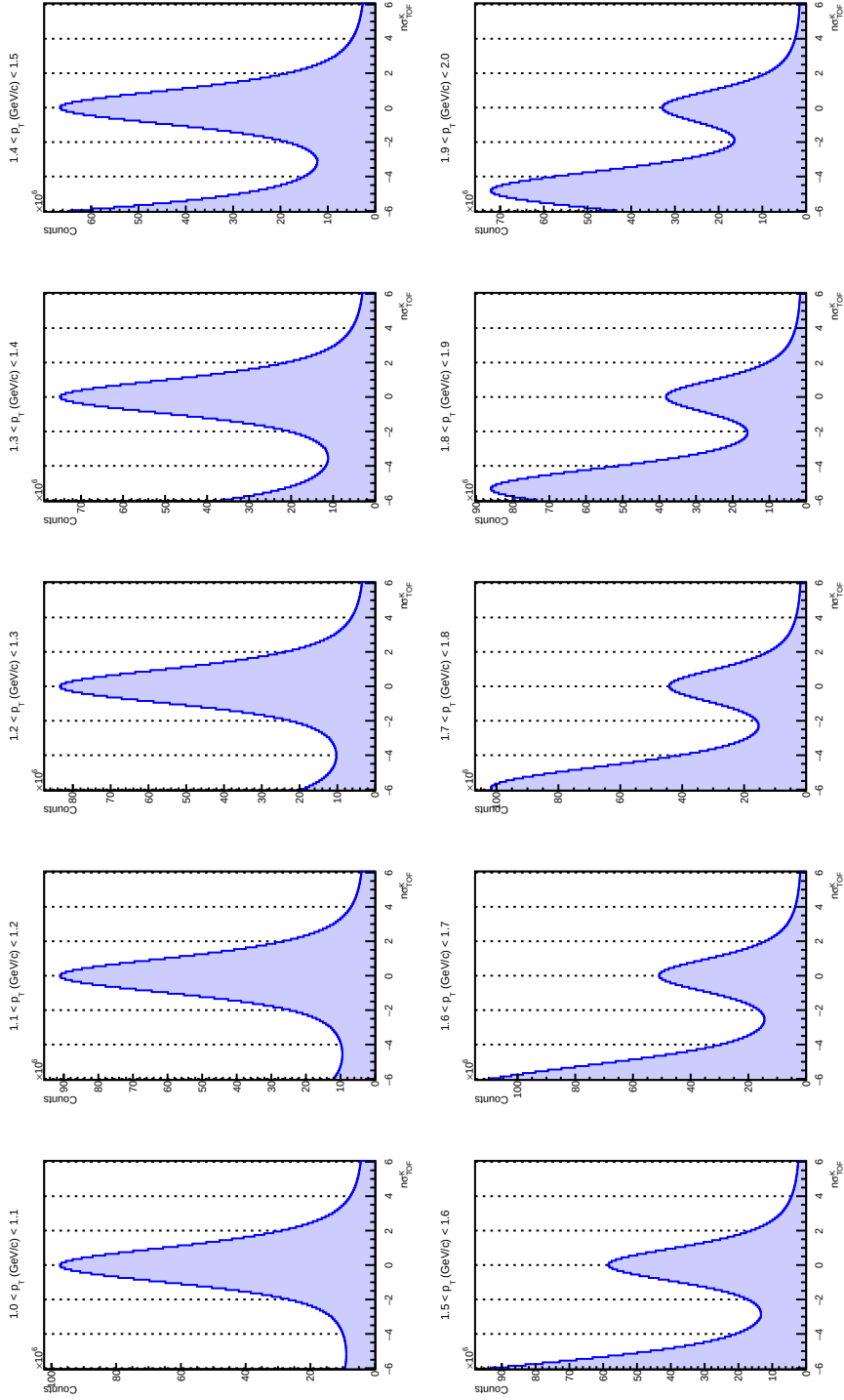


Figure A.32 – Distribution of TOF $n\sigma^K$ response for $1.0 \text{ GeV/c} < p_T < 2.0 \text{ GeV/c}$.

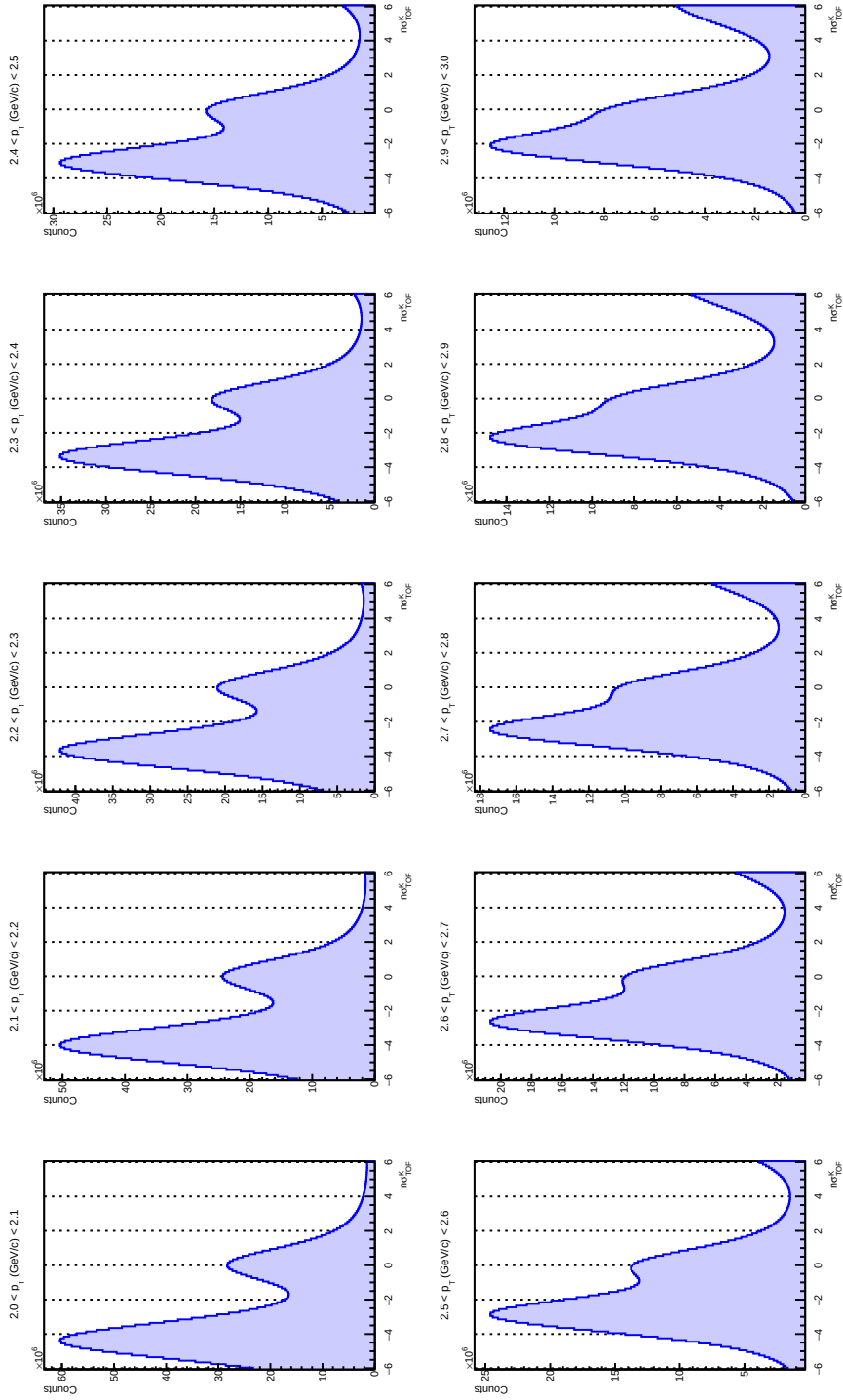


Figure A.33 – Distribution of TOF $n\sigma^K$ response for $2.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$.

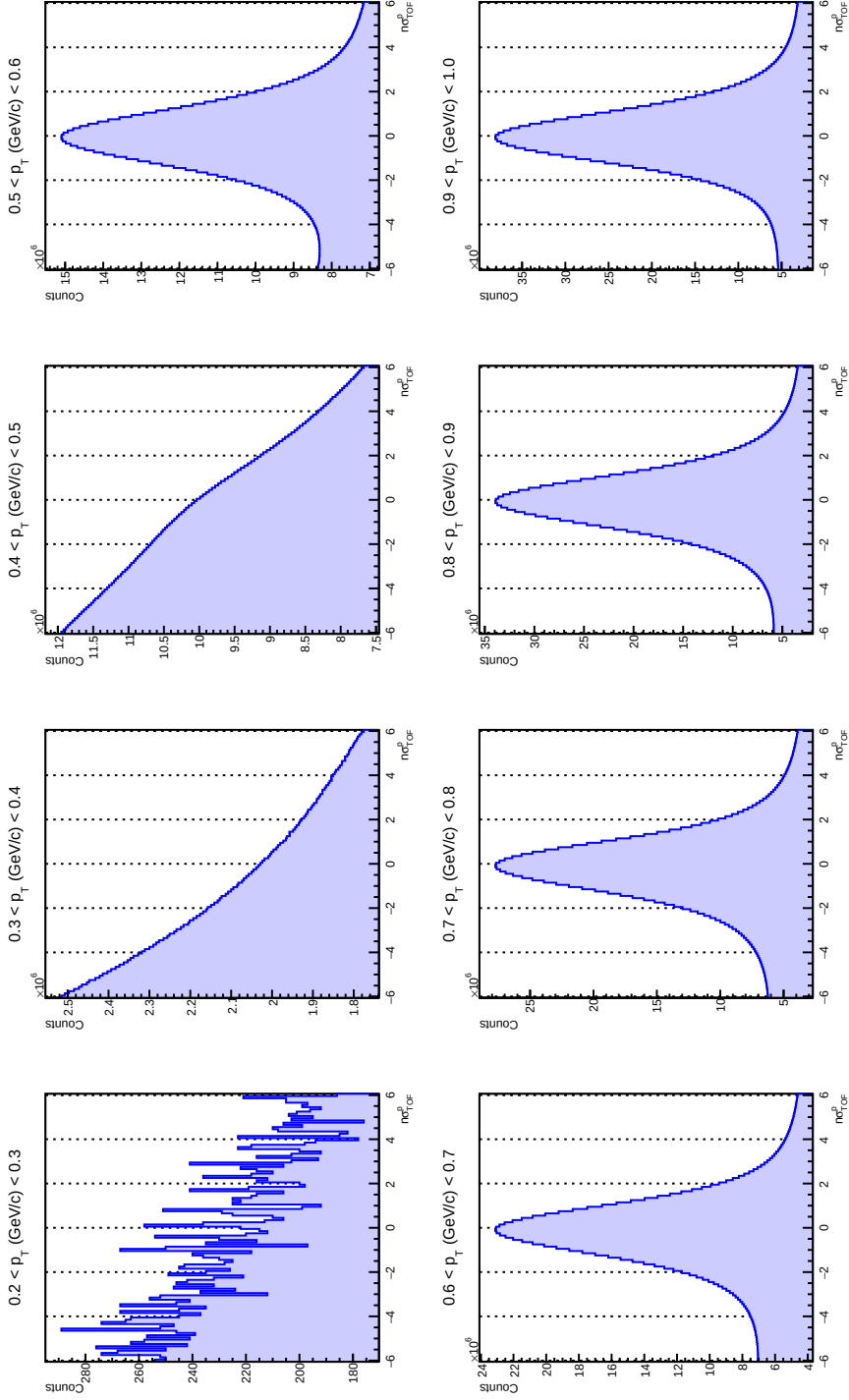


Figure A.34 – Distribution of TOF $n\sigma^P$ response for $0.2 \text{ GeV}/c < p_T < 1.0 \text{ GeV}/c$.

