

Warsaw University of Technology

DISCIPLINE OF SCIENCE - PHYSICAL SCIENCES

FIELD OF SCIENCE - NATURAL SCIENCES

Ph.D. THESIS

Daniela Ruggiano, M.Sc.

**Exploring the baryon correlation puzzle via
multiplicity-dependent two-particle angular correlations
in pp, p–Pb, and Pb–Pb collisions at the LHC energies**

Supervisors:

Professor Adam Kisiel, Ph.D.,D.Sc.

Małgorzata Janik, Ph.D.,D.Sc.

Warsaw 2025

Streszczenie

by Daniela Ruggiano

Fundamentalne pytania dotyczące powstawania jednych z najbardziej obfitych cząstek we wszechświecie, protonów, oraz złożonych mechanizmów leżących u podstaw produkcji barionów pozostają w dużej mierze bez odpowiedzi, stawiając znaczące wyzwania przed fizyką wysokich energii. Niniejsze badanie opiera się na analizie korelacji kątowych między parami cząstek, aby rzucić światło na te mechanizmy i poprawić nasze rozumienie leżących u podstaw procesów fizycznych. Badanie korelacji kątowych jest jednym z najskuteczniejszych narzędzi do tego celu, otwierając możliwości badania zjawisk fizycznych, takich jak mini-dżety, statystyki kwantowe Bosego-Einsteina i Fermiego-Diraca oraz różnorodne prawa zachowania, które same w sobie stanowią podstawę mechanizmu produkcji barionów. To właśnie te złożone interakcje ujawniają wzajemne zależności rządzące oddziaływaniami cząstek w zderzeniach wysokich energii. Każdy z tych efektów stanowi odrębne źródło korelacji i wykazuje unikalne zachowanie w przestrzeni $\Delta\eta, \Delta\phi$ (gdzie $\Delta\eta$ to różnica pseudopospieszności, a $\Delta\phi$ to różnica kąta azymutalnego dwóch cząstek), co sprawia, że każda korelacja między parami cząstek jest wyjątkowa. Najnowsze wyniki eksperymentalne dla zderzeń proton-proton przy energii $\sqrt{s} = 7$ TeV ujawniły antykorelację w rozkładach cząstek, która stanowi wyzwanie dla istniejących modeli Monte Carlo. To obserwacja doprowadziła do pojawienia się tzw. „zagadki korelacji barionów”. Mimo że przeprowadzono już kilka badań w tym obszarze, nadal pozostaje on otwarty dla dalszej eksploracji i zrozumienia. W tej pracy doktorskiej dodano nowy element do zagadki korelacji barionów, analizując zachowanie antykorelacji, ale także porównując funkcje korelacji mezonów. Wykorzystując zaawansowane możliwości identyfikacji cząstek w eksperymencie ALICE przy Wielkim Zderzaczu Hadronów (LHC), po raz pierwszy w ALICE przeprowadzono badanie funkcji korelacji kątowych dla par cząstek $\pi^+\pi^+ + \pi^-\pi^-$, $\pi^+\pi^-$, $K^+K^+ + K^-K^-$, K^+K^- , $pp + \bar{p}\bar{p}$ oraz $p\bar{p}$, w różnych klasach krotności i w różnych systemach zderzeń:

IV

proton-proton (pp), proton-ołów (p-Pb) oraz ołów-ołów (Pb-Pb) przy energiach LHC. Dotychczasowe wyniki uzyskane w ALICE w przeważającej mierze opierały się na wykorzystaniu definicji ilorazu prawdopodobieństw. Jednak podejście to ma swoje ograniczenia w zastosowaniu do różnych klas krotności, głównie ze względu na spodziewany współczynnik skalowania $1/N$, gdzie N reprezentuje liczbę cząstek w każdej klasie. Aby przezwyciężyć to ograniczenie, wprowadzono alternatywną metodę wykorzystującą przeskalowaną funkcję korelacji dwucząstkowych, koncepcję pierwotnie zaproponowaną przez współpracę STAR. Badanie korelacji kątowych może dostarczyć nowych spostrzeżeń na temat podstawowej fizyki rządzącej interakcjami cząstek, stawiając kluczowe pytania dotyczące mechanizmów produkcji barionów oraz natury silnych oddziaływań. Ta analiza stanowi ważną podstawę dla przyszłych badań eksperymentalnych i pracy teoretyków nad udoskonaleniem istniejących modeli.

Słowa kluczowe – korelacje kątowe, eksperyment ALICE, Large Hadron Collider (LHC), małe systemy, zderzenia ciężkich jonów, plazma kwarkowo-gluonowa, korelacje dwucząstkowe hadronów, zależność od centralności, zależność od krotności.

Abstract

Doctor of Philosophy

Exploring the baryon correlation puzzle via multiplicity-dependent two-particle angular correlations in pp, p–Pb, and Pb–Pb collisions at the LHC energies

by Daniela Ruggiano

The fundamental queries surrounding the creation of one of the most abundant particles in the universe, protons, and the intricate mechanisms underlying the production of baryons remain largely unanswered, posing significant challenges in high-energy physics. This study fully investigates the angular correlations between pairs of particles to illuminate these mechanisms and improve our understanding of the underlying physical processes. The study of angular correlations is one of the most effective tools one has for that purpose, opening up the possibility of studying physical phenomena such as mini-jets, quantum statistics, and various conservation laws, which are themselves the basis of the baryon production mechanism and from which the complex interplay governing particle interactions in high-energy collisions is revealed. Each of these effects is a distinct correlation source and exhibits individual behavior in $\Delta\eta, \Delta\phi$ space (where $\Delta\eta$ is the pseudorapidity difference and $\Delta\phi$ is the azimuthal angle difference of two particles), which is why each pair particle correlation is unique.

Recent experimental results of proton-proton collisions at the energy of $\sqrt{s} = 7$ TeV have revealed an anticorrelation in particle distributions that poses a challenge to existing Monte Carlo models. This observation has led to the emergence of what is called the “baryon correlation puzzle”. Although several studies have already been conducted, it remains an area for further exploration and understanding. In this thesis, a new piece is added on the baryon correlation puzzle, analyzing the behavior of anticorrelation but also comparing with the correlation functions of mesons. Taking advantage of the advanced particle identification capabilities of the ALICE experiment at the Large Hadron Collider (LHC), a first study in ALICE of the angular correlation functions for pairs of particles, $\pi^+ \pi^+ + \pi^- \pi^-$, $\pi^+ \pi^-$, $K^+ K^+ + K^- K^-$, $K^+ K^-$, $pp + \bar{p}\bar{p}$, and

$p\bar{p}$ is done across different multiplicity classes and various collision systems: proton-proton (pp), proton-lead (p-Pb), and lead-lead (Pb-Pb) at LHC energies.

Previous results obtained in ALICE employed the probability ratio definition. However, this approach has limitations when applied to different multiplicity classes, mainly because of the underlying scaling factor of $1/N$, where N represents the number of particles within each class. To isolate this effect, an alternative method is introduced using a rescaled two-particle correlation function, a concept originally proposed by the STAR collaboration.

By investigating angular correlations new insights into the underlying physics governing these particle interactions and the mechanisms of baryon production can be provided. Although our analysis does not lead to definitive conclusions, it lays important groundwork for future investigations and encourages theorists to refine and improve existing models.

Keywords – angular correlations, ALICE experiment, Large Hadron Collider (LHC), small systems, heavy-ion collisions, quark-gluon plasma, hadron two-particle correlations, centrality dependence, multiplicity dependence.

Acknowledgements

Acknowledgments may seem like the easiest part to write, yet they are among the most challenging—not because of a lack of gratitude, but because it is hard to single out individuals in a group that has become like a second family to me. Over the years, I have come to realize that I can always rely on each of you, and for that, I am truly grateful.

First and foremost, I want to express my deepest gratitude to you, Professor Adam. Your vast knowledge and passion for the subject have been a constant source of inspiration. You have a unique gift for making complex ideas engaging and easy to understand. I am truly thankful for your attitude, guidance, support, and encouragement throughout these years.

A heartfelt thank you to you, Małgosia, my mentor in every sense of the word. With unwavering patience, you guided me step by step, sharing your passion for research. Your strength, intelligence, and kindness have been a constant source of motivation. This project would not have been possible without you. I am truly grateful to have had the best supervisor I could have ever wished for. Thank you.

Lukasz, I am deeply grateful for your constant support over the past four years. Whatever the challenges, you have always been ready to listen, advise and help. Your generosity and availability have never failed me and your contribution to this work has been invaluable.

Georgy, a special thanks to you for making me feel at home in a foreign country more than once. Your kindness, your patience, your countless coffee breaks and your thoughtful advice were like a safe port in an unknown land.

To my amazing colleagues Kuba, Kasia, Zuzia, Pritam, Marta, Alice, Erina, and Maja, thank you for making long days at the office, trips to CERN, and outings so much more enjoyable. A special word to you, Kuba, your energy chocolates have made my working days much better, and your love for Star Wars has been a cultural enrichment for me. I can't wait to watch the last three films!

And finally there is you, my koleżanka, my friend, my confidante, my roommate, sometimes even my supervisor, my traveling companion, my coffee companion, my source of laughter and support, Wioletka. I cannot thank you enough. These four years would not have been the same without you, in fact, I am not even sure I would still be here without you. You have taught me

VIII

so much, especially how to grow and become more mature. If this work exists, it is also thanks to you. I wish everyone had a Viola in their life, because having one makes everything more special.

I want to sincerely thank the people who are always close to me whenever I return to Italy. No matter how much time passes, they are and always will be my home to me and I look forward to seeing you because I love spending time with you. First of all, my dear friend Armando. We have known each other since we were 15 years old and our bond has never faded. In these four years, I have appreciated our friendship even more because I never expected that despite the distance, we would always be able to stay close and see each other whenever I would come home. Thank you for always being there when I have my moments of frustration, when I call you and say, "Arma', let's go out, and you pay for me!". The next drink will be on me, PROMISE! Mariarosa – I thank you for always listening and understanding me, especially during the difficult moments of this journey. Most of all, I appreciate the moments of joy you bring whenever I return. I always miss your coffee and our long chats when I am away. Carmen – the one who moves mountains just to see me every time I come back. I adore you and your presence always lifts my spirit like nothing else. With you, I always laugh. Denise – even though we don't talk often, we never miss a chance to see each other when I'm home. I love to catch up and gossip with you. Antonio Nappa – thank you for being the cornerstone of our group. You never miss an opportunity to organize our outings and bring us all together. You are really special, Anto. Alberto – thank you for simply being yourself. Your cheerfulness and lightheartedness always manage to lift my mood. Gigi Ferre – your jokes and energy always bring so much positivity. Thank you for the moments we share whenever we get the chance, they always take me back to the days spent in . I love you all.

To you, Eli, my strong pillar. Thank you for always being an inspiration with your determination, your intelligence and your success. Thank you for always being there, even after these four years apart. I still remember that coffee together, just before we left, when I confided in you my fear that I would not make it and that things might change. With your confidence, you told me that nothing would change and that we would never lose each other. And indeed you were right about one thing, although our lives have changed, you are still there laughing with me, consoling me, worrying about me but above all listening to me. Thank you.

To you, Riccio, thank you for being a constant presence, even abroad. Thank you because with a simple video call - which often turns into hours of chatting - you have always managed to calm me down in moments of anger and advise me without ever making a mistake. You are one of the wisest people I know. I thank you for all the times you kept me company on

weekends when I felt lonely, but especially for helping me so much at the beginning of this journey, explaining some physics to me and helping me with my English.

Ilenia, you are the sister that life gave me more than 20 years ago. We have shared everything, from dancing to friendships, travels, or simply a whole life. It may seem trivial, but despite the distance, you are always there, more than anyone else. Your morning messages, the video calls that bridge the gap, and every time I come back it's like I never left. You support me and listen to me and, even from afar, it feels like you are right here, that you know every detail of my life. You know me better than I know myself and you show me this with unexpected messages or calls full of strength and affection. You know when I am sad, anxious or happy and each time this knowledge surprises me and gives me strength. You are home for me. I love you.

Finally, last but most important, I want to dedicate these words to my family: my mom, my dad, my Geggi, and my dog Ringo. I can never thank you enough for the unconditional love you give me, and words will never be enough to express how much you mean to me. To you, mamma, who always calls me just to check how I'm doing. To you, who never gets tired of asking about my day, with the same excitement as on my first day of school. Every time I come home, you make everything feel like a celebration. You are the purest form of love that exists. You are the rock of our family, always giving us strength and support. To you, babbo, who for always telling me that I am the most important thing of your life. You never says no to me and always treats me like a princess. To you, Geggi. You are my everything. Even though we don't always get along and we don't see each other often, I know we will always be there for one another. My love for you is endless and unconditional. To my sweet Ringo, who has taught me what it truly means to love unconditionally since the day he came into our family. I dedicate all of this to you because you are and will always be the most important part of my life. I LOVE YOU.



Contents

Abstract	III
Abstract	V
1 Introduction	1
2 The Physics of Heavy-Ion Collisions at Relativistic Energies	3
2.1 Standard model	3
2.2 Quantum Chromodynamics	5
2.3 Quark-Gluon Plasma	7
2.4 Evolution of Heavy-Ion Collisions	10
2.4.1 Initial stage	10
2.4.2 Pre-equilibrium stage	11
2.4.3 QGP formation and expansion	12
2.4.4 Hadronization	13
2.4.5 Freeze-Out	13
2.5 Collective phenomena in HIC	14
2.5.1 Reaction Plane	15
2.5.2 Anisotropic flow	16
2.5.2.1 Directed flow	17
2.5.2.2 Elliptical flow	18
2.5.2.3 Radial flow	20
2.6 Are Collective Phenomena Present in Small Systems?	21
2.6.1 The role of pp and p-Pb in respect to Pb-Pb collision	21
3 Monte Carlo Event Generators	23
3.1 String fragmentation	25
3.1.1 Multiparton interactions and colour reconnections	27
3.2 The MC event generators	29

3.2.1	PYTHIA	29
3.2.2	EPOS	30
3.2.3	DPMJET	32
3.2.4	HIJING	33
3.2.5	AMPT	33
3.2.6	CALM model	35
4	Two-particle Angular correlations	37
4.1	Reference frame	37
4.2	Observables	38
4.2.1	Pseudorapidity	38
4.2.2	Rapidity	39
4.2.3	Azimuthal Angle	39
4.3	The $\Delta y \Delta \phi$ two-particle angular correlation	39
4.3.1	Probability ratio correlation function	41
4.3.2	Rescaled two-particle correlation functions	42
4.4	Sources of angular correlations	44
4.4.1	Conservation laws	45
4.4.2	Jets	47
4.4.2.1	MiniJets	48
4.4.2.2	Jet quenching	48
4.4.3	Quantum Statistical and Final-State Interaction Effects	51
4.4.4	Resonances	52
4.4.5	Photon conversion	54
4.4.6	Flow structure	55
4.4.7	Ridge structure – collectivity in small systems?	56
5	Baryon Correlation Puzzle	59
5.1	Baryon and Meson Correlation functions	59
5.2	The puzzle	62
5.2.1	Dependence on Transverse Momentum	62
5.2.2	Coulomb interaction, Fermi-Dirac QS, and other baryons	63
5.3	2017 – today	63
5.4	What next?	68

6	LHC at CERN	69
6.1	ALICE experiment	70
6.1.1	V0 detector	71
6.1.2	Inner Tracking System	73
6.1.2.1	Silicon Pixel Detectors	74
6.1.2.2	Silicon Drift Detectors	75
6.1.2.3	Silicon Strip Detectors	75
6.1.3	Time Projection Chamber	76
6.1.4	Time-of-Flight	78
6.2	Particle identification	78
6.3	Software environment	81
7	Data analysis	85
7.1	Event Selection	85
7.2	Multiplicity and centrality selection	86
7.3	Track Selection	87
7.4	Particle Identification	91
7.5	Two-track particle pairs selections	92
7.6	Purity and Efficiency Corrections	98
7.6.1	Purity	98
7.6.1.1	Purity in pp collisions	99
7.6.1.2	Purity in p–Pb collisions	101
7.6.1.3	Purity in Pb–Pb collisions	102
7.6.2	Correction factor estimation	105
7.6.2.1	Correction factor in pp collisions	105
7.6.2.2	Correction factor in p–Pb collisions	108
7.6.2.3	Correction factor in Pb–Pb collisions	109
7.6.3	Correction of Signal and Background Distributions	110
8	Two-Particle Angular Correlation Analysis in small systems	115
8.1	Results from pp Collisions Across Four Multiplicity Classes	117
8.1.1	Estimation of N_{av} for Multiplicity Classes in Experimental Data: Method Consolidation	117
8.1.2	2D $\Delta y \Delta \phi$ correlation functions	122
8.1.3	$\Delta \phi$ projections and comparison to MC models	126
8.2	Results from pp Collisions Across Thirteen Multiplicity Classes	135

8.2.1	2D $\Delta y \Delta \varphi$ correlation functions	135
8.2.2	$\Delta \varphi$ projections	140
8.2.3	Comparison to MC models	143
8.3	Results from p–Pb collision	147
8.3.1	N_{av} values	147
8.3.2	2D $\Delta y \Delta \varphi$ correlation function	147
8.3.3	Projection of $\Delta y \Delta \varphi$ correlation functions	152
8.3.4	Comparison to MC models	152
8.4	Small Systems in Focus: pp vs. p–Pb	160
8.5	Summary of Angular Correlation Studies in Small Systems	164
9	Two-Particle Angular Correlation Analysis in HIC	169
9.1	Results from Pb–Pb collision	171
9.1.1	Estimation of N_{av} in Pb–Pb collision	171
9.1.2	2D $\Delta y \Delta \varphi$ correlation function	171
9.1.3	$\Delta \varphi$ projections	178
9.1.4	Comparison between MC models and data	179
9.2	Summary of Angular Correlation Studies in HIC	195
10	Comparative Insights into pp, p–Pb, and Pb–Pb Collision Systems	197
11	Summary and Conclusions	201
A	Monte Carlo Simulations	207
A.1	Estimation of N_{av}	207
A.2	MC Closure test in pp collision	210
A.3	MC Closure test in p–Pb collision	210
A.4	MC Closure test in Pb–Pb collision	211
B	Systematic Uncertainties	219
B.1	Systematic Uncertainties in pp Collisions	220
B.1.1	Systematic Analysis Across Four Multiplicity Classes	222
B.1.2	Systematic Analysis Across Thirteen Multiplicity Classes	226
B.2	Systematic uncertainties in p–Pb collision	230
B.3	Systematic uncertainties in Pb–Pb collision	234
	Bibliography	239

List of Figures

2.1	The elementary particles within the Standard model [5].	4
2.2	α_s as a function of the energy scale Q compared to experimental constraints. Picture from Ref. [16].	6
2.3	Compression and heating of matter before the deconfined phase transition. Picture from Ref. [24].	8
2.4	Energy density as a function of temperature calculated from lQCD. Picture from Ref. [25].	9
2.5	The QCD phase diagram features two distinct phases: the hadronic phase, representing ordinary nuclear matter, and the quark-gluon plasma phase. At zero baryon density, the phase transition occurs as a smooth crossover. Picture from Ref. [26].	10
2.6	The evolution of a heavy-ion collision at LHC energies. Picture from Ref. [27].	11
2.7	A schematic view of a heavy-ion collision. The impact parameter b is shown as well as the spectator nucleons and the participant nucleons. Picture from Ref. [28].	12
2.8	Interaction volume created after a non-central heavy-ion collision. The spatial anisotropy is transformed into anisotropy of momentum distribution of the produced particles. Picture from Ref. [32].	15
2.9	Left: The overlapping region obtained from lQCD computations. Picture from Ref. [35]. Right: The second, third and fourth cross-flow components. Picture from Ref. [36].	17
2.10	Schematic view of directed flow.	18
2.11	Schematic view of elliptic flow.	19

2.12	In the first panel: the anisotropic flow coefficients v_n are presented as a function of the centrality classes for the $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV Pb–Pb collisions. In the second panel the ratios of v_n for these two energies are shown. In the last panel, various predictions from hydrodynamical models are also presented for comparison. Picture from Ref. [41].	20
2.13	Schematic view of radial flow.	21
3.1	Illustration of a proton–proton collision in a typical Monte Carlo event generator. Each color corresponds to different stages involved in event generation. Picture from Ref. [57].	24
3.2	Space-time diagram of $q\bar{q}$ pair in their rest frame. 1) Beginning of the evolution; 2) 1/4 of full period, maximum tension in the string; 3) q and $\bar{q}$ are back to their initial positions, but have their momenta swapped; 4) 3/4 of full period, maximum tension in the string; 5) full period, the system is back to its initial state. Picture from Ref. [64].	26
3.3	$q\bar{q}$ system in its rest frame with multiple string breakings. Picture from Ref. [64].	27
3.4	Two dipoles and three dipoles CR possibilities. For two dipoles, they can either have (a) a simple reconnection (a.k.a. a swing) or (b) a formation of a connected junction and anti-junction system. Three dipoles can form (c) disconnected junction and anti-junction systems. Picture from Ref. [65].	28
3.5	Elementary parton–parton scattering: hard scattering in the medium is preceded by the emission of partons (initial-state space cascade); these ladder partons, being usually off-shell, emit other partons ladder (final-state time cascade). The complete picture, also includes remnants that are an important source of particle production. Picture from Ref. [69]. . .	30
3.6	On the left, a schematic overview of the AMPT model in its default configuration, and on the right, the string melting version. In the default mode, hadronization is modeled using the Lund string fragmentation mechanism, where strings formed after parton scattering fragment into hadrons. In contrast, the string melting version converts all excited strings into partons, and hadronization proceeds via parton recombination (coalescence), where nearby partons combine to form hadrons based on their spatial and momentum proximity.	34

4.1	Illustration of the polar angle θ between the momenta of the particles, which are deflected by the magnetic field of the detector, and the beam axis. Credits to Wioleta Rzęsa.	38
4.2	Schematic view of the azimuthal angle. Credits to Wioleta Rzęsa.	40
4.3	The left panel displays the signal distribution, the middle panel shows the background distribution, and the right panel presents the correlation function, calculated as the ratio of the signal to the background.	41
4.4	Multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all charge pair combinations in $\sqrt{s} = 7$ TeV pp collisions, simulated using Pythia Perugia-0. Picture from Ref. [83].	43
4.5	Contribution of different sources that influence the overall shape of the $\Delta\eta\Delta\phi$ correlation function from pp collision at $\sqrt{s} = 7$ TeV. Picture from Ref. [83].	45
4.6	Momentum conservation contribution in $\Delta\eta, \Delta\phi$ correlation function by using CALM model. Picture from Ref. [80].	46
4.7	Minijets contribution in $\Delta\eta, \Delta\phi$ correlation function by using CALM model. Picture from Ref. [83].	48
4.8	Schematic overview of particles from the same jets (top) and particles correlated in opposite jets (bottom) from an azimuthal perspective.	49
4.9	Comparison of two-particle azimuthal distributions for central d–Au collisions to those seen in pp and central Au–Au collisions. Picture from Ref. [88].	50
4.10	Angular correlation functions in $\Delta\eta, \Delta\phi$ space for like and unlike-sign pions and protons, illustrating the contributions of quantum statistical and final-state interaction effects. Picture from Ref. [91].	52
4.11	The ratios K^{*0}/K (panels (a) and (b)) and ϕ/K (panels (c) and (d)) are analyzed across different collision systems: pp, d–Au, p–Pb, Cu–Cu, Au–Au, and Pb–Pb. Panels (a) and (c) show these ratios as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ for K^{*0}/K and ϕ/K in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Panels (b) and (d) depict the ratios for various systems as a function of $\sqrt{s_{NN}}$, alongside predictions from a grand-canonical thermal model at a freezeout temperature of 156 MeV. Picture from Ref. [94].	53

4.12	Correlation function in $\Delta\eta\Delta\phi$ space from Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV with ATLAS. The correlation is studied in the centrality class 20–30% showing a double ridge structure typical of the flow effects. Picture from Ref. [96].	55
4.13	$\Delta\phi$ correlation function from Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV with ATLAS. The near-side peaks reflect the “ridge” instead of the autocorrelations from jet fragments. The superimposed solid lines (thick-dashed lines) indicate contributions from individual v_n components (sum of the first six components). Picture from Ref. [96].	56
4.14	Ridge structure from pp collision at $\sqrt{s} = 13$ TeV with ALICE in high-multiplicity class. Picture from Ref. [97].	57
5.1	Correlation functions $\Delta\eta\Delta\phi$ for unlike-sign pairs of pions, kaons, and protons (top row) and like-sign pairs of pions, kaons, and protons (bottom row). Picture from Ref. [4].	60
5.2	$\Delta\eta$ integrated projections of correlation functions for unlike-sign pairs of pions, kaons, and protons (top row) and like-sign pairs of pions, kaons, and protons (bottom row). The ALICE data are represented by the black circles, while the dashed colored lines are the Monte Carlo models. Picture from Ref. [4].	61
5.3	Correlation functions for combined pairs of pp+ $\bar{p}\bar{p}$ for two transverse momentum intervals (a) $0.5 < p_T < 1.25$ GeV/c and (b) $1.25 < p_T < 2.5$ GeV/c. Panel (c) shows $\Delta\eta$ integrated projections. Statistical (bars) and systematic (boxes) uncertainties are plotted. Picture from Ref. [4].	62
5.4	$\Delta\eta\Delta\phi$ correlation functions for like-sign and unlike-sign lambda particles. The study is conducted to verify the influence of Coulomb interaction. Picture from Ref. [4].	64
5.5	$\Delta\eta\Delta\phi$ correlation functions for non-identical proton-lambda pair particles. The study is conducted to verify the influence of Fermi-Dirac quantum statistics. Picture from Ref. [4].	64
5.6	Angular correlation function $R_2(\Delta y\Delta\phi)$ of like-sign (left) and unlike-sign (right) protons in Au + Au collisions at mid centrality 30%–40% and $0.4 < p_T < 2.0$ GeV/c in different beam energies from 7.7 GeV (top left) to 200 GeV (bottom right). Picture from Ref. [85].	65

5.7	Per-trigger yields in $(\Delta y, \Delta \varphi)$ for Ξp (left), $\Xi \Lambda$ (middle), and $\Xi \Xi$ (right) particle pair with the same baryon number, measured in pp collisions at $\sqrt{s} = 13$ TeV. Picture from Ref. [108].	65
5.8	Correlation functions for Ξp , $\Xi \Lambda$, and $\Xi \Xi$ pairs, as a function of $\Delta \varphi$ ($ \Delta y < 1$). Black circles and grey squares denote opposite- and same-baryon-number correlations, respectively, with their difference (OB–SB) shown in the lower panels. Error bars indicate statistical uncertainties, while shaded boxes show systematic ones. ALICE data are compared to model predictions: PYTHIA 8 Monash (blue), PYTHIA 8 with junctions (green), junctions and ropes (yellow), EPOS-LHC (red), and HERWIG 7 (pink). Picture from Ref. [108].	66
5.9	$\Delta \eta \Delta \varphi$ correlation functions for like-sign pions, kaons and, protons in pp collision at $\sqrt{s} = 13$ TeV. PYTHIA8 model, represented by the black line is not able to reproduce the anticorrelation for like-sign protons. Picture from Ref. [111].	67
6.1	CERN accelerator complex. Picture from Ref. [117].	70
6.2	The ALICE experiment at LHC. Picture from Ref. [118].	71
6.3	Segmentation of the V0A/V0C arrays. Picture from Ref. [119].	72
6.4	Layout of the ITS. Picture from Ref. [122].	73
6.5	A schematic layout of the ALICE Time Projection Chamber. Picture from Ref. [124].	77
6.6	The energy loss as a function of momentum over charge, as measured by the ALICE TPC from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Picture from Ref. [125].	80
6.7	Particle velocity β as a function of momentum detected by TOF detector from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. Picture from Ref. [125].	81
6.8	The MonALISA system provides a real-time overview of the ALICE GRID network. On its interactive map, dots represent the locations of computing centers worldwide that are part of the ALICE GRID infrastructure, which facilitates data storage and analysis for the experiment. The color of each dot indicates the current operational status of the corresponding computing center.	83

7.1	φ as a function of y distribution for positive pions, kaons, and protons in the highest (0–20%) and lowest (70–100%) multiplicity classes from pp collision at $\sqrt{s} = 13$ TeV.	89
7.2	p_T vs φ distribution for positive pions, kaons, and protons on the left column and for negative pions, kaons and protons on the right column in the highest (0–20%) multiplicity classes from pp collision at $\sqrt{s} = 13$ TeV.	90
7.3	$N_{\sigma\text{TPC}}$ vs $N_{\sigma\text{TOF}}$ distributions for the Monte Carlo dataset from Pb–Pb collision system at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for all particle types studied and for the highest (0–20%), middle (50–60%), and lowest (80–90%) centrality classes.	93
7.4	Schematic view of the $\Delta\varphi^*$ angle in the azimuthal space. Picture from Ref. [131].	94
7.5	$\Delta\eta\Delta\varphi^*$ correlation functions performed for experimental data from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for all multiplicity classes and for four radii (0.8, 1.2, 1.6, and 2.0) cm for like-sign pions.	96
7.6	$\Delta\eta\Delta\varphi^*$ correlation functions performed for experimental data from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the highest and the lowest multiplicity class and for four radii (0.8, 1.2, 1.6, and 2.0) cm for like-sign kaons and protons.	97
7.7	Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2017 period from pp collision at $\sqrt{s} = 13$ TeV.	99
7.8	Contamination levels from pp collision at $\sqrt{s} = 13$ TeV, in samples of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/ c for pions, and 0.5–2.5 GeV/ c for kaons and protons.	100
7.9	Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2016 period from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	101

7.10	Contamination grid of p–Pb samples at $\sqrt{s_{\text{NN}}} = 5.02$ TeV of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/ c for pions, and 0.5–2.5 GeV/ c for kaons and protons.	102
7.11	Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2017 period from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	103
7.12	Contamination levels from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, in samples of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/ c for pions, and 0.5–2.5 GeV/ c for kaons and protons.	104
7.13	Efficiency as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.	106
7.14	Contamination from secondary particles as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.	107
7.15	Correction factor as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.	107
7.16	The left panel shows the secondary contamination, while the right panel displays the efficiency, both as functions of p_T for p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	108
7.17	Correction factor as a function of p_T for pions, kaons, and protons in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	109
7.18	On the left the secondary contamination and on the right the efficiency both as a function of p_T from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	110
7.19	Correction factor as a function of p_T for pions, kaons, and protons in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	110
8.1	The p_T spectra, as published in Ref. [132], were reproduced using data from Ref. [133]. The spectra are shown for pions, kaons, and protons for the 10 available multiplicity classes.	118

8.2	The comparison of the p_T spectra is shown between the public data, represented by empty rhombuses, and the experimental data, represented by filled rhombuses, for pions, kaons, and protons. Different colors indicate the various multiplicity classes analyzed.	119
8.3	Comparison of $\Delta\phi$ projections of rescaled two-particle correlation functions using N_{av} from experimental data (red markers) and public data (solid lines) for all particle pairs across four multiplicity classes.	121
8.4	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	122
8.5	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	123
8.6	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	123
8.7	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	124
8.8	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	124
8.9	$\Delta y\Delta\phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	125

- 8.10 $\Delta\phi$ projections of correlation functions using the probability ratio definition. All four multiplicity classes are plotted on the same canvas for each particle. 129
- 8.11 $\Delta\phi$ projections of correlation functions using the rescaled two-particle correlation function definition. All four multiplicity classes are plotted on the same canvas for each particle. 130
- 8.12 $\Delta\phi$ projections of correlation functions computed using the probability ratio definition. Comparison with MC models was made for like-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data. 131
- 8.13 $\Delta\phi$ projections of correlation functions computed using the probability ratio definition. Comparisons with MC models were made for unlike-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data. 132
- 8.14 $\Delta\phi$ projections of correlation functions computed using the rescaled two-particle correlation function. Comparisons with MC models were made for like-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data. 133
- 8.15 $\Delta\phi$ projections of correlation functions computed using the rescaled two-particle correlation function. Comparisons with MC models were made for unlike-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data. 134

8.16	$\Delta y \Delta \varphi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition for like-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.	136
8.17	$\Delta y \Delta \varphi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition for unlike-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.	137
8.18	$\Delta y \Delta \varphi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition for like-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.	138
8.19	$\Delta y \Delta \varphi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition for unlike-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.	139
8.20	$\Delta \varphi$ projections of correlation functions from pp collision at $\sqrt{s} = 13$ TeV within $\Delta y < 1$ for like- and unlike-sign pions, kaons, and protons in multiplicity classes, using the probability ratio definition. Statistical uncertainties (bars) and systematic uncertainties (boxes) are both drawn with the color associated with the corresponding multiplicity class.	141
8.21	$\Delta \varphi$ projections of correlation functions from pp collision at $\sqrt{s} = 13$ TeV within $\Delta y < 1$ for like- and unlike-sign pions, kaons, and protons in multiplicity classes, using the rescaled two-particle correlation function definition. Statistical uncertainties (bars) and systematic uncertainties (boxes) are both drawn with the color associated with the corresponding multiplicity class.	142
8.22	Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the probability ratio definition for like-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.	143
8.23	Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the probability ratio definition for unlike-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.	144

8.24	Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the rescaled two-particle correlation function definition for like-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.	145
8.25	Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the rescaled two-particle correlation function definition for unlike-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.	146
8.26	$\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	149
8.27	$\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	149
8.28	$\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	150
8.29	$\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	150
8.30	$\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.	151

- 8.31 $\Delta y \Delta \varphi$ correlation functions from p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes. 151
- 8.32 $\Delta \varphi$ projections of correlation functions described using the definition of probability ratio. For each particle, the four multiplicity classes are drawn on the same canvas. 154
- 8.33 $\Delta \varphi$ projections of correlation functions described using the definition of the rescaled two-particle correlation function. For each particle, the four multiplicity classes are drawn on the same canvas. 155
- 8.34 Data comparison with MC models using probability ratio definition for like-sign particles and for the four classes of multiplicity analyzed. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p–Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data. 156
- 8.35 Data comparison with MC models using probability ratio definition for unlike-sign particles and for the four classes of multiplicity analyzed. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p–Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data. 157
- 8.36 Data comparison with MC models using the rescaled two-particle correlation function definition for like-sign particle pairs and the four multiplicity classes involved. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p–Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data. . . . 158

8.37	Data comparison with MC models using the rescaled two-particle correlation function definition for unlike-sign particle pairs and the four multiplicity classes involved. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p–Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data.	159
8.38	Comparison of the $\Delta\phi$ projections between pp and p–Pb collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV, respectively. The comparison is made for all particles and overall multiplicity classes analyzed using the probability ratio definition.	161
8.39	Projections of Δy of correlation functions using the probability ratio definition for unlike-sign pions. The correlation functions in different multiplicity classes show a monotonic trend, with an increase in the function as multiplicity decreases.	162
8.40	Comparison of the Δy $\Delta\phi$ correlation functions between pp and p–Pb collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV, respectively. The comparison is made for all particles and across all multiplicity classes analyzed using the rescaled two-particle cumulant definition.	163
9.1	$\Delta y \Delta\phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign pions across the seven centrality analyzed.	171
9.2	$\Delta y \Delta\phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign pions across the seven centrality analyzed.	172
9.3	$\Delta y \Delta\phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign kaons across the seven centrality analyzed.	172
9.4	$\Delta y \Delta\phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign kaons across the seven centrality analyzed.	173
9.5	$\Delta y \Delta\phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign protons across the seven centrality analyzed.	173

9.6	$\Delta y \Delta \varphi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for unlike-sign protons across the seven centrality analyzed.	174
9.7	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for like-sign pions across the seven centrality analyzed.	175
9.8	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for unlike-sign pions across the seven centralities analyzed.	175
9.9	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for like-sign kaons across the seven centralities analyzed.	176
9.10	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for unlike-sign kaons across the seven centralities analyzed.	176
9.11	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for like-sign protons across the seven centralities analyzed.	177
9.12	$\Delta y \Delta \varphi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for unlike-sign protons across the seven centralities analyzed.	177
9.13	$\Delta \varphi$ projections of correlation functions described using the definition of probability ratio. For each particle, the 7 centrality classes are drawn on the same canvas.	181
9.14	$\Delta \varphi$ projections of correlation functions described using the definition of rescaled two-particle correlation function. For each particle, the 7 centrality classes are drawn on the same canvas.	182
9.15	The comparison of $\Delta y \Delta \varphi$ correlation functions with MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is presented using the probability ratio definition for like-sign pions across all centrality classes included in the analysis.	183

9.16	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign pions and for all centrality classes involved in the analysis.	183
9.17	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for like-sign kaons and for all centrality classes involved in the analysis.	184
9.18	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign kaons and for all centrality classes involved in the analysis.	184
9.19	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for like-sign protons and for all centrality classes involved in the analysis.	185
9.20	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign protons and for all centrality classes involved in the analysis.	185
9.21	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign pions and all centrality classes involved in the analysis.	186
9.22	Comparison between $\Delta y \Delta \varphi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign pions and all centrality classes involved in the analysis.	186

9.23	Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign kaons and all centrality classes involved in the analysis.	187
9.24	Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign kaons and all centrality classes involved in the analysis.	187
9.25	Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign protons and all centrality classes involved in the analysis.	188
9.26	Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign protons and for all centrality classes involved in the analysis.	188
9.27	Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for like-sign pions and for all centrality classes involved in the analysis.	189
9.28	Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign pions and for all centrality classes involved in the analysis.	189
9.29	Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for like-sign kaons and for all centrality classes involved in the analysis.	190

- 9.30 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign kaons and for all centrality classes involved in the analysis. 190
- 9.31 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for like-sign protons and for all centrality classes involved in the analysis. 191
- 9.32 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the probability ratio definition for unlike-sign protons and for all centrality classes involved in the analysis. 191
- 9.33 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign pions and all centrality classes involved in the analysis. . . 192
- 9.34 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign pions and all centrality classes involved in the analysis. . 192
- 9.35 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign kaons and all centrality classes involved in the analysis. . . 193
- 9.36 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign kaons and all centrality classes involved in the analysis. . 193
- 9.37 Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign protons and all centrality classes involved in the analysis. . 194

9.38	Comparison between $\Delta y \Delta \varphi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign protons and for all centrality classes involved in the analysis.	194
10.1	Comparison of pp, p–Pb, and Pb–Pb $\Delta y \Delta \varphi$ correlation functions at the LHC energies for all particles using probability ratio definition.	198
10.2	Comparison of pp, p–Pb, and Pb–Pb $\Delta y \Delta \varphi$ correlation functions at the LHC energies for all particles using rescaled two-particle correlation function definition.	200
A.1	The left panel shows the particle spectra as a function of p_T after applying selection cuts, without corrections for the correction factor. The middle panel illustrates the corrected spectra, also as a function of p_T . The right panel displays the total number of events as a function of multiplicity. These plots correspond to π^- particles in the 0–20% multiplicity class, derived from Monte Carlo reconstructed data from pp collisions at $\sqrt{s} = 13$ TeV.	208
A.2	MC closure test using data from pp collision at $\sqrt{s} = 13$ TeV is performed by using the probability ratio definition for all particle pairs and across all multiplicity classes selected.	212
A.3	MC closure test using data from pp collision at $\sqrt{s} = 13$ TeV is performed by using the rescaled two-particle correlation function for all particle pairs and across all multiplicity classes selected.	213
A.4	MC closure test using data from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is performed by using the probability ratio definition for all particle pairs and across all multiplicity classes selected.	214
A.5	MC closure test using data from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is performed by using the rescaled two-particle correlation function for all particle pairs and across all multiplicity classes selected.	215
A.6	The Monte Carlo closure test is conducted for all particles and all centrality classes involved in the analysis using the probability ratio definition from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The upper plots display the projection onto $\Delta \varphi$ for both reconstructed and generated correlation functions, while the lower plots show the relative error.	216

A.7	The Monte Carlo closure test is conducted for all particles and all centrality classes involved in the analysis using the rescaled two-particle correlation function definition from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The upper plots display the projection onto $\Delta\varphi$ for both reconstructed and generated correlation functions, while the lower plots show the relative error.	217
B.1	Systematic uncertainties for like- and unlike-sign pairs across four multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition. Each variation is color-coded, with the black solid line representing the final combined uncertainties.	224
B.2	Systematic uncertainties for like- and unlike-sign pairs across four multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition. Each variation is color-coded, with the black solid line representing the final combined uncertainties.	225
B.3	Systematic uncertainties estimated for like-sign and unlike-sign particle pairs for the (0–0.17%), (20–30%), (60–70%), and (90–100%) multiplicity classes, using the probability ratio definition from pp collision at $\sqrt{s} = 13$ TeV. Each variation is color-coded, with the black solid line indicating the final combined uncertainties.	228
B.4	Systematic uncertainties estimated for like-sign and unlike-sign particle pairs for the (0–0.17%), (20–30%), (60–70%), and (90–100%) multiplicity classes, using the rescaled two-particle correlation function definition from pp collision at $\sqrt{s} = 13$ TeV. Each variation is color-coded, with the black solid line indicating the final combined uncertainties.	229
B.5	Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the four selected multiplicity classes using the probability ratio definition from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Each variation is color-coded, and the black solid line indicates the final combined uncertainties.	232
B.6	Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the four selected multiplicity classes using the rescaled two-particle correlation function definition from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Each variation is color-coded, and the black solid line indicates the final combined uncertainties.	233

- B.7 Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the selected centrality classes, based on the probability ratio definition from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Each variation is calculated using the relative error R_r and is represented by a different color, with the black solid line indicating the final combined uncertainties. 235
- B.8 Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the selected centrality classes, based on the rescaled two-particle correlation function from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Each variation is calculated using the relative error R_r and is represented by a different color, with the black solid line indicating the final combined uncertainties. 237

List of Tables

4.1	Conservation laws for all the particle species studied.	47
8.1	N_{av} value estimated using experimental data for the four multiplicity classes analyzed, i.e 0–20%, 20–40%, 40–70% and 70–100%. These values are obtained for pions, kaons, and protons.	120
8.2	N_{av} values are estimated from published data [132] for the four multiplicity classes analyzed, i.e., 0–20%, 20–40%, 40–70%, and 70–100%. These values are obtained for pions, kaons, and protons.	120
8.3	N_{av} value estimated using experimental data from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the four multiplicity classes analysed, i.e 0–20%, 20–40%, 40–70% and 70–100%. These values are performed for pions, kaons and protons.	147
9.1	N_{av} value estimated using experimental data from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the 7 centrality classes analyzed for pions, kaons and protons.	171
10.1	$dN_{ch}/d\eta$ values for pp, p–Pb, and Pb–Pb collision system from the literature and adapted to the multiplicity and centrality classes used in the analysis.	197
A.3	N_{av} values for reconstructed and true data from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for all particles and centrality classes analyzed.	209
A.1	Comparison of N_{av} values between reconstructed and true Monte Carlo data from pp collision at $\sqrt{s} = 13$ TeV for pions, kaons, and protons across the analyzed multiplicity classes.	209
A.2	Comparison of N_{av} values between reconstructed and true Monte Carlo data from p–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for pions, kaons, and protons across the analyzed multiplicity classes.	209

- B.1 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the probability ratio definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 222
- B.2 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 223
- B.3 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. The table estimates the range of absolute error influence on the peak from the highest to the lowest multiplicity class. 223
- B.4 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the probability ratio definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 226
- B.5 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 227
- B.6 Influence of the systematic uncertainties on the maximum of the correlation functions performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 227

- B.7 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the probability ratio definition from p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown. 230
- B.8 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is calculated as the average over all the bins. 231
- B.9 Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, the range of absolute error influence on the peak is estimated from the highest to the lowest multiplicity class. 231
- B.10 Summary of all systematic uncertainties studies performed for all particle pairs using the probability ratio definition from Pb–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, the range of uncertainties for the highest and the lowest multiplicity classes is shown. 236
- B.11 Summary of all systematic uncertainties studies performed for all particle pairs using the rescaled two-particle correlation function from Pb–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, the range of uncertainties for the highest and the lowest multiplicity classes is shown. 236
- B.12 Summary of all uncertainties for all particle pairs using the rescaled two-particle correlation function. The table shows the range of values indicating each uncertainty’s impact on the correlation function maximum, for the highest and the lowest centrality classes. 236

*Alla mia famiglia, che ci ha creduto
prima che ci credessi io.*

*A te che piu' di chiunque altro avresti
voluto esserci.*

Chapter 1

Introduction

The Big Bang theory predicts that equal amounts of matter and antimatter were produced in the primordial universe [1]. However, the observable universe predominantly comprises matter, with antimatter being exceedingly rare. This stark imbalance, known as the matter-antimatter asymmetry, remains one of the deepest mysteries of modern physics. Understanding the fate of antimatter is crucial for unveiling the true nature of our universe.

Investigating this asymmetry necessitates studying the mechanisms behind particle production, a topic central to physics for decades. In the 1970s, R. Feynman and R. Field introduced the pivotal concept of jet production [2], outlining the rules governing particle creation and their correlations. These correlations, dictated by energy distribution and conservation laws, offer profound insights into particle physics. However, limitations in experimental data leave many questions unresolved. Early experiments, such as electron-positron (e^+e^-) collisions at $\sqrt{s} = 29$ GeV [3], revealed an unexpected anticorrelation for antiproton-antiproton pairs. At the time, this phenomenon was attributed to the high energy required for producing proton pairs in jets. More recently, studies at the Large Hadron Collider (LHC), particularly with the ALICE experiment at $\sqrt{s} = 7$ TeV in proton-proton (pp) collisions [4], revisited these observations. These results ushered in a new era of baryon correlation studies, leading to deeper investigations into the observed anticorrelations in baryon-baryon pairs and beyond. Notably, studies of mesonic particle pairs have provided an independent means of exploring the influence of various interaction mechanisms, offering crucial data points for probing a wide range of physical processes.

The LHC, and particularly the ALICE detector, plays a central role in probing these questions. ALICE is uniquely equipped to study strongly interacting matter under extreme conditions, such as quark-gluon plasma formation. Beyond heavy-ion physics, ALICE provides valuable benchmarks through its analysis of pp and proton-nucleus

(p–A) collisions, helping to unravel the complexities of particle interactions in diverse environments.

This thesis explores particle correlations emerging from high-energy collisions, offering a window into the dynamics and structure of the systems produced. For the first time in ALICE, angular correlations in the $\Delta y \Delta \varphi$ space are analyzed for pairs of identified particles—pions, kaons, and protons—across varying multiplicity classes and three distinct collision systems: pp, p–Pb, and Pb–Pb. By examining these interactions, this work explores various physical phenomena that shape the structure of the correlation function, aiming to shed light on several still-unknown mechanisms—not only in the production of baryons but also in the behavior of mesons.

The techniques applied here aim to advance our understanding of particle generation in high-energy hadronic and nuclear collisions, while improving existing Monte Carlo models that struggle to replicate the anticorrelation observed at $\sqrt{s} = 7$ TeV. Ultimately, the results help address the broader question of matter-antimatter asymmetry, providing crucial perspectives on one of the most fundamental mysteries of the universe.

Chapter 2

The Physics of Heavy-Ion Collisions at Relativistic Energies

2.1 Standard model

The Standard Model is a well-established theory that describes the fundamental particles and forces, with the exception of gravity, which govern the behavior of matter in the universe. It unifies the electromagnetic, weak, and strong nuclear forces, describing how these interactions influence elementary particles. According to the Standard Model, matter comprises fundamental particles known as quarks and leptons, which are point-like fermions with a spin of $1/2$. These particles are divided into three families. Quarks, based on their electric charge, are classified into two groups: the up (u), charm (c), and top (t) quarks, each with a charge of $+2/3$ of a proton, and the down (d), strange (s), and bottom (b) quarks, each with a charge of $-1/3$. Neutrinos (ν_e , ν_μ , and ν_τ) are electrically neutral. The first family consists of the u and d quarks, along with the electron and electron neutrino (ν_e). Most of the matter we observe, including atoms, is made up of these particles. For instance, protons are composed of two up quarks and one down quark (uud), while neutrons contain two down quarks and one up quark (udd). The second and third families resemble the first but are only produced in high-energy collisions. Particles from these higher generations, like s, c, t, and b quarks, are more massive and quickly decay into lighter, first-generation particles. While leptons (such as electrons and neutrinos) have been observed as free particles, quarks are always found in composite particles called hadrons. Hadrons come in two forms: mesons, which consist of two quarks, and baryons, made of three quarks. Every particle in the Standard Model has a corresponding antiparticle, identical in mass, spin, and lifetime but with opposite electric charge, baryon number, or lepton number.

For example, each quark (q) is associated with an antiquark ($\bar{q}$). Quantum numbers are conserved in fundamental interactions, which affect particle-antiparticle pairs through conservation of charge, strangeness, baryon number, or lepton number.

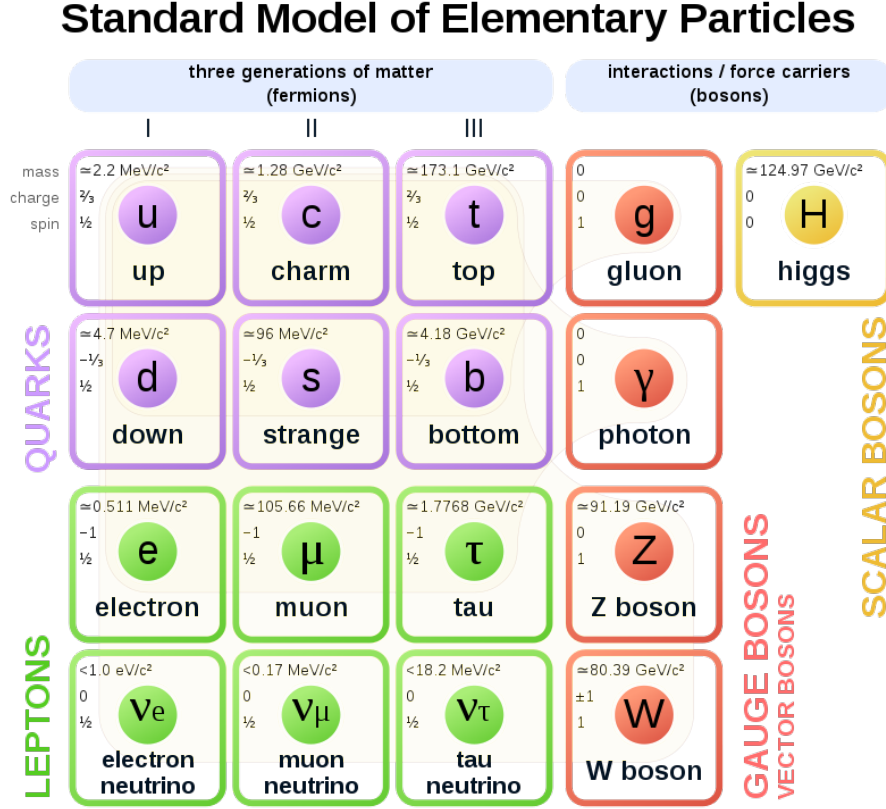


FIGURE 2.1: The elementary particles within the Standard model [5].

The Higgs boson, another key part of the Standard Model, is an elementary particle associated with the Higgs field, which permeates the entire universe and gives mass to other fundamental particles. It was first proposed in the mid-1960s by Peter Higgs, after whom the particle is named and later discovered in 2012 at the LHC [6, 7]. While the Higgs boson's mass is not predicted by the Standard Model, experiments conducted by the ATLAS and CMS collaborations have measured it to be approximately $125 \text{ GeV}/c^2$ [8, 9].

The particles that mediate the four fundamental forces are also included in the Standard Model. These include the photon, which mediates the electromagnetic force; the W^+ , W^- , and Z^0 bosons for the weak force; and eight gluons for the strong force.

Unlike the fermions mentioned earlier, these force-carrying particles are bosons, possessing an integer spin of 1. The Standard Model does not incorporate gravity, as at microscopic scales and the energy levels accessible with current particle accelerators, gravitational effects are negligible. Fig. 2.1 provides a schematic overview of all the particles in the SM.

2.2 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is a gauge field theory that explains the strong interactions between quarks and gluons, both of which possess a property known as "color". QCD is a key part of the Standard Model of particle physics, specifically within the $SU(3) \times SU(2) \times U(1)$ framework. This theory was formulated in 1973 by European physicists Heinrich Fritzsch and Harald Leutwyler, alongside American physicist Murray Gell-Mann [10], drawing an analogy to Quantum Electrodynamics (QED), which describes the electromagnetic force. In QCD, color functions similarly to electric charge in QED, playing a vital role in strong interactions.

The concept of "color" as an intrinsic property of quarks was first proposed by O.W. Greenberg in 1964 [11] and later refined by Y. Nambu and M. Y. Han in 1965 [12]. It was introduced to resolve a key problem: how quarks with identical quantum properties can coexist within hadrons without violating the Pauli exclusion principle. This issue arises in examples such as the baryons Δ^{++} (uuu), Δ^- (ddd), and Ω^- (sss). These particles are made entirely of quarks of the same flavor and spin, and they are spin 3/2 baryons. The physical properties of these baryons indicate that three identical quarks occupy the same S-wave orbital and share the same spin wave function. However, quarks are fermions, which means they must obey the Pauli exclusion principle: no two fermions can exist in the same quantum state. To resolve this apparent contradiction, physicists proposed the existence of a new quantum property—"color." In this context, "color" does not relate to visible colors but instead represents a unique attribute of subatomic particles. Each quark carries one of three "color charges": red, green, or blue, while antiquarks carry the corresponding "anti-colors" [13]. This additional property allows quarks to satisfy the Pauli exclusion principle by distinguishing them even when all their other quantum numbers are identical.

Quarks interact through gluons, which mediate the strong force much like photons mediate electromagnetic interactions in QED. However, gluons carry color charge and couple to quarks through the strong coupling constant, denoted as α_s [14]. Notably, α_s

is not fixed; it varies with the momentum transfer Q^2 , which is why it is referred to as the running coupling constant, defined as follows:

$$\alpha_s(Q^2) = \frac{16\pi^2}{(11 - \frac{2}{3}N_f)\ln(Q^2/\Lambda_{QCD}^2)}. \quad (2.1)$$

Λ_{QCD} is a scale parameter in QCD, typically around 200 MeV [15], which describes the boundary condition of the first-order differential equation used to calculate the α_s and N_f is the number of free light quarks.

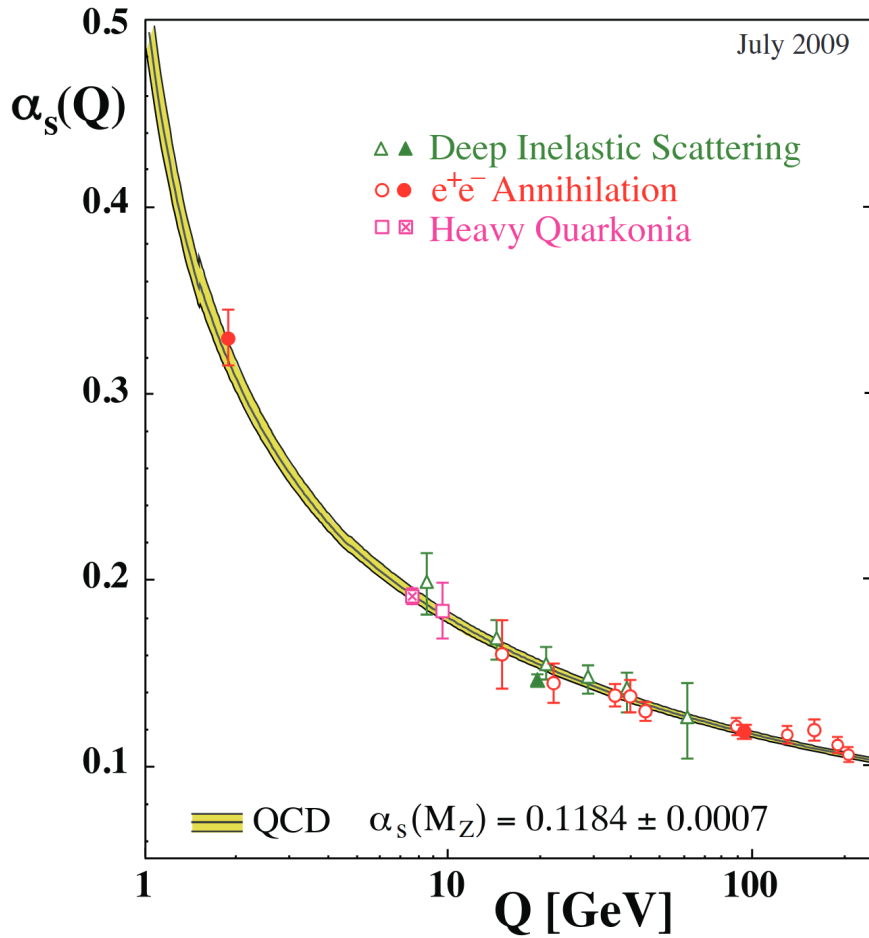


FIGURE 2.2: α_s as a function of the energy scale Q compared to experimental constraints. Picture from Ref. [16].

As shown in Fig. 2.2, α_s increases at low momentum transfers (large distances), which leads to a stronger interaction between quarks and gluons. As two quarks are pulled apart, the increasing α_s causes the strong interaction to grow more intense.

Eventually, the energy stored in the system becomes so large that it becomes energetically more favorable to create a new quark-antiquark pair rather than continue separating the original quarks. This phenomenon, known as "confinement" [17, 18, 19], ensures that quarks cannot exist in isolation and color confinement imposes that quarks are always bound together in color-neutral combinations, such as baryons or mesons.

Conversely, at high momentum transfers (short distances), α_s decreases, causing the interaction between quarks and gluons to weaken, allowing them to behave almost as free particles. This phenomenon, termed "asymptotic freedom" [20, 21, 22], was discovered by David Gross, Frank Wilczek, and David Politzer in 1973 and was the key to the understanding of the strong nuclear force. Asymptotic freedom is particularly important in studying QCD matter at extremely high temperatures, such as those present in the early universe or created in heavy-ion collisions at particle accelerators.

In Quantum Chromodynamics (QCD), two principal approaches are used to investigate the behavior of quarks and gluons: perturbative QCD (**pQCD**) and lattice QCD (**lQCD**). **pQCD** is effective at high energy scales where the strong coupling constant, α_s , becomes sufficiently small to allow for the application of perturbation theory. In this high-energy regime, quark and gluon interactions can be systematically calculated by expanding them in powers of α_s , which is especially useful for analyzing phenomena such as jet formation and hard scattering events in high-energy particle collisions [23]. However, as energy decreases and α_s grows, perturbative techniques lose their validity. For the study of QCD in the low-energy domain, where the strong coupling becomes large and perturbation theory breaks down, **lQCD** is employed. This non-perturbative method uses a discretized space-time lattice to solve QCD equations numerically. **lQCD** is crucial for understanding non-perturbative phenomena like quark confinement and hadron structure, which are inaccessible to perturbative methods [17]. The combination of **pQCD** and **lQCD** thus provides a comprehensive toolkit for studying the full spectrum of QCD behavior across different energy scales.

2.3 Quark-Gluon Plasma

The QCD predicts that quarks and gluons can exist in a deconfined state, known as a QGP. The potential energy between a quark and an antiquark is mediated by gluons, and this energy increases proportionally to the separation distance. At zero temperature, the linear potential confines quarks within hadrons, as the energy

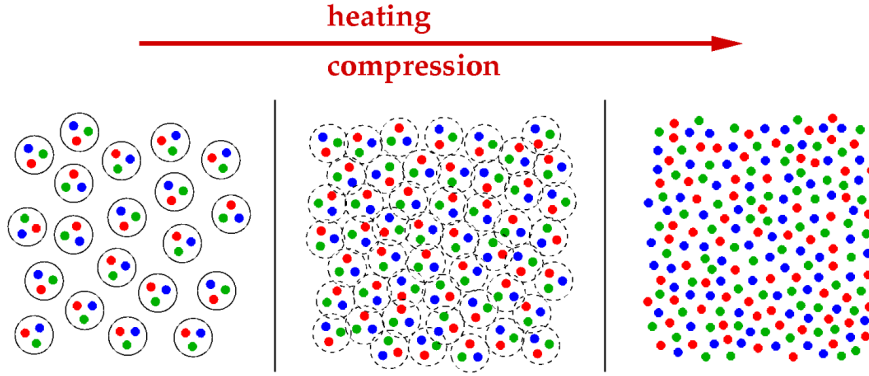


FIGURE 2.3: Compression and heating of matter before the deconfined phase transition. Picture from Ref. [24].

required to separate quarks increases with their distance. If the gluon field energy between the quark and the remaining hadron components becomes sufficient to create a quark–antiquark pair, the gluon field splits into two regions, each of which forms a new hadron, thus ensuring that quarks remain confined. This mechanism effectively prevents the isolation of free quarks. However, deconfinement of quarks can occur under conditions of extreme nuclear density. When nuclear matter is compressed to a sufficiently high density, hadrons are forced to stay close together and quarks can no longer distinguish their original partners. At sufficiently short distances between quarks and their neighbors, attractive forces become weaker, allowing quarks to move over a larger volume. This process is called deconfinement. In addition to high nuclear densities, deconfinement can also occur at elevated temperatures. At high temperatures, new quark–antiquark pairs are produced, reducing the distance between quarks and effectively causing the boundaries of hadrons to disappear.

The deconfinement phase transition has been extensively studied using various phenomenological approaches, including IQCD. Numerical calculations within IQCD provide critical insights into the thermodynamic properties of the QGP, such as pressure, energy density, and entropy density. Figure 2.4 represents the energy density divided by T^4 (the number of degrees of freedom in the system) as a function of the temperature relative to the critical temperature. When the temperature exceeds this critical value, the number of degrees of freedom increases, indicating the formation of QGP.

IQCD offers insight into how temperature varies with baryon chemical potential

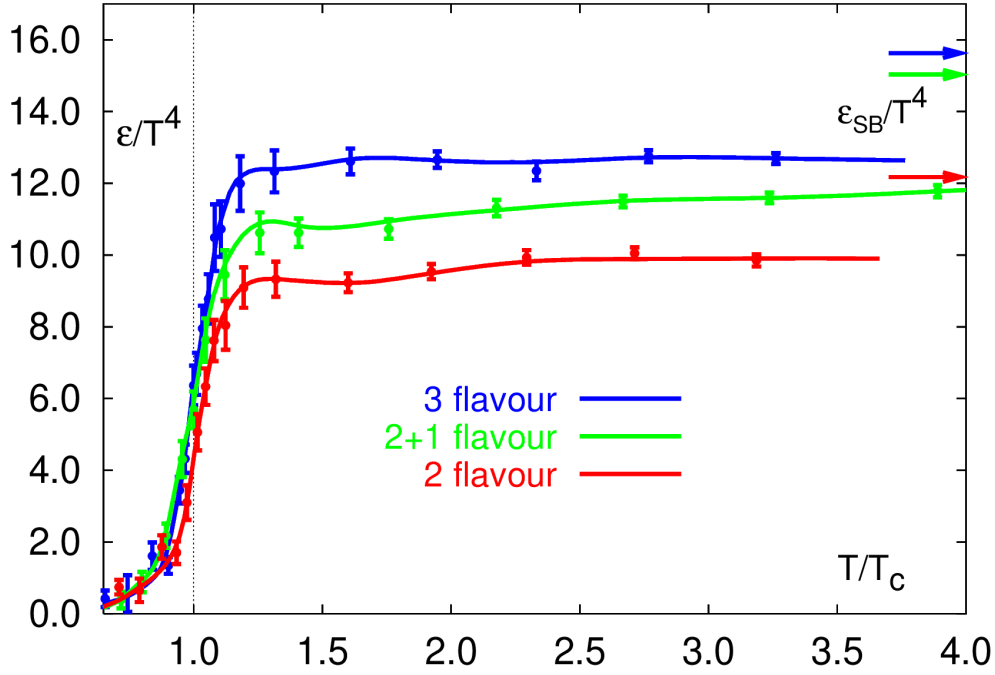


FIGURE 2.4: Energy density as a function of temperature calculated from IQCD. Picture from Ref. [25].

(μ_B) during phase transitions. These transitions involve shifts between different states of matter due to changes in external thermodynamic conditions. As shown in the QGP phase diagram in Fig. 2.5, there's a blue line showing where the phase transition happens. At temperatures that aren't too high and at non-zero μ_B , the transition is thought to be first-order. At high temperatures, quarks and gluons are in a free state, while at lower temperatures and higher baryon densities, a color superconducting phase can emerge. In this regime, matter is compressed to densities far beyond that of atomic nuclei, as expected in the cores of neutron stars. When two neutron stars merge, the extreme conditions can resemble those created in high-energy collisions, and the resulting gravitational wave emission provides complementary insight into the behavior of strongly interacting matter. As μ_B approaches zero, it becomes possible for the system to change its state without crossing a phase transition line, also called as second-order transition. In this scenario, the system undergoes a cross-over, where both the QGP and hadronic phases coexist under specific thermodynamic conditions.

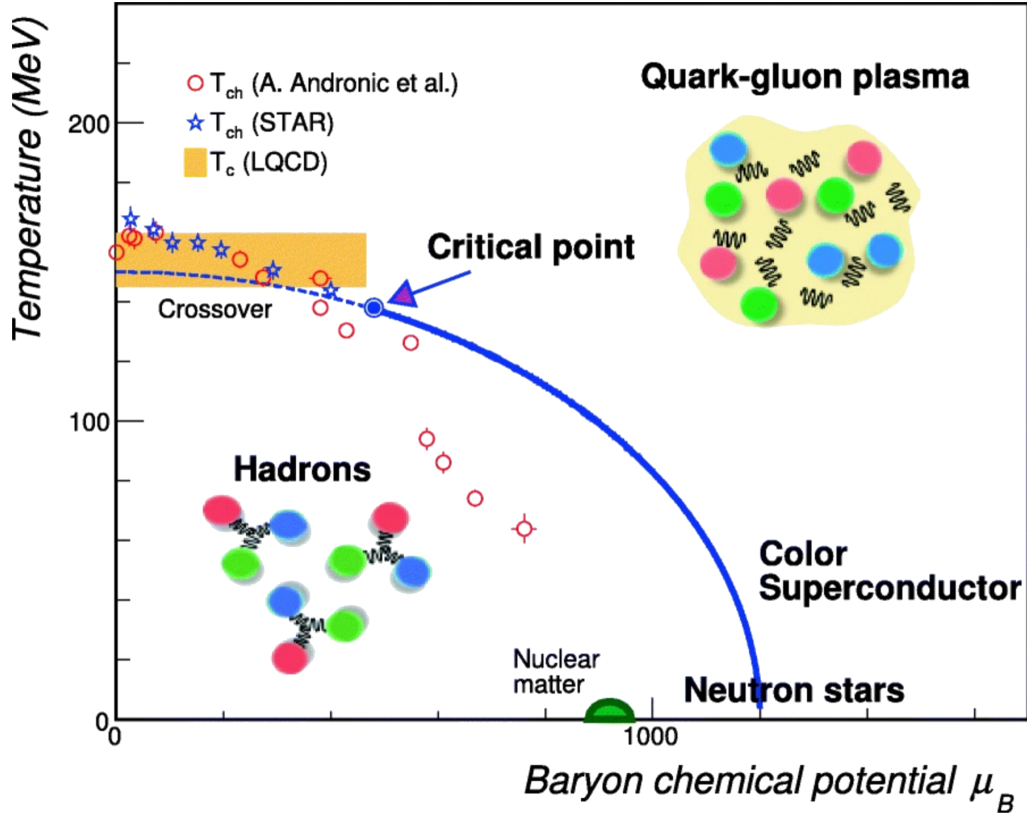


FIGURE 2.5: The QCD phase diagram features two distinct phases: the hadronic phase, representing ordinary nuclear matter, and the quark-gluon plasma phase. At zero baryon density, the phase transition occurs as a smooth crossover. Picture from Ref. [26].

2.4 Evolution of Heavy-Ion Collisions

With the advent of large-scale experiments such as the Relativistic Heavy-Ion Collider (RHIC), operational since 2000, and the LHC, which started operation at CERN in 2008, the signatures of the QGP have become increasingly evident. The enormous energy available – up to 200 GeV at RHIC and up to $\sqrt{s} = 14$ TeV at LHC – makes it possible to recreate the QGP in the laboratory. The evolution of heavy-ion collisions (HIC) is described in various stages, as illustrated in Fig. 2.6.

2.4.1 Initial stage

In a heavy-ion collision, the initial phase plays a crucial role in determining the evolution of the system and the properties of the QGP. During the collision, energy is deposited in the region where the two nuclei overlap, creating an asymmetric energy

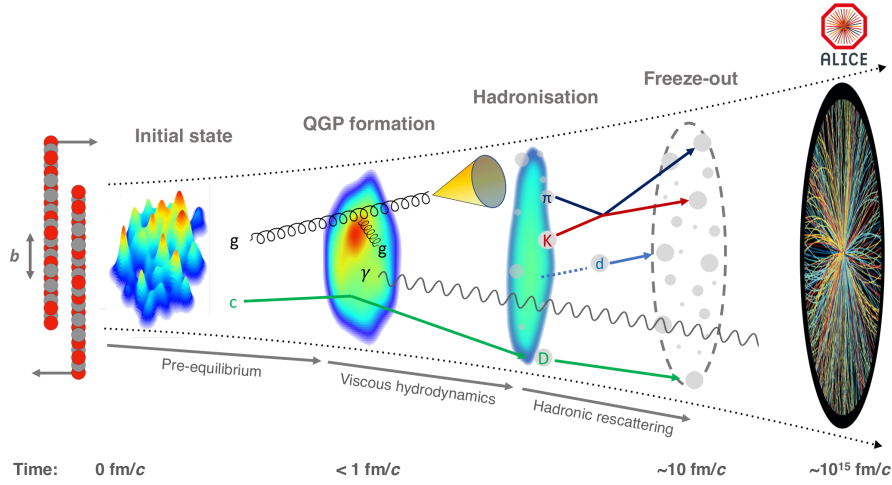


FIGURE 2.6: The evolution of a heavy-ion collision at LHC energies. Picture from Ref. [27].

distribution. This anisotropy means that the energy is not spread out uniformly in all directions. Instead, the energy density is higher in some regions and lower in others. These spatial differences in the initial energy density help shape the flow of particles in the final state of the collision. This flow is what we observe as collective particle motion. To investigate the properties of the QGP, such as its shear viscosity (which quantifies its resistance to flow), it is crucial to accurately model the early stages of the collision. A widely used approach for simulating this phase is the Monte Carlo Glauber model, which provides insights into the initial conditions of the collision and allows for the extraction of key information about the QGP from experimental data. The Glauber model is particularly effective in describing the geometry of nuclear collisions, with the impact parameter (b) being a critical measure of the overlap between the colliding nuclei. A small impact parameter corresponds to a central collision, where a larger number of nucleons participate in the interaction. Nucleons that actively engage in the collision are termed "participants", while those that do not are referred to as "spectators". For a more detailed discussion of the Glauber model, see Ref. [29].

2.4.2 Pre-equilibrium stage

During the collision a myriad of particles are generated, including quarks, gluons, and other subatomic entities, which are initially in a highly excited and non-equilibrium state. In this initial phase, these particles interact in a complex manner, scattering with

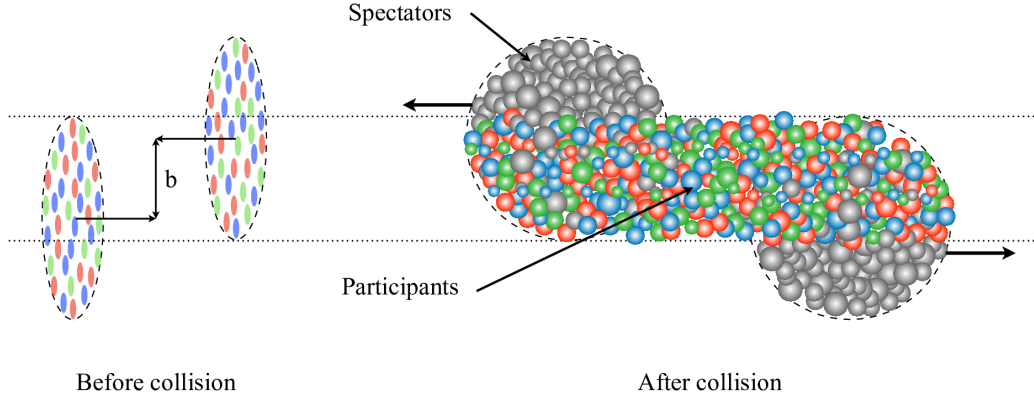


FIGURE 2.7: A schematic view of a heavy-ion collision. The impact parameter b is shown as well as the spectator nucleons and the participant nucleons. Picture from Ref. [28].

each other and gradually moving towards thermal equilibrium. The process of thermalisation occurs extremely rapidly, within a few femtometers per c (10^{-23} seconds) of the initial impact. This rapid transition marks the shift from initial chaos to a more balanced state where the QGP can emerge, laying the foundation for all subsequent developments.

2.4.3 QGP formation and expansion

Once the system has thermalized, quarks and gluons are free to move throughout the volume. The expansion of the QGP occurs rapidly due to the high-pressure gradient resulting from the intense energy density in the initial stage. This expansion takes place both longitudinally and transversely relative to the original beam axis of the colliding nuclei. As the expansion continues, it causes the system to cool down. During this expansion, the QGP exhibits behavior surprisingly similar to that of a perfect fluid¹

¹A real fluid exhibits significant viscosity, while a perfect fluid is a fluid fully characterized by its bulk density at rest (ρ_m) and isotropic pressure (p), with the lowest possible nearly negligible viscosity. The closest known physical realization of a perfect fluid is the quark-gluon plasma [30].

with extremely low viscosity². This is reflected in experimental data showing distinctive flow patterns, particularly an elliptical flow, indicating the presence of significant collective motion within the QGP, that will be discussed in the Sec. 2.5. This fluid-like behavior suggests that the QGP is governed by strong interactions that result in a high degree of coherence, allowing it to act as a nearly perfect liquid.

2.4.4 Hadronization

After the expansion, the QGP begins to cool, and once temperatures drop below approximately 170 MeV, quarks and gluons can no longer stay in the so-called deconfined state. They start to bind together again, transitioning from the QGP into hadronic matter in a process called hadronization. Hadronization can occur through various mechanisms, such as fragmentation or recombination (or coalescence). In the process of fragmentation, quark and gluon jets undergo a series of break-up events, resulting in the formation of smaller hadronic units. This process is a common event in high-energy particle collisions, especially when momentum transfer is high, causing energetic partons to fragment into hadronic jets. In contrast, recombination occurs when quarks in close proximity come together to directly form hadrons. This mechanism is more efficient in environments where a large number of quarks are produced in close proximity, such as in heavy-ion collisions. For example, quarks and antiquarks can undergo recombination to form mesons, whereas three quarks can combine to create baryons. After hadronization, the system remains a dense, interacting medium of hadrons, known as the hadron gas. In this phase, mesons and baryons scatter and evolve as the system cools and expands. As the temperature drops, interactions between hadrons become increasingly rare. While quark-gluon dynamics are no longer dominant, hadrons continue to interact through the strong force, exchanging energy and momentum.

2.4.5 Freeze-Out

Freeze-out represents the final stage of system evolution and is commonly described by chemical freeze-out and kinetic freeze-out. It is important to note that these are

²The ratio of shear viscosity to entropy density (η/s), is used to quantify the resistance in a fluid. In the case of QGP, is close to the theoretical lower bound set by quantum mechanics, known as the Kovtun-Son-Starinets (KSS) bound, which is $\eta/s = 1/4\pi$ in natural units. This is one of the lowest viscosities ever observed in nature.

not separate moments in time, but rather different aspects of the same process, distinguished for conceptual clarity. During chemical freeze-out, the system continues to expand and cool, with inelastic particle collisions ceasing. This cessation reduces entropy and marks the point at which the relative abundances of particle species stabilize. At this stage, no new particles are created or destroyed, and the composition of particles such as protons, neutrons, pions, kaons, and other hadrons becomes fixed. The system reaches chemical equilibrium at a temperature near the critical value of approximately 160–170 MeV, inferred from particle ratios observed in the collision, such as the ratio of pions to kaons, as discussed in Ref. [31]. These experimental ratios are compared with theoretical models of particle production, and the temperature that best matches the data provides an estimate of the chemical freeze-out temperature. This temperature represents the threshold at which quarks and gluons transition into hadrons. The particle ratios detected during this phase offer crucial insights into the chemical and thermal conditions of the system at freeze-out.

Following the chemical freeze-out, particles continue to interact with one another through elastic collisions. These collisions result in the exchange of momentum but do not affect the type or identity of the particles involved. This final phase is designated as kinetic freeze-out. The moment these elastic collisions cease marks the point at which particles no longer interact and begin to move freely towards the detectors. At this stage, the momenta of the particles are "frozen," whereby their energy and direction remain constant from this point onwards. The momentum distribution observed in the detectors is reflective of the conditions that prevailed at the time of kinetic freeze-out.

2.5 Collective phenomena in HIC

After the initial phase of a heavy-ion collision, the QGP is formed under extreme conditions of temperature and density. This leads to strong pressure gradients that drive a variety of collective behaviors, indicative of how the QGP evolves. Also, these collective phenomena highlight the QGP's behavior as a near-perfect fluid with low viscosity. By examining kinematic observables, we can better understand the fluid-like nature of the QGP and trace its evolution from a hydrodynamic perspective.

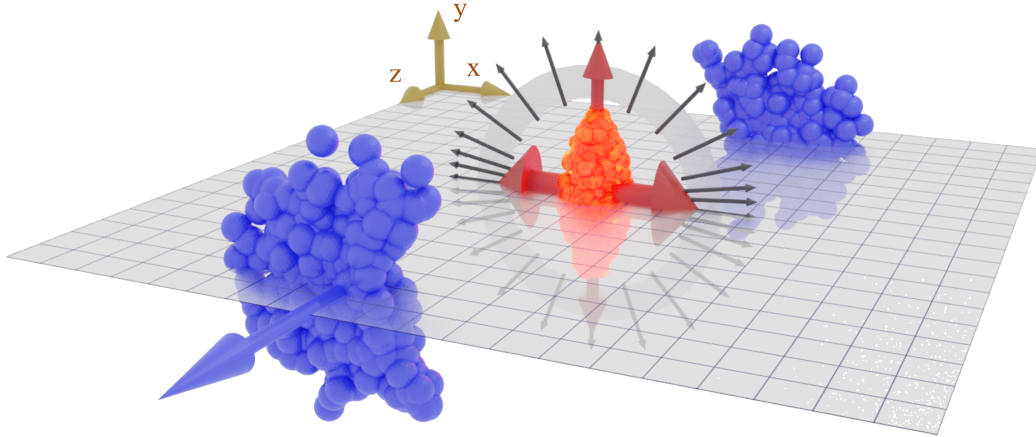


FIGURE 2.8: Interaction volume created after a non-central heavy-ion collision. The spatial anisotropy is transformed into anisotropy of momentum distribution of the produced particles. Picture from Ref. [32].

2.5.1 Reaction Plane

The reaction plane is a key concept in understanding the geometry and dynamics of heavy-ion collisions. It is defined by the impact vector of the colliding nuclei and the beam axis, typically aligned with the z -axis, along the direction of the nuclei's motion. The impact vector lies in the x - z plane as is shown in Fig. 2.8, establishing the spatial relationship between the two colliding nuclei. The orientation of the reaction plane plays a pivotal role in shaping the distribution and flow of particles produced in the collision. While distinct from the detector reference frame, which will be introduced later in Sec. 4.1, the reaction plane provides a consistent reference point or axis to analyze and understand patterns in how particles are distributed after the collision. These patterns are studied using "two-particle correlations" which are a key topic in the thesis.

For instance, the inhomogeneous direction or anisotropies of particle emission can indicate collective flow or jet structures. By extending these analyses to include additional variables, such as the relative angles or separations between particles, one can disentangle flow effects from other mechanisms of particle production. These concepts, along with the formal introduction of azimuthal angle (φ) and pseudorapidity (η), will be developed in detail in a later chapter. This section offers only a general overview of the reaction plane's relevance to the study at hand.

2.5.2 Anisotropic flow

Anisotropic flow refers to the momentum asymmetry observed in final-state particles, which is closely tied to the geometry of the collision in the transverse plane and how matter expands within it. The flow patterns reflect the energy and pressure gradients in the transverse plane caused by the non-centrality of the collision. The distribution of nucleons involved (N_{part}) is inhomogeneous in these collisions, generating spatial anisotropy primarily along the shortest axis of the interaction zone, which corresponds to the x-axis in the reaction plane. The interaction zone assumes an almond shape, as shown in Fig. 2.8, with higher energy density along the shortest axis. This leads to stronger pressure gradients in that direction, driving the expansion of the produced matter. As a result, the matter expands more rapidly along the shorter axis than along the longer axis.

The degree of anisotropy can be quantified through the use of Fourier coefficients, which serve to measure the extent of momentum asymmetry exhibited by the emitted particles. The emission of particles in heavy-ion collisions is characterized by the azimuthal angle, φ , relative to the reaction plane. The distribution of particles, $N(\varphi)$, as a function of the azimuthal angle can be expressed through a Fourier series [33]

$$N(\varphi) = N_0 \left(1 + \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_n)) \right). \quad (2.2)$$

Here, N_0 represents the average particle yield, Ψ_n corresponds to the orientation of the reaction plane of the n -th order in the xy -plane [34], and v_n are the Fourier coefficients that quantify the magnitude of the flow, as described below:

$$v_n = \int_0^{2\pi} \frac{dN}{d\varphi} \cos[n(\varphi - \Psi_n)] d\varphi = \langle \cos[n(\varphi - \Psi_n)] \rangle \quad (2.3)$$

The first-order coefficient, v_1 , represents directed flow, while the second-order coefficient, v_2 , corresponds to elliptic flow. The third-order coefficient, v_3 , is associated with triangular flow, with higher-order coefficients (v_4, v_5 , etc.) describing increasingly complex flow patterns. Figure 2.9 illustrates some examples of the overlap region based on IQCD calculations. The shape of the interaction volume is more intricate than the simple almond-shaped approximation, resulting in significant contributions from higher-order flow components.

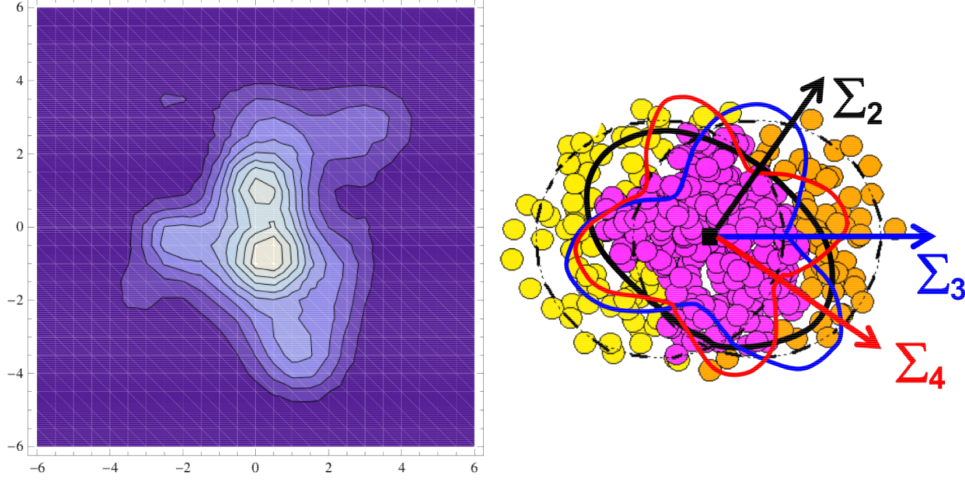


FIGURE 2.9: Left: The overlapping region obtained from IQCD computations. Picture from Ref. [35]. Right: The second, third and fourth cross-flow components. Picture from Ref. [36].

The study of flow is fundamental to this analysis, as the v_n coefficients play a significant role in modelling the correlation functions, giving rise to distinct, and often dominant, structures in the η - ϕ distribution, which will be introduced and discussed in Sec. 4.4.6. In particular, the effects of elliptical and radial flow are prominent. Radial flow is particularly important because elliptical flow, which is central to our study, represents a second order effect of radial flow, highlighting their interdependent relationship. In the following section, a detailed description of the most important flow components, which contribute to the angular correlation analysis, will be provided.

2.5.2.1 Directed flow

The directed flow (v_1) [37] represents the lateral movement of particles along the reaction plane and is produced in the pre-equilibrium phase of the collision. A schematic representation of the directed flow is shown in Fig. 2.10. This flow is fundamental to an understanding of the initial stages of the collision and the dynamics of nuclear matter, as it reflects the pressure gradients and transport properties that emerge immediately following the collision. The strength of the directed flow is connected to the impact parameter of the collision. In central collisions, where the impact parameter is nearly zero, the system exhibits a high degree of symmetry. Consequently, the pressure gradients are uniform in all directions within the reaction plane, leading to little or no directed flow. In contrast, in peripheral collisions, where the impact parameter is

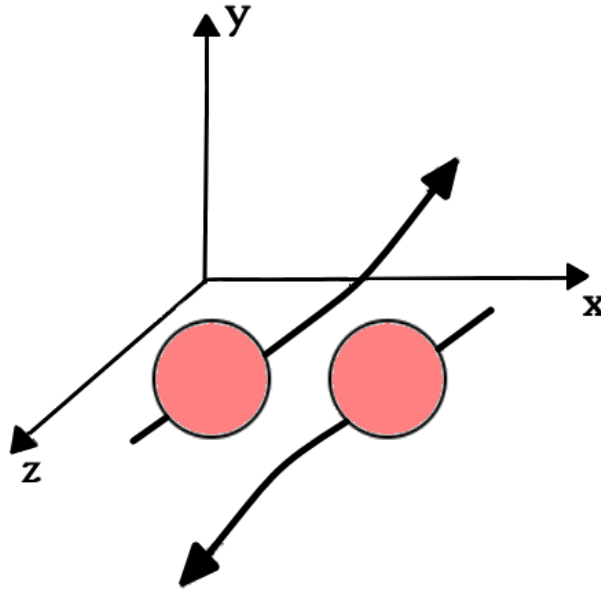


FIGURE 2.10: Schematic view of directed flow.

larger, the geometry of the system becomes asymmetrical. Here, the pressure gradients are strongest along the x -axis of the reaction plane, resulting in a pronounced directed flow.

The intensity of directed flow also varies with the energy of the collision. At lower energies, directed flow is more pronounced because emitted particles, such as protons and nuclear fragments, retain a strong correlation with the motion of the colliding nuclei. This motion is primarily along the x -axis, creating a significant asymmetry in the pressure gradients that drive particle flow. At high energies, such as those at the LHC, directed flow exhibits a characteristic pattern driven by collision symmetry. Particles emitted at forward and backward rapidities experience flow in opposite directions, resulting in a net zero-directed flow when integrated over a symmetric rapidity range. As the system rapidly transitions into a QGP, the directed flow approaches zero, while elliptic flow remains nonzero after integration and becomes more pronounced [38].

2.5.2.2 Elliptical flow

Elliptic flow (v_2) [39] represents an important observable in HIC, offering substantial insights into the collective behavior of the QGP. Indeed, the study of v_2 has suggested that the matter produced during QGP formation behaves like a nearly perfect fluid with very low viscosity. Hydrodynamic models that describe the evolution of the QGP

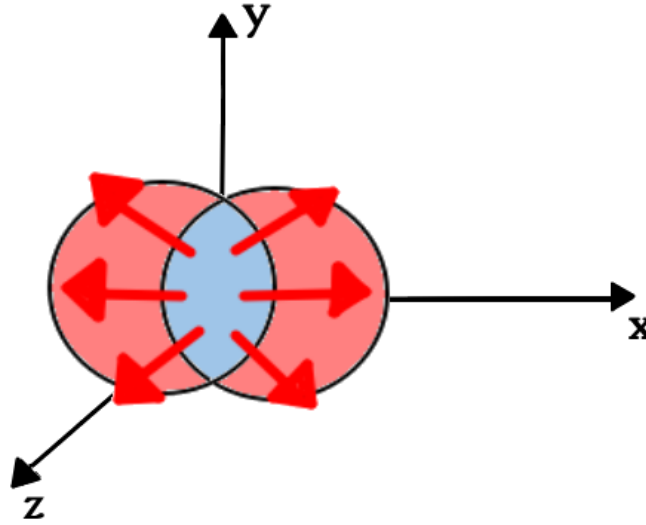


FIGURE 2.11: Schematic view of elliptic flow.

can successfully replicate elliptic flow [34, 40]. This indicates that the medium is highly efficient at converting spatial anisotropy into momentum anisotropy, see Fig. 2.11. Elliptic flow (v_2) is most pronounced in non-central collisions, where the overlap region between the colliding nuclei is highly asymmetrical. In contrast, in central collisions, the overlap region is nearly symmetric, resulting in a v_2 that approaches zero. This trend is illustrated in Fig. 2.12, which shows results from the ALICE Collaboration for Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 2.76$ TeV. The data, represented by the red filled and open squares, respectively, demonstrate the transition from minimal v_2 in central collisions to significantly higher values in non-central collisions. Notably, the nonzero elliptic flow observed even in central collisions is primarily driven by event-by-event fluctuations. Even when the impact parameter is zero, initial-state fluctuations can still generate a finite elliptic asymmetry.

When the colliding nuclei partially overlap, an almond-shaped region forms in the x-y plane, leading to anisotropic pressure gradients. This spatial anisotropy results in stronger pressure gradients along the short x-axis of the overlap region, causing a higher frequency of particle emissions in this direction. The outcome is the formation of an elliptic flow, characterized by an anisotropic momentum distribution. At the LHC, measurements from ALICE show that elliptic flow remains consistently positive because the collision remnants move away so rapidly that they have no significant influence on the interaction region.

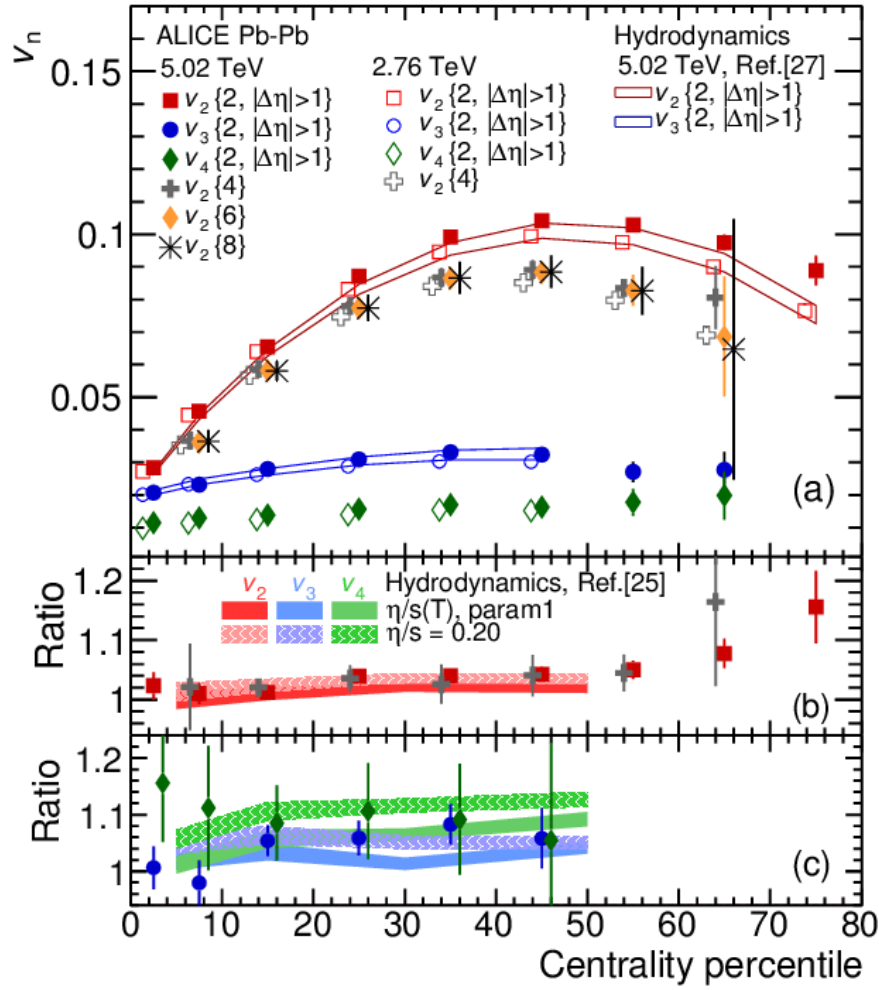


FIGURE 2.12: In the first panel: the anisotropic flow coefficients v_n are presented as a function of the centrality classes for the $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV Pb–Pb collisions. In the second panel the ratios of v_n for these two energies are shown. In the last panel, various predictions from hydrodynamical models are also presented for comparison. Picture from Ref. [41].

