

MEASUREMENT OF ω AND η MESONS VIA THEIR
THREE PION DECAY WITH ALICE IN PP COLLISIONS AT
 $\sqrt{s} = 7$ TEV

FLORIAN JONAS

MASTER THESIS



AG ANDRONIC
INSTITUT FÜR KERNPHYSIK
WESTFÄLISCHE WILHELMS-UNIVERSITÄT
MÜNSTER

SEPTEMBER 2018



FLORIAN JONAS

MEASUREMENT OF ω AND η MESONS VIA THEIR THREE PION
DECAY WITH ALICE IN PP COLLISIONS AT $\sqrt{s} = 7$ TEV

First referee:

Priv.-Doz. Dr. Christian Klein-Bösing

Second referee:

Prof. Dr. Anton Andronic

Supervision:

Daniel Mühlheim & Friederike Bock

Note:

Some minor errors have been fixed in this version of the thesis. It therefore differs slightly from the version given to the referees.

ABSTRACT

A Large Ion Collider Experiment ([ALICE](#)) is an experiment at the Large Hadron Collider ([LHC](#)), focussing on heavy-ion physics, in particular on the so-called Quark-Gluon Plasma ([QGP](#)), a state of strongly interacting matter in which quarks and gluons exist as unconfined particles. One way to probe this medium is the measurement of direct photons that escape the medium and can be measured as an excess over a photonic background. Most of this background originates from hadronic decays and precise knowledge of hadron production in a collision, especially the production of neutral mesons, is therefore crucial for such measurements in order to properly describe their background. Furthermore, neutral meson cross sections are used to test and constrain theory predictions of meson production, making production cross section measurements valuable for theory and experiment alike.

In this thesis, differential invariant cross sections of ω and η meson production are measured in proton-proton collisions at $\sqrt{s} = 7$ TeV via their decay to $\pi^+\pi^-\pi^0$. For the first time, all available methods to measure photons at mid-rapidity within [ALICE](#) are used to reconstruct the ω meson, allowing to access a wide momentum range. The production cross section of η mesons is measured for the first time in the three pion decay channel at this collision energy, serving as a supplement and cross check for the well established $\eta \rightarrow \gamma\gamma$ measurement. The obtained cross sections are found to be consistent with existing measurements at this centre-of-mass energy, as well as reasonably well described by PYTHIA predictions. Furthermore ω/π^0 and η/π^0 ratios are presented, both of which are underestimated by PYTHIA predictions but mostly consistent with previous measurements.

ZUSAMMENFASSUNG

A Large Ion Collider Experiment ([ALICE](#)) ist ein Experiment am Large Hadron Collider ([LHC](#)) mit physikalischem Fokus auf Schwerionen Kollision, im Speziellen auf das so genannte Quark-Gluon Plasma ([QGP](#)), ein Zustand stark wechselwirkender Materie in dem Quarks und Gluonen als ungebundene Teilchen existieren. Eine Möglichkeit dieses Medium zu erforschen ist die Messung von direkten Photonen, welche das Medium verlassen und dann als Überschuss über einem photonischen Hintergrund gemessen werden können. Dieser kommt zum größten Teil aus hadronischen Zerfällen und folglich ist genaue Kenntnis über Hadronenproduktion in Kollisionen, speziell die Produktion von neutralen Mesonen, wesentlich um in solchen Messungen den Hintergrund zu beschreiben. Ausserdem werden neutrale Mesonen Wirkungsquerschnitte verwendet um Theorievorhersagen zu testen und einzuschränken, und machen so die Messung von Produktionswirkungsquerschnitten zu einem wichtigen Werkzeug für Theorie und Experiment.

In dieser Arbeit werden die differentiellen Wirkungsquerschnitte der Produktion von ω und η Mesonen in Proton-Proton Kollisionen bei $\sqrt{s} = 7$ TeV über ihren Zerfall zu $\pi^+\pi^-\pi^0$ gemessen. Zum ersten Mal werden hierbei alle in [ALICE](#) bei mittleren Rapiditäten verfügbaren Methoden zur Photonenmessung zur Rekonstruktion des

ω Mesons verwendet, die es so erlauben einen großen Impulsbereich abzudecken. Der Produktionswirkungsquerschnitt des η Mesons wird bei dieser Kollisionsenergie zum ersten Mal in diesem Zerfallskanal gemessen, und dient so als Erweiterung und Gegenprobe für die gut etablierte $\eta \rightarrow \gamma\gamma$ Messung. Die bestimmten Wirkungsquerschnitte sind konsistent mit existierenden Messungen bei dieser Schwerpunktsenergie und werden zusätzlich gut von PYTHIA Vorhersagen beschrieben. Ferner werden ω/π^0 und η/π^0 Verhältnisse präsentiert, welche beide von PYTHIA unterschätzt werden, jedoch weitestgehend konsistent mit anderen Messungen sind.

ACKNOWLEDGMENTS

I want to use this opportunity to thank everybody who helped and supported me throughout this thesis! Foremost, I want to thank Priv.-Doz. Dr. Christian Klein-Bösing and Prof. Dr. Anton Andronic for reviewing this thesis. I am also especially grateful to Daniel Mühlheim and Friederike Bock for their supervision during which they took plenty of their time to answer my questions and give advice. Moreover, I want to thank Dr. Constantin Loizides for his ongoing support during my time at CERN and beyond. It was a pleasure working with my colleagues and I want to especially thank Hendrik Poppenborg for proofreading this thesis and the many interesting discussions we had – also aside of work.

Finally, I want to thank my family for their ongoing love and support – without them my studies and this thesis wouldn't be possible.

CONTENTS

1	INTRODUCTION	1
2	THEORETICAL BACKGROUND	3
2.1	Quarks, Gluons and Quantum Chromodynamics	3
2.1.1	The Standard Model	3
2.1.2	Quantum Chromodynamics	4
2.1.3	Quarks in Hadrons	6
2.2	Particle Production in Hadron-Hadron Collisions	8
2.2.1	Kinematic Variables	8
2.2.2	Hadron-Hadron Collisions	9
2.3	The Quark-Gluon Plasma	12
2.4	Particle Interaction with Matter	16
3	EXPERIMENTAL SETUP	19
3.1	The Large Hadron Collider (LHC)	19
3.2	A Large Ion Collider Experiment (ALICE)	20
3.2.1	Inner Tracking System (ITS)	21
3.2.2	Time Projection Chamber (TPC)	22
3.2.3	Transition Radiation Detector (TRD)	23
3.2.4	Time-Of-Flight Detector (TOF)	23
3.2.5	Photon Spectrometer (PHOS)	23
3.2.6	Electromagnetic Calorimeter (EMCal)	24
3.2.7	VZERO Detector	25
3.3	The Analysis Framework	26
3.4	Track and Vertex Reconstruction	26
3.4.1	Primary Vertex	26
3.4.2	Charged Particle Tracking	27
3.4.3	Secondary Vertices	28
4	DATA SETS AND MONTE CARLO SIMULATIONS	31
4.1	Run Selection	31
4.2	Monte Carlo Simulations	32
4.3	Event Selection	32
5	CHARGED PION MEASUREMENT	37
5.1	Track Selection	37
5.2	Pion Identification	38
6	PHOTON MEASUREMENT	41
6.1	Photon Measurement with the EMCal	41
6.2	Photon Measurement with the PHOS	44
6.2.1	Cluster Selection	45
6.2.2	Quality Assurance	46
6.3	Photon Reconstruction with the PCM	50

7	NEUTRAL PION RECONSTRUCTION	55
7.1	Invariant Mass Method	55
7.2	Neutral Pion Selection	57
8	NEUTRAL MESON ANALYSIS	59
8.1	Neutral Meson Reconstruction	59
8.1.1	Background Description	60
8.1.2	Signal Extraction	63
8.2	Spectra Corrections	69
8.3	Evaluation of Systematic Uncertainties	71
8.4	Invariant Meson Cross Sections & Combination of Measurements	76
9	RESULTS	83
10	SUMMARY & OUTLOOK	89
A	ADDITIONAL FIGURES	91
A.1	Background Studies	91
A.2	Signal Extraction	92
A.3	Systematic Uncertainties	102
A.4	Combination of Measurements	106
B	ADDITIONAL TABLES	107
	LIST OF FIGURES	111
	LIST OF TABLES	115
	ACRONYMS	116
	BIBLIOGRAPHY	119

INTRODUCTION

Questions about the structure, origin and evolution of our universe, have long been only in the domain of philosophy: Atomistic ideas that our world consists of literally indivisible (atomos) objects, reach back as far as the 5th c. BCE to Leucippus and his student Democritus, and their ideas would spark metaphysical debates for centuries to come [1]. The question of the origin of the universe was of great interest for philosophers throughout history as well, especially in the medieval times, where the question about the worlds beginning was closely tied to a theological debate about the existence of god. However, answers for these fundamental questions used to be out of reach for scientific methods, limiting the debates to different logical and metaphysical arguments.

The scientific developments of the last century after all brought us to a point, where we finally have the opportunity to tackle those questions empirically: At the Large Hadron Collider (LHC) – the most powerful particle accelerator to date – two protons, heavy nuclei or a combination of the two can be collided. The high energy densities reached in these collisions do not only allow us to probe and create particles that we believe are the most basic constituents of matter; they furthermore allow us to learn about the early stages of our universe and its evolution by studying the evolution of the collision itself.

This thesis is carried out as part of A Large Ion Collider Experiment (ALICE), one of four experiments at the LHC, dedicated to heavy-ion physics. Its research focusses on strongly interacting matter and the so-called Quark-Gluon Plasma (QGP), a phase in which quarks and gluons exist as unconfined particles. The formation of this medium, which existed only milliseconds after the big bang, is expected in Pb-Pb collisions at LHC energies, and supported by measurements up to this point. Learning about this state of strongly interacting matter not only allows us to probe the early evolution of our universe and push physics closer to its origin, it also improves our knowledge of strong interaction in general and therefore can answer some of the remaining questions about the structure of the universe itself [2].