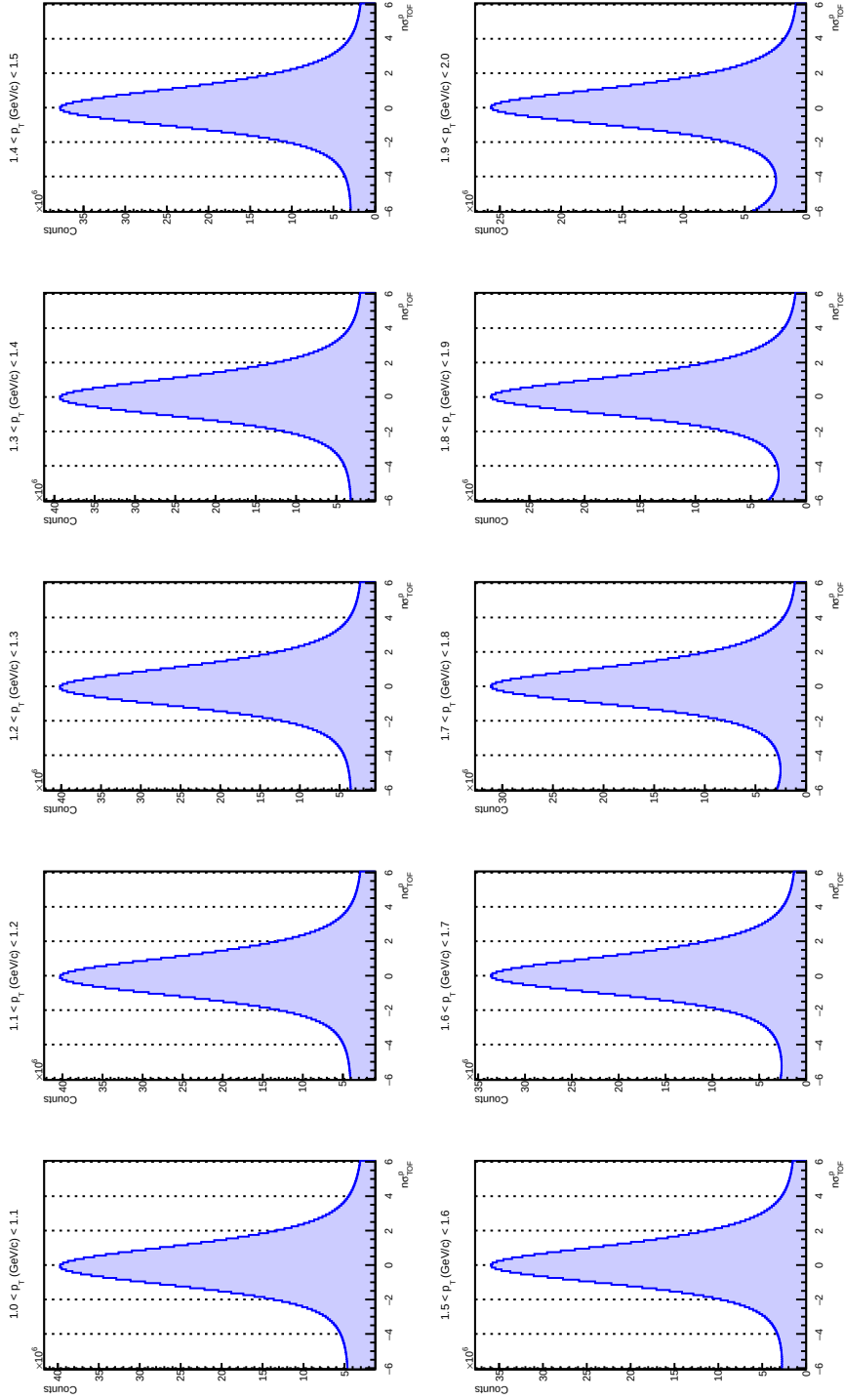


Figure A.35 – Distribution of TOF $n\sigma^P$ response for $1.0 \text{ GeV}/c < p_T < 2.0 \text{ GeV}/c$.

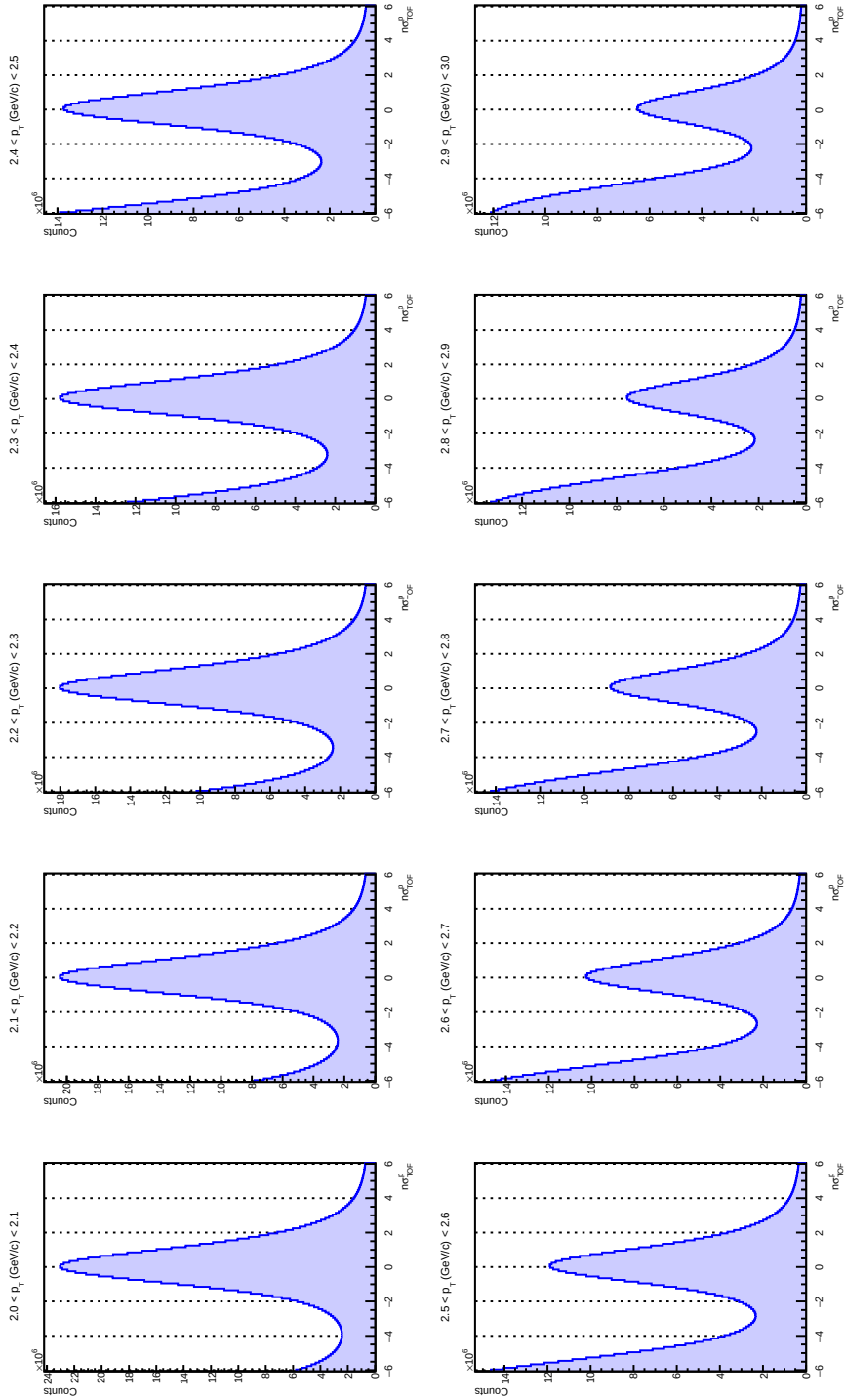


Figure A.36 – Distribution of TOF $n\sigma^P$ response for $2.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$.