2.5.2.3 Radial flow

Radial flow [42] is a collective movement of matter away from the center of the collision in the transverse directions, see Fig. 2.13. The intense pressure gradient that is formed following the collision is responsible for driving the expansion, which in turn results in an increase in the transverse momentum (p_T) of the particles. The push is more pronounced for heavier particles, such as protons and kaons than for lighter particles, such as pions, due to the additional velocity imparted to these particles by the

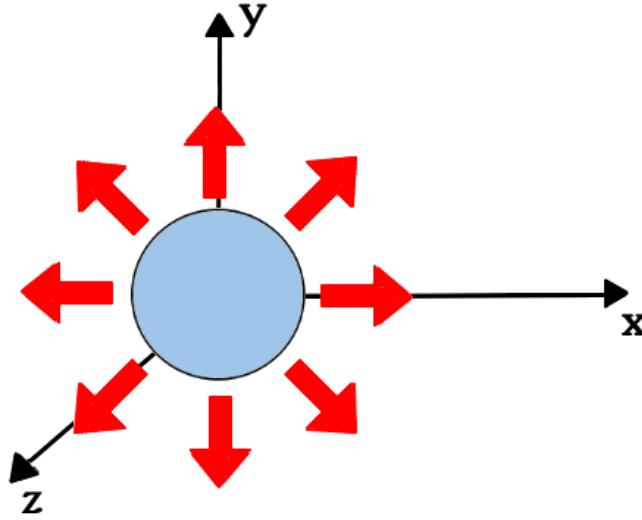


FIGURE 2.13: Schematic view of radial flow.

collective flow, which superimposes upon their thermal motion. This behavior is reflective of the nature of the collective expansion, whereby particles with greater mass receive a more significant boost from the hydrodynamic expansion of the system. In experiments such as those conducted at RHIC and the LHC, radial flow is analyzed by examining the transverse momentum distributions of particles produced in collisions [43, 44]. By fitting these spectra to hydrodynamic models, researchers are able to extract information about the speed of the radial expansion and its evolution during the collision. A strong radial flow signal is indicative of a rapid thermodynamic transformation and expansion of the matter produced, providing key information on the dynamics of the QGP and the nature of the phase transition back to hadronic matter as the system cools.

2.6 Are Collective Phenomena Present in Small Systems?

2.6.1 The role of pp and p-Pb in respect to Pb-Pb collision

In large systems such as Pb-Pb or Au-Au collisions, the high density of interacting nucleons allows for the emergence of collective behavior, a defining characteristic of the QGP. This state of matter behaves as an almost perfect fluid with near-zero viscosity. However, it was long believed that small systems, like pp [45], p-Pb [46, 47, 48], d-Au [49] at LHC and RHIC, could not produce such a medium or exhibit collective

effects due to their limited size. Small systems were thought to lack the conditions necessary for QGP formation or the emergence of collective behavior, which is typically associated with larger, more complex interactions.

One of the most attractive questions in nuclear physics over the past decades has been whether collective phenomena, similar to those observed in large-scale heavy-ion collisions, can emerge in small systems. This question arises from the fact that models originally developed to describe heavy-ion collisions, such as EPOS LHC, DPMJET and AMPT (see Sec 3.2.2, 3.2.3 and 3.2.5), were surprisingly successful when applied to small systems. These models, initially aimed at providing insights into QGP formation and collective effects in Pb–Pb collisions, managed to describe experimental data from smaller systems as well [50, 51, 52, 53, 54]. Recent experimental results at the LHC and RHIC have uncovered evidence of collective behavior in smaller systems [55], notably the "ridge" structure, which displays unexpected long-range correlations. This phenomenon will be discussed in detailed in Sec. 4.4.7. Some theories suggest that it arises from initial-state effects, such as gluon saturation [56], which could create these long-range correlations before the actual collision occurs. Other perspectives point to final-state effects, such as hydrodynamic flow, as potential explanations for the ridge's appearance.

Regardless of its origin, observing the ridge in small systems has fundamentally shifted our understanding. It challenges the notion that collective behavior is exclusive to large systems and opens new theoretical pathways to explore the dynamics of smaller collisions. Once considered simple benchmarks for validating heavy-ion collision data, small systems are now recognized as valuable environments for studying the emergence of collective phenomena across different system sizes. These findings suggest that small-systems physics may contain key insights for the larger understanding of QGP and collective behavior, encouraging a reconsideration of the boundaries between small and large collision systems in nuclear physics.

One of the main goals of this study is to see how collective effects, which are seen in large heavy-ion collisions, appear in smaller collision systems like pp and p–Pb. By using the two-particle correlation functions studies and looking at different levels of particle multiplicity, one can learn how these effects change as the number of particles in the collision changes. This will help to understand the differences between collisions where most of the energy is concentrated in a few particles versus those where the energy is spread out across many particles.

Chapter 3

Monte Carlo Event Generators: Simulating the Journey from Hard Scatter to Detector

A Monte Carlo event generator is a fundamental computational tool in high-energy physics, used to simulate particle collisions. These simulations are essential for making theoretical predictions and for interpreting experimental results. Using random sampling, event generators model the complex interactions that occur when high-energy particles collide, including processes governed by QCD and electroweak theory. Figure 3.1 illustrates a typical structure of pp collision in Monte Carlo event generators. Each color corresponds to a specific stage involved in the simulation. The hard scattering process is the starting point, in which a large momentum is transferred. The term “hard” refers to the high momentum transfer involved, which allows for a perturbative treatment of the interaction, making it possible to compute cross-sections using the methods of pQCD. The hard scattering results in a more interesting event generation stage when the incoming and outgoing partons involved in the hard scattering generate the **parton shower**. This is a sequential step-by-step process that is formulated as an evolution in momentum transfer scale. How partons are distributed is described by parton distribution functions (PDFs) that represent the probability densities to find a parton carrying a momentum fraction x at a squared energy scale Q^2 [58]. The parton shower evolves through successive branching processes, where each parton can split into two or more lower-energy partons, continuing the shower until the partons reach a lower energy threshold. At this point, the perturbative phase ends, and the partons transition to a non-perturbative phase, where they undergo hadronization forming stable hadrons such as protons, neutrons, and pions [59]. The transition

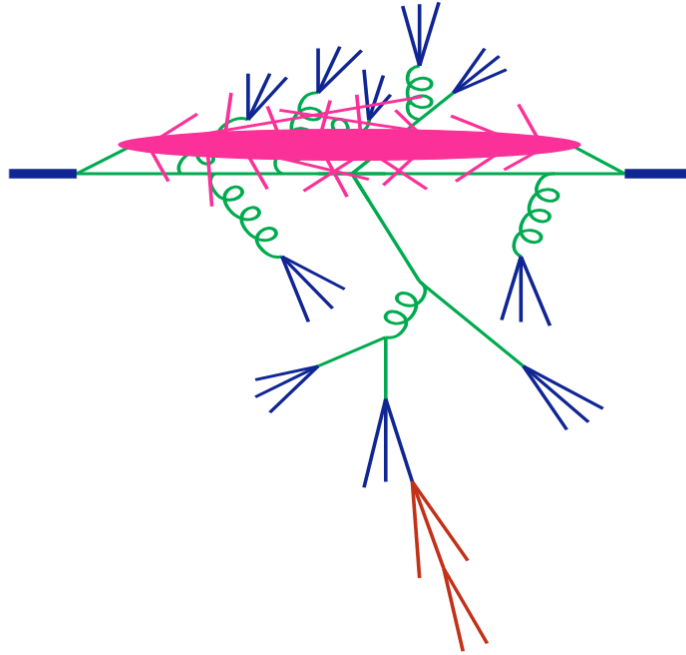


FIGURE 3.1: Illustration of a proton–proton collision in a typical Monte Carlo event generator. Each color corresponds to different stages involved in event generation. Picture from Ref. [57].

from the perturbative to the non-perturbative phase marks the beginning of [hadronization](#), where partons combine to form stable hadrons such as protons, neutrons, and pions [59]. Due to the confinement property of QCD, quarks and gluons cannot exist in isolation. Instead, they form bound states through mechanisms described by phenomenological models. Two widely used models for hadronization are the string model (implemented in PYTHIA) and the cluster model (used in HERWIG) [60]. However, hadronization is not the only complexity in the collision. During the collision, the protons appear to be flattened into extremely thin pancakes due to Lorentz contraction as they move at near-light speeds. The actual collision occurs when these flattened discs overlap completely in space-time. While the hard scattering dominates the event, this overlap creates a high probability of additional interactions beyond the primary scattering. These secondary interactions between the remnants of the colliding protons give rise to the [underlying event](#) [57]. Underlying events refer to all activities not included in the hard scattering. They are associated with effects such as Multi-Parton Interactions (MPI), where additional parton–parton scatterings occur; initial-

and final-state radiation, which involves soft products emitted before and after the collision; and "beam–beam remnants," which are *what remains after a parton is knocked out of each of the initial two beam hadrons* [61]. The last stage of the simulation is about the fact that many hadrons produced are inherently **unstable particles** which decay into lighter particles. This process is vital for analyzing the final state of particle interactions, as most of the particles observed in experiments are decay products rather than the initially produced hadrons. Event generators simulate these decay processes by sampling branching ratios and known lifetimes from comprehensive resources such as the Particle Data Group review [62]. Each particle has a distinct life time that determines its existence before decay. The decay occurs following the principles of quantum mechanics. It is subject to conservation laws, including energy, momentum, angular momentum, and quantum numbers such as charge, baryon number, and lepton number. Monte Carlo simulations accurately model these decay processes, which are crucial for fully understanding the event signature, identifying specific particle interactions, and investigating potential new physics phenomena within the experimental data.

This study utilizes several Monte Carlo event generators to compare their predictions with experimental data. Before delving into an overview of the specific models used in the analysis, a detailed explanation of string fragmentation—a key mechanism for modeling hadronization—is provided. String fragmentation is a fundamental component of many generators employed in this study, including PYTHIA, HIJING, EPOS, and the default version of AMPT. Given its critical role in these models, a thorough understanding is essential.

3.1 String fragmentation

The production of quarks in a collision is accompanied by the formation of a string structure, representing the color flux stretched between the initial $q\bar{q}$, which is connected by the action of gluon fields.

When the quark–antiquark pair moves away, the energy stored in the string increases due to the strong force, with the binding potential dominated by the linear term $V(r) \approx kr$. Ultimately, the string elongates until it becomes unstable and disintegrates, resulting in the formation of new $q\bar{q} \rightarrow q\bar{q}' + q'\bar{q}$ pairs from the vacuum, which in turn leads to the creation of hadrons. This process is repeated until the available energy is exhausted, at which point the system stabilizes as a collection of hadrons. Nevertheless, this process is not a simple one in the case of baryons, which are particles

composed of three quarks. These dynamics are captured using a space-time diagram [63] as is illustrated in Fig. 3.2. At time $t = 0$, the quarks are initially close, sharing a kinetic energy $E_k = \sqrt{s}$. As they move apart, their kinetic energy is gradually converted into potential energy $E_p = k\Delta x$, reaching its maximum at $t = \sqrt{s}/2k$. At this point, the quarks reverse direction and begin to move toward each other, eventually reaching $t = \sqrt{s}/k$ when they meet but move in opposite directions. This back-and-forth motion, or "yo-yo" effect, has a period $\tau = 2\sqrt{s}/k$. During this oscillation, when the energy is sufficiently high, new qq or $\bar{q}\bar{q}$ pairs may form along the string. If the initial energy is large enough, the string can break multiple times, creating additional strings. These successive string breakings can be represented in a space-time diagram illustrated in Fig. 3.3, where the string is fragmented into various hadrons.

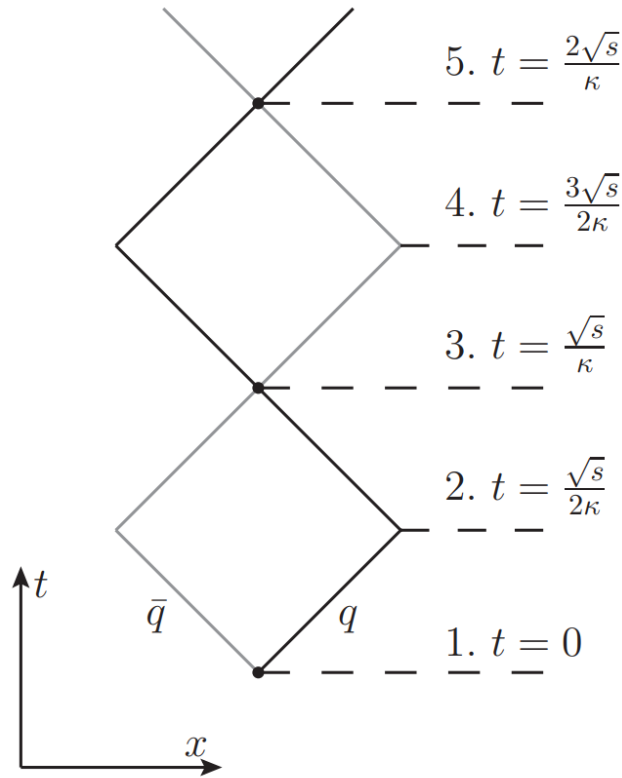


FIGURE 3.2: Space-time diagram of $q\bar{q}$ pair in their rest frame. 1) Beginning of the evolution; 2) 1/4 of full period, maximum tension in the string; 3) q and $\bar{q}$ are back to their initial positions, but have their momenta swapped; 4) 3/4 of full period, maximum tension in the string; 5) full period, the system is back to its initial state. Picture from Ref. [64].

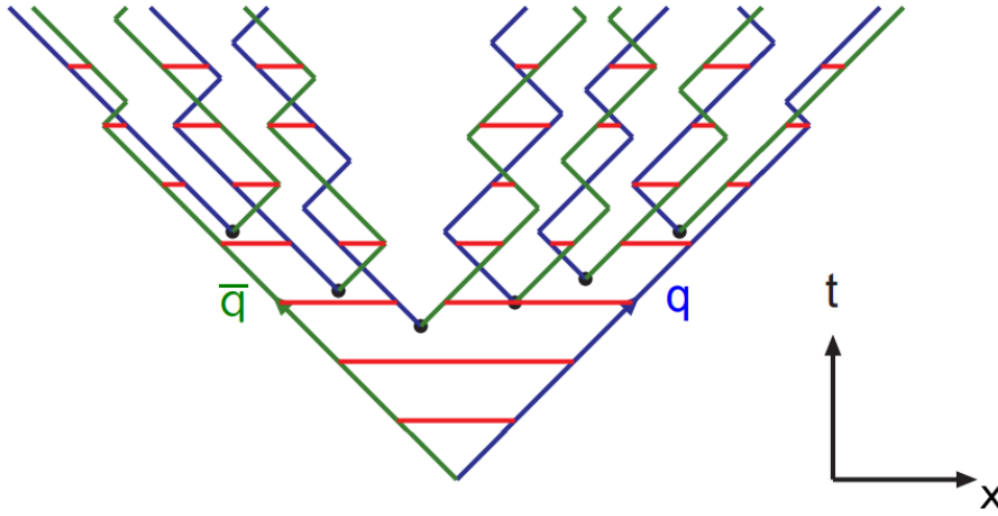


FIGURE 3.3: $q\bar{q}$ system in its rest frame with multiple string breakings. Picture from Ref. [64].

When we take into account pp collisions, the fragmentation picture becomes more complicated since multiple partons from the colliding protons participate in the reaction. This leads to two phenomena called multiparton interactions and colour reconnections.

3.1.1 Multiparton interactions and colour reconnections

In hadronic collisions, multiple parton scatterings lead to the creation of coloured particles in both the initial and final states. A simple model assumes these scatterings occur independently, contributing equally to the momentum distribution and multiplicity of final state hadrons. However, it was shown that the average transverse momentum increases with particle multiplicity, indicating a more complex collective behavior in the hadronization stage, where partons from different scatterings become correlated. The concept of colour rearrangement (CR) is used to explain how the multiple scattering of partons in hadronic collisions affects particle production [65]. Partons interact and, after each interaction, form color strings between the scattered partons and the remaining hadron remnants. These color strings break and produce new hadrons. In other words, the partons are connected by "color" forces, and when these forces break, they create new particles. When multiple dispersions occur in a single collision, the chromatic connections of these different dispersions can be reorganized. Instead of

producing completely new sets of hadrons for each scattering, the chromatic connections of successive scatterings are connected to the previous ones. This reduces the number of low-energy soft hadrons produced by each additional scattering but still allows the transverse momentum (the momentum perpendicular to the collision axis) to increase. This explains why the number of particles increases, but the transverse momentum also increases when more scattering occurs.

This QCD-CR model, which influences jet shapes and particle mass reconstructions, has been introduced in event generators such as the Pythia model. In the standard configuration of PYTHIA, baryons are created through the formation of diquark pairs along the string using the diquark model [66], while this model includes the possibility for junction formation, adding an additional mechanism for baryon creation [65]. Junctions can be formed by two dipoles reconnecting into a junction–anti-junction pair connected by a new colour line as in Fig. 3.4b, or by three dipoles reconnecting to separate junction—anti-junction systems as in Fig. 3.4c. This refined understanding helps

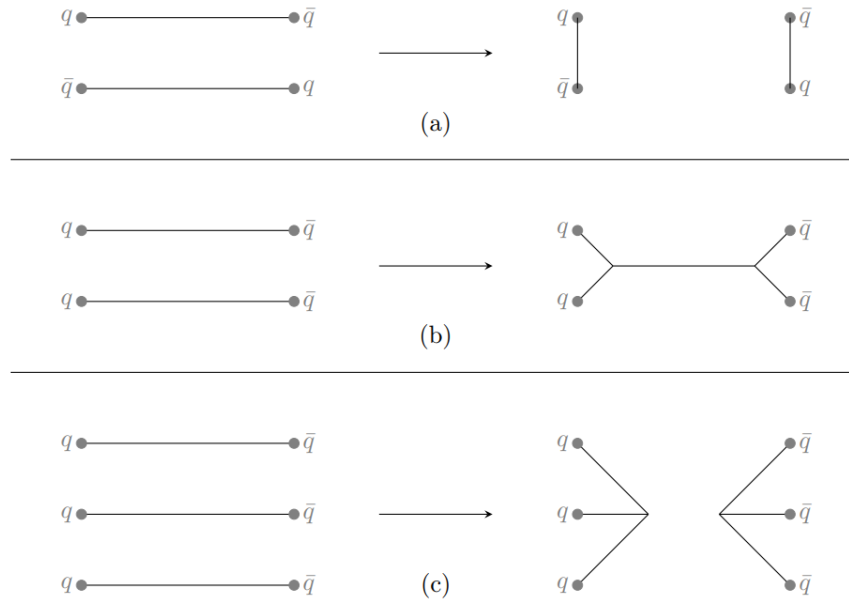


FIGURE 3.4: Two dipoles and three dipoles CR possibilities. For two dipoles, they can either have (a) a simple reconnection (a.k.a. a swing) or (b) a formation of a connected junction and anti-junction system. Three dipoles can form (c) disconnected junction and anti-junction systems. Picture from Ref. [65].

explain hadronization, jet formation, and transverse momentum distributions in complex particle collisions. In PYTHIA8, colour reconnections are included in the default

configuration.

3.2 The MC event generators

This section will give a general overview of the models used in this thesis, describing their main components and their use in high-energy collisions.

3.2.1 PYTHIA

PYTHIA, short for "Python for Heavy Ion Collisions," is a widely-used event generator in high-energy physics, specifically designed to simulate particle collisions, such as proton-proton interactions. Originally developed by Torbjörn Sjöstrand and collaborators, the latest version, PYTHIA 8, represents a significant advancement over its predecessors [67]. A key feature of PYTHIA 8 is its implementation of Lund's string model [68] for simulating the hadronization process. This model describes the formation of color-connected strings between partons, which subsequently fragment into observable particles, as detailed in Sec. 3.1. PYTHIA 8 integrates pQCD for modeling hard scatterings with phenomenologically motivated approaches for soft hadronic interactions, crucial for simulating the UE.

An important feature of PYTHIA 8 is its ability to simulate minijets, which are defined as collimated sprays of particles produced by hard scatterings in high-energy collisions, typically arising from pQCD processes in the early stages of the collision. These minijets are influenced by the UE and soft particle production due to their relatively low energy. In this analysis, minijets are one of the primary phenomena responsible for generating the shape of the correlation function, a feature that will be explored in more detail in the next chapter. The presence of minijets is expected to be observable when comparing theoretical predictions with experimental data, as demonstrated in the results presented in Secs. 8.1.3 and 8.2.3 for pp collisions at $\sqrt{s} = 13$ TeV.

Another significant strength of PYTHIA 8 is its ability to simulate photon radiation in both the initial and final states, which is crucial for processes such as jet production and lepton scattering. By accurately accounting for these contributions, PYTHIA 8 ensures a realistic representation of event structures, facilitating direct comparisons with experimental observations.

3.2.2 EPOS

EPOS stands for Energy Parton Off-Shell which includes the Energy conserving quantum mechanical multiple scattering approaches, based on **P**artons (parton ladders), **O**ff-shell remnants, and **S**plitting of parton ladders. Figure 3.5 illustrates the various components produced through parton-parton scattering.

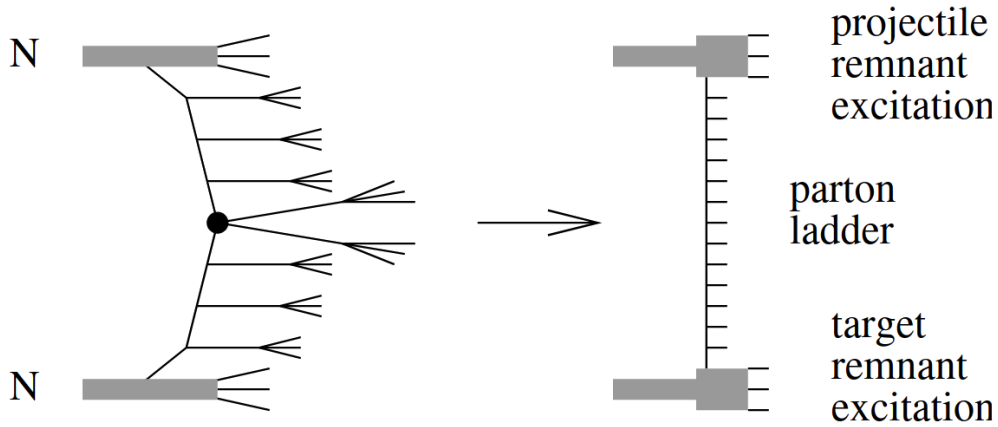


FIGURE 3.5: Elementary parton-parton scattering: hard scattering in the medium is preceded by the emission of partons (initial-state space cascade); these ladder partons, being usually off-shell, emit other partons ladder (final-state time cascade). The complete picture, also includes remnants that are an important source of particle production. Picture from Ref. [69].

A widely used version, EPOS LHC, was specifically developed to model the dynamics of collisions at the LHC. This model is renowned for its ability to reproduce collective phenomena, such as flow, typically observed in large systems like heavy-ion collisions, but which have also been seen in smaller systems such as pp and p-Pb interactions at LHC energies [70]. A key feature that enables EPOS LHC to simulate these effects is its *core-corona* approach. This differentiates between two regions of the collision: the dense, central *core*, where particles are produced through collective hydrodynamic processes, and the more diffuse *corona*, where particle production is governed by non-collective interactions similar to those in pp collisions. The core represents the part of the system where the energy density is high enough to drive hydrodynamic expansion, while the corona involves more standard parton scatterings and hadronization. This division allows EPOS LHC to realistically model both the collective properties of the

event and the more isolated particle interactions outside the core, enabling it to match a broad range of experimental data [71]. Additionally, EPOS LHC incorporates the effects of MPI and integrates collective dynamics within the MPI framework. This allows the model to better simulate soft processes and the underlying event, which is critical for accurately describing particle production in small collision systems at the LHC. Another key component is the model's use of 3D hydrodynamic evolution to simulate the behavior of bulk matter produced in collisions. This hydrodynamic approach is essential for explaining the anisotropic flow patterns and collective motion observed in final-state particle distributions. By including hydrodynamics, EPOS LHC successfully reproduces the unexpected flow effects seen in smaller systems like p-Pb collisions at the LHC¹ [52]. In practical terms, EPOS LHC has been widely used for simulating pp collisions, providing a comprehensive description of particle production, jet formation, and the structure of the underlying event. It has also played an important role in understanding p-Pb collisions, giving valuable insights into the interaction between collective flow effects and hard scattering processes. EPOS LHC's ability to describe phenomena such as ridge structures and flow behavior, which are typically expected in large systems, underscores its versatility and predictive power. Furthermore, the model has been applied to heavy-ion collisions (e.g., Pb-Pb), where its hydrodynamic modeling and core-corona structure have proven effective in explaining key bulk observables such as elliptic flow [69].

This versatility and precision make EPOS LHC an essential tool for high-energy physics research, allowing for deeper insights into the physics of particle interactions at the LHC and providing agreement with experimental data.

In the context of this work, EPOS is an important model for comparing results from pp collisions at $\sqrt{s} = 13$ TeV and p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. With its physical foundations, one expects that the EPOS model can reproduce the minijet structure in the angular correlations and is particularly useful for studying collective phenomena in small systems, such as flow and ridge structures. More details on the results from these comparisons are provided in Secs. 8.1.3, 8.2.3, and 8.3.4.

¹The models successfully reproduce collective phenomena even in small systems, which can sometimes lead to confusion when trying to understand the underlying dynamics.

3.2.3 DPMJET

The DPMJET (Dual Parton Model Jet) event generator is a used tool for simulating high-energy hadronic and nuclear collisions, including those at the LHC. The Dual Parton Model (DPM) provides the theoretical foundation for this event generator, which employs concepts from Regge theory² and QCD postulating the exchange of Pomerons³, that lead to the creation of parton ladders between colliding particles. The DPMJET event generator has been designed to model a wide variety of phenomena, including both soft and hard scattering processes, MPI, particle fragmentation, and jet production. The processes of soft and hard scattering are described by both non-perturbative and perturbative QCD processes. In the majority of collisions with low momentum transfer, soft scattering is the dominant process. In contrast, hard processes are characterized by higher momentum transfer and are responsible for the production of jets and high-energy phenomena, including the creation of heavy quarks. Additionally, the model incorporates MPI, which occurs within a single collision. These contribute to the underlying event and result in higher particle multiplicities. Subsequently, DPMJET simulates hadronization. The model employs the string fragmentation mechanism, which is similar to that used by PYTHIA, see Sec. 3.1. This process is critical for accurately modeling the final state of the collision and for understanding phenomena such as jet formation, whereby high-energy quarks and gluons fragment into collimated sprays of hadrons [72].

The DPMJET event generator is employed in this study for comparison with the results from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. By analyzing the phenomena simulated in the model, a better understanding of minijet structures, long-range correlations, and the ridge structure associated with Pomeron exchange is achieved, which are fundamental to the underlying physics in p–Pb collisions. These various contributions combine to produce a correlation structure that one can expect from the experimental data, which is essential for understanding particle production and jet formation in high-energy collisions. A detailed comparison is provided in Sec. 8.3.4.

²Regge theory is a framework in particle physics that describes the behavior of scattering amplitudes at high energies by associating them with the exchange of trajectories, called Regge trajectories, which relate the angular momentum of particles to their mass.

³A Pomeron is a theoretical concept in particle physics that models the exchange of a color-neutral gluon combination, explaining soft and diffractive scattering in high-energy hadron collisions.

3.2.4 HIJING

The Monte Carlo Heavy-Ion Jet Interaction Generator (HIJING) model was developed to study the initial phase of high-energy nucleon-nucleon, nucleus-nucleus, and nucleon-nucleus collisions [73, 74, 75]. An essential feature of the HIJING model is its approach to the treatment of soft interactions, which is based on the diquark-quark string model with the incorporation of gluon fields. The model also incorporates the production of mini-jets using a pQCD approach, following the framework of the PYTHIA model, which includes both initial and final state radiation. This radiation describes the emission of gluons or photons by partons before and after the hard scattering event, respectively. Another important aspect of HIJING is its ability to model nuclear shadowing, which occurs when the parton distribution functions inside a nucleus are modified compared to those in a single proton or neutron. This phenomenon helps researchers understand how nearby nucleons in a nucleus influence the behavior of partons, particularly at high energies. HIJING's shadowing model is especially useful for studying how these modifications affect particle production, with a focus on gluons, which dominate at high energy densities. Furthermore, HIJING allows researchers to investigate jet quenching, which refers to the loss of energy by partons as they traverse the hot and dense quark-gluon plasma (QGP), as discussed in Sec. 4.4.2.2.

Although the HIJING model does not include a hydrodynamic description of collective phenomena in heavy-ion collisions, it is primarily employed in this work to describe minijet production in Pb–Pb collision systems. A discrepancy is anticipated, given that flow patterns, which are the dominant feature in Pb–Pb collisions, are not captured by this model. The results of comparing the HIJING model with experimental data are presented in Sec. 9.1.4.

3.2.5 AMPT

The A Multi-Phase Transport (AMPT) model is a computational framework used to simulate pp, p–A, and A–A systems. This model plays a significant role in understanding the underlying dynamics of these collisions by providing a detailed description of both partonic and hadronic interactions throughout the entire process. The AMPT model [76, 77, 78] is comprised of several essential elements. In the initial stage, the model generates partons using the HIJING model, which describes the initial production of particles through a combination of hard and soft QCD processes. Subsequently, the parton phase is simulated using Zhang's Parton Cascade (ZPC) model

which employs pQCD-derived cross-sections to model the dispersion between partons. As the system cools, the partons undergo hadronization, which can be modeled through string fragmentation in the default AMPT model or parton coalescence in the string-melting version [78] as is shown in Fig. 3.6. In the default AMPT, the fragmen-

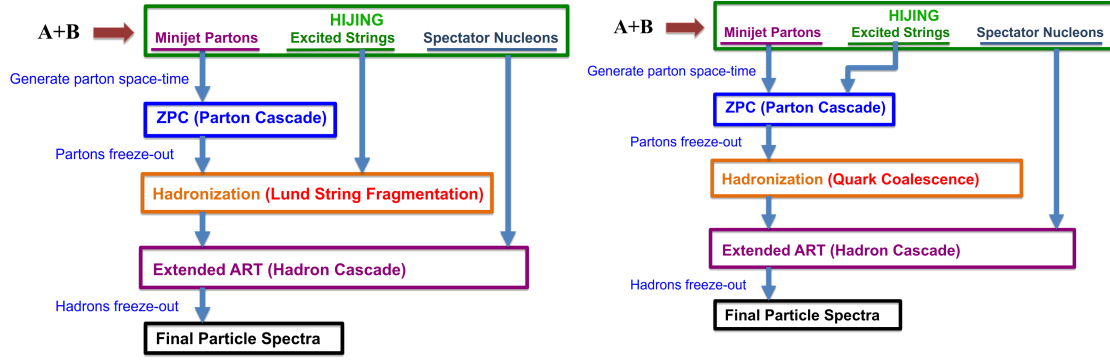


FIGURE 3.6: On the left, a schematic overview of the AMPT model in its default configuration, and on the right, the string melting version. In the default mode, hadronization is modeled using the Lund string fragmentation mechanism, where strings formed after parton scattering fragment into hadrons. In contrast, the string melting version converts all excited strings into partons, and hadronization proceeds via parton recombination (coalescence), where nearby partons combine to form hadrons based on their spatial and momentum proximity.

tation occurs by the Lund model (see Sec. 3.1), as observed in PYTHIA [59] or HIJING [73]. In the context of parton coalescence, the hadronization mechanism is initiated when quarks and antiquarks fuse to form hadrons after the partonic phase is completed in a high-energy nuclear collision. This process differs from string fragmentation in that coalescence assumes that quarks in the deconfined QGP directly recombine to produce hadrons based on their proximity in phase space (i.e., how close they are in position and momentum space). The AMPT model has been developed to study large systems. In such systems, the string-melting version of AMPT is frequently employed to describe the behavior of partons as they interact and eventually coalesce into hadrons. This process is of critical importance for the understanding of the properties of the QGP. The model has been particularly effective in reproducing collective flow phenomena, such as elliptic flow, and offering significant insights into jet quenching and partonic energy loss, which occur when high-energy partons traverse the dense medium created in these collisions [79]. Furthermore, the AMPT model is employed in smaller systems, such as pp and p-Pb collisions, to serve as a foundation for comprehending collective behavior in nuclear collisions. It has been demonstrated that

collective flow phenomena can manifest in smaller systems under specific conditions. p–A collisions offer a unique opportunity for researchers to investigate the influence of nuclear matter on particle production and parton interactions. The AMPT model is a valuable tool for studying medium effects, such as nuclear shadowing and parton energy loss, in these collisions. Additionally, the model can be used to investigate whether collective phenomena, analogous to those observed in larger systems, occur in intermediate-size systems, which can provide insights into the transition between pp and A–A dynamics.

Given that AMPT is a comprehensive event generator capable of reproducing a wide range of phenomena in the correlation function space, it is employed in this thesis to simulate the correlation function in Pb–Pb collisions. The model effectively captures minijet structures and flow patterns, with expected agreement, as will be discussed in detail in Sec. 9.1.4.

3.2.6 CALM model

The CALM model ("ConservAtion Laws Model") [80] is a Monte Carlo event generator developed in C++ using the ROOT framework [81]. Originally designed to study how conservation laws manifest in angular correlation functions (discussed further in Sec. 4.4.1), the model's application was later extended to simulate and analyze minijets.

Unlike previous models, which incorporate numerous physical effects that can influence the correlation functions, the CALM model is intentionally minimalist. Its simplicity allows for a better understanding of the fundamental contributions of conservation laws alone. By isolating these effects, the CALM model provides insight into what should be expected in the angular correlation functions when only conservation laws are at play.

The event generation process in CALM is underpinned by the GENBOD algorithm [82], a widely used N-body Monte Carlo generator that computes the phase-space distribution of particles. GENBOD operates under the constraints of global energy and momentum conservation, making it a powerful tool for simulating particle interactions. In the CALM model, the user specifies key parameters such as the total event multiplicity, the masses of the particles to be produced, and the total energy available for distribution. GENBOD then generates the four-momenta of the particles, ensuring that all events adhere strictly to conservation laws.

In addition to standard event generation, the CALM model is used to simulate minijets, which are compact sprays of particles moving in a collimated direction. Minijets in CALM are always produced in pairs, reflecting the back-to-back jet production commonly observed in particle collisions. Each minijet contains at least two particles, with GENBOD invoked separately to generate the particles within each jet.

By focusing exclusively on conservation laws, the CALM model provides a streamlined yet effective framework for studying angular correlations and the structural properties of minijets. Its ability to isolate the effects of conservation laws makes it a valuable tool for understanding these phenomena. For further details, see Ref. [80], [83].

Chapter 4

Two-particle Angular correlations

Angular correlations between two particles represent a fundamental tool in high-energy physics, offering insights into the mechanisms of particle production, collective behavior in heavy-ion collisions, and the properties of the QGP formed under extreme conditions.

4.1 Reference frame

To describe two-particle angular correlations and related observables, it is essential to define a reference frame. This frame provides a coordinate system in which the motion and interactions of particles can be described with respect to specific axes. In particle physics experiments, the reference frame is typically chosen based on the experimental setup or the direction of the particle beams. For the ALICE detector at the LHC, as detailed in Sec. 6.1, the laboratory frame is employed. This frame is aligned with the beam axis (the z -axis), reflecting the direction of the incoming beams and providing a natural reference for the experiment. In this frame, the z -axis corresponds to the beam direction, while the x - and y -axes define the transverse plane, which is perpendicular to the beam axis. The longitudinal motion of particles is characterized along the z -axis, while their transverse motion is described within the x - y plane. The ALICE detector utilizes this frame to track the trajectories of charged particles. The magnetic field in the detector bends the particle tracks within the transverse plane, enabling the measurement of (p_T) .

In studies of two-particle correlations, the relative pseudorapidity ($\Delta\eta$) or rapidity (Δy) and the relative azimuthal angle ($\Delta\phi$) between the two particles are commonly

used. Pseudorapidity (η) quantifies the longitudinal separation of particles with respect to the beam axis, while transverse momentum and the azimuthal angle (ϕ) describe the particle's motion in the transverse plane. By measuring the differences in η (or y) and ϕ , two-dimensional correlation functions can be constructed.

4.2 Observables

4.2.1 Pseudorapidity

Pseudorapidity (η) is a commonly used variable in high-energy physics to describe the angle of a particle relative to the beam axis. It is defined as:

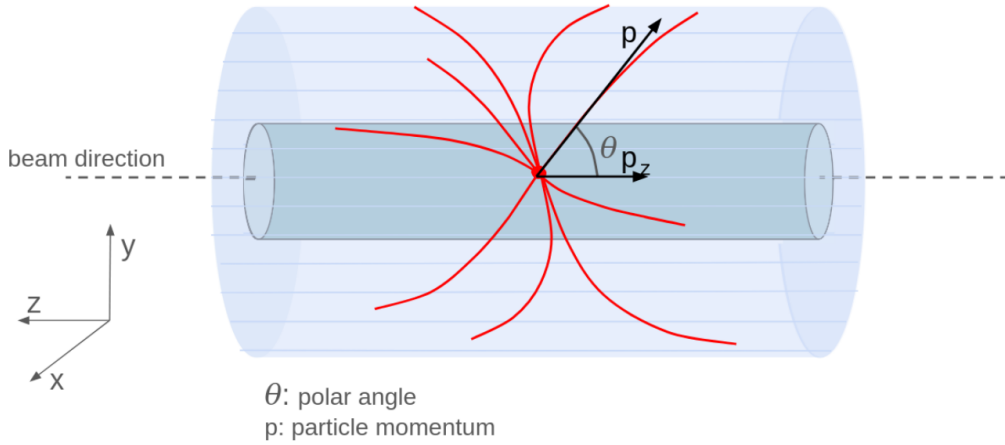


FIGURE 4.1: Illustration of the polar angle θ between the momenta of the particles, which are deflected by the magnetic field of the detector, and the beam axis. Credits to Wioleta Rzęsa.

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (4.1)$$

where θ is the polar angle, which is the angle between the particle's momentum and the beam axis, as illustrated in Fig. 4.1. This figure specifically depicts the polar angle in the ALICE detector, where the trajectory of the tracks are influenced by the magnetic field of the detector. The difference in pseudorapidity, $\Delta\eta = \eta_1 - \eta_2$, represents the longitudinal separation between two particles.

4.2.2 Rapidity

Rapidity (y) is another essential observable, particularly in systems where longitudinal motion plays a significant role. It is preferred for studying angular correlations between particles in relativistic collisions due to its precise incorporation of particle kinematics. Defined as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z c}{E - p_z c} \right) \quad (4.2)$$

where E is the energy and p_z is the longitudinal momentum along the beam axis. The difference in rapidity, $\Delta y = y_1 - y_2$, provides a way to analyze the momentum space separation between two particles and is particularly useful in identifying collective behaviors, such as flow.

In the context of the complex phenomena observed in high-energy collisions at the LHC, pseudorapidity (η) has become a crucial variable in hadron collision experiments. Its primary advantage lies in its simplicity, as it can be easily determined from the angle of the particle relative to the beam axis.

However, in this thesis, where kinetic observables are available thanks to the ALICE detector's ability to identify particles, more precise variables such as rapidity are employed. The Lorentz-invariant nature of rapidity with respect to boosts along the beam direction ensures consistency across different reference frames, making it particularly well-suited for particles with significant masses. In the high-energy regime, where the particle masses become negligible, rapidity closely approximates pseudorapidity ($y \approx \eta$).

4.2.3 Azimuthal Angle

The azimuthal angle (φ) is the angle in the plane perpendicular to the beam direction (transverse plane), typically measured relative to the x-axis, which is the horizontal axis, as is shown in Fig. 4.2. The difference in azimuthal angle between two particles is calculated as $\Delta \varphi = \varphi_1 - \varphi_2$.

4.3 The $\Delta y \Delta \varphi$ two-particle angular correlation

In high-energy particle physics, angular correlations provide a crucial tool for understanding the underlying dynamics of particle interactions. By analyzing the angular

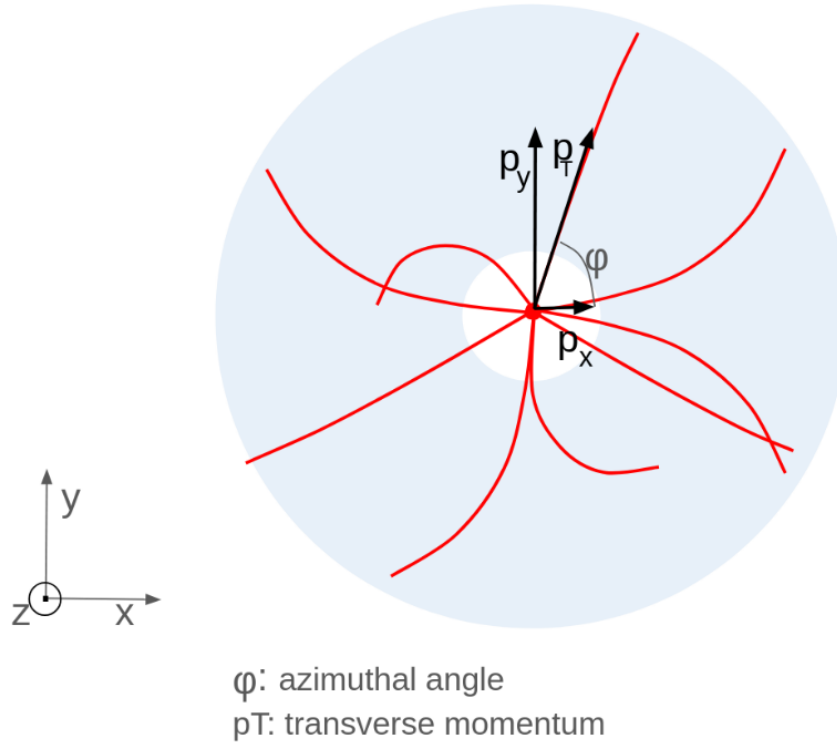


FIGURE 4.2: Schematic view of the azimuthal angle. Credits to Wioleta Rzęsa.

distribution of particles in relation to each other, one can investigate various properties of the collision process, such as the relative momentum and geometry of the produced particles. In this thesis, the correlation functions are computed in the $\Delta y \Delta \varphi$ angular space. These angular correlations can be used to explore a range of phenomena, such as particle production mechanisms, flow patterns, and medium effects, which will be discussed in detail later.

The two-particle correlation function $C(y_1, \varphi_1, y_2, \varphi_2)$ can be expressed as:

$$C(y_1, \varphi_1, y_2, \varphi_2) = \frac{P_{12}(y_1, \varphi_1, y_2, \varphi_2)}{P_1(y_1, \varphi_1)P_2(y_2, \varphi_2)}. \quad (4.3)$$

Here, $P_{12}(y_1, \varphi_1, y_2, \varphi_2)$ represents the probability of finding two particles with pseudorapidities y_1 and y_2 , and azimuthal angles φ_1 and φ_2 . The $P_1(y_1, \varphi_1)P_2(y_2, \varphi_2)$ is the product of the single-particle distributions assuming independent emission.

When $C = 1$, the particles are emitted independently. $C > 1$ indicates a positive

correlation, meaning that the particles are more likely to be emitted together at the given pseudorapidities and angles. Viceversa, $C < 1$ means negative correlation or suppression of paired emission.

4.3.1 Probability ratio correlation function

The two-particle correlation function, often referred to as the **probability ratio correlation function**, is a measure of the relations between particle pairs produced in high-energy collisions. Experimentally, this correlation is expressed in terms of a ratio of signal and background distributions, which reflect physical two-particle and single-particle correlations, respectively. The correlation function is defined as:

$$C_P(\Delta y, \Delta \phi) = \frac{S(\Delta y, \Delta \phi)}{B(\Delta y, \Delta \phi)}. \quad (4.4)$$

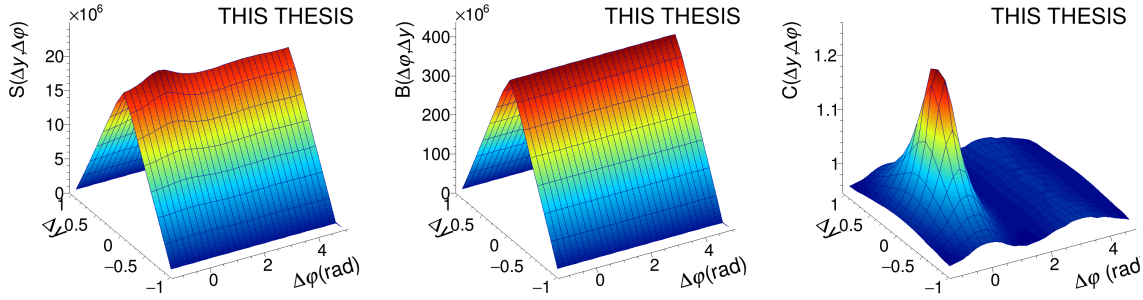


FIGURE 4.3: The left panel displays the signal distribution, the middle panel shows the background distribution, and the right panel presents the correlation function, calculated as the ratio of the signal to the background.

$S(\Delta y, \Delta \phi)$ represents the signal distribution, constructed from particle pairs originating from the same event. It is given by:

$$S(\Delta y, \Delta \phi) = \frac{1}{N_{\text{pairs}}^{\text{signal}}} \frac{d^2 N_{\text{pairs}}^{\text{signal}}}{d\Delta y d\Delta \phi}, \quad (4.5)$$

where $N_{\text{pairs}}^{\text{signal}}$ is the total number of pairs in the signal. The signal typically shows a peak around $(\Delta y, \Delta \phi) \approx (0,0)$, indicating strong correlations between particles in both rapidity and azimuthal angle, as illustrated in Fig. 4.3. The observed peak is

overlaid on a triangular-shaped background, which results from the convolution of two expected uniform rapidity distributions in a Lorentz boost invariant system. This background distribution is not an artifact or error, but rather an intrinsic feature of the approximate boost invariance, further modified by detector acceptance effects. To extract specific correlations beyond these expected contributions, the background must be subtracted.

Direct subtraction based on a theoretical triangular component may seem a valid approach; however, this method is insufficient. The system under consideration approximates ideal momentum invariance only within a limited range of rapidity, and additional acceptance effects further modify the observed correlations. Consequently, the theoretical expectation cannot be directly applied in its exact form. Instead, a data-driven approach is needed, in which the background is constructed from experimental data. This ensures a more accurate isolation of the relevant physical correlations while preserving consistency with the theoretical expectation. This is achieved by constructing an additional background distribution, $B(\Delta y, \Delta\varphi)$ using the event-mixing technique. In this approach, particles from different events are paired to ensure that the background reflects pairs of unrelated particles. The resulting background distribution is defined as:

$$B(\Delta y, \Delta\varphi) = \frac{1}{N_{\text{pairs}}^{\text{mixed}}} \frac{d^2 N_{\text{pairs}}^{\text{mixed}}}{d\Delta y d\Delta\varphi}, \quad (4.6)$$

where $N_{\text{pairs}}^{\text{mixed}}$ represents the total number of mixed-event pairs. The mixed-event pairs are constructed by combining particles from ten different events with similar vertex and multiplicity conditions to replicate the uncorrelated background observed in the signal distribution closely. Event mixing is crucial because it isolates the true signal from the influence of acceptance which is not interesting, allowing experimentalists to focus on genuine correlations between particle pairs from the same event.

4.3.2 Rescaled two-particle correlation functions

The probability ratio approach discussed above introduces an expected multiplicity scaling proportional to $1/N$, where N represents the event multiplicity. This effect was identified by analyzing the correlation functions in pp collisions at $\sqrt{s} = 7$ TeV using the Pythia_Perugia model [84], as shown in Fig. 4.4 from Ref. [83].

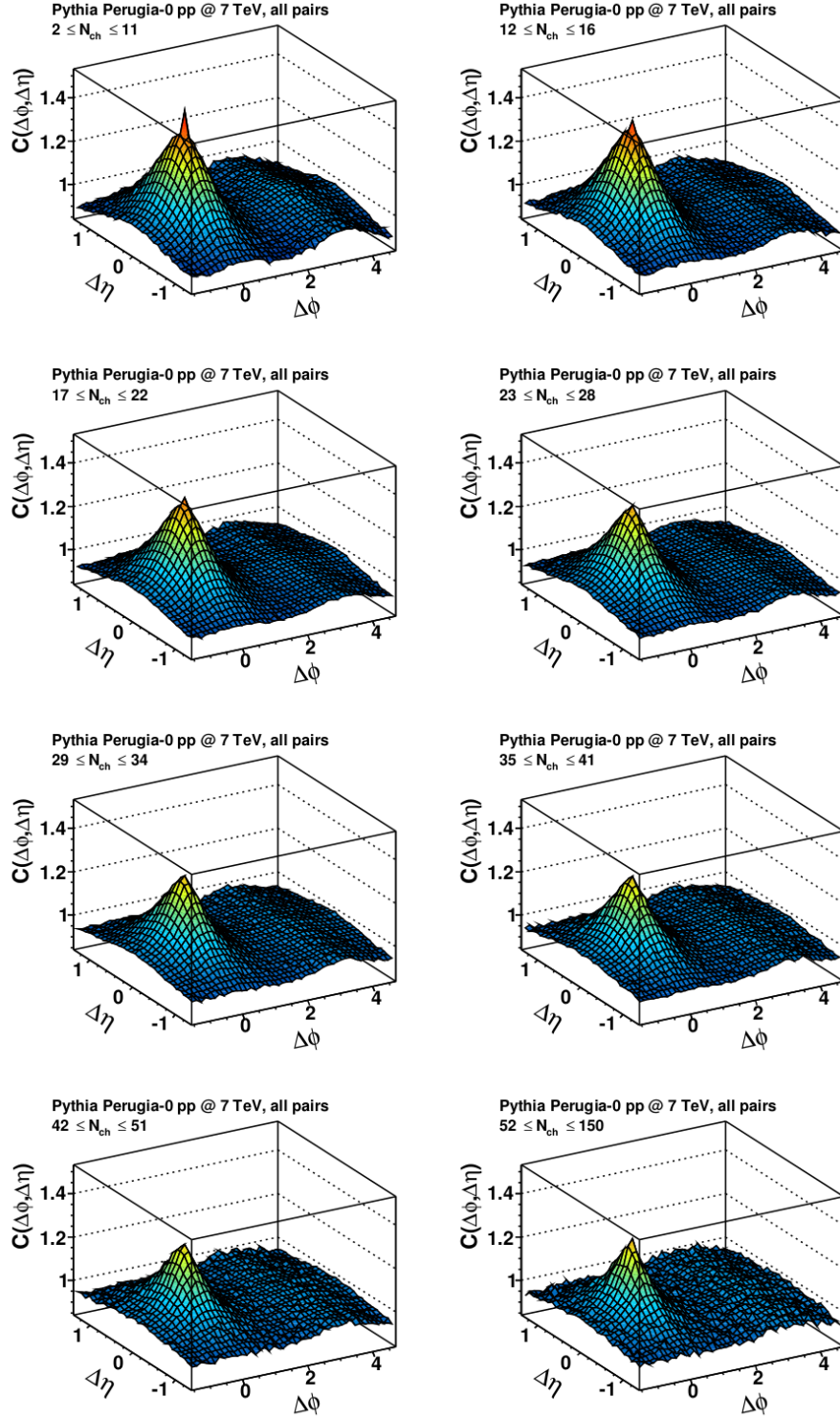


FIGURE 4.4: Multiplicity dependence of the $\Delta\eta\Delta\phi$ correlation function for all charge pair combinations in $\sqrt{s} = 7$ TeV pp collisions, simulated using Pythia Perugia-0. Picture from Ref. [83].

The expected $1/N$ scaling implies that correlation functions, while physically meaningful, have inherent limitations when applied across different multiplicity classes. In high-multiplicity events, where the number of particle pairs is larger, one would naturally expect stronger correlations. However, due to the imposed scaling, the opposite trend is observed. Conversely, in lower-multiplicity events, where fewer particle pairs are present, the correlation magnitude appears enhanced. This systematic effect must be considered when interpreting correlation functions in different multiplicity regimes.

To address this issue, a new formulation, known as the **rescaled two-particle correlation function**, has been introduced. Inspired by the work of the STAR Collaboration [85], this method provides a refined approach to studying these correlations. The removal of the $1/N$ scaling follows the same principle as background subtraction in correlation analyses. Just as the background is divided out to isolate the correlation of interest, the rescaled two-particle method removes the multiplicity dependence to highlight additional underlying physics. Both the probability ratio approach and the rescaled correlation function capture genuine correlations; neither is incorrect, but they serve different analytical purposes. The consistency of results across these methods confirms their validity, justifying the use of the rescaled correlation function to explicitly remove the $1/N$ contribution.

The rescaled two-particle correlation function is defined experimentally as:

$$C_R(\Delta y, \Delta \varphi) = \frac{1}{2\pi} \left\langle \frac{dN_a}{d\varphi} \right\rangle (C_P - 1), \quad (4.7)$$

where C_P refers to the probability ratio correlation function discussed previously in Sec. 4.3.1, and $N_{av} = \frac{1}{2\pi} \left\langle \frac{dN_a}{d\varphi} \right\rangle$ represents the average number of charged particles of a-type, N_a produced in the analyzed multiplicity classes within $|y| < 0.5$.

4.4 Sources of angular correlations

The correlation function is influenced by various physical phenomena as is shown in Fig. 4.5, each contributing to its overall shape and resulting in distinct behaviors for each analyzed particle pair. This section will examine each of these contributions individually.

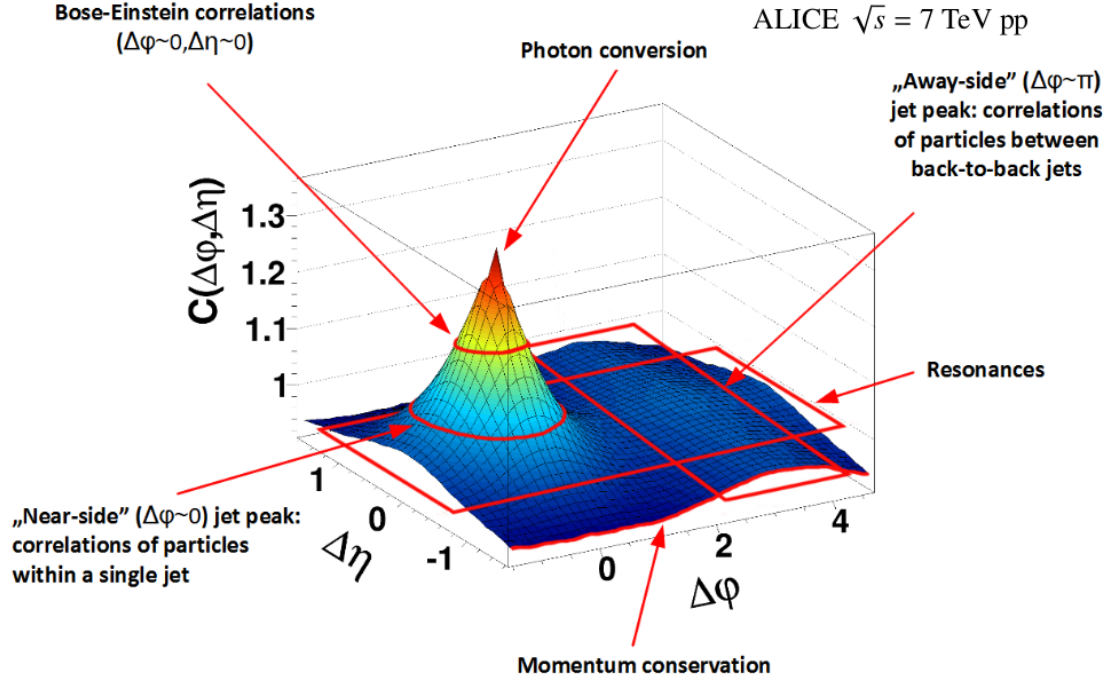


FIGURE 4.5: Contribution of different sources that influence the overall shape of the $\Delta\eta\Delta\phi$ correlation function from pp collision at $\sqrt{s} = 7$ TeV. Picture from Ref. [83].

4.4.1 Conservation laws

The particles produced after the collision must obey the conservation of momentum, energy, and charge on a global scale. For instance, momentum conservation requires that the total momentum of all produced particles adds up to zero. As a result, when two particles are emitted, their momenta are often anticorrelated, meaning that if one particle is emitted in a particular direction, the other tends to be emitted in the opposite direction. This phenomenon produces distinct patterns in the angular correlation function, as shown in Fig.4.6. These patterns, reproduced by the CALM model (described in Sec.3.2.6), demonstrate how conservation laws manifest in angular space, with no other physical phenomena involved. A detailed discussion of how global momentum conservation can introduce correlations — even in the absence of dynamical interactions — is presented in Ref [86], where the impact on femtoscopic correlation functions is analyzed. Although their study focuses on femtoscopy, the same conservation-driven mechanisms can also affect angular correlation measurements. Similarly, energy conservation limits the total energy available for particle production, influencing

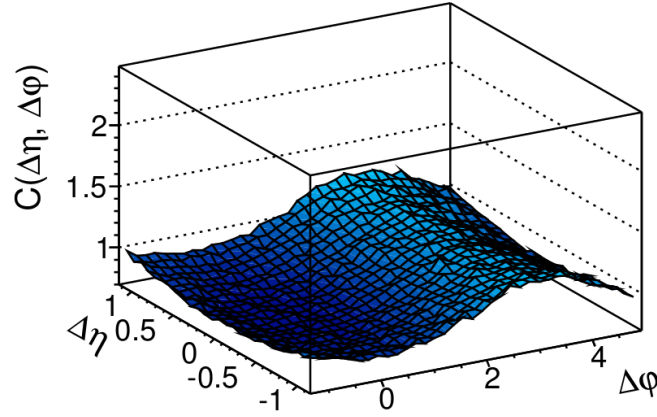


FIGURE 4.6: Momentum conservation contribution in $\Delta\eta, \Delta\phi$ correlation function by using CALM model. Picture from Ref. [80].

how energy is distributed among emitted particles. For example, if two particles are emitted, the energy, which depends on mass and momentum, must be shared between them. If one particle takes a significant portion of the energy, the energy available for other particles decreases, affecting their momentum and angular distribution. Additionally, charge conservation ensures that particles of opposite charge are often produced together, leading to charge-dependent angular correlations. As a result, particle pairs with the same charge are classified as like-sign pairs, while pairs with opposite charges are termed unlike-sign pairs. Other quantum numbers, such as strangeness and baryon number, are also balanced, with equal numbers of strange quarks and antiquarks, as well as baryons and antibaryons, being produced. Moreover, collective phenomena, such as anisotropic flow in heavy-ion collisions, are shaped by the conservation of momentum and energy, which further influence the observed particle correlations. Altogether, these conservation laws impose fundamental constraints on particle behavior, leaving measurable effects on angular correlations.

Studies have shown that conservation laws operate not only globally but can also manifest locally within parton fragmentation. In its rest frame, a parton fragments isotropically, leading to an enhanced particle flow due to its initial momentum. This process must conserve momentum, charge, strangeness, and baryon number. While gluons conserve only momentum, quarks also retain these additional quantum numbers, imposing further constraints beyond global conservation laws. Local conservation is not a trivial assumption and requires dedicated investigation. The degree to

which momentum, charge, and baryon number remain locally conserved within pseudorapidity ($\Delta\eta$) and azimuthal ($\Delta\phi$) correlations is an open question. For instance, in the fragmentation of jets emerging from the QGP in heavy-ion collisions, it is unclear whether the baryon number is always locally preserved, as this depends on the dynamics of the fragmentation process. Correlation analyses offer a direct probe into whether these conservation laws imprint the expected signatures on the observed distributions.

Here, the Tab. 4.1 presents the conservation laws that apply to the various particle species studied.

TABLE 4.1: Conservation laws for all the particle species studied.

particles	conservation laws			
	momentum	charge	strangeness	baryon number
pions	✓	✓		
kaons	✓	✓	✓	
protons	✓	✓		✓

Conservation of momentum and charge are fundamental principles that apply universally to all particles in the system. These laws ensure that, in any interaction, total momentum and charge remain constant. Conservation of strangeness applies to all particles with a nonzero quantum number of strangeness, including kaons, which are the particles of interest in this analysis. In interactions involving these particles, the total strangeness must be conserved, that is, the number of strange quarks before and after the interaction must be in equilibrium. Similarly, conservation of the number of baryons applies to all baryons, including protons, which are the baryons of interest in this work. This principle ensures that the total number of baryons remains constant in any interaction.

4.4.2 Jets

Jets are concentrated flows of particles created when partons scatter during collisions [87]. Due to confinement, these partons cannot exist independently; instead, they quickly undergo the hadronization process, generating a series of particles that roughly follow the direction of the parton's original momentum. This sequence forms a visible jet, appearing as a narrow, high-energy particle cone.

4.4.2.1 MiniJets

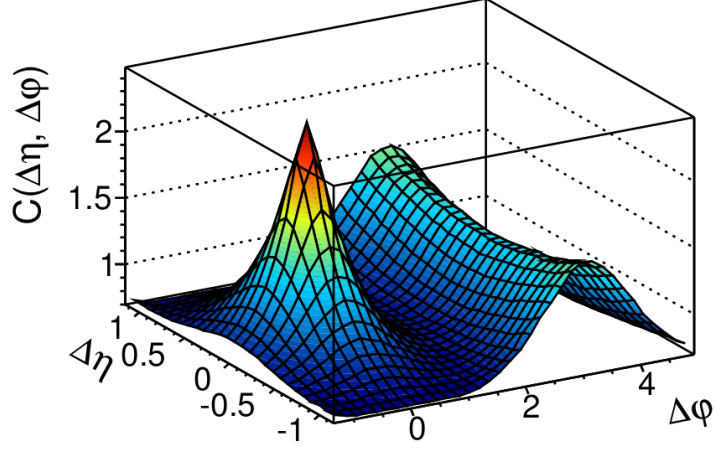


FIGURE 4.7: Minijets contribution in $\Delta\eta, \Delta\phi$ correlation function by using CALM model. Picture from Ref. [83].

In the context of particle physics, the term "minijet" is often used to describe jets resulting from scatterings with lower momentum transfer. Typically, minijets contribute to the correlation functions in both the near and away side regions, as shown in Fig. 4.7. In this figure, the characteristic structure of minijets in the $\Delta\eta\Delta\phi$ angular space is reproduced using the CALM model, as described in Sec. 3.2.6, which includes no other physical phenomena. The figure displays the correlation of neutral pion pairs with a pronounced peak in the near-side region and a long ridge in the away-side region.

If the two correlated particles come from the same jet as is shown in the top Fig. 4.8, this leads to the formation of particle pairs with small angles $\Delta\eta$ and $\Delta\phi$. Such particle pairs form a minijet peak centered at $(0,0)$, referred to as the near-side peak. In contrast, the particles in the bottom panel of Fig. 4.8 originate from two opposing jets, moving in opposite directions with $\Delta\phi$ close to 180° . However, this configuration lacks dependency on the polar angle, θ , as θ varies based on the spatial orientation of the jets. Therefore, across multiple events and jet alignments, Δy appears uniformly distributed, creating a wide ridge along $\Delta\phi = \pi$, termed the away-side ridge.

4.4.2.2 Jet quenching

In HIC, the behavior of jets is notably altered due to the creation of QGP. Unlike in pp collisions, where jets commonly form a clear opposing structure, the presence of

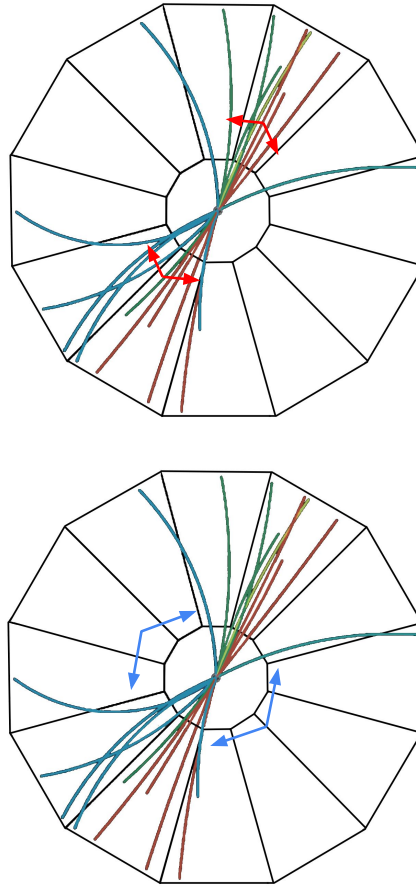


FIGURE 4.8: Schematic overview of particles from the same jets (top) and particles correlated in opposite jets (bottom) from an azimuthal perspective.

the QGP disrupts this arrangement. Minijets that emerge in the QGP interact intensively with the medium's quarks and gluons, leading to substantial energy loss, a phenomenon referred to as jet quenching. This jet quenching effect arises when partons moving through the QGP lose energy through processes like gluon radiation and particle collisions within the medium. As a result, the jet yield on the opposite side decreases, often showing a reduced or absent peak in this region. Significant jet quenching effects have been observed in high-transverse-momentum particles in central Au–Au collisions at RHIC and in central Pb–Pb collisions at the LHC, underscoring jets as precise tools for probing the QGP.

Experiments on asymmetric collisions, such as p–Pb at the LHC and light-nucleus–Au at RHIC, reveal collective effects comparable to those observed in symmetric collisions. These phenomena can be explained either by models assuming a thermally equilibrated medium in the final state or by models without a QGP, relying instead on significant initial-state fluctuations in the incoming wave functions. This raises an important question: does the QGP form in smaller, asymmetric systems that were previously considered too small to achieve quasi-equilibrium?

An example of jet quenching is presented in Fig. 4.9, where the azimuthal two-particle correlation function is compared across different collision systems, including pp, d–Au, and Au–Au. In heavy-ion collisions, the away-side region ($\Delta\phi > \pi/2$) ex-

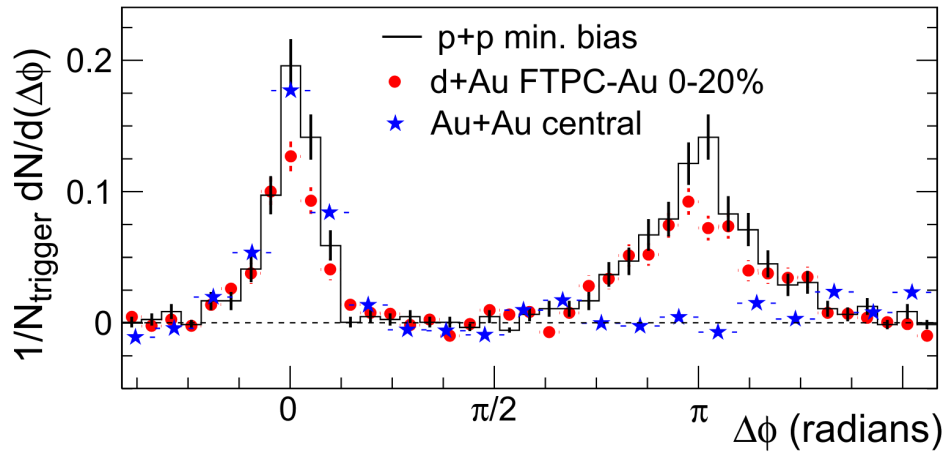


FIGURE 4.9: Comparison of two-particle azimuthal distributions for central d–Au collisions to those seen in pp and central Au–Au collisions. Picture from Ref. [88].

hibits no visible jet structure, unlike smaller systems. This provides clear evidence of the jet quenching phenomenon. The absence of jet quenching in small systems has been explored experimentally [89]. While theoretical models attempt to estimate quenching effects in these systems, the lack of experimental evidence leaves many questions unresolved. The limited jet quenching observed in small collisions continues to challenge our understanding of QGP formation, posing significant experimental and theoretical investigations [90].

4.4.3 Quantum Statistical and Final-State Interaction Effects

Quantum statistical effects (QS) and final-state interactions (FSI) play a crucial role in shaping angular correlations. QS effects, governed by Bose-Einstein and Fermi-Dirac statistics, influence the behavior of identical particles in momentum space. The Bose-Einstein statistics describe bosons, such as pions and kaons, which can occupy the same quantum state due to their indistinguishable nature. This property leads to enhanced clustering in momentum space, producing a characteristic peak in angular correlations around $(\Delta\eta, \Delta\phi) \approx (0, 0)$. This phenomenon is driven by quantum interference, where the overlapping wave functions of identical bosons constructively interfere, increasing the likelihood of their simultaneous detection. In contrast, fermions, such as protons, are described by Fermi-Dirac statistics and are subject to the Pauli exclusion principle, which prevents them from occupying the same quantum state. This results in a suppression of clustering in momentum space, manifesting as less pronounced peaks or even depletions in the near-side region of angular correlation functions.

Final-state interactions further modify angular correlations by altering particle trajectories after their emission. The Coulomb interaction, arising from the electrostatic force between charged particles, has a pronounced effect on angular distributions. For like-sign particles, such as protons or $\pi^+\pi^+$ pairs, the repulsive Coulomb force reduces the probability of detecting the particles at small relative angles, suppressing the near-side peak in the correlation function. Conversely, for oppositely charged pairs like $\pi^+\pi^-$, the attractive Coulomb force increases the likelihood of particles being detected at small angles, enhancing the near-side peak. The strong interaction, a short-range force acting over distances on the order of ~ 1 fm, also plays a pivotal role in shaping angular correlations.

FSI and QS effects (as well as the space-time properties of the particle-emitting source) form the basis of the femtoscopy technique. While femtoscopy is traditionally formulated in terms of relative momentum or invariant mass, its influence is also visible in two-particle angular correlations, particularly in the near-side region. This cross-talk between femtoscopic methods and angular correlation studies allows for complementary insights into the underlying physics, especially in the investigation of short-range quantum and interaction effects.

The combined effects of QS and FSI are clearly evident in experimental data [91], particularly in the analysis of like- and unlike-sign pion and proton correlations.

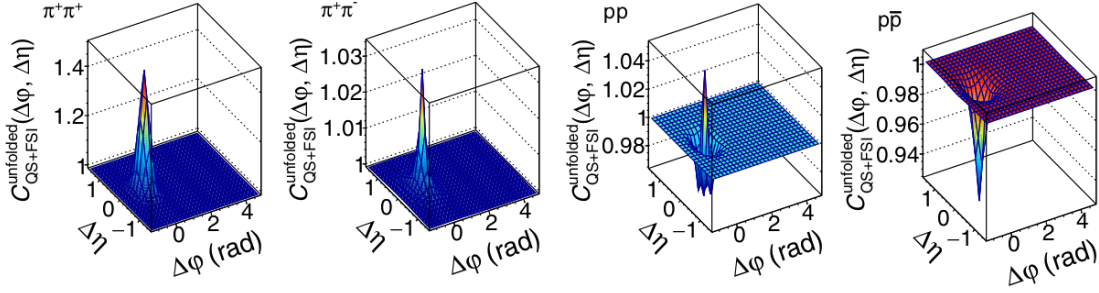


FIGURE 4.10: Angular correlation functions in $\Delta\eta, \Delta\phi$ space for like and unlike-sign pions and protons, illustrating the contributions of quantum statistical and final-state interaction effects. Picture from Ref. [91].

As shown in Fig. 4.10, the correlation function for $\pi^+\pi^+$ pairs exhibits a prominent peak around $(\Delta\eta, \Delta\phi) \approx (0,0)$, with a magnitude of approximately 1.4. This peak is attributed to the Bose-Einstein quantum statistical effect, which enhances the probability of close spacing in momentum space for identical bosons. In contrast, the Coulomb FSI effect is observed in $\pi^+\pi^-$ correlations, where the magnitude of the near-side peak is significantly smaller, reaching only about 1.03. For pp pairs, a distinct depletion around $(\Delta\eta, \Delta\phi) \approx (0,0)$ is observed, accompanied by a narrow peak at the exact center. While the depletion can be explained by wide-range energy-momentum conservation effects, the narrow peak at $(0,0)$ is confirmed to arise from the strong interaction between two protons. $p\bar{p}$ correlations also display a depletion, due to the inelastic channels of the strong interaction, such as annihilation processes. Thanks to the detailed analysis presented in [91], it is understandable how QS and FSI collectively shape the structure of angular correlations in $\Delta\eta, \Delta\phi$ space, revealing the intricate interplay between quantum interference and interparticle forces.

4.4.4 Resonances

Resonances are extremely short-lived particles, decaying on the order of 10^{-23} seconds. Their behaviors have been extensively studied in a range of collision systems, including p-p, d-Au, and Au-Au, which reveal sharper, more distinct resonance peaks in smaller systems with limited medium effects. In contrast, larger systems show altered resonance characteristics, providing indirect insight into the properties and behavior of the QGP formed in high-energy collisions [92]. The Intersecting Storage Rings (ISR) and PHOBOS experiments contributed significantly to understanding resonance effects in two-particle angular correlations, showing that short-lived resonances such as

the ρ , K^* , and ϕ mesons produce characteristic peaks in angular distributions due to clustering of their decay products. The ISR experiment [93], demonstrated that the decay of a meson can create structures around $\Delta\varphi = \pi$, where two particles move in opposite directions. Any two-body decay with a decay energy (Q-value) much larger than its transverse momentum will exhibit similar behavior to these mesons. In contrast, three-body decays can generate different structures, such as near-side peaks or contributions to the longitudinal ridge. The PHOBOS experiment investigated the longitudinal structure around $\Delta\eta \approx 0$ at collision energies of $\sqrt{s} = 200$ GeV and $\sqrt{s} = 410$ GeV. Their findings indicated that the observed correlation patterns were consistent with ISR simulation studies using a low-mass resonance gas model (including ρ , ω , and η mesons). STAR and ALICE experiments have further demonstrated that these reso-

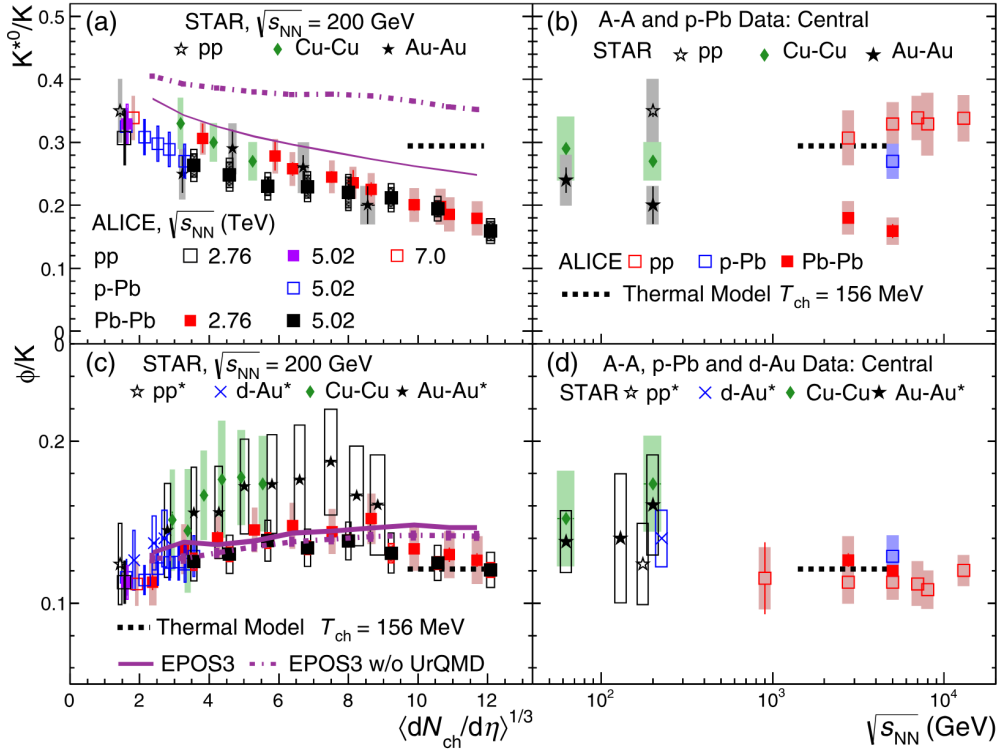


FIGURE 4.11: The ratios K^{*0}/K (panels (a) and (b)) and ϕ/K (panels (c) and (d)) are analyzed across different collision systems: pp, d—Au, p—Pb, Cu—Cu, Au—Au, and Pb—Pb. Panels (a) and (c) show these ratios as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$ for K^{*0}/K and ϕ/K in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Panels (b) and (d) depict the ratios for various systems as a function of $\sqrt{s_{NN}}$, alongside predictions from a grand-canonical thermal model at a freezeout temperature of 156 MeV. Picture from Ref. [94].

nance decay patterns are influenced by collision energy and centrality as is shown in

Fig. 4.11: in central or high-energy collisions, peaks associated with resonance decays often broaden or diminish, likely due to interactions with the surrounding medium. This indicates that some resonances decay within the QGP, where their decay products experience scattering or absorption due to medium effects, resulting in modified correlation signals [95, 94].

4.4.5 Photon conversion

Photon conversion is a physical phenomenon that contaminates the angular space $\Delta\eta\Delta\phi$, manifesting as a narrow spike at $(\Delta\eta, \Delta\phi) = (0, 0)$. This spike arises when a high-energy photon interacts with matter, often a nucleus, and transforms into an electron-positron pair traveling in the same direction, resulting in a small angular separation. For this process to take place, the photon must have sufficient energy, given by $\hbar\nu$, where $\hbar$ is the reduced Planck constant and ν is the photon's frequency, to exceed twice the electron's rest energy, approximately 1.022 MeV.

The standard experimental cuts used to select particles of interest, such as pions, kaons, and protons, are often insufficient to eliminate the contamination caused by electrons from photon conversion. To address this issue, specific cuts must be applied at the level of the correlation function to remove this unwanted phenomenon, ensuring an accurate and clean analysis of the particle correlations of interest.

4.4.6 Flow structure

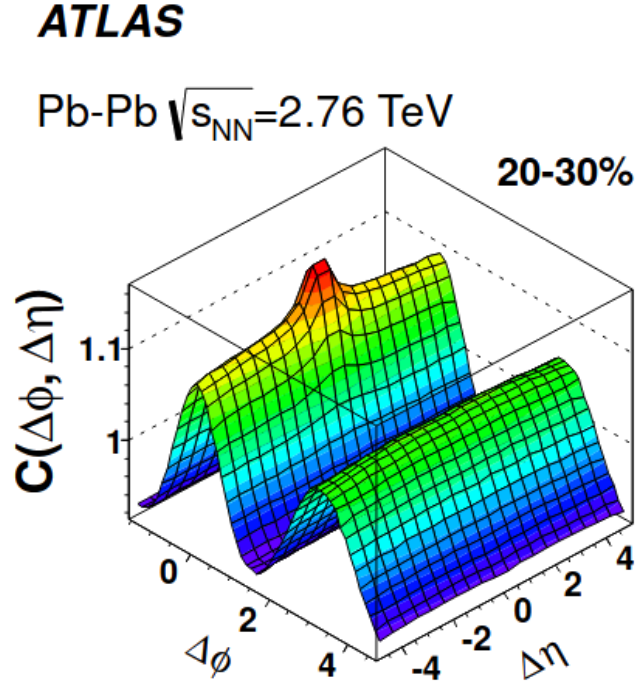


FIGURE 4.12: Correlation function in $\Delta\eta\Delta\phi$ space from Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV with ATLAS. The correlation is studied in the centrality class 20–30% showing a double ridge structure typical of the flow effects. Picture from Ref. [96].

Collective effects, as previously detailed in Sec. 2.5, create correlations between particles, which are reflected in the anisotropy parameter $v_2 = \langle \cos(2\phi) \rangle$, referred to as elliptic flow. This results in a cosine-like oscillation with a $\cos(2\Delta\phi)$ dependence. As shown in Fig. 4.12, a double ridge structure is formed in both near-side and away-side regions.

One can decompose the correlation by projecting the 2D into the $\Delta\phi$ axis and getting information on the flow by using the harmonic Fourier series, as is shown in Fig. 4.13. As one can see higher-order harmonics, v_n , can shape the correlation function in complex ways.

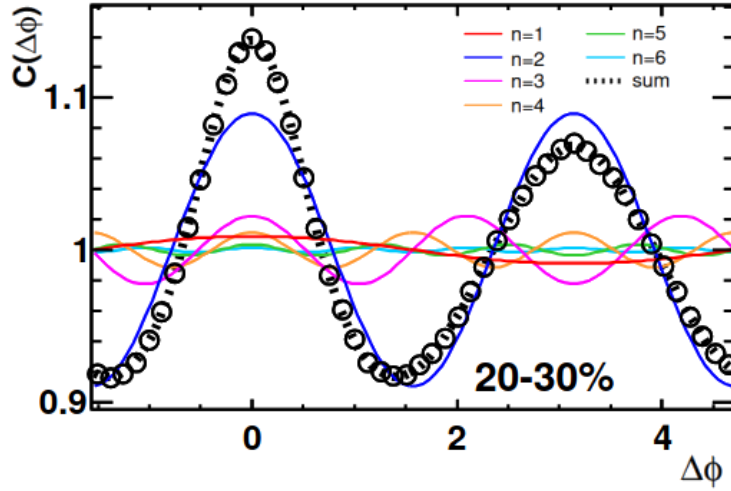


FIGURE 4.13: $\Delta\phi$ correlation function from Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV with ATLAS. The near-side peaks reflect the “ridge” instead of the autocorrelations from jet fragments. The superimposed solid lines (thick-dashed lines) indicate contributions from individual v_n components (sum of the first six components). Picture from Ref. [96].

4.4.7 Ridge structure – collectivity in small systems?

Experimental evidence at the LHC has shown signs of collective effects in small systems, such as pp and p–Pb collisions. The observed long-range correlations, often referred to as “ridge” phenomena, suggest collective behavior similar to that in heavy-ion collisions, though the exact mechanisms behind these effects are still an area of active research. In Fig. 4.14 a typical ridge structure is shown.

At RHIC, the ridge first appeared in Au–Au collisions, where STAR Collaboration [98] and PHOBOS [99] detected unexpected long-range, near-side correlations extending over large pseudorapidity ranges. This distinctive correlation was later termed the “ridge” due to its continuous structure along the pseudorapidity axis. Early interpretations linked it to collective behaviors in the QGP, as hydrodynamic models—describing the flow of particles in a nearly perfect fluid state—could partly explain these patterns. The RHIC results thus hinted that the QGP formed in heavy-ion collisions behaves like a low-viscosity fluid. With the LHC’s higher collision energies in 2010, pronounced ridge structures emerged in Pb–Pb collisions, intensifying the observable effects of collective flow. The CMS [46], ATLAS [100], and ALICE [47] collaborations all reported these enhanced ridge correlations, further supporting a connection between the ridge and collective behavior associated with the QGP. In a surprising development in 2012,

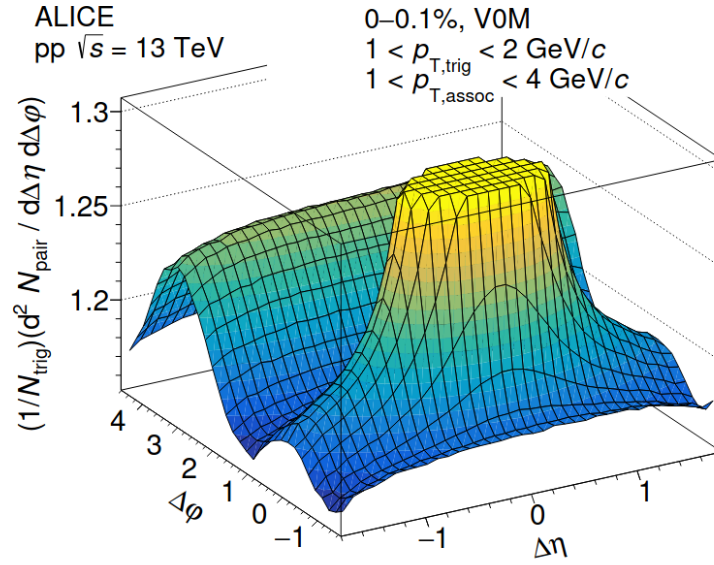


FIGURE 4.14: Ridge structure from pp collision at $\sqrt{s} = 13$ TeV with ALICE in high-multiplicity class. Picture from Ref. [97].

CMS identified a ridge pattern in high-multiplicity pp collisions [45], while it appeared to be absent under minimum-bias¹ triggers and at low p_T ; however, it becomes visible at higher p_T . Under high-multiplicity triggers², the ridge-like feature appears across both low and high p_T ranges. Soon after, similar findings emerged in p-Pb collisions [46, 47, 100] challenging assumptions that QGP effects only occur in large collision systems.

Theoretical interpretations of the ridge phenomenon attribute its origin to a combination of initial-state effects and collective behavior. Initial-state models include gluon saturation and structures described by the Color Glass Condensate framework, while final-state explanations focus on hydrodynamic flow under high-density conditions, suggesting that even small systems might exhibit medium collective behavior at extreme energies. Competing theories also invoke mechanisms such as gluonic flux tubes and other forms of collective phenomena. This duality—the ridge arising from either initial-state dynamics or final-state flow—remains the subject of intense investigation. Growing evidence suggests a hybrid explanation, where both mechanisms contribute. In large systems, the ridge is strongly linked to collective flow driven by hydrodynamic

¹A minimum bias trigger is designed to capture a broad and representative sample of collision events, minimizing selection bias by including events across a wide range of particle production.

²A high-multiplicity trigger selectively records events with a large number of produced particles (high multiplicity), often linked to extreme collision conditions or collective effects.

expansion. In smaller systems, the debate continues over whether the ridge primarily originates from initial conditions or emerges from collective behavior at high multiplicity. Very recent experimental results from HERA [101] and LEP [102] have provided critical insights, though they highlight notable inconsistencies. For instance, ALICE recently reported significant ridge yields in high-multiplicity events [97, 103], contrasting earlier findings from e^+e^- annihilation studies, where no substantial ridge structure was observed. Similarly, CMS has documented long-range elliptic anisotropies in pp collisions [104], adding further complexity to understanding ridge formation across different collision systems.

Chapter 5

Baryon Correlation Puzzle

I hereby declare that the results presented in the following chapter were obtained by the ALICE Collaboration and are not part of the original work conducted for this thesis.

In this chapter, the primary motivation behind initiating this work will be explained in detail.

5.1 Baryon and Meson Correlation functions

Recent results from ALICE on correlation functions in angular space ($\Delta\eta, \Delta\phi$) for mesonic and baryonic pairs have been highly significant, particularly in advancing the understanding of baryon production mechanisms. The correlation functions—discussed in the previous chapter—are shaped by various physical phenomena, each contributing uniquely to their form. This results in distinct behavior for each particle pair analyzed. The study of pp collisions at $\sqrt{s} = 7$ TeV, conducted with the ALICE experiment at the LHC [4], investigated correlations among like-sign and unlike-sign pions, kaons, and protons. As shown in Fig. 5.1, a near-side peak is observed for all particles, except for like-sign protons, with varying magnitudes.

For like-sign pions, the primary contributors to the near-side peak are minijets and Bose-Einstein quantum statistics. In contrast, for unlike-sign pions, the peak arises from a combination of minijet contributions and Coulomb interactions. While the peak for unlike-sign pions appears smaller in magnitude compared to like-sign pions, it is mainly a difference in the scale along the z-axis. However, the peak for unlike-sign pions is still smaller in magnitude when compared to that of unlike-sign kaons. This difference can be attributed to the fact that multiple physical phenomena contribute

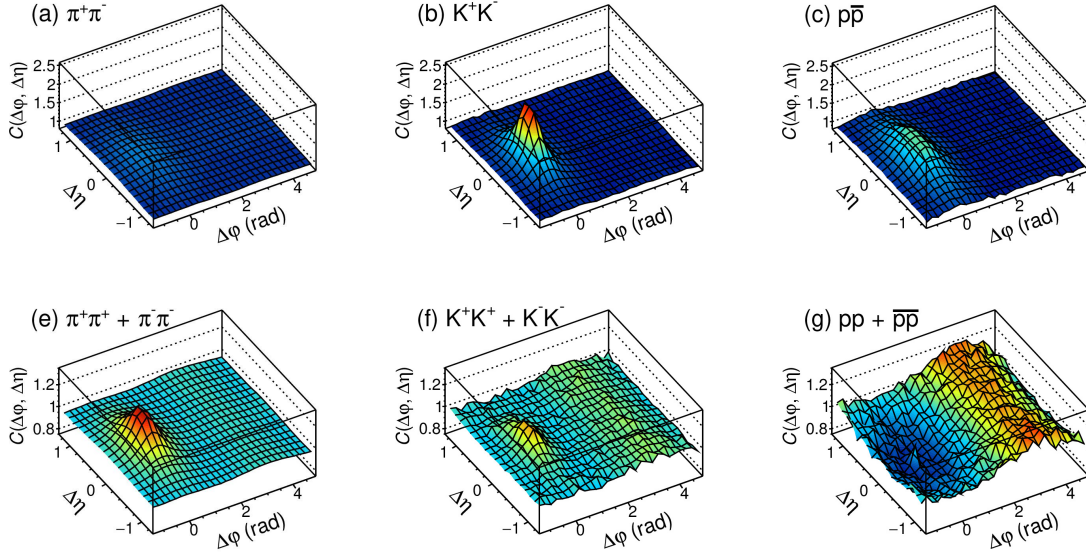


FIGURE 5.1: Correlation functions $\Delta\eta\Delta\phi$ for unlike-sign pairs of pions, kaons, and protons (top row) and like-sign pairs of pions, kaons, and protons (bottom row). Picture from Ref. [4].

to the near-side region for kaons, including minijets, Coulomb interactions, and resonances such as ϕ , which decay into K^+K^- pairs. Notably, local strangeness conservation plays a crucial role by increasing the statistics for the creation of K^+K^- pairs, as it ensures a balance of strange quarks before and after the interaction. This mechanism further strengthens the correlation for unlike-sign kaons. For like-sign kaons, the near-side peak is smaller in magnitude compared to unlike-sign kaons, which can be attributed to the absence of resonances and Coulomb repulsion. The main contributions to the near-side peak for like-sign kaons come from minijets, and Bose-Einstein effects. In the case of unlike-sign protons, a pronounced near-side peak is observed, although it is smaller in magnitude than that for unlike-sign kaons due to the absence of resonances. The main contributions to the near-side peak for unlike-sign protons are minijets and the local conservation of baryon number, which ensures an enhancement of the near-side correlation for unlike-sign proton pairs, consistent with expectations based on conservation laws. In contrast, like-sign protons reveal a novel anticorrelation, appearing as a dip at $\Delta\eta\Delta\phi \sim (0,0)$. Notably, this dip is accompanied by a narrow peak at the center, attributable to strong interaction effects.

The findings were compared with specific Monte Carlo models in Fig. 5.2, including PYTHIA6.4 Perugia-0, Perugia-2011 [105, 84], PYTHIA8 [67, 106], and PHOJET

[107], which are designed to simulate high-momentum fragmentation (i.e., jets). The

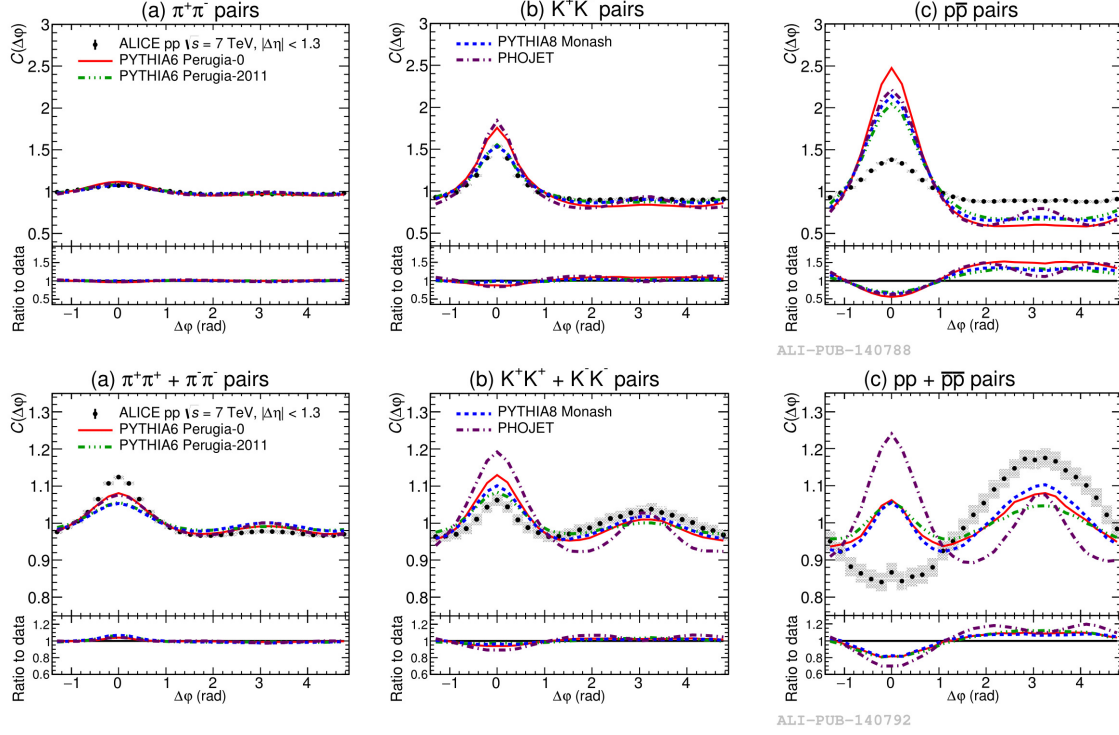


FIGURE 5.2: $\Delta\eta$ integrated projections of correlation functions for unlike-sign pairs of pions, kaons, and protons (top row) and like-sign pairs of pions, kaons, and protons (bottom row). The ALICE data are represented by the black circles, while the dashed colored lines are the Monte Carlo models. Picture from Ref. [4].