In this thesis, the production of ω and η mesons is measured in proton-proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, which were recorded by ALICE in 2010. Both mesons are reconstructed using their $\pi^+\pi^-\pi^0$ decay channel. This requires the measurement of the charged pions using ALICE's tracking capabilities, as well as a reconstruction of the neutral pions via their decay into two photons. In this thesis, all methods available in ALICE to measure photons will be used: Its two calorimeters, the Electromagnetic Calorimeter (EMCal) and the Photon Spectrometer (PHOS), as well as the so-called Photon Conversion Method (PCM), which allows to measure photons via pair conversions. In addition, two hybrid approaches are used for the neutral pion reconstruction which combine calorimeter photon measurements with the PCM.

Meson measurements have a variety of motivations:

1. The obtained cross sections can be used to test Quantum Chromodynamics (QCD) – the theory used to describe strong interaction: Hard processes, which means processes with high (enough) momentum transfer Q^2 , can be described quantitatively by perturbative QCD (pQCD). However, a Parton Distribution Function (PDF) – describing the momentum distribution within the colliding nucleons – as well as a Fragmentation Function (FF), which relates the outgoing partons to the hadrons produced in the collision, are needed as additional input to calculate production cross sections. Comparing meson measurements with existing pQCD calculation allows to put constraints on PDF and FF and therefore improves the power of pQCD to make quantitative predictions.
2. The obtained cross sections are needed as input for other analysis such as direct photon [3] and di-electron [4] measurements: To measure direct photons, a precise knowledge of all photons originating from hadronic decays is needed, which is directly linked to the cross sections of the hadrons themselves. The measurement of ω mesons is important in particular, given the fact that it is the third biggest contribution to all decay photons. Likewise, the measurement of leptons originating from heavy flavour decays requires a precise knowledge of the lepton background originating from all non-heavy flavour decays and therefore this analysis relies on meson measurements as well.
3. Because quantitative predictions using pQCD are only valid for hard processes, particle production through soft processes with low momentum transfer Q^2 can not be described perturbatively any longer. Monte Carlo (MC) particle generators like PYTHIA or PHOJET, which are widely used in particle physics, have to rely on phenomenological models, as well as experimental data used to adjust certain parameters, in order to describe particle production in this regime. Comparing the measured production of neutral mesons with the predictions made by MC generators such as PYTHIA allows to test and constrain the models and adjustments used by the generator to describe particle production.
4. Measurements of ω meson properties, such as mass and width, can give important insights into QGP properties: In presence of the medium, a decrease of the mesons mass as well as a drastic increase in width is expected, due to a partial restoration of chiral symmetry in the hot/dense medium. A variety of theoretical predictions exist for such in-medium modifications and measurements are needed to test the models available [5, 6].

This thesis is structured as follows: After this introduction and motivation, Chap. 2 elaborates the theoretical prerequisites needed for this analysis, including a discussion of the mesons which are subject of this thesis; asking how they are created and how they can support the quest to improve knowledge of the QGP. After outlining the experimental setup in Chap. 3, i.e. the LHC and ALICE, the rest of this thesis follows the course of the analysis: First, the datasets and their selection – the input of the analysis – are discussed in Chap. 4. The following chapters deal with the measurement of charged pions, photons and neutral pions – the ingredients needed for the ω and η reconstruction. The reconstruction procedure for these mesons is finally covered in Chap. 8 before selected results are presented in Chap. 9. Finally, this thesis concludes with a summary and brief outlook in Chap. 10.

THEORETICAL BACKGROUND

In this chapter, a brief introduction into the theoretical prerequisites needed for the analysis presented in this thesis is given. The first section introduces the Standard Model, which describes the elementary particles and their interactions, with special focus on the strong interaction and the underlying theory of QCD and its implications. Furthermore, the quark model is described, including a discussion of the mesons measured in this thesis. The second section gives an introduction into hadron-hadron collisions, the nomenclature needed to describe them, as well as insights into particle production. The third section outlines the important properties of the QGP, where this medium is expected to form and how one can probe it experimentally. The final section gives a brief overview of the possible interactions of particles with matter which is needed to understand the detection principles used in ALICE.

2.1 QUARKS, GLUONS AND QUANTUM CHROMODYNAMICS

2.1.1 *The Standard Model*

What is the universe made of on the most fundamental level and how do these constituents interact with one another? Physicist's answer to this question – and probably one of the greatest achievements of modern physics – is the Standard Model of particle physics which has been tested in many experiments throughout the last century and is able to explain most phenomena encountered in particle physics. This Quantum Field Theory (QFT) distinguishes between two types of matter fields: The quarks and the leptons which are themselves divided into three families or generations. There are six different quarks (up, down, charm, strange, top and bottom), which carry a colour and electro-weak charge, and three types of leptons (e, μ and τ) and their corresponding neutrinos (ν_e, ν_μ, ν_τ), which only carry a electro-weak charge. Interactions within the Standard Model are described by three fundamental forces: The electromagnetic force, the strong force and the weak force. Gravitation is not part of the Standard Model and negligible on the small scales of particle interactions. Each force is mediated by a gauge boson with spin 1: The electromagnetic force, which is described by the theory of Quantum Electrodynamics (QED), is mediated by a photon which couples to the electric charge but does not carry a charge itself. Strong interaction is described by Quantum Chromodynamics (QCD) and the corresponding strong force is mediated by 8 different gluons. They couple to the colour charge (red, green, blue), but unlike the photon the gluons carry a colour charge themselves. This leads to a variety of interesting phenomena, such as confinement and asymptotic freedom, that will be covered in the following section. The force-carrying particles of the weak interaction are the charged W^+ and W^- and the neutral Z boson. Apart from the quarks and fermions, which carry spin 1/2, and the bosons with spin 1 that mediate the fundamental forces, there is a scalar boson with spin 0 called Higgs. It is described as an excitation of a scalar Higgs field and the initially massless particles

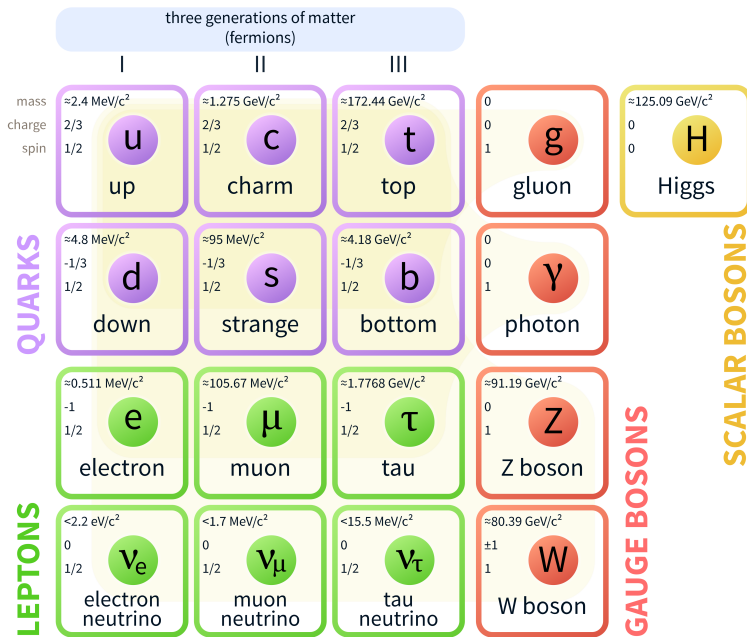


Figure 2.1: Overview of the fundamental particles of the Standard Model [7].

interact with this field and gain their masses. The observation of this particle at the LHC in 2012 was one of the last missing verifications of the Standard Model. An overview of the particles contained in the Standard Model of particle physics and a selection of their properties can be found in Fig. 2.1. The summary of the Standard Model presented in this section has been compiled using Ref. [8–11].

2.1.2 Quantum Chromodynamics

The underlying symmetry of QCD is the $SU(3)$ group, the special unitary group in three dimensions. This group consists of 8 independent 3×3 matrices with determinant one that can be represented using the 8 Gell-Mann matrices. These matrices correspond to the 8 gluons in colour space and can operate on one another, as well as a set of 3-vectors representing the quarks in colour space, where the three dimensions correspond to the three colour charges. Therefore gluons can couple to quarks as well as to other gluons and the latter is referred to as self-interaction. It arises due to the fact that the generators of $SU(3)$ symmetry group do not commute, making QCD a so-called non-Abelian gauge theory. Leptons do not carry a colour-charge and therefore do not interact strongly [12].

The possible couplings of quarks and gluons by QCD can be found in Fig. 2.2. The vertex of a quark and gluon interaction (left) is analogue to the one describing the interaction between a photon and a quark in QED. However, the two additional vertices arise due to gluon-gluon self interaction. The strength of the interaction at the vertex is quantified by the coupling strength g_s of QCD which is related to the coupling “constant” via $\alpha_s = g_s^2/4\pi$. The coupling constant α_s is apart from the masses of the quarks m_q the only free parameter in QCD and therefore its value can not be derived theoretically and has to be measured in experiments. It can be shown that the coupling constant of QCD, rather than being (almost) constant like

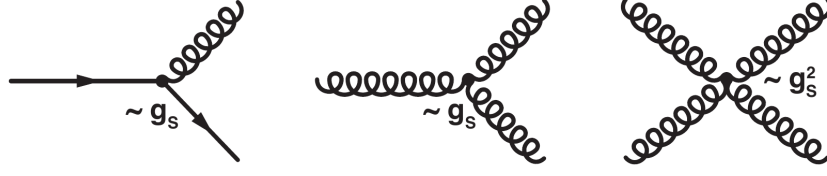


Figure 2.2: The fundamental vertices of QCD, where quarks are represented by solid lines and gluons by curled lines [9].

the coupling constant $\alpha_{e.m.} \approx 1/137$ for QED, depends heavily on the momentum Q^2 that is transferred in an interaction. Leading-order pQCD calculations show that the coupling constant is given by:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f) \ln \frac{Q^2}{\Lambda^2}}, \quad (2.1)$$

where N_f is the number of quark flavours and Λ is a scale parameter that describes the energy at which the coupling would diverge. However, this does not imply that QCD physically diverges at a momentum transfer Λ^2 , it only states that it diverges within the treatment of pQCD and that actual full QCD has to be treated non-perturbatively below this scale, which is of the order $\Lambda \approx 200$ MeV [9, 13].