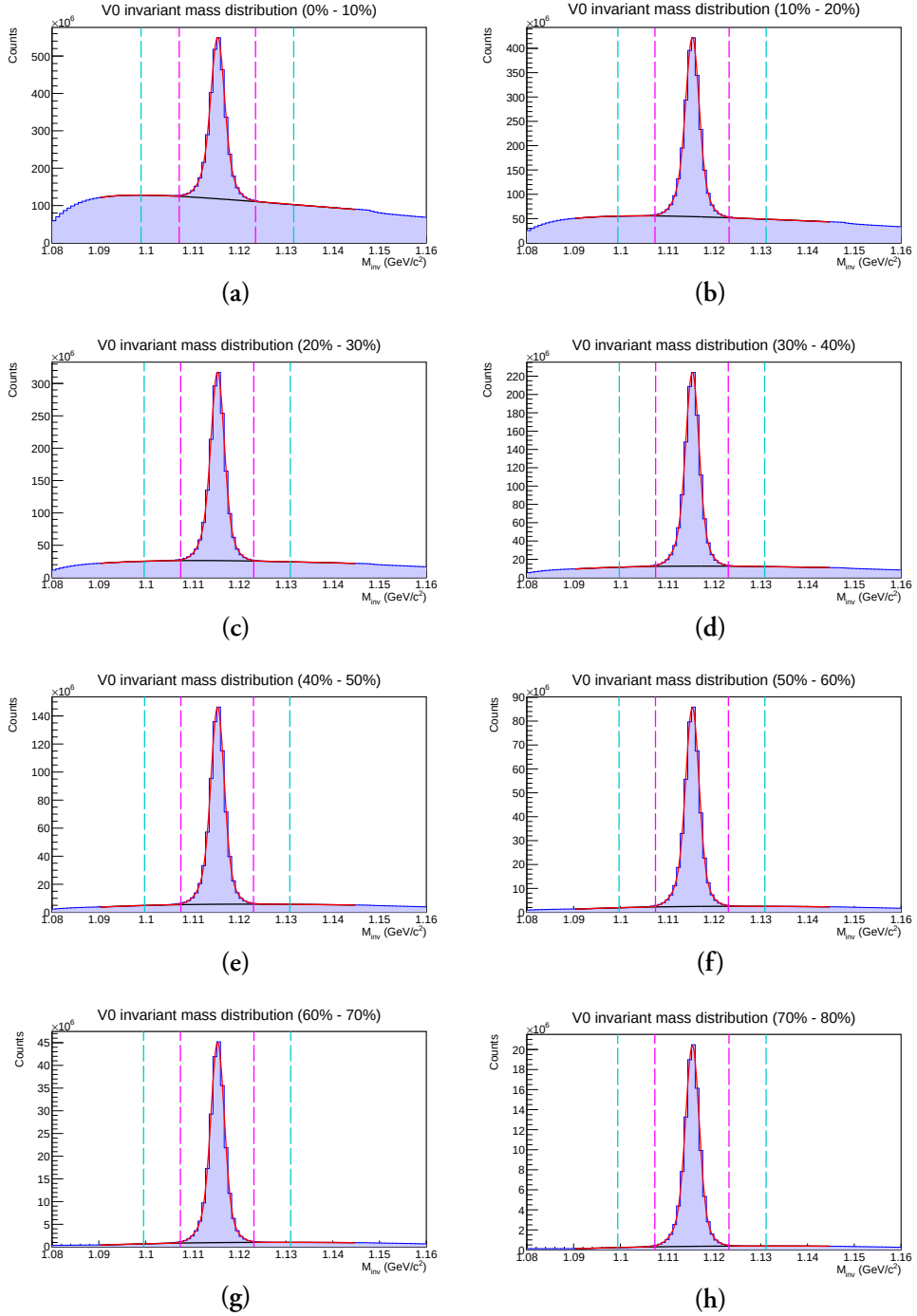


Figure A.37 – Invariant mass distribution of Λ candidates in various centrality intervals. The solid red and black lines belong to the signal and background fits, while the dashed purple and cyan lines indicate the SGNL and SB regions.

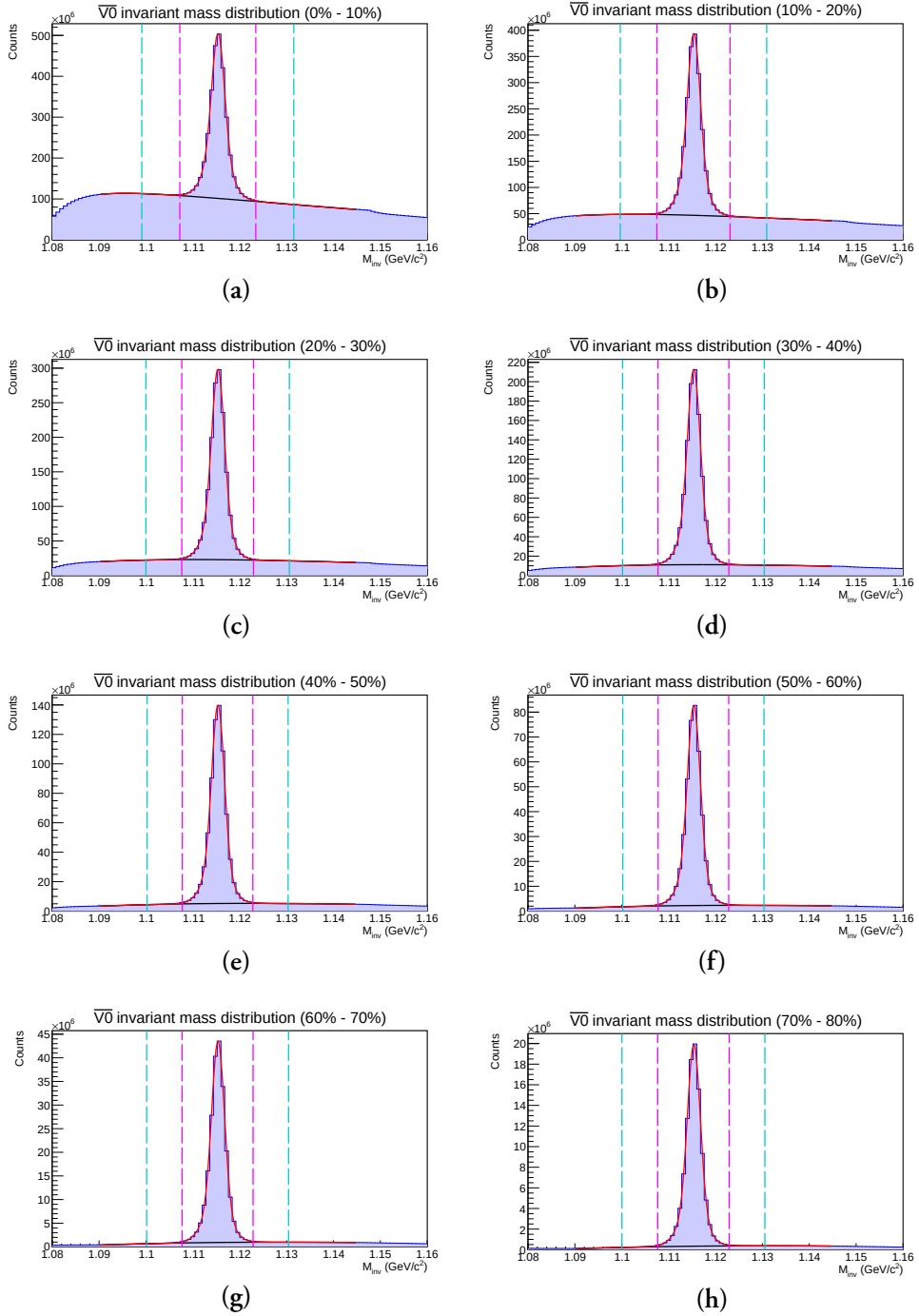
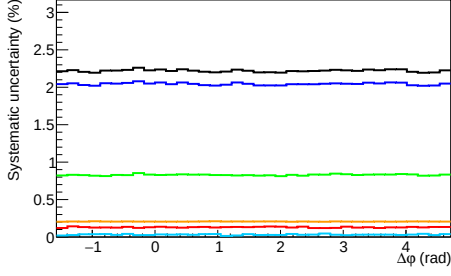
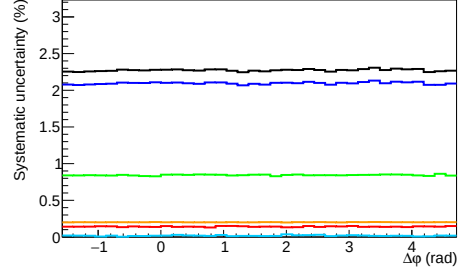


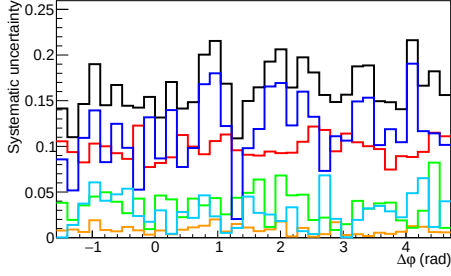
Figure A.38 – Invariant mass distribution of $\bar{\Lambda}$ candidates in various centrality intervals. The solid red and black lines belong to the signal and background fits, while the dashed purple and cyan lines indicate the SGNL and SB regions.



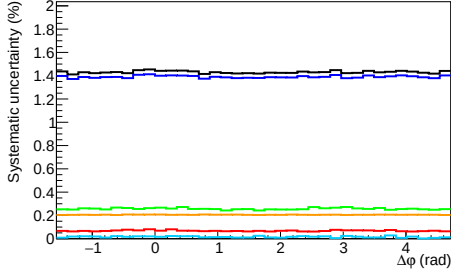
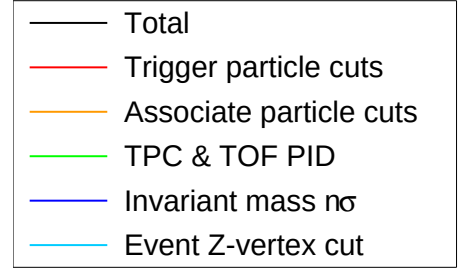
(a)



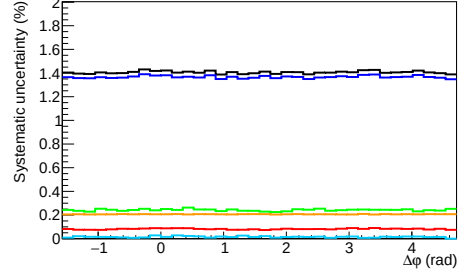
(b)



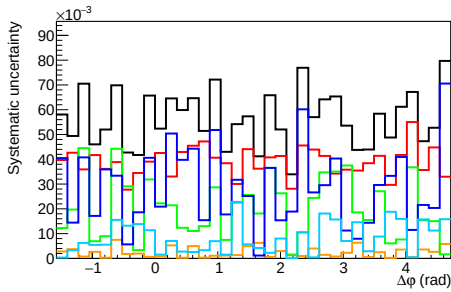
(c)



(d)

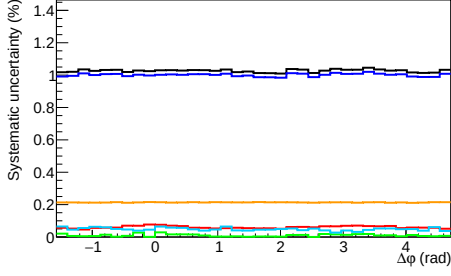


(e)

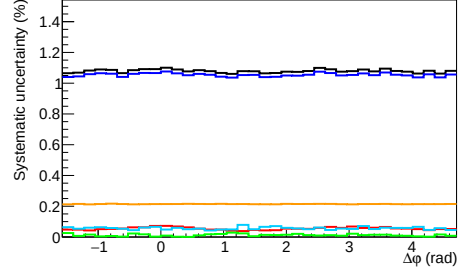


(f)

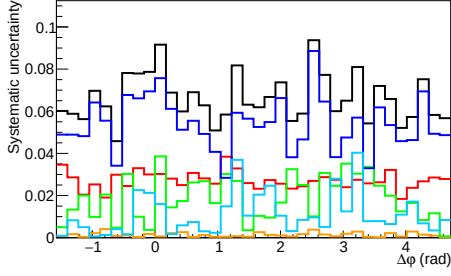
Figure A.39 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - \pi$ correlations, (b, e) same-sign $\Lambda - \pi$ correlations and (c, f) $\Lambda - \pi$ balance functions. Centrality classes are (a, b, c) 0% – 10% and (d, e, f) 10% – 20%.



