

To flow or not to flow

**A study of elliptic flow and nonflow
in proton-proton collisions in ALICE**





A catalogue record is available from the Utrecht University Library.

ISBN: 978-90-393-5705-7

Copyright © 2011 by N. van der Kolk

All rights reserved. No part of this book may be reproduced, stored in a database or retrieval system, or published, in any form or in any way, electronically, mechanically, by print, photoprint, microfilm or any other means without prior written permission of the author.

Cover design: N. van der Kolk

Typeset using L^AT_EX and printed by Ipskamp Drukkers, Enschede, The Netherlands.

To flow or not to flow

A study of elliptic flow and nonflow in proton-proton collisions in ALICE

**Over het meten van elliptische flow en nonflow
in proton-protonbotsingen met de ALICE-detector**

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag
van de rector magnificus, prof. dr. G.J van der Zwaan, ingevolge het besluit
van het college voor promoties in het openbaar te verdedigen op woensdag
25 januari 2012 des middags te 12.45 uur

door

Naomi van der Kolk

geboren op 4 oktober 1979 te Eindhoven

Promotoren:

Prof. dr. Th. Peitzmann

Prof. dr. R.J.M Snellings

"It would be so nice if something would make sense for a change"

Alice in Wonderland - Lewis Carroll

Contents

1. Introduction	1
1.1 The Standard Model	2
1.2 Quantum Chromodynamics	4
1.3 The Quark Gluon Plasma	6
1.4 Kinematic variables	9
1.5 Proton-proton collisions	10
1.6 Heavy ion collisions	11
1.7 Signatures of the QGP	12
1.8 Thesis outline	14
2. Elliptic Flow	17
2.1 Radial flow in heavy ion collisions	18
2.2 Anisotropic flow in heavy ion collisions	18
2.3 Elliptic flow in heavy ion collisions	20
2.3.1 Centrality dependence	21
2.3.2 Transverse momentum and particle species dependence	22
2.3.3 Energy dependence	24
2.3.4 Eccentricity fluctuations	25
2.3.5 Nonflow correlations	27
2.4 Elliptic flow in proton-proton collisions	27
3. The ALICE Detector	31
3.1 The Large Hadron Collider	32
3.2 The ALICE detector	33
3.3 Subdetectors	35
3.3.1 Inner Tracking System	35
3.3.2 Time Projection Chamber	36
3.3.3 The Forward Multiplicity Detector and the VZERO counters	37
3.4 Event reconstruction in the ALICE off-line framework	37
3.4.1 Minimum bias event selection	37
3.4.2 Event reconstruction	38
3.4.3 Tracking	38
3.4.4 Alignment and calibration	39
4. Analysis Methods	41
4.1 Scalar product method	43
4.2 Cumulant method	46
4.3 Lee–Yang zeroes method	47
4.4 An event plane estimate without nonflow effects	51
4.5 Analysis software	52

4.6	Validation using Monte Carlo simulations	52
4.6.1	Applicability of the analysis methods	53
4.7	Discussion.	59
5.	Correlations in proton-proton collisions	63
5.1	Data sample	64
5.1.1	Event selection.	64
5.1.2	Track selection	64
5.1.3	Kinematic cuts	66
5.1.4	Efficiency and purity	67
5.2	Correlation measurements using the scalar product method.	68
5.2.1	Pseudorapidity gap dependence in simple Monte Carlo events.	69
5.2.2	Pseudorapidity gap dependence in PYTHIA events.	72
5.2.3	Pseudorapidity gap dependence in 7 TeV proton-proton data	75
5.2.4	Discussion	78
6.	Conclusions and Summary	81
A.	Extending the η-range	87
B.	Estimating nonflow in Pb-Pb collisions from proton-proton collisions	95
B.1	Analysis method	96
B.2	Validation of the method using a simple Monte Carlo model	98
B.3	Scaling with the centre of mass energy	99
B.4	Centrality dependence in Pb-Pb collisions	101
B.5	Discussion.	105
	References	109
	Samenvatting	115
	Curriculum Vitae	119

1

Introduction

People have always wondered and asked questions about the world we live in. Questions like “*How did it come into existence?*” and “*What is matter made of?*”. Today, many people believe that the universe was formed in the *Big Bang* and that the matter we are made of can be described by the *Standard Model*. The standard model describes matter at the most fundamental particle level, the smallest scale of size. Ordinary matter consists of tiny atoms, which have a core circled by an electron cloud and a lot of empty space. The core of an atom, the nucleus, consists of protons and neutrons. Those are again build up by elementary particles called quarks. It is these quarks and the electrons, which do not have any known internal structure, as well as other elementary particles that are described by the standard model. Even with the insights the standard model has already provided, there are still a lot of unanswered questions. Heavy ion collisions are used to study some of these, for instance questions about the nature of the strong force and about the state of matter in the first microseconds after the Big Bang.

1.1 The Standard Model

The Standard Model is at this moment the best description of all known elementary particles and the forces that act between them (see e.g. [1]). When describing elementary particles and their interactions the unit of energy used is the electron volt (eV)[†]. In order to describe also other physical quantities, like mass, momentum and temperature, in terms of eV, the speed of light (c) and Planck’s constant ($\hbar$) are set to 1.

A particle is considered elementary if it has no known substructure. Elementary particles are divided into 3 generations as illustrated in Figure 1.1. These three generations differ in the mass of the particles but in other aspects they are equivalent. Each generation is divided into two quarks and two leptons. So in total there are 6 types of quarks called flavours: up (u) and down (d), charm (c) and strange (s), top (t) and bottom (b). The top quark is the heaviest, about 10^5 times as heavy as the up or down quark, and was therefore only discovered 30 years after the discovery of the bottom quark, when accelerators with high enough energy became available. The leptons are the electron (e), muon (μ), tau (τ) and their corresponding neutrinos (ν_e, ν_μ, ν_τ).

Each particle has a corresponding antiparticle; a particle with the same mass but with the opposite electrical charge[‡]. The electrical charge of the electron, muon and tau is -1 , the neutrinos are uncharged and the quarks have a fractional charge: u, c and t have charge $+2/3$ and d, s and b have charge $-1/3$.

Another property of particles is their spin. Spin is the internal angular momentum of the particle. The amount of spin is quantised. Compared to the basic unit all elementary particles have spin $1/2$.

There are four fundamental forces: the electromagnetic force, mediated by the photon (γ), the weak force, mediated by the W and Z gauge bosons (W^+, W^-, Z^0), the strong force,

[†]One eV is the energy an electron gains when passing through an electric field with a potential difference of 1 Volt. It is equal to $1.602 \cdot 10^{-19}$ Joule.

[‡]The basic unit of electrical charge is the charge of the electron, it is thus set to 1. For historical reasons the electron now actually has charge -1 .

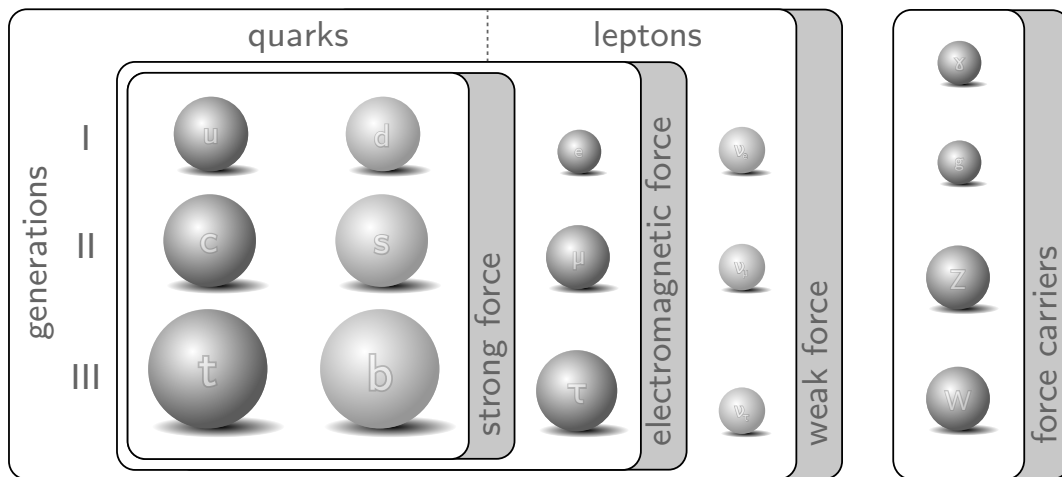


Figure 1.1: Elementary particles of the Standard Model.

mediated by the gluons (g) and gravity, mediated by the not-yet-discovered graviton. The photon and the gluons are massless, while the W and Z bosons are very massive. The force mediators (γ , W^+ , W^- , Z^0 and g) have spin 1, the graviton has spin 2. All the elementary particles can interact via the weak force, those who are electrically charged interact additionally via the electromagnetic force and the quarks can also have interactions via the strong force.

While electrons, muons, taus and neutrinos can be observed, single quarks have never been seen. They are always bound together inside other particles. These bound states are called hadrons. There are combinations of one quark and an anti-quark called mesons, and combinations of three quarks called baryons. For example, the proton consists of two u quarks and one d quark, making the total charge of the proton $+1$. The neutron is electrically neutral consisting of one u quark and two d quarks. Normal everyday matter is made up of protons, neutrons and electrons, thus members of the first generation of elementary particles. Particles in, or formed by, the second and third generation are unstable and will decay into the lighter particles of the first generation.

Hadrons exist with spins of multiples of $1/2$, depending on how the spins of the constituent quarks combine. Mesons have integer spin and baryons half-integer spin. Particles with half-integer spin are called fermions, making all baryons, leptons and quarks fermions. The force mediators and all mesons, i.e. particles with integer spin, are called bosons.

A reaction involving particles, either a collision between two particles or a decay of one particle into other particles, follows certain rules. These rules have been deduced by studying carefully which kind of reactions occur and which kind do not occur in nature. Energy and momentum need to be conserved, while mass is not conserved. This allows particles to decay into lighter particles and it allows particles to be created from the available kinetic energy in a collision.

The amount of electrical charge is conserved in any reaction. Furthermore a baryon does not change into a meson, so the net number of baryons in a reaction is conserved. This means that the number of quarks minus the number of anti-quarks in any reaction is constant. There are many more numbers like this, called quantum numbers, that have to be conserved in any reaction between particles. Anti-particles have charge-like quantum numbers opposite to their corresponding particles.

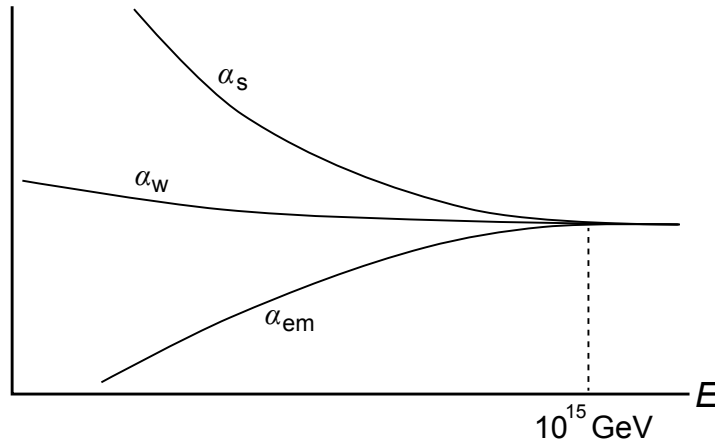


Figure 1.2: The running of the coupling constants with the energy involved in the interaction.

4

The standard model includes a formalism to describe the electromagnetic and weak forces (the electro-weak theory) and it describes the strong force with quantum chromodynamics (QCD) (see e.g. [2]). The main shortcoming of the standard model is that it does not describe gravity. In everyday life we only observe gravity and electro-magnetism because these are long range forces while the weak and strong interactions are short ranged. The weak interaction is seen in radio-active decays and the strong interaction binds the quarks together in hadrons and the nucleons inside the nucleus of an atom.

The strength of the force is characterised by its coupling α . This coupling depends on the energy involved in the interaction. At energies which can be observed in daily life the coupling of all forces is very different. The coupling α_s for the strong interactions is of order 1, while for the weak interactions $\alpha_w = 1/29$, for the electro-magnetic interactions $\alpha_{em} = 1/137$ and gravity is much weaker still. However, as the energy goes up the coupling constants approach each other and may at some high energy be equal, as is illustrated in Figure 1.2. This might make it possible to describe all forces in a single formalism: a grand unified theory. The energy scale at which this could happen, 10^{15} GeV, is however not accessible in current experiments, and may not be for quite some time.

In Figure 1.2 one can see that α_s decreases strongly with energy. Also α_w decreases but at a much lower rate. α_{em} is smallest and increases with energy. While α_w is larger the weak force is relatively weaker than the electrodynamic force because of the large mass of its mediators. The decrease with energy of the strong interaction gives very different behaviour of the quarks which are bound by this force compared to other particles. The next section will go into more detail about the strong force which is described by the theory of Quantum Chromodynamics.

1.2 Quantum Chromodynamics

The strong force binds quarks together by the exchange of gluons. But unlike the electromagnetic force, where electrically uncharged photons interact with charged particles, the gluons themselves are charged and can also interact with each other. The charge in this case is called colour charge and it comes in 3 varieties: red (r), green (g) and blue (b). These are just conveniently chosen names and have nothing to do with normal everyday

colours. Quarks have a colour charge and anti-quarks anti-colour (anti-red ($\bar{r}$), anti-green ($\bar{g}$) and anti-blue ($\bar{b}$)). The gluons have a colour and an anti-colour. From group theory it follows that there are 8 distinct gluons [1].

Hadrons, the bound states of quarks, are always neutral with respect to colour charge; they either have equal amounts of red, green and blue or they have one colour and its anti-colour. The quarks making the hadron are called valence quarks (3 for baryons, 2 for mesons). Besides these valence quarks hadrons also consist of gluons and a sea of quark-anti-quark pairs. These sea quarks exist only virtually, which means they do not need to have their proper mass. Only half of the momentum of a hadron is carried by its valence quarks. The other half is carried by the gluons. The sea quarks carry little momentum.

The sum of the bare masses of the u and d valence quarks in the proton is not equal to the proton mass. This is due to the a cloud of virtual quarks and gluons *dressing* the quark inside the hadron making the difference between the bare mass (called current mass) and the constituent quark mass.

The potential due to the strong force between two quarks increases as they are separated, while the potential due to the electromagnetic force between two charged particles diminishes with distance. With increasing distance the potential energy between the two quarks increases without limit. It would, therefore, take an infinite amount of energy to completely separate them. This is why they are never seen as a single particle but are always confined in a colour neutral hadron. This is called *confinement*. However, when two quarks are close to one another, as they are inside a hadron, they interact only weakly. Within this small volume they almost resemble free particles. This is known as *asymptotic freedom*.

Two quarks formed in a collision behave for a short time as free particles before their separation distance increases as they fly away from each other. The classical string model describes the interaction between two quarks as a confined colour flux tube, or a string. Inside the flux tube there is a colour electric field, outside there is no field. When the separation between the two quarks is more than the diameter of a hadron, about 1 fm (10^{-15} m), the potential is so large that new quark-anti-quark pairs are formed by fragmenting the stretching string between them. A lot of these extra pairs are formed as the two quarks fly away from each other. They combine into hadrons and form a jet of particles in the direction of motion of the original quark. The string model explained above is an effective way of describing particle production but the real underlying theory is QCD.

Perturbation theory is mostly used when making calculations in particle physics. It can be applied to QCD (perturbative QCD) only when $\alpha_s \ll 1$. When α_s is of order 1 perturbative calculations cannot be done anymore. For this regime a numerical method, lattice QCD, has been developed. In lattice QCD the equations are solved numerically on lattice space-time points. Calculations on the lattice predict that a phase transition can occur from hadronic matter to a gas of deconfined quarks and gluons: the Quark Gluon Plasma (QGP).

This phase transition is shown in Figure 1.3, where the energy density ε normalised to T^4 as a function of temperature normalised to T_c calculated from lattice QCD is shown. It

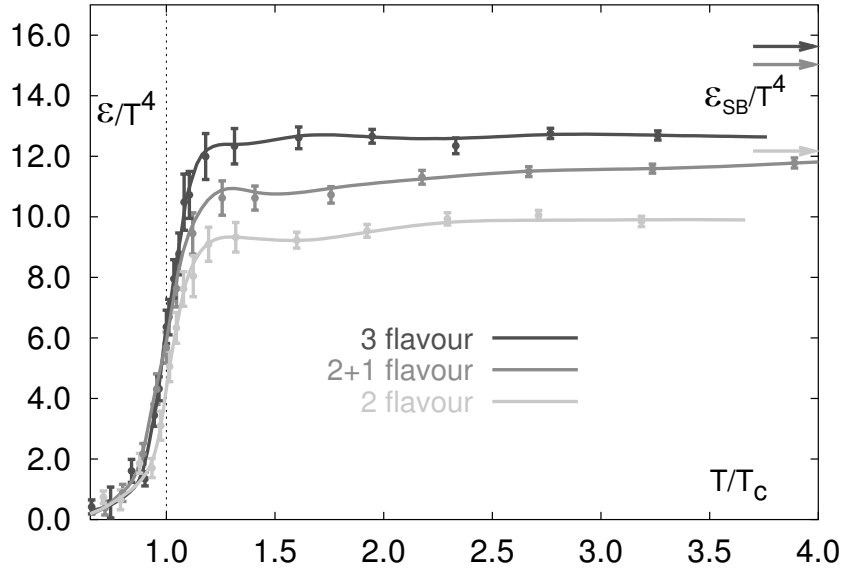


Figure 1.3: Results from lattice QCD calculations for the relation between energy density normalised to T^4 and temperature normalised to T_c from [3]. The results are valid for a zero net baryon number density for different combinations of quark flavours and masses. The sudden increase at T_c suggest a phase transition. The arrows at the right axis indicate the ideal gas limits.

shows 3 curves which each have a different combination of quark masses and flavours (2 light quarks, 3 light quarks and 2 light quarks plus 1 heavier quark). The calculations are done with a zero net baryon number density. For all three curves the energy density suddenly increases rapidly as a result of a phase transition where more degrees of freedom become available. This happens at the critical temperature T_c which is around 170 MeV. The properties of the QGP phase are difficult to calculate as they depend on too many parameters, such as the quark masses. In the figure the saturation values are compared to the corresponding ideal gas limits (arrows at the right vertical axis) which they can never exceed.

1.3 The Quark Gluon Plasma

Figure 1.4 illustrates the nuclear phase diagram, with the temperature T on the vertical axis and the net baryon number density the horizontal axis. Normal nuclear matter has a finite net baryon number density, meaning there are more baryons than anti-baryons, and a low temperature. If the density of the nuclear matter is increased at a fixed temperature the nuclear matter becomes more and more compressed. At the critical density, which is about 5 times larger than the density of normal nuclear matter, the matter undergoes a phase transition to a deconfined phase consisting of quarks and gluons. If one keeps the density constant and increases the temperature the matter first changes in a gas of hadrons in which the quarks are still confined before it undergoes a phase transition to the deconfined QGP. In the early universe, the state of the matter just after the Big Bang is believed to be a high temperature QGP at zero net baryon density. As the universe expanded the system cooled down and quarks and gluons were confined into hadrons. With high energy heavy ion collisions such a high temperature QGP might be reproduced for a short period of time. The elliptical area shown by the dashed line in the figure

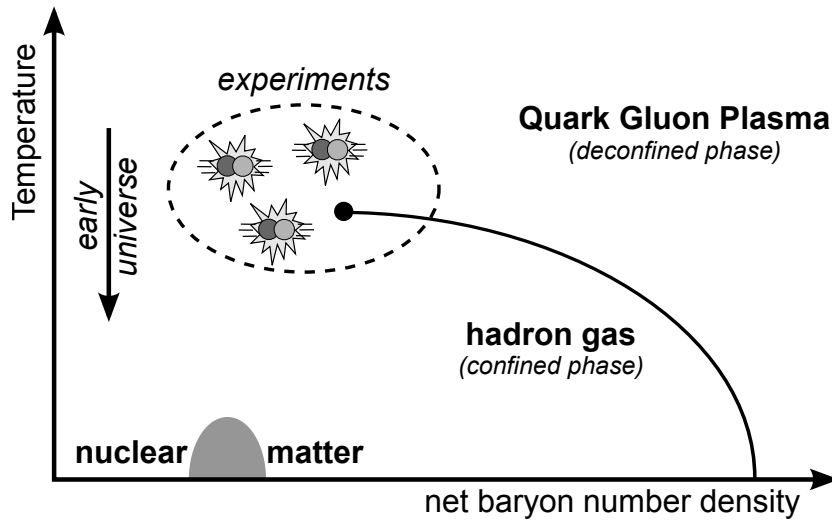


Figure 1.4: Phase diagram of nuclear matter.

indicates the state that one intends to reach with high energy nuclear collisions. This is the state where high density and temperature may be achieved in the early phase of the collision after which it will expand and cool down again.

The transition between confined and deconfined matter is a first order phase transition for a large range in the net baryon number density. Close to the temperature axis the line of the first order phase transition stops in a tricritical point and beyond that the phase transition is a smooth crossover. The location of the tricritical point depends on the bare masses of the light quarks (u , d and s). A first order phase transition has a discontinuity in the energy density because of the latent heat involved in the transition. A second order phase transition or a crossover do not have a discontinuity. The number of degrees of freedom which become available during the phase transition depends on the temperature: if high enough also the heavier quarks can participate.

Phase transitions can be described by thermodynamics. For thermodynamics to be applicable to a system, that system has to be in thermal equilibrium. If a system of particles is in thermal equilibrium, it can be described in terms of macroscopic states (a gas or a liquid) instead of in terms of movements of individual particles. This is convenient as equilibrium phases and phase transitions involve interactions on a large distance scale, where α_s is large. This means that QCD calculations are difficult and a different way to describe the system is welcome. Thermal equilibrium can be reached if the mean free path of the particles in a system is much smaller than the size of that system. The mean free path is the average distance a particle travels before it interacts with another particle. It depends on the interaction probability, called the *cross section*, and the particle density. If the mean free path is larger than the size of the system, no equilibration can occur because the particle has left the system before it collides with another particle. If, on the other hand, the mean free path is much smaller than the system size the particles will have many collisions inside the system and equilibration can occur. The formalism of ideal thermodynamics assumes a static system, while the system formed in a heavy ion collision evolves with time. Under the same assumption of local thermal equilibrium the equations of motion of relativistic hydrodynamics can be used to describe the time evolution of the system.

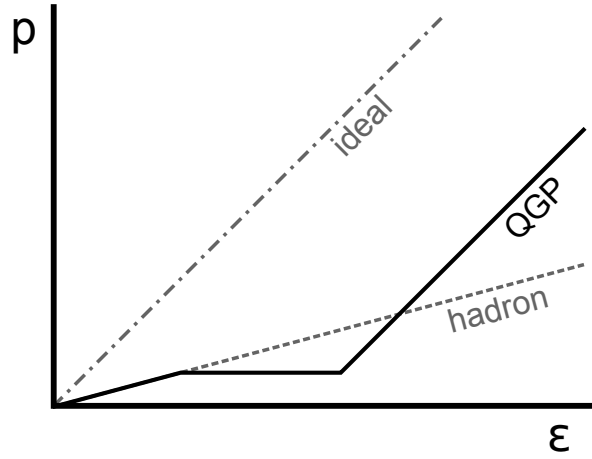


Figure 1.5: Relation between pressure p and energy density ε for a simple scenario for the transition between a hadron gas and a ideal gas of quarks and gluons. The solid line illustrates this. Before and after the transition the system is described by a different equation of state; an ideal gas (dot-dashed line) or a hadron gas (dotted line).

The hydrodynamic model

A hydrodynamical model is determined by the *equation of state* (EOS), the initial conditions and the decoupling conditions. The equations of motion are found from energy-momentum conservation and baryon number conservation. To solve them an extra ingredient is needed: the equation of state. The equation of state gives the relation between pressure p and energy density ε . The equation of state before and after a phase transition is different, as illustrated in Figure 1.5. In the QGP phase the equation of state is that of an ideal gas of quarks and gluons, based on asymptotic freedom, during the first order phase transition the pressure stays constant and after the transition the equation of state is that of a hadron gas.

A hydrodynamic model also needs initial conditions as an input. Initial conditions include the initial time, energy density and velocities. The outcome of the hydrodynamic calculation depends on this choice of initial conditions. However, the real initial condition in heavy ion collisions is not known. Different models are used and the results are compared to experimental data. In the most simple approximation the nuclei are completely stopped in the collision and the initial system is therefore at rest. In reality it takes some time for the system to thermalise and thus the system is already in motion at the point where hydrodynamics becomes applicable. The initial time fixes this beginning of the hydrodynamical expansion. It is not well known but should be of the order of $1 \text{ fm}/c$, which is the time it takes for the nuclei to cross each other. Depending on the initial density profile different regions of the system might thermalise at different times. In hydrodynamic calculations initial conditions are taken from either Glauber model calculations [4,5] or Colour Glass Condensate (CGC) [6] model calculations.

With time the system expands and cools down, and the mean free path grows until it is of the order of the system size. At that point the hydrodynamic expansion stops and particles do not interact anymore, they stream away from each other. This is called *kinetic freeze-out* and the lower the temperature is at which this happens the longer hydrodynamics is applicable to the evolution of the collision. The kinetic freeze-out temperature is not very

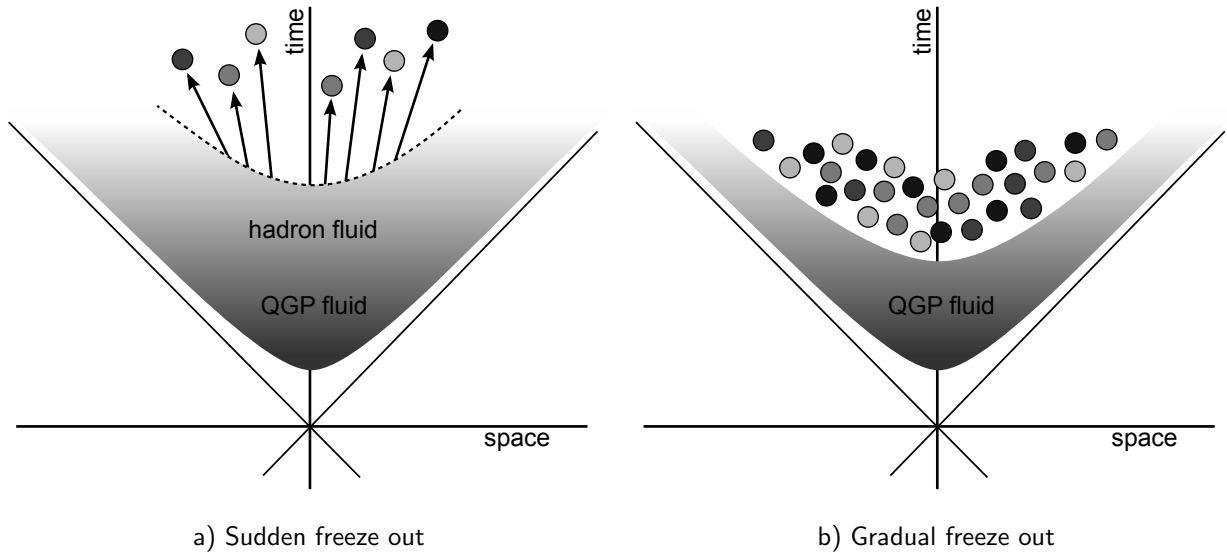


Figure 1.6: Evolution in time (vertical axis) and space (horizontal axis) of a collision in which a QGP was formed. In (a) the QGP phase is described as a fluid. As it cools and expands it changes in a fluid of hadrons until it reaches the freeze-out temperature (dotted curve). At this temperature the hadrons stop interacting and stream away. In (b) the QGP is also described as a fluid, however the hadron phase is described as a gas. The decrease of interactions between hadrons is gradual.

well known. To compare the hydrodynamic model to experiments the transition from the bulk system before kinetic freeze-out to individual particles afterwards has to be included in the model. Figure 1.6 illustrates two examples of the way in which this can be done: sudden freeze-out and gradual freeze-out. Sudden freeze-out is overly simplified, but is nevertheless often used in hydrodynamic calculations. The QGP phase is described as a fluid which changes into a fluid of hadrons as it cools and expands. At the kinetic freeze-out temperature the mean free path goes from zero (ideal fluid) to infinity (free streaming): the hadrons stop interacting and stream away. More refined and realistic are gradual freeze-out models, where for instance a finite mean free path is used. The QGP phase is described as a fluid and the hadron phase as a gas. The decrease of interactions between hadrons is gradual.

When describing experimental data using the hydrodynamic model, different combinations of initial conditions, equations of state and freeze-out conditions can be combined in order to fit the data in the best way.

1.4 Kinematic variables

The relevant kinematic variables for the description of particle interactions, like collisions or particle decays, are introduced in this section. A particle with energy E has a momentum given by $\mathbf{p} = \gamma m \mathbf{v}$, where γ is the Lorentz factor $1/\sqrt{1 - v^2/c^2}$ which depends on the relative velocity v compared to the speed of light c , m is the mass of the particle and $\mathbf{v}$ its velocity vector.

In particle colliders the transverse component of the momentum p_t is mostly used, it is the component perpendicular to the particle beam axis. The z -axis of the coordinate system

is usually chosen along this beam axis. The azimuthal angle φ of the particle is the angle in the x - y plane, perpendicular to the beam axis. The polar angle θ is the angle in the z - y plane, relative to the beam axis.

A closely related variable is the pseudorapidity η defined as $\eta = -\ln(\tan(\theta/2))$, which is preferred as it is independent of Lorentz boosts along the beam axis. Pseudorapidity is related to the rapidity, $y = -\ln(E + p_L/E - p_L)$, and the two are equivalent when the particle mass can be neglected compared to the momentum.

1.5 Proton-proton collisions

10 A collision between two protons can have many forms. In an elastic collision the two protons stay intact as mass and kinetic energy are conserved. These kind of collisions are not of interest for this thesis.

In inelastic collisions mass is not conserved and particles can be created from the available kinetic energy. Inelastic proton-proton collisions are divided into non-diffractive, single or double diffractive.

In diffractive collisions one (single diffractive) or both (double diffractive) of the incoming protons are excited to a higher mass state (no quantum numbers are exchanged). Particles are formed in the subsequent decay of this higher mass state. These particles are usually found at rapidities close to that of the parent proton.

In non-diffractive collisions quantum numbers are exchanged between the incoming protons in for instance a hard scattering between a quark or gluon in one proton with a quark or gluon in the other proton. The constituent particles of the proton, valence quarks, sea quarks and gluons, are called *partons*. Each parton carries a fraction of the momentum of the proton. This fraction is characterised by parton distribution functions which give the probability of finding a parton of a certain type with a momentum fraction x . In the hard scattering between the two partons momentum is transferred and through the process of string fragmentation many particles are created from the available energy. The hard interaction can result in one or more jets of particles depending on the process that occurred. The probability for processes to occur depends on the momentum of the partons and increases when more energy is available in the collision. Prior to and after their hard interaction the partons can radiate gluons or photons which by hadronisation form more particles.

The other partons, that did not take part in the hard scattering, in the protons will interact with each other in interactions involving smaller energy exchange. All partons eventually combine again into colour neutral hadrons that, if unstable, will decay into lighter particles. In such a collision many particles are produced around midrapidity, in contrast to diffractive collisions where the produced particles are found at larger rapidities.

In proton-proton collisions the volume of the interaction region is generally too small to form a QGP state. In order to study the QGP heavier particles are collided such as the ions of heavy elements. Proton-proton collisions are used as the reference system to which observations in heavy ion collisions are compared.

1.6 Heavy ion collisions

Ions of heavy elements, such as lead or gold, consist of many nucleons (protons and neutrons). A first guess of how a collision between two heavy ions looks like is a superposition of many independent nucleon-nucleon collisions. Of course the collisions that the nucleons can experience are not independent, which makes the collision a lot more complex. A nucleon of one nucleus can collide with many nucleons of the other nucleus and in this way it loses a large part of its energy in the collision region. Because of this energy loss a nucleon slows down as it passes through the nucleus, called *nuclear stopping*. The amount of stopping determines how much energy is lost by the nucleon. This energy is available for the production of particles. The energy density in the collision region can become very high due to this deposited energy and if it is high enough a QGP can be formed, which will exist only for a short time because the system cools as it expands after the collision. When the system gets below the critical temperature it enters a mixed phase until all quarks are again bound inside hadrons. As the energy in the system decreases inelastic scattering between particles stops and particle species are fixed. This is called *chemical freeze-out*. Shortly after that also elastic scattering ceases at kinetic freeze-out. The particle distributions as they are then will be measured by the detectors of heavy ion experiments. They reflect the state of the system at that time in its evolution. These measurements can then be compared to models like hydrodynamics in order to understand the evolution of the collision and determine the temperature and equation of state of the system formed in the collision. For instance the chemical freeze-out temperature can be determined from fits to measured particle production ratios, as the number of particles produced of a given species depends only on the chemical freeze-out temperature and the net baryon number density.

11

Centrality

Two colliding nuclei can hit each other in different ways. They can hit each other *head-on* in what is called a central collision or just touch at the edges in a so called peripheral collision, or anything in between these extremes. How much the nuclei overlap when colliding is called the centrality of the collision. If the overlap region is larger, more nucleons participate in the collision and the system that is formed is expected to be closer to conditions necessary to form a QGP. Thus the properties of the matter formed in the collision depends on its centrality. For this reason analysis of heavy ion collision data is done in centrality bins. The centrality depends on the impact parameter b , which is the distance between the centres of the colliding nuclei, as illustrated in Figure 1.7.

In reality the edge of the nucleon is not as sharp as in the figure. It has a density distribution with a rapid decrease near the edge. The impact parameter b , and thus the centrality, is not directly measurable. But the number of participating nucleons, the participants, can be related to the number of particles produced in the collision: the multiplicity. The dependence of the number of participants on the impact parameter can be calculated for any given nuclear density distribution. This can be done with the Glauber model [4,5]. It is a geometrical model of the two colliding nuclei incorporating multiple interactions

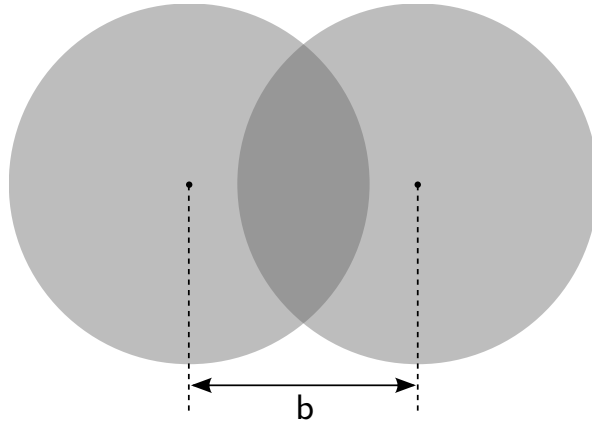


Figure 1.7: Definition of the impact parameter in a heavy ion collision.

and relating the impact parameter to the number of participants and the number of nucleon-nucleon collisions.

1.7 Signatures of the QGP

The formation of a QGP in a collision experiment cannot be directly observed. The matter formed in the collision cools down first, the quarks hadronise, the unstable hadrons decay and it is these final stable hadrons that can be observed in a detector. From these particles information should be extracted about the early stage of the collision. One needs to find measurable quantities which depend on properties of this early stage. It appears that there is no single unique signal which can unambiguously prove the formation of a QGP in the evolution of a heavy ion collision. However, there are several signatures that might indicate the presence of a QGP. A few of these signatures will be introduced below. When interpreting measurements in heavy ion collisions a comparison must always be made to a system where no QGP was formed, like proton-proton collisions at the same centre of mass energy. In that way effects coming from the QGP can be separated from effects which are already present in proton-proton collisions. Another comparison can be made with nucleon-nucleus (e.g. p-Pb) collisions. These include the rescattering and energy loss of the nucleon traversing the nucleus, but again not the effects from a QGP.

Dileptons

In the QGP volume a quark and anti-quark can interact to form a lepton-anti-lepton pair, e.g. e^+e^- , which is called a dilepton. The probability of such a process depends on the thermodynamic properties of the QGP. Leptons do not have a colour charge and do not interact with the quarks and gluons via the strong interaction. They therefore have a good chance of leaving the reaction volume and reaching a detector undisturbed. Their measured momentum distribution reflects the momentum distribution of the quarks and gluons in the QGP. This momentum distribution is different from a distribution originating from a superposition of independent proton-proton collisions.

Photons

Quarks and anti-quarks in the QGP can annihilate to form a photon and a gluon. Similarly a gluon and a quark can interact to form a photon and a quark. Just like the leptons photons do not interact strongly and can therefore easily reach a detector. The momentum distribution of these photons reflects the temperature of the QGP.

J/Ψ suppression

The J/Ψ particle is a bound state of c and $\bar{c}$. It can be formed in the initial hard scattering stage of a collision. Inside the QGP the interaction between the c and $\bar{c}$ is weakened and this can cause the $c\bar{c}$ pair to be dissociated completely if the energy is high enough. Dissociation happens at temperatures in the range 100 to 200 MeV. The c and $\bar{c}$ each then combine with light quarks to form hadrons. This means that the yield of J/Ψ from a system where a QGP was present is lower than from a system without a QGP.

13

Strangeness enhancement

In a proton-proton collision strange quark pairs ($s\bar{s}$) can be formed from the available kinetic energy. Strange quarks are not present in the protons before the collision. The probability to form a strange quark pair is small and therefore the number of strange particles, hadrons formed when the s and $\bar{s}$ pair with other quarks, produced in the collision is also small. In a nucleus-nucleus collision the probability to form $s\bar{s}$ is larger. When a QGP is formed in such a collision the probability is expected to increase even more. An enhancement in the number of strange quarks, and thus in the number of strange hadrons, is a signal of the presence of a QGP.