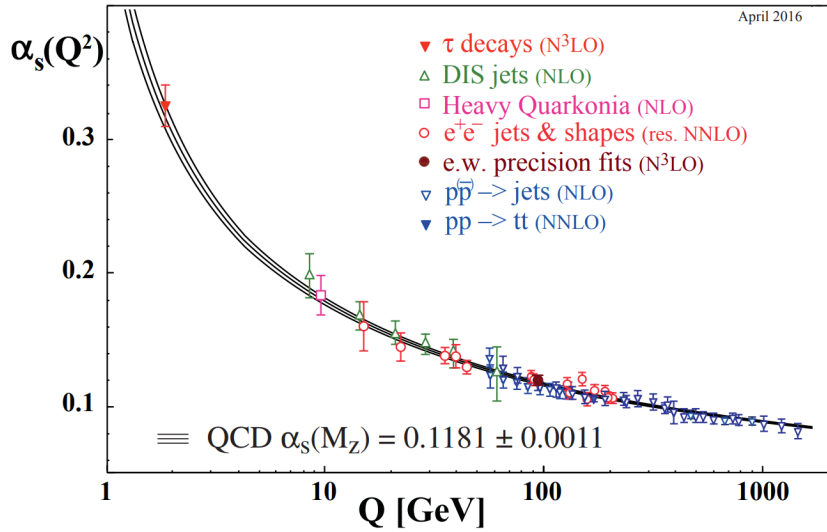


Figure 2.3: Different measurements of the coupling constant α_s obtained through different experiments and methods at different momentum transfers Q . The acronyms in the brackets specify the order used in pQCD calculations that went into the extraction of α_s [14].

Fig. 2.3 shows α_s as a function of momentum transfer Q , where the points with the corresponding uncertainties represent various measurements of α_s performed by different experiments. The acronyms in the brackets next to the measurements specify the highest order of the pQCD calculations that went into the extraction of α_s . All results are fitted using a function for α_s similar to the one expressed in (2.1) and the world average of $\alpha_s(M_Z)$ is given, where M_Z stands for the mass of the Z

boson [14]. Describing α_s in terms of M_Z as an energy scale is commonly used when comparing coupling constants obtained using different techniques. One can see that the coupling constant is small for high momentum transfer Q or small distances. This property of QCD is called asymptotic freedom and this high momentum region can be described within pQCD. However, the coupling becomes large for decreasing momentum and one has to resort to non-perturbative techniques in this regime, such as QCD calculations on a discrete lattice in space and time. These calculations suggest that for large enough distances r the potential V of QCD is given by:

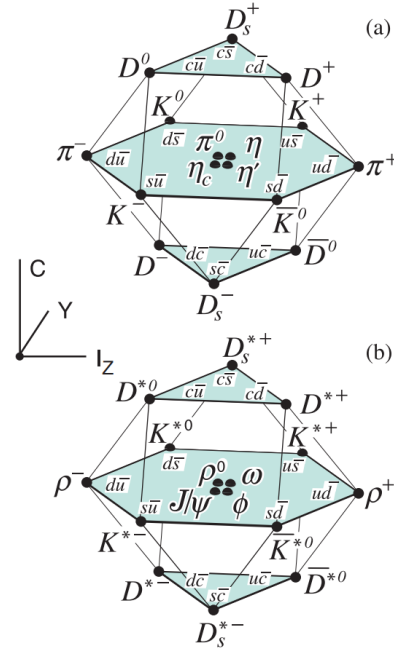
$$V(r) \sim \kappa r, \quad (2.2)$$

where κ is a constant that was experimentally determined to be $\kappa \sim 1 \text{ GeV}$ [11]. This energy increase with distance is the reason why it is energetically favourable for coloured particles to arrange themselves in bound colourless systems called hadrons. The hypothesis that all coloured objects are confined to colourless states is called colour confinement and so far there have been no observations of free quarks or gluons, supporting the colour confinement hypothesis [13].

2.1.3 Quarks in Hadrons

In the previous section it was stated that quarks and gluons are confined to exist in bound colourless states called hadrons. In this section, the different types of hadrons, the mesons and the baryons are elaborated with special focus on the properties of the mesons analysed in this thesis.

MESONS A meson is a quark-antiquark pair ($q\bar{q}'$), where q stands for the quark and $\bar{q}'$ stands for the anti-quark. The quark carries one of the three colour charges and the anti-quark carries the corresponding anti-colour, resulting in an overall colour neutral state. If only the three lightest quarks are considered, there are 9 possible $q\bar{q}'$ combinations which are grouped into an octet and a singlet according to an $SU(3)$ flavour symmetry, not to be confused with the exact colour $SU(3)$. If moreover the heavier charm quark c is considered as well, there are 16 possible states which are grouped into a 15-plet and a singlet following the rules of the $SU(4)$ group. However, this symmetry is badly broken due to the c quarks heavier mass. For each of the possible $q\bar{q}'$ combinations the spins of the quarks have to be taken into account, which can arrange themselves to be parallel ($s = 1$) or antiparallel ($s = 0$), as well as a possible orbital angular momentum l of the bound state. The spin of the meson J is then given



by $|l - s| \leq J \leq |l + s|$. The parity P of the meson is defined via $(-1)^{l+1}$ and in addition the C-parity is given as $C = (-1)^{l+s}$ for mesons that are made up of quark and antiquark with same flavour. All mesons are then grouped in J^{PC} multiplets, where the mesons with no angular orbital momentum $l = 0$ are called pseudoscalars (0^{-+}) and vectors (1^{--}) and the mesons with an orbital excitation $l = 1$ are called scalars (0^{++}), axial vectors (1^{++} and 1^{+-}) and tensors (2^{++}) [14].

The diagrams in Fig. 2.4 show the pseudoscalar (a) and the vector mesons (b), considering the quark flavours u, d, c and s . The axis represent three quantum numbers of the mesons which can be obtained by adding up the quantum numbers of the constituent quarks: The charm C , the hypercharge Y and the z-component of the isospin I_z . The mesons analysed in this thesis are the ω meson, which belongs to the vector mesons (1^{--}), and the η meson, which belongs to the pseudoscalar mesons (0^{-+}).

The ω meson has a mass of $M_\omega = (782.65 \pm 0.12) \text{ MeV}/c^2$ and a full decay width of $\Gamma_{\text{Tot}} = (8.49 \pm 0.08) \text{ MeV}/c^2$. The decay channel $\omega \rightarrow \pi^+ \pi^- \pi^0$ is the most probable one with a branching ratio of $\Gamma_{\pi^+ \pi^- \pi^0} / \Gamma_{\text{Tot}} = (89.2 \pm 0.7) \%$ and is therefore used in this analysis to reconstruct the ω meson. In the future, one could also try to access the meson via the $\omega \rightarrow \pi^0 \gamma$ decay. However, the lower branching ratio $\Gamma_{\pi^0 \gamma} / \Gamma_{\text{Tot}} = (8.28 \pm 0.28) \%$ as well as the lower reconstruction efficiency when measuring in total three photons¹ aggravate the reconstruction in this channel. The wave function of the ω meson is defined via the mixing:

$$\omega = \psi_8 \sin \theta_V + \psi_1 \cos \theta_V, \quad (2.3)$$

where $\theta_V = 36.4^\circ$ is the mixing angle for vector mesons and ψ_1 and ψ_8 are two of the $SU(3)$ wave functions given by:

$$\begin{aligned} \psi_1 &= \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \\ \psi_8 &= \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}). \end{aligned} \quad (2.4)$$

Even though ψ_1 and ψ_2 contain contributions from u, d and s flavours, the contribution from the strange flavour almost cancels out completely in the mixing and therefore the ω can be considered as a superposition state of only the light flavours u and d [14]. Measurements of ω production in pp collisions have been carried out so far at $\sqrt{s} = 62 \text{ GeV}$ using the CERN Intersecting Storage Rings (ISR) [15], at $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ with the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) [16, 17] and very recently also at $\sqrt{s} = 7 \text{ TeV}$ with ALICE [18], where solely the PHOS has been used to reconstruct the neutral pion.

The η meson has a mass of $M_\eta = (547.862 \pm 0.017) \text{ MeV}/c^2$ and decay width of just $\Gamma_{\text{Tot}} = (1.31 \pm 0.05) \text{ keV}/c^2$. This meson has already been extensively studied with ALICE in this collision system at a variety of centre-of-mass energies such as $\sqrt{s} = 2.76 \text{ TeV}$ [19], 7 TeV [20] and 8 TeV [21], but also in others collision systems such as p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ [22] and recently also in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ [23]. The decay channel used to reconstruct the η meson in these analyses is its most probable decay via $\eta \rightarrow \gamma\gamma$ which has a branching ratio of $\Gamma_{\gamma\gamma} / \Gamma_{\text{Tot}} = (39.41 \pm 0.20) \%$. However, in this thesis the η meson is reconstructed via

¹ The neutral pion decays via $\pi^0 \rightarrow \gamma\gamma$ with a branching ratio of $\Gamma_{\gamma\gamma} / \Gamma_{\text{Tot}} = (98.823 \pm 0.034) \%$ [14].