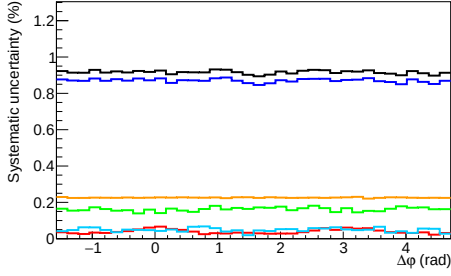
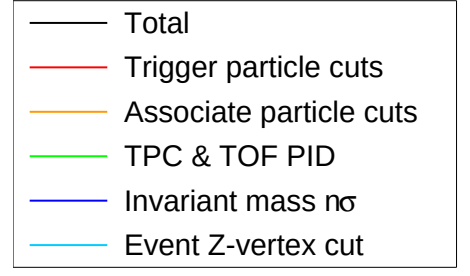
(a)



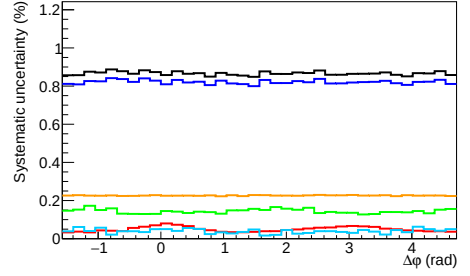
(b)



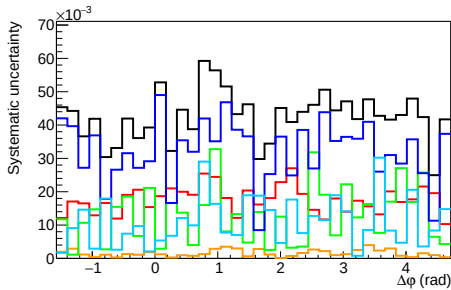
(c)



(d)

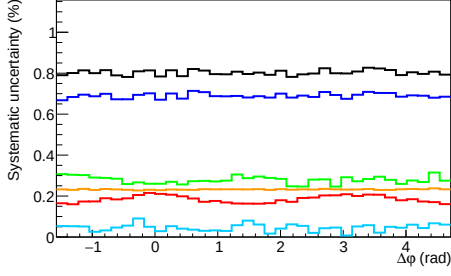


(e)

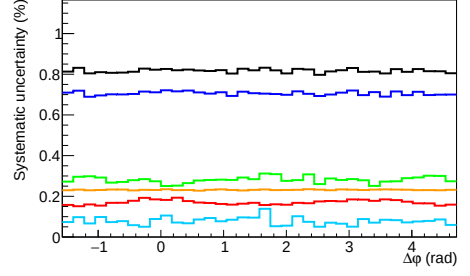


(f)

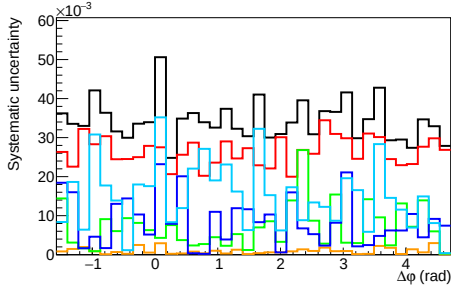
Figure A.40 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - \pi$ correlations, (b, e) same-sign $\Lambda - \pi$ correlations and (c, f) $\Lambda - \pi$ balance functions. Centrality classes are (a, b, c) 20% – 30% and (d, e, f) 30% – 40%.



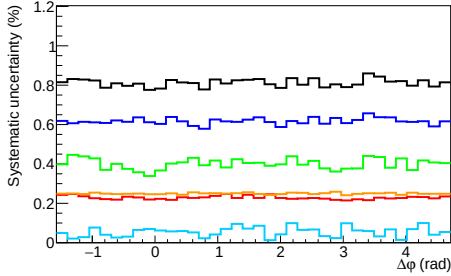
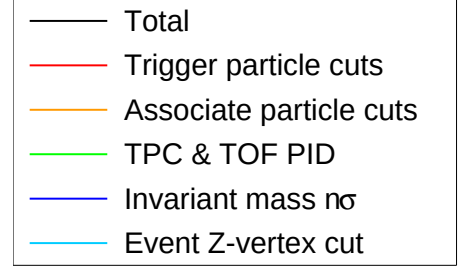
(a)



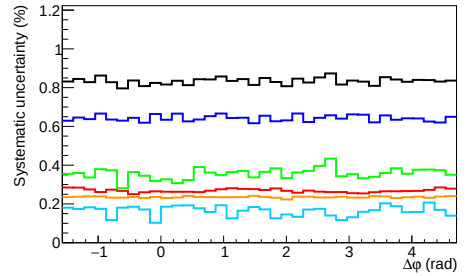
(b)



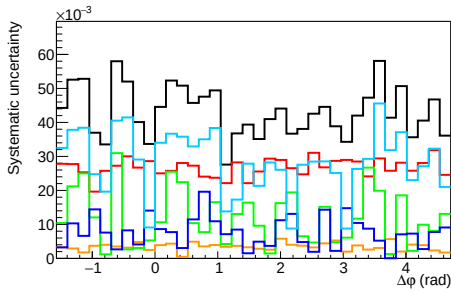
(c)



(d)

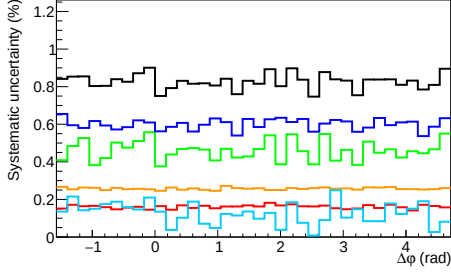


(e)

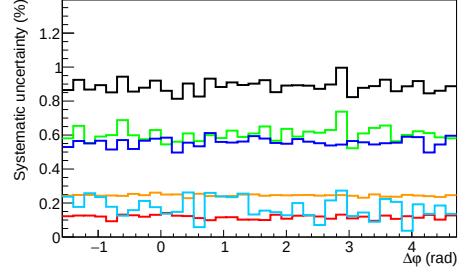


(f)

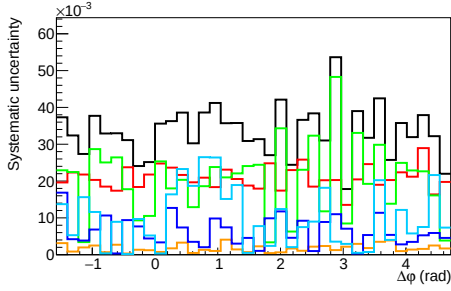
Figure A.41 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - \pi$ correlations, (b, e) same-sign $\Lambda - \pi$ correlations and (c, f) $\Lambda - \pi$ balance functions. Centrality classes are (a, b, c) 40% – 50% and (d, e, f) 50% – 60%.



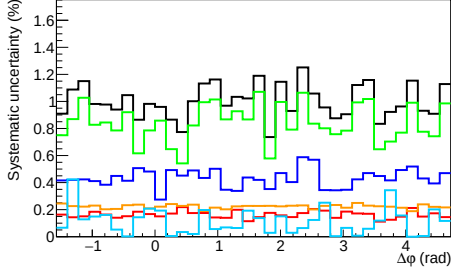
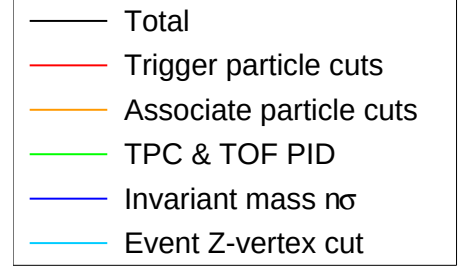
(a)



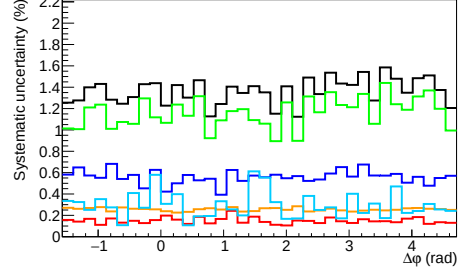
(b)



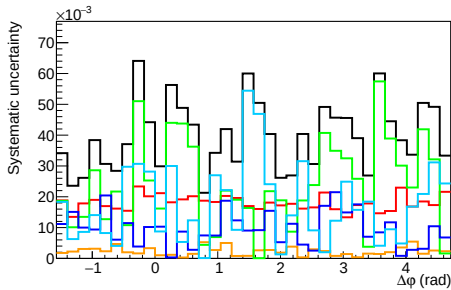
(c)



(d)

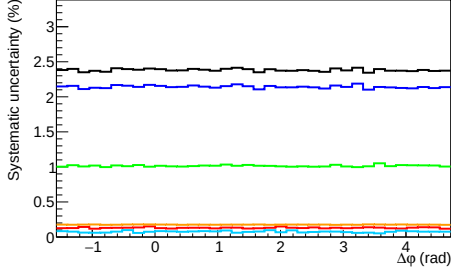


(e)

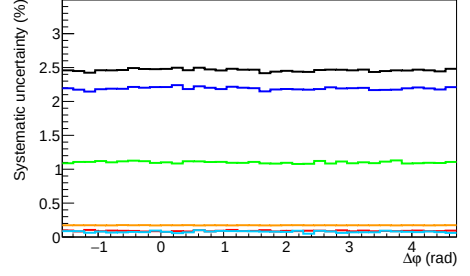


(f)

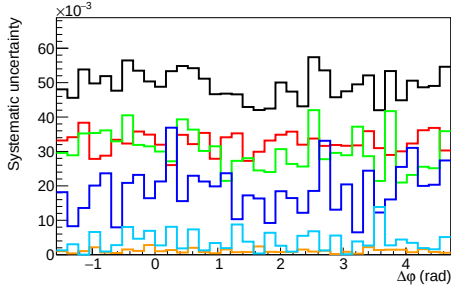
Figure A.42 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\phi$ projections of the (a, d) opposite-sign $\Lambda - \pi$ correlations, (b, e) same-sign $\Lambda - \pi$ correlations and (c, f) $\Lambda - \pi$ balance functions. Centrality classes are (a, b, c) 60% – 70% and (d, e, f) 70% – 80%.