Monte Carlo (MC) models provide a reasonable description of the experimental results for mesons. However, it is important to emphasize that none of these models include quantum-statistical effects. Consequently, the near-side correlation strength for identical pions and kaons is expected to be weaker in the models compared to the experimental data. Both PYTHIA6.4 tunes, Perugia-0 and Perugia-2011, yield results in good agreement with the observations: Perugia-0 shows better performance for pions, while Perugia-2011 provides more accurate results for kaons. While the models successfully replicate meson correlation functions, they show significant limitations when applied to baryon correlations. For $p\bar{p}$ pairs, the MC models fail to reproduce the data quantitatively. In the case of pp and $\bar{p}\bar{p}$ pairs, the models are unable to capture the anticorrelations observed in the experimental results, underscoring their inadequacy in accurately describing baryon interactions.

These findings suggest *the need for modification of particle production mechanisms and/or modification of fragmentation functions in Monte Carlo models* [4]. This could imply that the models accurately describe the hadronization process but that jet fragmentation is not the dominant mechanism in particle production for the measured data, or that the fragmentation mechanisms in PYTHIA and PHOJET are incomplete. If the latter, this would further suggest an additional, unidentified mechanism that suppresses the production of multiple baryon–antibaryon pairs within a single fragmentation event [4].

5.2 The puzzle

Numerous studies have attempted to disentangle the observed anticorrelation, assembling a complex puzzle of potential contributing factors. The main influences explored in the literature are described below:

- Dependence on transverse momentum;
- Coulomb interaction effects;
- Fermi-Dirac quantum statistics;
- Comparisons with other baryon pairs.

5.2.1 Dependence on Transverse Momentum

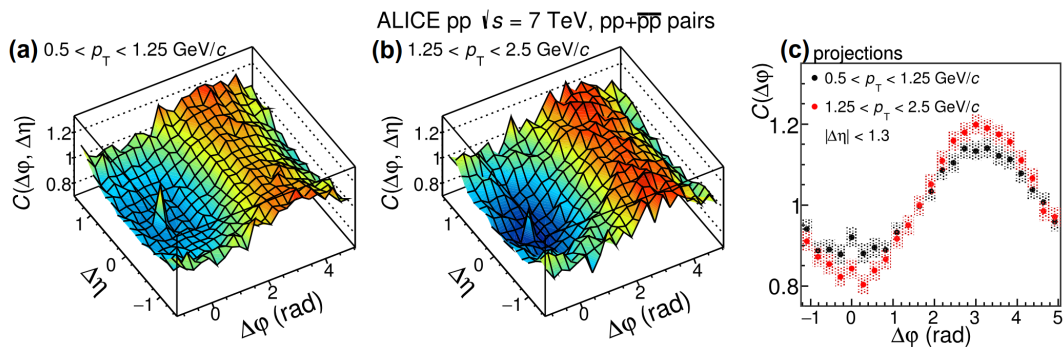


FIGURE 5.3: Correlation functions for combined pairs of $pp+\bar{p}\bar{p}$ for two transverse momentum intervals (a) $0.5 < p_T < 1.25$ GeV/c and (b) $1.25 < p_T < 2.5$ GeV/c. Panel (c) shows $\Delta\eta$ integrated projections. Statistical (bars) and systematic (boxes) uncertainties are plotted. Picture from Ref. [4].

To investigate whether part of the observed anticorrelation is influenced by momentum transfer during the interaction, the $pp+\bar{p}\bar{p}$ sample was divided into two ranges of transverse momentum: $0.5 < p_T < 1.25$ GeV/ c and $1.25 < p_T < 2.5$ GeV/ c . This momentum dependence was studied because the initial hypothesis for the anticorrelation was linked to energy conservation effects [3]. If energy conservation were the dominant factor, it would be expected that higher transverse momentum (and thus higher energy) would reduce the significance of energy-related effects. As shown in Fig. 5.3, the results indicate even stronger anticorrelation for particles with higher transverse momenta, suggesting that energy conservation alone is unlikely to fully explain the observed behavior. This suggests that other factors, beyond simple energy conservation, may contribute to the observed anticorrelation.

5.2.2 Coulomb interaction, Fermi-Dirac QS, and other baryons

The study of anticorrelation was further expanded to assess the impact of additional effects, such as Coulomb interaction and Fermi-Dirac quantum statistics, using pairs of Lambda particles. Since Λ particles are neutral, $\Lambda\Lambda$ and $\bar{\Lambda}\bar{\Lambda}$ pairs are unaffected by Coulomb interactions. Similarly, $p\Lambda$ and $\bar{p}\bar{\Lambda}$ pairs are non-identical, so Fermi-Dirac statistics¹ do not impact their correlations. As illustrated in Fig. 5.4 and Fig. 5.5, the anticorrelation remains evident in both particle pairs. This observation suggests that Coulomb and Fermi-Dirac effects play only a minor role implying that the observed anticorrelation may be a general feature of all baryon pairs.

5.3 2017 – today

Since the 2017 paper from ALICE [4], many studies were carried out to add more pieces to the puzzle. In Fig. 5.6, the STAR Collaboration examines the energy dependence of baryon correlations [85]. The left panel shows that like-sign protons exhibit stronger anticorrelation at higher beam energies, while the right panel reveals an increased annihilation effect in unlike-sign protons as energy rises.

Following the 2017 ALICE publication, studies of pp collisions at $\sqrt{s} = 13$ TeV were conducted. These investigations extended baryon-pair analyses to include correlations

¹Fermi-Dirac statistics apply only to identical fermions, suppressing correlations at short distances due to the Pauli exclusion principle, which prevents two identical fermions from occupying the same quantum state.

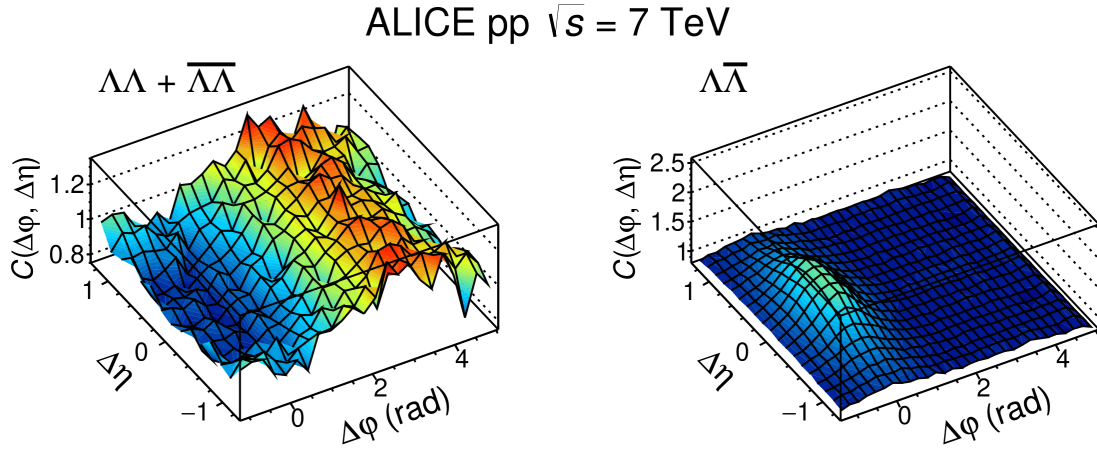


FIGURE 5.4: $\Delta\eta\Delta\phi$ correlation functions for like-sign and unlike-sign lambda particles. The study is conducted to verify the influence of Coulomb interaction. Picture from Ref. [4].

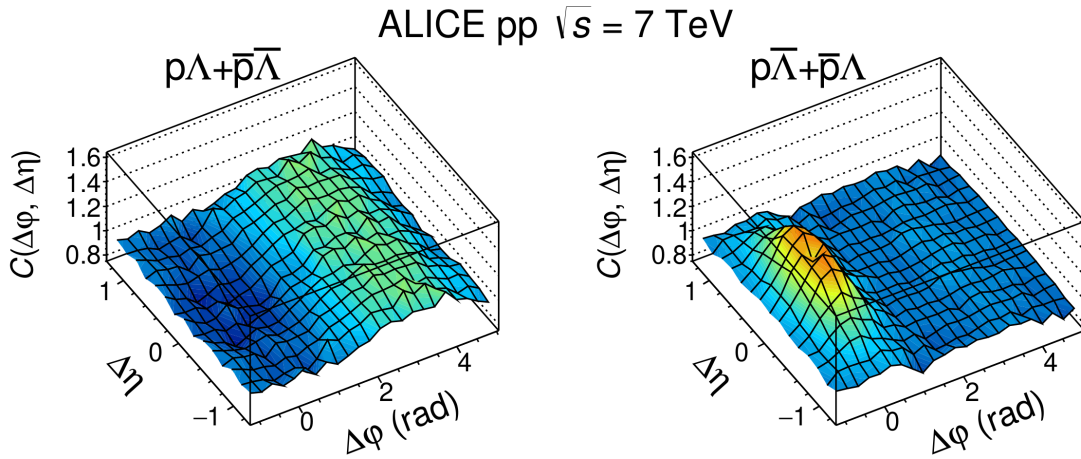


FIGURE 5.5: $\Delta\eta\Delta\phi$ correlation functions for non-identical proton-lambda pair particles. The study is conducted to verify the influence of Fermi-Dirac quantum statistics. Picture from Ref. [4].

involving charged Ξ baryons and identified hadrons [108]. Particular attention was given to the distribution of strangeness in correlations between the doubly-strange Ξ baryon and mesons or baryons containing a single strange quark, such as the K and Λ particles. By incorporating strange baryons, the analysis aimed to explore how properties like electric charge, strangeness, spin, and shared quark content influence the shape of the correlation function.

These studies, which were not feasible at lower energies, are presented in Figs. 5.7 and 5.8. Notably, an anticorrelation is observed for particle pairs with the same baryon

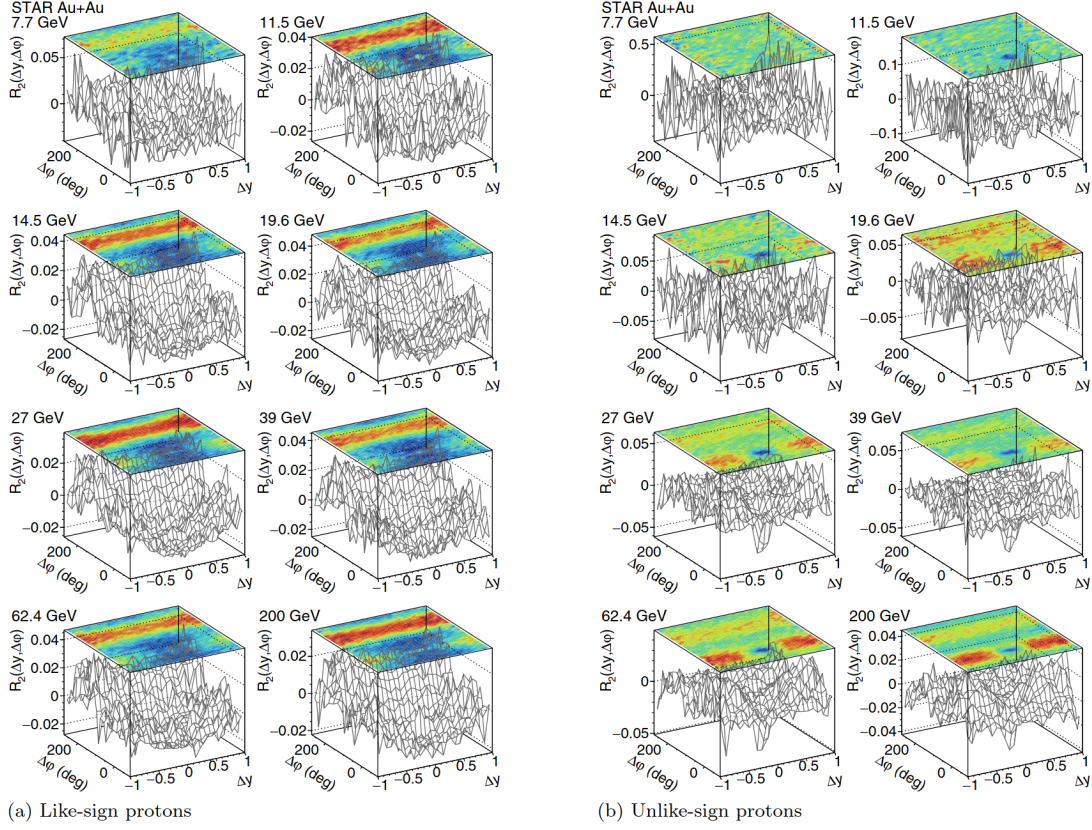


FIGURE 5.6: Angular correlation function $R_2(\Delta y, \Delta \phi)$ of like-sign (left) and unlike-sign (right) protons in Au + Au collisions at mid centrality 30%–40% and $0.4 < p_T < 2.0$ GeV/c in different beam energies from 7.7 GeV (top left) to 200 GeV (bottom right). Picture from Ref. [85].

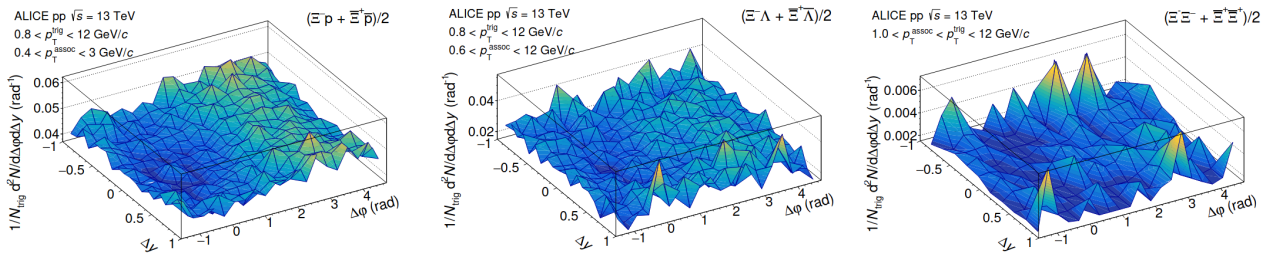


FIGURE 5.7: Per-trigger yields in $(\Delta y, \Delta \phi)$ for Ξp (left), $\Xi \Lambda$ (middle), and $\Xi \Xi$ (right) particle pair with the same baryon number, measured in pp collisions at $\sqrt{s} = 13$ TeV. Picture from Ref. [108].

number. HERWIG 7 [109, 110], which incorporates its color reconnection model along with a mechanism for non-perturbative gluon splittings—essential for describing strangeness enhancement through the production of $s\bar{s}$ pairs—appears to reproduce

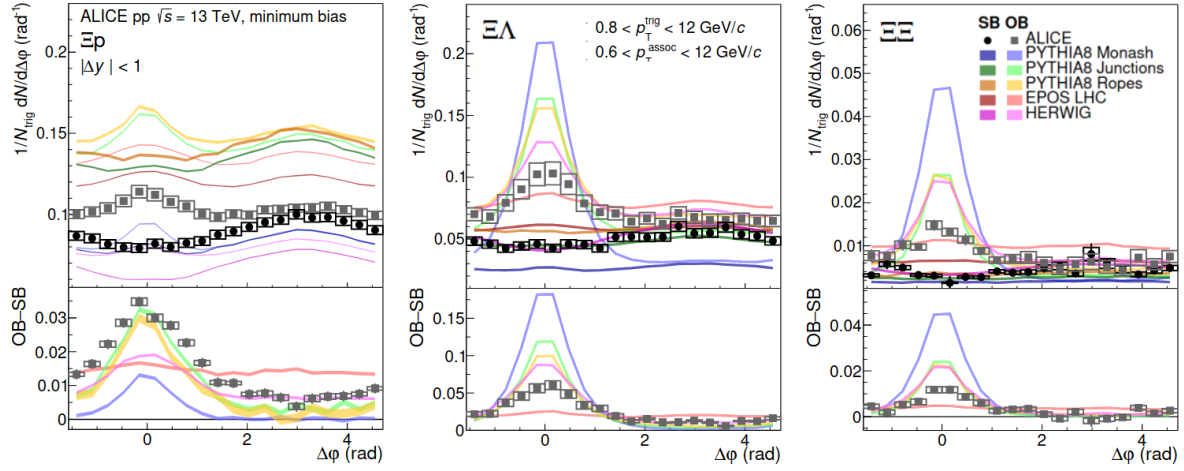


FIGURE 5.8: Correlation functions for $E p$, $E \Lambda$, and $E E$ pairs, as a function of $\Delta\phi$ ($|\Delta y| < 1$). Black circles and grey squares denote opposite- and same-baryon-number correlations, respectively, with their difference (OB-SB) shown in the lower panels. Error bars indicate statistical uncertainties, while shaded boxes show systematic ones. ALICE data are compared to model predictions: PYTHIA 8 Monash (blue), PYTHIA 8 with junctions (green), junctions and ropes (yellow), EPOS-LHC (red), and HERWIG 7 (pink). Picture from Ref. [108].

this behavior qualitatively. Conversely, various tuned versions of PYTHIA 8 fail to reproduce the observed baryon anticorrelations, as shown in Fig. 5.9 for pp and $\bar{p}\bar{p}$ pairs, as well.

From the theory side, a lot of improvements have been made. In 2019, T. Sjöstrand, a key figure behind the Lund model and the PYTHIA Monte Carlo generator, highlighted unresolved questions surrounding baryon production in proton-proton collisions. He cited that “*the real problem is baryon production [...] it is clear we still lack some fundamental insight on baryon production, at least in the string context*” [112]. His remarks pointed to the need for deeper understanding, particularly in the context of high-multiplicity events. Other studies were made within the AMPT model [113], in which a detailed analysis of two-baryon correlations suggested that the observed baryon-baryon and antibaryon-antibaryon anticorrelations in pp collisions stem from a combination of factors like initial parton-level correlations, quark coalescence, and finite parton system expansion. Recent advancements within the PYTHIA framework introduced two specific modifications to address baryon anticorrelation phenomena [114]. The first modification, the “one-baryon” policy, restricts a single string from producing more than one baryon, eliminating forward correlations but

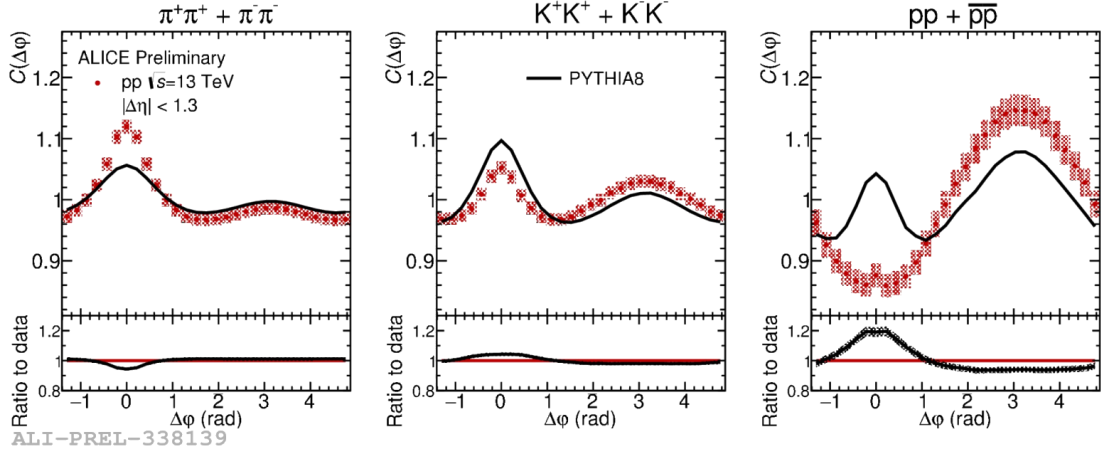


FIGURE 5.9: $\Delta\eta\Delta\phi$ correlation functions for like-sign pions, kaons and, protons in pp collision at $\sqrt{s} = 13$ TeV. PYTHIA8 model, represented by the black line is not able to reproduce the anticorrelation for like-sign protons. Picture from Ref. [111].

reducing the total baryon yield. The second, the “always-baryon” policy, ensures that every string break produces a baryon, compensating for the reduced yield and achieving better alignment with experimental results. These adjustments suggest that previously unaccounted-for Pauli-exclusion principle effects at the quark level could be responsible for the discrepancies between experimental data and existing string-based models. Another recent study [115] explored the role of gluon kinks in PYTHIA simulations, proposing that suppressing these kinks could reduce the (mini-)jet-like correlations observed in the model, further refining its accuracy.

These theoretical developments and the experimental results underscore the intricate nature of baryon production and correlations in proton-proton collisions. They highlight the interplay of initial-state effects, hadronization processes, and the potential emergence of partonic matter in small collision systems. To address these open questions, this thesis presents a detailed examination of correlation functions across various multiplicity classes for three different collision systems (pp, p-Pb, and Pb-Pb) aiming to provide fresh insights into particle production mechanisms and the origin of baryon anticorrelations.

5.4 What next?

The motivation for this thesis has been thoroughly outlined, establishing the foundation for studying two-particle correlation functions across different collision systems. The primary objectives are twofold: to compare these correlations among the three systems to uncover and better understand the underlying physics, and to analyze different multiplicity classes, enabling comparisons based on $dN_{\text{ch}}/d\eta$ values across systems. This multiplicity-dependent study is critical for understanding how angular correlations evolve with varying event activity.

The multiplicity dependence of angular correlations offers valuable insights for refining event generators and improving theoretical models, aiming to capture the complexities of high-energy collisions more accurately. High-multiplicity events, characterized by a larger number of multi-parton interactions (MPIs), provide a richer environment for exploring subleading color effects, such as color reconnection. In high-multiplicity scenarios, the finite number of color states in QCD becomes a constraining factor, increasing the likelihood of interactions between partons and amplifying the role of color reconnection. This enhances the formation of baryonic clusters or strings as more partons, moving in similar directions, combine effectively. In contrast, low-multiplicity events, with fewer MPIs and partons, exhibit weaker color reconnection effects and fewer opportunities for such interactions. These contrasting behaviors across multiplicity classes are essential for a comprehensive understanding of the mechanisms driving high-energy collisions.

In the next part of this thesis, the analysis will focus on the correlation function in small collision systems, such as pp and p-Pb collisions, across different multiplicity classes for pions, kaons, and protons of like and unlike charge. The pp collision analysis will be extended from 4 multiplicity classes to 13, incorporating events triggered by a high-multiplicity trigger. The study will include the Pb-Pb collision system, where the selected particle pairs will be analyzed across 7 centrality classes. Finally, a comprehensive comparison among the three systems will be performed to uncover underlying similarities and differences. Details regarding the applied cuts and particle selection criteria are provided in full.

Chapter 6

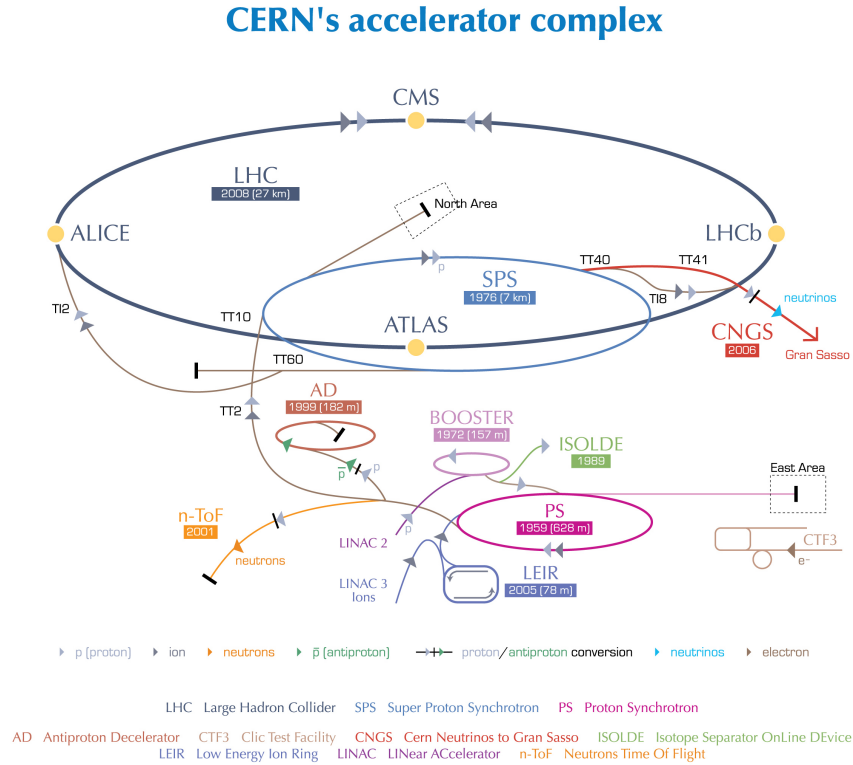
LHC at CERN

The Large Hadron Collider (LHC) [116] at CERN, near Geneva on the Swiss-French border, is the world's most powerful particle accelerator. This facility was designed to collide protons and lead ions at energies of up to $\sqrt{s} = 14$ TeV for proton–proton collisions and $\sqrt{s_{\text{NN}}} = 5.52$ TeV for lead–lead collisions, although these target energies have been gradually approached over time.

The LHC occupies a 27-kilometer ring-shaped tunnel buried approximately 100 meters underground. Inside, two beams of particles circulate in opposite directions within separate beam pipes at nearly the speed of light. The beams are directed to collide at specific points along the ring, where four main experiments—ALICE, ATLAS, CMS, and LHCb—are positioned to detect and analyze the particles created in these high-energy interactions.

The LHC's journey began on September 10, 2008, when it circulated its first proton beams. However, a malfunction in a magnet circuit shortly afterward led to a temporary halt. Following repairs, the accelerator resumed operations in 2009, and on March 30, 2010, it achieved its first high-energy collisions at $\sqrt{s} = 7$ TeV. During Run 1, the maximum energy reached was $\sqrt{s} = 8$ TeV in pp collision and $\sqrt{s_{\text{NN}}} = 2.76$ TeV in Pb–Pb collision as a precaution following the initial incident. After the first Long Shutdown, the LHC was upgraded to handle higher energies, reaching $\sqrt{s} = 13$ TeV during Run 2. A further upgrade took place from 2019 to 2022, which enabled the LHC to set a new record in 2022 with Run 3, where pp collisions reached $\sqrt{s} = 13.6$ TeV and Pb–Pb collisions attained $\sqrt{s_{\text{NN}}} = 5.36$ TeV.

An overview of the LHC and the entire CERN accelerator complex is shown in Fig. 6.1. Several smaller accelerators serve as essential intermediate stages for gradually accelerating particles before injecting them into the LHC. These accelerators also support their own independent and successful research programs, contributing valuable findings across various areas of particle physics.



European Organization for Nuclear Research | Organisation européenne pour la recherche nucléaire

© CERN 2008

FIGURE 6.1: CERN accelerator complex. Picture from Ref. [117].

6.1 ALICE experiment

ALICE, or "A Large Ion Collider Experiment", is one of the four main detectors at CERN's LHC, located near Saint Genis-Pouilly, France. ALICE is specially designed to study heavy-ion collisions, primarily involving lead (Pb–Pb) nuclei, to recreate and analyze a unique state of matter that existed just after the Big Bang, the QGP. ALICE also conducts pp and p–Pb collision studies. These serve as crucial benchmarks, providing comparative data to better interpret the results of heavy-ion collisions and enhance our understanding of QGP formation and the strong force governing nuclear matter.

ALICE's advanced detection systems and international collaboration of over 1.800 scientists allow it to probe the early universe's conditions, offering deep insights into the fundamental structure of matter and the nature of strong interactions under extreme temperatures and densities. Figure 6.2 shows the ALICE experiment along with its various subdetectors. The detector is an impressive structure, measuring 16 meters in height, 16 meters in width, and 26 meters in length. A key feature of ALICE

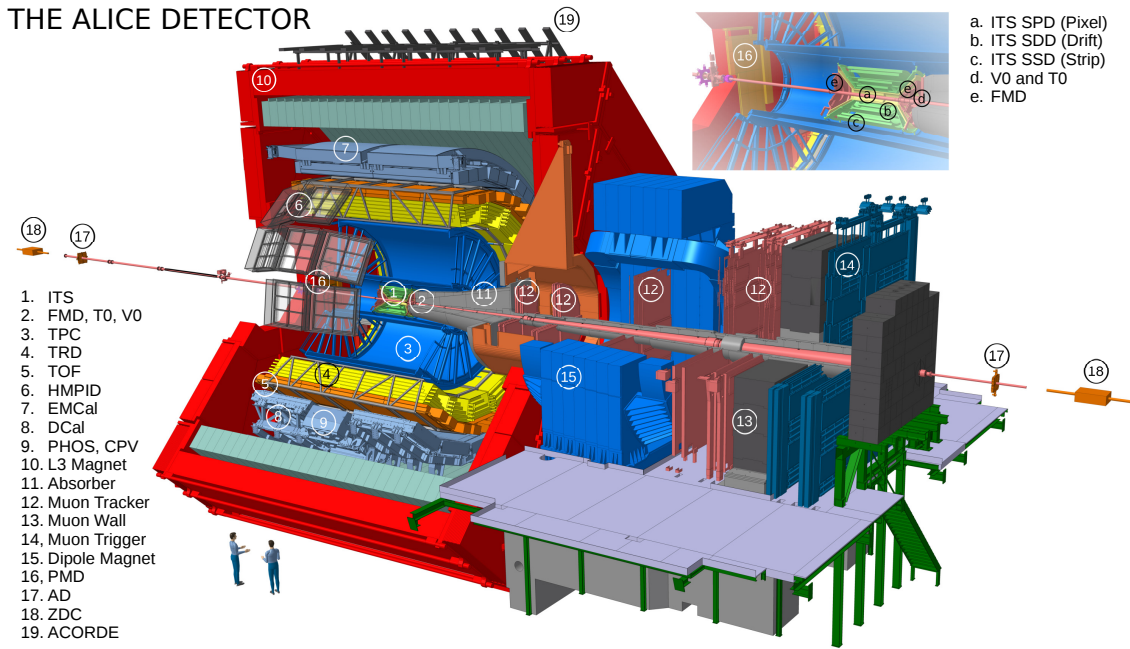


FIGURE 6.2: The ALICE experiment at LHC. Picture from Ref. [118].

is its outstanding tracking and particle identification capabilities, which span a wide momentum range—from just a few MeV/c up to 100 GeV/c. This extensive range enables the study of a broad spectrum of physics, from "soft" to "hard" interactions.

This work relies on several key detectors, detailed in the following paragraphs. The V0 detector determines multiplicity classes, which are crucial for event categorization. At the heart of the central barrel, the Inner Tracking System (ITS) plays a pivotal role in track reconstruction. The Time Projection Chamber (TPC) supports both track reconstruction and particle identification, with the Time of Flight (TOF) detector further enhancing the resolution of particle identification. These detectors collectively form the basis of the analyses conducted in this study.

6.1.1 V0 detector

The V0 detector, also referred to as VZERO, is a pair of forward scintillator arrays located symmetrically on either side of the interaction point, with one array covering the A side ($2.8 < \eta < 5.1$) and the other the C side ($-3.7 < \eta < -1.7$) [119]. These arrays, called V0A and V0C, are composed of two disks of plastic scintillator tiles, each modestly segmented into eight sections and read out via optical fibers, as is illustrated

in Fig. 6.3. The detector's pseudorapidity coverage ensures that both sides of the interaction point are adequately measured. However, due to the lower segmentation of the scintillator arrays, each segment registers a higher average number of hits, as each segment covers a larger area. The VZERO system is important in event trigger-

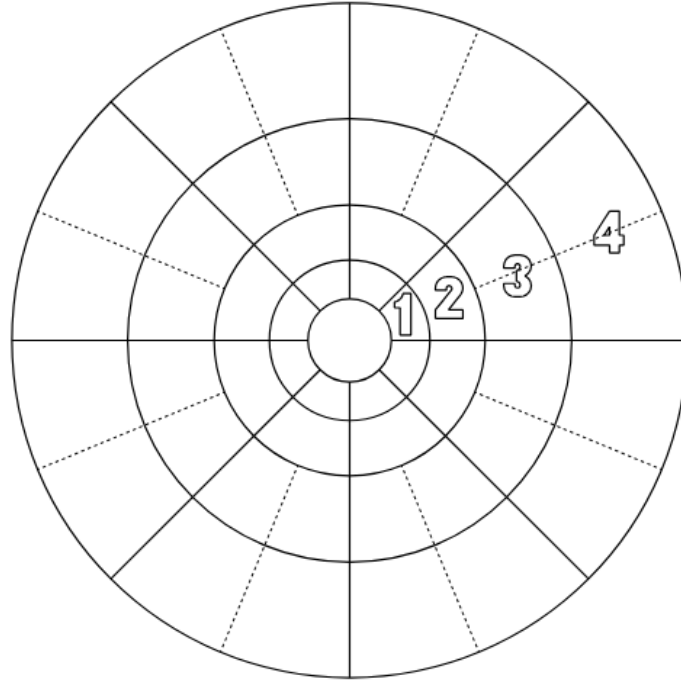


FIGURE 6.3: Segmentation of the V0A/V0C arrays. Picture from Ref. [119].

ing and particle multiplicity measurements in ALICE. It provides minimum-bias (MB) triggers for the central barrel detectors during both pp and Pb–Pb collisions by detecting events with varying numbers of charged particles, ranging from single-particle to high-multiplicity interactions. Additionally, it measures charged-particle multiplicity based on the energy deposited in the scintillators. By utilizing simulations, the relationship between the total charge collected in specific VZERO rings and the number of primary particles emitted into the corresponding pseudorapidity ranges is determined. This allows the calculation of charged-particle multiplicity, $dN_{\text{ch}}/d\eta$, in eight pseudorapidity bins, each corresponding to a VZERO ring [120].

A key function of the VZERO system is to deliver the Level 0 (L0) centrality trigger by applying energy thresholds, while also suppressing background signals, such as those from asymmetric beam-gas events or secondary particles originating in the

vacuum chamber. Although its timing resolution of approximately 0.6 ns limits its precision for determining the interaction vertex or event timing, it is highly effective in background rejection and enhances the performance of the di-muon arm. The VZERO also contributes to reaction plane determination and anisotropic flow studies, which are crucial for understanding the collective behavior of the matter created in heavy-ion collisions. With its reliable design and ability to operate in high-radiation environments, the VZERO detector remains an essential component for data collection and analysis in ALICE.

6.1.2 Inner Tracking System

The ITS [121] is located in the center of the ALICE detector. It plays an important role in

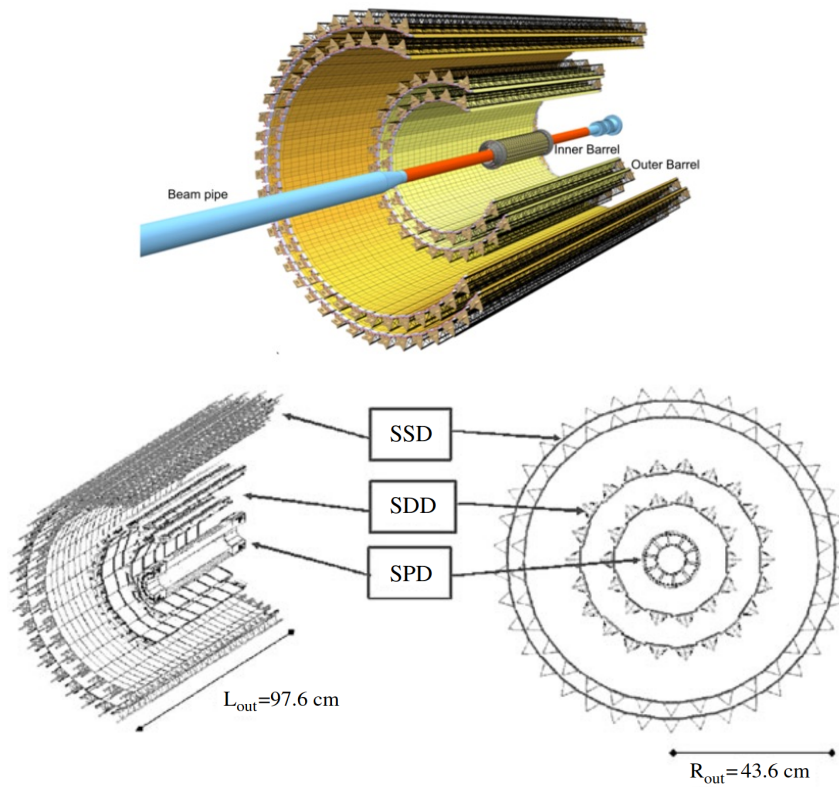


FIGURE 6.4: Layout of the ITS. Picture from Ref. [122].

determining the primary vertex with a resolution better than 100 micrometers, which is essential for accurate event reconstruction. Additionally, the ITS helps in reconstructing secondary vertices necessary for analyzing the decays of charm hadrons and hyperons. It also enables the tracking and identification of low-momentum particles,

while enhancing the momentum and angular resolution for particles reconstructed by the TPC [122].

For LHC Runs 1 and 2, the ITS consisted of six cylindrical layers, see Fig. 6.4, incorporating two layers each of Silicon Pixel Detectors (SPD), Silicon Drift Detectors (SDD), and Silicon Strip Detectors (SSD). This design provides high-precision tracking and vertex measurements, which are vital for studying the particle interactions in heavy-ion collisions.

6.1.2.1 Silicon Pixel Detectors

The ALICE SPD [123] is an integral part of the ITS and consists of two barrel layers positioned at radii of 3.9 cm and 7.6 cm, each with an active length of 28.3 cm along the beamline, offering excellent tracking coverage close to the interaction point. The detector is designed to operate in high-charged particle environments with particle densities greater than 50 particles per square centimeter, requiring excellent spatial resolution and granularity. To achieve this, the SPD features a fine pixel pitch of $50\ \mu\text{m} \times 425\ \mu\text{m}$, with a total of 8,192 pixels arranged in a matrix of 256 rows and 32 columns per chip. This arrangement provides a spatial resolution of approximately $12 \times 100\ \mu\text{m}$ in the radial ($r\phi$) and longitudinal (z) directions, essential for resolving fine details in particle tracks. The pixel design allows for precise measurement of transverse momentum, benefiting from the low material budget of the detector, with a combined thickness of $350\ \mu\text{m}$ for the silicon sensor and its readout chip, ensuring minimal multiple scattering and preserving particle track accuracy. The SPD was constructed to endure the high-radiation environment near the interaction point, ensuring its reliability and longevity during long-term operations at the LHC. Its two layers cover pseudorapidity ranges of $|\eta| < 2$ for the inner layer and $|\eta| < 1.4$ for the outer layer, providing optimal coverage for particles in the central and forward regions of the detector.

In summary, the SPD's combination of high granularity, fine resolution, low material budget, and robustness against radiation makes it an indispensable tool for studying the intricate dynamics of particle interactions in the ALICE experiment at the LHC. This robust design renders the SPD a pivotal component for the investigation of intricate particle dynamics in ALICE.

6.1.2.2 Silicon Drift Detectors

The Silicon Drift Detectors (SDDs) [123] is situated between the SPD and the Silicon Strip Detector (SSD). The detectors comprise two layers, situated at approximately 15 cm and 24 cm from the beamline. Each detector module is rectangular in design, with dimensions of 7.5 cm (anode) $\times$ 7.0 cm (drift) $\times$ 300 μm (thickness). The detector's sensitive regions are segmented into 256 anodes with a pitch of 294 μm and 292 cathodes with a pitch of 120 μm , allowing for fine granularity and precise spatial resolution. The SDDs use drift-time measurements to accurately determine the transverse position of incoming particles, with the anode segmentation contributing to the longitudinal positioning. This design achieves a spatial resolution on the order of $35 \times 25 \mu\text{m}$ in the radial ($r\phi$) and longitudinal (z) directions. By analyzing the drift time and energy deposition in each pixel, the SDDs enable precise tracking of low-momentum electrons, in particular, through enhanced particle identification capabilities. The SDDs are sensitive to small ionization signals, which are crucial for detecting low-momentum particles, making them invaluable for various physics analyses, including electron tracking and particle identification. In addition, the SDDs play a crucial role in track reconstruction. They bridge the gap between the SPD and SSD, providing highly detailed information on particle trajectories and enabling the reconstruction of continuous tracks starting from the collision point. This functionality is vital for measuring transverse momentum and reconstructing complex particle interactions. The SDDs are also key to vertex reconstruction. They work alongside other ITS layers to determine the precise location of primary and secondary vertices, which is essential for understanding particle decay processes and improving the accuracy of tracking measurements.

Overall, the SDDs contribute to the tracking performance of the ITS by offering excellent precision and granularity, essential for accurate particle tracking and momentum measurements across a wide range of collision events.

6.1.2.3 Silicon Strip Detectors

The SSD [123] is situated at the outermost layer located at radii of approximately 24 cm and 38 cm from the beamline. The SSD plays a crucial role in enhancing track reconstruction by providing precise measurements of particle trajectories, particularly in the outer regions of the ITS, and is essential for achieving high-quality tracking over a broad range of pseudorapidities. The SSD covers the acceptance range of $|\eta| < 0.97$, facilitating accurate tracking in the region beyond the SPD and SDD detectors. The

SSD is composed of a 1698 modules, each one consisting of a 1536-strip double-sided silicon sensors. These are designed to provide excellent resolution in the transverse plane, with each sensor module comprising single-sided strips with a pitch of $95\text{ }\mu\text{m}$. The strips are oriented along the radial direction of the detector, with each strip representing a precise measurement of the transverse position of the incoming particle. The spatial resolution of the SSD is primarily determined by the strip pitch and the precision of the readout electronics. With a strip pitch of $95\text{ }\mu\text{m}$, the transverse resolution is typically $60\text{--}100\text{ }\mu\text{m}$, while the resolution on the longitudinal side is about $800\text{ }\mu\text{m}$. This resolution allows for high-precision tracking, providing an essential contribution to the reconstruction of particle tracks, particularly in heavy-ion collisions, where the particle multiplicity is high. In addition to particle tracking, the SSD, as for the SPD and SDD, plays a key role in vertex reconstruction by contributing to the determination of primary and secondary vertex positions with high accuracy. This capability is particularly critical for studying decays of short-lived particles and reconstructing particle interactions in heavy-ion collisions. By linking the tracks from the inner layers of the ITS (SPD and SDD) to the TPC, the SSD provides continuous, high-resolution measurements of particle trajectories across the entire ITS. This integration is essential for improving the precision of momentum measurements and particle identification, particularly in high-density collision environments.

Overall, the SSD contributes significantly to the tracking performance of the ITS, offering exceptional spatial resolution and precise measurements of particle trajectories. This makes the SSD an indispensable component for particle tracking, momentum measurement, and vertex reconstruction in the ALICE experiment, particularly in the challenging environment of heavy-ion collisions.

6.1.3 Time Projection Chamber

The TPC of ALICE, shown in Fig. 6.5, is located in the central barrel, just beyond the ITS. It features a cylindrical structure extending from 85 cm to 247 cm from the interaction point and covers a pseudorapidity range of $|\eta| < 0.9$. It is a gas detector with an effective volume of 90 m^3 , filled with a $\text{Ne} - \text{CO}_2 - \text{N}_2$ gas mixture. A drift field of 100 kV is maintained between the central electrode, located at the centre of the detector ($z = 0$), and the two reading planes at $z = \pm 2.5\text{ m}$. As the largest TPC ever built, it serves as a high-granularity 3D tracker capable of reconstructing thousands of charged particle tracks in the extreme environment of heavy ion collisions. When a charged par-

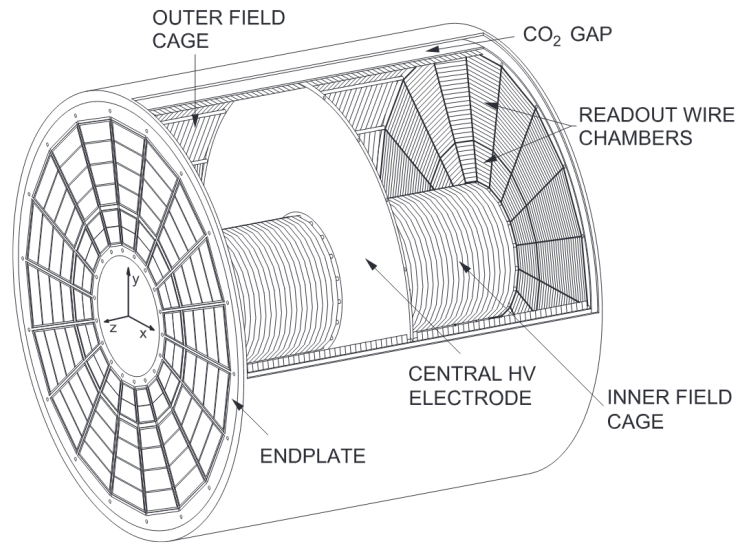


FIGURE 6.5: A schematic layout of the ALICE Time Projection Chamber.
Picture from Ref. [124].

particle passes through the TPC, it ionizes the surrounding gas, releasing electrons along its path. These electrons drift toward the readout planes under a uniform electric field, with their drift velocity carefully calibrated. The time it takes for the electrons to reach the readout plane, known as drift time¹, determines the particle's position along the z -axis (the beam direction). The readout plane records the transverse (x, y) coordinates of the particle's path based on where the electrons hit. The readout plane of the TPC consists of 570132 pads, arranged in a grid with three different pad sizes. These pads form the cathode of multi-wire proportional chambers located at the TPC end caps. The end caps are divided into 18 trapezoidal sectors, each optimized for track density by splitting them radially into two chambers, each with varying pad sizes. The pads are arranged in 159 radial rows. The detector operates in discrete time intervals, capturing signals as the electrons drift toward the end caps. The signal strength is proportional to the number of electrons, allowing the TPC to track the particle's path with sub-millimeter precision. By combining the signals from successive time intervals, the TPC reconstructs the 3D trajectory of the particle. In addition to track reconstruction, the TPC plays an important role in particle identification, as explained in detail in the 6.2 section.

¹The total drift time of the electrons is about $100 \mu\text{s}$. A dead time of about $200 \mu\text{s}$ is then applied to neutralize the environment of electrons that can distort the amplification region by drifting back to the barrel after reaching the end plates. This results in a total time of about $300 \mu\text{s}$ per read operation.

6.1.4 Time-of-Flight

The TOF detector is situated in the central barrel of the experiment, encircling the Transition Radiation Detector (TRD)², which lies between the TPC and the TOF. The TOF covers a pseudorapidity range of $|\eta| < 0.9$ and extends radially from 3.7 to 3.99 meters from the beam axis. The TOF detector is composed of a cylindrical array of Multi-gap Resistive Plate Chambers (MRPCs), which serve as highly efficient detection elements. When a charged particle passes through an MRPC, it ionizes the gas inside, creating an electron avalanche. The resulting electrical signals are collected by readout electrodes to precisely measure the particle's time of flight. The MRPCs are optimized for fast timing and excellent spatial resolution, achieving an intrinsic time resolution of approximately 80 ps. They are arranged to provide full azimuthal coverage and a wide pseudorapidity range, enabling comprehensive particle identification across the central barrel of the detector. This timing information, combined with momentum measurements from the TPC, allows the TOF system to accurately distinguish between particles of different masses.

6.2 Particle identification

Particle identification (PID) is one of the most important features of the ALICE detector, which, unlike other experiments, offers very high resolution due to the use of both the TPC and TOF detector.

The TPC provides precise information on particle momentum, charge, and energy loss (dE/dx). By measuring the specific energy loss (dE/dx), the TPC can distinguish between particle species based on their velocity and charge, as described by the Bethe-Bloch formula

$$\langle dE/dx \rangle = A_1 \cdot \frac{z^2}{\beta^2} \left[\ln \left(A_2 \cdot \frac{\beta^2}{1 - \beta^2} \right) - \beta^2 \right], \quad (6.1)$$

where $A_{1,2}$ are constants depending on the properties of the material (gas), while z and β are the charge number and velocity of the particle. The ionisation electrons produced by the passage of a charged particle drift towards the end plates of the TPC under the

²The Transition Radiation Detector is used for electron identification and jet triggering, delivering a trigger decision in about 7 microseconds. Since this analysis focuses on charged particles identified as pions, kaons, and protons, the TRD is not discussed in detail in the main text.

influence of an electric field. These electrons carry information about the particle's relativistic momentum, which can be expressed as:

$$p = \frac{m \cdot \beta}{\sqrt{1 - \beta^2}}, \quad (6.2)$$

where m corresponds to the rest mass of the particle. The final energy loss dependence on momentum and mass can be then described:

$$\langle dE/dx \rangle = A_1 \cdot z^2 \cdot \frac{m^2 + p^2}{p^2} \left[\ln \left(A_2 \cdot \frac{p^2}{m^2} \right) - \frac{p^2}{m^2 + p^2} \right]. \quad (6.3)$$

Eq. 6.3 implies that the average measured energy loss, as a function of the momentum has different functional shape depending on the mass of the particle. This property is used to determine the mass, and consequently species, of the particle based on its measured momentum and energy loss. The Bethe-Bloch curves for the TPC, together with (dE/dx) measurements from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 6.6. The black curves represent theoretical predictions for the energy loss of different particle species based on their mass. The 2D histogram shows recorded tracks characterized by their measured energy loss and momentum. Due to detector resolution effects, the measured energy loss may deviate slightly from the expected values, forming a band around the theoretical predictions. At higher momenta, the energy loss bands for different particle species overlap, making identification less reliable. In such cases, additional information from other ALICE sub-detectors is required.

The primary purpose of the TOF system is to measure the time a particle takes to travel from the interaction point to the detector. Since particles with different masses and momenta travel at different velocities, this measurement directly provides the particle's velocity, enabling effective particle identification. The precise detection time of these signals allows for an accurate calculation of the particle's time of flight, t_{TOF} . The measured t_{TOF} is then compared with the expected time for a particle traveling at the speed of light, enabling the determination of its velocity. Using momentum measurements from the TPC or ITS, the particle's mass can be calculated through the relativistic relation:

$$\beta = \frac{v}{c} = \frac{L}{t_{TOF} \cdot c}. \quad (6.4)$$

Here, L is the known distance traveled by the particle, and t_{TOF} is its measured time of

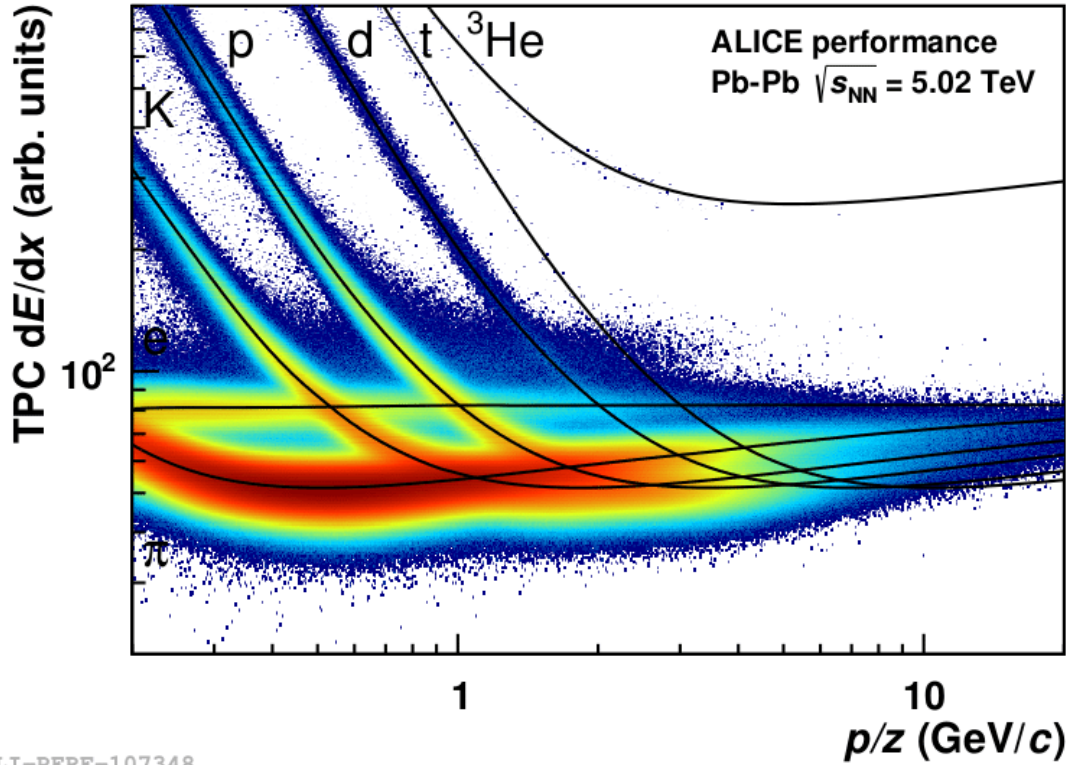


FIGURE 6.6: The energy loss as a function of momentum over charge, as measured by the ALICE TPC from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Picture from Ref. [125].

flight. This method is particularly effective at distinguishing particle species such as pions, kaons, and protons, especially in the intermediate momentum range. Figure 6.7 illustrates an example of particle velocity (β) as a function of momentum for species detected in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The figure demonstrates the ability of the TOF system to separate particles based on their unique velocity profiles. Due to its placement at a considerable distance from the interaction point, not all particles reach the TOF detector. Low-momentum particles, in particular, may be absorbed or bent back into the TPC due to magnetic field effects. Consequently, the TOF system is typically employed for particle identification in the higher momentum range, where the TPC alone lacks sufficient resolution to differentiate between particle species.

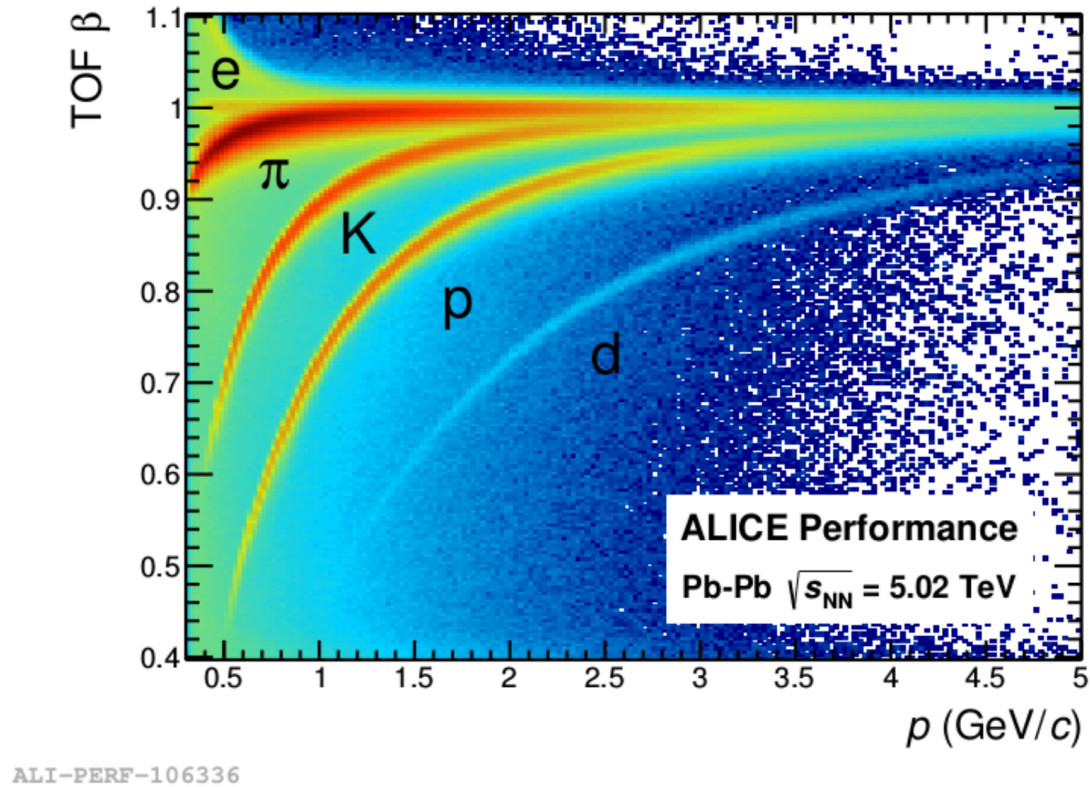


FIGURE 6.7: Particle velocity β as a function of momentum detected by TOF detector from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Picture from Ref. [125].

6.3 Software environment

This study analyzed data from ALICE Run 2 for various collision systems. For pp collisions at $\sqrt{s} = 13$ TeV, data collected during 2016, 2017, and 2018 were utilized. The analysis of p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV was based on data from 2017, while the dataset from 2015 was used for Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

The data for this analysis were stored in AOD (Analysis Object Data) files, which have been optimized for efficient access and analysis. The AOD format retains the information necessary for this analysis from the ESD files. These latter contain the complete reconstruction information, which is not required for the majority of studies. Therefore, the processing of this complete data format is not justified from a resource point of view. Due to their large size and high resource requirements, ESD files are filtered into smaller, leaner AOD files.

Both ESD and AOD files are analyzed using the *AliRoot* framework, which is an

extension of the ROOT framework. This framework was developed with the specific intention of addressing the simulation, reconstruction, and analysis requirements of ALICE. AliRoot, written in C++, utilizes the object-oriented programming paradigm to provide a modular and flexible environment. It integrates large existing libraries, such as GEANT 3 [126], GEANT 4 [127], FLUKA [128], and JETSET [129], along with other pre-existing codes, to simulate particle interactions and detector responses. AliRoot is used not only for data acquisition but also for simulation and event reconstruction. This publicly available software framework serves as the backbone of the ALICE data processing pipeline, enabling complex analyses across the collaboration. For this specific analysis, the code is developed in the *AliFemto* and *AliFemtoUser* sections within the ALICE analysis framework, *AliPhysics*, available in the AliPhysics GitHub repository [130]. The management of the substantial quantity of data generated presents a considerable challenge, as no single entity is capable of supplying the requisite computing power or storage capacity. In order to meet these demands, ALICE has adopted a grid computing infrastructure, namely the ALICE Grid Environment (AliEn). Grid computing builds upon the concept of the World Wide Web (WWW), facilitating the sharing of computational resources and data storage, as well as information. In this system, computing centres from diverse institutions collaborate by connecting to a global Grid network. Data generated by the experiment are distributed to these centres in accordance with their storage and computing capabilities. Scientists conducting the analysis can send their work without concern for the physical location of the data. The Grid infrastructure oversees task allocation and data access, ensuring the optimal utilisation of resources. To oversee and enhance this extensive system, ALICE employs MonALISA, a real-time instrument for monitoring the performance and activity of computing nodes within the Grid. MonALISA provides a comprehensive overview of the Grid, showcasing the geographical distribution and operational status of the computing centres that are connected to the ALICE Grid. As illustrated in Fig. 6.8, this distributed Grid encompasses institutions from across the globe, collectively fulfilling ALICE's computing requirements. By integrating the AliEn framework with Grid technologies, ALICE ensures the efficient management and analysis of its extensive datasets. This infrastructure enables scientists from diverse locations to collaborate seamlessly, accessing and processing data as needed to advance physics research.

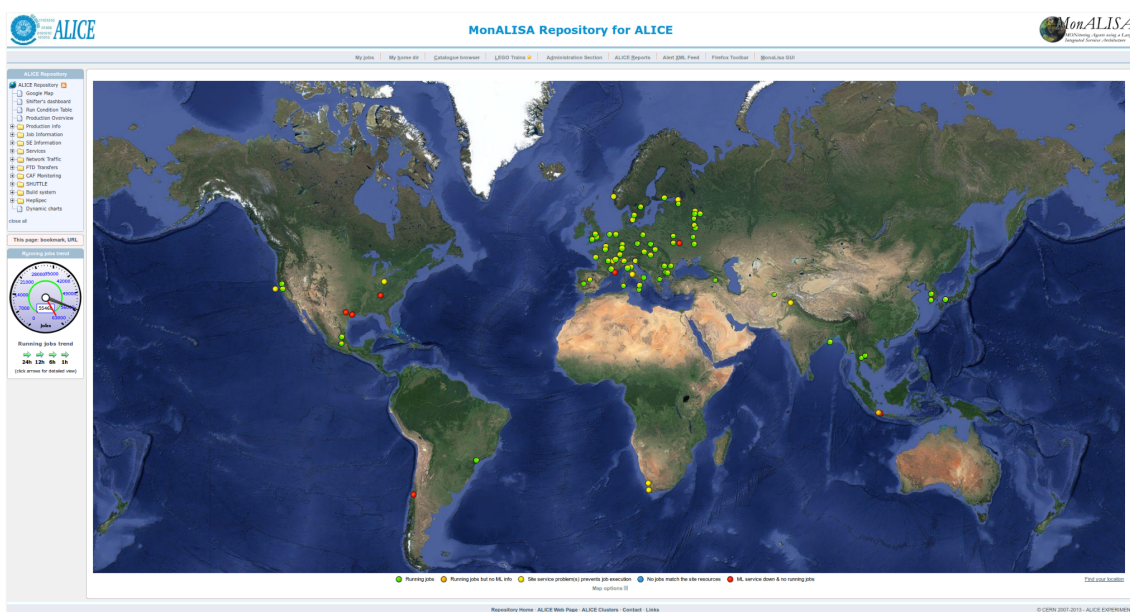


FIGURE 6.8: The MonALISA system provides a real-time overview of the ALICE GRID network. On its interactive map, dots represent the locations of computing centers worldwide that are part of the ALICE GRID infrastructure, which facilitates data storage and analysis for the experiment. The color of each dot indicates the current operational status of the corresponding computing center.

Chapter 7

Data analysis

In the following chapter, I declare that I have performed the quality control procedures for the selection of pions, kaons, protons, and their antiparticles. I have defined and finalized the analysis settings, ensuring strict selection criteria. Furthermore, I have conducted the procedures for purity, efficiency, and correction. All these analysis steps were carried out using data from pp, p–Pb, and Pb–Pb collisions within the framework of the ALICE collaboration.

This chapter provides a detailed description of the event selection, track selection, and particle identification processes for like-sign and unlike-sign pion, kaon, and proton pairs in pp, p–Pb, and Pb–Pb collisions. To enable meaningful comparison across these collision systems, it is essential to apply consistent selection criteria for events and tracks.

7.1 Event Selection

The data were recorded using both minimum bias (MB) and high multiplicity (HM) triggers. The MB trigger captures all inelastic interactions within the detector, being activated when coincident hits from charged particles are detected in both the V0A and V0C systems. In contrast, the HM trigger is based on the multiplicity of hits in the outer layer of the SPD, with a typical threshold of 80–100 hits. This trigger is particularly useful for studying rare phenomena, such as charged or neutral jets, in pp collisions. Only collisions with an event vertex within 10 cm from the center of the detector along the beam axis are accepted to the analysis. Additionally, specific selection criteria to remove pile-up collisions¹ were applied. After applying the selection

¹Pile-up occurs when multiple collisions happen simultaneously within a single bunch crossing. These additional collisions can introduce extraneous tracks that interfere with the analysis. To address

criteria, approximately 1×10^9 events in pp collisions at $\sqrt{s} = 13$ TeV, 5×10^8 events in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, and 3×10^8 events in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV were selected for this analysis.

7.2 Multiplicity and centrality selection

The analysis examines events across various multiplicity and centrality classes to understand better the complex mechanisms of color reconnection and hadronization in QCD. High-multiplicity events, which are distinguished by a greater number of multiparton interactions, create an environment rich in subleading color effects. These effects are amplified due to the finite number of color states in QCD, making phenomena like color reconnection more pronounced. Color reconnection is crucial for baryon production, as it influences how partons reorganize themselves during hadronization. In high-multiplicity events, partons moving in similar directions are more likely to interact, promoting the formation of baryonic clusters or strings.

The classification of centrality and multiplicity in this analysis follows an established framework developed by the ALICE collaboration, as described in [55]. This scheme ensures consistency across studies by using the same centrality and multiplicity estimators. The Collaboration’s work is trusted to have been done accurately, allowing reliance on their methodology for the analysis.

In A–A collisions, centrality is typically determined by correlating the measured particle multiplicity distribution with the number of nucleon–nucleon collisions (N_{coll}), as predicted by the Glauber model. For the Pb–Pb analysis in this work, the centrality classes are defined in intervals of 0–20%, 20–40%, 40–50%, 50–60%, 60–70%, 70–80%, and 80–90%. The most central events correspond to the 0–20% range, which includes the highest-multiplicity collisions, while the most peripheral class considered is 80–90%, as the 90–100% range is excluded due to limited statistics. This classification enables a systematic study of collision geometry and its effect on particle production, from nearly head-on interactions, where the overlap region between nuclei is maximal, to peripheral events, where only a small number of participating nucleons contribute to the interaction.

In smaller systems such as pp and p–Pb collisions, the relation between multiplicity and N_{coll} is much weaker. This is because particle production in these systems is

this, specialized algorithms and selection criteria devised by the ALICE Data Preparation Group (DPG) are employed to identify and exclude such events.

dominated by fluctuations, making it difficult to reliably estimate centrality based on multiplicity alone. As a result, relying on multiplicity to define centrality in pp and p–Pb can introduce significant biases. To address this, results for these systems are typically reported either for the full minimum-bias sample or divided into multiplicity classes, which are not directly linked to N_{coll} . In this analysis, pp and p–Pb events recorded by ALICE are grouped into multiplicity classes as a percentage of the total inelastic cross-section, such as 0–20%, 20–40%, 40–70%, and 70–100%. Additionally, the pp collision analysis includes a more granular division of multiplicity classes, exploiting the high-multiplicity trigger to study rare, extremely high-multiplicity events, such as those corresponding to the 0–0.17% multiplicity class.

7.3 Track Selection

The analysis uses tracks reconstructed within the kinematic acceptance defined by $|y| < 0.5$, with (p_T) ranging from 0.2 to 2.5 GeV/ c for pions, and from 0.5 to 2.5 GeV/ c for kaons and protons. The lower p_T selections were selected based on the p_T dependence of dE/dx (see Fig. 6.6 in Sec. 6.2), ensuring minimal contamination. Specifically, for kaons and protons, the minimum p_T was set to 0.5 GeV/ c for two reasons: (i) below this threshold, the number of kaons and protons is significantly reduced, and (ii) to enhance particle identification, where TOF is used for better separation starting from this p_T value.

Particle trajectories were reconstructed using the ITS and the TPC detectors, following a multi-step process using the Kalman algorithm [122]. The tracking process begins at the outer edge of the TPC, where initial track candidates are found. These are used as starting points for the fitting algorithm, which moves inward to the center of the TPC. After that, the ITS takes over and extends the tracks as close as possible to the primary vertex. The second phase involves tracking from the primary vertex to the outer edge of the TPC. In the third phase, the track is readjusted to the primary vertex, first using the TPC and then using the ITS.

For a track to be included in the analysis, it must contain at least 70 clusters. Each cluster corresponds to the ionization signal produced as a particle passes through the TPC, recorded on a specific pad row. Although the TPC can have up to 159 pad rows, some clusters may be missed due to detector dead zones or signals below the detection threshold. Tracks with significant gaps in their trajectory, indicated by large spatial points where clusters are missing, or tracks associated with false signals are excluded

from the analysis. The quality of the trajectory is assessed using the chi-square (χ^2) per cluster, with two degrees of freedom per cluster. Tracks with a χ^2 per cluster greater than 4.0 are rejected to ensure that only high-quality trajectories are considered. At the ITS stage, each track must include at least one hit in the SPD. This requirement ensures that the track is accurately linked to the primary vertex. The SPD's proximity to the collision point and its high spatial resolution enable precise tracking of particle positions. To guarantee that only primary-particle tracks were selected and minimize contributions from the background and secondary particles, a requirement was imposed that each track must closely approach the primary interaction vertex. This proximity is quantified using the Distance of Closest Approach (DCA), with specific thresholds applied depending on the collision system. In pp and p-Pb collisions, the DCA to the primary vertex was constrained to less than $0.0182 + 0.0350/(p_T/(\text{GeV}/c))^{-1.1}$ cm in the transverse plane corresponded to XY plane and less than 1 cm along the beam axis. For Pb-Pb collisions, particle reconstruction is based only on information from the TPC. However, when considering the DCA from the primary vertex, the measurement incorporates both ITS and TPC information. In the transverse plane, the DCA is constrained to be less than $0.0105 + 0.0350/(p_T/(\text{GeV}/c))^{-1.1}$ cm and less than 1 cm along the beam axis.

Basic quality assurance (QA) plots for the Monte Carlo data from pp collisions at $\sqrt{s} = 13$ TeV, taken during the 2017 period, are shown in Figs. 7.1 and 7.2. The QA plots are displayed for the highest and lowest multiplicity classes, covering positive and negative pions, kaons, and protons. In the ϕ - y distributions shown in Fig. 7.1, each entry represents a single particle, with colors indicating the number of entries within the acceptance, convolved with the detector efficiency. While a uniform distribution in both ϕ and rapidity (y) is expected, specific structures are evident due to the geometry, efficiency, and intrinsic characteristics of the TPC and TOF detectors. For pions, the plot on the x -axis stops at 0.5, reflecting the rapidity acceptance and the inclusion of TOF in the particle identification (PID) at this point. In contrast, kaons and protons exhibit higher contamination levels, with their plots extending to 0.7 and 0.9, where particle counts diminish, as shown by the blue regions. A gap near $(0, -1.5)$ is visible, attributed to the PHOTon Spectrometer (PHOS) partially obstructing the TOF detector. The QA plots represent the highest and lowest multiplicity classes in pp collisions, corresponding to the 0–20% and 70–100% multiplicity ranges, respectively. The reduced number of entries in the 70–100% class reflects the smaller number of events in this category rather than any issue with detector performance.

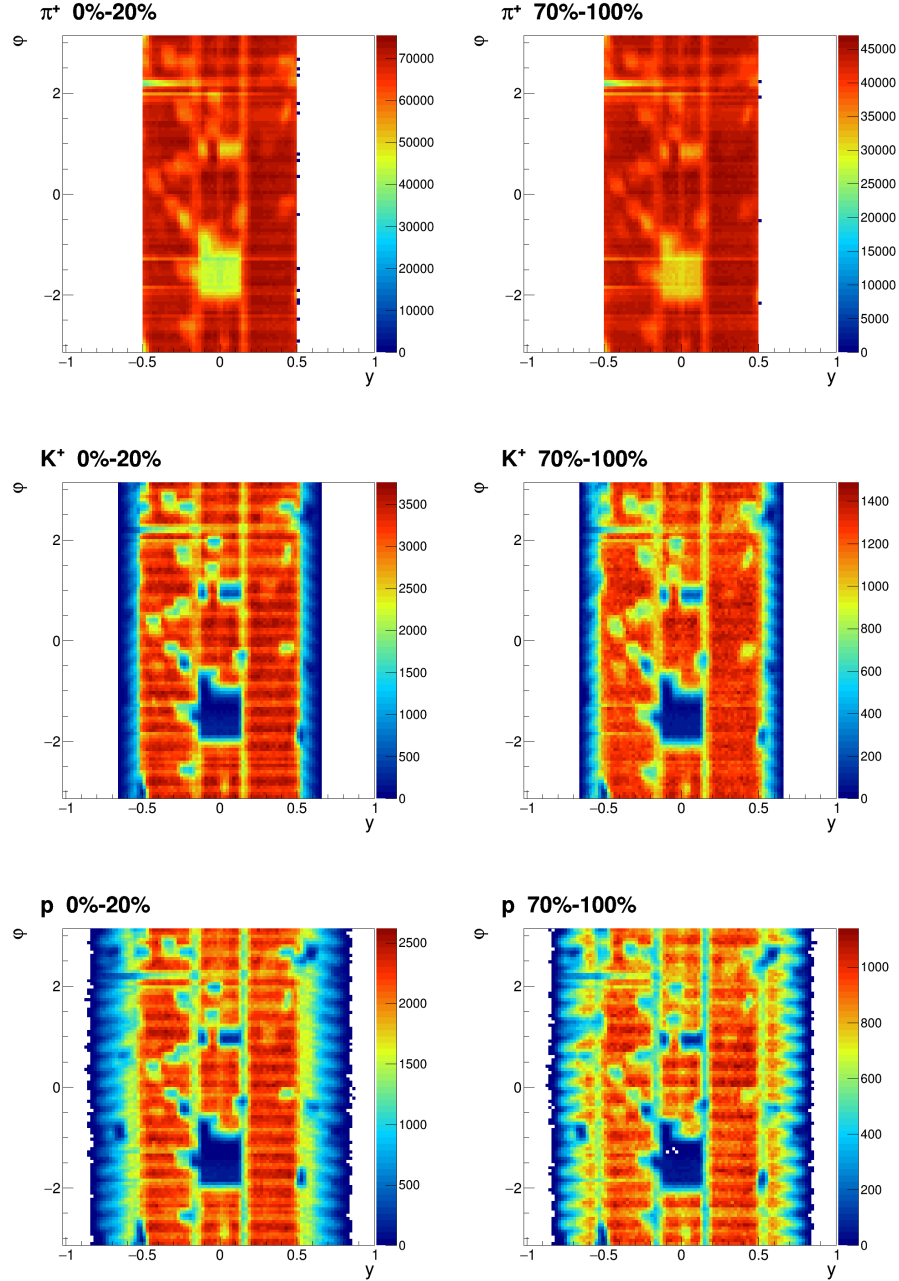


FIGURE 7.1: ϕ as a function of y distribution for positive pions, kaons, and protons in the highest (0–20%) and lowest (70–100%) multiplicity classes from pp collision at $\sqrt{s} = 13$ TeV.

Figure 7.2 displays the ϕ – p_T distribution, where the z-axis represents the number of entries in the single-particle distribution. The color scale, ranging from red to blue, indicates the expected particle counts, with higher densities represented in red. Results

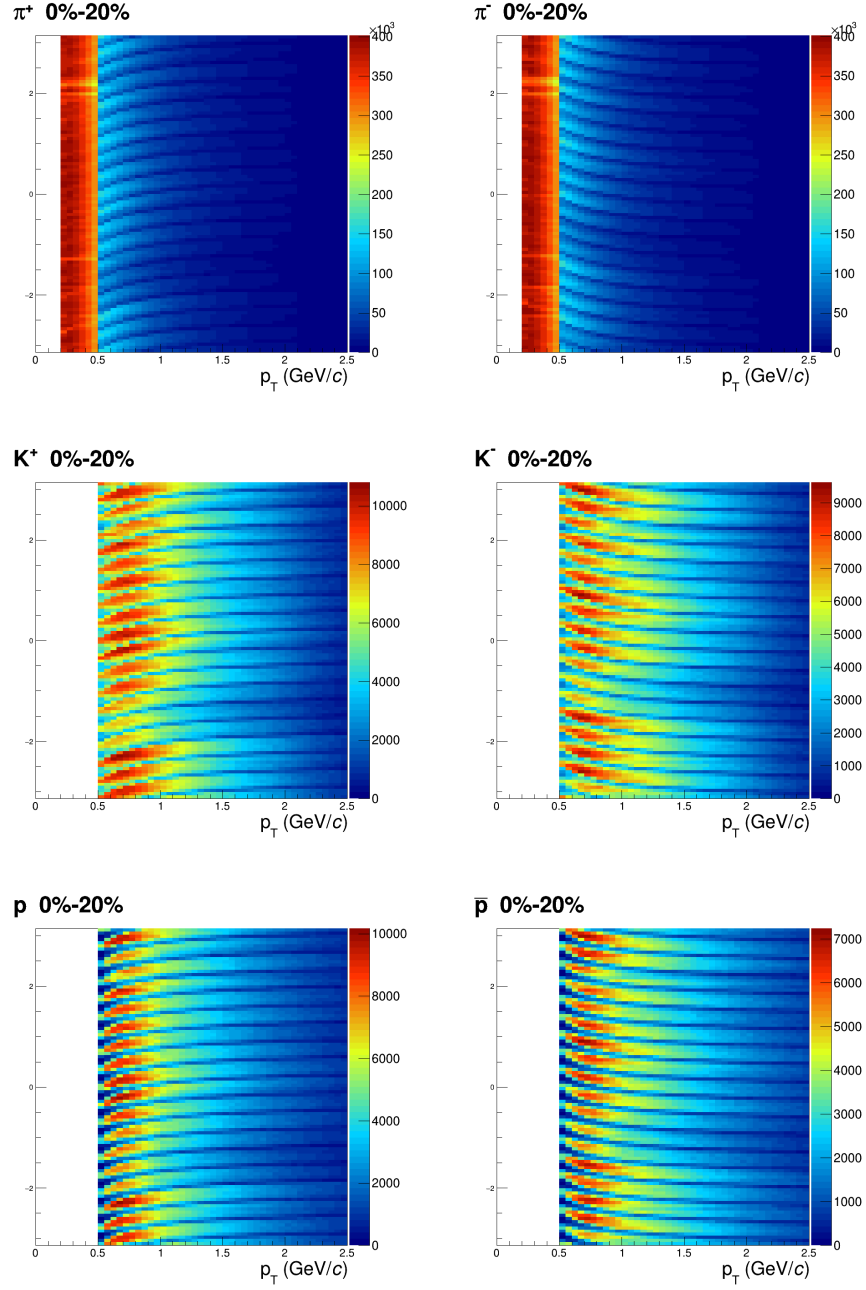


FIGURE 7.2: p_T vs ϕ distribution for positive pions, kaons, and protons on the left column and for negative pions, kaons and protons on the right column in the highest (0–20%) multiplicity classes from pp collision at $\sqrt{s} = 13$ TeV.

are shown for positive and negative pions, kaons, and protons in the highest multiplicity class (0–20%). The influence of TPC sectors is evident, with distinct deviations for

positively and negatively charged particles due to the magnetic field. For pions within a p_T range of 0.2 to 2.5 GeV/ c , a gap around 0.5 is marked by the inclusion of the TOF detector in the PID. This feature is absent in the kaon and proton plots because their p_T ranges start at 0.5 GeV/ c .

QA checks were conducted on all experimental and Monte Carlo datasets, covering a range of particle species, collision systems, multiplicity classes, and centrality intervals. These single-particle distributions provide insight into the complex structure of the detector efficiency. Specifically, the plots are analyzed for patterns that could indicate differences in detector acceptance, such as variations between sectors of the TPC, edge effects, or momentum-dependent features. For example, the transverse momentum dependence arises due to the varying curvature of tracks in the TPC. These expected patterns are captured in the QA plots. By examining and identifying the anticipated structures, one can confidently verify the accuracy of the data. However, if unexpected structures are detected, it suggests potential issues with the data. In such cases, the data undergoes reanalysis or rejection to maintain the integrity of the analysis.

Without separating the mixed-event background from the signal, such complexities would propagate into the correlation functions, as was described in Sec. 4.3.1.

7.4 Particle Identification

Particle identification, detailed in Sec. 6.2, is performed using data from the TPC and TOF detectors. The PID technique relies on the N_σ method, where σ represents the uncertainty associated with the measured signal, either from the Bethe-Bloch curve (for the TPC) or the time-of-flight (for the TOF). Experimentally, the uncertainty has been found to follow a Gaussian distribution and σ is associated with the standard deviation of the distribution. If the signal from the TPC detector is analyzed, the corresponding value is $N_{\sigma\text{TPC}}$, and if the TOF signal is considered, it is $N_{\sigma\text{TOF}}$. The selections used in this analysis for pp, p–Pb, and Pb–Pb collision systems are as follows:

- particle are accepted:
 - $p_T < 0.5 \text{ GeV}/c$: $N_\sigma = |N_{\sigma\text{TPC}}| < 2.0$;
 - $p_T > 0.5 \text{ GeV}/c$: $N_\sigma = \sqrt{N_{\sigma\text{TPC}}^2 + N_{\sigma\text{TOF}}^2} < 2.0$;
- particle are rejected:

- if the track passes the $N_{\sigma, PID} < 3$ for more than one particle species.

Figure 7.3 show the $N_{\sigma TPC}$ vs $N_{\sigma TOF}$ distribution for positive and negative pions, kaons, and protons from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for the highest (0–20%), middle (50–60%), and lowest (80–90%) centrality classes. The distribution gives us information about how far the signal of TPC and TOF is from theoretical predictions.

7.5 Two-track particle pairs selections

Pairs of particles emitted from collisions with nearly identical momenta and small angular separations $(\Delta y, \Delta \phi) \approx (0, 0)$ are influenced by effects such as track merging and track splitting. **Track merging** occurs when two spatially close tracks are mistakenly reconstructed as a single track, leading to a deficit of close pairs relative to unaffected pairs [131]. In contrast, **track splitting** arises when a single track is incorrectly reconstructed as two closely spaced tracks, resulting in an excess of close pairs compared to an uncorrelated sample [131]. To mitigate the bias introduced by these effects, a cut is applied to the track separation, removing affected pairs from both the Signal distribution (correlated pairs) and the Background distribution (uncorrelated pairs) in the correlation function.

The selections used to eliminate split tracks consist of two components. The first is the *share quality*, which measures the difference between the number of clusters shared by two tracks on the same TPC pad row and the total number of clusters belonging to those tracks. If the share quality is positive, the tracks share more clusters than they have individually, indicating a potential splitting issue. The second component is the *share fraction*, defined as the fraction of shared clusters relative to the total clusters of the two tracks. Since split tracks typically share a significant portion of their clusters, pairs with a share fraction greater than 5% are excluded. These criteria are applied across pp, p–Pb, and Pb–Pb collision systems to ensure the reliability of the correlation functions.

In the case of p–Pb and Pb–Pb collisions, where the high density of particles increases the probability of track reconstruction errors, an additional approach, referred to as the **Radial Distance Method**, is employed. This method examines the pair’s separation using specific variables designed to identify problematic pairs.

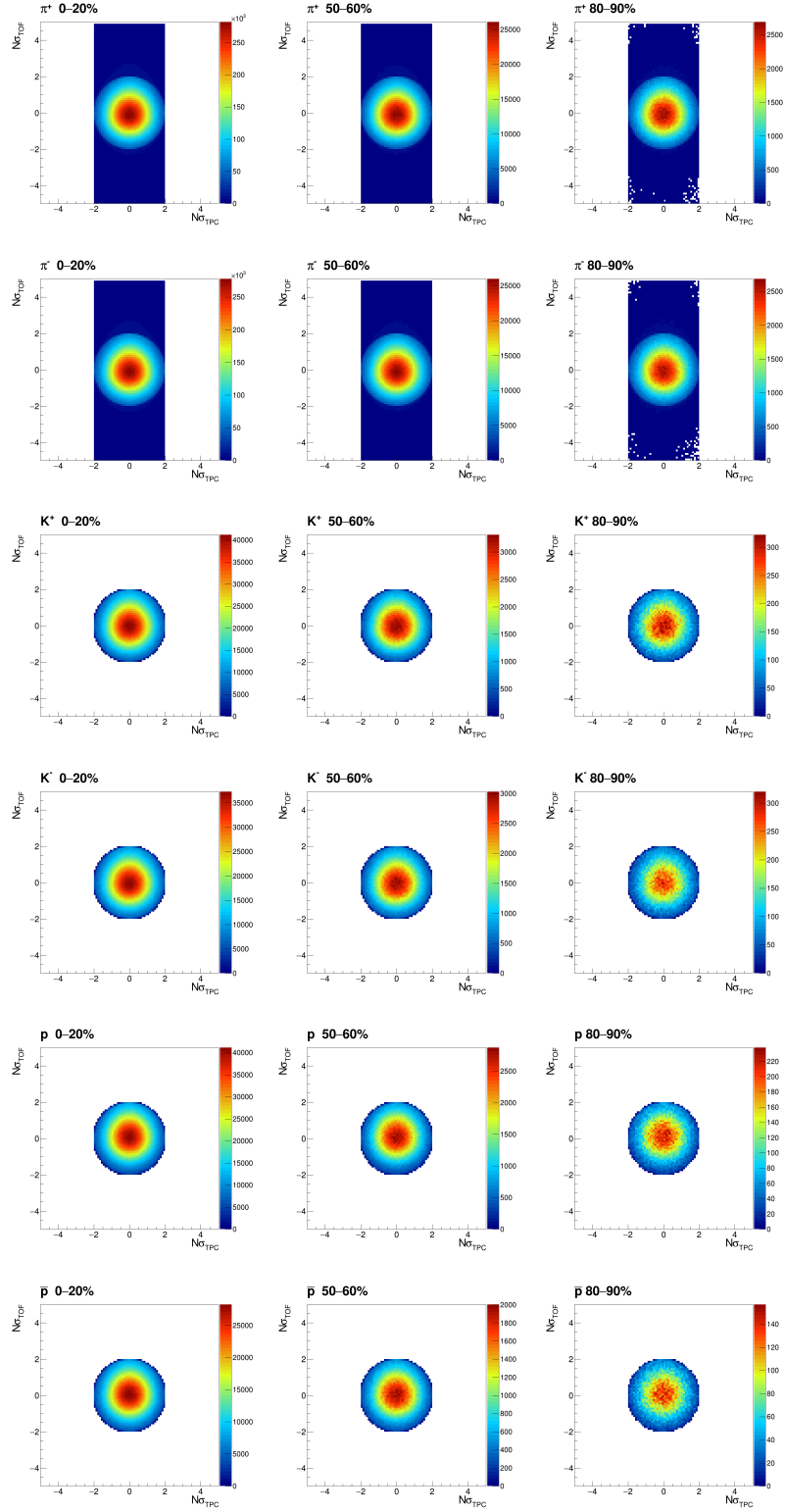


FIGURE 7.3: $N_{\sigma_{\text{TPC}}}$ vs $N_{\sigma_{\text{TOF}}}$ distributions for the Monte Carlo dataset from Pb–Pb collision system at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for all particle types studied and for the highest (0–20%), middle (50–60%), and lowest (80–90%) centrality classes.

- $\Delta\varphi^*$, the adjusted angular difference in azimuth, measures how far apart the tracks are in the horizontal plane. Unlike $\Delta\varphi$, which represents the geometric azimuthal angle at the vertex, $\Delta\varphi^*$ accounts for the curvature of particle trajectories caused by the magnetic field. It is defined as:

$$\Delta\varphi^* = \Delta\varphi_2^* - \Delta\varphi_1^* = \varphi_2 - \varphi_1 + \arcsin\left(-\frac{0.3B_z R}{2p_{T2}}\right) - \arcsin\left(-\frac{0.3B_z R}{2p_{T1}}\right), \quad (7.1)$$

where φ_1 and φ_2 are the azimuthal angles of the tracks at the vertex, p_{T1} and p_{T2} are their transverse momenta, B_z is the magnetic field strength in the z -direction, and R is the radial distance from the collision point where the tracks are measured. By incorporating these corrections, $\Delta\varphi^*$ provides a precise description of the particle trajectories as observed in the detector.

- $\Delta\eta$ measures the separation of the tracks in pseudorapidity space, which is related to the polar angle.

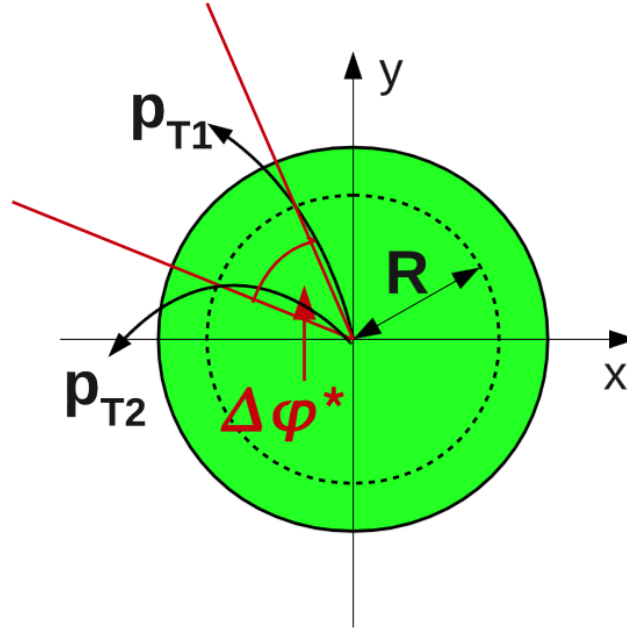


FIGURE 7.4: Schematic view of the $\Delta\varphi^*$ angle in the azimuthal space. Picture from Ref. [131].

The areas where these errors (such as merging or splitting) occur depend on the type of beam and the detector geometry. Within the ITS, located between 0.2 m and 0.8 m from the collision point, reconstruction errors are minimal and broadly distributed.

At larger distances, from 0.8 m to 2.5 m, corresponding to the volume of the TPC, these inefficiencies become more significant due to increased track densities and longer trajectories. To address this, the Radial Distance Method calculates $\Delta\varphi^*$ for particle pairs at radial positions ranging from 0.8 m to 2.5 m, with calculations performed at every 0.01 m increment. For p–Pb and Pb–Pb analyses, the following selection criteria are applied:

- $\Delta\varphi^* \geq 0.05$ radians.
- $\Delta\eta \geq 0.015$ radians.

Figures 7.5 and 7.6 show the correlations between $\Delta\varphi^*$ and $\Delta\eta$ for like-sign pions, kaons, and protons, based on Monte Carlo-reconstructed data. Similar analyses were also performed for oppositely charged particle pairs.

For like-sign pions, as shown in Fig. 7.5, the white rectangle represents the applied cuts in $\Delta\varphi^*$ and $\Delta\eta$. These selections ensure that the correlation remains stable across different radial and multiplicity classes, demonstrating their consistency and reliability throughout the TPC volume. Notably, the physical structures near (0,0) persist across all radii, confirming that the cuts do not inadvertently suppress significant correlation features. This validates the effectiveness of the selection criteria in isolating the relevant correlation signals. For like-sign kaons and protons, as shown in Fig. 7.6, the selection criteria have minimal impact on the final correlation function, primarily due to lower statistics compared to pions. However, the cuts are still carefully optimized to ensure that no meaningful physical structures are lost. Despite the reduced statistics, the observed correlation features remain intact, confirming that the selections preserve the underlying physical signals without introducing distortions. Once these cuts are established, they are applied to both the signal and background distributions to remove particle pairs that could introduce artificial correlations due to merging or splitting effects.