$\eta \rightarrow \pi^+ \pi^- \pi^0$, which is only the third biggest contribution to the total decay width, with a branching ratio of $\Gamma_{\pi^+ \pi^- \pi^0} / \Gamma_{\text{Tot}} = (22.92 \pm 0.28) \%$ [14]. The measurement in the three pion decay channel is further aggravated by the required additional measurement of the charged pions, as well as the two photons originating from the neutral pion. Nonetheless, the η meson is reconstructed alongside the ω meson via the three pion decay in this analysis which allows to test the validity of the methods used to reconstruct both mesons by checking the consistency of the obtained results with the $\eta \rightarrow \gamma\gamma$ measurement. The wavefunction of the η meson is also given by a mixing of ψ_1 and ψ_8 which is:

$$\eta = \psi_8 \cos \theta_P - \psi_1 \sin \theta_P, \quad (2.5)$$

where θ_P is the mixing angle of pseudoscalar mesons. However, this mixing is not yet as sharply defined experimentally or theoretically as it is for vector mesons [14]. Nonetheless, the contribution of strange flavours is not negligible in this case.

BARYONS The baryon is a bound state of three quarks (qqq), where each of the quarks carries one of three colours, resulting in an overall colourless object. In an analogue manner as illustrated for the mesons, the possible qqq combinations can be grouped into multiplets according to $SU(3)$ flavour symmetry if only u, d and s quarks are considered or grouped according to $SU(4)$ if the c quark is taken into account as well. Well known baryons consisting of only light quarks are the proton (uud) and the neutron (udd) which make up the nuclei of the elements. According to QCD, also other colourless configurations are possible, such as e.g. pentaquarks ($qqqq\bar{q}$), which have been recently observed by the LHCb collaboration [24]. Because baryons are not the focus of this thesis, the reader is referred to Ref. [14] for a detailed review of baryons.

2.2 PARTICLE PRODUCTION IN HADRON-HADRON COLLISIONS

In this section, important kinematic variables that are used throughout this thesis are introduced. Then an introduction into hadron-hadron collisions is given, shedding light on how one can describe them and how particles like the mesons studied in this thesis are produced.

2.2.1 Kinematic Variables

When describing a collision of two particles at colliders, the particles have to be treated relativistically and their four vector momenta in the rest frame are given by $p_1 = (E_1, \mathbf{p}_1)$ and $p_2 = (E_2, \mathbf{p}_2)$. The energy available in the centre-of-mass frame of the collision can be described by using one of the Lorentz invariant Mandelstam variables s . Considering e.g. two colliding particles with same momentum in opposite directions $\mathbf{p}_1 = \mathbf{p}$ and $\mathbf{p}_2 = -\mathbf{p}$, the Mandelstam variable s is given by:

$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\mathbf{p} - \mathbf{p})^2 = (E_1 + E_2)^2 \quad (2.6)$$

and therefore $\sqrt{s}$ describes the energy available in the centre-of-mass frame. When two hadrons collide, the particles created in the collision will on average propagate in

the plane transverse to the beam axis, which is the axis describing the trajectories of the colliding hadrons. It is therefore useful to describe particle momenta p by using only the transverse component p_T , which is defined as:

$$p_T = \sqrt{p_x^2 + p_y^2}, \quad (2.7)$$

if the z -axis is chosen to be along the beam axis. In an analogue manner the transverse mass m_T can be obtained via:

$$m_T^2 = E^2 - p_z^2 = m^2 + p_T^2, \quad (2.8)$$

where m is the invariant mass of the particle given by

$$m^2 = p^\mu p_\mu = E^2 - \mathbf{p}^2. \quad (2.9)$$

Because the particles created in a collision are boosted along the beam direction, it is common to use the rapidity y instead of angles. The rapidity is defined as:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.10)$$

where E and p_z describe the energy and the longitudinal momentum of the measured particle respectively. Even though the rapidity itself is not a Lorentz invariant property, the difference of two rapidities Δy is Lorentz invariant and therefore Δy can be determined in any frame without knowledge of the longitudinal boost. However, the energy and momentum of the measured particle needs to be known to determine the rapidity. If only the angle θ between the particles momentum and the beam axis is known, the pseudorapidity η can be determined, which is given by:

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right) = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_z}{|\mathbf{p}| - p_z} \right). \quad (2.11)$$

As can be deduced from Eq. 2.11, the pseudorapidity η coincides with the rapidity y for particles with high momentum [11, 13].

2.2.2 Hadron-Hadron Collisions

When describing physical processes such as particle production or the interaction of colliding particles, the cross sections σ is used. When quantifying e.g. the interaction of a beam of particles of type a with particles of type b in a target, the interaction rate per target particle r_b is proportional to the flux ϕ_a via:

$$r_b = \sigma \phi_a, \quad (2.12)$$

where σ is the interaction cross section which has dimensions of an area and is usually expressed in the unit 1 barn $\equiv 10^{-28} \text{ m}^2$. The cross section therefore quantifies the probability for a certain physical process to occur, where a greater cross section corresponds to a higher probability of occurrence. Furthermore, the cross section can also be expressed as a function of some final state variables, which is referred to as a differential cross section [11].

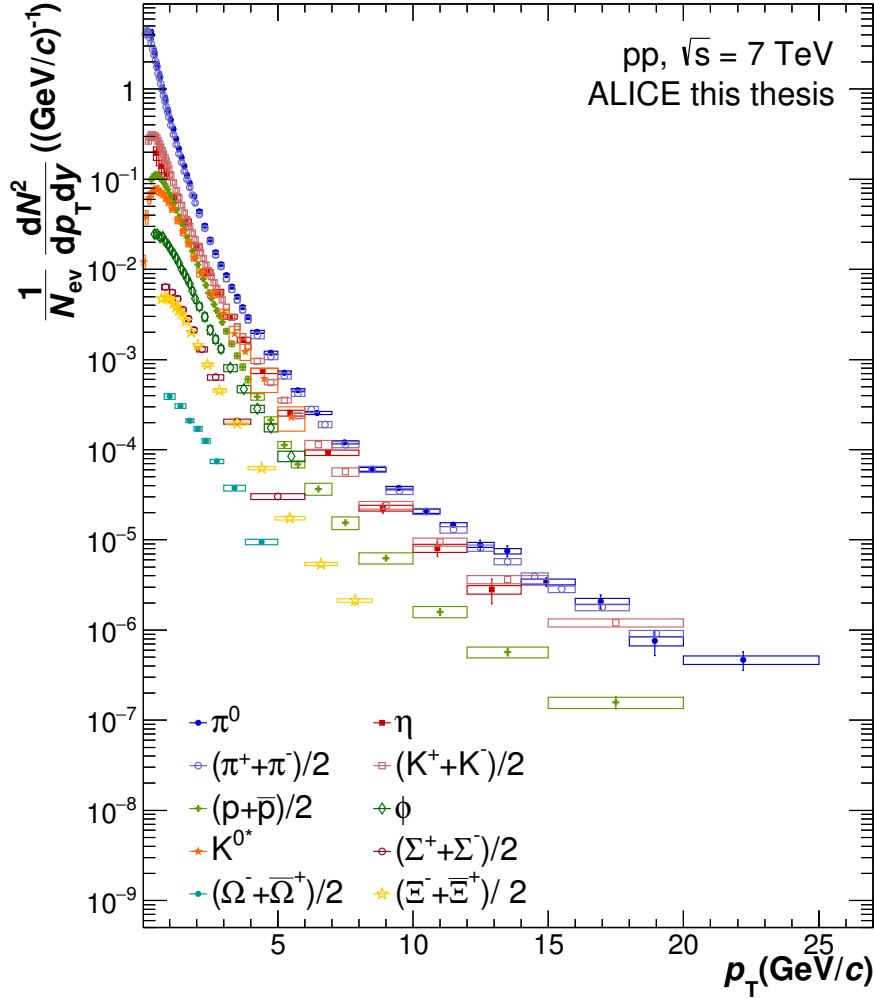


Figure 2.5: Differential yields of a variety of particles produced in pp collisions at $\sqrt{s} = 7$ TeV measured by ALICE. Statistical uncertainties are shown as error bars and systematical uncertainties are represented by open boxes. The data is shown in this plot is taken from [25, $\pi^\pm$], [20, π^0], [20, η], [25, $K^\pm$], [25, $p/\bar{p}$], [26, Φ], [26, K^{0*}], [27, $\Sigma^\pm$], [28, $\Omega^-/\bar{\Omega}^+$] and [27, $\Xi^-/\bar{\Xi}^+$].

The total cross section σ_{tot} of a pp collision at $\sqrt{s} = 7$ TeV is about 98 mb [29] and can be divided into two contributions: The two protons can interact via an elastic scattering process, where the two colliding protons do not lose any energy, and they can scatter inelastically, resulting in an energy loss of the colliding nucleons which then can be used for particle production. Elastic collisions have a cross section of $\sigma_{\text{el}} \approx 25$ mb [29], thus contributing with about 26% to the total cross section. The most probable interaction of the two protons is therefore the inelastic scattering with a cross section σ_{inel} of about 73 mb [30]. The inelastic scattering itself can be divided into an contribution due to diffractive processes ($\approx 30\%$ of σ_{inel}), in which either one (Single Diffraction) or both (Double Diffraction) of the protons become excited after the collision and produce a small number of particles during de-excitation, and nondiffractive inelastic collisions ($\approx 70\%$ of σ_{inel}), in which the colliding protons lose a great amount of their energy, consequently resulting in production of many particles [13, 30].

Fig. 2.5 shows the number of hadrons produced per event per transverse momentum and rapidity interval dp_T and dy in pp collisions at $\sqrt{s} = 7$ TeV, where different ALICE measurements have been combined [20, 25–28]. The vertical bars show the statistical uncertainty of the measured yield, whereas the boxes represent the systematic uncertainties. Most of the hadrons produced in a collision are charged- and neutral pions, followed by charged kaons and η mesons².