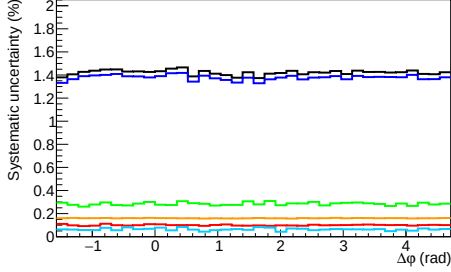
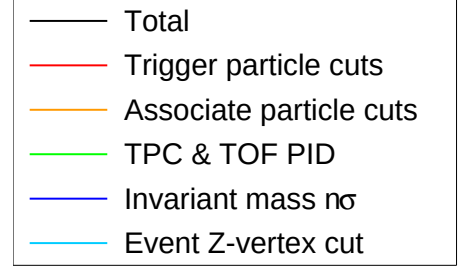
(a)



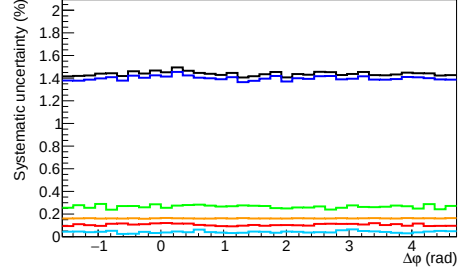
(b)



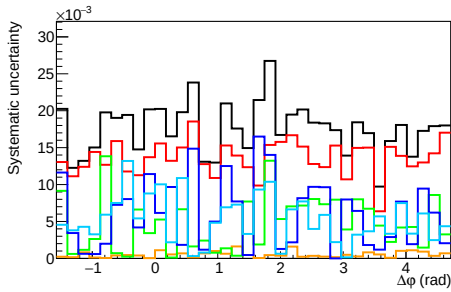
(c)



(d)

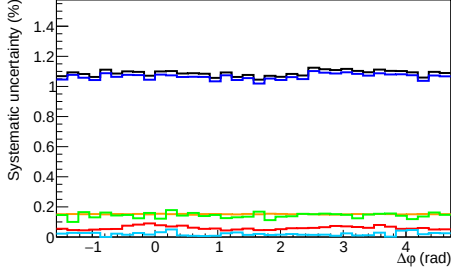


(e)

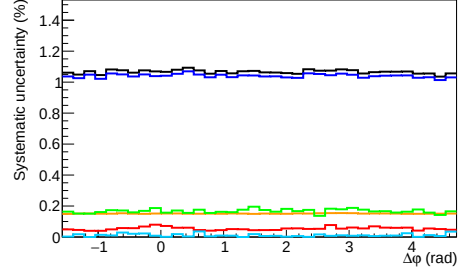


(f)

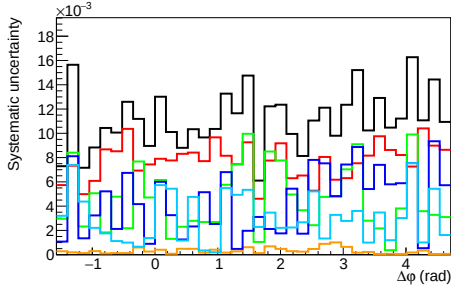
Figure A.43 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - K$ correlations, (b, e) same-sign $\Lambda - K$ correlations and (c, f) $\Lambda - K$ balance functions. Centrality classes are (a, b, c) 0% – 10% and (d, e, f) 10% – 20%.



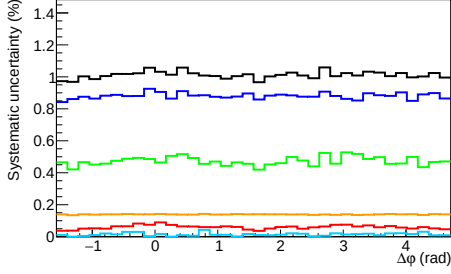
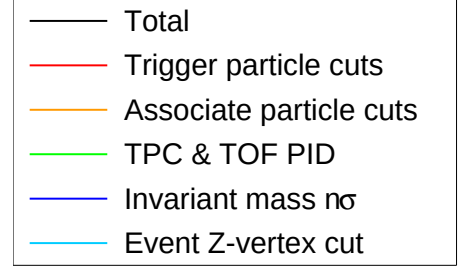
(a)



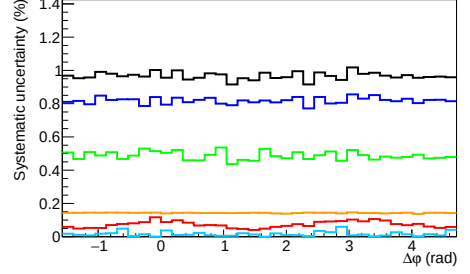
(b)



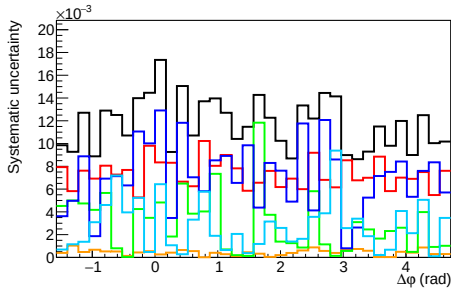
(c)



(d)

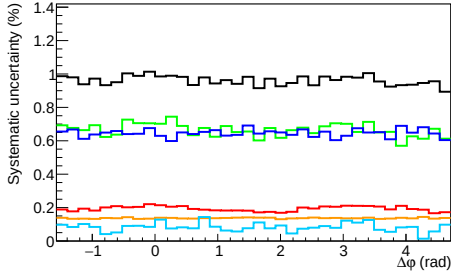


(e)

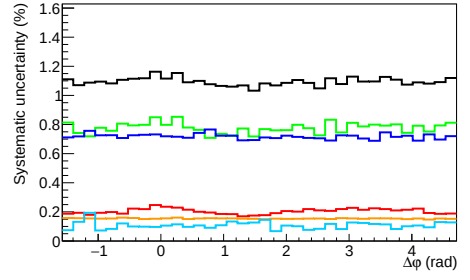


(f)

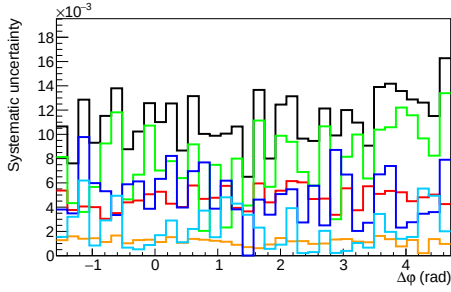
Figure A.44 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - K$ correlations, (b, e) same-sign $\Lambda - K$ correlations and (c, f) $\Lambda - K$ balance functions. Centrality classes are (a, b, c) 20% – 30% and (d, e, f) 30% – 40%.



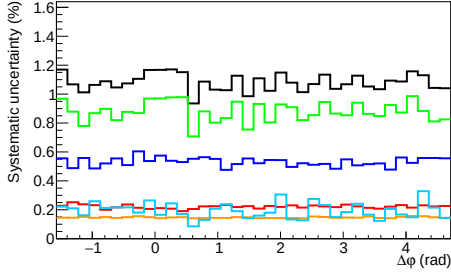
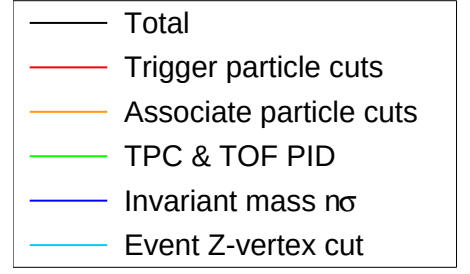
(a)



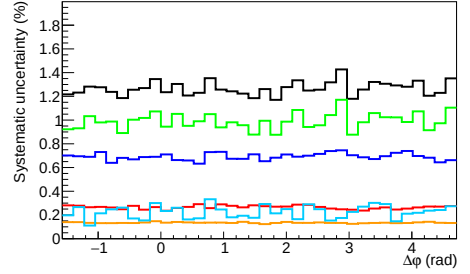
(b)



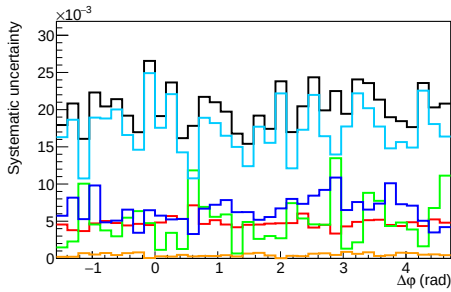
(c)



(d)

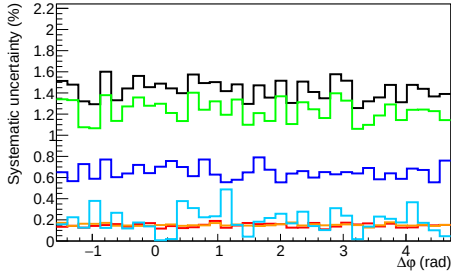


(e)

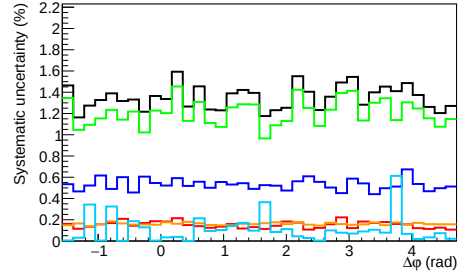


(f)

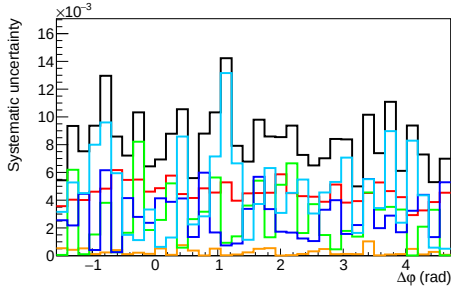
Figure A.45 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - K$ correlations, (b, e) same-sign $\Lambda - K$ correlations and (c, f) $\Lambda - K$ balance functions. Centrality classes are (a, b, c) 40% – 50% and (d, e, f) 50% – 60%.



