



PSEUDORAPIDITY DEPENDENCE OF LONG-RANGE CORRELATIONS

WITH ALICE IN Pb-Pb, Xe-Xe, AND
p-Pb COLLISIONS

FREJA THORESEN

PSEUDORAPIDITY DEPENDENCE OF LONG-RANGE CORRELATIONS

WITH ALICE IN $PB-PB$, $XE-XE$, AND $P-PB$
COLLISIONS

FREJA THORESEN

NIELS BOHR INSTITUTE,
UNIVERSITY OF COPENHAGEN

PRINCIPAL SUPERVISOR

Prof. JJ. Gaardhøje

SUPERVISOR

Assoc. Prof. C. H. Christensen

CHAIR OF COMMITTEE

Prof. P. Hansen

COMMITTEE MEMBER

Prof. S. Masiocchi

COMMITTEE MEMBER

Prof. J. Ollitrault

© Freja Thoresen 2020

Pseudorapidity dependence of long-range correlations with ALICE in
Pb–Pb, Xe–Xe, and p–Pb collisions

PhD Thesis, University of Copenhagen

xiv + 156 pages; illustrated, with bibliographic references

Set in 9/11 pt Palatino Linotype using pdf_{La}T_EX with the Tufte-~~La~~_EX
package

Thesis submitted on 6 April 2020 and defended on 30 April 2020
for the completion of the PhD in Physics
at the Niels Bohr Institute, University of Copenhagen.

First printing, April 2020



UNIVERSITY OF
COPENHAGEN

Abstract

At the LHC, the strongly interacting Quark-Gluon Plasma is created in heavy-ion collisions. The collisions can be studied at ALICE. One measurable of the created plasma is anisotropic flow. The anisotropic flow measurements are closely related to the initial conditions of the collision, and to the expansion of the plasma.

This work presents flow measurements as a function of pseudorapidity with data from the Time-Projection Chamber (TPC) and the Forward Multiplicity Detector (FMD). The Generic Framework is used to calculate the flow coefficients. The non-uniform acceptance and non-uniform efficiency of the detectors can be corrected by using particle weights in the Generic Framework. The Forward Multiplicity Detector (FMD) at ALICE, needs further corrections since it receives background signal from particles created from material interactions. The flow coefficients, v_n , are presented over a large range in pseudorapidity ($-3.5 \leq \eta \leq 5$) in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV, Xe–Xe with $\sqrt{s_{\text{NN}}} = 5.44$ TeV, and early results for p–Pb with $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The flow coefficients are measured with 2- and 4-particle cumulants with $|\Delta\eta| > 0.8$ and $|\Delta\eta| > 2$. The difference between $v_2\{2, |\Delta\eta| > 0.8\}$ and $v_2\{2, |\Delta\eta| > 2\}$ implies changes in the decorrelation of the flow vectors or non-flow effects between the two methods. The decorrelation effect of the flow vectors is studied with a decorrelation ratio $r_{n,n}$, which is presented for Pb–Pb and p–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The decorrelation of the flow vectors are more significant for p–Pb than for Pb–Pb. The AMPT model is compared to the flow measurements in pseudorapidity, and the comparisons show a qualitative agreement with the measurements.

Dansk resumé

Hos LHC bliver det stærkt interagerende Quark-Gluon-plasma skabt i kollisioner af tunge ioner. Disse kollisioner kan studeres hos ALICE. En af målingerne af det skabte plasma, er anisotropisk flow. Målingerne af anisotropisk flow er tæt knyttet til de oprindelige betingelser for kollisionen og ekspansionen af plasmaet.

Ved hjælp af Time-Projection Chamber (TPC) og Forward Multiplicity Detector (FMD) præsenterer denne afhandling flow målinger som en funktion af pseudorapiditet. Generic Framework bruges til at beregne flow koefficienterne. Detektornes acceptans og effektivitet kan korrigeres for ved hjælp af partikelvægte i Generic Framework. Forward Multiplicity Detector (FMD) hos ALICE har brug for yderligere korrektioner, da den modtager baggrundssignaler fra partikler skabt af materiale interaktioner. Flow koefficienterne, v_n , præsenteres over et stort interval i pseudorapiditet ($-3,5 \leq \eta \leq 5$) i Pb–Pb kollisioner med $\sqrt{s_{NN}} = 5,02$ TeV, Xe–Xe med $\sqrt{s_{NN}} = 5,44$ TeV, og tidlige resultater for p–Pb med $\sqrt{s_{NN}} = 5,02$ TeV. Flow koefficienterne måles med 2- og 4-partikel kumulanter med $|\Delta\eta| > 0,8$ og $|\Delta\eta| > 2$. Forskellen mellem $v_n\{2, |\Delta\eta| > 0,8\}$ og $v_n\{2, |\Delta\eta| > 2\}$ indebærer ændringer i enten dekorrelationen af flow vektorerne eller non-flow mellem de to metoder. Dekorrelationseffekten af flow vektorerne studeres gennem et dekorrelationsforhold $r_{n,n}$, som præsenteres for Pb–Pb og p–Pb kollisioner med $\sqrt{s_{NN}} = 5,02$ TeV. Dekorrelationen af flowvektorerne er mere signifikant for p–Pb end for Pb–Pb. AMPT-modellen sammenlignes med flow målingerne i pseudorapiditet, og sammenligningerne viser en kvalitativ overensstemmelse med målingerne.

Acknowledgement

First of all, thanks to my supervisor Jens Jørgen Gaardhøje and co-supervisor Christian Holm Christensen. Jens Jørgen has provided me with much guidance and good advice throughout my PhD. Christian has been kind to keep his office door open at all times, where I can bother him with multiple physics discussions over the years. Also, thanks to both my supervisors for taking the time to read the thesis and provide me with many useful comments. I would also like to thank the other members of the heavy-ion group in Copenhagen: Børge, Ian, Kristjan, Hans, Christian B., and You. It has been a pleasant working atmosphere in the heavy-ion group, with our weekly meetings.

Thanks to Christian Bourjau for helping me in the early years of my PhD, by teaching me about the analysis software, and always ready to answer questions, even when busy. Thank you to Vytautas for always being ready to discuss our complaints over a beer, and for the travels, we have had together. Thank you Yuko for being my fellow comrade in using the FMD, and the helpful discussions when you were in Copenhagen, but also otherwise online. The PhD would not have been the same without the beers at Søernes with both present and prior PhD students. So thanks to Katarina, Lais, Meera, Jean-Loup, and Fabian. Thanks to my office mates, Joachim, Emil, Zlatko, and Jean-Loup, for always being up for a game of hangman during the coffee break. Thank you, Zuzanna for helping with submitting the trains when I was running the last analysis, and I wish you the best of luck for your PhD.

Thanks to my family and my friends for supporting me during my PhD, and reminding me to take breaks in stressful times. Thank you, Lars, for always being there for me.

Disclaimer

The results of this thesis use ALICE data and ALICE simulated data. The figures in this thesis are from the authors own work, and has not been approved by the ALICE collaboration. The analysis in this thesis is however approved, and results have been presented at conferences [1, 2, 3]. The figures in this thesis have changed since then (by improving the analysis), and are not made public yet by the ALICE collaboration.

Illustrations in this thesis with no citation in the figure text, are made by the author.

To Lars, my own world, pulling me towards him by gravity [4]

Contents

Abstract	iii
Dansk resume	v
Acknowledgement	vii
Disclaimer	vii
1 Introduction	1
1.1 The Quark Gluon Plasma at the LHC	2
1.2 Outline of Thesis	2
2 Heavy Ion Physics	3
2.1 Elementary particles and the Standard Model	4
2.1.1 Elementary particles	4
2.1.2 Early universe	5
2.2 Quark Gluon Plasma	7
2.2.1 Evolution of the Quark-Gluon Plasma	7
2.2.2 Coordinate system	8
2.2.3 Overlap of the Heavy ions	8
2.2.4 Signatures of the QGP	9
2.2.5 Hydrodynamics	11
2.2.6 pQCD based models	13
2.3 Anisotropic Flow	15
2.3.1 Flow in Heavy-ion Collisions	15
2.3.2 Measurements of Anisotropic Flow	17
2.3.3 Pseudorapidity dependence	18
2.3.4 Factorisation of flow coefficients and decorrelation of symmetry plane	19
3 Methods	25
3.1 Cumulants	26
3.1.1 Cumulants in flow analysis	26
3.1.2 Expectation values	26
3.1.3 Q-cumulant	27
3.1.4 Flow fluctuations	30
3.2 Generic Framework	31
3.2.1 Reference flow	31
3.2.2 Differential flow	32

3.3	Cumulant methods using short- and long-range η -gaps	33
3.3.1	Cumulants with narrow η -gaps	33
3.3.2	Cumulants with wide η -gaps	34
3.3.3	Methods with three sub-events	34
3.3.4	Decorrelation of symmetry plane	35
4	Experiment	37
4.1	The Large Hadron Collider	38
4.1.1	CERN accelerator complex	38
4.2	A Large Ion Collider Experiment (ALICE)	40
4.2.1	Overview	40
4.2.2	Inner Tracking System (ITS)	41
4.2.3	Time Projection Chamber (TPC)	42
4.2.4	Forward Multiplicity Detector (FMD)	42
4.2.5	V0 detector (V0A, V0C)	43
4.2.6	Reconstructions and Data formats	44
5	Analysis	47
5.1	Event Selection	48
5.1.1	Overview	48
5.1.2	Centrality estimators	50
5.2	Track selection	52
5.2.1	Reconstructions	52
6	Corrections	53
6.1	Overview of Corrections	54
6.1.1	Uncorrected results	54
6.2	Non-uniform Acceptance	55
6.2.1	Central regions	55
6.2.2	Forward regions	57
6.2.3	φ distribution per run	60
6.3	Non-uniform Efficiency	61
6.3.1	Approach	61
6.3.2	p_T in the TPC	64
6.4	Correction for secondary particles	65
6.4.1	Origin of secondary particles in the FMD	65
6.4.2	Estimation of smearing	66
6.4.3	Consistency checks	70
6.4.4	Reconstruction of the FMD using track references	76
7	Results and Discussion	83
7.1	Summary of uncertainties	84
7.1.1	Statistical uncertainties	84
7.1.2	Systematical uncertainties	84
7.2	Measurements of flow coefficients	87
7.2.1	Reference flow in the central region of pseudorapidity	87
7.2.2	η -gaps in differential measurements	88

7.2.3	Flow measurements in Pb–Pb collisions	89
7.2.4	Flow measurements in Xe–Xe collisions	91
7.2.5	Flow measurements in p–Pb collisions	93
7.3	Decorrelation effects	95
7.3.1	$r_{n,n}$ in Pb–Pb collisions	95
7.3.2	$r_{2,2}$ in p–Pb collisions	96
7.4	Comparisons to published data	97
7.4.1	Integrated flow measurements	97
7.4.2	Flow coefficients as a function of pseudorapidity	98
7.4.3	Rapidity scaling	99
7.5	Model comparisons	100
8	Conclusion	103
8.1	Concluding remarks	104
8.1.1	Summary	104
8.1.2	Outlook	104
	Bibliography	109
	Appendices	111
A	Generic Framework with detector segments	111
A.1	Particle correlations with a segmented detector	111
A.2	Calculating the correction by induction	112
A.3	Toy simulation	113
B	Methods	115
B.1	The four-particle cumulants with a η -gap	117
C	NUA	118
C.1	Systematics for interpolation in the FMD	118
C.2	LHC15highIR	119
C.3	LHC16q	120
C.4	Global tracks	121
C.5	FMD	122
D	Non-uniform Efficiency	123
D.1	Hybrid tracks	123
E	Additional material for the secondary correction	124
E.1	Monte Carlo closure with track references	124
E.2	Reconstruction of the FMD using track references	125
E.3	Choices for reconstruction	129
E.4	Other approaches to extract the secondary correction	130
E.5	Comparison to prior work	136
E.6	Dimensions in φ	137
F	Xe–Xe	138
G	Systematics	139
G.1	Pb–Pb	139
G.2	Xe–Xe	140
G.3	Forward-backward symmetry in η	141
H	Additional Results	144

H.1	Decorrelation	144
H.2	Centrality scaling	145
H.3	Comparisons to previous results	147
H.4	Comparisons to AMPT	149
I	Analysis Code	150
I.1	Analysis Classes	150
I.2	Datasets	150
List of Figures		156

I Introduction

1.1 The Quark Gluon Plasma at the LHC

At the LHC, a new kind of matter is created. Although this matter is new in the mind of its observers, it is a bit of a misnomer. The matter created at the LHC is thought to be one of the oldest forms of matter in the Universe; presumably, present about a millionth of a second after the birth of the Universe in the Big Bang. In the Quark-Gluon plasma, which existed after the Big Bang, the quarks and gluons were assumed to be asymptotically free. Asymptotic freedom means that the strong coupling constant (α_s) is weak enough for the particles not to be confined within hadrons. At the CERN in Switzerland, the Large Hadron Collider (LHC), is colliding particles in the effort to create the strongly interacting Quark-Gluon Plasma (sQGP). The sQGP is a nearly perfect fluid. To study the strongly interacting Quark-Gluon plasma created at the LHC, a combination of different measurements combined with various theories can bring us closer to an understanding of Quark-Gluon Plasma which existed shortly after the Big Bang.

One of the essential pieces of evidence for the creation of the strongly interacting Quark-Gluon Plasma at ALICE is the collectivity of the matter, which is characterized by the Fourier coefficients of the azimuthal distributions, called anisotropic flow.

The measurement central to this thesis is anisotropic flow as a function of pseudorapidity. Anisotropic flow is closely related to the initial state of the heavy-ion collision at ALICE. The measurements can be explored as integrated measurements or as a function of p_T and η . In this thesis, the dependency of flow on pseudorapidity is explored in Pb–Pb and Xe–Xe collisions. Early results of p–Pb are also presented.

1.2 Outline of Thesis

In chapter 2, heavy-ion physics is introduced. Chapter 3 explains selected methods available for measuring anisotropic flow, and also the chosen methods used in this thesis. The methods use sub-events from the central and forward detectors. The detectors in the ALICE experiment are introduced in Chapter 4. Chapter 6 goes through the event and track selection.

Chapter 6 goes through the various corrections of the measurements, in particular in the forward directions of pseudorapidity. This chapter is by far the most extensive of the thesis, as is typical for experimental work. The art of experimental analysis lies not so much in the processing of the observations, but in finding the needed corrections and understanding the associated uncertainties. The calculations of flow are straight-forward; what comes before (data selection), and after (corrections) is where the experimental art lies.

Finally, chapter 7 exhibits and discusses the results.

II Heavy Ion Physics



2.1 Elementary particles and the Standard Model

The four known forces in our Universe are gravity, the electromagnetic, weak nuclear, and strong nuclear forces. The successful model describing the interactions between the three of the four forces and the elementary particles is the Standard Model. Gravity has not yet been successfully included in the Standard Model. The elementary particles are the smallest known fundamental constituents of matter in the Universe. The classification of the elementary particles is given by their quantum numbers, such as spin, mass, charge, colour charge, and their interactions with each other.

2.1.1 Elementary particles

The Standard Model consists of the elementary particles summarized in Figure 2.1, which are the building blocks of our Universe. There are three main groups of particles: leptons, quarks, and bosons, of which the leptons and quarks are split into three generations.

The electromagnetic force is mediated through the photons, which interact only with electric charges. Since the photon only interacts with charged particles, consequently it can not interact with itself. The Z and W bosons mediate the weak nuclear force, which accounts for particle decays via quark transformations. The electro-weak theory is the combined theory of the electromagnetic and weak nuclear force.

		Generation			Bosons	
		I	II	III	Force carriers	
Quarks	u_p	$s = 1/2$ $Q = 2/3 e$ $m = 2.3 \text{ MeV}/c$	C_{charm} $s = 1/2$ $Q = 2/3 e$ $m = 1.28 \text{ MeV}/c$	t_{op} $s = 1/2$ $Q = 2/3 e$ $m = 173.2 \text{ MeV}/c$	g_{luon} $s = 1$ $Q = 0$ $m = 0$	H_{iggs} $s = 0$ $Q = 0$ $m = 125.7 \text{ MeV}/c$
	d_{own}	$s = 1/2$ $Q = -1/3 e$ $m = 4.8 \text{ MeV}/c$	S_{trange} $s = 1/2$ $Q = -1/3 e$ $m = 95 \text{ MeV}/c$	b_{ottom} $s = 1/2$ $Q = -1/3 e$ $m = 4.8 \text{ GeV}/c$	γ_{photon} $s = 1$ $Q = 0$ $m = 0$	
Leptons	e_{lectron}	$s = 1/2$ $Q = -1 e$ $m = 0.51 \text{ MeV}/c$	μ_{uon} $s = 1/2$ $Q = -1 e$ $m = 105.7 \text{ MeV}/c$	τ_{au} $s = 1/2$ $Q = -1 e$ $m = 1.777 \text{ GeV}/c$	W_{boson}^{+} $s = 1$ $Q = \pm 1$ $m = 80.4 \text{ GeV}/c$	
	ν_{neutrino}^e	$s = 1/2$ $Q = 0$ $m < 2 \text{ eV}/c$	$\nu_{\text{neutrino}}^{\mu}$ $s = 1/2$ $Q = 0$ $m < 2 \text{ eV}/c$	$\nu_{\text{neutrino}}^{\tau}$ $s = 1/2$ $Q = 0$ $m < 2 \text{ eV}/c$	Z_{boson}^0 $s = 1$ $Q = 0$ $m = 91.2 \text{ GeV}/c$	

Figure 2.1: The elementary particles of the Standard Model. The colours correspond to which particles can interact with each other. For example, the gluon interacts with quarks, and hence have the same colour code in this figure. The photon can interact with charged leptons and quarks. The W and Z bosons are responsible for particle decays and interact with both leptons and quarks. The Higgs particle interacts with quarks, leptons, and bosons.

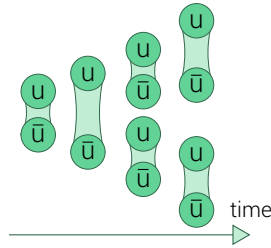


Figure 2.2: A creation of a new quark-antiquark pair from the increasing potential between the two quarks.

The interactions between quarks are mediated through the gluons by the strong force. The quarks and gluons have *color charges*, which are red, green, and blue. For the quarks to combine into a hadron, they need to have a color sum of *zero*, e.g. red + green + blue = 0 and blue + anti-blue = 0. The quarks can have a single colour charge, but the gluons have a linear combination of colour and anti-colour charges. There are eight gluons (the 9'th is colour neutral). The interactions between the quarks and gluons are described by Quantum Chromodynamics (QCD).

In normal matter (at room temperature), the quarks and gluons can not be free because they are bound by the strong force. This is called *color confinement*. If one tries to separate, e.g., two bound quarks, the field between them will become energetic enough to create a new quark + anti-quark pair, see Figure 2.2.

Since the gluons have colour charges, the gluons are free to radiate gluons, i.e., interact with other gluons, in contrast to the photon. The phenomenon *anti-screening* causes particles with colour charges to continually be surrounded by a colour field [5]. The gluon self-interactions create the anti-screening, which qualitatively means that the colour field around the particles with a colour charge gets stronger with increasing distance (e.g., opposite to the case of the electromagnetic force), which then causes the potential to increase between colour charges [6]. However, in the case of *asymptotic freedom*, a high-momentum particle can penetrate the colour field [7]. Asymptotic freedom is possible with the coupling constant $\alpha_s \ll 1$ at large momentum transfers. Figure 2.3 shows the QCD coupling constant dependence on the energy scale. Asymptotic freedom is possible to achieve at the Big Bang since the energy scale is massive and corresponding length scale small [8].

2.1.2 Early universe

In the early Universe, less than a millionth of a second after the Big Bang, it is believed that matter was in an extremely hot and dense phase called the Quark-Gluon Plasma (QGP). In this early stage, quarks and gluons are assumed to be asymptotically free [10]. After the QGP era, the hadron formation happened about 10^{-6} seconds after the Big Bang. In this period, the quarks combined into light hadrons, like protons and neutrons. At a later time of 10 seconds after the Big Bang, the protons and neutrons formed nuclei. The first minutes after the Big Bang are depicted in Figure 2.4.

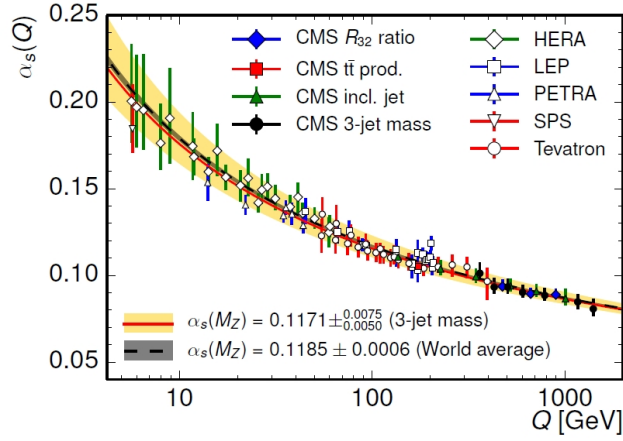


Figure 2.3: The QCD coupling constant dependence on momentum transfer scale (Q) [9]. The black line with grey uncertainty band is the world average of $\alpha_s(Q)$ evolution, and the red line with the yellow uncertainty band is $\alpha_s(Q)$ determined from the invariant 3-jet mass. A large Q means short distance, and therefore α_s decreases with distance between the interacting particles. This is what gives rise to asymptotic freedom.

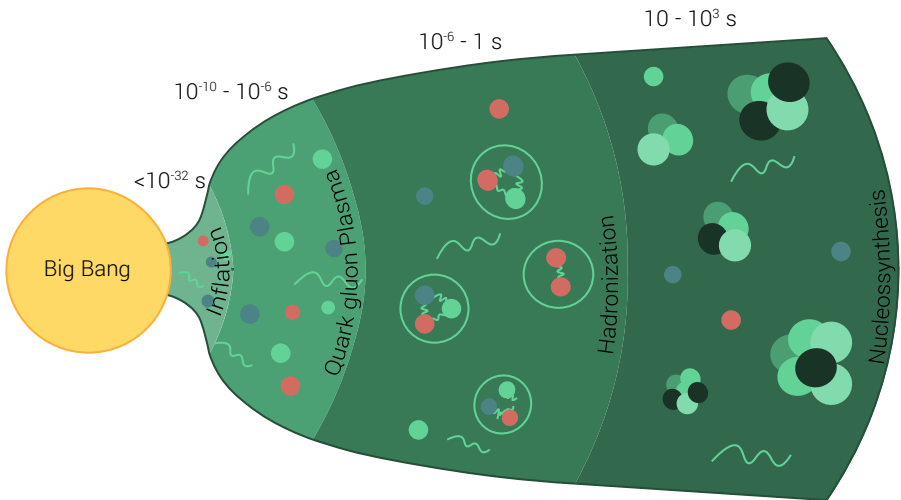


Figure 2.4: Sketch of the early Universe and approximate time scale. Less than 10^{-36} seconds the Big Bang, the Universe expanded rapidly, which is called inflation. After the inflation, the Quark-Gluon Plasma governed, until about 10^{-6} seconds, whereafter the quarks began to hadronize. After the hadronization, the hadrons combined into nuclei, where this period lasted until about 10^3 seconds.

2.2 Quark Gluon Plasma

Many theories try to describe the formation and evolution of the QGP created at experiments such as ALICE or RHIC. An important part of describing a physical phenomenon is well-defined measurements. When measuring the properties of the QGP, a lot of different measurements are combined to extract information about the plasma. It is, in this case, difficult to claim to have created the QGP in an experimental setting without the use of more than one observable. In this section, a few of the most important measurables and theories for the QGP are described, while flow measurements are dealt with in the next section (2.3).

2.2.1 Evolution of the Quark-Gluon Plasma

The Quark-Gluon Plasma created at RHIC and LHC is the *strong interacting* Quark-Gluon Plasma (sQGP). The QGP was thought to be a deconfined matter which behaved as a gas of almost-free quarks and gluons [11, 12]. Instead, what was found was a strongly interacting fluid [13].

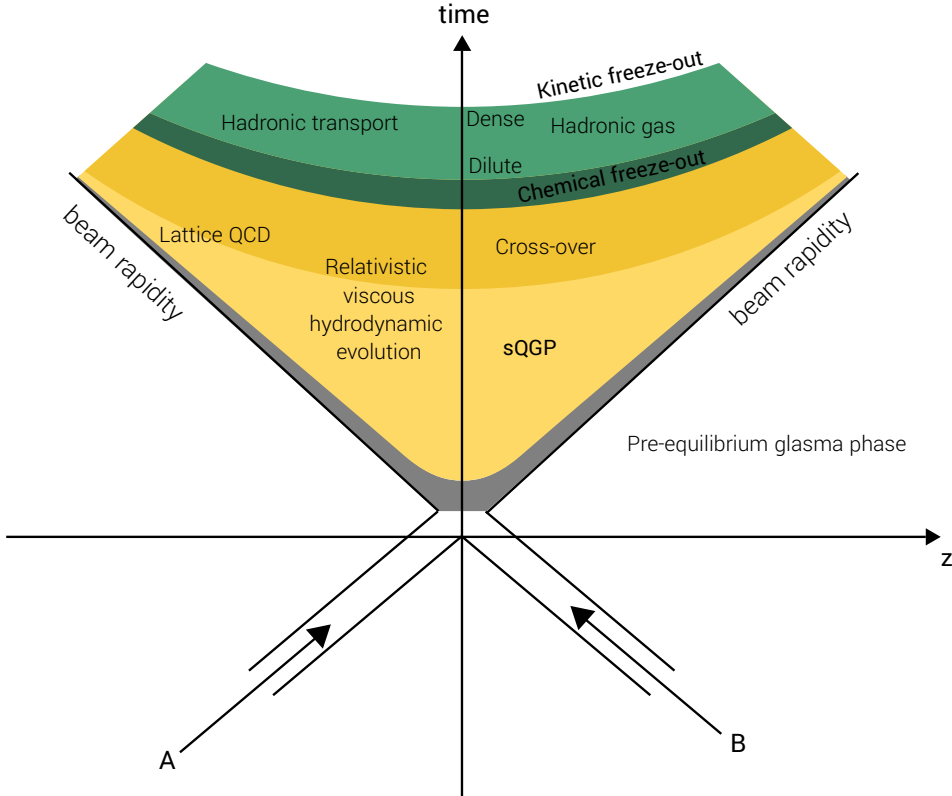


Figure 2.5: The evolution of the system created by the two colliding heavy ions (A and B). After the collision, the system enters a pre-equilibrium phase, before evolving into the sQGP state. After the system reaches chemical freeze-out, the particles are a hadronic gas.

The evolution of the QGP in a collision is depicted in Figure 2.5. The plasma begins in a pre-equilibrium phase, where one model attempting to describe this phase is Color Glass Condensate (CGC) [14]. In CGC, the incoming projectiles are saturated with low momentum gluons, which produce strong colour fields during the collision, giving rise to an initial state which is out of equilibrium. The initial state is called glasma and exists before the QGP. Once the system has reached equilibrium in the collision, the most popular theory is that the system undergoes a hydrodynamic evolution. It has been found that the hydrodynamical system has a minimal shear viscosity and is, therefore, often referred to as a *perfect liquid* [15]. The shear viscosity is the resistance against deformations in a fluid. When the shear viscosity is minimal, it means that the particles (gluons and quarks) are still strongly interacting, which is the reason for the name *sQGP* (strongly interacting quark-gluon plasma) [13].

2.2.2 Coordinate system

The z direction is along the beamline. The place where the particles collide is called the interaction point. The interaction point is measured in the z -direction along the beamline and denoted IP_z . The y -axis is vertical, while the x -axis is horizontal with respect to the beamline. The azimuthal angle φ is around the beamline axis, and the polar angle θ is the angle to the beam axis. In particle physics, the *rapidity* is normally used,

$$y = 1/2 \ln[(E + p_z)/(E - p_z)]. \quad (2.1)$$

Pseudorapidity is defined as

$$\eta = -\ln[\tan(\theta/2)] \quad (2.2)$$

which is the coordinate used at the LHC. For particles travelling at relativistic speeds, it is a reasonable assumption that $m \ll p$ which means that $E \rightarrow p$. Therefore for relativistic particles $y \approx \eta$.

Pseudorapidity is often used in place of y since the mass of the particles is not always experimentally measured. It is also important to note that differences between the rapidities of two particles are Lorentz-invariant under boosts along the z -axis. Therefore the pseudorapidity is the desired choice for describing the position of a particle.

2.2.3 Overlap of the Heavy ions

The volume of the interacting region in a nucleus-nucleus collision depends on the impact parameter (b) of the collision. b is the transverse distance between the centres of the two colliding nuclei. The impact parameter can not be directly measured in a collision, nor can other geometrical quantities such as N_{part} (no. participants in a collision), N_{spec} (no. spectators in a collision) or N_{coll} (no. binary collisions) be directly measured. Instead, the measurable is *centrality*. Centrality is experimentally defined as [16]

$$c_{exp} = \frac{1}{\sigma_{vis}} \int_X^\infty dX \frac{d\sigma_{vis}}{dX'} = \frac{1}{N} \int_X^\infty dX' \frac{dN}{dX'} \quad (2.3)$$

where $d\sigma_{vis}/dX$ is the full measured distribution of X over the visible cross-section σ_{vis} , which is defined in terms of minimum bias triggers. Theoretically, centrality of a single collision is [16]

$$c_b = \frac{1}{\sigma_{inel}} \int_0^b \frac{d\sigma_{inel}}{db'} db' \quad (2.4)$$

If $\sigma_{vis} \approx \sigma_{inel}$ and $X(b)$ is reasonable [17], then $c_b \approx c_{exp}$ [16].

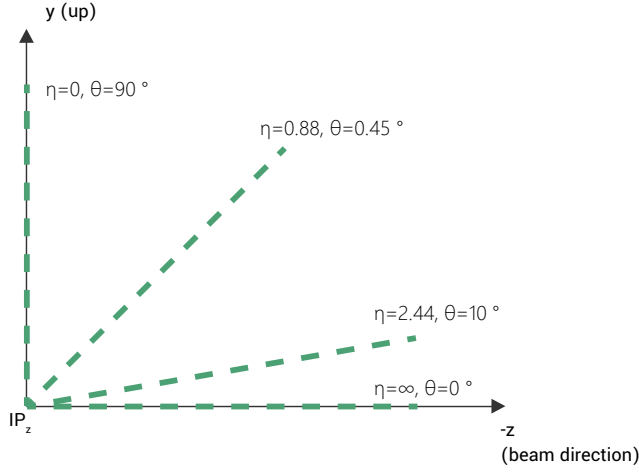


Figure 2.6: Sketch of the coordinate system at ALICE in the vertical plane. ALICE is formed as a cylinder with its centre at the interaction point (IP_z).

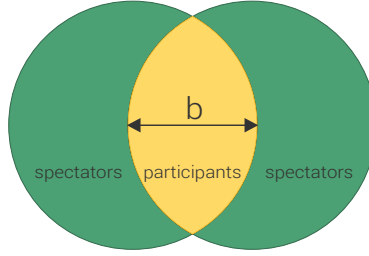


Figure 2.7: Illustration of the impact parameter in a heavy-ion collision. The spectators are the particles which are not taking part in the collision, and the participants are the particles colliding and interacting with each other.

2.2.4 Signatures of the QGP

A selection of experimental signatures of the QGP is anisotropic flow (introduced in Section 2.3), jet quenching, quarkonium, and strangeness enhancement.

Jet Quenching

Perhaps one of the most intuitive probes of the QGP is jet quenching. Already by looking at a heavy-ion collision in an event display, for example, as in Figure 2.8, it is clear that there is an asymmetry in the energies of the dijet. Jet quenching arises when a high p_T jet travels through the hot and dense medium and loses energy to the medium [18]. If a jet pair is created at the edge of the plasma then, when they travel in opposite directions, one jet will have travelled through the medium, and the other one not. In this case, the energy of the jet with the highest p_T is compared to the opposite side jet. The jet that travelled through the medium will have less energy and a wider radius due to interactions within the medium.

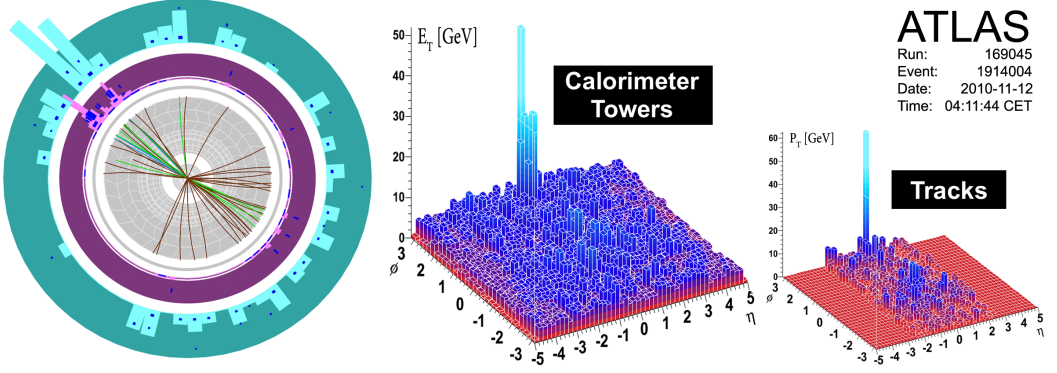


Figure 2.8: Jet quenching reported by ATLAS [19]. The event display shows a highly asymmetric dijet event, with one jet with $E_T > 100$ GeV, and no recoiling jet. The recoil can be seen instead as dispersed energy deposits widely over the azimuth.

Quarkonium

Quarkonium is a flavourless meson, whose constituents are a heavy quark and its anti-quark. It was predicted that colour deconfinement by the QGP, would lead to quarkonium suppression since a sufficiently hot deconfined medium can dissolve any quarkonium binding [20]. The different quarkonia will dissolve at different temperatures. The quarkonium suppression is therefore referred to as the "melting" of quarkonia, or the "QGP thermometer." One of the most famous probes of the category of quarkonium is the J/Ψ , which has constituents $c\bar{c}$, as in Figure 2.9. Quarkonium suppression is relative to the collisions, where we do not assume a medium (pp collisions), and therefore the ratio of yields would differ because of medium effects. The nuclear modification factor defined as [21]

$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{T_{AA} \cdot d^2\sigma_{pp}/dp_T d\eta}. \quad (2.5)$$

where T_{AA} is the nuclear overlap function in nucleus collisions, which is evaluated with a Glauber Monte Carlo calculation [22]. R_{AA} can generally understood as

$$R_{AA} = \frac{\text{yield in A + A}}{\langle N_{coll} \rangle \cdot \text{yield in p + p}}. \quad (2.6)$$

where $\langle N_{coll} \rangle$ the the average of number of elementary pp collisions in an A–A collision.

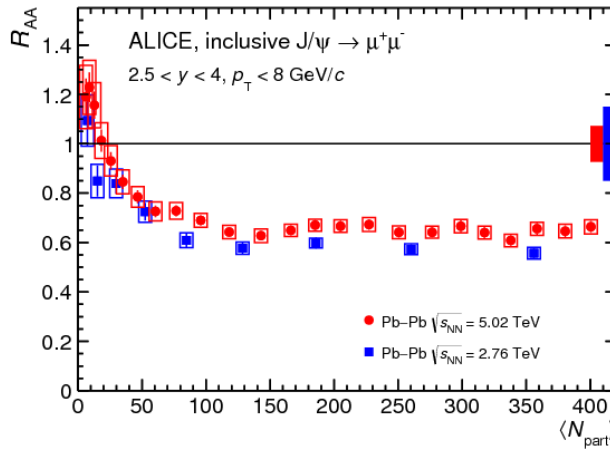


Figure 2.9: The nuclear modification factor for $J/\Psi \rightarrow \mu^+\mu^-$ at ALICE [23]. The production of J/Ψ is suppressed with respect to pp collisions at small centralities (large N_{part}). At small centralities $N_{\text{part}} < 20$, close to pp conditions, the R_{AA} is closer to one, as is expected.

Strangeness enhancement

Since strange quarks are not present as valence quarks in the initial state but are sufficiently light, they can be created in the collision by, e.g., gluon splittings ($g \rightarrow s\bar{s}$). The creation of strange quarks in the collision will increase the ratio of strange and non-strange particles [24]. In string fragmentation models, the production of strange quarks is generally reduced compared to the production of up and down quarks since the strange quark is heavier. The strangeness suppression in, e.g., p-p collisions, is an important parameter in Monte-Carlo models. Compared to the p-p collisions, there is a relative increase of strangeness production in heavy-ion collisions, as shown in Figure 2.10. The Figure shows the yield of different strange particles ($K_0, \Lambda, \Sigma, \Omega$) relative to the yield of pions.

2.2.5 Hydrodynamics

Relativistic hydrodynamics is often used for describing the evolution of the Quark-Gluon plasma. In the hydrodynamical model, it is assumed that there is a local thermodynamic equilibrium. In contrast to standard thermodynamics, relativistic hydrodynamics allows for a system whose pressure and temperature vary in space and time, although slow enough to have local thermodynamic equilibrium still [26]. This means that the mean free path of a particle between two collisions is much smaller than all the characteristic dimensions of the system [26]. These conditions for the fluid equations are also referred to as inviscid or ideal-fluid equations. For the hydrodynamical evolution, the energy-momentum is conserved,

$$\partial_\mu T^{\mu\nu} = 0 \quad (2.7)$$

where $T^{\mu\nu}$ is the energy-momentum tensor, with T^{00} is the energy density (ϵ), T^{0j} is the momentum components, T^{i0} is the energy flux components, and T^{ij} is the flux along axis i with the j^{th} component of momentum. The current is also conserved,

$$\partial_\mu N_i^\mu = 0 \quad (2.8)$$

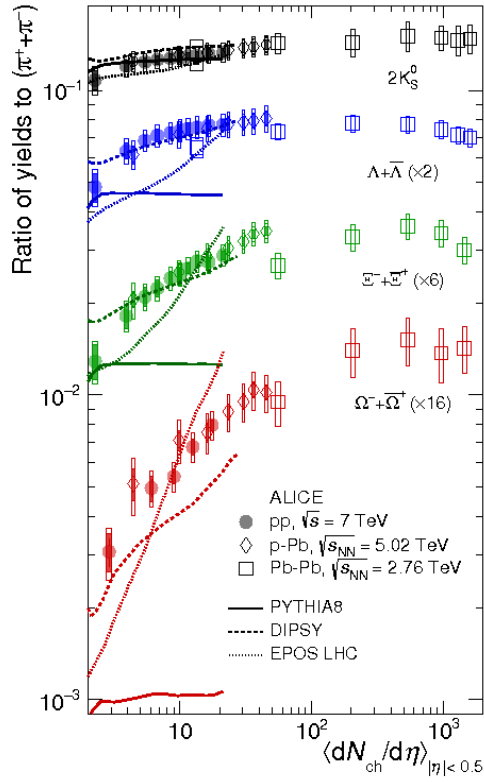


Figure 2.10: Strangeness enhancement reported by ALICE [25]. There is an increase of the yield ratios to pions as a function of $\langle dN_{ch}/d\eta \rangle$ up to $\langle dN_{ch}/d\eta \rangle \approx 100$, and then a flattening for higher values. The model calculations in the figure are from microscopic string fragmentation models (Pythia8, Dipsy, and EPOS-LHC). Of these models, DIPSY seems to describe the overall trend.

where N_i^H represents any conserved current, e.g. net baryon number current. In hydrodynamics, we have the second law of thermodynamics,

$$\partial S \geq 0 \quad (2.9)$$

ensuring that the entropy is not decreasing.

Viscous Hydrodynamics

In viscous hydrodynamics the transport coefficients are introduced, which includes the *shear* (η) and *bulk* (ζ) viscosities [27]. The bulk viscosity was initially neglected in hydrodynamical simulations, but it has been shown that a non-zero value is necessary to describe measurements of flow and transverse momentum [28]. The shear viscosity is measured by tuning of models to data and the minimum value is for charged particles $\eta/s \approx 0.08 \pm 0.05$ [29]. There may also be a temperature dependence of the shear viscosity in heavy-ion collisions [30].

2.2.6 pQCD based models

Quantum Chromodynamics (QCD) is generally applicable to heavy-ion collisions, but they are computationally costly. Simple processes with a large momentum transfer (Q), and therefore a $\alpha_s \ll 1$, can be studied with perturbative QCD (pQCD). Generally, heavy-ion models are based on the following steps:

- Initial conditions
- Partonic interactions
- Conversion from the partonic to the hadronic matter
- Hadronic interactions

Although, treated differently in the models.

HIJING

Heavy Ion Jet Interaction Generator (HIJING) is a pQCD inspired Monte Carlo generator [31]. HIJING creates multiple mini jets and is combined with the Lund-type model for soft interactions. HIJING can not reproduce the flow coefficients in the data (HIJING has zero flow), and therefore the model is sometimes used as an estimator for non-flow¹. The model does not contain any flow, and therefore if a measurement of flow in HIJING gives a positive result, there is fundamentally something wrong with the method of calculating the flow coefficients.

AMPT

A Multi-Phase Transport Model (AMPT) aims to describe all stages of the heavy-ion collision [32]. AMPT tries to couple the parton evolution to the transport coefficients of hydrodynamics. The initial conditions are obtained from HIJING, and Lund strings make the hadronization phase of AMPT. AMPT does, in contrast to HIJING, produce non-zero flow coefficients. The AMPT model is available with or without string melting. In the default AMPT without string melting, the partons from the mini-jets

¹Non-flow is discussed in more detail in Chapter 3

undergo a Zhang's Parton Cascade (ZPC), and then they are recombined with their parent strings. In the AMPT model with string melting, the strings and minijets are fragmented into partons, before they are passed into ZPC.

2.3 Anisotropic Flow

Anisotropic flow refers to a measurement of the preferred direction or *collectivity* of the particles that are produced in a heavy-ion collision. In heavy-ion collisions, the rapid expansion of the system causes the particles to be boosted by a common velocity field. Spatial anisotropies arise from the overlap of the two heavy ions or fluctuations in the initial state. The spatial anisotropies cause anisotropy in the momentum space of the created particles through the evolution of the system. In recent years there have been many developments in the understanding of anisotropic flow and how to measure it. This chapter introduces flow coefficients, factorization, and decorrelation of the symmetry plane, with highlights of some of the most important flow results concerning this thesis.

2.3.1 Flow in Heavy-ion Collisions

In the case of the ions not colliding head-on, there will be an anisotropy in the initial geometrical state of the collision, which will result in an almond shape of interacting particles. Due to the pressure gradients being more significant in the x -direction than in the y -direction, the medium will have a more substantial expansion along x , see Figure 2.11.

The anisotropic flow measurements and the successful descriptions from hydrodynamics, demonstrated that the QGP is strongly coupled, and behaves almost like a perfect fluid [33, 34]. Since the anisotropic flow is present, it means that the mean-free-path is very small [27]. If there were a long mean free path, it would correspond the particles to spread out in a more or less random direction from the collision [27]. The fluctuations are also crucial in flow measurements since the overlap is not only elliptic but also contains other shapes from initial state fluctuations of the dissolution of colliding nucleons (e.g., triangular shapes), which can come from the non-uniform density of particles in the ions.

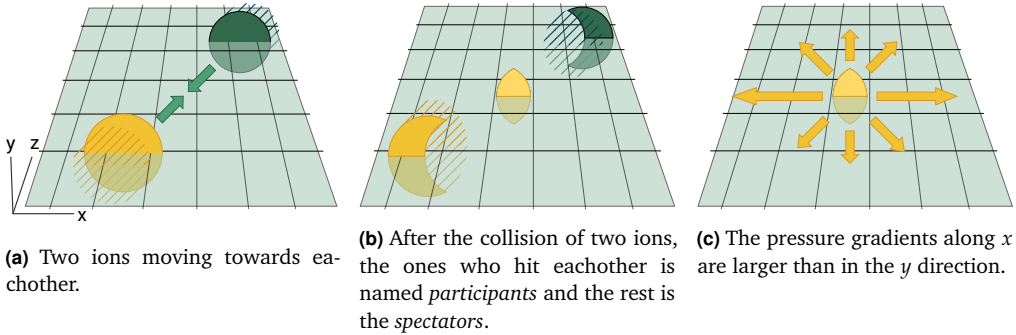


Figure 2.11: Illustration of a heavy ion collision. The plane is the *event plane*. When two heavy-ions collide, there will be an overlap of the nuclei, which will collide. After the collision, the expansion of the plasma is greater in the x -direction than in the y -direction, which gives rise to the elliptic anisotropic flow coefficient.

Anisotropic flow can be measured by performing a Fourier expansion of the azimuthal distribution of particles,

$$\frac{dN}{d\varphi d\eta} \propto f(\varphi) = \frac{1}{2\pi} \left[1 + 2 \sum_{n=1}^{\infty} v_n(\eta) \cos(n[\varphi - \Psi_n]) \right] \quad (2.10)$$

where Ψ_n is the n -th order symmetry plane, φ is the azimuthal angle of the produced particles and the coefficient v_n is the n -th order flow harmonic. To determine the anisotropy of the distributed particles, we measure the Fourier coefficients of Equation 2.10 by [35],

$$v_n = \langle \cos(n[\varphi - \Psi_n]) \rangle \quad (2.11)$$

Each Fourier or flow coefficient reflects a different type of spatial anisotropy, which are: v_1 = directed flow, v_2 = elliptic flow, v_3 = triangular flow, v_4 = quadratic flow etc. The different flow coefficients are shown in the illustration in Figure 2.12. When adding the coefficients in the Fourier expansion, the resulting function will give the shape of the final state particles, as shown in Figure 2.13.

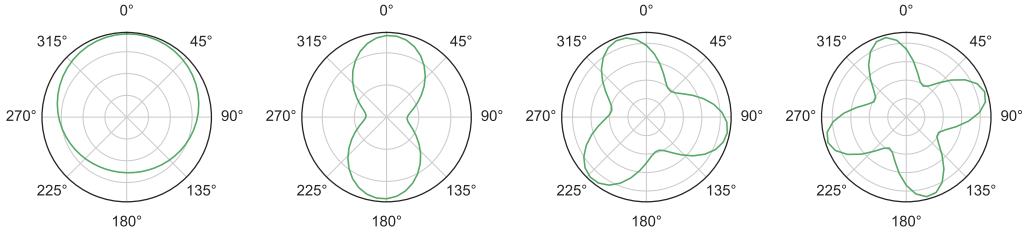


Figure 2.12: Illustration of the flow coefficients: v_1, v_2, v_3 and v_4 .

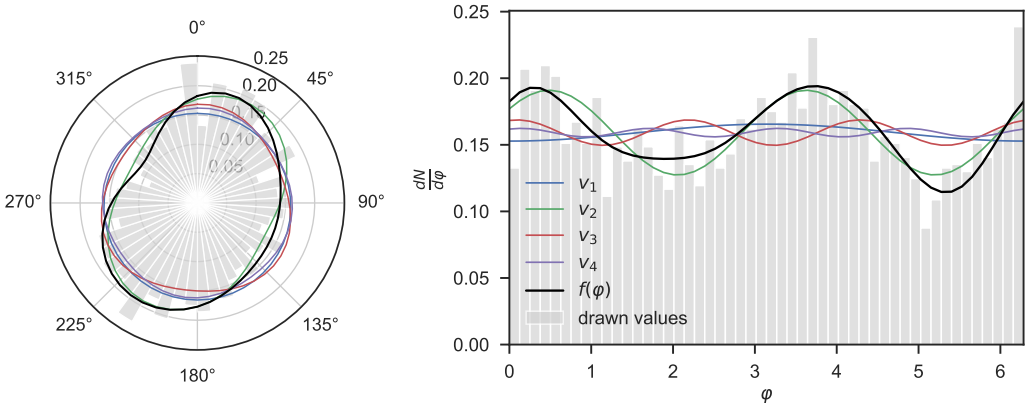


Figure 2.13: Illustration of combination of flow coefficients obtained from a toy Monte Carlo simulation.

Related to the flow coefficients in Equation 2.11, the n^{th} order complex anisotropic flow vector is

$$V_n = v_n e^{in\Psi_n} \quad (2.12)$$

such that $v_n = |V_n|$. The flow coefficients v_n are related to the initial spatial anisotropy vectors $\mathcal{E}_n$ which are [36]

$$\mathcal{E}_n = \epsilon_n e^{in\Phi_n} = \frac{\langle r_n e^{in\phi} \rangle}{\langle r_n \rangle} \quad (2.13)$$

for $n > 1$. The radial position in the transverse plane is r and ϕ is the azimuthal angle of the particles. The eccentricities vary from event to event, hence causing fluctuations in the v_n coefficients. When the nucleons within the projectiles changes from one collision to another, so does the overlapping region of the two heavy-ions. In Figure 2.14, a sketch is shown for the overlapping region of the two heavy-ions and the initial geometries.

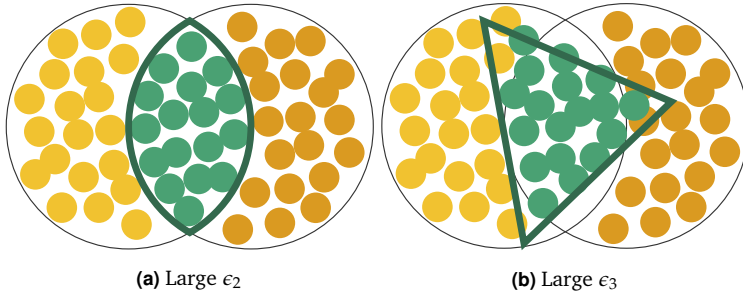


Figure 2.14: Illustration of the eccentricity of two collisions. The left figure shows an initial condition where the 2nd order eccentricity is large, while on the right figure it shows an initial condition where the 3rd order eccentricity is large.

2.3.2 Measurements of Anisotropic Flow

Early studies of anisotropic flow mainly focused on elliptic flow (second harmonic flow) v_2 , which originates from the almond shape of the produced matter in the collision. Currently, more focus is also on the fluctuations of the flow coefficients, due to the fluctuations in the initial state of heavy-ion collisions, which includes nucleon positions and colour charges within the colliding nuclei [37]. One consequence of the fluctuations are in the magnitude of v_2 in *central collisions*. Since the almond shape is not present in central collisions by the overlap of the nuclei, the origin of v_2 is from other initial state effects. Another consequence is the presence of v_3 and v_4 at all centralities, which is also an effect caused by fluctuations [38, 39].

The centrality dependence of integrated flow at midrapidity measured by the ALICE collaboration is in Figure 2.15. The results compare v_n measured in Pb-Pb at 2.76 TeV and 5.02 TeV. The integrated flow increases as a function of centrality, up to 40-50 % in centrality. v_2 has the strongest centrality dependence, compared to v_3 and v_4 . A η -gap between the particles considered is used to suppress correlations that are not due to the collective expansion.

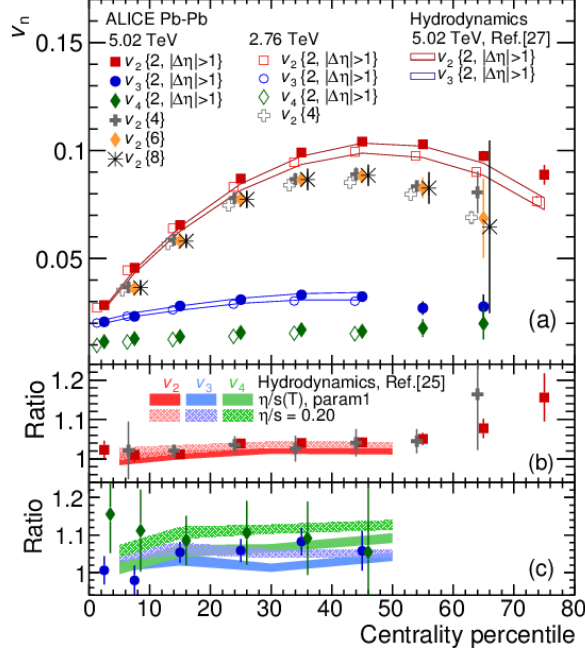


Figure 2.15: ALICE integrated flow measurements[40]. In part (a) of the figure the color lines are anisotropic flow integrated over the p_T range $0.2 < p_T < 5.0$ GeV/c, as a function of centrality for two-particle (with $|\Delta\eta| > 1$ and multi-particle cumulants. The flow coefficients, v_n , are measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ (open markers) and $\sqrt{s_{NN}} = 5.02$ TeV (closed markers). Ratios between $v_n\{2, |\Delta\eta| > 1\}$, and $v_2\{4\}$ between Pb-Pb collisions at 5.02 TeV and 2.76 TeV are in (b) and (c). Hydrodynamical calculations are also presented [41, 42].

2.3.3 Pseudorapidity dependence

The flow coefficients have a dependence on pseudorapidity; where the coefficients are higher at central rapidities than at forward rapidities [43]. The pseudorapidity dependence arises from $v_n(\eta)$, and it can contain an effect from the decorrelation of the symmetry plane, see Figure 2.16. The decorrelation of the symmetry plane is sometimes referred to as the *twist* of the symmetry plane since that is one possible origin of the decorrelation effect.