Parton energy loss

Partons with a high momentum generate high momentum hadrons. However, when these partons traverse the dense QGP system they lose energy resulting in a reduced yield of high momentum hadrons. The suppression can be characterised by the nuclear modification factor R_{AA} , which is the ratio of the yield of charged hadrons in nucleus-nucleus (A-A) collisions and the yield in proton-proton collisions scaled by the number of such collisions an A-A collision corresponds to. The amount of suppression gives a measure of the density of the system in the A-A collision. The nuclear modification factor R_{AA} is one if an A-A collision would correspond to a superposition of independent proton-proton collisions.

The effects of parton energy loss can also be seen in the azimuthal distribution of back-to-back jets that are formed from a hard scattering between partons. If the parton loses energy by traversing the QGP before hadronisation the resulting jet will have a lower total energy: the jet is quenched. It can also be totally stopped inside the system. In events where jets are produced back-to-back, at the edge of the collision volume, the path through the system of one of the partons leading to a jet is much longer than for the other. This jet is quenched or totally suppressed while the other suffers almost no quenching.

By locating jets in an event and then looking for the jet in the opposite hemisphere this quenching can be clearly seen. Such quenching is not present in proton-proton collisions and points to a dense system.

The Hanbury-Brown-Twiss effect

The Hanbury-Brown-Twiss effect (HBT) was first discovered when using interferometry to measure the size of stars some 50 years ago [7]. This same effect can be used in heavy ion collisions to measure the size of the reaction volume. For heavy ion collisions pion intensity interferometry [8] is used. Pions are the lightest mesons and are produced in abundance in heavy ion collisions. The momentum of one pion is correlated to the momentum of another identical pion if they are emitted from a (partially) chaotic source. This momentum correlation, of two identical pions detected in coincidence, is related to the Fourier transform of a function of the phase-space distribution of the source. In this way information about the distribution of matter at the time of pion emission can be found. HBT analysis can also give an estimate of the lifetime of the system. From the volume of the system the energy density can be found.

Collective flow

The properties of the formed system in a heavy ion collision can be studied from the azimuthal momentum distribution of the emitted particles. If the system was in thermal equilibrium, the resulting pressure generates a common velocity in the outgoing particles: *collective flow*. The term collective flow includes a common radial expansion, affecting the thermal spectra of outgoing particles, and an anisotropic expansion, affecting the spatial orientation of particle momenta. The first component is called *radial flow*, the second *anisotropic flow*. The most dominant contribution to anisotropic flow is called *elliptic flow*. Collective flow is sensitive to the equation of state of the hydrodynamically expanding system.

1.8 Thesis outline

This chapter has introduced the concepts of elementary particles, the strong force, the quark gluon plasma and heavy ion collisions. These concepts are important for understanding the research topic of this thesis: elliptic flow. Elliptic flow has been introduced only briefly in this chapter. The next chapter treats elliptic flow in more detail and presents measurements and model predictions. Elliptic flow can be measured in various ways and some of these methods are described in Chapter 4. These methods have been implemented in the analysis framework of the ALICE detector (Chapter 3) which is designed for the measurement of high energy heavy ion collisions in the Large Hadron Collider (LHC). In Chapter 5 the analysis of proton-proton collisions recorded by ALICE during the first year of data taking is discussed. The thesis concludes with a summary and discussion of the results in English and Dutch.



Elliptic Flow

Parts of this chapter are described in:

T. Hirano, N. van der Kolk, A. Bilandžić, *Hydrodynamics and Flow*, The Physics of the Quark-Gluon Plasma Introductory Lectures, Lecture Notes in Physics, **785**: 139-178 (2010).

The main topic of this thesis is elliptic flow. It is the most dominant contribution to anisotropic flow, which was briefly introduced in the previous chapter. Elliptic flow will be treated in detail in this chapter.

If in a heavy ion collision a system is formed in which particles undergo multiple interactions, leading to local thermal equilibrium and a common velocity distribution, that system will show collective effects in its subsequent evolution. The evolution of the system can then be described by fluid dynamics (hydrodynamics). The collective motion, or collective flow, is sensitive to the strength of the interactions between particles and the hydrodynamical equation of state of the system. Collective flow was first observed at the Bevelac in 1984 [9]. It builds up over the entire evolution of the system and is therefore sensitive to the combined effect of the equation of state of the system in all its different phases. At low centre of mass energies collective flow mostly reflects the properties of hadronic matter, at higher centre of mass energies the contribution from a partonic phase (possibly the QGP) becomes more and more dominant.

2.1 Radial flow in heavy ion collisions

The system formed in a heavy ion collision is surrounded by vacuum. Together with the density profile of the system this gives rise to a pressure gradient from the dense centre to the boundary of the system. In central heavy ion collisions this pressure gradient is radially symmetric and gives a boost to all particles that are formed in the system, pushing them radially outward. This means that on top of their thermal motion (governed by classical Maxwell-Boltzmann statistics) the particles get a radial velocity component. The radial velocity component results in an increase of the momentum ($\mathbf{p} = m \mathbf{v}$) which is proportional to the mass of the particle. Therefore, the effect of radial flow is most pronounced for heavy particles. The transverse momentum spectra of, in particular heavy particles, are influenced by radial flow, flattening them at low p_t .

When thermodynamics is used to describe the evolution of the system the measured transverse momentum spectra can be compared to the model predictions. The effect of different equations of state, which affect the radial flow through the pressure gradient, is more pronounced in the spectra of heavier particles and as such these particles can be used to constrain the models.

2.2 Anisotropic flow in heavy ion collisions

For non-central heavy ion collisions the shape of the interaction region depends on the impact parameter $\mathbf{b}$ of the collision. The impact parameter $\mathbf{b}$ is defined by the distance between the centres of the two colliding nuclei (illustrated in Figure 1.7). Together with the z -axis (beam direction) it defines the reaction plane, of which the azimuthal angle is Ψ_R . Such a non-central heavy ion collision is illustrated in Figure 2.1. It shows the two heavy ions just after they have collided. In the middle the reaction volume is elliptically shaped, while the spectators (particles outside the overlap between the two nuclei) continue in the beam direction z .

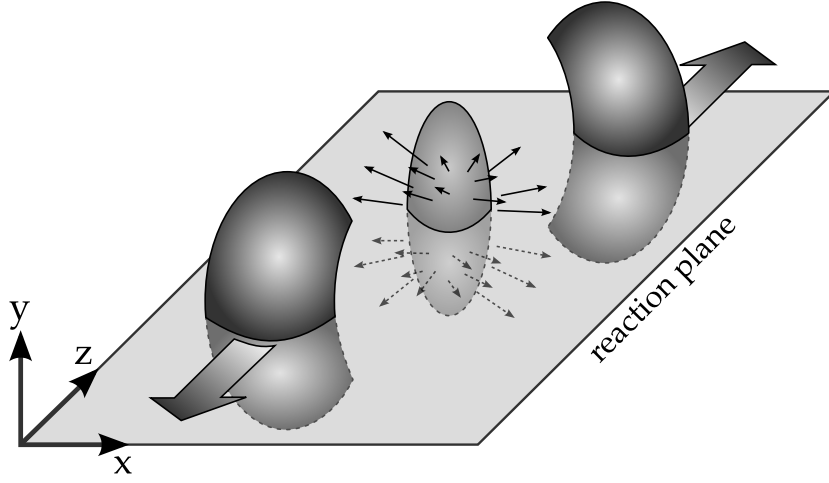


Figure 2.1: Illustration of a non-central heavy ion collision with an elliptical reaction volume which is symmetric with respect to the reaction plane.

In a collision between two protons particles are produced isotropically in the transverse plane. This means that in a heavy ion collision, where many protons collide, particle production is isotropic as well if all these proton-proton collisions are independent of each other. If, on the other hand, in the collision system particles undergo multiple interactions the azimuthal transverse momentum distribution is modified due to the anisotropy of the reaction volume. This can be characterised by the Fourier expansion of the momentum distribution with respect to the reaction plane angle Ψ_R ,

$$E \frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_R)) \right). \quad (2.1)$$

Here E is the particle energy, $\mathbf{p}$ the momentum and p_t its transverse component, y is the rapidity and φ the azimuthal angle, v_n are the Fourier coefficients. Because of the symmetry with respect to the reaction plane the sine terms in the expansion vanish. The Fourier coefficients can be calculated in the following way,

$$v_n(p_t, y) = \langle \cos(n(\varphi - \Psi_R)) \rangle_p. \quad (2.2)$$

The brackets denote an average over all particles (p) in the event. Note that v_n , being the average of a cosine, is always smaller than 1.

At zero impact parameter the reaction volume is spherical resulting in a uniform azimuthal distribution of particles, while at a finite impact parameter the reaction volume is anisotropic and the coefficients v_n will be nonzero. Each Fourier coefficient (harmonic) reflects a different type of anisotropy. The first four harmonics are illustrated in Figure 2.2. The first harmonic v_1 represents an overall shift of the distribution in the transverse plane and is called *directed flow*. The second harmonic v_2 represents an elliptical volume and is called *elliptic flow*. The third harmonic (triangular flow) gives a triangular modulation and the fourth a squared. For matter at midrapidity (around $\eta = 0$) the second harmonic, elliptic flow, is dominant.

Directed flow is seen at small angles to the particle beam (large pseudorapidity) and, because $\langle \cos(\varphi) \rangle_p$ is an odd function of pseudorapidity, it is zero at midrapidity. Directed flow is a result of the pressure in the system and is therefore sensitive to the compressibility

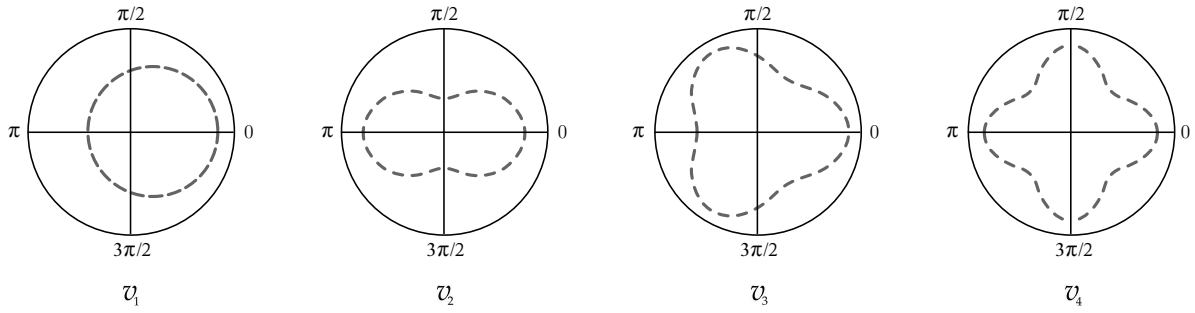


Figure 2.2: Illustration of the first four harmonics in the transverse plane, v_1 , v_2 , v_3 and v_4 .

of the created matter. It depends on collision centrality: it is maximum for semi-central collisions and vanishes for central collisions, due to symmetry, and for very peripheral collisions due to the lack of a sizable pressure gradient.

20

2.3 Elliptic flow in heavy ion collisions

As mentioned before elliptic flow is the most dominant modulation of the azimuthal particle production at midrapidity. Figure 2.3 illustrates that elliptic flow can only build up if an anisotropic reaction volume is present as well as multiple interactions between the particles. The figure shows the elliptically shaped reaction volume and the way in which particles are emitted from that volume. The resulting azimuthal particle distribution is shown as well. The left side of the figure illustrates that when no secondary interactions are present, which means the mean free path of the particles is much larger than the typical size of the system, the azimuthal distribution of the outgoing particles depends only on the symmetry of the production process and is not affected by the asymmetry of the reaction volume. When the mean free path is very small compared to the typical system size hydrodynamics can be used to describe the space-time evolution of the system and a pressure gradient is present in the reaction volume. The right side of the figure illustrates that more particles are emitted along the shorter axis where the pressure gradient is much larger than along the vertical axis, due to the geometry. The amplitude of the resulting modulation in the azimuthal distribution is the elliptic flow coefficient. Due to multiple interactions the initial spatial anisotropy of the reaction volume is transferred into an anisotropic transverse momentum distribution.

The initial spatial anisotropy, which is characterised by the spatial eccentricity ε_x , is defined by,

$$\varepsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}, \quad (2.3)$$

where x is taken in the impact parameter direction and y according to Figure 2.1 and the brackets denote an average over the transverse plane weighted with the initial density. If the system is elongated along the y -axis the spatial eccentricity is positive. The spatial eccentricity decreases during the evolution of the system because particles are emitted preferably along the short axis of the ellipse, making the particle distribution more and more spherical. At the same time the anisotropy in momentum space ε_p increases until it

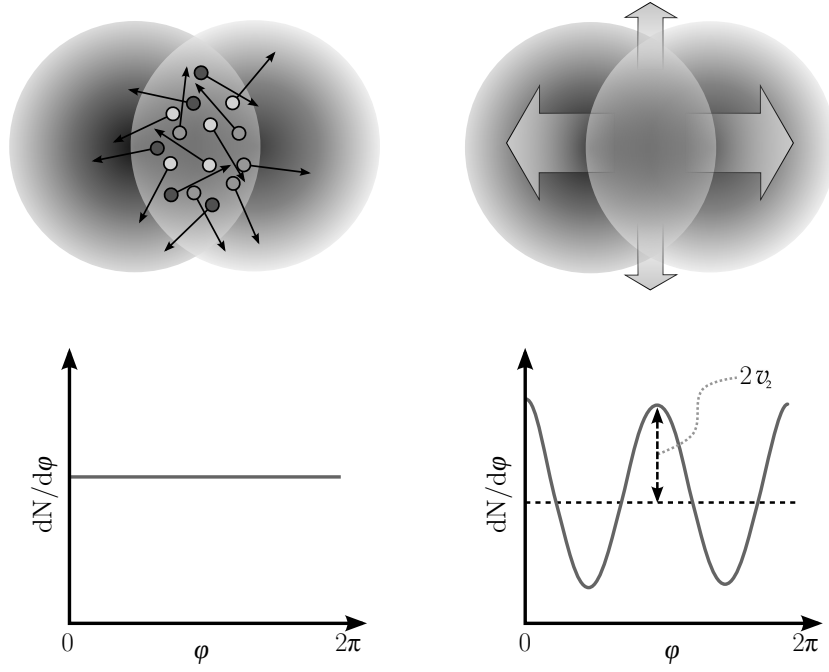


Figure 2.3: Illustration of the azimuthal distribution of particles emitted from an anisotropic reaction volume in case of a large mean free path (left) and small mean free path (right).

finally saturates. Most of the anisotropy in the transverse momentum distribution comes from the early stage of the evolution of the system making elliptic flow sensitive to the partonic phase, if present, of the system.

By using hydrodynamics to describe the evolution of non-central heavy ion collisions and comparing these models to measured data one can learn about the equation of state of the matter and about the velocity of sound in the matter. According to ideal hydrodynamics v_2 is proportional to the initial spatial eccentricity [10],

$$v_2 \propto \varepsilon_x . \quad (2.4)$$

The proportionality constant depends on the speed of sound c_s in the matter. The speed of sound depends on the equation of state of the matter through

$$c_s^2 = \frac{dp}{d\varepsilon} , \quad (2.5)$$

where p is the pressure and ε the energy density. A softer equation of state, with smaller c_s , produces smaller elliptic flow.

2.3.1 Centrality dependence

Elliptic flow depends on the event centrality: multiple scattering increases with centrality while the spatial eccentricity decreases. These two effects combined make elliptic flow low in central and in very peripheral collisions and maximum in mid-central collisions. Results of elliptic flow measurements as a function of centrality from the STAR experiment [11] are shown in Figure 2.4, where indeed the described dependence is seen. The results are shown for four different analysis methods which will be discussed in Chapter 4.

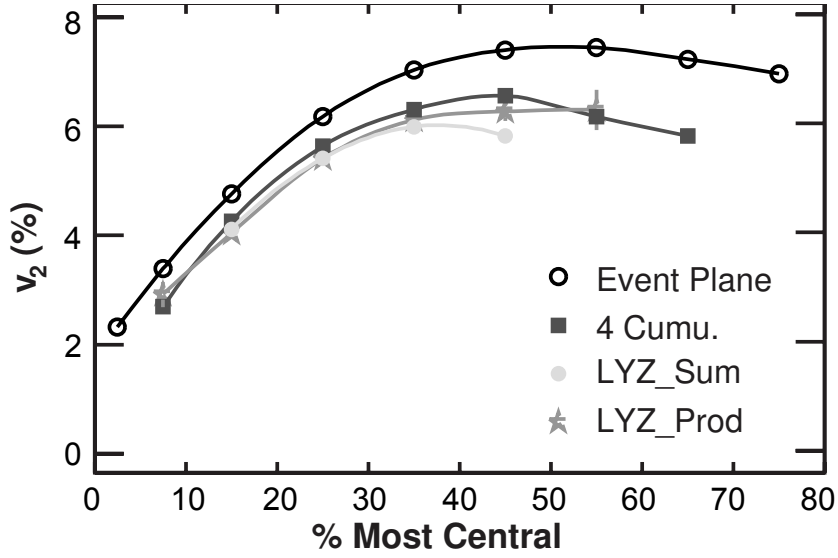


Figure 2.4: Elliptic flow of charged hadrons as a function of the event centrality for Au-Au collisions at 200 GeV [11].

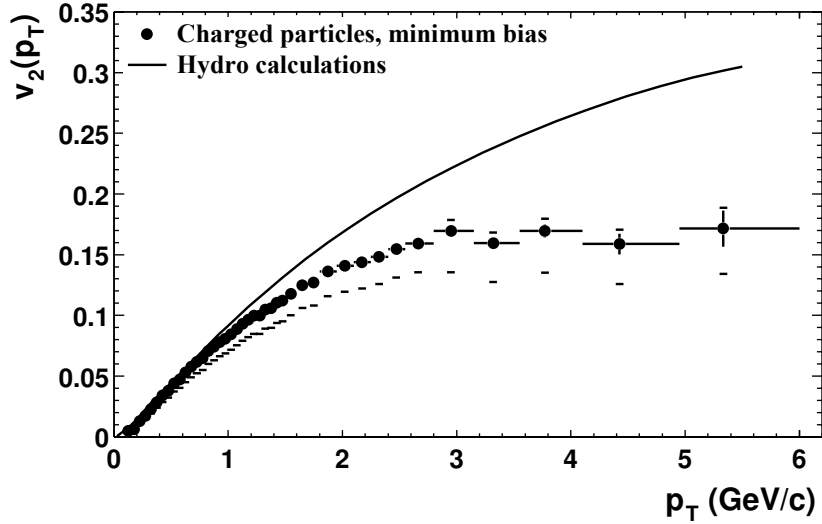


Figure 2.5: Elliptic flow of charged hadrons as a function of p_t for Au-Au collisions at 130 GeV compared to a hydrodynamic calculation [12].

2.3.2 Transverse momentum and particle species dependence

The transverse momentum dependence of elliptic flow is shown in Figure 2.5 for Au-Au collisions at 130 GeV [12]. At low p_t v_2 rises linearly and then levels off. The p_t dependence can be well describes by hydrodynamics up to $p_t \approx 1$ GeV, as can be seen in the figure. At higher p_t the contribution from particles that are not correlated to the reaction plane grows, which results in a deviation from thermodynamic behaviour.

The particles that are not correlated to the reaction plane originate from the initial hard scatterings in the collision and because their energy is high they do not participate in many rescatterings. They are thus not thermalised nor do they participate in the collective motion. However, an azimuthal anisotropy in particle production is seen also at high p_t . Depending on their orientation with respect to the reaction plane the high p_t particles have to traverse more or less matter in which they lose energy by medium induced gluon

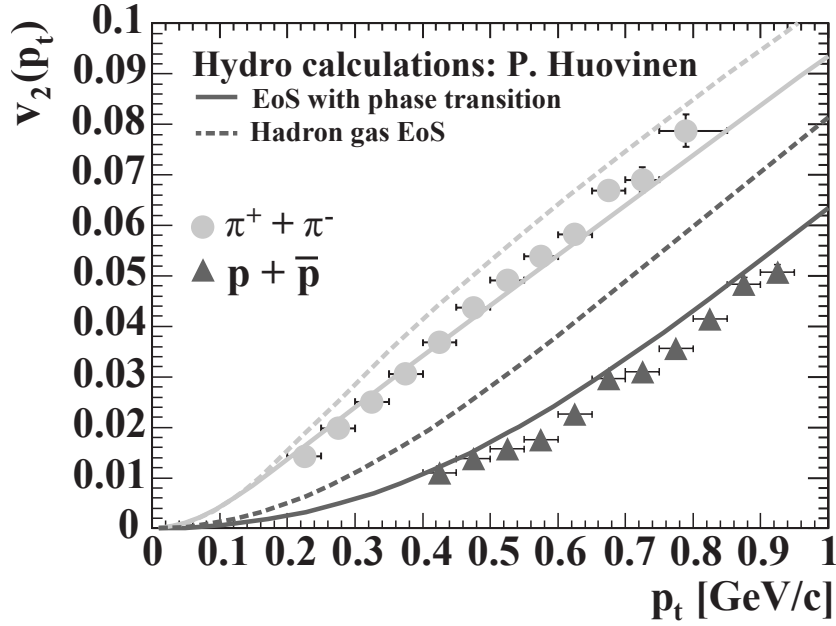


Figure 2.6: Elliptic flow of pions and protons as a function of p_t for Au-Au collisions at 130 GeV together with two hydrodynamic calculation using different equations of state [16].

radiation. This path length dependence energy loss also creates an azimuthal anisotropy in the particle momenta [13–15].

The transverse momentum dependence of v_2 for different particle species is sensitive to the equation of state. This is clearly illustrated in Figure 2.6 [16] where $v_2(p_t)$ from Au-Au collisions at 130 GeV is shown for pions and protons for $p_t < 1$ GeV where it is well described by hydrodynamics. The figure clearly shows that elliptic flow is ordered by the mass of the particles, as is predicted by ideal hydrodynamic calculations: $v_{2,\text{baryon}} < v_{2,\text{meson}}$. This mass ordering is caused by the presence of radial flow which boosts particles to higher momenta [17]. The momentum gain is larger for heavier particles resulting in a flattening of the transverse momentum spectra of heavy particles. This, in its turn, results in a decrease of v_2 at low p_t and a shift towards higher p_t of the linear rise of $v_2(p_t)$ [18].

In Figure 2.6 the data is compared to hydrodynamic models with two different equations of state: that of a hadron gas (dotted line) and that of a system with a phase transition from a QGP to a hadron gas (solid line). Clearly the latter describes the data better. The effect of the phase transition is more pronounced in the heavier protons because they are more influenced by the collective velocity which is sensitive to the equation of state.

At intermediate p_t particle production by coalescence or recombination [19, 20] predicts that v_2 depends on the quark content of the particle [21],

$$v_{2,\text{meson}}(p_t) \approx 2 v_{2,\text{quark}}\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_{2,\text{baryon}}(p_t) \approx 3 v_{2,\text{quark}}\left(\frac{p_t}{3}\right). \quad (2.6)$$

Coalescence depends on the quark degrees of freedom being dominant at hadronisation and results in $v_{2,\text{baryon}} > v_{2,\text{meson}}$. A scaling of v_2 with the number of constituent quarks versus a scaled p_t should result in all hadrons falling on a universal curve. Figure 2.7 shows that this is approximately seen in the data which suggests that collectivity developed in the partonic stage of the collision [22].

In Equation 2.6 the assumption is made that all quarks have the same elliptic flow. This may not be the case, strange quarks may have a smaller v_2 than up and down quarks at

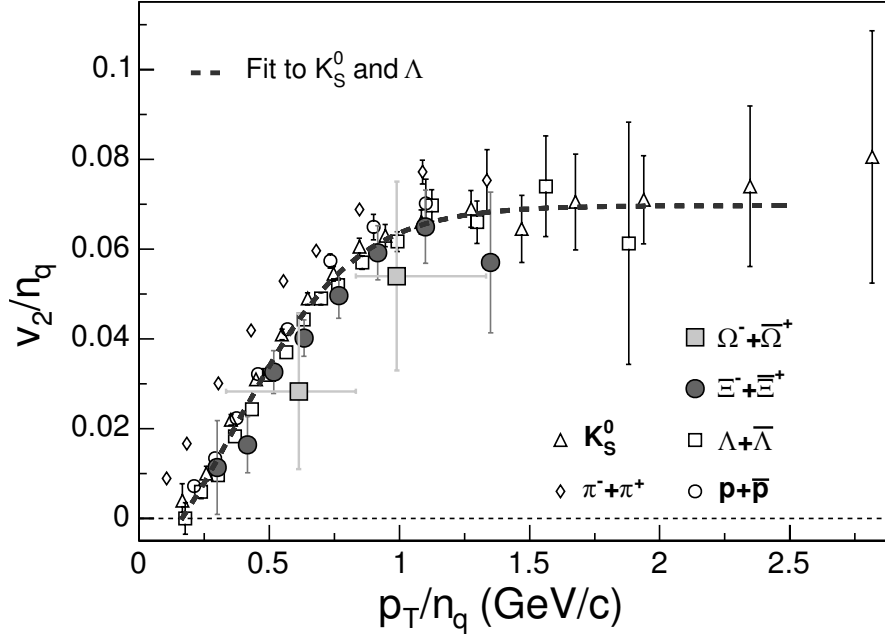


Figure 2.7: v_2 as a function of p_t both rescaled by the number of quarks n_q for various particle species for Au-Au collisions at 200 GeV [22].

high p_t because they lose less energy in the medium and at low p_t because of their mass. Such a difference between quarks results in a dependence of v_2 based on the strangeness content of a particle.

2.3.3 Energy dependence

Figure 2.8 shows elliptic flow as a function of the centre of mass energy of the collision, $\sqrt{s_{NN}}$, from many different experiments [23]. At low centre of mass energies, below 100 MeV, the collision interaction is dominated by the attractive nuclear mean field. The two nuclei are attracted towards each other and form a rotating system which emits particles in the rotating plane, producing in-plane elliptic flow [24,25]. At higher energies individual nucleon-nucleon collisions start to dominate, they produce a positive pressure which deflects the projectile and target fragments away from each other. Particles produced in the interaction region cannot escape in the reaction plane due to the presence of the spectator nucleons resulting in out of plane elliptic flow [26] (squeeze-out). Because of the Lorentz contraction of the colliding nuclei, the spectators are also contracted. The spectators leave the interaction region after a time of the order $2R/\gamma$, where R is the nuclear radius and γ the Lorentz contraction factor. When the spectators are no longer present particles are free to move in any direction in the transverse plane. The pressure gradient which is largest in-plane pushes them in this direction producing in-plane elliptic flow. A transition from out of plane, $\langle \cos(2\varphi) \rangle < 0$, to in-plane, $\langle \cos(2\varphi) \rangle > 0$, occurs when the Lorentz contraction becomes significant. The in-plane elliptic flow increases with the centre of mass energy. At ultra-relativistic energies the nuclei are almost transparent and most of the energy stays in the longitudinal direction (along the beam direction). The transverse momenta of produced particles are mostly of the order of a few hundred MeV while the longitudinal momenta are of the order of a few GeV. At such energies the

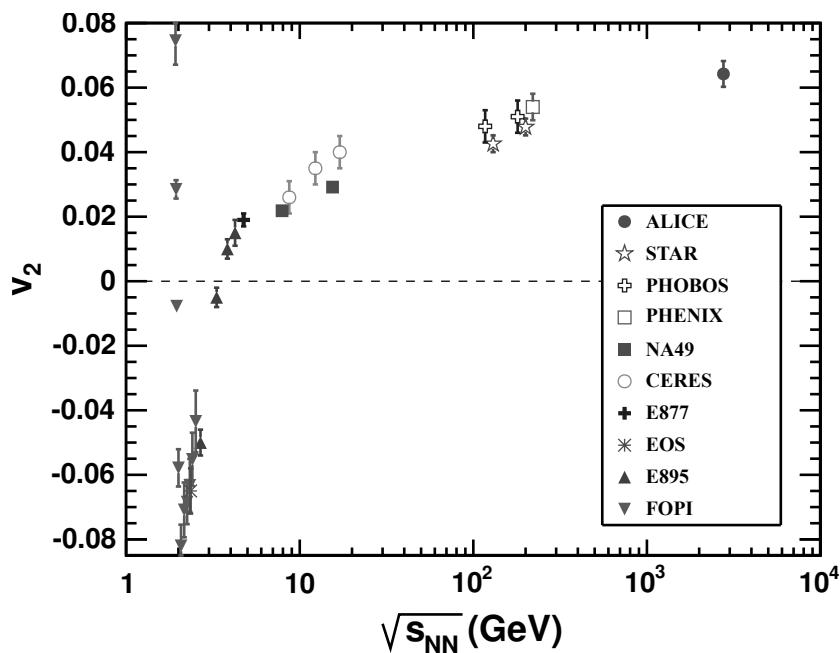


Figure 2.8: Elliptic flow as a function of the centre of mass energy $\sqrt{s_{NN}}$ from many different experiments [23].

transverse momentum dependence of elliptic flow is roughly given by,

$$\frac{dv_2(p_t)}{dp_t} \approx \frac{v_2}{\langle p_t \rangle}. \quad (2.7)$$

Between the STAR and ALICE experiments $v_2(p_t)$ does not increase [23], which means that the increase in v_2 , of about 30%, is caused by an increase in the mean transverse momentum $\langle p_t \rangle$ of the produced particles. The mean p_t increases because the radial flow does increase with collision energy as a result of the higher initial energy density [18].

By studying the ratio of v_2 over the spatial eccentricity one can test whether the system approaches the ideal hydrodynamic limit. The spatial eccentricity is in practise not measurable and has to be calculated, making it dependent on the assumed model. Figure 2.9 shows v_2/ε as a function of the multiplicity density $(1/S) dN_{ch}/dy$ from several experiments [27].

Elliptic flow at different energies and impact parameters follows a single curve which reaches the hydrodynamic limit (Equation 2.4) for Au-Au data at 200 GeV. The hydrodynamic limits are indicated with horizontal lines in the figure. The disagreement between the data and hydrodynamic calculations at lower energies is generally interpreted as a sign of incomplete thermalisation. In [28] the authors show that even for the most central Au-Au events at 200 GeV the data is best described by viscous hydrodynamics and that this viscous correction becomes more important at LHC energies because the contribution from the partonic phase of the system is expected to be larger. The viscosity can be constrained by viscous hydrodynamic model fits to v_2/ε as well as to $v_2(p_t)$.

2.3.4 Eccentricity fluctuations

For spherical nuclei the colliding system is symmetric under reflections with respect to the reaction plane. However, due to fluctuations in the positions of individual nucleons,

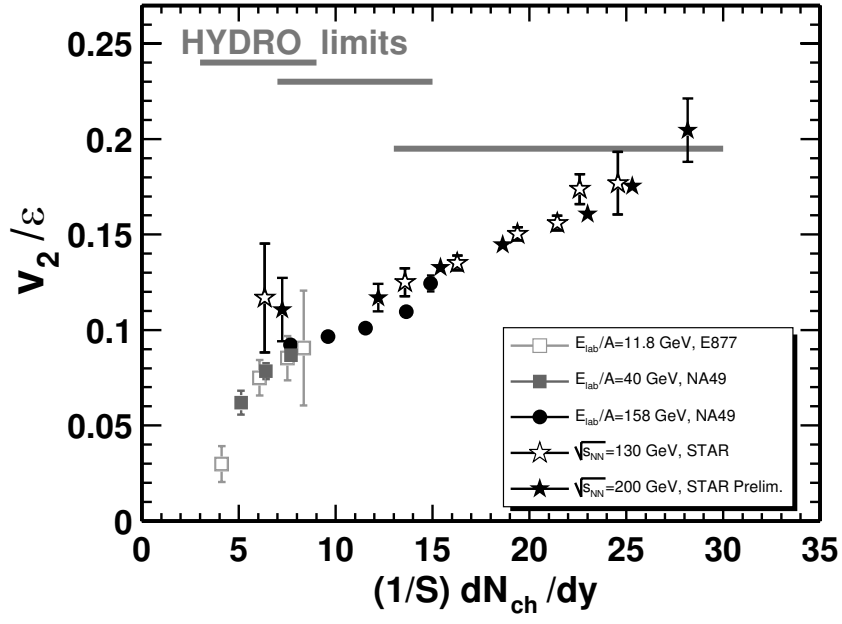


Figure 2.9: v_2/ε as a function of the multiplicity density $(1/S)dN_{ch}/dy$ from several experiments [27].

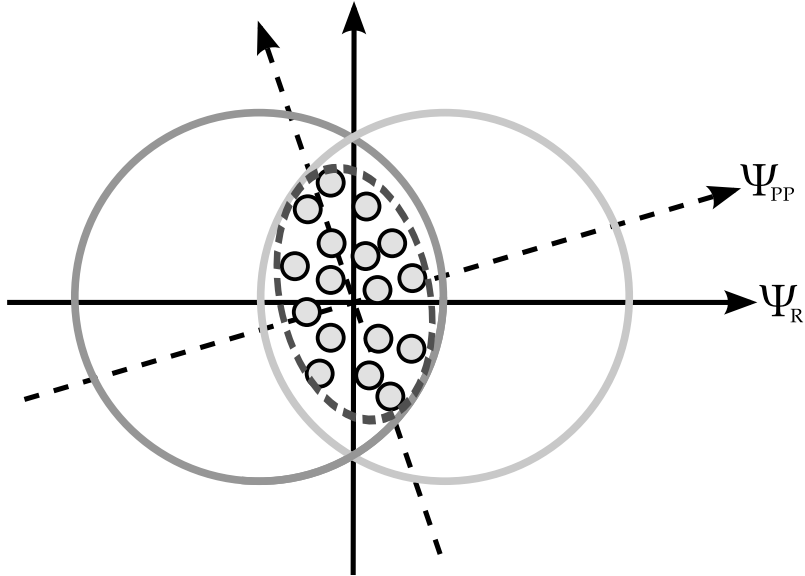


Figure 2.10: Illustration of the difference between the geometrical eccentricity and reaction plane and the eccentricity and reaction plane defined by the position of participant nucleons.

the distribution of particles in the reaction volume is not strictly symmetric on an event by event basis. Therefore the participant eccentricity is defined from the actual spatial distribution of the participants, the shifted coordinates in Figure 2.10, and can be different from the geometrical overlap region.

Also the reaction plane from this participant distribution, the participant plane Ψ_{pp} , deviates from the geometrical one, Ψ_R . The size of fluctuations in the geometry can be estimated from Monte Carlo Glauber calculations. Due to these fluctuations in the spatial eccentricity for a fixed impact parameter, also the elliptic flow v_2 will fluctuate and is given by a distribution rather than a single value. These fluctuations will be most pronounced in very peripheral collisions as the interaction region is small.

2.3.5 Nonflow correlations

Anisotropic flow is a multi-particle phenomenon, which means it is a correlation between all particles in an event. Other correlations exist between particles, but these typically only involve a few particles. Particles can be correlated because they are decay products of the same mother particle, or because they belong to the same (mini)jet, or because of momentum conservation or HBT correlations. These azimuthal correlations between n-tuples of particles, that are not related to the reaction plane are collectively known as *nonflow*. The existence of nonflow correlations is important when measuring anisotropic flow, as these correlations need to be removed from the measurement (see Chapter 4).

The characteristics of nonflow correlations are not well known and they cannot be calculated analytically as is done for flow correlations. These nonflow correlations are expected to exist mostly between few particles that are close to each other in pseudorapidity[†]. In that respect they can be distinguished from flow correlations which extend over all particles independent of pseudorapidity.

2.4 Elliptic flow in proton-proton collisions

At the high centre of mass energy of proton-proton collisions at the LHC the multiplicity might reach values comparable to those of heavy ion collisions at lower energies, where collective behaviour has been observed. It is natural to ask if in these proton-proton collisions collectivity can be seen as well. Indeed many predictions have already been made about the presence of elliptic flow in proton-proton collisions in, among others, [29–37].

In order for elliptic flow to arise in proton-proton collisions an anisotropic reaction volume is needed as well as multiple interactions between particles which can lead to local thermalisation. Predictions of elliptic flow typically use two approaches to creating this anisotropy. Either a homogeneous parton density profile is used for the proton such that the eccentricity of the overlap region depends, just as in nuclear collisions, on the impact

[†]Jets emitted back to back give long range correlations, however, nonflow is dominated by particles decaying into a few other particles as those processes are much more abundant.

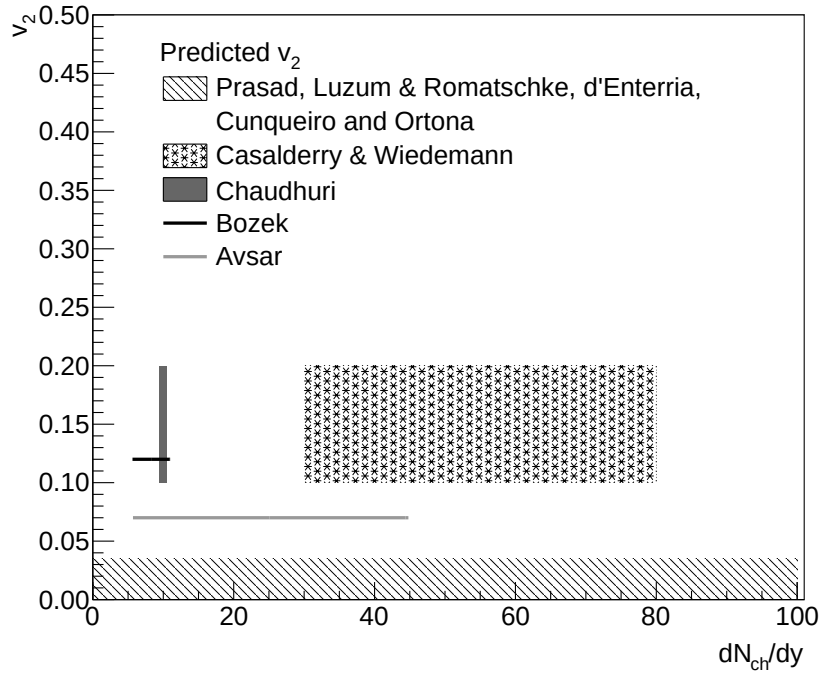


Figure 2.11: Predictions of v_2 for proton-proton collisions at 14 TeV as a function of dN/dy .

parameter. Alternatively the formation of so called *hot spots* that create an anisotropy are considered.