As visible in Fig. 2.5, most of the particles are produced with low transverse momentum ($p_T \lesssim 2$ GeV) and their spectra can be described with an exponential $e^{-\alpha p_T}$ [31]. The processes that produce these so-called soft particles have a low momentum transfer Q^2 and therefore can not be described perturbatively. In order to describe how these particles are produced, one has to rely on phenomenological hadronization models, such as string models [12], which are commonly used in MC event generators, such as PYTHIA, to describe hadronization. In these models, the colour field between two quarks is described by a string which is eventually broken by fluctuating $q\bar{q}$ pairs that absorb the energy of the field. The newly formed $q\bar{q}$ pair is connected by a string as well and the process of string breaking continues until the energy of the $q\bar{q}$ pairs is low enough to form a bound hadron state. String breaking can not be described from first principle and the string models differ in how they describe the breaking of a string. A widely used model is the Lund model, which describes the creation of a $q\bar{q}$ pair via a tunneling probability that is suppressed depending on the produced quark's mass and momentum [12, 13].

The hadrons created with $p_T \gtrsim 2$ GeV mostly originate from processes with high momentum transfer Q^2 and the momentum distribution of these so-called hard particles follows a power law in p_T rather than an exponential. The high momentum transfer has several consequences: The interaction will take place on a small time and length scale of $\tau \ll 0.1$ fm/c [9] and the coupling constant α_s will be small enough to treat the interaction within pQCD. However, the substructure of the colliding hadrons is not as simple as implied in Sec. 2.1.3. Instead, the constituent quarks will constantly interact with each other and a sea of gluons will fluctuate to virtual $q\bar{q}$ pairs. Luckily, this complex dynamic substructure does not have to be considered due to the short time and length scale: The constituents of one hadron only “see” one constituent of the other hadron “frozen” in time and consequently both partons can be treated as free particles during their interaction. This allows to factorize the inelastic hard cross section for the production of a given hadron into different contributions, breaking down a problem otherwise unsolvable in pQCD into determinable parts [9, 12, 32]:

- The Parton Distribution Function (PDF) describes the probability to find a parton (e.g. gluon, up-quark, ...) within each of the colliding hadrons that carries a certain fraction of the total momentum of the hadron. The PDFs of the colliding hadrons have to be obtained experimentally and depend on the momentum scale Q^2 [11].
- A partonic cross section that describes only the two interacting partons (e.g. the most common process in hadron collisions is the scattering of two quarks

² Please note that the differential yields of the ω and η meson, which are measured via their three pions decay channel as part of this thesis, are not shown in this figure. Their production cross sections are presented in Chap. 9.

$qq' \rightarrow qq'$). The partonic cross section can be calculated in pQCD because α_S is small [12].

- The Fragmentation Function (FF) describes the scattering probability of a given parton into a certain hadron. It is dependent of the fraction of the partons momentum the hadron is carrying, as well as the momentum transfer Q^2 of the underlying process. These functions can not be described fully perturbatively. Instead, phenomenological schemes have to be used in addition to deal with the parton showers arising from pQCD calculations [9, 14].

The brief outline of how hadron production can be described theoretically showed that predictions are complicated and rely on hadronization models, as well as several inputs, such as a PDF and FF. The measurement of hadron production cross sections is essential to constrain theory calculations and therefore improve their predictive power.

2.3 THE QUARK-GLUON PLASMA

Because of the weakening of the strong interaction with increasing momentum transfer – known as asymptotic freedom – one expects a transition from a state of matter in which quarks and gluons are bound to hadrons, to a state in which the quarks and gluons can be treated as free particles. This consequence of asymptotic freedom was proposed independently in the mid-seventies by Collins and Perry [33], and Cabibbo and Parisi [34] and the new phase of strongly interacting matter later called Quark-Gluon Plasma (QGP). A transition of hadronic matter to the QGP is expected to take place at extreme temperatures or densities. Former were present about 10^{-5} s after the Big Bang and latter are e.g. reached in the core of neutron stars [35]. In order to address this extreme state of matter experimentally, the conditions needed for the QGP to form have to be provided in a controlled environment. Relativistic heavy-ion collisions can provide high temperatures as well as high baryon densities, depending on the energy of the colliding nucleons. Research of the QGP using heavy-ion collisions began in the late 1980's at Conseil Européen pour la Recherche Nucléaire (CERN) and Brookhaven National Laboratory (BNL) and the data gathered over the years strongly suggests the successful creation of the QGP in the early stages of relativistic heavy-ion collisions [36].

A sketch of the phase diagram of QCD can be found in Fig. 2.6. The transition at high energies and low baryon chemical potential μ_B is the relevant region at energies reached in Pb-Pb collisions at the LHC. The critical temperature T_c of the transition can be calculated using lattice QCD calculations and results range from $T_c = 150 \sim 200$ MeV [35] – a temperature about 100 000 times hotter than in the centre of the Sun. The large variation is due to a difference in normalization schemes that include either only the light quark flavours (up and down) or in addition also the heavier strange quark [38]. The corresponding energy density needed for the phase transition to occur is $(0.7 \pm 0.2) \text{ GeVfm}^{-3}$ [38]. Moreover, the energy densities reached in a collision can be estimated using the Bjorken formula [36], which is given by:

$$\epsilon_{\text{BJ}} = \frac{1}{S_{\perp} \tau} \left. \frac{dE_T}{d\eta} \right|_{\eta=0}. \quad (2.13)$$

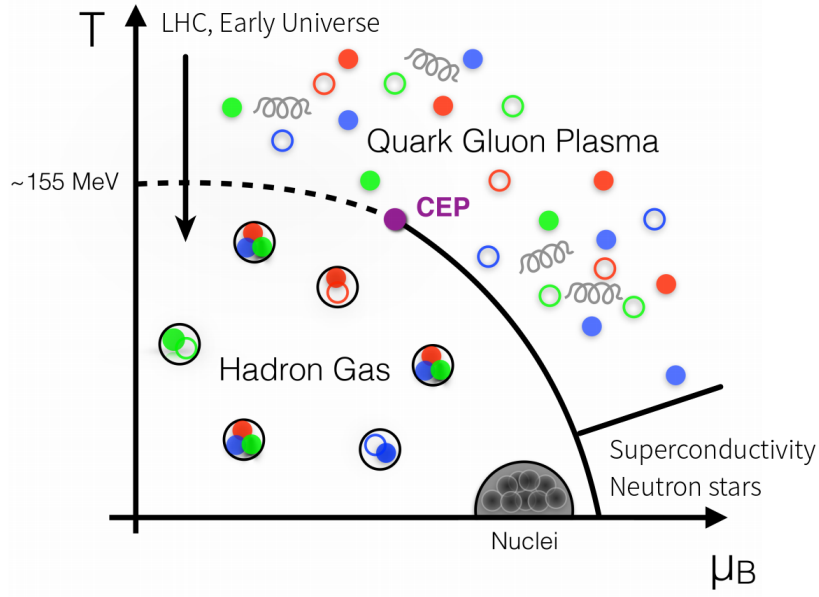


Figure 2.6: Sketch of the QCD phase diagram. The arrow at the top left illustrates the phase transition from QGP to hadronic matter at high temperatures and low baryon chemical potential that took place in the early universe and still does in today's relativistic heavy-ion collisions. Figure adapted from Ref. [37].

Here $S_{\perp}$ is the transverse overlap area of the colliding nuclei, τ is the formation time of the medium and $dE_T/d\eta$ is the measurable transverse energy per unit of pseudo-rapidity. The energy density reached in 0 – 5 % central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE has been estimated in this way to be (12.3 ± 1.0) GeV/fm³ [39], exceeding the calculated critical energy density for a phase transition to occur by a factor of ten. Therefore, the energy densities reached in Pb-Pb collisions are sufficient for the QGP to be created. After its creation in the initial stage of the collision it rapidly expands and cools down – moving along the arrow in Fig. 2.6 – and finally rehadronizes to hadronic matter after only about 10^{-22} s [38].

Given the short lived nature of the QGP, in order to probe its properties one needs to find signatures, in particular particles produced during the QGP's time evolution, that allow to draw inference about the presence of the QGP from measurable observables. Two of those signatures are discussed briefly in the following, with focus on those, where a measurement of the neutral mesons can contribute to knowledge about the QGP.

HADRON SPECTRA MODIFICATIONS One important source of information about the QGP are the final-state hadrons that are produced in the collision. When measuring their spectra in pp collisions, where the formation of the QGP should not be possible, and comparing them to measurements in Pb-Pb collisions, where the QGP should be present, two main modifications of the hadron spectra are expected due to the presence of the medium: At low transverse momenta ($p_T \lesssim 3$ GeV/c) a modification of the spectra is expected due to a radial flow of the medium in outward direction. At high transverse momenta ($p_T \gtrsim 3 - 8$ GeV/c) hadrons originating from jet fragmentation are expected to be suppressed due to the presence of the QGP, which is known as “jet quenching”. This is because the quarks and gluons, which

were scattered with a high momentum transfer in the initial stage of the collision and then create the jet, have to traverse the QGP and consequently lose energy by interacting with it [40].