The pseudorapidity dependence on v_2 was measured by PHOBOS (Figure 2.17 (b)) in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The measurement was the first measurement of v_2 as a function of η at RHIC. The result from PHOBOS showed a "pointy" shape of $v_2(\eta)$, but in measurements at higher energies at the LHC, this trend was not found. The second, third, and fourth flow coefficients as a function of η was measured by ALICE in Pb-Pb at 2.76 TeV [43], see Figure 2.17 (a) for a comparison

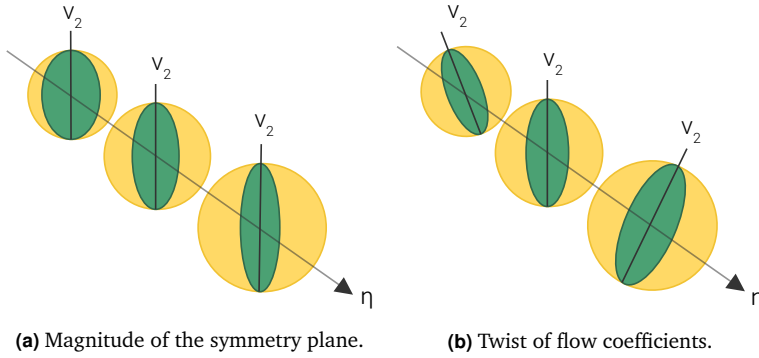


Figure 2.16: Illustration of the magnitude and twist of the flow coefficients and symmetry plane.

to 1+3D hydrodynamical calculations. The comparison shows that a hydrodynamical calculation cannot represent the data. This leads to a need for either a different parameterization of the shear viscosity η/s or further investigations into the initial state model.

In recent years the subevent method has been the preferred approach. The subevent method will correlate particles with a distance in η between them, such that the measurement will not be contaminated by non-flow. Non-flow is correlations not related to the common symmetry plane, e.g. correlations from jets and particle decays. Although separating the particles in η , complicates the measurement, since, at these distances, the measurement will be influenced by factorization of the flow coefficients and decorrelation of the symmetry plane.

CMS measured $v_n(\eta)$ in Pb–Pb and p–Pb collisions as seen in Figure 2.18. The CMS results show the centrality dependence of both v_2 and v_3 . The CMS results use three subevents, where particles from central, backward, and forward regions in η are considered.

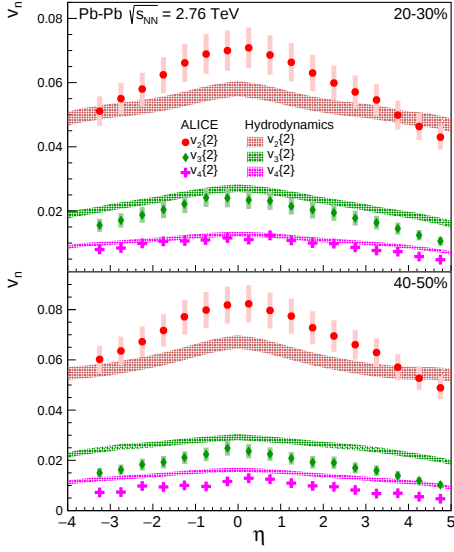
There is a noticeable difference in the pseudorapidity dependence of elliptic flow coefficients when comparing Figure 2.17 and Figure 2.18. The results from CMS, the elliptic flow dependence on pseudorapidity is smaller than from the PHOBOS and ALICE results. ATLAS has also reported a small pseudorapidity dependency (for Pb–Pb at 2.76 TeV)[45], similar to that of CMS.

The longitudinal scaling of the flow measurements can be done as a function of the rest frame of one of the colliding nuclei. The shift is approximated by $\eta - y_{beam}$ [47], where y_{beam} is the beam rapidity. In Figure 2.19, elliptic flow measurements were found to be independent of $\sqrt{s_{NN}}$, in the rest frame of the colliding nuclei.

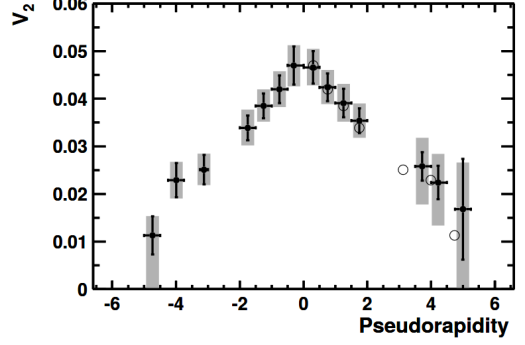
2.3.4 Factorisation of flow coefficients and decorrelation of symmetry plane

The flow measurements assume factorisation of the measurables and no decorrelation of the symmetry plane. Nevertheless, in some cases, factorisation breaking and signs of decorrelations effects of the symmetry plane can be shown [37, 48].

It is common practice to correlate particles with a large pseudorapidity gap when measuring the flow coefficients. The pseudorapidity gap can be used to remove or minimise contributions from non-flow effects, such as resonance decays and jet production. The pseudorapidity gap method, however, does assume that flow coefficients at different rapidities can be factorised. If the assumption



(a) $v_2\{2\}$, $v_3\{2\}$, and $v_4\{2\}$ as a function of η measured with ALICE [43]. The data is compared to a hydrodynamical calculation.



(b) Elliptic flow, averages over centrality, measured by PHOBOS at RHIC in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV [44]. The black error bars are the statistical errors and the black boxes are the systematical error. The points on the negative side are reflected around $\eta = 0$ on the positive side as open circles.

Figure 2.17: Previous results from PHOBOS and ALICE.

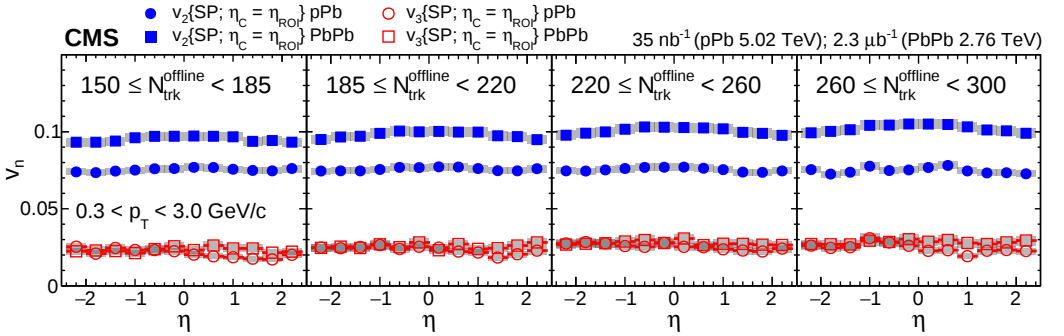


Figure 2.18: v_2 and v_3 measured in p-Pb and Pb-Pb systems with CMS at respectively $\sqrt{s_{NN}} = 5.02$ and $\sqrt{s_{NN}} = 2.76$ TeV [46]. The v_n results use the furthest available η -gap in CMS. η_{ROI} is the pseudorapidity region with the particles of interest, and η_C is one of the three reference regions (the two other reference regions are in the forward and backward regions of pseudorapidity). The grey boxes are the systematic uncertainties.

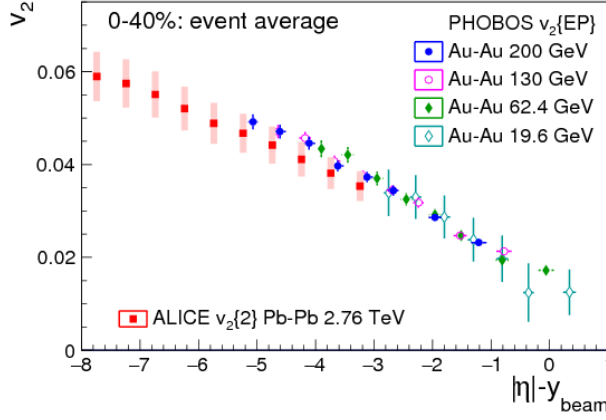


Figure 2.19: Elliptic flow as observed in the rest frame of one of the projectiles, using the beam rapidity $|\eta| - y_{beam}$, for the event average of 0 – 40% [43]. The Pb–Pb results are from ALICE [43], and the Au–Au results are from PHOBOS [47]. The vertical lines are the statistical errors, and the boxes are the systematic errors. For PHOBOS results, only the statistical errors are shown.

of independent particle emission holds, then v_n can be factorised,

$$\langle v_n(\eta_a) v_n(\eta_b) \rangle = \langle v_n(\eta_a) \rangle \langle v_n(\eta_b) \rangle \quad (2.14)$$

A measure of factorization is given by the factorization ratio

$$f_2(|\Delta\eta| = |\eta_a - \eta_b|) = \frac{\langle v_n(\eta_a) v_n(\eta_b) \rangle}{\langle v_n(\eta_a) \rangle \langle v_n(\eta_b) \rangle}. \quad (2.15)$$

which is unity if Equation 2.14 holds true. The factorisation is important when using multi-particle cumulants since these methods assume that Equation 2.14 is true. The preliminary factorization results are in Figure 2.20 from ALICE. The conclusion from these figures was that for factorisation to hold, at least a η -gap of 2 is required [49].

However, the fluctuations may also have an influence on the flow coefficients, even with the large pseudorapidity gap. This may lead to fluctuations in the final state symmetry plane at different pseudorapidities. If we take into account that there might be a pseudorapidity dependence on the symmetry planes, the flow coefficients measured using pseudorapidities η_a , and η_b are

$$\langle v_n(\eta_a) v_n(\eta_b) \rangle \neq \langle v_n(\eta_a) v_n(\eta_b) \cos(n(\Psi_n(\eta_a) - \Psi_n(\eta_b))) \rangle \quad (2.16)$$

Figure 2.21 shows results from ATLAS on the decorrelation of the symmetry plane and factorisation of the flow coefficients, where the measurement is [50]

$$r_{2|2;1}(\eta) = \frac{\langle v_n(-\eta) v_n(\eta_{ref}) \cos kn(\Psi_n(-\eta) - \Psi_n(\eta_{ref})) \rangle}{\langle v_n(\eta) v_n(\eta_{ref}) \cos kn(\Psi_n(\eta) - \Psi_n(\eta_{ref})) \rangle} \quad (2.17)$$

If η is close to η_{ref} the flow coefficients may not factorize, and if they are far apart, there might be a decorrelation effect of the symmetry plane. Another possible effect in the ATLAS result is if there are fluctuations in the magnitude of the flow coefficients at opposite η regions, i.e. if $v_n(\eta_a) \neq v_n(-\eta_a)$.

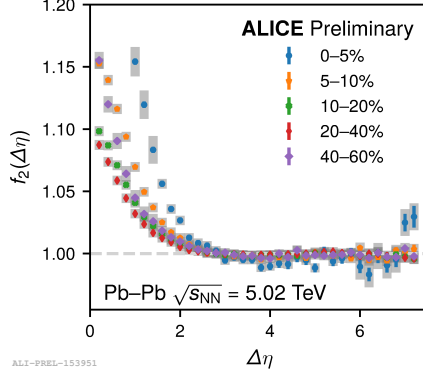


Figure 2.20: Projection of the factorization ratio $f_2(\eta_a, \eta_b)$ onto $\Delta\eta$ for various centralities [49]. The systematic uncertainties are the grey shaded areas, and the statistical uncertainties are given as the error bars. The factorization ratio shows that in the region of $|\Delta\eta| < 2$ exhibits a strong centrality dependence, while at $|\Delta\eta| > 2$ there is no centrality dependence, and the ratio is approximately one.

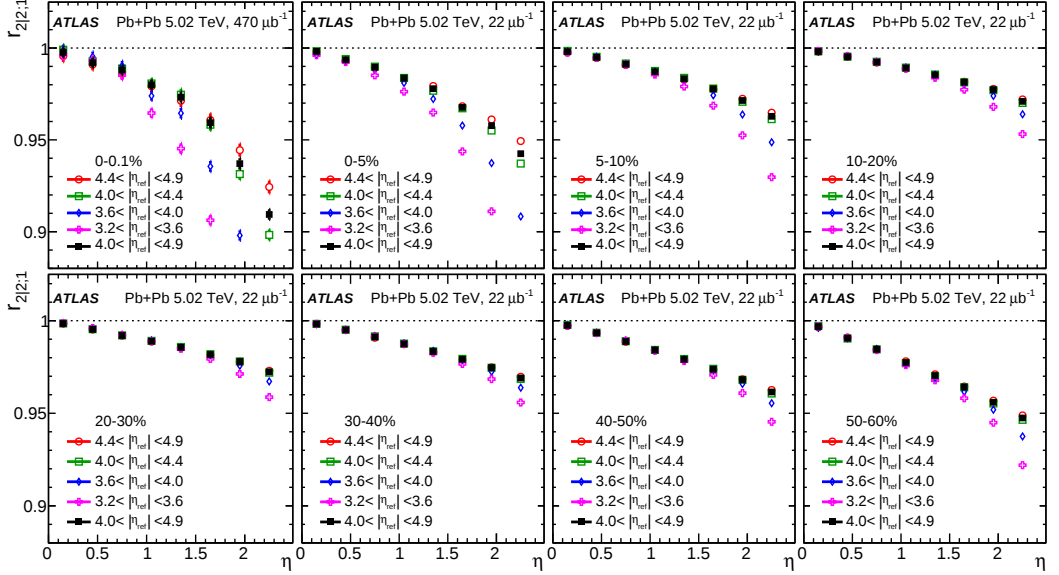


Figure 2.21: ATLAS $r_{2|2,1}$ measurements for different η_{ref} ranges with Pb–Pb at 5.02 TeV [51]. The panels show the results for different centrality ranges. The error bars are statistical errors.

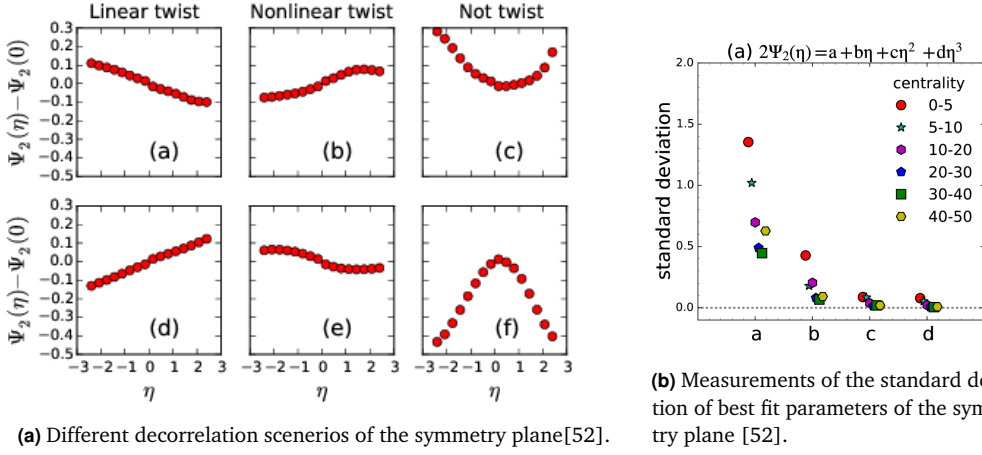
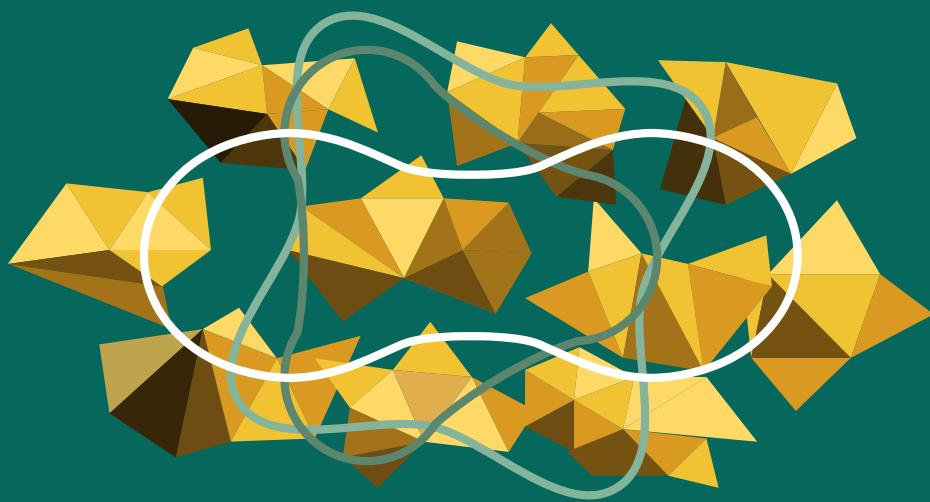


Figure 2.22: Hydrodynamical simulation results for the decorrelation of the symmetry plane [52]. The fit of the symmetry plane shows that the standard deviation is largest for a, and b. The symmetry plane has the largest decorrelation as a function of pseudorapidity in the centrality of 0 – 5%.

The results show that if the correlated particles are close in pseudorapidity, there is a larger deviation from 1 of the $r_{2,2|1}$ ratio, then if there is a large separation in pseudorapidity.

In Figure 2.22 (a) the different decorrelation cases are shown for 6 hydrodynamical events-by-event simulations [52]. To determine if the decorrelation effect was mainly from twist of the symmetry plane, or from random simulations, the event plane angle was fitted by a polynomial, $\Psi_n(\eta) = a + b\eta + c\eta^2 + d\eta^3$ [52]. Non-zero b means there is a linear twist of the event plane angles, c and d is for the non-linear twist or pure fluctuations of the event plane angles. Since the event-averaged values of the fitting coefficients cancel, the measurable is instead the standard deviations. The results are in 2.22 (b). The large value of σ_b indicates that the strong decorrelation along the longitudinal direction comes from a linear twist of the event angles [52].

III Methods



3.1 Cumulants

Methods to calculate flow coefficients are many, and always under discussion. The original method was to use the Event Plane (EP) method [35]. The method includes an explicit approximation of the symmetry plane, before the calculation of the flow coefficients. This did, however, introduce an inaccurate determination of the symmetry plane Ψ_n , which directly influenced the calculations of v_n [53]. At the moment, the most used methods are the scalar product method and the Q -cumulant method. Since the Q -cumulant method is used in this thesis, this section introduces the 2- and 4-particle cumulants, and how to obtain the flow coefficients using the cumulants.

3.1.1 Cumulants in flow analysis

The goal of using n -particle cumulants is to obtain the flow coefficients in Equation 2.11. The 2-particle and 4-particle cumulants averaged over all particles are defined as [54]

$$\langle 2 \rangle \equiv \langle e^{in(\varphi_1 - \varphi_2)} \rangle = \frac{1}{\binom{M}{2} 2!} \sum_{j,k,j \neq k}^M e^{in(\varphi_j - \varphi_k)} \quad (3.1)$$

$$\langle 4 \rangle \equiv \langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle = \frac{1}{\binom{M}{4} 4!} \sum_{j,k,l,m,j \neq k \neq l \neq m}^M e^{in(\varphi_j + \varphi_k - \varphi_l - \varphi_m)} \quad (3.2)$$

where M is the multiplicity and constraints $j \neq k$ and $j \neq k \neq l \neq m$ is to avoid correlations between the same particles. The correlations between the same particles is named *auto-correlations*. The averages of the 2- and 4-particle cumulants of all events are [54]

$$\langle \langle 2 \rangle \rangle \equiv \langle \langle e^{in(\varphi_1 - \varphi_2)} \rangle \rangle = \frac{\sum_{i=1}^N \omega_{\langle 2 \rangle, i} \langle 2 \rangle_i}{\sum_{i=1}^N \omega_{\langle 2 \rangle, i}} \quad (3.3)$$

$$\langle \langle 4 \rangle \rangle \equiv \langle \langle e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)} \rangle \rangle = \frac{\sum_{i=1}^N \omega_{\langle 4 \rangle, i} \langle 4 \rangle_i}{\sum_{i=1}^N \omega_{\langle 4 \rangle, i}} \quad (3.4)$$

with $\omega_{\langle 2 \rangle}$ and $\omega_{\langle 4 \rangle}$ as the event weights. The event weights are the number of combinations of particles pairs [55],

$$\omega_{\langle 2 \rangle} = M(M-1) \quad (3.5)$$

$$\omega_{\langle 4 \rangle} = M(M-1)(M-2)(M-3) \quad (3.6)$$

where M is the multiplicity of the over all particles in the sums.

3.1.2 Expectation values

If there are two observables x_1 and x_2 which are independently distributed, then their joint probability distribution $f(x_1, x_2)$ is [54],

$$f(x_1, x_2) = f_{x_1}(x_1) f_{x_2}(x_2), \quad (3.7)$$

However, if the observables are statistically dependent, then there exists a genuine 2-particle correlation $f_c(x_1, x_2)$, and the joint probability distribution function is then [54],

$$f(x_1, x_2) = f_{x_1}(x_1) f_{x_2}(x_2) + f_c(x_1, x_2). \quad (3.8)$$

where $f_c(x_1, x_2)$ is the genuine 2-particle probability distribution function. In terms of expectation values [54],

$$E[e^{in(\varphi_1 - \varphi_2)}] = E[e^{in\varphi_1}]E[e^{-in\varphi_2}] + E_c[e^{in(\varphi_1 - \varphi_2)}] \quad (3.9)$$

where E_c is by definition the 2-particle cumulant.

In the case of flow analysis, the observables are [54],

$$\begin{aligned} x_1 &\equiv e^{in\varphi_1} \\ x_2 &\equiv e^{-in\varphi_2} \end{aligned} \quad (3.10)$$

The the 2-particle cumulant is [54],

$$E_c[e^{in(\varphi_1 - \varphi_2)}] = E[e^{in(\varphi_1 - \varphi_2)}] - E[e^{in\varphi_1}]E[e^{in\varphi_2}] \quad (3.11)$$

For a perfect detector, e.g. with uniform azimuthal acceptance, the expectation values of Equations 3.10 and 3.10 are zero, hence [54]

$$E_c[e^{in(\varphi_1 - \varphi_2)}] = E[e^{in(\varphi_1 - \varphi_2)}]. \quad (3.12)$$

For the 4-particle cumulant, the expectations values are [54],

$$\begin{aligned} E[e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)}] &= E[e^{in(\varphi_1 - \varphi_3)}]E[e^{in(\varphi_2 - \varphi_4)}] \\ &\quad + E[e^{in(\varphi_1 - \varphi_4)}]E[e^{in(\varphi_2 - \varphi_3)}] \\ &\quad + E_c[e^{in(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)}] \end{aligned} \quad (3.13)$$

therefore to get the 4-particle cumulant, we must subtract all the 2-particle cumulants. The 2- and 4-particle unbiased estimators of the cumulants (E_c) are then as follows [54]

$$c_n\{2\} = \langle\langle 2 \rangle\rangle = \langle v_n^2 \rangle \quad (3.14)$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2 = \langle v_n^4 \rangle - 2 \cdot \langle v_n^2 \rangle^2 = -\langle v_n^4 \rangle \quad (3.15)$$

and the flow coefficients can be obtained by [54, 56]

$$v_n\{2\} = \sqrt{c_n\{2\}} \quad (3.16)$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}. \quad (3.17)$$

3.1.3 Q-cumulant

The Q-cumulant method is based on using cumulants to calculate multi-particle correlations [55], which can then be used to calculate the Fourier coefficients in Equation 2.11. Multi-particle correlations are limited by computational power since a loop is needed over all possible particle multiplets. The advantage of using cumulants is that we only need to loop over all particles once. This opens up the possibility of measuring higher-order cumulants, which would be very expensive in computational power otherwise.

The Q-cumulant method prescribes calculating the per-event Q-vector defined by,

$$Q_n = \sum_{j=1}^M e^{in\varphi_j}. \quad (3.18)$$

The Q -vector is evaluated for each flow harmonic n . This vector can be used to calculate correlations between the particles,

$$Q_n Q_n^* = |Q_n|^2 = \sum_{j,k=1}^M e^{in(\varphi_j - \varphi_k)} \quad (3.19)$$

The Q -cumulant method can be used to calculate reference flow or differential flow. The reference flow is the integrated flow, and the differential flow may be dependent on η or p_T . The advantage of using reference flow is that the particles in the differential flow are correlated with all the particles used for reference flow. This will improve the precision and decrease the statistical errors of the measurements.

Reference Flow

For the reference flow results, the single-event 2-particle correlation is,

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{\omega_{\langle 2 \rangle}}, \quad (3.20)$$

where M is the multiplicity and $\omega_{\langle 2 \rangle}$ are the weights from Equation 3.5. The correlations are subsequently *averaged* over all events. M is subtracted in the denominator to subtract the auto-correlations

$$|Q_n|^2 = \sum_{j,k=1}^M e^{in(\varphi_j - \varphi_k)} = \sum_{j,k=1, j \neq k}^M e^{in(\varphi_j - \varphi_k)} + M \quad (3.21)$$

The particles used in the sum is referred to as *reference particles* (RP). When Q is used in future calculations, it always refers to the vector with reference particles. The single-event 4-particle correlation is [55]

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2[\text{Re}[Q_{2n} Q_n^* Q_n^*]] + 2(M-2) \cdot |Q_n|^2 - M(M-3)}{\omega_{\langle 4 \rangle}} \quad (3.22)$$

where the terms after $|Q_n|^4$ are the auto-correlations.

Differential Flow

The differential flow is calculated using reference particles and *particles of interest*. The particles of interest can for instance be particles within a p_T region or η region. The 2-particle cumulant used for differential flow analysis is [55]

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q} \quad (3.23)$$

where p_n is the vector with the particles of interest, m_q is number of particles which both appear in the p_n -vector and Q_n -vector, m_p is the multiplicity of the particles of interest, and M is the multiplicity of the reference particles. Since the reference and particles of interest are being correlated, the result is

$$d_n \{2\} = \langle \langle 2' \rangle \rangle = \langle v'_n v_n \rangle \quad (3.24)$$

where the v'_n is the differential flow measurement. In order to get the differential flow measurement, the result is scaled by the reference flow measurement

$$v'_n \{2\} = \frac{d_n \{2\}}{c_n \{2\}} = \frac{\langle v'_n v_n \rangle}{\sqrt{\langle v_n^2 \rangle}} \quad (3.25)$$

assuming that the result factorises, i.e. $\langle v'_n v_n \rangle = \langle v'_n \rangle \langle v_n \rangle$.

The differential 4-particle cumulant is

$$\begin{aligned} \langle 4' \rangle &= [p_n Q_n Q_n^* Q_n^* - q_{2n} Q_n Q_n^* - 2 \cdot M p_n Q_n^* - 2 m_q |Q_n|^2 \\ &+ 7 q_n Q_n^* - Q_n q_n^* + q_{2n} Q_{2n}^* + 2 \cdot p_n Q_n^* + 2 m_q M - 6 m_q] / \omega_{\langle 4' \rangle} \end{aligned} \quad (3.26)$$

with

$$\omega_{\langle 4' \rangle} = (m_p M - 3 m_q)(M - 1)(M - 2). \quad (3.27)$$

The q_n vector is the vector containing the particles which are in both the Q - and p -vectors. To get the 4-particle cumulant, the 2-particle cumulant needs to be subtracted as in the reference flow case,

$$d_n\{4\} = \langle \langle 4' \rangle \rangle - 2 \cdot \langle \langle 2' \rangle \rangle \langle \langle 2 \rangle \rangle. \quad (3.28)$$

Since $\langle e^{in(\phi + \varphi_1 - \varphi_2 - \varphi_3)} \rangle = v'_n v_n^3$, the result is

$$v'_n\{4\} = \frac{-d_n\{4\}}{(-c_n\{4\})^{3/4}} = \frac{-\langle v'_n v_n^3 \rangle + 2 \langle v_n^2 \rangle \langle v'_n v_n \rangle}{\langle v_n^4 \rangle^{3/4}} = \frac{\langle v'_n v_n^3 \rangle}{\langle v_n^4 \rangle^{3/4}} \quad (3.29)$$

assuming factorization.

η -gaps and non-flow

Short-range correlations are highly influenced by particle decays and jets. The correlations between particles, e.g. in a jet, are high, although these correlations are not related to the common symmetry plane. The collective behaviour of the plasma is therefore not well represented by short-range correlations, and the short-range correlations are considered to be non-flow. Non-flow defined as correlations not related to the common symmetry plane. To try to exclude non-flow, a pseudorapidity gap between the particles can be used. E.g., for the calculation of reference flow, we can divide the samples into two sub-samples A and B , with $A \neq B$:

$$\langle 2 \rangle = \frac{Q_n^A Q_n^{B*}}{M_A M_B} \quad (3.30)$$

and for the differential calculation, the equation is

$$\langle 2' \rangle = \frac{p_n^A Q_n^{B*}}{m_p^A M_B} \quad (3.31)$$

which is the same as Equation 3.23, but where m_q and the q -vector are zero. Note that this method only works if $v_n^A = v_n^B$, which is only true if they are chosen from opposite η -regions in a symmetric system. With this, v'_n becomes[57]

$$v'_n\{2, |\Delta\eta| > X\} = \frac{\langle v_n^{A'} v_n^B \rangle}{\sqrt{\langle v_n^A v_n^B \rangle}} \quad (3.32)$$

where X is the distance in pseudorapidity between regions A and B .

If the system is asymmetric $v_n(-\eta) \neq v_n(\eta)$, the two sub-event method can not be used. But three sub-events may be used instead, where one does not assume equality of the flow coefficients from different pseudorapidity regions

$$v'_n\{2\} = \sqrt{\frac{\langle v_n^{A'} v_n^B \rangle \langle v_n^{A'} v_n^C \rangle}{\langle v_n^B v_n^C \rangle}} \quad (3.33)$$

since v_n^B and v_n^C cancel directly, if they factorize, i.e. $\langle v_n^B \rangle \langle v_n^C \rangle = \langle v_n^B v_n^C \rangle$.

Decorrelation of the symmetry plane

In the calculations of reference flow, and differential flow, with η -gaps, the symmetry plane is assumed to cancel out. However, if that is not the case, then the difference of the symmetry plane of the two η -regions, will have an effect on the measurement of flow. E.g. if a calculation of reference flow is made with two reference regions, one at η^A and the other at η^B , then the calculation is as follows

$$\langle 2 \rangle = \frac{Q_n^A Q_n^{B'} \cdot \cos[n(\Psi_n^A - \Psi_n^B)]}{M_A M_B} \quad (3.34)$$

where the cancellation of the cosine term only happens if $\Psi_n^A = \Psi_n^B$. If that is not the case, then there exist a decorrelation of the symmetry plane.

3.1.4 Flow fluctuations

There is a systematic bias in flow analysis with 2- and 4-particle cumulants, which arises from the selection criteria on reference particles and particles of interest. The systematic bias for the calculation of reference flow measurements is [58]

$$v_n\{2\} \equiv \langle v_n^2 \rangle^{1/2} \approx \langle v_n \rangle + \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle} \quad (3.35)$$

$$v_n\{4\} \equiv (-\langle v_n^4 \rangle + 2\langle v_n^2 \rangle^2)^{1/4} \approx \langle v_n \rangle - \frac{1}{2} \frac{\sigma_{v_n}^2}{\langle v_n \rangle} \quad (3.36)$$

where σ_v is the variance of the flow coefficients. The 2-particle correlation is systematically enhanced, and the 4-particle correlation is systematically suppressed by the same amount. When calculating the differential flow, the reference flow is used in the calculation. This causes a different bias from the fluctuations [59],

$$v'\{2\} \approx \langle v' \rangle \left(1 + \rho \frac{\sigma_{v'} \sigma_v}{\langle v' \rangle \langle v \rangle} - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle^2} \right) \quad (3.37)$$

where ρ is the correlation coefficient between reference flow and differential flow, and it is defined in the range $[-1, 1]$. Depending on the value of ρ , $v_n\{2\}$ can either be enhanced or suppressed by the fluctuations. The correlation $\rho = 1$ happens when v and v' are perfectly correlated, and $\rho = -1$ is when v and v' are entirely anti-correlated. For the 4-particle cumulant, the effect is,

$$v'\{4\} \approx \langle v' \rangle \left(1 - \rho \frac{\sigma_{v'} \sigma_v}{\langle v' \rangle \langle v \rangle} + \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle^2} \right) \quad (3.38)$$

Again, the effect of the fluctuations is dependent on the value of ρ . In Section 7.2, the flow fluctuations are considered, since $v_n\{2\}$ and $v_n\{4\}$ are influenced differently by flow fluctuations.

3.2 Generic Framework

The Generic Framework can be used to simplify otherwise complicated calculations of particle correlations. It also includes using weights on the p - and Q -vectors, which can be used for non-uniform acceptance or non-uniform efficiency. If the detector has an inefficiency in some parts of its acceptance, it can bias the final result of the flow coefficients. The Generic Framework is used in this thesis for calculating the flow coefficients.

3.2.1 Reference flow

The Generic Framework [59] uses a weighted Q -vector

$$Q_{n,l} = \sum_{k=1}^M w_k^l e^{in\varphi_k} \quad (3.39)$$

where the weights can correct for efficiency or non-uniform acceptance. From this definition it follows that,

$$Q_{-n,l} = Q_{n,l}^* \quad (3.40)$$

We define the *Numerator* (N) and the *Denominator* (D) for m -particle cumulants as

$$N\langle m \rangle_{n_1, n_2, \dots, n_m} = \sum_{\substack{k_1, k_2, \dots, k_m=1 \\ k_1 \neq k_2 \neq \dots \neq k_m}}^M \omega_{k_1} \omega_{k_2} \dots \omega_{k_m} \cdot e^{i(n_1\varphi_{k_1} + n_2\varphi_{k_2} + \dots + n_m\varphi_{k_m})}$$

$$D\langle m \rangle_{n_1, n_2, \dots, n_m} = \sum_{\substack{k_1, k_2, \dots, k_m=1 \\ k_1 \neq k_2 \neq \dots \neq k_m}}^M \omega_{k_1} \omega_{k_2} \dots \omega_{k_m} = N\langle m \rangle_{0,0,\dots,0}$$

In the case of correlation of 2-particle correlations, these reduce to

$$N\langle 2 \rangle_{n_1, n_2} = Q_{n_1,1} Q_{n_2,1} - Q_{n_1+n_2,2} \quad (3.41)$$

$$D\langle 2 \rangle_{n_1, n_2} = N\langle 2 \rangle_{0,0} = Q_{0,1}^2 - Q_{0,2} \quad (3.42)$$

The reference flow can then be calculated by

$$\langle \langle 2 \rangle \rangle = \frac{\sum_{i=1}^{\text{events}} D\langle 2 \rangle_{n, -n, i} N\langle 2 \rangle_{n, -n, i}}{\sum_{j=1}^{\text{events}} D\langle 2 \rangle_{n, -n, j}} \quad (3.43)$$

For the 4-particle cumulant, the numerator is

$$\begin{aligned} N\langle 4 \rangle_{n_1, n_2, n_3, n_4} = & Q_{n_1,1} Q_{n_2,1} Q_{n_3,1} Q_{n_4,1} - Q_{n_1+n_2,2} Q_{n_3,1} Q_{n_4,1} - Q_{n_2,1} Q_{n_1+n_3,2} Q_{n_4,1} \\ & - Q_{n_1,1} Q_{n_2+n_3,2} Q_{n_4,1} + 2Q_{n_1+n_2+n_3,3} Q_{n_4,1} - Q_{n_2,1} Q_{n_3,1} Q_{n_1+n_4,2} \\ & + Q_{n_2+n_3,2} Q_{n_1+n_4,2} - Q_{n_1,1} Q_{n_3,1} Q_{n_2+n_4,2} + Q_{n_1+n_3,2} Q_{n_2+n_4,2} \\ & + 2Q_{n_3,1} Q_{n_1+n_2+n_4,3} - Q_{n_1,1} Q_{n_2,1} Q_{n_3+n_4,2} + Q_{n_1+n_2,2} Q_{n_3+n_4,2} \\ & + 2Q_{n_2,1} Q_{n_1+n_3+n_4,3} + 2Q_{n_1,1} Q_{n_2+n_3+n_4,3} - 6Q_{n_1+n_2+n_3+n_4,4} \end{aligned} \quad (3.44)$$

This equation can be reduced when doing 4-particle correlations, where one chooses $n, n, -n, -n$

$$\begin{aligned}
N\langle 4 \rangle_{n,n,-n,-n} &= Q_{n,1} Q_{n,1} Q_{-n,1} Q_{-n,1} - Q_{2n,2} Q_{-n,1} Q_{-n,1} - 4Q_{n,1} Q_{0,2} Q_{-n,1} \\
&+ 2Q_{n,3} Q_{-n,1} + 2Q_{0,2} Q_{0,2} \\
&+ 2Q_{-n,1} Q_{n,3} - Q_{n,1} Q_{n,1} Q_{-2n,2} + Q_{2n,2} Q_{-2n,2} \\
&+ 4Q_{n,1} Q_{-n,3} - 6Q_{0,4}
\end{aligned} \tag{3.45}$$

The η -gap can also be used for 4-particle cumulants. If Q_n is chosen from region A, and Q_{-n} is chosen from region B, and the regions are not overlapping, then the 4-particle cumulant reduces to (derivation in Appendix section B.1)

$$N\langle 4 \rangle_{n,n,-n,-n} = \langle 2 \rangle_{n,n} \langle 2 \rangle_{-n,-n}. \tag{3.46}$$

3.2.2 Differential flow

The Generic Framework can also be used for the differential flow calculations. The p -vector contains the particles of interest, and the q -vector is the overlap particles. The numerator and denominator for 2-particle cumulant for differential flow with a gap are,

$$N\langle 2' \rangle_{n_1, n_2} = p_{n_1,1} Q_{n_2,1} - q_{n_1+n_2,2} \tag{3.47}$$

$$D\langle 2' \rangle_{n_1, n_2} = N\langle 2' \rangle_{0,0} \tag{3.48}$$

$$= p_{0,1} Q_{0,1} - q_{0,2}. \tag{3.49}$$

And for the 4-particle cumulant they are,

$$\begin{aligned}
N\langle 4 \rangle_{n,n,-n,-n} &= p_{n,1} \cdot Q_{n,1} \cdot Q_{-n,1} \cdot Q_{-n,1} - q_{2n,2} \cdot Q_{-n,1} \cdot Q_{-n,1} - Q_{n,1} \cdot q_{0,2} \cdot Q_{-n,1} \\
&- p_{n,1} \cdot Q_{0,2} \cdot Q_{-n,1} + 2 \cdot q_{-n,3} \cdot Q_{-n,1} - Q_{n,1} \cdot Q_{-n,1} \cdot q_{0,2} \\
&+ Q_{0,2} \cdot q_{0,2} - p_{n,1} \cdot Q_{-n,1} \cdot Q_{0,2} + q_{0,2} \cdot Q_{0,2} \\
&+ 2 \cdot Q_{-n,1} \cdot q_{n,3} - p_{n,1} \cdot Q_{n,1} \cdot Q_{-2n,2} + q_{2n,2} \cdot Q_{-2n,2} \\
&+ 2 \cdot Q_{n,1} \cdot q_{-n,3} + 2 \cdot p_{n,1} \cdot Q_{-n,3} - 6 \cdot q_{0,4}
\end{aligned} \tag{3.50}$$

$$\begin{aligned}
D\langle 4' \rangle_{n_1, n_2, n_3, n_4} &= N\langle 4' \rangle_{0,0,0,0} \\
&= p_{0,1} Q_{0,1}^3 - 3q_{0,2} Q_{0,1}^2 - 3p_{0,1} Q_{0,1} Q_{0,2} + 3q_{0,2} Q_{0,2} \\
&+ 6q_{0,3} Q_{0,1} + 2p_{0,1} Q_{0,3} - 6q_{0,4}.
\end{aligned} \tag{3.51}$$

In the results in this thesis, the Generic Framework is used to calculate the 2- and 4-particle differential flow measurements as a function of pseudorapidity.

3.3 Cumulant methods using short- and long-range η -gaps

In the standard Q -cumulant method, the reference particles can be chosen from the same region as the particles of interest. If the reference particles and particles of interest are in the same regions of pseudorapidity, the measurement of flow includes short-range correlations. Short-range correlations are usually considered as non-flow since the origin of short-range collisions can be from, e.g. jets. Therefore in the following, only methods with a η -gap between reference particles and particles of interest are introduced. When a region is split, it will influence the number of reference particles available. The preferable scenario is to have a reference region with a high number of particles, separated in η from the differential region.

The methods presented in this section will have different influences from the decorrelation effect. The methods are constructed such that some of them will minimize the decorrelation effect, and some will maximize the effect. By constructing different η -gaps, both decorrelation, and non-flow effects will be studied. The non-flow effects are mostly present in short-range correlations, and the decorrelation effects are present in long-range correlations.

In the following methods, region A , B , C , and D are used for the flow calculations. Region A is at extreme negative pseudorapidity ($\eta < A \ll 0$), B at small negative pseudorapidity ($B < \eta < 0$), C at small positive pseudorapidity ($0 < \eta < C = -B$), and D at large positive pseudorapidity ($0 \ll D < \eta$).

3.3.1 Cumulants with narrow η -gaps

In this method, the reference particles are chosen from region B or C , as seen in Figure 3.1. This will, however, limit the η -gap possible in B - C correlations, since both regions are in central pseudorapidity. Increasing the gap for B - C correlations will also decrease the statistical uncertainty for the flow measurements. For the A and D regions, the η -gap is larger, since the distance to the reference particles chosen from region B and C . In this method, the particles of interest are always correlated with the reference particles in the opposite region of η .

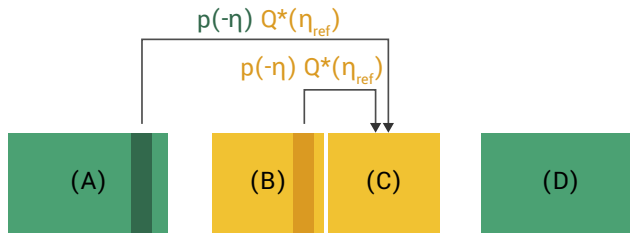


Figure 3.1: η -gap method using region A , B , C , and D . The dark slices correspond to where the particles of interest are chosen from, and the end of the arrow to where the corresponding reference particles are chosen from. E.g., particles of interest from region B are correlated with reference particles in region C .

E.g. for differential flow calculations in region B , the flow coefficients are as follows,

$$\langle v_n^B \rangle = \frac{\langle v_n^B v_n^C \rangle}{\sqrt{\langle v_n^B v_n^C \rangle}} \quad (3.52)$$

Equation 3.52 assumes that the reference flow is symmetric in η , i.e. $\langle v_n^B \rangle = \langle v_n^C \rangle$.

If one assumes no cancellation of the symmetry plane from different η regions, the coefficients are

$$\langle v_n^B \rangle \approx \frac{\langle v_n^B v_n^C \cdot \cos[n(\Psi_n^B - \Psi_n^C)] \rangle}{\sqrt{\langle v_n^B v_n^C \cdot \cos[n(\Psi_n^B - \Psi_n^C)] \rangle}} \quad (3.53)$$

Note that Ψ_n^B is the symmetry plane in the differential region and Ψ_n^B the average symmetry plane in the reference region.

3.3.2 Cumulants with wide η -gaps

The main reason to choose a method with a large η -gap, is to exclude short-range non-flow contributions to the flow coefficients. Assuming symmetry in pseudorapidity of the flow coefficients, $\langle v_n^A \rangle = \langle v_n^D \rangle$, the η -gap method can be used. In this method, the reference particles are chosen from the forward regions of pseudorapidity, which are region A and D, as seen in Figure 3.2. As in the previous method, the particles of interest are chosen to be correlated with the reference regions on the opposite side of pseudorapidity.

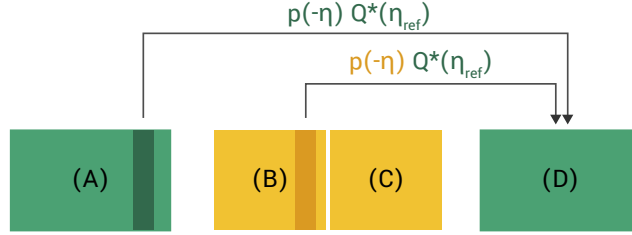


Figure 3.2: η -gap method using region A, B, C, and D. The dark slices correspond to where the particles of interest are chosen from, and the end of the arrow to where the corresponding reference particles are chosen from. E.g., particles of interest from region B are being correlated with reference particles in region D.

E.g. for v_n^B , the calculation is

$$\langle v_n^B \rangle = \frac{\langle v_n^B v_n^D \rangle}{\sqrt{\langle v_n^A v_n^D \rangle}} \quad (3.54)$$

If one considers the decorrelation effect in region B, the flow coefficients become

$$\langle v_n^B \rangle = \frac{\langle v_n^B v_n^D \cdot \cos[n(\Psi_n^B - \Psi_n^D)] \rangle}{\sqrt{\langle v_n^A v_n^D \cdot \cos[n(\Psi_n^A - \Psi_n^D)] \rangle}} \quad (3.55)$$

3.3.3 Methods with three sub-events

If one does not want to assume that symmetry of the flow coefficients ($\langle v_n^A \rangle = \langle v_n^D \rangle$ and $\langle v_n^B \rangle = \langle v_n^C \rangle$), the three subevent method can be used¹, as shown in Figure 3.3. The three sub-event method

¹For asymmetric systems like p–Pb, the flow coefficients might not be symmetric in η , and the three subevent is preferred.

considered in this thesis is

$$\langle v_n^B \rangle = \sqrt{\frac{\langle v_n^B v_n^A \rangle \langle v_n^B v_n^D \rangle}{\langle v_n^A v_n^D \rangle}}. \quad (3.56)$$

Since the particles of interest will be correlated with both v_n^A and v_n^B , the reference flow is directly cancelled, without any assumptions on forward-backward symmetry in pseudorapidity. For the B and C regions, the short-range the non-flow contributions will be low. For region B' , the calculation is

$$\langle v_n^B \rangle = \sqrt{\frac{\langle v_n^B v_n^A \rangle \cdot \cos(n(\Psi_n^B - \Psi_n^A)) \cdot \langle v_n^B v_n^D \rangle \cdot \cos(n(\Psi_n^B - \Psi_n^D))}{\langle v_n^A v_n^D \rangle \cdot \cos(n(\Psi_n^A - \Psi_n^D))}} \quad (3.57)$$

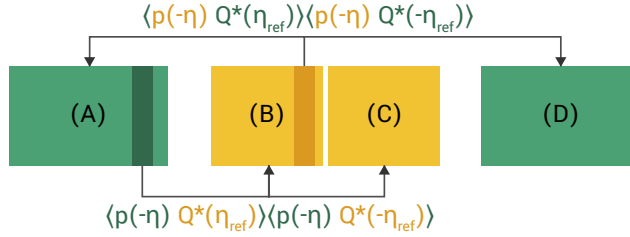


Figure 3.3: η -gap method with three subevents using region A, B, C, and D. The dark slices correspond to where the particles of interest are chosen from, and the end of the arrow to where the corresponding reference particles are chosen from. E.g., particles of interest from region B are being correlated with reference particles in regions D and A. The forward and central regions in this method do not use the same reference region, since the central regions use the forward regions as reference, and vice versa for the forward regions.

3.3.4 Decorrelation of symmetry plane

The flow fluctuations are measured by $r_{n,n}$. $r_{n,n}$ is measured between the n^{th} -order flow vectors in backward-forward intervals of η . The measurement is averaged over all events in a given centrality, and is defined by [50] [51]

$$r_{n,n}(\eta, \eta_{ref}) = \frac{\langle p_n(-\eta) Q_n^*(\eta_{ref}) \rangle}{\langle p_n(\eta) Q_n^*(\eta_{ref}) \rangle} \quad (3.58)$$

$$= \frac{\langle [v_n(-\eta) v_n(\eta_{ref})] \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{ref})) \rangle}{\langle [v_n(\eta) v_n(\eta_{ref})] \cos n(\Psi_n(\eta) - \Psi_n(\eta_{ref})) \rangle}. \quad (3.59)$$

The reference region, η_{ref} , is common to both the numerator and denominator of Equation 3.58. A schematic of the measurement is in Figure 3.4.

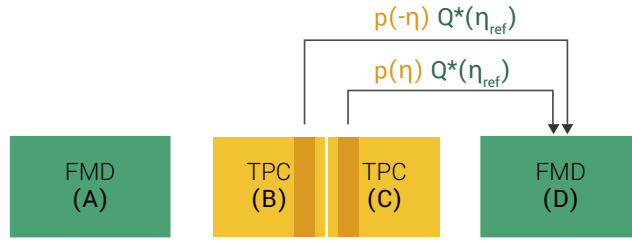
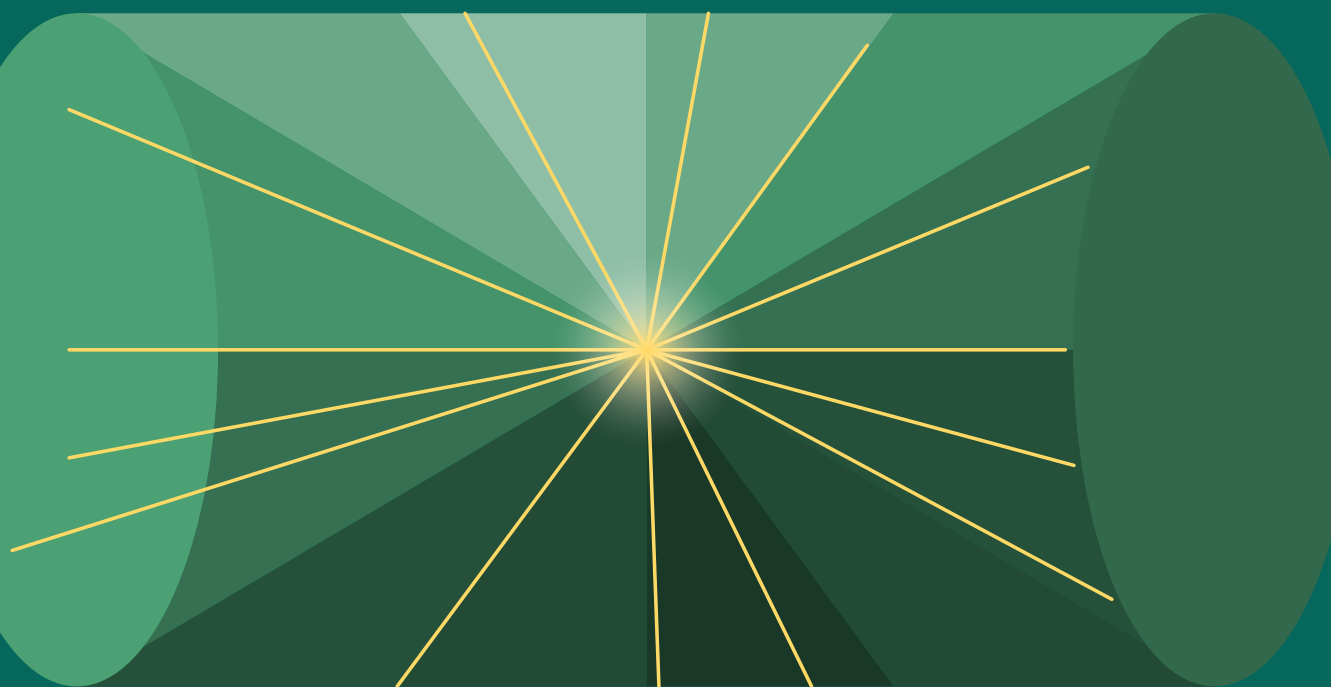


Figure 3.4: Sketch of calculation of $r_{n,n}$. The calculation of $r_{n,n}$ is using three sub-events: region B, C and D. The dark slices correspond to where the particles of interest are chosen from, and the end of the arrow to where the corresponding reference particles are chosen from. Particle from region B and C are being correlated with particles from region D.

IV Experiment



4.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is the largest accelerator in the world. The LHC is 27 km in circumference and is located at CERN, crossing the border between Switzerland and France. The particle acceleration and detector coordination system of the LHC are described in this section. The LHC was initially designed to collide lead ions and protons. In 2018 Xenon ions were also collided, and Oxygen ions might be next. The ALICE detector is the only detector at LHC specially designed for heavy-ion physics. An overview of the ALICE detector and detailed information of the sub-detectors used in this analysis is introduced in Section 4.2.

4.1.1 CERN accelerator complex

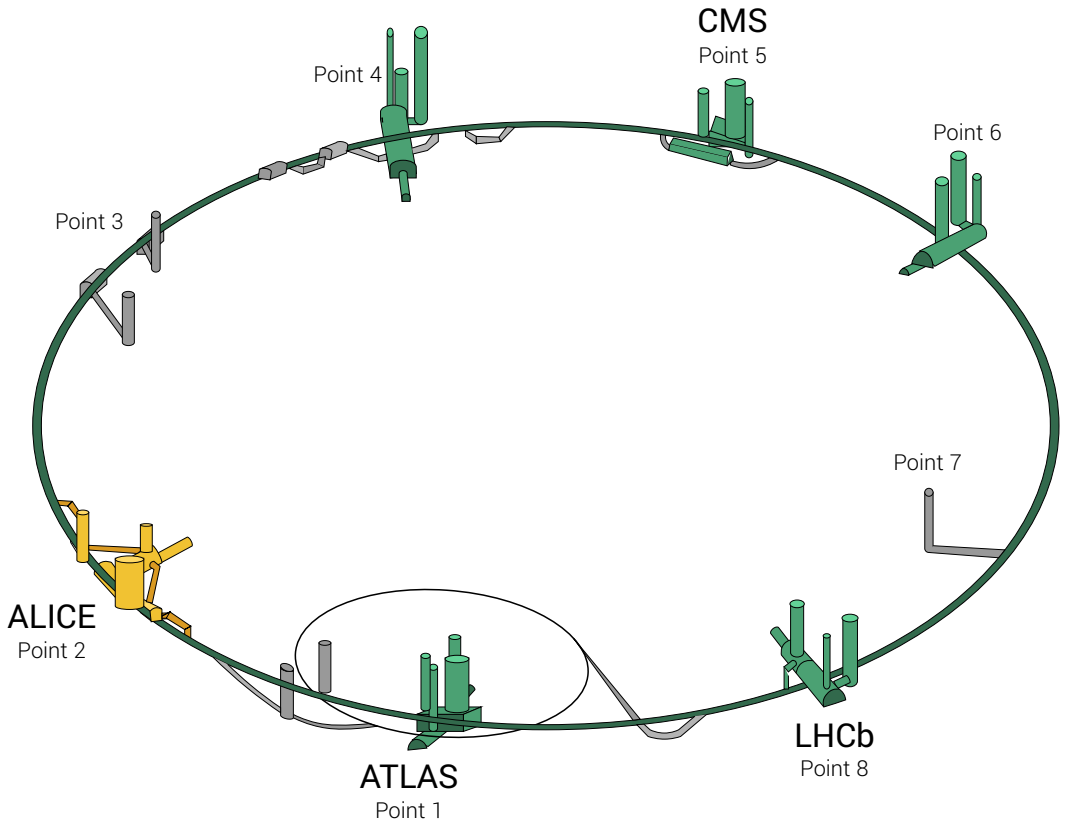


Figure 4.1: Visualization of the LHC with the four large experiments and additional access points.