The parton density inside protons increases with energy as more and more gluons with small fractional momenta are formed. At high enough energy the proton can be viewed as a dense object and collisions between protons can be compared to collisions between light nuclei at lower energies. In this scenario collectivity can arise due to multiple parton interactions and elliptic flow can arise if the reaction volume is anisotropic. The collision system can then be discussed in terms of hydrodynamics. Several authors, d'Enterria *et al.* [29], Prasad *et al.* [30], Ortona *et al.* [31], Luzum and Romatschke [32], use this scenario together with the assumption that elliptic flow in proton-proton collisions has the same dependence on eccentricity, overlap area and particle multiplicity as observed in heavy ion collisions. The authors have used different proton density profiles and assumptions for the surface diffuseness which results in different predictions for the magnitude of v_2 . All predictions of this kind predict values of v_2 between zero and 0.035.

Elliptic flow predictions based on anisotropy due to hot spots reach much higher values for v_2 , up to 0.2. The partons in a proton are located in a few hot spots and all hadronic interactions occur in such hot spots, or interaction regions. These hot spots are distributed randomly according to the density profile of the proton and have a homogeneous Gaussian density distribution. The participant eccentricity is calculated from the position of the hot spots which means that also for central proton-proton collisions the eccentricity can be nonzero. Depending on model parameters, such as the number of hot spots and their size, different values for v_2 are predicted. Casalderry-Solana and Wiedemann [33] predict v_2 between 0.1 and 0.2 for proton-proton events with dN/dy larger than 30. Bozek [34] predicts $v_2 = 0.12$ for events with $5.6 < dN/dy < 11$. A similar prediction is reached by Chaudhuri [35]; $v_2 = 0.15 \pm 0.05$ for events with $dN/dy = 10$. Cunqueiro *et al.* [36] predict a much lower value of $v_2 = 0.035$ (not specifying the multiplicity), a value similar to

the results from hydrodynamic calculations with a homogeneous energy density profile. Using a full Monte Carlo simulation with detailed evolution of proton structure functions, multiple collisions, partonic showers and hadronisation, Avsar *et al.* [37] reach a prediction for events with $5.5 < dN/dy < 45$ of $v_2 \approx 0.07$.

All predictions discussed here have been done for a centre of mass energy of 14 TeV. They are summarised in Figure 2.11 where the predicted values of v_2 are plotted versus the multiplicity dN/dy at midrapidity for one unit in rapidity. The predictions where no multiplicity range was specified are plotted over the whole multiplicity region and are taken together as they are similar in value (hedged region). Other predictions apply to a specific multiplicity region or were only given for a small multiplicity range.

While some of the predicted values for v_2 are quite high, the contribution of v_2 to the measured particle correlations has to be higher than the contribution from nonflow correlations in proton-proton collisions if it is to be measured. Nonflow is more dominant for collisions with a small multiplicity. In Chapter 5 the feasibility of elliptic flow measurements in proton-proton events at 7 TeV is studied.



The ALICE Detector

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a 27 km long circular proton accelerator and collider located at CERN (Organisation européenne pour la recherche nucléaire) near Geneva. It is the most powerful particle accelerator ever built. The LHC aims at the discovery of the Higgs particle, one of the missing ingredients of the standard model, as well as at the understanding of the nature of dark matter and dark energy, the dominance of matter over anti-matter and the properties of the matter that existed just after the Big Bang.

The protons are accelerated in two rings in opposite direction and are held in orbit by a system of superconducting magnets with magnetic fields of up to 8.33 T at 14 TeV. The LHC ring has 8 arcs and 8 straight sections. Each straight section is 528 m long and can host an experimental area. In four of these the main LHC experiments are located as illustrated in Figure 3.1. The ATLAS detector, located at point 1, and the CMS detector, located at point 5, are designed for the study of proton-proton collisions and are optimised for the discovery of the Higgs particle. The LHCb detector, at point 8, is designed to study the anomaly between matter and anti-matter through the precision measurements of b quarks. At point 2 the ALICE detector is located which is build to study collisions between lead (Pb) ions. Collisions of lead ions are provided to the experiments by the LHC at a maximum centre of mass energy of 5.5 TeV per nucleon pair.

Close to point 2 and 8 the two particle beams are injected into the LHC, the two beams then cross each other only at the points where the experiments are located. Each proton beam will ultimately consist of a maximum of 2808 bunches of 10^{11} protons that are 25 ns apart, providing a bunch collision rate of 40 MHz.

The study of rare physics signals requires as many collisions as possible. The number of occurrences of a certain type of event per second N_{event} in the LHC collisions depends on the cross-section of that event σ_{event} and the *luminosity* L of the collider

$$N_{\text{event}} = L\sigma_{\text{event}} . \quad (3.1)$$

The luminosity depends on the properties of the particle beams, like the density of particles in a bunch, the revolution frequency and the angle at which the two beams cross at an intersection point. The LHC peak luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for ATLAS and CMS. LHCb can handle only $10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The peak luminosity for the Pb-Pb collisions will be $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ at a bunch crossing each 100 ns as the ALICE detector is restricted by its read out time. The luminosity for proton-proton collisions at the ALICE detector is lowered, by defocussing the beams and displacing the two beam centres, to the order of $10^{30} \text{ cm}^{-2}\text{s}^{-1}$.

The LHC project has been approved in 1994. After many years of design and construction it was ready to start operations in 2008. The first protons circulated through the beam pipe on September 10 of that year. Unfortunately a mere 9 days into its operation a major magnetic quench caused much damage to the machine which postponed its running by another year. The first proton-proton collisions took place on the 23rd of November 2009 at a centre of mass energy of 900 MeV. Collisions at 2.36 TeV took place on November 30. In 2010 the LHC collided protons at 7 TeV and at the end of that year (8 November 2010) the first Pb-Pb collisions at 2.76 TeV took place.

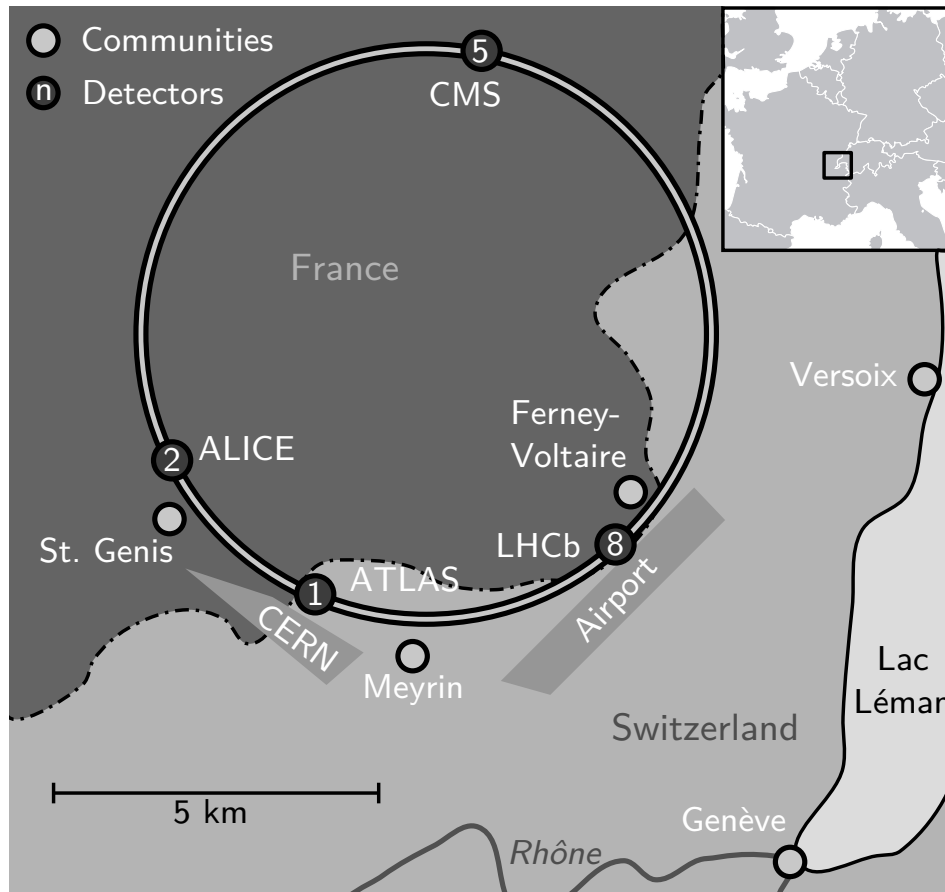


Figure 3.1: An illustration of the LHC ring with the location of the four major experiments: ATLAS, ALICE, CMS and LHCb, indicated.

3.2 The ALICE detector

ALICE is short for A Large Ion Collider Experiment; the ALICE detector is dedicated to the study of heavy ion collisions. It will study in detail the behaviour of nuclear matter at high density and temperature as is described in Chapter 1. ALICE is one of the four major experiments at the LHC and is located at intersection point 2, 40 m below ground level.

ALICE is a general purpose detector designed to measure and identify hadrons, leptons and photons produced in the collision over a large momentum range, $100 \text{ MeV} < p_t < 100 \text{ GeV}$. It has an overall dimension of $16 \times 16 \times 26 \text{ m}^3$ and a weight of about 10.000 tonnes. Figure 3.2 illustrates the ALICE detector. It consists of a central barrel around the interaction region inside a solenoidal magnet with a field strength of up to 0.5 T. The magnet has a length of 12 m and an inner radius of 5 m. The central barrel covers the pseudorapidity range $|\eta| < 0.9$ over the full azimuth. It houses the Inner Tracking System (ITS) which is a six layer silicon detector. The ITS is located directly around the beam pipe and is used to determine the primary interaction vertex as well as secondary vertices of heavy flavour and strange particle decays. It is used for tracking of low momentum particles and particle identification. The main tracking detector, positioned around the ITS, is a large cylindrical Time Projection Chamber (TPC). It is chosen because of its efficient and robust tracking capabilities. The inner radius is determined by the maximum acceptable track density and the outer radius by the length required to get a good tracking

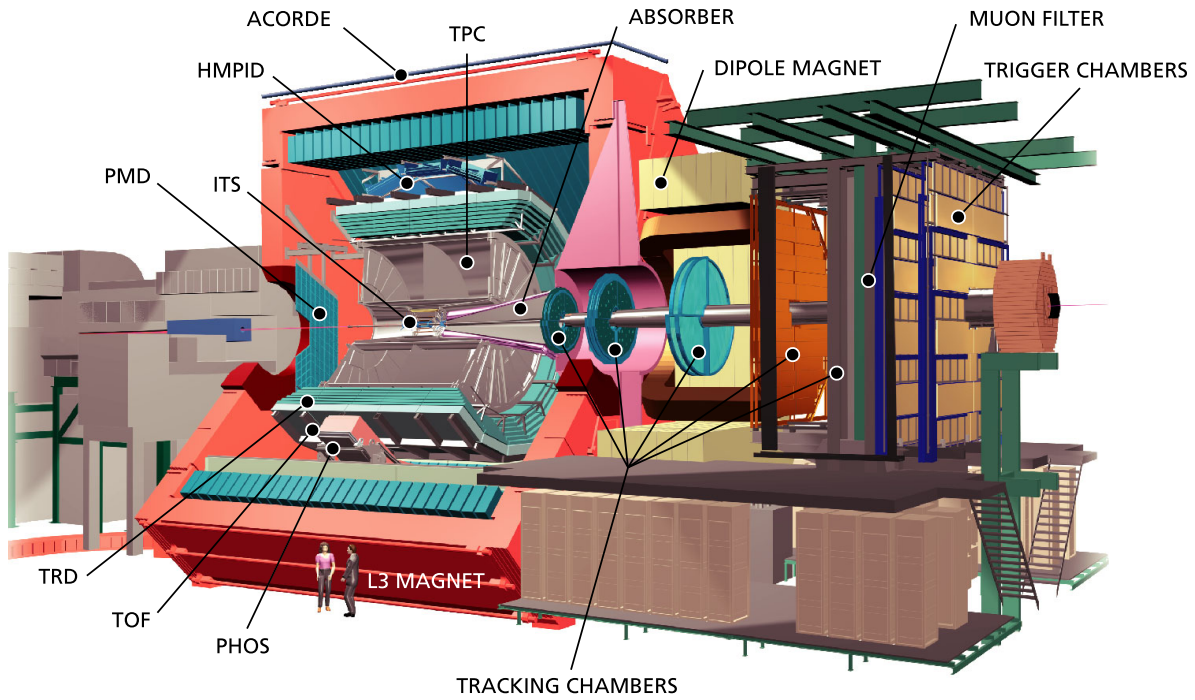


Figure 3.2: An illustration of the ALICE detector with all the subdetectors indicated.

and particle identification resolution. The Transition Radiation Detector (TRD), outside the TPC, is used to improve the momentum resolution at high momenta and to identify electrons. The Time Of Flight detector (TOF) is dedicated to particle identification of charged hadrons. Particle identification at high momenta is done by the High Momentum Particle Identification Detector (HMPID). The Photon Spectrometer (PHOS) identifies photons and neutral mesons. A second calorimeter, the Electro-Magnetic Calorimeter (EMCal), provides a trigger for high p_t particles and improves the measurements of jets. In the forward and backward direction close to the beam pipe a number of small detectors are installed. The T0 detector measures the event time, the V0 provides a minimum bias trigger. The charged particle multiplicity is measured by the Forward Multiplicity Detector (FMD) and the photon multiplicity by the Photon Multiplicity Detector (PMD). The Zero Degree Calorimeters (ZDC) positioned close to the beam pipe at a distance of 116 m from the interaction region, measures the centrality of the collisions by measuring the number of spectator nucleons.

To one side of the central solenoid the forward muon spectrometer measures muon pairs from quarkonia decay. It covers the pseudorapidity range $2.5 < \eta < 4.0$. It consists of absorbers, 14 tracking and triggering chambers and a warm dipole magnet with a horizontal magnetic field perpendicular to the beam axis. The field integral is 3 Tm. The polarity of both magnets (the solenoid and dipole) can be reversed.

The design of ALICE is driven by the huge amount of particles produced in each Pb-Pb collision; the detector has to be able to find all the individual tracks. Theoretical predictions based on extrapolations from previous heavy ion experiments at lower energies predict 1500 to 4000 particles at mid-rapidity and ALICE has been designed for this maximum multiplicity. For this reason a Time Projection Chamber is chosen as the main tracking detector, it can provide a large number of points on each track. The Pb-Pb collision have a frequency of 10 MHz. This rate gives enough time for the TPC

to process each collision. The tracking of particle trajectories uses 3 dimensional hit information with many points per track. The ALICE detector is described in the ALICE technical proposal [38–40] and in [41]. Its expected performance and its physics goals are described in the ALICE Physics Performance Report [42,43].

ALICE was designed for physics observables close to mid-rapidity, where the energy density is maximum. Many of these observables are dependent on particle mass or flavour which makes particle identification important. In ALICE particle identification is done in many ways: ionisation energy loss in the ITS and TPC, time of flight in the TOF, transition radiation (TRD), Cherenkov radiation (HMPID), calorimetry (PHOS and ECal), muon filters and topological decay reconstruction.

3.3 Subdetectors

35

This section will give more details about those subdetectors which were used for the analysis discussed in this thesis. For the analysis of differential elliptic flow the azimuthal angle, φ , of a track and its transverse momentum, p_t , are needed. For an accurate angle determination the primary vertex should be known, it is provided by the ITS. The track momenta are determined by the TPC and for low momenta by the ITS.

3.3.1 Inner Tracking System

The Inner Tracking System (ITS) [44] surrounds directly the beam pipe around the interaction region. Being the closest to the interaction its goal is to determine the location of the interaction vertex and of secondary vertices, which are the locations at which short lived particles decay. It will also provide track and momentum determination for low momentum particles, less than 200 MeV, that do not reach the TPC as well as for particles in the dead areas of the TPC. Including information from the ITS in tracks that are reconstructed in the TPC improves their momentum and angle resolution. Because multiple scattering of particles within the material of the detector itself affects the momentum resolution and vertex measurements the amount of material is minimised to less than 8% of a radiation length.

The layout of the ITS is presented in Figure 3.3a. It consists of 6 cylindrical layers of silicon detectors around the beam pipe which has a radius of 3 cm. Close to the beam pipe the particle density is very high, up to 50 cm^{-2} , and a high spatial resolution is needed to distinguish individual tracks. The two innermost layers are positioned at a radius of 3.9 and 7.6 cm and consist of silicon pixels (SPD) which give true two dimensional hit information. The position of the primary vertex is determined from the combined information from these two layers. The third and fourth layer, at 15 and 24 cm, consist of silicon drift detectors (SDD). These detectors give, just as the silicon pixels, two-dimensional information. They use the drift time of the charge deposited when a particle passes through the detector together with the segmentation through cathode strips to determine the position of the particle. The two outermost layers, at 39 and 44 cm, consist of double sided silicon strip detectors (SSD) which provide a match between the tracks

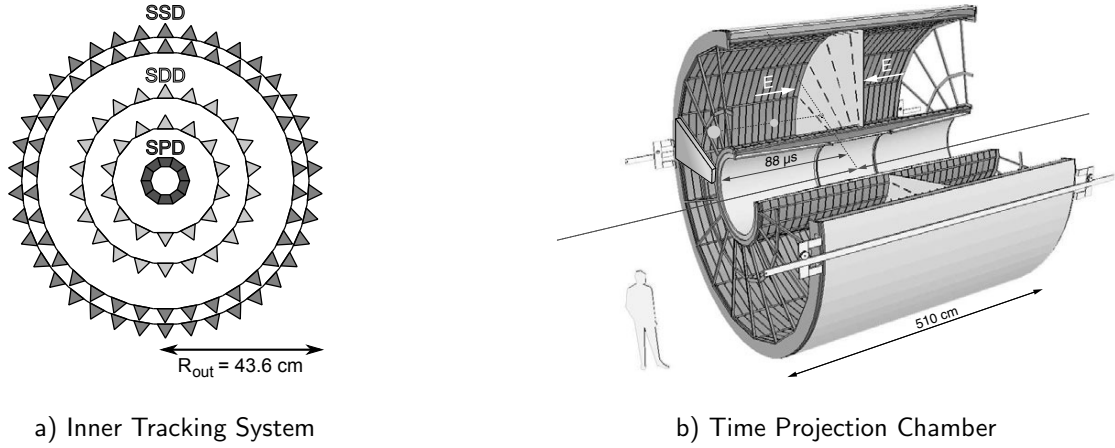


Figure 3.3: Schematic layout of the ITS and TPC subdetectors.

reconstructed in the ITS and the TPC. For these layers the track density is much lower than for the inner layers, below 1 cm^{-2} .

The ITS covers a pseudorapidity range of $|\eta| < 0.9$ for events with an interaction vertex within 5 cm along the beam direction. The first SPD layer has a larger coverage, $|\eta| < 2$. Together with the FMD the SPD is used to measure the charged particle multiplicity over a wide continuous range in η .

As a charged particle traverses the ITS it will pass through each layer and generate a signal. This gives six points to which a track can be fitted. From the fitted track the charge and momentum of the particle can be found. From the deposited energy in the four outer layers the most likely species of that particle can be determined.

3.3.2 Time Projection Chamber

Surrounding the ITS is the Time Projection Chamber (TPC) [45], the main tracking device of ALICE optimised to provide charged particle momentum measurements with a good two track separation.

As illustrated in Figure 3.3b the TPC consists of a cylindrical field cage with an inner radius of 85 cm and an outer radius of 250 cm. The length in the beam direction is 5 m. The volume is divided in two by the central electrode which is held at 100 kV with respect to the end plates 2.5 m away. It is filled with 90 m^3 drift gas (Ne/CO₂/N₂ in the proportion 90/10/5) in which electrons are freed by ionisation of the gas by a passing charged particle. The electrons are transported towards the end plates at either side of the volume. Their maximum drift time is $90 \mu\text{s}$. At the end plates the electrons give a signal in the multi-wire proportional chambers with cathode pad readout which are mounted in 18 trapezoidal sectors on each side of the TPC. This layout creates small dead areas in the TPC azimuthal acceptance between the sectors (10% of the total acceptance).

To ensure minimal multiple scattering and low secondary particle production in the TPC the total material of the TPC is minimised to 3% of a radiation length.

Particle tracks are reconstructed from a maximum of 160 reconstructed clusters and the particle type can be inferred from the deposited energy by the passing particle. The

pseudorapidity range available for full length tracks is $|\eta| < 0.9$, and $|\eta| < 1.5$ is possible for shorter tracks with a reduced momentum resolution.

3.3.3 The Forward Multiplicity Detector and the VZERO counters

Elliptic flow analysis at larger rapidities can be done with the Forward Multiplicity Detector (FMD) [46] and the VZERO counters [46]. The FMD is designed to measure the charged particle multiplicity in the forward region of the ALICE detector. It consists of 5 rings of silicon strip detectors positioned at 3 different locations along the beam pipe. It covers the pseudorapidity range of $-3.4 < \eta < -1.7$ and $1.7 < \eta < 5.0$. Depending on the ring it is divided into 20 or 40 azimuthal sectors. The strip segmentation is such that each strip is hit by one particle on average and not more than three for central Pb-Pb events. The VZERO detector consists of two rings of segmented scintillator counters around the beam pipe on either side of the interaction point. They record both the amplitude and timing of signals produced by charged particles. It is used to trigger on minimum bias events (see next section) and to estimate the centrality in Pb-Pb collisions. The pseudorapidity range is $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$ and it has 8 sectors in azimuth. Both detectors measure charged particles based on the deposited energy of a passing particle, as the signal of a detector element is proportional to the number of particles that have traversed that element.

37

3.4 Event reconstruction in the ALICE off-line framework

ALICE uses the simulation, reconstruction and analysis framework AliRoot [47] which is a collection of C++ classes build on the already available ROOT [48] framework. The reconstruction of particle trajectories from the detector signals, the quality of the data, the simulation of physics events and detectors is all handled by this common system.

3.4.1 Minimum bias event selection

The main purpose of the minimum bias event selection is to select collisions of beam particles with a high efficiency and the lowest possible bias. Trigger bits, that indicate whether a detector was triggered or not, are set during data taking for all trigger detectors. Events are then selected on a desired logical combination of these trigger bits. Minimum bias events are selected by a combination of the triggers in the SPD and VZERO detectors [43, 49]. At least one charged particle is required in the ALICE acceptance, which means either the SPD or VZERO should have been triggered. These triggers have to be in coincidence with the bunch crossing, in order to reject background events due to beam-gas or beam-halo interactions. The bunch crossing is established by the Beam Pickup for Timing of eXperiments (BPTX) [50, 51], which are part of the LHC and which provide signals centrally for all LHC experiments. Two beam pickups are placed at 150 m at each side of the ALICE interaction point. These beam pickups are sensitive to the passage of a bunch and thus they provide accurate timing of the LHC bunches.

3.4.2 Event reconstruction

The event reconstruction starts with a local reconstruction of clusters in each detector. Clusters are sets of adjacent (in space or time) signals from the smallest sensitive units of a detector and they are assumed to be generated by one particle crossing that detector. Then the primary vertex is reconstructed and particle tracks are fitted to the clusters, particle types are identified as well as secondary vertex positions. The final output of the reconstruction is the Event Summary Data (ESD), an object in which all reconstructed data is stored. Physics analysis of the ALICE data is generally based on these ESDs.

The simulation of Monte Carlo events is integrated in AliRoot and the reconstruction of those simulated events is identical to the reconstruction of real events. The detector response to generated particles in the Monte Carlo event is simulated using GEANT3 [52], which is a tool that performs the tracking of particles through an experimental setup and simulates the detector response.

3.4.3 Tracking

The global ALICE coordinate system is a right handed coordinate system with the z -axis along the beam pipe in the direction opposite the muon arm and the y -axis pointing up. The origin is defined by the intersection of the z -axis with the central membrane plane of the TPC. Reconstructed track parameters are defined in this reference frame.

Track reconstruction is done in several steps starting with the determination of the primary vertex. The primary vertex location is found from the clusters in the two SPD layers. After all tracks are reconstructed the primary vertex position is recalculated from the full track information. It can be reconstructed with a resolution of $100\ \mu\text{m}$.

The track reconstruction is done using the Kalman filtering technique in which track recognition and fitting are done simultaneously [42]. The Kalman filter needs input values into the algorithm for the track parameters and their covariance matrix. These seeds are found in the outer layer of the TPC, as the TPC is the best tracking detector in ALICE and the track density is lowest at its outer layer. The track candidates are extrapolated through the TPC towards the primary vertex. Two options are saved for each track: one is constrained to the primary vertex for finding primary particles, the other is not in order to find secondary particles from decays or secondary interactions. When the track fitting reaches the ITS, clusters are found to match the track to prolong it as close as possible to the primary vertex. Again constrained and unconstrained track parameters are kept for each track. At the end of the tracking procedure the option which gives the best fit is kept.

After ITS clusters are added to the track candidates, the remaining ITS clusters are combined into ITS-only tracks that were not found in the TPC because of their low momentum or because of dead areas in the TPC acceptance.

After all the ITS clusters are added to the tracks, the Kalman filter is reversed and the tracking is done from the inside outwards. In this tracking step improperly assigned clusters are eliminated which improves the track quality. The fitting is also continued outside the TPC in the TRD, TOF and HMPID. The filter is again reversed for a final refit

of the tracks back towards the primary vertex. With this refit the track parameters at the vertex are found. Secondary tracks can then be used to reconstruct decay vertices.

Particle identification of a track is done for charged hadrons by combining the information from the assigned clusters in the ITS, TPC, TRD, TOF and HMPID and for electrons from clusters in the TPC, TRD and EMCal.

The two innermost layers of the ITS can be used as an independent detector in analysis. A cluster in the first layer and one in the second layer, together with the primary vertex can form a *tracklet* [53]. The tracklets were used in the first ALICE publications on the charged particle multiplicity [49, 54]. Because the SPD layers are so close to the beam pipe the contamination with secondaries is very low. Tracklets are selected based on two quantities: $\Delta\varphi$ and $\Delta\theta$. If one takes a straight line from the primary vertex to each cluster, then for each pair of a cluster in the first layer together with a cluster in the second layer, the difference in azimuth $\Delta\varphi$ and the difference in the polar angle $\Delta\theta$ are considered. For each pair an elliptical cut on these two quantities is applied ($\Delta\theta_{cut} = 0.025$ rad and $\Delta\phi_{cut} = 0.08$ rad), if the pair survives the cut it is labelled a tracklet. If more than one cluster in the second layer forms a valid pair with a cluster in the first layer, the pair with the smallest angle differences is kept. The number of false combinations which passes this cut is very small ($\approx 1\%$) for proton-proton collisions. For Pb-Pb it is much larger (20% to 30%) depending on the centrality of the collision. Tracklets can be used in an analysis where the momentum of the particles is of no interest as it cannot be reconstructed from two SPD clusters only.

3.4.4 Alignment and calibration

In order to perform reliable tracking the relative position of the ITS compared to the TPC must be known, as well as the position of the ITS layers. The relative alignment of the ITS and TPC is found using a Kalman filter approach using cosmic ray data taken in 2008 and proton-proton data taken in 2009 [55]. Cosmics have a high momentum and do not suffer from multiple scattering in the detector material. With zero magnetic field in the ALICE solenoid the tracks of these particles are straight which makes them ideal for alignment. For the internal ITS alignment the position and orientation in space of each of the 2198 ITS modules has to be known. During the assembly the position of all modules with respect to their support frames was measured, these (relative) positions have been verified and improved using the 2008 cosmic ray data and proton-proton collisions with and without magnetic field [56]. The found misalignment of modules is taken into account in the track reconstruction by an additional uncertainty on the position of the ITS clusters.

The tracking algorithm should also take into account the time dependent variation in the electron drift velocity in the TPC [55]. This variation is of the order of 2% and is caused by the gas pressure following the ambient pressure variations. The change in the drift velocity results in a change in the z-coordinate of the track of the order of centimetres. The changing gas pressure is monitored during data taking and the rate of change is low enough for it to be taken into account in the Kalman filter.

The reconstruction of raw data is processed in several passes, where in each new pass the detector alignment and calibration is improved based on results of the previous pass.

Analysis Methods

Parts of this chapter are described in:

A. Bilandžić, N. van der Kolk, J.-Y. Ollitrault, R. Snellings, *Event-plane flow analysis without non-flow effects*, Phys. Rev. C, **83**: 014909 (2011).

N. van der Kolk and J.-Y. Ollitrault, *Reaction plane from Lee-Yang Zeroes for elliptic flow analysis in ALICE*, Indian Journal of Physics, **85**: 1069-1073 (2011).

N. van der Kolk and J.-Y. Ollitrault, *Flow analysis methods in ALICE Event plane from Lee-Yang zeroes*, Proceedings of the 8th Conference Quark Confinement and the Hadron Spectrum, 122, Mainz, Germany (2008).

In this chapter analysis methods for the measurement of elliptic flow v_2 are discussed. Elliptic flow is defined as the average cosine of the azimuthal angle φ of particles with respect to the reaction plane angle Ψ_R

$$v_2 = \langle \cos(2(\varphi_i - \Psi_R)) \rangle_p , \quad (4.1)$$

where the brackets denote the average over all particles p . The relevant angles, φ and Ψ_R , are illustrated in Figure 4.1 which also illustrated the pseudorapidity η . The p_t and η dependence of elliptic flow, differential elliptic flow $v_2(p_t, \eta)$, is found by dividing the φ_i in small bins in p_t or η .

One of the first methods that was developed is the so called event plane method [57], which is based on estimating the reaction plane angle and correlating particles to it. Since then many alternative methods have been developed to improve the elliptic flow measurements. The methods implemented for flow analysis with the ALICE detector are treated in this chapter, starting from 2-particle correlation methods to multi-particle correlation methods up to the Lee–Yang zeroes method, a genuine all-particle correlation method. The formalisms for elliptic flow discussed here can be applied to other harmonics v_n as well. These generalisations are not given here as this thesis does not deal with the other harmonics.

All analysis methods discussed in this chapter are based on the flow vector $\mathbf{Q}$. Its x -component and y -component are given by,

$$\begin{aligned} Q_x &= |Q| \cos(2\Psi_Q) = \sum_{j=1}^M w_j \cos(2\varphi_j) , \\ Q_y &= |Q| \sin(2\Psi_Q) = \sum_{j=1}^M w_j \sin(2\varphi_j) . \end{aligned} \quad (4.2)$$

Here Ψ_Q is the azimuthal angle of $\mathbf{Q}$ and is an estimate of the reaction plane angle Ψ_R , the sum runs over all azimuthal particle angles, φ_j , in an event and w_j is a weight to optimise the measurement.

To simplify calculations the complex representation of the flow vector is used,

$$\mathbf{Q} = Q_x + iQ_y = |Q| e^{i2\Psi_Q} = \sum_{j=1}^M w_j e^{i2\varphi_j} . \quad (4.3)$$

Using the same complex notation v_2 can be written as

$$v_2 = \left\langle e^{i2(\varphi_j - \Psi_R)} \right\rangle_p . \quad (4.4)$$

This notation is valid because particle production is symmetric with respect to the reaction plane and the probability to emit a particle in direction ϕ relative to the reaction plane is the same as in direction $-\phi$. This results in the average sine being zero, while the cosine survives ensuring that v_2 remains a real number.

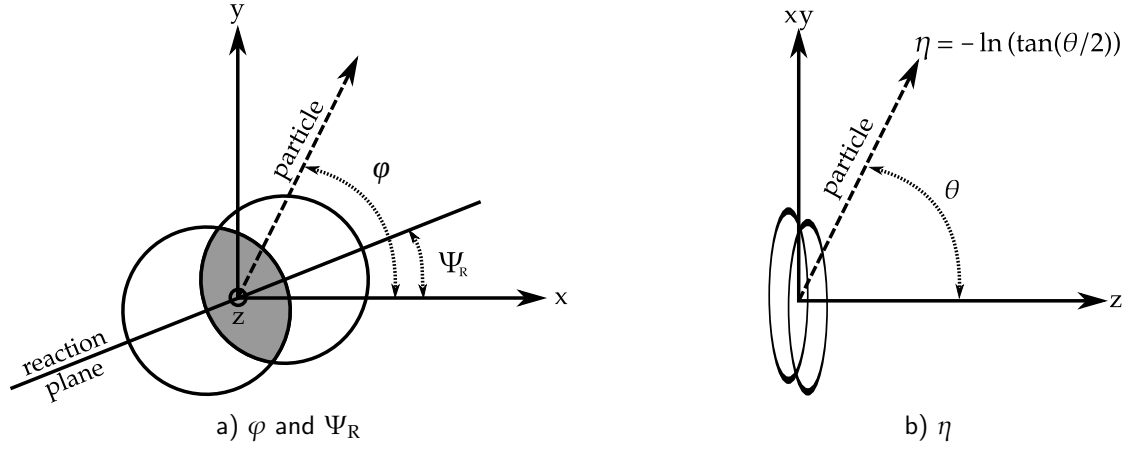


Figure 4.1: Illustration of the relevant angles, φ and Ψ_R , and pseudorapidity η .

4.1 Scalar product method

The scalar product method [58] correlates particles to the flow vector and uses the length of the flow vector as a weight in the average over events. Because the length of the flow vector is proportional to the elliptic flow value, using it as a weight reduces the statistical error (by maximising the measured elliptic flow signal).

The method is based on the scalar product of a particle, $\mathbf{u} = e^{i2\varphi}$, with the complex conjugate of the flow vector $\mathbf{Q}^*$,

$$\begin{aligned}
 \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_P &= \frac{1}{M} \sum_{i=k}^M \mathbf{u}_k \sum_{j=1, j \neq k}^M \mathbf{u}_j^* \\
 &= \frac{1}{M} \sum_{k,j=1, j \neq k}^M e^{i2(\varphi_k - \varphi_j)} \\
 &= \frac{1}{M} \sum_{k,j=1, j \neq k}^M e^{i2(\varphi_k - \Psi_R - \varphi_j + \Psi_R)} \\
 &= \frac{1}{M} \sum_{k=1}^M e^{i2(\varphi_k - \Psi_R)} \sum_{j=1, j \neq k}^M e^{-i2(\varphi_j - \Psi_R)} \\
 &= M v_2^2.
 \end{aligned} \tag{4.5}$$

The above shows that the 2-particle correlations in an event can be used to estimate v_2 . The estimate of v_2 from the scalar product method is given by

$$v_2\{\text{SP}\} = \frac{\left\langle \left\langle \mathbf{u}(p_t, \eta) \cdot \frac{\mathbf{Q}^*}{M_Q} \right\rangle_P \right\rangle_e}{\sqrt{\left\langle \left\langle \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B^*}{M_B} \right\rangle_e \right\rangle_e}}, \tag{4.6}$$

where the subscript e indicates an average over events. This definition is modified with respect to the originally proposed Equation 4 from [58].

To avoid auto-correlation the particle $\mathbf{u}$ has to be subtracted from $\mathbf{Q}$ in the numerator if it happens to be part of this sum. This subtraction has to be done before calculating the scalar product.

Following Equation 4.5 the numerator of Equation 4.6 gives v_2^2 , the denominator removes the square making $v_2\{\text{SP}\}$ an estimate of v_2

$$\left\langle \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B^*}{M_B} \right\rangle_e = \langle v_2^2 \rangle_e . \quad (4.7)$$

The vectors $\mathbf{Q}_A$ and $\mathbf{Q}_B$ are two flow vectors constructed from two particle subsets, consisting of respectively M_A and M_B particles, called *subevents*. The sum of $\mathbf{Q}_A$ and $\mathbf{Q}_B$ is the flow vector $\mathbf{Q}$ and M_Q is the sum of M_A and M_B . The two subevents are chosen in different pseudorapidity intervals and such that they do not overlap.

Taking the square root in the denominator of Equation 4.6 implies that the following should be valid;

$$\langle v_2^2 \rangle_e = \langle v_2 \rangle_e^2 . \quad (4.8)$$

This means that events with approximately the same elliptic flow value should be selected for the measurement. Because elliptic flow depends on the centrality of the collision as described in Chapter 2, the analysis is done in centrality bins. The centrality of a collision can be related to the multiplicity, which means that in practise multiplicity bins are used. The spread in multiplicity within such a bin can influence the measurement because an average over many events is taken. Another event-by-event fluctuation in M_Q is caused by the fact that $\mathbf{Q}$ is the sum of $\mathbf{Q}_A$ and $\mathbf{Q}_B$. Due to the statistical nature of particle emission the two subevents will not contain the same number of particles. The difference in M_A and M_B can be quite large in events with a small number of particles like peripheral Pb-Pb or proton-proton collisions. This is especially true for the latter because each individual proton-proton event is not necessarily symmetric. This spread in the subevent multiplicity introduces an event-by-event fluctuation in M_Q even in events with the same total multiplicity. Requesting that both subevents contain the same number of particles would severely bias the event sample towards symmetric events. These fluctuations in multiplicity are corrected for by dividing the flow vectors, event by event, by their multiplicity.