In the pp analysis, in addition to the share quality and share fraction requirements used to mitigate merging and splitting effects, an alternative approach is employed to address potential impacts on the correlation, such as photon conversion, which produces a narrow peak. As discussed in Sec. 4.4.5, this arises from track misidentification. To mitigate bias, a method called **minimum average separation** is applied. This method calculates the invariant mass of an electron-positron pair originating from photon decay, where the invariant mass is ideally zero. Therefore, pairs with an invariant mass below 0.2 are discarded. Furthermore, photon conversions occur at the same

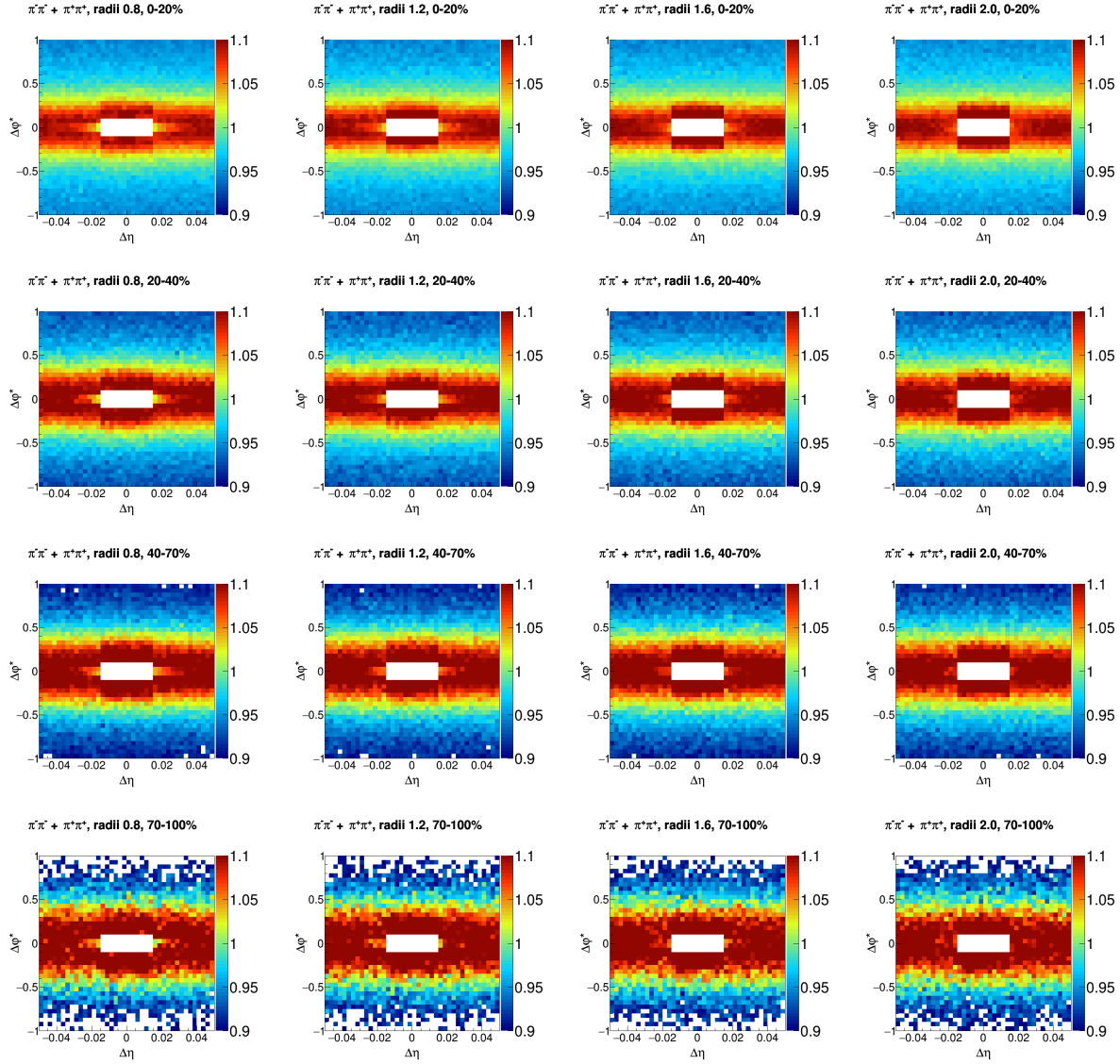


FIGURE 7.5: $\Delta\eta\Delta\phi^*$ correlation functions performed for experimental data from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for all multiplicity classes and for four radii (0.8, 1.2, 1.6, and 2.0) cm for like-sign pions.

pseudorapidity. Although the transverse plane may exhibit a slight angular difference due to the bending of the magnetic field, the polar angle for both particles should remain identical, as there is no reason for their directions to diverge. To further minimize misidentification and ensure the selected tracks align with the expected characteristics of photon conversions, a cut on the polar angle difference of approximately 0.008 radians is applied. This cut is designed to very strictly remove only those particles with a small difference in $\Delta\theta$. This ensures that potential candidates from photon conversion

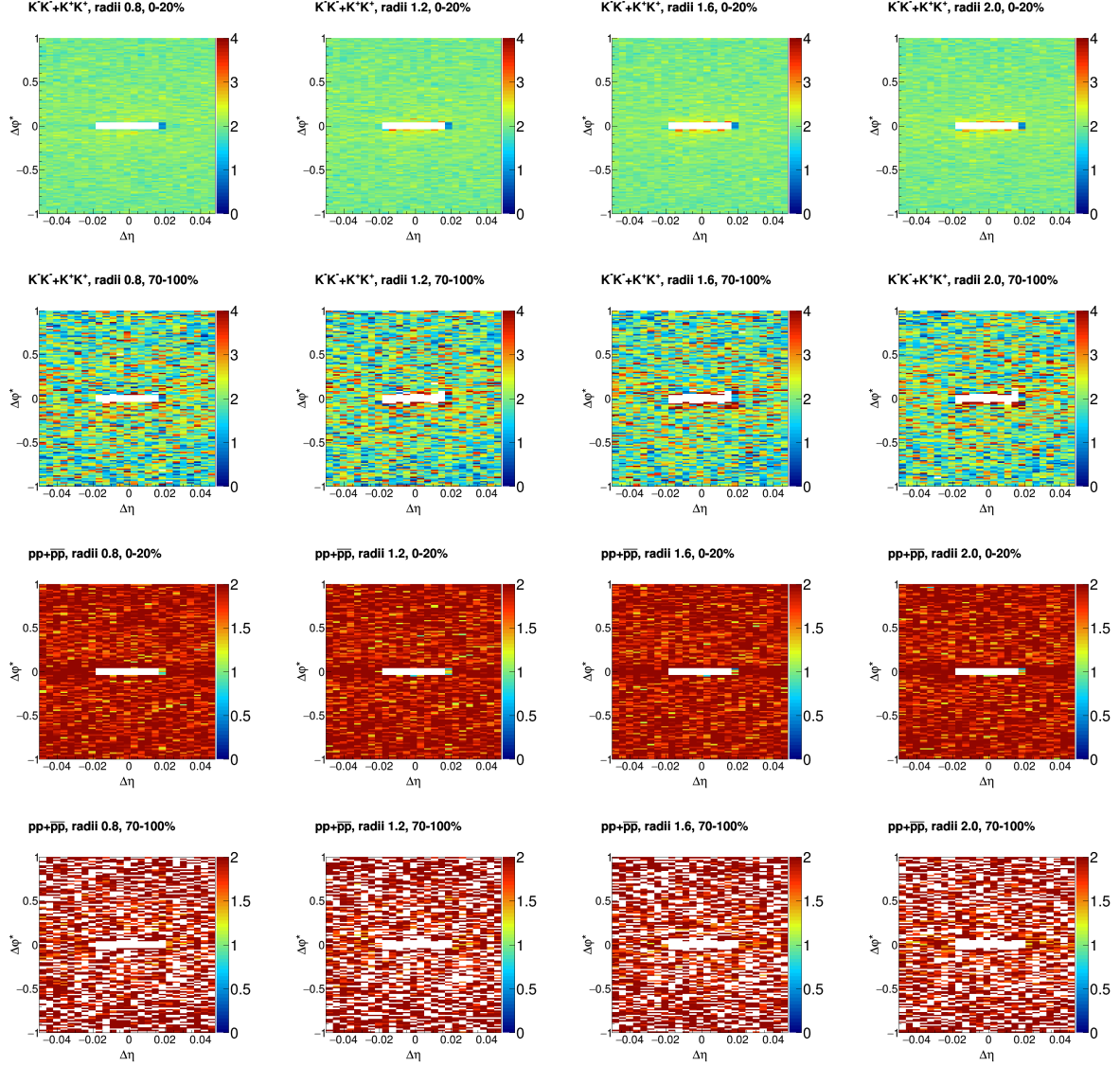


FIGURE 7.6: $\Delta\eta\Delta\phi^*$ correlation functions performed for experimental data from p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for the highest and the lowest multiplicity class and for four radii (0.8, 1.2, 1.6, and 2.0) cm for like-sign kaons and protons.

are effectively removed. It is important to note that only pairs fulfilling both criteria—the invariant mass cut and the polar angle difference cut—are discarded, thus ensuring a more stringent selection of tracks.

7.6 Purity and Efficiency Corrections

7.6.1 Purity

Purity is a measure of how accurately a sample reflects the presence of particles of the desired type. Specifically, it represents the percentage of correctly identified particles of the target species (e.g., species A) relative to the total number of particles in the sample. Mathematically, purity (P) is defined as:

$$P = 1 - C_{\text{PID}}, \quad (7.2)$$

where C_{PID} (contamination) is the fraction of particles in the sample that do not belong to species A. A purity of 1 (or 100%) indicates no contamination, meaning every particle in the sample belongs to the desired species. In simpler terms, the higher the purity, the "cleaner" the sample, with fewer misidentified or unwanted particles.

To evaluate the quality of PID purity, dedicated Monte Carlo (MC) simulations are employed, providing detailed information about the particles in each event. This process involves comparing *Monte Carlo true data* with *Monte Carlo reconstructed data* to derive the purity. The MC true data represents the simulated particle-level information generated by Monte Carlo event generators, offering a precise depiction of the underlying physics processes without being affected by detector resolution, acceptance, or inefficiencies. The reconstructed MC data are obtained by running the real MC data through a full detector simulation and reconstruction, replicating the same conditions and limitations found in the real experimental data. This process begins with particles from the MC truth sample being propagated through the detector volume and materials using the GEANT3 [126] transport package. The transport package not only models the particle transport, but also simulates the detector response at the final stage. This comprehensive simulation provides a realistic representation of how the particles interact with the detector, replicating the conditions and limitations found in real experimental data. In this thesis, the analysis relies on various Monte Carlo generators tailored to pp, p–Pb, and Pb–Pb collisions, which are detailed in subsequent sections. These simulations are aligned with the corresponding experimental data and account for all technical aspects of data acquisition.

PID purity is determined by comparing the distributions (e.g., p_T) of particles that meet the selection criteria and are verified as true pions, kaons, or protons, with the distribution of all particles passing the same selection requirements, regardless of their

true identity. This approach enables the evaluation of purity by assessing the selection's ability to correctly identify the target particles while minimizing contamination.

7.6.1.1 Purity in pp collisions

Figure 7.7 presents the purity of pions, kaons, and protons obtained using Monte Carlo reconstructed data from the 2017 period at $\sqrt{s} = 13$ TeV, corresponding to the PYTHIA8_Monash13 generator. For all particle species, the purity of particles is con-

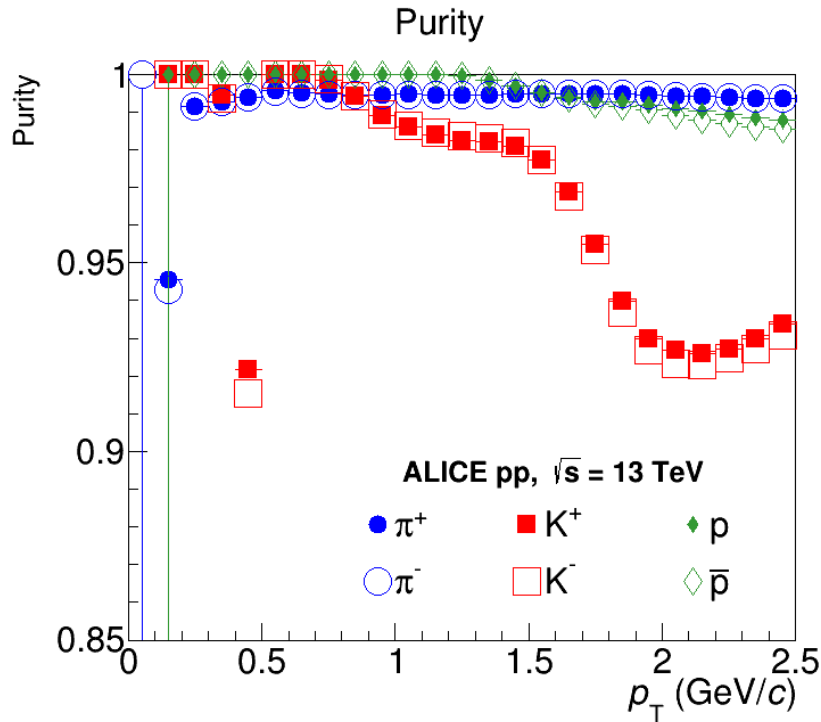


FIGURE 7.7: Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2017 period from pp collision at $\sqrt{s} = 13$ TeV.

sistent with that of antiparticles, as evidenced by the similar behavior of filled and empty markers. The kaon sample exhibits a noticeable dip at 0.5 GeV/c, which can be attributed to the overlap between the electron and kaon signals in the dE/dx energy loss plot measured in the TPC, as shown in Fig. 6.6. However, this contamination does not impact the purity of the sample, as the selected p_T range for kaons is between 0.5 and 2.5 GeV/c, effectively excluding the affected region. Additionally, kaons exhibit lower purity compared to pions and protons, primarily due to contamination from secondary particles such as pions and electrons, which overlap with the kaon PID region

(as shown in Fig. 6.6 from Sec. 6.2). This contamination occurs during the selection process. Despite this, the overall purity remains high, with kaon purity exceeding 98%, and pion and proton purity exceeding 99%.

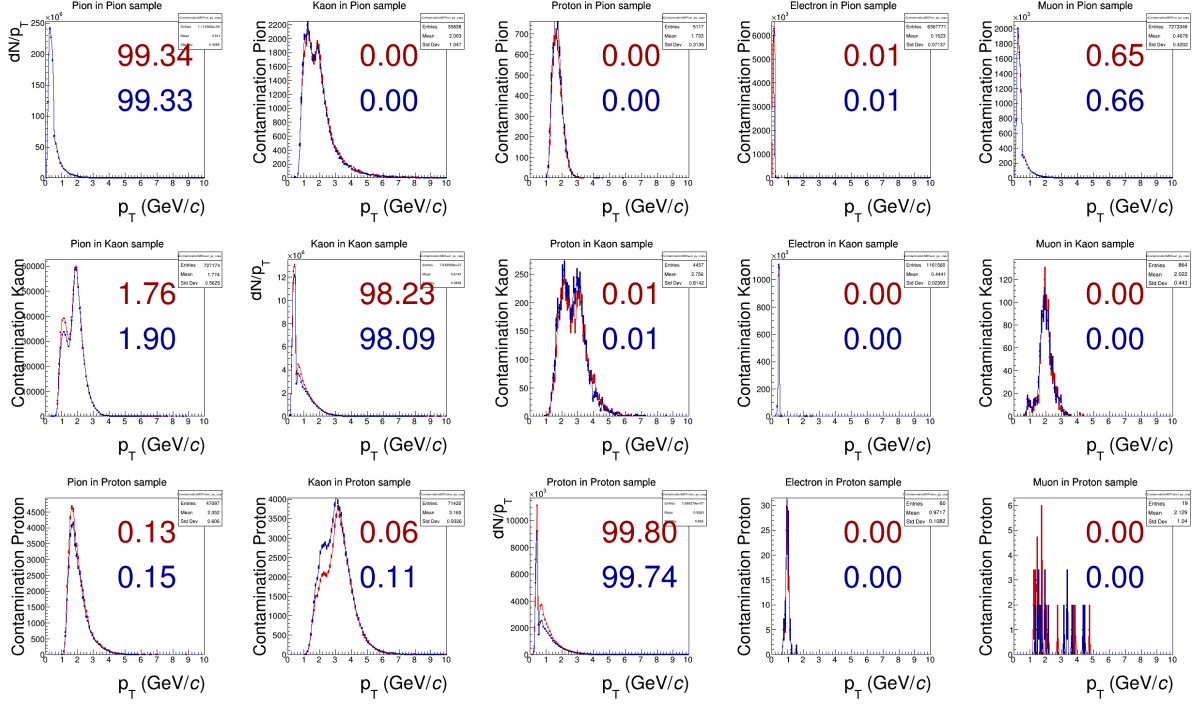


FIGURE 7.8: Contamination levels from pp collision at $\sqrt{s} = 13$ TeV, in samples of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/ c for pions, and 0.5–2.5 GeV/ c for kaons and protons.

The percentage composition of pions, kaons, protons, electrons, and muons in each particle sample is illustrated in Fig. 7.8. The rows of the histograms correspond to the pion, kaon, and proton samples, while the columns represent the contributions from pions, kaons, and protons. Contributions from electrons and muons are negligible. The histograms are color-coded, with red representing particles and blue representing antiparticles. The associated values, shown in the same color, indicate the percentage purity of the observed samples within the selected p_T ranges: 0.2–2.5 GeV/ c for pions and 0.5–2.5 GeV/ c for kaons and protons. The pion sample shows negligible contamination, whereas the kaon sample exhibits a 2% contamination from pions, which slightly lowers its purity. The proton sample maintains high purity with minimal contamination.

7.6.1.2 Purity in p–Pb collisions

Similar results regarding purity and contamination were obtained for p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using a reconstructed Monte Carlo dataset from the 2017 period which corresponds to the DPMJET MC generator. Figure 7.9 illustrates behavior simi-

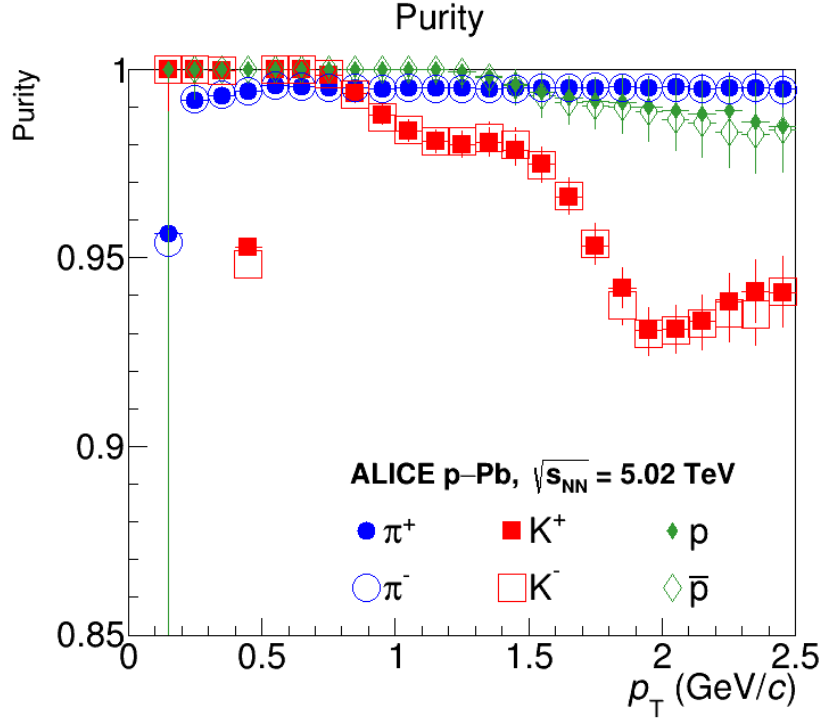


FIGURE 7.9: Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2016 period from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

lar to that observed in the pp analysis, including a drop at $0.5 \text{ GeV}/c$ for kaons. However, this feature is not relevant for the current analysis, as the p_T range selected for kaons begins at $0.5 \text{ GeV}/c$. The figure highlights the high purity levels, which is calculated within the p_T ranges chosen for each particle. For pions and protons an integrated purity exceeding 99%, while for kaons, the purity gradually decreases at higher p_T values. Overall, as shown in the grid in Fig. 7.10 the kaon sample maintains an integrated purity above 98%, with approximately 1.5% contamination from pions.

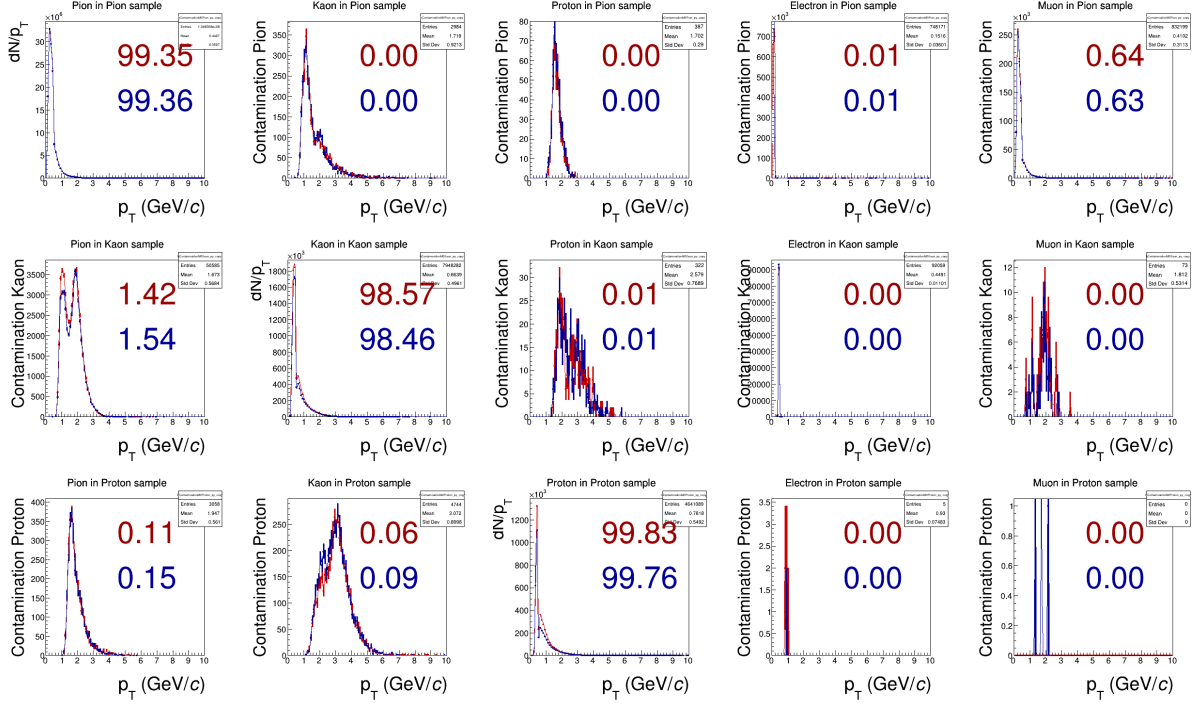


FIGURE 7.10: Contamination grid of p-Pb samples at $\sqrt{s_{NN}} = 5.02$ TeV of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/c for pions, and 0.5–2.5 GeV/c for kaons and protons.

7.6.1.3 Purity in Pb–Pb collisions

The particle purity in Pb–Pb collisions was evaluated using a 2017 dataset at $\sqrt{s_{NN}} = 5.02$ TeV, simulated with the AMPT model. The purity trends closely resemble those observed in pp and p–Pb collisions.

For pions, the purity is approximately 97%, with contamination primarily from muons, which contribute 2.3%. The kaon sample also achieves a purity of around 97%, with a ~2% contamination from misidentified pions during the PID process. Protons exhibit the highest purity, exceeding 99%.

These purity and contamination results are summarized in Fig. 7.11 and Fig. 7.12.

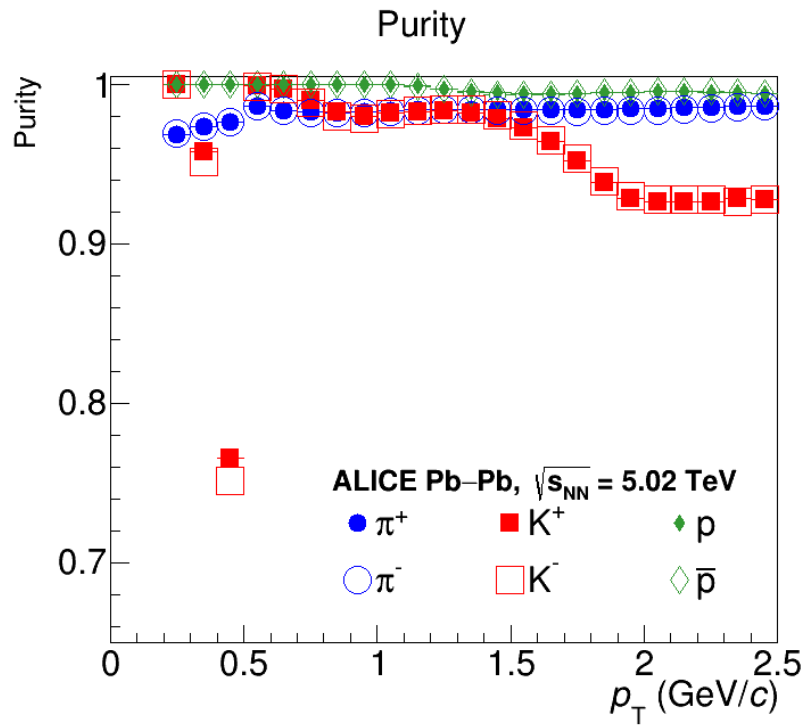


FIGURE 7.11: Purity distribution as a function of p_T using Monte Carlo reconstructed data from 2017 period from Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV.

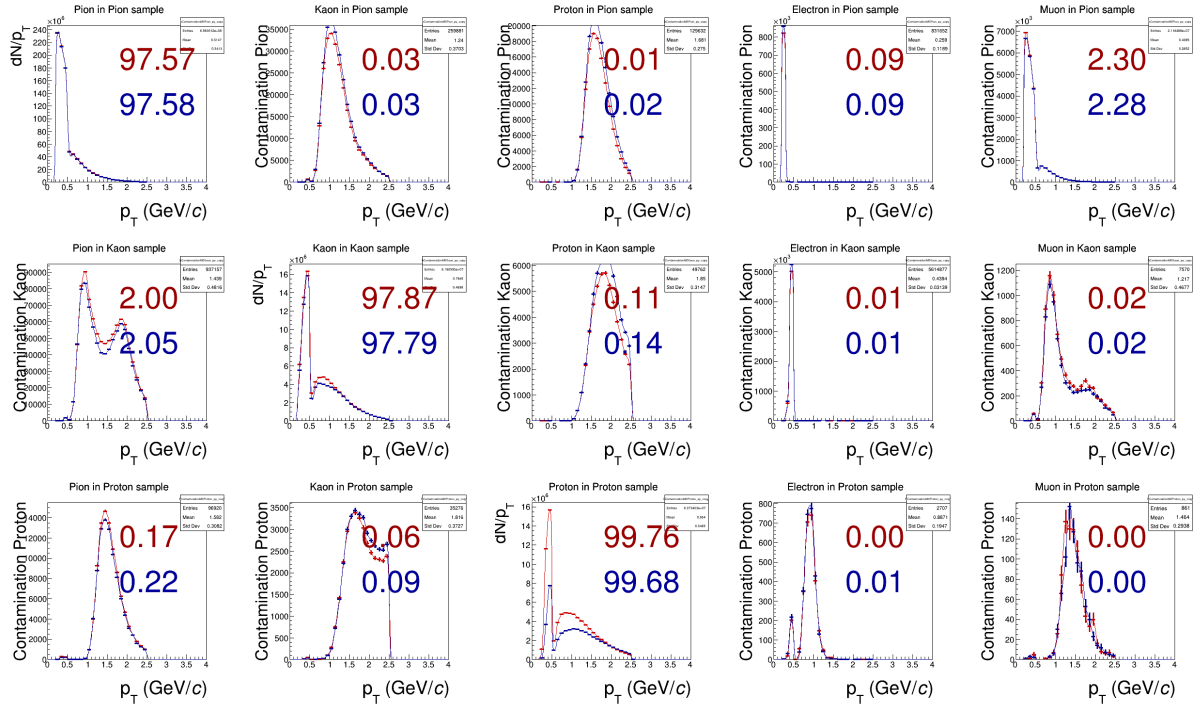


FIGURE 7.12: Contamination levels from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV, in samples of pions (top), kaons (middle), and protons (bottom), including contributions from pions, kaons, protons, electrons, and muons. Particles are represented in red, and antiparticles in blue. Sample purity was evaluated within the analyzed p_T ranges: 0.2–2.5 GeV/ c for pions, and 0.5–2.5 GeV/ c for kaons and protons.

7.6.2 Correction factor estimation

The $\Delta y \Delta \phi$ correlation functions were corrected following a procedure designed to address key experimental biases that could influence the analysis results. This correction process involved comparing *Monte Carlo true data* with *Monte Carlo reconstructed data* to derive the correction factors. Through this comparison, the number of correctly identified particles and contributions from secondary and primary particles were determined. Using this information, three distributions were obtained as functions of p_T : the tracking efficiency ϵ , the contamination from secondaries C_{sec} , and the correction factor f . These distributions ensure a robust correction of the correlation functions by accounting for detector effects and particle misidentification. The following subsections will be organized based on the three analyzed collision systems, with the corresponding figures provided for the respective distributions.

7.6.2.1 Correction factor in pp collisions

To obtain the proper value of correlation functions unaffected by inefficiencies, a correction factor, f , is introduced, defined as:

$$f = \frac{1 - C_{\text{sec}}}{\epsilon}, \quad (7.3)$$

where C_{sec} represents the contamination from secondary particles, and ϵ is the tracking efficiency.

The ϵ is the ratio of the number of measured primary particles to the number of primary particles that would have been measured in an ideal detector:

$$\epsilon = \frac{N_{\text{primaries}}^{\text{survived}}}{N_{\text{primaries}}^{\text{generated}}}. \quad (7.4)$$

The efficiency is shown in Fig. 7.13. At low p_T , the efficiency rises steeply with increasing transverse momentum. The observed steep decline around $p_T \sim 0.5 \text{ GeV}/c$ for identified particles corresponds to the transition where the TOF detector becomes a contributing factor in the PID process for $p_T > 0.5 \text{ GeV}/c$.

An interesting observation is that for pions and kaons, the efficiency for like-sign and unlike-sign particles is very similar. This is evident from the overlapping empty and filled markers in the plots. In contrast, protons show a notable efficiency difference

between particles and antiparticles. This disparity arises because protons experience greater contamination from material interactions compared to antiprotons, as clearly visible in Fig. 7.14.

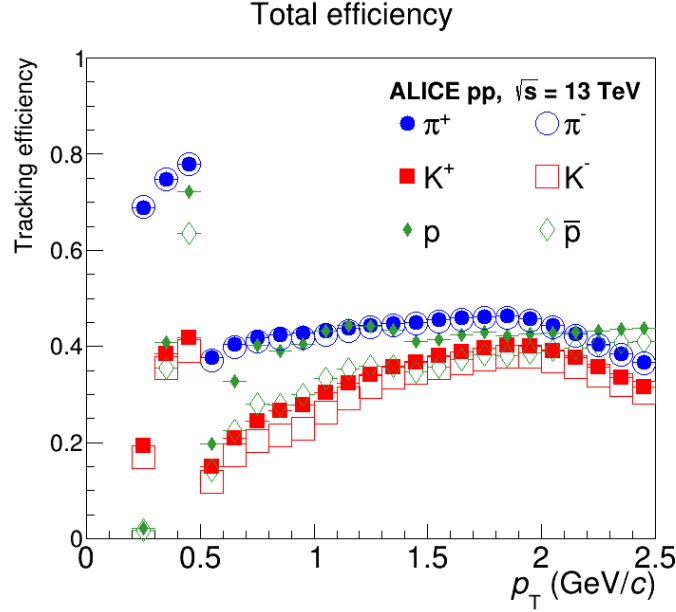


FIGURE 7.13: Efficiency as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.

The C_{sec} is defined as the ratio of the number of measured secondary particles to the total number of measured particles:

$$C_{\text{sec}} = \frac{N_{\text{secondaries}}^{\text{survived}}}{N_{\text{primaries}}^{\text{survived}} + N_{\text{secondaries}}^{\text{survived}}}. \quad (7.5)$$

The dependence of C_{sec} on p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV is shown in Fig. 7.14. The contamination from particles misidentified as primaries is particularly significant in the case of protons. This is primarily due to the substantial number of secondary protons originating from interactions with surrounding materials, introducing a notable background that affects the measurements. This contamination is especially problematic for protons with $p_T < 0.5$ GeV/ c , where the contribution of secondary particles is extremely large, as is shown in Fig. 7.14. In contrast, for pions and kaons, the contamination from secondaries is almost negligible.

Using the defined observables, such as ϵ and C_{sec} , the correction factor distribution, f , is obtained and shown in Fig. 7.15.

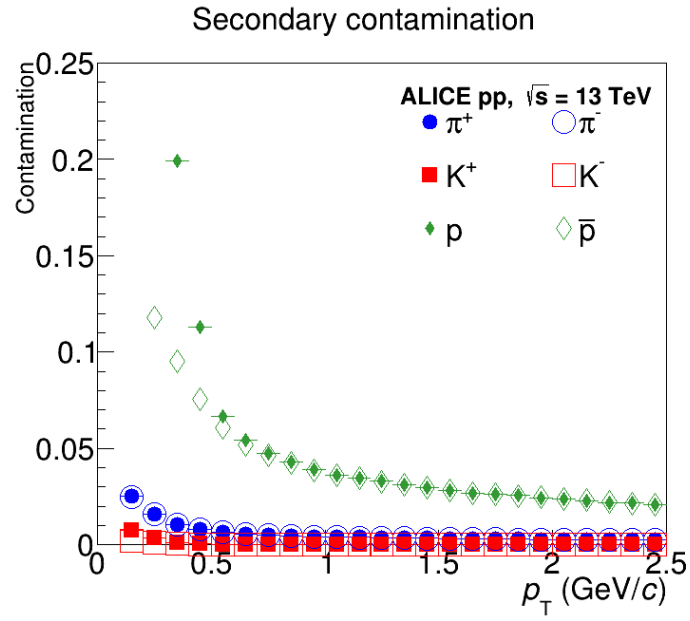


FIGURE 7.14: Contamination from secondary particles as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.

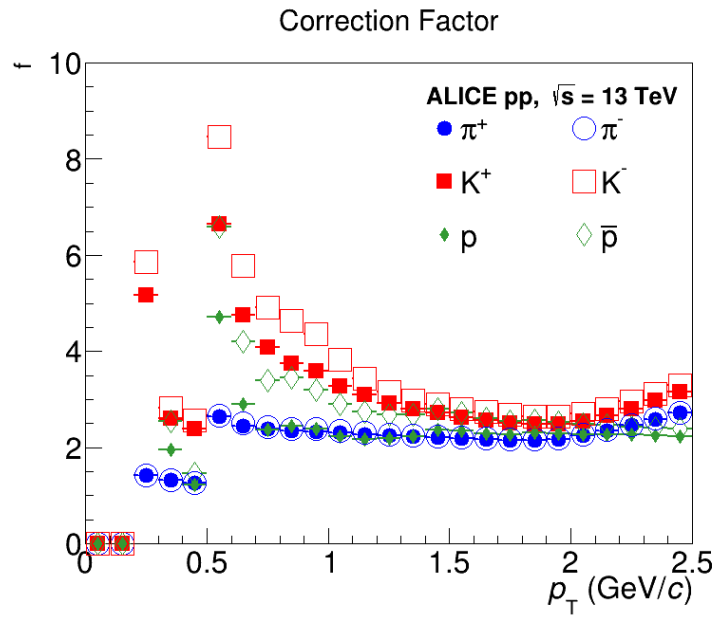


FIGURE 7.15: Correction factor as a function of p_T for pions, kaons, and protons in pp collisions at $\sqrt{s} = 13$ TeV.

7.6.2.2 Correction factor in p–Pb collisions

As discussed earlier for the estimation of the correction factor in the pp analysis, the same procedure was applied to determine the correction factor for the p–Pb analysis. Figures 7.16 and 7.17 present the secondary particle contamination, efficiency, and the resulting correction factor, all evaluated as functions of p_T .

In the p–Pb analysis, the trends are similar to those observed in the pp collision analysis. The secondary contamination plot reveals significant contamination for protons and antiprotons, whereas it is almost negligible for pions and kaons. The total efficiency shows a noticeable drop around 0.5 GeV/ c , attributable to the inclusion of the TOF in particle identification. Among the particles, pions exhibit the highest efficiency, followed by protons, which lie in the middle with a clear efficiency difference between protons and antiprotons. Kaons show lower efficiency compared to pions.

The correction factor plot reflects these trends, with its structure directly shaped by the secondary contamination and efficiency distributions. These quantities are critical for correcting the correlation functions, ensuring that detector effects and systematic biases are properly accounted for.

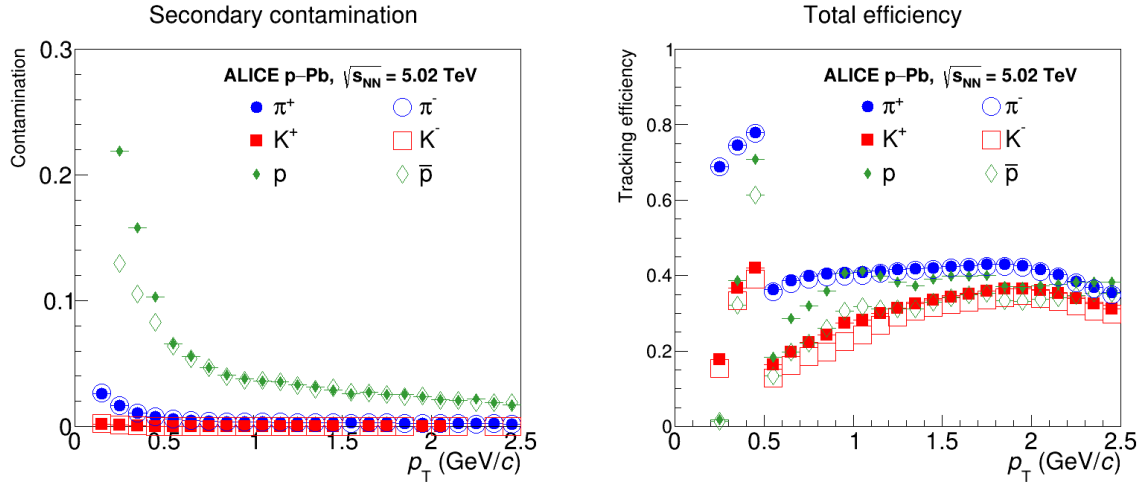


FIGURE 7.16: The left panel shows the secondary contamination, while the right panel displays the efficiency, both as functions of p_T for p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

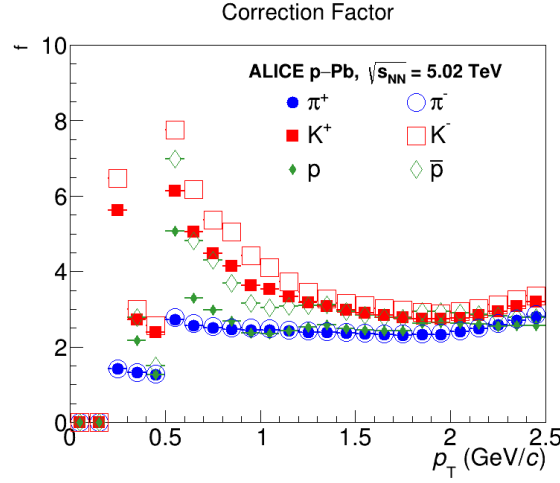


FIGURE 7.17: Correction factor as a function of p_T for pions, kaons, and protons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

7.6.2.3 Correction factor in Pb–Pb collisions

Secondary particles, originating from material interactions or decays, predominantly affect the proton sample, with contamination values ranging from approximately 0.5 at low p_T to around 0.2 at higher p_T , due to the higher particle density produced in Pb–Pb collisions. Despite this, the correction factor is estimated without explicitly accounting for secondary particle contamination. This approach is supported by Monte Carlo closure tests, detailed in Appendix A, which demonstrated that excluding this correction produces better agreement between the reconstructed and true MC data. While the significant impact of secondary contamination is acknowledged, the improved consistency of the results justifies omitting this correction in the Pb–Pb analysis.

However, for pions and kaons, the impact of secondary particles is minimal, resulting in negligible contamination for these species. Consequently, the correction factor for pions and kaons remains largely unaffected and can be reliably estimated without explicitly including secondary particle contributions.

Figures 7.18 and 7.19 present the distributions of contamination from secondary particles, the efficiency, and the resulting correction factors as functions of p_T . These results are derived from reconstructed Pb–Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV, highlighting the varying levels of contamination and their subsequent impact on the correction factor for different particle species.

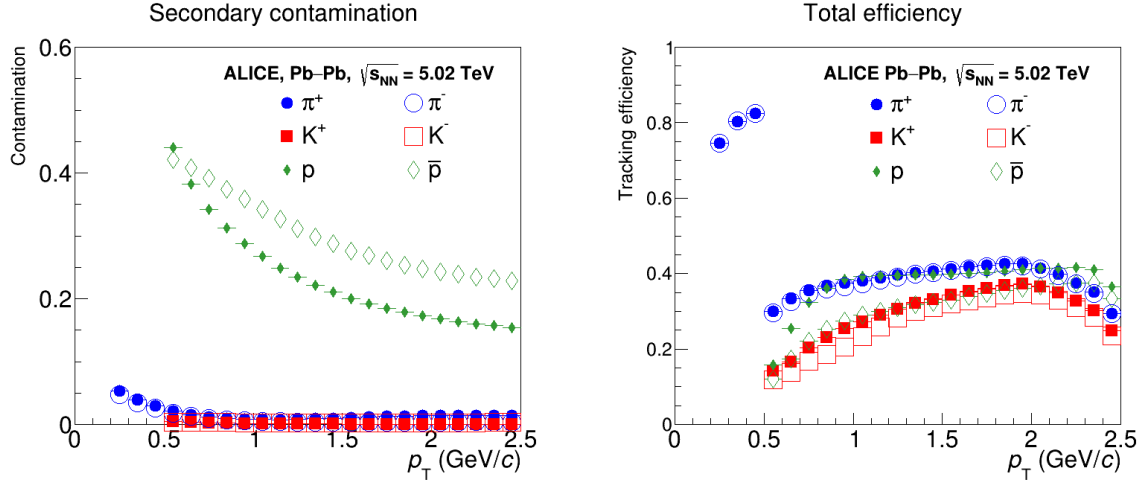


FIGURE 7.18: On the left the secondary contamination and on the right the efficiency both as a function of p_T from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV.

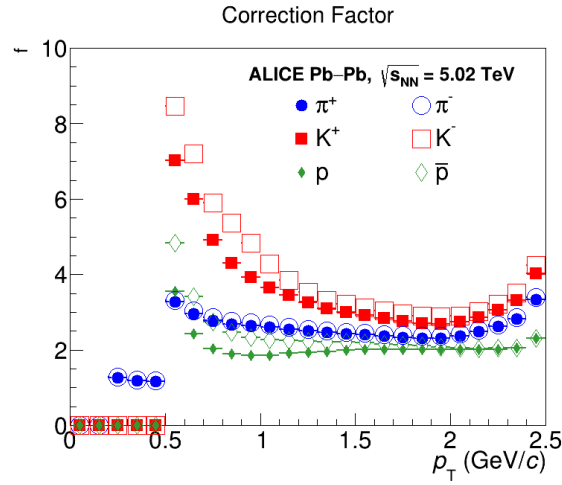


FIGURE 7.19: Correction factor as a function of p_T for pions, kaons, and protons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

7.6.3 Correction of Signal and Background Distributions

The correction factor is applied to both the signal and background distributions for each particle pair to mitigate all potential experimental biases. The signal distribution,

corrected for efficiency losses, is calculated using the correction factor f :

$$S'(\Delta y, \Delta \varphi) = \sum_{p_{T,1}, p_{T,2}} f(p_{T,1}, p_{T,2}) \cdot S(\Delta y, \Delta \varphi, p_{T,1}, p_{T,2}), \quad (7.6)$$

where S is the uncorrected signal distribution.

The background distribution is corrected similarly:

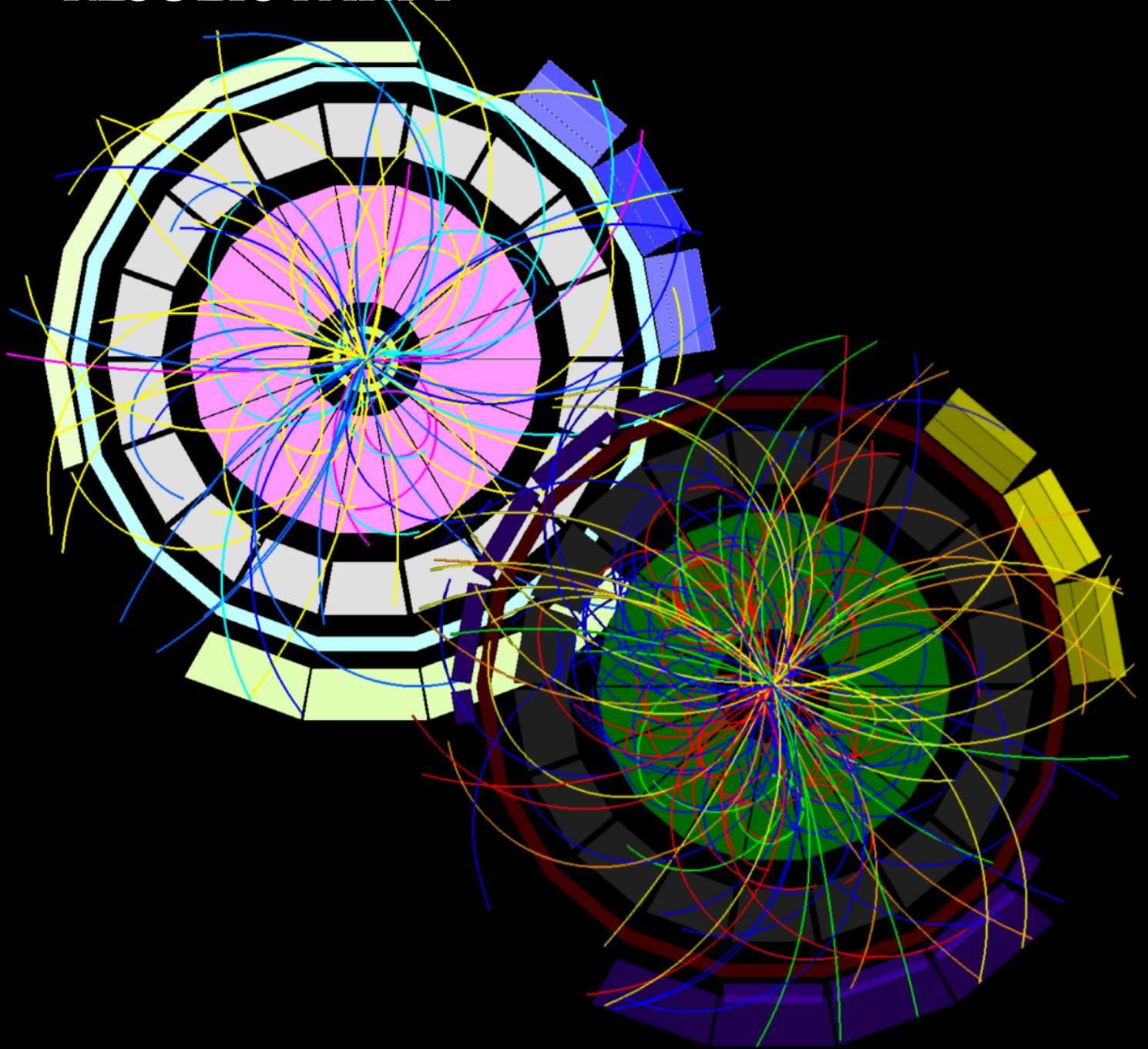
$$B'(\Delta y, \Delta \varphi) = \sum_{p_{T,1}, p_{T,2}} f(p_{T,1}, p_{T,2}) \cdot B(\Delta y, \Delta \varphi, p_{T,1}, p_{T,2}), \quad (7.7)$$

where B is the uncorrected background distribution.

In both corrected distributions, S' and B' , the correction factor $f(p_{T,1}, p_{T,2})$ is defined as the product of individual corrections for each particle's transverse momentum, $f(p_{T,1}) \cdot f(p_{T,2})$. Also, the summation runs over all transverse momentum bins ($p_{T,1}$ and $p_{T,2}$) to account for the contributions from different momentum ranges. By dividing the corrected signal and background distributions, the efficiency-corrected experimental correlation function is given as:

$$C(\Delta y, \Delta \varphi) = \frac{N_{\text{pairs}}^{\text{mixed}}}{N_{\text{pairs}}^{\text{signal}}} \frac{S'(\Delta y, \Delta \varphi)}{B'(\Delta y, \Delta \varphi)}. \quad (7.8)$$

RESULTS PART I



Two-particle Angular Correlation
in pp and p-Pb Collision Systems

Chapter 8

Two-Particle Angular Correlation Analysis in small systems

Declaration

I hereby declare that the work presented in the following chapter is the result of my analysis conducted within the ALICE collaboration. This study focuses on the $\Delta y \Delta \phi$ correlation functions of identified pions, kaons, protons, and their corresponding antiparticles in pp and p–Pb collision systems, categorized into different multiplicity classes for each system. The analysis is performed by using the probability ratio and rescaled two-particle correlation function definitions.

Specifically, I performed the following tasks:

- ☐ *Performed quality assurance of particle selection for pions, kaons, and protons (and their antiparticles).*
- ☐ *Defined and finalized the analysis settings.*
- ☐ *Carried out purity, efficiency, and correction procedures.*
- ☐ *In pp analysis, validated the rescaled two-particle correlation function method and estimated N_{av} values across four multiplicity classes for each particle species.*
- ☐ *Performed Monte Carlo closure tests to validate the correction procedures for both correlation function definitions, as detailed in Appendix A.*
- ☐ *Evaluated systematic uncertainties for both correlation function definitions, as detailed in Appendix B.*

- Calculated the 2D $\Delta y \Delta \varphi$ correlation functions using both correlation function definitions.
- Performed projections onto the azimuthal direction using both correlation function definitions.
- Compared the results with Monte Carlo models using both definitions.
- Analyzed and compared multiplicity classes between pp and p–Pb collision systems.
- Presented the analysis, separated for pp and p–Pb systems, at various stages of progress within the collaboration.
- Defended the results for acceptance during the preliminary approval for both collision systems.
- Extended the pp analysis from four to thirteen multiplicity classes after obtaining preliminary approval, following the full workflow described above.
- Defended the results over thirteen multiplicity classes during the paper proposal approval.
- Contributed to writing the analysis note and preparing the publication, in collaboration with other members of the ALICE collaboration.

This analysis was primarily conducted by me, with invaluable guidance and contributions from my supervisors and colleagues, including Małgorzata Janik, Łukasz Graczykowski, and Adam Kisiel.

8.1 Results from pp Collisions Across Four Multiplicity Classes

The initial analysis focuses on pp collision data at $\sqrt{s} = 13$ TeV. This was conducted using both the probability ratio and the rescaled two-particle correlation function definitions across four multiplicity classes: 0–20%, 20–40%, 40–70%, and 70–100%. The analysis was later extended to 13 multiplicity classes: HM (0–0.17%), 0–1%, 1–5%, 5–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, 60–70%, 70–80%, 80–90%, and 90–100%.

For both approaches, the accuracy of the applied cuts was verified through Monte Carlo closure tests. This technical procedure involves comparing reconstructed MC data with the corresponding generated data to confirm that all cuts, selections, and corrections were correctly implemented. These checks were performed across all multiplicity classes and for both correlation function definitions. Details about the MC closure test can be found in Appendix A.

At the outset of this work, one key task was to validate the method related to the rescaled two-particle correlation function in the $\Delta y \Delta \phi$ angular space. This definition, inspired by the STAR Collaboration [98], was introduced in ALICE for the first time. As outlined in Sec. 4.3.2, the required normalization factor for this method was determined, with the details provided in Secs. 8.1.1 and 8.3.1.

8.1.1 Estimation of N_{av} for Multiplicity Classes in Experimental Data: Method Consolidation

The $\Delta y \Delta \phi$ correlation function, defined as a probability ratio, is compared to the rescaled two-particle correlation function. Calculating the latter required an estimate of N_{av} , the average number of particles produced in the multiplicity classes under analysis. The estimation of N_{av} from experimental data was carried out as follows: first, quality assurance plots were used to count the number of particles reconstructed in each multiplicity class after applying selection cuts. Efficiency corrections were then applied to account for detector effects. Finally, the corrected particle counts for each multiplicity class were divided by the total number of events in that class, yielding the N_{av} values. To validate this approach, the experimental method was cross-checked against an alternative method used in previous studies. Specifically, N_{av} values were also estimated using data published by ALICE Collaboration [132].

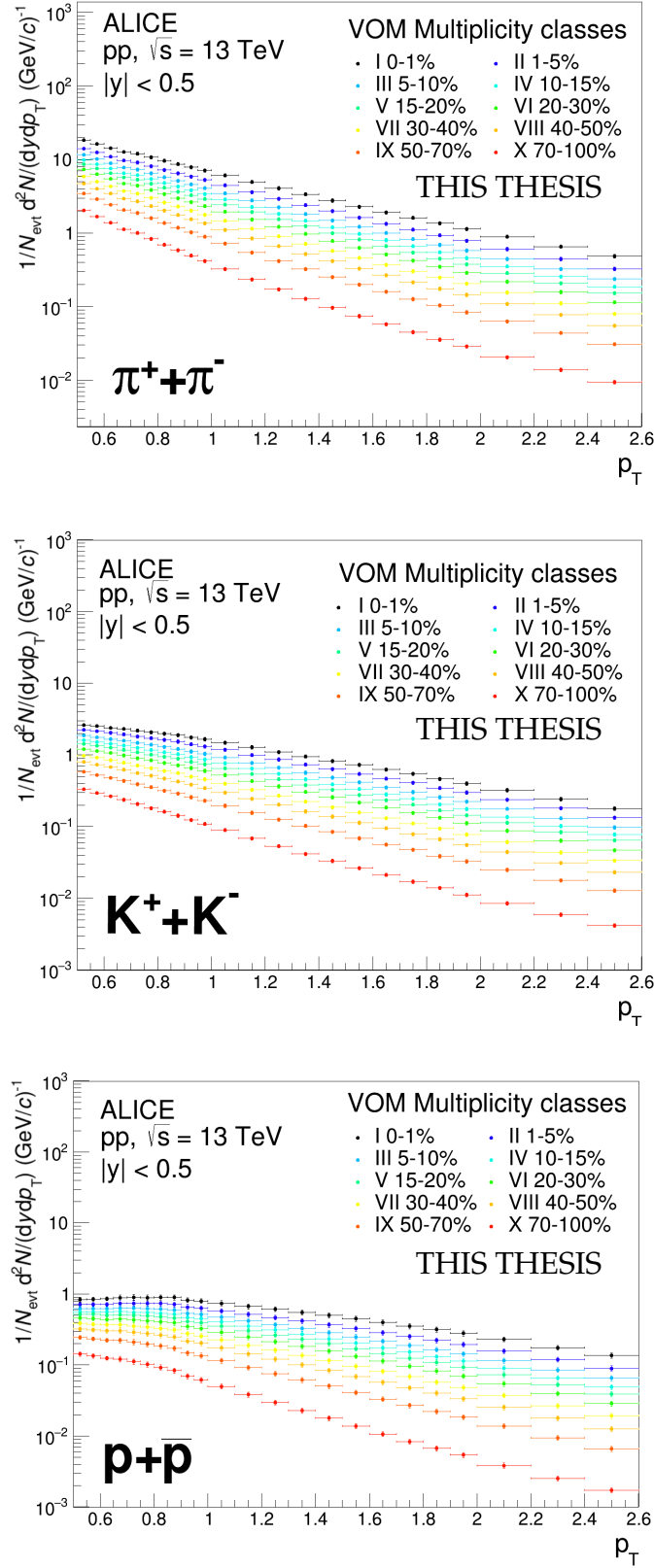


FIGURE 8.1: The p_T spectra, as published in Ref. [132], were reproduced using data from Ref. [133]. The spectra are shown for pions, kaons, and protons for the 10 available multiplicity classes.

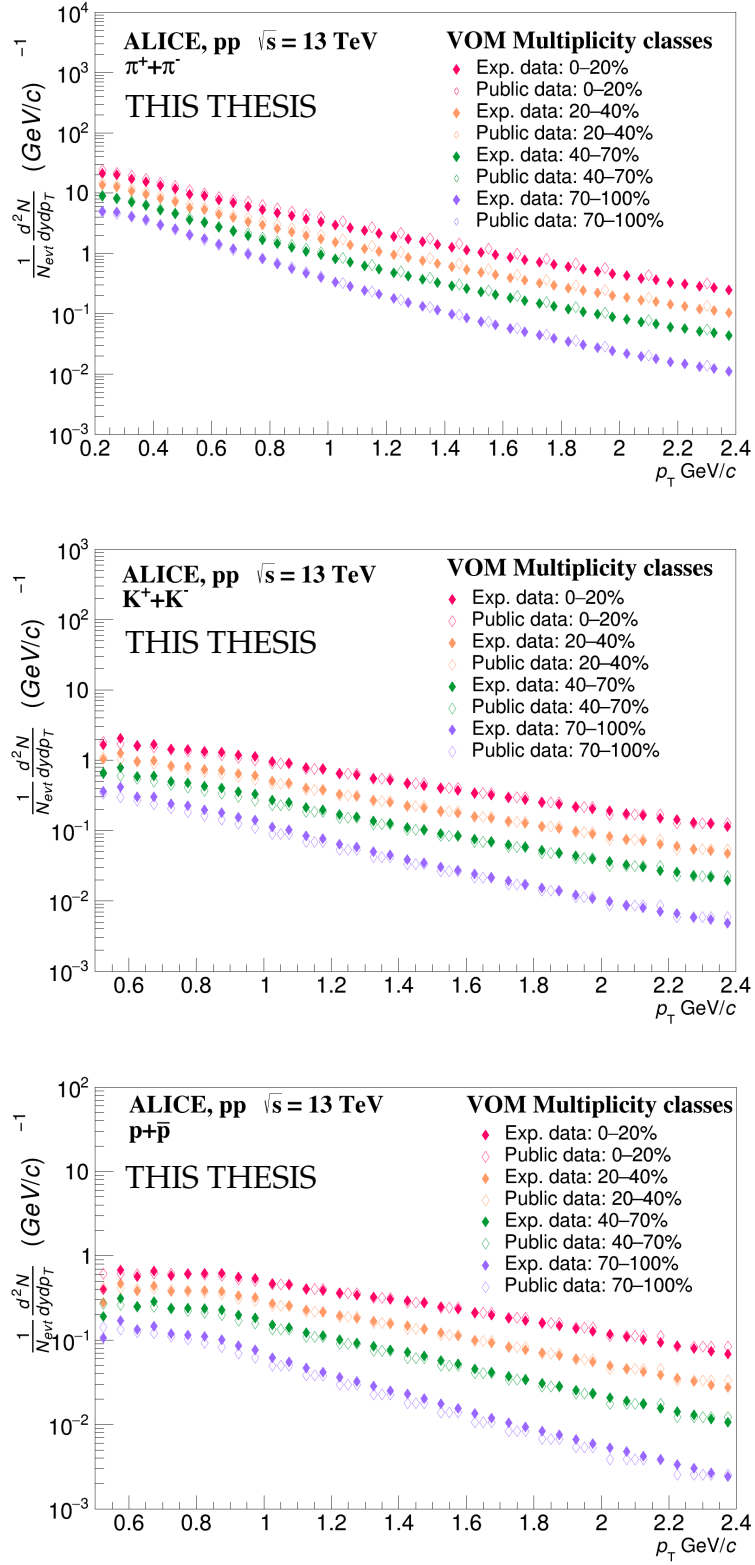


FIGURE 8.2: The comparison of the p_T spectra is shown between the public data, represented by empty rhombuses, and the experimental data, represented by filled rhombuses, for pions, kaons, and protons. Different colors indicate the various multiplicity classes analyzed.

The referenced publication provided N_{av} values for 10 multiplicity classes for pions, kaons, and protons, as illustrated in Figs. 8.1. These values were subsequently adjusted to align with the four multiplicity classes used in this analysis. The corresponding p_T spectra were compared, as illustrated in Fig. 8.2. The comparison shows that the spectra are consistent and comparable. Specifically, the N_{av} values extracted from these plots for the experimental data and published one were compared numerically, as presented in Tab. 8.1 and Tab. 8.2, revealing very similar values.

TABLE 8.1: N_{av} value estimated using experimental data for the four multiplicity classes analyzed, i.e 0–20%, 20–40%, 40–70% and 70–100%. These values are obtained for pions, kaons, and protons.

N_{av} Experimental values				
	Multiplicity 0–20%	Multiplicity 20–40%	Multiplicity 40–70%	Multiplicity 70–100%
<i>Pions</i>	5.5	3.25	2.07	1.33
<i>Kaons</i>	0.65	0.35	0.2	0.1
<i>Protons</i>	0.33	0.19	0.11	0.06

TABLE 8.2: N_{av} values are estimated from published data [132] for the four multiplicity classes analyzed, i.e., 0–20%, 20–40%, 40–70%, and 70–100%. These values are obtained for pions, kaons, and protons.

N_{av} Public data values				
	Multiplicity 0–20%	Multiplicity 20–40%	Multiplicity 40–70%	Multiplicity 70–100%
<i>Pions</i>	5.38	3.07	1.75	0.88
<i>Kaons</i>	0.63	0.33	0.17	0.07
<i>Protons</i>	0.31	0.17	0.09	0.04

The N_{av} values were used to compute the rescaled two-particle correlation function, comparing the $\Delta\phi$ projections shown in Fig. 8.3. For pions and kaons, the results are in good agreement within systematic uncertainties. However, notable discrepancies appear for protons, especially in low-multiplicity classes. These discrepancies arise from the event selection criteria, which require at least two particles to construct the correlation function, and the lower abundance of protons, which affects low-multiplicity classes more. Despite these differences, cross-validation between the two sets shows good agreement. Therefore, for the final analysis of the rescaled two-particle correlation function, N_{av} will be derived from experimental data.

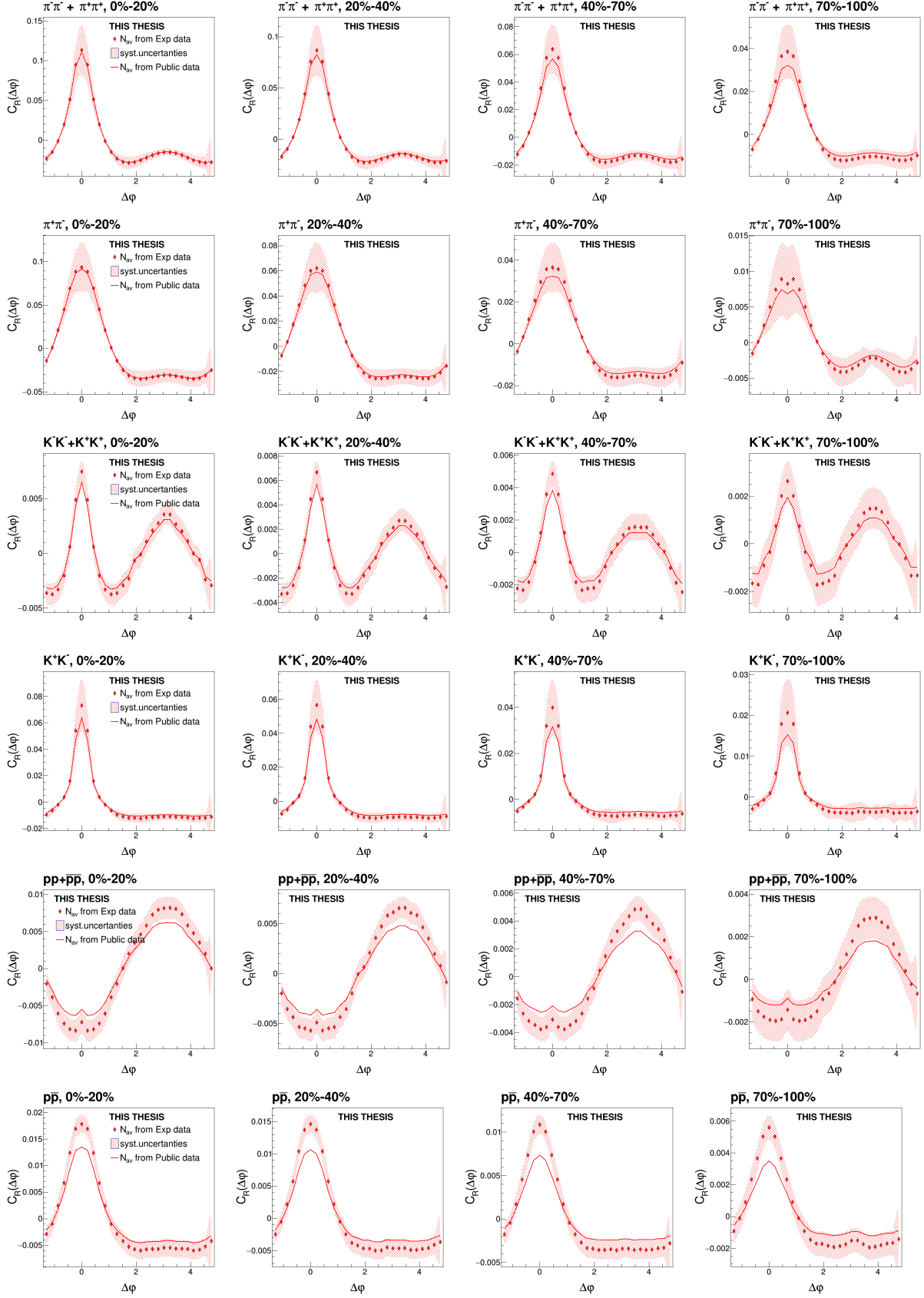


FIGURE 8.3: Comparison of $\Delta\phi$ projections of rescaled two-particle correlation functions using N_{av} from experimental data (red markers) and public data (solid lines) for all particle pairs across four multiplicity classes.

8.1.2 2D $\Delta y \Delta \varphi$ correlation functions

From Fig. 8.4 to Fig. 8.9, a comparison between the two definitions of the correlation function is presented. The probability ratio definition is labeled as $C_P(\Delta y, \Delta \varphi)$, while the rescaled two-particle correlation function is denoted as $C_C(\Delta y, \Delta \varphi)$ ¹.

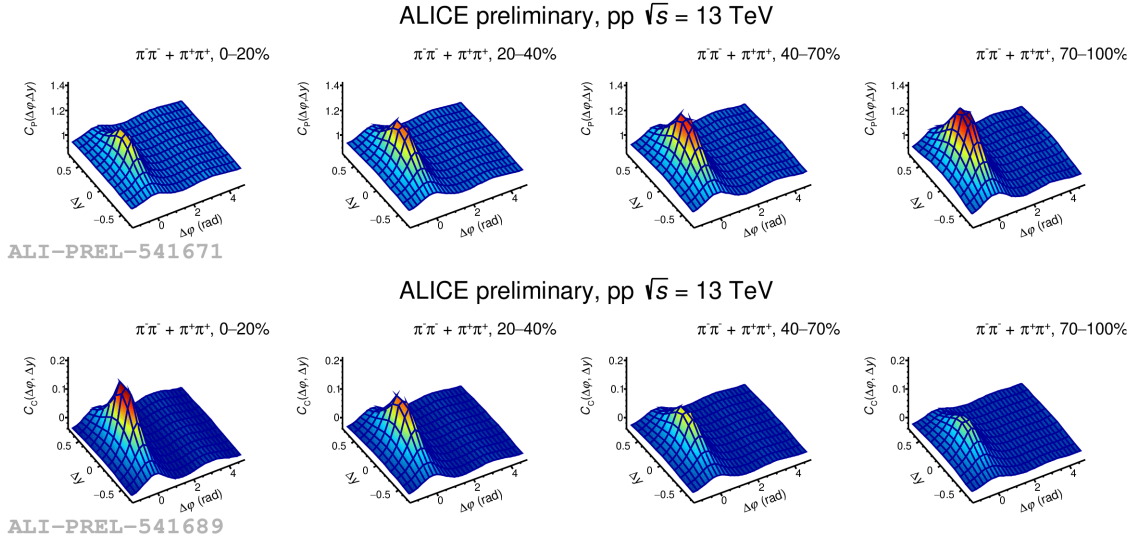


FIGURE 8.4: $\Delta y \Delta \varphi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

According to the definition of the probability ratio, the correlation function increases in magnitude as the multiplicity class decreases, primarily due to the expected scaling factor of $\sim 1/N$. In contrast, the rescaled two-particle correlation functions more accurately capture the actual number of events within each multiplicity class. Both definitions are valid, each emphasizing different aspects of the data, which is why both are employed in the analysis.

A consistent trend is observed for all particle types except for unlike-sign pions. Specifically, while the correlation function generally increases with higher multiplicities, unlike-sign pions show a similar pattern in both definitions of the correlation

¹The notation of rescaled two-particle correlation function described in Sec. 4.3.2, differs because the name of the correlation function was finalized after the preliminary results for pp and p–Pb collisions. C_C is used here, where the "C" stands for cumulant as originally defined. Since these results are preliminary, it is not possible to change the notation at this stage. However, the calculation remains the same as described in Sec. 4.3.2.

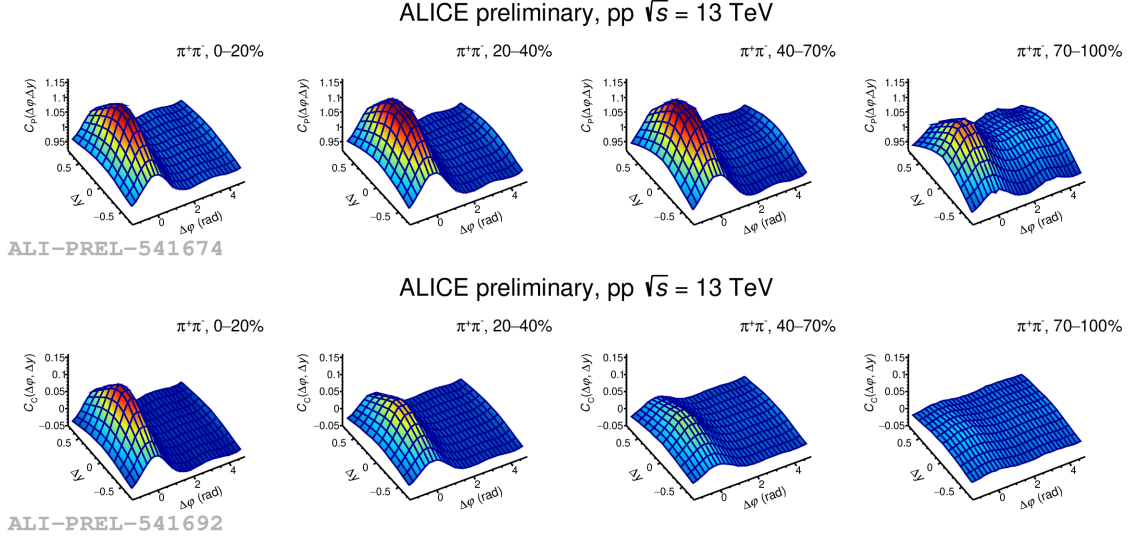


FIGURE 8.5: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

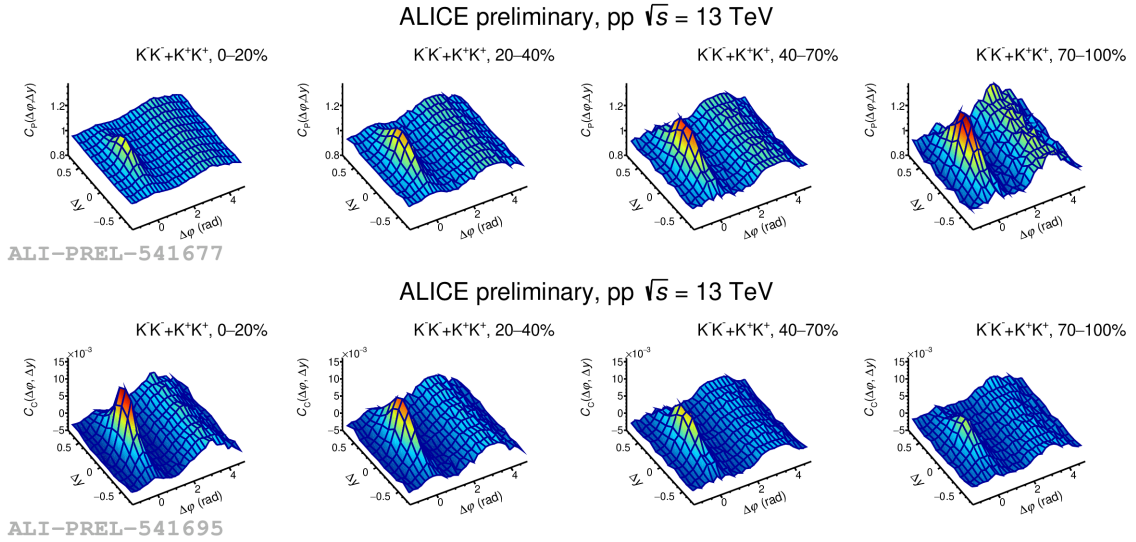


FIGURE 8.6: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

function. This behavior arises because $\pi^+ \pi^-$ pairs are influenced by resonances that do not contribute to a distinct peak in the near-side region. Instead, these resonances

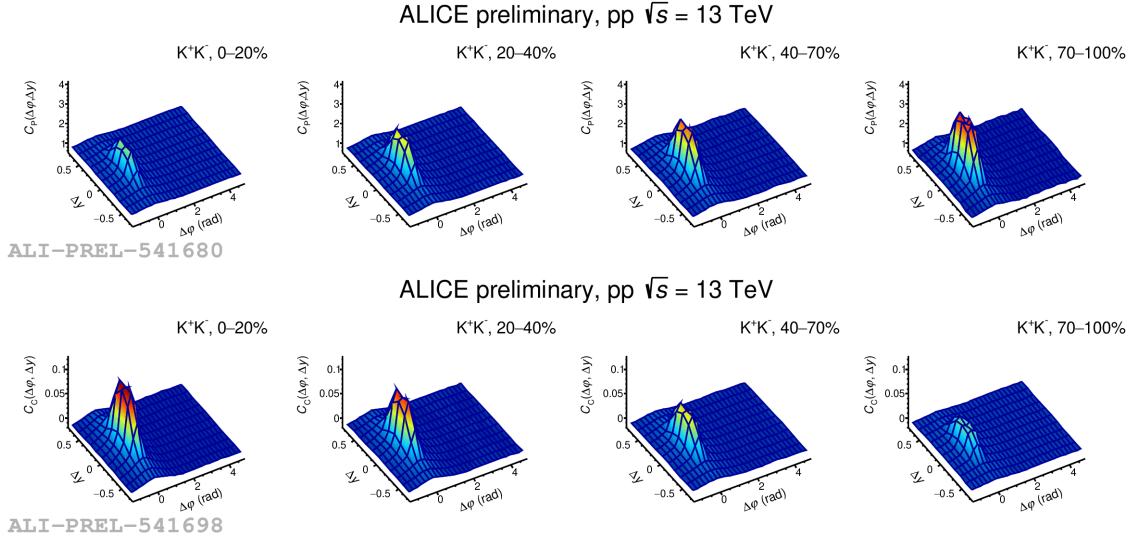


FIGURE 8.7: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

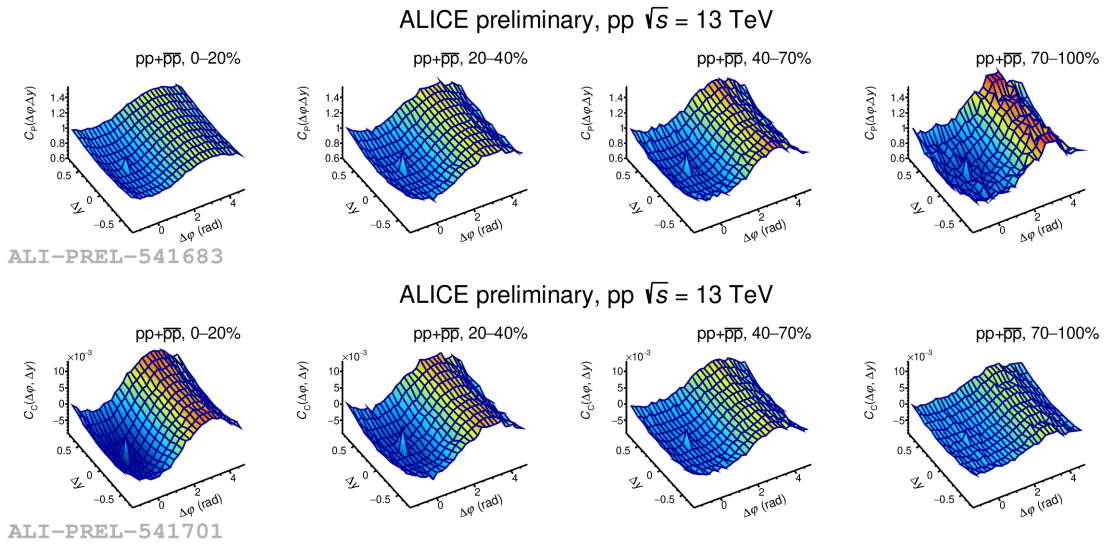


FIGURE 8.8: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

create a structure known as the longitudinal ridge, which extends across the entire $\Delta \phi$ range and is centered around $\Delta y \approx 0$ [93]. This structure is typical of a large energy

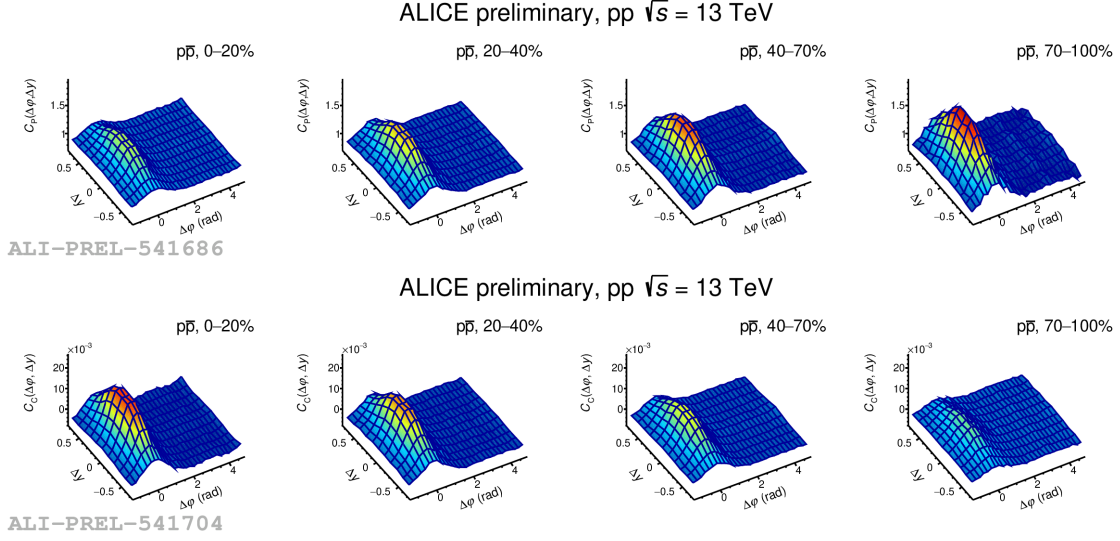


FIGURE 8.9: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

release from the resonance during decay or from a three-body decay.

Another effect of resonances is observed for unlike-sign kaons, which exhibit a distinctive structure in the space of $(\Delta y, \Delta \phi)$ at $(0,0)$, the so-called ring structure, due precisely to the ring-like shape. This behavior arises because many $K^+ K^-$ pairs originate from ϕ resonances, which decay with a very small energy release [95]. A dedicated study, using theoretical models such as Pythia Perugia-0, and Phojet, demonstrated a strong connection to ϕ resonances. Specifically, when $K^+ K^-$ pairs with an invariant mass corresponding to the ϕ resonance are subtracted, the ring structures in the correlation function vanish [83].

Generally, for all particle pairs, in the near-side region, a typical minijet structure is observed, except for like-sign protons, which exhibit a depletion accompanied by a small peak in the $(\Delta y, \Delta \phi)$ space at $(0,0)$. This peak is visible across the four multiplicity classes and is attributed to final-state interactions, as demonstrated in a dedicated study [91]. The anticorrelation appears to become stronger with increasing multiplicity when using the rescaled two-particle correlation functions, indicating that the larger the particle multiplicity, the stronger the anticorrelation.

8.1.3 $\Delta\phi$ projections and comparison to MC models

In this section, the azimuthal distributions of the correlation functions from the pp collision analysis at $\sqrt{s} = 13$ TeV are presented, categorized into four multiplicity classes, and compared with MC model predictions.

Figures 8.10 and 8.11 show the projections of the correlation functions onto $\Delta\phi$, using the probability ratio and the rescaled two-particle cumulant definitions, respectively. Systematic uncertainties are indicated in all plots by colored boxes overlaid on the correlation functions. These uncertainties were independently estimated for both the probability ratio and the rescaled two-particle cumulant definitions. For the probability ratio, the relative uncertainties are presented, and their magnitude increases with decreasing multiplicity. In contrast, the systematic studies with the rescaled two-particle correlation functions were performed by using absolute uncertainties, which remain consistent in magnitude across all multiplicity classes. Additional details regarding the systematic uncertainty estimation can be found in Appendix B.

For each particle type, the projections are overlaid across the four multiplicity classes. As shown in Fig. 8.10, the distributions decrease with increasing multiplicity class. In contrast, Fig. 8.11 shows that the distributions increase with higher multiplicity classes. These trends are consistent with the patterns discussed in previous sections. An interesting behavior is observed for like-sign kaons. In the case of the probability ratio definition, a slight difference between the multiplicity classes is visible. However, when the rescaled two-particle correlation function is used, no multiplicity dependence is observed, indicating that the correlations become independent of multiplicity.

From the 1D projections, the dominance of minijet structures becomes even more apparent, particularly in mesonic correlations. However, for like-sign protons, as observed in the 2D angular correlations, a distinct anticorrelation is seen. In the probability ratio definition, this anticorrelation is stronger in lower multiplicity classes, while in the rescaled two-particle correlation function, the anticorrelation becomes more pronounced in higher multiplicity classes.

Another behavior observed in the 1D projections is the effect of resonances on unlike-sign pions. Specifically, in the case of the probability ratio, the correlation function in the 70–100% multiplicity range, which would typically show the largest amplitude, instead exhibits a small near-side peak. This behavior arises because the correlation does not increase in amplitude but instead generates a longitudinal ridge,

as seen clearly in the 2D plots. In the case of the rescaled two-particle correlation function, resonances still influence the correlation, but their effect is less pronounced in the projections due to the overall smaller magnitude of the correlation. For unlike-sign kaons, the small dip caused by ϕ resonances is not visible in the projections, as it is averaged over the entire Δy range.

The correlation functions measured in this work are compared with the predictions of MC models. For the pp analysis, PYTHIA8_Monash13 [134] and EPOS_LHC [70] both at $\sqrt{s} = 13$ TeV were used for the comparison, which are described in detailed in Sec. 3.2.1 and 3.2.2. Both definitions are presented in the figures as follows: the upper plots display the projections onto $\Delta\phi$, while the bottom panels show the ratio to the data. The ratio provides a quantitative measure of how the models differ from the experimental results, offering insights into the order of magnitude of these discrepancies.

Figures 8.12 and 8.13 show the comparison of the azimuthal projections for like- and unlike-sign particle pairs with MC models, respectively, using the probability ratio definition. Both models qualitatively reproduce the experimental data for pions and kaons, but not quantitatively, due to the absence of QS effects in the models. In particular, both models exhibit a very pronounced away-side peak. For PYTHIA8, this arises from the structure of minijets and back-to-back jets, while in EPOS_LHC, it is attributed to the inclusion of collective phenomena in the model, which could potentially explain the presence of QGP-like effects in small collision systems such as pp collisions. However, neither model agrees with the data for unlike-sign particles, where the away-side correlation is nearly flat. For like-sign protons, the models fail to reproduce the observed anticorrelation, although they show reasonable agreement on the away side, which reflects the typical back-to-back jet structure. For unlike-sign protons, PYTHIA8 exhibits significantly higher magnitudes compared to the results, while EPOS_LHC appears to agree better on the near side at lower multiplicities but fails to reproduce the away side.

Figures 8.14 and 8.15 compares the results using the rescaled two-particle correlation function definition for like- and unlike-sign particle pairs, respectively. With this definition, the correlation functions exhibit an opposite trend across the multiplicity classes. In general, better agreement is observed between the models and the data for meson correlations. For like-sign pions, the models appear to agree well with the data within the uncertainties, and similar agreement is observed for unlike-sign pions.

Notably, the correlation retains its behavior consistently from higher to lower multiplicity classes. The same trend is seen for both like- and unlike-sign kaons. For like- and unlike-sign protons, the trends observed with the probability ratio definition remain consistent. The models fail to reproduce the anticorrelation across all multiplicity classes. For unlike-sign protons, EPOS_LHC matches the near-side correlation reasonably well but fails to describe the away side, while PYTHIA8 qualitatively captures the shape but not the magnitude.

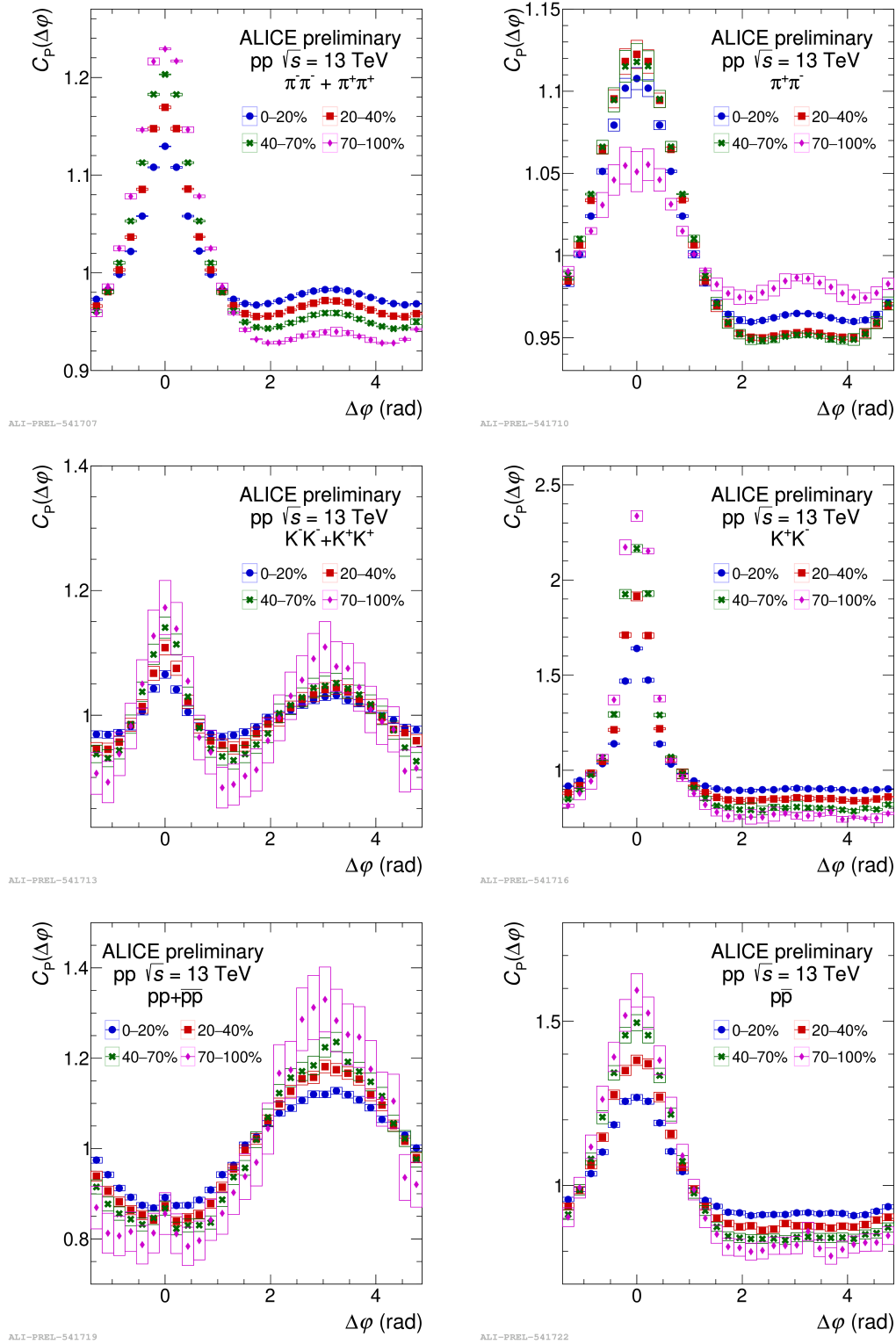


FIGURE 8.10: $\Delta\phi$ projections of correlation functions using the probability ratio definition. All four multiplicity classes are plotted on the same canvas for each particle.

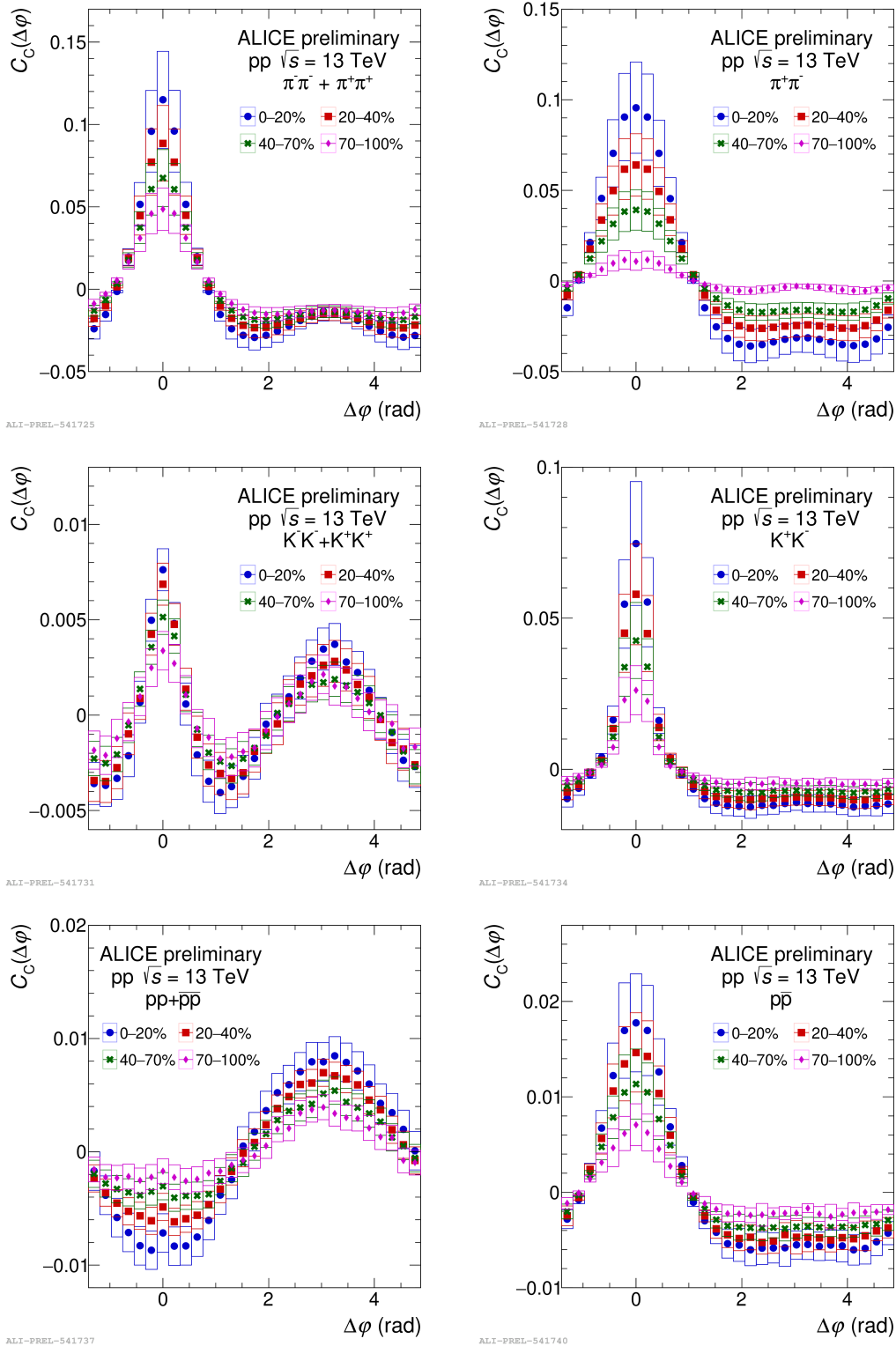
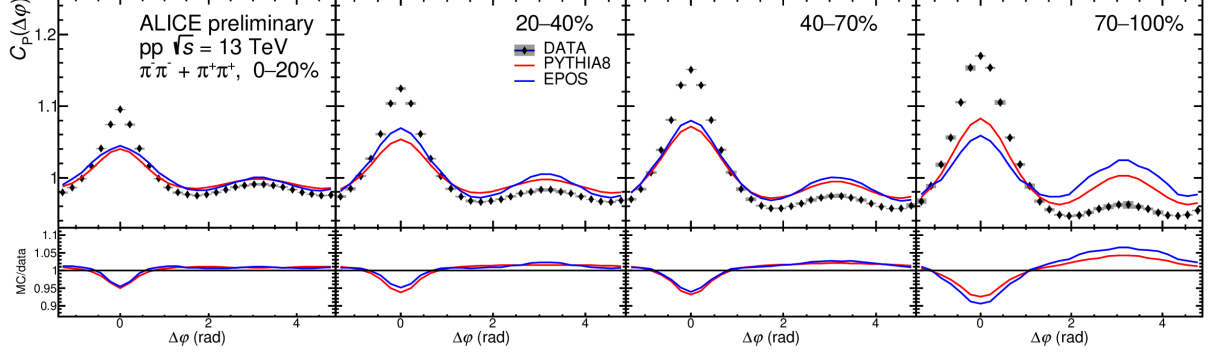
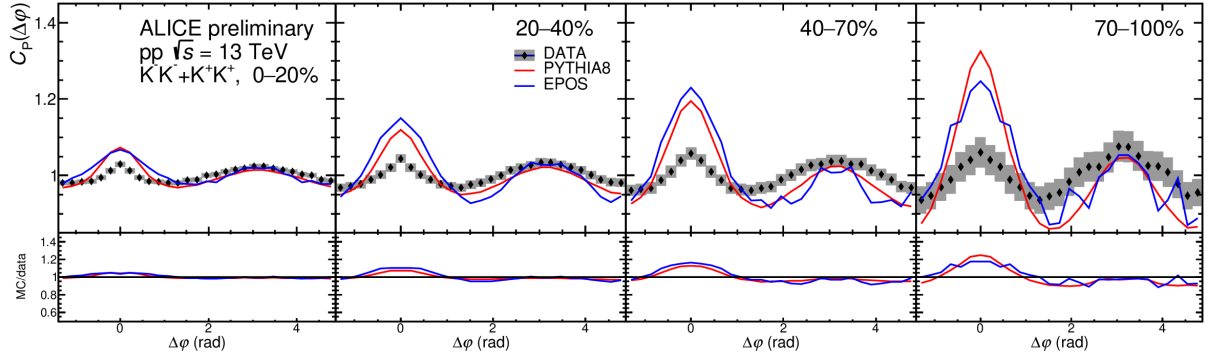


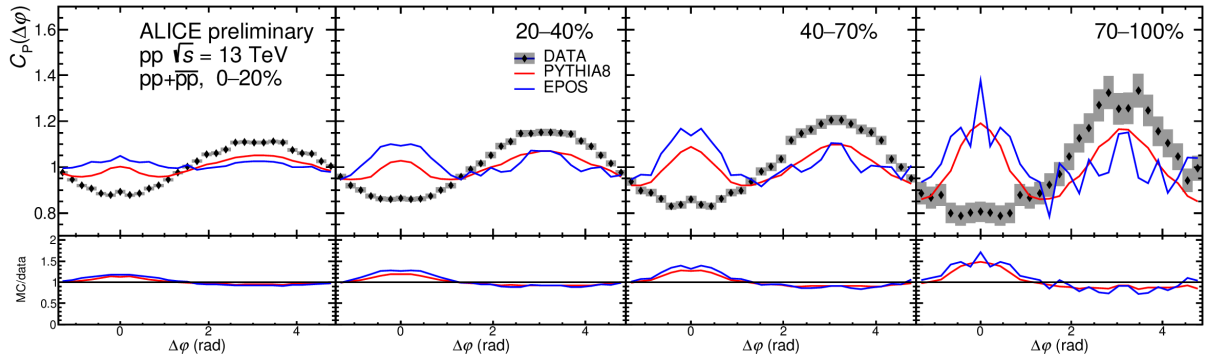
FIGURE 8.11: $\Delta\phi$ projections of correlation functions using the rescaled two-particle correlation function definition. All four multiplicity classes are plotted on the same canvas for each particle.