Four major experiments are placed along with the Large Hadron Collider, as shown in Figure 4.1. At these four experiments, there are collision points. The CMS and ATLAS detectors are general-purpose experiments, LHCb is used to study differences in matter and anti-matter with the b quark. ALICE is an experiment for heavy-ion physics, which is the detector used for this analysis.

The beam starts to be accelerated in the Booster and is after that injected for further acceleration in the Proton Synchrotron (PS) accelerator. After the PS accelerates up to about 25 GeV (for protons), the particles are injected into Super Proton Synchrotron SPS, where they reach an energy level of 450 GeV. The final step is the Large Hadron Collider (LHC) accelerator. When the LHC is colliding protons, the protons can reach maximal energy of 7 TeV, corresponding to 14 TeV centre-of-mass energy. The lead ions nucleus constituents can get maximal energy of 5.02 TeV.

4.2 A Large Ion Collider Experiment (ALICE)

ALICE is the general-purpose, heavy-ion experiment. It focuses on the physics of QCD, the part of the Standard Model that describes the strong nuclear force. The detector can measure particles of low energies at high resolution and identify different particle species. At the LHC, there are three main collision systems available: Pb-Pb, p-Pb, and p-p. Furthermore, Xe-Xe collisions were also made in 2018. The ALICE Collaboration consists of over 1900 members from more than 170 institutions in 40 countries [60].

4.2.1 Overview

ALICE is a cylinder-shaped experiment, plus a muon arm, with the interaction point at the centre. The dimensions of the ALICE experiment is $(16 \times 16 \times 26)\text{m}^3$. Tracking detectors in the central barrel is divided into the Inner Tracking System (ITS), a six-layer silicon detector, and the Time-Projection Chamber (TPC). The Transition Radiation Detector (TRD) is also used for tracking in the central regions and improving the p_T resolution at high momentum. Near the beam pipe, the two detectors FMD and V0 are placed for measuring particle multiplicities in the forward regions and centrality and triggering, respectively.

In this thesis, the V0 detector is used for centrality determination and triggering. The FMD is used for analysis in the forward direction of pseudorapidity, and the TPC is used for the central regions of pseudorapidity. The TPC is combined with the ITS for the reconstruction of tracks. These detectors will be described in this section.

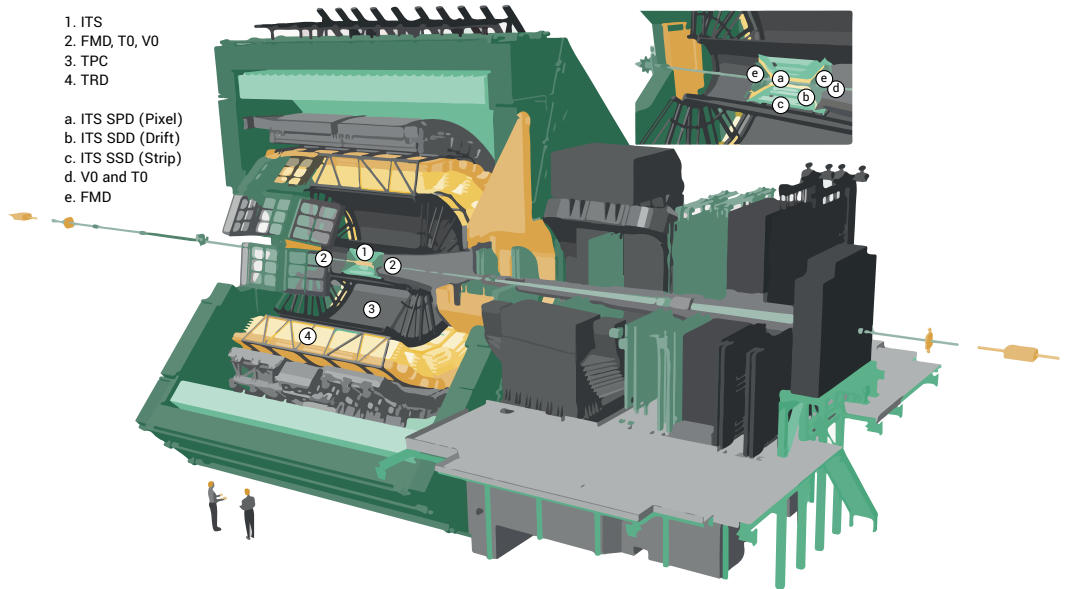


Figure 4.2: The ALICE detector. Only the detectors used in this thesis are highlighted, for a full figure see [60], from which this figure is also derived from.

Detector	Acceptance (η)	Position (m)	Dimension (m ²)	Channels
Central				
TPC	± 0.9 at $r = 2.8m$ ± 1.5 at $r = 1.4m$	0.848, 2.466	readout 32.5m ²	557568
ITS layer 1,2 (SPD)	$\pm 2, \pm 1.4$	0.039, 0.076	0.21	9.8 M
ITS layer 3,4 (SDD)	$\pm 0.9, \pm 0.9$	0.150, 0.239	1.31	133000
ITS layer 5,6 (SSD)	$\pm 0.97, \pm 0.97$	0.380, 0.430	5.0	2.6 M
Forward				
FMD1	$3.62 < \eta < 5.03$	inner: 3.2	0.266	51200
FMD2	$1.7 < \eta < 3.68$	inner: 0.834 outer: 0.752		
FMD3	$-3.4 < \eta < -1.7$	inner: -0.628 outer: -0.752		
V0-A	$2.8 < \eta < 5.1$	3.4	0.548	32
V0-C	$-1.7 < \eta < -3.7$	-0.897	0.315	32

Table 4.1: Summary of the ALICE detector subsystems used in this analysis[61].

4.2.2 Inner Tracking System (ITS)

The main purposes of the ITS is to provide high resolution tracking to detect low momentum particles, resolve decay vertices and determine the interaction point. The ITS is also used in combination with the TPC for track reconstructions. The detector surrounds the beam pipe and is split into three different detectors (in order of closeness to the beam pipe): SPD, SDD, and SSD. Using the three silicon subdetectors, the ITS can determine the interaction point position with a resolution of about $100\mu\text{m}$. Therefore the ITS is used in practically all physics analysis in ALICE. The ITS consists of six cylindrical layers of silicon detectors, located at distances from the beam pipe between 4 and 43 cm. In order to achieve a high resolution of the interaction point, Silicon Pixel Detectors (SPD) are used for the innermost two layers. The Silicon Drift Detectors (SDD) are the next two layers, and the two outmost layers are the micro-Strip Detectors (SSD).

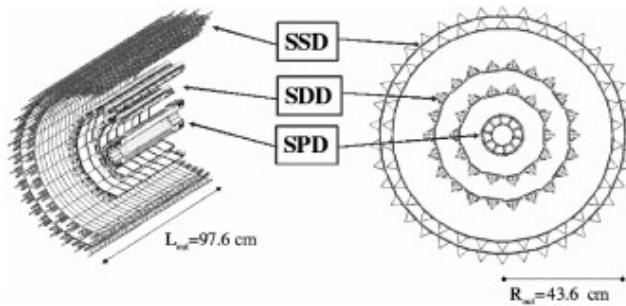


Figure 4.3: A schematic view of the inner tracking system at ALICE [62]. The inner tracking system consist of the Silicon Pixel Detector (SPD), the Silicon Drift Detector(SDD), and the Silicon Strip Detector (SSD).

4.2.3 Time Projection Chamber (TPC)

The TPC is the main tracking detector in ALICE and is placed in the central barrel. The volume of the TPC is filled with a Ne/CO₂/N₂ or an Ar/CO₂ gas combination. When a charged particle traverse through the TPC, it ionizes the gas molecules, creating electrons and positive ions along its trajectory. The TPC has a field cage, which maintains a uniform electrostatic field that causes a drift of the ionized particles. The electrons will travel towards the endcap readout chambers and the positive ions towards the central cathode.

The TPC is used (combined with the other central barrel detectors), for charged-particle momentum measurements with good track separation, particle identification, and vertex determination. In combination with the other central barrel detectors, the range in up to ± 0.9 in pseudorapidity, but the TPC can provide up to about $|\eta| = 1.5$ although with reduced momentum resolution. The measurable p_T range is from 0.1 GeV/c up to 100 GeV/c.

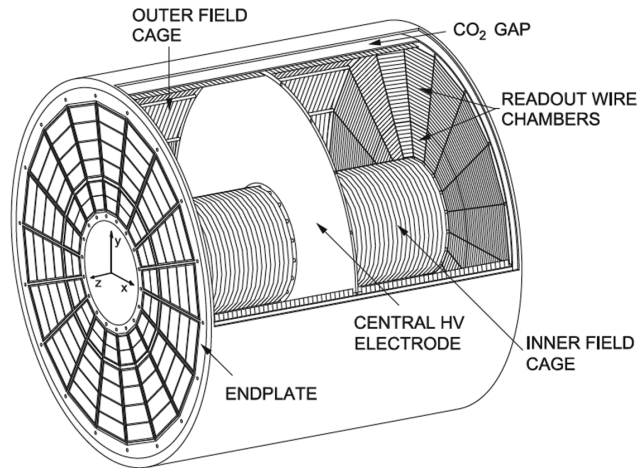


Figure 4.4: A schematic view of the Time Projection Chamber (TPC) at ALICE [63]. A high voltage electrode is at the centre of the drift volume. The endplates are divided into 18 sectors with 36 readout chambers on each sector.

4.2.4 Forward Multiplicity Detector (FMD)

The Forward Multiplicity Detector (FMD) is used for this analysis because of its high resolution in pseudorapidity in the forward rapidity regions of ALICE. The FMD consists of three sub-detectors: FMD1, FMD2, and FMD3. Both FMD2 and FMD3 have two rings: an outer ring and an inner ring. FMD1 consists of only an inner ring.

The FMD is a silicon strip detector. When a charged particle moves through the detector, the particle will deposit energy, which can then be readout. In the channels of the FMD, the deposited charge is collected, and the resulting signal is digitalized. The digitalized signal gives information about the most probable number of particles that hit the detector segment. These values do not need to be integer values.

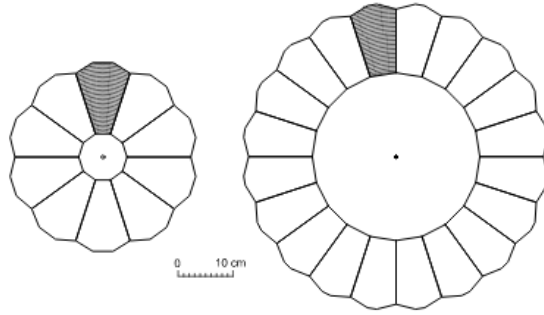


Figure 4.5: On the left, an inner ring of the FMD is shown with ten modules [64]. On the right, an outer ring of the FMD with 20 modules is shown [64].

4.2.5 V0 detector (V0A, V0C)

The VZERO detector is placed on both sides of the interaction point. The detectors are scintillator arrays, both consisting of four rings. When a charged particle traverses the scintillators, photons are created and sent to photomultipliers. The photomultipliers enhance the signal by creating a shower of electrons. Since the V0 detector has a sparse resolution in φ (see Figure 4.6), the detector is not ideal to use for differential flow analysis, but it can be used for reference regions in the cumulants. The VZERO detectors' primary purpose is to work as a trigger and also measure the centrality distribution.

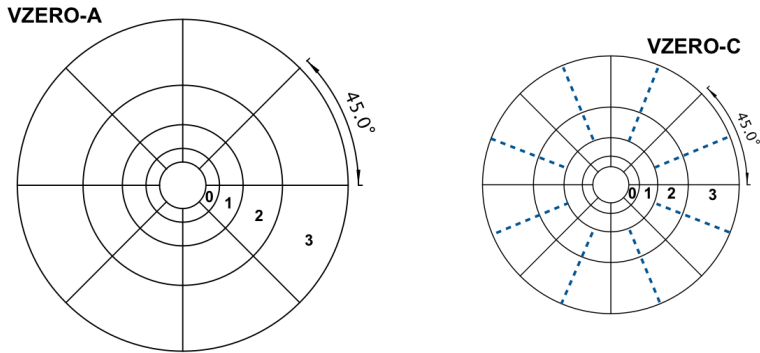


Figure 4.6: A schematic view of V0-A and V0-C [65]. Both detectors are divided into 4 rings with 8 segments. The scintillator segments on both sides of the dashed lines are connected to the same photomultiplier.

4.2.6 Reconstructions and Data formats

The main reconstruction steps from raw data to Analysis Object Data (AOD) are shown in Figure 4.7 for event generators (models) and data. When the data is recorded, files with reconstruction points are made as part of the reconstruction of particles from the signals in the detectors (*Raw data*¹ in Figure 4.7). The primary vertex measured with the SPD is used to build track seeds. After the track reconstruction, the primary vertex is recalculated with the tracks. When the tracks and primary vertex is reconstructed, the output is the Event Summary Data (ESD). The ESDs go through a filtering process, where for the FMD, the signal per strip is filtered into an object with the position (η, φ) and multiplicity of the particles. The output is the AOD object, which is the final data used for physics analysis. The exact filtering process for the FMD is in detail in Section 6.4.4. It is of particular importance when dealing with signals from secondary particles (background in the detector).

Monte Carlo simulations are used at ALICE to simulate detector effects and physics. The event generator (top level of Figure 4.7) is responsible for simulating the particles according to the theoretical model of the collisions. The *primary particles*[66] are particles generated by the event generator and are commonly used as the particles containing information about the collision and evolution of the plasma. The primary particles are therefore used to calculate model values of flow coefficients, e.g., when performing a Monte-Carlo closure test². The particles are then simulated through the detectors, creating hits. The track references are a product of the simulation through the detectors. Track references contain information on all processes; for instance, if there is a particle hit in some material, a track reference is created at the process. The references are used in Section 6.4, as an essential part of analyzing the effect of secondary particles created in material interactions. There is a separate filtering process for the track references, described in detail in Section 6.4.3. After the hits are created, the detector response is made. The detector response makes a realistic estimation of how the hits are translated into signals in the detectors. The rest of the reconstruction process is the same as for data.

¹Raw data typically consists of ADC, and TDC counts, which, combined with the knowledge of geometry, e.g. calibrations are transformed into (x, y, z, t) -points. From these coordinates, the reconstructions of tracks etc. can be made.

²The Monte-Carlo closure test is described and performed in Sections 6.4.3 and 6.3.1

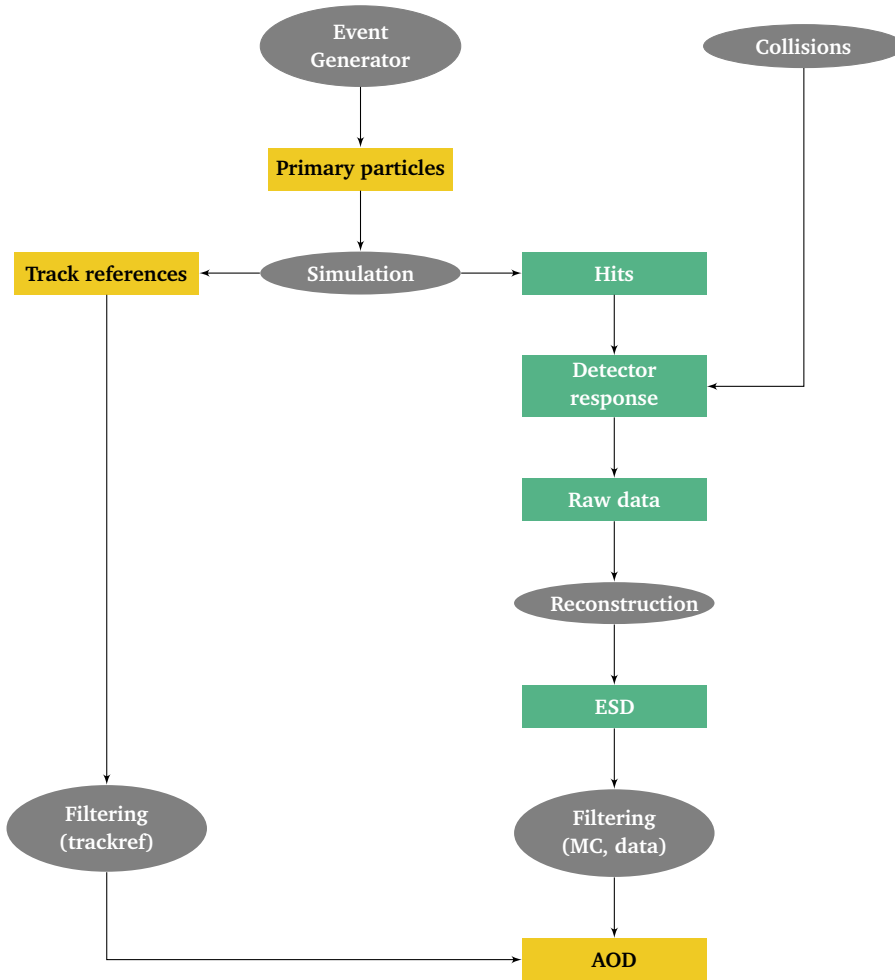


Figure 4.7: Visualization of from event generator to data format. The grey ovals are the processes, the yellow boxes are data formats used specifically in this thesis, and the green boxes are the steps between. The event generator creates the primary particles, according to the model. In the simulation step, the particle are simulated through the ALICE detectors, creating hits and track references. In the simulation, the detector responses are made, similarly to when there is an collision. After the detector reponses, the raw data is the output. The raw data goes through a reconstruction process, of which the output is the ESD objects. The ESD objects goes through a filtering process, and the AOD object is the final data object used for analysis. In this thesis, the track references are also filtered, such that the final output object is similar to the AOD object.

V Analysis



5.1 Event Selection

The event selection in this analysis uses a minimum bias trigger. This means that there are no main criteria for which kind of events which are chosen, except for the criteria that an event must have happened¹. The events are divided into vertex position and centrality estimations. There are several methods for determining centrality, depending on which detector one uses. The vertex position is only determined by the Inner Tracking System (ITS), but tight cuts can be applied to the vertex determination if needed.

5.1.1 Overview

In this analysis, the dataset LHC15o is used². LHC15o is taken with Pb–Pb at 5.02 TeV. For the AODs the event selection was carried out by the AliEventCuts class [67]. The AliEventCuts class is used for all ALICE analyses, made by specialists making the cuts on the different quantities, such as centrality and vertex. An extra cut on the correlation between V0 and FMD was applied for the selection of good events. In Figure 5.1, the vertex position, and centrality are shown before and after the event cuts. The centrality has a flat distribution before and after the event cuts. The flat distribution is what is expected from the data since there is a flat probability of the lead ions to collide with different overlaps. The vertex position is cut at $|\text{IP}_z| > 10$ since the efficiency of the detectors decreases drastically for these vertex positions since they are centred at $\text{IP}_z = 0$.

The V0AND trigger was used in this analysis for the selection of minimum bias events. The V0AND trigger requires a time coincidence between the V0A and V0C.

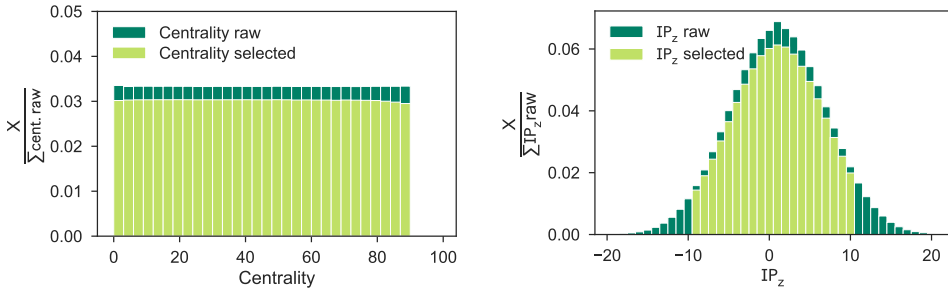


Figure 5.1: Vertex position and centrality before and after event selection.

The requirements for the events in this analysis are:

- **Trigger by minimum bias**
- **DAQ complete**
- **Centrality**
 - Multiplicity and V0M must be correlated (Figure 5.2), for rejection of pile-up events.
 - CL0 and V0M must be linearly correlated (Figure 5.3), for rejection of pile-up events.

¹Although, the efficiency or acceptance of the detectors may introduce a selection bias.

²A full list of all data, and Monte-Carlo datasets are in Appendix I.2

- **Vertex reconstruction was succesful.**

- SPD vertex reconstruction was succesful.
- Track vertex reconstruction was succesful.
- the SPD and track vertices are compatible within their uncertainties.
- The resolution of the SPD vertex must be at least 0.25 cm.
- The vertex is within $-10 \leq IP_z \leq 10$.

- **FMD**

- FMD-V0 correlations are used to reject pile-up events (Figure 5.5).
- The event has hits in the forward and backward regions of pseudorapidity in the FMD

A summary of all cuts used are in Figure 5.4, and the losses of events from various cuts. About 75 % of all input events are lost due to cuts. Most of the losses come from AliEventCuts, which are cuts set by the ALICE collaboration, and not specific to this analysis. Further cuts on this analysis are mainly from demanding good events using FMD and the SPD. These cuts are specially designed for this analysis.

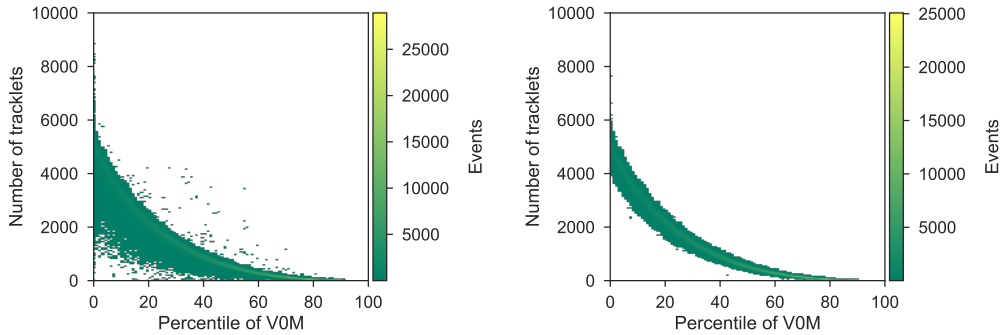


Figure 5.2: Multiplicity and V0M percentile before and after event cuts. Left: Before event cuts. Right: After event cuts.

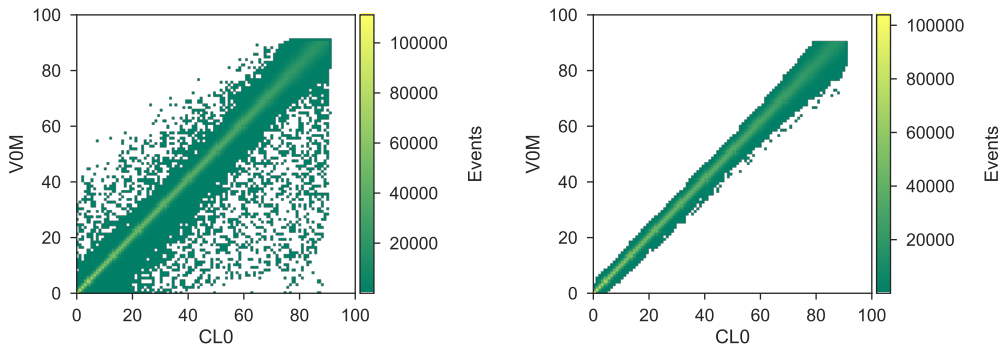


Figure 5.3: CL0 and V0M percentile before and after event cuts. Left: Before event cuts. Right: After event cuts.

5.1.2 Centrality estimators

The centrality estimators available in ALICE, which is used in this analysis are

- **CL0** is an estimator which measures centrality by using the number of clusters in the inner layer of the SPD
- **CL1** is an estimator which measures centrality by using the number of clusters in the outer layer of the SPD
- **V0A** uses the amplitude measured by the V0 detector on the A-side
- **V0M** uses the sum of amplitudes measured by the V0 detector in both A- and C-side

The V0A centrality estimator is usually only used for asymmetric systems, such as p–Pb since the multiplicity is asymmetric. V0M is used in the analysis for Pb–Pb. CL0 and CL1 is used as a variation when assigning systematics. Usually, analyses use the V0M centrality estimator since it does not have an overlap with the TPC. However, in this analysis, a bias can be caused by the overlap between the FMD and V0 detectors. In Appendix G, the difference between using V0M, CL0, and CL1 were checked, and the systematic can be found in the summary plots in the section. The bias caused by the selection of a centrality estimator was mostly below 2 %.

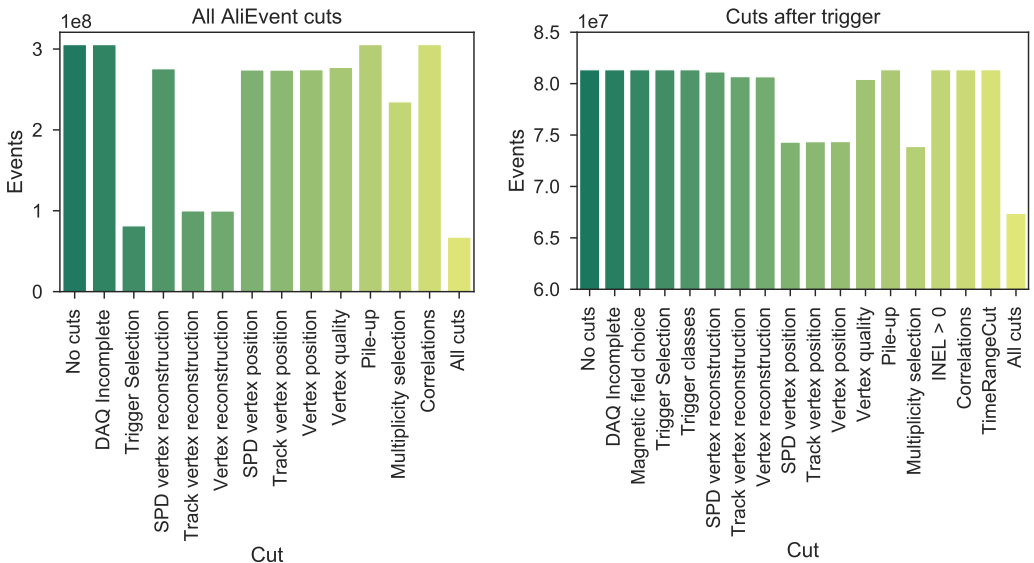


Figure 5.4: Event cuts.

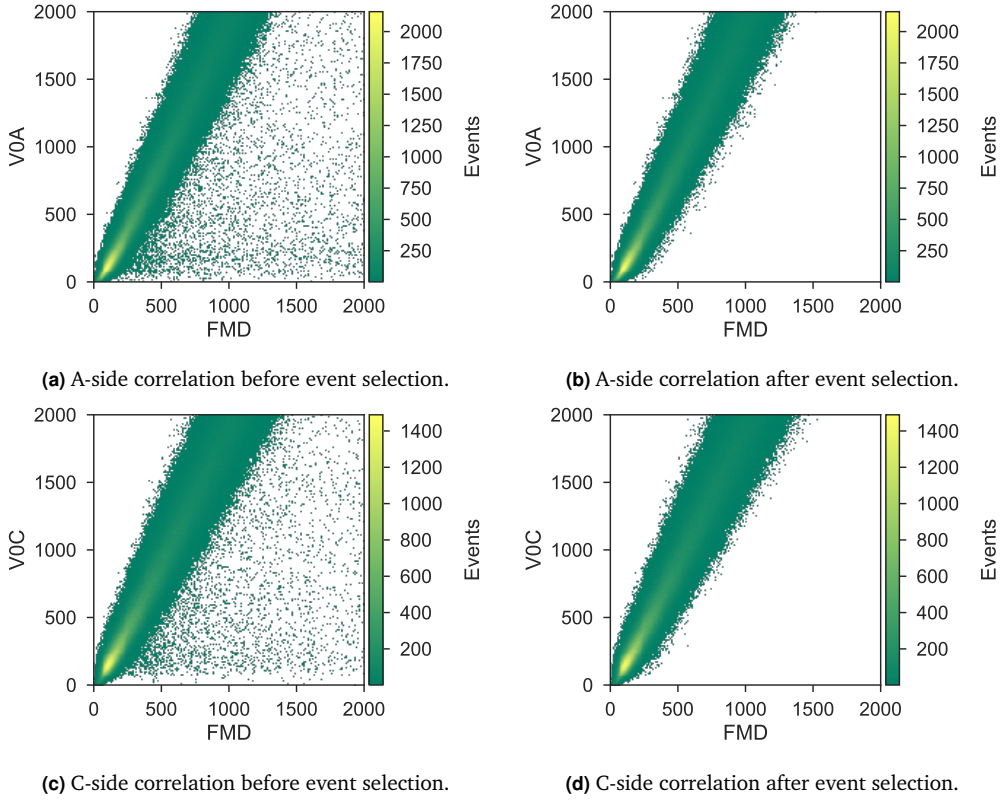


Figure 5.5: FMD hits vs. V0 hits.

5.2 Track selection

In the TPC, there are several methods for reconstructing tracks. In the FMD, there are no variations for the reconstruction of data, but it is explored in Monte-Carlo in Section 6.4.4. In this section, the qualities required for a track to be selected for analysis, and the variations of track selection for determining systematic uncertainties, are introduced.

5.2.1 Reconstructions

The ALICE framework provides different track reconstructions, among others, there are TPC only tracks, hybrid tracks, and global tracks. The *TPC only* tracks only use the information in the TPC for the reconstruction of the tracks. *Global* tracks use information in the TPC, SPD, and SDD for the reconstruction of tracks. The *hybrid* tracks use both global and TPC only information.

The *global* tracks are chosen for the analysis. The global tracks require information from both ITS and TPC for reconstruction, meaning that there must be a full track reconstructed with these detectors. Since both detectors need to have a hit for the track to be a reconstructed global track, therefore the very low p_T particles are not available; hence a cut on p_T is made at 0.2 GeV to select good tracks. The hybrid tracks are used as a systematic variation. The hybrid tracks have looser cuts than the global tracks for reconstruction qualities. The conditions on the global tracks are

- The minimum number of TPC clusters used for the track fit is 70
- The track must have at least one hit in the SPD detector
- Distance of closest approach (DCA) in the z -direction is less than 2 cm
- Distance of closest approach (DCA) in the xy -plane is less than 0.0182 scaled by the particles p_T

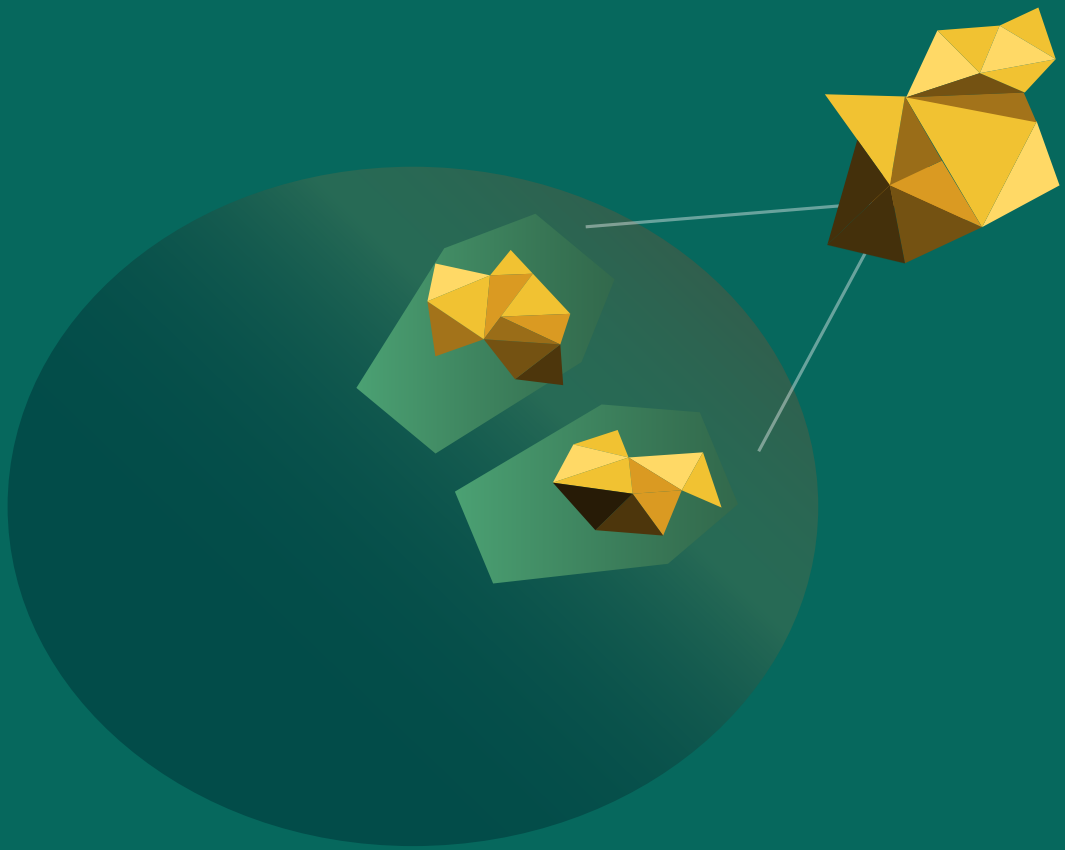
DCA is the distance of the closest approach for a track to the primary vertex position. This can both be considered in the xy -plane and in the z -plane. A p_T cut of 0.2 GeV is also applied to the particles. The efficiency goes down for high p_T particles, which can be corrected for, as seen in Section 6.3, but the limitation is more of Monte-Carlo statistics. The multiplicity for high p_T particles decreases drastically, and therefore it was not possible with the statistics available to sufficiently determine the efficiency of particles with more than 5 GeV/ c .

The variations to determine the systematic error on track selection are:

- **Track type**
 - Hybrid tracks
- **DCA**
 - DCA $_z$ (< 5 cm, < 10 cm)
 - DCA $_{xy}$ (< 15 cm, < 20 cm)
- **No. TPC clusters**
 - more than 80
 - more than 90

An overview of the systematic uncertainties assigned for track selection is in Appendix G.

VI Corrections



6.1 Overview of Corrections

The analysis corrects for detector effects and differences in the TPC and FMD. The most significant correction is the correction for secondaries in the FMD. The secondary particles can smear the azimuthal distributions of the measured particles, which will decrease the flow signal. The other large correction is for kinematic differences in the TPC and FMD. This causes a shift in the magnitude of the flow coefficients between the FMD and TPC since the detectors do not have a comparable kinematic selection of particles.

6.1.1 Uncorrected results

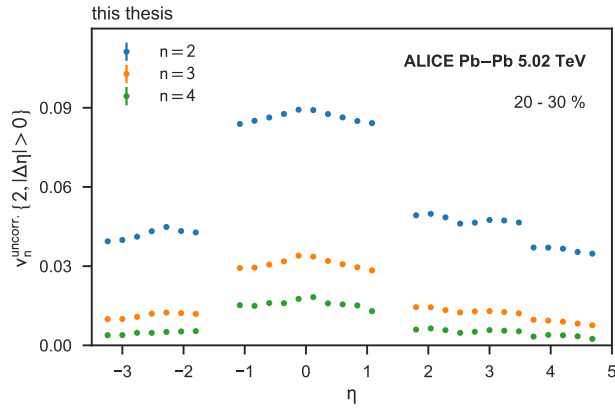


Figure 6.1: The uncorrected v_n coefficients measured by the 2-particle cumulant with TPC reference. $|\Delta\eta| > 0.0$ in TPC and $|\Delta\eta| > 1.0$ in FMD. The forward regions are affected by the background from secondary particles in the FMD. The central regions have higher values of v_n , since the acceptance of the p_T measurements in the TPC, is different to that of the FMD. Both the forward and central regions need corrections for non-uniform acceptance and efficiency.

In Figure 6.1 the uncorrected, direct result of the flow coefficients using the TPC as reference region is shown. In summary, the corrections are

- Non-uniform Acceptance
- Non-uniform efficiency
 - Extrapolation to $p_T = 0$ in the TPC
- Correction for signal of secondaries in the FMD
 - Residual correction for the reconstruction of track references in the FMD

6.2 Non-uniform Acceptance

The TPC and FMD have inefficiencies, that can depend on e.g. the vertex position of a collision, pseudorapidity, or vary over time with running conditions. The variations over time is described by run numbers, where a single run number corresponds to one data taking. The dependence of run numbers can come from if there was a particular problem in the detector for a single run, which might not otherwise be an inefficiency. These inefficiencies can be corrected for by using weights in the per-event flow-vector calculations. The effect of the corrections is a, on average, uniform distribution of the azimuth angle (φ) as the orientation of the collision plane is random in each collision. The cause of non-uniform acceptance in the data from the detectors can be because of detector inefficiencies, e.g., a broken segment. It can also be dependent on the reconstruction of tracks, in case of an inefficiency in the reconstruction algorithms.

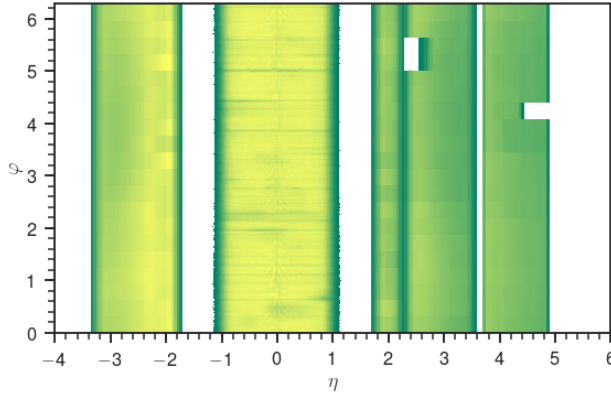


Figure 6.2: Coverage in (φ, η) with the TPC and FMD detectors. There are no corrections applied in the figure. The coverage is averaged over the range $[-10 \leq IP_z \leq 10]$.

6.2.1 Central regions

The approach to correct for non-uniform acceptance in azimuth is to count the number of particle hits over many events, and then calculate the weight that needs to be applied for the distribution of φ to be flat. The distribution of particles in the TPC is in Figure 6.3(a). This distribution has a deficiency of particles near the edges of the TPC. The edges of the TPC with the deficiencies are removed for analysis (Figure 6.3(b)), by requiring that when summing overall events, at least one particle hit must be present in each bin in azimuth. The non-uniform acceptance weights are calculated as a function of pseudorapidity (η) and the z -coordinate of the primary interaction point (IP_z)

$$\frac{d^3\omega_{NUA}}{d\eta d\varphi dIP_z} = \frac{d^3N_{ch}/d\eta d\varphi dIP_z}{d^2\langle N_{ch} \rangle_\varphi / d\eta dIP_z}. \quad (6.1)$$

The averages of the particles in the TPC along φ is in Figure 6.3, from which the final ω_{NUA} weights are calculated (Figure 6.3(d)).

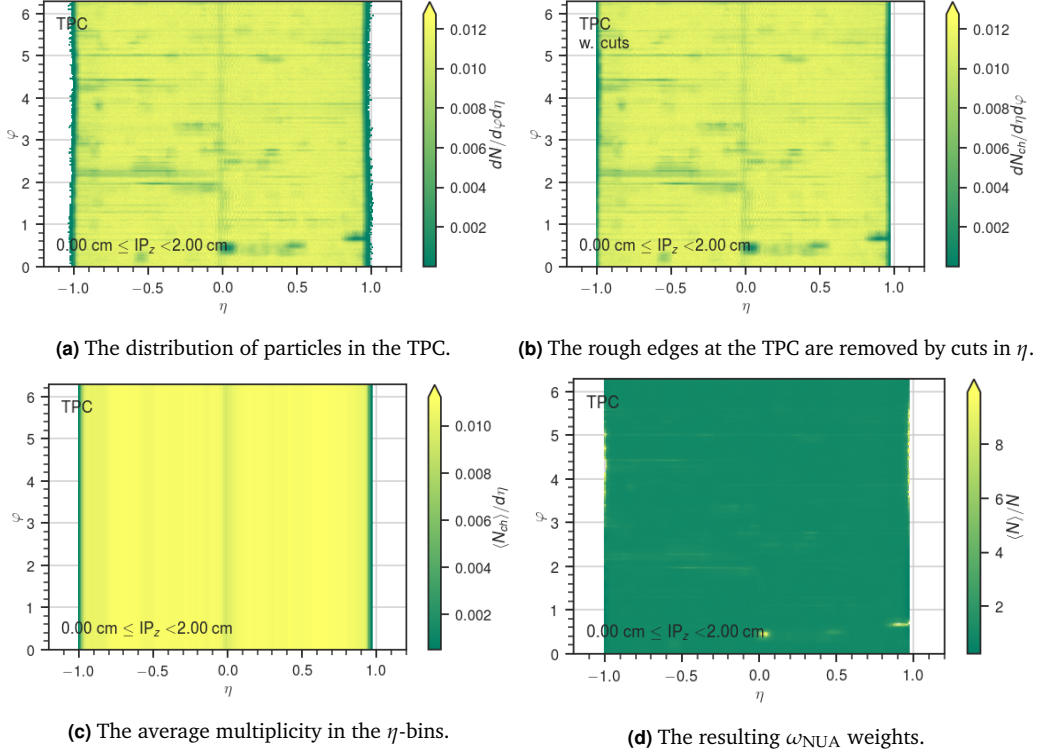


Figure 6.3: Procedure of getting NUA weights for the TPC. The particle distribution in the TPC before any corrections is in (a). In (b) the edges of the TPC is removed, by the requirement that each η -bin must have full acceptance in ϕ . In (c) the average number of particles overall events for each η -bin is calculated. The NUA weights, ω_{NUA} , are calculated from the ratio of the averaged particle distributions (c) over the particles distributions (b). The resulting weights are in (d).

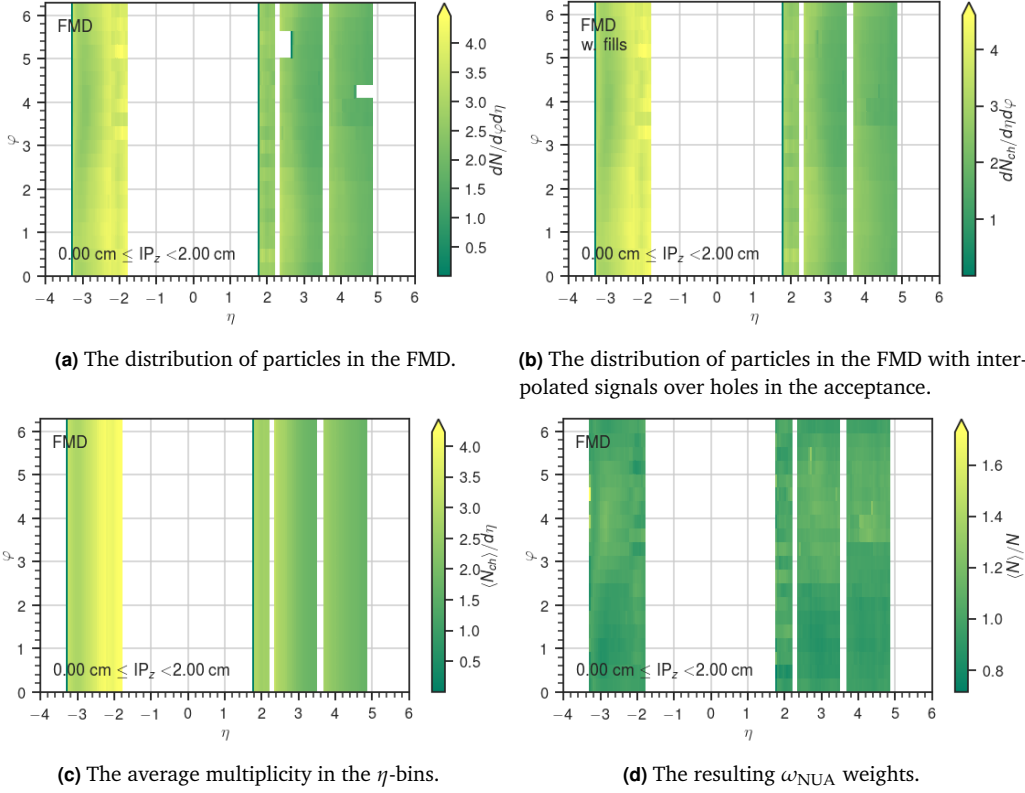


Figure 6.4: The particle distribution in the FMD before any corrections is in (a). In (b) the acceptance holes of the FMD are filled with interpolated values from neighbouring bins. In (c) the average number of particles over all events for each η -bin is calculated. The NUA weights, ω_{NUA} , are calculated from the ratio of the averaged particle distributions (c) over the particles distributions (b). The resulting weights are in (d).

6.2.2 Forward regions

The FMD consist of three sub-detectors: FMD1, 2, and 3. In FMD1 and 2, there is one acceptance hole in each, as seen in Figure 6.4. The acceptance holes need to be corrected for, and in this thesis, the chosen method is an interpolation over these holes. The interpolation is of neighbouring multiplicity weights in the same η -bin. For example, the interpolation of the acceptance hole in FMD1, the interpolation is as follows,

$$\omega_{\text{hole}}(\eta_{\text{bin}}, \phi_{\text{bin}}) = \frac{\omega(\eta_{\text{bin}}, \phi_{\text{bin}+1}) + \omega(\eta_{\text{bin}}, \phi_{\text{bin}-1})}{2}. \quad (6.2)$$

where ω is the multiplicity weight.

An analysis of the effect of the interpolation of the acceptance holes in the FMD was performed. This pseudo-experiment was done by making fake holes in the acceptance of primary particles and then interpolating the holes. The result of the test is in Figure 6.5 with v_2 calculated using the 2-particle cumulant with the TPC as reference region. The effect is only present in the η -bins with the acceptance holes, and the rest is unity. In Figure 6.6, the difference between v_n calculated with primaries, and

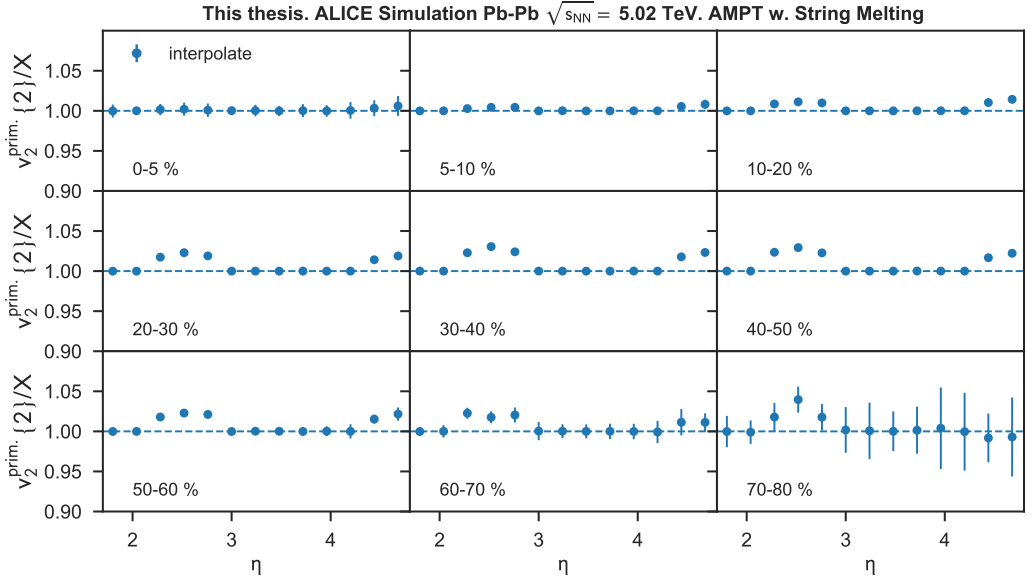


Figure 6.5: v_2 calculated using primary particles divided by v_2 calculated using primary particles with interpolation of simulated acceptance holes. For the numerator v_2 was calculated with the 2-particle cumulant using primary particles in an AMPT simulation. The denominator was calculated with the same methods and particles, but with the acceptance holes first introduced, and then corrected for. Therefore the deviation from one is the correctness of the interpolation method. Only the points containing the acceptance holes are affected by the interpolation, and the rest are one. The deviation from one is used as additional correction, and a systematic uncertainty is applied in the ranges of pseudorapidity with the acceptance holes.

v_n calculated with primary particles in the FMD with the interpolated acceptance hole is shown. The difference is applied as a correction to the data analysis and assigned as a systematic uncertainty for the η -bins affected by the acceptance holes.

Resolution in φ in the FMD

When calculating flow coefficients, the equations generally assume that the detectors have infinite resolution. But for the FMD, it has a resolution of 20 divisions in φ . The resolution of the FMD causes the flow coefficients to decrease with a small amount. Due to the resolution, a correction needs to be applied, which is given by [59]

$$E[\langle 2 \rangle_{n,-n}] = v_n^2 \frac{\sin^2(n\pi/N_{\text{sectors}})}{(n\pi/N_{\text{sectors}})^2} + v_{N_{\text{sectors}}-n}^2 \frac{\sin^2\left(\frac{(n-N_{\text{sectors}})\pi}{N_{\text{sectors}}}\right)}{\left(\frac{(n-N_{\text{sectors}})\pi}{N_{\text{sectors}}}\right)^2}. \quad (6.3)$$

In the case of n much smaller than $N_{\text{sectors}}/2$, an approximation is used instead [59],

$$E[\langle 2 \rangle_{n,-n}] \approx v_n^2 \frac{\sin^2(n\pi/N_{\text{sectors}})}{(n\pi/N_{\text{sectors}})^2} \quad (6.4)$$

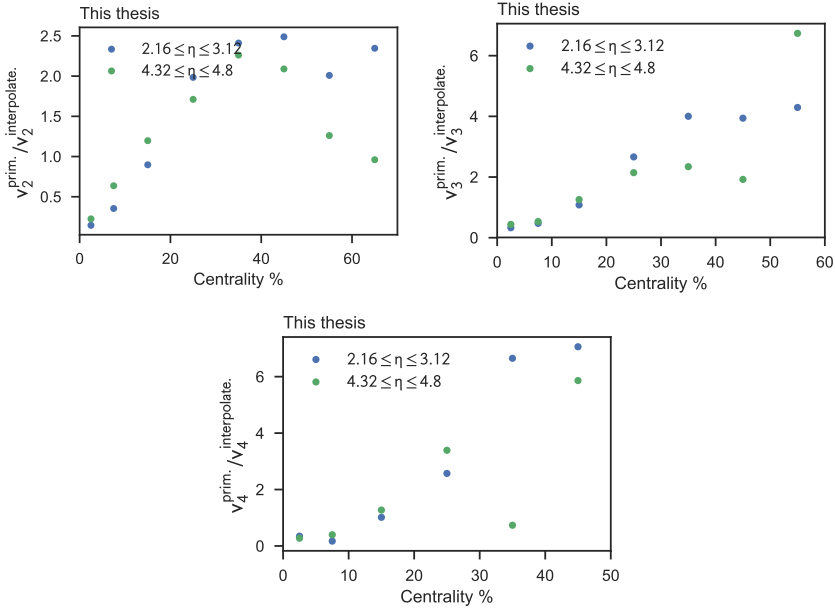


Figure 6.6: The systematic uncertainties for NUA interpolation for v_n at the η -regions affected by the acceptance holes.

The correction is e.g., about $\approx 3\%$ for v_2 . The effect of the correction is also in Figure 6.7 for the case with 20 segments in φ .

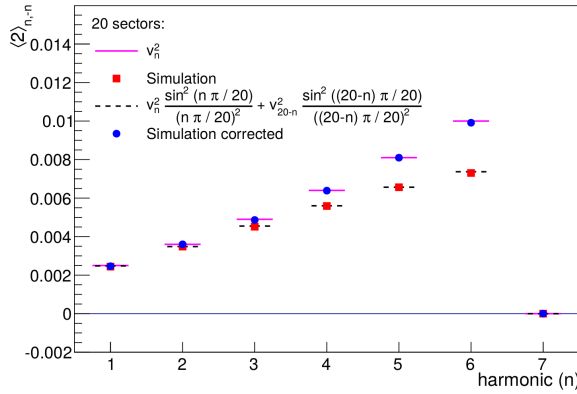


Figure 6.7: Toy model test of the resolution correction performed in Bizlandic et. al. [59].

6.2.3 φ distribution per run

The non-uniform acceptance can differ from run to run. Therefore the φ distributions are plotted for the FMD and TPC to check whether separate corrections per run are needed. In Figure 6.8 the φ distributions for the TPC for runs with a positive magnetic field is shown. The deviations of the φ distributions for different runs are within 3 %, and therefore the same weights can be used. The same is shown for the FMD in Figure 6.9. For the rest of the runs used in this thesis, see Appendix C.