To quantify the modification of the spectra when comparing heavy-ion (AA) collisions to pp collisions, the nuclear modification factor R_{AA} is used which is given by:

$$R_{AA}(p_T) = \frac{d^2N/dp_T dy|_{AA}}{\langle T_{AA} \rangle \cdot d^2\sigma/dp_T dy|_{pp}}. \quad (2.14)$$

This factor is the ratio between the spectra in pp and heavy-ion collisions, scaled

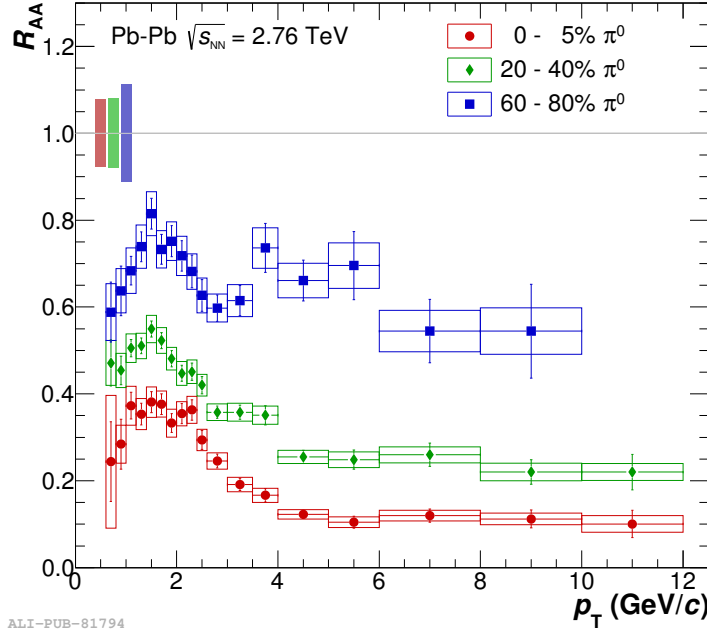


Figure 2.7: Nuclear modification factor R_{AA} calculated from measured neutral pion spectra in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE [40]. Vertical error bars represent the statistical uncertainties, whereas boxes represent systematic uncertainties.

with the nuclear overlap function $\langle T_{AA} \rangle$, which can be determined using Glauber model simulations [40]. Fig. 2.7 shows the nuclear modification factor R_{AA} which was evaluated using measured neutral pion spectra for different centrality classes in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [40]. A suppression of the neutral pion spectra in Pb-Pb collisions can be seen for all three centrality classes, yet the greatest suppression is found for the most central collisions in the 0 – 5 % centrality class, which is attributed to the energy loss due to the presence of the medium.

DIRECT PHOTONS Photons are produced during all stages of heavy-ion collisions and then escape almost unaffected to the detector, due to their lack of strong interaction. When two incoming partons of the colliding hadrons scatter with high momentum transfer, so-called prompt direct photons can be produced. Their measurement and comparison to pQCD calculation allows to test theory assumptions and probe the parton distribution in the colliding hadrons [41]. These photons dominate the direct photon spectrum at high transverse momenta ($p_T \gtrsim 5 \text{ GeV}/c$) [3]. Thermal direct photons are produced within the plasma, e.g. via the annihilation process $q + \bar{q} \rightarrow \gamma + g$. The rate of their production and their momentum distribution

depends on the distribution of the partons in the medium and therefore measuring direct thermal photons allows to probe the properties of the QGP – e.g. its temperature – at the time of their production [13]. The contribution of thermal direct photons is expected at low transverse momenta ($p_T \lesssim 4 \text{ GeV}/c$). However, the measurement of direct photons, especially at low p_T , is aggravated due to the third and largest contribution of photons originating from hadronic decays [3]. Precise knowledge of this background of decay photons is therefore crucial when trying to measure a signal of direct photons.

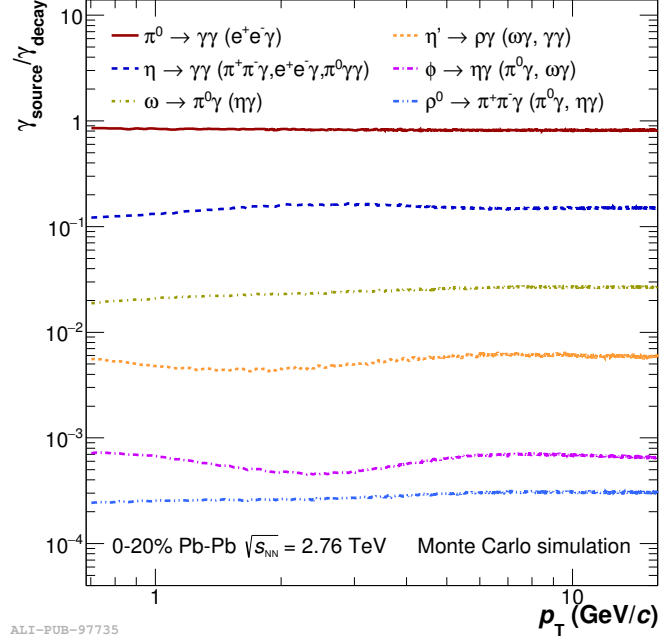


Figure 2.8: Contributions to decay photons originating from different hadrons as a function of transverse momentum. The spectra of the respective hadrons were used as input for a MC simulation of their decays into photons, in order to estimate their contribution to the total amount of decay photons [3].

Fig. 2.8 shows the different contributions to decay photons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, which were obtained using MC simulations of the respective hadron's decay into photons [3]. The largest contribution to decay photons are neutral pions, followed by the η and ω meson. Measuring the cross sections of these mesons is therefore crucial to determine the decay photon background, given the fact that the amount of decay photons is directly linked to the number of particles present that produce them.

If the yield of decay photons γ_{decay} is known, the direct photon yield γ_{direct} can be indirectly measured as an excess over the decay photon yield via:

$$\gamma_{\text{direct}} = \gamma_{\text{incl}} - \gamma_{\text{decay}} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\text{incl}}. \quad (2.15)$$

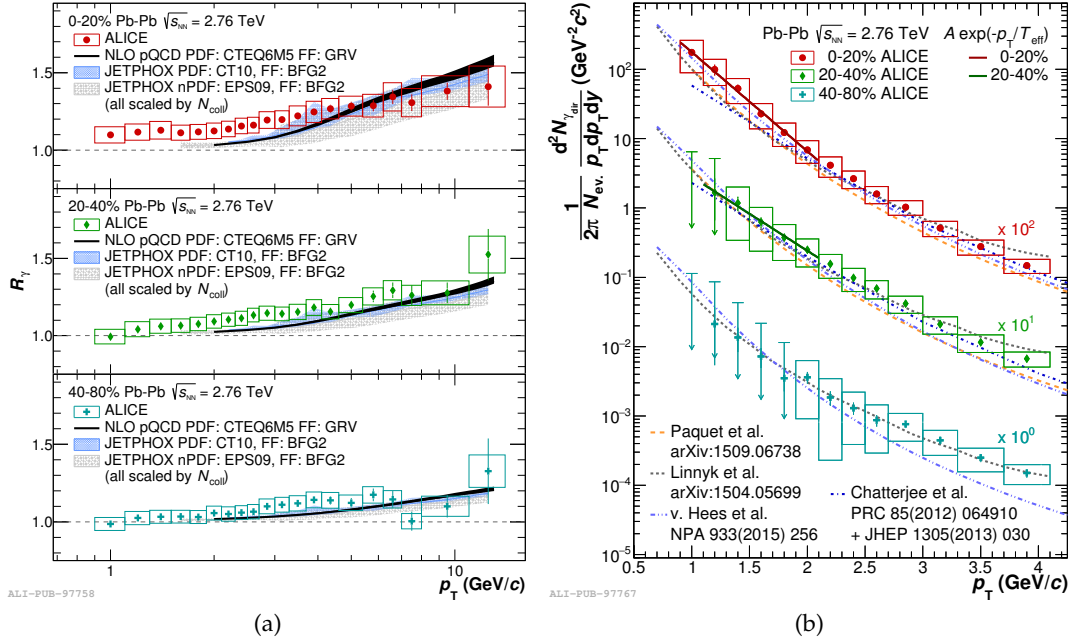


Figure 2.9: Left: Measurement of the double ratio R_γ in three different centrality classes, compared with different pQCD calculations. Right: Direct photon spectra measured in three different centrality classes compared to calculations using different models that incorporate formation of a QGP [3].

Here γ_{incl} is the yield of all measured photons and $R_\gamma = \gamma_{incl}/\gamma_{decay}$ is the so-called double ratio³, where $R_\gamma > 1$ corresponds to a direct photon signal. Fig. 2.9 shows the double R_γ (left) and the p_T differential invariant yield of direct photons (right) measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for three different centrality classes. In mid-central and most-central collisions (0 – 20 % and 20 – 40 %) a direct photon signal can be observed even at low transverse momenta $p_T \lesssim 2$ GeV/c, where the contributions from thermal direct photons are expected. Furthermore, the measurements agree within uncertainties with a variety of models which incorporate the formation of a QGP. For a detailed discussion see Ref. [3].

2.4 PARTICLE INTERACTION WITH MATTER

In this section the interaction of charged particles and photons with matter will be briefly discussed, focussing on the energies and particles relevant in this analysis (photons, electrons and charged pions). Because interaction of particles with matter and their resulting energy loss are the foundation of every particle detector, an overview of these interactions will be useful to have in mind when ALICE's detectors are introduced in Chap. 3.

³ It is a double ratio, because it is actually calculated via:

$$R_\gamma = \left(\frac{\gamma_{incl}}{\pi^0} \right)_{\text{meas}} / \left(\frac{\gamma_{decay}}{\pi^0_{\text{param}}} \right)_{\text{sim}}, \quad (2.16)$$

where π^0_{param} is a parametrization of the measured π^0 spectra, which is simply denoted as π^0 . If R_γ is calculated this way, one profits from some of the largest uncertainties partially or completely cancelling [42].