ALI-PREL-541743

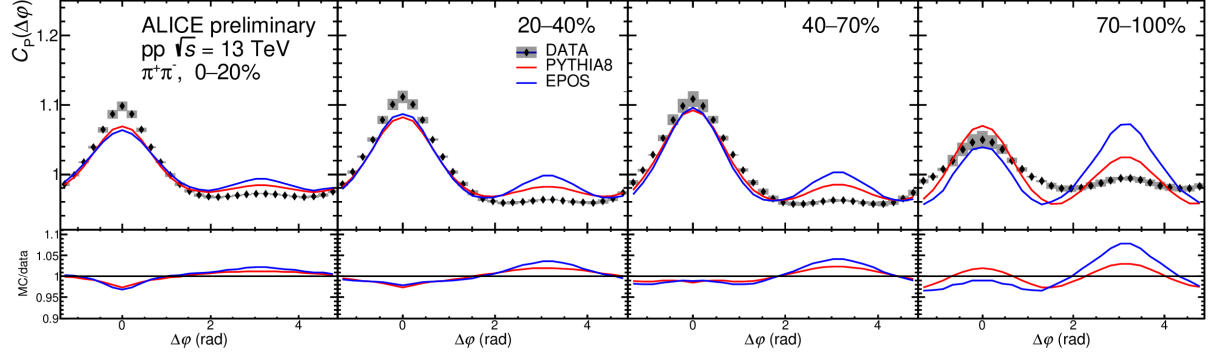


ALI-PREL-541749

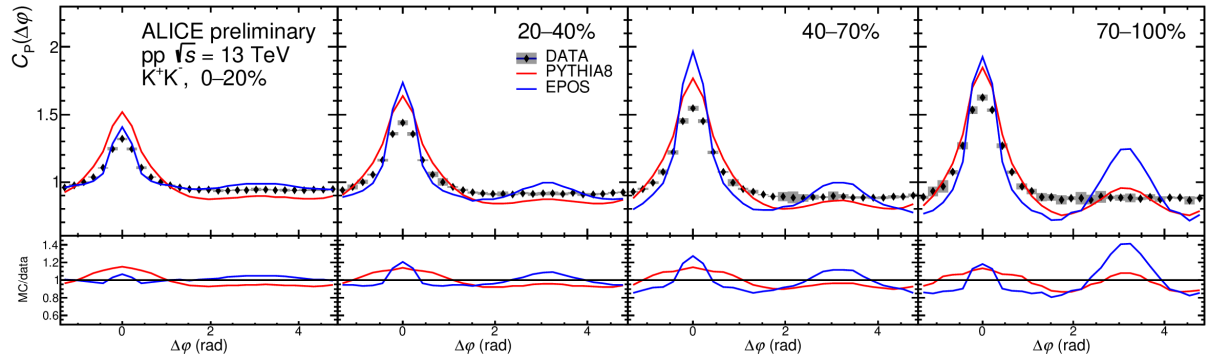


ALI-PREL-541755

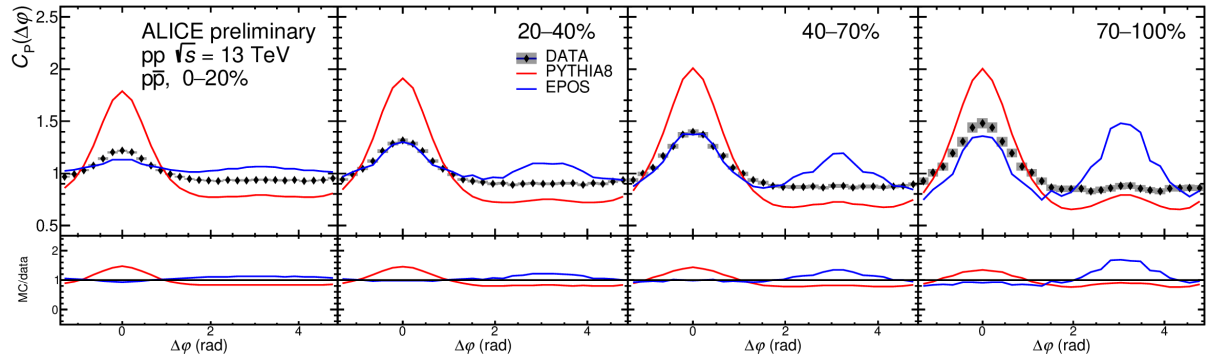
FIGURE 8.12: $\Delta\phi$ projections of correlation functions computed using the probability ratio definition. Comparison with MC models was made for like-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data.



ALI-PREL-541746

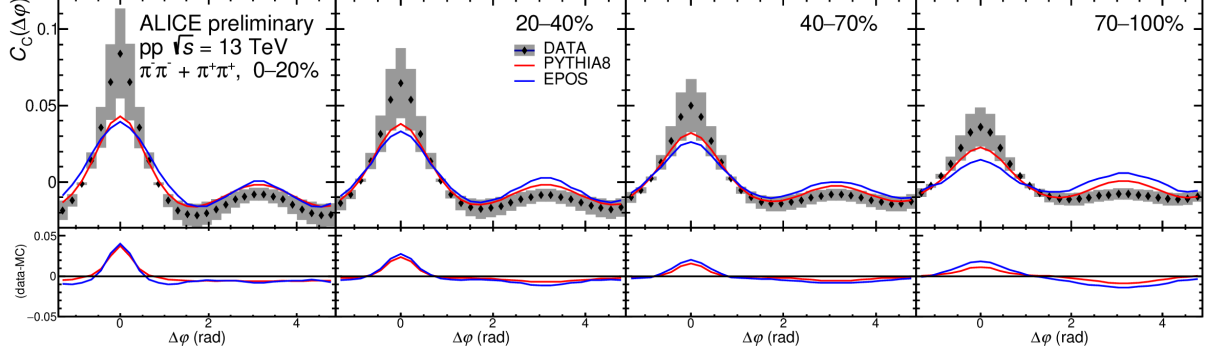


ALI-PREL-541752

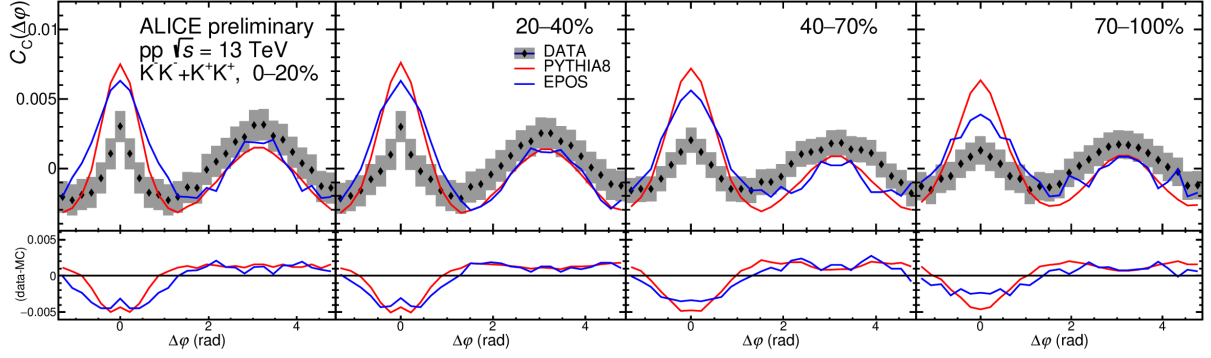


ALI-PREL-541758

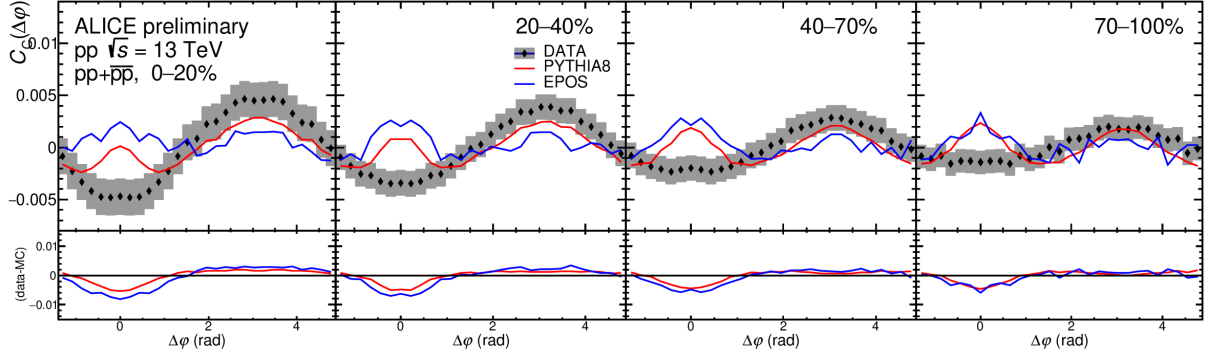
FIGURE 8.13: $\Delta\phi$ projections of correlation functions computed using the probability ratio definition. Comparisons with MC models were made for unlike-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data.



ALI-PREL-541761

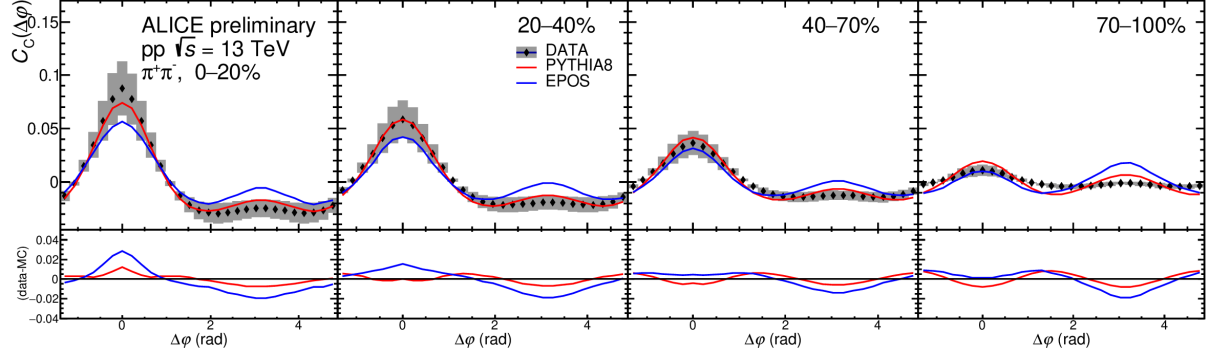


ALI-PREL-541767

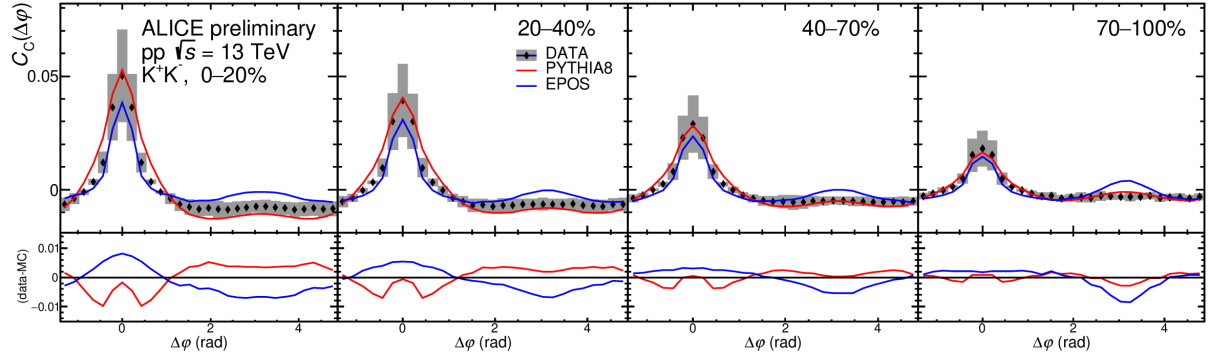


ALI-PREL-541773

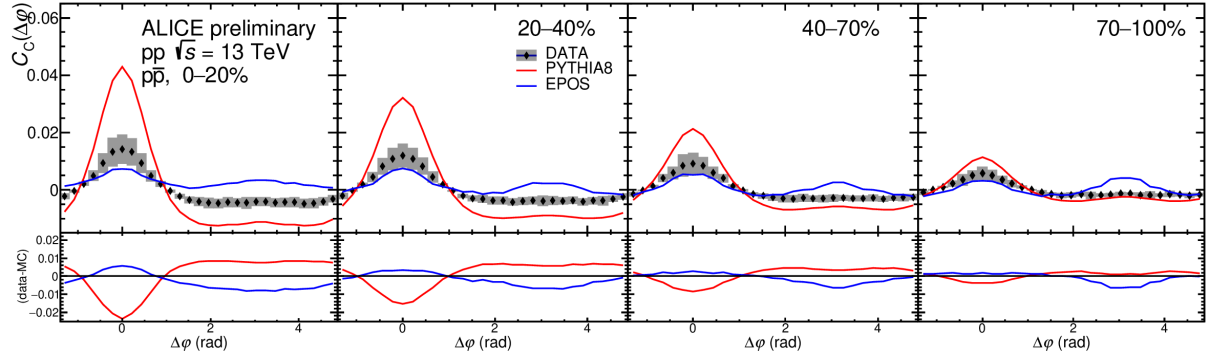
FIGURE 8.14: $\Delta\phi$ projections of correlation functions computed using the rescaled two-particle correlation function. Comparisons with MC models were made for like-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data.



ALI-PREL-541764



ALI-PREL-541770



ALI-PREL-541776

FIGURE 8.15: $\Delta\phi$ projections of correlation functions computed using the rescaled two-particle correlation function. Comparisons with MC models were made for unlike-sign pions, kaons, and protons across the four multiplicity classes involved in this analysis. The red solid line is the PYTHIA8_Monash13 model and in blue the EPOS lhc model. The black markers are the ALICE data with their respective uncertainties. The box below shows the relationships between each model and the actual data.

8.2 Results from pp Collisions Across Thirteen Multiplicity Classes

In the next section, all figures are presented without the PRELIMINARY status, as the analysis across thirteen multiplicity classes is directly included in the paper currently in preparation.

The analysis, originally conducted over four multiplicity classes, was extended to the maximum feasible number of multiplicity classes at the request of theorists. The underlying motivation from theorists is that high-multiplicity events, characterized by a greater number of multi-parton interactions, provide a richer environment for sub-leading color effects, such as color reconnection, compared to low-multiplicity events. In high-multiplicity scenarios, the finite number of color states in QCD becomes a limiting factor, increasing the probability of interactions between partons and amplifying the role of color reconnection. This process leads to more efficient formation of baryonic clusters or strings, as the abundance of partons moving in similar directions enhances the probability of their combination. Conversely, low-multiplicity events, with fewer multi-parton interactions and partons involved, exhibit weaker color reconnection effects and fewer opportunities for such interactions.

For the extended analysis, the same procedure, cuts, and selection criteria were consistently applied across all 13 multiplicity classes to ensure uniformity and reliability. The following subsection presents the 2D plots for both the probability ratio and the rescaled two-particle correlation function definitions. These will be followed by projections onto the azimuthal direction and, finally, a comparison with Monte Carlo models.

8.2.1 2D $\Delta y \Delta \phi$ correlation functions

Figures 8.16 and 8.17 present the $\Delta y \Delta \phi$ correlation functions for like- and unlike-sign pions, kaons, and protons, respectively, using the probability ratio definition. The results correspond to high-multiplicity events in the 0–0.17%, 20–40%, 60–70%, and 90–100% centrality classes. For clarity and conciseness, only a subset of multiplicity classes is shown in the 2D plots.

Similarly, Figs. 8.18 and 8.19 presents the corresponding correlation functions using the rescaled two-particle correlation function definition.

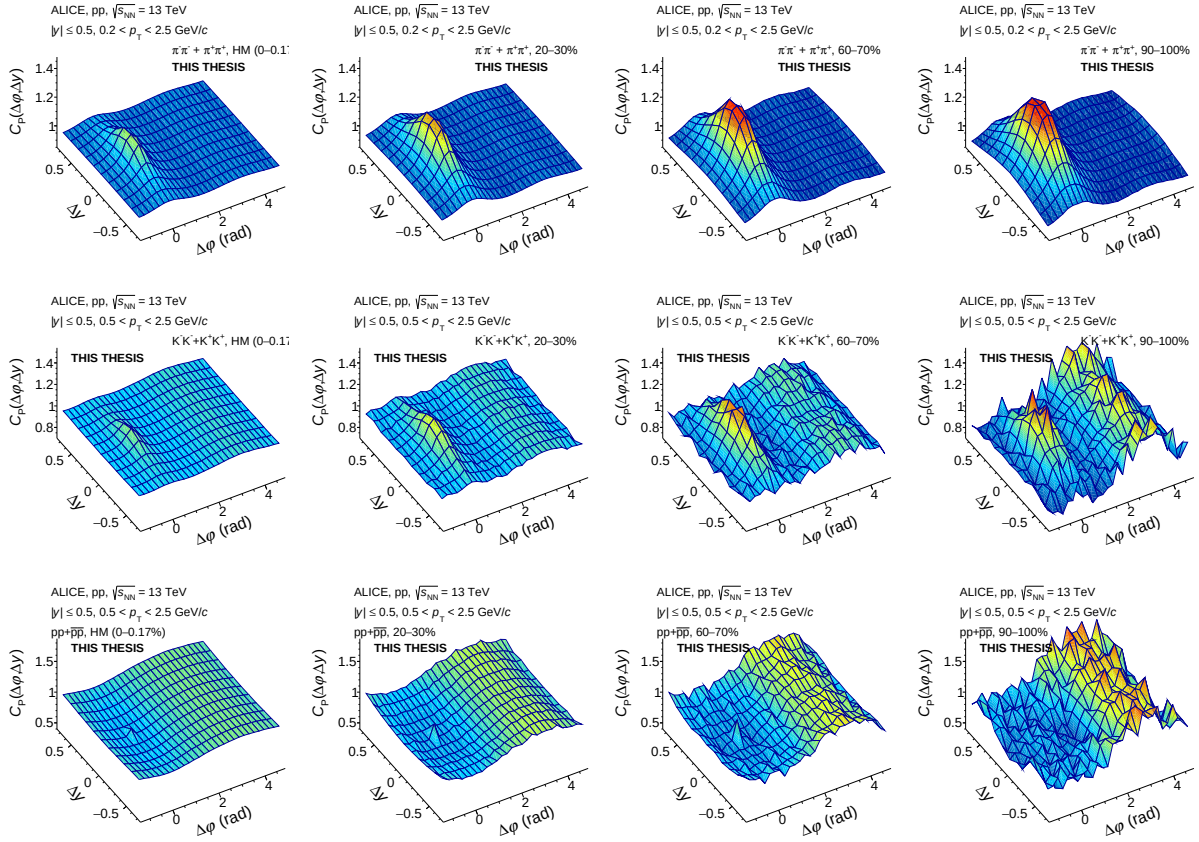


FIGURE 8.16: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition for like-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.

As seen in the analysis of four multiplicity classes, the correlation trends remain consistent across the expanded set of multiplicity classes. By dividing the multiplicity classes into 13, the physical phenomena are more clearly exhibited in the plots. In particular, HM correlation functions offer deeper insight into the underlying physics. In all cases, the dominant contribution to the correlation functions for both like- and unlike-sign pions and kaons comes from the minijets. Additionally, for like-sign pions and kaons, Bose-Einstein correlations are evident, leading to an enhancement in the near-side region, while the away-side region shows the typical back-to-back jet structure. For unlike-sign pions and kaons, in addition to the minijet structure, which is the main contributor, Coulomb and strong interactions further enhance the peak in the near-side region. In the case of unlike-sign kaons, the conservation of strangeness plays a significant role, leading to a highly pronounced, narrow peak with a ring-like structure at $(\Delta y, \Delta \phi) = (0, 0)$, which has been observed in the previous four-class analysis, is due to

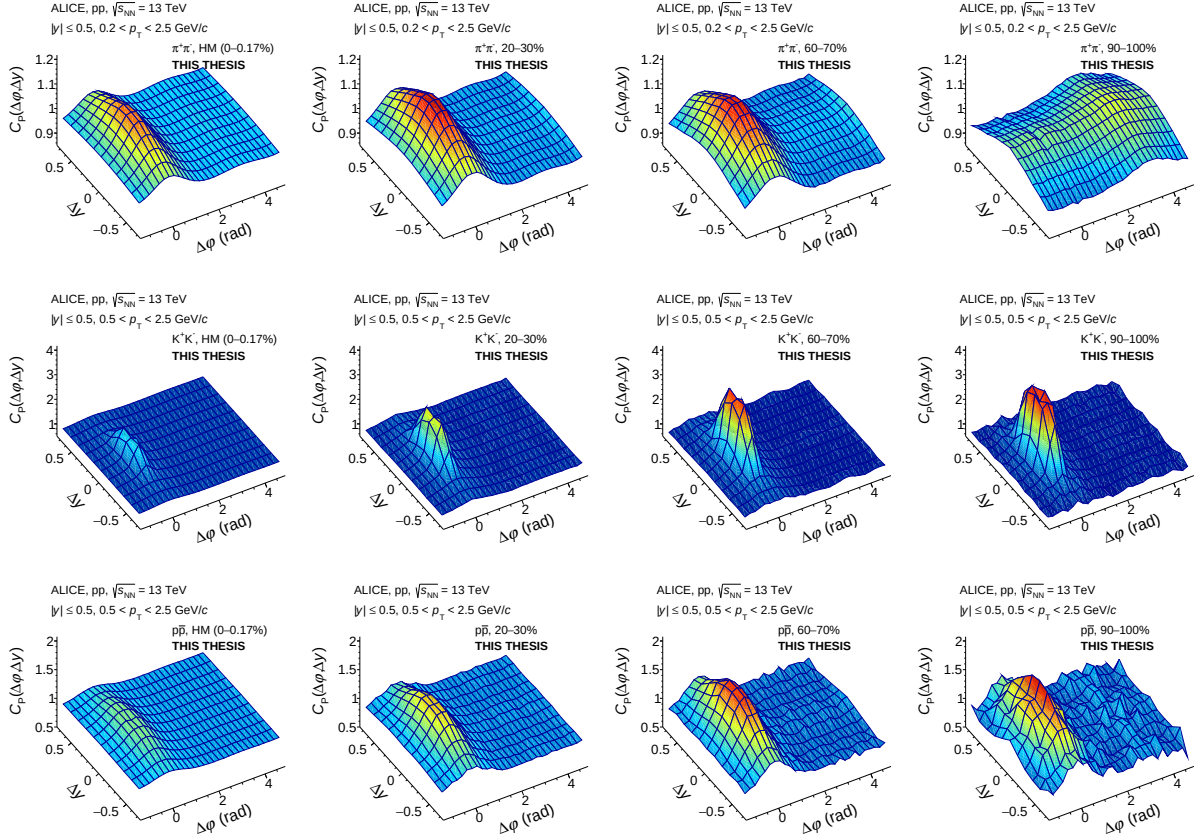


FIGURE 8.17: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition for unlike-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.

a ϕ resonances [83]. For like-sign protons, the anticorrelation is particularly strong in the HM class, with a small peak observed in the $(\Delta y, \Delta \phi)$ at (0,0), indicative of strong interactions, as described in the previous section of the analysis over four multiplicity classes. An interesting feature, not visible in the analysis with four multiplicity classes, is the dip that appears in the unlike-sign proton correlation in the high-multiplicity class. This phenomenon arises from strong interaction effects, where the annihilation of unlike-sign protons contributes to the observed dip. This effect was discussed in Sec. 4.4.3.

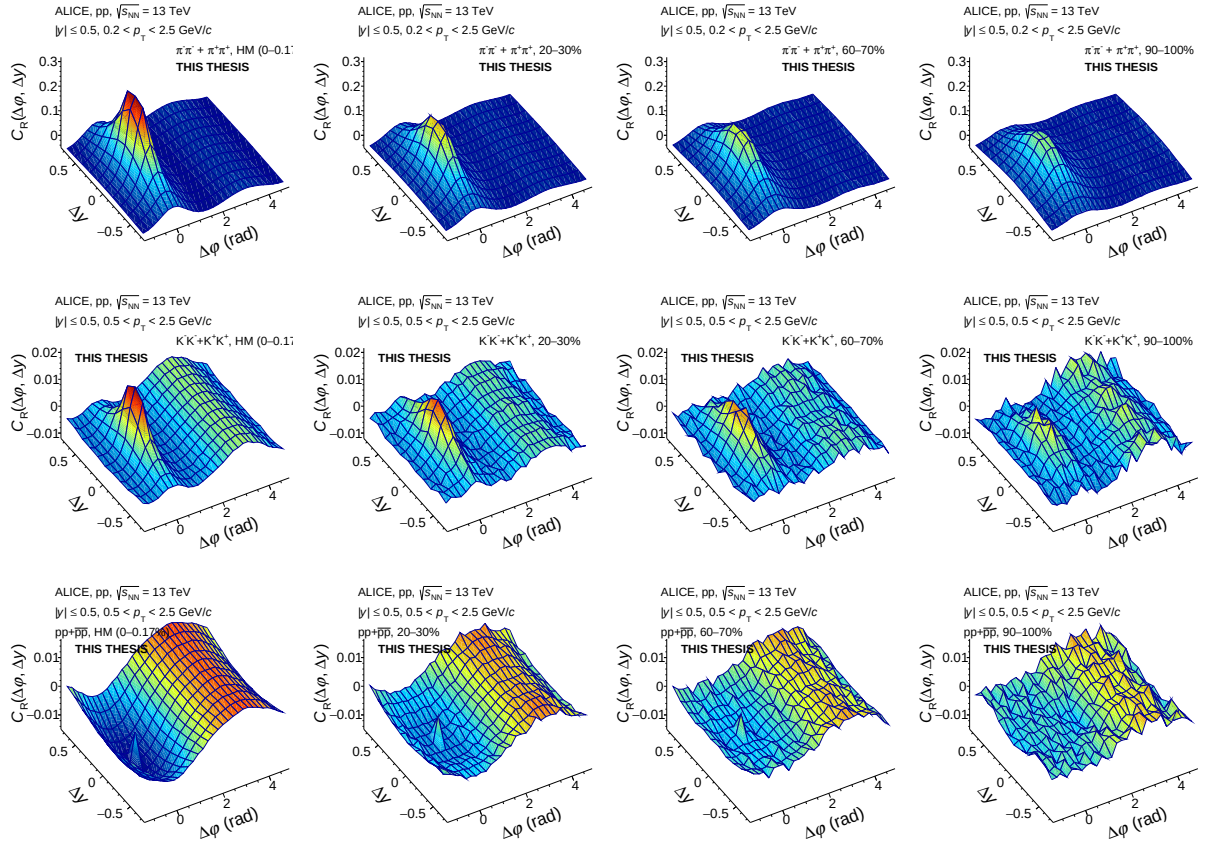


FIGURE 8.18: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition for like-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.

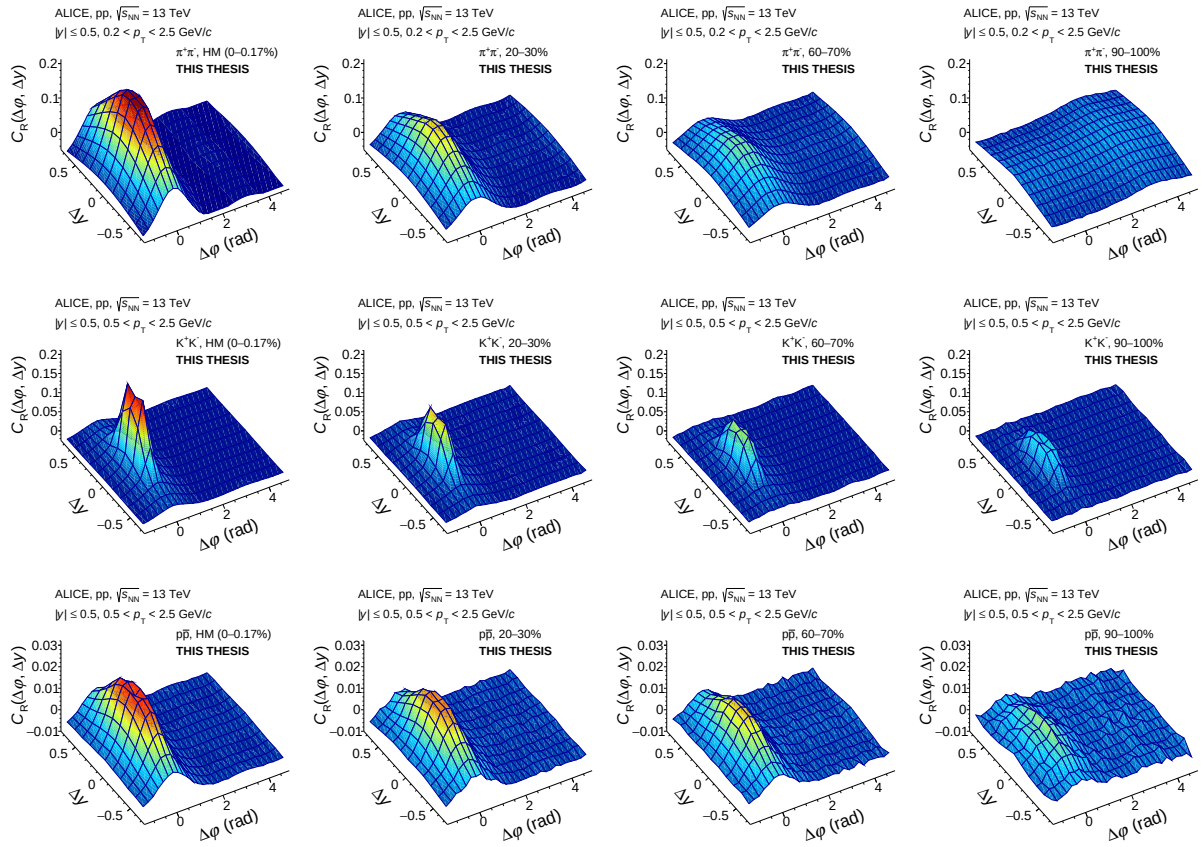


FIGURE 8.19: $\Delta y \Delta \phi$ correlation functions from pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition for unlike-sign particle pairs in HM (0–0.17%), mid (20–30%, 60–70%), and low (90–100%) multiplicity classes.

8.2.2 $\Delta\phi$ projections

Figures 8.20 and 8.21 present the $\Delta\phi$ projections of like-sign and unlike-sign correlation functions, integrated over the full $|\Delta y| < 1$ acceptance range. These correspond to the probability ratio and rescaled two-particle correlation function definitions, respectively. The thirteen multiplicity classes are clearly visible as projections in the azimuthal direction, enabling a detailed comparison across multiplicity classes.

The plots include both statistical and systematic uncertainties. Statistical uncertainties are displayed as error bars directly on the correlation functions, while systematic uncertainties are shown as colored boxes at the bottom of each plot. Each color represents a specific correlation function for a given multiplicity class, and the same color scheme is consistently applied across all classes. Systematic uncertainties were analyzed separately for each correlation function type. For the probability ratio, relative uncertainties were used, and their magnitude increases for lower multiplicity due to limited statistics. In contrast, the rescaled two-particle correlation function uses absolute uncertainties, which exhibit a consistent trend across all multiplicity classes, with one notable exception: for unlike-sign pions, systematic uncertainties show a clear decrease, transitioning from larger values at high multiplicity to smaller values at low multiplicity. In the case of correlation functions defined by the probability ratio, the $1/N$ multiplicity scaling causes the distributions to appear higher for lower multiplicity classes. This behavior, previously observed for four multiplicity classes, is clearly visible here, especially for unlike-sign pions. The $\pi^+\pi^-$ distribution confirms the presence of resonances, particularly evident in the lower multiplicity classes.

The behavior observed for other particle types is consistent with previous findings. By employing the rescaled two-particle correlation function, the correlations show a notable dependence on multiplicity. As illustrated in Fig. 8.21, the distributions for all particle types increase with multiplicity. An exception is observed for like-sign kaons, where the correlation functions appear largely independent of multiplicity, with all distributions overlapping.

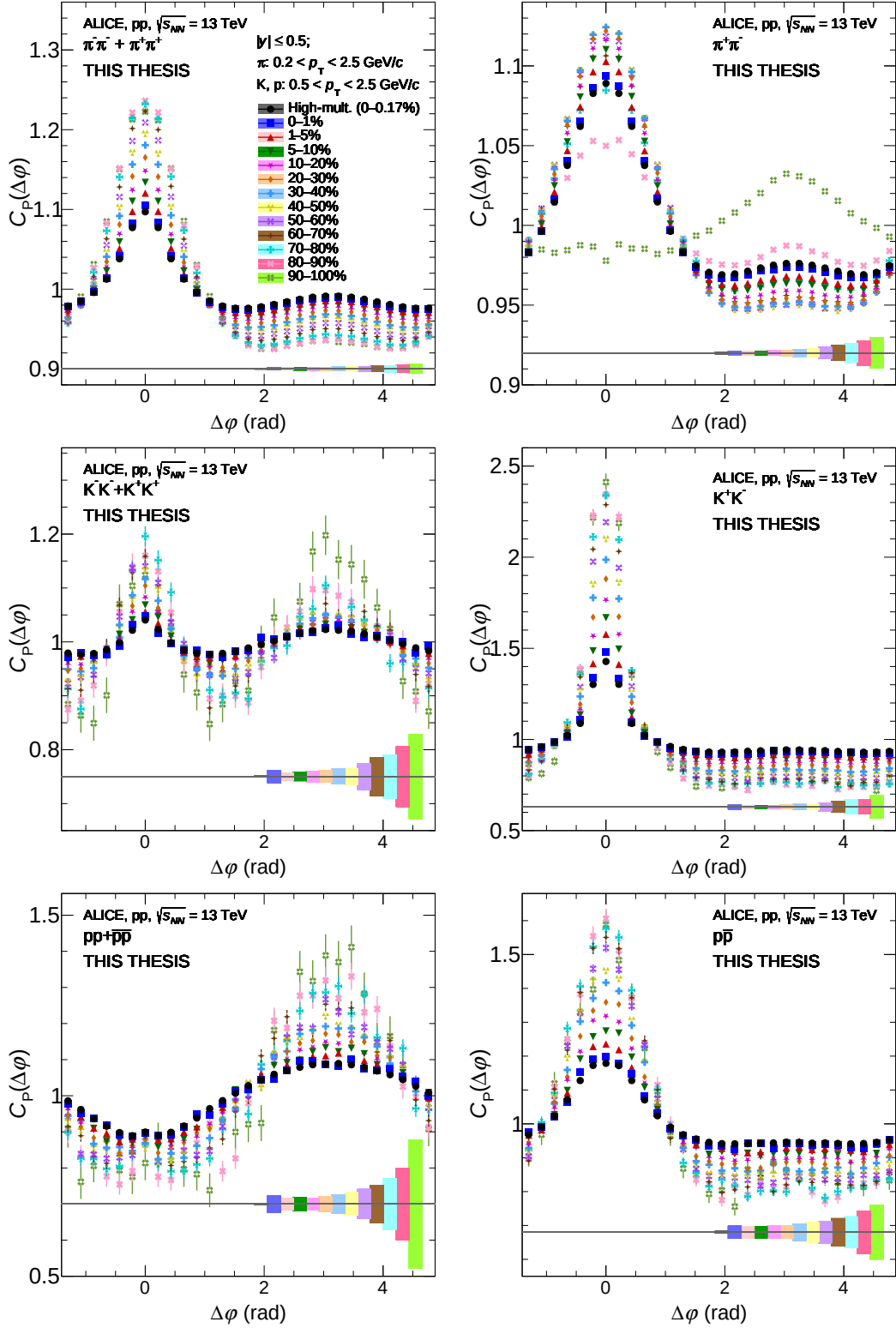


FIGURE 8.20: $\Delta\phi$ projections of correlation functions from pp collision at $\sqrt{s} = 13$ TeV within $\Delta y < 1$ for like- and unlike-sign pions, kaons, and protons in multiplicity classes, using the probability ratio definition. Statistical uncertainties (bars) and systematic uncertainties (boxes) are both drawn with the color associated with the corresponding multiplicity class.

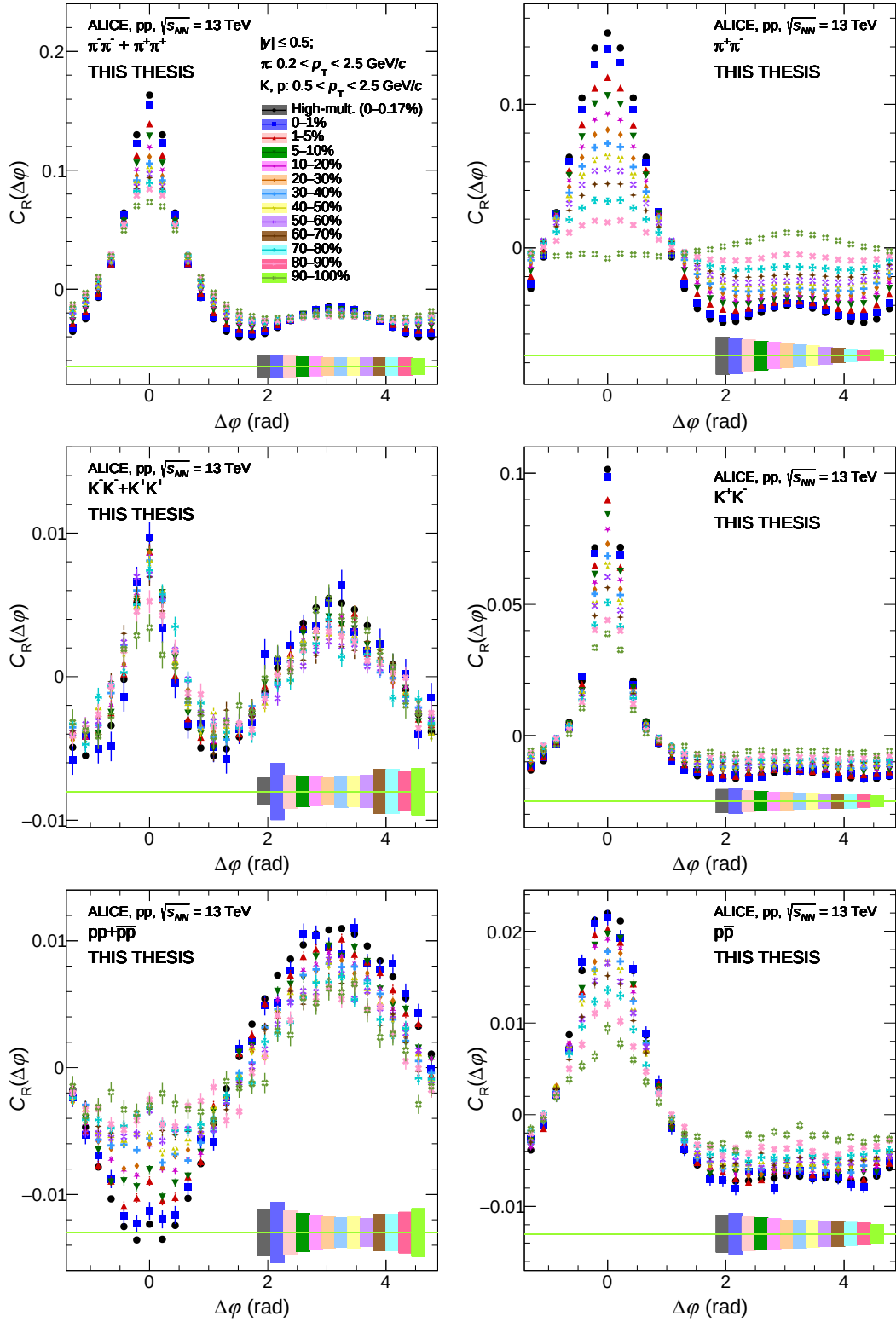


FIGURE 8.21: $\Delta\phi$ projections of correlation functions from pp collision at $\sqrt{s} = 13$ TeV within $\Delta y < 1$ for like- and unlike-sign pions, kaons, and protons in multiplicity classes, using the rescaled two-particle correlation function definition. Statistical uncertainties (bars) and systematic uncertainties (boxes) are both drawn with the color associated with the corresponding multiplicity class.

8.2.3 Comparison to MC models

The results from both correlation function definitions were compared with the same MC models used in the analysis across four multiplicity classes: PYTHIA8_Monash 2013 and EPOS LHC, at $\sqrt{s} = 13$ TeV in pp collisions. Figures 8.22 and 8.23 present the azimuthal two-particle angular correlations for like-sign and unlike-sign pions, kaons, and protons across the highest (0–1%), middle (20–30% and 60–70%), and lowest (90–100%) multiplicity classes using the probability ratio definition. Meanwhile,

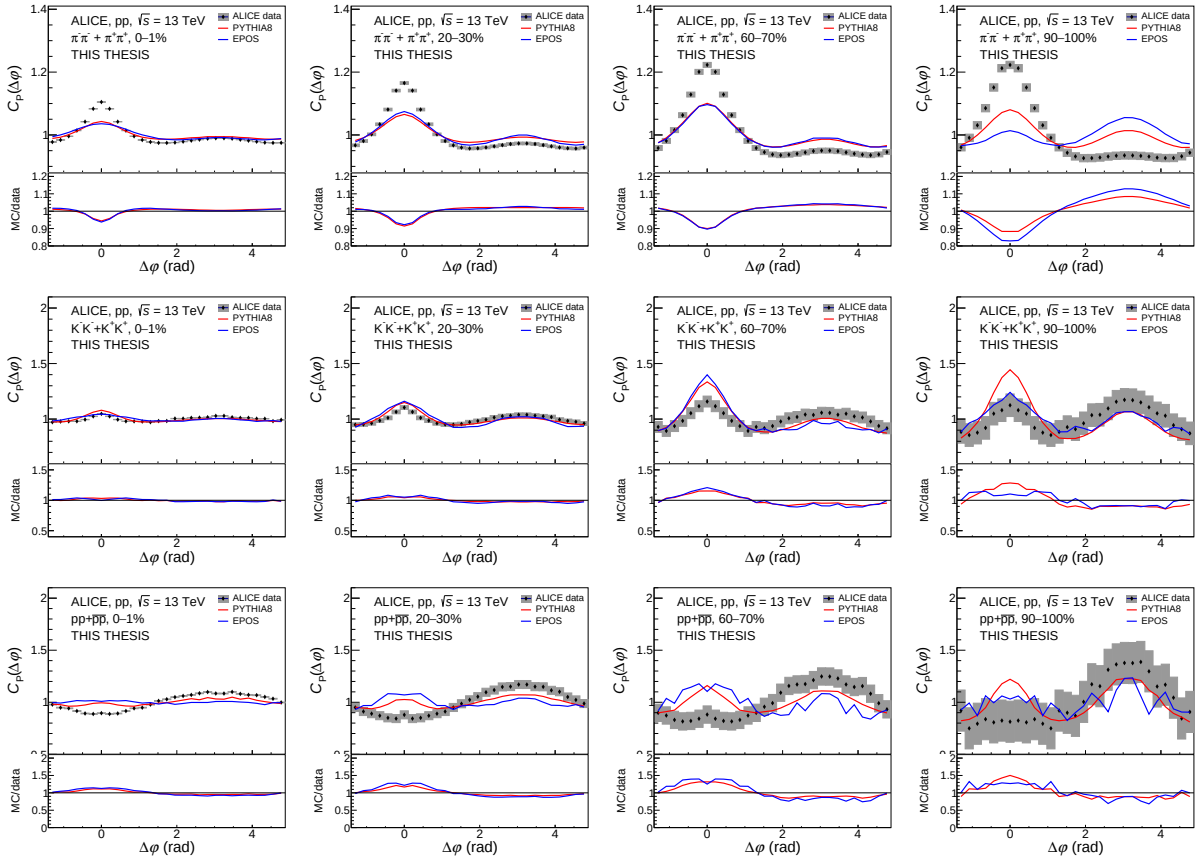


FIGURE 8.22: Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the probability ratio definition for like-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.

Figures 8.24 and 8.25 illustrate the same comparison for the rescaled two-particle correlation functions. The same multiplicity classes were used for both definitions, though the presentation of rescaled results is more compact due to space constraints.

The comparison is displayed on the upper plots, showing the projection in the azimuthal direction for experimental data and MC models, while in the bottom plots, the

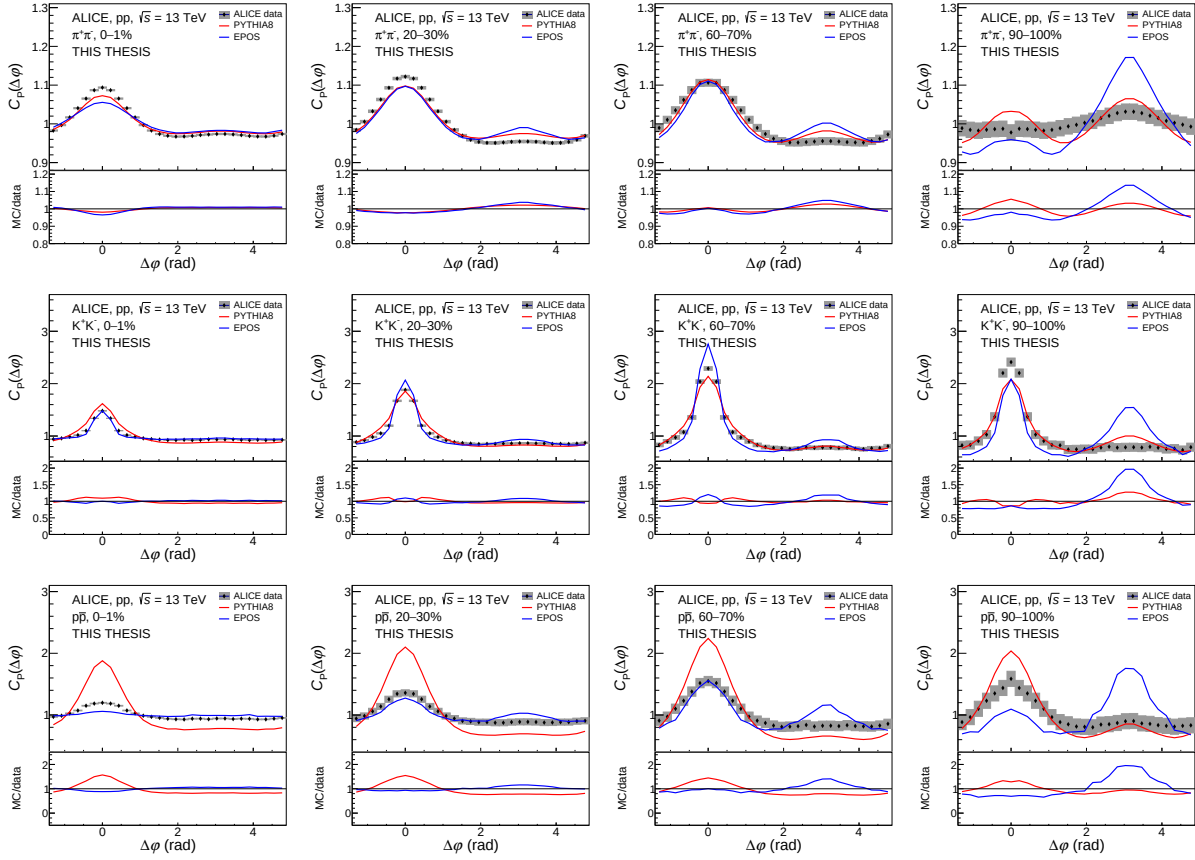


FIGURE 8.23: Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the probability ratio definition for unlike-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.

ratio of the models with the data is shown giving the magnitude of the discrepancy between them.

The definitions exhibit similar trends in both correlation function formulations when comparing experimental data with MC model predictions. Overall, the MC models reproduce the experimental results for mesons quite well. Since the models do not incorporate QS effects, the experimental data exhibit larger correlations than the model predictions. For unlike-sign pions in the lowest multiplicity class, the models fail to describe the correlation. In scenarios with a low particle multiplicity, it is hypothesized that the probability of a π^+ and π^- being close to each other in phase space decreases. This is attributed to a higher probability of charge and momentum balancing occurring at 180 degrees. As a result, the near-side peak in the correlation function is suppressed. For like-sign kaons, good agreement is observed in

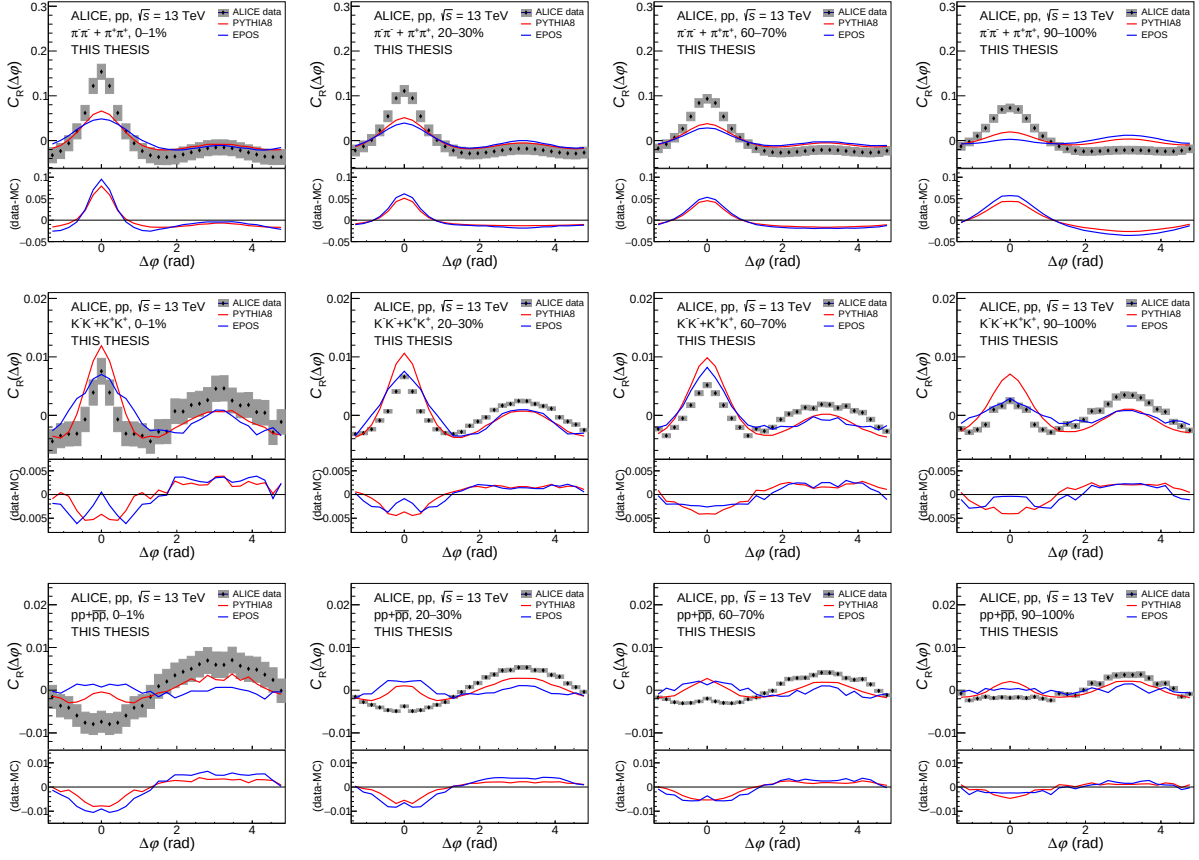


FIGURE 8.24: Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the rescaled two-particle correlation function definition for like-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.

both the near-side and away-side regions, particularly at lower multiplicity for both correlation function definitions. For unlike-sign kaons, the agreement is reasonable in the near-side region; however, the models fail to capture the away-side structure, especially at lower multiplicity classes.

Despite these successes, the models are unable to describe the anticorrelations. For unlike-sign protons, while EPOS LHC does not reproduce the data either qualitatively or quantitatively, PYTHIA8 qualitatively matches the correlation trends. In certain multiplicity classes, PYTHIA8 even achieves good agreement within the experimental uncertainties.

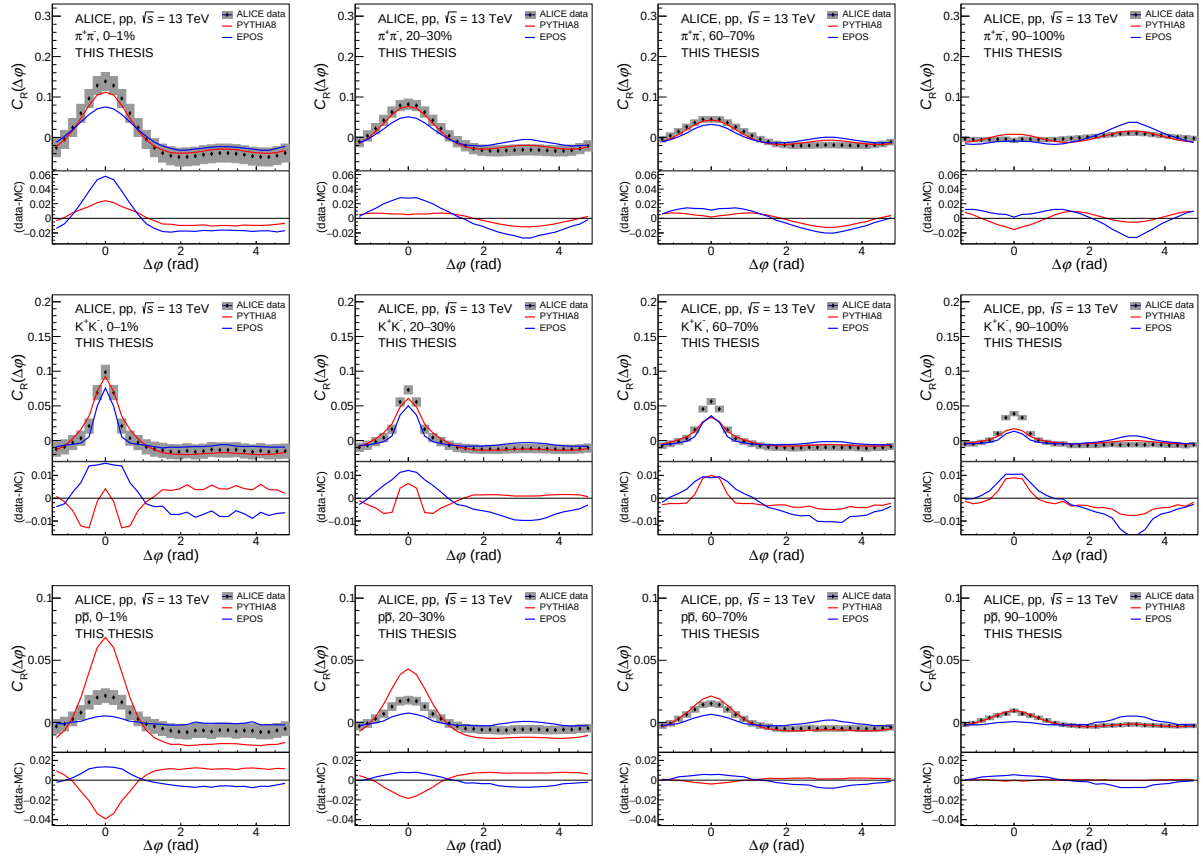


FIGURE 8.25: Comparison of pp collision data at $\sqrt{s} = 13$ TeV with PYTHIA8 and EPOS_LHC using the rescaled two-particle correlation function definition for unlike-sign particle pairs in the (0–1%), (20–30%), (60–70%), and (90–100%) multiplicity classes.

8.3 Results from p–Pb collision

The analysis, previously conducted for pp collisions, was repeated by using data recorded in 2016 period from p–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for both the correlation functions introduced.

8.3.1 N_{av} values

The value of N_{av} , determined in the pp collision analysis, was deemed valid and consequently applied to the p–Pb analysis for defining the rescaled two-particle correlation functions.

The value of N_{av} were calculated, as was done in the pp collision analysis. This method has been previously tested where the values were cross-checked against public data. The results demonstrated good experimental agreement between the calculated values and published data, within systematic uncertainties. Consequently, in the subsequent p–Pb collision analysis, N_{av} values were estimated using the same method. The estimated values are presented in the following Tab. 8.3.

Experimental N_{av} values from p–Pb collision

	Multiplicity 0–20%	Multiplicity 20–40%	Multiplicity 40–70%	Multiplicity 70–100%
<i>Pions</i>	12.2	7.8	4.8	2.1
<i>Kaons</i>	0.81	0.5	0.28	0.1
<i>Protons</i>	0.79	0.5	0.31	0.12

TABLE 8.3: N_{av} value estimated using experimental data from p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the four multiplicity classes analysed, i.e 0–20%, 20–40%, 40–70% and 70–100%. These values are performed for pions, kaons and protons.

8.3.2 2D $\Delta y \Delta \phi$ correlation function

Correlation functions are plotted and compared between the probability ratio and rescaled two-particle correlation functions across all analyzed particles and multiplicity classes. Figures from 8.26 to 8.31 illustrate the comparison between these two definitions.

Using the definition of the likelihood ratio, the correlation function increases significantly for lower multiplicity classes due to the expected multiplicity scaling $\sim 1/N$.

In contrast, the rescaled two-particle correlation function mitigates this issue by providing a representation that more accurately reflects the actual number of events in each multiplicity class. While both correlation functions are valid and capture genuine correlations, they emphasize different aspects of the data.

Like-sign pions exhibit the characteristic structures associated with minijets and Bose-Einstein correlations, including a pronounced peak in the near-side region. A similar structure is observed for like-sign kaons. Interestingly, for like-sign pions, a small dip is observed at $(\Delta y, \Delta \phi) = (0, 0)$, a feature not present in the pp analysis due to the lower density of particle pairs compared to p-Pb collisions.

For unlike-sign pions, a similar ring-like structure is observed in the near-side region, as previously noted for unlike-sign kaons. This effect arises from resonances that decay with small angular separation at $(\Delta y, \Delta \phi) = (0, 0)$, rather than producing a longitudinal ridge structure as seen in pp collision analyses. Specifically, the near-side structure is attributed to ρ^0 resonances, which decay into $\pi^+ \pi^-$ pairs with minimal Q energy release, contributing to the observed ring structure [93]. A comparable effect is evident in unlike-sign kaons, particularly when the rescaled two-particle correlation function is used. In contrast, the probability ratio tends to obscure this phenomenon due to trivial multiplicity scaling. Notably, ϕ resonances introduce a ring-like structure on the near-side peak, consistent with previous observations [83].

In case of like-sign protons, a depletion around $(\Delta y, \Delta \phi)$ at $(0, 0)$ is observed also in p-Pb collisions across all multiplicity classes. After removing the expected multiplicity scaling, the anticorrelations appear stronger in high-multiplicity classes. The small peak in the center of the anticorrelation region, as previously observed in the pp analysis, has been associated with strong interactions [91].

An important physical effect, previously identified when the pp analysis was extended from 4 to 13 multiplicity classes, is annihilation, which is visible for unlike-sign protons and appears as a dip in the $(\Delta y, \Delta \phi) = (0, 0)$. In pp collisions, this phenomenon was only visible in the highest multiplicity class (0–0.17%). However, in p-Pb collisions, due to the higher particle density, the annihilation effect is observed across all multiplicity classes. When studied using the rescaled two-particle correlation function, the effect becomes more pronounced with increasing multiplicity, indicating a direct association with particle density.

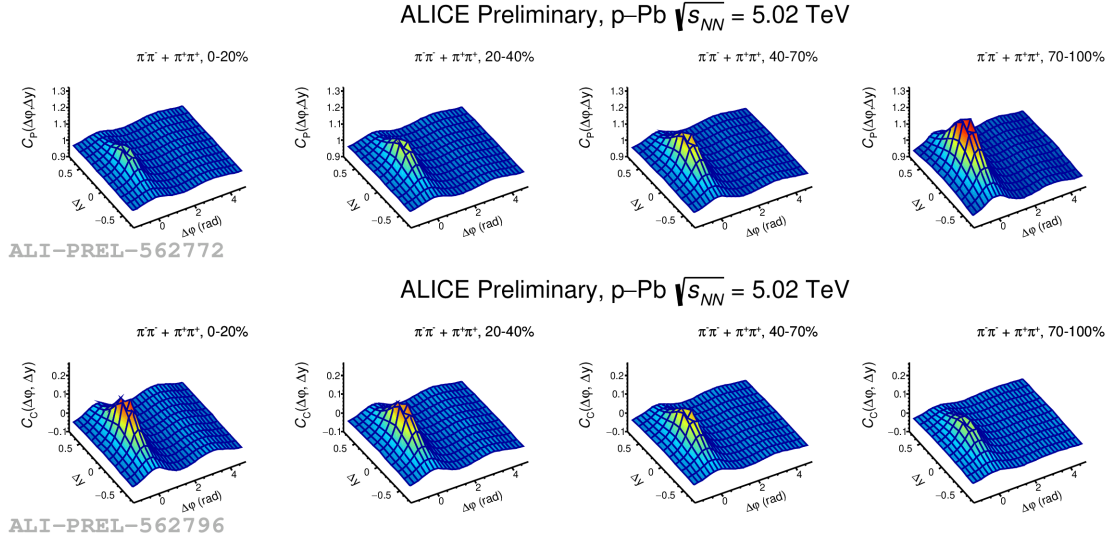


FIGURE 8.26: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

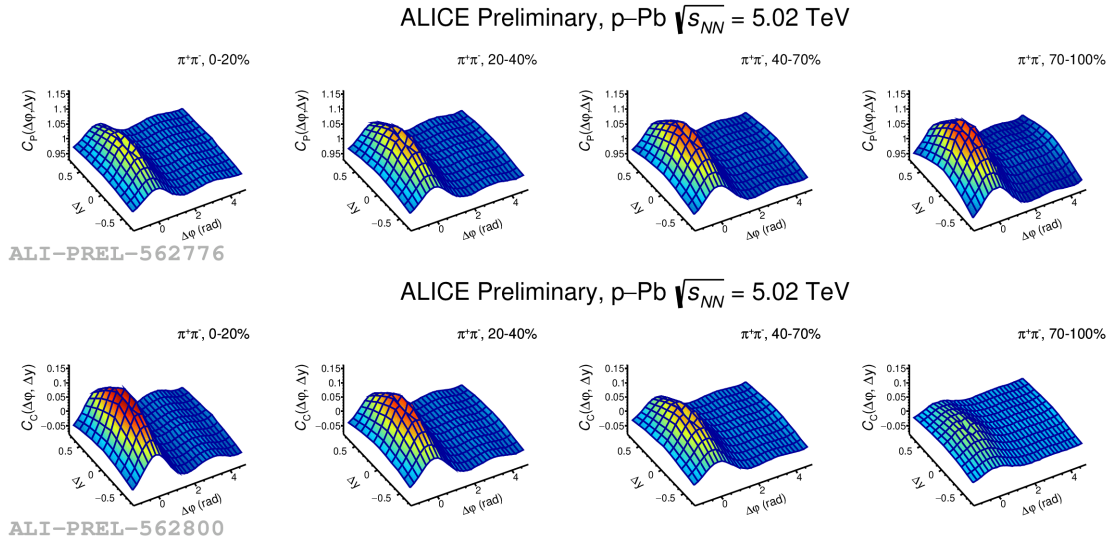


FIGURE 8.27: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign pions across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

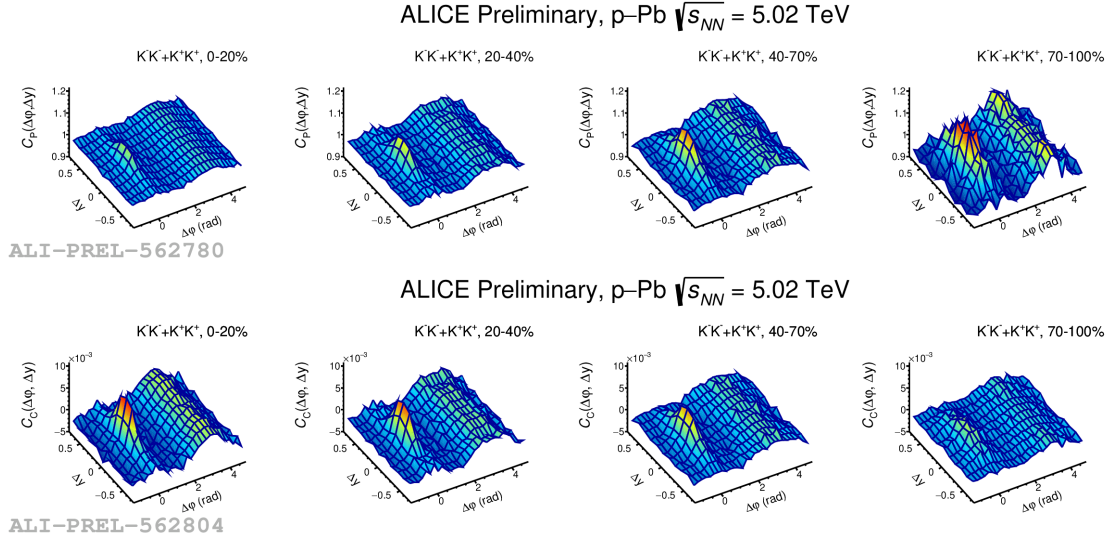


FIGURE 8.28: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

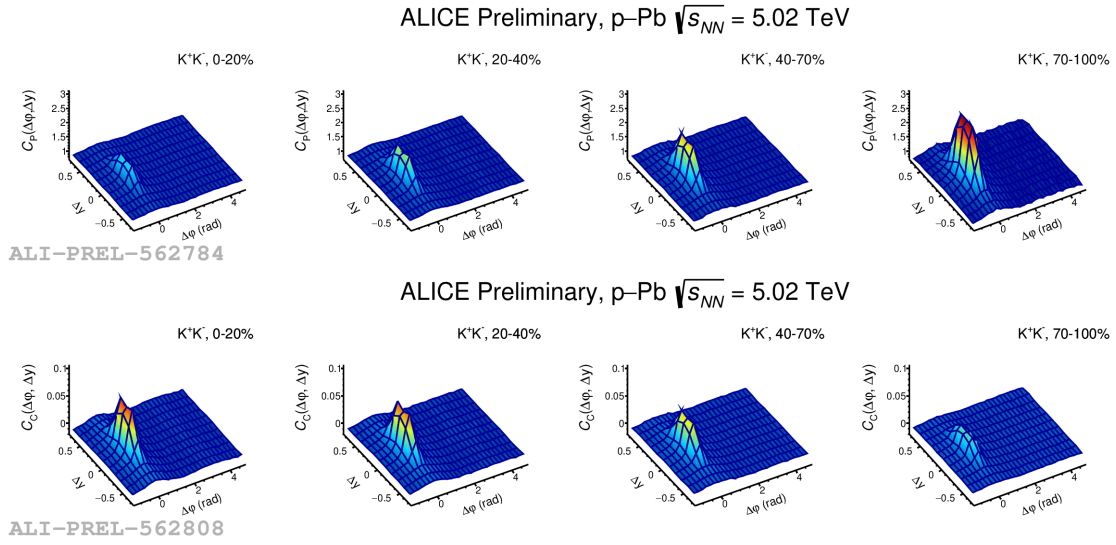


FIGURE 8.29: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign kaons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

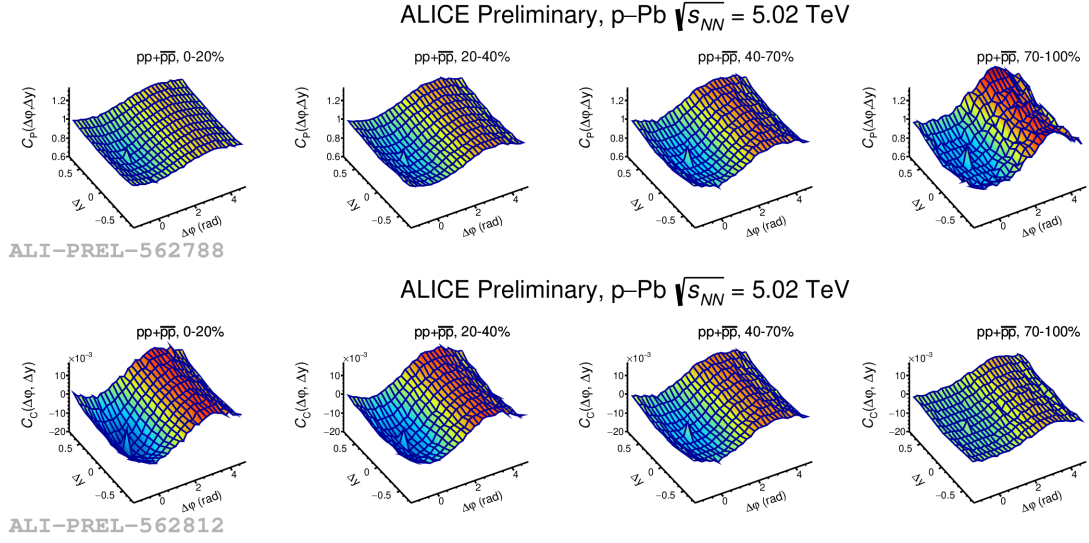


FIGURE 8.30: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for like-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

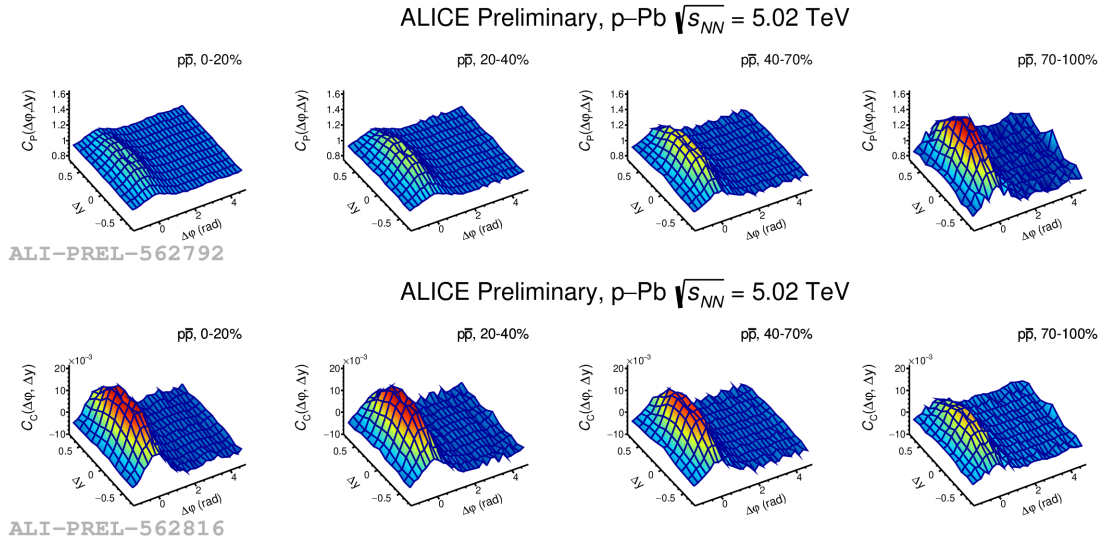


FIGURE 8.31: $\Delta y \Delta \phi$ correlation functions from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using the probability ratio definition (top row) and the rescaled two-particle correlation function (bottom row). The results are shown for unlike-sign protons across the [0–20%], [20–40%], [40–70%], and [70–100%] multiplicity classes.

8.3.3 Projection of $\Delta y \Delta \varphi$ correlation functions

The integrated $\Delta \varphi$ projections from this analysis of p–Pb collisions are presented in Figs. 8.32 and 8.33, for probability ratio and rescaled two-particle correlation function definitions, respectively.

The projection onto the azimuthal direction provides a clearer representation of the behavior of the correlation functions. As seen in the 2D plots, the probability ratio combines physical phenomena with trivial multiplicity scaling, resulting in an increase in the distributions as one moves toward lower multiplicity classes. In contrast, the rescaled two-particle correlation function reveals a more explicit dependence on multiplicity. By effectively disentangling physical correlations from the scaling effects, the rescaled distributions show an opposite trend: the higher the multiplicity, the larger the correlation function.

While many of the physical phenomena discussed in detail using the 2D plots are also evident in the azimuthal projections, some features are obscured due to the integration over the full Δy range.

For both correlation function definitions, systematic uncertainties are illustrated on the projections as empty colored boxes, corresponding to the color of each correlation function for each multiplicity class. Further details on the systematic uncertainties, including all values and separate plots, are provided in Appendix B.

8.3.4 Comparison to MC models

Predictions from MC models are compared with the measured correlations. The MC event generators used for this analysis are DPMJET [72] and EPOS_LHC [135], both at $\sqrt{s} = 5.02$ TeV.

The projections of models on the azimuthal direction, based on the probability ratio and rescaled two-particle cumulant definitions, are compared with ALICE data in Figs. 8.34 8.35 and 8.36 8.37, respectively. The figures follow a similar design to those used in the pp analysis. The upper plots depict the projections onto $\Delta \varphi$, while the bottom panels present the ratio to the data. This ratio serves as a quantitative indicator of the discrepancies between the models and the experimental results, highlighting their magnitude.

Starting with the probability ratio definition shown in Figs. 8.34 and 8.35 for like- and unlike-sign particle pairs, respectively, it is clear that neither model fully describes

the data. Neither model includes quantum statistical effects, which prevents a meaningful qualitative comparison for like- and unlike-sign pions. However, both models succeed quantitatively in reproducing the minijet structures in the near-side and away-side regions. For kaons, a better agreement is observed. EPOS_LHC provides a more accurate description of like-sign kaons at lower multiplicities, whereas DPMJET better reproduces the behavior of unlike-sign kaons. In contrast, both models fail to describe like- and unlike-sign protons. No anticorrelation is visible in the models, and there is neither qualitative nor quantitative agreement for unlike-sign protons.

With the rescaled two-particle correlation functions, the results appear notably different, as shown in Fig. 8.36 and 8.37 for like- and unlike-sign particle pairs, respectively. For like- and unlike-sign pions, as well as kaons, EPOS_LHC fails to reproduce the away-side features but shows qualitative agreement for most meson correlations. DPMJET, on the other hand, provides a better description of meson correlations, capturing both the near-side and away-side structures. For like-sign protons, both models fail to reproduce the observed anticorrelation. However, for unlike-sign protons, DPMJET achieves agreement within the uncertainties, while EPOS_LHC fails to describe the away-side but shows reasonable agreement on the near-side.

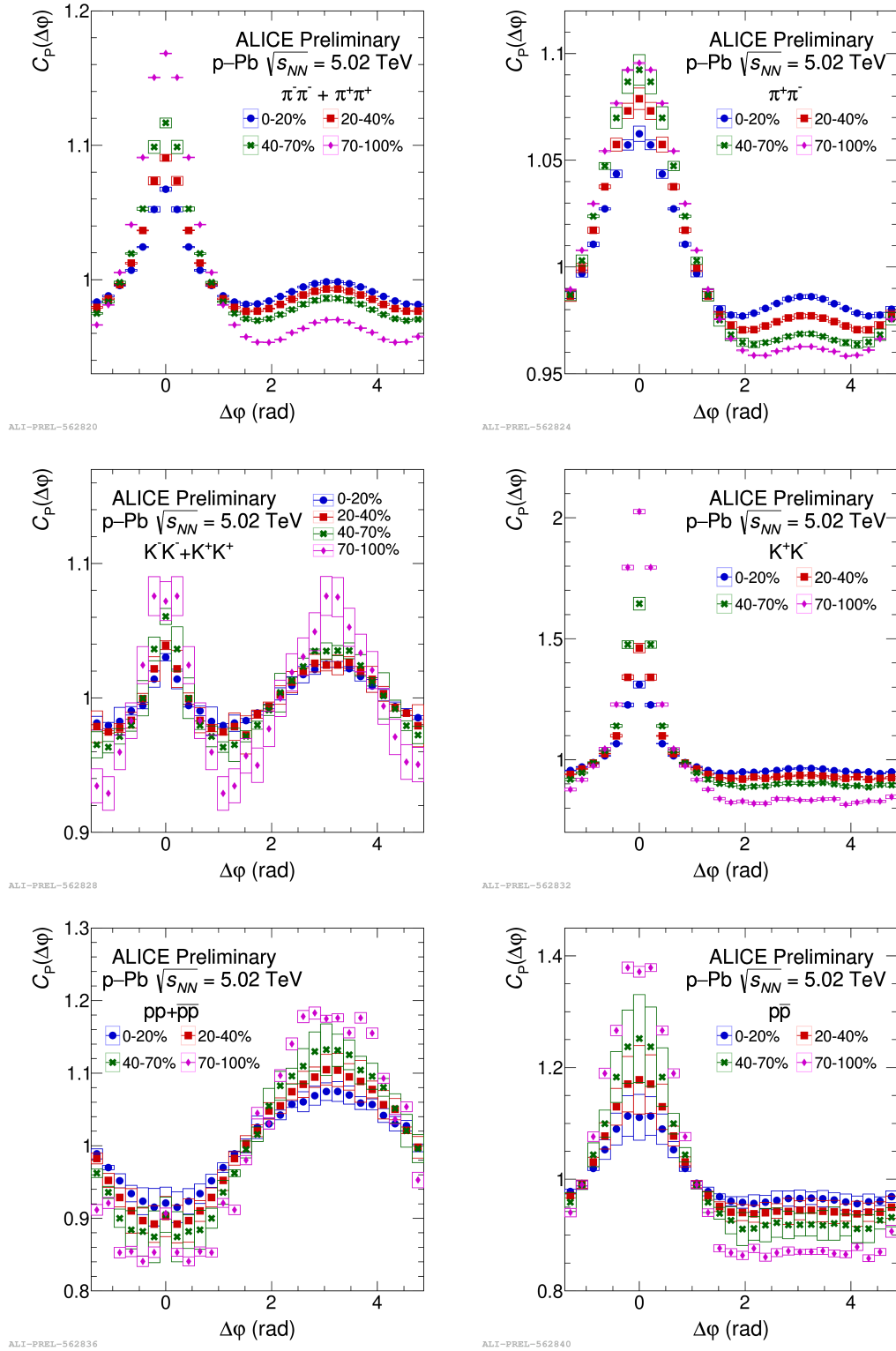


FIGURE 8.32: $\Delta\phi$ projections of correlation functions described using the definition of probability ratio. For each particle, the four multiplicity classes are drawn on the same canvas.

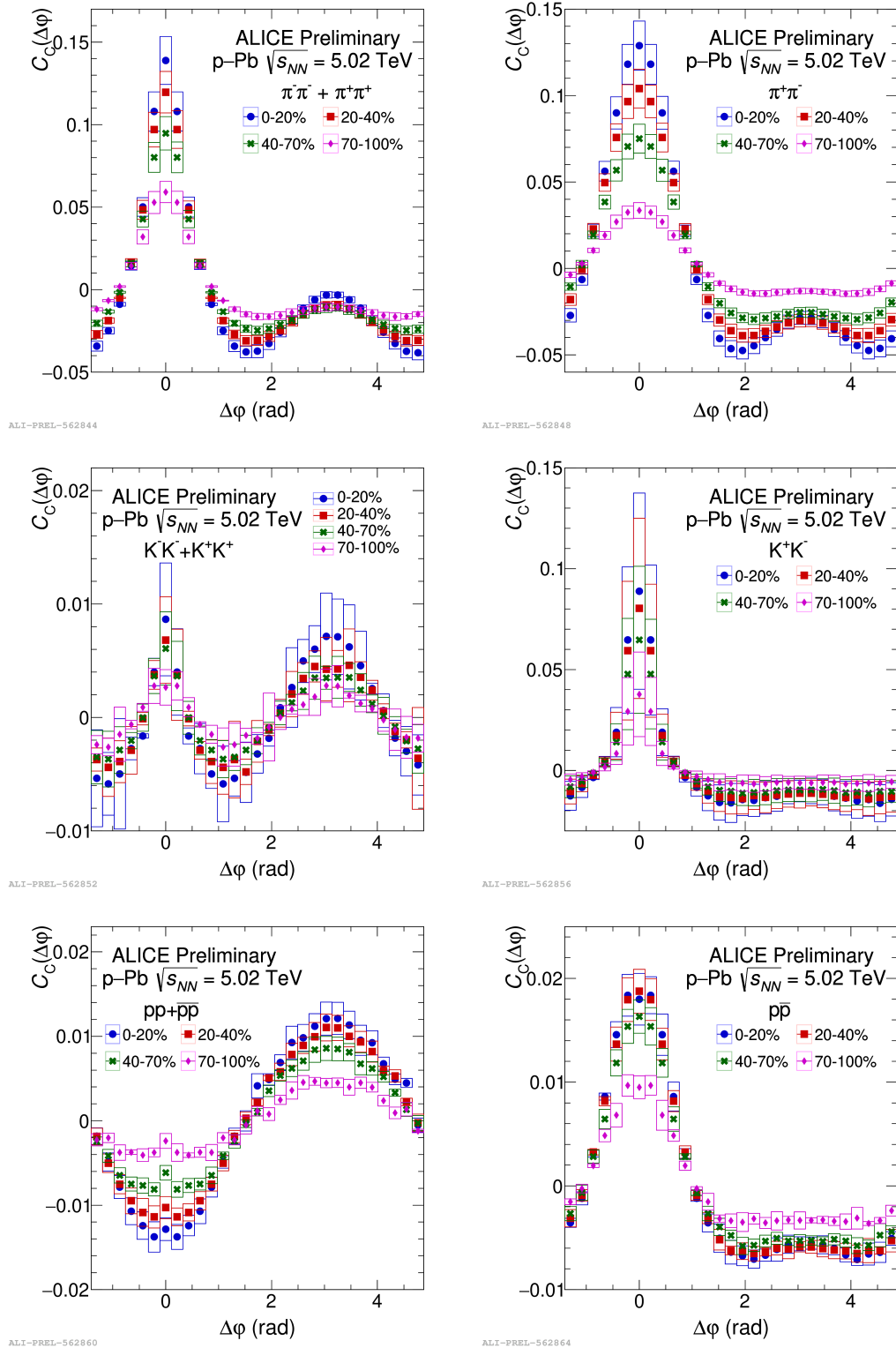
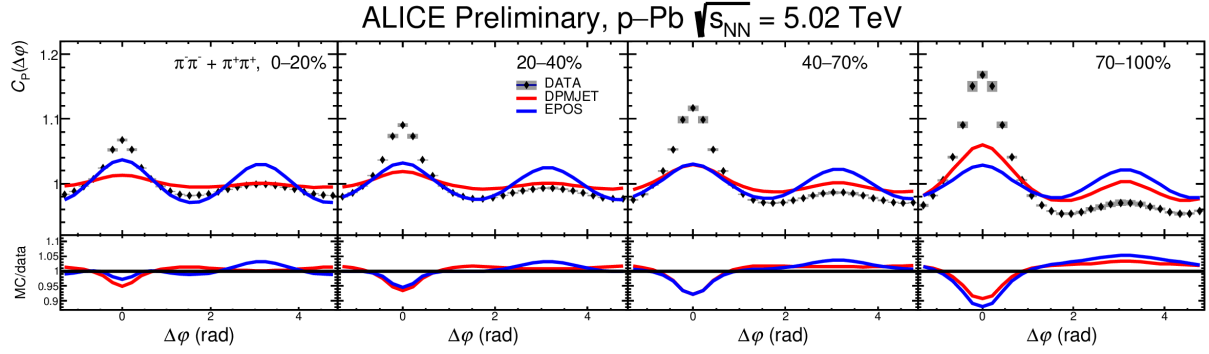
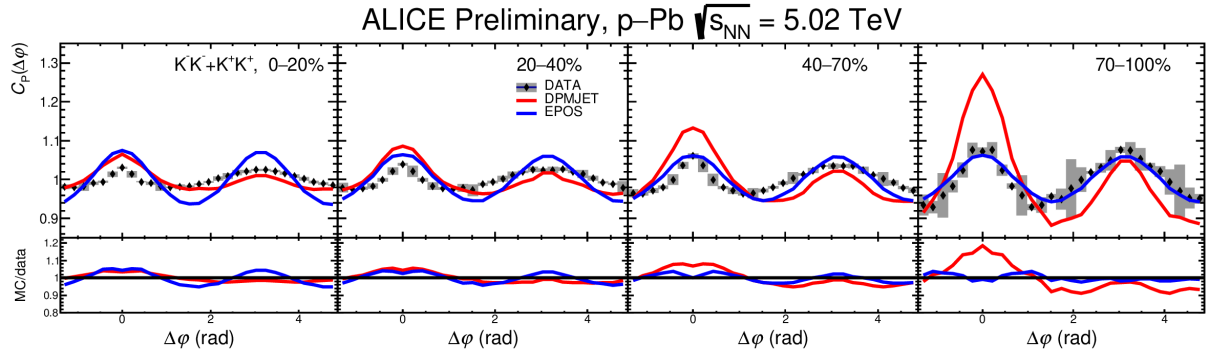


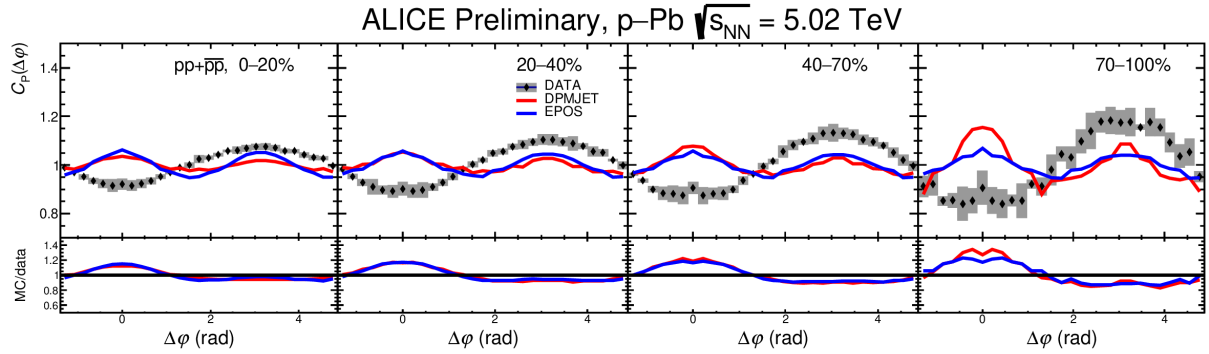
FIGURE 8.33: $\Delta\phi$ projections of correlation functions described using the definition of the rescaled two-particle correlation function. For each particle, the four multiplicity classes are drawn on the same canvas.



ALI-PREL-562868

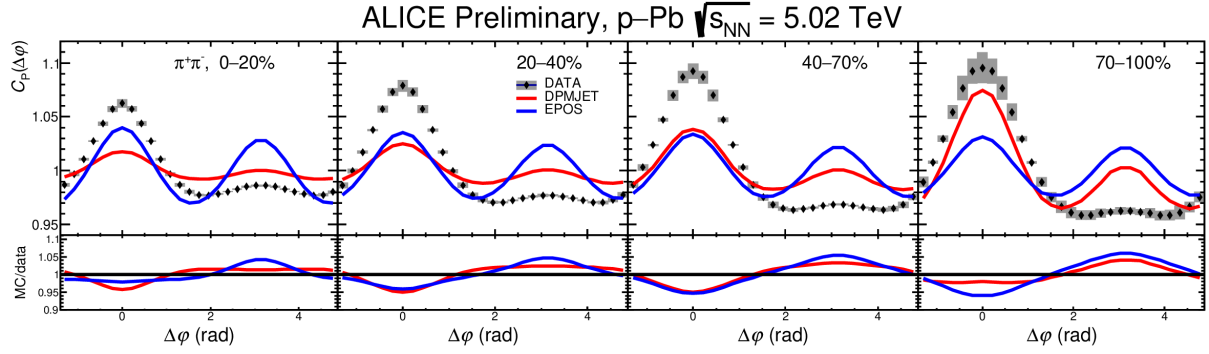


ALI-PREL-562876

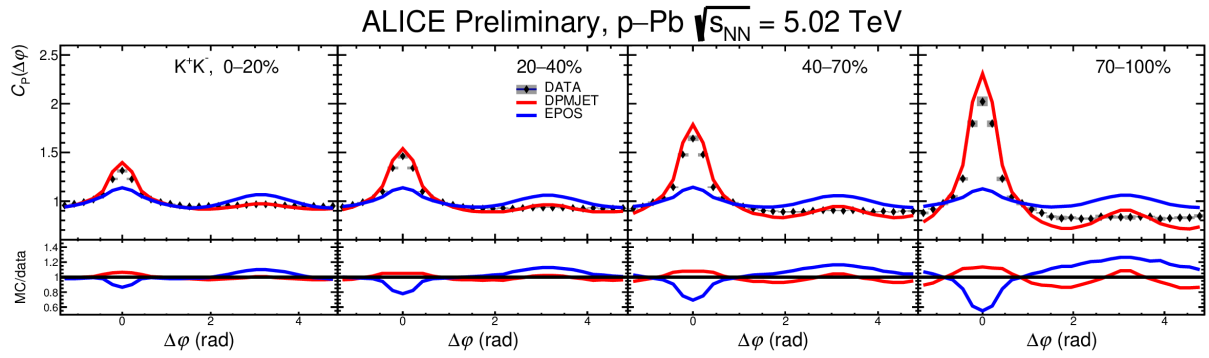


ALI-PREL-562884

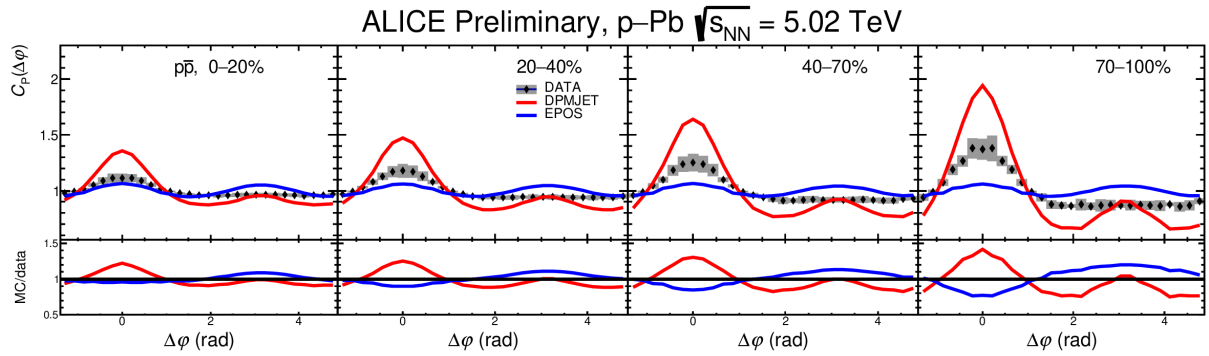
FIGURE 8.34: Data comparison with MC models using probability ratio definition for like-sign particles and for the four classes of multiplicity analyzed. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p-Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data.