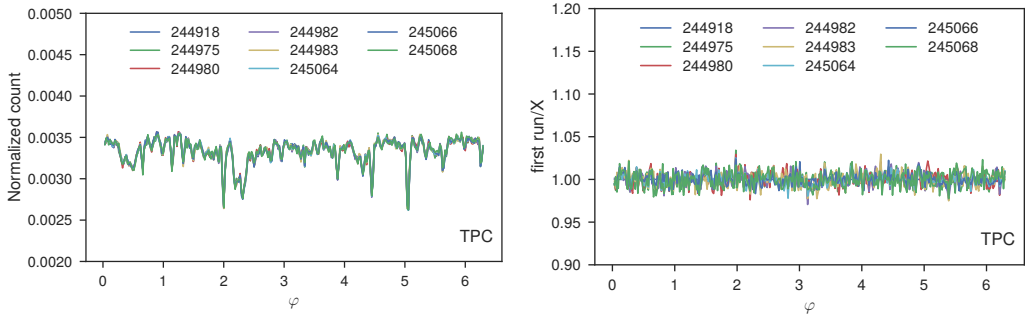


Figure 6.8: φ distributions in the TPC per runs with a positive magnetic field with Pb–Pb collisions at 5.02 TeV.

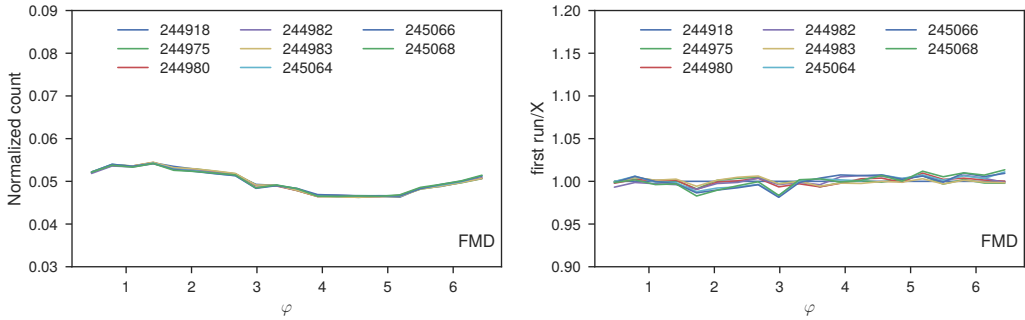
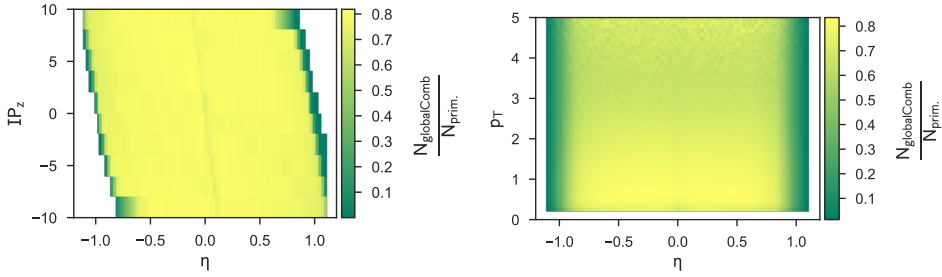


Figure 6.9: φ distributions in the FMD per runs with a positive magnetic field with Pb–Pb collisions at 5.02 TeV.

6.3 Non-uniform Efficiency

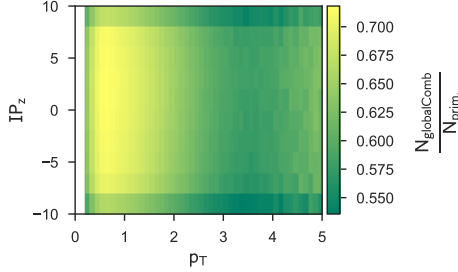
When reconstructing particle tracks, there are different choices of reconstruction and selection of the tracks. The different reconstruction algorithms efficiencies can be determined in Monte Carlo simulations with ALICE, where the signal from the primary particles is compared to the signal from the reconstructed particles. The inefficiencies that can arise from the selection and reconstruction of tracks will be corrected by calculating weights to be applied in the flow-vectors.

6.3.1 Approach



(a) The efficiency as a function of vertex position and η .

(b) The efficiency as a function of p_T and η .



(c) Efficiency as a function of vertex position and p_T .

Figure 6.10: Efficiency for global tracks in the TPC. The efficiency is low for the vertex positions of $8 < |IP_z| < 10$ cm, and it is also shown that the efficiency in p_T is lowest in the range of approximately 4 – 5 GeV/c. In each vertex position, the efficiency goes down for large $|\eta|$. There the efficiency are lower at the edges of the TPC, with $|\eta| \approx 1$.

The Monte Carlo dataset used for the efficiency studies is an AMPT production for Pb–Pb at 5.02 TeV. The AMPT production is anchored to a data taking period, by having the settings as in the real data taking (e.g. the field of the magnets). The Monte Carlo production contains information about the primary and reconstructed particle distributions. In the TPC, there are inefficiencies at the edges of the detector, which may depend on the z vertex. The TPC also has inefficiencies in p_T , since it may not be able to correctly determine the momentum of a particle.

The efficiencies are corrected in p_T , IP_z and η by the weight calculated from the ratio of reconstructed and primary tracks,

$$\frac{d\omega_{NUE}}{d\eta dz dp_T} = \frac{[dN/dp_T d\eta dz]^{reco.}}{[dN/dp_T d\eta dz]^{prim.}}. \quad (6.5)$$

The efficiency weights are shown in Figure 6.10 for *global* tracks (defined in Section 5.2).

Monte Carlo closure for non-uniform efficiency corrections

The global reconstructed and the primary tracks are used for calculation of the flow coefficients in the Monte Carlo production. Since the primary tracks represent tracks with perfect efficiency, they are used for comparison of the reconstructed tracks. The closure test includes comparing $v_n^{prim.}$ and $v_n^{recon.}$, where $v_n^{recon.}$ use the global reconstructed tracks. The in the calculation of $v_n^{recon.}$, the flow vectors are correction for non-uniform efficiency and non-uniform acceptance, by using the weights introduced in Equations 6.1 and 6.5.

In Figure 6.11, the ratio of $v_2^{prim.}$ and $v_2^{recon.}$ (with and without NUA and NUE corrections) is shown, and Figure 6.12 shows the closure test for v_3 . For v_2 , there is not a big difference between using the corrections, and not applying any corrections. This means that v_2 in the central regions of pseudorapidity are not affected greatly by NUE and NUA. The closure test for v_3 , on the other hand, shows a greater improvement when using the NUA and NUE weights in the flow vectors.

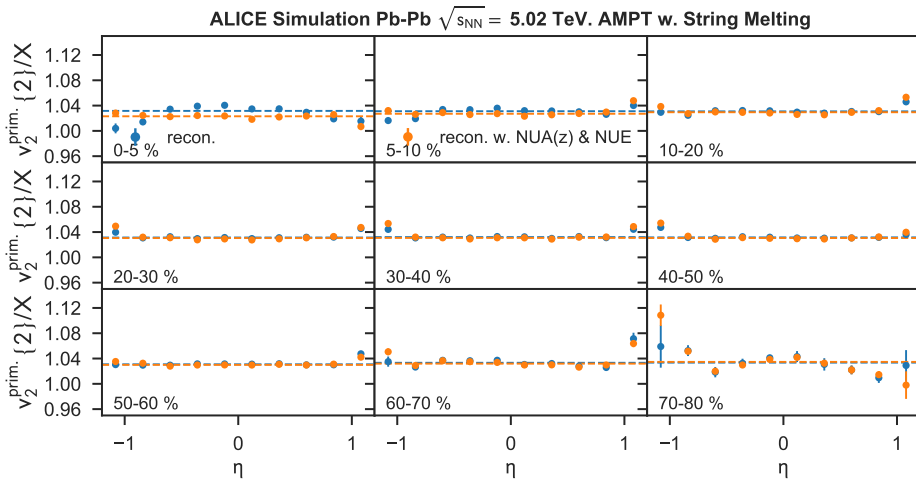


Figure 6.11: $v_2^{prim.}$ divided by the uncorrected $v_2^{recon.}$, and the corrected $v_2^{recon.}$. The calculations of v_2 with and without corrections, do not have a significant difference between them.

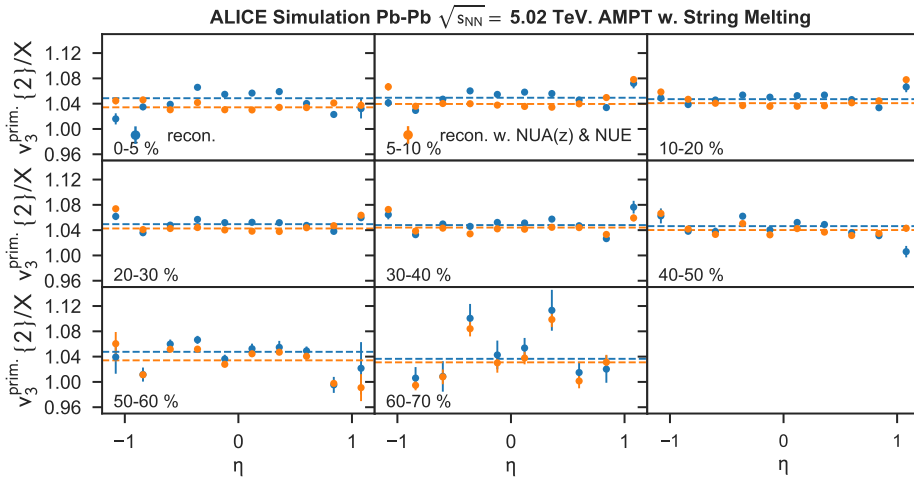


Figure 6.12: $v_3^{\text{prim.}}$ divided by the uncorrected $v_3^{\text{recon.}}$, and the corrected $v_3^{\text{recon.}}$. The calculation of v_3 with the corrected flow vectors, are closer to v_2 calculated with primary particles, than for v_2 with the uncorrected flow vectors.

6.3.2 p_T in the TPC

The FMD can measure all particles with $p_T > 0$, and the TPC can measure particles with $p_T > 0.2$. This means that the kinematic selections in the FMD and TPC are not comparable. To correct for this, a study was made in an AMPT Monte Carlo production with Pb-Pb at 5.02 TeV. The study was made by calculating v_n for primaries with no p_T cut, and primaries with $0.2 \leq p_T \leq 5$ GeV. By using the primary particles, there are no detector effects in the calculations, and the only remaining difference is from the kinematic cut. The results are in Figure 6.13. A variation was made by using the upper cut of 3 GeV instead, and the systematic uncertainty is assigned as the difference of the two methods, and also a systematic assigned for averaging over n . The correction for the difference of kinematic regions in the FMD and TPC was found to be,

$$\omega_{p_T} = \frac{v_n^{p_T > 0 \text{ GeV/c}}}{v_n^{p_T > 0.2 \text{ GeV/c}}} = 0.86. \quad (6.6)$$

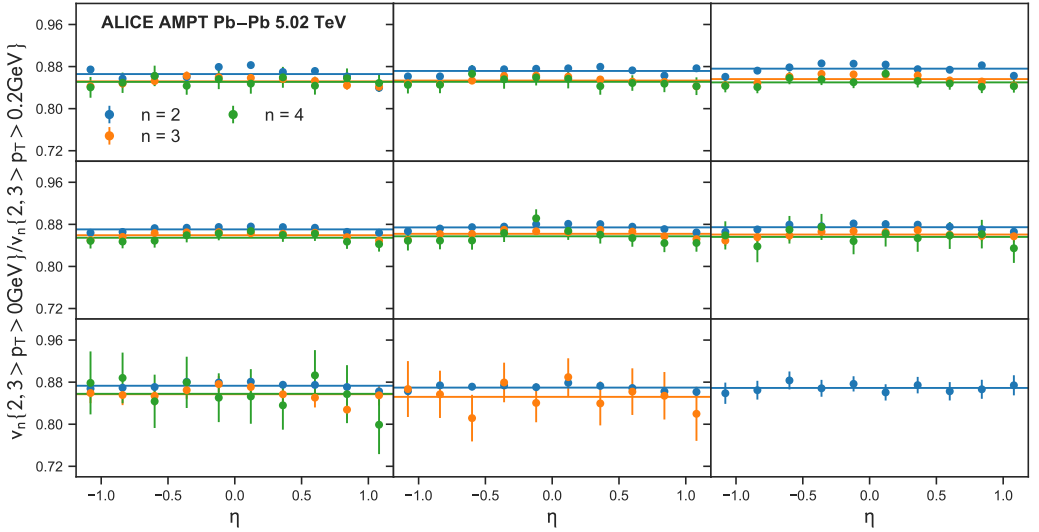


Figure 6.13: v_2 measured using the 2-particle cumulant and primary particles. The Figure shows the difference on v_2 when using a p_T cut of $0.2 < p_T < 5$ GeV/c and no p_T cut on the selection of primary particles.

6.4 Correction for secondary particles

In ALICE, secondary particles are created, which do not directly relate to the physics studied. A secondary particle can, e.g., be created because its mother particle has travelled through a detector or support material for detectors. Consequently, the secondary particle does not relate to the physics from the collision but from a material interaction. The signal from the secondary particles has to be corrected for. When a particle interacts with material, an outgoing new particle can be created. The outgoing secondary particle can have a deflection in the azimuthal direction with respect to the primary particle. This is not a problem when a detector has tracking, such that each particle track can be reconstructed. But if a detector does not have tracking capabilities, it is not possible to directly remove the signal from the secondary particle.

In this section, a new method for removing the background from secondary particles using a non-tracking detector is introduced. The Forward Multiplicity Detector (FMD) is used in this analysis, but the method is considered general and can also be used in other detectors.

6.4.1 Origin of secondary particles in the FMD

The FMD has a background signal from secondary particles, which mostly originate from interactions with material. Since the FMD does not have tracking, it is not trivial to recover the primary signal. The multiplicity distribution of charged particles and their origin is shown in Figure 6.14. The Figure illustrates that there is a clear dependence on the production of secondaries as a function of pseudorapidity. The dependency arises because of the difference in the material surrounding the FMD. In some regions of pseudorapidity, there are twice as many secondary charged particles hitting the FMD, as there are primary. In Figure 6.15, the origins of secondary particles from material interactions are illustrated.

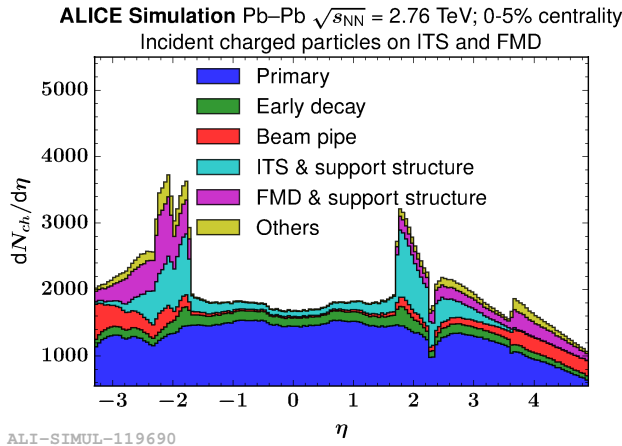


Figure 6.14: Multiplicity densities of charged particles hitting the SPD and FMD in a HIJING simulation with GEANT3 as transport code for 0 – 5% central events [49]. Most secondary particles origin from material interactions in the FMD and ITS support structure. Particles from the beam pipe also has left a significant signal in the most forward pseudorapidity regions.

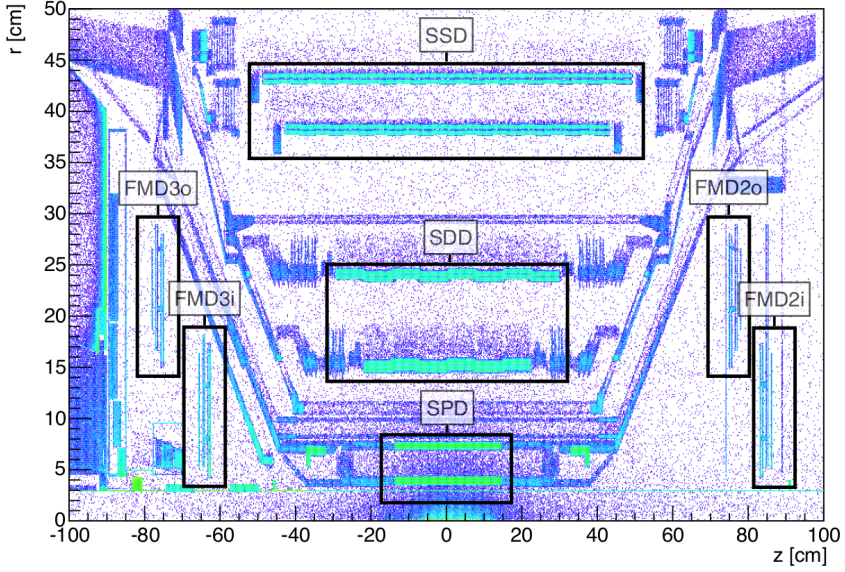


Figure 6.15: Origin of the secondary particles, which give a signal in the FMD2 and FMD3 [57]. The six ITS layers are clearly visible, as well as the support structure of the ITS also has a large contribution of the secondary particles.

6.4.2 Estimation of smearing

The approach to correct for the secondary particles in the FMD is to estimate the smearing per particle [49]. If there are no secondary particles, the probability distribution of the particles φ is a sum of delta functions

$$P(\varphi) = \sum_{\varphi_p}^{\text{no. particles}} \delta(\varphi - \varphi_p). \quad (6.7)$$

When more secondary particles are created, the signal of the primary particle is deflected in φ , as seen in Figure 6.16. Since the interest is in the change in azimuthal angles ($\Delta\varphi$) of the detected particles to calculate the flow coefficients, a correction to the correlated distribution, instead of the single-particle distributions, can be introduced. The correlated distribution is a convolution of the probability functions distributed by $P(\varphi)$

$$P_{\Delta}(\Delta\varphi) = P(\varphi_1) \circ P(\varphi_2). \quad (6.8)$$

By performing a Fourier transform of $P_{\Delta}(\Delta\varphi)$ the flow coefficients is the result. However, when there are secondaries distributed around the primaries, $P_{\Delta}(\Delta\varphi)$ is smeared by a smearing function $f(\varphi)$. The $f(\varphi)$ function will be referred to as the *smearing function*. In this analysis the particles from the FMD are correlated with the particles in the TPC. Here it is assumed that we have a perfect signal in the TPC, i.e. with no or little smearing from secondary particles. Therefore it is only one of the probability densities which are smeared by $f(\varphi)$. The secondaries around the primaries will result in the smeared probability distribution [49]

$$P(\varphi'_1) = f(\varphi_1) \circ P(\varphi_1), \quad (6.9)$$

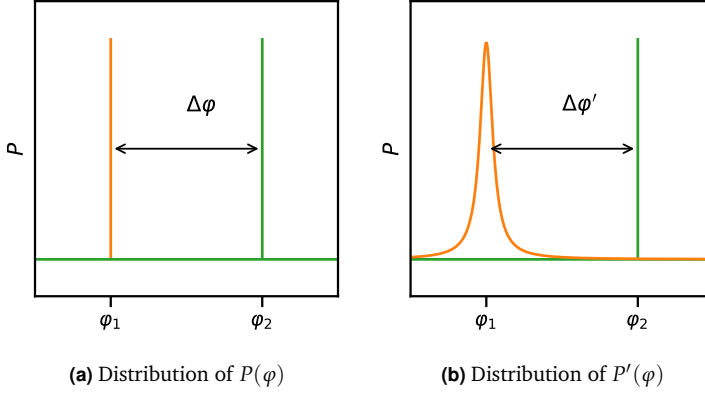


Figure 6.16: Probability distribution of two particles.

where $\circ$ denotes a convolution. The correlated distribution is then [49]

$$P'_\Delta(\Delta\varphi') = f(\varphi_1) \circ P(\varphi_1) \circ P(\varphi_2) = f(\varphi) \circ P_\Delta(\Delta\varphi). \quad (6.10)$$

In terms of the measurement of harmonics, the measured signal is¹

$$\begin{aligned} \langle \langle v'_n v_n \rangle \rangle^{\text{measured}} &= \mathcal{F}\{f(\varphi) \circ P_\Delta(\Delta\varphi)\} \\ &= \mathcal{F}\{f(\varphi)\} \cdot \mathcal{F}\{P_\Delta(\Delta\varphi)\} \\ &= \mathcal{F}\{f(\varphi)\} \cdot \langle \langle v'_n v_n \rangle \rangle^{\text{primary}}. \end{aligned} \quad (6.11)$$

where $\mathcal{F}()$ is the Fourier transformation. Therefore if we know $f(\varphi)$, we can extract $P_\Delta(\Delta\varphi)$ and obtain the flow coefficients.

To extract the smearing function, information of all interactions is needed. This information is stored in the *track references* from simulations. The track references contain information on every material interaction each particle goes through. Therefore it is possible to check if a particle hit the detector and the history of where it came from. The history of the particle is important in this case since the information of the primary mother particle is needed. If there is a hit in the FMD, we search for the origin of the particles and calculate

$$\Delta\varphi = \varphi_{\text{hit}} - \varphi_{\text{primary}}, \quad (6.12)$$

where φ_{hit} is the azimuthal angle of the particle hit in the FMD (with φ given by the resolution of the detector), and φ_{primary} is the azimuthal angle of the primary mother. A sketch of the definition of the mother particle and the secondary particle with a hit in the FMD is in Figure 6.17.

¹The convolution theorem of the Fourier transform is that a Fourier transform of a convolution becomes the product of the Fourier transforms of the convoluted functions

$$\mathcal{F}[x(t) \star y(t)] = \mathcal{F}[x(t)] \cdot \mathcal{F}[y(t)].$$

where $\star$ denotes a convolution.

When the correlations are obtained, the next step is to extract the smearing function with fits or numerical methods. The $\Delta\phi$ distribution is in Figure 6.18. Cauchy distributions are fitted to the $\Delta\phi$ distributions²

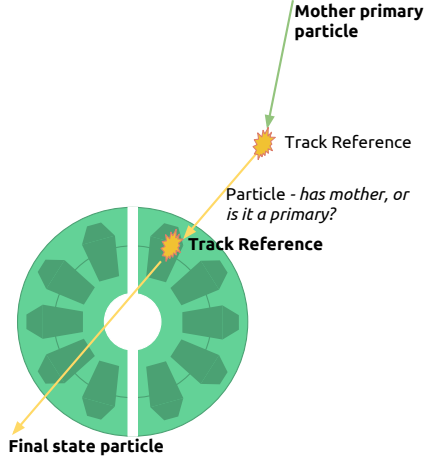


Figure 6.17: Sketch of an incoming primary particle and outgoing secondary particle with a hit in the FMD.

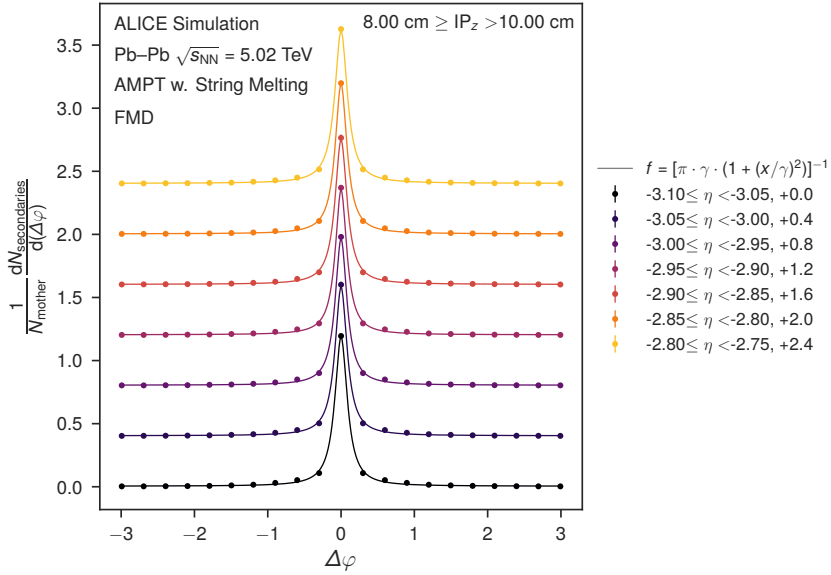


Figure 6.18: The distribution of a secondary particle around its primary mother particle. The curves are shifted by a constant, for clarity.

²Several methods were tested to extract the secondary correction, and they are described in detail in Appendix E.4. Since closure tests showed that the Fast Fourier Transform was the best method, only this correction is described in this chapter.

Fast Fourier Transform

The Fast Fourier Transform (FFT)[68] is an algorithm to calculate the discrete Fourier transform. Since the distributions in Figure 6.18 is the smearing functions, $f(\varphi)$, the result of the Fourier transform is $\mathcal{F}\{f(\varphi)\}$. As calculated in Equation 6.11, the correction for the effect of secondary particles in the FMD is $\mathcal{F}\{f(\varphi)\}$, and the correction is in Figure 6.19.

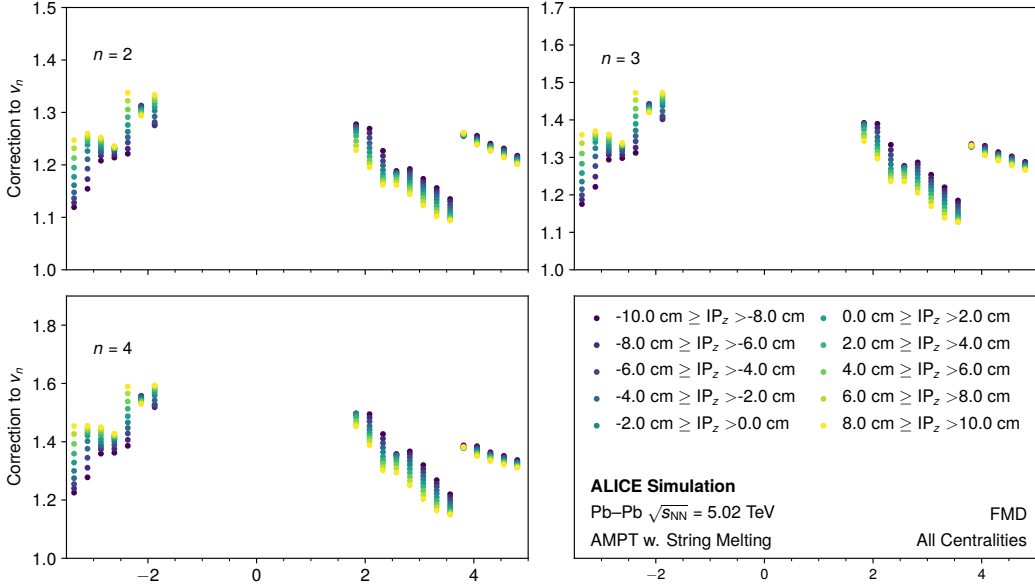


Figure 6.19: Result of a Fast Fourier Transform for v_2 , v_3 , and v_4 of the $\Delta\varphi$ distribution in Figure 6.18.

The secondary correction is vertex dependent, since depending on the position of the collision, particles may traverse more or less material. Therefore the correction at negative pseudorapidity is larger for $8.0 \text{ cm} \geq IP_z \geq 10.0 \text{ cm}$, caused by more material, but for $-10.0 \text{ cm} \geq IP_z \geq -8.0 \text{ cm}$ more particles evade the material and the correction is smaller. The Monte-Carlo production is AMPT for Pb-Pb at 5.02 TeV. The Monte-Carlo has the physics simulation determined by AMPT, and then the particles travel through the simulated ALICE detector. The correction increases with the harmonic n , but maintains more or less the same shape.

6.4.3 Consistency checks

A Monte-Carlo closure test was performed to test if the correction works. The approach of applying the correction and the Monte Carlo closure test is in Figure 6.20. The reconstruction steps shown in the Figure is a less detailed version of Figure 4.7, but it is the same process. The track references are filtered to data, such that the filtering is similar to that of data. The track references are then analysed to obtain the $v_n^{\text{trackref.uncorr.}}$ result, which is uncorrected. To get the corrected result, the $\mathcal{F}[f(\Delta\varphi)]$ correction from Figure 6.19 is applied. The corrected $v_n^{\text{trackref.corr.}}$ coefficients are compared to $v_n^{\text{prim.}}$ values, to check if the correction is sufficient. The comparison of $v_n^{\text{trackref.corr.}}$ and $v_n^{\text{prim.}}$ is the Monte Carlo closure test. The result of the closure test for v_2 is in Figure 6.21. The flow coefficient v_2 was calculated using the FMD for differential flow and primaries in the central region for reference flow. This means that there is no contribution to smearing or other effects from the reference regions. The differential flow was calculated using information from track references. If there is a track reference in the FMD with a hit, the particle is stored. In cases where one particle leaves several hits in the detector, this is merged into a single particle signal. Overall, the correction seems to be working well, but in the upcoming checks, the efficiency is further investigated. The results for the Monte Carlo closure test for v_3 and v_4 are in Appendix E.1.

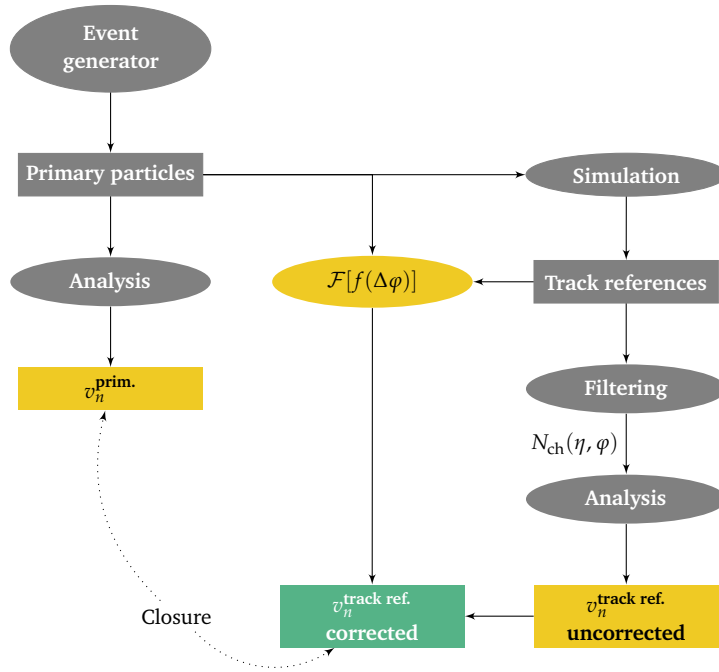


Figure 6.20: The approach of applying the correction, and testing with Monte Carlo closure. The track references are filtered and analysed, which gives the $v_n^{\text{track.ref}}$ uncorrected results. To correct the coefficients, the correction of $\mathcal{F}[f(\varphi)]$ is applied, and the result is then the $v_n^{\text{track.ref}}$ corrected coefficients. To check if the correction is efficient, the corrected $v_n^{\text{track.ref}}$ coefficients are compared to $v_n^{\text{prim.}}$. The $v_n^{\text{prim.}}$ coefficients are calculated using only primary particles, and therefore the measurement contains no detector effects.

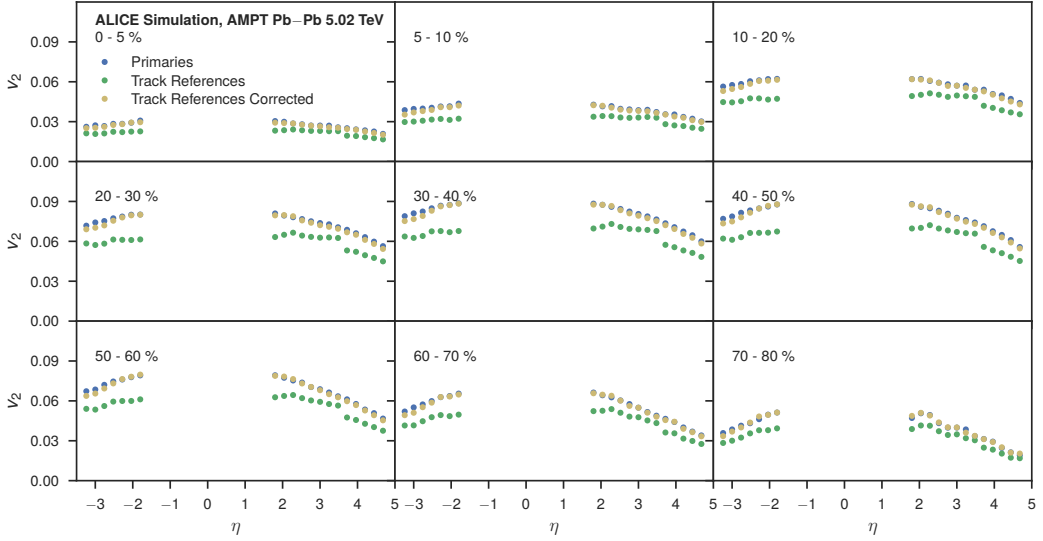


Figure 6.21: Monte-Carlo closure test for the secondary correction extracted with the Fast Fourier Transform for v_2 . The Monte-Carlo production is AMPT with Pb-Pb at 5.02 TeV.

Material

The simulations can have differences in the description of material compared to the actual material in the real, so a systematic study of the influence of material description was made. The datasets used are LHC17h5a, LHC17h5b and LHC17h5c. LHC17h5a has 10% extra material, LHC17h5b has the normal settings and LHC17h5c has -10% material. All of these datasets are for Pb–Pb at 5.02 TeV with AMPT. The correction for v_2 , v_3 and v_4 was made, and the ratios of the resulting correction for each dataset are in Figure 6.22. The ratios will determine the systematic uncertainty of the correction for secondaries from material estimation.

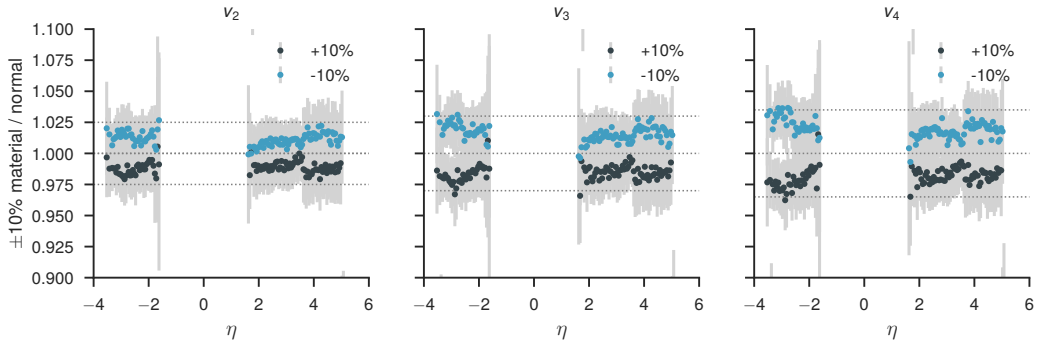


Figure 6.22: The secondary correction dependency of different material densities. The systematics assigned are 2.5 % for v_2 , 3.0 % for v_3 and 3.5 % for v_4 .

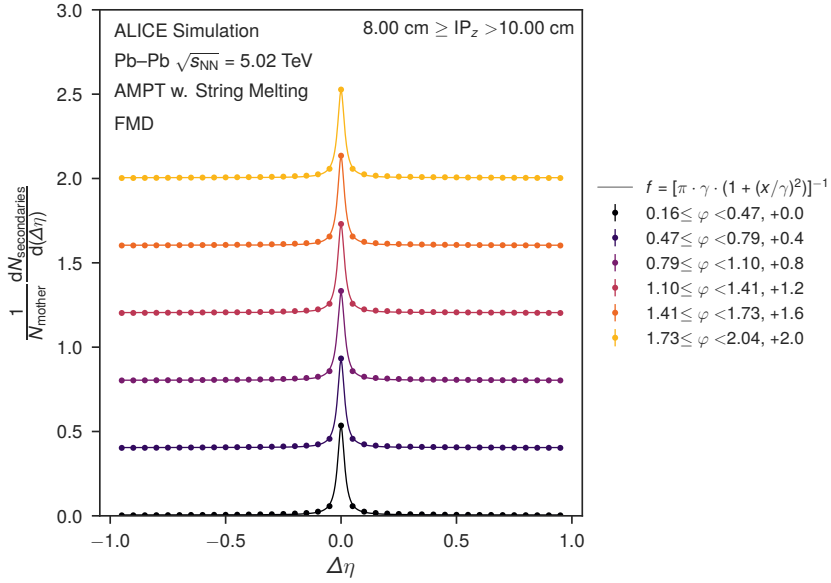


Figure 6.23: The distribution of a secondary particle around its primary mother particle in η . The curves are shifted by a constant, for clarity.

Smearing in η

The secondary particles have a smearing in φ , but they can also dilute the η resolution. In Figure 6.23 the $\Delta\eta$ distribution is shown as a function of φ . The $\Delta\eta$ distributions are fitted by the Cauchy(Lorentz) functions

$$f(x, x_0, \gamma) = \frac{1}{\pi\gamma} \left[\frac{\gamma^2}{(x - x_0)^2 + \gamma^2} \right]. \quad (6.13)$$

In Figure 6.23, $x = \Delta\eta$, and the distribution is centered at zero, $x_0 = 0$, and γ is the width of the distributions. The resulting γ -values from the fits are in Figure 6.24. There is no dependence on vertex position and φ within the uncertainties. The smearing is small enough to be negligible, since the η resolution used in the analysis ($\Delta\eta = 0.24$) is larger than the widths found and shown in Figure 6.23.

Centrality

To check if the correction is dependent on centrality, experiments with the Fast Fourier Transform was performed. In Figure 6.25, the ratio of the mean of the correction overall centralities divided by the correction from one centrality is shown. The results show that there is not a clear dependency on the FFT correction on centrality. Since the correction is based on smearing per primary particle, it should also not change by the number of particles in the collision, which centrality corresponds to.

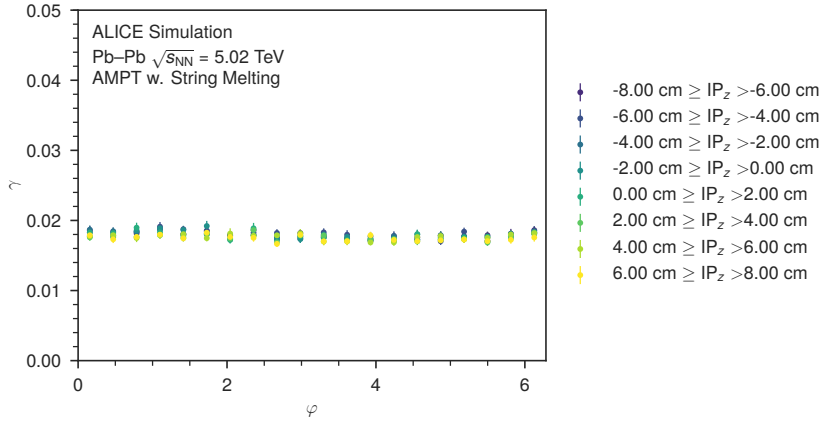


Figure 6.24: γ -values from all fits in Figure 6.23, where the errors are also determined by the fit.

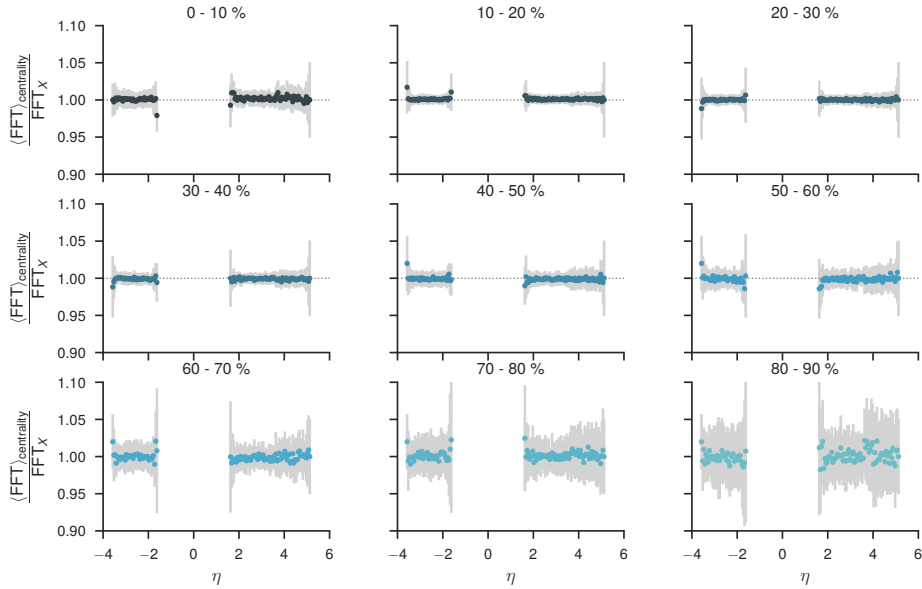


Figure 6.25: Correction by FFT at different centralities.

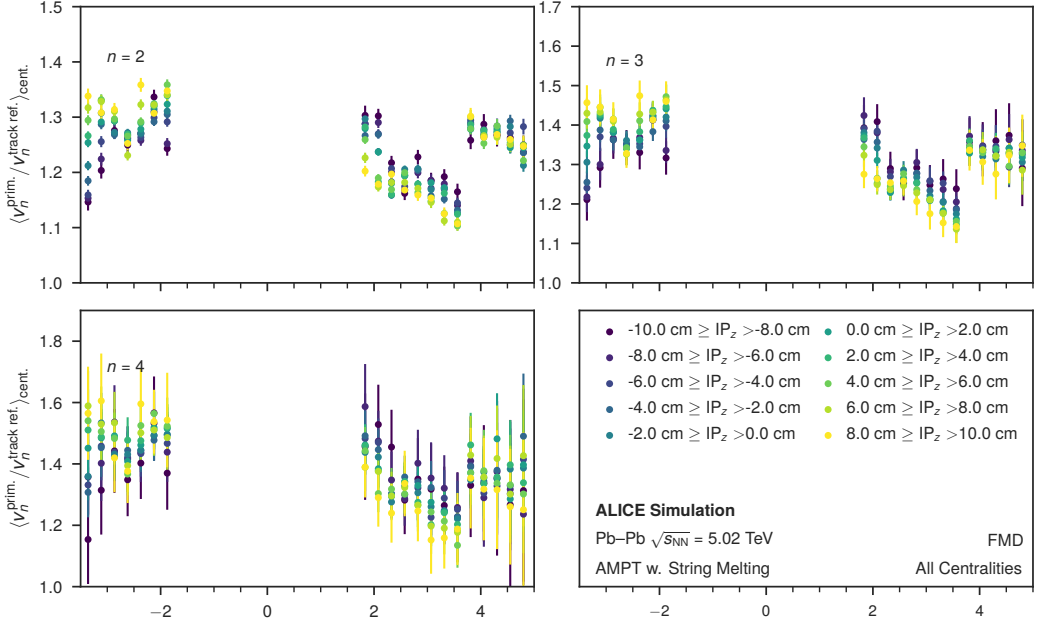


Figure 6.26: The correction estimated from primary particles for the effect of secondaries on v_n . The correction is determined through the ratio of v_n calculated using primary particles, and v_n calculated using reconstructed AODs.

		$n = 2$	$n = 3$	$n = 4$
$\eta < 0$	a	-0.053 ± 0.004	-0.074 ± 0.006	-0.049 ± 0.013
	b	0.897 ± 0.009	0.839 ± 0.015	0.899 ± 0.027
$\eta > 0$	a	0.013 ± 0.002	0.018 ± 0.003	0.014 ± 0.006
	b	0.973 ± 0.005	0.95 ± 0.008	0.958 ± 0.015

Table 6.1: The best-fit parameter for the systematic in Figure 6.27

The correction estimated from primary particles

The true correction can be measured by taking the ratio of v_n measured with track references and v_n measured with primary particles. The result of the ratios as a function of IP_z and η is in Figure 6.26. qualitatively, it shows a dependency similar to the result of the Fast Fourier Transform (Figure 6.19). There was not found a dependency of vertex position and centrality when taking the ratio of the true correction and the FFT correction. Therefore the ratio in Figure 6.27 was merged over centrality and vertex position. The difference between the true and FFT corrections is taken as a systematic uncertainty of the secondary correction. Since the difference has a dependency on η , the systematic uncertainty is also dependent on η and n . To smoothen the systematic uncertainty, linear fits were made, and the best-fit parameter values are in Table 6.1. The systematic is largest for large pseudorapidities.

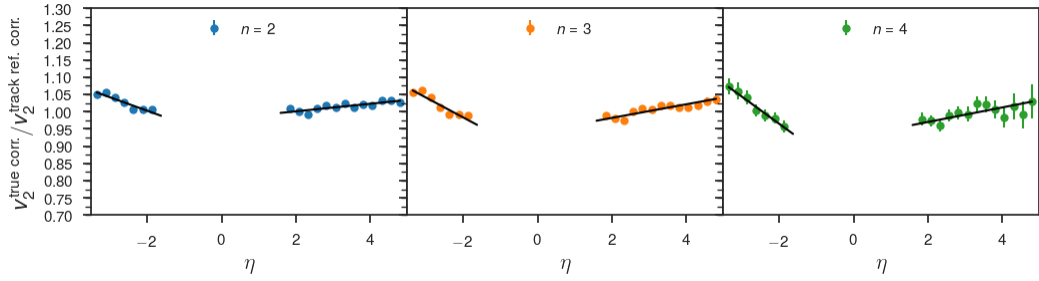


Figure 6.27: The correction estimated from primary particles divided by the FFT correction. The values are averaged over centrality and vertex. There is a general shape to the deviation, and it scales with n . The difference can arise from the primary particles in the simulation, which are supposed to hit the FMD, deviates so much from their path that no hit is created with a track reference in the FMD. This effect can not be corrected with this method.

6.4.4 Reconstruction of the FMD using track references

For the analysis of the secondaries, all information and history of the mc particles is necessary. Therefore in this analysis, a reconstruction from track references to AOD was made, as seen in Figure 6.29. This is a simpler subset of the reconstruction of the ESDs. A more complicated and realistic reconstruction from track references could not be made since it becomes almost impossible to keep track of the history of single particles in the advanced clustering algorithms.

The FMD reconstruction from ESD to AOD is in Figure 6.28. The reconstruction starts with an ESD object, and several reconstruction steps mostly contain sharing filter and acceptance corrections³. The sharing filter corrects for sharing, which is if a particles energy loss in the FMD is distributed over 1 or more strips[64, 69], and one might need to merge the signals of adjacent strips. After the sharing filter process, the output is the signal per strip without the split signals over several strips. The density calculator, calculates the inclusive charged particle densities, from energy loss fits. After the multiplicity densities are calculated, multiplicities are corrected for secondary particles⁴, and for acceptance. After the corrections, the reconstruction is at its final step, and the output is the FMD AOD object.

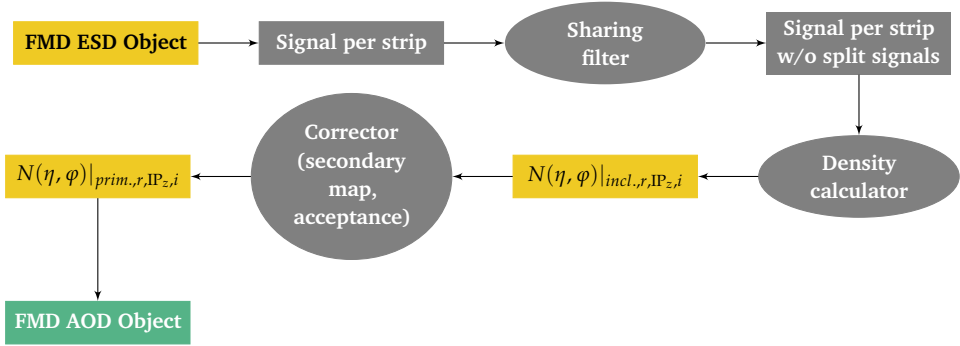


Figure 6.28: FMD reconstruction from ESDs. In the sharing filter process, the object is corrected for sharing, which is when a particles energy loss is distributed over more than one strip. After the sharing filtering, the output is the signal per strip without split signals. The density calculator calculates the multiplicity of particles from energy loss fits, and the output is then the inclusive charged particles. The data then undergoes correction processes, which corrects for background signals and acceptance in the FMD. After the corrections, the data should be comparable to the primary particles and is finally collected into the FMD AOD object, which can be used for analysis.

In Figure 6.29, which is the reconstruction made in this analysis, the track references are reconstructed, into an object similar to the AOD object. The The sharing filter process from track references are made in a similar fashion to that of the data reconstruction in Figure 6.28. The large difference between Figure 6.29 and 6.28, is that Figure 6.29 does not go through energy loss analysis, but uses the information from the Monte Carlo simulation, to get the multiplicities instead. Therefore there is a great difference in the two reconstructions, and the difference needs to be assigned to the data, before the correction for the secondaries in the FMD can be applied (from Section 6.4.2).

In Figure 6.30 the difference in the calculated v_n between these two reconstructions is shown. There is a large difference between to two reconstructions, and therefore the reconstruction of the track references needs to be corrected.

³A detailed description of the reconstruction of the FMD can be found in C. H. Christensens thesis[64, 69]

⁴this is an option, and is not always included in the reconstruction

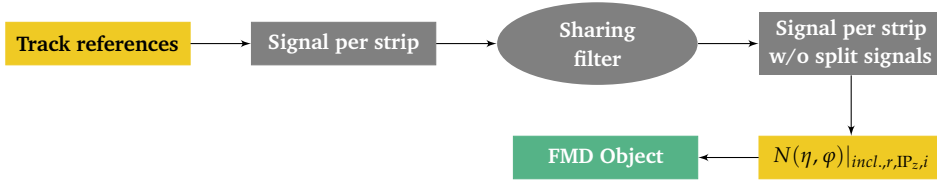


Figure 6.29: FMD reconstruction from Track References. In the sharing filter process, the object is corrected for sharing, which is when a particle creates more than one hit (track reference) in the FMD. The output of the track reference sharing filter is the signal per strip without any split signals. The final data object consist of inclusive particles in the FMD.

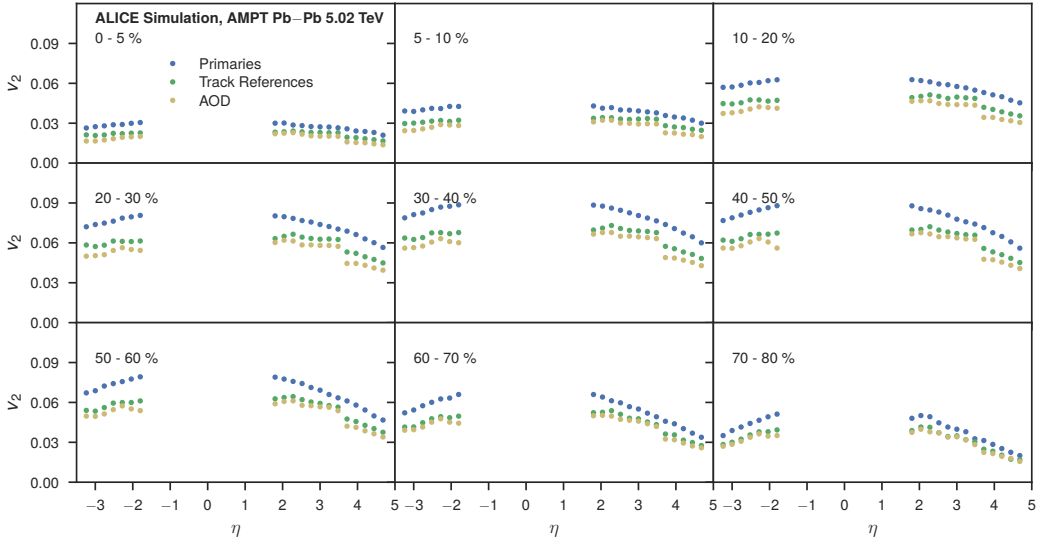


Figure 6.30: The v_2 determined from FMD data reconstructed with track references, AOD and primaries. The track references are reconstructed as in Figure 6.29, and the AOD data is reconstructed as in Figure 6.28.

Because of the difference of reconstructions in Figure 6.30, a correction need to be applied. The v_2 using track reference reconstruction is higher than the v_2 measured using the FMD AOD reconstruction. In Figure 6.31 the ratio of v_n calculated with reconstructed track references(as the process in Figure 6.29) and the reconstructed AODs(as the process in Figure 6.28) has a dependency on centrality. Since statistics are sparse, the strategy is to normalise the ratios from Figure 6.31 by the average value over centralities, and then extrapolate the correction using fits. The normalisation is used to make the fitting procedures easier. The purpose of doing the extrapolation is to get the correction at a high resolution, and without any influences from statistical fluctuations since they will be smoothened out by the fitting procedures.

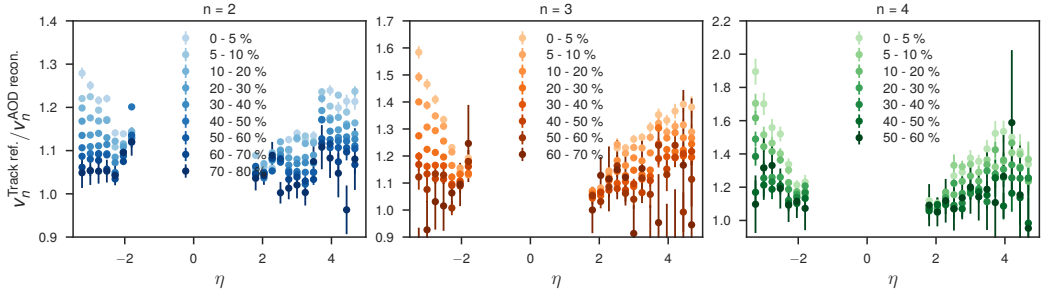


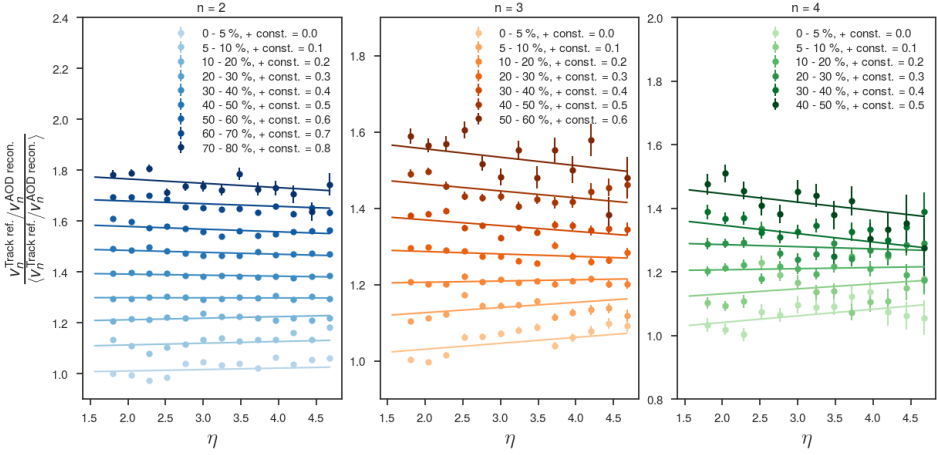
Figure 6.31: Ratio of v_n using the FMD with reconstruction from track references and AODs for different centralities. The ratio is higher for central collisions, than for peripheral collisions.