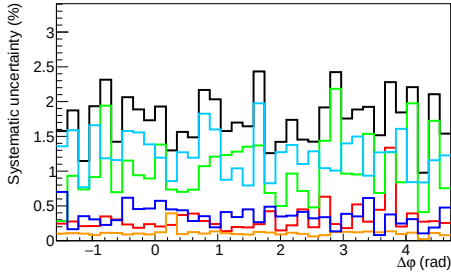
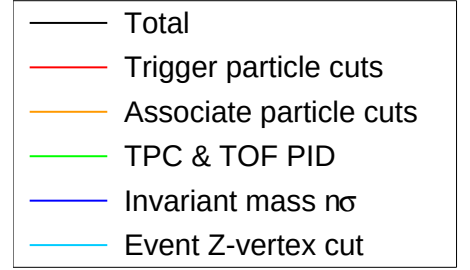
(a)



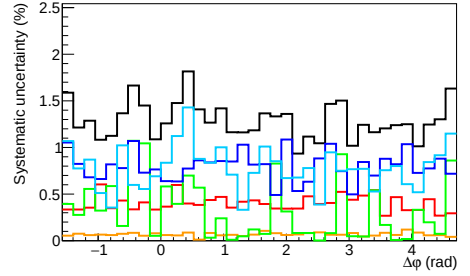
(b)



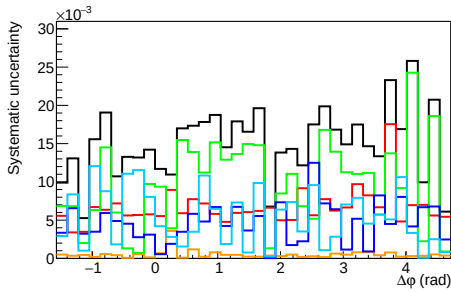
(c)



(d)

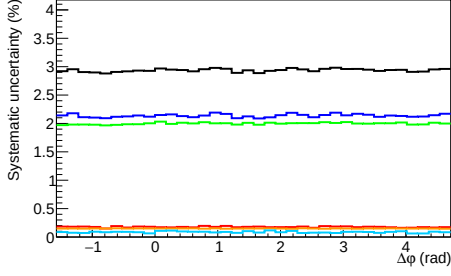


(e)

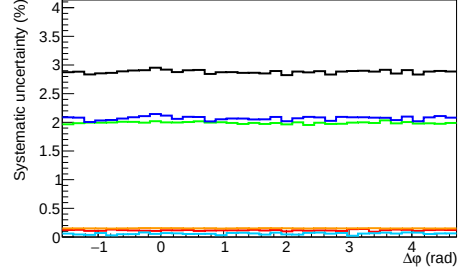


(f)

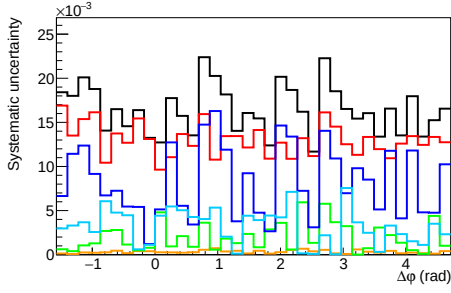
Figure A.46 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - K$ correlations, (b, e) same-sign $\Lambda - K$ correlations and (c, f) $\Lambda - K$ balance functions. Centrality classes are (a, b, c) 60% – 70% and (d, e, f) 70% – 80%.



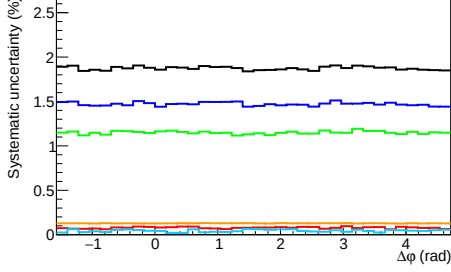
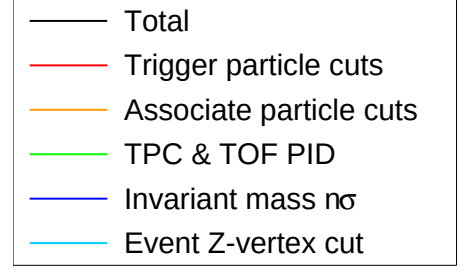
(a)



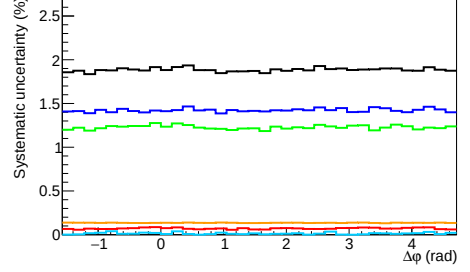
(b)



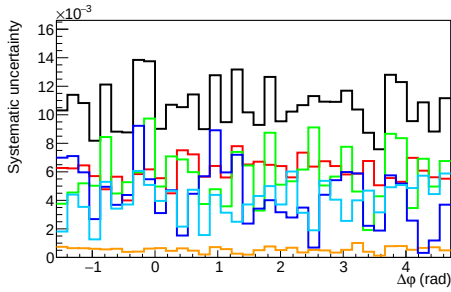
(c)



(d)

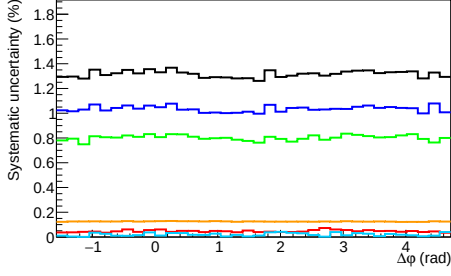


(e)

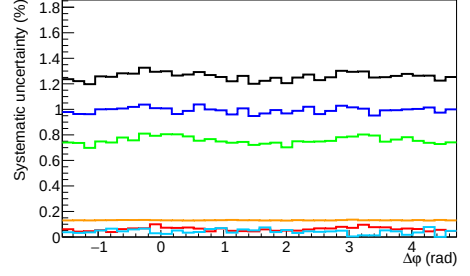


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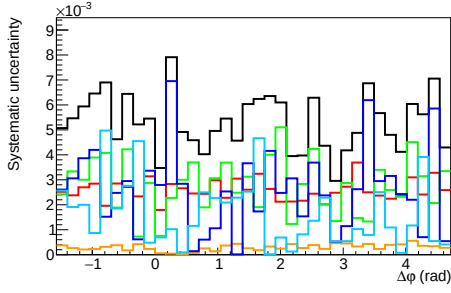
Figure A.47 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - p$ correlations, (b, e) same-sign $\Lambda - p$ correlations and (c, f) $\Lambda - p$ balance functions. Centrality classes are (a, b, c) 0% – 10% and (d, e, f) 10% – 20%.



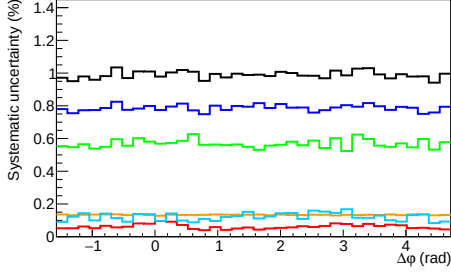
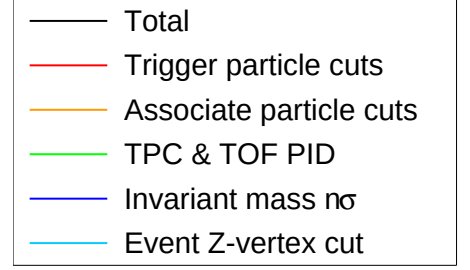
(a)



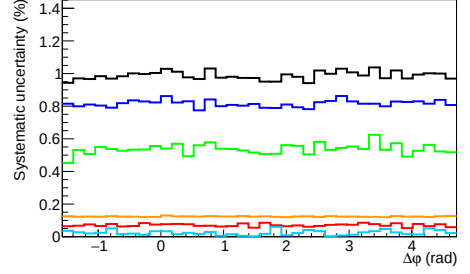
(b)



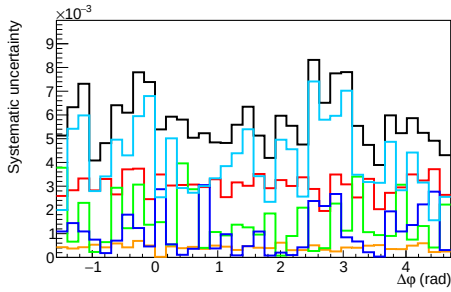
(c)



(d)

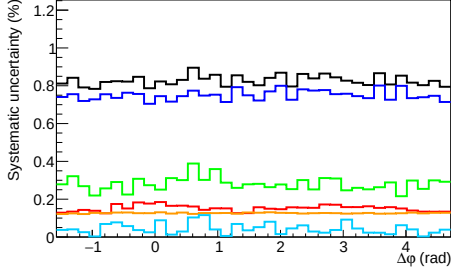


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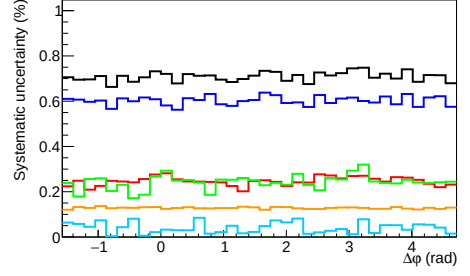


(f)

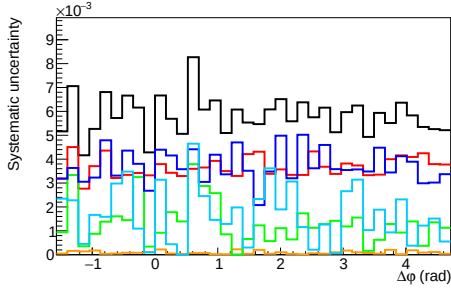
Figure A.48 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - p$ correlations, (b, e) same-sign $\Lambda - p$ correlations and (c, f) $\Lambda - p$ balance functions. Centrality classes are (a, b, c) 20% – 30% and (d, e, f) 30% – 40%.