The scalar product is sensitive to nonflow correlations, which are correlations not related to the event plane. Nonflow typically involves only a few particles, in contrast to elliptic flow which involves all particles in an event. Because the scalar product method uses 2-particle correlations to estimate elliptic flow the nonflow also contributes to the measured correlation. Because nonflow mostly extends over a small range in pseudorapidity its contribution can be suppressed by separating the subevents in pseudorapidity. The magnitude of the nonflow contribution cannot be calculated analytically, but can be studied in Monte Carlo simulations and estimated from proton-proton collisions or very peripheral Pb-Pb collisions (see Appendix B).

Fluctuations in the flow signal itself also influence its measurement [59]. These are caused by event-by-event fluctuations of the initial eccentricity of the overlap region of the two

nuclei, the positions of participants and the impact parameter. Flow fluctuations are defined as

$$\sigma_{v_2}^2 = \langle v_2^2 \rangle_e - \langle v_2 \rangle_e^2 . \quad (4.9)$$

In Equation 4.8 fluctuations are assumed to be negligible. Flow fluctuations add to the measured flow signal, thus the scalar product method will overestimate the flow signal due to both nonflow and flow fluctuations.

The statistical error is propagated assuming that the measurement errors follow a normal distribution. The error on a measured quantity is then given as the standard deviation σ of its distribution. The error on a nonlinear function of these measured quantities is found based on its approximation in the form of a first order Taylor series expansion

$$f = f^0 + \sum_{i=1}^n \frac{\partial f}{\partial x_i} x_i , \quad (4.10)$$

where $\partial f / \partial x_i$ is the partial derivative with respect to variable x_i . For a function $f(a, b)$ the error follows from,

$$\sigma_f^2 = \left(\frac{\partial f}{\partial a} \right)^2 \sigma_a^2 + \left(\frac{\partial f}{\partial b} \right)^2 \sigma_b^2 + 2 \frac{\partial f}{\partial a} \frac{\partial f}{\partial b} \text{cov}(a, b) . \quad (4.11)$$

The last term, $\text{cov}(a, b)$, appears when a and b are correlated with each other. This covariance is given by,

$$\text{cov}(a, b) = E[ab] - E[a]E[b] . \quad (4.12)$$

Here $E[x]$ is the expectation value of x . Applying this to the scalar product method gives the following statistical error

$$\sigma_{v_2}^2 = \frac{\sigma_{uQ}^2}{QaQb} + \frac{(uQ)^2 \sigma_{QaQb}^2}{4 (QaQb)^3} - \frac{uQ \left\langle \left\langle \mathbf{u} \cdot \frac{\mathbf{Q}^*}{M_Q} \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B}{M_B} \right\rangle_p \right\rangle_e}{(QaQb)^2} + \frac{(uQ)^2}{QaQb} , \quad (4.13)$$

where uQ is short for $\left\langle \left\langle \mathbf{u} \cdot \frac{\mathbf{Q}^*}{M_Q} \right\rangle_p \right\rangle_e$ and $QaQb$ is short for $\left\langle \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B}{M_B} \right\rangle_e$. The method assumes that the detector is perfect, in the sense that it has a uniform azimuthal acceptance. Of course in reality a detector always has small areas of reduced acceptance, for instance dead channels or space between two sectors with cabling and support structures; even a whole sector could fail. The resulting nonuniform azimuthal acceptance can be corrected for by using the inverse of the azimuthal distribution of particles, averaged over many events, as a weight for each particle. This method however fails if there are real large gaps in the acceptance because such a profile cannot be inverted. Another disadvantage is that it requires an additional loop over the events.

A correction can also be performed by subtracting the average value of the measured quantities in the calculation as will be outlined in the following. A function of two variables $f(a, b)$ can be factorised in an uncorrelated and a correlated part

$$f(a, b) = f(a) f(b) + f_c(a, b) . \quad (4.14)$$

Applying this to 2-particle correlations gives the following

$$\langle e^{2i(\varphi_i - \varphi_j)} \rangle_p = \langle e^{2i(\varphi_i - \varphi_j)} \rangle_{\text{correlated}} + \langle e^{2i\varphi_i} \rangle_p \langle e^{2i\varphi_j} \rangle_p. \quad (4.15)$$

To measure elliptic flow, only the correlated part is of interest. The uncorrelated term vanishes for a perfect detector, however, not for a real detector with inefficiencies. This term has to be subtracted in the calculation of elliptic flow. For the scalar product method the correction takes the following form

$$v_2(p_t, \eta) = \frac{\left\langle \left\langle \mathbf{u} \cdot \frac{\mathbf{Q}}{M_Q} \right\rangle_p \right\rangle_e - \left\langle \langle \sin(\varphi) \rangle_p \right\rangle_e \left\langle \frac{\sin(\Psi_Q)}{M_Q} \right\rangle_e - \left\langle \langle \cos(\varphi) \rangle_p \right\rangle_e \left\langle \frac{\cos(\Psi_Q)}{M_Q} \right\rangle_e}{\sqrt{\left\langle \left\langle \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B}{M_B} \right\rangle_p \right\rangle_e - \left\langle \frac{\sin(\Psi_A)}{M_A} \right\rangle_e \left\langle \frac{\sin(\Psi_B)}{M_B} \right\rangle_e - \left\langle \frac{\cos(\Psi_A)}{M_A} \right\rangle_e \left\langle \frac{\cos(\Psi_B)}{M_B} \right\rangle_e}}. \quad (4.16)$$

46

Here φ is the azimuthal angle of the particle, $\mathbf{u}$ and Ψ_A and Ψ_B the angles of the subevent flow vectors.

4.2 Cumulant method

To overcome the bias from nonflow multi-particle correlation methods have been developed. Because anisotropic flow is a correlation between all particles while nonflow correlations involve only few particles, multi-particle correlation methods can provide a less biased flow estimate. The cumulant method [60,61] uses multi-particle correlations to measure elliptic flow. The second order cumulant gives an estimate of elliptic flow, $v_2\{2\}$, based on the correlations existing between two particles, while the fourth order cumulant gives an estimate, $v_2\{4\}$, based on the correlations existing between four particles, excluding correlations between two particles. One can go to higher orders and for each of these the correlations between a smaller number of particles are removed. This is the strength of the cumulant method, that it removes systematically all lower order correlations, which means nonflow can be significantly reduced. As most of the nonflow correlations come from decays involving two particles, a large fraction of the nonflow is already removed when using the fourth order estimate for elliptic flow. Each of the estimates of v_2 from the different order cumulants is independent of the others. Agreement between these estimates in a measurement increases the reliability of the result. The different order cumulants for the second harmonic, $c_2\{n\}$, can be found from the flow vector $\mathbf{Q}$ in the following way (Equations 30 and 33 from [61])

$$c_2\{2\} = \left\langle \frac{|\mathbf{Q}|^2 - M}{M(M-1)} \right\rangle_e, \quad (4.17)$$

$$c_2\{4\} = \left\langle \frac{|\mathbf{Q}|^4 + |\mathbf{Q}_4|^2 - 2 \text{Re}[\mathbf{Q}_4 \mathbf{Q}^* \mathbf{Q}^*] - 4(M-2)|\mathbf{Q}|^2}{M(M-1)(M-2)(M-3)} + \frac{2}{(M-1)(M-2)} \right\rangle_e - 2(c_2\{2\})^2.$$

While $\mathbf{Q}$ is the flow vector associated with v_2 , $\mathbf{Q}_4$ is the flow vector corresponding to the fourth harmonic v_4 . Including this term removes the interference from v_4 in the v_2 measurement.

Cumulants of odd orders, like $c_2\{3\}$, vanish in the average over many events because they include a factor $\langle \cos \Psi_R \rangle_e$ which is zero for a detector with perfect acceptance. For

cumulants of even order such dependence on the reaction plane angle is cancelled out. Only these even cumulants $c_2\{2k\}$ (k is an integer) are therefore of interest in the analysis. The cumulants are calculated such that auto-correlations are not included and lower order correlations are subtracted. In calculating the average over events each event is weighted with the number of possible two or four particle combinations. With such weights the effect of multiplicity fluctuations is severely reduced [61].

The different order estimates of elliptic flow can be calculated from these cumulants (Equation 24 and 25 from [61])

$$v_2\{2\} = \sqrt{c_2\{2\}} \quad \text{and} \quad v_2\{4\} = \sqrt[4]{-c_2\{4\}}. \quad (4.18)$$

The above description of the method is valid for a perfect detector. For a real detector the same correction techniques can be applied as described for the scalar product method in the previous section.

As already mentioned, nonflow adds to the measurement of v_2 and cannot be calculated analytically. It is therefore usually represented by δ_m . The second order estimate $v_2\{2\}$ is influenced by δ_2 , while the fourth order estimate is only influenced by δ_4 , because lower order nonflow is suppressed in the cumulant method. The contribution of δ_2 to the cumulant $c_2\{2\}$ has strength $1/(M-1)$, while the contribution of δ_4 to the cumulant $c_2\{4\}$ has strength $1/((M-1)(M-3))$ [62], which gives a contribution to $v_2\{4\}$ which is smaller than the contribution of δ_2 to $v_2\{2\}$.

With respect to fluctuations in the value of v_2 different order cumulants are affected differently. The second order cumulant overestimates the flow signal in the presence of fluctuations, while the fourth order underestimates it. The combined effect of nonflow and fluctuations on the second and fourth order estimate of v_2 are given by

$$\begin{aligned} v_2\{2\}^2 &= \langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta_2, \\ v_2\{4\}^2 &= \left(2 \langle v_2^2 \rangle^2 - \langle v_2^4 \rangle \right)^{\frac{1}{2}} = \langle v_2 \rangle^2 - \sigma_{v_2}^2 + \delta_4. \end{aligned} \quad (4.19)$$

The term due to fluctuations was derived from a Taylor series expansion (up to the second order in σ_{v_2}) with the assumption that σ_{v_2} is much smaller than v_2 [63]. The equation for $v_2\{4\}$ applies to all multi-particle estimates. The true elliptic flow value is found in-between the upper and lower limits given by the 2-particle and multi-particle estimates. Unfortunately the effect of nonflow and flow fluctuations cannot be disentangled by combining the second and fourth order cumulants [64] as the difference between them is $2\sigma_{v_2}^2 + \delta_2 - \delta_4$. In practise only upper and lower limits can be given by using different order cumulants in parallel.

4.3 Lee–Yang zeroes method

Compared to the scalar product method the cumulants have the advantage that nonflow of lower orders is removed. The fact that all lower orders are removed implies that for reducing nonflow it is best to go to high orders. This is provided by the Lee–Yang zeroes method, which is the equivalent of the infinite order cumulant. In the Lee–Yang zeroes

method [65–67] all particles in the event are correlated with each other. The method is inspired by the theory of phase transitions published in 1952 by Lee and Yang [68].

They have used the concept of generating functions to study the correlations between many particles. Generating functions are an ideal tool to find the members of an unknown sequence. The generating function is a simple formula for the sum of a power series and its coefficients are the unknown sequence. Generating functions can also give approximate answers for the asymptotic behaviour of a sequence, in cases where exact answers are very difficult to obtain.

It is this latter property of generating functions that is used in the Lee–Yang zeroes method to estimate the correlations between all particles in an event. For a comprehensive review on generating functions see [69].

To study elliptic flow the following generating function is chosen (Equation 3 from [66])

$$G(z) = \langle g^\theta(z) \rangle_e \equiv \langle e^{zQ^\theta} \rangle_e, \quad (4.20)$$

where z is a complex variable and Q^θ a projection of the flow vector $\mathbf{Q}$ on an arbitrary reference direction 2θ with respect to the x -axis (Equation 2 from [66])

$$Q^\theta = Q_x \cos(2\theta) + Q_y \sin(2\theta). \quad (4.21)$$

The generating function generates the cumulants c_k (Equation 4 from [66])

$$\ln G(z) \equiv \sum_{k=1}^{\infty} \frac{c_k}{k!} z^k. \quad (4.22)$$

The first two terms in this power series expansion give the average and variance of Q^θ (Equation 5 from [66])

$$c_1 = \langle Q^\theta \rangle_e \quad \text{and} \quad c_2 = \langle (Q^\theta)^2 \rangle_e - \langle Q^\theta \rangle_e^2. \quad (4.23)$$

These cumulants c_k scale with M^k in the presence of elliptic flow while they scale with M when no collectivity is present. For large k the contribution due to elliptic flow is thus large compared to other contributions. The asymptotic behaviour of c_k for large k is determined by the radius of convergence of the power series expansion of Equation 4.22. This means it is determined by the singularity of $\ln G(z)$ which lies closest to the origin in the complex plane. The singularities of $\ln G(z)$ are the zeroes of $G(z)$.

When elliptic flow is present in a system the averages can be evaluated with respect to the reaction plane which gives (Equation 9 from [66])

$$c_1 = \langle Q^\theta | \Psi_R \rangle_e = Mv_2 \cos(2(\Psi_R - \theta)). \quad (4.24)$$

In the central limit approximation, when M is large, the probability distribution of Q^θ is Gaussian for fixed Ψ_R which means terms c_3 and higher can be neglected. The generating function with respect to Ψ_R can then be written as (Equation 21 from [65])

$$\langle e^{zQ^\theta} | \Psi_R \rangle_e = e^{c_2 z^2 / 2 + Mv_2 z \cos(2(\Psi_R - \theta))}. \quad (4.25)$$

Averaging over Ψ_R , assuming that c_2 is independent of Ψ_R , gives a theoretical expression for $G(z)$ (Equation 10 from [66]), denoted by $G_{cl}(z)$ because it corresponds to the central limit approximation,

$$G_{cl}(z) = e^{c_2 z^2/2} I_0(Mv_2 z), \quad (4.26)$$

where I_0 is the modified Bessel function. The first zeroes of $G_{cl}(z)$ lie on the imaginary axis at (Equation 11 from [66])

$$z_0 = ir_0 = i \frac{j_{01}}{Mv_2}, \quad (4.27)$$

and at $-z_0$. Here $j_{01} \approx 2.405$ is the first positive root of the Bessel function $J_0(x)$. Clearly, elliptic flow v_2 is completely determined by z_0 .

By identifying $G(z)$ with $G_{cl}(z)$, an estimate of v_2 can now be found (Equation 12 from [66])

$$v_2^\theta = \frac{j_{01}}{Mr_0^\theta}, \quad (4.28)$$

where the superscript indicates that the estimate might depend on θ .

The first zero r_0^θ is found from the first minimum of $|G(z)|^2$ and not from $G(z)$ because, due to statistical fluctuations, the zeroes of $G(z)$ are slightly off the imaginary axis.

In [65] the authors show that if the analysis is performed for several equally spaced values of θ the final statistical error is reduced by a factor of almost 2, because the projections are not necessarily strongly correlated. Although the reduction is maximal in the case when θ goes to infinity, they show that in practise 5 projections are sufficient.

The final estimate of v_2 , $v_2\{LYZ\}$, is obtained by averaging over v_2^θ . For a perfect detector r_0^θ is independent of θ because of the azimuthal symmetry. Averaging over several values of θ washes out the effect of detector inefficiencies.

An alternative generating function can also be used (Equation 3 from [67])

$$G^\theta(ir) \equiv \left\langle \prod_{j=1}^M [1 + ir \cos(2(\varphi_j - \theta))] \right\rangle_e. \quad (4.29)$$

This is called the *product generating function*, while the generating function in Equation 4.20 is called the *sum generating function*.

These two generating functions have the same zeroes. The modulus of the generating function has a value of 1 for $r = 0$, it then decreases and oscillates, as is illustrated in Figure 4.2 for Monte Carlo events with $v_2 = 0.05$ and $M = 900$. The first minimum in the figure is r_0^θ . The product generating function, illustrated here, becomes unstable due to numerical fluctuations, this does not happen in case of the sum generating function.

In practise the range of r for which $G(z)$ is calculated should be chosen small to save on computing time, especially for the product generating function, however it should be large enough to include the first minimum, which means its range should be tuned during the analysis.

The correction needed for auto-correlations for the sum generating function is very small and need not be applied. In case of the product generating function auto-correlations are

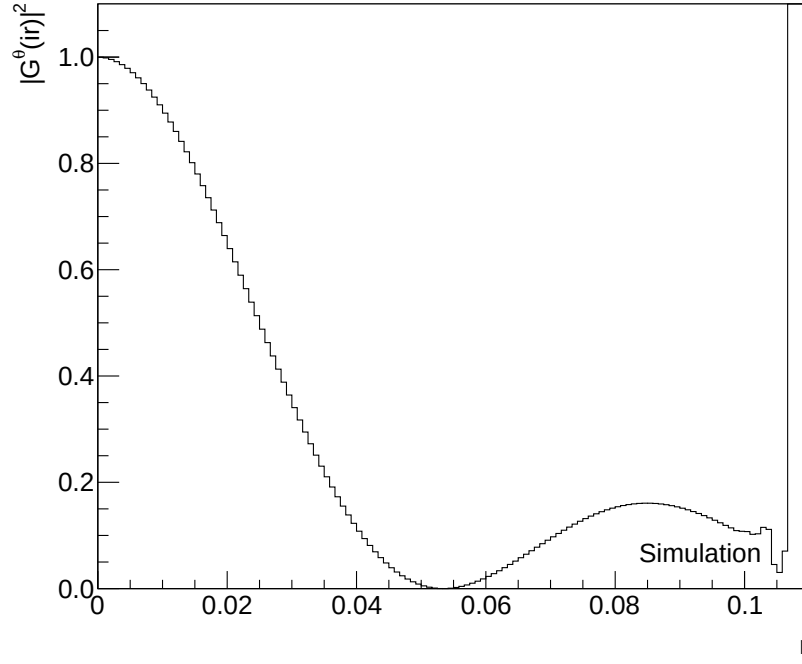


Figure 4.2: The modulus squared of the product generating function for simple Monte Carlo events with $v_2 = 0.05$ and $M = 900$. The data set consists of 10^6 events. The modulus has a value of 1 for $r = 0$, it then decreases and oscillates before it becomes unstable due to numerical fluctuations. The first zero $r_0^\theta = 0.053$, which corresponds to the input elliptic flow value according to Equation 4.28.

not present. The product generating function is therefore expected to give more accurate results when nonflow correlations are weak. However, it requires more computing time and in the presence of strong nonflow correlations it is no improvement over the sum generating function [65].

Differential elliptic flow $v_2(p_t, \eta)$ can be calculated with the knowledge of r_0^θ in a second loop over the events from the following equations

$$\frac{v_2^\theta(p_t, \eta)}{v_2^\theta M} = \text{Re} \left(\frac{\left\langle \left\langle \cos(2(\varphi - \theta)) e^{ir_0^\theta Q^\theta} \right\rangle_p \right\rangle_e}{\left\langle Q^\theta e^{ir_0^\theta Q^\theta} \right\rangle_e} \right), \quad (4.30)$$

for the sum generator function (Equation 12 from [65]) and

$$\frac{v_2^\theta(p_t, \eta)}{v_2^\theta M} = \text{Re} \left(\frac{\left\langle \left\langle g^\theta(ir_0^\theta) \frac{\cos(2(\varphi - \theta))}{1 + ir_0^\theta \cos(2(\varphi - \theta))} \right\rangle_p \right\rangle_e}{\left\langle \frac{dg^\theta(ir)}{d(ir)} \text{ at } r=r_0^\theta \right\rangle_e} \right), \quad (4.31)$$

for the product generating function (Equation 9 from [67]).

In the estimate of $v_2(p_t, \eta)$ provided by the Lee–Yang zeroes method the contribution from nonflow correlations is maximally suppressed, detector acceptance effects are corrected for and auto-correlations are not included. The main limitation of the Lee–Yang zeroes method is its statistical error. It depends strongly on the inverse of the resolution parameter

$$\chi \approx v_2 \sqrt{M}. \quad (4.32)$$

Equation 62 from [65] gives a more precise definition of χ . In order to maximise χ , and minimise the statistical error, as many particles as possible should be used for each event in the analysis.

4.4 An event plane estimate without nonflow effects

Besides the analysis of anisotropic flow other observables like particle spectra, HBT radii and jets can be studied as a function of the reaction plane. The event plane given by the event plane method is often used for these analysis. Such an analysis is, however, biased by nonflow.

The Lee–Yang zeroes method can also provide an estimate of the reaction plane [70]. It can be recast in a form similar to the event-plane method (Equation 3 from [70])

$$v_2\{\text{LYZ}\} = \left\langle \left\langle W_R \cos(2(\varphi - \Psi_R)) \right\rangle_P \right\rangle_e. \quad (4.33)$$

Here Ψ_R is the event plane and W_R is the event weight. This event weight depends on the length of the flow vector. By using the event weight both auto-correlations and nonflow effects are automatically removed. First, one has to calculate r_0^θ as described in the previous section. With the knowledge of r_0^θ and the sum generating function the event plane Ψ_R and event weight W_R are found from the following complex number (Equation A1 from [70])

$$D^\theta = \frac{r_0^\theta}{j_{01}} \left\langle Q^\theta e^{ir_0^\theta Q^\theta} \right\rangle_e = \frac{\left\langle \frac{d g^\theta(ir)}{d(ir)} \text{ at } r=r_0^\theta \right\rangle_e}{V_2^\theta}. \quad (4.34)$$

For each event W_R and Ψ_R are defined by (Equation A2 from [70]),

$$\begin{aligned} W_R \cos(2\Psi_R) &= \left\langle \text{Re} \left(\frac{e^{ir_0^\theta Q^\theta}}{D^\theta} \right) \cos(2\theta) \right\rangle_\theta, \\ W_R \sin(2\Psi_R) &= \left\langle \text{Re} \left(\frac{e^{ir_0^\theta Q^\theta}}{D^\theta} \right) \sin(2\theta) \right\rangle_\theta. \end{aligned} \quad (4.35)$$

The angular brackets denote an average over θ . Note that the value of Ψ_R depends on the sign chosen for W_R . But, because changing the sign of W_R amounts to shifting the angle $2\Psi_R$ by π , that choice does not affect the value of v_2 from Equation 4.33.

The probability distribution of $\mathbf{Q}$ is a narrow peak centred at v_2 when $\chi \gg 1$, the event weight is then close to one for all events. If χ is smaller the distribution will be broader and the event weight is negative for some events. These negative weights are needed to subtract the nonflow contribution. Because they also subtract part of the flow signal the global normalisation of the weight increases as χ decreases. Figure 4.3 shows the event weight W_R as a function of the length of the flow vector $\mathbf{Q}$ (solid line) together with the probability distribution of $\mathbf{Q}$ (dashed line) for two realistic values of the resolution parameter χ . The figure shows clearly that the probability distribution of $\mathbf{Q}$ is more peaked for the higher χ and the weights are smaller.

The advantage of this method is that with using the event weight all nonflow correlations are removed. The disadvantage is that at least two passes over the data are needed.

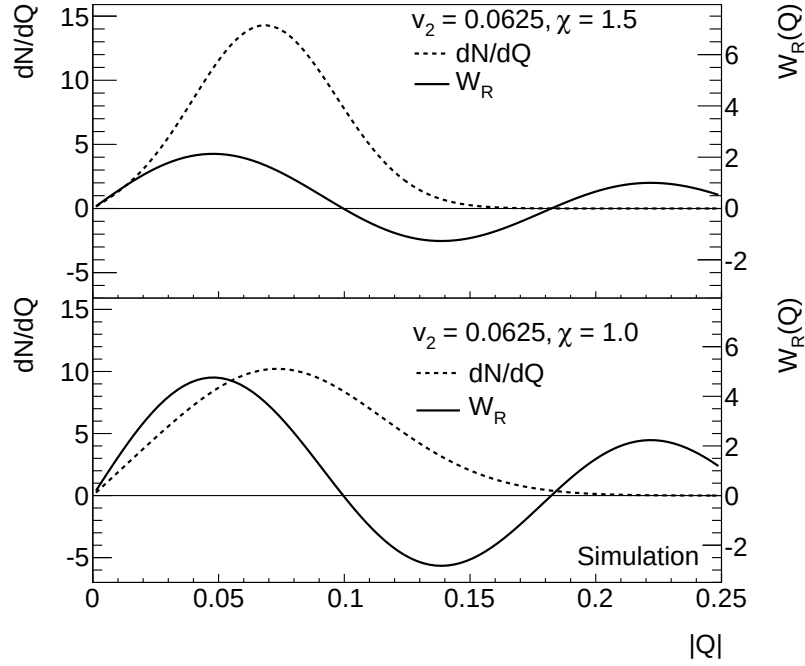


Figure 4.3: The probability distribution of Q (dashed line), and the event weight W_R (solid line) for $v_2 = 0.0625$ for two values of χ : top $\chi = 1.5$, bottom $\chi = 1.0$. These distributions are calculated using Equation 6 and 15 from [70].

4.5 Analysis software

The analysis methods have all been implemented within one common library within the ALICE analysis framework AliRoot. From the Event Summary Data (ESD) events and tracks are selected for the analysis (see Section 5.1.1) and their kinematic information (p_t , η and φ) is stored in a simpler object called the *flowevent*. This flowevent serves as input to the analysis code enabling a simultaneous analysis with different analysis methods on one common input. All final output histograms have a standard range and bin size which allows the direct comparison of the results of the different analysis methods.

4.6 Validation using Monte Carlo simulations

The analysis code has been validated with the help of Monte Carlo simulations of heavy ion collisions. The THERMINATOR [71] program (THERMal heavy-IoN generATOR) simulates realistic Pb-Pb events that include all known stable particles and unstable resonances, but no hard scattering processes. The THERMINATOR model assumes that the matter produced in the collision is in thermal equilibrium and that the chemical and kinetic freeze-out occur at the same temperature. At this single freeze-out particle abundances are determined by the temperature and baryon chemical potential via the Cooper-Frye formalism [72]. Particle velocities are composed of thermal motion and collective expansion of the system based on the blastwave model [73,74]. This means elliptic flow is automatically included in events generated with THERMINATOR.

In order to compare the result of the analysis methods to the true generated elliptic flow and confirm that they correctly reproduce this value, a method was added to the flow

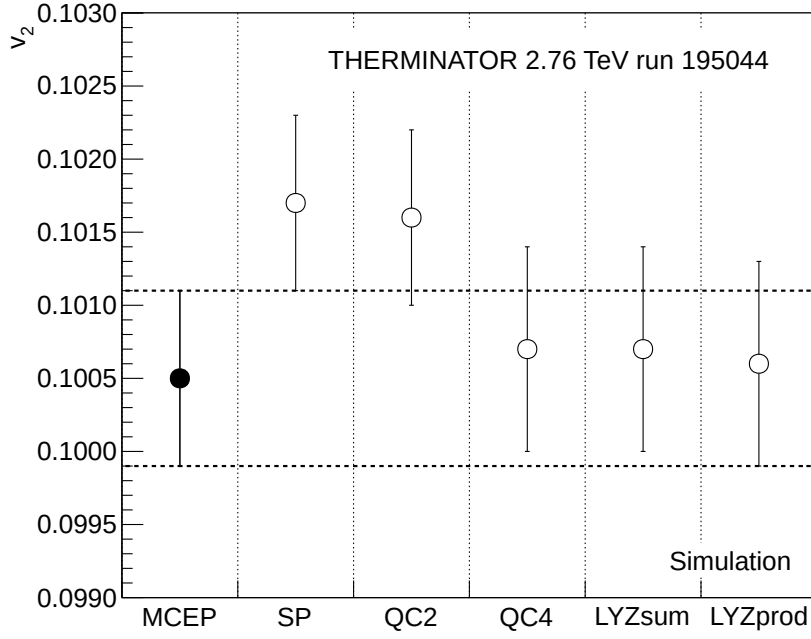


Figure 4.4: Estimates of v_2 from different analysis methods indicated on the x -axis (see text) for Monte Carlo Pb-Pb data at 2.76 TeV. MCEP gives the reference directly calculated from the Monte Carlo truth.

analysis code which calculates v_2 directly from Equation 4.1,

$$v_2\{\text{MCEP}\} = \left\langle \left\langle \cos(2(\varphi_i - \Psi_{\text{MC}})_p) \right\rangle_p \right\rangle_e. \quad (4.36)$$

Here Ψ_{MC} is the reaction plane angle as given for each event by the Monte Carlo generator. Figure 4.4 shows the, over p_t and η , integrated elliptic flow of all the available methods together with $v_2\{\text{MCEP}\}$ on 1854 Monte Carlo Pb-Pb events generated with THERMINATOR. The analysis methods are indicated on the x -axis: SP for scalar product, QC2 for the second order cumulant method, QC4 for the fourth order cumulant method, LYZsum for the Lee–Yang zeroes method with the sum generating function and LYZprod for the Lee–Yang zeroes method with the product generating function. Because the elliptic flow in these events is high and the multiplicity as well (the average multiplicity is 720), multi-particle methods reproduce the input and the 2-particle methods only slightly overestimate. The nonflow component is small for these events, it consists of correlations due to decays, but does not include jets.

In Figure 4.5 the differential elliptic flow is shown for the scalar product method (circles) and the Lee–Yang zeroes methods (triangles), together with the true input elliptic flow (grey band). Both analysis methods reproduce the input which validates their implementation in the ALICE analysis software. Not shown are the second and fourth order cumulant results. The second order cumulant gives a similar result as the scalar product method, while the fourth order cumulant coincides with the Lee–Yang zeroes results.

4.6.1 Applicability of the analysis methods

A more detailed study of the applicability of the different methods is done using a much simpler simulation model. It does not simulate realistic physics events but its

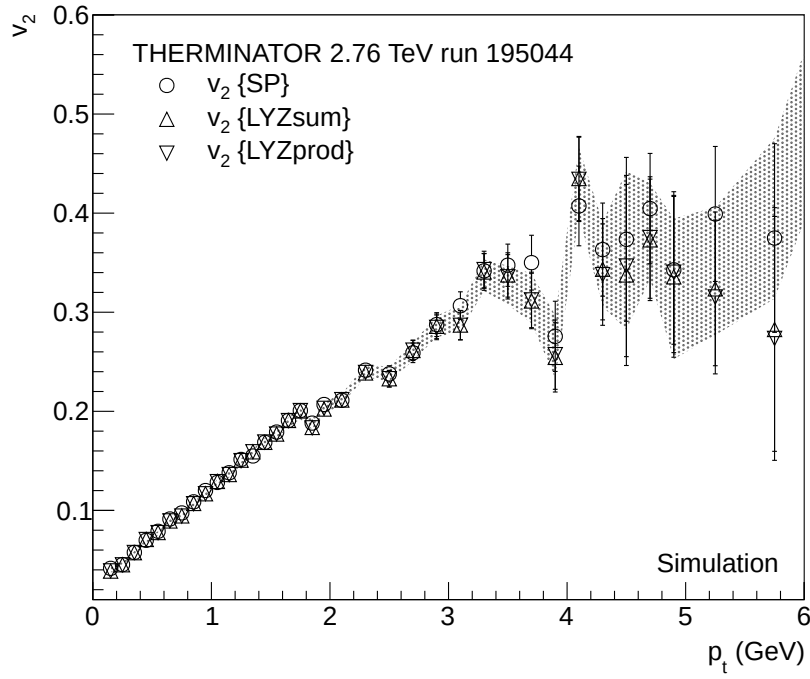


Figure 4.5: Estimates of $v_2(p_t)$ for Monte Carlo Pb-Pb data at 2.76 TeV from the scalar product method, $v_2\{\text{SP}\}$ (circles), and the Lee–Yang zeroes methods, $v_2\{\text{LYZsum}\}$ (triangles pointing up) and $v_2\{\text{LYZprod}\}$ (triangles pointing down), compared to $v_2\{\text{MCEP}\}$ (grey band). Not shown are $v_2\{\text{QC2}\}$ and $v_2\{\text{QC4}\}$ which are similar to, respectively, $v_2\{\text{SP}\}$, and $v_2\{\text{LYZsum}\}$ and $v_2\{\text{LYZprod}\}$.

events contain precisely known correlations which makes it a valuable tool to find the circumstances in which the various analysis methods will fail. Events are simulated by sampling tracks from the azimuthal distribution described in Equation 2.1 where the transverse momentum follows a Boltzmann distribution, and the multiplicity and elliptic flow value are given as input parameters. The applicability of an analysis method depends on the systematic and statistical errors associated with that method.

Systematic errors

The systematic error arises from how well elliptic flow can be distinguished from nonflow and a random distribution of particles that do not participate in the collective flow. The Lee–Yang Zeroes method produces a spurious flow in the absence of elliptic flow correlations. This spurious value depends on the average number of particles q that are correlated with each other (Equation 46 from [65]), $v_2 = q/M$, where M is the multiplicity. Even for independent particle emission, $q = 1$, the method yields a value for v_2 . This means that v_2 can only be measured if $v_2 \gg 1/M$. This restriction on v_2 due to nonflow correlations is more strict for methods which correlate less particles. For $v_2\{4\}$ it should be larger than $(1/M)^{3/4}$ and for $v_2\{2\}$ much larger than $(1/M)^{1/2}$ to be measurable (Equation 19 from [60]). The 2-particle methods have the largest systematic error due to nonflow correlations, while this error is minimal for the Lee–Yang zeroes method. In the case of Pb-Pb collisions these limits become important for very central events, where v_2 is small, and peripheral events where the multiplicity is small. For proton-proton collisions these limits really restrict the analysis, as the multiplicity is low and most likely elliptic flow is absent.

Statistical errors

The statistical error depends, besides of course on the number of events in the sample, on the relative strength of the elliptic flow compared to the fluctuations due to a finite multiplicity characterised by the resolution parameter χ (see Equation 4.32). This poses another restriction on the applicability of the analysis methods. The resolution parameter χ has a value typically between 0.5 and 2.5. For the Lee–Yang zeroes method the statistical error grows fastest as it depends exponentially on $1/\chi$. It is therefore important to use as many particles as possible in constructing the flow vector $\mathbf{Q}$ to maximise χ . Also properly chosen weights can maximise χ . The minimum value of χ where the method can still safely reconstruct elliptic flow is calculated in [65] (Equation 80) to be

$$\chi_0 = \frac{j_{01}}{\sqrt{2 \ln N}}, \quad (4.37)$$

55

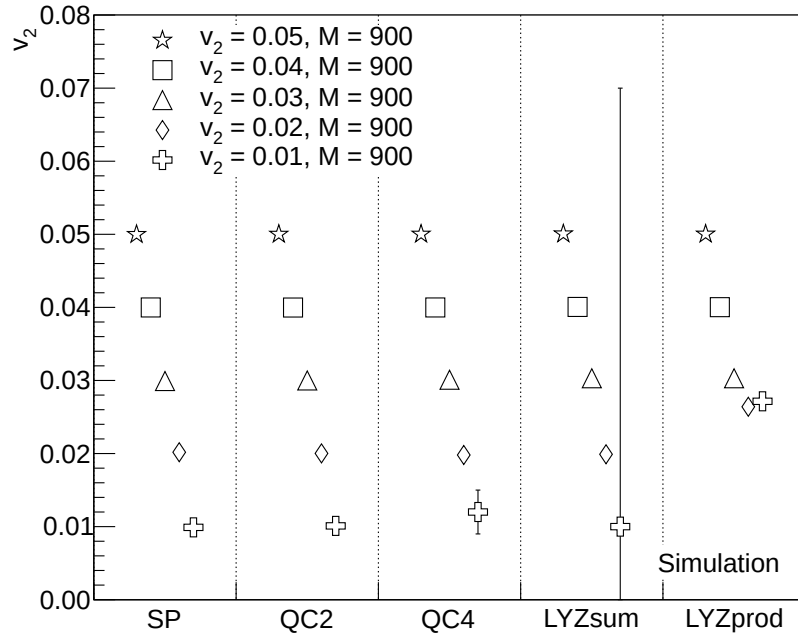
where N is the number of events in the sample and $j_{01} \approx 2.405$ is the first root of the spherical Bessel function $J_0(x)$. The cumulant method and the scalar product method have a smaller statistical error, where that from the 2-particle methods is smallest. The statistical error for the cumulants scales with $1/\sqrt{NM}v_2$ (Equation 78 from [61]). In the presence of large fluctuations due to the finite multiplicity, especially when the elliptic flow as well as the multiplicity are small, the cumulants can have the wrong sign, which means that particular cumulant cannot be used to estimate v_2 . A wrong sign of the cumulants can also be caused by dominant nonflow correlations.

Results from the simple simulation

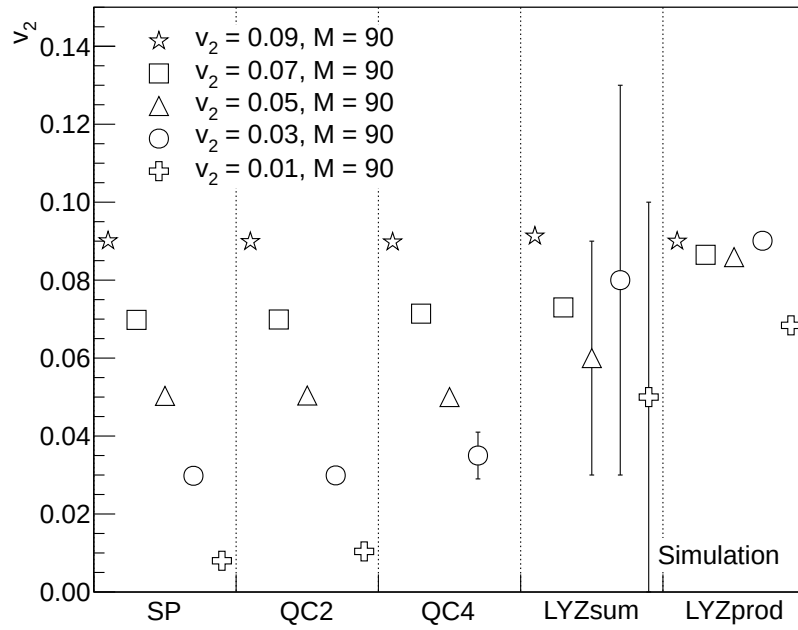
Figure 4.6 shows the analysis results on simulated events with an increasing value for the integrated elliptic flow at fixed input multiplicity for two different multiplicities, 10^6 events with 900 particles (a) and 10^6 events with 90 particles (b).