INTERACTION OF CHARGED PARTICLES Relativistic heavy charged particles interact electromagnetically with the medium they are traversing by ionisation of its atoms. At intermediate energies ($0.1 \lesssim \beta\gamma \lesssim 1000$) their energy loss per unit length is given by the Bethe-Bloch equation [14]:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]. \quad (2.17)$$

Here z is the charge number of the incident particle, Z and A are the atomic number and atomic mass of the absorber and $\beta = v/c$ is the speed of the incident particle expressed as a fraction of the speed of light c . The other quantities are material dependent constants and corrections and the reader is referred to Ref. [14] for further elaborations. The mean energy loss rate in different absorber materials can be seen

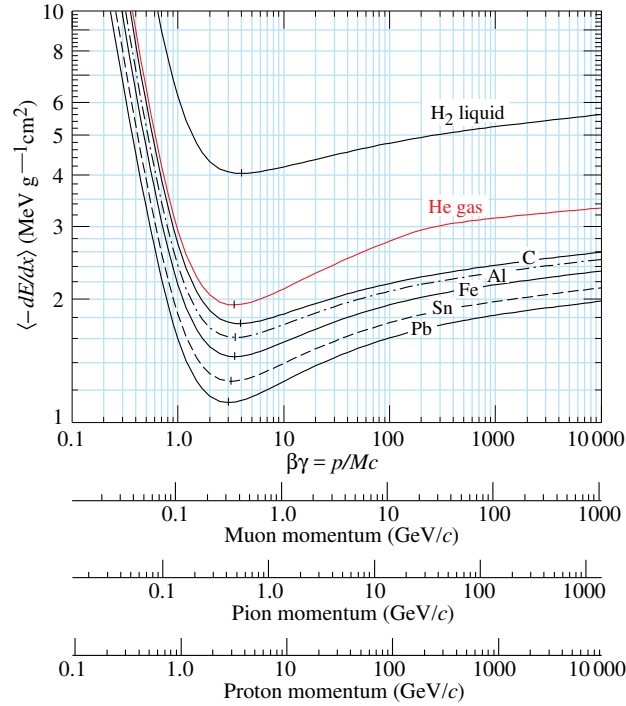


Figure 2.10: Mean energy loss rate per unit length of heavy particles at intermediate energies for different absorber materials [14].

as a function of $\beta\gamma = p/Mc$ in Fig. 2.10, where the corresponding momenta of different particles are plotted in addition. One finds a weak dependence on the absorber material and the greatest energy loss for slow particles. Interaction of electrons and positrons with matter is more complicated to describe than the energy loss of heavy particles, because in this case one has to e.g. consider the electrons spin and the fact that they interact with the same kind of particle – the electrons of the atoms of the absorber. For electrons (positrons) the energy loss due to ionization dominates for energies below a critical energy of approximately $E_C \sim \frac{800}{Z} \text{ MeV}$. However, for larger energies the electron (positron) loses most of its energy due the radiation of a photon, which is called Bremsstrahlung [11, 14].

INTERACTION OF PHOTONS WITH MATTER Fig. 2.11 shows the total photon cross sections in lead. At low energies, photons interact with the absorber via the photo-

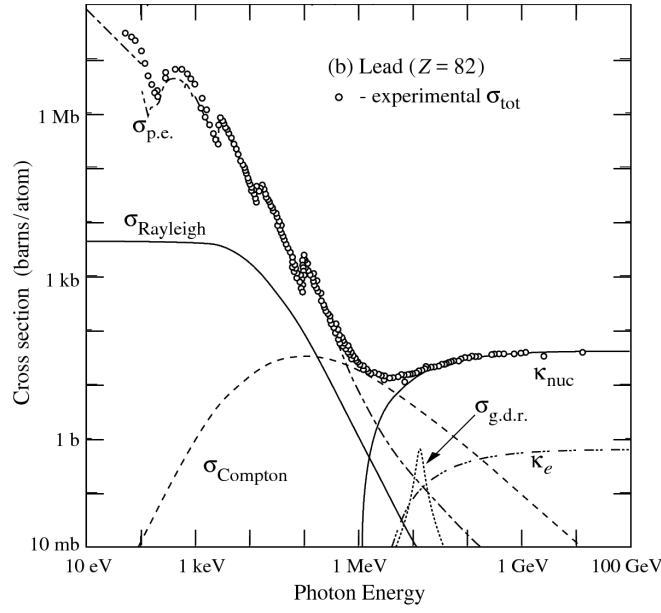


Figure 2.11: Total cross sections of photons and the different contributions, shown for a lead absorber. The most important contributions are the atomic photoelectric effect ($\sigma_{p.e.}$), Compton scattering (σ_{Compton}) and pair production in the field of the nucleus (κ_{nuc}). For definitions and further discussion of the other contributions shown, please refer to Ref. [14].

electric effect ($\sigma_{p.e.}$), in which the atomic electron absorbs the photon and gets ejected from the atom. With increasing energy Compton scattering (σ_{Compton}) becomes the dominant process of interaction, where the photon is only scattered off the electron instead of getting absorbed. Highly energetic photons ($p_T \gtrsim 10 \text{ MeV}$) mainly interact with the absorber by pair creation (κ_{nuc}) in the field of the nucleus, in which a e^+e^- pair is produced. This pair creation by a photon is also called photon conversion and is the most probable interaction of photons with matter at the energies relevant in this analysis.

EXPERIMENTAL SETUP

This chapter gives an overview of the experimental setup that is used in this analysis. In the first section, a quick introduction to the accelerator is given, which provides the pp as well as heavy-ion collisions. The second section then gives a more detailed account of the [ALICE](#) experiment. Moreover, [ALICE](#)'s sub-detectors are described, with special focus to those used in this analysis.

3.1 THE LARGE HADRON COLLIDER (LHC)

The Large Hadron Collider ([LHC](#)) [[43](#)] is a particle accelerator located at [CERN](#) in the old tunnel of the Large Electron-Positron Collider ([LEP](#)) about 100 m underground. The [LHC](#) consists of two rings containing counter-rotating beams of particles that can be collided at four different interaction points, which are distributed along the 26.7 km circumference of the accelerator. It operates using superconducting magnets, cooled to a temperature below 2 K, which allows for magnetic fields of more than 8 T. This corresponds to a maximum energy of 7 TeV per proton beam or a total of $\sqrt{s} = 14$ TeV in the centre-of-mass frame. Because the [LHC](#) design was constrained by the limited size of the [LEP](#) tunnels, the two rings are embedded in a “two-in-one” magnet design, in which the rings are magnetically coupled to each other. This offers a less flexible but on the other hand more cost and space effective design than two separate rings. The particles accelerated at the [LHC](#) are mainly protons (pp). However, also heavy-ions, i.e. lead ions (Pb-Pb), can be collided, and each year about a month is dedicated to heavy-ion operation. Furthermore, collisions of protons and heavy-ions (p-Pb) are possible, allowing to probe the intermediate regime between pp and Pb-Pb collisions. Because the magnets can only operate within a certain range, the protons need to be pre-accelerated. This is done using [CERN](#)'s accelerator complex, shown in [Fig. 3.1](#), which contains a variety of “recycled” older accelerators, which are now used for pre-acceleration. First, the protons, which were obtained from hydrogen atoms, are accelerated using the Linear Accelerator 2 ([LINAC 2](#)) to energies of 50 MeV. The Proton Synchrotron Booster ([PS BOOSTER](#)) then accelerates the protons up to 1.4 GeV after which they get injected into the Proton Synchrotron ([PS](#)) that accelerates them to 25 GeV. The protons then get sent to the last pre-acceleration stage in the Super Proton Synchrotron ([SPS](#)), where they get accelerated to 450 GeV before finally getting injected into the two beam pipes of the [LHC](#).

Four experiments are located at the [LHC](#)'s interaction points, covering a broad scope of physics within and beyond the Standard Model ([SM](#)): The AToroidal LHC ApparatuS ([ATLAS](#)) [[45](#)] and Compact Muon Solenoid ([CMS](#)) [[46](#)] are general purpose detectors focussing mainly on pp collisions. A big motivation and a benchmark in the design phase of these experiments was the search for the Higgs boson, which is essential to the consistency of the [SM](#). It was successfully measured by [ATLAS](#) and [CMS](#) in 2012 [[47](#), [48](#)] and since then its properties have been measured more

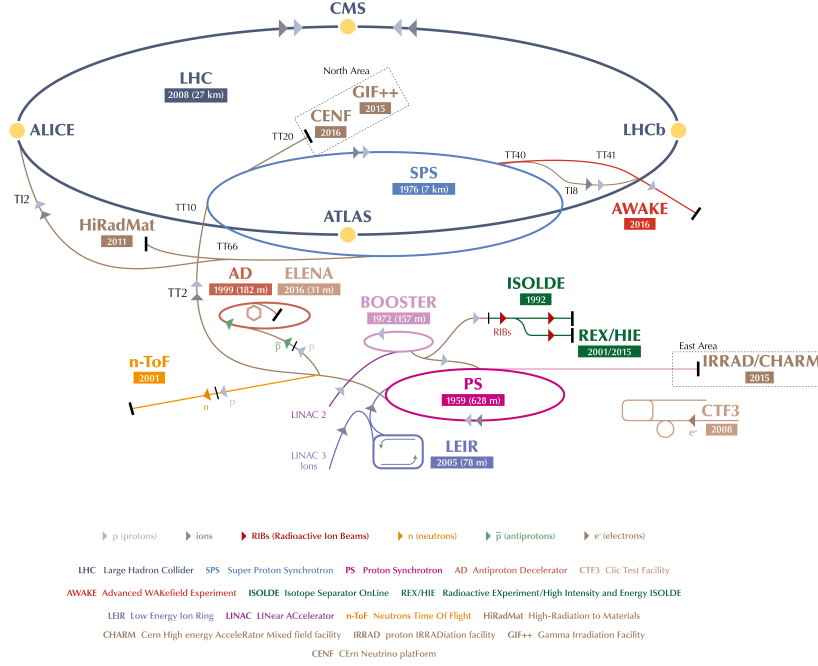


Figure 3.1: Overview of CERN's acceleration complex and experiments [44].

and more precisely with improving statistics¹. The searches by **ATLAS** and **CMS** for physics beyond the **SM** include e.g. the search for rare decays of supersymmetric particles or new heavy gauge bosons. The **LHCb** experiment [50] is focussing on heavy flavour physics. By measuring rare decays and CP violation of hadrons containing beauty and charm quarks, such as the B mesons, with high precision, they are searching for new physics beyond the **SM** that might reveal itself indirectly in their precision measurements. **ALICE** [51], as part of which this analysis is carried out, is the only experiment dedicated to heavy-ion physics and will be covered in the following section.