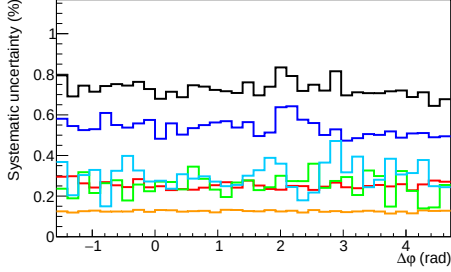
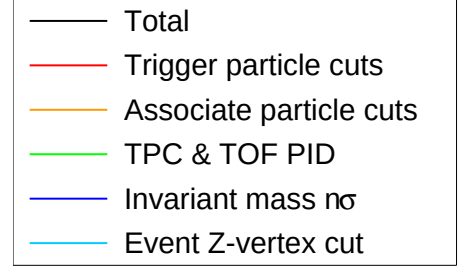
(a)



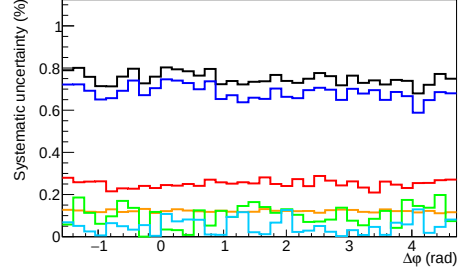
(b)



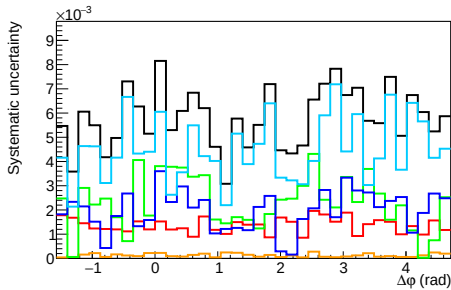
(c)



(d)

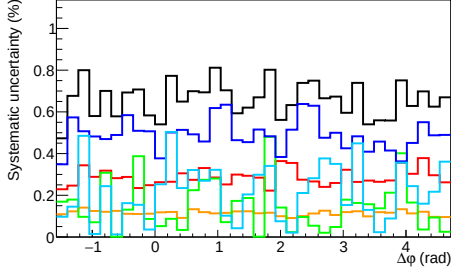


(e)

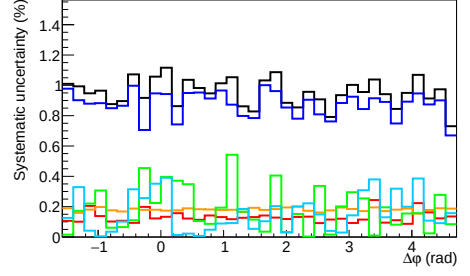


(f)

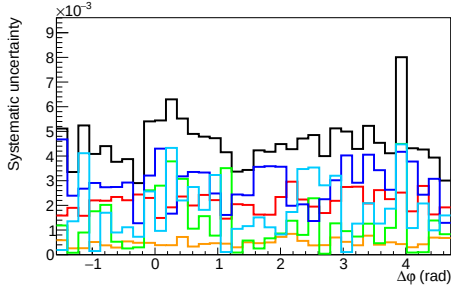
Figure A.49 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\varphi$ projections of the (a, d) opposite-sign $\Lambda - p$ correlations, (b, e) same-sign $\Lambda - p$ correlations and (c, f) $\Lambda - p$ balance functions. Centrality classes are (a, b, c) 40% – 50% and (d, e, f) 50% – 60%.



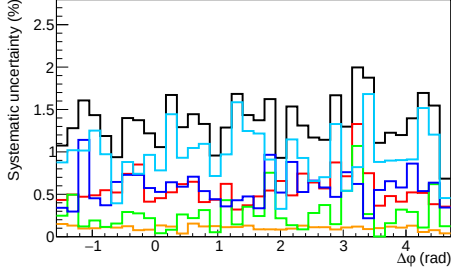
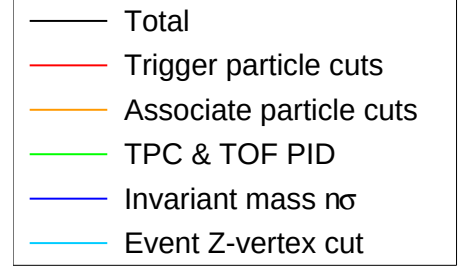
(a)



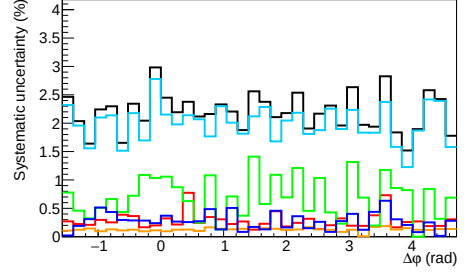
(b)



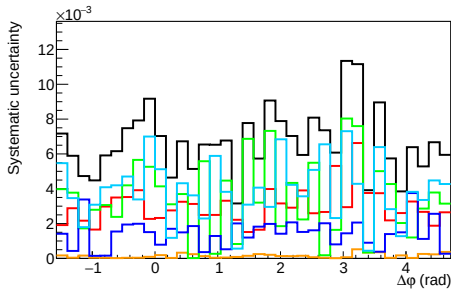
(c)



(d)



(e)



(f)

Figure A.50 – Summary of systematic uncertainties from each source at different centrality classes, for the $\Delta\phi$ projections of the (a, d) opposite-sign $\Lambda - p$ correlations, (b, e) same-sign $\Lambda - p$ correlations and (c, f) $\Lambda - p$ balance functions. Centrality classes are (a, b, c) 60% – 70% and (d, e, f) 70% – 80%.

Bibliography

- [1] J. Adolfsson, *Study of Ξ – Hadron Correlations in pp Collisions at $\sqrt{s} = 13$ TeV Using the ALICE Detector*. Doctoral Thesis (Monograph), Lund University, Faculty of Science, Department of Physics, 2020.
- [2] O. V. Rueda, *Study of the production of π , K and p in pp collisions at $\sqrt{s} = 13$ TeV as a function of the Transverse Sphericity and the Relative Transverse Activity*. Doctoral Thesis (Monograph), Lund University, Faculty of Science, Department of Physics, 2022.
- [3] A. F. Nassirpour, *The Shape of Strangeness: Transverse Sphericity and Underlying Event studies of φ and its relation to Ξ in $\sqrt{s} = 13$ TeV pp Collisions*. Doctoral Thesis (Monograph), Lund University, Faculty of Science, Department of Physics, 2022.
- [4] O. Matonoha, *Production of strangeness in partonic interactions at the LHC*. Doctoral Thesis (Monograph), Lund University, Faculty of Science, Department of Physics, 2023.
- [5] Particle Data Group, “History of the universe.” <https://particleadventure.org/history-universe.html>. Accessed on 31 January 2026.
- [6] CERN, “ALICE bags about twelve billion heavy-ion collisions.” <https://home.web.cern.ch/news/news/experiments/alice-bags-about-twelve-billion-heavy-ion-collisions>. Accessed on 31 January 2026.
- [7] Zi-wei Lin and C.M. Ko, “Baryon number fluctuation and the quark gluon plasma,” *Phys. Rev. C*, vol. 64, p. 041901, Mar. 2001.
- [8] MissMJ, Cush, “Standard Model of Elementary Particles.” https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg. Accessed on 11 September 2025.
- [9] G. Kane, *Modern Elementary Particle Physics: Explaining and Extending the Standard Model*. Cambridge University Press, second ed., 2017.
- [10] M. Thomson, *Modern Particle Physics*. Cambridge University Press, third ed., 2018.
- [11] S. Troitsky, “Unsolved problems in particle physics,” *Phys. Usp.*, vol. 55, pp. 72–95, 2012.

- [12] D0 Collaboration, “Observation of the top quark,” *Phys. Rev. Lett.*, vol. 74, pp. 2632–2637, Apr. 1995.
- [13] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” *Phys. Lett. B*, vol. 716, no. 1, pp. 1–29, Sep. 2012.
- [14] CMS Collaboration, “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC,” *Phys. Lett. B*, vol. 716, no. 1, pp. 30–61, Sep. 2012.
- [15] P. W. Higgs, “Broken Symmetries and the Masses of Gauge Bosons,” *Phys. Rev. Lett.*, vol. 13, no. 16, pp. 508–509, 1964.
- [16] G. Venkataraman, *Quantum revolution II - QED: The Jewel of Physics*. Universities Press, 1997.
- [17] Wikipedia contributors, “Quantum electrodynamics.” https://en.wikipedia.org/w/index.php?title=Quantum_electrodynamics&oldid=1307923069. Accessed on 25 October 2025.
- [18] Wikipedia contributors, “Quantum chromodynamics.” https://en.wikipedia.org/w/index.php?title=Quantum_chromodynamics&oldid=1314601281. Accessed on 2 November 2025.
- [19] Physics Stack Exchange, “How does screening reduce effective charge?.” <https://physics.stackexchange.com/questions/760222/how-does-screening-reduce-effective-charge>. Accessed on 1 October 2025.
- [20] P. A. Zyla *et al.* (Particle Data Group), “Review of Particle Physics,” *Prog. Theor. Exp. Phys.*, vol. 2020, no. 8, p. 083C01, 2020 and 2021 update.
- [21] S. Hashimoto, J. Laiho and S.R. Sharpe (Particle Data Group), “Lattice Quantum Chromodynamics.” <https://pdg.lbl.gov/2019/reviews/rpp2018-rev-lattice-qcd.pdf>. Accessed on 8 December 2025.
- [22] A. Bazavov *et al.*, “Equation of state in (2+1)-flavor QCD,” *Phys. Rev. D*, vol. 90, p. 094503, Nov. 2014.
- [23] CBM Collaboration, “The compressed baryonic matter (CBM) experiment at FAIR—physics, status and prospects,” *Phys. Scripta*, vol. 98, no. 3, p. 034006, Feb. 2023.
- [24] E. V. Shuryak, “Quark-Gluon Plasma and Hadronic Production of Leptons, Photons and Psions,” *Phys. Lett. B*, vol. 78, p. 150, 1978.
- [25] K. Nagata, “Finite-density lattice QCD and sign problem: Current status and open problems,” *Prog. Part. Nucl. Phys.*, vol. 127, p. 103991, Sep. 2022.
- [26] M. G. Alford, K. Rajagopal, and F. Wilczek, “QCD at finite baryon density: Nucleon droplets and color superconductivity,” *Phys. Lett. B*, vol. 422, pp. 247–256, 1998.