Figure 6.32 shows the fits of the normalized values. The fits were performed separately for $\eta > 0$ and $\eta < 0$. Several fitting functions were tested, and the best fit was for $\eta > 0$ a linear function, and for $\eta < 0$ an exponential function. The corresponding χ^2_ν and parameter values are in Figure 6.33 for v_2 , and for v_3 and v_4 it is in Appendix in Figure E.5 and E.6.

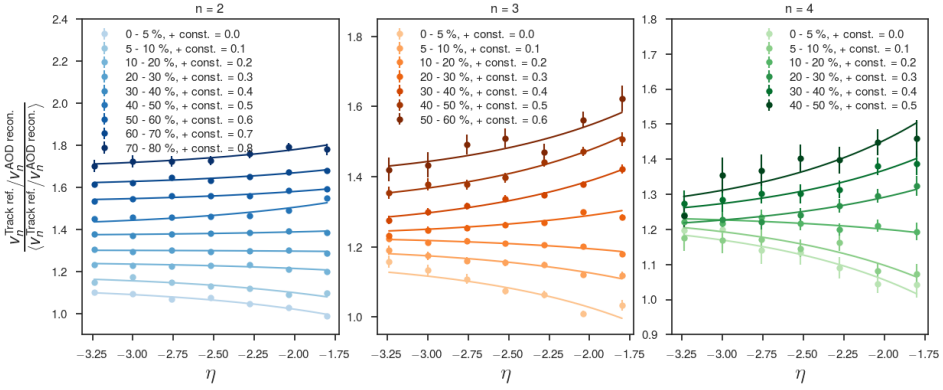
In summary, the approach is as follows:

- calculate mean ratio = $\langle v_n^{\text{track ref.}} / v_n^{\text{AOD recon.}} \rangle_{\text{cent.}}$
- calculate norm. ratio = $\frac{v_n^{\text{track ref.}} / v_n^{\text{AOD recon.}}}{\langle v_n^{\text{track ref.}} / v_n^{\text{AOD recon.}} \rangle_{\text{cent.}}}$ per centrality
- Fit normalized ratio separately for $\eta > 0$ and $\eta < 0$
- Fit parameters from $\eta > 0$ and $\eta < 0$
- Get correction determined from fitted parameters

Using the fits the correction values were extrapolated, and the comparison to extrapolated vs. $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$ is in Figure 6.35. Since the reconstruction ratios are well determined by the direct ratios at low centralities, these will be used as the correction in data. The fitted reconstruction ratios are used for higher centralities instead.



(a) Normalized $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$ per centrality for $\eta > 0$. The data is fitted by $y = a \cdot \eta + b$.



(b) Normalized $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$ per centrality for $\eta < 0$. The data is fitted by $y = a \cdot \exp(\eta) + b$.

Figure 6.32: Fitting of normalized $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$ per centrality.

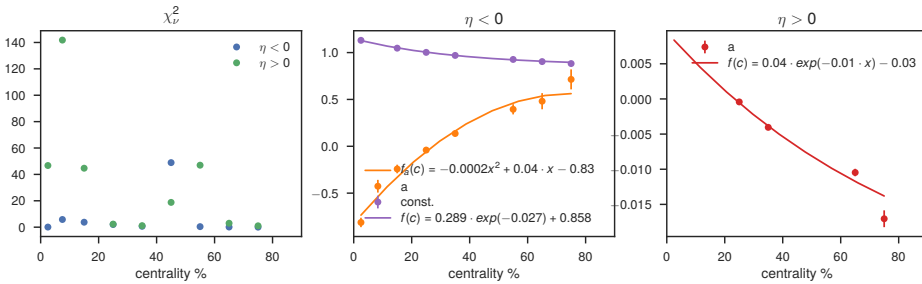


Figure 6.33: The parameters from the fits in Figure 6.32 with parabel and exponential functions.

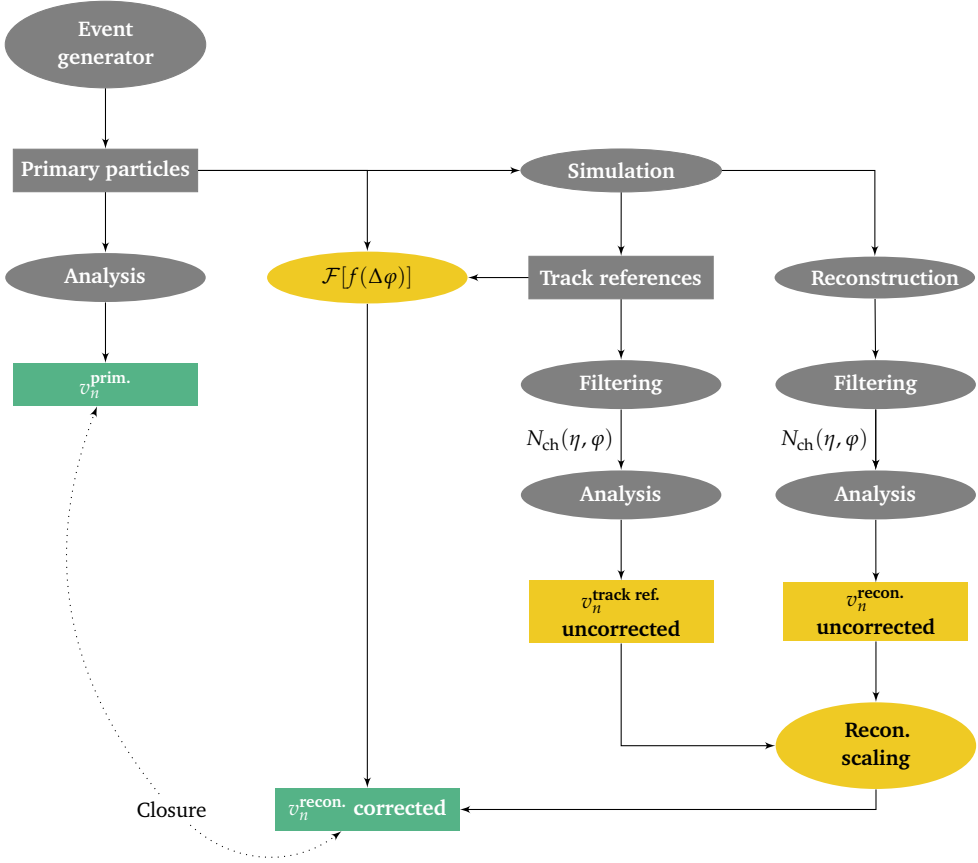


Figure 6.34: The approach of applying the correction, and testing with Monte Carlo closure. The track references are filtered and analysed, which gives the $v_n^{\text{track.ref}}$ uncorrected results. The uncorrected track reference and AOD results, $v_n^{\text{track.ref}}$ and $v_n^{\text{recon.}}$, are analysed to get the correction for the track reference reconstruction, as described in this section. To correct the $v_n^{\text{recon.}}$ coefficients, the correction of $\mathcal{F}[f(\varphi)]$ is applied, and the result is then the $v_n^{\text{recon.}}$ corrected coefficients. The Monte Carlo closure correction is also applied to the $v_n^{\text{recon.}}$ coefficients.

Consistency checks

The ratio in Figure 6.36. The systematic error for the reconstruction ratio is then the standard deviation of the extrapolated values over the ratios from Figure 6.36.

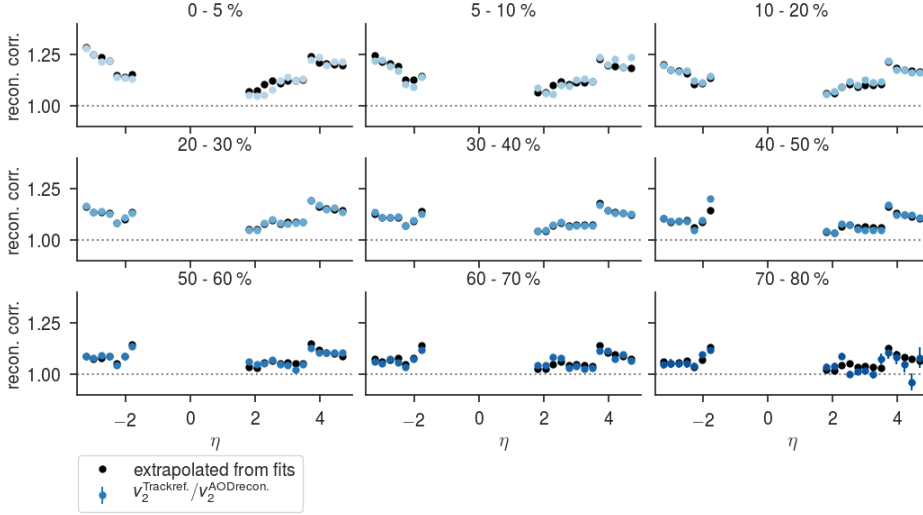


Figure 6.35: Extrapolated correction vs. $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$.

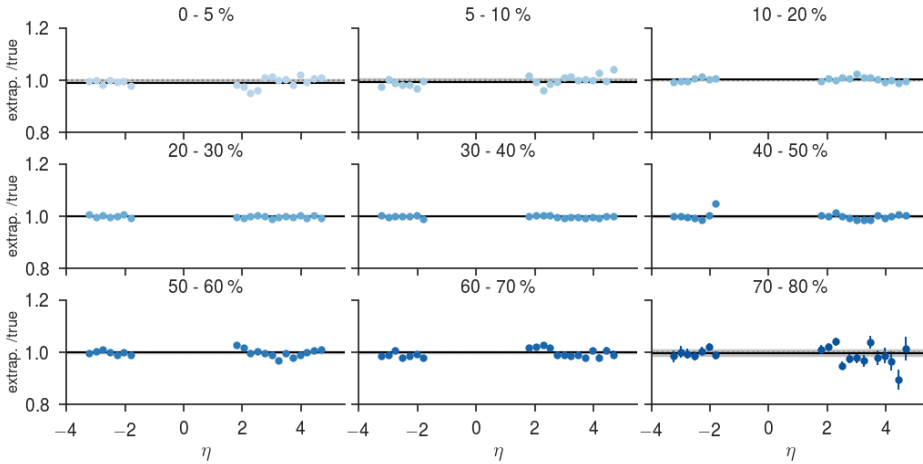


Figure 6.36: Comparison of $v_n^{\text{Track ref.}} / v_n^{\text{AOD recon.}}$ and the extrapolated values. A systematic error is assigned for the reconstruction correction by taking the standard deviation of $v_n^{\text{Track ref.}} / v_n^{\text{AOD recon.}}$.

Variation of reconstruction

There are two available reconstructions for the FMD in the AMPT production LHC17i2f. AOD217 is the normal calibrated reconstruction, and AOD is a reconstruction with applied multiplicity correction for secondaries. The difference between the reconstructions are in Figure 6.37.

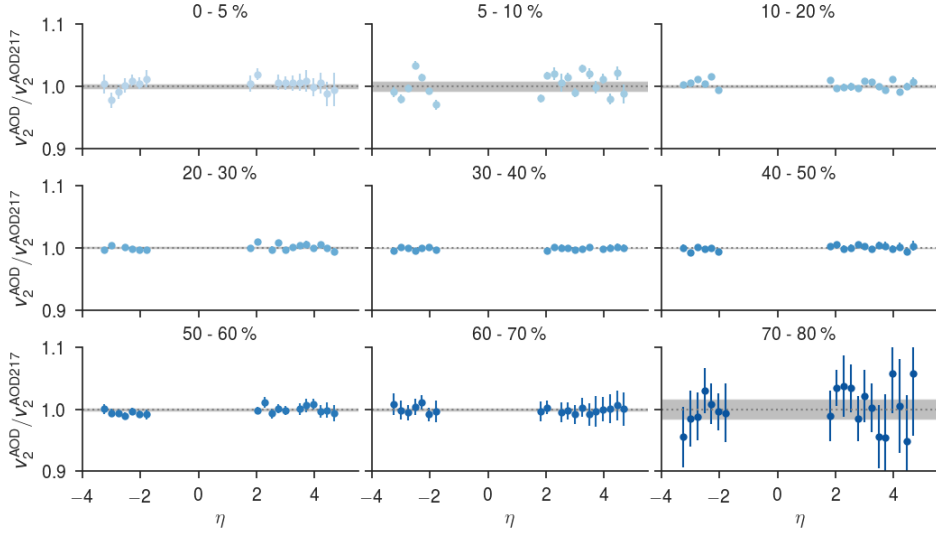
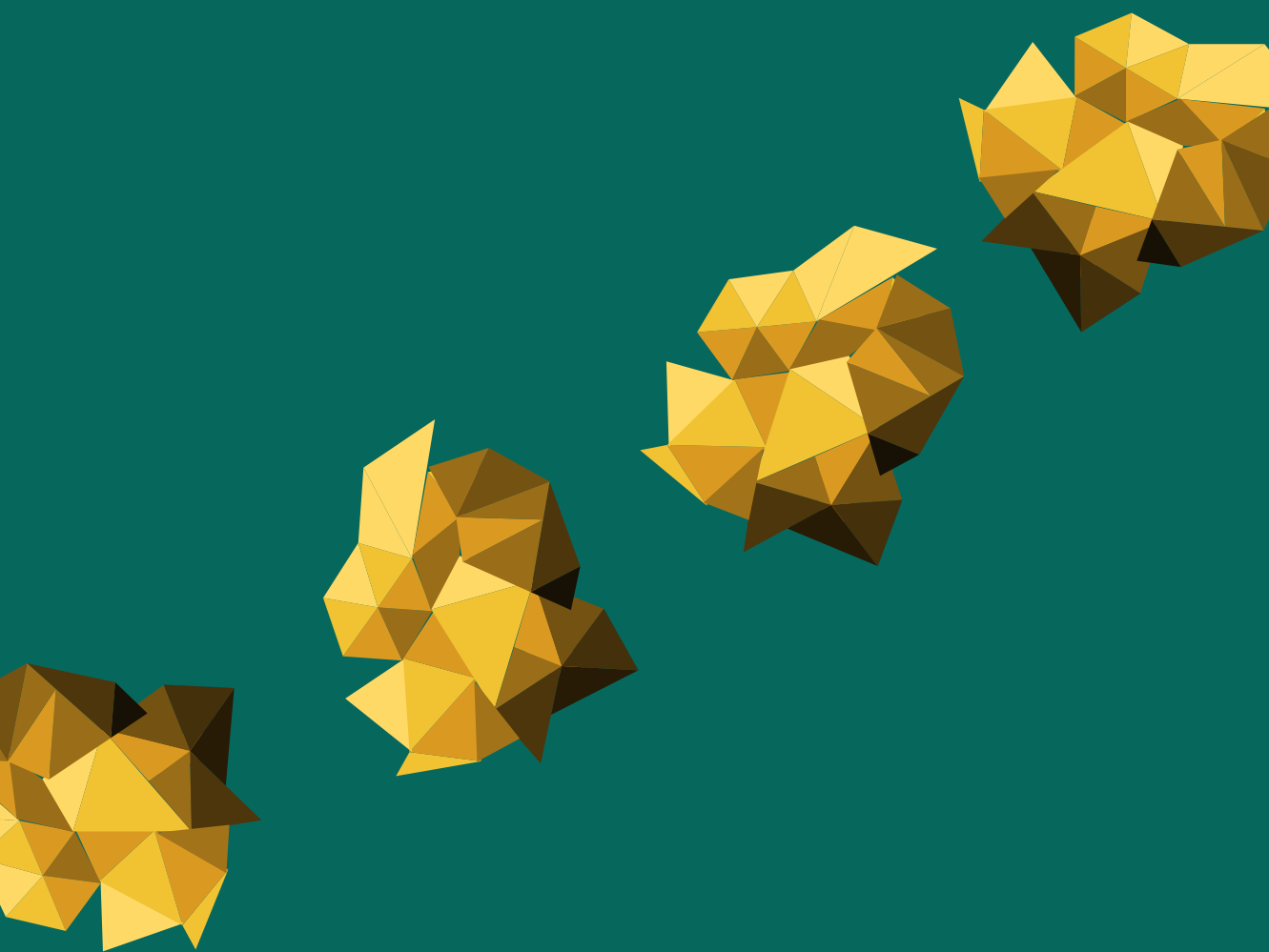


Figure 6.37: Ratio of v_2 with the two possible reconstructions of the FMD. AOD is reconstructed using a multiplicity correction, and the multiplicity correction does not correct AOD217.

VII Results and Discussion



7.1 Summary of uncertainties

In this section, the methods for estimation of uncertainties on the measurements are introduced. The statistical errors are determined by the bootstrapping method [70], and the systematical errors are evaluated with the Barlow check[71].

7.1.1 Statistical uncertainties

The bootstrapping method is used to determine the statistical uncertainties of the measurements. The bootstrapping method was developed by Bradly Efron (1979), and the approach is [72] (adapted to the measurements of v_n)

- Calculate the mean v_n of the full data sample
- Divide the sample into N equal-sized subsamples at random
- For some number, B , of pseudo-experiments
 - Select at random, with replacement, N of the subsamples
 - Calculate v_n over these N subsamples
- Calculate the standard deviation of v_n over the B pseudo-experiments

The simulation is performed by sampling from the original sample N times with replacement. *With replacement* means the probability to draw a sample is exactly $1/N$ for all N in the simulation[72].

7.1.2 Systematical uncertainties

The systematical uncertainties for the flow measurements in the central and forward regions of pseudorapidity are studied separately. Systematics for the corrections for secondary particles in the FMD were estimated in Section 6.4.3 for centrality and Section 6.4.3 for material description. The correction for secondaries did not have a significant dependence on centrality, but the correction did depend on material density, for which a systematic uncertainty was assigned, which depends on the harmonic n . For the FMD the systematic checks are

- Efficiency and variation of the track reference correction of the FMD (Section 6.4.4)
- Material variation (Section 6.4)
- Interpolation of the acceptance holes (Section 6.2)
- Residual systematic of the secondary correction (Section 6.4)

In the central region of pseudorapidity, the TPC was used for analysis. The corrections for the flow-vectors in the TPC are for NUE and NUA. The systematical uncertainties for these corrections were determined by a Monte Carlo closure test, which is in Section 6.3. The p_T extrapolation to $p_T > 0$ in the TPC was determined with Monte Carlo, and systematic uncertainties were related to the averaging of the correction over n , and a variation in the kinematic cuts. The rest of the systematic checks for the central region of pseudorapidity, was done by making variations in the track selections in the data used for analysis. In summary, the systematic uncertainties for the TPC involves,

TPC	0-5 %	5-10 %	10-20 %	20-30 %	30-40 %	40-50 %	50-60 %
$v_2\{2\}$ sys. [%]	3.1	2.3	1.9	1.5	1.4	1.4	1.4
$v_3\{2\}$ sys. [%]	3.9	3.0	2.2	2.0	2.3	2.1	2.7
$v_4\{2\}$ sys. [%]	6.4	5.2	5.9	6.2	3.5	6.6	—
$v_2\{4\}$ sys. [%]	-	4.8	2.0	1.8	1.5	1.5	3.3

Table 7.1: Systematic uncertainties for the measurements of the flow coefficients in the TPC for each centrality.

- DCA cut in z
- DCA cut in xy
- Track selections
- Minimum no. clusters
- p_T correction (Section 6.3.2)
- NUE closure (Section 6.3)

Furthermore, global uncertainties, such as centrality estimation(using the CL0 and V0M centrality estimators) and overall symmetry over pseudorapidity, are estimated in both the central and forward regions of pseudorapidity.

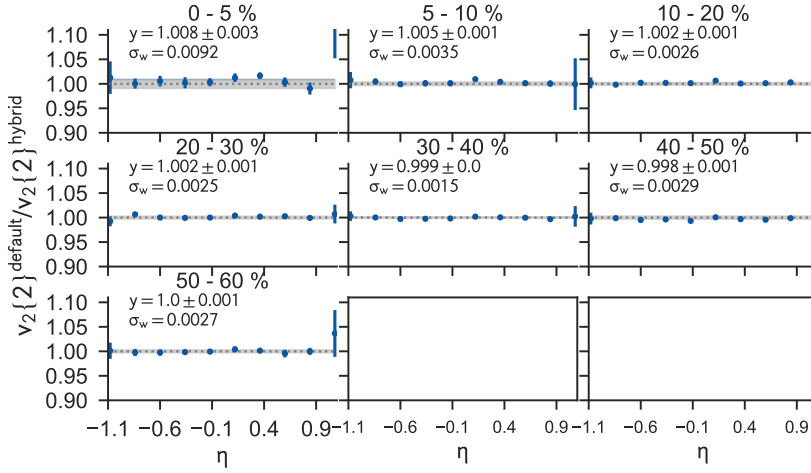
The systematic uncertainties¹ are evaluated by the ratio of variations to the default. The standard deviation of the ratio is then the assigned as the systematic uncertainty if it is significant. An example of the estimation of a systematic uncertainty from a variation is in Figure 7.1.

The Barlow test [71] is concerns whether a systematic uncertainty from a variation should be assigned, given the statistical uncertainties of the measurements. The variations are significant, compared to the statistical uncertainties of the data, if the following condition holds true

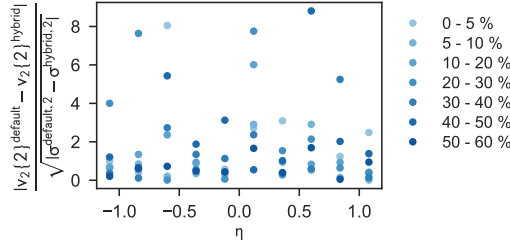
$$\frac{|x_{\text{default}} - x_{\text{variation}}|}{\sqrt{|\sigma_{\text{default}}^2 \pm \sigma_{\text{variation}}^2|}} > 1. \quad (7.1)$$

The plus sign in the denominator is used when the variables are correlated, which is the case in this analysis since the variables have an overlap in their selection criteria. If the ratio is less than one, meaning that the variation is within one (combined) standard deviation, then the variation is insignificant, and thus not considered a systematic uncertainty. With the ratio in Equation 7.1 less than one, it basically means that the results are not different; therefore, there should not be any systematic uncertainty assigned to the variation.

¹Additional plots for systematics are in Appendix G.



(a) v_2 calculated using global tracks divided by v_2 calculated using hybrid tracks. A constant is fitted to the points, and the weighted standard deviation is calculated.



(b) The Barlow check performed for the variation of tracks in (a). If the Barlow condition is more than one, the systematic uncertainty is assigned.

Figure 7.1: An example of a systematic check with a variation of track selection. The v_2 coefficient is calculated with the default track selection (global tracks), and v_2 is calculated with the variation of the track selection (hybrid tracks). The ratio of the flow coefficients with the default selection, and the variation, is in (a). A weighted mean is calculated, which is y in the plot, and the weighted standard deviation (σ_w) is also calculated and shown in the plot. The weighted standard deviation is also shown as the grey box around the data points in (a).

FMD	0-5 %	5-10 %	10-20 %	20-30 %	30-40 %	40-50 %	50-60 %
$v_2\{2\}$ sys. [%]	4.7	4.4	4.2	4.2	4.2	4.1	4.5
$v_3\{2\}$ sys. [%]	5.7	4.6	4.3	4.6	5.2	5.6	6.9
$v_4\{2\}$ sys. [%]	8.6	8.9	7.7	8.4	9.3	11.1	-
$v_2\{4\}$ sys. [%]	-	4.3	4.1	4.1	4.1	4.1	4.5

Table 7.2: Systematic uncertainties for the measurements of the flow coefficients in the FMD for each centrality. The η -dependent systematic uncertainty from Figure 6.27 is not included in the table, but it is included when assigning the final systematic uncertainties.

7.2 Measurements of flow coefficients

This section goes through all measurements of flow coefficients performed in this thesis. The results are presented using different η -gaps. The reference and differential flow dependence on η -gaps in the central region of pseudorapidity is studied. The flow coefficients, $v_2\{2\}$, $v_3\{2\}$, $v_4\{2\}$, and $v_2\{4\}$, are presented in a wide range in pseudorapidity ($-3.5 < \eta < 5$) for Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV. For Xe–Xe collisions with $\sqrt{s_{\text{NN}}} = 5.44$, the available statistics are limited, and therefore only $v_2\{2\}$ and $v_3\{2\}$ are presented. Preliminary results for $v_2\{2\}$ is also presented for p–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the three-subevent method.

7.2.1 Reference flow in the central region of pseudorapidity

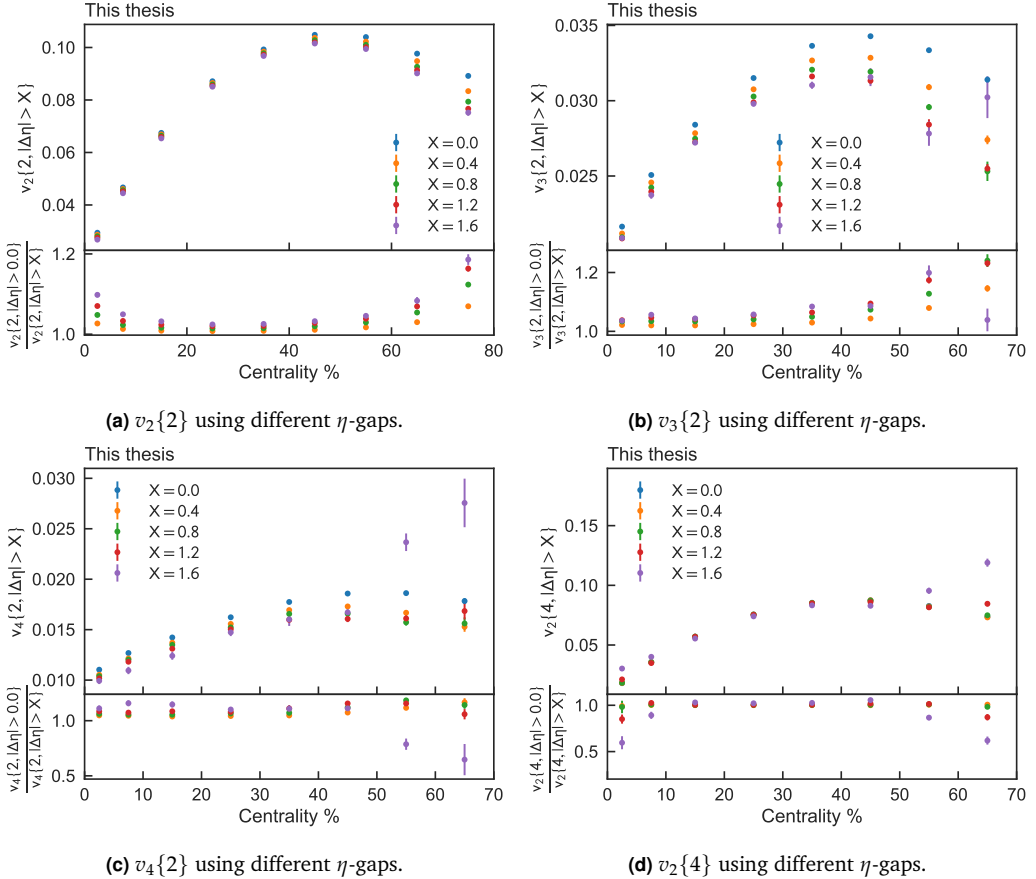


Figure 7.2: Two- and four-particle reference flow measurements at mid rapidity using different pseudorapidity gaps between the reference particles. The reference flow measurements are calculated using the TPC. Only statistical errors are shown. The magnitude of the flow measurements decrease, with an increasing η -gap. Ratios of reference flow measured with the smallest gap ($|\Delta\eta| > 0$), to reference flow with larger gaps ($|\Delta\eta| > X$) are in the lower panel of the plots.

The reference flow measured in at mid rapidity with the TPC is in Figure 7.2. The reference flow measurements are shown using different η -gaps.

The flow coefficients $v_n\{2\}$ show a strong dependency on the magnitude of the η -gaps. The decrease of the reference flow as a function of separation in pseudorapidity can arise from non-flow being excluded, or from pseudorapidity dependence of v_n . Previous results in Figure 2.17 showed that v_n is at its maximum at $\eta \approx 0$. To know if the increasing gaps suppress non-flow, or expresses flow dependence of pseudorapidity, we need to calculate $v_n(\eta)$ and investigate the pseudorapidity dependence of the flow signal, as we increase the pseudorapidity gap. The elliptic flow, calculated with the 4-particle cumulant, $v_2\{4\}$, shows a minor dependence on the magnitude of the η -gap. At larger centralities, the flow coefficients measured with $|\Delta\eta| > 1.6$ increase rapidly, contrary to all other measurements with a η -gap. The increase of the reference flow with $|\Delta\eta| > 1.6$ at large centralities can be caused by the limited statistics available, since when increasing the η -gap, the number of particles used in the calculation of reference flow decreases. The η -gap of 1.6, in combination with the total number of particles decreasing as a function of centrality, might be the cause of the flow coefficients fluctuating to higher values at large centralities.

7.2.2 η -gaps in differential measurements

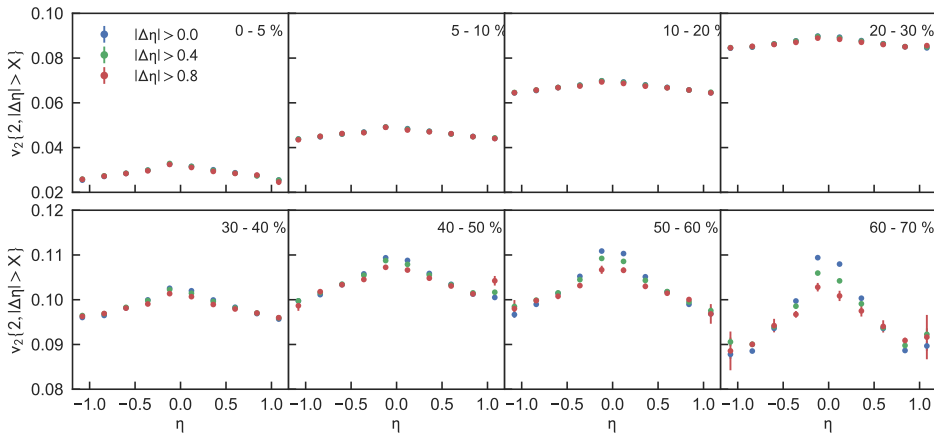


Figure 7.3: Measurements of v_2 using the 2-particle cumulant with reference particles chosen from the TPC. The elliptic flow is measured with different η -gaps. Only the statistical errors are shown.

The effect of using η -gaps in the calculation of flow, can be studied in the differential flow measurements as a function of pseudorapidity. In Figure 7.3 the elliptic flow coefficients are shown as a function of pseudorapidity, with varying η -gaps. In Figure 7.3, it is shown that increasing the η -gap will decrease the magnitude of the flow coefficients at most central pseudorapidity ($|\eta| \approx 0$). From these results alone, it is not certain that the effect is from non-flow only or the decorrelation of the symmetry plane (or both).

In the calculation of the flow coefficients ($v_n(\eta)$), the particles of interest do not have the same separation in pseudorapidity to the reference particles. For example with $|\Delta\eta| > 0.8$, for $v_n(\eta \approx 0)$, the η -gap is $|\Delta\eta| \approx 0.8$, and for $v_n(\eta \approx 1)$, the η -gap is $|\Delta\eta| \approx 1.6$. It is therefore important to notice that the notation $|\Delta\eta| > X$ should be taken literally, since X is the *lower bound* on the separation, and

the pseudorapidity gap effectively increases with the pseudorapidity of the differential flow coefficient $v_n(\eta)$. This follows from the method introduced in Figure 3.1, where the reference particles are chosen to have opposite sign pseudorapidity relative to the particles of interest.

7.2.3 Flow measurements in Pb–Pb collisions

In Figure 7.4 the results for v_2 , v_3 and v_4 calculated using the TPC as reference region (the method described in Figure 3.1) are shown. The η -gap for the particles of interest in the TPC is $|\eta| > 0.8$ and the η -gap for the particles of interest in the FMD is $|\eta| > 2.6$. The v_2 measurements show a strong dependence on centrality, while v_3 and v_4 have a weak dependence on centrality. The flow measurements in the central region of pseudorapidity are extrapolated to $p_T > 0$, as described in Section 6.3.2, to make the measurements comparable to those at forward pseudorapidity.

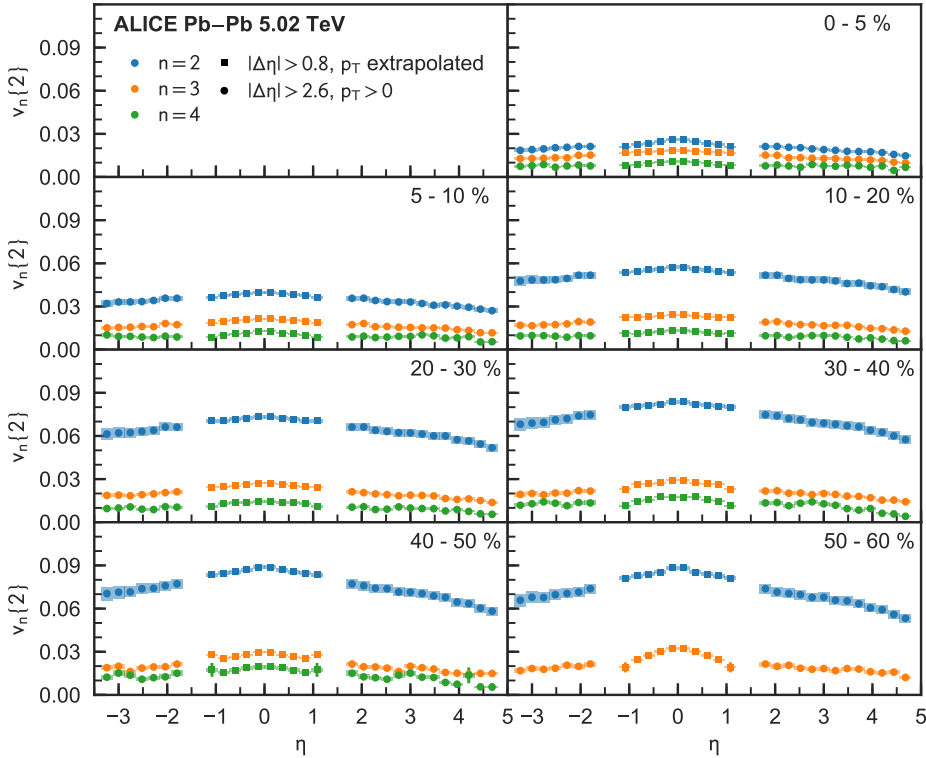


Figure 7.4: The differential flow measurements, $v_n\{2\}(\eta)$, measured with the 2-particle cumulant and choosing reference particles from the TPC in Pb–Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV. The choice of the reference particles gives $|\Delta\eta| > 0.8$ in the central regions of pseudorapidity and $|\Delta\eta| > 2.6$ in the forward regions of pseudorapidity.

Since the FMD is located at forward rapidities at ALICE, it can be used for calculations of flow coefficients with a large η -gap. In Figure 7.5, the v_2 coefficient is measured using a large pseudorapidity gap between the reference particles and the particles of interest, by using the FMD as a reference region. The measurement of v_2 with the large gap is compared to v_2 measured with the 4-particle

cumulant. As seen in Figure 7.2 (d), $v_2\{4\}$ does not change much when increasing the η -gap between the particles. Therefore in Figure 7.5, the four-particle cumulant is calculated by having a η -gap of 0 to minimise the statistical uncertainties, and by choosing the reference particles from the TPC.

When using 2-particle correlations with a modest pseudorapidity gap (> 0.8) at midrapidity, we see a peaked distribution as a function of pseudorapidity. However, as seen in Figure 7.5, when we use 4-particle cumulants or a large pseudorapidity gap (> 2) at midrapidity, we see that the distribution flattens significantly. By using a bigger η -gap, the effects from non-flow, factorisation and decorrelation of symmetry plane are different, than to the case of the modest η -gap. If there are remaining short-range non-flow effects in Figure 7.4, then they should be fully suppressed with the large gap in Figure 7.5. However, the decrease of $v_2\{2\}$ can also come from decorrelation of the symmetry plane. It has been shown [50, 51] that the decorrelation of the symmetry plane depends on the distance in η between the correlators. This will also be discussed in Section 7.3. Factorization breaking has been shown up to $\Delta\eta > 2$ [49], therefore for the flow coefficients in Figure 7.4 with a η -gap less than 2, can be in a regime where factorisation is broken, and the formalism to extract differential flow breaks down.

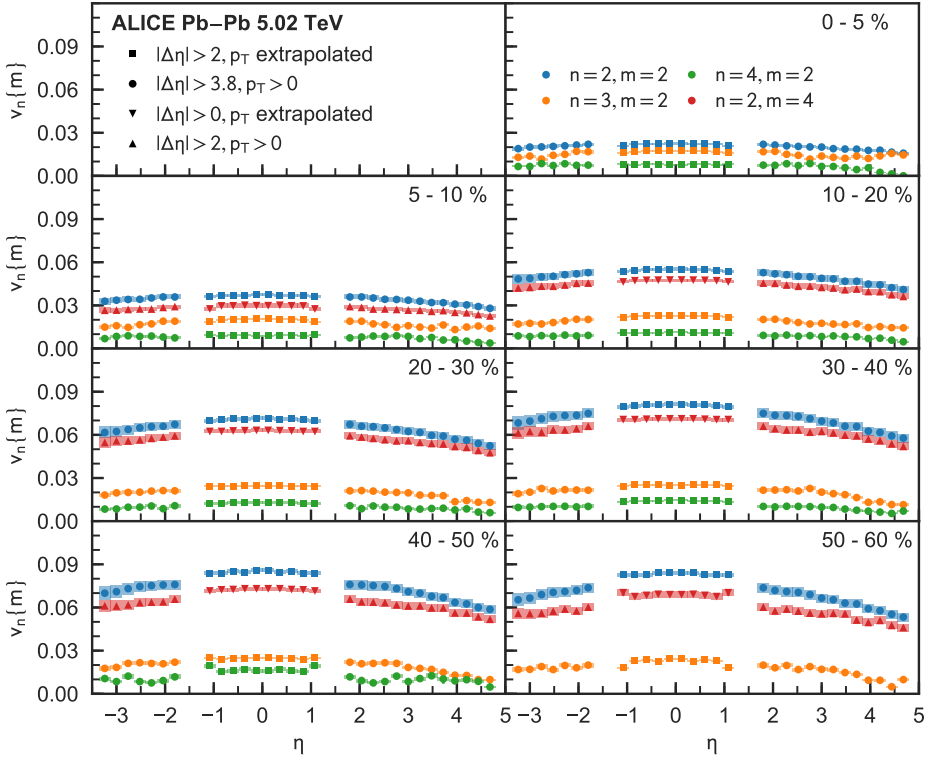


Figure 7.5: Two-particle cumulant with reference particles chosen from the FMD and 4-particle cumulant with reference particles chosen from the TPC in Pb–Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV. $|\Delta\eta| > 2.0$ in TPC and $|\Delta\eta| > 3.8$ in FMD for the two-particle cumulant and $|\Delta\eta| > 0.0$ in TPC and $|\Delta\eta| > 2$ in FMD for the four-particle cumulant.

The four-particle cumulant result shows a similar dependence on pseudorapidity as the 2-particle cumulant with a large gap, although with a change in magnitude. The differences in magnitude of $v_2\{2\}$ and $v_2\{4\}$ arise from the 2- and 4-particle cumulants being influenced differently from flow fluctuations (Section 3.1.4). Since the shape is the same, it suggests the 2-particle cumulant with the large η -gap has excluded the non-flow signals sufficiently.

7.2.4 Flow measurements in Xe-Xe collisions

The pseudorapidity dependence of flow coefficients in Xe–Xe collisions at 5.44 TeV is shown in Figure 7.6 and 7.7. $v_4\{2\}$ and $v_2\{4\}$ could not be calculated because of the limited data available². Figure 7.6 shows the results with $|\Delta\eta| > 0.4$. The results for Xe–Xe shows a similar trend as the results for Pb–Pb, but with a slight shift of magnitude. The Xe–Xe results could not be studied with $|\Delta\eta| > 0.8$, since the results become statistically unstable. In Figure 7.7 the Xe–Xe results with a large pseudorapidity gap ($|\Delta\eta| > 2$) are shown, which exhibits a flatter curve in the central regions of pseudorapidity, compared to Figure 7.6.

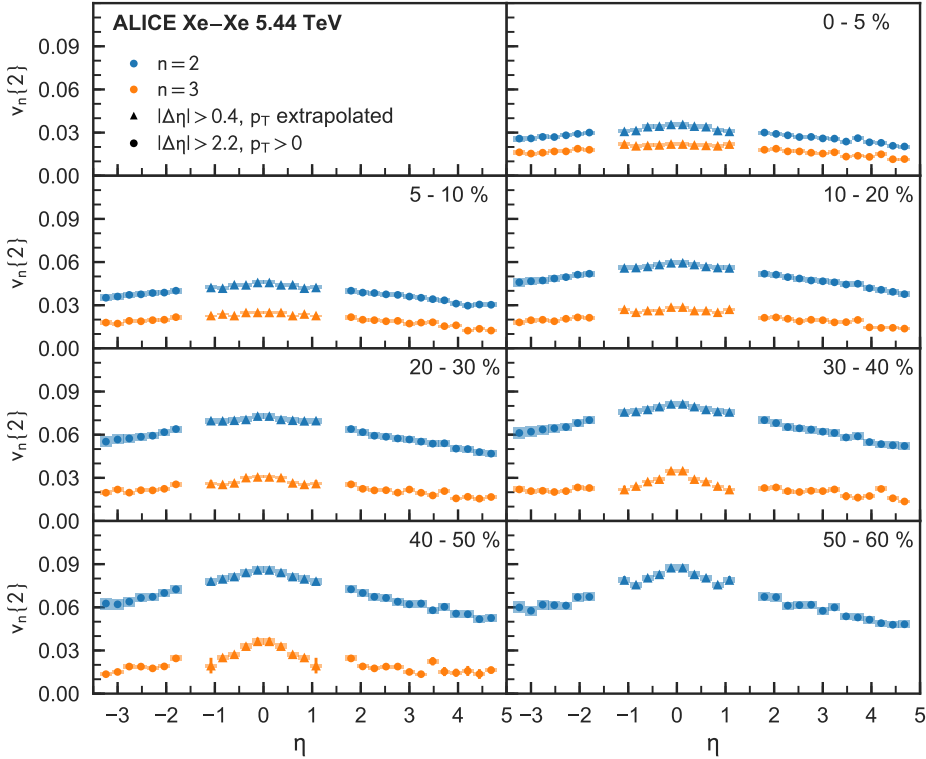


Figure 7.6: The differential flow measurements, $v_n\{2\}(\eta)$, measured with the 2-particle cumulant and choosing reference particles from the TPC in Xe–Xe collisions with $\sqrt{s_{\text{NN}}} = 5.44$ TeV. The choice of the reference particles gives $|\Delta\eta| > 0.4$ in the central regions of pseudorapidity and $|\Delta\eta| > 2.2$ in the forward regions of pseudorapidity.

²For the Xe–Xe collisions, only two data runs are available.

At the moment of writing, there are no viable simulations available in ALICE (with full detector simulation) for Xe–Xe collisions. Therefore the same corrections as for Pb–Pb for the secondary particles in the FMD is used. Since the correction for reconstructing the track references of the FMD is dependent on centrality (Section 6.4.4), it was shifted accordingly to the Xe–Xe centrality, assuming that the effect remains the same. The number of tracklets versus V0M percentile for Pb–Pb and Xe–Xe is in Appendix F, where it is shown how the centrality distribution when shifted for Pb–Pb, roughly corresponds to the Xe–Xe centrality distribution. The sources of systematic uncertainty on the secondary correction in Xe–Xe collisions are assumed to be the same as for Pb–Pb collisions with the same numerical values. An additional systematic for Xe–Xe is assigned for this assumption, and it is based the symmetry in forward and backward regions of pseudorapidity. Since the correction for the effect of secondaries in the FMD is asymmetric, the corrected results should be symmetric. If the corrected results are not symmetric at forward rapidity, it is because of the inefficiency of the secondary correction.

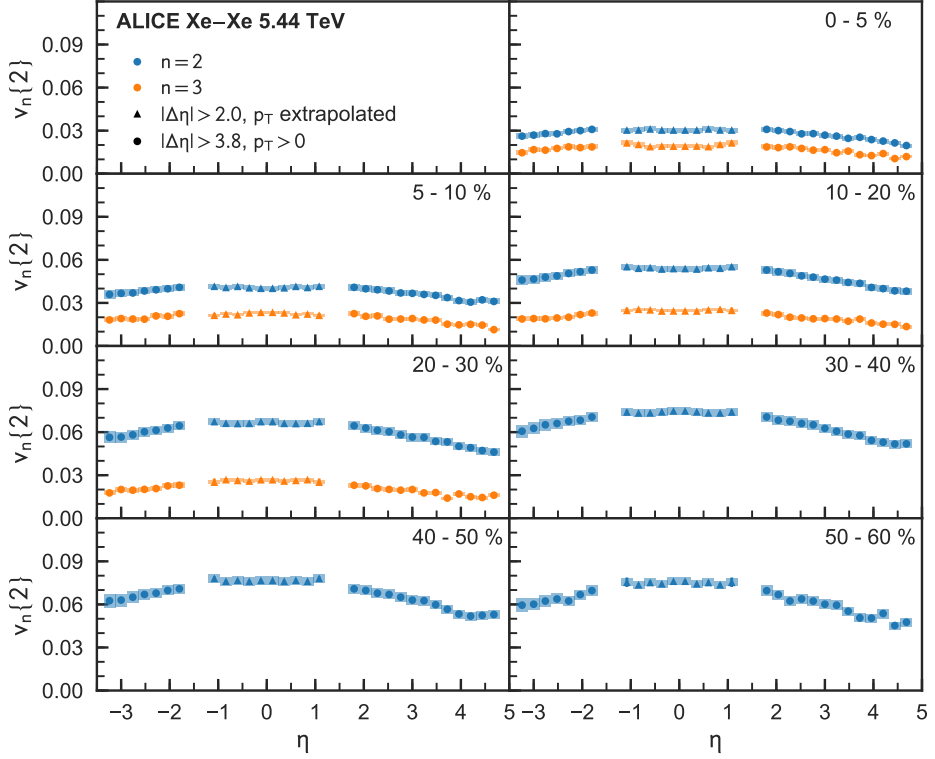


Figure 7.7: Two-particle cumulant with reference particles chosen from the FMD in Pb–Pb collisions with $\sqrt{s_{NN}} = 5.02$ TeV. $|\Delta\eta| > 2.0$ in TPC and $|\Delta\eta| > 3.8$ in FMD for the two-particle cumulant.

7.2.5 Flow measurements in p–Pb collisions

The elliptic flow coefficients calculated with the three-subevent method (introduced in Section 3.3.3) in p–Pb at 5.02 TeV is in Figure 7.8. When using the three-subevent method, the particles of interest in at mid rapidity are using both the forward- and backward pseudorapidity regions of the FMD as reference regions. The forward- and backward regions use the central regions as reference regions. Overall, this means that the η -gap is 1, and symmetry of the reference regions, i.e. $\eta_{\text{ref}} = -\eta_{\text{ref}}$, cannot be assumed. The effect of the secondary particles in the FMD was corrected by a ratio of v_n calculated with primary particles, and v_n calculated with the reconstructed particles. The correction is

$$c_s = \frac{v_2^{\text{prim.}}}{v_2^{\text{uncorr.}}} \quad (7.2)$$

The correction is an effective Monte Carlo correction, and it was chosen instead of the more detailed approach outlined in Section 6.4, to create a quick look at the results. A more detailed analysis of the p–Pb system is left for future work. The correction for secondaries, in this case, does not depend on vertex position, since the statistical uncertainties do not allow it. The p_T correction is determined by using the same approach as for Pb–Pb. The systematic uncertainties assigned in Figure 7.8 are a rough estimate, by using three times the systematic uncertainties from Pb–Pb. The magnitude of the systematic uncertainties was based on overestimating the systematic uncertainties from ALICE preliminary results (which are not from this work), which can be found in Appendix H.3, Figure H.7.

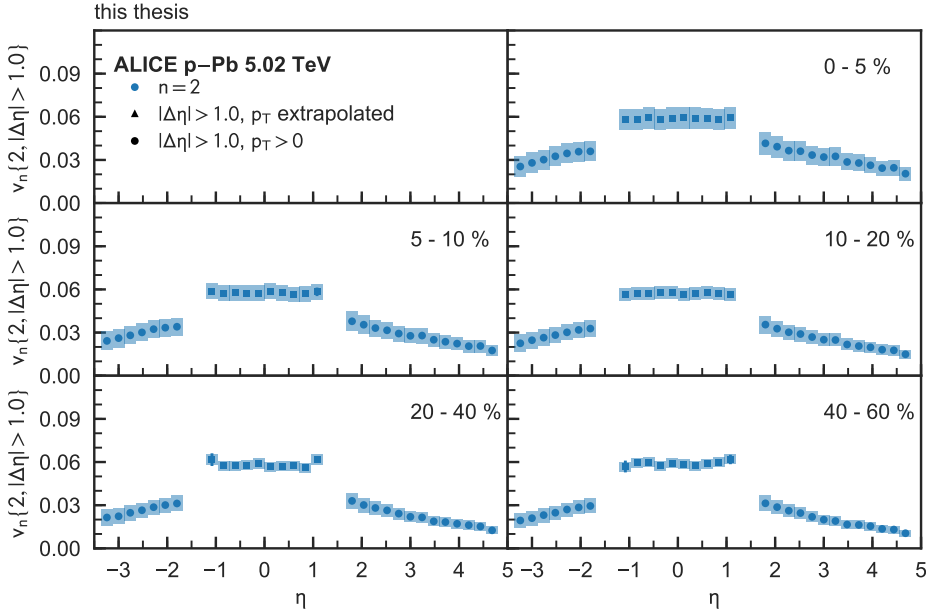


Figure 7.8: Measurements of $v_n\{2, |\Delta\eta| > 1.0\}$ using the two-particle cumulant with three sub-events in p–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

In Figure 7.8 there is a large difference in the magnitude of v_2 at central regions and forward regions. The effect can be caused by the choice of the method for calculating the flow coefficients. Since the distances between the particles of interest, and reference particles, are very different for forward and central regions in this case, it can cause different decorrelations of the symmetry plane. The difference in the magnitude of the decorrelation effect of the symmetry plane in the central and forward regions, and be the cause of the gap between the two. Further investigations are needed to be able to narrow down the origin of the shift of magnitude of v_2 between the forward and central regions in Figure 7.8.

7.3 Decorrelation effects

In long-range correlations, there can be an effect of decorrelation of the symmetry plane. In short-range correlations the effects are non-flow and breaking of factorization. The observable in this section is based on the ratio of two correlations: the correlation between particles at η and η_{ref} and the correlation between particles at $-\eta$ and η_{ref} .

7.3.1 $r_{n,n}$ in Pb–Pb collisions

The decorrelation effect is studied with Equation 3.58, which is

$$r_{n,n}(\eta, \eta_{\text{ref}}) = \frac{\langle [v_n(-\eta)v_n(\eta_{\text{ref}})] \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{\text{ref}})) \rangle}{\langle [v_n(\eta)v_n(\eta_{\text{ref}})] \cos n(\Psi_n(\eta) - \Psi_n(\eta_{\text{ref}})) \rangle}. \quad (3.58)$$

where p is the flow-vector of the particles of interest, and Q is the flow-vector of the reference particles. When $\eta \approx 0$, the decorrelation ratio $r_{n,n} \approx 1$, if the flow coefficients are symmetric in η , since both the numerator and denominator have the same η -gap. In the $r_{n,n}$ measurement, a large value of $|\eta|$ decreases the gap between η and η_{ref} , and increases the gap between $-\eta$ and η_{ref} . If the decorrelation of the symmetry plane increases as a function of pseudorapidity, the numerator of $r_{n,n}$ will be smaller than the denominator, hence $r_{n,n}(\eta)$ will decrease. However, if there are any remaining short-range non-flow effects, the denominator will increase.

The $r_{2,2}$ result³ is in Figure 7.9. The systematic uncertainties cancel out in the ratio of $r_{2,2}$, therefore only the statistical errors are shown. When the reference region is $2.8 < \eta_{\text{ref}} < 3.2$, the deviation from unity as a function of pseudorapidity is less than if the reference region is chosen from $2.0 < \eta_{\text{ref}} < 2.4$.