ALI-PREL-562872



ALI-PREL-562880



ALI-PREL-562888

FIGURE 8.35: Data comparison with MC models using probability ratio definition for unlike-sign particles and for the four classes of multiplicity analyzed. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p-Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data.

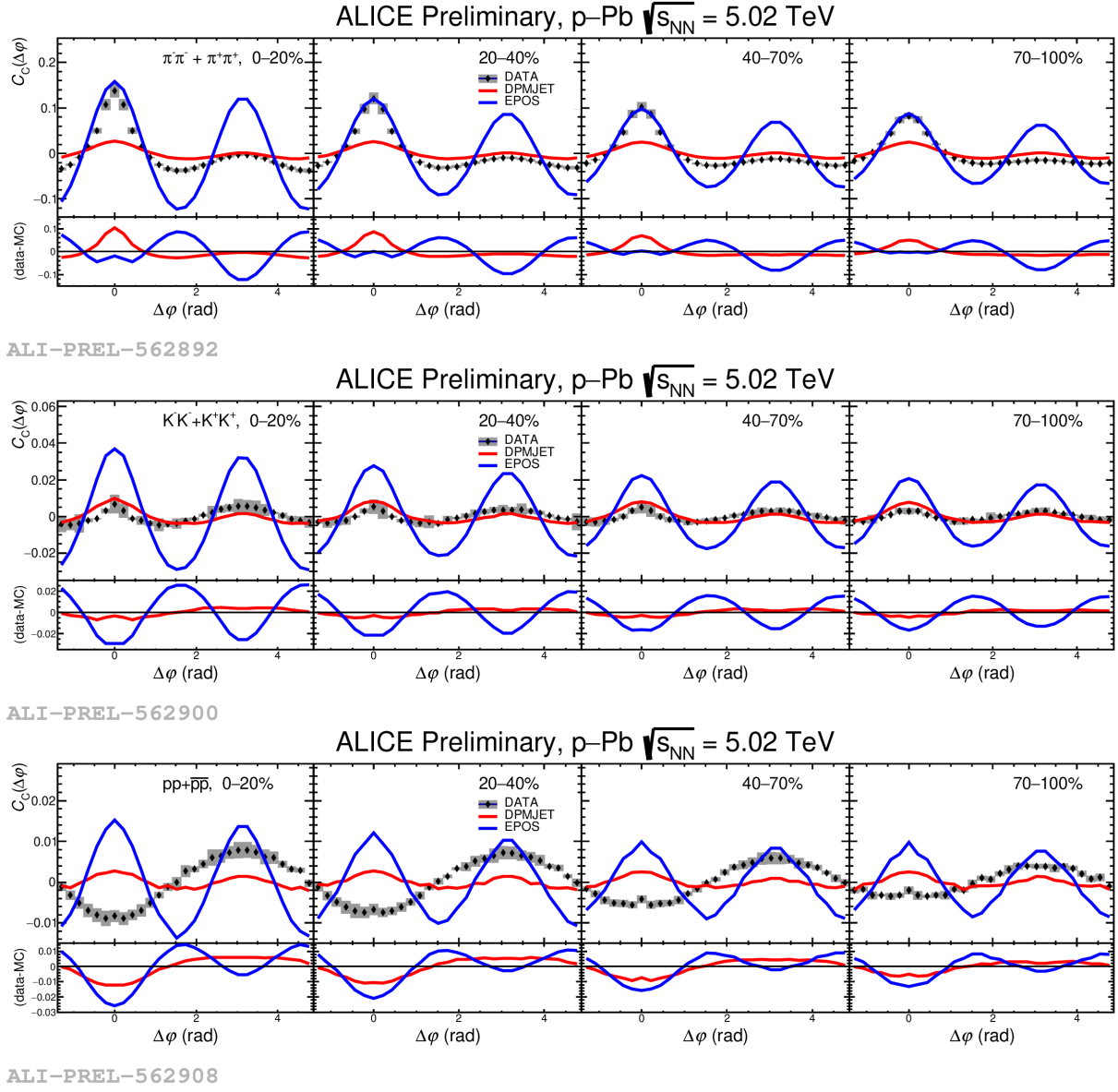
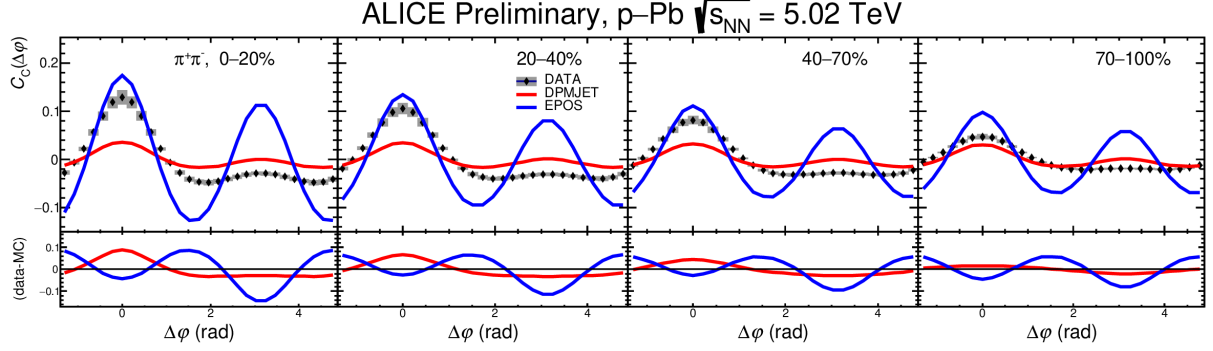
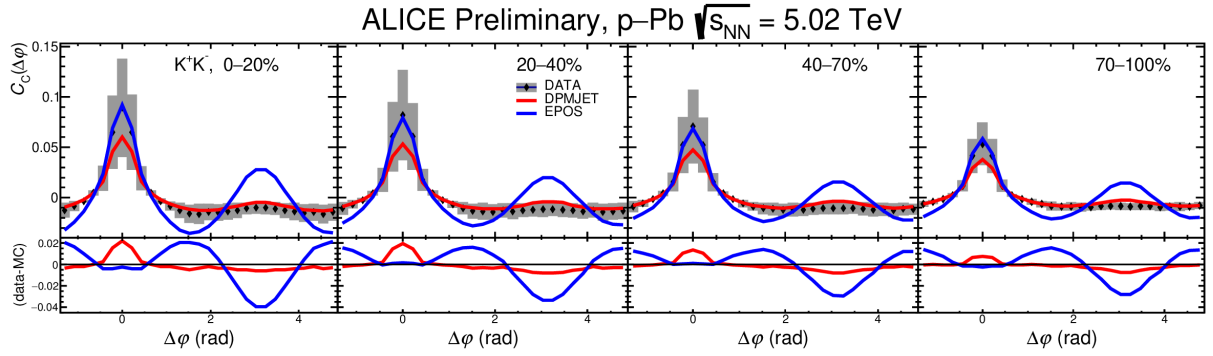


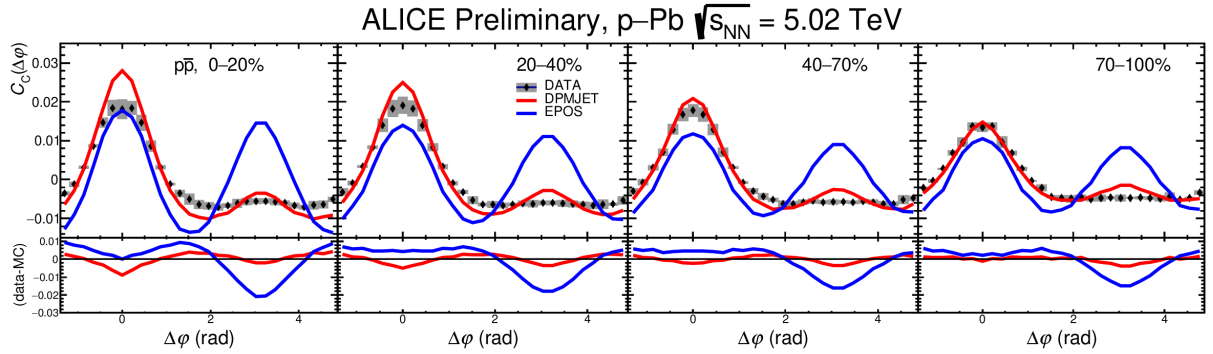
FIGURE 8.36: Data comparison with MC models using the rescaled two-particle correlation function definition for like-sign particle pairs and the four multiplicity classes involved. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p-Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data.



ALI-PREL-562896



ALI-PREL-562904



ALI-PREL-562912

FIGURE 8.37: Data comparison with MC models using the rescaled two-particle correlation function definition for unlike-sign particle pairs and the four multiplicity classes involved. The red solid line is the DPMJET model and in blue the EPOS_LHC model. The black markers are the ALICE experimental data from p-Pb collision with their respective uncertainties. The box below shows the ratio between each model and the actual data.

8.4 Small Systems in Focus: pp vs. p–Pb

The results of pp collisions in 4 multiplicity classes were compared with those of p–Pb collisions. This comparison allows to obtain information on how the correlation functions and thus the different contributing physical phenomena vary for each multiplicity class in small collision systems. This comparison is carried out separately for each definition, as shown in the plots below.

The measured correlation functions for like- and unlike-sign pions, kaons, and protons are shown in Fig. 8.38 using the probability ratio definition. Both pp and p–Pb correlation functions exhibit very similar shapes, suggesting that the physical phenomena occurring in both collision systems are closely related. In both systems, a distinct peak for meson correlations appears in the near-side region of $(\Delta y, \Delta \varphi)$ around $(0,0)$, which can be attributed to at least three physical effects: mini-jets, resonance decays, and femtoscopic correlations (Bose-Einstein correlations). While these phenomena occur in a similar manner in both systems, their intensities may differ, as it was described in details in the previous sections. However, due to the obscuring influence of $1/N$ scaling effects, direct comparison between the two systems in the probability ratio definition is challenging.

A slight difference is observed for unlike-sign pions in pp collisions. More specifically, resonance decays can contribute to the near-side peak of the correlation function, as observed in the 2D plots for p–Pb collisions (Fig. 8.27), or produce a ridge at $\Delta y = 0$ (extending in $\Delta \varphi$), as seen in pp collisions (Fig. 8.5) [93, 136]. In pp collisions, the $\pi^+ \pi^-$ correlation functions do not exhibit a monotonic behavior with multiplicity. At lower multiplicities, the near-side region does not show a clear increase; instead, a longitudinal ridge at $\Delta y = 0$ is formed. However, the projection in Fig. 8.39 reveals that, in terms of multiplicity, correlations increase at lower multiplicities, a trend not visible in p–Pb collisions. In p–Pb collisions, this effect, which is clearly visible in the 2D plots, is not apparent in the projection onto $\Delta \varphi$ due to the integration over the full Δy range.

In Fig. 8.40, the correlation functions for pp and p–Pb collisions are computed using the rescaled two-particle correlation function definition. These functions suggest that the number of correlated particles increases more rapidly than other particles (underlying events). Both collision systems show a multiplicity dependence in their correlation functions. In particular, in p–Pb collisions, the correlations are stronger than in pp collisions due to the higher multiplicity. Moreover, for baryon–baryon correlations, where anticorrelations are observed, the anticorrelation is stronger in p–Pb collisions

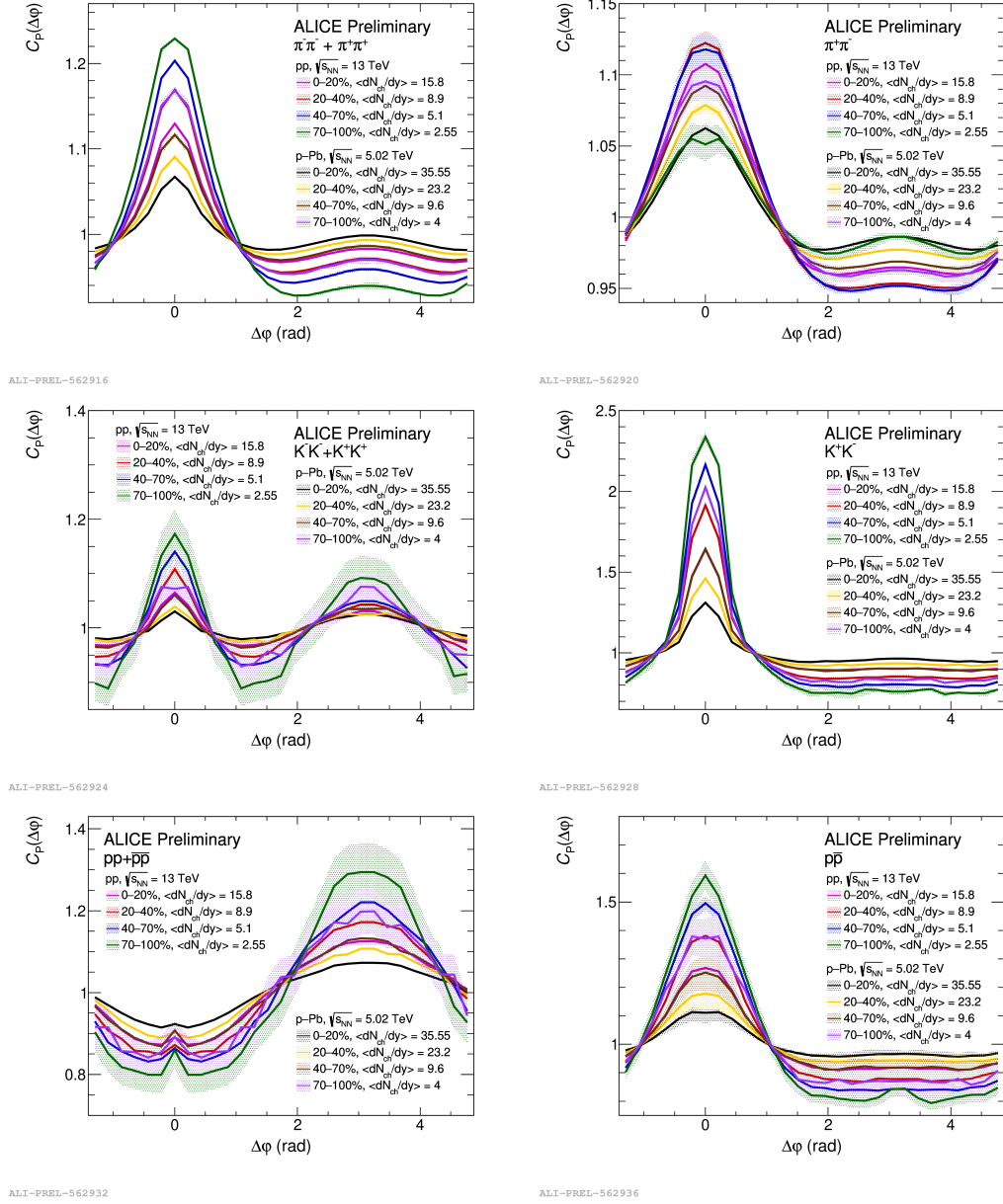


FIGURE 8.38: Comparison of the $\Delta\phi$ projections between pp and p-Pb collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV, respectively. The comparison is made for all particles and overall multiplicity classes analyzed using the probability ratio definition.

compared to pp collisions.

For proton-antiproton correlations, the highest multiplicity class (0–20%) in pp collisions shows a stronger correlation than in p-Pb collisions. This is attributed to the annihilation phenomenon, visible in the correlation function as an anti-peak at $\Delta\phi = 0$.

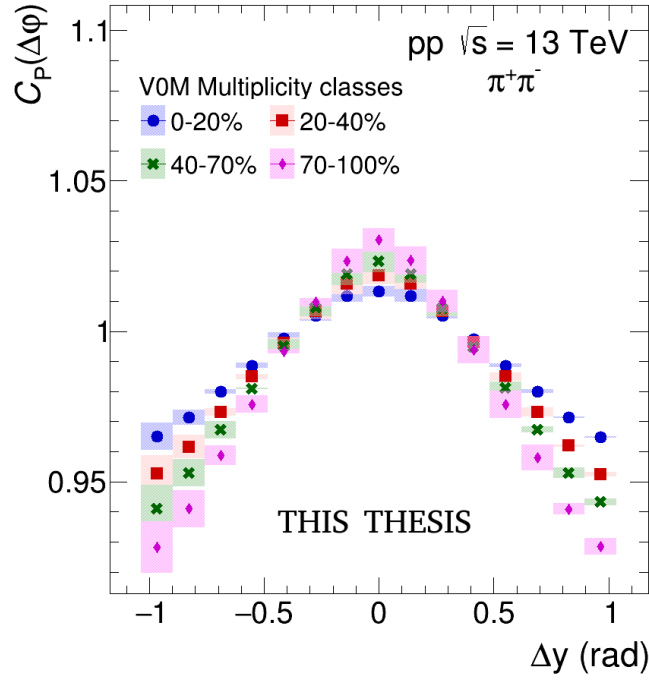


FIGURE 8.39: Projections of Δy of correlation functions using the probability ratio definition for unlike-sign pions. The correlation functions in different multiplicity classes show a monotonic trend, with an increase in the function as multiplicity decreases.

This physical effect has been studied using femtoscopy with PYTHIA8 Monte Carlo simulations of pp collisions at $\sqrt{s} = 13$ TeV [91]. The observed depletion in $p\bar{p}$ correlations due to the strong interaction is qualitatively consistent with the STAR Collaboration's findings in Au–Au collisions, confirming that the anticorrelation in proton pairs with different signs is caused by baryon-antibaryon annihilation [85]. Therefore, comparing the 0–20% multiplicity class in pp collisions with the correlation function is challenging.

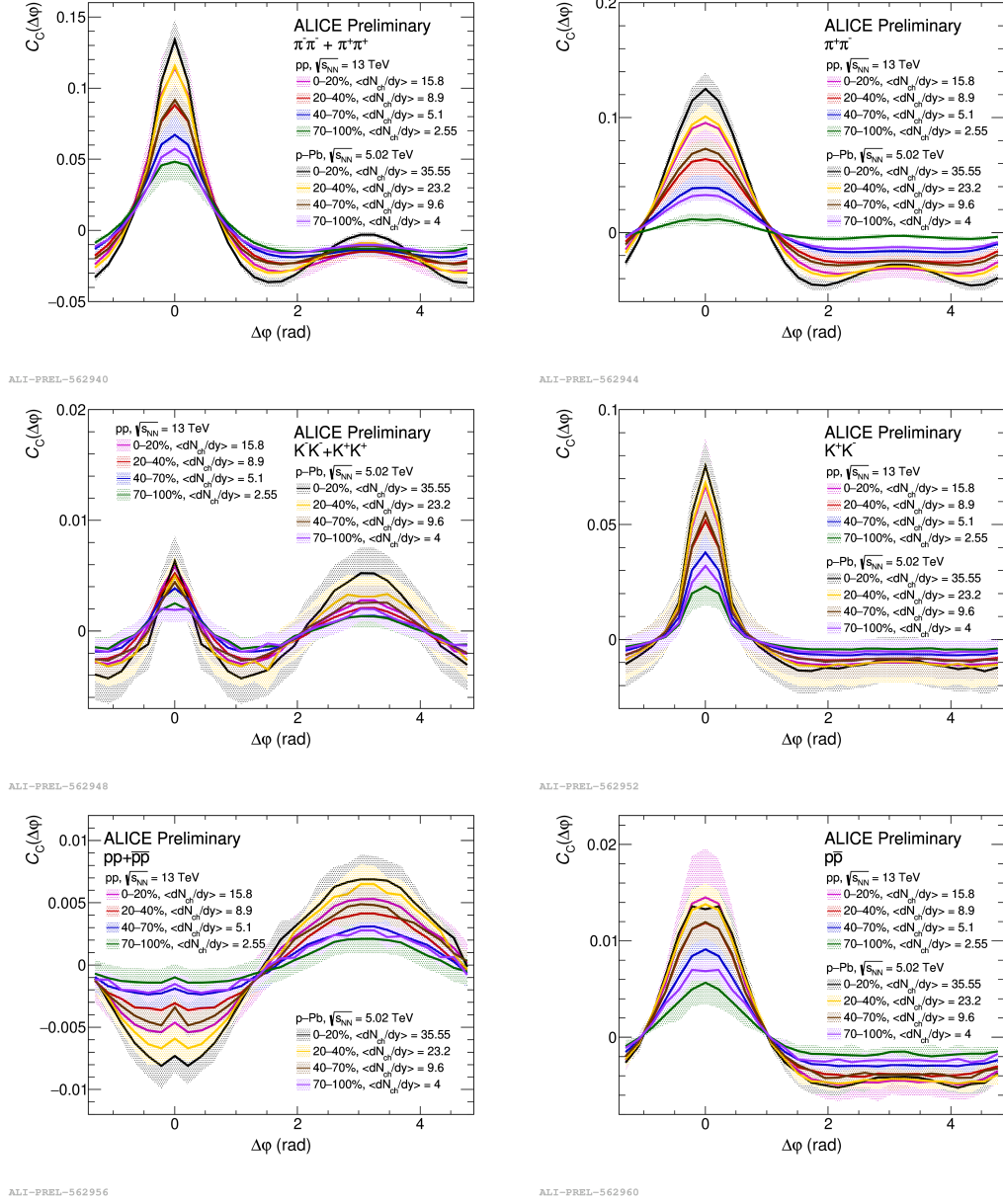


FIGURE 8.40: Comparison of the Δy $\Delta\phi$ correlation functions between pp and p-Pb collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV, respectively. The comparison is made for all particles and across all multiplicity classes analyzed using the rescaled two-particle cumulant definition.

8.5 Summary of Angular Correlation Studies in Small Systems

In the first part of this work, a dedicated study of two-particle angular correlations in $\Delta y, \Delta\phi$ space was performed for small collision systems. By analyzing like- and unlike-sign pion, kaon, and proton pairs across different multiplicity classes, a new methodology was developed. It was observed that the probability ratio correlation function exhibits a dependence on $1/N$ multiplicity. This implies that while the probability ratio captures physical correlations, these correlations are intrinsically linked to multiplicity effects. To address this, rescaled two-particle correlation functions were introduced, allowing for a more focused investigation of different physical aspects. The primary goal of this study was to investigate and better understand the anticorrelation observed for like-sign protons across varying multiplicities and collision systems like pp and p-Pb. This depletion observed in pp collisions at $\sqrt{s} = 7$ TeV at $(\Delta\eta\Delta\phi)$ at $(0, 0)$, is also present at higher energies, specifically in pp collisions at $\sqrt{s} = 13$ TeV, across different multiplicity classes. Moreover, this anticorrelation persists in denser collision systems, such as p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV. A clear multiplicity dependence is observed: when using the definition of rescaled two-particle correlation functions, the anticorrelation becomes even stronger in higher multiplicity classes. However, none of the models in pp and p-Pb collision systems were able to reproduce it.

Such an analysis, initially focused on studying anticorrelations, has revealed several intriguing phenomena when comparing different particle species, such as mesons and baryons, across various multiplicity classes and collision systems.

One key observation emerges when comparing different particle species, as these phenomena would not be apparent from a single plot. Specifically, unlike-sign particle pairs show an absence of the typical back-to-back jet structure in the away-side region. In contrast, for like-sign particle pairs, the correlation structures differ significantly across species. Like-sign pions exhibit a narrow away-side correlation, while like-sign kaons display a pronounced back-to-back jet structure, nearly as strong as the near-side peak. This effect is even more pronounced for like-sign protons, where no minijet signatures are observed in the near-side region, but a strong back-to-back jet structure dominates the away-side region.

For unlike-sign pairs, this absence raises fundamental questions about the nature of jet correlations in small systems, particularly since the away-side region for unlike-sign pairs is not well described by existing models. In both pp and p-Pb collisions,

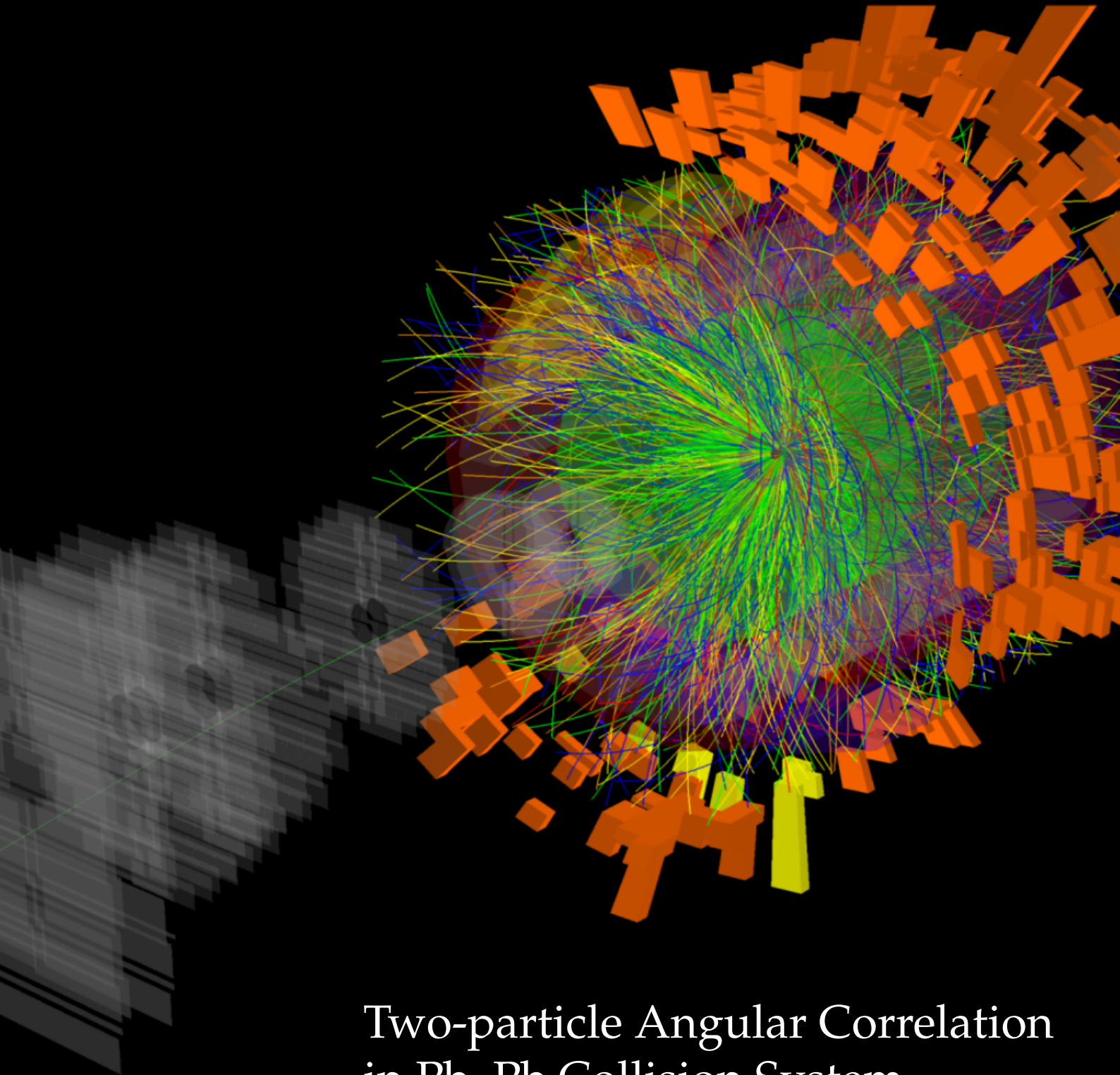
PYTHIA8, which does not incorporate collective effects, predicts back-to-back jets that are absent in the data. Similarly, EPOS and DPMJET, which include collective effects, also fail to describe the observed correlations. This discrepancy prompts further questions: why can't PYTHIA8 reproduce the away-side? Could this indicate a form of jet quenching? And if so, why are these effects not reproduced by EPOS and DPMJET?

Another intriguing finding concerns the multiplicity dependence of like-sign kaons. Using the probability ratio method, a slight variation across multiplicities is visible, as is shown in Fig. 8.38. However, after removing the trivial multiplicity scaling, like-sign kaon correlations for both pp and p-Pb systems appear to be independent of multiplicity as illustrated in the Fig. 8.40, as they overlap across different classes.

Another noteworthy feature is the dip observed at $\Delta y, \Delta \varphi \approx (0, 0)$ for unlike-sign protons, which is attributed to annihilation, FSI effect. This effect is expected to be independent of multiplicity, as it depends only on the size of the source, not on the number of particles involved. However, the results suggest otherwise. Interestingly, no sign of this annihilation effect is seen in pp collisions across four multiplicity classes. Yet, when extending the study to 13 multiplicity classes, the annihilation feature becomes prominent in the highest multiplicity class (0–0.17%). In p-Pb collisions, this phenomenon is observed across all multiplicity classes. This raises the question: why does the annihilation effect become more significant in high-density environments, despite its expected independence from multiplicity?

In summary, this study serves as an exploratory experimental analysis aimed at verifying and extending previous findings from pp collisions at $\sqrt{s} = 7$ TeV [4]. The methodology for studying the correlations across different multiplicity classes was successfully developed and applied, revealing new insights in both pp and p-Pb collisions. These findings prompt numerous new questions, which were quite extensively thought. Future studies will be essential to fully understand these intriguing phenomena and their implications for particle correlations in small systems.

RESULTS PART II



Two-particle Angular Correlation
in Pb–Pb Collision System

Chapter 9

Two-Particle Angular Correlation Analysis in HIC

Declaration

I hereby declare that the work presented in the following chapter is the result of my analysis conducted within the ALICE collaboration. This study focuses on the $\Delta y \Delta \phi$ correlation functions of identified pions, kaons, protons, and their corresponding antiparticles in Pb–Pb collision systems, categorized into seven different centrality classes which are 0–20%, 20–40%, 40–50%, 50–60%, 60–70%, 70–80%, 80–90%. The analysis is performed by using the probability ratio and rescaled two-particle correlation function definitions.

Specifically, I performed the following tasks:

- ☐ *Performed quality assurance of particle selection for pions, kaons, and protons (and their antiparticles).*
- ☐ *Defined and finalized the analysis settings.*
- ☐ *Carried out purity, efficiency, and correction procedures.*
- ☐ *Estimation of N_{av} values across the seven centrality classes for each particle species, based on the pp, and p–Pb method estimation.*
- ☐ *Performed Monte Carlo closure tests to validate the correction procedures for both correlation function definitions, as detailed in Appendix A.*
- ☐ *Evaluated systematic uncertainties for both correlation function definitions, as detailed in Appendix B.*

- *Calculated the 2D $\Delta y \Delta \phi$ correlation function using both correlation function definitions.*
- *Performed projections onto the azimuthal direction using both correlation function definitions.*
- *Compared the results with Monte Carlo models using both definitions.*
- *Analyzed and compared the three collision systems using both definitions.*
- *Presented the analysis at various stages of progress within the collaboration.*
- *Defended the results for acceptance during the preliminary approval.*
- *Defended the results in HIC in different centralities and the comparison of the results across the three collision systems during the paper proposal approval.*
- *Contributed to writing the analysis note and preparing the publication, in collaboration with other members of the ALICE collaboration.*

This analysis was primarily conducted by me, with invaluable guidance and contributions from my supervisors and colleagues, including Małgorzata Janik, Łukasz Graczykowski, and Adam Kisiel.

9.1 Results from Pb–Pb collision

9.1.1 Estimation of N_{av} in Pb–Pb collision

Consistent with the approach employed in small systems, the N_{av} values required for the rescaled definition was determined accordingly and shown in the following Tab 9.1.

Experimental N_{av} values from Pb–Pb collision							
centrality classes	0–20%	20–40%	40–50%	50–60%	60–70%	70–80%	80–90%
<i>Pions</i>	501.4	233	115.4	66.4	34.5	16	7
<i>Kaons</i>	66	31	15	8.3	4	1.7	0.7
<i>Protons</i>	24.3	12.4	6.5	3.8	2	0.95	0.4

TABLE 9.1: N_{av} value estimated using experimental data from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the 7 centrality classes analyzed for pions, kaons and protons.

9.1.2 2D $\Delta y \Delta \varphi$ correlation function

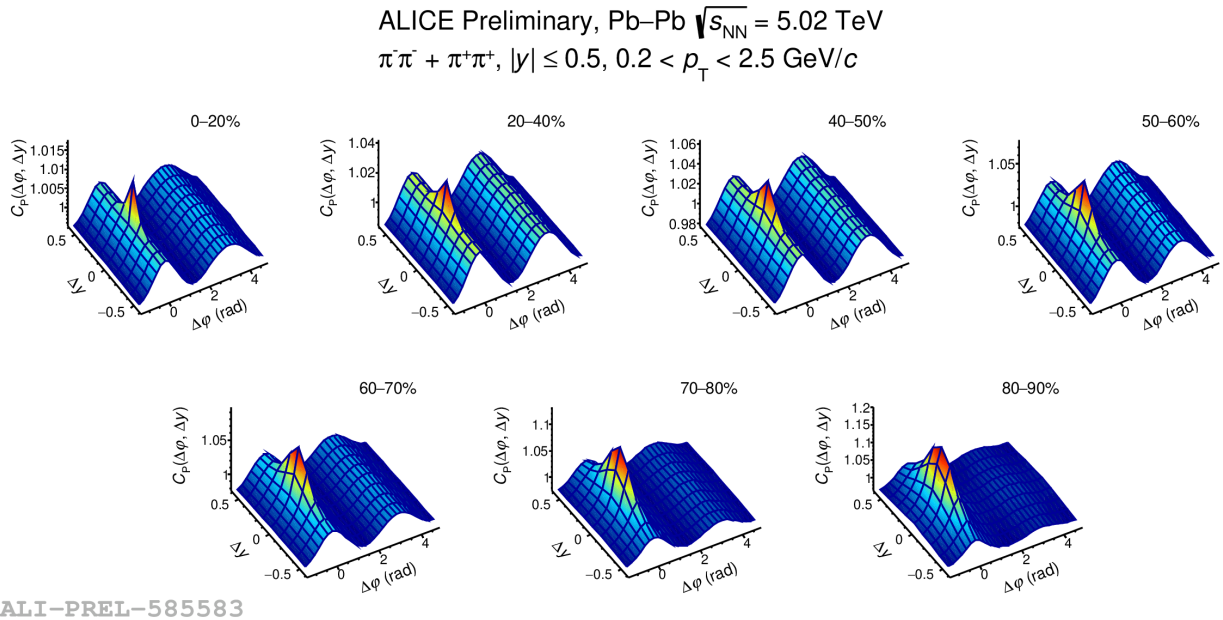


FIGURE 9.1: $\Delta y \Delta \varphi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are shown for like-sign pions across the seven centrality analyzed.

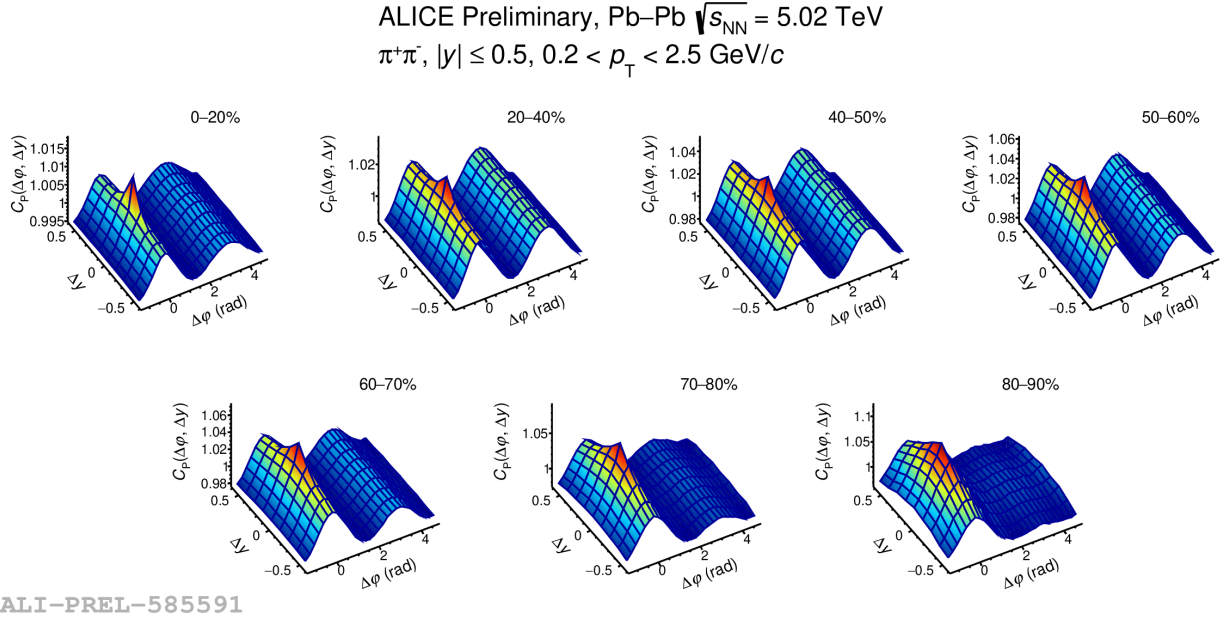


FIGURE 9.2: $\Delta y \Delta \phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign pions across the seven centrality analyzed.

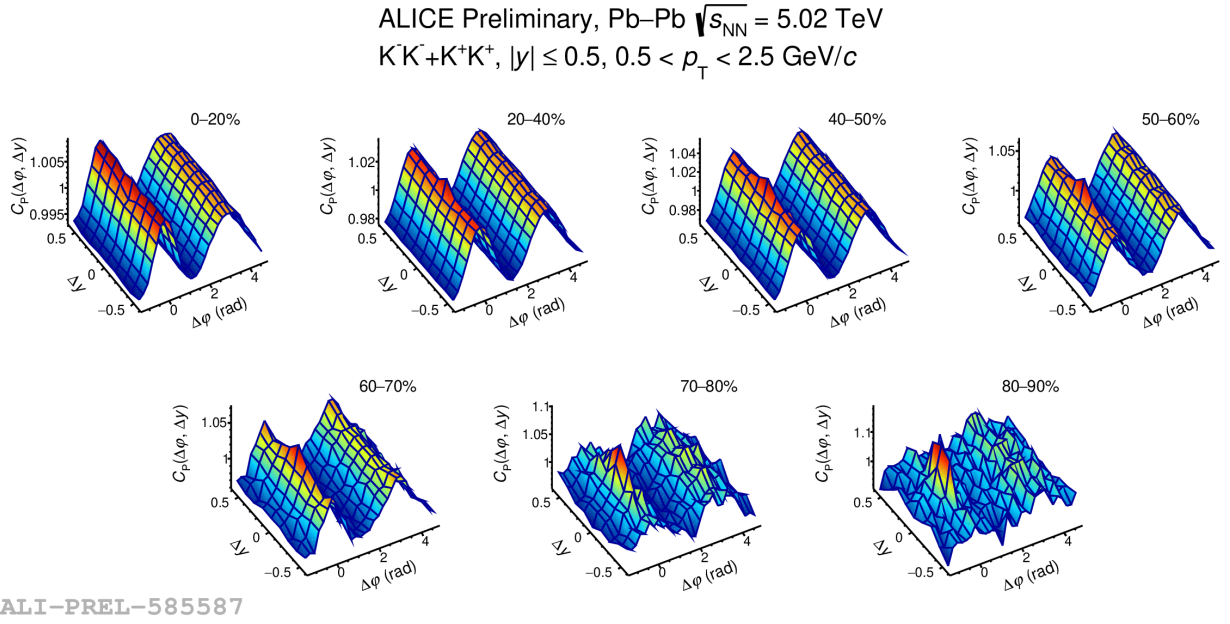


FIGURE 9.3: $\Delta y \Delta \phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign kaons across the seven centrality analyzed.

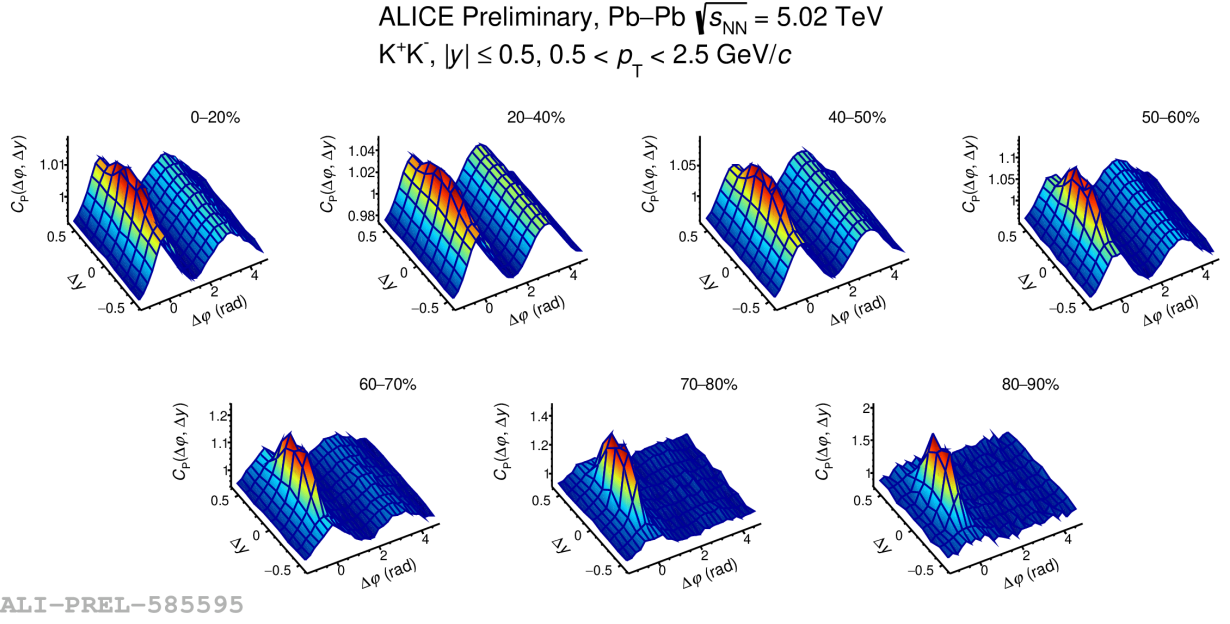


FIGURE 9.4: $\Delta y \Delta \phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign kaons across the seven centrality analyzed.

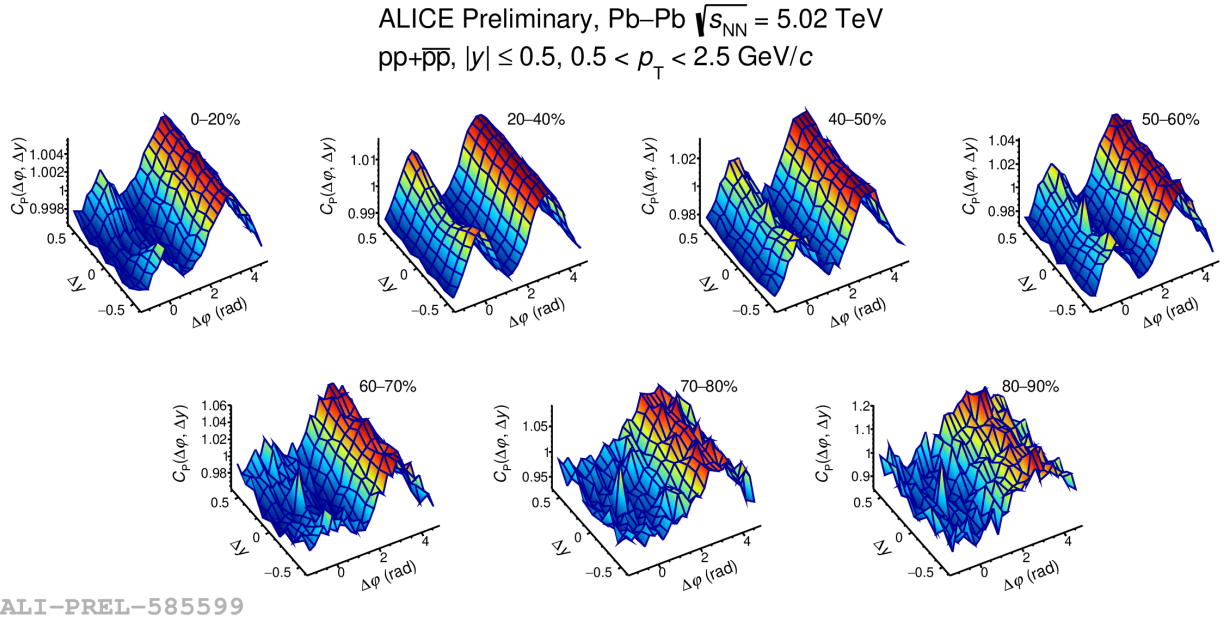


FIGURE 9.5: $\Delta y \Delta \phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign protons across the seven centrality analyzed.

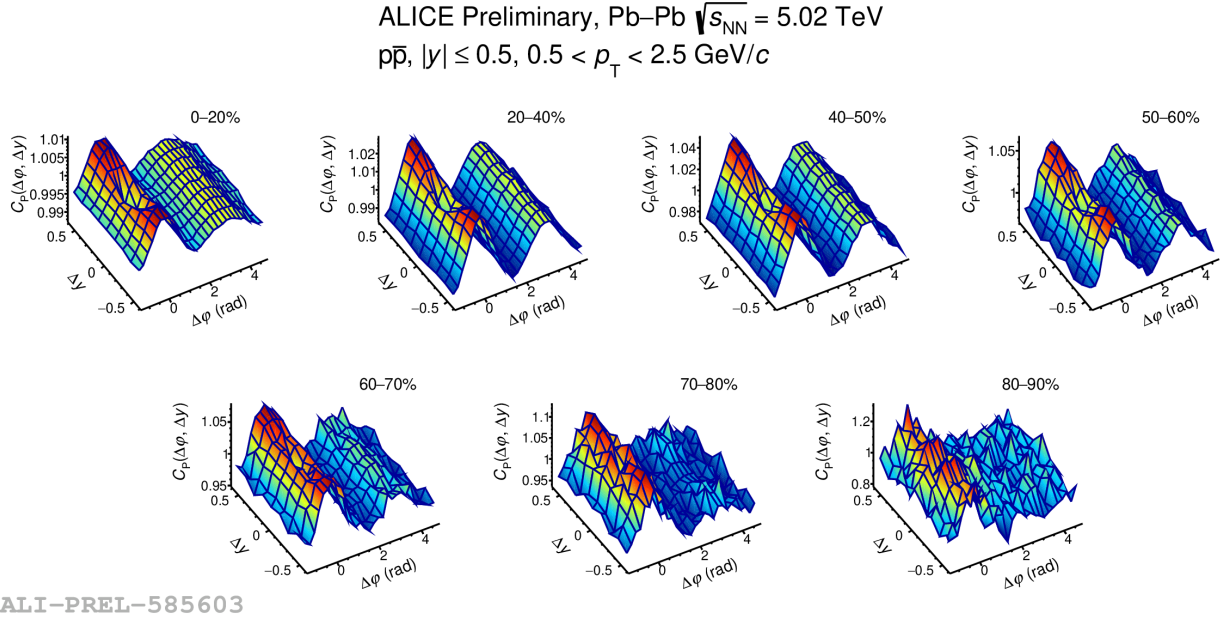


FIGURE 9.6: $\Delta y \Delta \phi$ correlation functions using the probability ratio definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign protons across the seven centralities analyzed.

The correlation functions, defined as a probability ratio, are presented from Figs. 9.1 to 9.6. As observed in analyses of small collision systems, this definition reveals that the correlation function increases as centrality decreases, following the expected scaling of $\sim 1/N$. Conversely, the rescaled two-particle correlation function, shown from Figs. 9.7 to 9.12, exhibits the opposite trend. To better highlight these behaviors, one could plot the functions for different centrality classes using the same z-axis range. However, due to the rapid increase in the number of correlated particles with centrality, such an approach would primarily display the largest correlation function, rendering those from lower centrality classes nearly flat. Instead, the increasing trend for the probability function and the decreasing trend for the rescaled two-particle correlation function can be inferred from the z-axis values or more directly from the projections shown in the next section.

The physics underlying the correlation functions, regardless of the definition used, remains the same. In general, one observes a strong influence of flow effects in mid-to-high centrality classes, which became less strong in lower centrality classes. A pronounced peak is seen for both like-sign and unlike-sign pions and kaons, originating from the longitudinal flow along the Δy range. This suggests that minijets, which dominate these correlation functions, are very pronounced in contrast to the flow effects.

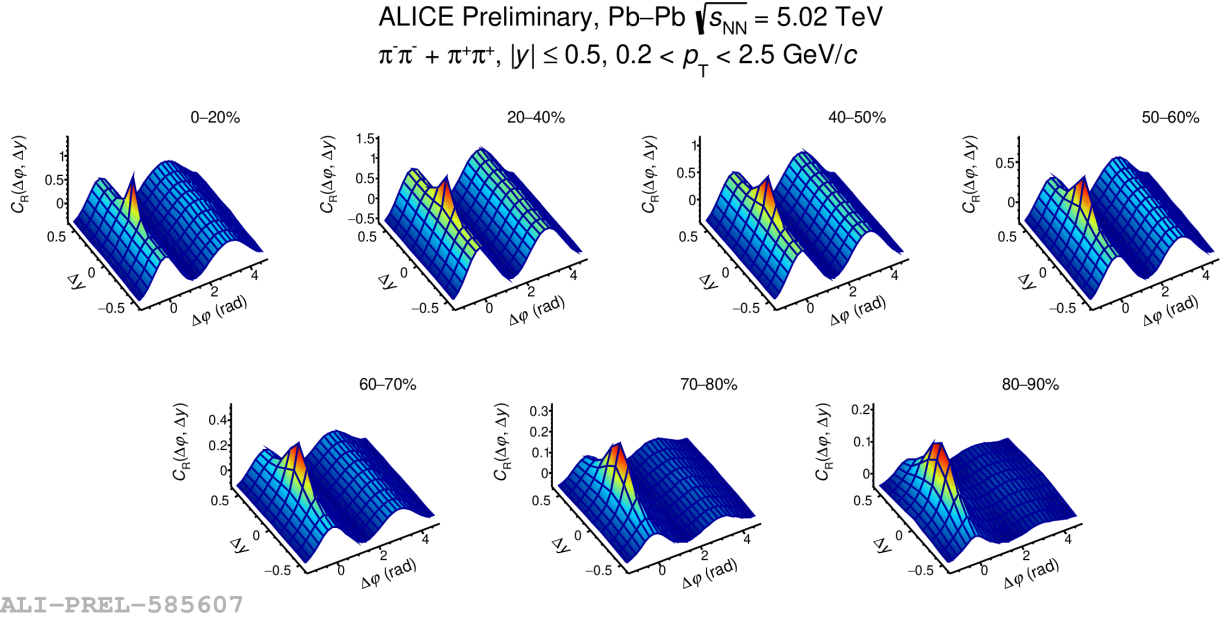


FIGURE 9.7: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign pions across the seven centralities analyzed.

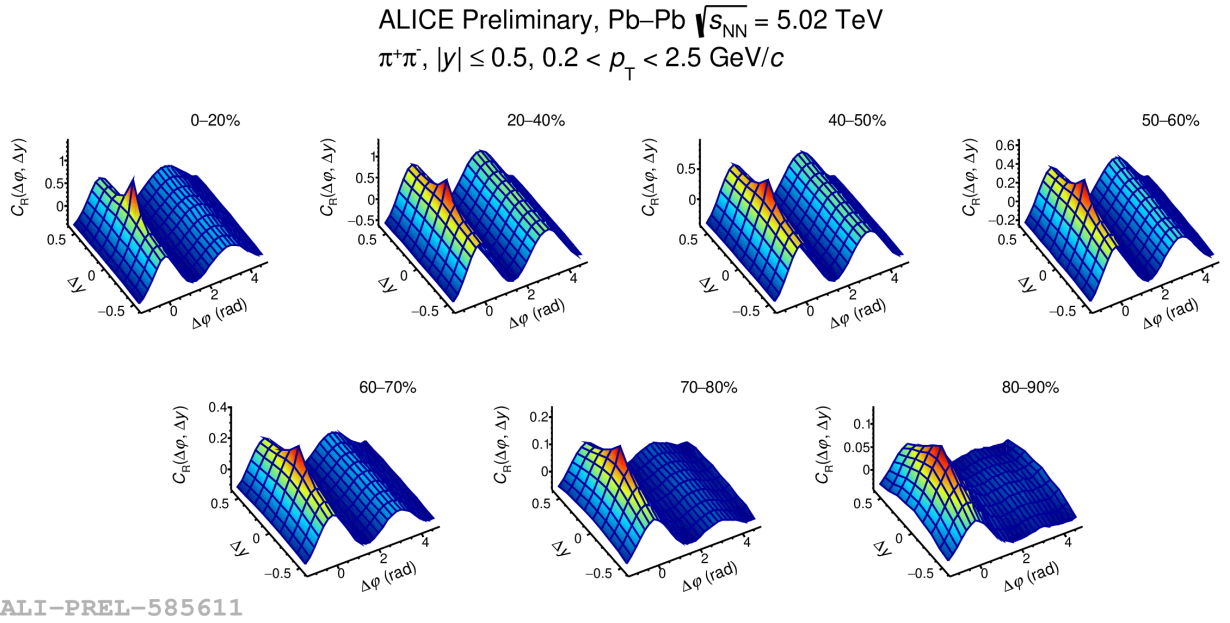
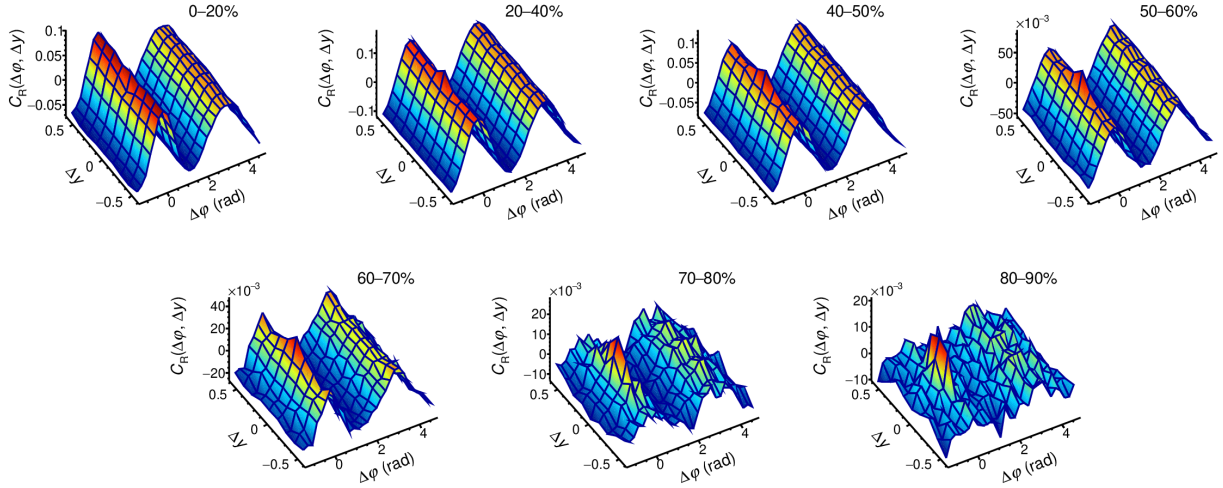


FIGURE 9.8: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign pions across the seven centralities analyzed.

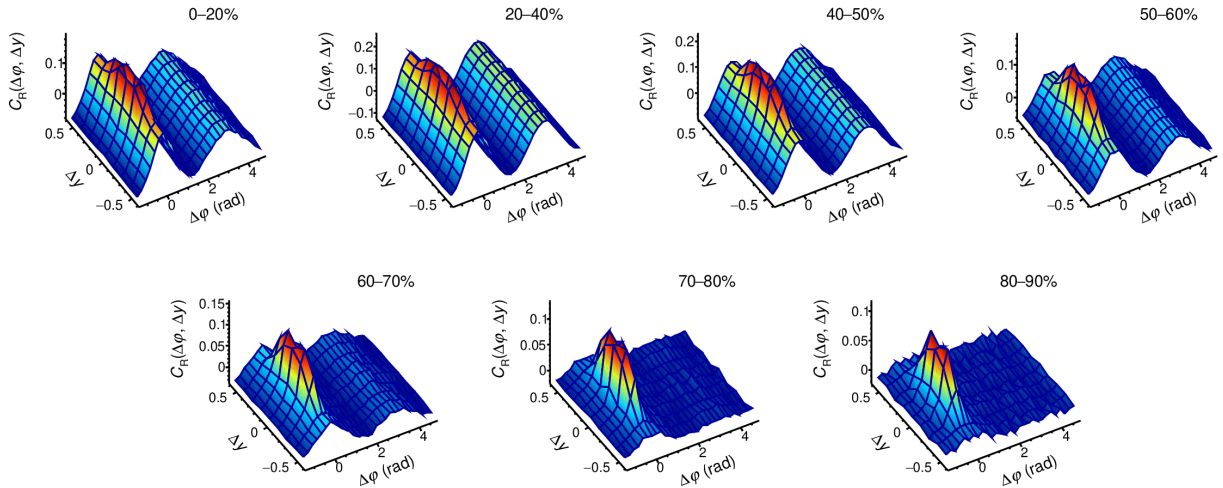
ALICE Preliminary, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
 $K^+K^- + K^+K^+$, $|y| \leq 0.5$, $0.5 < p_T < 2.5$ GeV/c



ALI-PREL-584979

FIGURE 9.9: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign kaons across the seven centralities analyzed.

ALICE Preliminary, Pb–Pb $\sqrt{s_{NN}} = 5.02$ TeV
 K^+K^- , $|y| \leq 0.5$, $0.5 < p_T < 2.5$ GeV/c



ALI-PREL-585616

FIGURE 9.10: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign kaons across the seven centralities analyzed.

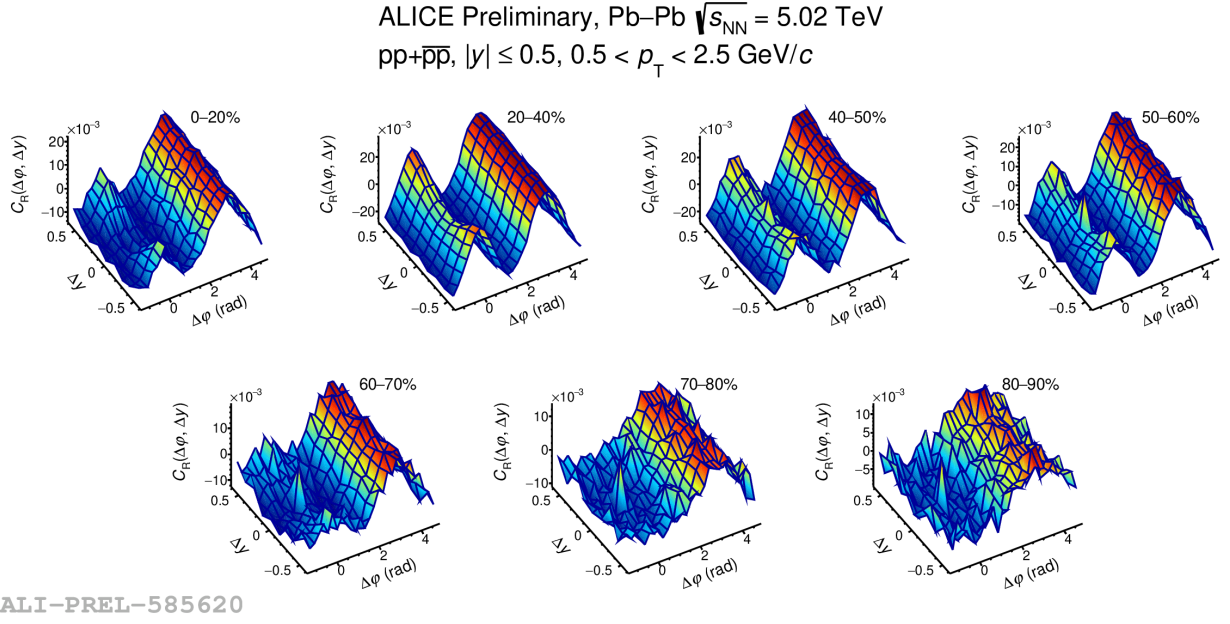


FIGURE 9.11: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for like-sign protons across the seven centralities analyzed.

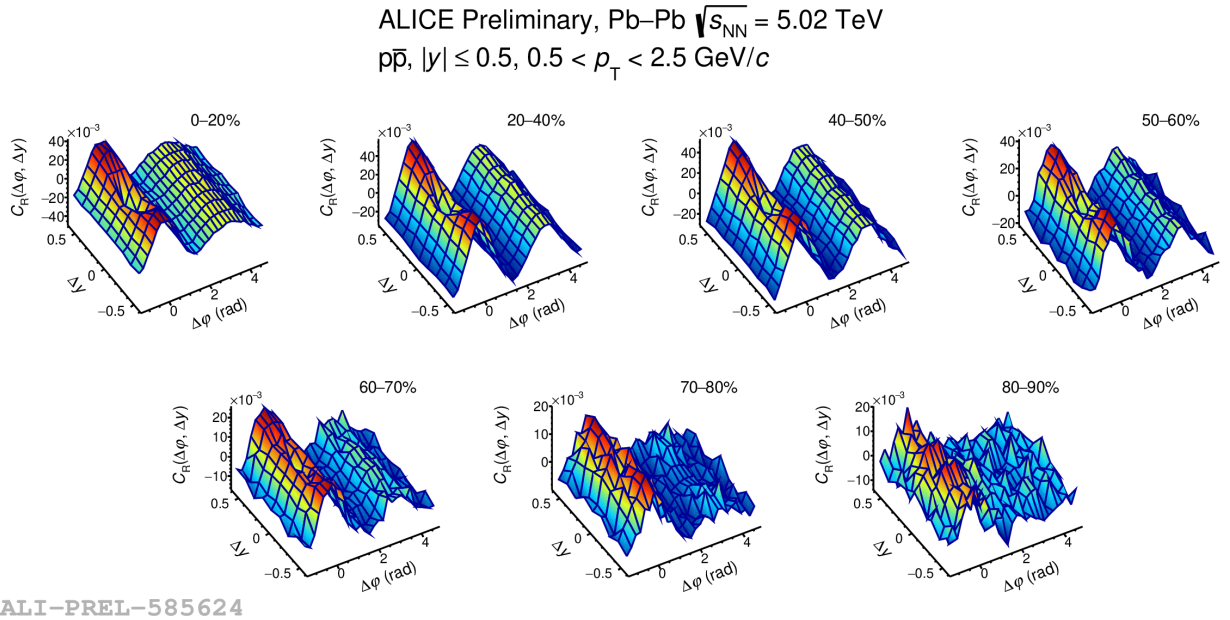


FIGURE 9.12: $\Delta y \Delta \phi$ correlation functions using the rescaled two-particle correlation function definition from Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for unlike-sign protons across the seven centralities analyzed.

For like-sign pions and kaons, QS effects enhance the near-side peak in the correlation functions. Unlike-sign pions and kaons, on the other hand, exhibit the typical minijet structure, modulated by flow effects. In the case of unlike-sign pions, a narrow peak appears above the flow background, attributed to FSI within the minijet structure. Resonance contributions to unlike-sign pion correlations are minimal compared to what was observed in pp and p–Pb collisions. In contrast, for unlike-sign kaons, FSI effects are also present, but the influence of the ϕ resonance is more pronounced than in pp and p–Pb collisions, leading to the characteristic ring-like correlation structure.

For like-sign protons, a clear anticorrelation is observed. Notably, this pronounced suppression in heavy-ion collisions is nontrivial, as one might expect a smaller depletion in magnitude compared to pp and p–Pb collisions. However, as shown in Figs. 9.5, 9.11, this effect is so strong that it dominates over the flow contributions. The characteristic peak at $(\Delta y, \Delta\phi) = (0, 0)$, typically attributed to strong interactions, is absent in the higher multiplicity classes (0–20% and 20–40%). This absence is due to the increase in the femtoscopic source size, which, in larger collider systems with a source size of around 5 femtometers, leads to the flattening of the correlation function. As a result, the correlation no longer contributes to the $\Delta\eta\Delta\phi$ distribution. This behavior is a distinctive feature of pp and $\bar{p}\bar{p}$ correlations, where the source size plays a crucial role in diminishing the correlation. Similarly, the annihilation effect for unlike-sign protons is notably stronger in Pb–Pb collisions compared to smaller systems such as pp and p–Pb, reflecting the denser environment characteristic of heavy-ion collisions.

9.1.3 $\Delta\phi$ projections

Figures 9.13 and 9.14 show the projections onto $\Delta\phi$ for the probability ratio and the rescaled two-particle correlation function, respectively.

Both statistical and systematic uncertainties are shown in the plots, with error bars representing statistical uncertainties and shaded boxes denoting systematic uncertainties. Systematic uncertainties are calculated as the square root of the sum of the fits performed for each variation as described in Appendix B.3. Colors are used to distinguish correlation functions and uncertainties across different centralities. Using the probability ratio definition, one can observe that the systematic uncertainties increase as centrality decreases. In contrast, the rescaled two-particle correlation functions exhibit systematic uncertainties of similar magnitude across all centralities. For the probability ratio, significant fluctuations are observed at lower centralities. To reduce the

statistical error bars, the largest contributing variation for the 80–90% centrality class was fitted, and the resulting value was added as a statistical error.

In contrast, the rescaled two-particle correlation function eliminates the $\sim 1/N$ scaling, resulting in behavior that does not strictly follow centrality classes. Instead, flow effects play a dominant role, particularly in mid-centralities such as 20–40% and 40–50%. At lower centralities, the influence of flow becomes nearly negligible, showing the physical phenomena described in the 2D section.

9.1.4 Comparison between MC models and data

Figures 9.15 to 9.20 present comparisons between the data and MC model predictions using the probability ratio definition, while Figs. 9.21 to 9.26 illustrate the same comparisons using the rescaled two-particle correlation function definition. The AMPT model is represented by the red line, and the HIJING model by the blue line. In each figure, the upper panels display projections onto $\Delta\phi$, while the lower panels show the ratio to the data, providing a quantitative measure of discrepancies between models and experimental results.

For the probability ratio definition, the HIJING model (discussed in Sec. 3.2.4) significantly underestimates the observed correlations. This is expected since HIJING does not account for flow effects and is primarily designed to describe minijet structures in Pb–Pb collisions. Conversely, the AMPT model, specifically the string melting version (Sec. 3.2.5), incorporates flow effects and shows qualitative agreement with the data, although some quantitative deviations remain.

In the case of like- and unlike-sign pions, the AMPT model qualitatively reproduces the correlation functions. For like-sign pions, it achieves quantitative agreement at high and mid-to-high centrality classes. However, at lower centralities, large discrepancies emerge because AMPT does not include quantum statistic effects, which become more pronounced as flow effects become negligible. Similarly, for unlike-sign pions, discrepancies arise due to the lack of Coulomb interactions in the model. For like- and unlike-sign kaons, as well as unlike-sign protons, the AMPT model performs well across all centrality classes, both qualitatively and quantitatively. However, for like-sign protons, the anticorrelation observed in the data is largely hidden by flow effects in the azimuthal projection, except at lower centralities. Despite this limitation, the AMPT model appears to align reasonably well with the data.

Using the rescaled two-particle correlation function, a similar trend is observed. Focusing on like- and unlike-sign protons, the AMPT model shows qualitative agreement in the presence of flow effects. However, at lower centralities, the model struggles to capture the proton-proton correlations, highlighting its limitations.

To further investigate the behavior of the AMPT model, comparisons were also made on the rapidity side. Figures 9.27 to 9.32 present results using the probability ratio definition, while Figures 9.33 to 9.38 show results using the rescaled two-particle correlation function. These rapidity projections were generated by integrating over $\Delta\varphi < \pi/2$.

For both definitions, the AMPT model fails to reproduce the like- and unlike-sign pion correlations, displaying a dip instead of the observed peak, both qualitatively and quantitatively. However, for like- and unlike-sign kaons, the model achieves good agreement across all centrality classes, remaining within the systematic uncertainties. Notably, the rapidity-side projection reveals that the AMPT model qualitatively reproduces the anticorrelation observed for like-sign protons. Furthermore, for unlike-sign protons, the AMPT model provides an accurate representation of the data.

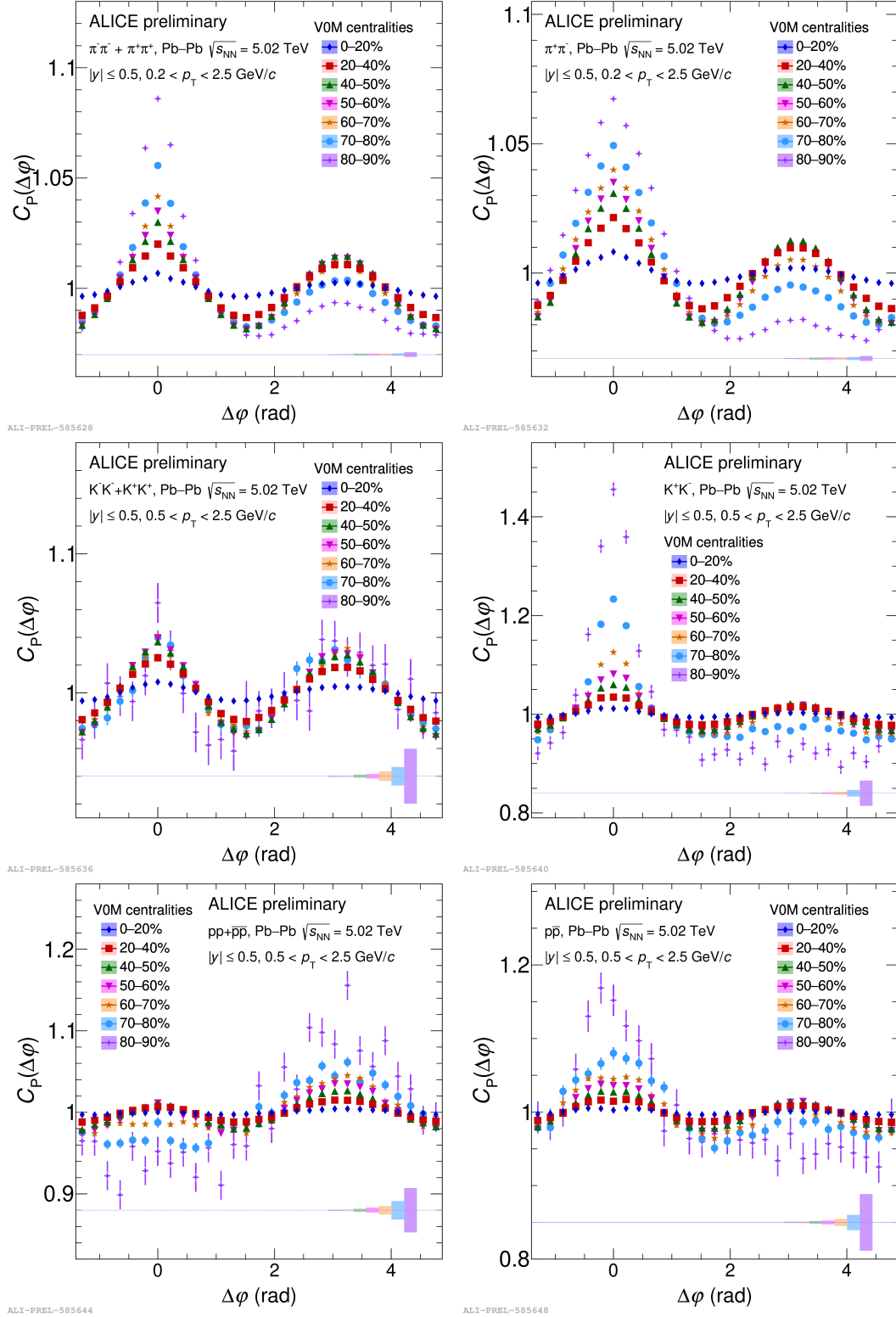


FIGURE 9.13: $\Delta\phi$ projections of correlation functions described using the definition of probability ratio. For each particle, the 7 centrality classes are drawn on the same canvas.

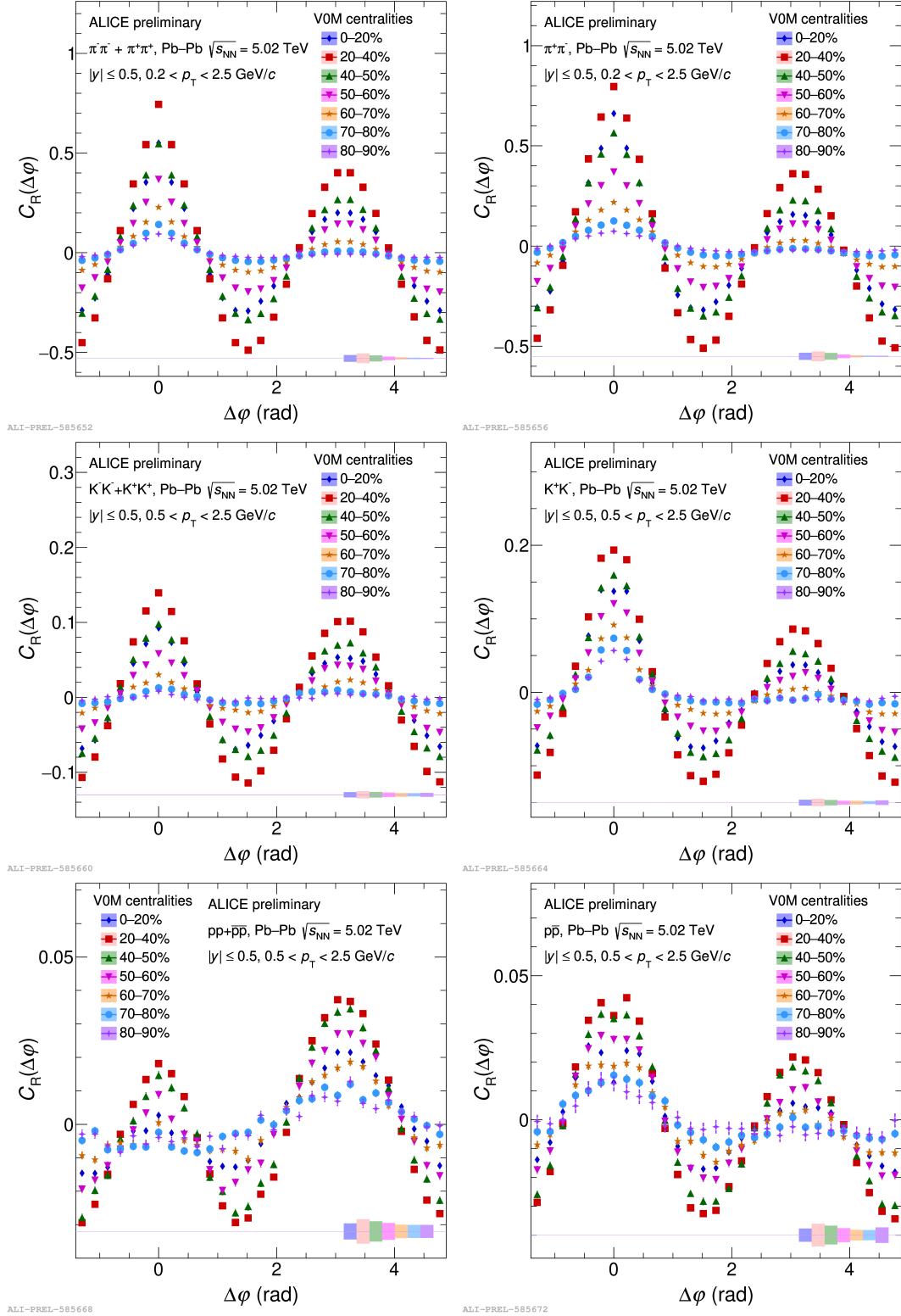


FIGURE 9.14: $\Delta\phi$ projections of correlation functions described using the definition of rescaled two-particle correlation function. For each particle, the 7 centrality classes are drawn on the same canvas.

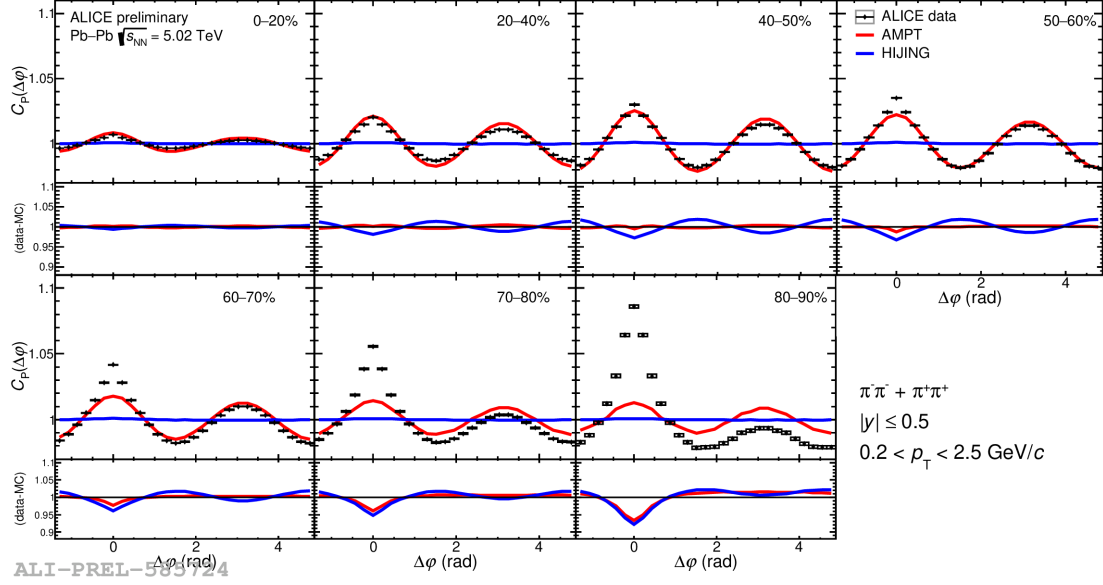


FIGURE 9.15: The comparison of $\Delta y \Delta \phi$ correlation functions with MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is presented using the probability ratio definition for like-sign pions across all centrality classes included in the analysis.

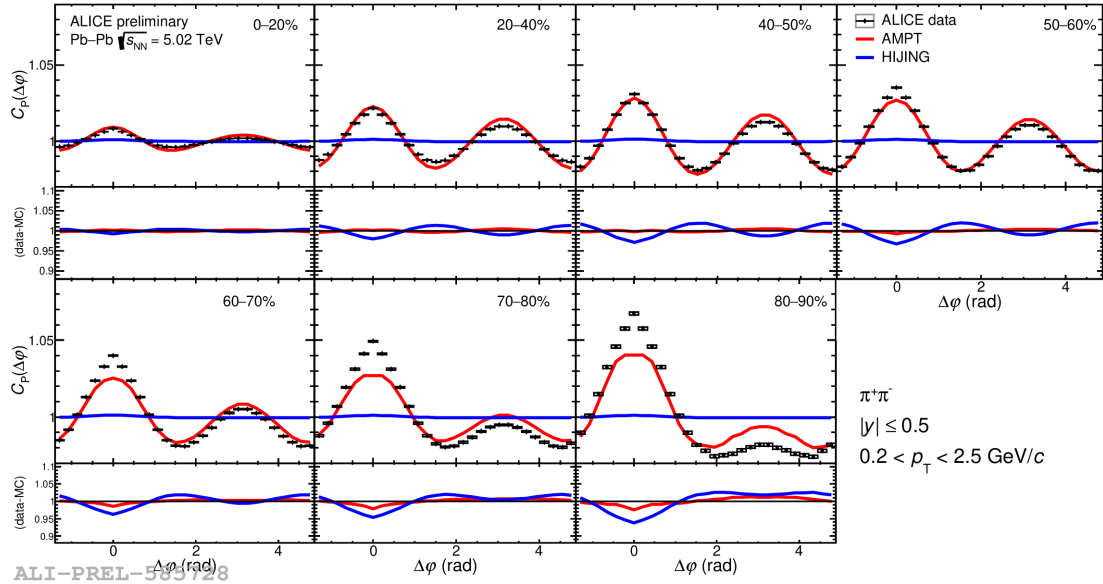


FIGURE 9.16: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign pions and for all centrality classes involved in the analysis.

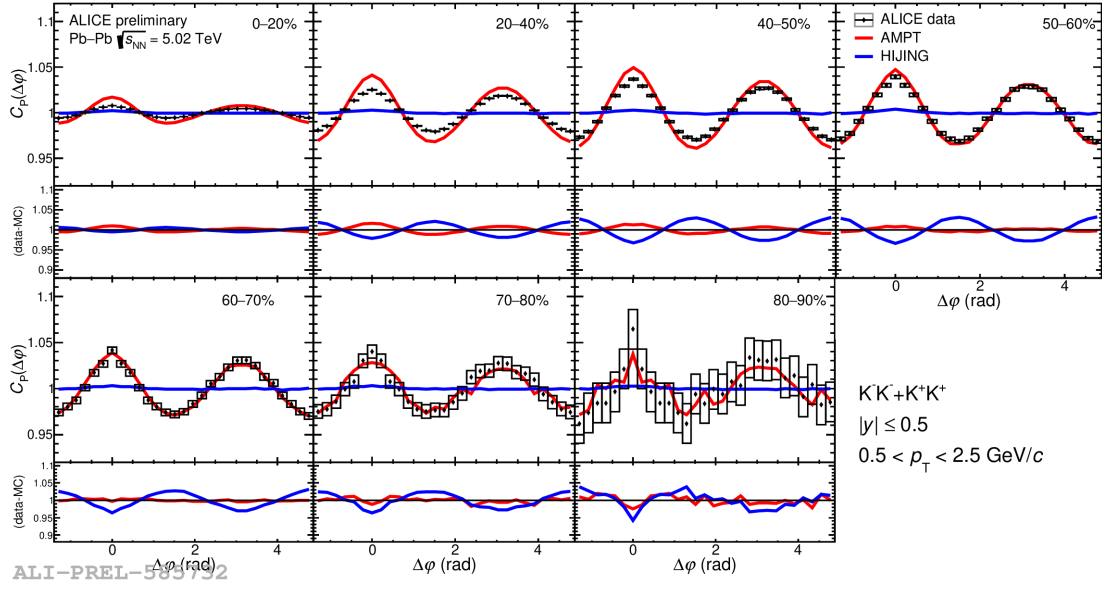


FIGURE 9.17: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for like-sign kaons and for all centrality classes involved in the analysis.

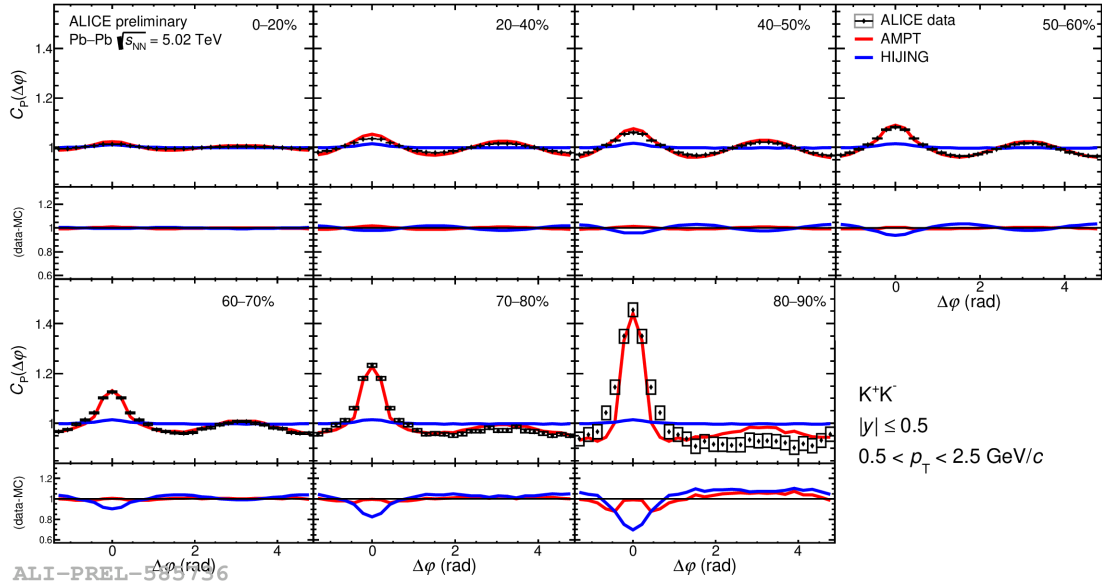


FIGURE 9.18: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign kaons and for all centrality classes involved in the analysis.

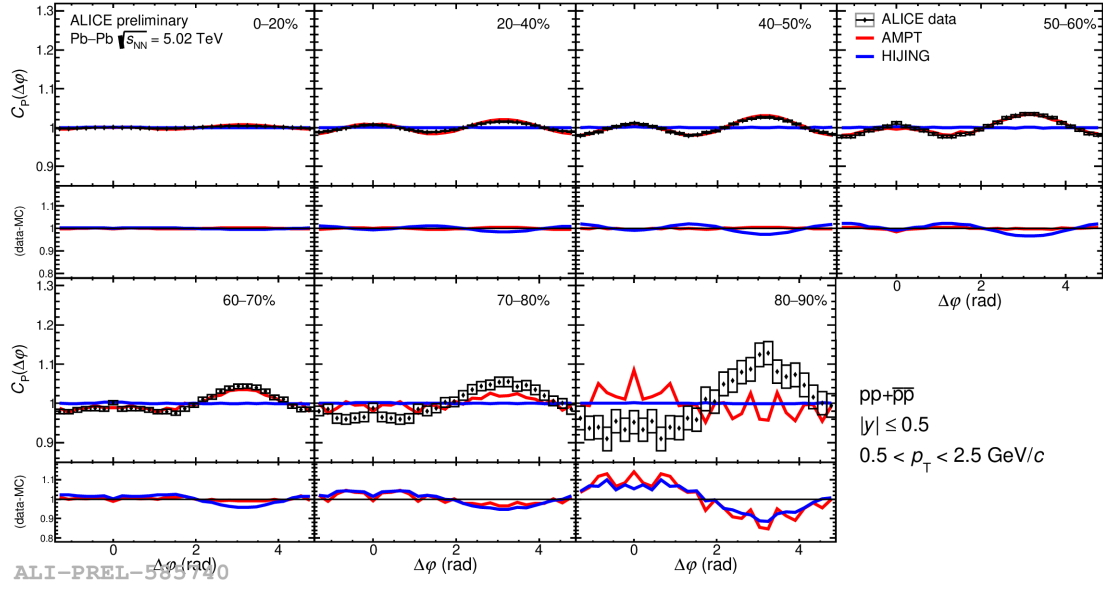


FIGURE 9.19: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for like-sign protons and for all centrality classes involved in the analysis.

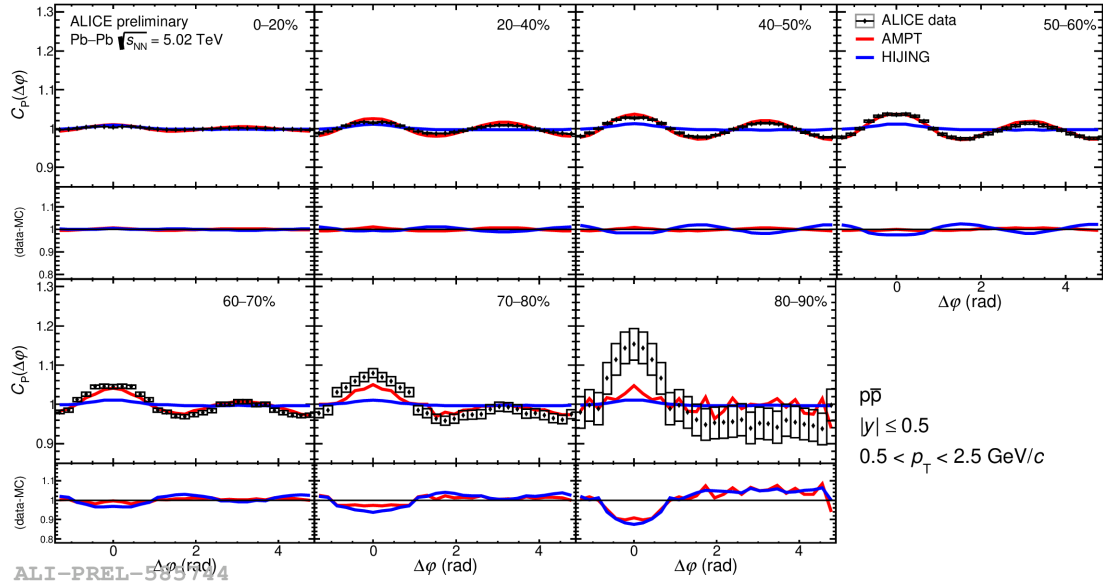


FIGURE 9.20: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign protons and for all centrality classes involved in the analysis.

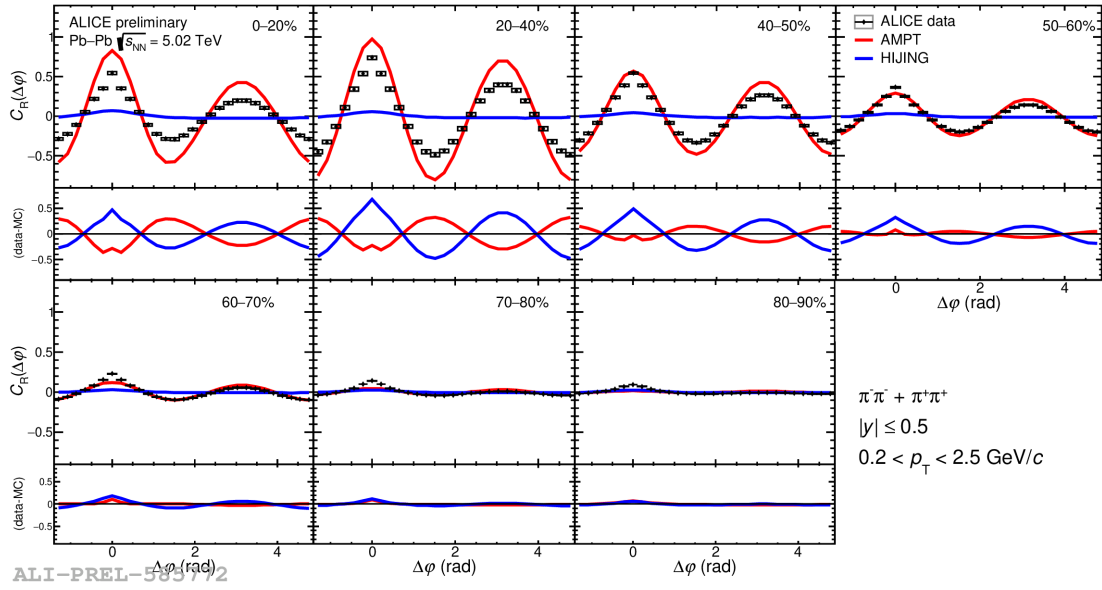


FIGURE 9.21: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign pions and all centrality classes involved in the analysis.

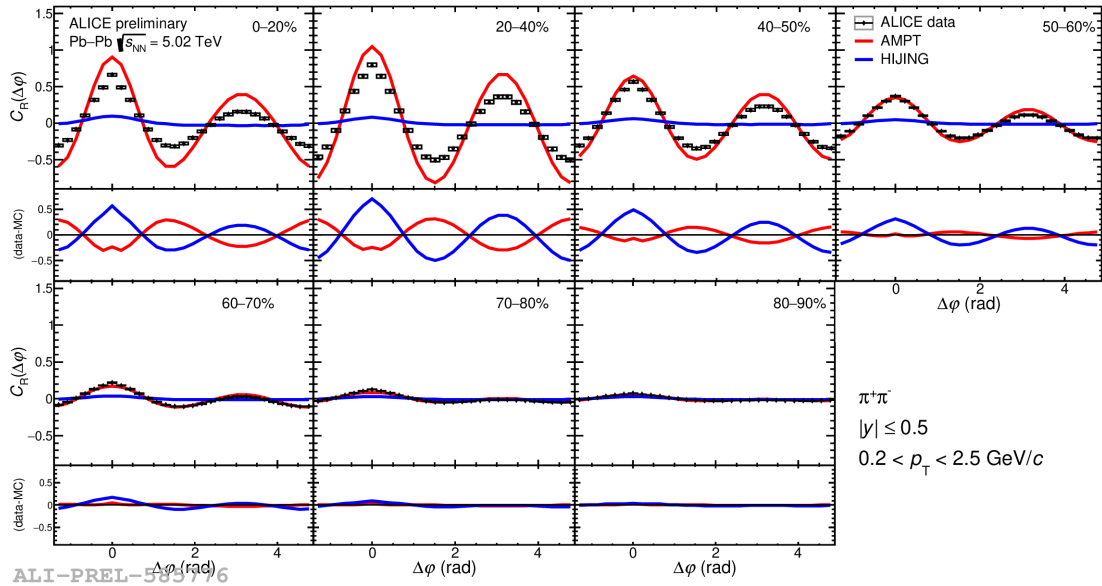


FIGURE 9.22: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign pions and all centrality classes involved in the analysis.