- [27] V. Koch, “Hadronic Fluctuations and Correlations,” in *Relativistic Heavy Ion Physics* (R. Stock, ed.), pp. 626–652, 2010.
- [28] H. Nastase, “Introduction to AdS-CFT.” <https://arxiv.org/pdf/0712.0689>. Accessed on 9 December 2025.
- [29] P. Kovtun, D. T. Son, and A. O. Starinets, “Viscosity in strongly interacting quantum field theories from black hole physics,” *Phys. Rev. Lett.*, vol. 94, p. 111601, 2005.
- [30] J. E. Bernhard, J. S. Moreland, and S. A. Bass, “Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma,” *Nature Phys.*, vol. 15, no. 11, pp. 1113–1117, Aug. 2019.
- [31] S. Navas *et al.* (Particle Data Group), “Review of particle physics,” *Phys. Rev. D*, vol. 110, no. 3, p. 030001, Aug. 2024.
- [32] Z. Sun, K. A. Beyer, Z. A. Mandrykina, I. A. Valuev, C. H. Keitel, and N. S. Oreshkina, “ ^{208}Pb Nuclear Charge Radius Revisited: Closing the Fine-Structure-Anomaly Gap,” *Phys. Rev. Lett.*, vol. 135, no. 16, p. 163002, Oct. 2025.
- [33] S. G. Weber and A. Andronic, “ALICE event display of a Pb-Pb collision at 5.02A TeV.” <https://cds.cern.ch/record/2202730>, 2016. General Photo.
- [34] ALICE Collaboration, “The ALICE experiment: a journey through QCD,” *Eur. Phys. J. C*, vol. 84, no. 8, p. 813, Aug. 2024.
- [35] W. Busza, K. Rajagopal, and W. van der Schee, “Heavy Ion Collisions: The Big Picture, and the Big Questions,” *Ann. Rev. Nucl. Part. Sci.*, vol. 68, pp. 339–376, 2018.
- [36] P. Braun-Munzinger and B. Dönigus, “Loosely-bound objects produced in nuclear collisions at the LHC,” *Nucl. Phys. A*, vol. 987, pp. 144–201, Jul. 2019.
- [37] CERN, “Centrality determination in heavy-ion collisions with the LHCb detector.” <https://cds.cern.ch/record/2789548/plots>. Accessed on 24 November 2025.
- [38] S. Ragoni, “Overview of the Latest ALICE UPC and Photonuclear Results,” *Acta Phys. Polon. Supp.*, vol. 18, no. 1, pp. 1–A47, 2025.
- [39] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, “Glauber modeling in high energy nuclear collisions,” *Ann. Rev. Nucl. Part. Sci.*, vol. 57, pp. 205–243, 2007.
- [40] M. van Leeuwen, “How we determine centrality.” <https://twiki.cern.ch/twiki/bin/view/ALICE/CentStudies>. Accessed on 26 November 2025.
- [41] J. F. Paquet, “Before hydrodynamics: initial conditions, energy deposition & pre-equilibrium dynamics.” https://webhome.phy.duke.edu/~jfp401/old_music_mannual/initial.html. Accessed on 26 November 2025.
- [42] J. Sun, “Physics of small systems.” https://indico.cern.ch/event/1139644/contributions/5344532/attachments/2710663/4706902/smallssystem_qm23_v2.pdf. Accessed on 25 November 2025.

- [43] J. Rafelski and B. Muller, “Strangeness Production in the Quark - Gluon Plasma,” *Phys. Rev. Lett.*, vol. 48, p. 1066, Apr. 1982. [Erratum: *Phys.Rev.Lett.* 56, 2334 (1986)].
- [44] ALICE Collaboration, “Centrality dependence of strange particle production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” Nov. 2025.
- [45] ALICE Collaboration, “Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys. Rev. Lett.*, vol. 116, no. 13, p. 132302, Feb. 2017.
- [46] A. Bilandzic, R. Snellings, and S. Voloshin, “Flow analysis with cumulants: Direct calculations,” *Phys. Rev. C*, vol. 83, p. 044913, 2011.
- [47] J. Jia, M. Zhou, and A. Trzupek, “Revealing long-range multiparticle collectivity in small collision systems via subevent cumulants,” *Phys. Rev. C*, vol. 96, no. 3, p. 034906, Sep. 2017.
- [48] T. Niida and Y. Miake, “Signatures of QGP at RHIC and the LHC,” *AAPPS Bull.*, vol. 31, no. 1, p. 12, May. 2021.
- [49] R. Baptista *et al.*, “Nuclear modification factor within a dynamical approach to the complex entropic index,” *Eur. Phys. J. A*, vol. 61, no. 11, p. 271, 2025.
- [50] ALICE Collaboration, “ Φ and K^{*0} Production in p-Pb and Pb-Pb Collisions with ALICE at the LHC,” *Springer Proc. Phys.*, vol. 261, pp. 679–682, 2021.
- [51] CERN, “CERN’s accelerator complex.” <https://home.cern/science/accelerators/accelerator-complex>. Accessed on 15 October 2025.
- [52] Guinness World Records, “Largest machine.” <https://www.guinnessworldrecords.com/world-records/103591-largest-machine>. Accessed on 16 November 2025.
- [53] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider,” *JINST*, vol. 3, p. S08003, 2008.
- [54] CMS Collaboration, “The CMS Experiment at the CERN LHC,” *JINST*, vol. 3, p. S08004, 2008.
- [55] LHCb Collaboration, “The LHCb Detector at the LHC,” *JINST*, vol. 3, p. S08005, 2008.
- [56] CERN, “ALICE upgrades during the LHC Long Shutdown 2.” <https://cds.cern.ch/record/2847599/plots>. Accessed on 17 October 2025.
- [57] ALICE Collaboration, “The ALICE experiment at the CERN LHC,” *JINST*, vol. 3, no. 08, p. S08002, 2008.
- [58] T. Tripathy, “Charged-particle production in pp collisions at 13.6 TeV and Pb-Pb collisions at 5.36 TeV with ALICE,” in *59th Rencontres de Moriond on QCD and High Energy Interactions: Moriond QCD 2025*, 2025.

- [59] Y. Melikyan, “Status and performance of the ALICE Fast Interaction Trigger,” *PoS*, vol. ICHEP2024, p. 921, Dec. 2024.
- [60] K. Roslon, “ALICE Fast Interaction Trigger upgrade,” *Nucl. Instrum. Meth. A*, vol. 1079, p. 170609, May 2025.
- [61] Romain Schotter, private Correspondence.
- [62] A. Isakov, “ALICE ITS2: overview and performance,” *JINST*, vol. 20, no. 07, p. C07026, Jul. 2025.
- [63] F. Reidt, “Upgrade of the ALICE ITS detector,” *Nucl. Instrum. Meth. A*, vol. 1032, p. 166632, Jun. 2022.
- [64] O. Groettvik, “ALICE ITS3: a bent stitched MAPS-based vertex detector,” *JINST*, vol. 19, no. 02, p. C02048, Feb. 2024.
- [65] ALICE collaboration, “Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector.” CERN Document Server, CERN-LHCC-2024-003 / ALICE-TDR-021, 2024.
- [66] CERN, “ALICE Time Projection Chamber.” <https://alice-tpc.web.cern.ch/>. Accessed on 11 November 2025.
- [67] P. Hauer, “The upgraded ALICE TPC,” *Nucl. Instrum. Meth. A*, vol. 1039, p. 167023, Sep. 2022.
- [68] ALICE collaboration, “Upgrade of the ALICE Time Projection Chamber.” CERN Document Server, CERN-LHCC-2013-020 / ALICE-TDR-016, 2014.
- [69] CERN, “ALICE TOF.” https://alice-collaboration.web.cern.ch/menu_projects/tof. Accessed on 15 November 2025.
- [70] S. Strazzi, “15 years young: The ALICE TOF detector in the LHC Run 3,” *Nucl. Instrum. Meth. A*, vol. 1077, p. 170521, Apr. 2025.
- [71] ALICE collaboration, “ALICE Time-Of-Flight system (TOF) : Technical Design Report.” CERN Document Server, CERN-LHCC-2000-012 / ALICE-TDR-8, 2000.
- [72] ALICE collaboration, “ALICE Time-Of-Flight system (TOF) : Technical Design Report addendum.” CERN Document Server, CERN-LHCC-2002-016 / ALICE-TDR-8, 2002.
- [73] I. Neutelings, “Pseudorapidity.” https://tikz.net/axis2d_pseudorapidity/. Accessed on 12 December 2025.
- [74] C. Bierlich *et al.*, “A comprehensive guide to the physics and usage of PYTHIA 8.3,” *SciPost Phys. Codeb.*, vol. 2022, p. 8, Nov. 2022.
- [75] CERN Application Software Group, “GEANT Detector Description and Simulation Tool.” CERN Program Library Long Writeup, 1993.

- [76] J. Alme *et al.*, “The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events,” *Nucl. Instrum. Meth. A*, vol. 622, pp. 316–367, 2010.
- [77] R. Schicker, “Overview of ALICE results in pp, pA and AA collisions,” *EPJ Web Conf.*, vol. 138, p. 01021, 2017.
- [78] AliceO2Group/O2Physics, “TrackSelectionTables.h.” <https://github.com/AliceO2Group/O2Physics/blob/048e50c2fab0faf7927875ee3cc934529ba4d12/Common/DataModel/TrackSelectionTables.h>.
- [79] AliceO2Group/O2Physics, “TrackSelectionDefaults.cxx.” <https://github.com/AliceO2Group/O2Physics/blob/048e50c2fab0faf7927875ee3cc934529ba4d126/Common/Core/TrackSelectionDefaults.cxx>.
- [80] T. Richert, Λ/K_s^0 Associated with a Jet in Central Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV Measured with the ALICE Detector. Doctoral Thesis (Monograph), Lund University, Faculty of Science, Department of Physics, 2016.
- [81] D. D. Chinellato and R. Schotter, “K0s, Lambda and AntiLambda production in Pb–Pb at 5.36 TeV.” <https://alice-notes.web.cern.ch/node/1540>, Feb. 2025.
- [82] ALICE Collaboration, “Measurements of Chemical Potentials in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys. Rev. Lett.*, vol. 133, no. 9, p. 092301, Aug. 2024.
- [83] D. Ruggiano, “Two-particle angular correlations of identified particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.” <https://alice-notes.web.cern.ch/node/1549>, August 2024.
- [84] S. Stapnes, “Instrumentation for high-energy physics.” <https://cds.cern.ch/record/1017827>. Accessed on 4 January 2026.
- [85] ALICE Collaboration, “Insight into particle production mechanisms via angular correlations of identified particles in pp collisions at $\sqrt{s} = 7$ TeV,” *Eur. Phys. J. C*, vol. 77, no. 8, p. 569, Aug. 2017.
- [86] H. Aihara *et al.*, “Study of baryon correlations in e^+e^- annihilation at 29-GeV,” *Phys. Rev. Lett.*, vol. 57, p. 3140, 1986.
- [87] Peter Christiansen, private Correspondence.
- [88] M. Bahr *et al.*, “Herwig++ Physics and Manual,” *Eur. Phys. J. C*, vol. 58, pp. 639–707, 2008.
- [89] C. Bierlich, G. Gustafson, L. Lönnblad, and A. Tarasov, “Effects of Overlapping Strings in pp Collisions,” *JHEP*, vol. 03, p. 148, Mar. 2015.
- [90] ALICE Collaboration, “Closing in on critical net-baryon fluctuations at LHC energies: Cumulants up to third order in Pb–Pb collisions,” *Phys. Lett. B*, vol. 844, p. 137545, 2023.

- [91] ALICE Collaboration, “General balance functions of identified charged hadron pairs of (π ,K,p) in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV,” *Phys. Lett. B*, vol. 833, p. 137338, Oct. 2022.
- [92] ALICE Collaboration, “Probing Strangeness Hadronization with Event-by-Event Production of Multistrange Hadrons,” *Phys. Rev. Lett.*, vol. 134, no. 2, p. 022303, Jan. 2025.
- [93] ALICE Collaboration, “Studying strangeness and baryon production mechanisms through angular correlations between charged Ξ baryons and identified hadrons in pp collisions at $\sqrt{s} = 13$ TeV,” *JHEP*, vol. 09, p. 102, Sep. 2024.