The results for $r_{3,3}$ are in Figure 7.10. The $r_{3,3}$ ratio exhibits a stronger decorrelation than the $r_{2,2}$ ratio. The measurements of $r_{3,3}$ have much larger statistical uncertainties, and therefore the results are only presented up to 40% centrality.

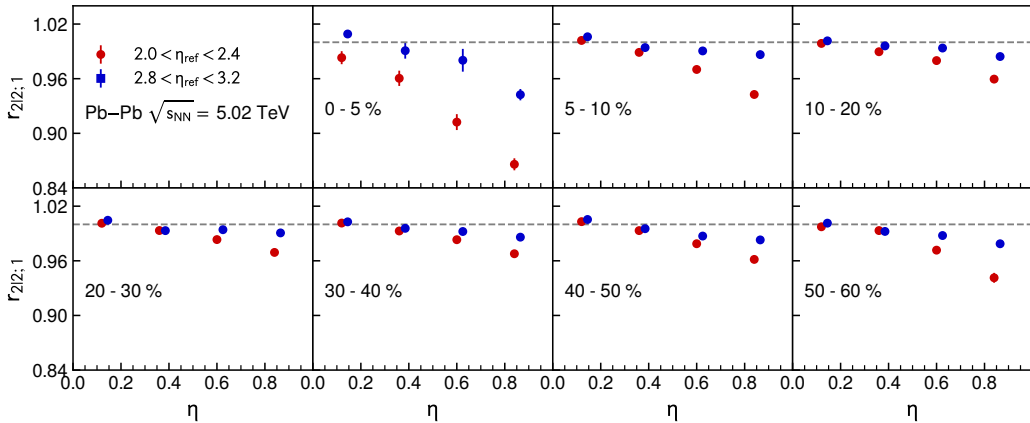


Figure 7.9: Measurements of $r_{2,2}$ with different choices for η_{ref} in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV. $r_{2,2}$ decreases faster as a function of pseudorapidity for the reference region $2.0 < \eta_{\text{ref}} < 2.4$ than for reference region $2.8 < \eta_{\text{ref}} < 3.2$.

³In Appendix H.1, the decorrelation ratio $r_{2,2}$ is also shown as a function of centrality and reference regions.

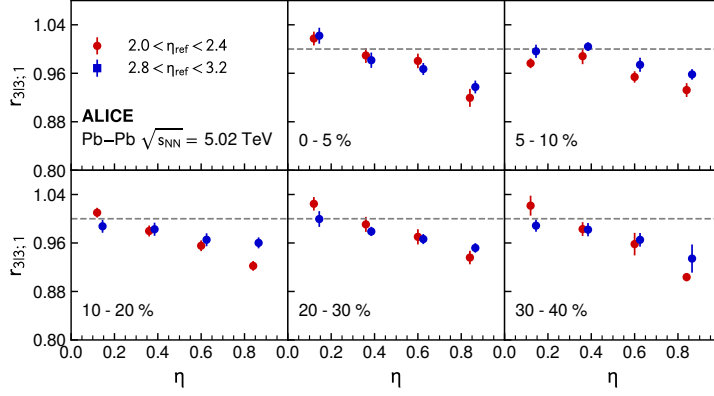


Figure 7.10: Measurements of $r_{3,3}$ with different choices for η_{ref} in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

7.3.2 $r_{2,2}$ in p–Pb collisions

The $r_{2,2}$ decorrelation ratio for p–Pb is in Figure 7.11. Compared to the decorrelation ratio in Pb–Pb, the p–Pb results show a much stronger decorrelation. The ordering of the $r_{2,2}$ with the reference regions is however similar. Since p–Pb is an asymmetric collision system, the flow coefficients may not be symmetric in pseudorapidity. Therefore the magnitude of the flow coefficients can be approximately cancelled by using [50]

$$\sqrt{r_n(\eta, \eta_{\text{ref}}) r_n(-\eta, -\eta_{\text{ref}})} \approx \sqrt{\frac{\langle \cos[n(\Psi_n(-\eta) - \Psi_n(\eta_{\text{ref}}))] \rangle \langle \cos[n(\Psi_n(\eta) - \Psi_n(-\eta_{\text{ref}}))] \rangle}{\langle \cos[n(\Psi_n(\eta) - \Psi_n(\eta_{\text{ref}}))] \rangle \langle \cos[n(\Psi_n(-\eta) - \Psi_n(-\eta_{\text{ref}}))] \rangle}} \quad (7.3)$$

such that the decorrelation of the symmetry plane can be studied in the p–Pb system.

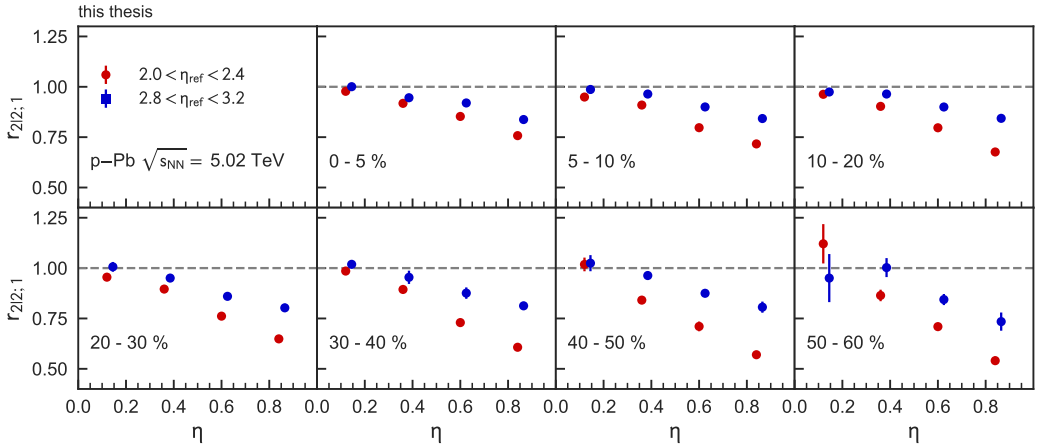


Figure 7.11: Measurements of $r_{2,2}$ with different choices for η_{ref} in p–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV. $r_{2,2}$ decreases faster as a function of pseudorapidity for the reference region $2.0 < \eta_{\text{ref}} < 2.4$ than for reference region $2.8 < \eta_{\text{ref}} < 3.2$.

7.4 Comparisons to published data

This section presents comparisons of the presented data to previously published results. The reference flow measurements are compared at the same energies, while the differential flow results as a function of pseudorapidity is compared at different collision energies. Finally, the flow measurements as a function of pseudorapidity is compared with published results with forward flow measurements, as a function of beam rapidity.

7.4.1 Integrated flow measurements

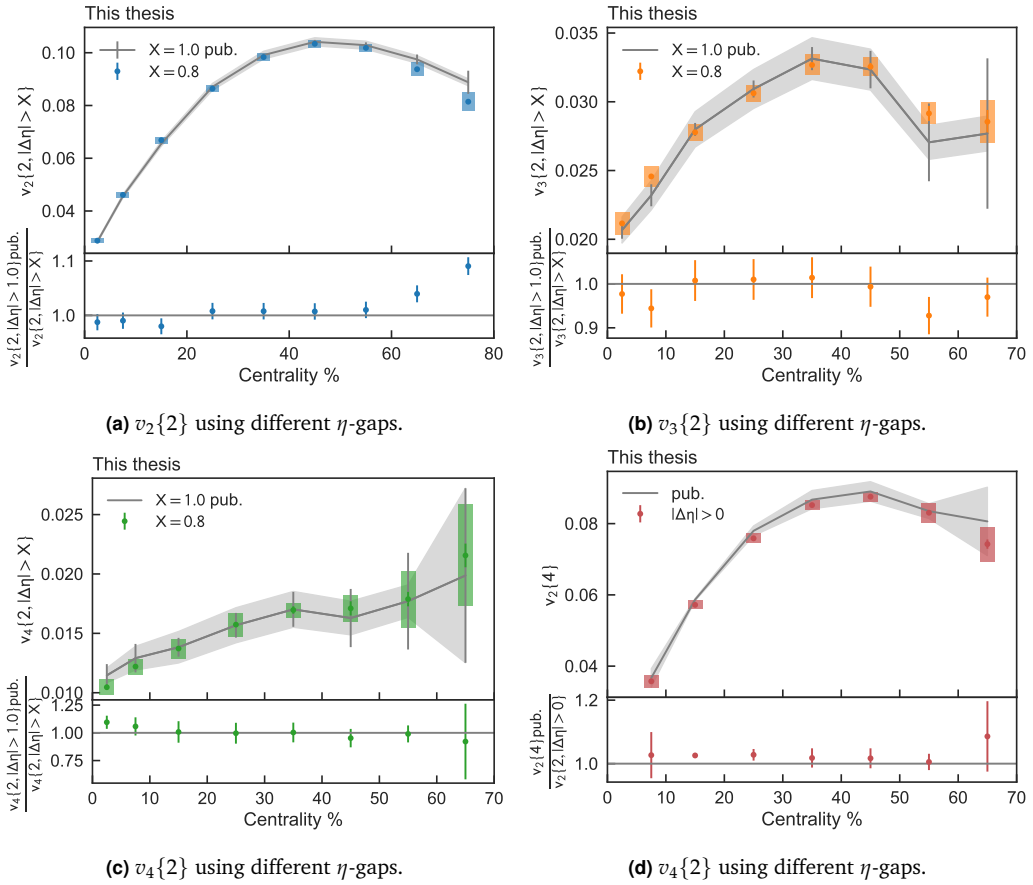


Figure 7.12: Comparison of $v_2\{2\}$, $v_3\{2\}$, $v_4\{2\}$ from published results [40] and results from this analysis. The published results use a η -gap of 1.0 for $v_n\{2\}$ and no gap for $v_2\{4\}$. The results from this thesis use a η -gap of 0.8 for $v_n\{2\}$ and a η -gap of 0.0 for $v_2\{4\}$.

The integrated flow measurements from this analysis are compared to published measurements from ALICE in Figure 7.12. The reference flow results from this analysis use the same pseudorapidity gap, as in the previously shown results (Figure 7.4). The η -gap is slightly smaller than in the published results.

The overall comparison shows a good agreement for $v_2\{2\}$, $v_3\{2\}$, $v_4\{2\}$ and $v_2\{4\}$ for the reference flow measurements, within the uncertainties.

7.4.2 Flow coefficients as a function of pseudorapidity

In Figure 7.13, the comparison of $v_n(\eta)$ is shown for Pb–Pb at 5.02 TeV (these results), and Pb–Pb at 2.76 TeV (published results by ALICE [43])⁴. The flow coefficients are higher for Pb–Pb at 5.02 TeV than at 2.76 TeV, which was also shown in Figure 2.15 for integrated flow measurements. The previous results did not use the η -gap method, but instead a subtraction of scaled flow coefficients from HIJING simulations to subtract the non-flow [57]. The non-flow correction was the largest contribution to the systematic uncertainties [57] in the results from Pb–Pb at 2.76 TeV.

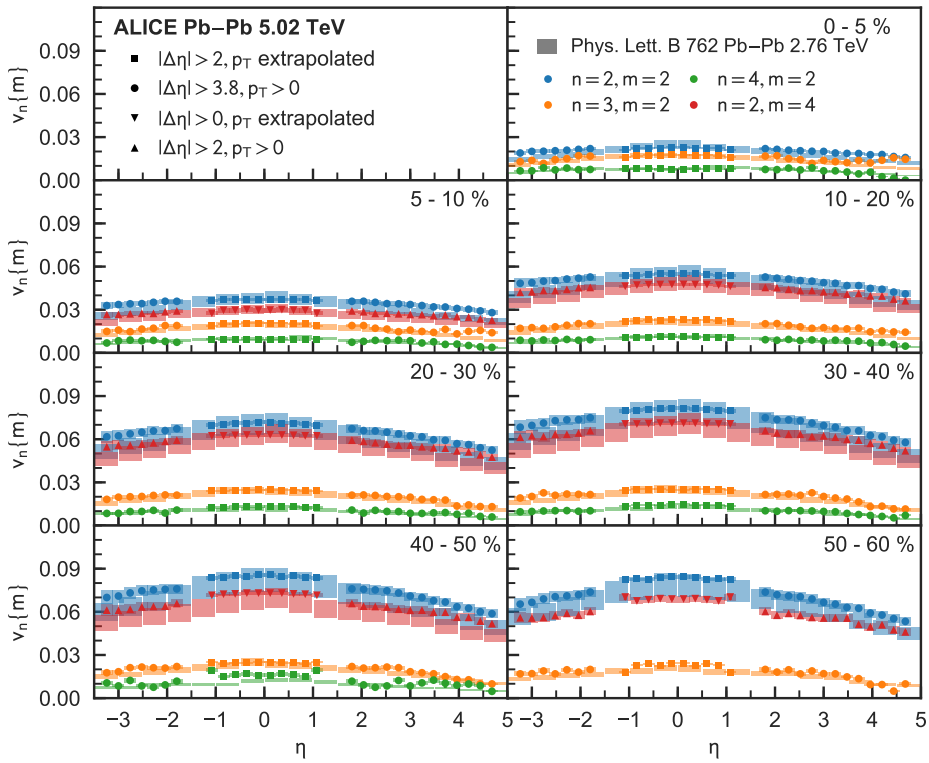


Figure 7.13: Comparison of $v_n(\eta)$ with Pb–Pb collisions at 2.76 and 5.02 TeV. The results for Pb–Pb with $\sqrt{s_{NN}} = 5.02$ TeV use the two-particle cumulant with reference particles chosen from the FMD and 4-particle cumulant with reference particles chosen from the TPC. This gives $|\Delta\eta| > 2.0$ in TPC and $|\Delta\eta| > 3.8$ in FMD for the two-particle cumulant and $|\Delta\eta| > 0.0$ in TPC and $|\Delta\eta| > 2$ in FMD for the four-particle cumulant. The results for Pb–Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV does not use the η -gap method, but uses non-flow subtraction instead.

⁴Comparison of the measurements flow coefficients using the TPC as reference region is in Appendix H.3.

7.4.3 Rapidity scaling

The slope of v_2 scales with $\eta - y_{\text{beam}}$ [47], where y_{beam} is the beam rapidity. The rapidity scaling of v_2 from different systems is in Figure 7.14. The results are presented for the central events with centrality 0 – 40%. The Pb–Pb and Xe–Xe results from this thesis, agree with the scaling with the beam rapidity found from previous results, with overlapping errors from the measurements from ALICE and PHOBOS. The conclusion is that the elliptic flow in the rest frame of a colliding nucleus is independent of the system energy $\sqrt{s_{\text{NN}}}$ in the centrality 0 – 40%.

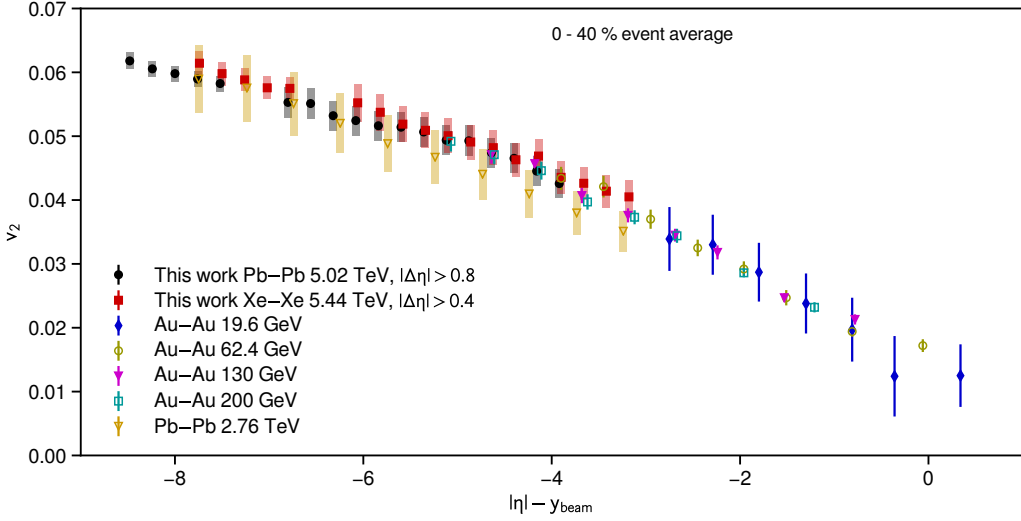


Figure 7.14: Comparison of beam rapidity scaling for v_2 with different collision systems and energies. For the results from PHOBOS [47], only the statistical errors are shown. The results from this analysis is Pb–Pb at 5.02 TeV and Xe–Xe at 5.44 TeV.

7.5 Model comparisons

In Figure 7.15, the flow measurements presented in this thesis are compared⁵ to flow measurements from AMPT production for Pb–Pb at 5.02 TeV. The AMPT calculation shows a similar trend to the data, but the flow coefficients from the AMPT production are generally overestimating the magnitude of the flow coefficients. At larger centralities, 50 – 60%, the AMPT calculation agrees more or less with data, also by the magnitude.

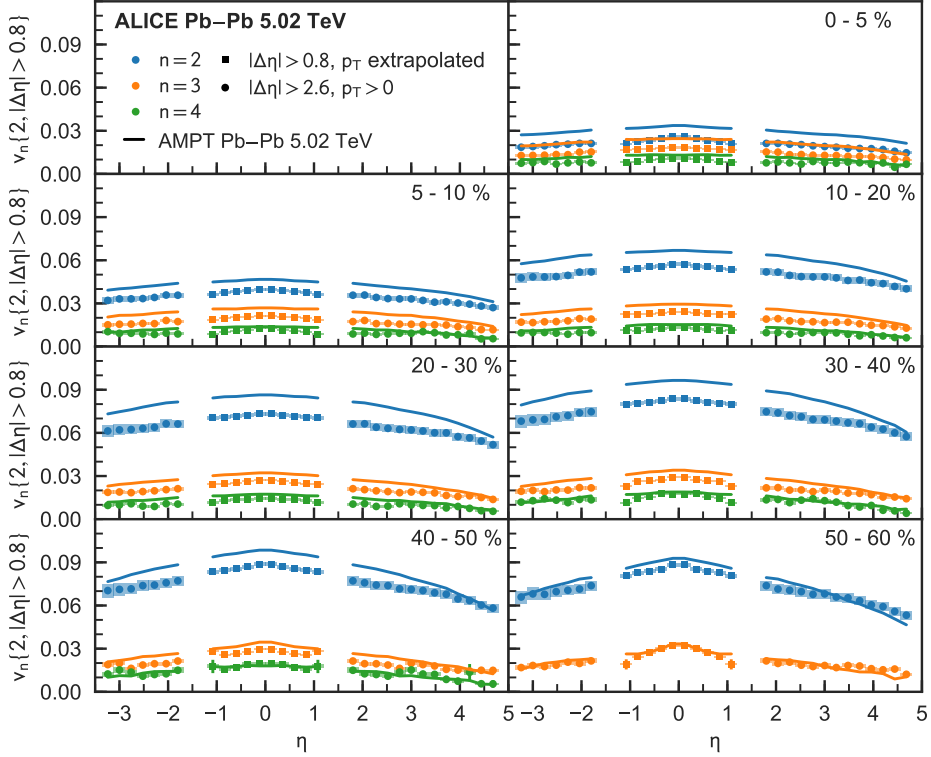


Figure 7.15: The differential flow measurements, $v_n\{2\}(\eta)$, measured with the 2-particle cumulant and chosing reference particles from the TPC in Pb–Pb collisions at 5.02 TeV. The choice of the reference particles gives $|\Delta\eta| > 0.8$ in the central regions of pseudorapidity and $|\Delta\eta| > 2.6$ in the forward regions of pseudorapidity. The results are compared to the AMPT model for Pb–Pb at 5.02 TeV.

⁵In Appendix H.4 the model comparison to the flow measurements with the FMD as reference region is shown.

In Figure 7.16, the decorrelation ratio $r_{2,2}$ is compared to AMPT with Pb–Pb at 5.02 TeV. The AMPT model qualitatively describes the magnitude difference in $r_{2,2}$ when using the reference regions $2.0 < \eta_{ref} < 2.4$ and $2.8 < \eta_{ref} < 3.2$. The AMPT model does however underestimate the decorrelation effect when using the reference region $2.0 < \eta_{ref} < 2.4$ in the most central collisions. The model slightly overestimates the decorrelation of $r_{2,2}$ when using the more forward reference region of $2.8 < \eta_{ref} < 3.2$.

The comparison for $r_{3,3}$ to AMPT is in Figure 7.17. The AMPT model describes the decorrelation of $r_{3,3}$ well, but since the statistical errors for both the model and the data are larger than for $r_{2,2}$, and it is harder to make a definitive conclusion.

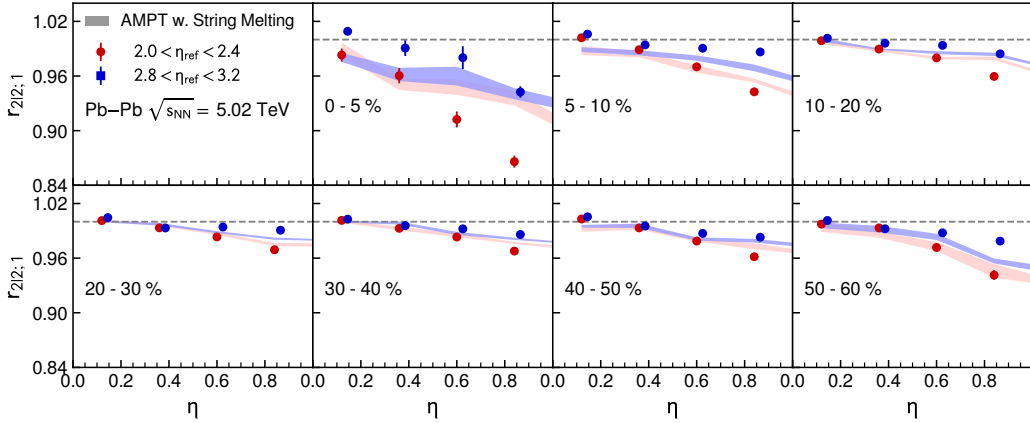


Figure 7.16: $r_{2,2}$ with different choices for η_{ref} in Pb–Pb collisions at 5.02 TeV. $r_{2|2,1}$ decreases faster as a function of pseudorapidity for the reference region $2.0 < \eta_{ref} < 2.4$ than for reference region $2.8 < \eta_{ref} < 3.2$. The AMPT model predictions are compared to the data.

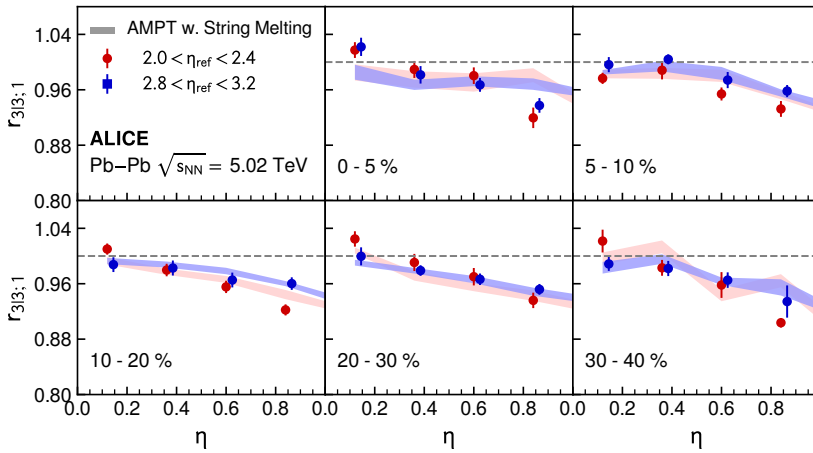


Figure 7.17: $r_{3,3}$ with different choices for η_{ref} in Pb–Pb collisions at 5.02 TeV. The AMPT model predictions are compared to the data.

VIII Conclusion

8.1 Concluding remarks

8.1.1 Summary

The anisotropic flow coefficients were studied in this thesis as a function of pseudorapidity in the range $-3.5 < \eta < 5$. The flow coefficients $v_n(\eta)$ was presented within a wide range in pseudorapidity for Pb–Pb and Xe–Xe collision systems, and also preliminary measurements for the p–Pb system. The flow coefficients were calculated using the Generic Framework, and various methods with different η -gaps were used.

The TPC and FMD detectors at ALICE were used for the flow analysis. Both detectors were corrected for non-uniform acceptance, and their efficiencies were studied. The analysis with the FMD detector required extensive studies of the background of secondary particles which originate from material interactions since the FMD is not a tracking detector. The correction for secondary particles uses information from track references from Monte Carlo simulations. The effect of using the methods and corrections presented in this thesis was that the resolution was increased in η , and systematics decreased overall, when comparing to ALICE results for v_n dependence on pseudorapidity in Pb–Pb collisions at 2.76 TeV. The flow results have a broad coverage in pseudorapidity, which has only been obtained previously by ALICE and PHOBOS at lower energies. The comparison to prior measurements as a function of beam rapidity shows that v_2 from different systems and collision energies scales similarly as a function of beam rapidity, which is the longitudinal scaling.

The decorrelation effect of the flow vectors was studied using the $r_{n,n}$ ratios for the Pb–Pb and p–Pb systems. The $r_{n,n}$ ratios presented showed that there is a significant difference in the flow measurements, depending on the separation of the particles involved in the correlations. The $r_{n,n}$ ratios and flow measurements for Pb–Pb were compared to an AMPT production, which showed a qualitative agreement.

The strongly interacting Quark-Gluon plasma, which is created at the LHC at CERN can be studied at the ALICE experiment. The plasma was found to be a nearly perfect fluid, and its transport coefficients can be determined using anisotropic flow measurements compared to theory. The anisotropic flow results are closely correlated with the initial state of the collision, and the expansion of the QGP. The anisotropic flow measurements from this thesis are in agreement with the previous conclusions of the strongly interacting Quark-Gluon plasma found at the LHC at CERN. The measurements from this thesis contributes to the current field, by providing information about the anisotropic flow dependence on pseudorapidity, and the decorrelation of the symmetry plane was also shown to be a significant effect when measuring the flow coefficients in pseudorapidity.

8.1.2 Outlook

In this thesis, v_2 for p–Pb at 5.02 TeV was shown with preliminary systematic uncertainties. Therefore the result shown had overestimated systematic uncertainties, and for future work, these should be determined with tighter bounds. Measurements of v_3 and v_4 for p–Pb at 5.02 TeV is left for future work.

Comparisons to 1+3D hydrodynamical calculations are planned for Pb–Pb and may be found in a future ALICE paper.

Bibliography

- [1] ALICE collaboration. Measurement of long-range two- and multi-particle correlations by ALICE. *Quark Matter 2019 Proceedings*, 2019.
- [2] ALICE collaboration. Pseudorapidity dependence of anisotropic flow in heavy ion collisions with ALICE. *European Physical Society 2019*, 2019.
- [3] ALICE collaboration. Pseudorapidity dependence of anisotropic flow in heavy ion collisions with ALICE (poster). *Quark Matter 2018*, 2018.
- [4] Isaac Newton. *Philosophiae naturalis principia mathematica*. William Dawson & Sons Ltd., London, 1687.
- [5] Frank Wilczek. Asymptotic Freedom: From Paradox to Paradigm. *Lecture given in acceptance of the Nobel Prize*, 2004.
- [6] K. Yagi, T. Hatsuda, and Y. Miake. *Quark-gluon plasma: From big bang to little bang*, volume 23. 2005.
- [7] Frank Wilczek. Asymptotic freedom. 1996.
- [8] David J. Gross. Asymptotic freedom and the emergence of QCD. In *The Rise of the standard model: Particle physics in the 1960s and 1970s. Proceedings, Conference, Stanford, USA, June 24-27, 1992*, pages 199–232, 1992.
- [9] Vardan Khachatryan et al. Measurement of the inclusive 3-jet production differential cross section in proton–proton collisions at 7 TeV and determination of the strong coupling constant in the TeV range. *Eur. Phys. J.*, C75(5):186, 2015.
- [10] Roman Pasechnik and Michal Šumbera. Phenomenological Review on Quark–Gluon Plasma: Concepts vs. Observations. *Universe*, 3(1):7, 2017.
- [11] I. Arsene et al. Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment. *Nucl. Phys.*, A757:1–27, 2005.
- [12] B. B. Back et al. The PHOBOS perspective on discoveries at RHIC. *Nucl. Phys.*, A757:28–101, 2005.
- [13] Miklos Gyulassy and Larry McLerran. New forms of QCD matter discovered at RHIC. *Nucl. Phys.*, A750:30–63, 2005.

- [14] Francois Gelis, Edmond Iancu, Jamal Jalilian-Marian, and Raju Venugopalan. The Color Glass Condensate. *Ann. Rev. Nucl. Part. Sci.*, 60:463–489, 2010.
- [15] Berndt Muller. From Quark-Gluon Plasma to the Perfect Liquid. *Acta Phys. Polon.*, B38:3705–3730, 2007.
- [16] Christian Bierlich et al. Confronting Experimental Data with Heavy-Ion Models: Rivet for Heavy Ions. 2020.
- [17] Giuliano Giacalone, François Gelis, Pablo Guerrero-Rodríguez, Matthew Luzum, Cyrille Marquet, and Jean-Yves Ollitrault. Evolution of fluctuations in the initial state of heavy-ion collisions from RHIC to LHC. 2019.
- [18] Miklos Gyulassy and Michael Plumer. Jet Quenching in Dense Matter. *Phys. Lett. B*, 243:432–438, 1990.
- [19] Georges Aad et al. Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.77$ TeV with the ATLAS Detector at the LHC. *Phys. Rev. Lett.*, 105:252303, 2010.
- [20] T. Matsui and H. Satz. J/ψ Suppression by Quark-Gluon Plasma Formation. *Phys. Lett.*, B178:416–422, 1986.
- [21] CMS Collaboration. Nuclear modification factor of d_0 mesons in pbbp collisions at $s_{nn}=5.02$ tev. *Physics Letters B*, 782:474 – 496, 2018.
- [22] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, and Peter Steinberg. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007.
- [23] Jaroslav Adam et al. J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Lett.*, B766:212–224, 2017.
- [24] P. Koch, Berndt Muller, and Johann Rafelski. Strangeness in Relativistic Heavy Ion Collisions. *Phys. Rept.*, 142:167–262, 1986.
- [25] Jaroslav Adam et al. Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions. *Nature Phys.*, 13:535–539, 2017.
- [26] Jean-Yves Ollitrault. Relativistic hydrodynamics for heavy-ion collisions. *Eur. J. Phys.*, 29:275–302, 2008.
- [27] Tetsufumi Hirano, Naomi van der Kolk, and Ante Bilandzic. Hydrodynamics and Flow. *Lect. Notes Phys.*, 785:139–178, 2010.
- [28] S. Ryu, J. F. Paquet, C. Shen, G. S. Denicol, B. Schenke, S. Jeon, and C. Gale. Importance of the Bulk Viscosity of QCD in Ultrarelativistic Heavy-Ion Collisions. *Phys. Rev. Lett.*, 115(13):132301, 2015.
- [29] Jonah E. Bernhard. *Bayesian parameter estimation for relativistic heavy-ion collisions*. PhD thesis, Duke U., 2018-04-19.
- [30] Kazuhisa Okamoto and Chiho Nonaka. Temperature dependence of transport coefficients of QCD in high-energy heavy-ion collisions. *Phys. Rev.*, C98(5):054906, 2018.

- [31] 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. *Comput. Phys. Commun.*, 83:307, 1994.
- [32] Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, and Subrata Pal. Multiphase transport model for relativistic heavy ion collisions. *Phys. Rev. C*, 72:064901, Dec 2005.
- [33] Sergei A. Voloshin, Arthur M. Poskanzer, and Raimond Snellings. Collective phenomena in non-central nuclear collisions. *Landolt-Bornstein*, 23:293–333, 2010.
- [34] Pasi Huovinen. Hydrodynamical description of collective flow. Chapter 1. pages 600–633, 2003.
- [35] S. Voloshin and Y. Zhang. Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions. *Z. Phys.*, C70:665–672, 1996.
- [36] B. Alver and G. Roland. Collision-geometry fluctuations and triangular flow in heavy-ion collisions. *Phys. Rev. C*, 81:054905, May 2010.
- [37] Ulrich Heinz, Zhi Qiu, and Chun Shen. Fluctuating flow angles and anisotropic flow measurements. *Phys. Rev.*, C87(3):034913, 2013.
- [38] B. Alver and G. Roland. Collision geometry fluctuations and triangular flow in heavy-ion collisions. *Phys. Rev.*, C81:054905, 2010. [Erratum: *Phys. Rev.*C82,039903(2010)].
- [39] K. Aamodt et al. Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. *Phys. Rev. Lett.*, 107:032301, 2011.
- [40] Jaroslav Adam et al. Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. Lett.*, 116(13):132302, 2016.
- [41] H. Niemi, K. J. Eskola, R. Paatelainen, and K. Tuominen. Predictions for 5.023 TeV Pb + Pb collisions at the CERN Large Hadron Collider. *Phys. Rev.*, C93(1):014912, 2016.
- [42] Jacquelyn Noronha-Hostler, Matthew Luzum, and Jean-Yves Ollitrault. Hydrodynamic predictions for 5.02 TeV Pb-Pb collisions. *Phys. Rev.*, C93(3):034912, 2016.
- [43] Jaroslav Adam et al. Pseudorapidity dependence of the anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett.*, B762:376–388, 2016.
- [44] B. B. Back et al. Pseudorapidity and centrality dependence of the collective flow of charged particles in Au+Au collisions at $s(NN)^{1/2} = 130$ -GeV. *Phys. Rev. Lett.*, 89:222301, 2002.
- [45] Georges 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. *Phys. Rev.*, C86:014907, 2012.
- [46] Albert M Sirunyan et al. Pseudorapidity and transverse momentum dependence of flow harmonics in pPb and PbPb collisions. *Phys. Rev.*, C98(4):044902, 2018.
- [47] B. B. Back et al. Energy dependence of elliptic flow over a large pseudorapidity range in Au+Au collisions at RHIC. *Phys. Rev. Lett.*, 94:122303, 2005.
- [48] Jiangyong Jia and Peng Huo. A method for studying the rapidity fluctuation and decorrelation of harmonic flow in heavy-ion collisions. *Phys. Rev.*, C90(3):034905, 2014.

- [49] Christian Bourjau. *Factorization of two-particle distributions measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector*. PhD thesis, University of Copenhagen, 2018.
- [50] Vardan Khachatryan et al. Evidence for transverse momentum and pseudorapidity dependent event plane fluctuations in PbPb and pPb collisions. *Phys. Rev.*, C92(3):034911, 2015.
- [51] Morad Aaboud et al. Measurement of longitudinal flow decorrelations in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with the ATLAS detector. *Eur. Phys. J.*, C78(2):142, 2018.
- [52] Long-Gang Pang, Hannah Petersen, Guang-You Qin, Victor Roy, and Xin-Nian Wang. Decorrelation of anisotropic flow along the longitudinal direction. *Eur. Phys. J.*, A52(4):97, 2016.
- [53] Matthew Luzum and Jean-Yves Ollitrault. Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions. *Phys. Rev.*, C87(4):044907, 2013.
- [54] A. Bilandzic. *Anisotropic flow measurements in ALICE at the Large Hadron Collider*. PhD thesis, 2011.
- [55] Ante Bilandzic, Raimond Snellings, and Sergei Voloshin. Flow analysis with cumulants: Direct calculations. *Phys. Rev.*, C83:044913, 2011.
- [56] Nicolas Borghini, Phuong Mai Dinh, and Jean-Yves Ollitrault. Flow analysis from cumulants: A Practical guide. In *International Workshop on the Physics of the Quark Gluon Plasma Palaiseau, France, September 4-7, 2001*, 2001.
- [57] A. C. Hansen. *Pseudorapidity dependence of the anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*. PhD thesis, October 2014.
- [58] Jean-Yves Ollitrault, Arthur M. Poskanzer, and Sergei A. Voloshin. Effect of flow fluctuations and nonflow on elliptic flow methods. *Phys. Rev.*, C80:014904, 2009.
- [59] Ante Bilandzic, Christian Holm Christensen, Kristjan Gulbrandsen, Alexander Hansen, and You Zhou. Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations. *Phys. Rev.*, C89(6):064904, 2014.
- [60] ALICE Collaboration. Alice collaboration. Homepage, 04 2020.
- [61] K. Aamodt et al. The ALICE experiment at the CERN LHC. *JINST*, 3:S08002, 2008.
- [62] P. Kuijer. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2004.
- [63] Dariusz Miskowiec. (W)hole new field: the new GEM Time Projection Chamber of ALICE. 12 2019.
- [64] Christian Holm Christensen, Jens Jorgen Gaardhoje, Kristjan Gulbrandsen, Borge Svane Nielsen, and Carsten Sogaard. The ALICE Forward Multiplicity Detector. *Int. J. Mod. Phys.*, E16:2432–2437, 2007.
- [65] E. Abbas et al. Performance of the ALICE VZERO system. *JINST*, 8:P10016, 2013.
- [66] The ALICE definition of primary particles. Jun 2017.

- [67] ALICE Collaboration. Alice collaboration. Homepage, 04 2020.
- [68] Scipy. Discrete fourier transform (numpy.fft).
- [69] Hans Hjersing Dalsgaard. *Pseudorapidity densities in $p+p$ and $Pb+Pb$ collisions at LHC measured with the ALICE experiment*. PhD thesis, January 2012.
- [70] Larry Wasserman. *All of Statistics: A Concise Course in Statistical Inference*. Springer Texts in Statistics. Springer, 2004.
- [71] Roger Barlow. Systematic errors: Facts and fictions. In *Advanced Statistical Techniques in Particle Physics. Proceedings, Conference, Durham, UK, March 18-22, 2002*, pages 134–144, 2002.
- [72] Christian Holm Christensen. Notes on statistics and data analysis. 2019.
- [73] ALICE Collaboration. Nittygriddy. Github.

Appendices

A Generic Framework with detector segments

The standard Q-cumulant Q -vector is the case of the Generic Framework Q -vector with all weights equal to one

$$Q_n = \sum_{k=1}^M e^{in\varphi_k} \quad (\text{A.1})$$

And using the equations for N and D with all particle weights equal to one, we get

$$N\langle 2 \rangle_{n,-n} = |Q_n|^2 - M \quad (\text{A.2})$$

$$D\langle 2 \rangle_{n,-n} = M(M-1) \quad (\text{A.3})$$

which is exactly the standard Q-cumulant method. Instead of having weights of 1, we will, in the next section, introduce the particle multiplicity in a detector segment as weights.

A.1 Particle correlations with a segmented detector

Introducing a case study of three particles: One particle p_1 is in one segment, while the other two particles p_2 and p_3 are in a different segment. The particles p_2 and p_3 are in the same segment, and therefore have the same coordinates and a multiplicity weight of 2. The coordinates of the particles are,

particle 1 : φ_1

particle 2 : φ_2

particle 3 : φ_3

Since $\varphi_2 = \varphi_3$ we introduce multiplicity weights ω ,

$$\varphi_2 = \varphi_3 = \varphi_{23}$$

$$\omega_1 = 1$$

$$\omega_{23} = \omega_1 + \omega_2 = 2$$

The weighted Q -vector is then

$$Q_{n,1} = e^{in\varphi_1} + 2 \cdot e^{in\varphi_{23}}, \quad (\text{A.4})$$

and squaring the vector gives

$$\begin{aligned}
 |Q_{n,1}|^2 &= (2e^{in\varphi_{23}} + e^{in\varphi_1}) \cdot (2e^{-in\varphi_{23}} + e^{-in\varphi_1}) \\
 &= 4e^{in(\varphi_{23}-\varphi_{23})} + e^{in(\varphi_1-\varphi_1)} \\
 &\quad + 2e^{in(\varphi_{23}-\varphi_1)} + 2 \cdot e^{in(\varphi_1-\varphi_{23})} \\
 &= 4 + 1 + 2 \cdot e^{in(\varphi_{23}-\varphi_1)} + 2 \cdot e^{in(\varphi_1-\varphi_{23})}
 \end{aligned} \tag{A.5}$$

The auto-correlation in this case should be 3, arriving from the correlations,

$$e^{in(\varphi_1-\varphi_1)} = 1$$

$$e^{in(\varphi_2-\varphi_2)} = 1$$

$$e^{in(\varphi_3-\varphi_3)} = 1$$

ie. a total of 3 should be subtracted from $|Q_n|^2$. The Generic Framework defines the auto-correlation to be subtracted in our case as,

$$\sum \omega^2 = \omega_1^2 + \omega_2^2 = 1^2 + 2^2 = 5 \tag{A.6}$$

This is because the Generic Framework also subtracts the correlations

$$e^{in(\varphi_2-\varphi_3)} = 1 \tag{A.7}$$

$$e^{in(\varphi_3-\varphi_2)} = 1 \tag{A.8}$$

which are correlations we want to keep, therefore the correction for the calculation of auto-correlations in this case would be 2.

A.2 Calculating the correction by induction

To simplify the calculations, we define $\Delta_{ij} = e^{in(\varphi_i-\varphi_j)}$, notice $\text{diag}(\Delta) = \{1\}$. The ω_s variable in the calculations note the sum of weights.

Two particles

We start by looking at the calculations when we have two particles in the same segment, i.e. two particles with weight and φ coordinates $(\omega_1, \varphi_1), (\omega_2, \varphi_2)$. The Q -vector is then,

$$\begin{aligned}
 Q_{n,1}Q_{n,-1} &= \sum_{k_1=1, k_2=1}^M e^{in(\varphi_{k_1}-\varphi_{k_2})} \\
 &= \omega_1^2 + \omega_2^2 + \omega_1\omega_2\Delta_{12} + \omega_1\omega_2\Delta_{21}
 \end{aligned} \tag{A.9}$$

$$Q_{0,2} = \sum_i^M \omega_i^2 = \omega_1^2 + \omega_2^2 \tag{A.10}$$

where the correlations we wish to subtract from $Q_{n,1}Q_{n,-1}$ is $\omega_1^2 + \omega_2^2$.

If we put the two particles in the same segment ($\varphi_1 = \varphi_2$) and introduce the multiplicity weight $\omega_s = \omega_1 + \omega_2$, the correlations are

$$\begin{aligned}
 Q_{n,1}Q_{n,-1} &= \omega_s^2 \\
 &= \omega_1^2 + \omega_2^2 + 2\omega_1\omega_2
 \end{aligned} \tag{A.11}$$

$$Q_{0,2} = \sum_i \omega_i^2 = \omega_s^2 = \omega_1^2 + \omega_2^2 + 2\omega_1\omega_2 \tag{A.12}$$

Three Particles

In the case of three particles with (ω_1, φ_1) , (ω_2, φ_2) and (ω_3, φ_3) the correlations are

$$\begin{aligned} Q_{n,1}Q_{n,-1} &= \omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_1\omega_2(\Delta_{12} + \Delta_{21}) \\ &\quad + \omega_2\omega_3(\Delta_{23} + \Delta_{32}) + \omega_1\omega_3(\Delta_{13} + \Delta_{31}) \end{aligned} \quad (\text{A.13})$$

$$Q_{0,2} = \sum_i \omega_i^2 = \omega_1^2 + \omega_2^2 + \omega_3^2. \quad (\text{A.14})$$

If the three particles are in the same segment, i.e. $\varphi_1 = \varphi_2 = \varphi_3, \omega_s = \omega_1 + \omega_2 + \omega_3$, the correlations are

$$Q_{n,1}Q_{n,-1} = \omega_s^2 \quad (\text{A.15})$$

$$\begin{aligned} &= \omega_1^2 + \omega_2^2 + \omega_3^2 + 2\omega_1\omega_2 + 2\omega_2\omega_3 + 2\omega_1\omega_3 \\ Q_{0,2} &= \sum_i \omega_i^2 = \omega_s^2 \quad (\text{A.16}) \\ &= \omega_1^2 + \omega_2^2 + \omega_3^2 + 2\omega_1\omega_2 + 2\omega_2\omega_3 + 2\omega_1\omega_3. \end{aligned}$$

n particles

The case of n particles in one segment, ie. $\varphi_1 = \dots = \varphi_n, \omega_s = \omega_1 + \dots + \omega_n$, the correlation is then

$$Q_{n,1}Q_{n,-1} = \omega_s^2 = \sum_{i,j=1}^n \omega_i\omega_j \quad (\text{A.17})$$

$$= \omega_1^2 + \dots + \omega_n^2 + \sum_{i,j=1, j \neq i}^n \omega_i\omega_j. \quad (\text{A.18})$$

Assuming ω are integers and non-negative,

$$\begin{aligned} \sum_{i,j=1, j \neq i}^m \omega_i\omega_j &= m(m-1) = \frac{m!}{(m-2)!} = \frac{\Gamma(m+1)}{\Gamma(m-1)} \\ &= \sum_j \omega_j(\omega_j - 1) \end{aligned} \quad (\text{A.19})$$

This leads to a correction of the auto-correlations for 2-particle cumulants,

$$\langle\langle 2 \rangle\rangle = \frac{\sum_{i=1}^{events} [N\langle 2 \rangle_i + [\sum_{j=1, \omega_j \neq 1}^{N_{segments}} \omega_j(\omega_j - 1)]]}{\sum_{i=1}^{events} [D\langle 2 \rangle_i + [\sum_{j=1, \omega_j \neq 1}^{N_{segments}} \omega_j(\omega_j - 1)]]}. \quad (\text{A.20})$$

A.3 Toy simulation

A toy simulation was made to test the Generic Framework, and the additional correction derived in the prior section. In the toy simulation, the $dN/d\eta$ and symmetry plane Ψ_2 distributions were made from a flat probability distribution. v_2 was set to a constant of 0.2, which is also seen in the $dN/d\varphi$ distribution in Figure A.1. All other harmonics are set to zero for simplicity.

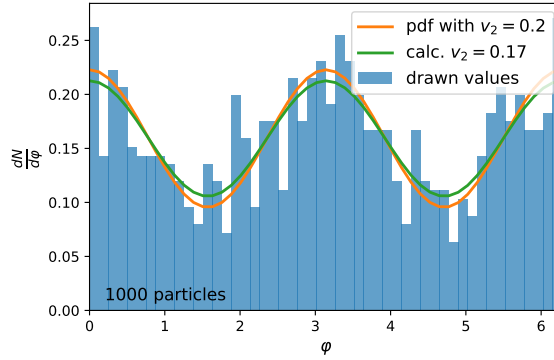


Figure A.1: Distribution of particles in φ .

In [59] a correction to v_n when using a detector with a resolution was introduced. The correction is to be multiplied on v_n is

$$\left[\frac{2\pi}{N} / \sin\left(\frac{2\pi}{N}\right) \right]^2, \quad (\text{A.21})$$

where N is the number of segments in φ . The correction in A.21 is for correlations using single-particle weights, which means that it only works if the multiplicity weights are equal to one. A test of the correction in Equation A.21 is in Figure A.2, and the correction worked as expected.

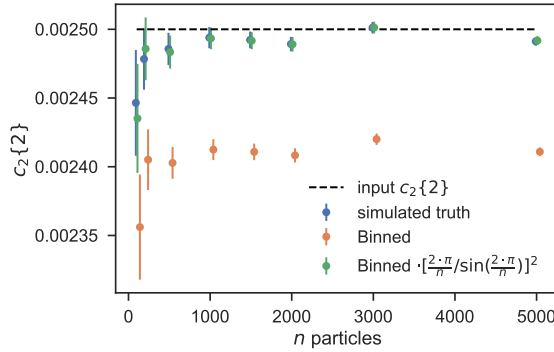


Figure A.2: $c_2\{2\}$ calculated for simulated particles, binned particles, and corrected binned particles. The *binned* particles means that the φ is limited in resolution, but all particles still have the weight of 1. 100000 events were produced with $v_2 = 0.2$.

When the particles weights are both multiplicity weighted and binned in φ , the correction from Equation A.20 also needs to be added. In Figure A.3, all of the corrections are shown and compared to the true distribution. The correction from Equation A.21 works well in combination with the correction in Equation A.20. A closer look at the final result of the corrections is in Figure A.4.

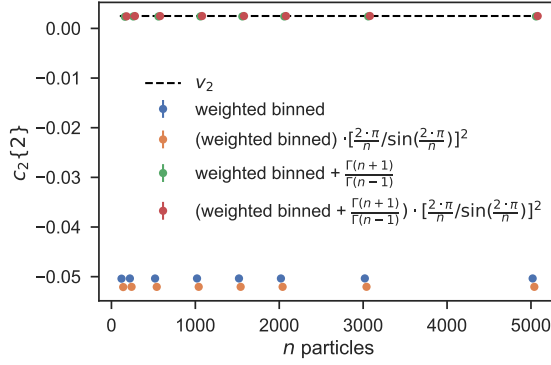


Figure A.3: $c_2\{2\}$ calculated for binned particles with multiplicity weights in the Q -cumulant method. The weights do not necessarily have to be one or an integer. 100000 events were produced with $v_2 = 0.2$.

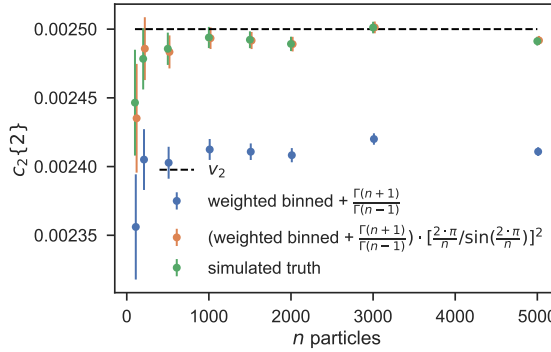


Figure A.4: $c_2\{2\}$ calculated for binned particles with multiplicity weights in the Q -cumulant method. The weights do not necessarily have to be one or an integer. 100000 events were produced with $v_2 = 0.2$.

B Methods

FMD and TPC as reference regions

The method proposed here is where the FMD particles of interest use the TPC as reference particles and vice versa. This means that there is a $\Delta\eta$ -gap of minimum 2 for both the FMD and TPC.

For region A,

$$\langle v_n'^A \rangle = \frac{\langle v_n'^A v_n^B \cdot \cos[n(\Psi_n'^A - \Psi_n^B)] \rangle}{\sqrt{\langle v_n^C v_n^B \cdot \cos[n(\Psi_n^C - \Psi_n^B)] \rangle}} \quad (\text{B.1})$$

and for region B

$$\langle v_n^B \rangle = \frac{\langle v_n^B v_n^D \cdot \cos[n(\Psi_n^B - \Psi_n^D)] \rangle}{\sqrt{\langle v_n^C v_n^B \cdot \cos[n(\Psi_n^C - \Psi_n^B)] \rangle}} \quad (\text{B.2})$$

It is also in Figure B.1

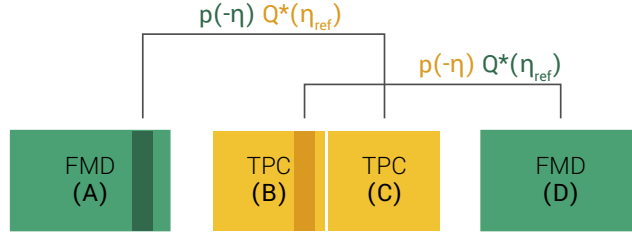


Figure B.1: η -gap method using the TPC (region B and C) and the FMD (region A and D). The dark slices correspond to where the particles of interest are chosen from, and the end of the line to where the corresponding reference particles are chosen from. E.g., particles of interest from region B are being correlated with reference particles in region D. In this method, the central regions B and C have a $\Delta\eta$ -gap of 2.0, and the forward regions A and D have a gap of $\Delta\eta$ -gap of 2.0. The forward and central regions in this method do not use the same reference region, since the central regions use the forward regions as reference, and vice versa for the forward regions.

Methods with 3 sub-events

Opposite side reference regions

The 3-subevent method can be used, when one does not want to assume that the reference regions have the same v_n . There is still a gap between all region of reference particles, but the TPC-TPC correlations can have only a limited gap.

$$\langle v_n^B \rangle = \sqrt{\frac{\langle v_n^B v_n^D \rangle \langle v_n^B v_n^C \rangle}{\langle v_n^C v_n^D \rangle}} \quad (\text{B.3})$$

since the particles of interest will be correlated with both v_n^C and v_n^D (see Figure 3.3). For the TPC the non-flow contributions are higher than in the FMD, and the decorrelation factor does not cancels out. For the FMD the non-flow contributions should be low, but the decorrelation does not cancel.

$$\langle v_n^B \rangle = \sqrt{\frac{\langle v_n^B v_n^C \rangle \cdot \cos(n(\Psi_n^B - \Psi_n^C)) \cdot \langle v_n^B v_n^D \rangle \cdot \cos(n(\Psi_n^B - \Psi_n^D))}{\langle v_n^C v_n^D \rangle \cdot \cos(n(\Psi_n^C - \Psi_n^D))}} \quad (\text{B.4})$$

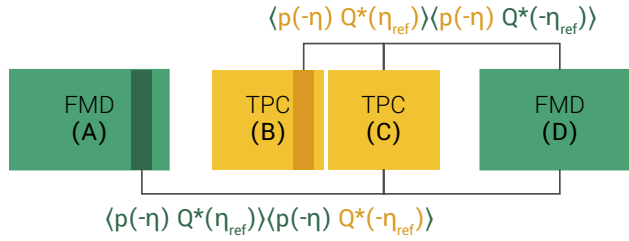


Figure B.2: η -gap method with 3 subevents using the TPC (region B and C) and the FMD (region A and D). The dark slices correspond to where the particles of interest are chosen from, and the end of the line to where the corresponding reference particles are chosen from. E.g., particles of interest from region B is being correlated with reference particles in region C and D. In this method, the central regions B and C have a gap of $\Delta\eta > 0.0$, and the forward regions A and D have a gap of $\Delta\eta > 2.0$. The forward and central regions in this method use the same reference regions. The reference regions are always chosen to be opposite of the differential regions.