The scalar product method and the second order cumulant method reproduce the input v_2 for all tested combinations of v_2 and M . This is expected as they do not suffer much from low statistics and there was no nonflow in the events. The fourth order cumulant only fails at the lowest v_2 and M . The Lee–Yang zeroes method with the sum generating function does well for the high multiplicity, where only for the lowest value of v_2 the statistical error blows up. For this data point indeed χ is only 0.3, which is too low for a reliable result. For the low multiplicity χ is below 0.7 for all data points except for the highest value of v_2 . The errors are therefore large, but the input values are still within one standard deviation of the measured values.

The Lee–Yang zeroes method with the product generating function however, does not perform so well when the multiplicity is low or when v_2 is low. This is due to the modulus of the generating function blowing up before the true first minimum is reached. This results in a too high measured v_2 due to a minimum caused by large fluctuations in the generating function, as can be clearly seen in Figure 4.7 which shows the modulus squared of the product generating function for events with $v_2 = 0.03$ and $M = 90$. The value of r where the product generating function blows up depends on the multiplicity of the events and is independent of the value of v_2 .



a)



b)

Figure 4.6: Estimates of v_2 from different analysis methods indicated on the x -axis for decreasing input v_2 at two different multiplicities M .

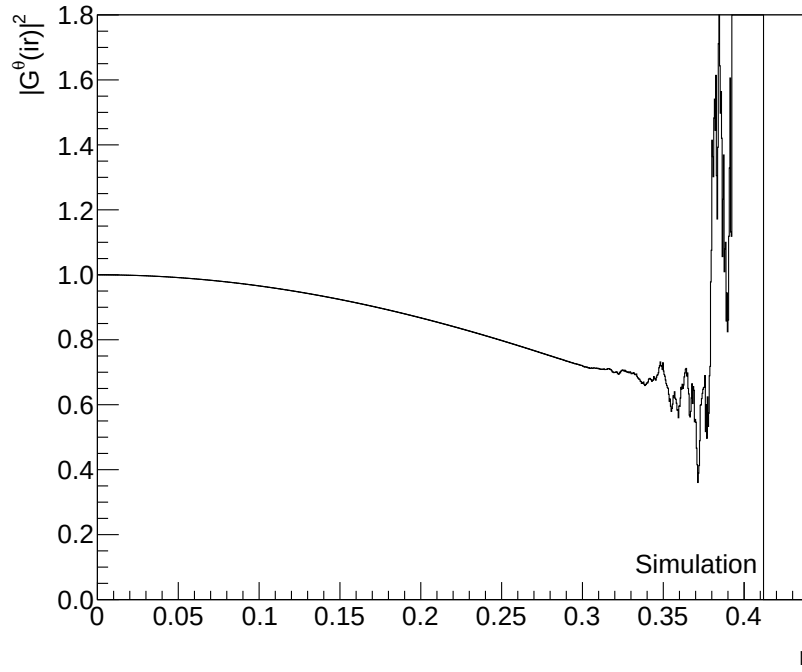


Figure 4.7: The modulus squared of the product generating function for events with $v_2 = 0.03$ and $M = 90$. The function blows up before the first minimum, expected at $r = 0.89$, is reached.

Results for a fixed elliptic flow value and a varying multiplicity are shown in Figure 4.8. For low multiplicities again errors for the multi-particle methods start to increase, for the Lee–Yang zeroes method sooner than for the fourth order cumulant method. This shows, together with the previous two figures that multi-particle methods cannot be used on events with a low multiplicity and a low value of v_2 , such as peripheral Pb–Pb or proton–proton events and confirms the described behaviour of the statistical errors which are largest for the Lee–Yang zeroes method.

The behaviour in the presence of fluctuations in the elliptic flow value is studied by varying the input value of v_2 event by event from a Gaussian distribution. The width of this distribution is varied in Figure 4.9. In accordance with Equation 4.19, the estimates from the 2-particle methods increase while the estimates from multi-particle methods decrease due to the fluctuations. The calculated values from Equation 4.19 are indicated in the figure with dotted lines. Clearly Equation 4.19 is not valid anymore for the largest fluctuation, as it was derived under the assumption that the fluctuation in v_2 is much smaller than v_2 itself.

Fluctuations in the multiplicity of the events are studied in the same way and are shown in Figure 4.10. Because in a sample of real events the multiplicity is not constant it is important that analysis methods are not influenced too much by this variation. The figure shows that this is indeed the case, save for the Lee–Yang zeroes by the largest multiplicity variation. Elliptic flow analysis on Pb–Pb events is done in centrality bins, which in practise means multiplicity bins. As long as those multiplicity bins are not too wide all analysis methods can be used.

Nonflow is added to the generated events by doubling the tracks such that each track occurs twice in the event. This is an extreme case of nonflow, and is not realistic in the sense that in real events not every particle takes part in nonflow correlations and that

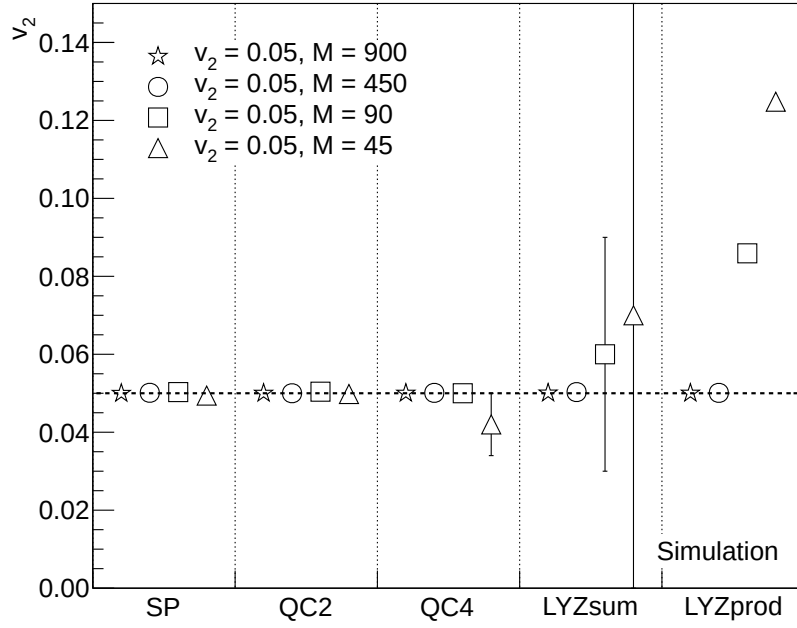


Figure 4.8: Estimates of v_2 from different analysis methods indicated on the x -axis for decreasing input multiplicity and fixed v_2 .

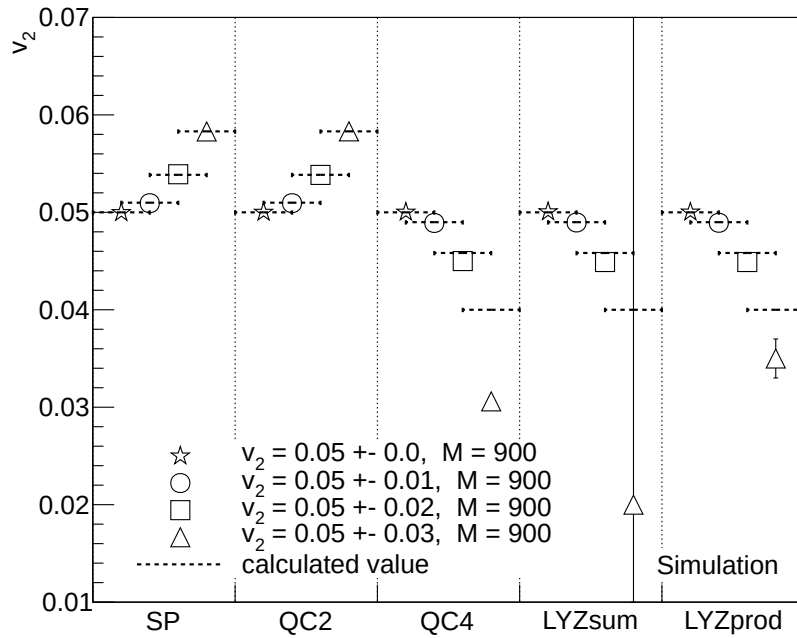


Figure 4.9: Estimates of v_2 from different analysis methods indicated on the x -axis for increasing width of the Gaussian input v_2 distribution at fixed multiplicity. The values calculated from Equation 4.19 are indicated with dotted lines.

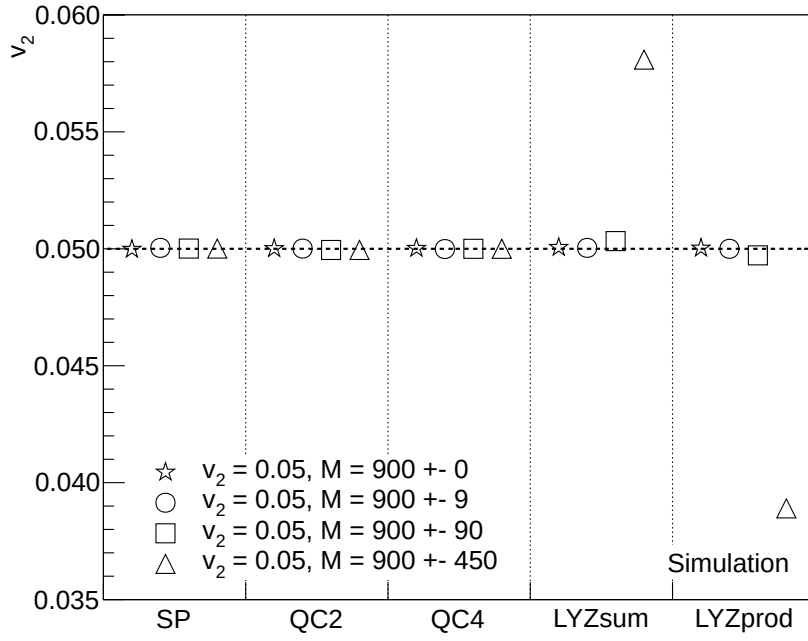


Figure 4.10: Estimates of v_2 from different analysis methods indicated on the x -axis for increasing width of the Gaussian input multiplicity distribution at fixed input v_2 .

two tracks are never exactly the same. Figure 4.11 shows the results when such nonflow is added to the events. As expected the multi-particle methods are not affected, while the second order cumulant is. The scalar product method by design suppresses small range correlations; a particle is never correlated to its replica for this extreme short range nonflow correlation. Longer range nonflow does bias the measurement (see Section 5.2.1) but the separation in pseudorapidity between the subevents can be used to reduce the nonflow contribution.

Naturally, a real detector does not have a perfectly uniform acceptance and for this the analysis methods should correct. The implemented corrections are tested by simulating events with the azimuthal angle sampled from a distribution which has two regions of reduced efficiency: 0.5 in $60^\circ < \varphi < 120^\circ$ and 0.01 in $300^\circ < \varphi < 320^\circ$. Figure 4.12 shows the results for an input elliptic flow of 0.05 and a reference particle multiplicity of 900 . All methods measure a value very close to the input which means the corrections are sufficient. The Lee–Yang zeroes method by design corrects for detector effects, as the average over the projection angle θ is taken. The cumulants and scalar product method have a correction implemented as explained Section 4.1. For the scalar product the relative deviation from the input v_2 is a bit higher compared to the other methods, but is still very small: 0.4% .

4.7 Discussion

The discussed analysis methods have different sensitivities to the presence of nonflow correlations: in multi-particle correlation methods nonflow correlations are suppressed and in the scalar product method a reduction of the nonflow contribution can be achieved by separating the subevents. They are differently influenced by fluctuations in the

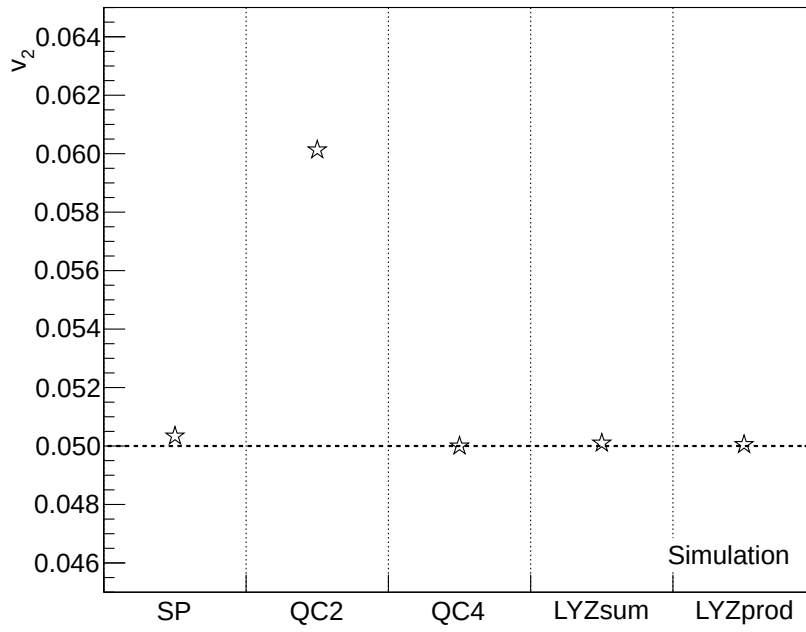


Figure 4.11: Estimates of v_2 from different analysis methods indicated on the x -axis for events with $M = 900$, $v_2 = 0.05$ and 2-particle nonflow.

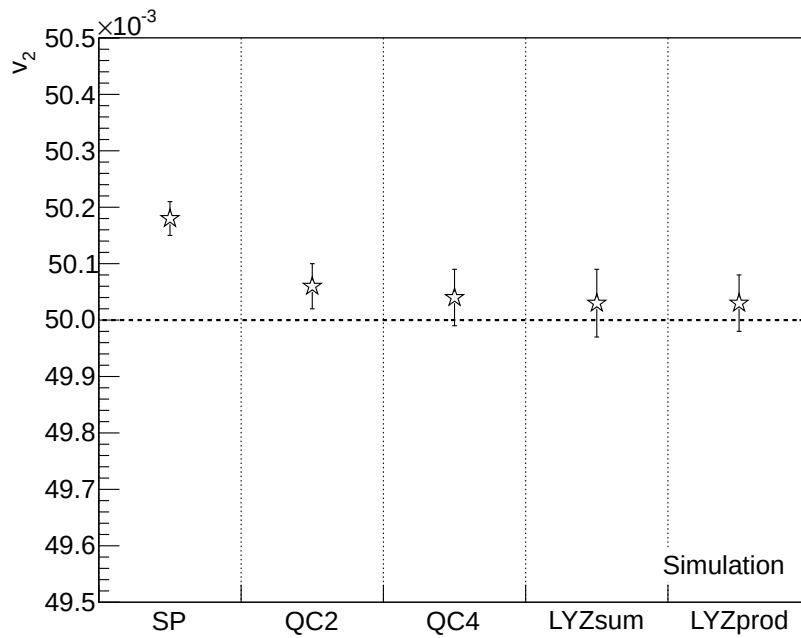


Figure 4.12: Estimates of v_2 from different analysis methods indicated on the x -axis for events with $M = 900$, $v_2 = 0.05$ and a nonuniform detector acceptance.

elliptic flow signal as well: 2-particle methods overestimate and multi-particle methods underestimate. Due to the combined effect of elliptic flow fluctuations and nonflow correlations only upper and lower limits for the elliptic flow in Pb-Pb collisions can be given (as described in Section 4.2) by combining the estimates of these different analysis methods. Although the scalar product method and the second order cumulant show the same behaviour it is beneficial to have independent estimates to check the reliability of the result.

These analysis methods have been developed and optimised for elliptic flow measurements in heavy ion collisions. The possibility of elliptic flow correlations in proton-proton collisions at the LHC is considered by many as discussed in Section 2.4. Due to the low multiplicities in proton-proton collisions the Lee–Yang zeroes methods cannot be used as is clear from Figure 4.8, unless the elliptic flow is high (see Figure 4.6b). The fourth order cumulant is less restricted by low multiplicities. For proton-proton collisions, however, the fourth order cumulant is shown to be positive in [75] which prevents a direct estimate of v_2 and is interpreted as caused by dominant nonflow correlations. In the scalar product method the short range nonflow contribution can be reduced by increasing the distance between the two subevents. This approach is chosen in this thesis to study the feasibility of elliptic flow measurements in proton-proton collisions, as described in the next chapter.



Correlations in proton-proton collisions

As discussed in Section 2.4, the energy density in proton-proton collisions at the LHC will be comparable to that of lower energy heavy ion collisions where collective behaviour has been observed. Because of this predictions have been made about the presence of elliptic flow in these proton-proton collisions. To set an upper limit on elliptic flow in proton-proton collisions at 7 TeV the scalar product method is used. The contribution of nonflow correlations to the measured 2-particle correlation is suppressed by increasing the separation between the two subevents used in this method. By suppressing the nonflow contribution smaller values of v_2 can be observed or excluded.

5.1 Data sample

The analysis has been done on run 117048 of the 7 TeV proton-proton data recorded in April 2010. In this particular run 1.5 million events were recorded.

5.1.1 Event selection

The event selection should bias the sample of events as little as possible while selecting only events that correspond to a real collision between two protons. Such collision events are selected with the help of the minimum bias trigger (see Section 3.4). This selection results in 1.36 million accepted minimum bias events in run 117048.

The selected events should have a well defined primary vertex: the position where the collision has taken place. Only events with a reconstructed primary vertex with a z -component that lies within the interval $|z| < 10$ cm are accepted, because for these events the reconstructed vertex position is unambiguously correlated to the true vertex position [43]. The distribution of the z -component (along the beam pipe) of the primary vertex in the minimum bias data sample is shown in Figure 5.1 and the accepted region in indicated by the vertical lines. While this selection reduces the event sample to 1.17 million events it does not bias it.

5.1.2 Track selection

In the accepted events tracks are selected that have a high quality and correspond, with a high probability, to primary particles. Primary particles are directly produced at the primary vertex, they decay (through weak processes) into secondary particles or produce secondary particles as they interact with the material in the ALICE detector. Especially secondary particles from interactions with the detector should be removed from the analysis as they represent the detector configuration and would make the analysis detector dependent.

Standard ALICE quality track cuts are applied to guarantee tracks that are reconstructed with high accuracy by the tracking algorithm (see Section 3.4). These cut parameters and their values are summarised in Table 5.1.

Tracks are only accepted when they are fitted to at least 80 of the 160 clusters in the TPC. The χ^2 per TPC cluster of the resulting fit should be less than 4 to reject tracks which are, nevertheless, badly fitted. A minimum of two of the six clusters in the ITS is requested as

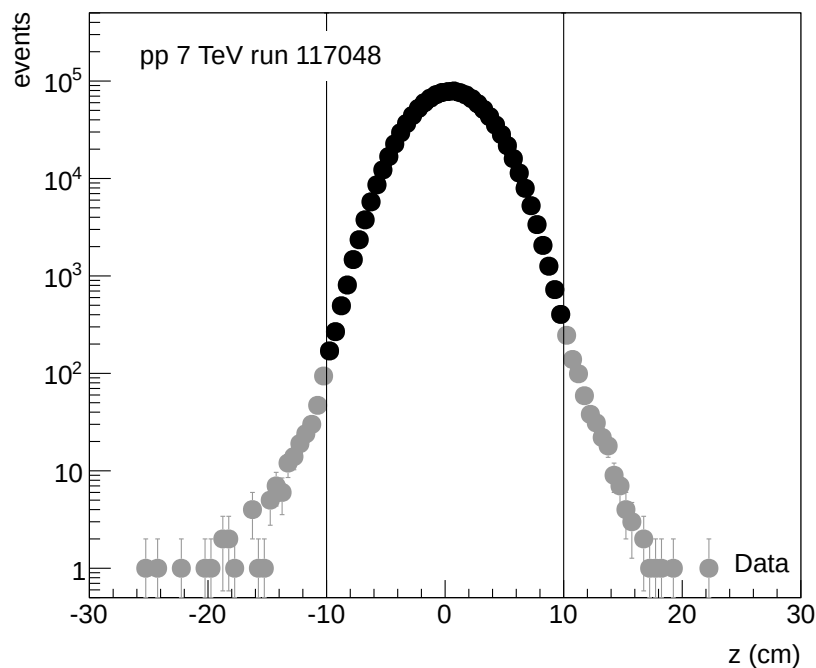


Figure 5.1: The z -coordinate of the position of the primary vertex for proton-proton data at 7 TeV. Events with a reconstructed vertex in the interval $|z| < 10$ cm (black points), indicated by two vertical lines, are accepted for analysis.

Table 5.1: Track cut parameters and their standard ALICE values

Track cut parameter	value
Number of TPC clusters per track	≥ 80
χ^2 per TPC cluster	< 4.0
Number of ITS clusters per track	≥ 2
TPC refit	true
ITS refit	true
Distance to vertex (DCA) xy	< 2.4 cm
Distance to vertex (DCA) z	< 3.2 cm

tracks that include clusters in the ITS can be better extrapolated to the vertex, such that their distance of closest approach (DCA) to the primary vertex is more precise.

To get the best parameters for the tracks both the TPC refit and the ITS refit bits were requested, this means that the tracks could be refitted in the final fitting pass (see Section 3.4.3). The ITS refit needs two clusters in the ITS, so that cut overlaps with requesting at least two clusters. Similarly, requesting the TPC refit overlaps partially with the request of at least 80 TPC clusters. Tracks which only have ITS clusters associated to them and no TPC clusters, called ITS only tracks, are removed by the TPC refit requirement.

Requesting ITS clusters in a track reduces the fraction of secondary tracks in the sample because many secondaries originate from the material between the ITS and TPC.

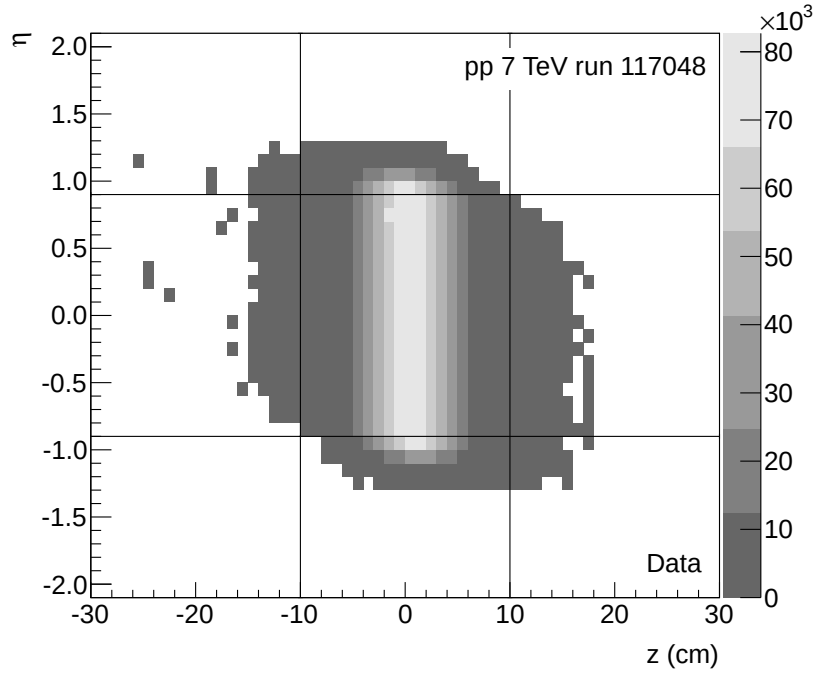


Figure 5.2: Pseudorapidity η as a function of the z -coordinate of the primary vertex for proton-proton data at 7 TeV. The two horizontal and vertical lines indicate the used cut values to exclude geometric acceptance effects.

The fraction of secondaries can be further reduced by cutting on the track DCA as a primary particle will pass much closer to the reconstructed interaction vertex than a secondary particle. For the analysis described in this thesis a cut on the DCA does not influence the measurement, as is demonstrated in Section 5.2.3 by restricting the DCA more severely. The used cut values, 2.4 cm for the DCA in the xy -plane and 3.2 cm in the z -plane, are based on the DCA resolution of the TPC.

5.1.3 Kinematic cuts

To maximise the resolution in the elliptic flow analysis, $\chi \approx v_2 \sqrt{M}$ (see Equation 4.32 and Section 4.6.1), the number of accepted tracks should be as large as possible. Ideally, no cuts should therefore be made on kinematic variables. However, a cut on the pseudorapidity of the tracks is needed to guarantee a uniform track acceptance.

In order to compare measurement results to model predictions the acceptance of tracks should be uniform in pseudorapidity because v_2 is found from the integral over tracks in the selected pseudorapidity region. Within $|\eta| < 0.9$ the geometric acceptance is uniform as can be seen in Figure 5.2 which shows the z -coordinate of the primary vertex versus the pseudorapidity η . The accepted region is indicated with two vertical and horizontal lines.

The multiplicity distribution after all track cuts is shown in Figure 5.3. The distribution peaks at low multiplicity, but events with multiplicities up to 100 occur in this data sample (1.17 million events).

The scalar product method requires at least two tracks in each event to be able to calculate the 2-particle correlations. For this study of elliptic flow in proton-proton collisions a

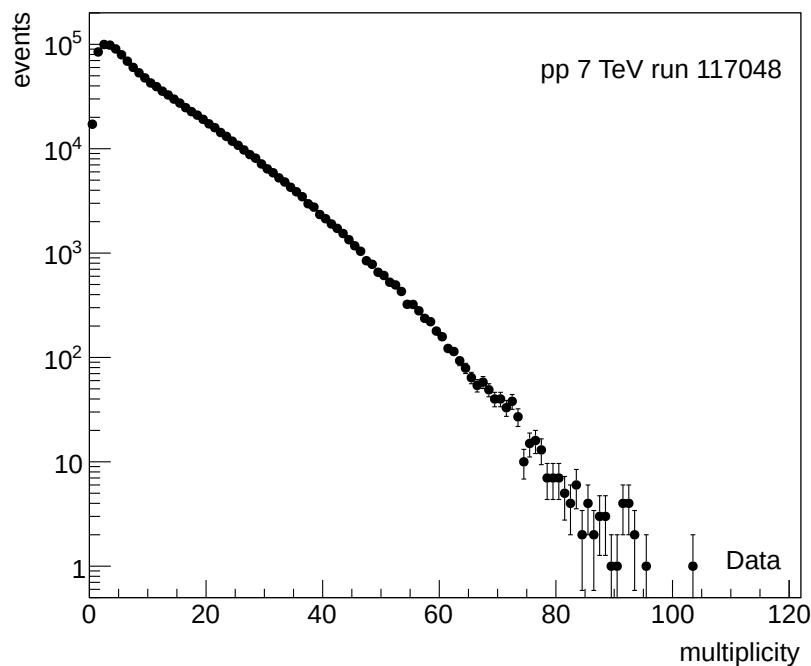


Figure 5.3: The track multiplicity distribution in proton-proton data at 7 TeV in the pseudorapidity range $|\eta| < 0.9$, after the track cuts described in the main text.

stricter cut of at least 10 accepted tracks in the events is used to guarantee the quality of the result.

5.1.4 Efficiency and purity

The efficiency of the detector to reconstruct and accept tracks in the chosen pseudorapidity range should be independent of pseudorapidity in order not to bias the elliptic flow integrated over pseudorapidity. The efficiency can be found from a Monte Carlo simulation where the generated particles can be compared to the reconstructed tracks.

The Monte Carlo data is produced centrally for the analysis in ALICE. For the simulation of proton-proton events the PYTHIA event generator [76] is used. PYTHIA contains hard and soft interactions, initial and final state parton showers, multiple scattering, fragmentation and decays. The simulated vertices in PYTHIA events are distributed according to the measured primary vertex distribution in proton-proton data and simulation parameters are tuned [77] such that the transverse momentum distribution of particles in the data is reproduced. The detector configuration at the time of data taking is used to simulate the detector response using GEANT3.

The Monte Carlo data set corresponding to run 117048 consists of 1.15 million minimum bias events of which 1.03 million pass the vertex z -coordinate cut.

Indeed the track finding efficiency is found to not depend strongly on η , as shown in Figure 5.4. The track finding efficiency is defined as the fraction of particles generated in the Monte Carlo event which are reconstructed in the detector and which pass the track selection described in the previous sections.

From the Monte Carlo data set, in which the origin of each track is known, the fraction of primary particles in the final track sample in the real data is estimated to be 89%. This

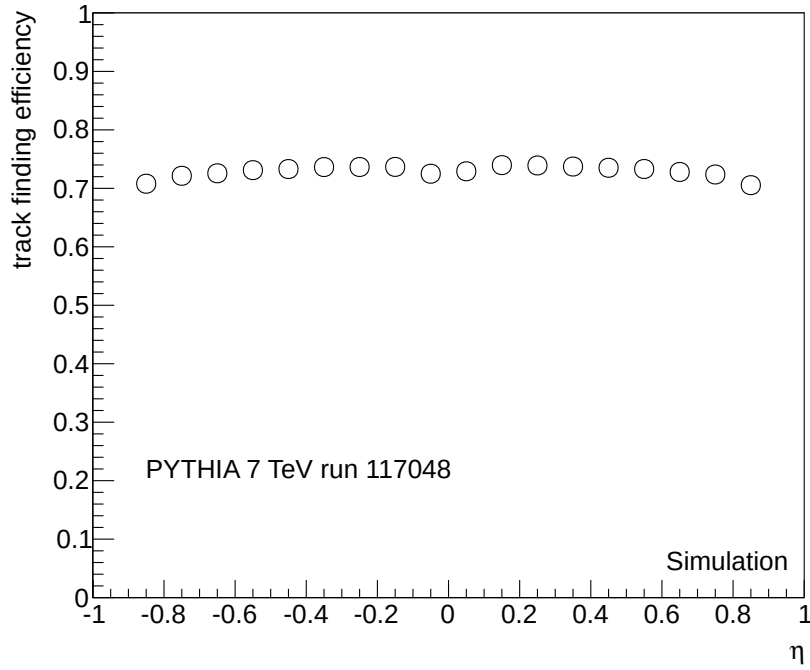


Figure 5.4: The track finding efficiency, as defined in the main text, in Monte Carlo (PYTHIA) proton-proton events at 7 TeV as a function of pseudorapidity.

fraction is called the *purity* and is defined as the number of accepted tracks corresponding to a primary particle divided by all accepted tracks. Primary tracks are generated directly in the Monte Carlo event, the secondaries are mainly due to particle decays, photon pair production and hadronic interactions with the material. In the PYTHIA Monte Carlo sample analysed the fractions of secondary particles produced by these processes are 0.67, 0.24 and 0.07 in the final accepted track sample. The remaining 0.02 come from Compton scattering, delta ray production and positron annihilation.

5.2 Correlation measurements using the scalar product method

As discussed in Section 4.7 the scalar product method is chosen to analyse correlations in proton-proton collisions. The method uses two subevent flow vectors $\mathbf{Q}_A$ and $\mathbf{Q}_B$ which yield $\mathbf{Q} = \mathbf{Q}_A + \mathbf{Q}_B$. The particles that are used to calculate these flow vectors are called *reference particles* (RP). The *particles of interest* (POI) are correlated to $\mathbf{Q}$, which gives the measurement result $v_2\{\text{SP}\}$ as a function of p_t or η of those POI.

Because particles are correlated to $\mathbf{Q}$ by the difference in azimuthal angles (see Equation 4.6), the probability distribution of Ψ_Q , the azimuthal angle of $\mathbf{Q}$, should be uniform in order not to bias the correlation. When analysing heavy ion data with a sizable elliptic flow a bias in the distribution can be corrected for, as discussed in Section 4.1, by using appropriate weights or by shifting the flow vector distribution. Those methods, however, are not applicable in the presence of strong nonflow correlations and small multiplicities like in proton-proton events (see Appendix A) and it is therefore important in this analysis to start with a uniform distribution.

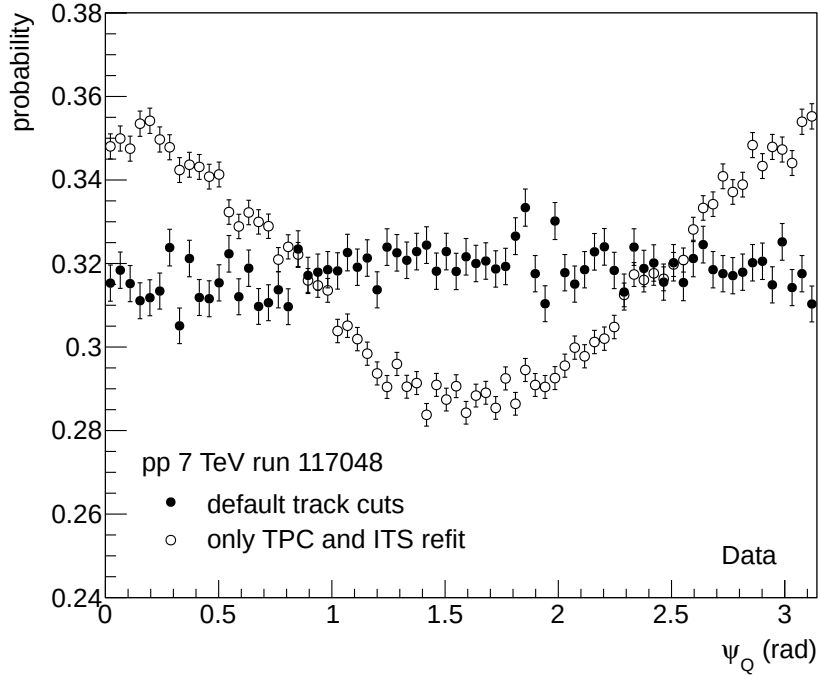


Figure 5.5: The probability distribution of the azimuthal angle of the flow vector, Ψ_Q , for two sets of cuts in proton-proton data at 7 TeV; the default cuts (solid circles) and only TPC and ITS refit (open circles). The subevents were defined in the range $0.5 < |\eta| < 0.9$.

The event and particle cuts described in the previous section indeed produce a uniform probability distribution in the proton-proton data which is shown in Figure 5.5 (solid circles) for subevents in the range $0.5 < |\eta| < 0.9$. For subevents in other pseudorapidity ranges the distribution is uniform as well. Also shown is the probability distribution if all cuts except the TPC refit and ITS refit are released (open circles). Releasing the cuts increases the track sample by a factor 2, however, the probability distribution is not uniform. This means that secondary particles from interactions with the material and badly fitted tracks bias the flow vector. Even though the available statistic is decreased the default cuts have to be used for the RP selection to guarantee a uniform distribution of the azimuthal angle of $\mathbf{Q}$ in the proton-proton data.

5.2.1 Pseudorapidity gap dependence in simple Monte Carlo events

Short range correlations (nonflow) can be suppressed by creating a pseudorapidity gap between the two subevents as well as a gap in pseudorapidity between the POI selection and the subevents. This section discusses how elliptic flow and nonflow correlations influence the measured 2-particle correlation as a function of the pseudorapidity gap between the subevents.

To control the correlations present in the studied simulated events, events were generated with a simple Monte Carlo simulation introduced Section 4.6.1. Realistic proton-proton Monte Carlo simulations will be discussed in the next section.

Events with elliptic flow $v_2 = 0.05$ were generated and nonflow was added by duplicating each generated track, which gives a maximal contribution to the 2-particle correlation because the angle difference between to such tracks is zero. To create a longer range

nonflow the pseudorapidity of the duplicated track can also be randomly distributed around the original pseudorapidity.

The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. This inner boundary is taken to be 0.1, 0.3, 0.5 and 0.7. The POI are selected in the range $|\eta| \leq 0.5$.

The following two quantities are studied as a function of $\eta_{\min}$:

$$v_2\{\text{subevents}\} \equiv \sqrt{\langle \mathbf{Q}_A/M_A \cdot \mathbf{Q}_B^*/M_B \rangle_e}, \quad (5.1)$$

which represents the average 2-particle correlation between particles in the subevents, and $v_2\{\text{SP}\}$ as given by Equation 4.6.

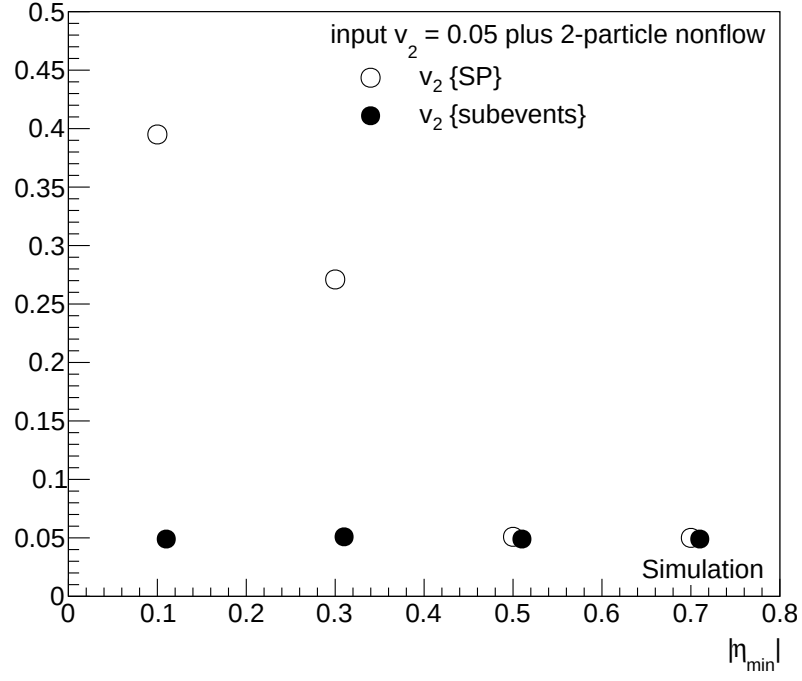
70

By construction $v_2\{\text{subevents}\}$ is not influenced by nonflow with a short range in pseudorapidity, but $v_2\{\text{SP}\}$ is influenced as long as the gap between the POI and the subevents is smaller than the range of the nonflow correlation. Therefore a decrease with $\eta_{\min}$ is expected. This behaviour is indeed seen in Figure 5.6 which shows $v_2\{\text{subevents}\}$ (solid circles) and $v_2\{\text{SP}\}$ (open circles) for nonflow from exact copied tracks in Figure 5.6a and nonflow with a range of 0.2 in pseudorapidity in Figure 5.6b. $v_2\{\text{subevents}\}$ does not depend on the gap size, while the correlation in $v_2\{\text{SP}\}$ decreases as less and less correlated pairs are included in the correlation between the POI and the flow vector $\mathbf{Q}$. $v_2\{\text{SP}\}$ reproduces the input elliptic flow for $\eta_{\min} = 0.5$ for nonflow with zero range and at $\eta_{\min} = 0.7$ for nonflow with range 0.2. This clearly shows that elliptic flow can be measured when the gap between the POI and the subevents is larger than the range of the nonflow which is present in the event.