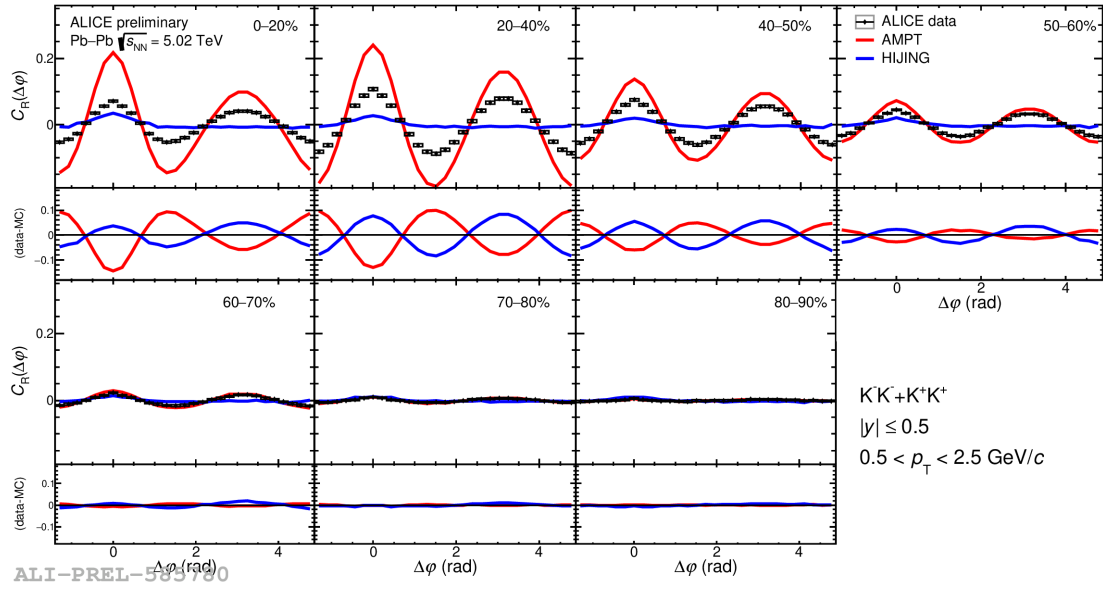


FIGURE 9.23: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign kaons and all centrality classes involved in the analysis.

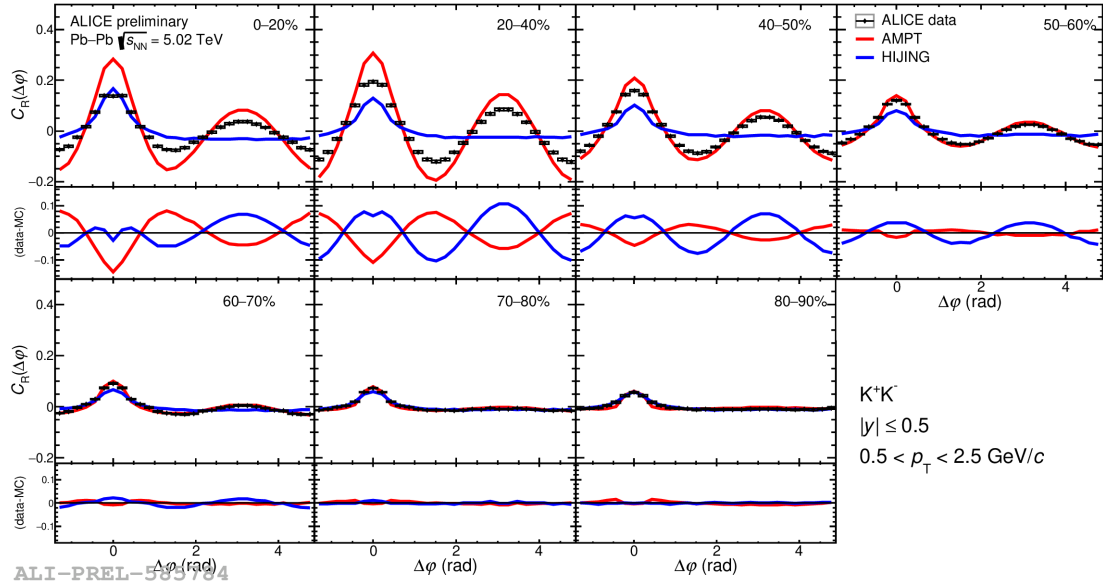


FIGURE 9.24: Comparison between $\Delta y \Delta \phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign kaons and all centrality classes involved in the analysis.

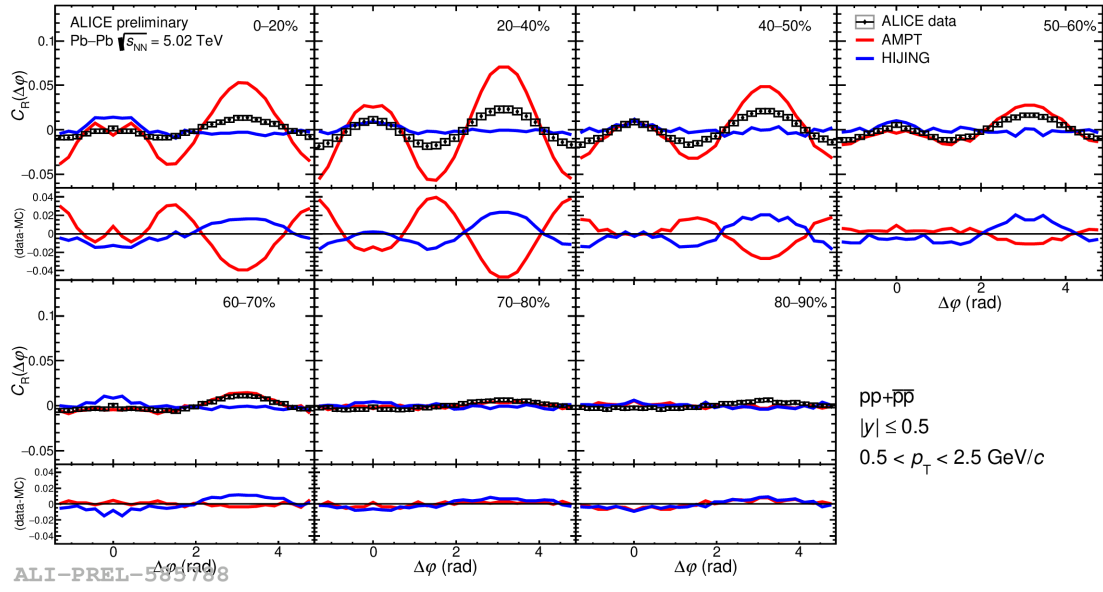


FIGURE 9.25: Comparison between $\Delta y\Delta\phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign protons and all centrality classes involved in the analysis.

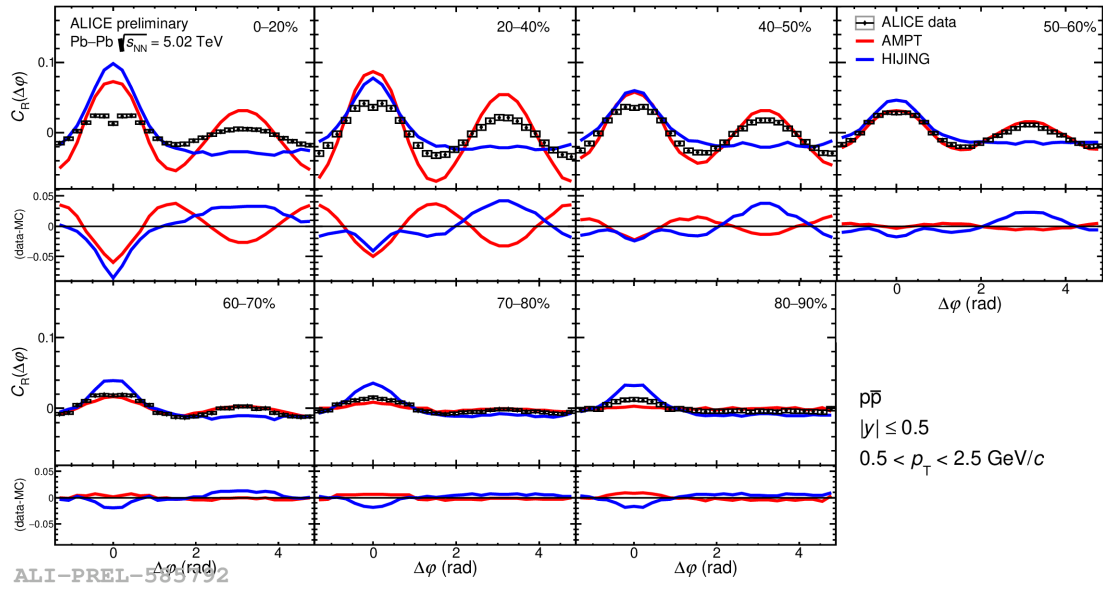


FIGURE 9.26: Comparison between $\Delta y\Delta\phi$ correlation functions and MC models (AMPT in red and HIJING in blue) projected onto the azimuthal direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign protons and for all centrality classes involved in the analysis.

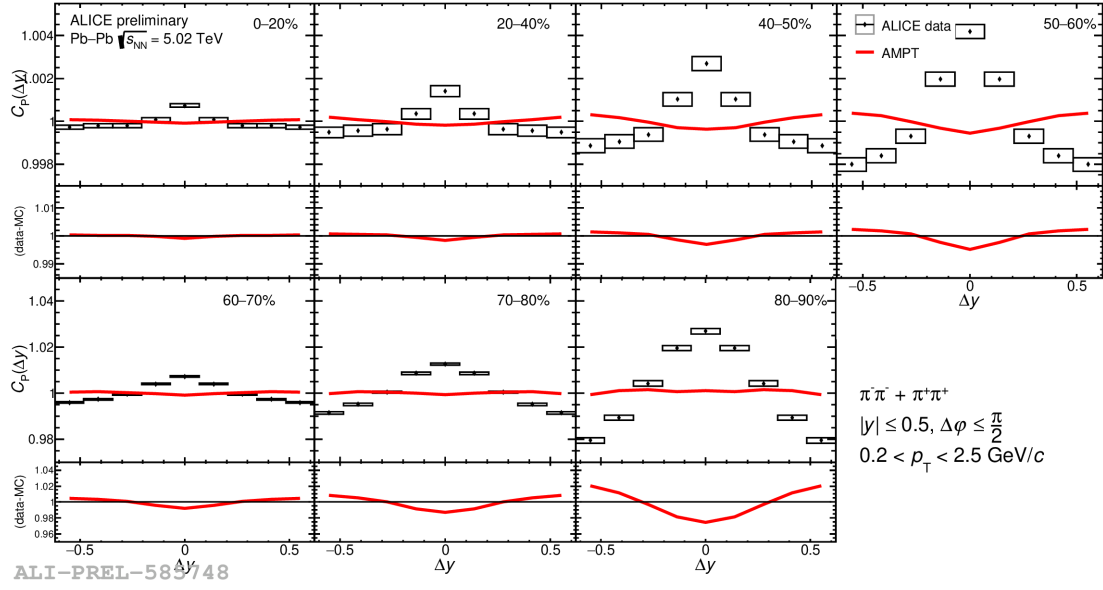


FIGURE 9.27: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for like-sign pions and for all centrality classes involved in the analysis.

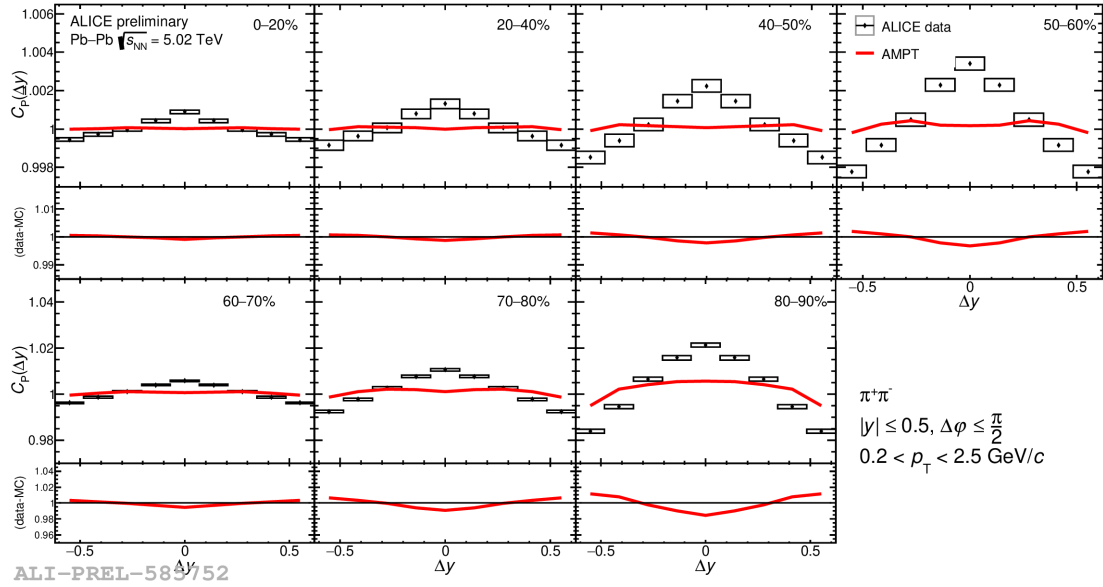


FIGURE 9.28: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign pions and for all centrality classes involved in the analysis.

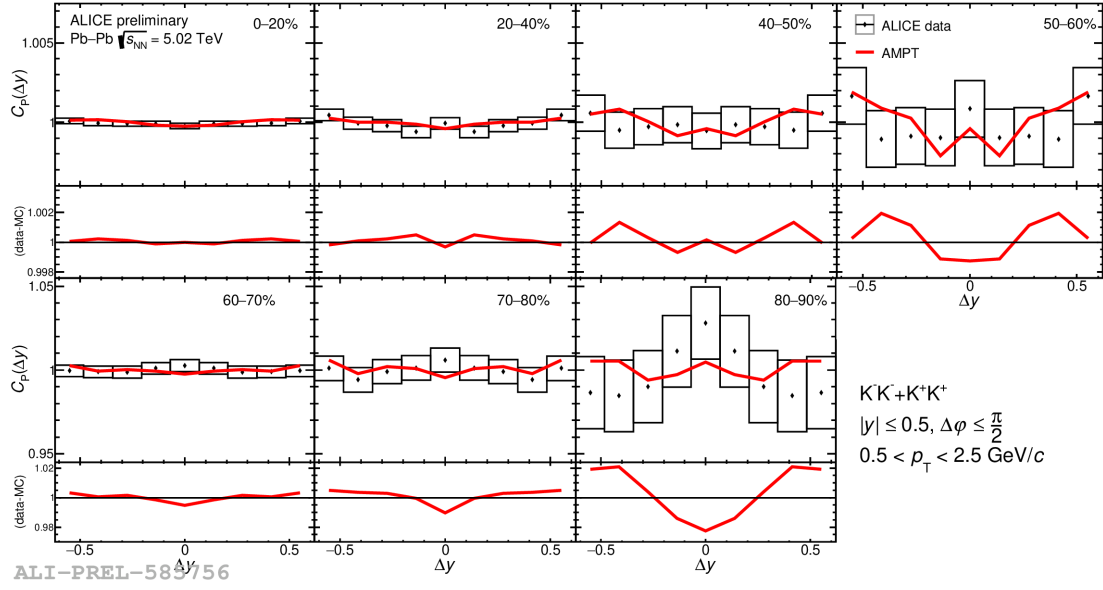


FIGURE 9.29: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for like-sign kaons and for all centrality classes involved in the analysis.

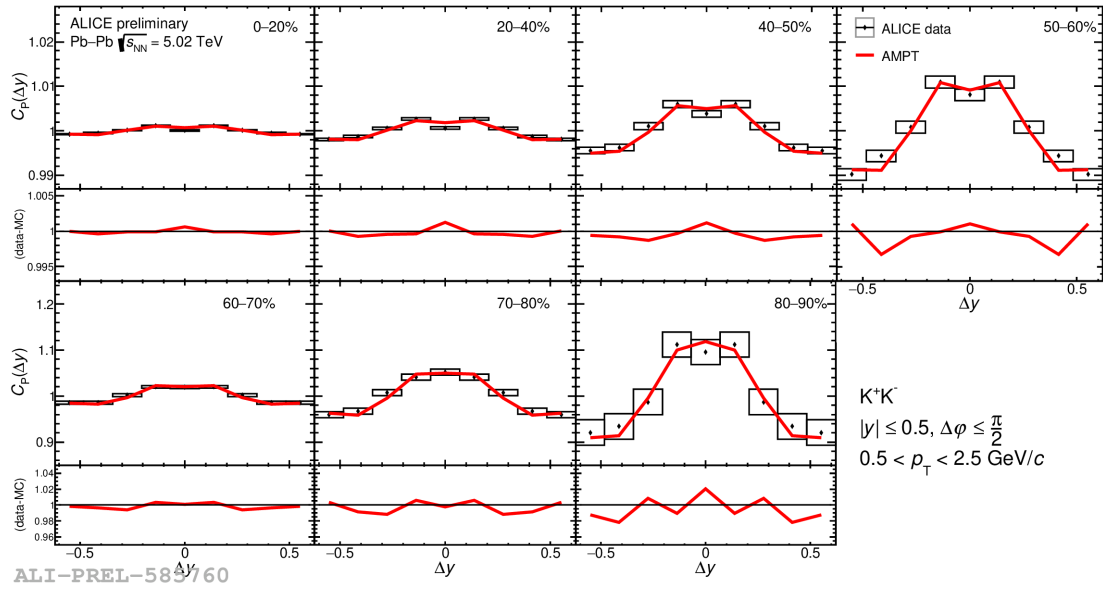


FIGURE 9.30: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign kaons and for all centrality classes involved in the analysis.

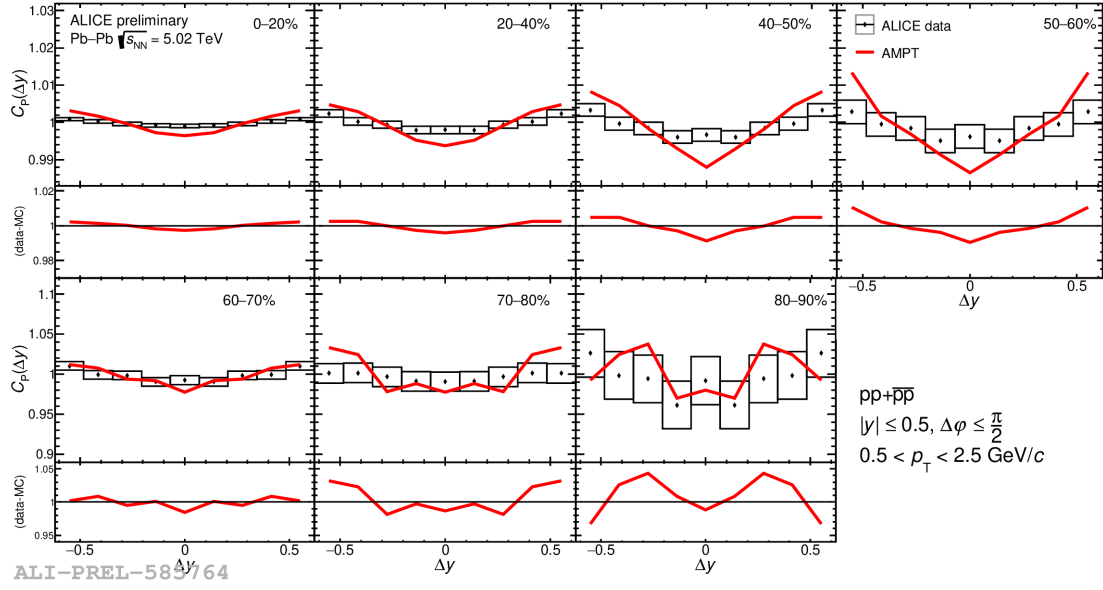


FIGURE 9.31: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for like-sign protons and for all centrality classes involved in the analysis.

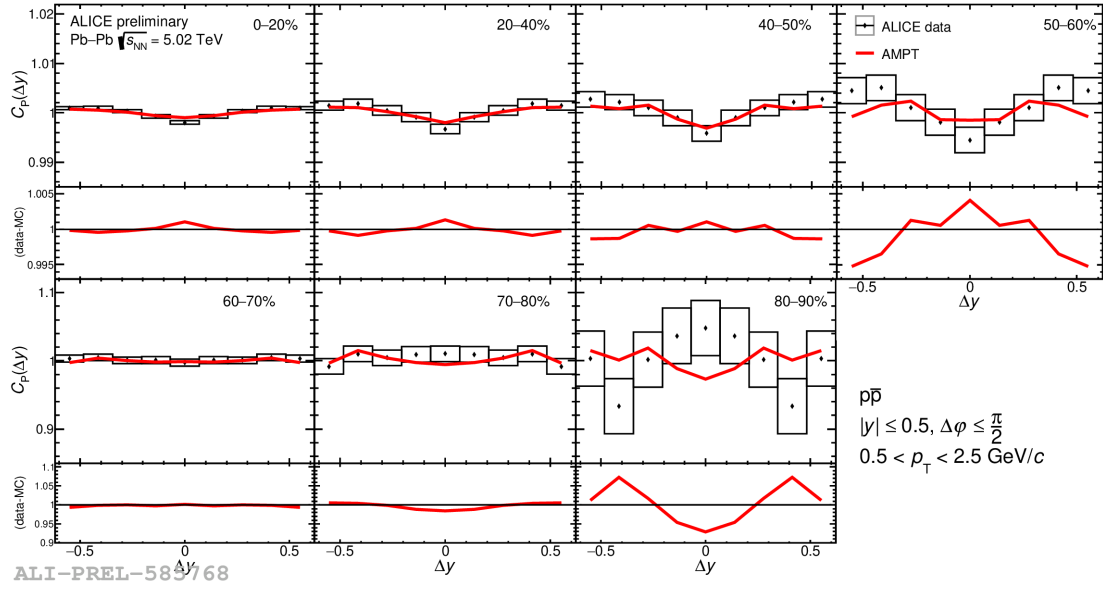


FIGURE 9.32: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the probability ratio definition for unlike-sign protons and for all centrality classes involved in the analysis.

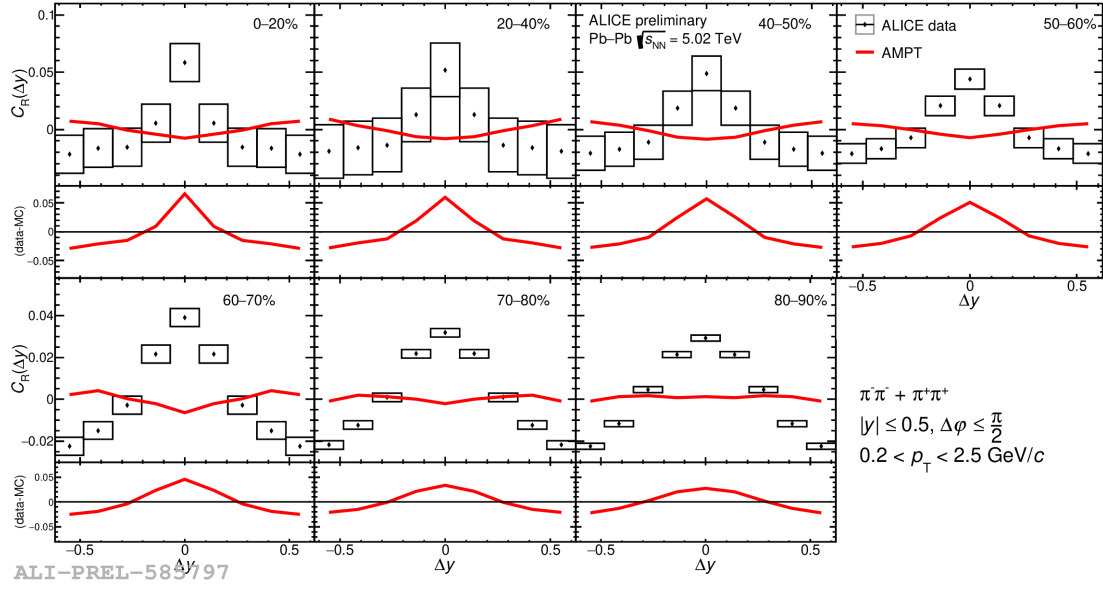


FIGURE 9.33: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign pions and all centrality classes involved in the analysis.

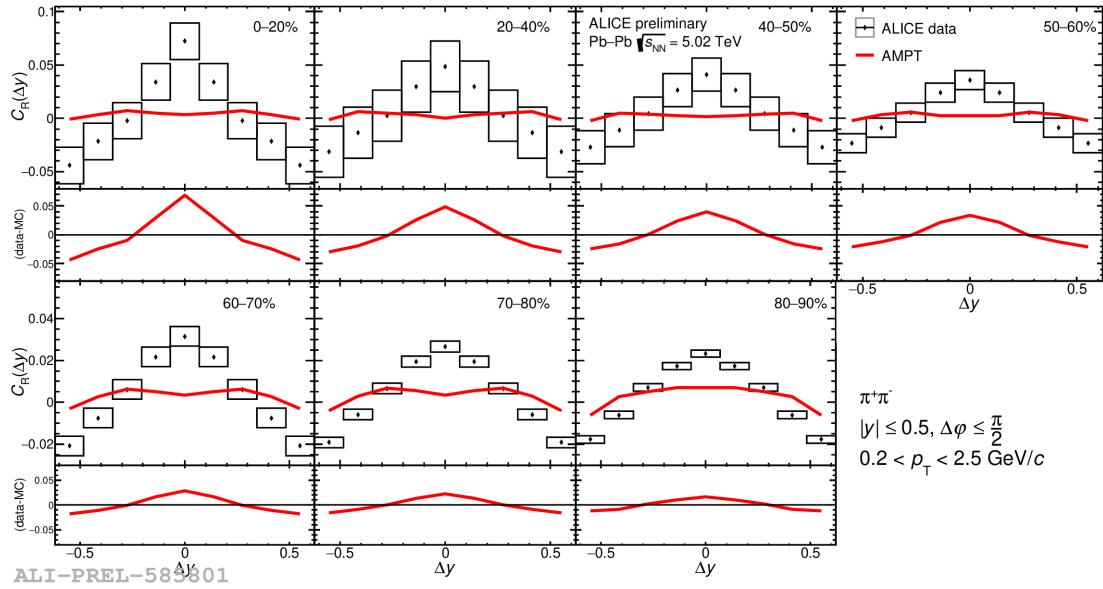


FIGURE 9.34: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign pions and all centrality classes involved in the analysis.

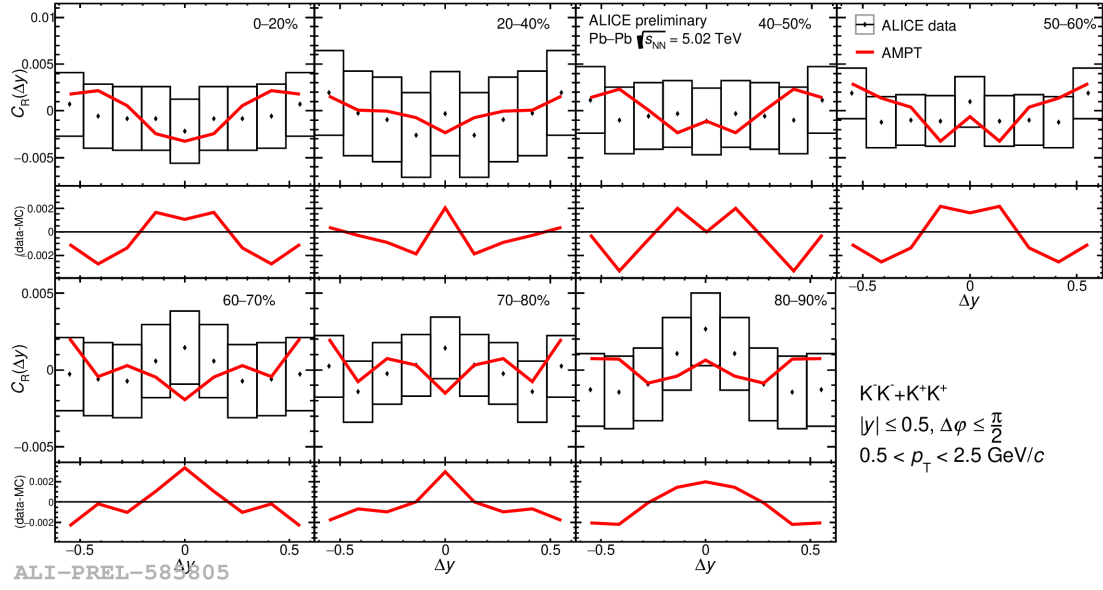


FIGURE 9.35: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign kaons and all centrality classes involved in the analysis.

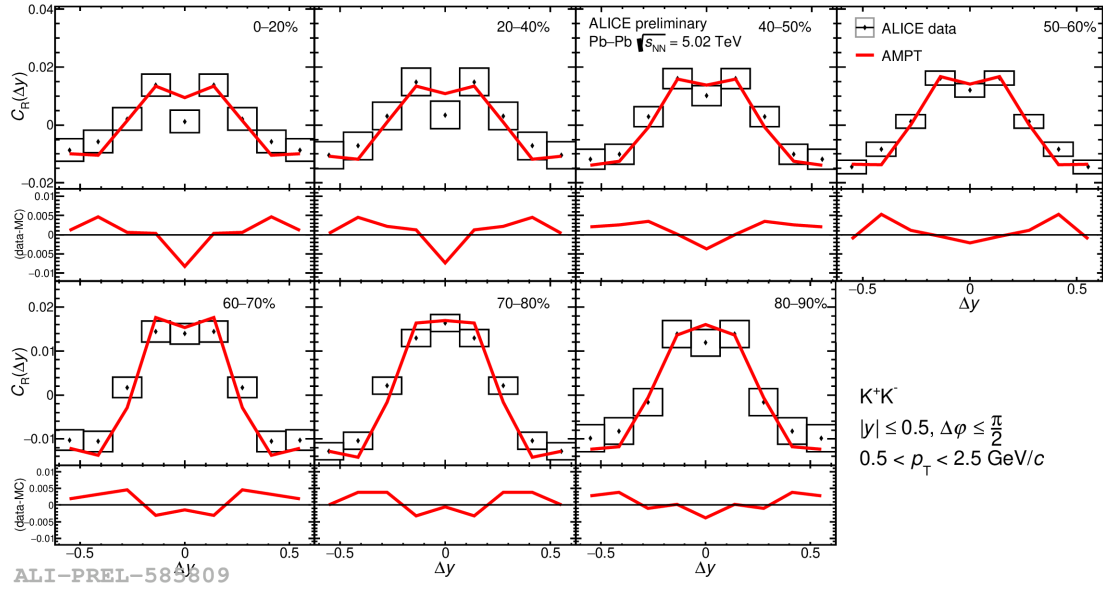


FIGURE 9.36: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign kaons and all centrality classes involved in the analysis.

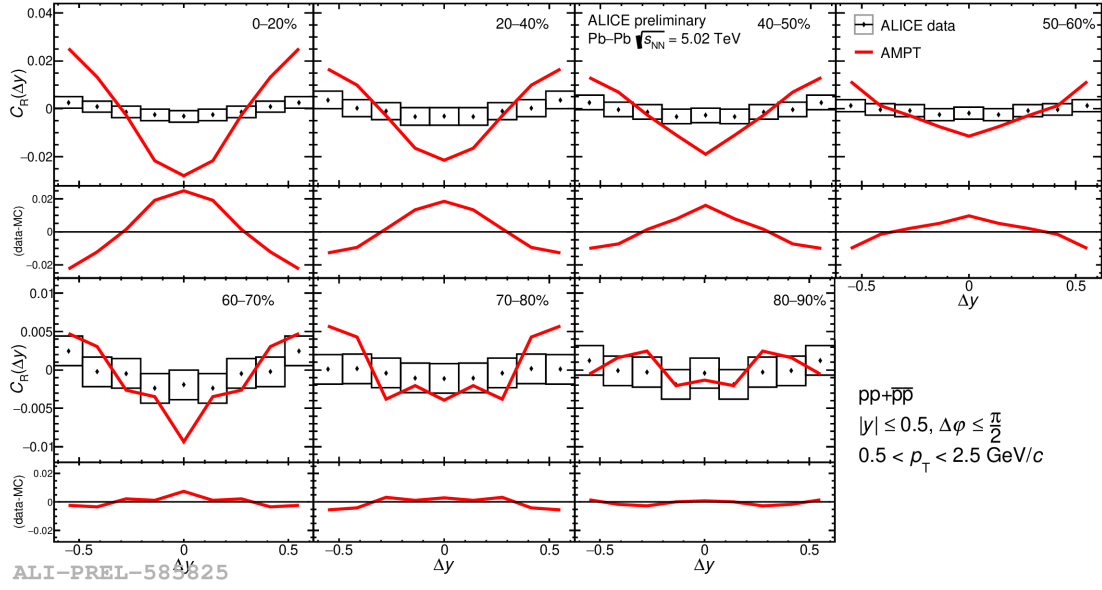


FIGURE 9.37: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for like-sign protons and all centrality classes involved in the analysis.

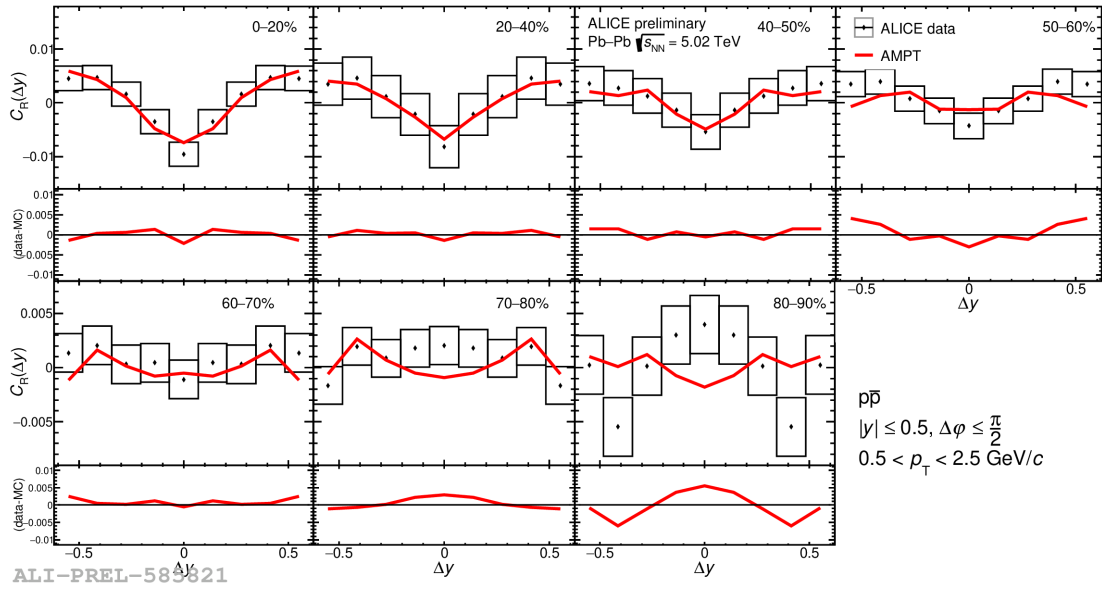


FIGURE 9.38: Comparison between $\Delta y \Delta \phi$ correlation functions and AMPT model projected onto the rapidity direction in Pb-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV by using the rescaled two-particle correlation function definition for unlike-sign protons and for all centrality classes involved in the analysis.

9.2 Summary of Angular Correlation Studies in HIC

The final part of this extensive study focused on angular correlations between two particles in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. This analysis, aimed at better understanding the anticorrelation observed for like-sign protons, was conducted for the first time at such high energies in HIC and across different centrality classes. Surprisingly, the results revealed a much stronger anticorrelation in HIC than anticipated. Given the higher particle densities in these collisions, one might expect an increased probability of finding proton-proton and antiproton-antiproton pairs within a minijet, which should, in principle, reduce the magnitude of the depletion. However, the opposite trend was observed: the anticorrelation became more pronounced with increasing centrality. This unexpected behavior introduces a new level of complexity to the interpretation of baryon correlations, offering new insights while raising intriguing, as yet unresolved questions. In addition, new questions also emerge from the study of other particle pairs. By examining each species of particles individually and comparing them with each other, new information is discovered.

In small collision systems, previous observations have revealed fundamental physical phenomena, such as the absence of an away-side structure for unlike-sign particle pairs and the apparent dependence of annihilation effects on multiplicity. In addition, correlations between kaons of like signs, when analyzed using the rescaled two-particle correlation function, show independence of multiplicity. Most of these effects, despite being largely influenced by flow in mid- to high-centrality events, persist in Pb–Pb collisions with significantly greater intensity due to the dense particle environment generated in such events. Although flow contributes significantly, several physical effects emerge with unexpected intensity beyond its influence, including the phenomenon of annihilation. As previously discussed for small systems, annihilation is an FSI effect that depends on the system size rather than the number of particles in a collision. Moreover, based on 2D plots shown in Figs. 9.6, 9.12 and the study in Ref. [91], one would expect a very narrow dip associated with annihilation. However, the 2D correlation function reveals a wider depletion than expected. Could this indicate the presence of additional effects beyond annihilation? Regarding the behavior of like-sign kaons, it's observed that unlike the multiplicity-independent behavior observed in small collisions, this is not reflected in the projections onto $\Delta\phi$ in HIC. Could this be attributed to the influence of flow? Since flow depends on centrality, it could have an impact on the magnitude of the observed correlations. To what extent does

the flow influence other effects, such as the strong anticorrelation observed for protons of like and unlike-sign?

Many intriguing effects are observed in this analysis that are somewhat surprising in HIC. However, the plots show that these effects often make only a minor contribution compared to the flow, which is a separate phenomenon that is well understood and studied independently. It would be extremely interesting to separate out the flow to better highlight these effects. However, this is a complex task that would require the development of new methodologies, which is beyond the scope of this work.

Chapter 10

Comparative Insights into pp, p-Pb, and Pb-Pb Collision Systems

This chapter presents a comparison of results obtained from three collision systems. The comparison is conducted using similar multiplicity classes, represented by the values of $dN_{\text{ch}}/d\eta$. These values were sourced from the literature [132, 137, 138] for each collision system and adjusted to match the multiplicity or centrality classes used in the three analyses. The degree of similarity in these values determines how comparable the correlation functions are.

TABLE 10.1: $dN_{\text{ch}}/d\eta$ values for pp, p-Pb, and Pb-Pb collision system from the literature and adapted to the multiplicity and centrality classes used in the analysis.

collision system	$dN_{\text{ch}}/d\eta$						
pp	0–20%	20–40%	40–70%		70–100%		
	19.1	9.18	5.1		2.55		
p-Pb	0–20%	20–40%	40–70%		70–100%		
	35.55	23.2	9.6		4		
Pb-Pb	0–20%	20–40%	40–50%	50–60%	60–70%	70–80%	80–90%
	1570	649	318	183	96.3	44.9	17.5

Table 10.1 provides the relevant $dN_{\text{ch}}/d\eta$ values, identifying the most comparable multiplicity and centrality classes: 0–20% for pp collisions ($dN_{\text{ch}}/d\eta = 19.1$), 20–40% for p-Pb collisions ($dN_{\text{ch}}/d\eta = 23.2$), and 80–90% centrality for Pb-Pb collisions ($dN_{\text{ch}}/d\eta = 17.5$).

In Fig. 10.1, the correlation functions for pp, p-Pb, and Pb-Pb collision systems are compared using the probability ratio definition.

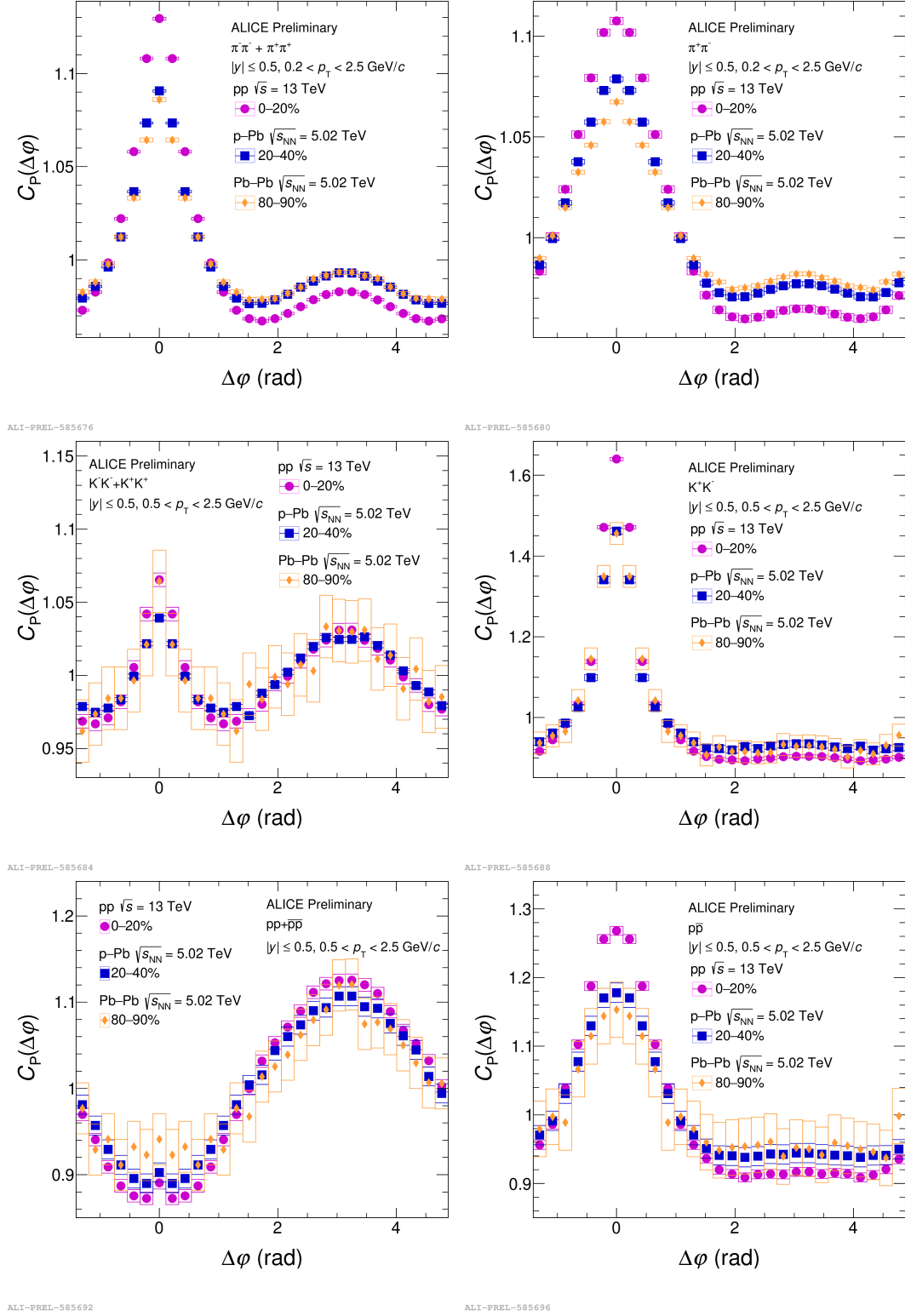


FIGURE 10.1: Comparison of pp, p-Pb, and Pb-Pb $\Delta y \Delta \phi$ correlation functions at the LHC energies for all particles using probability ratio definition.

The observed correlations result from a combination of trivial $1/N$ multiplicity scaling, and physical phenomena, such as minijets, resonance decays, quantum effects and final-state interactions. These combined effects lead to notable differences between the three systems, particularly for like- and unlike-sign pions, as well as unlike-sign kaons and protons. For like-sign kaons, no significant differences are observed across the multiplicity classes, as their correlations are largely independent of multiplicity scaling and primarily reflect their intrinsic physical interactions. Similarly, like-sign protons exhibit comparable behavior across the systems. Within the uncertainties, the data show a good agreement, indicating that the physical effects governing these correlations remain consistent across the collision systems and centrality classes. Using the rescaled two-particle correlation function, as shown in Fig. 10.2, the trivial $1/N$ scaling effects are effectively removed. The comparison demonstrates good agreement between the systems. The correlation functions for pp and p -Pb collisions are nearly identical within the uncertainties for all particle pairs, despite the $dN_{\text{ch}}/d\eta$ values used for the comparison not being perfectly matched. For the Pb-Pb system, a less pronounced correlation is observed. This reduction is not due to a smaller $dN_{\text{ch}}/d\eta$ value compared to pp and p -Pb collisions but is likely attributable to differing underlying physics, such as the formation of the QGP in heavy-ion collisions.

When analyzing Fig. 10.2 particle by particle, distinct trends become evident. For like-sign pions, a stronger peak in the correlation function is observed in pp and p -Pb collisions compared to Pb-Pb collisions. This difference can be attributed to the enhanced influence of certain physical phenomena in smaller systems. In pp and p -Pb the convolution of mini-jets and quantum effects are more pronounced as they face less suppression from the denser environment and collective effects present in larger systems like Pb-Pb. For unlike-sign pions and kaons, the Pb-Pb system shows a smaller peak than pp and p -Pb collisions. This is likely because, in smaller systems, particles are primarily produced from minijets, leading to stronger correlations. In contrast, in Pb-Pb collisions, particles also originate from the bulk QGP matter, which is less localized and leads to weaker correlations through minijets. For like-sign kaons, the behavior remains consistent across all systems and definitions, indicating no dependence on multiplicity or centrality. For like-sign protons, an anticorrelation is observed across all collision systems. For unlike-sign protons, a pronounced dip at the origin (0,0) is observed in Pb-Pb collisions due to the annihilation phenomenon. In pp and p -Pb collisions, this feature appears only at higher multiplicity classes, which are not used in the current comparison.

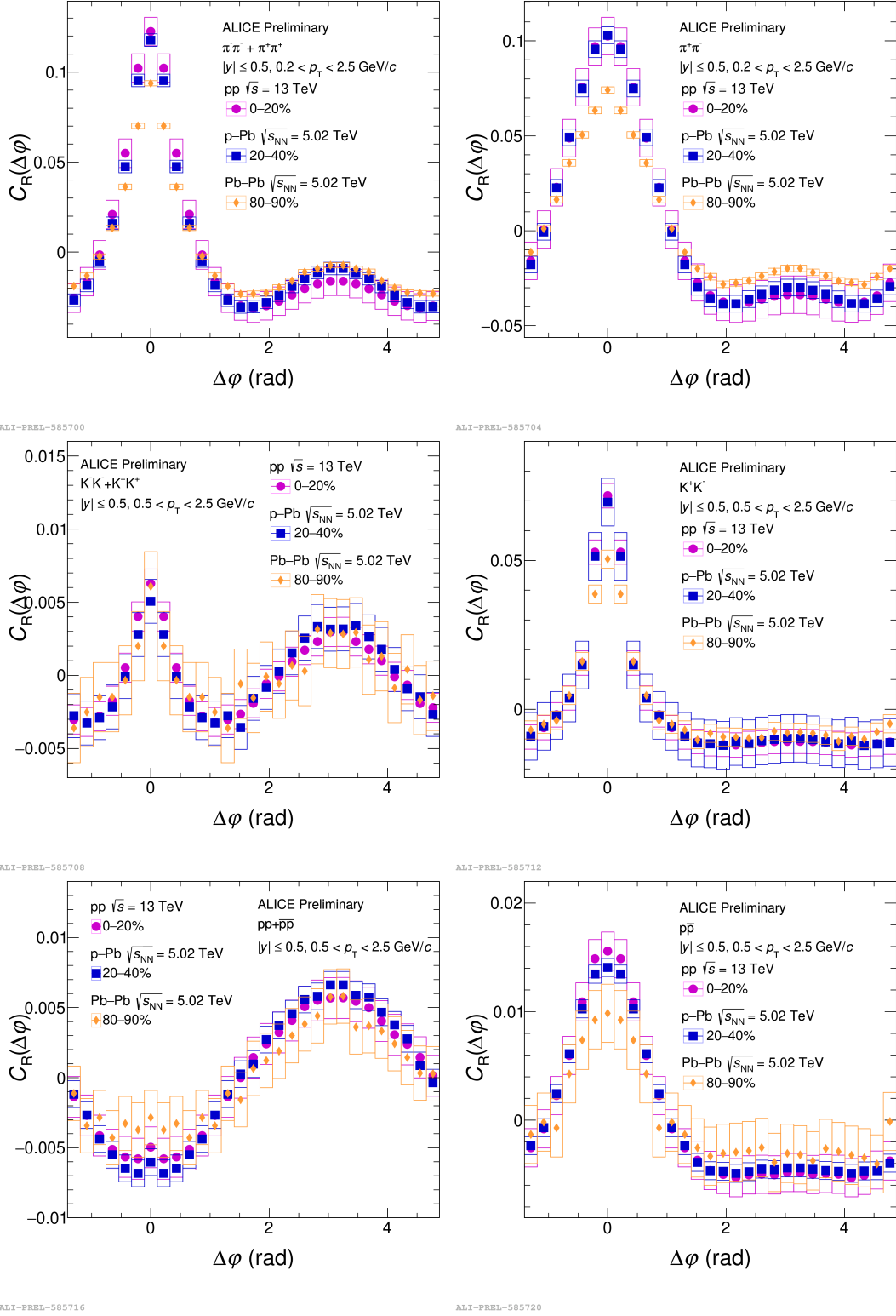


FIGURE 10.2: Comparison of pp, p-Pb, and Pb-Pb $\Delta y \Delta \phi$ correlation functions at the LHC energies for all particles using rescaled two-particle correlation function definition.

Chapter 11

Summary and Conclusions

This thesis presents an *explorative experimental analysis* concerning the study of two-particle angular correlations for identified pions, kaons, and protons, considering both like-charge and opposite-charge pairs, across various multiplicity classes and collision systems. The initial motivation for this work arose from the study of two-particle angular correlations in pp collisions at $\sqrt{s} = 7$ TeV, where an unexpected anticorrelation was observed for the first time. This surprising result prompted further investigations into the phenomenon, which was later found to be a common feature in baryon pairs. Extensive studies have explored various physical phenomena to explain the origins of this anticorrelation, but no models have been able to fully reproduce the observed behavior, leading to what can be described as an intriguing puzzle in baryon correlation studies. The goal of this work was to contribute to solving this puzzle by providing new insights through the analysis presented here.

The initial analysis of two-particle correlation functions in pp collisions at $\sqrt{s} = 13$ TeV used the probability ratio correlation function. However, this method did not account for the expected $1/N$ scaling effect across different multiplicity classes. To address this limitation, a new methodology was developed by introducing a new definition of the correlation function in ALICE, the rescaled two-particle correlation function.

Using both definitions, the first analysis was performed in pp collisions at $\sqrt{s} = 13$ TeV, focusing on like-sign and unlike-sign pions, kaons, and protons across four multiplicity classes: 0–20%, 20–40%, 40–70%, and 70–100%. After completing this initial analysis for pp collisions, the same procedure was extended to the same analysis in p–Pb collisions across 13 multiplicity classes under the request of theorists. The p–Pb collision system at $\sqrt{s_{NN}} = 5.02$ TeV have been studied as well across the 4 multiplicity classes corresponded to 0–20%, 20–40%, 40–70%, and 70–100%, employing the same cuts, selections, and analysis procedures used in the pp case.

For both pp and p–Pb collisions, the analysis followed a consistent methodology. Quality assurance procedures were applied to ensure proper selection, track reconstruction, and particle identification for pions, kaons, protons, and their antiparticles. The analysis settings were carefully defined, finalized, and implemented, including the application of purity, efficiency, and correction procedures. In the case of pp collisions, the rescaled two-particle correlation function method was validated, and the average number of particles, N_{av} , was estimated for each particle species across the four multiplicity classes and compared to public data. Monte Carlo closure tests were conducted to validate the correction procedures for both correlation function definitions. Additionally, systematic uncertainties were carefully evaluated, and the 2D $\Delta y \Delta \phi$ correlation function was calculated using both definitions, with projections onto the azimuthal direction performed. The results were compared with Monte Carlo models to assess the agreement with experimental data.

The same methodology was applied for Pb–Pb collision analysis at $\sqrt{s_{NN}} = 5.02$ TeV. To ensure a proper comparison with small collision systems results, the analysis was performed using the same cuts, selection, and particle identification for pions, kaons, and protons. The study was carried out across 7 centrality classes: 0–20%, 20–40%, 40–50%, 50–60%, 60–70%, 70–80%, and 80–90%. All steps conducted for pp and p–Pb were repeated for Pb–Pb, and the 2D results were obtained using both definitions, along with projections onto the azimuthal direction and comparisons with Monte Carlo models.

For pp collisions at $\sqrt{s} = 13$ TeV, the probability ratio definition showed significant discrepancies between the models and the data, particularly for unlike-sign particles and the anticorrelation observed for like-sign protons. Both the PYTHIA8 and EPOS_LHC models qualitatively reproduced meson correlations but failed to account for the anticorrelation in protons. The rescaled two-particle correlation function definition improved the agreement, especially for mesons, but the models still struggled with proton correlations.

In p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, neither EPOS_LHC nor DPMJET fully captured the observed correlations, with both models failing to reproduce the anticorrelation for like-sign protons. However, DPMJET provided a better description of meson correlations, particularly in the near-side and away-side regions. The rescaled two-particle correlation function yielded more pronounced differences, with EPOS_LHC showing qualitative agreement for mesons but failing to reproduce the away-side features. DPMJET offered a better overall description of meson correlations and also

showed reasonable agreement for unlike-sign protons.

In Pb–Pb collisions, the results indicated that the AMPT model, which incorporates flow effects, provided better agreement with the data than the HIJING model, which primarily focused on minijet structures and neglected collective effects. While AMPT reproduced meson correlations well along the azimuthal axis, surprisingly also the like- and unlike-sign protons show an agreement, even if some limitations in AMPT’s ability to describe proton correlations at lower centralities. The rapidity projections revealed that the AMPT model captured proton-antiproton correlations well but struggled with pion correlations.

The study also compared the correlation functions for pp, p–Pb, and Pb–Pb collision systems. The results showed significant differences in the correlation functions between the systems, influenced by effects such as $1/N$ scaling, minijets, flow, resonance decays, final-state interactions and other phenomena. Using the rescaled two-particle correlation function, the $1/N$ scaling effects were effectively removed, and the results showed a good agreement between pp and p–Pb collision systems, with the correlation functions being nearly identical within uncertainties. In contrast, the Pb–Pb system displayed a less pronounced correlation, which was attributed to the formation of the QGP in heavy-ion collisions.

This work has led to several important conclusions while also raising new questions that remain unanswered.

- Why is the characteristic back-to-back jet structure suppressed for unlike-sign particle pairs in all three collision systems?
- Why do like-sign kaons show no dependence on multiplicity when using the rescaled two-particle correlation function definition? Furthermore, in Pb–Pb collisions, is this apparent independence masked by the flow? How would the correlation functions appear if the flow were subtracted?
- The persistence of anticorrelation in heavy-ion collisions is nontrivial, but how strong is it? What would anticorrelation look like in the absence of flow?
- The annihilation phenomenon between protons and antiprotons is not expected to depend on the density of the system. Yet, why does it appear to do so? It is observed only in the high-multiplicity class of pp collisions, persists in p–Pb, and becomes significantly pronounced in Pb–Pb collisions.

The puzzle initially set out is revealed to be even more complex. Previously, mesonic correlation functions were considered a fundamental basis for comparing baryonic correlations. However, this study revealed that many new questions also arise from their behavior in different multiplicity classes. Addressing these questions—such as the subtraction of flow effects in Pb–Pb analyses—would require the development of a novel methodology, necessitating a separate dedicated study. Given the already extensive set of results in this work, such an endeavor is beyond the current scope of this thesis.

In conclusion, this study marks the first introduction of the rescaled two-particle correlation function within the ALICE collaboration. This approach provides new insights into the angular correlations between different multiplicity classes, offering a clearer representation of the actual number of events within a given class and facilitating the interpretation of the underlying physical phenomena. Additionally, this work presents, for the first time, a comparative analysis of angular correlations across three distinct collision systems: pp, p–Pb, and Pb–Pb. The results reveal strikingly similar correlation structures across all systems, suggesting that the underlying physics governing these small systems is largely comparable. However, subtle differences observed in Pb–Pb collisions point to the influence of the QGP.

Comparisons with theoretical models have provided qualitative insights into the observed correlation structures. However, further experimental and theoretical studies are necessary, particularly to better describe proton correlations, especially in small systems such as pp and p–Pb. The findings suggest that collective effects play a significant role even in small collision systems like p–Pb, while flow effects are crucial for understanding correlation structures in larger systems like Pb–Pb.

This thesis raises many open questions for which we currently lack answers. While we are not addressing these inquiries at this time, we anticipate that our findings will stimulate further discussions. We now look forward to insights from theorists to help clarify these issues and improve existing models. Future studies will build on this work by incorporating new elements into the puzzle. For example, understanding the role of mass in anticorrelation through the study of ϕ -p correlations. Additional studies will focus on the correlation function with D mesons to explore how the charm quark might influence the anticorrelation. Another key direction for future work is jet composition analysis, including calculating the number of protons in jets, which could provide deeper insights into the anticorrelation of baryons.

Ultimately, this work represents an important step in unraveling the complexity of baryon correlations in particle and heavy-ion collisions. Although many challenges remain, the methodologies introduced here, together with the key observations made, lay the foundation for future investigations. The interplay between experimental results and theoretical advances will be essential to deepen the understanding of various phenomena, improve theoretical models, and offer new insights related to the underlying physics.

Appendix A

Monte Carlo Simulations

A Monte Carlo (MC) closure test is performed to evaluate the accuracy of the correction procedure. This involves comparing the corrected reconstructed MC data with the corresponding MC true data to assess how effectively the corrections account for detector effects and biases. The closure test is conducted for pp, p-Pb, and Pb-Pb collisions across all multiplicity classes separately. It utilizes two distinct definitions of the correlation function: the probability ratio definition, as described in Sec.4.3.1, and the rescaled two-particle correlation function, detailed in Sec.4.3.2. These tests confirm that the correction procedure reliably reconstructs the underlying physical phenomena. Any remaining discrepancies indicate areas of Monte Carlo non-closure, which refers to the inability of simulation adjustments to fully reproduce experimental or theoretical expectations.

Regarding the analysis of pp collisions, as previously mentioned, the study was subsequently extended to 13 multiplicity classes. Since the efficiency and accuracy of the cuts are independent of multiplicity, this part of the analysis was not repeated. Instead, the results from the earlier analysis were considered sufficient for the 13-multiplicity class study.

A.1 Estimation of N_{av}

Before discussing the closure test across the three collision systems, it is important to first define how the N_{av} values for the rescaled two-particle correlation functions are determined. A successful closure test requires that the normalization factors for the reconstructed and true data align closely.

The N_{av} value for the reconstructed data is calculated as the ratio of selected particle

types to the total number of events within a given multiplicity class. The selected particles are those that satisfy all selection criteria and are subsequently corrected using the correction factor, f , which is applied individually for each multiplicity class. This process is illustrated in Fig. A.1.

Figure A.1 provides an example of the number of tracks and events, focusing on a single pion distribution in the highest multiplicity class (0–20%).

- **Left panel:** Shows the pions spectra as a function of p_T after applying selection cuts but without accounting for the correction factor. The discontinuity at $p_T = 0.5 \text{ GeV}/c$ is caused by the introduction of the TOF detector, which modifies particle identification and reconstruction.
- **Middle panel:** The p_T spectrum of pions, after applying the correction factor, becomes uniform. Additionally, the gap at $p_T = 0.5$ is no longer present.
- **Right panel:** Displays the total number of events as a function of multiplicity.

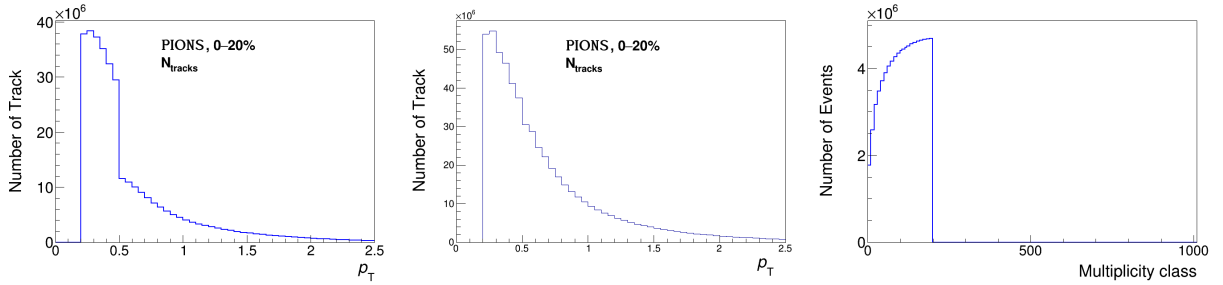


FIGURE A.1: The left panel shows the particle spectra as a function of p_T after applying selection cuts, without corrections for the correction factor. The middle panel illustrates the corrected spectra, also as a function of p_T . The right panel displays the total number of events as a function of multiplicity. These plots correspond to π^- particles in the 0–20% multiplicity class, derived from Monte Carlo reconstructed data from pp collisions at $\sqrt{s} = 13 \text{ TeV}$.

In contrast, the N_{av} value for the true data is calculated as the number of particles per type, requiring at least one particle of the specified type in each event, divided by the total number of events in the corresponding multiplicity class.

Tables in the following sections present the N_{av} values for both reconstructed and true data. These values, provided for all analyzed particles and multiplicity classes, allow for a detailed comparison of reconstruction performance across different collision systems.

TABLE A.3: N_{av} values for reconstructed and true data from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for all particles and centrality classes analyzed.

		0–20%	20–40%	40–50%	50–60%	60–70%	70–80%	80–90%
pions	N_{av}^{REC}	591	289.5	145	83.5	43.4	20.2	8.4
	N_{av}^{TRUE}	618	290	143.2	82.1	42.6	19.7	8
kaons	N_{av}^{REC}	75	37	17.9	10	5	2.2	0.9
	N_{av}^{TRUE}	83.1	38	18	10	5	2.25	0.89
protons	N_{av}^{REC}	42	19.5	9.1	4.9	2.4	1	0.37
	N_{av}^{TRUE}	42.6	18.7	8.6	4.6	2.2	0.96	0.34

TABLE A.1: Comparison of N_{av} values between reconstructed and true Monte Carlo data from pp collision at $\sqrt{s} = 13$ TeV for pions, kaons, and protons across the analyzed multiplicity classes.

	N_{av}^{REC} 0–20%	N_{av}^{TRUE} 0–20%	N_{av}^{REC} 20–40%	N_{av}^{TRUE} 20–40%	N_{av}^{REC} 40–70%	N_{av}^{TRUE} 40–70%	N_{av}^{REC} 70–100%	N_{av}^{TRUE} 70–100%
Pions	14.78	15.07	9.40	9.46	5.62	5.39	3.32	2.8
Kaons	1.61	1.72	0.98	1.05	0.51	0.57	0.32	0.28
Protons	0.96	1.04	0.67	0.66	0.34	0.38	0.18	0.2

TABLE A.2: Comparison of N_{av} values between reconstructed and true Monte Carlo data from p–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV for pions, kaons, and protons across the analyzed multiplicity classes.

	N_{av}^{REC} 0–20%	N_{av}^{TRUE} 0–20%	N_{av}^{REC} 20–40%	N_{av}^{TRUE} 20–40%	N_{av}^{REC} 40–70%	N_{av}^{TRUE} 40–70%	N_{av}^{REC} 70–100%	N_{av}^{TRUE} 70–100%
Pions	95.05	94.96	63.92	63.83	39.14	38.82	17.45	15.92
Kaons	11.09	10.14	7.8	6.82	4.9	4.15	2.01	1.69
Protons	5.27	5.81	3.53	3.88	2.16	2.36	0.97	0.98

As shown in Tables A.1, A.2, and A.3, the reconstructed and true data values for N_{av} are closely aligned, exhibiting similar trends across the three collision systems. However, a noticeable divergence appears in most peripheral collisions, likely due to limited statistics in these events. For protons, the reconstructed data shows a consistent overestimation of N_{av} compared to the generated (true) data. This discrepancy is attributed to the higher contamination from secondary particles affecting proton reconstruction. In contrast, for pions and kaons, where secondary particle contamination is minimal, the reconstructed and true values remain nearly identical, confirming the reliability of the results for these particle species.

A.2 MC Closure test in pp collision

The Monte Carlo closure test is performed by using MC reconstructed and true data from pp collision at $\sqrt{s} = 13$ TeV. The test is done for like and unlike-sign pions, kaons, and protons in the four multiplicity accounts for the analysis which are 0–20%, 20–40%, 40–70% and 70–100%.

Figure A.2 illustrates the closure test based on the *probability ratio definition*, while Fig. A.3 the MC closure test is performed by using the rescaled two-particle correlation functions.

For both figures, the upper panel shows the integrated $\Delta\phi$ projection for both reconstructed data and true data, represented by open diamonds and solid diamonds, respectively. The lower panel displays the relative error, calculated as $(MC_{\text{rec}} - MC_{\text{true}})/MC_{\text{rec}}$.

In the case of probability ratio, the results demonstrate strong agreement, with near-perfect alignment in some cases, between the reconstructed and true data, confirming the reliability of the correction procedure. In the case of rescaled two-particle correlation function, the results indicate a non-closure of approximately 10% in certain multiplicity classes. While this discrepancy arises in a correlation function that saturates near zero—making it relatively minor—it has been incorporated into the systematic uncertainties to ensure a comprehensive and reliable analysis.

A.3 MC Closure test in p–Pb collision

The Monte Carlo closure test is conducted for p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in the same way as is done for pp analysis. The test is applied to pions, kaons, and protons across four multiplicity classes: 0–20%, 20–40%, 40–70%, and 70–100%.

Figure A.4 presents the MC closure test conducted using the probability ratio definition, demonstrating highly satisfactory results. For pion and kaon pairs, the relative error remains consistently low, under 1%. For protons, the closure test indicates an error below 5% in the lower multiplicity classes, which is primarily attributed to limited statistics in these regions. Figure A.5 illustrate the MC closure test performed using the rescaled two-particle correlation function definition. The lower plots depict the relative error, revealing closure deviations of approximately 10% for the highest

multiplicity classes and up to 20% for the lowest multiplicity classes. For kaons and protons, the systematic errors are significantly higher. Nonetheless, the closure test results are still deemed reasonable, considering that the correlation functions saturate at 0. This saturation inherently limits the achievable precision.

A.4 MC Closure test in Pb–Pb collision

The MC closure test is repeated also for the Pb–Pb analysis at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for like- and unlike-sign pions, kaons, and protons and in the centrality selected which are 0–20%, 20–40%, 40–50%, 50–60%, 60–70%, 70–80%, and 80–90%.

Figure A.6 illustrate the MC closure test using the probability ratio definition, and Fig. A.7 show the closure test by using the rescaled two-particle correlation functions. In the case of probability ratio the closure test demonstrates good agreement between reconstructed and generated data. However, in the lower centrality classes, statistical fluctuations are noticeable, primarily due to the limited statistics available for the reconstructed data. The results in the upper plot for the rescaled two-particle correlation functions, where the $\Delta\phi$ projections are displayed for reconstructed and true data indicate that the closure test is satisfactory across all particle types. However, larger discrepancies are evident in the box below, where the relative error is performed. For the lower centrality classes (70–80% and 80–90%), non-closure is observed, attributed to limited statistics. To better verify the percentage of the non-closure, a linear fit was applied. Based on the fit results, the relative error is small—approximately 10% for some multiplicity classes and less than 5% for others. These errors are not substantial, considering that the correlation functions saturate at zero, minimizing their impact on the overall correlations.

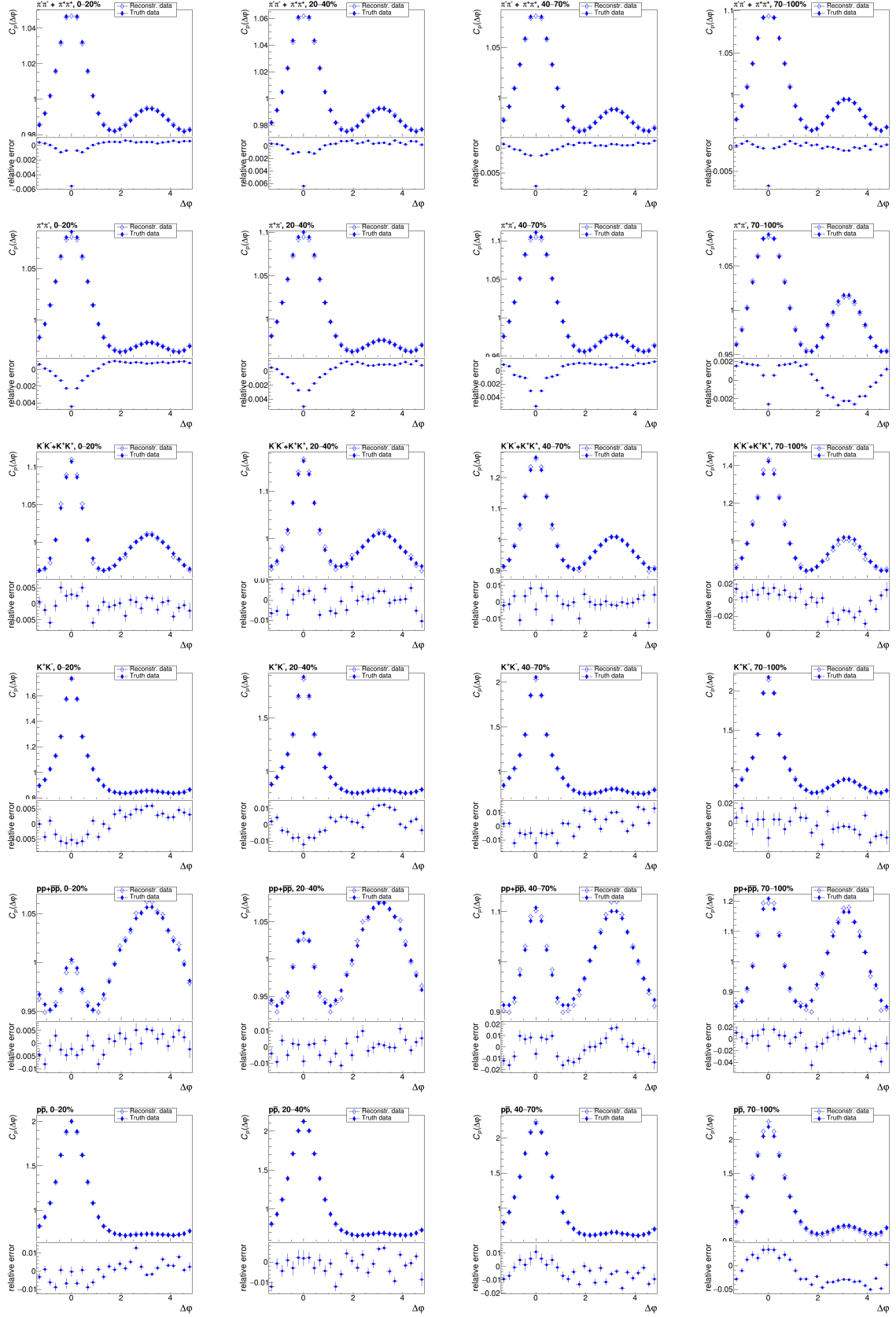


FIGURE A.2: MC closure test using data from pp collision at $\sqrt{s} = 13$ TeV is performed by using the probability ratio definition for all particle pairs and across all multiplicity classes selected.

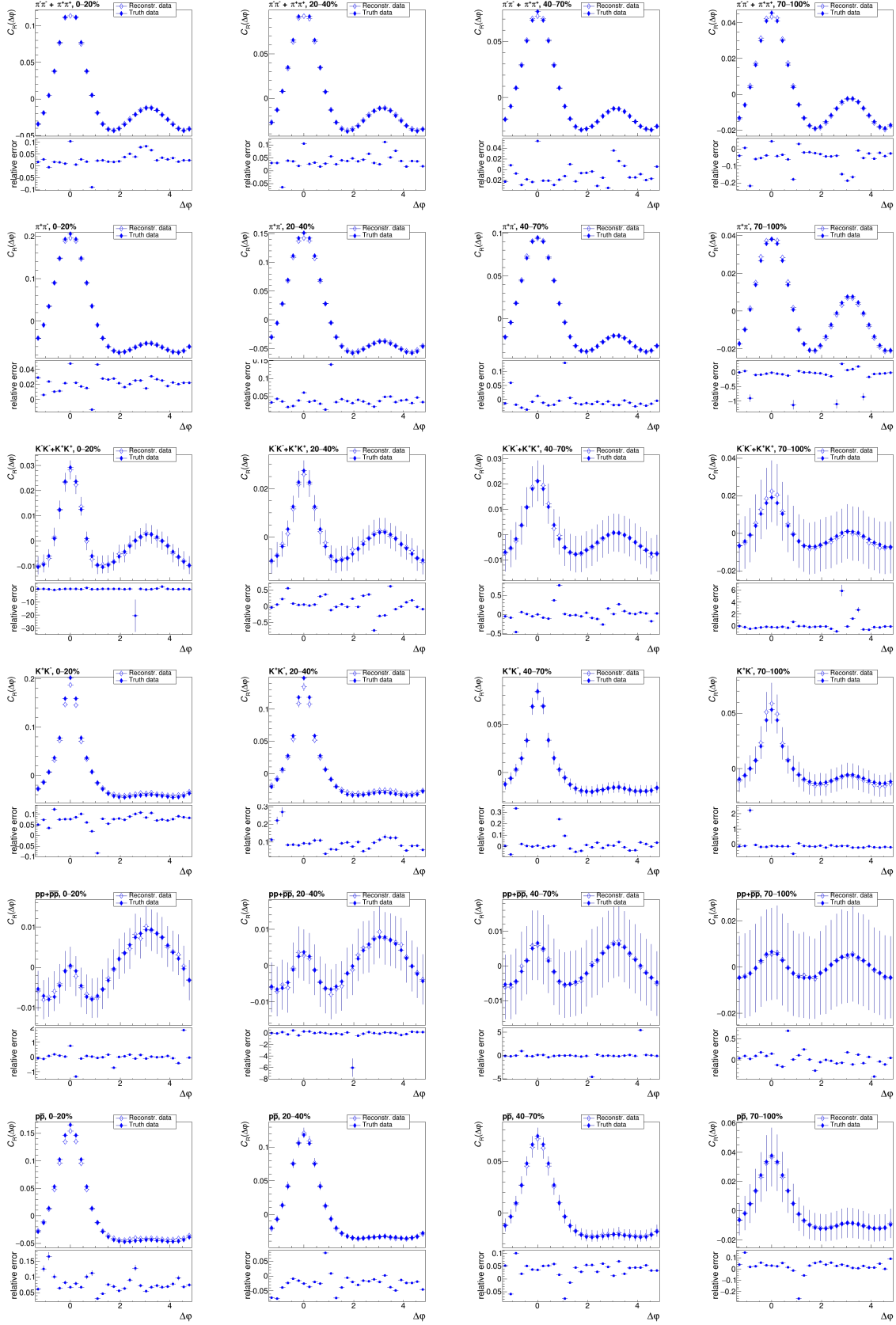


FIGURE A.3: MC closure test using data from pp collision at $\sqrt{s} = 13$ TeV is performed by using the rescaled two-particle correlation function for all particle pairs and across all multiplicity classes selected.

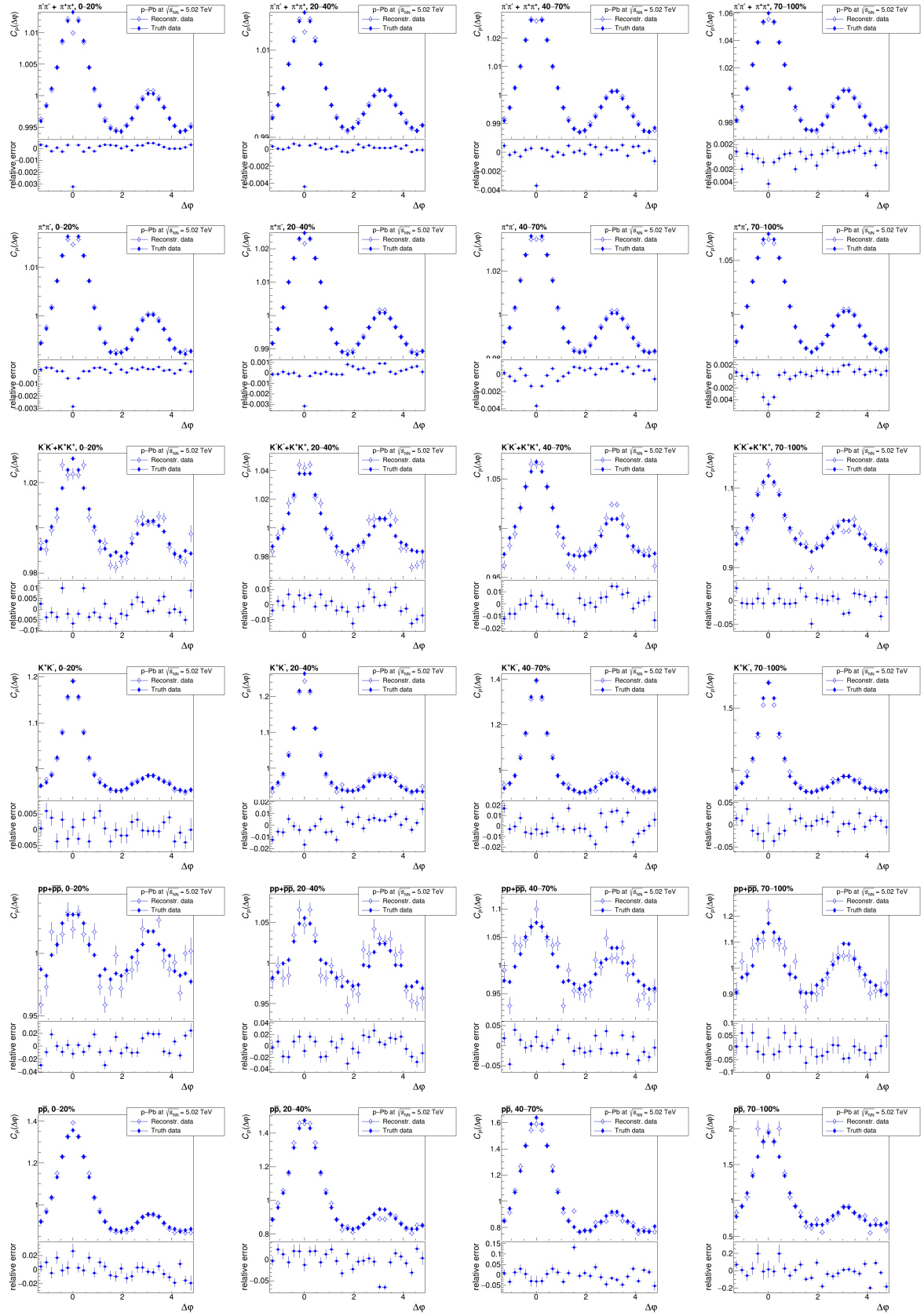


FIGURE A.4: MC closure test using data from p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV is performed by using the probability ratio definition for all particle pairs and across all multiplicity classes selected.

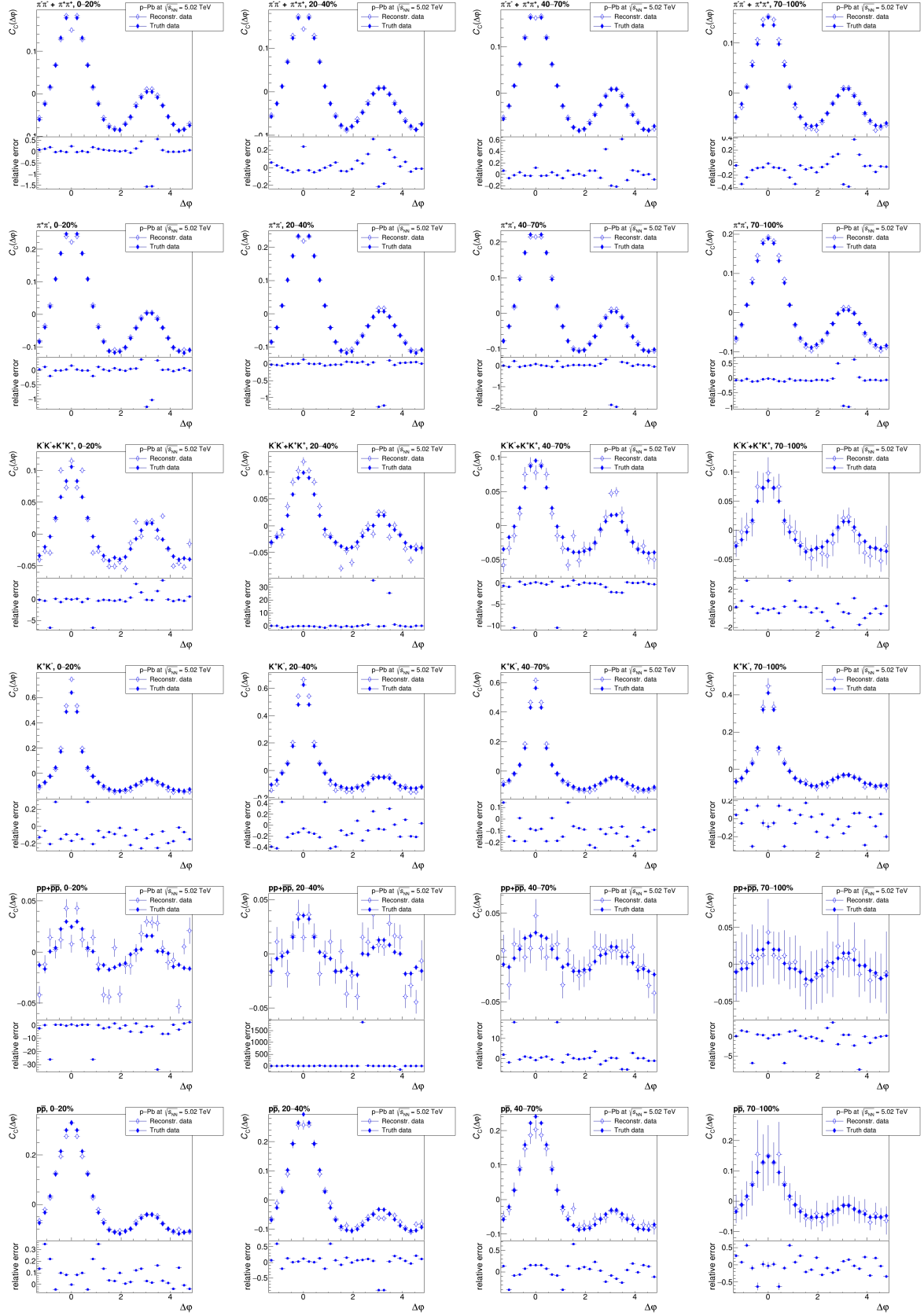


FIGURE A.5: MC closure test using data from p–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV is performed by using the rescaled two-particle correlation function for all particle pairs and across all multiplicity classes selected.

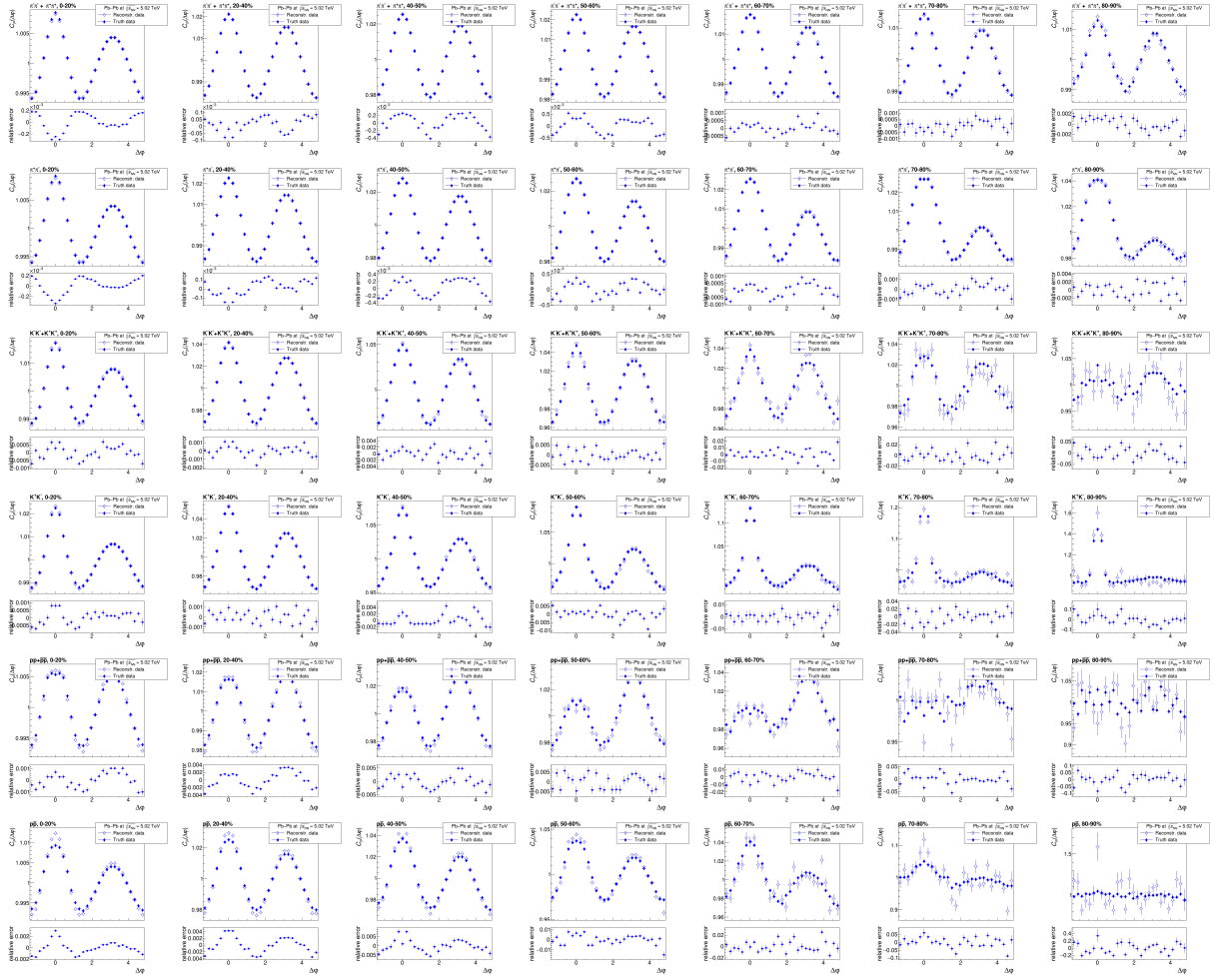
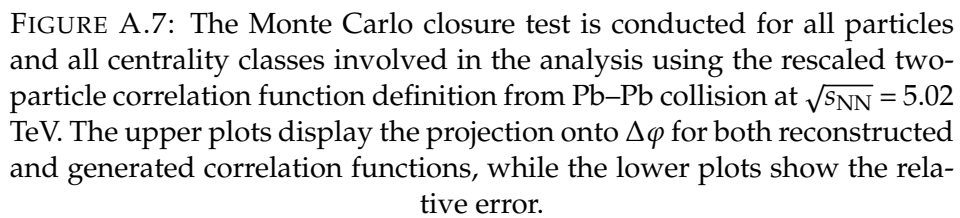


FIGURE A.6: The Monte Carlo closure test is conducted for all particles and all centrality classes involved in the analysis using the probability ratio definition from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. The upper plots display the projection onto $\Delta\phi$ for both reconstructed and generated correlation functions, while the lower plots show the relative error.



Appendix B

Systematic Uncertainties

Uncertainty in any measured quantity can generally be divided into two categories which are statistical and systematic. Statistical uncertainty arises from the limited size of the data sample and decreases as the amount of data increases or the experiment is repeated. Systematic uncertainty, on the other hand, is inherent to the methodology and persists irrespective of the number of repetitions, as it stems from the measurement approach itself. While statistical uncertainty is often calculated using established methods, the estimation of systematic uncertainty is less simple but equally important. Ideally, systematic uncertainty is estimated by performing the measurement in a completely independent experiment using different techniques.

This chapter addresses the systematic uncertainties associated with the analysis. To evaluate the reliability of the applied methods, including cuts, corrections, data selection, and particle identification, systematic checks are performed over the three collision system studied. These checks involved comparing different data distributions using both the probability ratio definition and the rescaled two-particle correlation function definition.

For the probability ratio definition, the relative error (R_r) is calculated as:

$$R_r = \frac{|A - B|}{A}. \quad (\text{B.1})$$

For the rescaled two-particle correlation function, which tends to saturate at zero, systematic uncertainty is assessed as an absolute error (R_a) using the formula:

$$R_a = |A - B|. \quad (\text{B.2})$$

In these definitions, R represents the partial systematic uncertainty. A is the baseline histogram without variations, and B is the histogram with variations applied. To determine the significance of partial uncertainties, the Barlow method is employed. The Barlow criterion (B) is defined as:

$$B = \frac{|A - B|}{\sqrt{|\sigma_A^2 \mp \sigma_B^2|}}, \quad (\text{B.3})$$

where subtraction in the denominator is applied when the predefined and systematic samples are fully correlated, such as when one is a subset of the other. A threshold value of 1 is used. If at least one-third of the Barlow control points exceed this threshold, the systematic variation is considered statistically significant and included in the final uncertainty calculation.

The total systematic uncertainty for the correlation functions is calculated as the quadrature sum of all statistically significant partial uncertainties:

$$\text{Full Uncertainty} = \sqrt{R_1^2 + R_2^2 + \dots + R_n^2}. \quad (\text{B.4})$$

This approach ensures that the final uncertainty reflects the contributions from all significant systematic variations, complementing the statistical uncertainties derived from the data. In the next sections the systematic uncertainties will be shown separately for pp, p-Pb, and Pb-Pb collision systems and for both definition used in this work.

B.1 Systematic Uncertainties in pp Collisions

As previously mentioned, the analysis of the correlation function in pp collisions was initially performed using four multiplicity classes and later expanded to include thirteen multiplicity classes, incorporating the high-multiplicity trigger. Systematic uncertainties were estimated separately for each multiplicity class included in the analysis. Consequently, this section is divided into two parts.

The default dataset, with its specific cuts and selections, is compared against variations that employ either looser or tighter cuts. If both variations satisfy Barlow's criterion, only the one contributing the most to the final systematic uncertainty is retained

to avoid redundancy. In the analysis of pp collisions, the sources of the study of systematic uncertainties which is included in the final evaluation after meeting Barlow's criterion are listed below. Notably, these sources are consistent across analyses performed with four and thirteen multiplicity classes, except for the PID method. In the four-multiplicity analysis, one identification method contributes more significantly to the overall uncertainty than the method used in the thirteen-multiplicity analysis.

- *Comparison between datasets:* This check ensures that the data collected across different periods show no significant discrepancies. If the datasets are consistent, they can be combined to improve statistical precision. The comparison is made between data recorded in 2016 period and 2017 period.
- *Event mixing:* The event mixing process was examined as a potential source of systematic uncertainty. The impact was assessed by varying the number of z-vertex bins, using 30 bins as the default and 10 bins as an alternative.
- *PID Method:*
 - **4-Multiplicity Analysis:** The default PID method was modified by maintaining the acceptance criteria while altering the rejection criteria. Specifically, tracks identified as belonging to multiple particle species were excluded from the analysis by removing particles within a 2σ range.
 - **13-Multiplicity Analysis:** The default PID method was adjusted by keeping the acceptance criteria unchanged but refraining from rejecting any particle type.
- *Pile-up dependence:* The influence of pile-up on the analysis was evaluated by comparing results with and without pile-up rejection.
- *Track selection:* Variations in the track selection criteria were considered, particularly the default DCA (distance of closest approach) requirements which are described in Sec. 7.3. The DCA criteria were modified from the default of $DCA_{xy} < 2$ cm and $DCA_z < 2.6$ cm to explore their impact.
- *MC closure test:* The MC closure test verified the correction procedure by comparing reconstructed Monte Carlo data to true simulated data. As described in Sec. A.2 of Appendix A, this test contributes to the systematic uncertainty of the rescaled two-particle correlation function, with an estimated error of approximately 10%.