B.1 The four-particle cumulants with a η -gap

$$Q_{n,1}Q_{n,1}Q_{-n,1}Q_{-n,1} = \sum_a \sum_b \sum_c \sum_d w_a w_b w_c w_d e^{in(\varphi_a + \varphi_b - \varphi_c - \varphi_d)} \quad (\text{B.5})$$

The cases that need to be subtracted are,

$$a = b \quad (\text{B.6})$$

$$c = d \quad (\text{B.7})$$

$$a = b \text{ \& } d = c \quad (\text{B.8})$$

$$(\text{B.9})$$

The term for $a = b$ is,

$$Q_{2n,2}Q_{-n,1}Q_{-n,1} \quad (\text{B.10})$$

The term for $c = d$ is,

$$Q_{-2n,2}Q_{n,1}Q_{n,1} \quad (\text{B.11})$$

and for $a = b, c = d$

$$Q_{2n,2}Q_{-2n,2} \quad (\text{B.12})$$

and this can be reduced to

$$Q_{n,1}Q_{n,1}Q_{-n,1}Q_{-n,1} - Q_{2n,2}Q_{-n,1}Q_{-n,1} - Q_{-2n,2}Q_{n,1}Q_{n,1} + Q_{-2n,2}Q_{n,1}Q_{n,1} \quad (\text{B.13})$$

$$= (Q_{n,1}Q_{n,1} - Q_{2n,2})(Q_{-n,1}Q_{-n,1} - Q_{-2n,2}) \quad (\text{B.14})$$

$$= \langle \langle 2 \rangle_{n,n} \langle 2 \rangle_{-n,-n} \rangle \quad (\text{B.15})$$

C NUA

C.1 Systematics for interpolation in the FMD

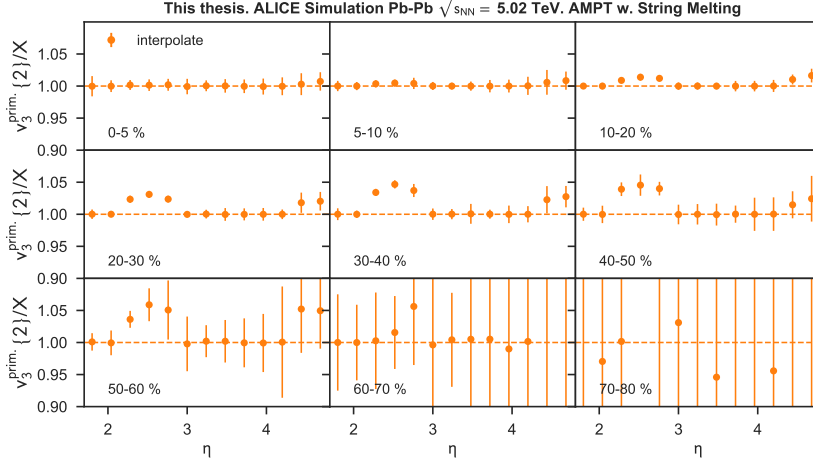


Figure C.1: v_3 calculated using primary particles divided by v_3 calculated using primary particles with interpolation of simulated acceptance holes. For the numerator v_2 was calculated with the 2-particle cumulant using primary particles in an AMPT simulation. The denominator was calculated with the same methods and particles, but with the acceptance holes first introduced, and then corrected for.

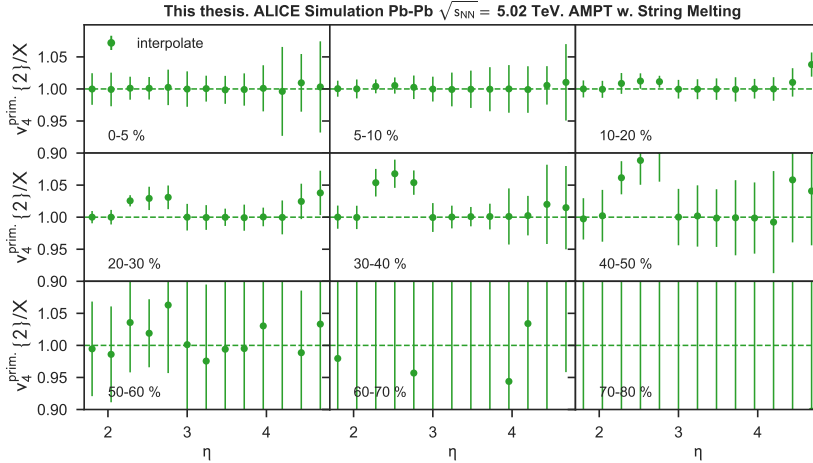


Figure C.2: v_4 calculated using primary particles divided by v_2 calculated using primary particles with interpolation of simulated acceptance holes. For the numerator v_4 was calculated with the 2-particle cumulant using primary particles in an AMPT simulation. The denominator was calculated with the same methods and particles, but with the acceptance holes first introduced, and then corrected for.

C.2 LHC15highIR

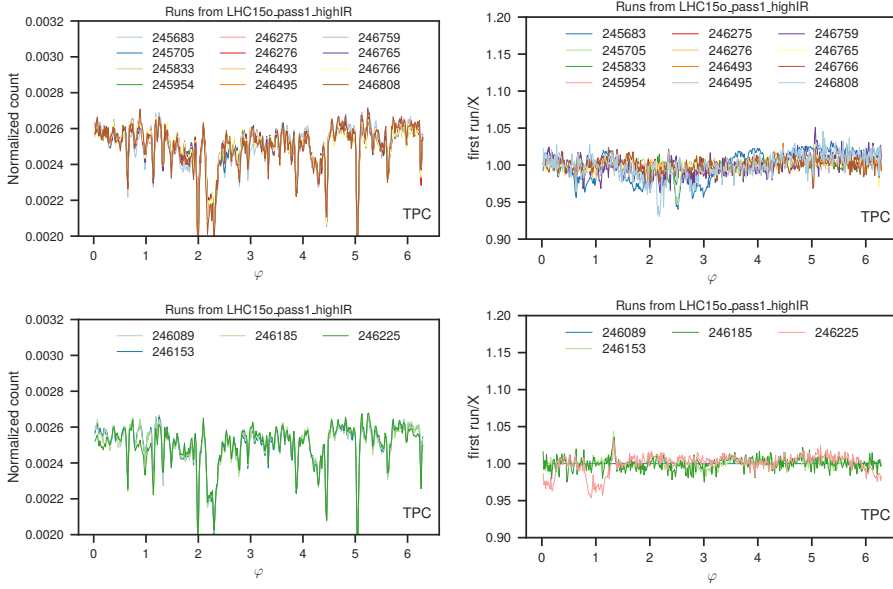


Figure C.3: ϕ distributions per run for LHC15o highIR period for the TPC.

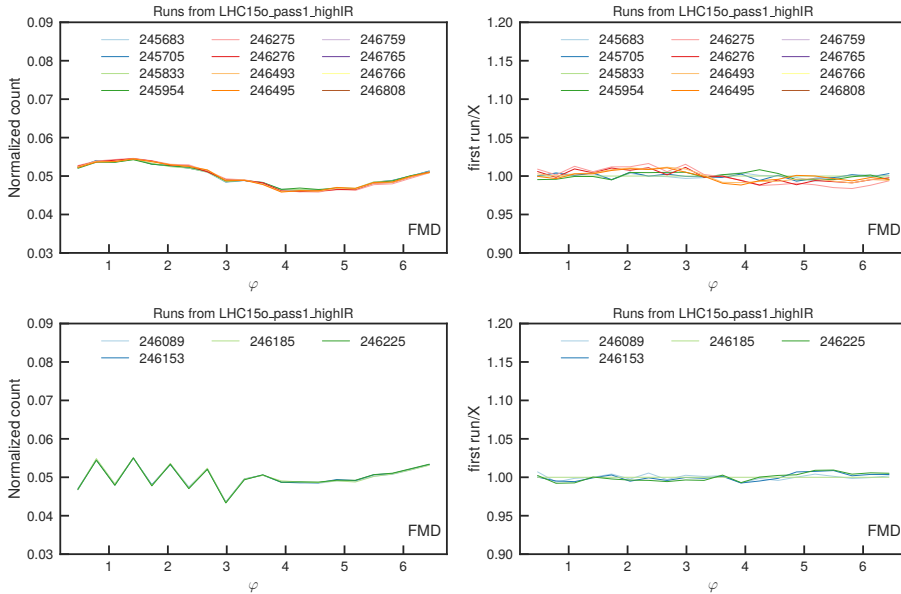


Figure C.4: ϕ distributions per run for LHC15o highIR period for the FMD.

C.3 LHC16q

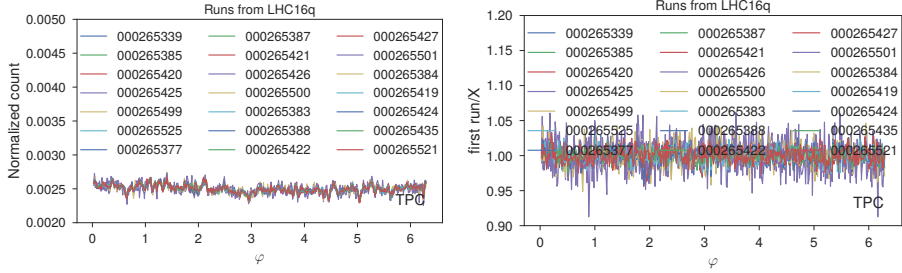


Figure C.5: ϕ distributions per run for 2016 p-Pb run in the TPC.

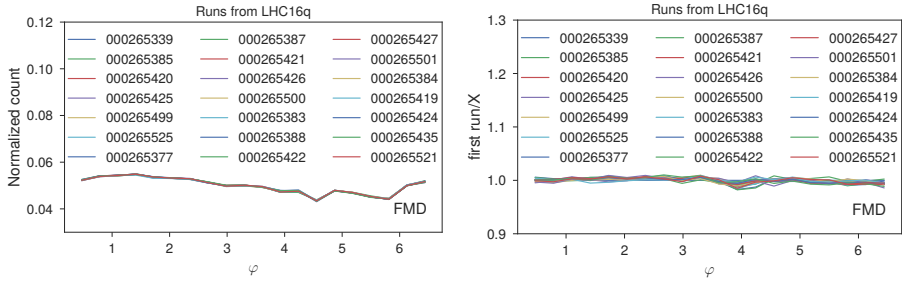


Figure C.6: ϕ distributions per run for 2016 p-Pb run in the FMD.

C.4 Global tracks

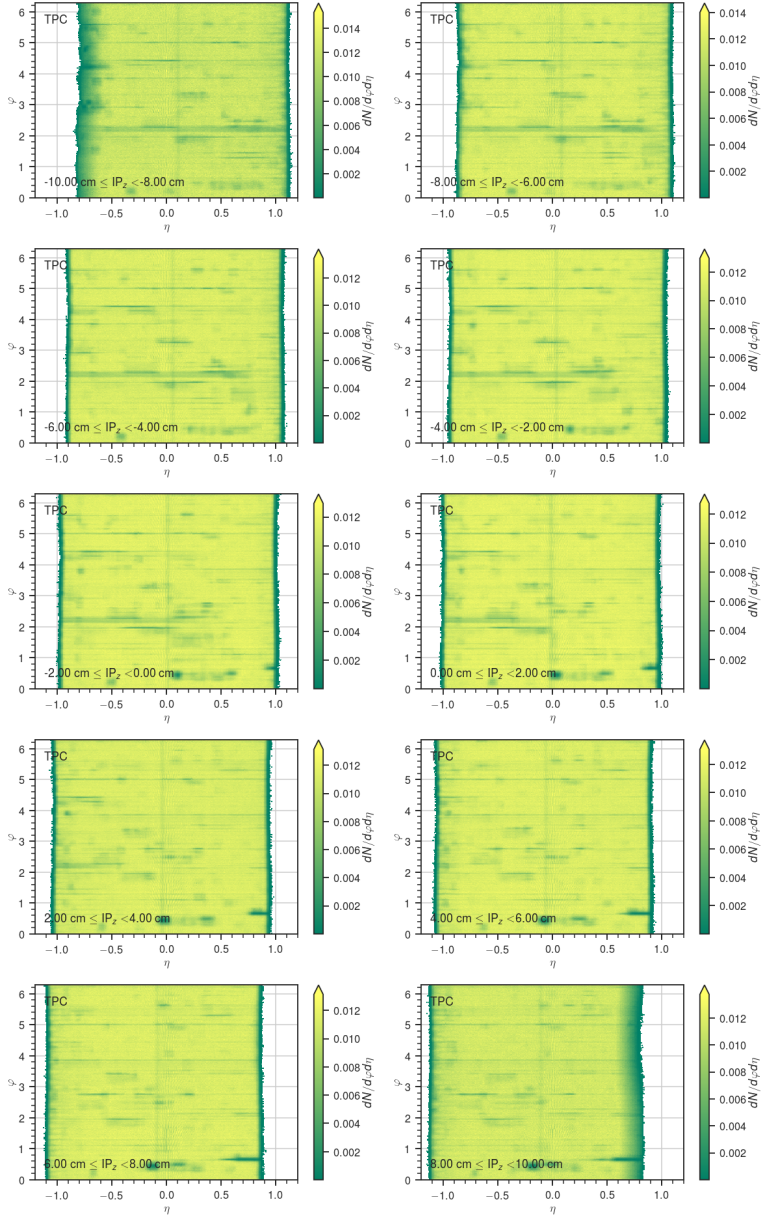


Figure C.7: Global tracks acceptance at different z -positions in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

C.5 FMD

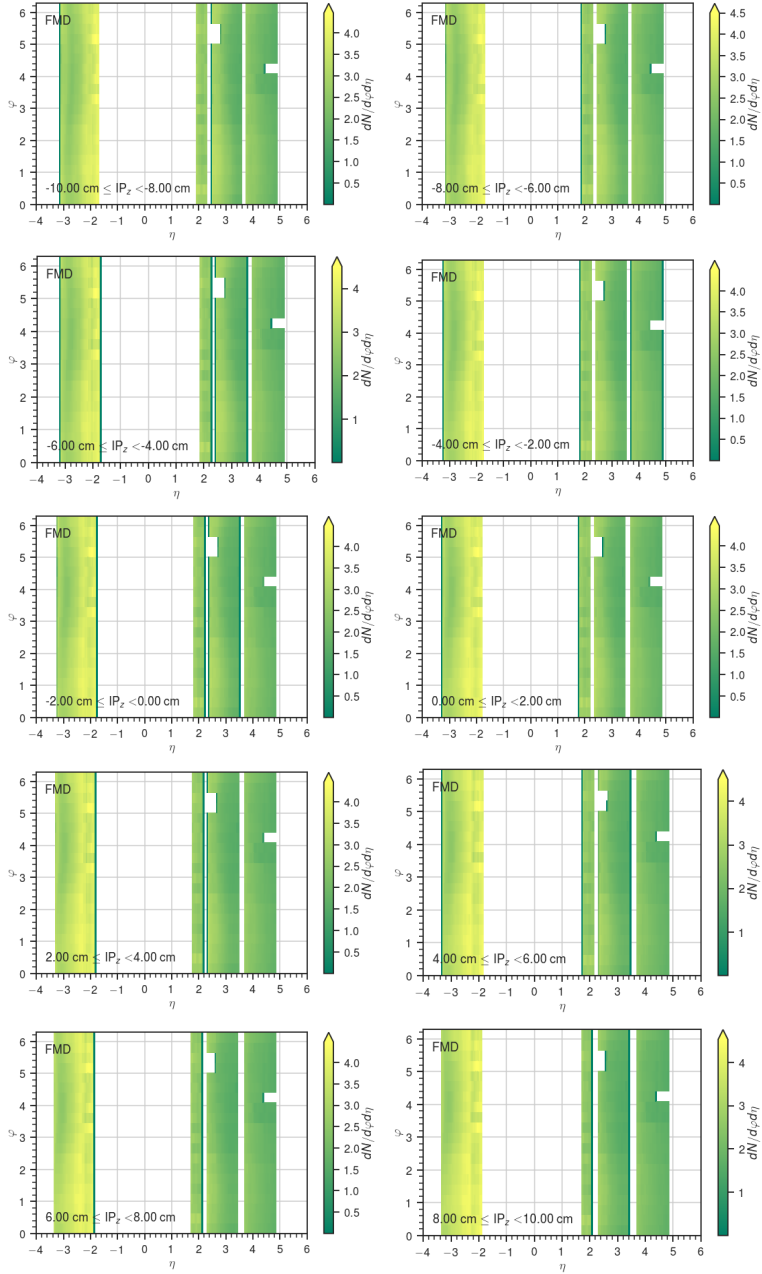
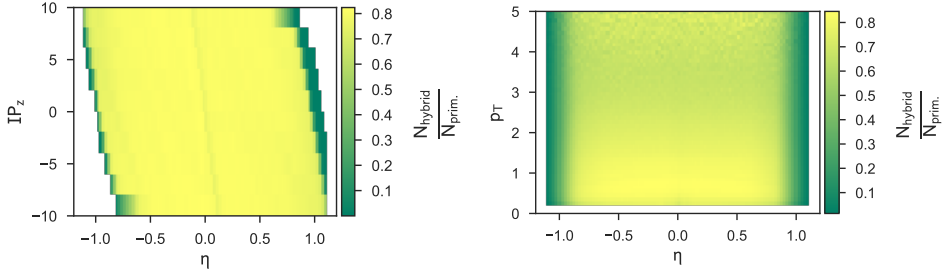


Figure C.8: FMD acceptance at different z -positions in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

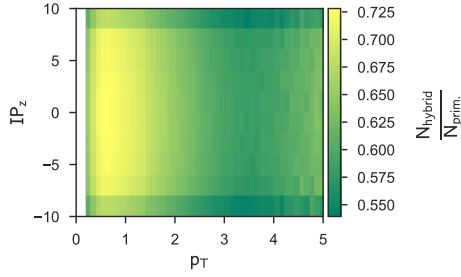
D Non-uniform Efficiency

D.1 Hybrid tracks



(a) Efficiency as a function of vertex position and η .

(b) Efficiency as a function of p_T and η .



(c) Efficiency as a function of vertex position and p_T .

Figure D.1: Efficiency for hybrid tracks in the TPC.

E Additional material for the secondary correction

E.1 Monte Carlo closure with track references

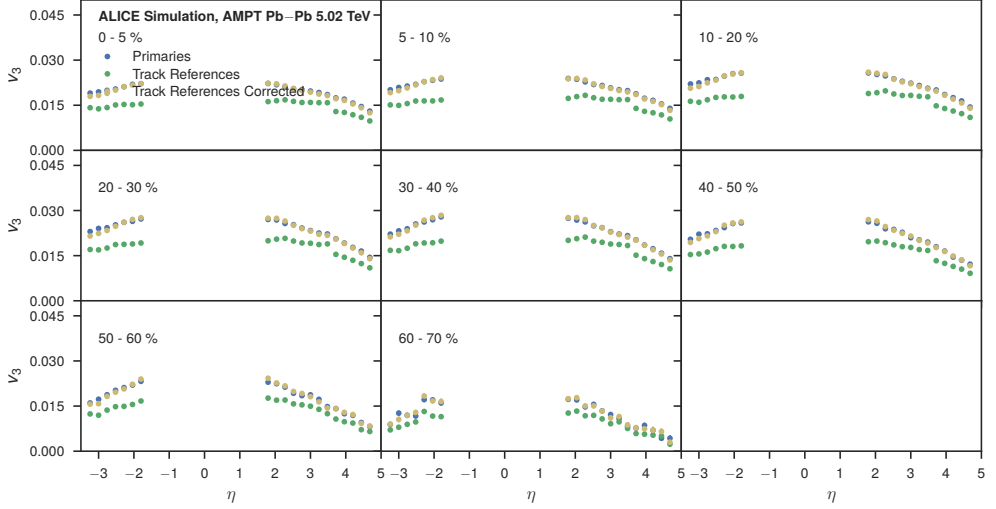


Figure E.1: The flow coefficient v_3 is calculated using primary particles and track references. After using the secondary correction, the measurement aligns roughly with $v_3^{\text{prim.}}$.

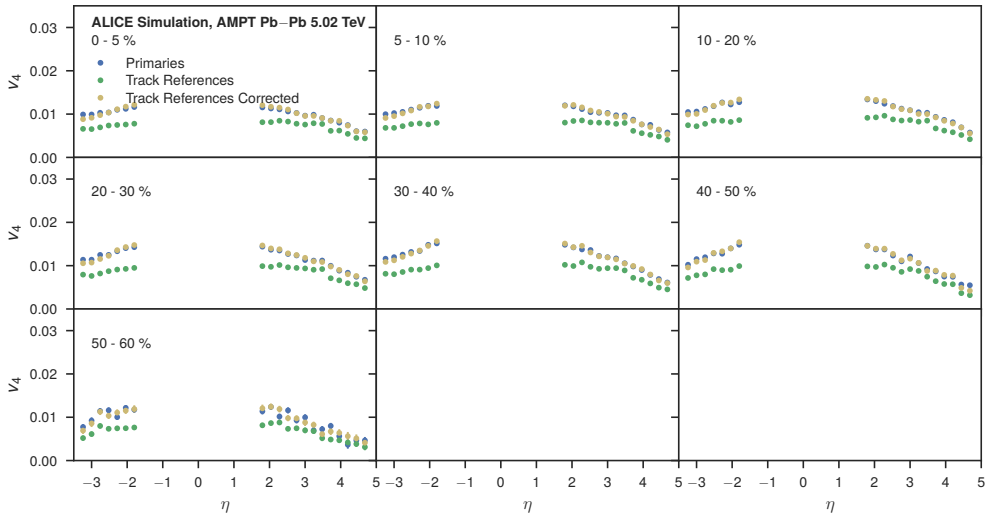


Figure E.2: The flow coefficient v_4 is calculated using primary particles and track references. After using the secondary correction, the measurement aligns roughly with $v_4^{\text{prim.}}$.

E.2 Reconstruction of the FMD using track references

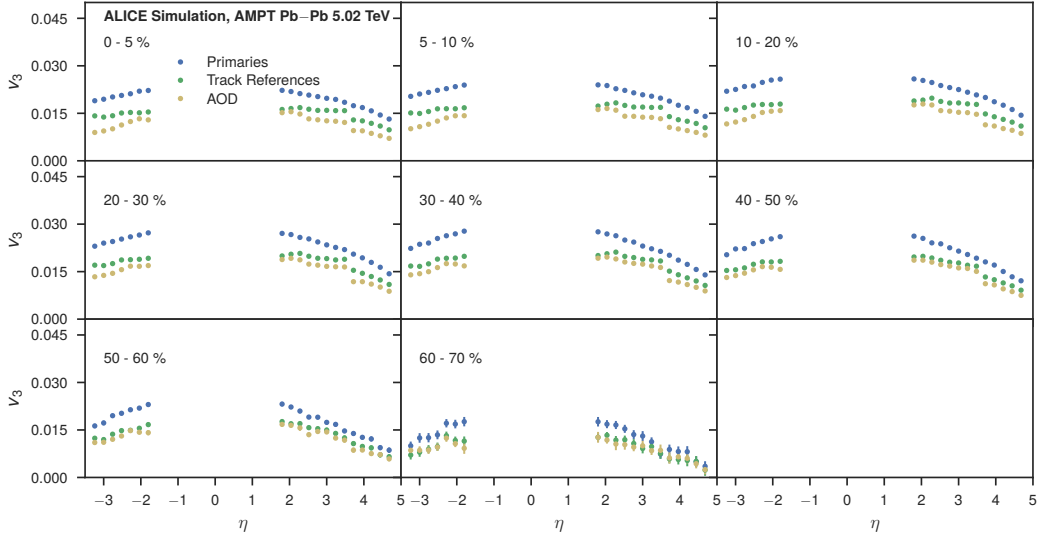


Figure E.3: The flow coefficient v_3 is calculated using primary particles, track references and the reconstructed FMD (from AOD).

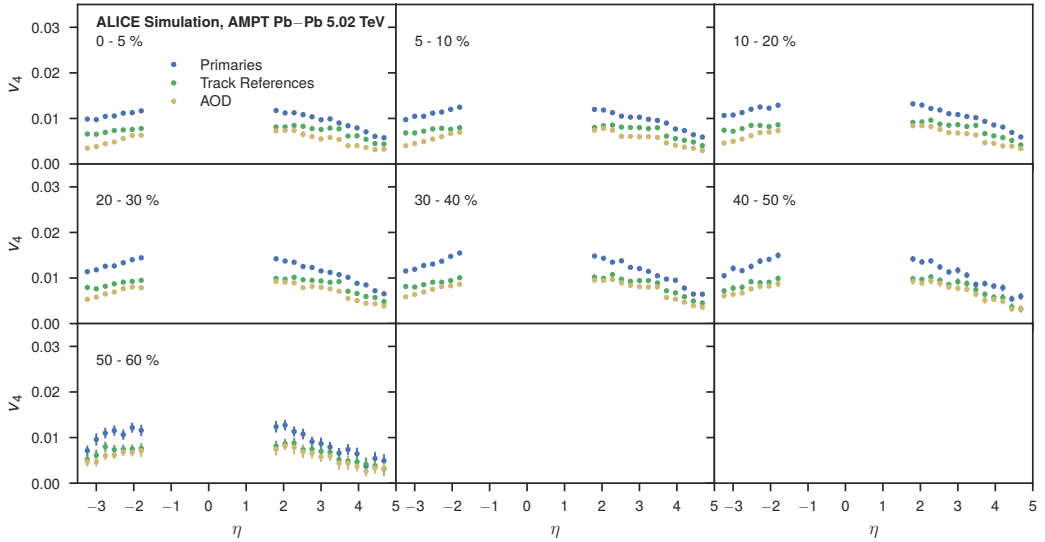
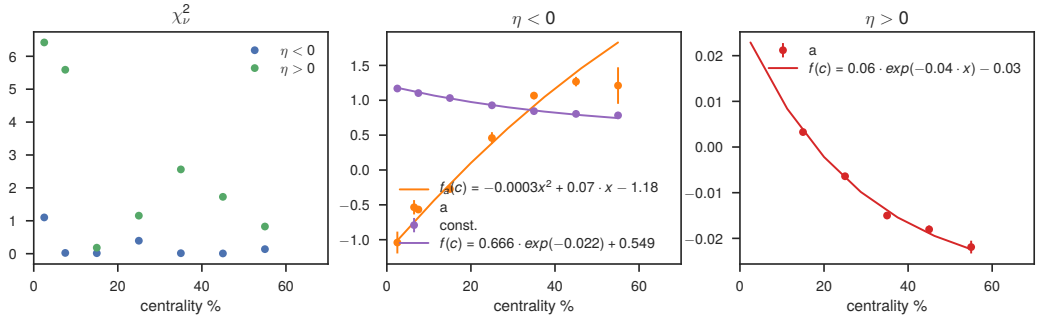
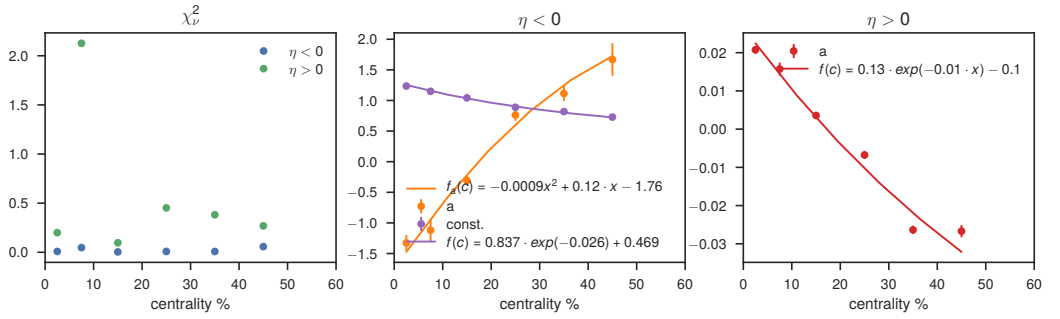


Figure E.4: The flow coefficient v_4 is calculated using primary particles, track references and the reconstructed FMD (from AOD).

Figure E.5: Parameters for the fits for v_3 from Figure 6.32.Figure E.6: Parameters for the fits for v_4 from Figure 6.32.

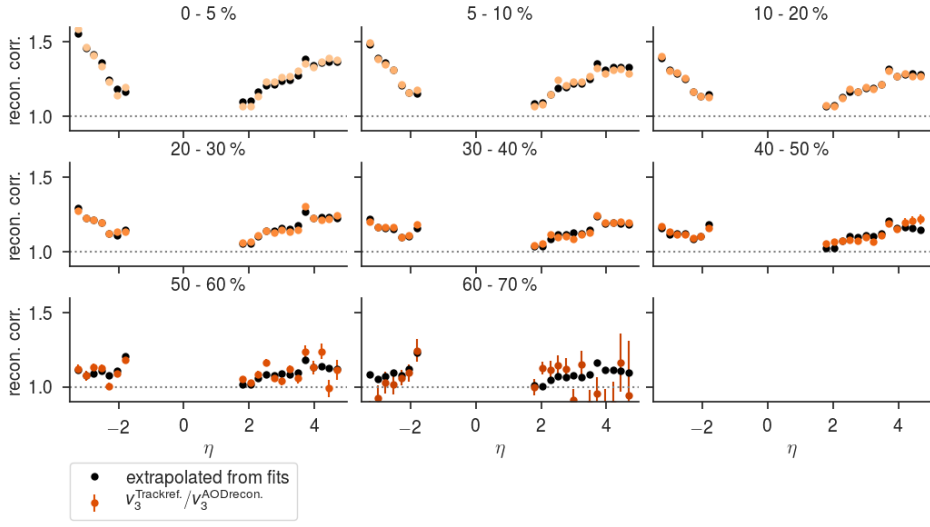


Figure E.7: Comparison of the extrapolated correction using fits and $v_3^{\text{Track ref.}}/v_3^{\text{AOD recon.}}$. The extrapolated values reach a high precision at large centralities.

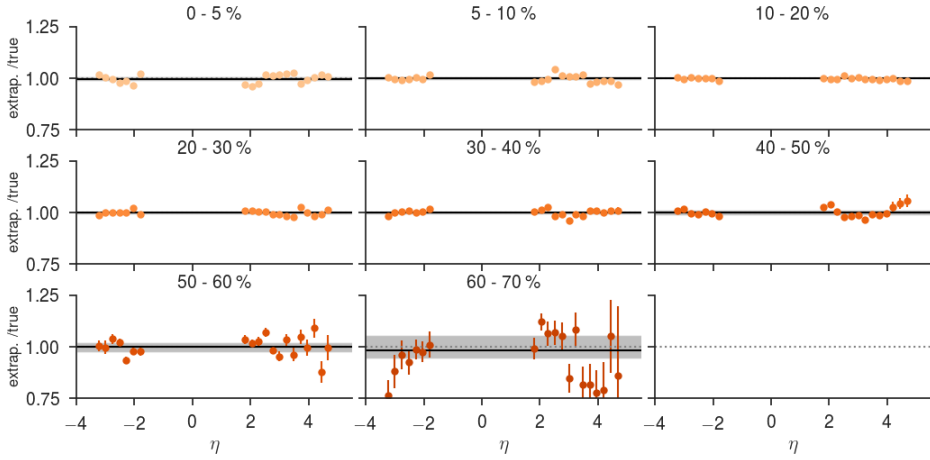


Figure E.8: Ratio of the extrapolated correction and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$.

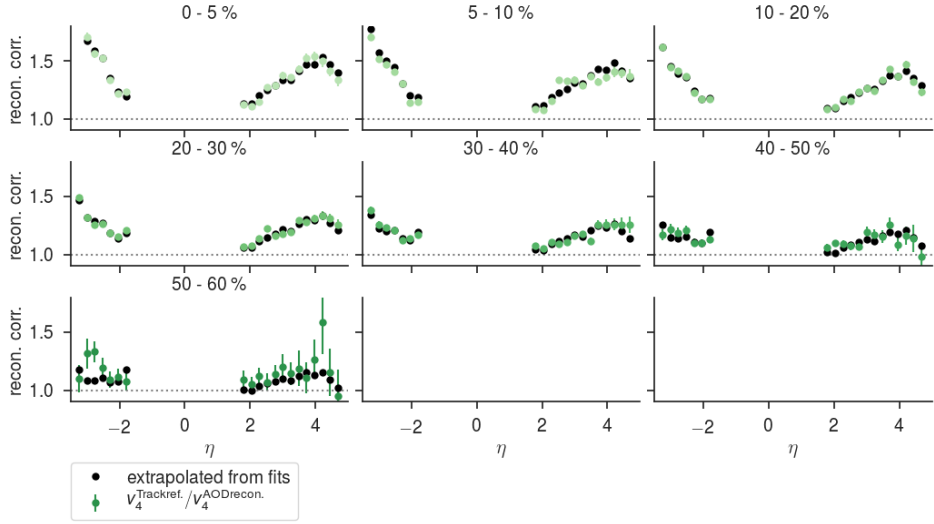


Figure E.9: Comparison of the extrapolated correction using fits and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$. The extrapolated values reach a high precision at large centralities.

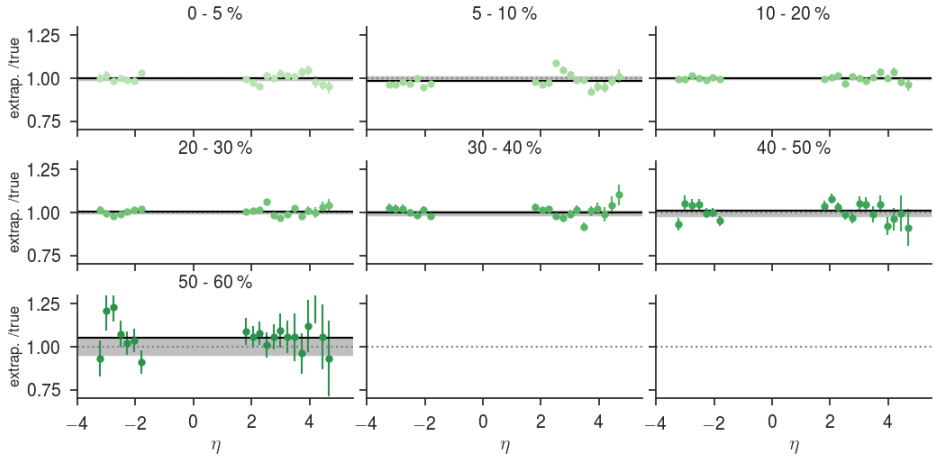


Figure E.10: Ratio of the extrapolated correction and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$.

E.3 Choices for reconstruction

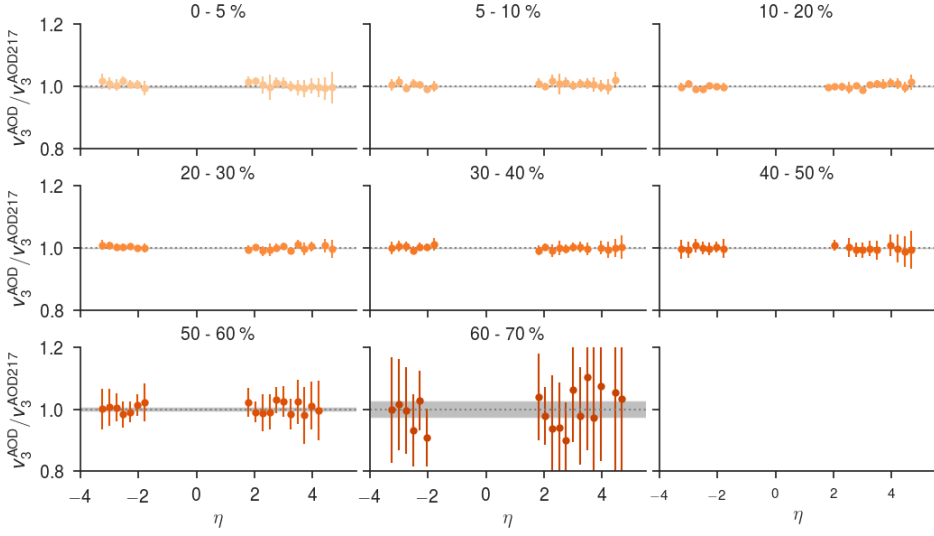


Figure E.11: Ratio of v_3 with the two possible reconstructions of the FMD. AOD is reconstructed using a multiplicity correction, and the multiplicity correction does not correct AOD217.

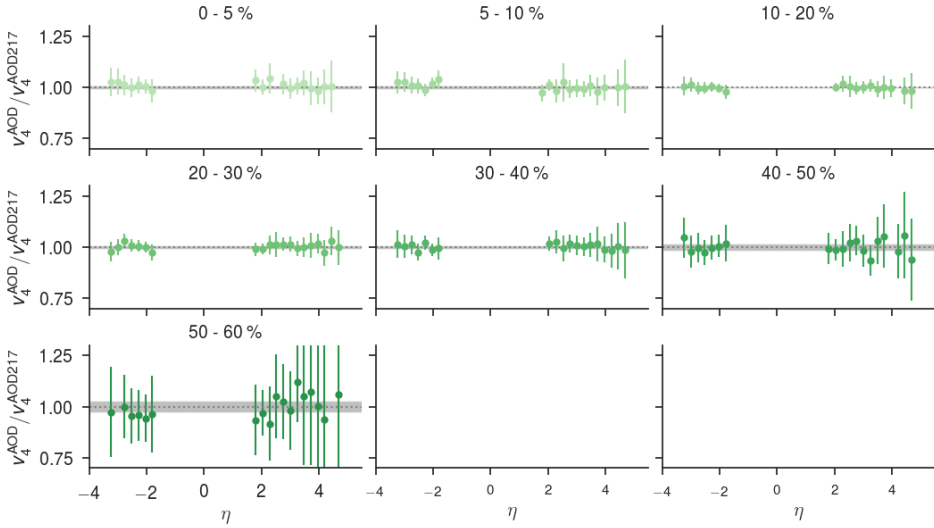


Figure E.12: Ratio of v_4 with the two possible reconstructions of the FMD. AOD is reconstructed using a multiplicity correction, and the multiplicity correction does not correct AOD217.

E.4 Other approaches to extract the secondary correction

Cauchy fits

The first method described here, is to fit the $\Delta\varphi$ distribution with a Cauchy distribution,

$$f(\Delta\varphi, \gamma, I) = I \left[\frac{\gamma^2}{\Delta\varphi^2 + \gamma^2} \right]. \quad (\text{E.1})$$

A Cauchy function is simple under a Fourier decomposition,

$$\mathcal{F}(I \left[\frac{\gamma^2}{\Delta\varphi^2 + \gamma^2} \right]) = I \cdot e^{-\gamma|n|} \quad (\text{E.2})$$

which makes it a nice candidate for $f(\varphi)$. If $f(\varphi)$ can be described by a Cauchy function, the measured signal is then

$$\langle \langle v'_n v_n \rangle \rangle^{\text{measured}} = e^{-\gamma \cdot |n|} \cdot \langle \langle v'_n v_n \rangle \rangle^{\text{prim.}}. \quad (\text{E.3})$$

Therefore we can make the correction by,

$$\langle \langle v'_n v_n \rangle \rangle^{\text{prim.}} = e^{\gamma \cdot |n|} \cdot \langle \langle v'_n v_n \rangle \rangle^{\text{measured}} \quad (\text{E.4})$$

where the amplitude I cancels out by the normalization to $v_0 = 1$.

Before fitting with the Cauchy distributions, the background of $dN/d\Delta\varphi$ is fitted with a constant. The fit performed is,

$$f(\Delta\varphi, \gamma, I) = I \left[\frac{\gamma^2}{\Delta\varphi^2 + \gamma^2} \right] + \text{const.} \quad (\text{E.5})$$

The Fourier decomposition of a constant is a delta function, which in this case will be ignored in the final Fourier transform. Therefore the signal of the background is not carried over into Fourier space.

The Cauchy fits are shown in Figure E.13. The Cauchy fits seem to follow the trend well, but it can not completely describe the distribution. The width, γ , of the distributions of $f(\varphi)$ can be extrapolated from the fits, and the final γ -vales are shown in Figure E.14. The width is all there is needed to apply the correction from the Cauchy method, as seen in Equation E.4.

Fast Fourier Transform with a constant

Another way of extracting the contribution to the correlated signal by secondary particles, it to perform a Fast Fourier Transform (FFT) of the $\Delta\varphi$ -distributions.

When the FFT was performed, the background was fitted with a constant first, just as when using a Cauchy function for a fit. This choice was made for consistency, to be able to compare the results from the FFT with the single Cauchy fit. The result of the FFT with subtracted constant is in Figure E.15.

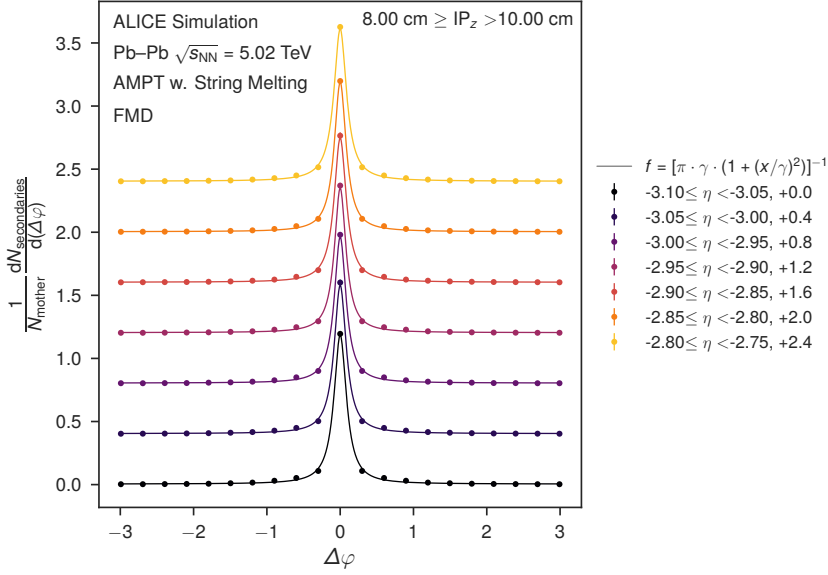


Figure E.13: The distribution of a secondary particle around its primary mother particle. The plots are shifted by a constant. All fits are in the appendix.

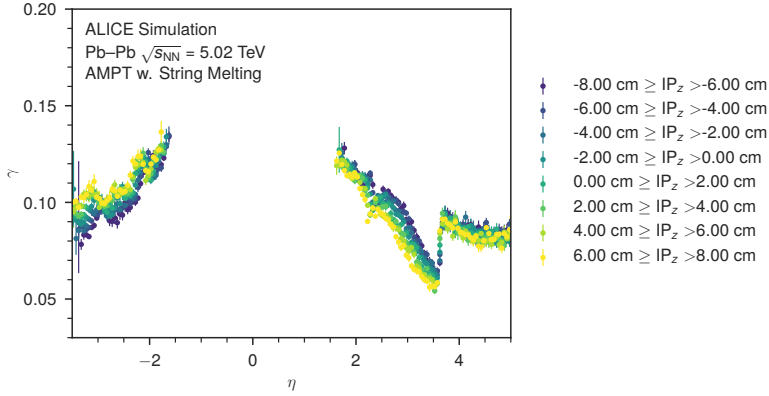


Figure E.14: γ -values from all fits in Figure E.13, where the errors are also determined by the fit. The γ -values are higher at lower rapidity, which is also expected from Figure 6.14. The γ -values as a function of vertex position is as anticipated. E.g. for the yellow points with $-10.00 \geq \text{IP}_z > -8$, we see that the γ -values are higher at negative η compared to positive η . This shows the asymmetry of the correction dependent on the IP_z -position.

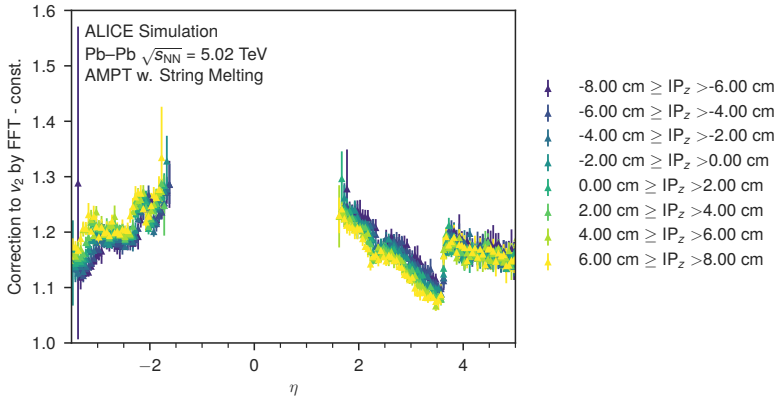


Figure E.15: Result of a Fast Fourier Transform for v_2 with a subtracted constant of the $\Delta\phi$ distribution of a mother and its secondary particle, where is secondary particle leaves a signal in the FMD.

Double Cauchy

The underlying shape of the $\Delta\phi$ distribution can be fitted by a broader Cauchy function to make a better fit. This will make the total fit a combination of two Cauchy functions, where we use only a percentage of each. This corresponds to the constant N in the equation since this will ensure that the function is only scaled by the amplitude, A . This makes sure that the function is still normalizable in a trivial way.

$$f(\phi) = A \cdot \left[N \cdot \frac{1}{\pi \cdot \gamma_1 \cdot (1 + (\phi/\gamma_1)^2)} + (1 - N) \cdot \frac{1}{\pi \cdot \gamma_2 \cdot (1 + (\phi/\gamma_2)^2)} \right] \quad (\text{E.6})$$

where $N \in [0, 1]$ and $A > 0$. When Fourier transforming the function, we get

$$\mathcal{F}[f(\phi)] = A \cdot \left[N \cdot \exp^{|n| \cdot \gamma_1} + (1 - N) \cdot \exp^{|n| \cdot \gamma_2} \right] \quad (\text{E.7})$$

When applying the correction extracted using two Cauchy functions, the amplitude A is normalized to $v_0 = 1$, and the correction is therefore

$$c_s^{\text{double Cauchy}} = N \cdot \exp^{|n| \cdot \gamma_1} + (1 - N) \cdot \exp^{|n| \cdot \gamma_2}. \quad (\text{E.8})$$

An example of some of the fits using two Cauchy functions is in Figure E.16. It shows that the optimal fit obtained of a broad and a slim Cauchy function. Using two Cauchy functions result in a much better representation of the data than the fit with a single Cauchy function.

The resulting correction is in Figure E.17. The correction from the double Cauchy fit is similar in shape and order to the prior corrections shown. It does have some outliers, and large error bars since the fit is not performing well in these areas.

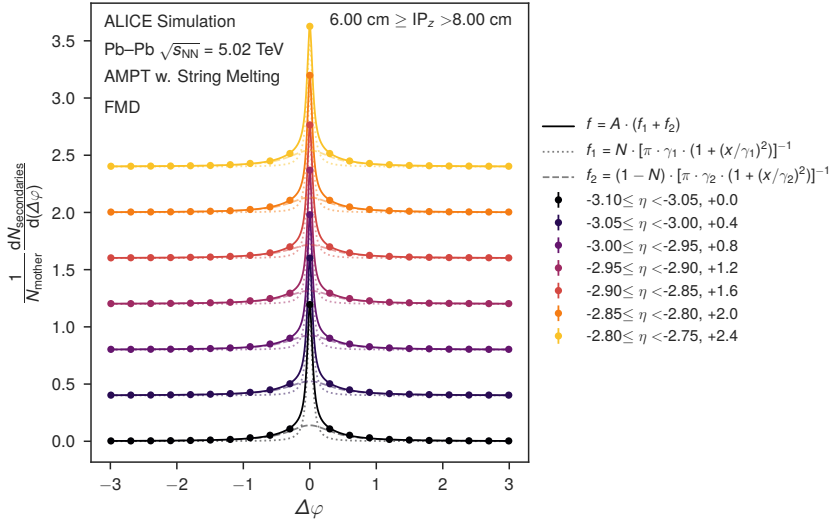


Figure E.16: The distribution of a secondary particle around its primary mother particle. The plots are shifted by a constant. The faded lines are the two Cauchy functions which are used to fit the distributions.

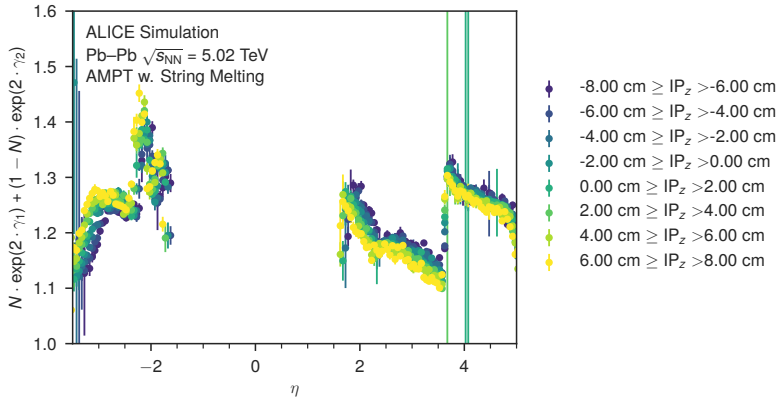


Figure E.17: γ -values from all fits, where the errors are also determined by the fit. The Correction value is the Fourier transformation of the function using two Cauchy fits.

Comparisons of Cauchy fits and Fast Fourier Transforms

All of the corrections seem to have a similar dependence on the z -vertex. For a single z vertex, the correction factors to v_2 using different methods are compared in Figure E.18. Overall in η , the single Cauchy and FFT w. a constant agrees well, although the FFT with a constant is overall lower. The double Cauchy and FFT has the same shape in η , and almost the same magnitude. For a closer view of the differences in the methods used, the ratios of the different methods are in Figure E.20. From this figure, it is concluded that the two methods which agree the most for correcting v_2 are the double Cauchy fit and the FFT. The single Cauchy methods agrees most with the FFT with the subtracted constant, but seem to be biased. To examine the differences in the methods, a correlation plot is shown in Figure E.19. In this plot, the data is divided up into the three different regions of the FMD, since the corrections are η dependent.

From these plots, it is concluded, that since the FFT and double Cauchy methods are both highly correlated and differ little in magnitude. The FFT and double Cauchy also have in common, that they estimate the underlying shape of $\Delta\phi$, and bring this signal into Fourier space. This means that $\mathcal{F}(f(\phi))$ is well determined.

Finally, the Fast Fourier Transform is used as the correction for secondaries. The double Cauchy has a weakness in that the fit is performed for $f(\phi)$, and then it is assumed that it completely behaves like a double Cauchy in Fourier space for higher harmonics. For the FFT, no assumptions are made. In the rest of this section, only the FFT is considered.

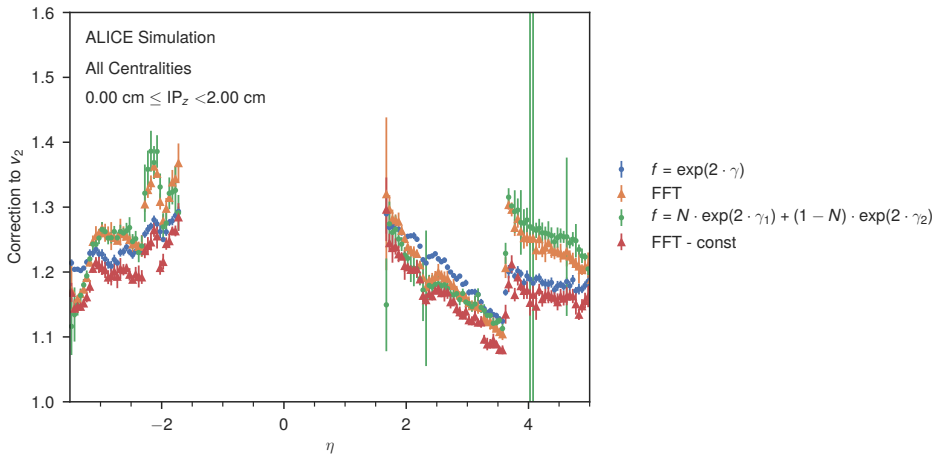


Figure E.18: Comparison of the correction values from different approaches. All of the methods are shown for one bin in the z -vertex. The methods are agreeing more in the positive η -range than in the negative. In $\eta > 3.5$, there is a shift when comparing, e.g. the double Cauchy fit and the single Cauchy fit. Generally, the correction values from the double Cauchy method is higher than the single Cauchy correction values.