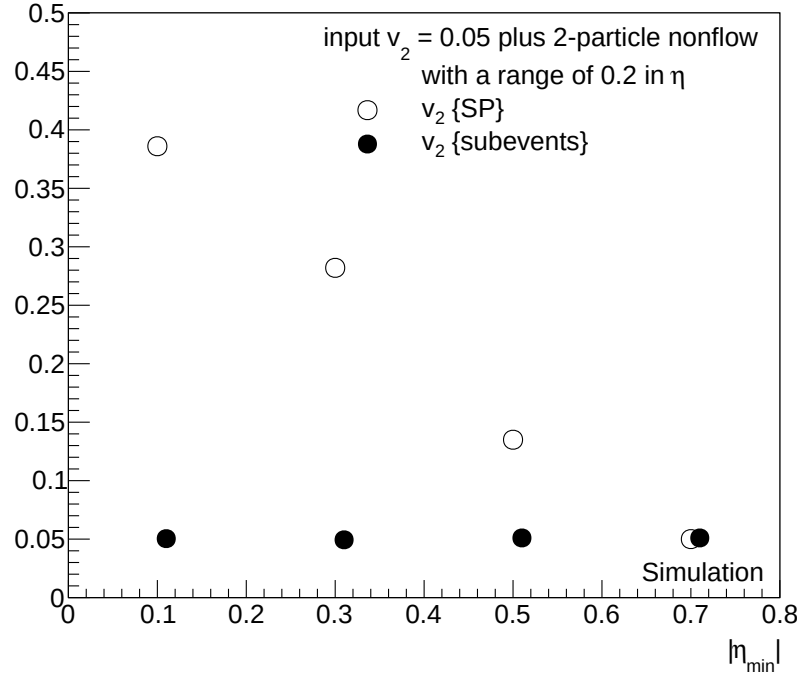
Because elliptic flow is a correlation that extents over all particles no dependence of the measured 2-particle correlation is expected for events that contain only correlation due to elliptic flow. Figure 5.7 confirms that this is true.

If, on the other hand, only nonflow is present the dependence on the pseudorapidity gap is determined by the range of the 2-particle correlations. If the nonflow range is larger than the gap between the subevents the measured 2-particle correlation does not depend on $\eta_{\min}$. If the range is smaller $v_2\{\text{subevents}\}$ will decrease as $\eta_{\min}$ increases. When no correlations are left between the two subevents $v_2\{\text{subevents}\}$ will be zero causing $v_2\{\text{SP}\}$ to increase without limit. Because $v_2\{\text{subevents}\}$ decreases $v_2\{\text{SP}\}$ increases with increasing $\eta_{\min}$ when only nonflow is present. $v_2\{\text{SP}\}$ increases because the separation between the POI and the subevents is smaller than between the two subevents, hence the denominator decreases faster than the numerator in $v_2\{\text{SP}\}$. The described behaviour is indeed seen in the simple simulation, shown in Figure 5.8, where the pseudorapidity of the duplicated track is varied in three different ranges around its original value.

When the range is 2 units of rapidity (triangles) there is no dependence on the pseudorapidity gap because the correlation range is larger than the gap in all cases. For a smaller range of 1.5 units (squares) $v_2\{\text{subevents}\}$ decreases for larger gaps, and $v_2\{\text{SP}\}$ correspondingly increases. For an even smaller range of 1 unit (circles) this effect is even more pronounced. This rapid increase in $v_2\{\text{SP}\}$ shows that the method is not usable when the correlation between the two subevents vanishes.



a)



b)

Figure 5.6: Dependence of the measured 2-particle correlation on the size of the pseudorapidity gap between the two subevents in the scalar product method for events generated according to a simple Monte Carlo model where correlations due to elliptic flow and nonflow are included. The data set consists of 10^6 events with multiplicity 60 and $v_2 = 0.05$. The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. The POI were selected in the range $|\eta| \leq 0.5$. $v_2 \{subevents\}$ (solid circles) and $v_2 \{SP\}$ (open circles) are shown for a short range nonflow (identical copied tracks) in (a) and a nonflow in the range of 0.2 in (b).

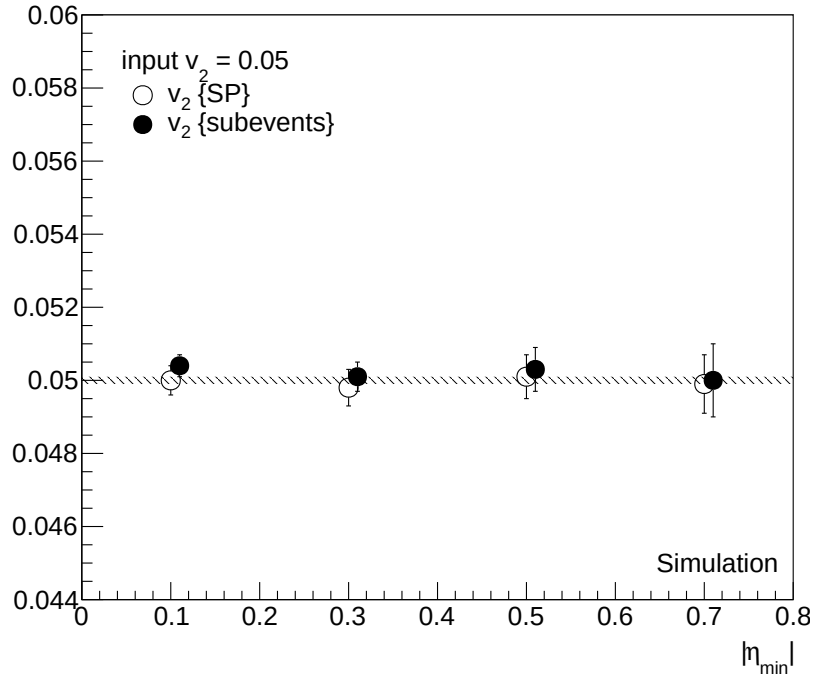


Figure 5.7: Dependence of the measured 2-particle correlations on the size of the pseudorapidity gap between the two subevents in the scalar product method for events generated according to a simple Monte Carlo model where only correlations due to elliptic flow are included. The data set consists of 10^6 events with multiplicity 60 and $v_2 = 0.05$. The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. The POI were selected in the range $|\eta| \leq 0.5$. $v_2\{\text{subevents}\}$ (solid circles) and $v_2\{\text{SP}\}$ (open circles) are shown as a function of $\eta_{\min}$.

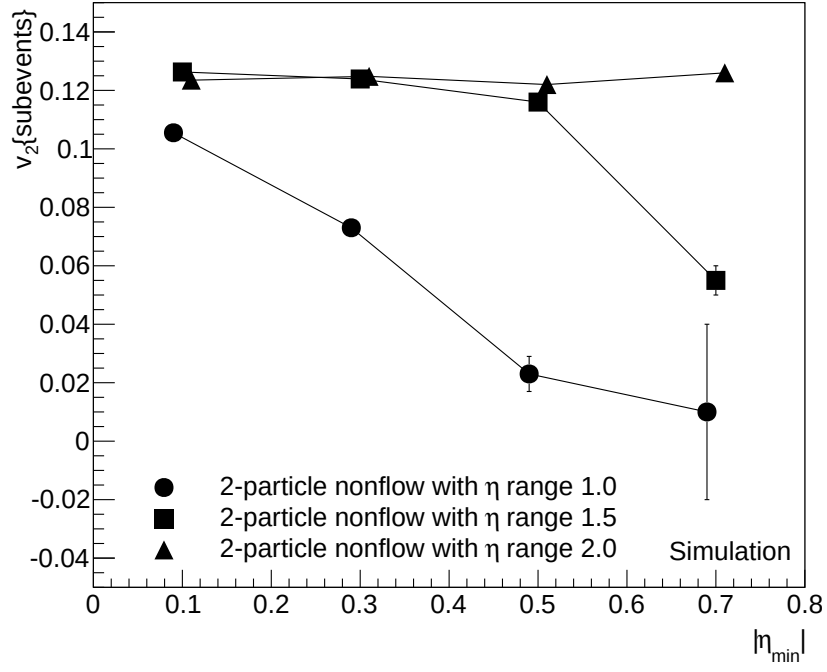
The simple Monte Carlo model confirms that in case of long range correlations, either due to elliptic flow or due to nonflow, no dependence on the gap size should be expected. In case of short range correlations there is a dependence.

5.2.2 Pseudorapidity gap dependence in PYTHIA events

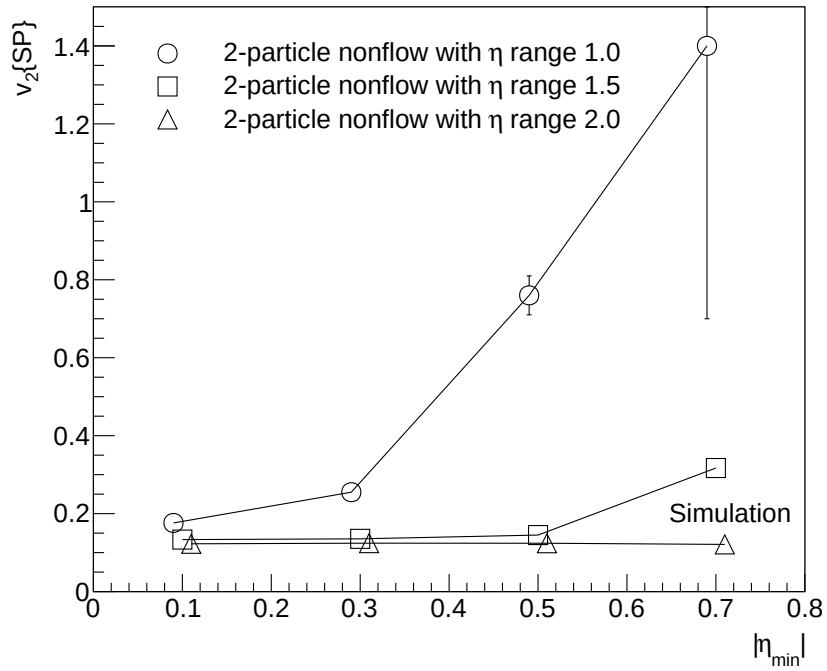
The Monte Carlo event generator PYTHIA produces realistic proton-proton events. In this section the dependence on the pseudorapidity gap between the two subevents in such events is studied. The Monte Carlo events correspond to the proton-proton data at 7 TeV; the parameters were tuned based on the real data and the same detector configuration was applied. No elliptic flow correlations are included in PYTHIA events as they are not part of the model. Elliptic flow has to be added to the centrally in ALICE produced PYTHIA data sets.

The PYTHIA events are studied by looking at the generated event, also called Monte Carlo truth, and at the reconstructed event for which the transport off all generated particles through the ALICE detector is simulated with GEANT3. The same event and track cuts as applied to real proton-proton data are applied to the reconstructed events. For the generated events only kinematic cuts are applied as track quality cuts are not defined for these events.

Figure 5.9 shows the pseudorapidity gap dependence of $v_2\{\text{subevents}\}$ and $v_2\{\text{SP}\}$ for generated events (crosses) and reconstructed events (circles). $v_2\{\text{subevents}\}$ decreases



a)



b)

Figure 5.8: Dependence of the measured 2-particle correlation on the size of the pseudorapidity gap between the two subevents in the scalar product method for events generated according to a simple Monte Carlo model where only correlations due to nonflow are included. The data set consists of 10^6 events with multiplicity 60. The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. The POI were selected in the range $|\eta| \leq 0.5$. $v_2\{\text{subevents}\}$ (a) and $v_2\{\text{SP}\}$ (b) are shown for 2-particle nonflow with a range of 2 units (triangles), 1.5 units (squares) and 1 unit (circles) in pseudorapidity.

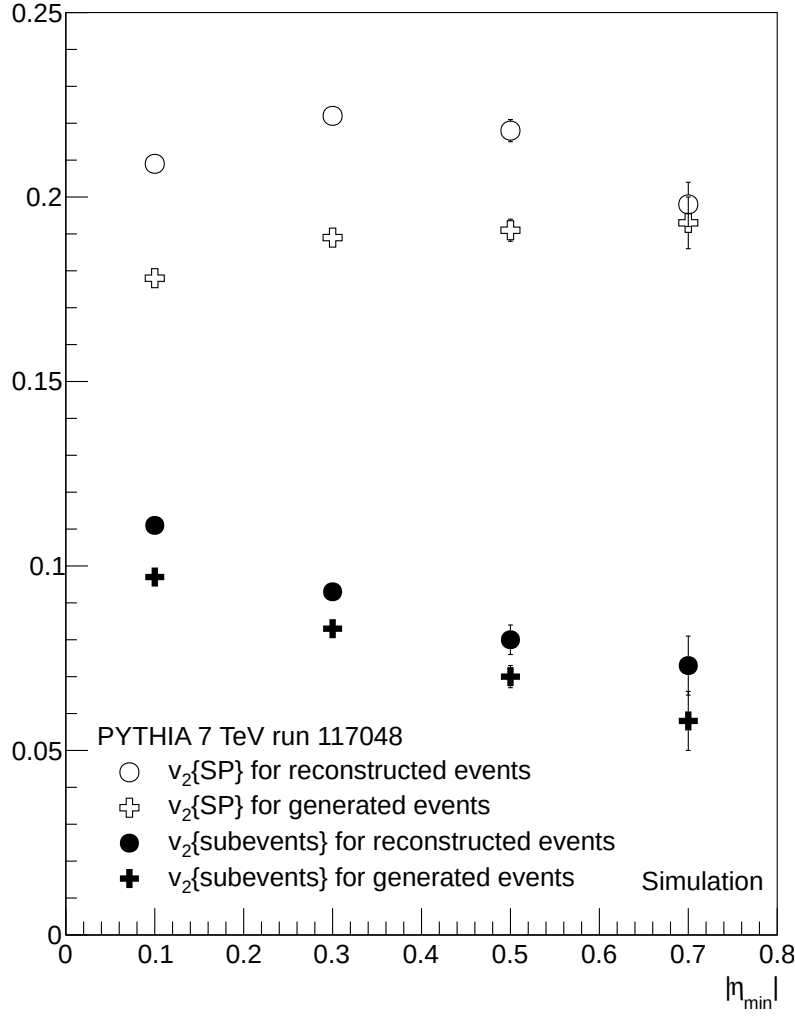


Figure 5.9: Dependence of the measured 2-particle correlation, on the size of the pseudorapidity gap between the two subevents in the scalar product method for 7-TeV proton-proton Monte Carlo events. The circles show the result from reconstructed events and the crosses the result from generated events. The full symbols show $v_2\{\text{subevents}\}$ and the open symbols show $v_2\{\text{SP}\}$. The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. The POI were selected in the range $|\eta| \leq 0.5$.

with increasing separation between the two subevents. The difference between the full reconstructed events and the generated events shows that the detector influences the measurement by changing track properties and adding new particles induced by the material. $v_2\{\text{SP}\}$ first increases and then decreases for the reconstructed events, while for the generated events it increases and then seems to become constant. The value of $v_2\{\text{SP}\}$ is about twice as high as $v_2\{\text{subevents}\}$. This is also seen in the simple Monte Carlo events with only nonflow correlations shown in Figure 5.8.

The measured 2-particle correlations are quite high in the PYTHIA Monte Carlo events. The minimum value of v_2 , such that its contribution can be seen in the measured correlation, is found from adding elliptic flow correlations to the already existing Monte Carlo events. Elliptic flow is added by modifying the azimuthal angles of particles such that they follow the probability distribution as given in Equation 2.1:

$$f(\varphi) = 1 + 2v_2 \cos(2(\varphi - \Psi_R)) . \quad (5.2)$$

A standard way to generate such a distribution, given the original uniform azimuthal particle distribution, is the inverse probability integral transform method [78]. It is a method for generating sample numbers at random from any probability distribution given its cumulative distribution function. The corresponding cumulative distribution function for the probability distribution above is

$$F(\varphi) = \varphi + v_2 \sin(2(\varphi - \Psi_R)) . \quad (5.3)$$

Given the original particle azimuthal angle φ_0 the new angle, which follows the probability distribution, corresponds to the value of φ for which $F(\varphi) = \varphi_0$. An elegant numerical way in which this equation can be solved is an iterative Newton-Raphson scheme. Note that this approach to generate an azimuthal distribution according to Equation 5.2 is only valid as long as this probability distribution is positive guaranteeing a monotonically rising cumulative distribution function, which restricts v_2 to values smaller than 0.5.

Elliptic flow with the following p_t dependence was added to the PYTHIA events

$$v_2 = \begin{cases} 0.5 v_{2,\text{sat}} p_t & \text{for } p_t \leq 2.0 \text{ GeV} \\ v_{2,\text{sat}} & \text{for } p_t > 2.0 \text{ GeV}. \end{cases} \quad (5.4)$$

The corresponding integrated elliptic flow depends on the p_t spectrum of the used events. Figure 5.10 shows the result of this test. On the x -axis the input integrated elliptic flow is indicated. The y -axis shows the measured values of $v_2\{\text{subevents}\}$ (solid circles) and $v_2\{\text{SP}\}$ (open circles) for $\eta_{\text{min}} = 0.7$ in the reconstructed events. The contribution of elliptic flow in $v_2\{\text{SP}\}$ only becomes visible above $v_2\{\text{input}\} = 0.15$, lower values cannot be distinguished. In $v_2\{\text{subevents}\}$ the elliptic flow contribution shows much sooner. This is caused by the lower nonflow contribution to $v_2\{\text{subevents}\}$ both due to the larger separation distance between the correlated particles and the possible pseudorapidity dependence of nonflow. Due to the nonflow contribution $v_2\{\text{subevents}\}$ is always larger than the elliptic flow in the event. When the elliptic flow contribution to the measured correlation is dominant, $v_2\{\text{SP}\}$ and $v_2\{\text{subevents}\}$ have a similar value, while they are very different when the nonflow contribution is dominant.

5.2.3 Pseudorapidity gap dependence in 7 TeV proton-proton data

In this section the measured 2-particle correlations in proton-proton data at 7 TeV are discussed and compared to the results from reconstructed PYTHIA events, which have been shown in the previous section.

First a comparison is made of the angle ϕ_{AB} between the two subevent flow vectors $\mathbf{Q}_A$ and $\mathbf{Q}_B$ because this angle shows if the two subevents are correlated. For uncorrelated subevents it is uniformly distributed. The angle is shown for proton-proton data (solid circles) and Monte Carlo events (open circles) in Figure 5.11a. In both the data and Monte Carlo small angles are favoured, which means the subevents are correlated. The slope is, however, different in the data compared to the Monte Carlo: the correlation strength is different.

To understand the dependence of ϕ_{AB} on flow and nonflow the simple Monte Carlo simulation model is used to generate events with randomly distributed tracks, events

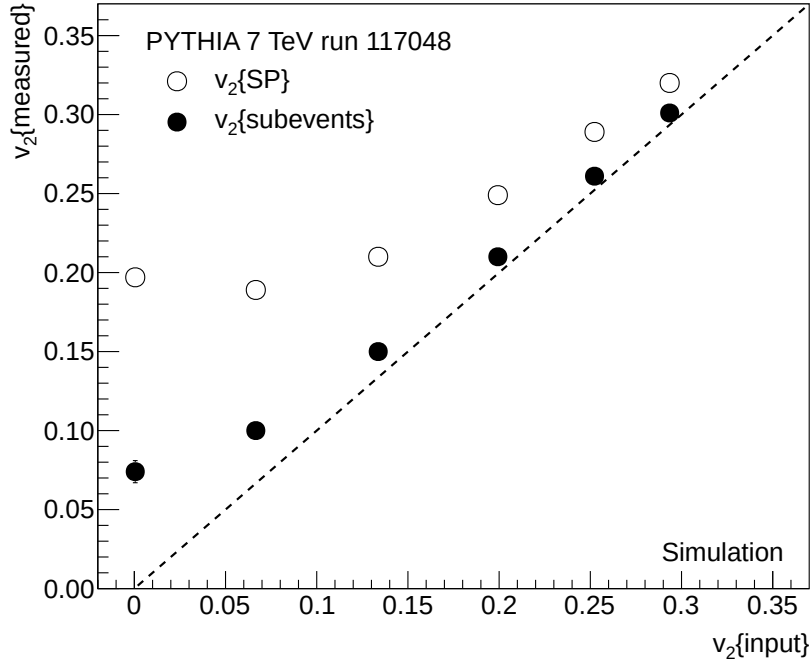


Figure 5.10: Elliptic flow added to Monte Carlo proton-proton events at 7 TeV. The measured 2-particle correlation $v_2\{\text{SP}\}$ (open circles) and $v_2\{\text{subevents}\}$ (solid circles) is compared to the input $v_2\{\text{input}\}$.

with elliptic flow ($v_2 = 0.05$) and events with nonflow of range 1 in pseudorapidity. Figure 5.11b shows ϕ_{AB} for these events. For randomly distributed tracks ϕ_{AB} is indeed uniform (triangles). For elliptic flow correlations the distribution is favoured towards small angles (squares), the same is true for long range 2-particle correlations (circles). A slope in the distribution of the angle between the two subevent flow vectors can be caused by both elliptic flow and nonflow correlations and the two cannot be distinguished easily.

The dependence on the pseudorapidity gap between the two subevents in the scalar product methods in 7 TeV proton-proton data is shown in Figure 5.12 (solid symbols), together with the result in Monte Carlo events (open symbols), shown before in Figure 5.9. $v_2\{\text{SP}\}$ is shown in circles and $v_2\{\text{subevents}\}$ in squares.

To investigate the dependence of the result on the track purity the measurement on the data is repeated with a more strict cut on the DCA. The cut value is changed from 3.2 cm (DCA_z) and 2.4 cm (DCA_{xy}) to 0.4 cm for both. This increases the total purity in the track sample from 89% to 95%. It is found that this change in purity results in a change in the measured 2-particle correlation of the same size as the statistical error. These changed results are included in Figure 5.12 (grey markers). The small effect this change in purity has on the measured 2-particle correlation means that the contribution to the correlation due to secondaries from decays, which are the main source of secondaries in the track sample, is not much different from the contribution of primary particles.

While the strength of the 2-particle correlation is smaller in the real proton-proton data compared to the Monte Carlo events, it follows the same dependence on the pseudorapidity gap size. This indicates the presence of a dominant short range correlation (nonflow) also in real proton-proton collisions, because PYTHIA has only correlations due to nonflow.

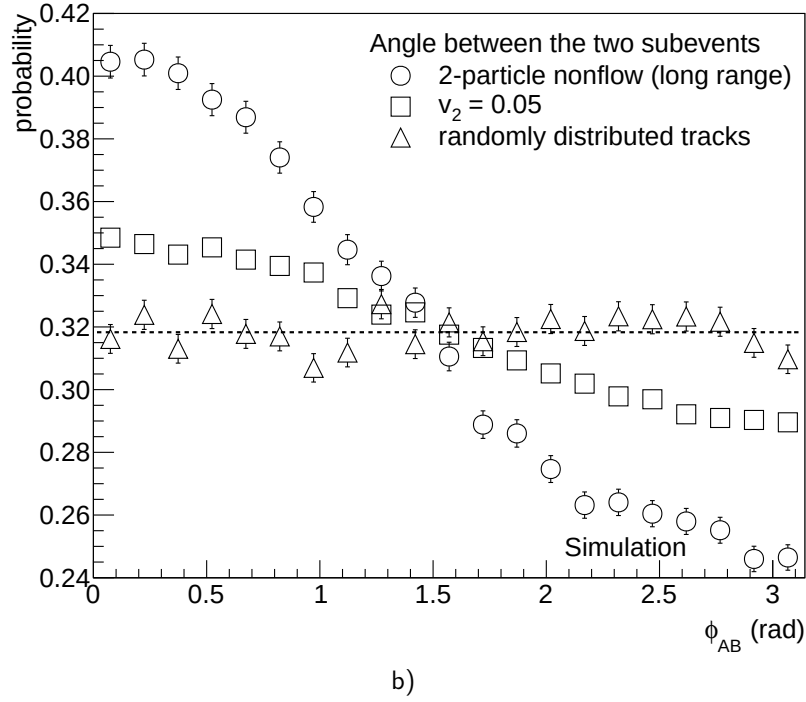
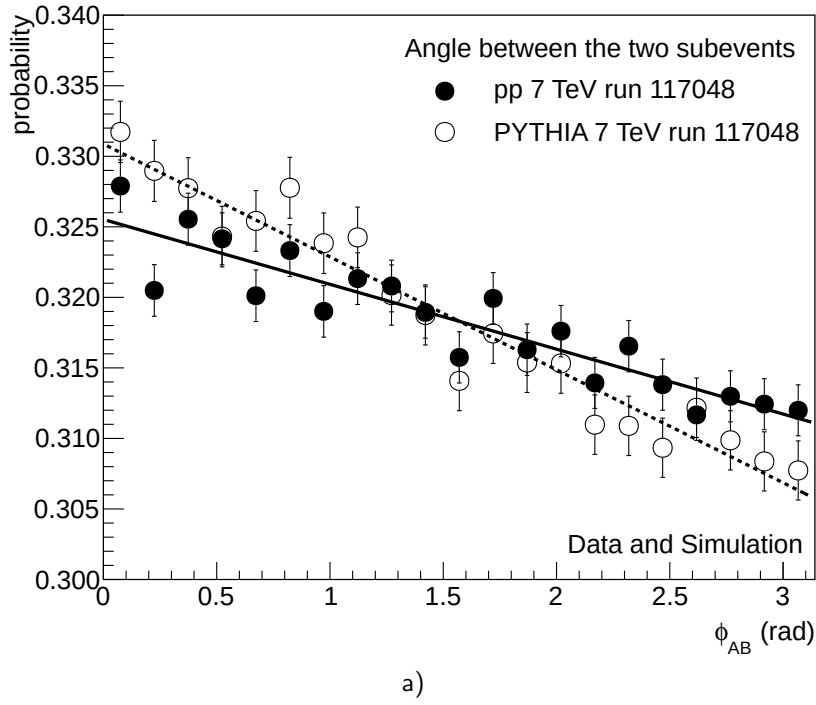


Figure 5.11: The distribution of the angle ϕ_{AB} between the two subevent flow vectors $\mathbf{Q}_A$ and $\mathbf{Q}_B$ in (a) proton-proton data at 7 TeV (solid circles) and corresponding Monte Carlo events (open circles), and in (b) for a simple Monte Carlo for events with only nonflow correlations (circles) with a pseudorapidity range of 1, for events with only elliptic flow correlations of strength $v_2 = 0.05$ (squares) and for events with randomly distributed tracks (triangles).

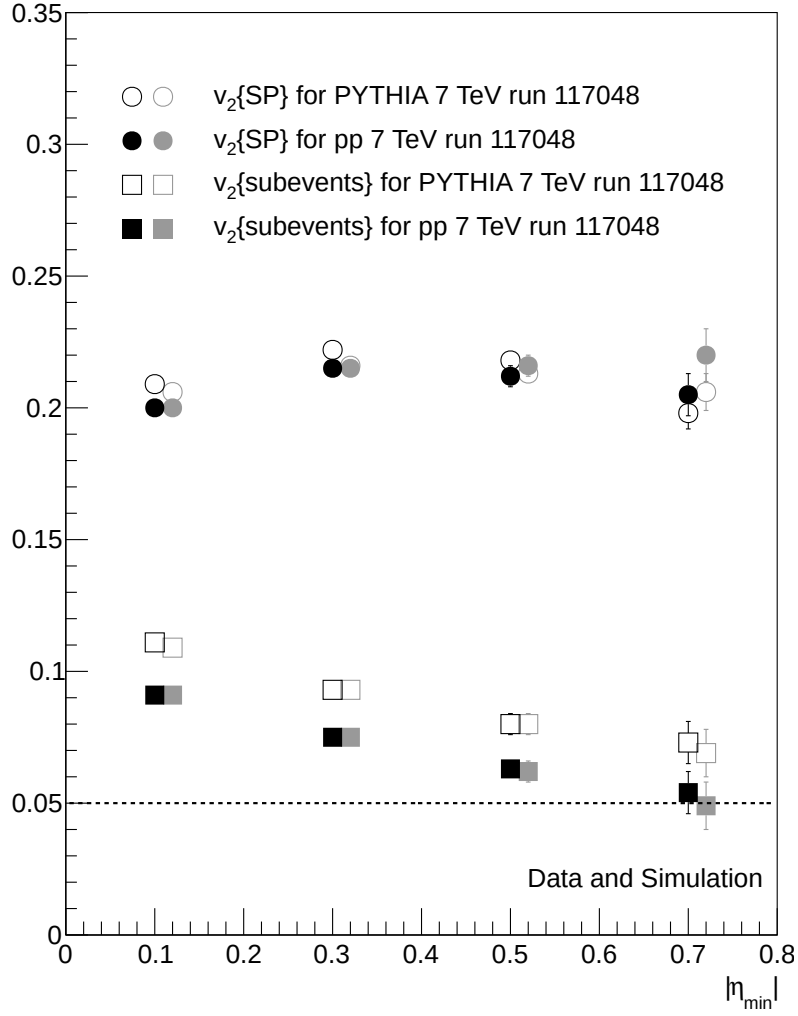


Figure 5.12: Dependence of the measured 2-particle correlation on the size of the pseudorapidity gap between the two subevents in the scalar product method for proton-proton data at 7 TeV (solid symbols) and a corresponding Monte Carlo (open symbols). $v_2\{\text{SP}\}$ is shown in circles and $v_2\{\text{subevents}\}$ in squares. The subevents are defined in the range $\eta_{\min} < |\eta| < 0.9$ where $\eta_{\min}$ is the inner boundary of the subevents. The POI were selected in the range $|\eta| \leq 0.5$. The grey symbols give the results for the same analysis with a stricter particle cut.

To investigate how the trend as a function of $\eta_{\min}$ continues larger gap sizes are needed than are available with tracks in the TPC. Larger gaps can only be achieved by using particle track information from other ALICE subdetectors. Unfortunately, correlations measured in other subdetectors cannot be matched to the present measurement, due to the difference in track sample and detector configuration, as is discussed in detail in Appendix A.

5.2.4 Discussion

The correlation between the two subevents $v_2\{\text{subevents}\}$ has proved to be a better measure than $v_2\{\text{SP}\}$ to find an upper limit on elliptic flow in proton-proton collisions. Based on the dependence on the gap size of $v_2\{\text{subevents}\}$ observed in proton-proton data at 7 TeV and corresponding Monte Carlo events the measured 2-particle correlations are

most likely dominated by nonflow because $v_2\{\text{subevents}\}$ decreases with increasing gap size.

The reached gap size is not large enough to conclude whether the correlation in proton-proton data will continue to decrease, pointing to an absence of long range correlations, or will become constant signalling long range correlations. The corresponding Monte Carlo events show the same trend, while in these events no long range correlations due to elliptic flow were simulated. This enforces the conclusion that in the proton-proton data nonflow is the dominant or only correlation.

An upper limit to the present elliptic flow correlations can be found because the elliptic flow contribution to correlation is always smaller than the measured value of $v_2\{\text{subevents}\}$. This means that v_2 in proton-proton collisions at 7 TeV with at least 10 tracks is less than 0.05, as can be seen in Figure 5.12. The fact that the difference between $v_2\{\text{subevents}\}$ and $v_2\{\text{SP}\}$ is large points to an even smaller value.

By comparing this upper limit to the predictions presented in Section 2.4 the predictions of Chaudhuri [35], Bozek [34] and Avsar [37] can be excluded. The predictions of Prasad [30], Luzum and Romatschke [32], d'Enterria [29], Cunqueiro [36] and Ortana [31] are too low to be excluded with the present measurement. To check those predictions a much larger η gap would be needed. The predictions of Casalduero and Wiedemann [33] refer specifically to high multiplicity events, which are present in the studied data sample but are not dominant. To test these predictions a study should be done with a higher minimum number of particles. This would be the logical next step in this analysis: to test the dependence on event multiplicity of the measured correlations in proton-proton collisions.

6

Conclusions & Summary

The standard model of particle physics describes all known elementary particles and the forces between them. The strong force, which binds quarks inside hadrons and nucleons inside nuclei, is described by the theory of Quantum Chromodynamics (QCD). This theory predicts a new state of matter at extreme temperatures and densities: the *Quark Gluon plasma* (QGP).

The ALICE experiment at the Large Hadron Collider (LHC) near Geneva was build to study this QGP by looking at collisions of the most heavy stable ions: lead (Pb) ions. In such collisions one hopes to achieve sufficient energy density for the creation of a QGP. One of the signatures of QGP formation in high energy heavy ion collisions is the presence of collective behaviour in the system formed during the collision. This collectivity manifests itself in a common velocity in all produced particles: a *collective flow*. The most dominant contribution to collective flow is *elliptic flow*, which originates from the anisotropic overlap region of the two nuclei in non-central collisions and is visible in the azimuthal distribution of the produced particles. Elliptic flow is related to the equation of state of the system and its degree of thermalisation.

Elliptic flow has been measured at different centre of mass energies. At the Relativistic Heavy Ion Collider (RHIC) the measurements of elliptic flow in collisions between gold (Au) ions at 200 GeV for the first time came close to the predicted ideal hydrodynamic limit, leading to the conclusion of a perfect liquid QGP. Disagreement at lower energies is attributed to incomplete thermalisation of the system. At the LHC the transverse momentum dependence of elliptic flow in 2.67 TeV Pb-Pb collisions is similar in size and is best described by hydrodynamics with a small viscous correction. The elliptic flow is build up in the first few fm/c, therefore the longer QGP lifetime at the LHC compared to RHIC does not influence it much.

Elliptic flow depends on the centrality of the collision. For very central events it is low due to the highly symmetric collision volume, while for peripheral events it is low because of a lack of thermalisation due to the low number of produced particles. Elliptic flow is highest for semi-peripheral collisions.

Because the centre of mass energy at the LHC is so high, predictions have been made of collective behaviour even in proton-proton collisions. These predictions are very divers and give values of v_2 between 0 and 0.2 using different models. The analysis presented in this thesis aims to set an upper limit on the presence of elliptic flow in 7 TeV proton-proton collisions.

Analysis methods

The analysis of elliptic flow is complicated by the presence of correlations between particles from other sources, summarised in the term *nonflow*. The measurement is also influenced by fluctuations in the initial anisotropy of the reaction volume. These fluctuations originate from variations in the positions of nucleons at a fixed centrality as well as from the finite width of the centrality bin on which the analysis is performed in heavy ion collisions.

Several analysis methods have become available over the years and have been implemented for elliptic flow analysis within the ALICE computing framework. The analysis

methods can be divided into those that use the correlations between two particles to estimate elliptic flow and those that use the correlations between more particles. These multi-particle correlation methods successfully reduce the contribution from nonflow, but are only applicable when the event multiplicity or the elliptic flow is high. 2-particle correlation methods are more widely applicable but cannot distinguish between flow and nonflow.

The result from 2-particle correlation methods and multi-particle correlation methods is influenced oppositely by fluctuations in the elliptic flow signal: the 2-particle methods overestimate and the multi-particle methods underestimate. Due to the combined effect of elliptic flow fluctuations and nonflow correlations only upper and lower limits for the elliptic flow in Pb-Pb collisions can be given by combining the estimates of these different analysis methods. Additionally, using two different methods, both based on either 2-particle correlations or multi-particle correlations, provides two independent estimates, which increases the reliability of the result.

All these analysis methods have been developed and optimised for elliptic flow measurements in heavy ion collisions where the multiplicity is high. Using these methods on proton-proton collisions is therefore challenging. Due to the low multiplicities in proton-proton collisions the multi-particle methods cannot be used to estimate elliptic flow unless the elliptic flow is very high. For the analysis of proton-proton collisions the scalar product method is therefore chosen. In the scalar product method the short range nonflow contribution can be reduced by increasing the distance in pseudorapidity between the two subevents used in this method. By reducing the nonflow contribution in this way an upper limit on elliptic flow is found for proton-proton collisions at 7 TeV.

An upper limit on v_2 in 7 TeV proton-proton collisions

The studied proton-proton data were recorded with the ALICE experiment at the LHC in the 2010 7 TeV proton-proton run. The subdetectors that have been used to reconstruct particle trajectories are the TPC and ITS, the main tracking detectors in the ALICE central barrel.

In proton-proton collisions large nonflow correlations are certainly present and might mask the elliptic flow correlation. The nonflow correlations have to be suppressed sufficiently such that the elliptic flow signal becomes detectable. Nonflow correlations are suppressed by increasing the separation in pseudorapidity of the two subevents in the scalar product method. How much this suppresses nonflow is shown to depend on the pseudorapidity range of the nonflow.