B.1.1 Systematic Analysis Across Four Multiplicity Classes

Using the R_r equation, the systematic uncertainty associated with the definition of the likelihood ratio was calculated. In Fig. B.1, the total systematic uncertainty is represented by the solid black line, incorporating all sources that passed Barlow’s criteria. Individual contributions to the uncertainty are color-coded in the same figure, aligned with the uncertainties discussed in the previous section for clarity and consistency. The maximum and minimum values of the uncertainty, calculated as the average across all bins for the highest and lowest multiplicity classes in each variation, are summarized in Table B.1. Comparing the trends shown in Fig. B.1 with the values in Table B.1, one can observe that while many uncertainties passed Barlow’s test and were included in the total uncertainty, most contributions appear to result from statistical fluctuations. Furthermore, in lower multiplicity classes, a noticeable increase in uncertainty is evident, likely due to reduced statistics and the amplified impact of statistical fluctuations.

TABLE B.1: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the probability ratio definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+pp̄	p̄p̄
Track selection	[0.034–0.1]%	[0.07–0.21]%	[0.2–1.25]%	[0.06–0.22]%	[0.32–2.18]%	[0.17–0.7]%
Event mixing	[0.04–0.01]%	[0.004–0.014]%	[0.04–0.28]%	[0.07–0.36]%	[0.064–0.43]%	[0.09–0.5]%
Pileup rejection	[0.002–0.008]%	[0.0015–0.01]%	[0.04–0.23]%	[0.043–0.2]%	[0.05–0.41]%	[0.05–0.26]%
PID method	[0.003–0.016]%	[0.0045–0.03]%	[0.17–0.7]%	[0.2–0.4]%	[0.06–0.31]%	[0.2–0.5]%
Data comparison	[0.06–0.16]%	[0.16–0.4]%	[0.37–2.35]%	[0.35–2.00]%	[0.63–4.9]%	[0.6–2.6]%

Using the definition of the rescaled two-particle correlation function, where the correlation functions saturate around zero, the absolute error equation (R_a) was employed to calculate the uncertainties, as they are shown in Fig. B.2. It is observed that the uncertainties exhibit a more structured shape compared to those calculated using the probability ratio definition. While one might expect the uncertainties to be similar—given that the rescaled two-particle correlation function is essentially a rescaling—the observed differences arise from the fact that when comparing the correlation functions ($|default - variation|$), the N_{av} value, which varies with the specific variation, must also be accounted for. This additional factor contributes to the differing uncertainties observed between the two definitions.

Nevertheless, the estimated uncertainties using the rescaled two-particle correlation function are generally lower than those calculated with the probability ratio definition. The MC closure test was included in the systematic uncertainties for the rescaled two-particle correlation function definition. An error of approximately 10% was observed in some multiplicity classes, which may appear significant given that the correlation function is rescaled to zero. However, the weight of this error is minimal compared to the total uncertainty. Table B.2 shows the absolute error for all particles and all multiplicity classes involved. For each variation, the values, calculated as the average over all the bins, were shown only for the highest and lowest multiplicity classes.

TABLE B.2: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+p $\bar{p}$	p $\bar{p}$
Track selection	[0.2–0.12]	[0.18–0.012]	[0.02–0.02]	[0.023–0.008]	[0.05–0.027]	[0.07–0.025]
Event mixing	[0.006–0.0027]	[0.008–0.003]	[0.005–0.0048]	[0.0076–0.0058]	[0.004–0.0039]	[0.0045–0.005]
Pileup rejection	[0.005–0.003]	[0.007–0.004]	[0.004–0.0068]	[0.0048–0.0055]	[0.0037–0.0064]	[0.003–0.004]
PID method	[0.75–0.41]	[0.92–0.12]	[0.087–0.05]	[0.38–0.16]	[0.12–0.04]	[0.15–0.05]
Data comparison	[0.18–0.09]	[0.43–0.2]	[0.083–0.12]	[0.2–0.13]	[0.097–0.125]	[0.08–0.08]
MC closure	[0.13–0.068]	[0.18–0.2]	[0.06–0.11]	[0.43–0.2]	[0.086–0.07]	[0.42–0.048]

Additional insights are obtained by examining the influence on the maximum of the correlation function, as reported in Tab. B.3. For certain variations, a significant systematic influence on the peak maximum is observed, particularly for like-sign kaons and protons. However, as illustrated in Fig. B.2, most of these variations are dominated by statistical fluctuations, which obscure the true impact of systematics on the correlation functions.

TABLE B.3: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. The table estimates the range of absolute error influence on the peak from the highest to the lowest multiplicity class.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+p $\bar{p}$	p $\bar{p}$
Track selection	[1.7–2.5]%	[1.9–1.1]%	[2.8–6.3]%	[0.3–0.3]%	[5.9–6.9]%	[3.9–3.5]%
Event mixing	[0.05–0.05]%	[0.09–0.25]%	[0.6–1.4]%	[0.1–0.2]%	[0.5–1]%	[0.25–0.7]%
Pile up rejection	[0.05–0.07]%	[0.09–0.3]%	[0.55–2.0]%	[0.06–0.2]%	[0.4–1.6]%	[0.16–0.6]%
PID method	[6.5–8.5]%	[9.6–11]%	[11.5–15.4]%	[5.1–6.3]%	[14.1–10.4]%	[8.7–7.9]%
Data comparison	[1.6–1.9]%	[4.5–17]%	[10–35]%	[2.6–5.1]%	[11.5–32]%	[4.5–12.1]%
MC closure test	[1.1–1.4]%	[1.3–5.9]%	[7.7–35]%	[0.8–4.5]%	[10.2–18]%	[4.9–10]%

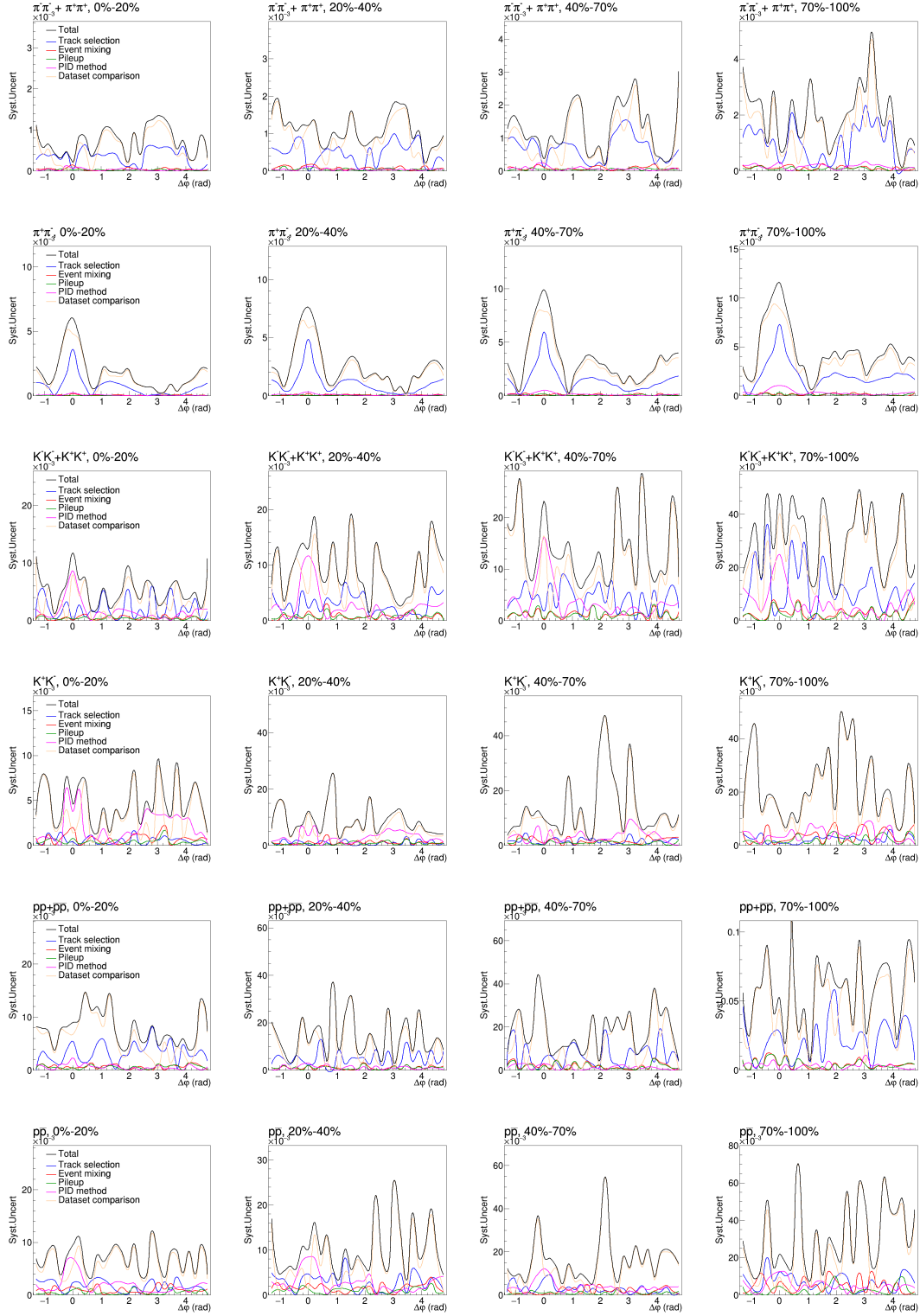


FIGURE B.1: Systematic uncertainties for like- and unlike-sign pairs across four multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV using the probability ratio definition. Each variation is color-coded, with the black solid line representing the final combined uncertainties.

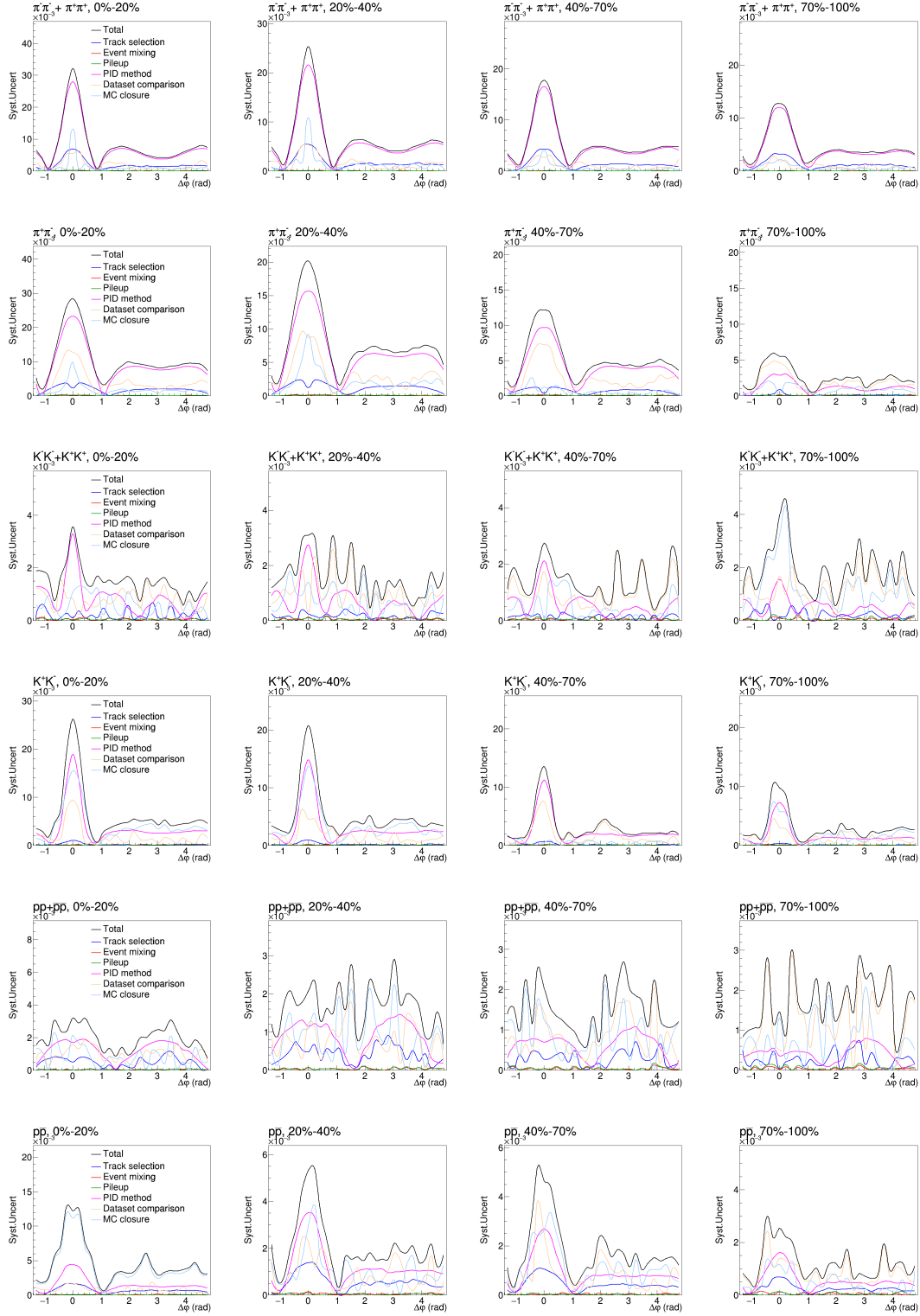


FIGURE B.2: Systematic uncertainties for like- and unlike-sign pairs across four multiplicity classes in pp collisions at $\sqrt{s} = 13$ TeV using the rescaled two-particle correlation function definition. Each variation is color-coded, with the black solid line representing the final combined uncertainties.

B.1.2 Systematic Analysis Across Thirteen Multiplicity Classes

Using the same method applied in the analysis of four multiplicity classes, the systematic uncertainties for the thirteen multiplicity classes were estimated. The estimation utilized the relative error for the probability ratio definition and the absolute error for the rescaled two-particle correlation function definition.

Figure B.3 presents the total uncertainties calculated using the probability ratio definition for all particle pairs for the highest (0–0.17%), the middle (20–30%, 60–70%) and lowest (90–100%) multiplicity classes. The uncertainties are predominantly influenced by statistical fluctuations, particularly for kaons and protons in both like-sign and unlike-sign pairs. For pions with like-sign pairs, the uncertainties exhibit a distinct shape. However, none of the variations across particle types and multiplicity classes passed the Barlow test. Consequently, all variations were included in the total systematic uncertainty. These results are presented in Tab. B.4, which reports the values for the highest multiplicity class (HM–[0–0.17%]) and the lowest multiplicity class (90–100%) for each variation included in the final uncertainty. This table corroborates the observations from the figure. Specifically, the largest contributions to the uncertainties arise from track selection and dataset comparison, especially for kaons and protons. Despite this, the plots clearly show that these systematic contributions are combined with statistical uncertainties, ensuring no additional concerns.

TABLE B.4: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the probability ratio definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+ \pi^+ + \pi^- \pi^-$	$\pi^+ \pi^-$	$K^+ K^+ + K^- K^-$	$K^+ K^-$	pp+pp̄	p̄p̄
Track selection	[0.02–0.55]%	[0.05–0.9]%	[0.02–3.25]%	[0.02–2.1]%	[0.05–5.1]%	[0.1–1.45]%
Event mixing	[0.0007–0.025]%	[0.0008–0.02]%	[0.01–0.6]%	[0.01–1.05]%	[0.02–0.73]%	[0.02–1.65]%
Pileup rejection	[0.0006–0.02]%	[0.0006–0.03]%	[0.009–0.65]%	[0.009–0.67]%	[0.02–1.1]%	[0.02–1.1]%
PID method	[0.007–0.01]%	[0.017–0.02]%	[0.02–0.4]%	[0.02–0.5]%	[0.04–0.9]%	[0.1–0.6]%
Data comparison	[0.014–0.17]%	[0.03–0.3]%	[0.09–6.9]%	[0.15–5.6]%	[0.2–14.8]%	[0.2–7.4]%

Figure B.4 shows the systematic uncertainties for all particle species for the highest (0–0.17%), the middle (20–30%, 60–70%) and lowest (90–100%) multiplicity classes, obtained using the rescaled two-particle correlation function. Unlike the previous definition, the systematic uncertainties here exhibit well-defined shapes, except like-sign kaons. Table B.5 summarizes the absolute error values for each variation, focusing on the High Multiplicity (0–0.17%) and 90–100% classes. The PID method emerges as the

dominant contributor to the uncertainties, while all other sources contribute comparatively smaller errors. Additional insights are provided in Table B.6, which compares

TABLE B.5: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
Track selection	[0.1–0.26]	[0.12–0.3]	[0.01–0.05]	[0.06–0.05]	[0.02–0.05]	[0.03–0.024]
Event mixing	[0.003–0.016]	[0.003–0.015]	[0.006–0.04]	[0.006–0.03]	[0.005–0.04]	[0.0026–0.025]
Pileup rejection	[0.003–0.016]	[0.003–0.015]	[0.006–0.04]	[0.006–0.03]	[0.005–0.04]	[0.002–0.022]
PID method	[1–0.65]	[1.3–0.12]	[0.09–0.07]	[0.5–0.22]	[0.2–0.07]	[0.2–0.06]
Data comparison	[0.015–0.056]	[0.03–0.08]	[0.02–0.12]	[0.04–0.13]	[0.02–0.15]	[0.015–0.07]

the systematic uncertainties to the maximum value of the correlation function. It is observed that, for like-sign kaons, fluctuations contribute more significantly, resulting in higher values. However, these values are not a concern, as they are convoluted with statistical errors. For other particles, a clear trend is evident: as the analysis moves to lower multiplicity classes, the percentage error increases. The PID method remains the primary contributor to these uncertainties, as previously confirmed by Table B.5 and illustrated in the corresponding Fig. B.4.

TABLE B.6: Influence of the systematic uncertainties on the maximum of the correlation functions performed for all pairs of particles involved and for the thirteen multiplicity classes selected using the rescaled two-particle correlation function definition from pp collision data at $\sqrt{s} = 13$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
Track selection	[0.76–3.6]%	[0.8–28.7]%	[1.2–9.7]%	[0.5–1.2]%	[1.7–7.8]%	[1.3–2.6]%
Event mixing	[0.017–0.2]%	[0.018–1.4]%	[0.6–6.7]%	[0.06–0.8]%	[0.45–5.7]%	[0.12–2.7]%
Pileup rejection	[0.02–0.2]%	[0.019–1.4]%	[0.6–6.6]%	[0.055–0.7]%	[0.45–6.1]%	[0.11–2.4]%
PID method	[6–8.8]%	[8.75–11.3]%	[9.15–12.3]%	[4.7–5.7]%	[16.2–10.9]%	[9.1–7]%
Data comparison	[0.09–0.77]%	[0.19–7.9]%	[1.8–22.7]%	[0.38–3.5]%	[1.6–22.7]%	[0.7–8]%

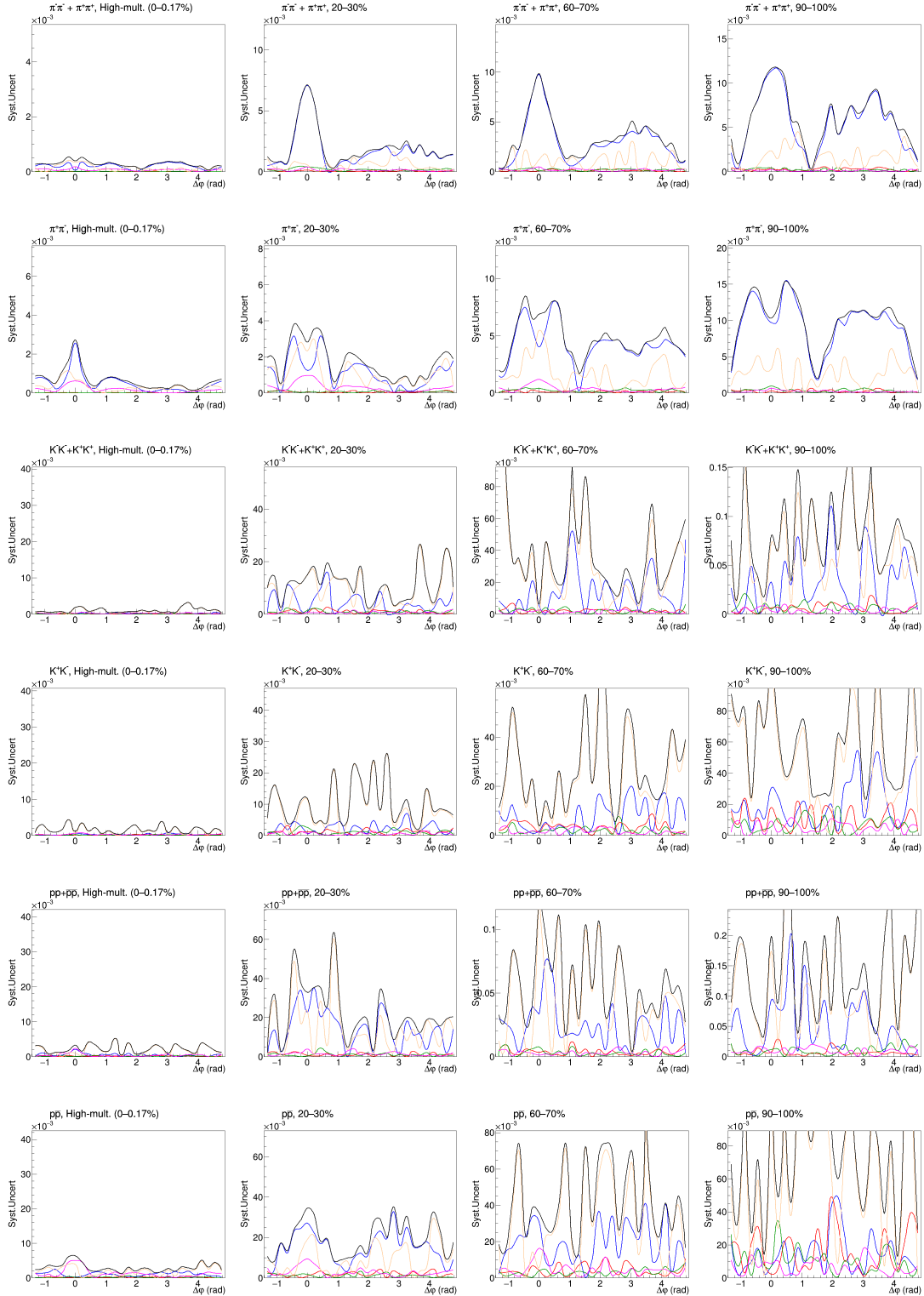


FIGURE B.3: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs for the (0–0.17%), (20–30%), (60–70%), and (90–100%) multiplicity classes, using the probability ratio definition from pp collision at $\sqrt{s} = 13$ TeV. Each variation is color-coded, with the black solid line indicating the final combined uncertainties.

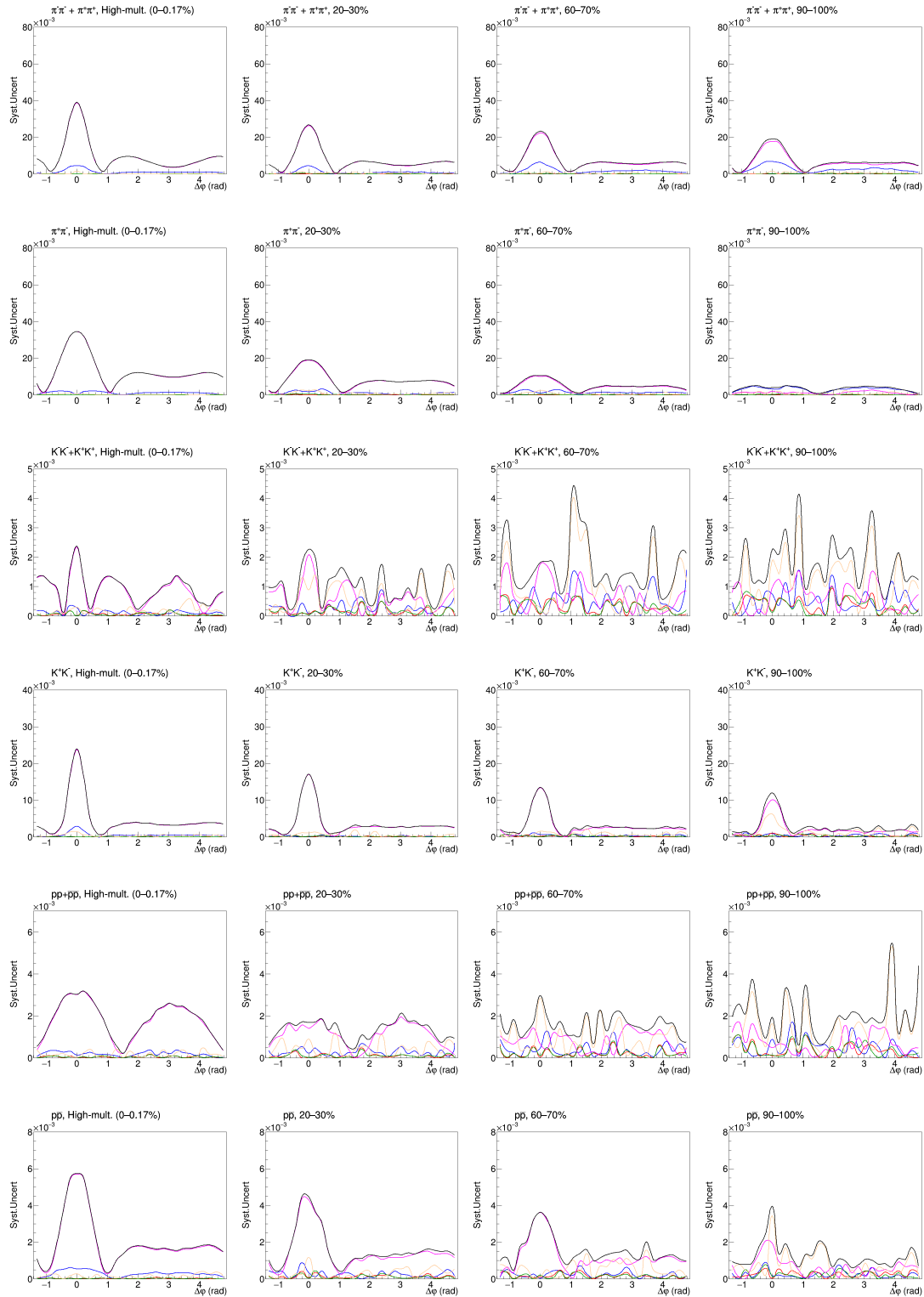


FIGURE B.4: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs for the (0–0.17%), (20–30%), (60–70%), and (90–100%) multiplicity classes, using the rescaled two-particle correlation function definition from pp collision at $\sqrt{s} = 13$ TeV. Each variation is color-coded, with the black solid line indicating the final combined uncertainties.

B.2 Systematic uncertainties in p–Pb collision

Following the same approach applied in the pp analysis, systematic variations were calculated for the p–Pb analysis. Based on the results obtained from the Barlow method to evaluate all possible variations, only four were considered significant for the final uncertainty estimation, as detailed below:

- *Event Mixing*: The number of bins was varied from the default 30 bins to 10 bins as a systematic check.
- *Pileup Dependence*: The impact of pileup was assessed by comparing results with and without pileup event rejection.
- *Track Selection*: Criteria for selecting particle pairs were varied by tightening the default cuts on DCA , which are described in Sec. 7.3, specifically to $DCA_{xy} < 2$ cm and $DCA_z < 2.6$ cm.
- *PID Method*: The default particle identification method was compared with an alternative approach where tracks identified as belonging to more than one particle species were excluded, removing particles within a 2σ range.

By using the probability ratio definition, as illustrated in Fig. B.5, all particle pairs, except for the like-sign kaons, exhibit a distinct shape. For like-sign kaons, however, the systematic uncertainties are minimal and largely masked by statistical fluctuations. This is reflected also in the numerical values summarized in Tab. B.7.

TABLE B.7: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the probability ratio definition from p–Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
Track selection	[0.05–0.2]%	[0.1–0.5]%	[0.2–1.1]%	[0.15–0.8]%	[1.0–2.7]%	[1.4–3.3]%
Event mixing	[0.009–0.03]%	[0.009–0.03]%	[0.2–1.0]%	[0.04–0.6]%	[0.2–1.5]%	[0.1–0.7]%
Pileup rejection	[0.008–0.03]%	[0.008–0.02]%	[0.2–1.1]%	[0.045–0.3]%	[0.2–1.5]%	[0.09–0.8]%
PID method	[0.03–0.09]%	[0.1–0.2]%	[0.2–1.1]%	[0.15–0.5]%	[0.3–2.2]%	[0.2–1.2]%

Figure B.6 illustrates the systematic uncertainties associated with the rescaled two-particle correlation function. For each source of variation, the uncertainties are expressed as absolute errors, given that the correlation functions approach saturation

near zero. The uncertainties exhibit a clear and consistent pattern, similar to those observed in the probability ratio definition. For like-sign kaons, a significant influence of statistical fluctuations is observed, which corresponds to the large systematic uncertainty values listed in Tables B.8 and B.9. Table B.8 provides the absolute errors, while Table B.9 summarizes the total error's impact on the maximum of the correlation functions. Notably, for like-sign kaons, the dominant contributions to the uncertainty arise from the PID method and track selection. However, as shown in the figure, these effects are largely overshadowed by statistical fluctuations.

TABLE B.8: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, for each variation listed, the range of uncertainties from the highest to the lowest multiplicity class is calculated as the average over all the bins.

	$\pi^+ \pi^+ + \pi^- \pi^-$	$\pi^+ \pi^-$	$K^+ K^+ + K^- K^-$	$K^+ K^-$	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
Track selection	[0.1–0.09]	[0.2–0.15]	[0.2–0.07]	[0.9–0.4]	[0.1–0.03]	[0.04–0.04]
Event mixing	[0.02–0.01]	[0.01–0.01]	[0.06–0.04]	[0.3–0.1]	[0.02–0.02]	[0.01–0.01]
Pileup variation	[0.02–0.01]	[0.006–0.007]	[0.05–0.03]	[0.2–0.07]	[0.02–0.02]	[0.01–0.02]
PID method	[0.4–0.2]	[0.45–0.1]	[0.1–0.05]	[0.4–0.2]	[0.07–0.04]	[0.07–0.03]

TABLE B.9: Summary of all systematic uncertainties studies performed for all pairs of particles involved and for all multiplicity classes using the rescaled two-particle correlation function definition from p–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In the table, the range of absolute error influence on the peak is estimated from the highest to the lowest multiplicity class.

	$\pi^+ \pi^+ + \pi^- \pi^-$	$\pi^+ \pi^-$	$K^+ K^+ + K^- K^-$	$K^+ K^-$	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
Track selection	[0.7–1.5]%	[1.9–4.5]%	[21–27]%	[9.9–10.2]%	[7.6–6.25]%	[2.2–3.9]%
Event mixing	[0.1–0.2]%	[0.09–0.3]%	[7.6–14]%	[3.3–3.6]%	[1.8–5.1]%	[0.7–1.4]%
Pileup variation	[0.1–0.2]%	[0.05–0.2]%	[5.6–12.5]%	[1.9–2]%	[1.6–5.1]%	[0.7–1.6]%
PID method	[2.6–3.5]%	[3.5–3.2]%	[12.9–20]%	[4.9–5.9]%	[5.9–7.9]%	[4.1–3.2]%

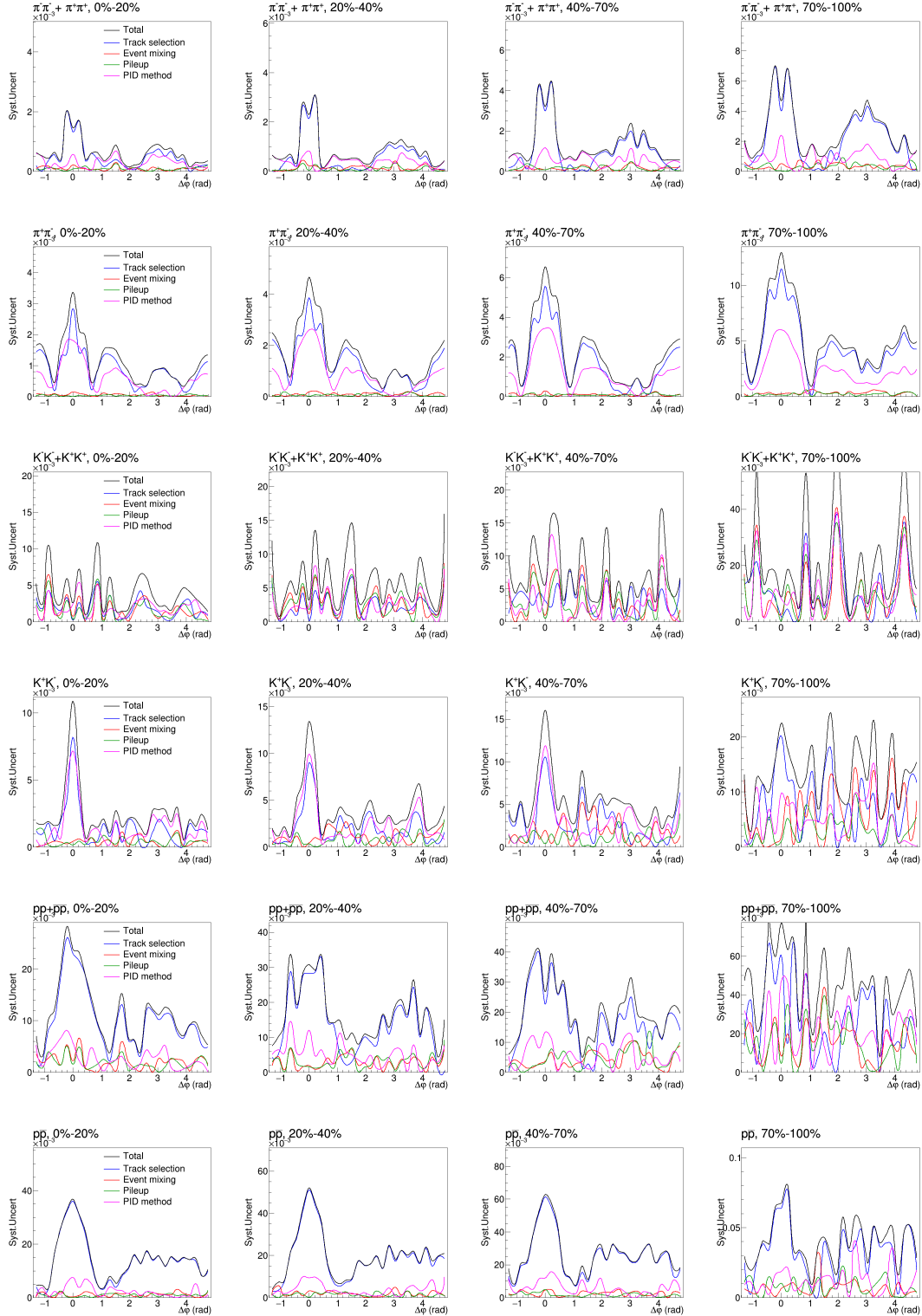


FIGURE B.5: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the four selected multiplicity classes using the probability ratio definition from p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. Each variation is color-coded, and the black solid line indicates the final combined uncertainties.

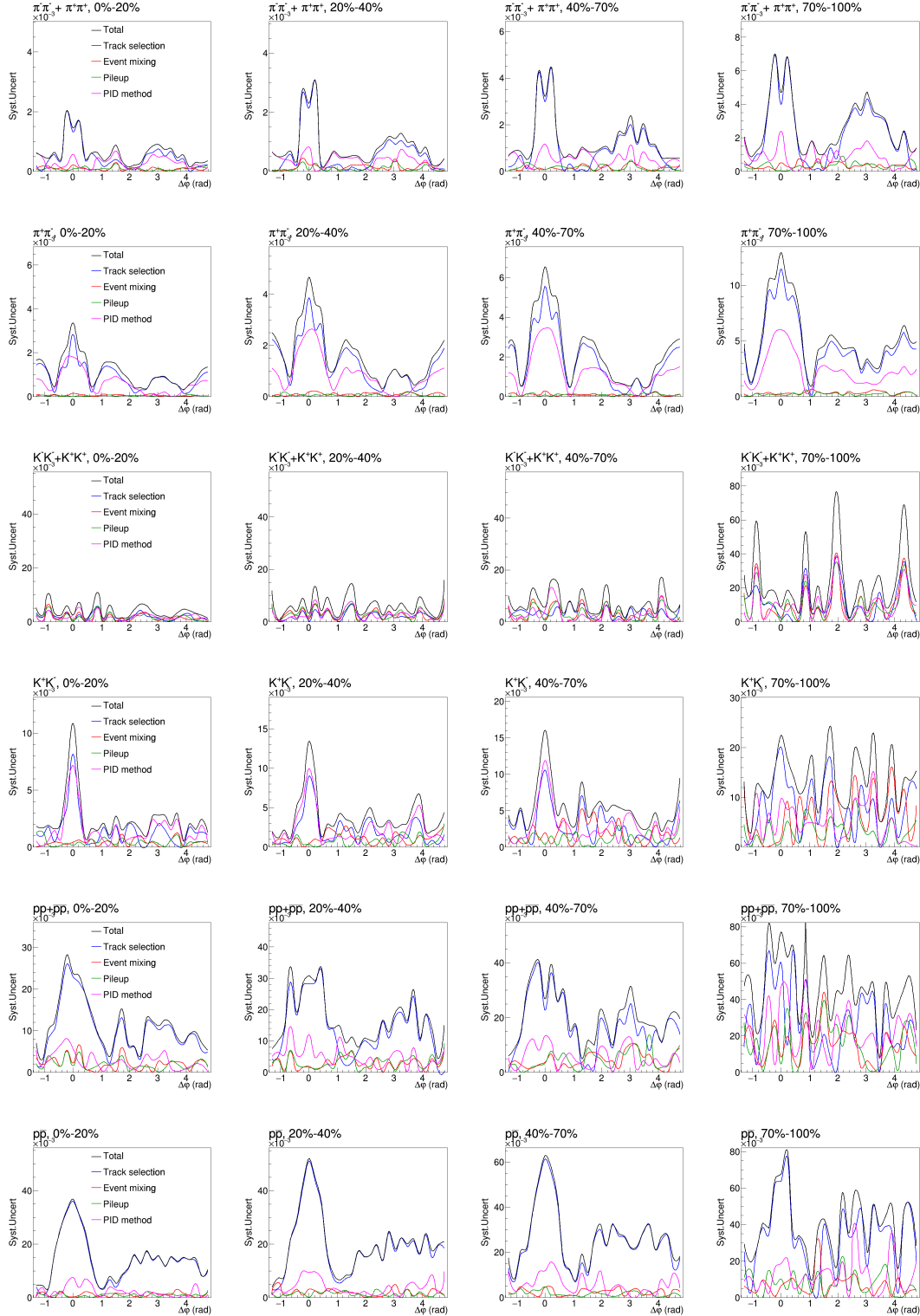


FIGURE B.6: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the four selected multiplicity classes using the rescaled two-particle correlation function definition from p-Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. Each variation is color-coded, and the black solid line indicates the final combined uncertainties.

B.3 Systematic uncertainties in Pb–Pb collision

From Pb–Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, the following systematic variations, which satisfied the Barlow criteria, were considered for the final uncertainties:

- *Pileup dependence*: The influence of pileup was evaluated by comparing results with and without pileup rejection;
- *PID method*: The default PID method was compared with an alternative approach that excluded tracks identified as belonging to multiple particle species, specifically removing particles within a 2σ overlap range;
- *Two-track cuts variation*: To evaluate the impact of two-track selection criteria, the analysis was repeated using looser parameters: $\Delta\eta = 0.02$ cm and $\Delta\varphi^* = 0.1$ rad;
- *Track selection*: The default track selection (see Sec 7.3), using ITS and TPC data with strict DCA cuts, was compared to a "hybrid" method designed to correct non-uniform φ acceptance caused by the ITS. To address acceptance gaps (see Fig. 7.1), TPC-only tracks were added to the ITS+TPC tracks, creating a hybrid sample. This approach applied looser DCA cuts ($DCA_{xy} < 2.4$ cm, $DCA_z < 3.2$ cm), increasing contamination from secondary particles.
- *Event mixing*: To study the influence of event mixing criteria, comparisons were made between z-vertex binning intervals of 2 cm and intervals of double this width;
- *DCA variation*: Correlation functions with the default DCA values were compared to those calculated with stricter, p_T -independent DCA cuts of 0.1 cm in the xy-plane and 1 cm along the z-axis;
- *Z-vertex position*: The event selection criterion requiring the z-vertex to be within 10 cm of the TPC center was varied to 7 cm to assess its impact;

Figure B.7 shows the systematic uncertainties estimated using the probability ratio definition, in which all variations exhibit minimal differences without significant systematic shifts, with the uncertainties primarily masked by statistical fluctuations. Table B.10 presents the systematic uncertainties for all particle species across centrality classes. For like- and unlike-sign pions, uncertainties remain small across all centralities. In contrast, kaons and protons show systematic uncertainties approaching 2% in

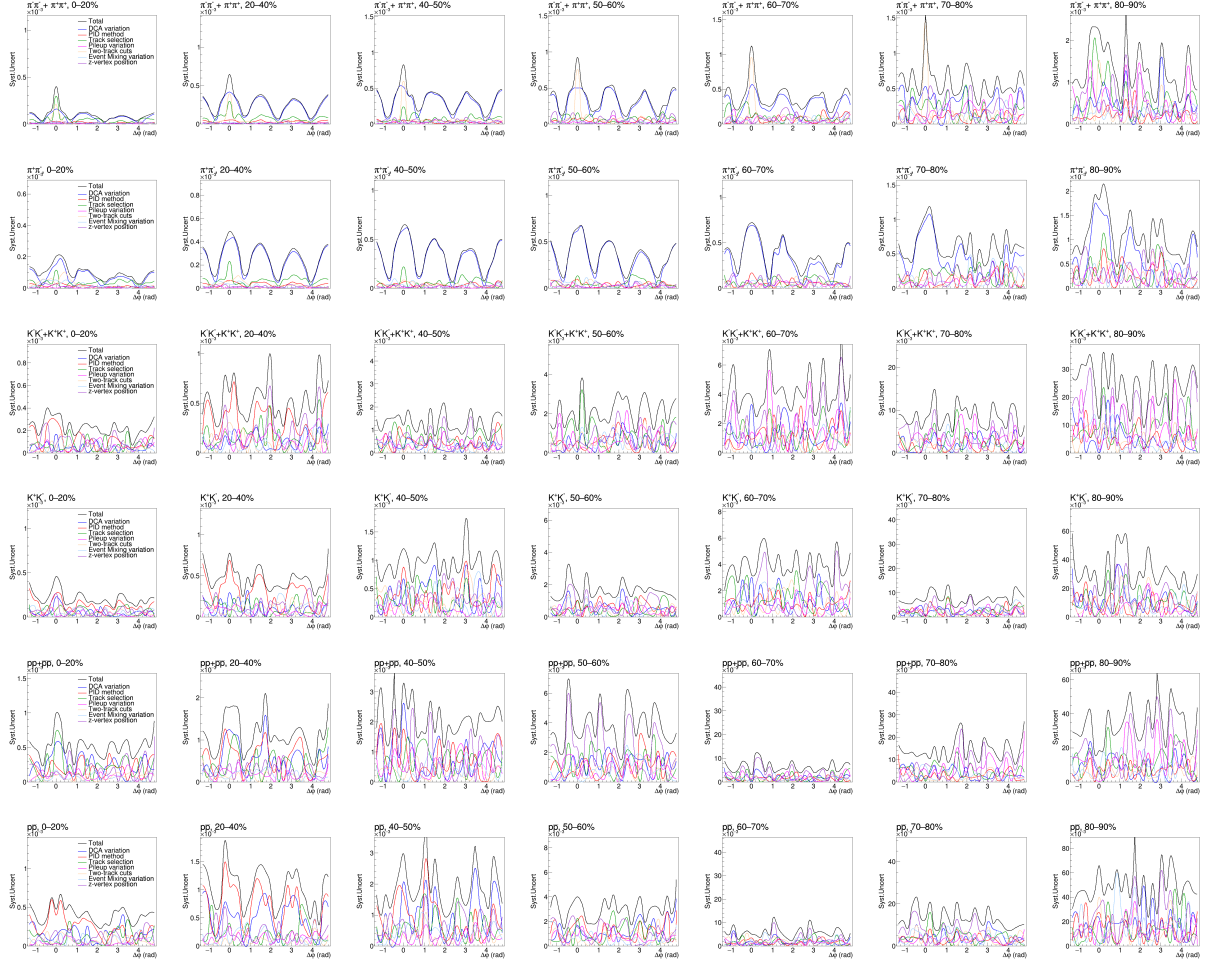


FIGURE B.7: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the selected centrality classes, based on the probability ratio definition from Pb–Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV. Each variation is calculated using the relative error R_r and is represented by a different color, with the black solid line indicating the final combined uncertainties.

the lowest centrality classes. However, as shown in Fig.B.7, most of these uncertainties are largely obscured by statistical fluctuations.

Using the rescaled two-particle cumulant, in Fig. B.8, a distinctive shape becomes more apparent, particularly for like- and unlike-sign pion pairs, following the same behavior as observed by using probability ratio definition. For other particle species, systematic uncertainties are minimal and primarily overshadowed by statistical fluctuations. Table B.11 presents the absolute errors for each variation in the highest and

TABLE B.10: Summary of all systematic uncertainties studies performed for all particle pairs using the probability ratio definition from Pb–Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV. In the table, the range of uncertainties for the highest and the lowest multiplicity classes is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
DCA variation	[0.007–0.045]%	[0.007–0.06]%	[0.005–0.55]%	[0.005–1.1]%	[0.025–0.8]%	[0.05–1.7]%
PID method	[0.001–0.02]%	[0.001–0.025]%	[0.01–0.5]%	[0.01–0.9]%	[0.02–0.7]%	[0.07–1.35]%
Track selection	[0.005–0.06]%	[0.003–0.03]%	[0.007–0.85]%	[0.0065–1.2]%	[0.02–1.2]%	[0.02–1.25]%
Pileup variation	[0.0003–0.05]%	[0.0003–0.02]%	[0.005–0.9]%	[0.0035–0.6]%	[0.009–1.4]%	[0.01–1.1]%
Two-track cuts	[0.002–0.03]%	[0.002–0.025]%	[0.004–0.5]%	[0.004–0.9]%	[0.007–0.6]%	[0.01–1.2]%
Event mixing	[0.0006–0.03]%	[0.002–0.03]%	[0.004–0.5]%	[0.005–1]%	[0.006–0.7]%	[0.01–1.65]%
Z-vertex position	[0.009–0.05]%	[0.001–0.03]%	[0.01–1.4]%	[0.006–1.3]%	[0.02–1.8]%	[0.02–2.1]%

TABLE B.11: Summary of all systematic uncertainties studies performed for all particle pairs using the rescaled two-particle correlation function from Pb–Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV. In the table, the range of uncertainties for the highest and the lowest multiplicity classes is shown.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
DCA variation	[0.6–0.05]	[0.6–0.06]	[0.1–0.06]	[0.15–0.1]	[0.2–0.05]	[0.15–0.1]
PID method	[0.2–0.03]	[0.2–0.035]	[0.2–0.06]	[0.26–0.1]	[0.1–0.05]	[0.12–0.1]
Track selection	[1.5–0.09]	[1.5–0.1]	[0.2–0.1]	[0.2–0.1]	[0.1–0.08]	[0.1–0.08]
Pileup variation	[0.025–0.07]	[0.03–0.065]	[0.2–0.1]	[0.04–0.08]	[0.04–0.1]	[0.02–0.07]
Two-track cuts variation	[0.15–0.03]	[0.2–0.03]	[0.04–0.05]	[0.045–0.1]	[0.03–0.04]	[0.03–0.07]
Event Mixing	[0.05–0.03]	[0.2–0.03]	[0.045–0.05]	[0.06–0.1]	[0.02–0.05]	[0.03–0.1]
Z-vertex	[0.07–0.05]	[0.07–0.04]	[0.1–0.15]	[0.006–0.15]	[0.07–0.1]	[0.04–0.1]

lowest centrality classes. While the values are very small, their influence on the correlation functions provides more meaningful insights. These impacts are detailed in Table B.12, which reports the effect of each systematic variation on the maximum of the correlation function, focusing on absolute errors in the highest and lowest centrality classes. In general, it can be seen that moving to lower centralities the absolute error

TABLE B.12: Summary of all uncertainties for all particle pairs using the rescaled two-particle correlation function. The table shows the range of values indicating each uncertainty's impact on the correlation function maximum, for the highest and the lowest centrality classes.

	$\pi^+\pi^+ + \pi^-\pi^-$	$\pi^+\pi^-$	$K^+K^+ + K^-K^-$	K^+K^-	pp+ $\bar{p}\bar{p}$	p $\bar{p}$
DCA variation	[1.1–0.5]%	[1–0.9]%	[1.3–7.6]%	[1–2.4]%	[7.8–4.1]%	[6–9]%
PID method	[0.3–0.3]%	[0.3–0.5]%	[2.4–7.8]%	[1.9–1.9]%	[4.6–3.6]%	[4.8–6.5]%
Track selection	[2.7–0.9]%	[2.3–1.7]%	[2–11.6]%	[1.6–2.1]%	[4.9–6.1]%	[3.5–5.9]%
Pileup variation	[0.04–0.7]%	[0.05–0.9]%	[0.6–11.9]%	[0.3–1.4]%	[1.7–7.2]%	[0.7–5]%
Two-track cuts variation	[0.3–0.35]%	[0.3–0.4]%	[0.5–6.8]%	[0.3–1.7]%	[1.3–3.1]%	[1–5.6]%
Event Mixing	[0.09–0.3]%	[0.2–0.4]%	[0.5–6.5]%	[0.4–1.9]%	[1.15–3.7]%	[1.3–7.5]%
Z-vertex	[0.1–0.6]%	[0.1–0.5]%	[1.1–19.4]%	[0.45–2.6]%	[3.4–9.2]%	[1.5–9.9]%

for the z-vertex makes a large contribution, but as can be seen from the plots in Fig. B.8

the error is covered by the statistical fluctuation, particularly for kaons and protons. For the general uncertainties estimated for protons, a large contribution is seen due to the lack of statistics.

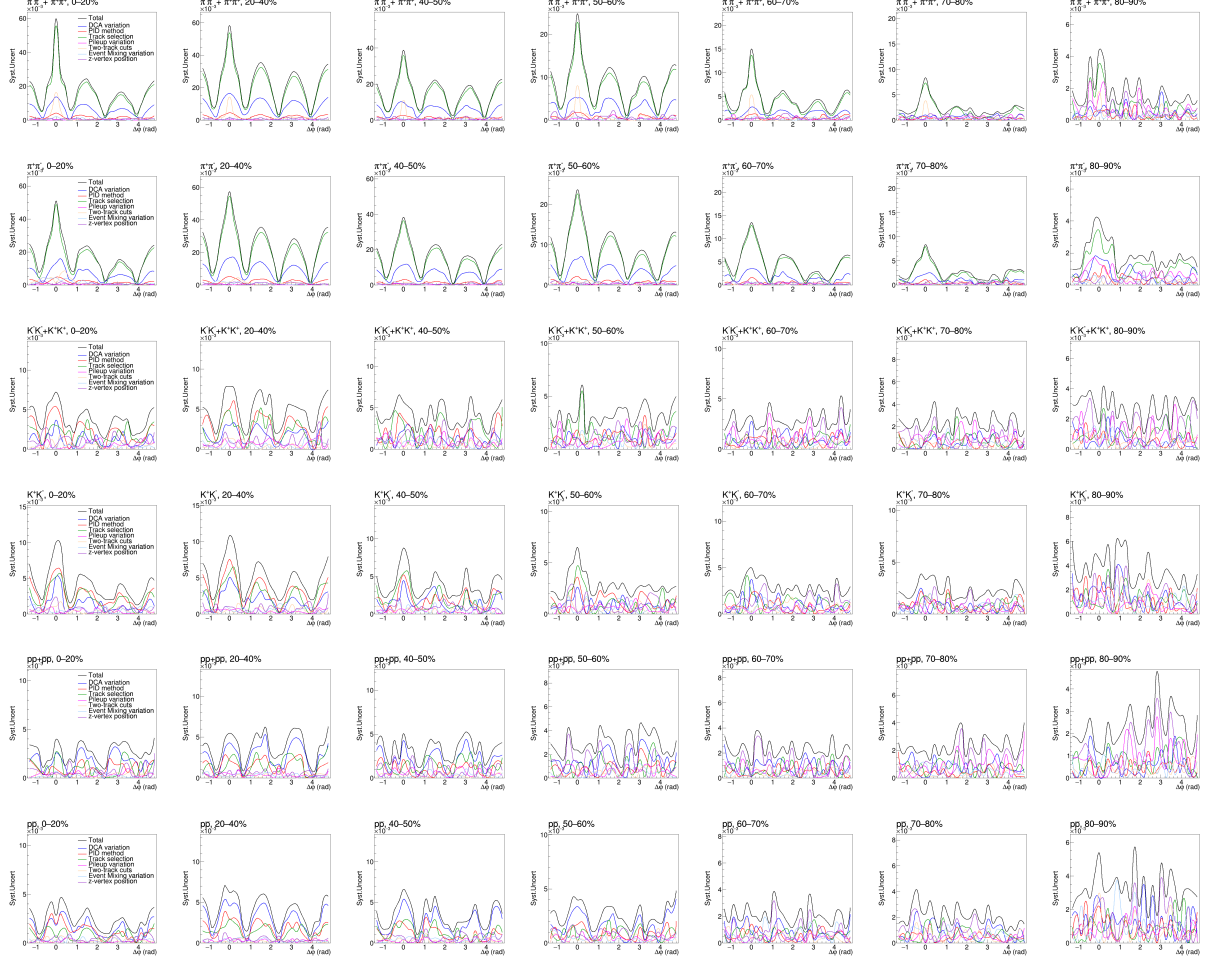


FIGURE B.8: Systematic uncertainties estimated for like-sign and unlike-sign particle pairs across the selected centrality classes, based on the rescaled two-particle correlation function from Pb–Pb collision at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Each variation is calculated using the relative error R_t and is represented by a different color, with the black solid line indicating the final combined uncertainties.

Bibliography

- [1] CERN. *The Matter-Antimatter Asymmetry Problem*. URL: <https://home.cern/science/physics/matter-antimatter-asymmetry-problem>.
- [2] R. D. Field and R. P. Feynman. “A Parametrization of the Properties of Quark Jets”. In: *Nucl. Phys. B* 136 (1978). Ed. by L. M. Brown, p. 1. DOI: 10.1016/0550-3213(78)90015-9.
- [3] H. Aihara et al. “Study of Baryon Correlations in e^+e^- Annihilation at 29 GeV”. In: *Phys. Rev. Lett.* 57 (25 1986), pp. 3140–3143. DOI: 10.1103/PhysRevLett.57.3140. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.57.3140>.
- [4] J. Adam et al. “Insight into particle production mechanisms via angular correlations of identified particles in pp collisions at $\sqrt{s} = 7$ TeV”. In: *The European Physical Journal C* 77.8 (Aug. 2017). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-017-5129-6. URL: <http://dx.doi.org/10.1140/epjc/s10052-017-5129-6>.
- [5] Wikipedia. *Standard Model*. URL: https://en.wikipedia.org/wiki/Standard_Model.
- [6] CERN. *The Higgs boson*. URL: <https://home.cern/science/physics/higgs-boson>.
- [7] Wikipedia. *Higgs boson*. URL: https://en.wikipedia.org/wiki/Higgs_boson.
- [8] CERN. *ATLAS sets record precision on Higgs boson’s mass*. July 2023. URL: <https://home.cern/news/news/physics/atlas-sets-record-precision-higgs-bosons-mass>.
- [9] CERN. *CMS precisely measures the mass of the Higgs boson*. January 2022. URL: <https://cms.cern/news/cms-precisely-measures-mass-higgs-boson>.
- [10] H. Fritzsch, Murray Gell-Mann, and H. Leutwyler. “Advantages of the Color Octet Gluon Picture”. In: *Phys. Lett. B* 47 (1973), pp. 365–368. DOI: 10.1016/0370-2693(73)90625-4.

- [11] O. W. Greenberg. “Spin and Unitary-Spin Independence in a Paraquark Model of Baryons and Mesons”. In: *Phys. Rev. Lett.* 13 (20 1964), pp. 598–602. DOI: 10.1103/PhysRevLett.13.598. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.598>.
- [12] M. Y. Han and Y. Nambu. “Three-Triplet Model with Double SU(3) Symmetry”. In: *Phys. Rev.* 139 (4B 1965), B1006–B1010. DOI: 10.1103/PhysRev.139.B1006. URL: <https://link.aps.org/doi/10.1103/PhysRev.139.B1006>.
- [13] Jean Letessier and Johann Rafelski. *Hadrons and Quark–Gluon Plasma*. Oxford University Press, 2002. ISBN: 978-1-009-29075-3, 978-0-511-53499-7, 978-1-009-29070-8, 978-1-009-29073-9. DOI: 10.1017/9781009290753.
- [14] Jerzy Bartke. *Introduction to relativistic heavy ion physics*. 2009.
- [15] M. Göckeler et al. “Determination of the Lambda parameter from full lattice QCD”. In: *Phys. Rev. D* 73 (1 2006), p. 014513. DOI: 10.1103/PhysRevD.73.014513. URL: <https://link.aps.org/doi/10.1103/PhysRevD.73.014513>.
- [16] Michiel Botje Lectures. *Lecture notes Particle Physics II, Asymptotic Freedom*. URL: <https://www.nikhef.nl/~h24/qcdcourse/section-6.pdf>.
- [17] Kenneth G. Wilson. “Confinement of quarks”. In: *Phys. Rev. D* 10 (8 1974), pp. 2445–2459. DOI: 10.1103/PhysRevD.10.2445. URL: <https://link.aps.org/doi/10.1103/PhysRevD.10.2445>.
- [18] G. ’t Hooft. “On the phase transition towards permanent quark confinement”. In: *Nuclear Physics B* 138.1 (1978), pp. 1–25. ISSN: 0550-3213. DOI: [https://doi.org/10.1016/0550-3213\(78\)90153-0](https://doi.org/10.1016/0550-3213(78)90153-0). URL: <https://www.sciencedirect.com/science/article/pii/0550321378901530>.
- [19] G. ’t Hooft. “Topology of the gauge condition and new confinement phases in non-abelian gauge theories”. In: *Nuclear Physics B* 190.3 (1981), pp. 455–478. ISSN: 0550-3213. DOI: [https://doi.org/10.1016/0550-3213\(81\)90442-9](https://doi.org/10.1016/0550-3213(81)90442-9). URL: <https://www.sciencedirect.com/science/article/pii/0550321381904429>.
- [20] David J. Gross and Frank Wilczek. “Ultraviolet Behavior of Non-Abelian Gauge Theories”. In: *Phys. Rev. Lett.* 30 (26 1973), pp. 1343–1346. DOI: 10.1103/PhysRevLett.30.1343. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.30.1343>.

- [21] David J. Gross and Frank Wilczek. “Asymptotically Free Gauge Theories. I”. In: *Phys. Rev. D* 8 (10 1973), pp. 3633–3652. DOI: 10.1103/PhysRevD.8.3633. URL: <https://link.aps.org/doi/10.1103/PhysRevD.8.3633>.
- [22] H. David Politzer. “Reliable Perturbative Results for Strong Interactions?” In: *Phys. Rev. Lett.* 30 (26 1973), pp. 1346–1349. DOI: 10.1103/PhysRevLett.30.1346. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.30.1346>.
- [23] John Collins. *Foundations of Perturbative QCD*. Vol. 32. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, July 2023. ISBN: 978-1-009-40184-5, 978-1-009-40183-8, 978-1-009-40182-1. DOI: 10.1017/9781009401845.
- [24] H. H. Dalsgaard. “Pseudorapidity Densities in p+p and Pb+Pb collisions at LHC measured with the ALICE experiment”. PhD thesis. CERN-THESIS-2011-241.
- [25] F. Karsch. “Lattice results on QCD thermodynamics”. In: *Nuclear Physics A* 698.1–4 (Feb. 2002), 199–208. ISSN: 0375-9474. DOI: 10.1016/S0375-9474(01)01365-3. URL: [http://dx.doi.org/10.1016/S0375-9474\(01\)01365-3](http://dx.doi.org/10.1016/S0375-9474(01)01365-3).
- [26] Takafumi Niida and Yasuo Miake. *Signatures of QGP at RHIC and the LHC*. 2021. arXiv: 2104.11406 [nucl-ex]. URL: <https://arxiv.org/abs/2104.11406>.
- [27] S. Acharya et al. “The ALICE experiment: a journey through QCD”. In: *The European Physical Journal C* 84.8 (Aug. 2024). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-024-12935-y. URL: <http://dx.doi.org/10.1140/epjc/s10052-024-12935-y>.
- [28] Roel Aaij et al. “Centrality determination in heavy-ion collisions with the LHCb detector”. In: *JINST* 17.05 (2022), P05009. DOI: 10.1088/1748-0221/17/05/P05009. arXiv: 2111.01607 [nucl-ex].
- [29] Michael L. Miller et al. “Glauber Modeling in High-Energy Nuclear Collisions”. In: *Annual Review of Nuclear and Particle Science* 57.1 (Nov. 2007), 205–243. ISSN: 1545-4134. DOI: 10.1146/annurev.nucl.57.090506.123020. URL: <http://dx.doi.org/10.1146/annurev.nucl.57.090506.123020>.
- [30] Wikipedia. *Perfect fluid*. URL: https://en.wikipedia.org/wiki/Perfect_fluid.

- [31] Peter Braun-Munzinger, Krzysztof Redlich, and Johanna Stachel. “Particle production in heavy-ion collisions”. In: *Quark–Gluon Plasma 3*. World scientific, Jan. 2004, 491–599. ISBN: 9789812795533. DOI: 10.1142/9789812795533_0008. URL: http://dx.doi.org/10.1142/9789812795533_0008.
- [32] David Dobrigkeit Chinellato. “Highlights from the ALICE collaboration”. In: *PoS ICHEP2020* (2021), p. 014. DOI: 10.22323/1.390.0014.
- [33] S. Voloshin and Y. Zhang. “Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions”. In: *Zeitschrift für Physik C Particles and Fields* 70.4 (May 1996), 665–671. ISSN: 1431-5858. DOI: 10.1007/s002880050141. URL: <http://dx.doi.org/10.1007/s002880050141>.
- [34] Jean-Yves Ollitrault. “Anisotropy as a signature of transverse collective flow”. In: *Phys. Rev. D* 46 (1 1992), pp. 229–245. DOI: 10.1103/PhysRevD.46.229. URL: <https://link.aps.org/doi/10.1103/PhysRevD.46.229>.
- [35] Guang-You Qin et al. “Translation of collision geometry fluctuations into momentum anisotropies in relativistic heavy-ion collisions”. In: *Physical Review C* 82.6 (Dec. 2010). ISSN: 1089-490X. DOI: 10.1103/physrevc.82.064903. URL: <http://dx.doi.org/10.1103/PhysRevC.82.064903>.
- [36] J.Jia. *ATLAS v_n results*. Quark Matter 2011, plenary talk.
- [37] A. M. Poskanzer and S. A. Voloshin. “Methods for analyzing anisotropic flow in relativistic nuclear collisions”. In: *Physical Review C* 58.3 (Sept. 1998), 1671–1678. ISSN: 1089-490X. DOI: 10.1103/physrevc.58.1671. URL: <http://dx.doi.org/10.1103/PhysRevC.58.1671>.
- [38] Wojciech Florkowski. *Phenomenology of Ultra-Relativistic Heavy-Ion Collisions*. Mar. 2010. ISBN: 978-981-4280-66-2.
- [39] Raimond Snellings. “Elliptic Flow: A Brief Review”. In: *New J. Phys.* 13 (2011), p. 055008. DOI: 10.1088/1367-2630/13/5/055008. arXiv: 1102.3010 [nucl-ex].
- [40] K. H. Ackermann et al. “Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV”. In: *Physical Review Letters* 86.3 (Jan. 2001), 402–407. ISSN: 1079-7114. DOI: 10.1103/physrevlett.86.402. URL: <http://dx.doi.org/10.1103/PhysRevLett.86.402>.
- [41] Jacopo Margutti. “Anisotropic flow and related phenomena in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE”. In: *J. Phys. Conf. Ser.* 832.1 (2017), p. 012049. DOI: 10.1088/1742-6596/832/1/012049.

- [42] C. M. Hung and E. Shuryak. "Equation of state, radial flow, and freeze-out in high energy heavy ion collisions". In: *Physical Review C* 57.4 (Apr. 1998), 1891–1906. ISSN: 1089-490X. DOI: 10.1103/physrevc.57.1891. URL: <http://dx.doi.org/10.1103/PhysRevC.57.1891>.
- [43] P. Huovinen et al. "Radial and elliptic flow at RHIC: further predictions". In: *Physics Letters B* 503.1–2 (Mar. 2001), 58–64. ISSN: 0370-2693. DOI: 10.1016/S0370-2693(01)00219-2. URL: [http://dx.doi.org/10.1016/S0370-2693\(01\)00219-2](http://dx.doi.org/10.1016/S0370-2693(01)00219-2).
- [44] S. S. Adler et al. "Identified charged particle spectra and yields in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV". In: *Physical Review C* 69.3 (Mar. 2004). ISSN: 1089-490X. DOI: 10.1103/physrevc.69.034909. URL: <http://dx.doi.org/10.1103/PhysRevC.69.034909>.
- [45] Vardan Khachatryan et al. "Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC". In: *JHEP* 09 (2010), p. 091. DOI: 10.1007/JHEP09(2010)091. arXiv: 1009.4122 [hep-ex].
- [46] S. Chatrchyan et al. "Observation of long-range, near-side angular correlations in p-Pb collisions at the LHC". In: *Physics Letters B* 718.3 (2013), pp. 795–814. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2012.11.025>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269312011768>.
- [47] Betty Abelev et al. "Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV". In: *Physics Letters B* 719.1 (2013), pp. 29–41. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2013.01.012>. URL: <https://www.sciencedirect.com/science/article/pii/S037026931300035X>.
- [48] B. Abelev et al. "Long-range angular correlations of π , K and p in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV". In: *Physics Letters B* 726.1–3 (Oct. 2013), 164–177. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2013.08.024. URL: <http://dx.doi.org/10.1016/j.physletb.2013.08.024>.
- [49] A. Adare et al. "Measurement of Long-Range Angular Correlation and Quadrupole Anisotropy of Pions and (Anti)Protons in Central $d + Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV". In: *Phys. Rev. Lett.* 114 (19 2015), p. 192301. DOI:

- 10.1103/PhysRevLett.114.192301. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.114.192301>.
- [50] K. Werner, Iu. Karpenko, and T. Pierog. ““Ridge” in Proton-Proton Scattering at 7 TeV”. In: *Phys. Rev. Lett.* 106 (12 2011), p. 122004. DOI: 10.1103/PhysRevLett.106.122004. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.106.122004>.
- [51] K. Werner et al. “Evidence for Flow from Hydrodynamic Simulations of p -Pb Collisions at 5.02 TeV from v_2 Mass Splitting”. In: *Phys. Rev. Lett.* 112 (23 2014), p. 232301. DOI: 10.1103/PhysRevLett.112.232301. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.112.232301>.
- [52] K. Werner et al. “Analyzing radial flow features in p -Pb and p - p collisions at several TeV by studying identified-particle production with the event generator EPOS3”. In: *Phys. Rev. C* 89 (6 2014), p. 064903. DOI: 10.1103/PhysRevC.89.064903. URL: <https://link.aps.org/doi/10.1103/PhysRevC.89.064903>.
- [53] Adam Bzdak and Guo-Liang Ma. “Elliptic and Triangular Flow in p -Pb and Peripheral Pb-Pb Collisions from Parton Scatterings”. In: *Phys. Rev. Lett.* 113 (25 2014), p. 252301. DOI: 10.1103/PhysRevLett.113.252301. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.113.252301>.
- [54] Piotr Bożek, Adam Bzdak, and Guo-Liang Ma. “Rapidity dependence of elliptic and triangular flow in proton-nucleus collisions from collective dynamics”. In: *Physics Letters B* 748 (2015), pp. 301–305. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2015.06.007>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269315004293>.
- [55] B. Abelev et al. “Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE”. In: *Phys. Rev. C* 88 (4 2013), p. 044909. DOI: 10.1103/PhysRevC.88.044909. URL: <https://link.aps.org/doi/10.1103/PhysRevC.88.044909>.
- [56] Yuri V. Kovchegov and Douglas E. Wertepny. “Long-range rapidity correlations in heavy-light ion collisions”. In: *Nuclear Physics A* 906 (2013), pp. 50–83. ISSN: 0375-9474. DOI: <https://doi.org/10.1016/j.nuclphysa.2013.03.006>. URL: <https://www.sciencedirect.com/science/article/pii/S0375947413003540>.
- [57] Michael H. Seymour and Marilyn Marx. *Monte Carlo Event Generators*. 2013. arXiv: 1304.6677 [hep-ph]. URL: <https://arxiv.org/abs/1304.6677>.

- [58] Scholarpedia. *Introduction to Parton Distribution Functions*. URL: http://www.scholarpedia.org/article/Introduction_to_Parton_Distribution_Functions.
- [59] Torbjörn Sjöstrand. "The Pythia event generator: Past, present and future". In: *Computer Physics Communications* 246 (Jan. 2020), p. 106910. ISSN: 0010-4655. DOI: 10.1016/j.cpc.2019.106910. URL: <http://dx.doi.org/10.1016/j.cpc.2019.106910>.
- [60] R.D. Field and D. Pines. *Applications Of Perturbative QCD*. Avalon Publishing, 1995. ISBN: 9780201483628. URL: <https://books.google.pl/books?id=2eWnAAAACAAJ>.
- [61] Rick D. Field. "The Underlying Event in Hard Scattering Processes". In: *eConf C010630* (2001). Ed. by Norman Graf, P501. arXiv: hep-ph/0201192.
- [62] M. Tanabashi et al. "Review of Particle Physics". In: *Phys. Rev. D* 98 (3 2018), p. 030001. DOI: 10.1103/PhysRevD.98.030001. URL: <https://link.aps.org/doi/10.1103/PhysRevD.98.030001>.
- [63] Jonatan Adolfsen. "Study of Ξ -Hadron Correlations in pp Collisions at $\sqrt{s} = 13$ TeV Using the ALICE Detector". Presented 11 Dec 2020. Lund U., 2020. URL: <https://cds.cern.ch/record/2750097>.
- [64] V. Vislavicius. *Identified Hadron Production as a Function of Event Multiplicity and Transverse Sphericity in pp Collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 13$ TeV with the ALICE*. Lund University, Faculty of Science, Department of Physics, 2018.
- [65] Leif Lönnblad and Harsh Shah. "A spatially constrained QCD colour reconnection in pp, p-A, A-A collisions in the Pythia8/Angantyr model". In: *The European Physical Journal C* 83.7 (July 2023). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-023-11778-3. URL: <http://dx.doi.org/10.1140/epjc/s10052-023-11778-3>.
- [66] Mauro Anselmino et al. "Diquarks". In: *Rev. Mod. Phys.* 65 (4 1993), pp. 1199–1233. DOI: 10.1103/RevModPhys.65.1199. URL: <https://link.aps.org/doi/10.1103/RevModPhys.65.1199>.
- [67] Torbjörn Sjöstrand, Stephen Mrenna, and Peter Skands. "A brief introduction to PYTHIA 8.1". In: *Computer Physics Communications* 178.11 (2008), pp. 852–867. ISSN: 0010-4655. DOI: <https://doi.org/10.1016/j.cpc.2008.01.036>. URL: <https://www.sciencedirect.com/science/article/pii/S0010465508000441>.

- [68] Bo Andersson. *The Lund Model*. Vol. 7. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, July 2023. ISBN: 978-1-009-40129-6, 978-1-009-40125-8, 978-1-009-40128-9, 978-0-521-01734-3, 978-0-521-42094-5, 978-0-511-88149-7. DOI: 10.1017/9781009401296.
- [69] Klaus Werner, Fu-Ming Liu, and Tanguy Pierog. “Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at the BNL Relativistic Heavy Ion Collider”. In: *Physical Review C* 74.4 (Oct. 2006). ISSN: 1089-490X. DOI: 10.1103/physrevc.74.044902. URL: <http://dx.doi.org/10.1103/PhysRevC.74.044902>.
- [70] T. Pierog et al. “EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider”. In: *Physical Review C* 92.3 (Sept. 2015). ISSN: 1089-490X. DOI: 10.1103/physrevc.92.034906. URL: <http://dx.doi.org/10.1103/PhysRevC.92.034906>.
- [71] K. Werner et al. “Evidence for hydrodynamic evolution in proton-proton scattering at 900 GeV”. In: *Phys. Rev. C* 83 (4 2011), p. 044915. DOI: 10.1103/PhysRevC.83.044915. URL: <https://link.aps.org/doi/10.1103/PhysRevC.83.044915>.
- [72] S. Roesler, R. Engel, and J. Ranft. “The Monte Carlo Event Generator DPMJET-III”. In: *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications*. Ed. by Andreas Kling et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2001, pp. 1033–1038. ISBN: 978-3-642-18211-2.
- [73] Xin-Nian Wang and Miklos Gyulassy. “hijing: A Monte Carlo model for multiple jet production in pp, pA, and AA collisions”. In: *Phys. Rev. D* 44 (11 1991), pp. 3501–3516. DOI: 10.1103/PhysRevD.44.3501. URL: <https://link.aps.org/doi/10.1103/PhysRevD.44.3501>.
- [74] Miklos Gyulassy and Xin-Nian Wang. “HIJING 1.0: A Monte Carlo program for parton and particle production in high energy hadronic and nuclear collisions”. In: *Computer Physics Communications* 83.2 (1994), pp. 307–331. ISSN: 0010-4655. DOI: [https://doi.org/10.1016/0010-4655\(94\)90057-4](https://doi.org/10.1016/0010-4655(94)90057-4). URL: <https://www.sciencedirect.com/science/article/pii/0010465594900574>.
- [75] Xin-Nian Wang. “A pQCD-based approach to parton production and equilibration in high-energy nuclear collisions”. In: *Physics Reports* 280.5 (1997), pp. 287–371. ISSN: 0370-1573. DOI: [https://doi.org/10.1016/S0370-1573\(96\)00057-4](https://doi.org/10.1016/S0370-1573(96)00057-4).

- 00022 – 1. URL: <https://www.sciencedirect.com/science/article/pii/S0370157396000221>.
- [76] Bin Zhang et al. “Multiphase transport model for relativistic nuclear collisions”. In: *Phys. Rev. C* 61 (6 2000), p. 067901. DOI: 10.1103/PhysRevC.61.067901. URL: <https://link.aps.org/doi/10.1103/PhysRevC.61.067901>.
- [77] Zi-Wei Lin et al. “Multiphase transport model for relativistic heavy ion collisions”. In: *Physical Review C* 72.6 (Dec. 2005). ISSN: 1089-490X. DOI: 10.1103/physrevc.72.064901. URL: <http://dx.doi.org/10.1103/PhysRevC.72.064901>.
- [78] Chao Zhang et al. “Update of a multiphase transport model with modern parton distribution functions and nuclear shadowing”. In: *Phys. Rev. C* 99 (6 2019), p. 064906. DOI: 10.1103/PhysRevC.99.064906. URL: <https://link.aps.org/doi/10.1103/PhysRevC.99.064906>.
- [79] Subrata Pal and Marcus Bleicher. “Medium information from anisotropic flow and jet quenching in relativistic heavy ion collisions”. In: *Journal of Physics: Conference Series* 420 (Mar. 2013), p. 012027. ISSN: 1742-6596. DOI: 10.1088/1742-6596/420/1/012027. URL: <http://dx.doi.org/10.1088/1742-6596/420/1/012027>.
- [80] Małgorzata Anna Janik, Łukasz Kamil Graczykowski, and Adam Kisiel. “Influence of quantum conservation laws on particle production in hadron collisions”. In: *Nuclear Physics A* 956 (Dec. 2016), 886–889. ISSN: 0375-9474. DOI: 10.1016/j.nuclphysa.2016.02.018. URL: <http://dx.doi.org/10.1016/j.nuclphysa.2016.02.018>.
- [81] Rene Brun and Fons Rademakers. “ROOT — An object oriented data analysis framework”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 389.1 (1997). New Computing Techniques in Physics Research V, pp. 81–86. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X). URL: <https://www.sciencedirect.com/science/article/pii/S016890029700048X>.
- [82] Frederick E James. *Monte Carlo phase space*. CERN Academic Training Lecture. CERN, Geneva, 1 May 1968. Geneva: CERN, 1968. DOI: 10.5170/CERN-1968-015. URL: <https://cds.cern.ch/record/275743>.

- [83] Małgorzata Janik. “Two-particle correlations as a function of relative azimuthal angle and pseudorapidity in proton-proton collisions registered by the ALICE experiment”. Presented 26 Feb 2015. Warsaw U. of Tech., 2014. URL: <https://cds.cern.ch/record/2093543>.
- [84] Peter Z. Skands. “Tuning Monte Carlo generators: The Perugia tunes”. In: *Physical Review D* 82.7 (Oct. 2010). ISSN: 1550-2368. DOI: 10.1103/PhysRevD.82.074018. URL: <http://dx.doi.org/10.1103/PhysRevD.82.074018>.
- [85] J. Adam et al. “Beam-energy dependence of identified two-particle angular correlations in $\sqrt{s_{NN}} = 7.7 - 200$ GeV Au + Au collisions”. In: *Phys. Rev. C* 101 (1 2020), p. 014916. DOI: 10.1103/PhysRevC.101.014916. URL: <https://link.aps.org/doi/10.1103/PhysRevC.101.014916>.
- [86] cki, familyi=k., given=Zbigniew, giveni=Z., „ and Mike Lisa. “Global conservation laws and femtoscopy of small systems”. In: *Phys. Rev. C* 78 (6 2008), p. 064903. DOI: 10.1103/PhysRevC.78.064903. URL: <https://link.aps.org/doi/10.1103/PhysRevC.78.064903>.
- [87] Ahmed Ali and Gustav Kramer. “Jets and QCD: A Historical Review of the Discovery of the Quark and Gluon Jets and its Impact on QCD”. In: *Eur. Phys. J. H* 36 (2011), pp. 245–326. DOI: 10.1140/epjh/e2011-10047-1. arXiv: 1012.2288 [hep-ph].
- [88] J. Adams et al. “Evidence from $d + Au$ Measurements for Final-State Suppression of High- p_T Hadrons in Au + Au Collisions at RHIC”. In: *Phys. Rev. Lett.* 91 (7 2003), p. 072304. DOI: 10.1103/PhysRevLett.91.072304. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.91.072304>.
- [89] Jannis Gebhard, Aleksas Mazeliauskas, and Adam Takacs. *No-quenching baseline for energy loss signals in oxygen-oxygen collisions*. 2024. arXiv: 2410.22405 [hep-ph]. URL: <https://arxiv.org/abs/2410.22405>.
- [90] James L. Nagle and William A. Zajc. “Small System Collectivity in Relativistic Hadronic and Nuclear Collisions”. In: *Annual Review of Nuclear and Particle Science* 68.1 (Oct. 2018), 211–235. ISSN: 1545-4134. DOI: 10.1146/annurev-nucl-101916-123209. URL: <http://dx.doi.org/10.1146/annurev-nucl-101916-123209>.

- [91] Łukasz Kamil Graczykowski and Małgorzata Anna Janik. “Unfolding the effects of final-state interactions and quantum statistics in two-particle angular correlations”. In: *Phys. Rev. C* 104 (5 2021), p. 054909. DOI: 10.1103/PhysRevC.104.054909. URL: <https://link.aps.org/doi/10.1103/PhysRevC.104.054909>.
- [92] B. Abelev et al. “ $K^*(892)^0$ and $\phi(1020)$ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”. In: *Phys. Rev. C* 91 (2 2015), p. 024609. DOI: 10.1103/PhysRevC.91.024609. URL: <https://link.aps.org/doi/10.1103/PhysRevC.91.024609>.
- [93] K. Eggert et al. “Angular correlations between the charged particles produced in pp collisions at ISR energies”. In: *Nuclear Physics B* 86.2 (1975), pp. 201–215. ISSN: 0550-3213. DOI: [https://doi.org/10.1016/0550-3213\(75\)90440-X](https://doi.org/10.1016/0550-3213(75)90440-X). URL: <https://www.sciencedirect.com/science/article/pii/055032137590440X>.
- [94] S. Acharya et al. “Production of $K^*(892)^0$ and $\phi(1020)$ in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”. In: *Phys. Rev. C* 106 (3 2022), p. 034907. DOI: 10.1103/PhysRevC.106.034907. URL: <https://link.aps.org/doi/10.1103/PhysRevC.106.034907>.
- [95] J. Adam et al. “ $K^*(892)^0$ and $\phi(1020)$ meson production at high transverse momentum in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”. In: *Physical Review C* 95.6 (June 2017). ISSN: 2469-9993. DOI: 10.1103/physrevc.95.064606. URL: <http://dx.doi.org/10.1103/PhysRevC.95.064606>.
- [96] G. Aad et al. “Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector”. In: *Phys. Rev. C* 86 (1 2012), p. 014907. DOI: 10.1103/PhysRevC.86.014907. URL: <https://link.aps.org/doi/10.1103/PhysRevC.86.014907>.
- [97] S. Acharya et al. “Emergence of Long-Range Angular Correlations in Low-Multiplicity Proton-Proton Collisions”. In: *Phys. Rev. Lett.* 132 (17 2024), p. 172302. DOI: 10.1103/PhysRevLett.132.172302. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.132.172302>.
- [98] G. Agakishiev et al. “Anomalous centrality evolution of two-particle angular correlations from Au-Au collisions at $\sqrt{s_{NN}} = 62$ and 200 GeV”. In: *Phys. Rev. C* 86 (6 2012), p. 064902. DOI: 10.1103/PhysRevC.86.064902. URL: <https://link.aps.org/doi/10.1103/PhysRevC.86.064902>.

- [99] B. Alver et al. “High Transverse Momentum Triggered Correlations over a Large Pseudorapidity Acceptance in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV”. In: *Phys. Rev. Lett.* 104 (6 2010), p. 062301. DOI: 10.1103/PhysRevLett.104.062301. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.104.062301>.
- [100] G. Aad et al. “Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{NN}}=5.02$ TeV Proton-Lead Collisions with the ATLAS Detector”. In: *Phys. Rev. Lett.* 110 (18 2013), p. 182302. DOI: 10.1103/PhysRevLett.110.182302. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.110.182302>.
- [101] I. Abt et al. “Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA”. In: *Journal of High Energy Physics* 2021.12 (Dec. 2021). ISSN: 1029-8479. DOI: 10.1007/jhep12(2021)102. URL: [http://dx.doi.org/10.1007/JHEP12\(2021\)102](http://dx.doi.org/10.1007/JHEP12(2021)102).
- [102] Anthony Badea et al. “Measurements of Two-Particle Correlations in e^+e^- Collisions at 91 GeV with ALEPH Archived Data”. In: *Physical Review Letters* 123.21 (Nov. 2019). ISSN: 1079-7114. DOI: 10.1103/physrevlett.123.212002. URL: <http://dx.doi.org/10.1103/PhysRevLett.123.212002>.
- [103] S. Acharya et al. “Multiplicity and event-scale dependent flow and jet fragmentation in pp collisions at $\sqrt{s} = 13$ TeV and in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”. In: *Journal of High Energy Physics* 2024.3 (Mar. 2024). ISSN: 1029-8479. DOI: 10.1007/jhep03(2024)092. URL: [http://dx.doi.org/10.1007/JHEP03\(2024\)092](http://dx.doi.org/10.1007/JHEP03(2024)092).
- [104] A. Hayrapetyan et al. “Observation of Enhanced Long-Range Elliptic Anisotropies Inside High-Multiplicity Jets in pp Collisions at $\sqrt{s} = 13$ TeV”. In: *Physical Review Letters* 133.14 (Sept. 2024). ISSN: 1079-7114. DOI: 10.1103/physrevlett.133.142301. URL: <http://dx.doi.org/10.1103/PhysRevLett.133.142301>.
- [105] Torbjörn Sjöstrand, Stephen Mrenna, and Peter Skands. “PYTHIA 6.4 physics and manual”. In: *Journal of High Energy Physics* 2006.05 (May 2006), 026–026. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2006/05/026. URL: <http://dx.doi.org/10.1088/1126-6708/2006/05/026>.
- [106] P. Skands, S. Carrazza, and J. Rojo. “Tuning PYTHIA 8.1: the Monash 2013 tune”. In: *The European Physical Journal C* 74.8 (Aug. 2014). ISSN: 1434-6052. DOI:

- 10.1140/epjc/s10052-014-3024-y. URL: <http://dx.doi.org/10.1140/epjc/s10052-014-3024-y>.
- [107] R. Engel, J. Ranft, and S. Roesler. “Hard diffraction in hadron-hadron interactions and in photoproduction”. In: *Physical Review D* 52.3 (Aug. 1995), 1459–1468. ISSN: 0556-2821. DOI: 10.1103/physrevd.52.1459. URL: <http://dx.doi.org/10.1103/PhysRevD.52.1459>.
- [108] S. Acharya et al. “Studying strangeness and baryon production mechanisms through angular correlations between charged Ξ baryons and identified hadrons in pp collisions at $\sqrt{s} = 13$ TeV”. In: *Journal of High Energy Physics* 2024.9 (Sept. 2024). ISSN: 1029-8479. DOI: 10.1007/jhep09(2024)102. URL: [http://dx.doi.org/10.1007/JHEP09\(2024\)102](http://dx.doi.org/10.1007/JHEP09(2024)102).
- [109] Manuel Bähr et al. “Herwig++ physics and manual”. In: *The European Physical Journal C* 58.4 (Nov. 2008), 639–707. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-008-0798-9. URL: <http://dx.doi.org/10.1140/epjc/s10052-008-0798-9>.
- [110] Johannes Bellm et al. “Herwig 7.0/Herwig++ 3.0 release note”. In: *The European Physical Journal C* 76.4 (Apr. 2016). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-016-4018-8. URL: <http://dx.doi.org/10.1140/epjc/s10052-016-4018-8>.
- [111] Małgorzata Anna Janik. “Studying baryon production using two-particle angular correlations”. In: *EPJ Web of Conferences* 235 (2020). Ed. by I. Vitev et al., p. 01004. ISSN: 2100-014X. DOI: 10.1051/epjconf/202023501004. URL: <http://dx.doi.org/10.1051/epjconf/202023501004>.
- [112] Torbjörn Sjöstrand. “Collective Effects: the viewpoint of HEP MC codes”. In: *Nuclear Physics A* 982 (2019). The 27th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter 2018, pp. 43–49. ISSN: 0375-9474. DOI: <https://doi.org/10.1016/j.nuclphysa.2018.11.010>. URL: <https://www.sciencedirect.com/science/article/pii/S0375947418303968>.
- [113] Liuyao Zhang et al. “Implication of two-baryon azimuthal correlations in pp collisions at LHC energies on the QGP”. In: *Physics Letters B* 829 (2022), p. 137063. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2022.137063>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269322001976>.

- [114] Noe Demazure, Víctor González Sebastián, and Felipe J. Llanes-Estrada. “Baryon Anticorrelations in PYTHIA”. In: *Few Body Syst.* 64.3 (2023), p. 57. DOI: 10.1007/s00601-023-01838-5. arXiv: 2210.02358 [hep-ph].
- [115] Leif Lönnblad and Harsh Shah. “Baryon correlations in Pythia”. In: *Eur. Phys. J. C* 83.12 (2023), p. 1105. DOI: 10.1140/epjc/s10052-023-12271-7. arXiv: 2309.01557 [hep-ph].
- [116] Lyndon Evans and Philip Bryant. “LHC Machine”. In: *Journal of Instrumentation* 3.08 (2008), S08001. DOI: 10.1088/1748-0221/3/08/S08001. URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08001>.
- [117] Christiane Lefèvre. “The CERN accelerator complex. Complexe des accélérateurs du CERN”. 2008. URL: <https://cds.cern.ch/record/1260465>.
- [118] Arturo Tauro. “ALICE Schematics”. General Photo. 2017. URL: <https://cds.cern.ch/record/2263642>.
- [119] P Cortese et al. “ALICE technical design report on forward detectors: FMD, T0 and V0”. In: (Sept. 2004).
- [120] The ALICE collaboration. “Performance of the ALICE VZERO system”. In: *Journal of Instrumentation* 8.10 (Oct. 2013), P10016–P10016. ISSN: 1748-0221. DOI: 10.1088/1748-0221/8/10/p10016. URL: <http://dx.doi.org/10.1088/1748-0221/8/10/P10016>.
- [121] G. Dellacasa et al. “ALICE technical design report of the inner tracking system (ITS)”. In: (June 1999).
- [122] F. Carminati et al. “ALICE: Physics Performance Report, Volume I”. In: *Journal of Physics G: Nuclear and Particle Physics* 30.11 (2004), p. 1517. DOI: 10.1088/0954-3899/30/11/001. URL: <https://dx.doi.org/10.1088/0954-3899/30/11/001>.
- [123] *ALICE Inner Tracking System (ITS): Technical Design Report*. Technical design report. ALICE. Geneva: CERN, 1999. URL: <https://cds.cern.ch/record/391175>.
- [124] J. Alme et al. “The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 622.1 (2010), pp. 316–367. ISSN: 0168-9002. DOI: <https://doi.org/10.1016/j.nima.2010.04.042>. URL: <https://www.sciencedirect.com/science/article/pii/S0168900210008910>.

- [125] R. Schicker. “Overview of ALICE results in pp, p–A and A–A collisions.” In: *EPJ Web Conf.* 138 (2017). 12 pages, 10 figures, Invited Talk at XXIII International Baldin Seminar on High Energy Physics Problems, September 19–24, 2016, Dubna, to be published in Seminar Proceedings, p. 01021. DOI: 10.1051/epjconf/201713801021. arXiv: 1701.04810. URL: <https://cds.cern.ch/record/2242545>.
- [126] R Brun et al. *The GEANT3 electromagnetic shower program and a comparison with the EGS3 code*. Tech. rep. Geneva: CERN, 1985. URL: <https://cds.cern.ch/record/159023>.
- [127] S. Agostinelli et al. “GEANT4—a simulation toolkit”. In: *Nucl. Instrum. Meth. A* 506 (2003), pp. 250–303. DOI: 10.1016/S0168-9002(03)01368-8.
- [128] Giuseppe Battistoni et al. “Applications of FLUKA Monte Carlo code for nuclear and accelerator physics”. In: *Nucl. Instrum. Meth. B* 269 (2011), pp. 2850–2856. DOI: 10.1016/j.nimb.2011.04.028.
- [129] Torbjorn Sjostrand. “High-energy physics event generation with PYTHIA 5.7 and JETSET 7.4”. In: *Comput. Phys. Commun.* 82 (1994), pp. 74–90. DOI: 10.1016/0010-4655(94)90132-5.
- [130] “AliPhysics: ALICE Analysis Repository”. In: (2024). URL: <https://github.com/alisw/AliPhysics>.
- [131] Johanna Gramling. “Azimuthally Sensitive Hanbury Brown–Twiss Interferometry measured with the ALICE Experiment”. Presented 13 Dec 2012. Heidelberg U., 2012. URL: <https://cds.cern.ch/record/1463351>.
- [132] S. Acharya et al. “Multiplicity dependence of π , K, and p production in pp collisions at $\sqrt{s} = 13$ TeV”. In: *The European Physical Journal C* 80.8 (Aug. 2020). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-020-8125-1. URL: <http://dx.doi.org/10.1140/epjc/s10052-020-8125-1>.
- [133] HEPData. *Multiplicity dependence of π , K, and p production in pp collisions at $\sqrt{s} = 13$ TeV*. URL: <https://www.hepdata.net/record/ins1784041>.
- [134] P. Skands, S. Carrazza, and J. Rojo. “Tuning PYTHIA 8.1: the Monash 2013 tune”. In: *The European Physical Journal C* 74.8 (Aug. 2014). ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-014-3024-y. URL: <https://doi.org/10.48550/arXiv.1404.5630>.

- [135] K. Werner et al. “The Physics of EPOS”. In: *EPJ Web Conf.* 52 (2013). Ed. by U. Genssch and M. Walter, p. 05001. DOI: 10.1051/epjconf/20125205001.
- [136] B. Alver et al. “Cluster properties from two-particle angular correlations in $p + p$ collisions at $\sqrt{s} = 200$ and 410 GeV”. In: *Phys. Rev. C* 75 (5 2007), p. 054913. DOI: 10.1103/PhysRevC.75.054913. URL: <https://link.aps.org/doi/10.1103/PhysRevC.75.054913>.
- [137] “Multiplicity dependence of pion, kaon, proton and lambda production in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”. In: *Physics Letters B* 728 (Jan. 2014), 25–38. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2013.11.020. URL: <http://dx.doi.org/10.1016/j.physletb.2013.11.020>.
- [138] “Analysis of the apparent nuclear modification in peripheral Pb–Pb collisions at 5.02 TeV”. In: *Physics Letters B* 793 (2019), pp. 420–432. ISSN: 0370-2693. DOI: <https://doi.org/10.1016/j.physletb.2019.04.047>. URL: <https://www.sciencedirect.com/science/article/pii/S0370269319302801>.