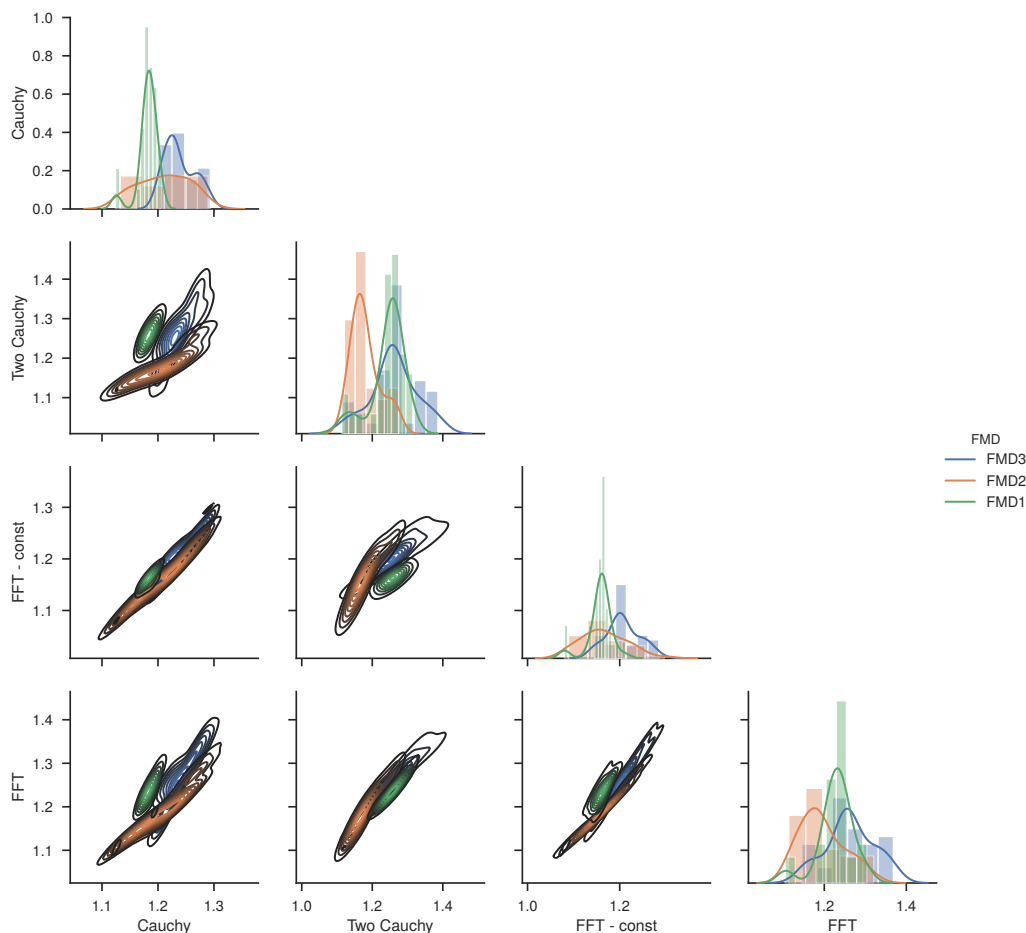


Figure E.19: Correlation and single distributions of the correction values from the different approaches described in this chapter. The distribution is split into sections of the FMD. One of the most correlated correction are the two Fast Fourier Transformations. It is also clear that the double Cauchy fit and FFT are quite correlated. The last correlated pair are the FFT - const and single Cauchy.

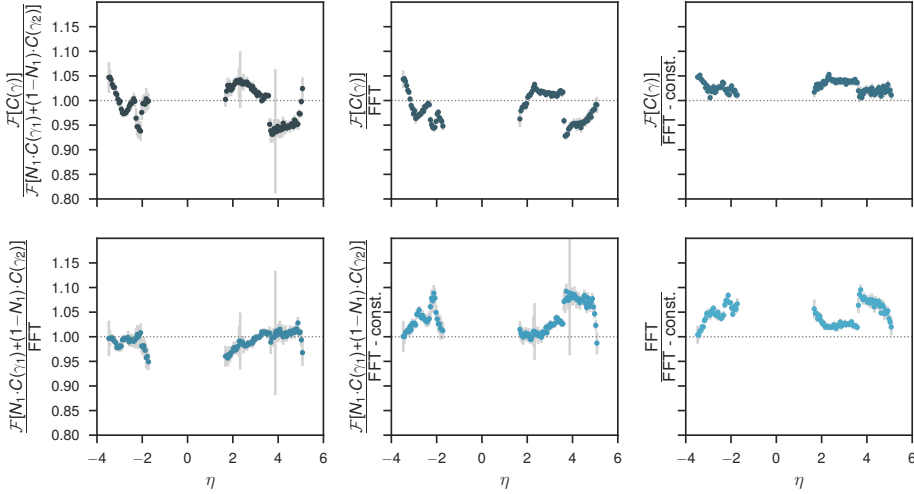


Figure E.20: Ratios of all the methods introduced in this section. The double Cauchy and FFT methods agree the most.

E.5 Comparison to prior work

The analysis using the FFT for correction of secondaries was used on a AMPT dataset from Pb-Pb with $\sqrt{s_{NN}} = 2.76$ TeV. The analysis for the Pb-Pb 2 TeV data used a MC ratio between v_n measured with reconstructed particles and primary particles. The comparison is in Figure E.21.

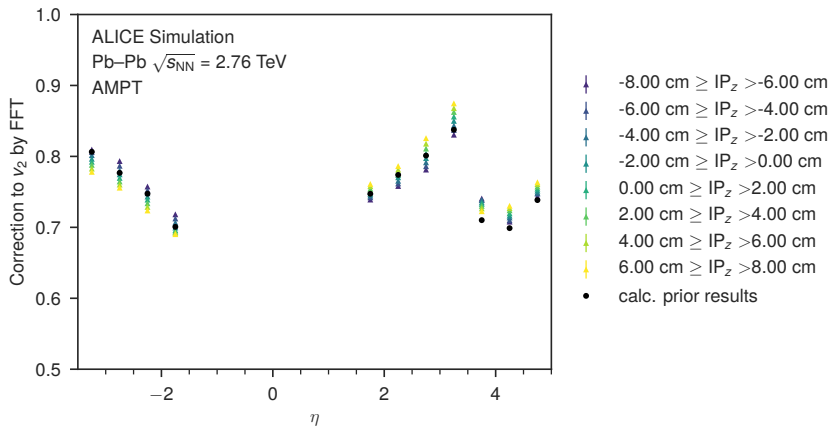


Figure E.21: Comparison of the correction from this work to prior methods [57].

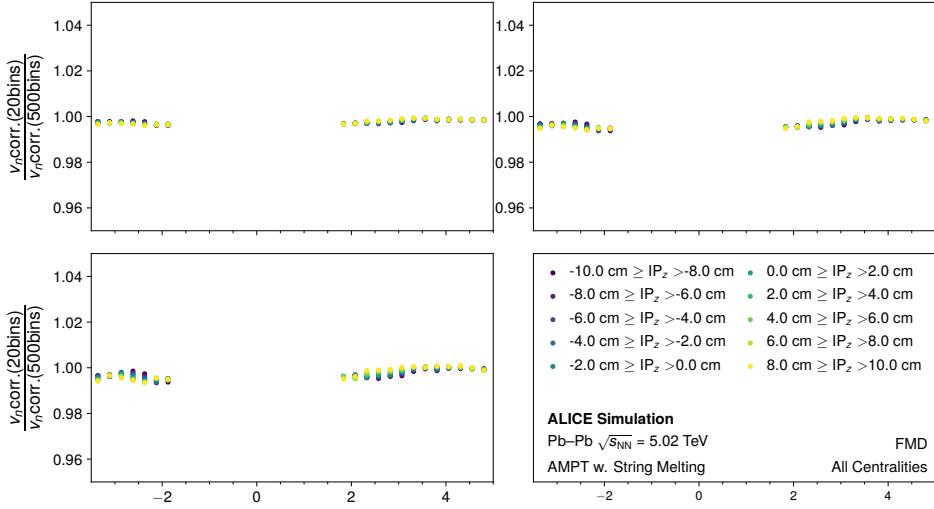
E.6 Dimensions in φ 

Figure E.22: The secondary correction extracting with 20 bins and 500 bins in φ . The dependency on vertex position is negligible and the average divergence from one is less than 0.5%.

F Xe-Xe

The centrality distributions for Pb–Pb and Xe–Xe collisions are in Figure F.1. The centrality distribution for Xe–Xe is comparable to Pb–Pb, when the Pb–Pb centrality distribution is shifted by 15%.

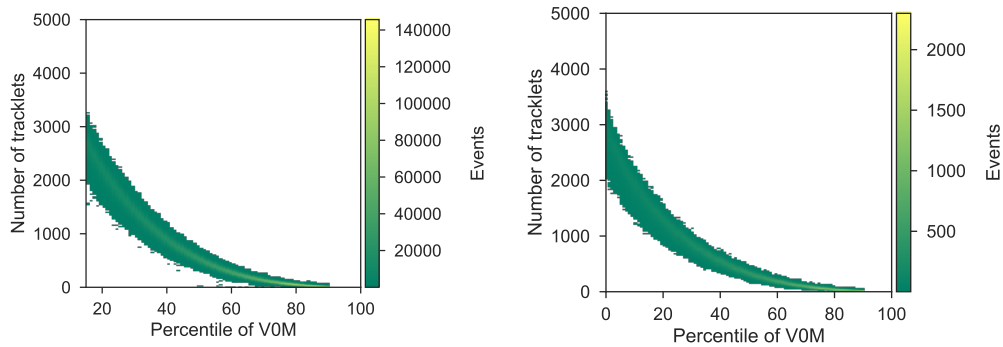


Figure F.1: Centralit and multiplicity for Pb-Pb and Xe-Xe. Left: Pb-Pb. Right: Xe-Xe.

G Systematics

G.1 Pb–Pb

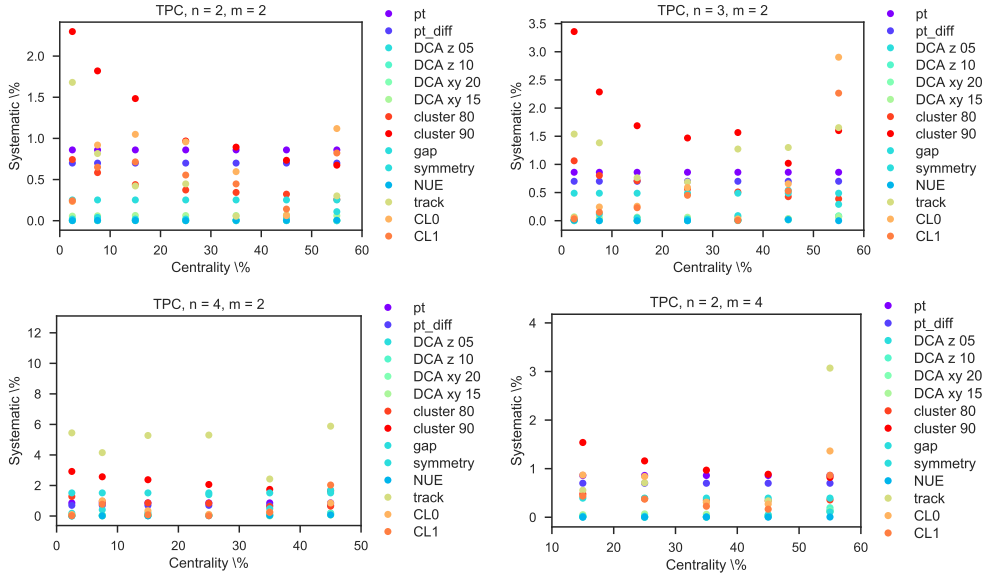


Figure G.1: Systematic uncertainties for the n^{th} flow coefficient using m -particle cumulants in the TPC with Pb–Pb collisions.

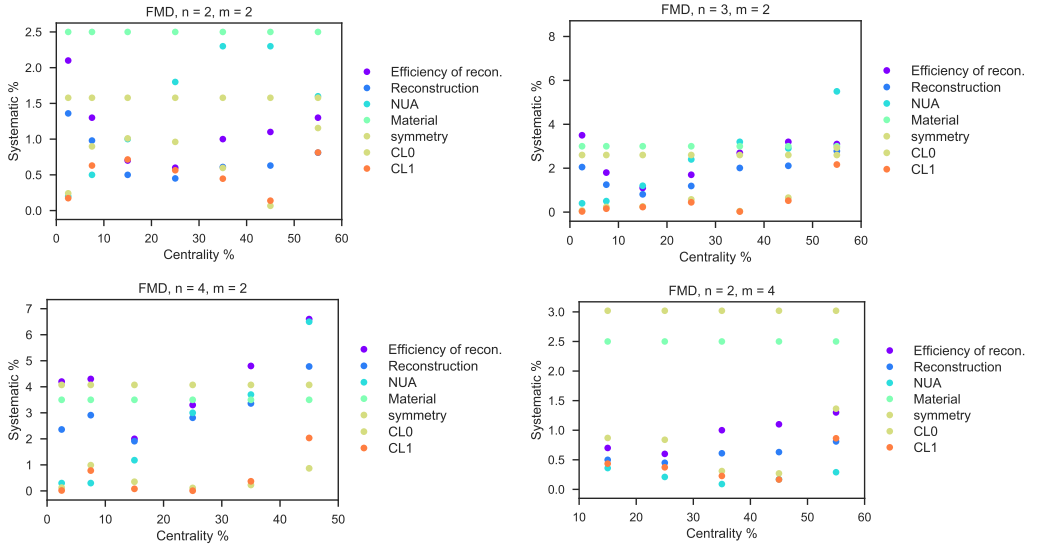


Figure G.2: Systematic uncertainties for the n^{th} flow coefficient using m -particle cumulants in the FMD with Pb-Pb collisions.

G.2 Xe-Xe

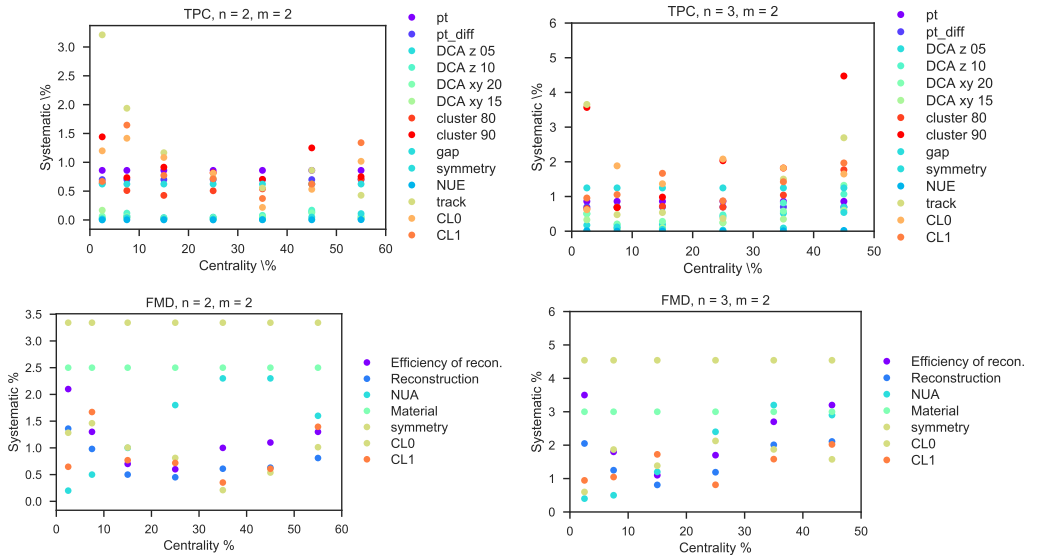


Figure G.3: Systematic uncertainties for the n^{th} flow coefficient using 2-particle cumulants in the TPC and FMD with Xe-Xe collisions.

G.3 Forward-backward symmetry in η

For the symmetric collision systems such as Xe–Xe and Pb–Pb the v_n measurements are expected to be symmetric around $\eta \approx 0$. If the coefficients are not symmetric, it can be because of v_n fluctuations or uncorrelated uncertainties in the corrections applied in the analysis. The symmetry check for Pb–Pb at 5.02 TeV is in Figure G.4. Since in the FMD much larger corrections are used than in the TPC, the corrections also have larger uncertainties. The systematic uncertainties for the secondary correction are not symmetric (as seen in Figure 6.32) and do not necessarily cancel in the forward-backward ratio of the flow coefficients, since the uncertainties are uncorrelated. In Figure G.4 the forward-backward symmetry is shown for the two- and four-particle cumulant with a small η -gap in Pb–Pb collisions. Figure G.5 shows the forward-backward symmetry for the two-particle cumulant with a large η -gap in Pb–Pb collisions. Figure G.6 shows the forward-backward symmetry in Xe–Xe collisions.

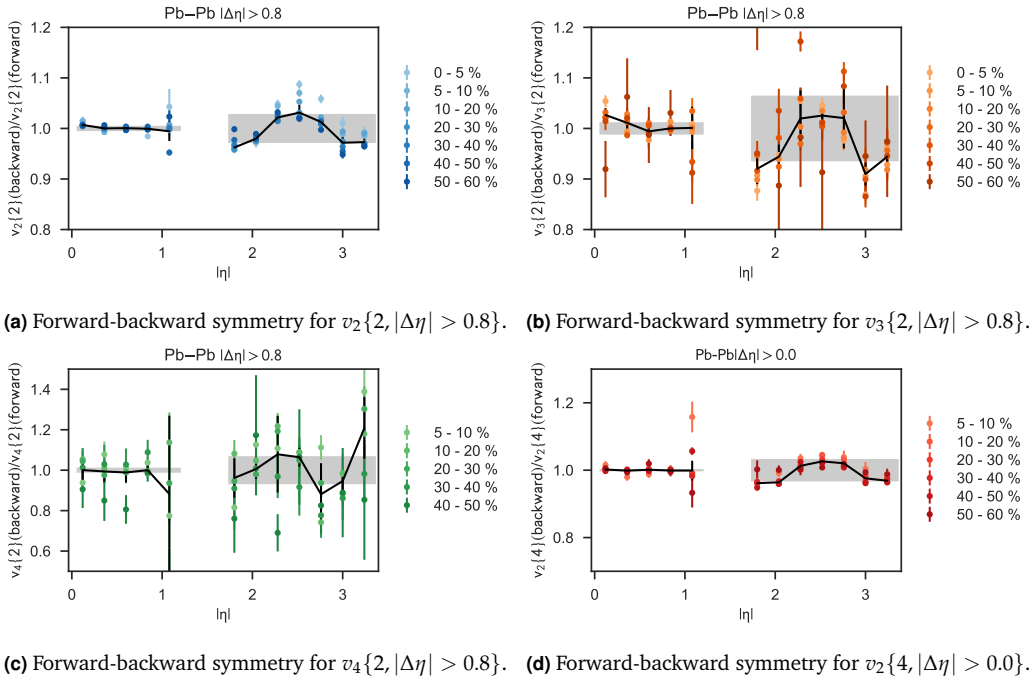
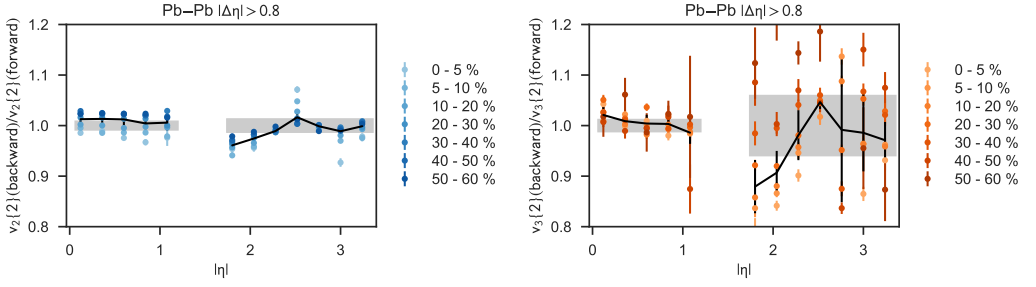
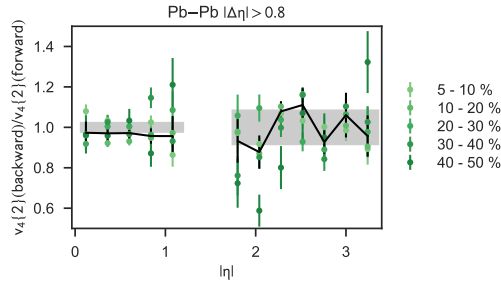


Figure G.4: Symmetry of flow coefficients in Pb–Pb with $\sqrt{s_{NN}} = 5.02$ TeV.



(a) Forward-backward symmetry for $v_2\{2, |\Delta\eta| > 2.0\}$. **(b)** Forward-backward symmetry for $v_3\{2, |\Delta\eta| > 2.0\}$.



(c) Forward-backward symmetry for $v_4\{2, |\Delta\eta| > 2.0\}$.

Figure G.5: Symmetry of flow coefficients in Pb-Pb with $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using the FMD as reference region.

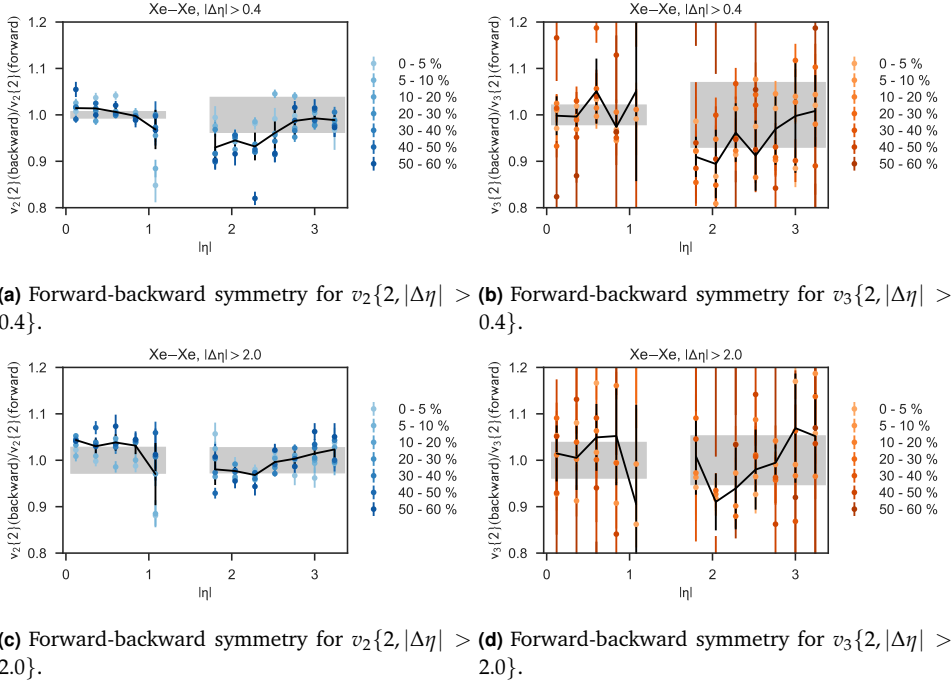


Figure G.6: Symmetry of flow coefficients in Xe–Xe with $\sqrt{s_{\text{NN}}} = 5.44$ TeV.

H Additional Results

H.1 Decorrelation

In Figure H.1, the decorrelation ratio is shown as a function of centrality. The deviation from one is highest for the most central collisions. In Figure H.2 the $r_{2,2}$ results are shown for different reference regions.

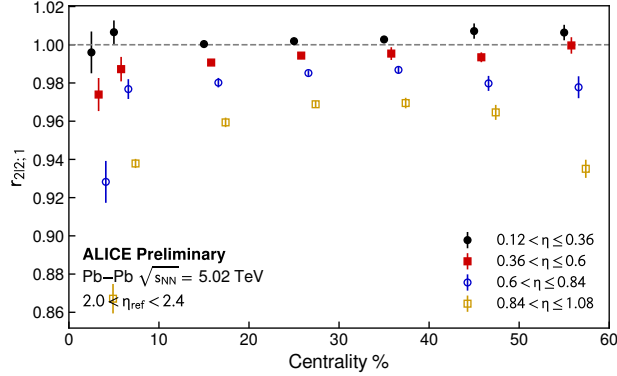


Figure H.1: $r_{2,2}$ centrality dependence with $2.0 < |\eta_{ref}| < 2.4$.

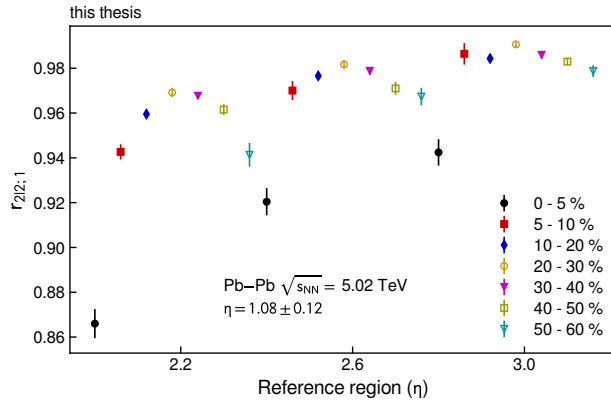


Figure H.2: $r_{2,2}$ as a function of reference region. $r_{n,n}$ is closer to unity, when the reference region increases.

H.2 Centrality scaling

In Figure H.3 the centrality scaling of Figure 7.4 is shown. For v_2 the shape at central pseudorapidity changes slightly as a function of centrality. For v_3 and v_4 there is no significant different in the pseudorapidity dependency, but there is still a difference in the magnitude. Since the ratio is not larger than one, the most central collisions has the least of the magnitudes of v_n .

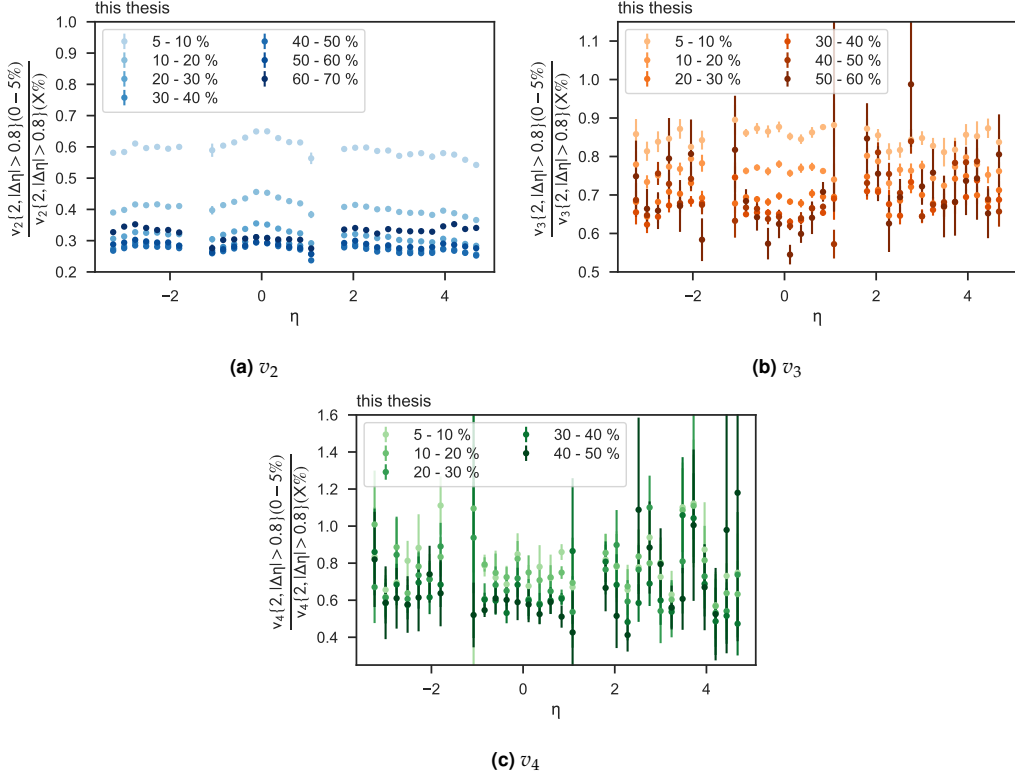


Figure H.3: Centrality dependence of $v_n\{2, |\Delta\eta| > 0.8\}$

The centrality scaling is shown in Figure H.4 for v_2 with a large gap using the FMD, and v_2 using the TPC as reference, but with 4-particle correlations. In contrast to Figure H.3, v_2 now shows no change in the shape of the pseudorapidity dependency at central pseudorapidity.

The difference between using a small gap, and a large gap at different centralities is shown in Figure H.5. At the forward regions, the two gap cases agree within the uncertainties, but for $\eta \approx 0$ there is a larger deviation from one, but up to 7.5 %.

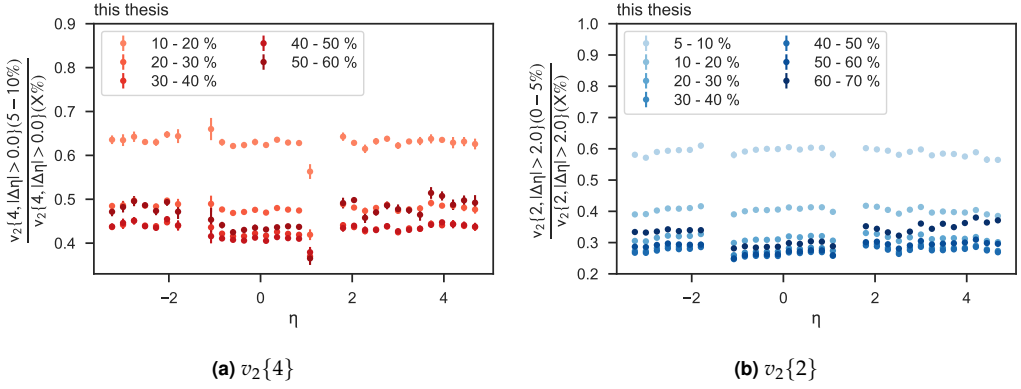


Figure H.4: Centrality dependence of $v_n\{2, |\Delta\eta| > 1.8\}$ and $v_2\{4, |\Delta\eta| > 0.0\}$

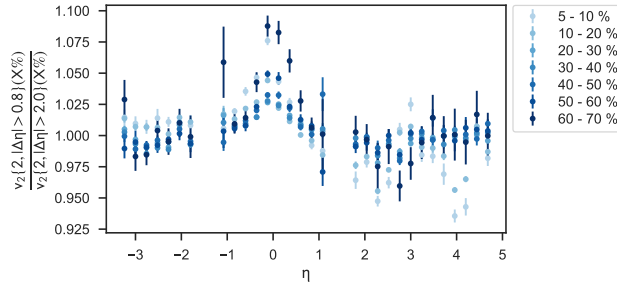


Figure H.5: Centrality dependence of the ratio of v_2 with a large and small gap.

H.3 Comparisons to previous results

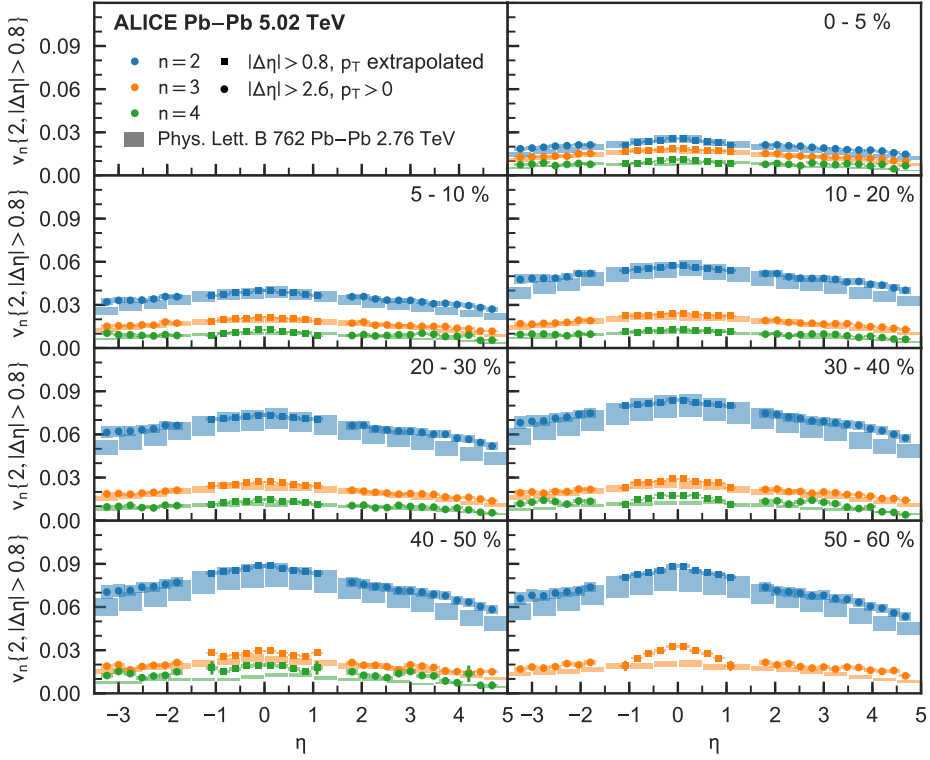


Figure H.6: The results for Pb-Pb with $\sqrt{s_{NN}} = 5.02$ TeV use the two-particle cumulant with reference particles chosen from the TPC. This gives $|\Delta\eta| > 0.8$ in TPC and $|\Delta\eta| > 2.6$ in FMD for the two-particle cumulant. The results for Pb-Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV does not use the η -gap method, but uses non-flow subtraction instead.

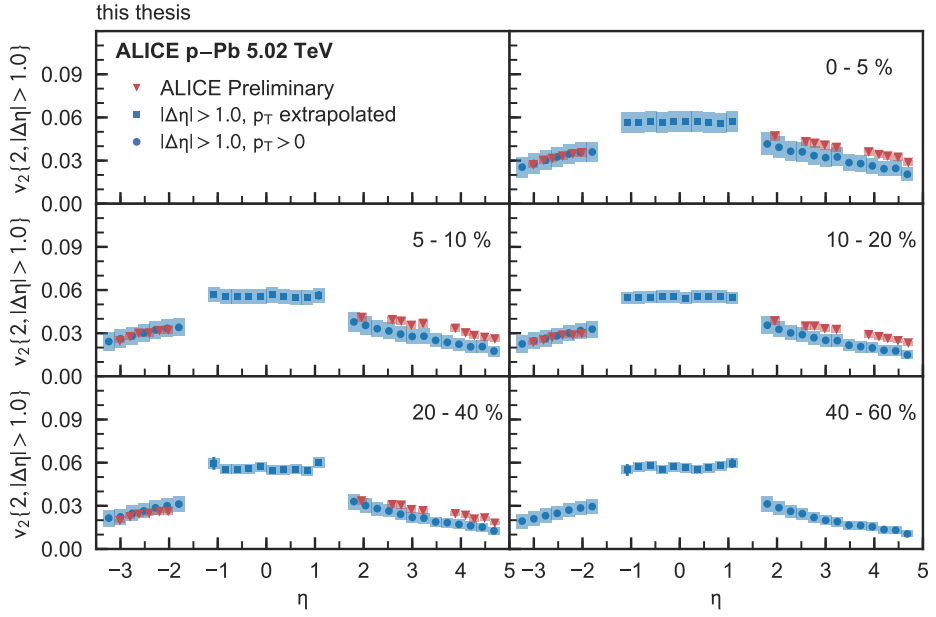


Figure H.7: Comparison of preliminary results in p-Pb. The red points are ALICE preliminary results [1], and the blue points are preliminary results from this thesis.

H.4 Comparisons to AMPT

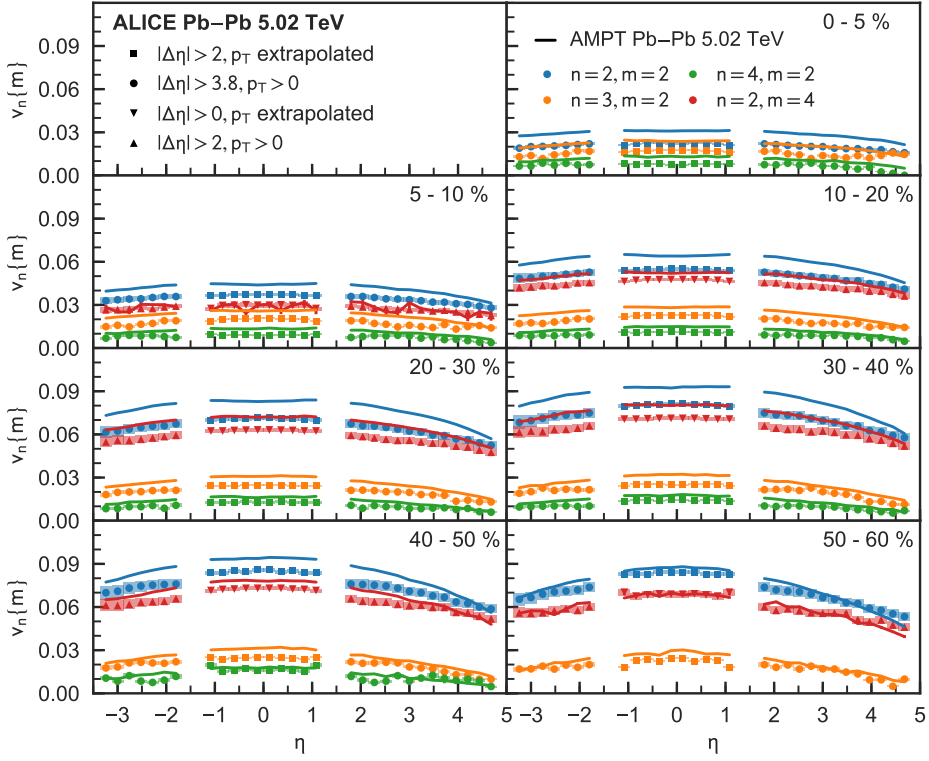


Figure H.8: The differential flow measurements, $v_n\{2\}(\eta)$, measured with the 2-particle cumulant and choosing reference particles from the FMD in Pb-Pb collisions at 5.02 TeV. The choice of the reference particles gives $|\Delta\eta| > 2.0$ in the central regions of pseudorapidity and $|\Delta\eta| > 3.8$ in the forward regions of pseudorapidity. The results are compared to the AMPT model for Pb-Pb at 5.02 TeV.

I Analysis Code

I.1 Analysis Classes

All analysis code is in <https://github.com/alisw/AliPhysics/tree/master/PWGCF/FLOW/Forward>. The analysis classes are

- **AliForwardTaskValidation** Event selection for both MC and data
- **AliForwardNUATask** Makes the NUA weights
- **AliForwardNUETask** Makes the NUE weights
- **AliForwardSecondariesTask**: Analysis of secondaries in the FMD. Requires track references.
- **AliForwardFlowRun2Task**: Runs the flow analysis

and the helper classes are

- **AliForwardSettings**: Containst the settings for all analysis
- **AliForwardFlowUtil**: Utility class for getting the data from the TPC and FMD, collecting the centralities from the estimators etc.
- **AliForwardWeights**: Connects the corrections to the task (secondary weights, NUA, NUE)
- **AliForwardResultStorage**: Converts output to TDirectories (makes the merging of outputs faster)
- **AliForwardGenericFramework**: Class for performing the flow calculations

The nittygriddy framework[73] was used to submit tasks to the grid.

I.2 Datasets

Data

name: LHC15o_pass5_lowIR

data pattern: pass5_lowIR/AOD/*/AliAOD.root

data directory: /alice/data/2015/LHC15o/

data type: AOD

run list: 244918, 244975, 244980, 244982, 244983, 245064, 245066, 245068, 246390, 246391, 246392

name: LHC15o_pass1_HIR

data pattern: pass1/AOD/*/AliAOD.root

data directory: /alice/data/2015/LHC15o/

data type: AOD

run list: 245683, 245705, 245833, 245954, 246089, 246153, 246185, 246225, 246275, 246276, 246493, 246495, 246759, 246765, 246766, 246808, 246809

name: LHC17n
data pattern: pass1/AOD227/*/AliAOD.root
data directory: /alice/data/2017/LHC17n/
data type: AOD
run list: 280234, 280235

name: LHC16q_fast
data pattern: pass1_FAST/AOD190/*/AliAOD.root
data directory: /alice/data/2016/LHC16q/
data type: AOD
run list: 265309, 265332, 265334, 265335, 265336, 265338, 265339, 265342, 265343, 265344, 265377, 265378, 265381, 265383, 265384, 265385, 265387, 265388, 265419, 265420, 265421, 265422, 265424, 265425, 265426, 265427, 265435, 265499, 265500, 265501, 265521, 265525

name: LHC16q_woSDD
data pattern: pass1_CENT_woSDD/AOD190/*/AliAOD.root
data directory: /alice/data/2016/LHC16q/
data type: AOD
run list: 265309, 265332, 265334, 265335, 265336, 265338, 265339, 265342, 265343, 265344, 265377, 265378, 265381, 265383, 265384, 265385, 265387, 265388, 265419, 265420, 265421, 265422, 265424, 265425, 265426, 265427, 265435, 265499, 265500, 265501, 265521, 265525

Monte Carlo Productions

name: LHC17i2f
data pattern: AOD/*/AliAOD.root, AOD217/*/AliAOD.root, and */AliESDs.root
data directory: /alice/sim/2017/LHC17i2f/
data type: AOD, AOD217, and ESD
run list: 244918, 244975, 244980, 244982, 244983, 245064, 245066, 245068

name: LHC17i2f_extra
data pattern: AOD/*/AliAOD.root, AOD217/*/AliAOD.root, and */AliESDs.root
data directory: /alice/sim/2017/LHC17i2_extra/
data type: AOD, AOD217, and ESD
run list: 244918, 244975, 244980, 244982, 244983, 245064, 245066, 245068, 246390, 246391, 246392

name: LHC17i2f_extra2
data pattern: AOD/*/AliAOD.root, AOD217/*/AliAOD.root, and */AliESDs.root
data directory: /alice/sim/2017/LHC17i2f_extra2/
data type: AOD, AOD217, and ESD
run list: 244918, 244975, 244980, 244982, 244983, 245064, 245066, 245068, 246390, 246391, 246392

name: LHC17f2a_cent_woSDD_fix

data pattern: AOD202/*/AliAOD.root

datadir: /alice/sim/2017/LHC17f2a_cent_fix/

datatype: AOD

run list: 265309 265332 265334 265335 265336 265338 265339 265342 265343 265344 265377
265378 265381 265383 265384 265385 265387 265388 265419 265420 265421 265422 265424
265425 265426 265427 265435 265499 265500 265501 265521 265525 267163 267164 267165
267166

name: LHC17f2a_fast_fix

data pattern: AOD202/*/AliAOD.root

datadir: /alice/sim/2017/LHC17f2a_cent_fix/

datatype: AOD

run list: 265309 265332 265334 265335 265336 265338 265339 265342 265343 265344 265377
265378 265381 265383 265384 265385 265387 265388 265419 265420 265421 265422 265424
265425 265426 265427 265435 265499 265500 265501 265521 265525 267163 267164 267165
267166

List of Figures

2.1	The elementary particles of the Standard Model.	4
2.2	A creation of a new quark-antiquark pair from the increasing potential between the two quarks.	5
2.3	The QCD coupling constant dependence on momentum transfer scale (Q).	6
2.4	Sketch of the early Universe and approximate time scale.	6
2.5	Evolution of the Quark-Gluon Plasma.	7
2.6	Sketch of the coordinate system at ALICE.	9
2.7	Illustration of the impact parameter in a heavy-ion collision.	9
2.8	Jet quenching reported by ATLAS.	10
2.9	J/Ψ suppression.	11
2.10	Strangeness enhancement.	12
2.11	Illustration of a heavy ion collision.	15
2.12	Illustration of the flow coefficients: v_1, v_2, v_3 and v_4	16
2.13	Illustration of combination of flow coefficients obtained from a toy Monte Carlo simulation.	16
2.14	Illustration of the eccentricity of two collisions.	17
2.15	ALICE integrated flow measurements.	18
2.16	Illustration of the magnitude and twist of the flow coefficients and symmetry plane.	19
2.17	Previous results from PHOBOS and ALICE.	20
2.18	v_2 and v_3 measured in p-Pb and Pb-Pb systems with CMS at respectively $\sqrt{s_{NN}} = 5.02$ and $\sqrt{s_{NN}} = 2.76$ TeV.	20
2.19	Elliptic flow as observed in the rest frame of one of the projectiles, using the beam rapidity $ \eta - y_{beam}$	21
2.20	Projection of the factorization ratio $f_2(\eta_a, \eta_b)$ onto $\Delta\eta$ for various centralities.	22
2.21	ATLAS $r_{2 2,1}$ measurements for different η_{ref} ranges with Pb–Pb at 5.02 TeV.	22
2.22	Hydrodynamical simulation results for the decorrelation of the symmetry plane.	23
3.1	η -gap method using B and C as reference regions.	33
3.2	η -gap method using the FMD as reference region.	34
3.3	η -gap three subevent method using opposite side reference regions	35
3.4	Sketch of calculation of $r_{n,n}$	36
4.1	Visualization of the LHC with the four large experiments and additional access points.	38
4.2	The ALICE detector.	40

4.3	A schematic view of the inner tracking system at ALICE.	41
4.4	A schematic view of the Time Projection Chamber (TPC) at ALICE.	42
4.5	The inner and outer rings of the FMD.	43
4.6	A schematic view of V0-A and V0-C.	43
4.7	Visualization of from event generator to data format.	45
5.1	Vertex position and centrality before and after event selection.	48
5.2	Multiplicity and V0M percentile before and after event cuts.	49
5.3	CL0 and V0M percentile before and after event cuts.	49
5.4	Event cuts.	50
5.5	FMD hits vs. V0 hits.	51
6.1	The uncorrected v_n coefficients measured by the 2-particle cumulant with TPC reference.	54
6.2	Coverage in (φ, η) with the TPC and FMD detectors.	55
6.3	Procedure of getting NUA weights for the TPC.	56
6.4	Procedure of getting NUA weights for the FMD.	57
6.5	Monte Carlo closure test for the interpolation of acceptance holes in the FMD.	58
6.6	Systematic for NUA interpolation.	59
6.7	Toy model test of the resolution correction performed in Bizlandic et. al. [59].	59
6.8	φ distributions in the TPC per runs with a positive magnetic field with Pb–Pb collisions at 5.02 TeV.	60
6.9	φ distributions in the FMD per runs with a positive magnetic field with Pb–Pb collisions at 5.02 TeV.	60
6.10	Efficiency for global tracks in the TPC.	61
6.11	$v_2^{\text{prim.}}$ divided by the uncorrected $v_2^{\text{recon.}}$, and the corrected $v_2^{\text{recon.}}$	62
6.12	$v_3^{\text{prim.}}$ divided by the uncorrected $v_3^{\text{recon.}}$, and the corrected $v_3^{\text{recon.}}$	63
6.13	2-particle cumulant with TPC reference with different p_T cuts for different centralities.	64
6.14	Origin of secondary particles.	65
6.15	x-ray depiction of origin of secondary particles.	66
6.16	Probability distribution of two particles.	67
6.17	Sketch of an incoming primary particle and outgoing secondary particle with a hit in the FMD.	68
6.18	The distribution of a secondary particle around its primary mother particle.	68
6.19	Result of a Fast Fourier Transform for v_2 , v_3 , and v_4	69
6.20	The approach of applying the correction, and testing with Monte Carlo closure.	70
6.21	Monte-Carlo closure test for the secondary correction extracted with the Fast Fourier Transform for v_2	71
6.22	The secondary correction dependency of different material densities.	71
6.23	The distribution of a secondary particle around its primary mother particle in η	72
6.24	γ -values from all fits in Figure 6.23, where the errors are also determined by the fit.	73
6.25	Correction by FFT at different centralities.	73
6.26	The correction estimated from primary particles for the effect of secondaries on v_n	74
6.27	The correction estimated from primary particles divided by the FFT correction.	75
6.28	FMD reconstruction from ESDs.	76
6.29	FMD reconstruction from Track References.	77

6.30	The v_2 determined from FMD data reconstructed with track references, AOD and primaries.	77
6.31	Ratio of v_n using the FMD with reconstruction from track references and AODs for different centralities.	78
6.32	Fitting of normalized $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$ per centrality.	79
6.33	The parameters from the fits in Figure 6.32 with parabel and exponential functions. . .	79
6.34	The approach of applying the correction to the FMD, and testing with Monte Carlo closure.	80
6.35	Extrapolated correction vs. $v_2^{\text{Track ref.}} / v_2^{\text{AOD recon.}}$	81
6.36	Comparison of $v_n^{\text{Track ref.}} / v_n^{\text{AOD recon.}}$ and the extrapolated values.	81
6.37	Ratio of v_2 with the two possible reconstructions of the FMD.	82
7.1	An example of a systematic check with a variation of track selection.	86
7.2	$v_n\{2\}$ and $v_2\{4\}$ reference flow measurements in the central region of pseudorapidity. .	87
7.3	2-particle cumulant with TPC reference for different gaps.	88
7.4	$v_n\{2, \Delta\eta > 0.8\}$ with TPC reference in Pb–Pb collisions.	89
7.5	$v_n\{2, \Delta\eta > 2.0\}$ with FMD reference in Pb–Pb collisions.	90
7.6	$v_n\{2, \Delta\eta > 0.4\}$ with TPC reference in Xe–Xe collisions.	91
7.7	$v_n\{2, \Delta\eta > 2.0\}$ with FMD reference in Xe–Xe collisions.	92
7.8	$v_n\{2, \Delta\eta > 1.0\}$ with the three sub-event method in p–Pb collisions.	93
7.9	$r_{2,2}$ with different choices for η_{ref} in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	95
7.10	$r_{3,3}$ with different choices for η_{ref} in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	96
7.11	$r_{2,2}$ with different choices for η_{ref} in p–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	96
7.12	Comparison of $v_2\{2\}$, $v_3\{2\}$, $v_4\{2\}$ from published results [40] and results from this analysis.	97
7.13	Comparison of $v_n(\eta)$ with Pb–Pb collisions at 2.76 and 5.02 TeV.	98
7.14	Comparison of beam rapidity scaling for v_2 with different collision systems and energies. .	99
7.15	$v_n\{2, \Delta\eta > 0.8\}$ with TPC reference compared to AMPT.	100
7.16	$r_{2,2}$ with different choices for η_{ref} compared to AMPT.	101
7.17	$r_{3,3}$ with different choices for η_{ref} compared to AMPT.	101
A.1	Distribution of particles in φ	114
A.2	$c_2\{2\}$ calculated for simulated particles, binned particles, and corrected binned particles. .	114
A.3	$c_2\{2\}$ calculated for binned particles with multiplicity weights in the Q-cumulant method. .	115
A.4	A close view of $c_2\{2\}$ calculated for binned particles with multiplicity weights in the Q-cumulant method.	115
B.1	η -gap method using the TPC and FMD as reference regions.	116
B.2	η -gap 3 subevent method using opposite side reference regions	117
C.1	Monte Carlo closure for NUA interpolation in the FMD for v_3	118
C.2	Monte Carlo closure for NUA interpolation in the FMD for v_4	118
C.3	φ distributions per run for LHC15o highIR period for the TPC.	119
C.4	φ distributions per run for LHC15o highIR period for the FMD.	119
C.5	φ distributions per run for 2016 p-Pb run in the TPC.	120
C.6	φ distributions per run for 2016 p-Pb run in the FMD.	120
C.7	Global tracks acceptance at different z-positions in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	121

C.8	FMD acceptance at different z-positions in Pb–Pb collisions with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	122
D.1	Efficiency for hybrid tracks in the TPC.	123
E.1	v_3 with track references, primaries, and track references corrected.	124
E.2	v_4 with track references, primaries, and track references corrected.	124
E.3	The flow coefficient v_3 calculated with track references, primary particles, and AODs.	125
E.4	The flow coefficient v_4 calculated with track references, primary particles, and AODs.	125
E.5	Parameters for the fits for v_3 from Figure 6.32.	126
E.6	Parameters for the fits for v_4 from Figure 6.32.	126
E.7	Comparison of the extrapolated correction using fits and $v_3^{\text{Track ref.}}/v_3^{\text{AOD recon.}}$. The extrapolated values reach a high precision at large centralities.	127
E.8	Ratio of the extrapolated correction and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$	127
E.9	Comparison of the extrapolated correction using fits and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$. The extrapolated values reach a high precision at large centralities.	128
E.10	Ratio of the extrapolated correction and $v_4^{\text{Track ref.}}/v_4^{\text{AOD recon.}}$	128
E.11	Ratio of v_3 with the two possible reconstructions of the FMD.	129
E.12	Ratio of v_4 with the two possible reconstructions of the FMD.	129
E.13	The distribution of a secondary particle around its primary mother particle.	131
E.14	γ -values from all fits.	131
E.15	Result of a Fast Fourier Transform for v_2 with a subtracted constant.	132
E.16	The distribution of a secondary particle around its primary mother particle.	133
E.17	γ -values from all fits.	133
E.18	Comparison of the correction values from different approaches.	134
E.19	Correlation and single distributions of the correction values from the different approaches.	135
E.20	Ratios of all the methods introduced in this section.	136
E.21	Comparison of the correction from this work to prior methods [57].	136
E.22	The secondary correction extracting with 20 bins and 500 bins in φ	137
F.1	Centrality and multiplicity for Pb–Pb and Xe–Xe.	138
G.1	Systematic uncertainties for the n^{th} flow coefficient using m -particle cumulants in the TPC with Pb–Pb collisions.	139
G.2	Systematic uncertainties for the n^{th} flow coefficient using m -particle cumulants in the FMD with Pb–Pb collisions.	140
G.3	Systematic uncertainties for the n^{th} flow coefficient using 2-particle cumulants in the TPC and FMD with Xe–Xe collisions.	140
G.4	Symmetry of flow coefficients in Pb–Pb with $\sqrt{s_{\text{NN}}} = 5.02$ TeV.	141
G.5	Symmetry of flow coefficients in Pb–Pb with $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using the FMD as reference region.	142
G.6	Symmetry of flow coefficients in Xe–Xe with $\sqrt{s_{\text{NN}}} = 5.44$ TeV.	143
H.1	$r_{2,2}$ centrality dependence with $2.0 < \eta_{\text{ref}} < 2.4$	144
H.2	$r_{2,2}$ as a function of reference region.	144
H.3	Centrality dependence of $v_n\{2, \Delta\eta > 0.8\}$	145
H.4	Centrality dependence of $v_n\{2, \Delta\eta > 1.8\}$ and $v_2\{4, \Delta\eta > 0.0\}$	146
H.5	Centrality dependence of the ratio of v_2 with a large and small gap.	146
H.6	Comparison of $v_n(\eta)$ with Pb–Pb collisions at 2.76 and 5.02 TeV.	147
H.7	Comparison of preliminary results in p–Pb.	148
H.8	$v_n\{2, \Delta\eta > 2.0\}$ with FMD reference in Pb–Pb collisions compared to AMPT.	149

PHD THESIS

NIELS BOHR INSTITUTE, FACULTY OF SCIENCE,
UNIVERSITY OF COPENHAGEN

PSEUDORAPIDITY DEPENDENCE OF LONG-RANGE CORRELATIONS