The measured 2-particle correlation is studied as a function of the gap in pseudorapidity between the two subevents for two observables: the measured 2-particle correlation from the scalar product method $v_2\{\text{SP}\}$ and the 2-particle correlation between the two subevents $v_2\{\text{subevents}\}$, which provides the reference value which is used in the calculation of $v_2\{\text{SP}\}$. In case of a dominant elliptic flow component there is no dependence on the gap size, while for a short range nonflow $v_2\{\text{subevents}\}$ goes down with increasing gap size and $v_2\{\text{SP}\}$ actually increases.

The dependence on the gap size, in 7 TeV proton-proton collisions points to a strong nonflow component, because $v_2\{\text{subevents}\}$ decreases with increasing gap size. The corresponding Monte Carlo data set shows the same dependence, while it only includes nonflow correlations. This enforces the conclusion that nonflow is the dominant or the only correlation in 7 TeV proton-proton data at the LHC.

By adding elliptic flow correlations to the Monte Carlo simulation an estimate can be made of the strength of these correlations at which they start to influence the 2-particle correlation measurement. For the studied data sample and pseudorapidity gap the elliptic flow has to be larger than 0.15 for it to start influencing the measurement result $v_2\{\text{SP}\}$ while $v_2\{\text{subevents}\}$ is influenced already below 0.1.

In this study $v_2\{\text{subevents}\}$ has proved to be a better measure than $v_2\{\text{SP}\}$ to find an upper limit on elliptic flow in proton-proton collisions. An upper limit to elliptic flow correlations can be found because the elliptic flow contribution to the measured correlation is always smaller than the measured value of $v_2\{\text{subevents}\}$. This means that v_2 in 7 TeV proton-proton collisions with at least 10 tracks is less than 0.05. The fact that the difference between $v_2\{\text{subevents}\}$ and $v_2\{\text{SP}\}$ is large points to an even smaller value.

Predictions of a higher v_2 for these events can be excluded. To exclude or confirm lower predicted values the nonflow contribution has to be further reduced.

Some predictions refer specifically to higher multiplicity events. To test these predictions a study should be done with a higher minimum number of particles. This would be the logical next step in this analysis: to test the dependence on event multiplicity of the measured correlations in proton-proton collisions.

The reached gap size with the central detectors in ALICE is not large enough to conclude whether $v_2\{\text{subevents}\}$ will continue to decrease, pointing to an absence of long range correlations, or will become constant pointing to long range correlations. Unfortunately, because nonflow is dependent on the detector configuration and the kinematic range of the track sample, as is discussed in Appendix A, analysis results from different subdetectors cannot be directly compared, something that can be done if elliptic flow is dominant.

In the case where all correlations in proton-proton collisions originate from nonflow, the nonflow contribution in Pb-Pb collisions can be estimated from proton-proton collisions, which is discussed in Appendix B, taking into account the restriction on detector configuration and track sample.



Extending the η -range

As has become clear in the analysis of 2-particle correlations in proton-proton collisions at 7 TeV, described in Chapter 5, the available range in η was not large enough to conclude whether the correlation will continue to decrease, pointing to an absence of long range correlations, or will become constant, pointing to a long range correlation. Values of v_2 below 0.05 cannot be excluded by using tracks from the TPC and ITS. Particle trajectory information from other subdetectors in ALICE has a broader pseudorapidity range.

In the elliptic flow analysis of heavy ion data forward detectors are often used to construct the flow vector in order to reduce the contribution from nonflow. In events with a large elliptic flow, results from analysis using different subdetectors are consistent because elliptic flow extends over the whole pseudorapidity range. For such events differences in detector acceptance can be corrected.

This appendix shows that with proton-proton data, where nonflow correlations are dominant, other subdetectors cannot be used to extend the η -range of the present analysis. When nonflow correlations are dominant the measured 2-particle correlation in each subdetector depends on the detector acceptance and on the sample of particles measured by that subdetector, therefore analysis results from different subdetectors will never match. Each subdetector can be used individually if enough different gap sizes can be made in that detector to see a trend as function of the gap size.

The fact that the measured 2-particle correlation depends on the detector acceptance and on the track sample will be shown here using tracklets from the SPD detector (see Section 3.4.3). The SPD consists of the two innermost layers of the ITS and has a pseudorapidity range of $|\eta| \leq 1.7$. The tracklets have a very high purity because they are very close to the beam pipe with very little material in between. They include particles with lower momentum than the tracks from TPC plus ITS, as these very low momentum particles do not reach the TPC. With the tracklets momentum information cannot be reconstructed, but when they are used for the reference particle selection this is not a problem.

Detector acceptance

The SPD has a few real gaps in its azimuthal acceptance, as is shown in Figure A.1. Because of this nonuniform detector acceptance the azimuthal track distribution depends on the primary vertex position; each event *sees* the gaps in the detector differently. This is illustrated in Figure A.2 where the φ distribution is shown for three ranges in the z -coordinate of the primary vertex. The azimuthal distributions in the two subevents are different as well for equal z -ranges because the detector inefficiency is not symmetric in pseudorapidity.

Such a nonuniform azimuthal acceptance is normally corrected for in elliptic flow analysis of heavy ion collisions as it biases the measured value of v_2 . The following will illustrate that for events where nonflow correlations are dominant this correction is not applicable. The correction for a nonuniform azimuthal acceptance for the scalar product method is given by Equation 4.16. Because the acceptance depends on the vertex position, a correction should be done in small bins in the vertex position z where the azimuthal distributions are (almost) the same. Because the analysed event sample is not large

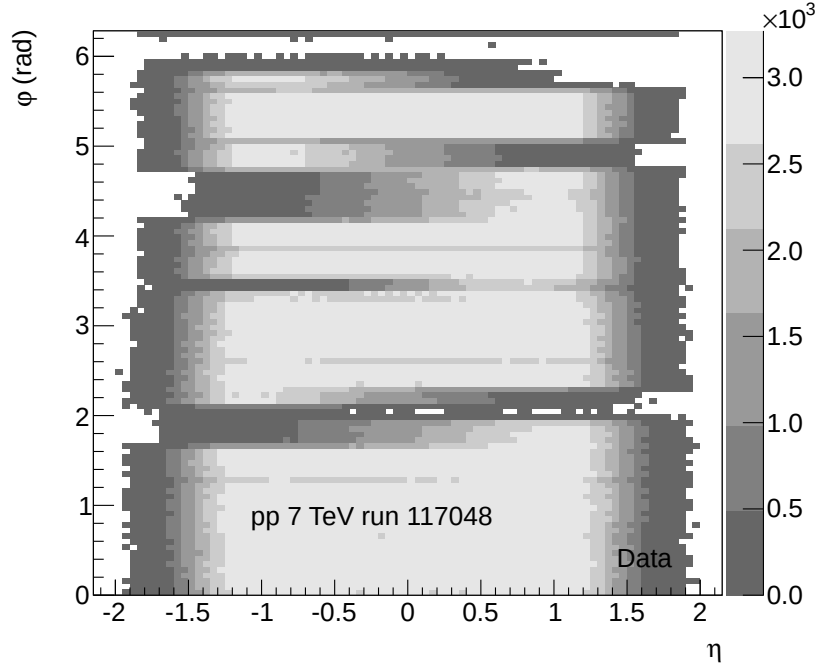


Figure A.1: The distribution of ϕ versus η of tracklets in proton-proton data at 7 TeV.

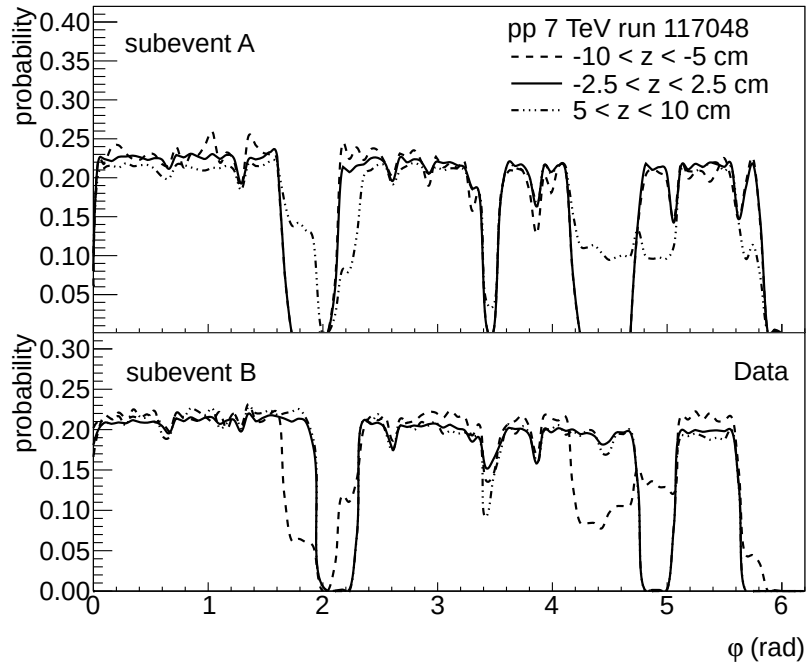


Figure A.2: The ϕ distribution of tracklets in proton-proton data at 7 TeV for three ranges of the vertex z -coordinate for subevent A ($-0.9 < \eta < -0.5$) in the upper panel and subevent B ($0.5 < \eta < 0.9$) in the lower panel.

Table A.1: Demonstration with a simple model that the correction on the flow vector does not work if nonflow is dominant.

Input	Acceptance	Measured $\left\langle \frac{Q_A}{M_A} \cdot \frac{Q_B}{M_B} \right\rangle_e$	Correction terms	Corrected $\left\langle \frac{Q_A}{M_A} \cdot \frac{Q_B}{M_B} \right\rangle_e$	$v_2\{\text{subevents}\}$
$v_2 = 0.05$	gaps	0.1286	$-0.0361 - 0.0900$	0.0024	0.049 ± 0.001
$v_2 = 0.02$ + nonflow	gaps	0.1369	$-0.0362 - 0.0901$	0.0106	0.1031 ± 0.0007
$v_2 = 0.02$ + nonflow	perfect	0.0059	$-0.0000 - 0.0000$	0.0059	0.0769 ± 0.0002

90

enough for such small bins the gaps are artificially made uniform in η by making large gaps over the whole η range which encompass the already present gaps. With this modification about half of the detector is taken out.

By making use of the simple Monte Carlo event generator (Section 4.6.1) the correction applied to this detector acceptance is tested for simulated events with dominant elliptic flow and for simulated events with dominant nonflow by comparing the measured correlation between the two subevents (Equation 5.1)

$$v_2\{\text{subevents}\} \equiv \sqrt{\left\langle \frac{Q_A}{M_A} \cdot \frac{Q_B^*}{M_B} \right\rangle_e}. \quad (\text{A.1})$$

Table A.1 shows the results of this test. For each input it gives the measured scalar product of the subevent flow vectors (the square of Equation A.1), the corrected value of this scalar product, the final measured correlation $v_2\{\text{subevents}\}$, and the correction terms appearing in the denominator of Equation 4.16 which are

$$-\left\langle \frac{\sin(\Psi_A)}{M_A} \right\rangle_e \left\langle \frac{\sin(\Psi_B)}{M_B} \right\rangle_e \quad \text{and} \quad -\left\langle \frac{\cos(\Psi_A)}{M_A} \right\rangle_e \left\langle \frac{\cos(\Psi_B)}{M_B} \right\rangle_e. \quad (\text{A.2})$$

From the values in the table it is clear that the correction works for events where correlations due to elliptic flow are dominant because the elliptic flow is reproduced even though half of the azimuthal acceptance is unavailable. When nonflow is dominant the correction does not work anymore; a different correlation is measured with gaps in the acceptance compared to the measured correlation with a perfect detector. This means that the nonflow correlation itself is changed by the presence of detector inefficiencies.

Indeed the correction on the flow vector was derived under the assumption of dominant elliptic flow as is the case in most Pb-Pb data. As discussed in Chapter 5 the correlations in proton-proton data are dominated by nonflow, which makes using this correction technique unreliable. The same applies to the correction using ϕ -weights. Because the nonflow correlation is changed by the detector acceptance a correction cannot be done.

Track sample

An additional reason why the results from tracks and tracklets cannot be compared directly is the difference in the measured track sample. The track sample for the same

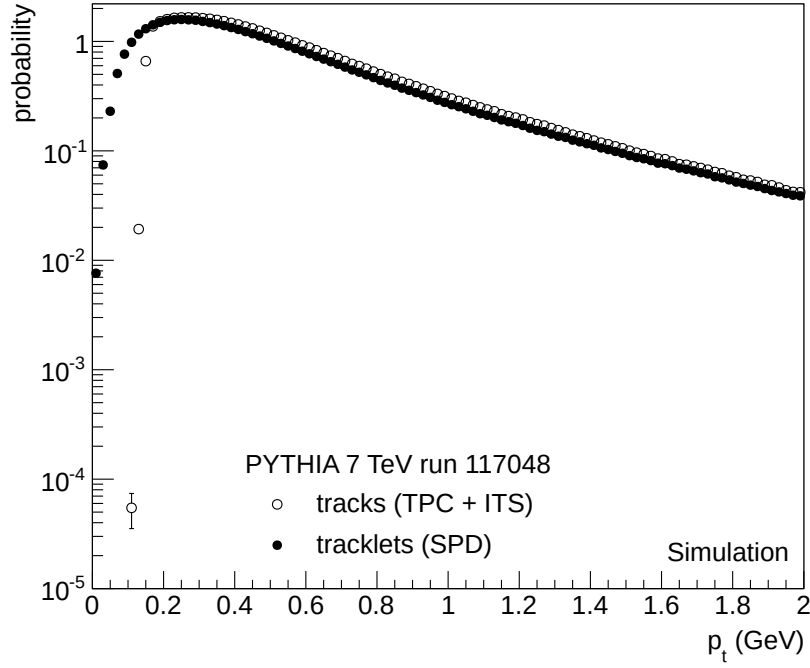


Figure A.3: The p_t distribution of Monte Carlo generated tracks reconstructed as either tracks (open circles) or tracklets (solid circles).

range of subevents will be different due to the difference in the accessible p_t range. With the generated particles in the Monte Carlo this difference can be visualised. Figure A.3 shows the p_t distribution of generated particles reconstructed as tracks and as tracklets. The range of the tracklets goes to much smaller p_t .

For events where elliptic flow is dominant this difference does not influence the measurement as the correlation between the subevents cancels the same elliptic flow contribution in the scalar product:

$$\frac{\left\langle \left\langle \mathbf{u}(p_t, \eta) \cdot \frac{\mathbf{Q}^*}{M_Q} \right\rangle_P \right\rangle_e}{\sqrt{\left\langle \left\langle \frac{\mathbf{Q}_A}{M_A} \cdot \frac{\mathbf{Q}_B^*}{M_B} \right\rangle_e \right\rangle}} = \frac{v_2(p_t, \eta) v_2}{\sqrt{v_2^2}} = v_2(p_t, \eta). \quad (\text{A.3})$$

For dominant nonflow this is not true anymore and the track sample determines the measured correlation.

In real data the p_t of the tracklets is not known so cannot be made the same as for the global tracks in order to match the two measurements, this can be done though in Monte Carlo events. It turns out, however, that even with cutting on the tracklet p_t the track sample does not become equal. This can be checked by comparing the unique Monte Carlo label of each track and tracklet. The difference is caused by particles that are reconstructed as tracks in the TPC and ITS while they are lost in the tracklets due to the gaps in the SPD, and similarly particles that are reconstructed in the tracklets which fall in the small dead areas of the TPC, and are thus not reconstructed as tracks.

Due to the minimum cut on the multiplicity of the reference particle selection and this different track sample also another subset of the events is selected. This could be an additional reason why the two measurements, on tracks and on tracklets, cannot be directly compared.

Analysis possibilities

The tracklets can be used in a separate analysis by measuring the 2-particle correlations with tracklets in the RP selection, over the total available pseudorapidity range for $\eta_{\min}$. That analysis is not included in this thesis. One has to be careful when interpreting the results of such an analysis, because the possible contribution from elliptic flow to the measured correlation will be biased by the detector acceptance. An upper limit on v_2 is therefore difficult to estimate.

Other subdetectors with a range at larger pseudorapidity are the FMD and the VO detector. Both detectors give a signal proportional to the number of particles that hit a certain sector. These particles also include secondaries created in the material of the detectors in front of the FMD and V0. This contamination can be high and cannot be corrected for on a particle level, only on a statistical basis. Just as in the tracklets no p_t information for the hits in these detectors is available.

The same restriction applies that the results cannot be directly compared to the tracks, but if a few different gap sizes can be made in one detector a trend can be seen as a function of the gap size. The investigation if these detectors can be used in practise falls outside the scope of this thesis.

Pb

Estimating nonflow in Pb-Pb collisions from
proton-proton collisions

In Pb-Pb collisions both elliptic flow and nonflow correlations are present. These two sources of correlations are not easily distinguishable. The nonflow component can be suppressed by using multi-particle analysis methods which are less sensitive to nonflow, as discussed in Chapter 4. Multi-particle methods are, however, restricted to high multiplicity and a high the value of v_2 and might therefore not be applicable at very central or very peripheral collisions, where one of these is low. This appendix investigates another method that is not so dependent on these parameters.

B.1 Analysis method

This method relies on the assumption that in proton-proton collisions only nonflow correlations are present, and that nonflow correlations in Pb-Pb correspond to a superposition of many proton-proton collisions. Therefore the nonflow contribution to the measured correlation in Pb-Pb collisions can be estimated directly from proton-proton collisions. As has been shown in Appendix A nonflow depends on the used track sample and on the detector configuration. When comparing measurements in proton-proton and Pb-Pb these conditions should be the same to make a fair comparison.

The numerator of the scalar product method (Equation 4.6) is calculated in both Pb-Pb and proton-proton collisions. The value found in proton-proton collisions is subtracted from the result in Pb-Pb collisions after which the elliptic flow is calculated. This correction procedure has been successfully applied by the STAR collaboration [79] on Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC). The numerator in the scalar product method is the average scalar product between a particle $\mathbf{u}$ and the flow vector $\mathbf{Q}$. For events that contain only correlations due to nonflow, this scalar product is proportional to the number of clusters of correlated particles N_c and to the number of 2-particle combinations between the M_c particles in the clusters

$$\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \propto \frac{N_c M_c (M_c - 1)}{M}. \quad (\text{B.1})$$

The brackets $\langle \rangle_p$ denote the average over the particles $\mathbf{u}$ and the number of 2-particle combinations is $M_c(M_c - 1)$. The total multiplicity M is equal to the number of clusters times the cluster multiplicity ($N_c M_c$). The proportionality is the average cosine of the angles between particles in a cluster. If the particles have a small separation angle their contribution to the scalar product is large.

The scalar product due to this kind of correlated clusters does not depend on the total multiplicity of the events, provided that the average number of particles M_c in a correlated cluster does not change with multiplicity. The scalar product can then be applied to both proton-proton and Pb-Pb collisions and will yield the same average value due to nonflow correlations. Of course, in Pb-Pb collisions the scalar product has contributions from both flow and nonflow. The nonflow contribution is equal in proton-proton and Pb-Pb. By subtraction of the scalar product measured in proton-proton the elliptic flow contribution in Pb-Pb collisions can be found

$$\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{\text{AA}} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{\text{PP}} = \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{\text{AA (flow)}}. \quad (\text{B.2})$$

The brackets $\langle \rangle_e$ denote the average over many events. Using the definitions introduced in Chapter 4 concerning the scalar product method (Section 4.1), the elliptic flow in Pb-Pb collisions can be calculated from the previous equation

$$\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP} = \langle M \rangle_e \langle \langle v_2(p_t, \eta) \rangle_p \rangle_e \langle v_2 \rangle_e. \quad (\text{B.3})$$

In the equation $\langle M \rangle_e$ is the average multiplicity in the flow vector $\mathbf{Q}$, v_2 is the integrated elliptic flow of the reference particles (RP) in the event and $v_2(p_t, \eta)$ the elliptic flow of the particle of interest (POI) $\mathbf{u}$. The integrated elliptic flow of the reference particles v_2 can be found by replacing $\mathbf{u}$ in Equation B.3 with a reference particle and then integrating over the RP transverse momentum range. The integral is weighted with the yield of the RP dN/dp_t as a function of p_t

$$\int_{p_t^{\min}}^{p_t^{\max}} \left(\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP} \right) \frac{dN}{dp_t} dp_t = \langle M \rangle_e \langle v_2 \rangle_e^2. \quad (\text{B.4})$$

The particle yield in this equation is the measured yield, which is not corrected for the track finding efficiency. The integrated elliptic flow value calculated here is therefore a reference value and cannot be quoted as a final result. The final integrated elliptic flow should be found from integrating the differential elliptic flow of the POI weighted with the fully corrected particle spectrum.

The differential elliptic flow of the particles of interest can now be found from Equation B.3 using v_2 found from Equation B.4

$$\langle \langle v_2(p_t) \rangle_p \rangle_e = \frac{\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP}}{\langle M \rangle_e \langle v_2 \rangle_e}. \quad (\text{B.5})$$

The error on the corrected $v_2(p_t)$ is calculated according to,

$$\left(\frac{\sigma_{v_2(p_t)}}{\langle v_2(p_t) \rangle} \right)^2 = \frac{\sigma_{\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA}}^2 + \sigma_{\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP}}^2}{\left(\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP} \right)^2} + \left(\frac{\sigma_{\langle M \rangle_e}}{\langle M \rangle_e} \right)^2 + \left(\frac{\sigma_{\langle v_2 \rangle_e}}{\langle v_2 \rangle_e} \right)^2. \quad (\text{B.6})$$

The error on the integrated elliptic flow σ_{v_2} is given by,

$$4 \left(\frac{\sigma_{\langle v_2 \rangle_e}}{\langle v_2 \rangle_e} \right)^2 = \left(\frac{\sigma_{\langle M \rangle_e}}{\langle M \rangle_e} \right)^2 + \frac{\sum_i^{p_t \text{ bins}} (dN/dp_t)_i^2 \left[\left(\sigma_{\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA}} \right)_i^2 + \left(\sigma_{\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP}} \right)_i^2 \right]}{\left(\sum_i^{p_t \text{ bins}} (\Delta_{uQ})_i (dN/dp_t)_i \right)^2} + \frac{\sum_i^{p_t \text{ bins}} (\Delta_{uQ})_i^2 (dN/dp_t)_i^2 \left(\frac{\sigma_{dN/dp_t}}{dN/dp_t} \right)_i^2}{\left(\sum_i^{p_t \text{ bins}} (\Delta_{uQ})_i (dN/dp_t)_i \right)^2}, \quad (\text{B.7})$$

where $\Delta_{uQ} = \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{AA} - \langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e^{PP}$. If there is no flow in the Pb-Pb events, in which case Δ_{uQ} approaches zero, the error rises without limit.

In the case of a nonuniform azimuthal detector acceptance in the Pb-Pb data the elliptic flow contribution is affected and a correction is needed. The nonflow contribution

depends on the detector configuration and cannot be corrected, as the correction simply is not known. In order to get a comparable nonflow measurement in Pb-Pb and proton-proton the detector acceptance should be the same and the correction has to be applied in both if it is needed in Pb-Pb. The bias on the elliptic flow component can be corrected for by shifting $\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p$ by the averages of the x and y components of $\mathbf{u}$ and $\mathbf{Q}$

$$\begin{aligned} \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p^{\text{corrected}} &= \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p - \langle \sin(\varphi) \rangle_p \langle \sin(\Psi_Q) \rangle_e \\ &\quad - \langle \cos(\varphi) \rangle_p \langle \cos(\Psi_Q) \rangle_e . \end{aligned} \quad (\text{B.8})$$

Here φ is the azimuthal angle of $\mathbf{u}$ and Ψ_Q the angle of the flow vector $\mathbf{Q}$.

B.2 Validation of the method using a simple Monte Carlo model

The correction for nonflow can be shown to work with a simple Monte Carlo simulation which was introduced in Chapter 4 and where the above assumptions are valid. Also the correction for a nonuniform detector can be shown to work with this model. For testing the subtraction of nonflow a few different configurations have been generated corresponding to the Pb-Pb and proton-proton situations. The input elliptic flow, $v_2 = 0.05$, for the Pb-Pb case was constant with p_t . The nonflow, applied in the Pb-Pb and proton-proton cases alike, was simulated by doubling all the generated tracks. For this artificial way of adding nonflow to an event with randomly distributed particles the value of $\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p$ can be calculated. Because $M = N_c M_c$ and the cosine of the separation angle between the duplicated pairs is exactly 1, the scalar product becomes, according to Equation B.1

$$\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p = M_c - 1 , \quad (\text{B.9})$$

confirming that the value of the scalar product only depends on the number of particles correlated to each other M_c and not on the total multiplicity. The correlation due to flow, however, does scale with multiplicity.

Table B.1 shows the results for this simple simulation and confirms the behaviour described above. The scalar product for the *flow plus nonflow* events (first row) is equal to the scalar product for events with only flow (second row) plus the scalar product of the events with only nonflow (fourth and fifth row). The fourth, fifth and sixth row show that the scalar product for nonflow depends indeed only on the cluster multiplicity. The second and third row show that for elliptic flow the scalar product does scale with the multiplicity.

Subsequently elliptic flow v_2 was calculated according to Equation B.5 with and without correcting for the nonflow. The results are presented in Table B.2. The correction removes the nonflow contribution and is therefore validated in this simple model.

To test the correction that must be applied in case of a nonuniform detector a set of events was simulated where two partial holes were introduced in the azimuthal acceptance, shown in Figure B.1. The multiplicity was sampled from a Gaussian distribution with mean 1000 and standard deviation 50. The input v_2 was also Gaussian, with mean 0.05 and

Table B.1: $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_{\mathbf{p}} \rangle_{\mathbf{e}}$ for different event types where $M = N_{\mathbf{c}} M_{\mathbf{c}}$

v_2	$N_{\mathbf{c}}$	$M_{\mathbf{c}}$	calculated $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_{\mathbf{p}} \rangle_{\mathbf{e}}$	measured $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_{\mathbf{p}} \rangle_{\mathbf{e}}$
0.05	900	2	5.50	5.50 ± 0.07
0.05	1800	1	4.50	4.50 ± 0.06
0.05	900	1	2.25	2.25 ± 0.03
0.0	90	2	1.00	1.01 ± 0.02
0.0	900	2	1.00	1.00 ± 0.02
0.0	900	3	2.00	2.01 ± 0.03

Table B.2: Subtracting nonflow in a simple model

$v_2\{\text{input}\}$	0.05
$v_2\{\text{uncorrected}\}$	0.05531 ± 0.00003
$v_2\{\text{corrected}\}$	0.05003 ± 0.00004

Table B.3: Correcting for non-uniform acceptance in $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_{\mathbf{p}} \rangle_{\mathbf{e}}$

non-uniform ϕ distribution	5.11 ± 0.02
corrected non-uniform ϕ distribution	2.35 ± 0.02
uniform ϕ distribution	2.32 ± 0.01

standard deviation 0.01. As a check the analysis was repeated with an uniform azimuthal acceptance. Table B.3 shows the result for the uncorrected, corrected and uniform case. The detector inefficiencies increase the scalar product by more than a factor two. The correction, however, removes this bias; the corrected result agrees with the result from the uniform acceptance.

B.3 Scaling with the centre of mass energy

Ideally the nonflow is estimated from proton-proton data at the same centre of mass energy as the Pb-Pb data. At the time of writing the centre of mass energies for the proton-proton and Pb-Pb data at the LHC differ. The LHC has run proton-proton with a centre of mass energy of 900 GeV and 7 TeV, and Pb-Pb at 2.76 TeV. The amount of nonflow might depend on the collision energy. In that case an interpolation must be made to the Pb-Pb energy in order to subtract the correct amount of nonflow estimated from the proton-proton data.

Figure B.2 shows $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_{\mathbf{p}} \rangle_{\mathbf{e}}$ for proton-proton data at 900 GeV (run 121039) and 7 TeV (run 117048) together with STAR results at 200 GeV [79]. The scalar product clearly increases with the collision energy. The same increase with energy is seen in proton-

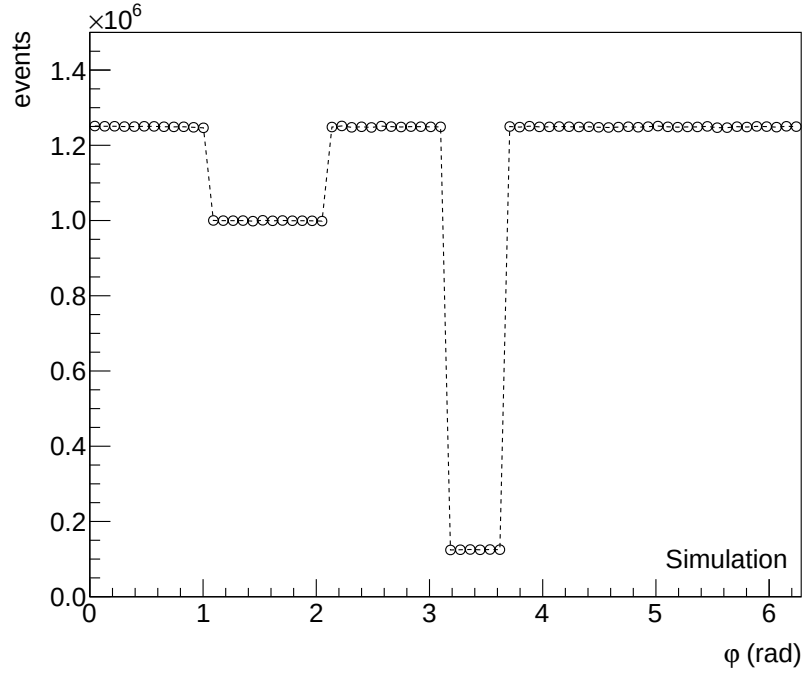


Figure B.1: The non-uniform azimuthal distribution used for testing the correction to $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$.

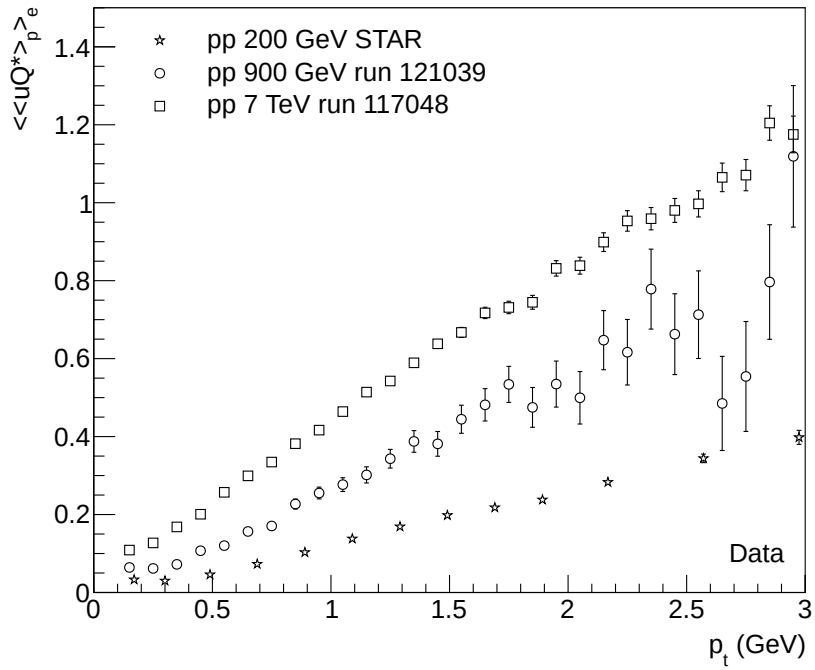


Figure B.2: $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ for proton-proton data at 900 GeV (circles) and 7 TeV (squares) together with STAR results (stars) at 200 GeV [79].

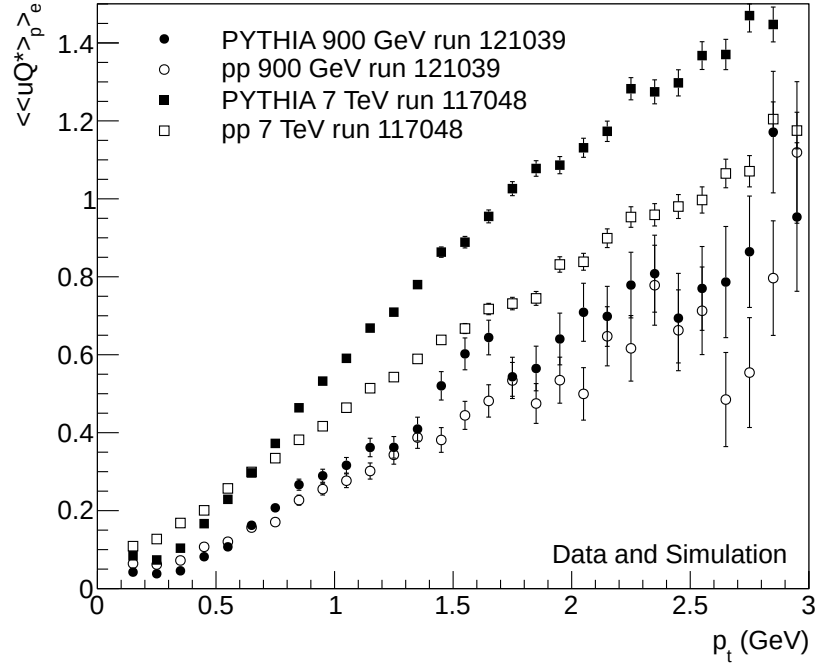


Figure B.3: $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ for proton-proton data and Monte Carlo at 900 GeV (open and solid circles) and 7 TeV (open and solid squares).

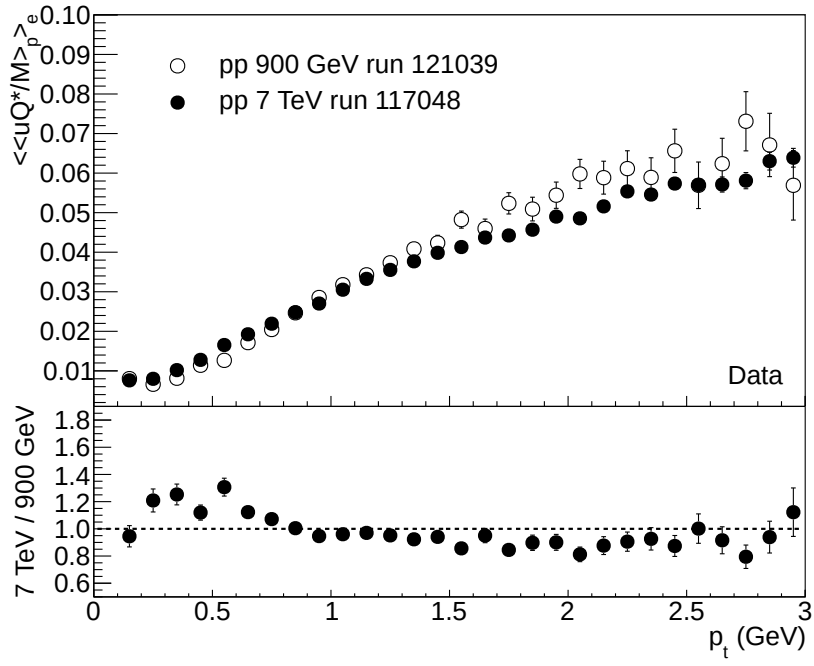
proton events generated with the PYTHIA Monte Carlo event generator, while at the same time PYTHIA clearly overestimates the size of the nonflow in proton-proton collisions at high p_t and underestimates for very low p_t . These results are shown together with the real data in Figure B.3.

The total multiplicity in proton-proton collisions increases with increasing centre of mass energy. This can be caused by an increase in the number of clusters, but also the structure of the clusters might change. The increase in the size of the nonflow can have multiple origins, but it seems reasonable that it should scale with the multiplicity. The following figure shows that this scaling indeed holds approximately both in the data and in Monte Carlo simulations. For Figure B.4 $\langle \langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ was scaled by the number of particles contributing to the flow vector $\mathbf{Q}$ in each event. Even though the shape of the p_t dependence differs in Monte Carlo and real data, the scaling with multiplicity is reproduced in PYTHIA.

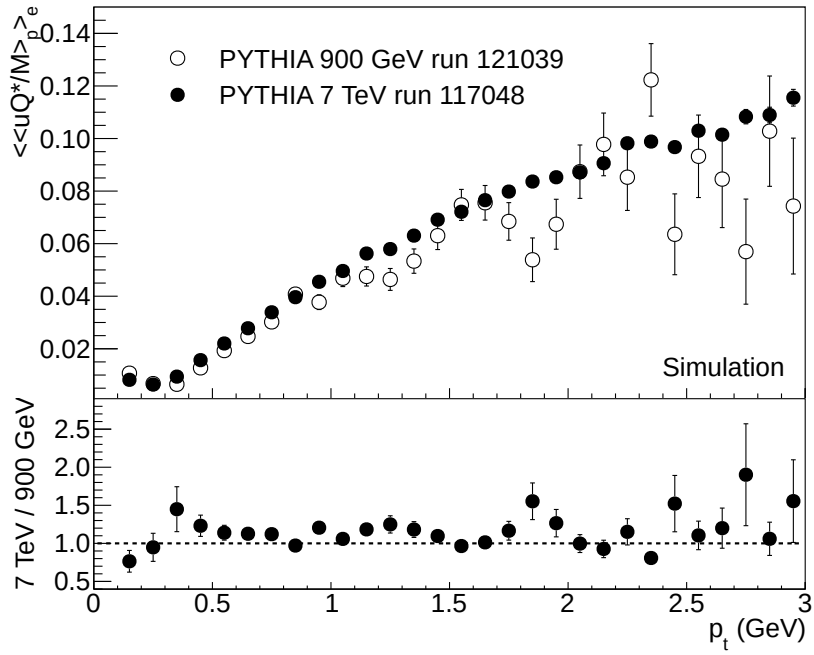
Looking more closely at the ratio of the two centre of mass energies a dependence on p_t in the data is visible, which means the scaling is not perfect. However, the deviation is small and therefore the scaling can be used for the interpolation to the current Pb-Pb energy. The uncertainty on the scaling should be absorbed in the systematic error.

B.4 Centrality dependence in Pb-Pb collisions

For the nonflow correction in Pb-Pb to be valid, the nonflow component should not depend on the centrality of the collision. In this section the Monte Carlo event generator HIJING [80] for the simulation of heavy ion collisions is used to test this assumption. HIJING does not by itself include elliptic flow in its events which makes it very suitable to study the nonflow behaviour. Events in several impact parameter ranges were generated



a) data



b) Monte Carlo

Figure B.4: $\left\langle \left\langle u \cdot \frac{Q^*}{M_Q} \right\rangle_{p_e} \right\rangle$ for proton-proton data (a) and Monte Carlo (b) at 900 GeV (solid circles) and 7 TeV (open circles), together with the ratio between the results at 7 TeV and 900 GeV.

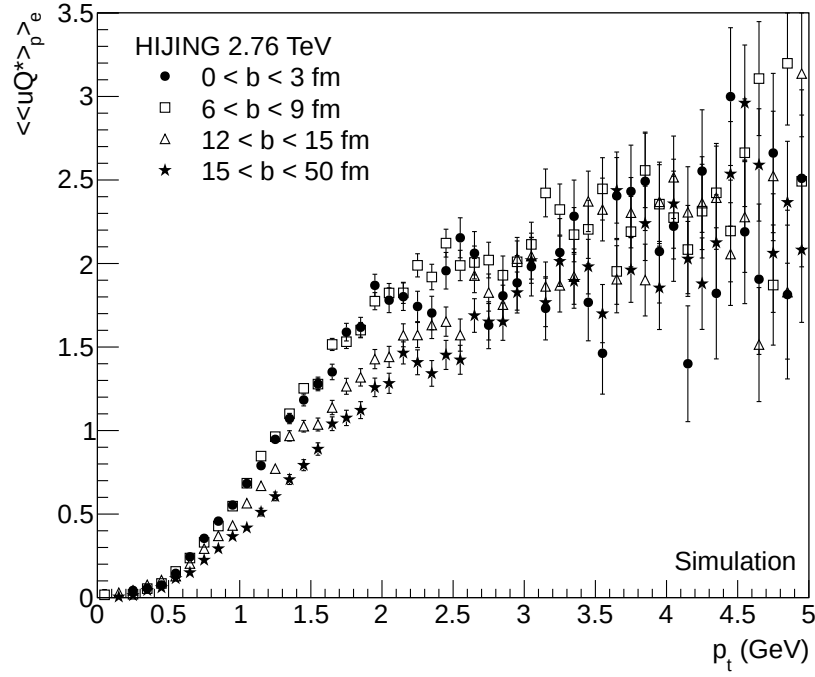


Figure B.5: $\langle\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ from Monte Carlo Pb-Pb events at 2.76 TeV without elliptic flow correlations as a function of p_t for four impact parameter ranges: 0-3 fm (solid circles), 6-9 fm (open squares), 12-15 fm (open triangles) and 15-50 fm (solid stars).

Table B.4: Integrated $\langle\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ in HIJING events at 2.75 TeV

impact parameter range	$\langle\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$
0-3 fm	0.396
6-9 fm	0.350
12-15 fm	0.336
15-50 fm	0.283

and analysed. Figure B.5 shows $\langle\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p \rangle_e$ as a function of p_t for four impact parameter ranges: 0-3 fm (solid circles), 6-9 fm (open squares), 12-15 fm (open triangles) and 15-50 fm (solid stars). At low p_t the nonflow correlations are higher for more central events. Above 3 GeV the correlations are the same.

This is even more clear in Figure B.6 which shows the ratio of the other impact parameter ranges over the most peripheral events. The nonflow correlations in soft processes in HIJING are changing with centrality (low p_t) while the nonflow originating from hard scatterings (high p_t) is unchanged. In [79] the correspondence at high p_t is taken as a proof that the nonflow is approximately constant with centrality. In HIJING, however, the nonflow correlations below 2.5 GeV do depend on the centrality of the collision. If the dependence is too strong the correction procedure discussed in this chapter is not valid.

To estimate the effect of this centrality dependence on the nonflow correction procedure, the data in Figure B.5 is integrated over p_t . Table B.4 gives the integrated values.

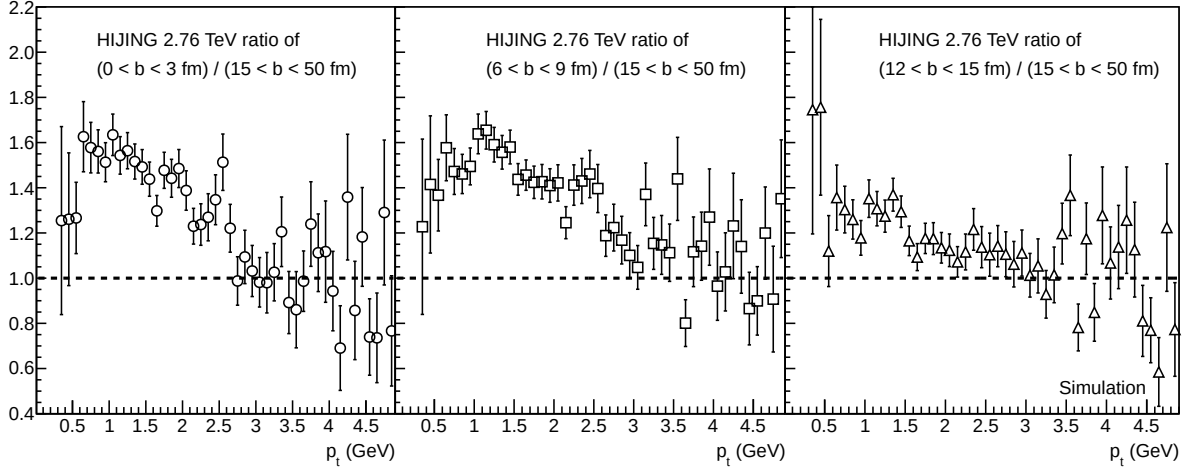


Figure B.6: The ratio between $\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p$ in different impact parameter ranges as a function of p_t . In the left panel in circles the ratio between the most central, 0-3 fm, and most peripheral, 15-50 fm. In the middle panel in squares the ratio between 6-9 fm and 15-50 fm and in the right panel in triangles the ratio between 12-15 fm and 15-50 fm.

The scalar product increases by a factor 1.4 between peripheral and central events. The effect that this difference has on the measurement of v_2 depends on the relative contribution of nonflow to the scalar product. By adding elliptic flow to the generated HIJING events the effect of subtracting too little nonflow on the estimate of v_2 was examined. Integrated elliptic flow of 0.02 was added to the most central events (impact parameter range 0-3 fm). This value is based on the elliptic flow measured in central Pb-Pb collisions at 2.76 TeV [23]. The dependence on p_t was parametrised with a linear rise with p_t up to 2 GeV and then a constant value,

$$v_2 = \begin{cases} 0.03 p_t & \text{for } p_t < 2.0 \\ 0.06 & \text{for } p_t \geq 2.0 \end{cases} \quad (\text{B.10})$$

Subsequently, v_2 was calculated according to Equation B.5 using the nonflow measurement from the same impact parameter range and also using the nonflow from the most peripheral events. Very peripheral Pb-Pb collisions are essentially the same as proton-proton collisions. Because in Monte Carlo generators the overall scaling depends on the tuning of parameters, the nonflow correction is done using the nonflow in the most peripheral events and not the nonflow from PYTHIA generated proton-proton events. Figure B.7 shows the resulting differential flow for the two cases together with the input function of v_2 . When subtracting the nonflow from peripheral events, the resulting v_2 is too high in the region between 1 and 2.5 GeV. In the ratio between the two measurements, shown in the lower panel of Figure B.7, this is clearly visible. When integrating the curves from Figure B.7 over p_t the integrated v_2 from the correction with peripheral events is 2.4% too high.

This is an optimistic estimate of the size of the effect, because the multiplicity in HIJING events is much higher than in real Pb-Pb data. As the flow component of the scalar product scales with the multiplicity its value is smaller for lower multiplicities, while the nonflow component is unchanged. This means that the relative contribution of the nonflow increases for decreasing multiplicity. The exercise was repeated with a scaled

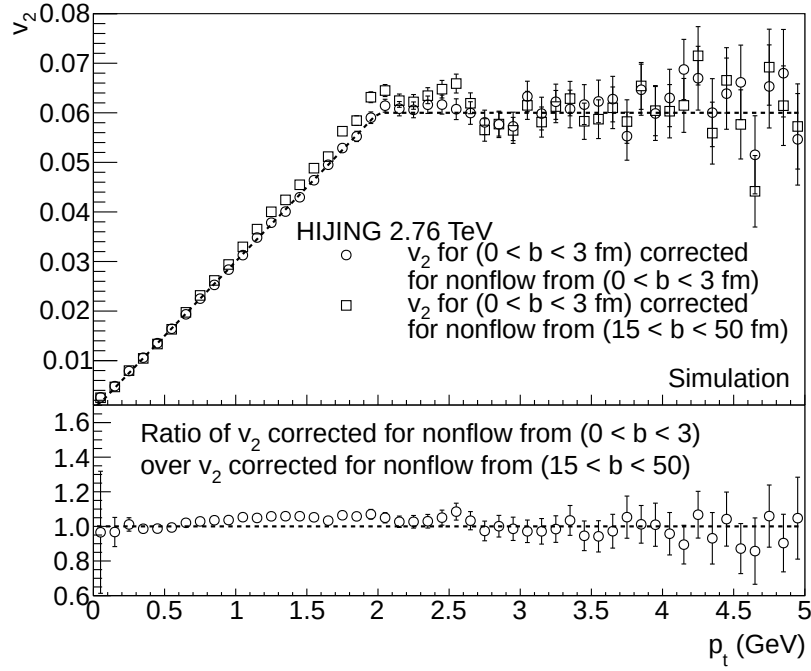


Figure B.7: Differential elliptic flow in Monte Carlo Pb-Pb events for two different corrections for nonflow together with the input v_2 function in the upper panel and their ratio in the lower panel. The two corrections are explained in the main text.

down flow contribution to the scalar product. The scaling factor was based on [23]. The resulting relative overestimate of v_2 was 6.5% in the most central events. For mid-central events the overestimation will be much smaller as the elliptic flow is much higher for these events and the difference in the nonflow from peripheral events is smaller. Also for mid-central events multi-particle analysis methods can be applied which automatically suppress nonflow. This method will be most useful for very central events and very peripheral events. For peripheral events the contribution from nonflow in the scalar product is dominant because of the low total multiplicity.

B.5 Discussion

The method of estimating nonflow measured in proton-proton collisions in order to subtract it in Pb-Pb is shown to work in principle. However, when doing this correction one has to take care that the same kinematic range for tracks and the same detector configuration was used in both proton-proton and Pb-Pb events. The method is based on the assumption that nonflow is the same in proton-proton and Pb-Pb collisions and that the only difference with respect to particle correlations is the presence of collective flow. It is quite possible that also with respect to nonflow correlations something more happens in Pb-Pb collisions which is not described by proton-proton collisions, e.g. the structure and size of (mini)jets might change, which would mean M_c has a different value. According to [79] these kind of effect, if present, are small.

A systematic uncertainty is introduced by the possible presence of a centrality dependence of the nonflow, as seen in HIJING Monte Carlo simulations. Unfortunately, there is no way to verify if in real Pb-Pb events the nonflow also changes with the centrality of the

collision. Pb-Pb events always have flow plus nonflow correlations and they cannot be clearly disentangled because of the additional effect of fluctuations on the measurement. The fact that PYTHIA simulations show the same behaviour as proton-proton data, while the size of the correlations is off, strengthens the trust in HIJING simulations to show the same behaviour as real Pb-Pb data. Measuring the centrality dependence of $\langle \mathbf{u} \cdot \mathbf{Q}^* \rangle_p$ in Pb-Pb data will confirm if for the most peripheral events, where no elliptic flow is present anymore, the nonflow is of the same order as measured in proton-proton collisions. The uncertainty in the centrality dependence should be taken into account in the systematic error when applying the nonflow correction. This systematic error is of the same order as the errors quoted in [23] for central Pb-Pb collisions.

References

- [1] D. J. Griffiths, *Introduction to elementary particles*, John Wiley & Sons, Inc. (1987).
- [2] I. J. R. Aitchison and A. J. Hey, *Gauge Theories of Particle Physics*, IOP Publishing Ltd (1989).
- [3] F. Karsch, *Lattice QCD at High Temperature and Density*, Lect. Notes Phys., **583**: 209–249 (2002).
- [4] R. J. Glauber and G. Matthiae, *High-energy scattering of protons by nuclei*, Nucl. Phys. B., **21**: 135–157 (1970).
- [5] R. J. Glauber, *Quantum Optics and Heavy Ion Physics*, Nucl. Phys. A., **774**: 3–13 (2006).
- [6] E. Iancu and R. Venugopalan, *The Color Glass Condensate and High Energy Scattering in QCD*, R.C. Hwa and X.-N. Wang (editors), *Quark Gluon Plasma, vol. 3*, World Scientific, Singapore (2004).
- [7] R. Hanbury Brown and R. Q. Twiss, *A Test of a New Type of Stellar Interferometer on Sirius*, Nature, **178**: 1046–1048 (1956).
- [8] M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, *Femtoscopy in relativistic heavy ion collisions: Two Decades of Progress*, Ann. Rev. Nucl. Part. Sci., **55**: 357–402 (2005).
- [9] H. A. Gustafsson *et al.*, *Collective Flow Observed in Relativistic Nuclear Collisions*, Phys. Rev. Lett., **52**: 1590–1593 (1984).
- [10] J.-Y. Ollitrault, *Anisotropy as a signature of transverse collective flow*, Phys. Rev. D, **46**: 229–245 (1992).
- [11] STAR collaboration, *Centrality dependence of charged hadron and strange hadron elliptic flow from $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions*, Phys. Rev. C., **77**: 054901 (2008).
- [12] STAR Collaboration, *Azimuthal Anisotropy and Correlations in the Hard Scattering Regime at RHIC*, Phys. Rev. Lett., **90**(3): 032301 (2003).
- [13] R. J. M. Snellings, A. M. Poskanzer, and S. A. Voloshin, *Anisotropic Flow at STAR* (1999), arXiv:9904003 [nucl-ex].
- [14] X.-N. Wang, *Jet quenching and azimuthal anisotropy of large p_T spectra in noncentral high-energy heavy-ion collisions*, Phys. Rev. C, **63**: 054902 (2001).
- [15] M. Gyulassy, I. Vitev, X.-N. Wang, and P. Huovinen, *Transverse expansion and high p_T azimuthal asymmetry at RHIC*, Phys. Lett. B, **526**: 301 – 308 (2002).
- [16] R. Snellings, *Anisotropic flow from RHIC to the LHC*, Eur. Phys. J. C, **49**: 87–90 (2007).
- [17] J.-P. Blaizot, *Theoretical conference summary*, Nucl. Phys. A., **698**: 360–371 (2002).
- [18] P. Huovinen, P. F. Kolb, U. Heinz, P. V. Ruuskanen, and S. A. Voloshin, *Radial and elliptic flow at RHIC: further predictions*, Physics Letters B, **503**: 58 – 64 (2001).
- [19] V. Greco, C. M. Ko, and P. Lévai, *Parton Coalescence and the Antiproton/Pion Anomaly at RHIC*, Phys. Rev. Lett., **90**: 202302 (2003).
- [20] R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, *Hadronization in Heavy-Ion Collisions: Recombination and Fragmentation of Partons*, Phys. Rev. Lett., **90**: 202303 (2003).
- [21] S. A. Voloshin, *Anisotropic flow*, Nuclear Physics A, **715**: 379c – 388c (2003).
- [22] STAR Collaboration, *Multistrange Baryon Elliptic Flow in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. Lett., **95**: 122301 (2005).
- [23] ALICE collaboration, *Elliptic Flow of Charged Particles in Pb-Pb Collisions at 2.76 TeV*, Phys. Rev. Lett., **105**: 252302 (2010).

- [24] M. B. Tsang *et al.*, *Azimuthal correlations between light particles emitted in ^{12}O induced reactions on ^{12}C and ^{197}Au at 400 MeV*, Phys. Lett. B, **148**: 265–269 (1984).
- [25] C. B. Chitwood *et al.*, *Light particle emission in ^{16}O induced reactions on ^{12}C , ^{27}Al , and ^{197}Au at $E/A=25$ MeV*, Phys. Rev. C., **34**: 858–871 (1986).
- [26] H. H. Gutbrod *et al.*, *A new component of the collective flow in relativistic heavy-ion collisions*, Phys. Lett. B, **216**: 267–271 (1989).
- [27] NA49 Collaboration, *Directed and elliptic flow of charged pions and protons in Pb + Pb collisions at 40A and 158A GeV*, Phys. Rev. C., **68**: 034903 (2003).
- [28] H. Masui, J.-Y. Ollitrault, R. Snellings, and A. Tang, *The centrality dependence of v_2/ϵ : the ideal hydro limit and η/s* , Nucl. Phys. A., **830**: 463c–466c (2009).
- [29] D. d’Enterria *et al.*, *Estimates of hadron azimuthal anisotropy from multiparton interactions in proton-proton collisions at 14 TeV*, Eur. Phys. J. C, **66**: 173–185 (2010).
- [30] S. K. Prasad, V. Roy, S. Chattopadhyay, and A. K. Chaudhuri, *Elliptic flow (v_2) in pp collisions at energies available at the CERN Large Hadron Collider: A hydrodynamical approach*, Phys. Rev. C., **82**: 024909 (2010).
- [31] G. Ortona, G. S. Denicol, P. Mota, and T. Kodama, *Elliptic flow in high multiplicity proton-proton collisions at $\sqrt{s} = 14$ TeV as a signature of deconfinement and quantum energy density fluctuations* (2009), arXiv:0911.5158 [hep-ph].
- [32] M. Luzum and P. Romatschke, *Viscous Hydrodynamic Predictions for Nuclear Collisions at the LHC*, Phys. Rev. Lett., **103**: 262302 (2009).
- [33] J. Casalderrey-Solana and U. A. Wiedemann, *Eccentricity Fluctuations Make Flow Measurable in High Multiplicity p-p Collisions*, Phys. Rev. Lett., **104**: 102301 (2010).
- [34] P. Bożek, *Observation of the Collective Flow in Proton-Proton Collisions*, Acta Phys. Polon. B, **41**: 837–844 (2010).
- [35] A. K. Chaudhuri, *Large elliptic flow in low multiplicity pp collisions at LHC energy $\sqrt{s} = 14$ TeV* (2009), arXiv:0912.2578 [nucl-th].
- [36] L. Cunqueiro, J. Dias de Deus, and C. Pajares, *Nuclear-like effects in proton-proton collisions at high energy*, Eur. Phys. J. C, **65**: 423–426 (2010).
- [37] E. Avsar, C. Flensburg, Y. Hatta, J.-Y. Ollitrault, and T. Ueda, *Eccentricity and elliptic flow in proton-proton collisions from parton evolution* (2010), arXiv:1009.5643 [hep-ph].
- [38] ALICE Collaboration, *ALICE: Technical proposal for a Large Ion collider Experiment at the CERN LHC*, CERN/LHCC 95-71 (1995).
- [39] ALICE Collaboration, *Alice Addendum to the Technical Proposal*, CERN/LHCC 96-32 (1996).
- [40] ALICE Collaboration, *Addendum 2 to the Technical Proposal*, CERN/LHCC 99-13 (1999).
- [41] ALICE collaboration, *The ALICE experiment at the CERN LHC*, J. Instrum., **3**: S08002 (2008).
- [42] ALICE collaboration, *ALICE: Physics Performance Report, volume I*, J. Phys. G: Nucl. Part. Phys., **30**: 1517–1764 (2004).
- [43] ALICE collaboration, *ALICE: Physics Performance Report, volume II*, J. Phys. G: Nucl. Part. Phys., **32**: 1295–2040 (2006).
- [44] ALICE Collaboration, *ALICE Technical Design Report of the Inner Tracking System (ITS)*, CERN/LHCC 99-12 (1999).
- [45] ALICE Collaboration, *ALICE Technical Design Report of the Time Projection Chamber*,

CERN/LHCC 2000-001 (2000).

- [46] ALICE Collaboration, *ALICE Technical Design Report on Forward detectors: FMD, T0 and V0*, CERN/LHCC 2004-025 (2004).
- [47] <http://aliweb.cern.ch/Offline/Activities/Analysis/AnalysisFramework/index.html>.
- [48] R. Brun and F. Rademakers, *ROOT: An object oriented data analysis framework*, Nucl. Instrum. Meth. A, **389**: 81–86 (1997).
- [49] ALICE collaboration, *Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV with ALICE at LHC*, Eur. Phys. J. C, **68**: 98–108 (2010).
- [50] F. Alessio, Z. Guzik, and R. Jacobsson, *LHCb Global Timing and Monitoring of the LHC Filling Scheme*, LHCb-PUB-2011-004 (2011).
- [51] L. Evans and P. Bryant, *LHC Machine*, J. Instrum., **3**: S08001 (2008).
- 112 [52] R. Brun *et al.*, *GEANT3 Users Guide*, CERN Data Handling Division, DD/EE/84-1 (1985).
- [53] D. Elia, J. F. Grosse-Oetringhaus, M. Nicassio, and T. Virgili, *The pixel detector based tracklet reconstruction algorithm in ALICE*, ALICE-INT-2009-021 (2009).
- [54] ALICE collaboration, *Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC*, Eur. Phys. J. C, **68**: 345–354 (2010).
- [55] M. Krzewicki, *Anisotropic flow of identified hadrons in heavy ion collisions at the LHC - from detector alignment and calibration to measurement*, Ph.D. thesis, Universiteit Utrecht (2011).
- [56] A. Rossi, *Alice Alignment, Tracking and Physics Performance Results* (2011), arXiv:1101.3491 [physics.ins-det].
- [57] A. M. Poskanzer and S. A. Voloshin, *Methods for analyzing anisotropic flow in relativistic nuclear collisions*, Phys. Rev. C., **58**: 1671–1678 (1998).
- [58] A. M. Poskanzer and S. A. Voloshin, *New Developments in Methods for Anisotropic Flow Analysis* (1998), LBNL Annual Report, R34, <http://ie.lbl.gov/nsd1999/rnc/RNC.htm>.
- [59] M. Miller and R. Snellings, *Eccentricity fluctuations and its possible effect on elliptic flow measurements* (2003), arXiv:0312008 [nucl-ex].
- [60] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, *Flow analysis from multiparticle azimuthal correlations*, Phys. Rev. C., **64**: 054901 (2001).
- [61] A. Bilandžić, R. J. M. Snellings, and S. A. Voloshin, *Flow analysis with cumulants: Direct calculations*, Phys. Rev. C., **83**: 044913 (2011).
- [62] N. Borghini, P. M. Dinh, and J.-Y. Ollitrault, *Thermalization and elliptic flow at RHIC* (2001), arXiv:111402 [hep-ph].
- [63] R. S. Bhalerao and J.-Y. Ollitrault, *Eccentricity fluctuations and elliptic flow at RHIC*, Phys. Lett. B, **641**: 260–264 (2006).
- [64] J.-Y. Ollitrault, A. M. Poskanzer, and S. A. Voloshin, *Effect of flow fluctuations and nonflow on elliptic flow methods*, Phys. Rev. C., **80**: 014904 (2009).
- [65] R. S. Bhalerao, N. Borghini, and J.-Y. Ollitrault, *Analysis of anisotropic flow with Lee–Yang zeroes*, Nucl. Phys. A., **727**: 373–426 (2003).
- [66] R. S. Bhalerao, N. Borghini, and J.-Y. Ollitrault, *Genuine collective flow from Lee–Yang zeroes*, Phys. Lett. B, **580**: 157–162 (2004).
- [67] N. Borghini, R. S. Bhalerao, and J.-Y. Ollitrault, *Anisotropic flow from Lee–Yang zeros: a practical guide*, J. Phys. G: Nucl. Part. Phys., **30**: S1213–S1216 (2004).

- [68] T. D. Lee and C. N. Yang, *Statistical Theory of Equations of State and Phase Transitions. II. Lattice Gas and Ising Model*, Phys. Rev., **87**: 410–419 (1952).
- [69] H. S. Wilf, *generatingfunctionology*, Academic Press, Inc. (1990).
- [70] A. Bilandžić, N. van der Kolk, J.-Y. Ollitrault, and R. Snellings, *Event-plane flow analysis without non-flow effects*, Phys. Rev. C., **83**: 014909 (2011).
- [71] A. Kisiel, T. Tałuć, W. Broniowski, and W. Florkowski, *THERMINATOR: THERMal heavy-IoN generATOR*, Comput. Phys. Commun., **174**: 669–687 (2006).
- [72] F. Cooper and G. Frye, *Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production*, Phys. Rev. D., **10**: 186–189 (1974).
- [73] E. Schnedermann, J. Sollfrank, and U. Heinz, *Thermal phenomenology of hadrons from 200A GeV S+S collisions*, Phys. Rev. C., **48**: 2462–2475 (1993).
- [74] F. Retière and M. A. Lisa, *Observable implications of geometrical and dynamical aspects of freeze-out in heavy ion collisions*, Phys. Rev. C., **70**: 044907 (2004).
- [75] A. Bilandžić, *Anisotropic flow analysis in the ALICE experiment*, AIP Conf. Proc., **1343**: 465–467 (2011).
- [76] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, J. High Energy Phys., **5**: 026 (2006).
- [77] P. Z. Skands, *Tuning Monte Carlo generators: The Perugia Tunes*, Phys. Rev. D., **82**: 074018 (2010).
- [78] L. Devroye, *Non-Uniform Random Variate Generation*, Springer-Verlag, New York (1986).
- [79] STAR collaboration, *Azimuthal Anisotropy and Correlations at Large Transverse Momenta in p+p and Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. Lett., **93**: 252301 (2004).
- [80] M. Gyulassy and X.-N. Wang, *Hijing 1.0: A Monte Carlo program for parton and particle production in high energy hadronic and nuclear collisions*, Comput. Phys. Commun., **83**: 307–331 (1994).

Het standaardmodel van de deeltjesfysica beschrijft alle, tot nu toe, bekende elementaire deeltjes en de krachten die tussen deze deeltjes werken. Zo is er de sterke kernkracht die ervoor zorgt dat quarks in hadronen opgesloten zijn en ook dat de nucleonen in een atoomkern bij elkaar blijven ondanks hun elektrische afstoting. De theorie die deze sterke kernkracht beschrijft heet quantumchromodynamica. Exacte berekeningen in deze theorie zijn moeilijk omdat de gluons, de deeltjes die de sterke kernkracht overdragen, ook onderling interacties aangaan. Daarentegen zijn numerieke berekeningen wel mogelijk en voorspellen deze het bestaan van een nieuwe fase van nucleaire materie bij extreem hoge temperaturen en dichtheden. Deze nieuwe fase heet het *quark gluon plasma* (QGP).

Het ALICE-experiment bij de LHC-versneller nabij Genève is gebouwd om een QGP kortstondig te laten ontstaan in de botsing tussen de kernen van twee loodatomen. Hierdoor kunnen de eigenschappen van het QGP bestudeerd worden. De vorming van een QGP in de botsing zal resulteren in een collectieve beweging van de deeltjes die uit de botsing ontstaan. Dit wordt *collectieve flow* genoemd. De meest dominante uitingvorm van deze collectiviteit is een voorkeursrichting van de ontstane deeltjes in het vlak loodrecht op de bundelpijp.

In een botsing tussen twee loodkernen waarbij deze elkaar maar gedeeltelijk raken is het reactievolume ellipsvormig. Door de opgebouwde druk in het reactievolume, die ontstaat omdat de deeltjes onderling veel interacties ondergaan, en door de ellipsvorm worden de deeltjes naar buiten gedrukt parallel aan de korte as van de ellips. Dit is zichtbaar in de azimuthale verdeling van geproduceerde deeltjes en wordt *elliptische flow* ofwel v_2 genoemd. De grootte van v_2 is gerelateerd aan de mate van thermisch evenwicht in het systeem en aan de toestandsvergelijking van het systeem.

De afgelopen decennia is elliptische flow bij steeds hogere botsingsenergieën bestudeerd. Voor het eerst is bij de Relativistic Heavy Ion Collider in de Verenigde Staten gebleken dat de gemeten waarde van v_2 in overeenstemming is met de voorspelling uit de ideale hydrodynamica. Het QGP lijkt zich als een perfecte vloeistof te gedragen. Bij de nog hogere botsingsenergie van de LHC heeft de gemeten v_2 als functie van de transverse impuls vergelijkbare waarden, maar modellen die een kleine viscositeit toevoegen beschrijven de data het beste. Elliptische flow wordt in het begin van de evolutie van het systeem opgebouwd en de langere levensduur van het QGP beïnvloedt daarom de grootte niet.

De centraliteit van de botsing is een maat voor de manier waarop de kernen elkaar raken. Bij een centrale botsing raken ze elkaar precies in het midden en is het reactievolume maximaal en cirkelvormig. Bij een perifere botsing raken de zijanten van de kernen elkaar net, waardoor het reactievolume klein en ellipsvormig is. De grootte van v_2 hangt af van deze centraliteit: hoog voor semi-perifere botsingen, en laag voor centrale botsingen en zeer perifere botsingen, omdat bij centrale botsingen er geen elliptisch reactievolume is en bij perifere botsingen het aantal gevormde deeltjes te klein is.

De hoge botsingsenergie van de LHC doet theoretici speculeren over de mogelijkheid van collectief gedrag in botsingen tussen protonen. De waarden van v_2 in deze voorspellingen liggen tussen 0 en 0.2 en zijn gebaseerd op diverse theoretische modellen. De in dit proefschrift beschreven analyse geeft een bovengrens voor de waarde van v_2 die aanwezig kan zijn in proton-protonbotsingen bij een energie van 7 TeV.

Analysemethoden

Buiten de correlaties tussen deeltjes door de collectieve beweging zijn er andere correlaties aanwezig. Deze worden samengevat in de term *nonflow*. De aanwezigheid van nonflow, in combinatie met fluctuaties in v_2 , maakt de meting van v_2 moeilijk.

In de loop van de tijd zijn er veel verschillende analysemethoden ontwikkeld. Ze kunnen worden ingedeeld in twee groepen: twee-deeltjescorrelatiemethoden en veel-deeltjescorrelatiemethoden. De veel-deeltjescorrelatiemethoden zijn ontwikkeld om de nonflowcorrelaties te onderdrukken aangezien deze alleen bestaan tussen kleine aantallen deeltjes. Ze zijn beperkt tot botsingen waarvoor het aantal geproduceerde deeltjes of v_2 hoog is. De twee-deeltjescorrelatiemethoden zijn minder beperkt toepasbaar maar kunnen geen onderscheid maken tussen flow- en nonflowcorrelaties.

De invloed van fluctuaties in v_2 op de gemeten waarde is tegengesteld voor twee-deeltjescorrelatiemethoden en veel-deeltjescorrelatiemethoden: de eerste overschatten de waarde terwijl de laatste juist onderschatten. Een boven- en ondergrens kunnen gevonden worden door verschillende methoden naast elkaar te gebruiken. Verschillende methoden met hetzelfde gedrag geven een onafhankelijke meting hetgeen de betrouwbaarheid van het resultaat vergroot.

Al de analysemethoden zijn ontwikkeld om toegepast te worden op botsingen van zware ionen waarbij grote hoeveelheden deeltjes ontstaan. Het gebruik ervan op proton-protonbotsingen waarbij het aantal geproduceerde deeltjes klein is, is daarom niet eenduidig. De veel-deeltjescorrelatiemethoden kunnen niet gebruikt worden voor deze botsingen tenzij de elliptische flow erg hoog is. Daarom is gekozen voor de inproduct-methode, een twee-deeltjescorrelatiemethode, die gebruik maakt van twee *subevents* waarmee de nonflowcorrelaties onderdrukt kunnen worden. Een subevent is een subset van de geproduceerde deeltjes. Door de twee subevents ver uitelkaar te kiezen worden correlaties over korte afstanden verwijderd. Nonflow bestaat voornamelijk uit dit soort korteaafstandcorrelaties terwijl elliptische flow een correlatie geeft tussen alle deeltjes en dus ook over lange afstanden. Door op deze manier de invloed van nonflow op de meting te verminderen kan een bovengrens aan de waarde van v_2 in 7 TeV proton-protonbotsingen gevonden worden.

Een bovengrens op v_2 in 7 TeV proton-protonbotsingen

Proton-protonbotsingen met een botsingsenergie van 7 TeV geregistreerd door het ALICE-experiment in 2010 zijn bestudeerd voor de studie die beschreven is in dit proefschrift. De banen van de deeltjes die ontstaan in deze botsingen zijn gereconstrueerd met behulp van de TPC (Time Projection Chamber) en ITS (Inner Tracking System), subdetectoren die voor dit doel zijn ontworpen.

Nonflowcorrelaties zullen overheersen in proton-protonbotsingen waardoor de aanwezige elliptische flow mogelijk niet zichtbaar is. Door de nonflowcorrelaties te onderdrukken kan de elliptische flow meetbaar worden. Hoe effectief de onderdrukking is, blijkt af te hangen van het bereik in pseudorapiditeit van de nonflowcorrelaties.

De analyse bestaat uit het variëren van de afstand tussen de subevents en het bestuderen van de invloed op de gemeten v_2 . Er is gekeken naar twee meetbare grootheden: de

gemeten twee-deeltjescorrelatie $v_2\{\text{SP}\}$ en de twee-deeltjescorrelatie tussen de subevents $v_2\{\text{subevents}\}$. Waarbij de laatste een grootte is die als referentie dient en gebruikt wordt in de berekening van $v_2\{\text{SP}\}$. Als correlaties voortkomen uit elliptische flow dan is er geen afhankelijkheid van de afstand tussen de subevents, terwijl bij nonflowcorrelaties $v_2\{\text{subevents}\}$ afneemt met de afstand en $v_2\{\text{SP}\}$ zelfs toeneemt.

De resultaten van deze analyse op 7 TeV-protondata suggereren een dominante nonflow-component omdat $v_2\{\text{subevents}\}$ afneemt. Dezelfde afhankelijkheid van de afstand is te zien in Monte Carlo data waarin alleen maar nonflowcorrelaties aanwezig zijn. Het lijkt dat in de data voornamelijk of alleen maar correlaties veroorzaakt door nonflow aanwezig zijn.

De minimale waarde die de elliptische flow moet hebben om de gemeten waarde van v_2 te beïnvloeden is te vinden door aan de Monte Carlo simulatie elliptische flow correlaties toe te voegen. Hieruit volgt dat deze groter moet zijn dan 0.15 om zichtbaar te worden in $v_2\{\text{SP}\}$ en groter dan 0.1 om $v_2\{\text{subevents}\}$ te beïnvloeden.

In deze studie is gebleken dat $v_2\{\text{subevents}\}$ geschikter is om een bovengrens voor v_2 te vinden dan $v_2\{\text{SP}\}$. Deze bovengrens kan gevonden worden omdat de gemeten waarde van $v_2\{\text{subevents}\}$ altijd groter is dan de aanwezige elliptische flow. Dit betekent dat voor proton-proton botsingen bij een botsingsenergie van 7 TeV, waarbij tenminste 10 deeltjes gemeten zijn, v_2 maximaal een waarde van 0.05 heeft. Omdat het verschil tussen $v_2\{\text{subevents}\}$ en $v_2\{\text{SP}\}$ aanzienlijk is, wat niet het geval is bij een dominante elliptische flow, is de waarde van v_2 zeer waarschijnlijk nog lager dan dat. Voorspellingen van een hogere v_2 dan 0.05 kunnen dus uitgesloten worden. Sommige voorspellingen zijn alleen van toepassing voor een groter gemiddeld aantal deeltjes dan 10; over deze voorspellingen kan nog geen uitspraak gedaan worden. De volgende stap in de analyse is daarom ook het onderzoeken van de afhankelijkheid van het aantal deeltjes en de vergroting van het gat tussen de subevents zodat nog kleinere waarden van de elliptische flow uitgesloten kunnen worden.

De maximale afstand tussen de twee subevents is niet groot genoeg om te kunnen concluderen of $v_2\{\text{subevents}\}$ zal blijven afnemen, wat duidt op dominante korteafstandscorrelaties, of dat de waarde constant zal blijven, wat duidt op een langeafstandscorrelatie. Nonflowcorrelaties blijken afhankelijk te zijn van de detectorconfiguratie en het kinematische bereik van de deeltjes. Dit is beschreven in Appendix A. Dit betekent dat resultaten verkregen in verschillende subdetectoren binnen ALICE niet met elkaar vergeleken kunnen worden, iets dat wel mogelijk is in het geval van dominante elliptische flow.

Als het zo is dat alle correlaties aanwezig in proton-proton botsingen veroorzaakt worden door nonflow, kunnen proton-proton botsingen gebruikt worden om de contributie van nonflow in lood-loodbotsingen af te schatten. Deze toepassing is beschreven en getest in Appendix B.

Curriculum Vitae

1998–1999	HAVO Regionaal Opleidingen Centrum Eindhoven
1999–2003	Technische Natuurkunde / Applied Physics (cum laude) Fontys Hogescholen Eindhoven
2003–2006	Experimental Physics Institute of Subatomic Physics, Utrecht University
2006–2011	Promotieonderzoek / PhD research project ALICE group at Nikhef, Amsterdam