3.2 A LARGE ION COLLIDER EXPERIMENT (ALICE)

A Large Ion Collider Experiment (**ALICE**) is a general-purpose detector focussing on heavy-ion collisions with the aim of exploring strongly interacting matter in extreme conditions. As discussed in Sec. 2.3, the **QGP** – a state of matter in which quarks and gluons are deconfined – is expected to form at high energy densities reached in heavy-ion collision. The experiment was consequently designed keeping in mind the extreme conditions present in heavy-ion collisions, in particular high charged-particle multiplicities of up to $dN/dy \approx 8000$ in most central collisions. Moreover, sub-detector choices are motivated by the requirements imposed by the physics observables serving as probes for **QGP** properties. Measurement of these probes requires **ALICE** to measure particle momenta over a large range from tens of MeV/c

¹ See e.g. Ref. [49] for the recent (at the time of writing this thesis) measurement of Higgs coupling to top quarks.

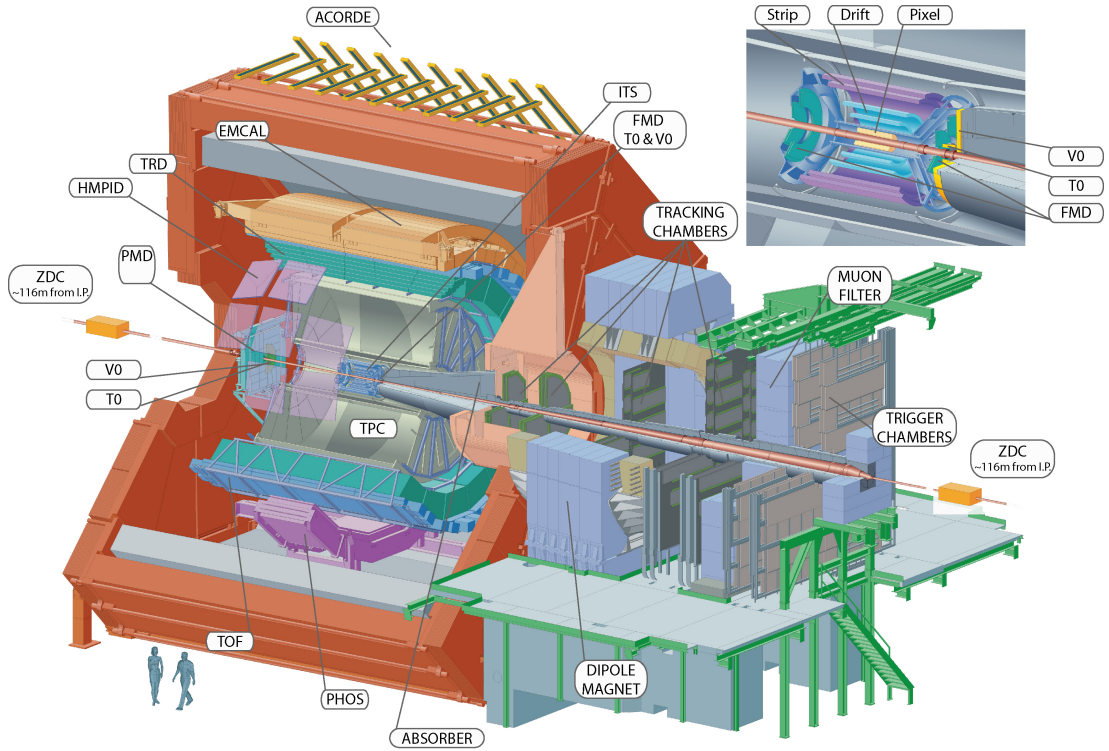


Figure 3.2: Schematic layout of the ALICE detector [53]. A close-up of the ITS is shown in the top right corner.

(e.g. direct photon contribution is expected at low momenta) to over 100 GeV/c (e.g. for jet physics). Furthermore good capabilities for Particle Identification (PID) are required [51, 52].

The ALICE detector has overall dimensions of $16 \times 16 \times 26 \text{ m}^3$ and consists of two main parts: The central barrel containing the detectors used for tracking, calorimetry and PID and a forward part dedicated to muon measurements. The central part is embedded in a L3 solenoid magnet which provides a magnetic field of 0.5 T during normal operation, bending charged particle trajectories and thus allowing to measure their momentum. In total, ALICE consists of 18 sub detectors which are shown in Fig. 3.2. The following sections will give an overview of the sub detectors relevant to this thesis.

3.2.1 Inner Tracking System (ITS)

The Inner Tracking System (ITS) [54] is closest to the beam pipe and is shown in the top right corner of Fig. 3.2. It consists of six cylindrical layers of silicon detectors which are located between 4 and 43 cm away from the collision point in radial direction, covering the full azimuth and rapidity range of $|\eta| < 0.9$. The two innermost layers are called Silicon Pixel Detector (SPD) and are used to determine the position of the primary vertex, which is interaction point of the two colliding particles, as well as secondary vertices from strange, charm and beauty particles with high precision. The layers consist of highly granular two-dimensional matrix of silicon pixels positioned at radii of 3.9 and 7.6 cm, where the innermost layer has a larger rapidity coverage of $|\eta| < 1.98$. The next two layers located at radii of 15 and 23.9 cm make up the Silicon

Drift Detector (**SDD**). Analogue to the **SPD**, a two dimensional design was chosen in order to deal with very high particle densities of up to 90 tracks per cm^2 that occur this close to the primary vertex. The two outermost layers located at radii of 38 and 43 cm, where particle densities below one track per cm^2 are expected, are made up of double sided Silicon Strip Detectors (**SSD**). These two layers are used to match tracks between the **ITS** and Time Projection Chamber (**TPC**), which is **ALICE**'s main tracking detector. Moreover, the **ITS** assists **PID** at low momenta ($p < 100 - 200 \text{ MeV}/c$) by dE/dx measurements in the **SDD** and **SSD**. These low momentum tracks are bend so much in the magnetic field that they do not reach the **TPC**. When used together with the **TPC**, the **ITS** also improves the momentum resolution of high momentum particles, because the hits in the **ITS** increase the total number of space points that can be used for particle tracking, which will be discussed in Sec. 3.4.2. In this analysis, the **ITS** is used for tracking and primary vertex reconstruction but not for **PID** in order to maintain sufficiently high statistics. For a more in depth description of the **ITS**, please refer to Ref. [54].

3.2.2 Time Projection Chamber (TPC)

The main detector that is used for tracking in **ALICE** is the Time Projection Chamber (**TPC**) [55] which is shown in the schematic in Fig. 3.3. It allows measurement of charged particles across a wide p_T -range of about $0.1 \text{ GeV}/c$ up to 100 GeV and good **PID** via dE/dx measurements, especially at low momenta $p \lesssim 1 \text{ GeV}/c$, despite the high track density occurring in heavy-ion collisions [56].

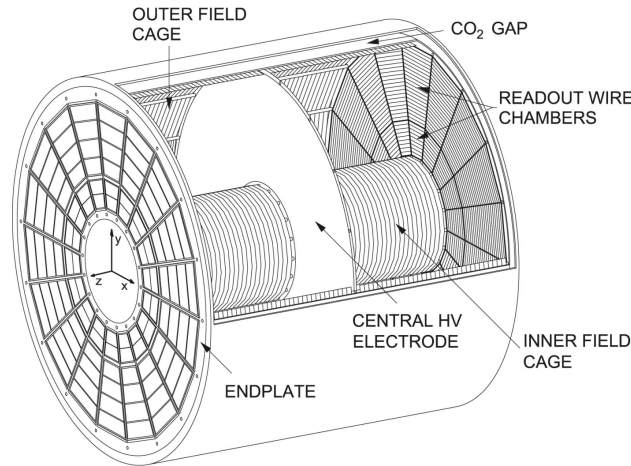


Figure 3.3: Schematic 3D view of the **TPC** [57].

In 2010, the cylindrical **TPC** was filled with 90 m^3 of $\text{Ne}/\text{CO}_2/\text{N}_2$ gas (90%/10%/5%) and its active volume covers a radial range from 84.8 to 246.6 cm and 500 cm along the beam axis. The volume is divided by an aluminised Mylar foil held at about 100 kV which acts as the drift electrode of the detector. When a charged particle traverses the **TPC**, it ionizes the gas along its trajectory and the freed electrons drift towards either of the end plates of the detector with a maximum drift time of $92 \mu\text{s}$. There the electron gets detected by Multi Wire Proportional Chambers with pad readout and the position of the drift electron together with a measurement of its drift time then allows to reconstruct the particles trajectory. Furthermore, the curvature of

the trajectory, caused by the magnetic field of the L3 magnet, allows to measure the particles momentum.

In this analysis, the TPC is used for tracking of charged pions and electrons, their identification as well as the reconstruction of secondary vertices, in particular the conversion points of photons.

3.2.3 Transition Radiation Detector (TRD)

Even though the TPC offers especially good PID capabilities at momenta below 1 GeV/c, distinguishing electrons from pions at higher momenta is more challenging due to their similar energy loss. The Transition Radiation Detector (TRD) [58] was designed to identify electrons above 1 GeV/c by exploiting their transition radiation when passing through a radiator. In addition to the radiator, each detector module consists of a drift chamber filled with Xe/CO₂ (85%/15%) gas. The gas is ionized by traversing particles and the transition radiation photons are converted at the beginning of the drift region. The resulting electrons then drift towards anode wires, where they produce a signal on the readout pads. Apart from the TRD's capabilities to identify electrons, it can also be used to measure specific energy loss and as a tracking device in addition to the TPC, improving the momentum resolution of tracking at high p_T . The detector modules are arranged in 18 super modules, containing 30 modules each. However, when the data used in this analysis was recorded in 2010, only 7 out of 18 super modules were already installed.

Even though using the TRD in this analysis would indeed purify the electron signal, it would also reduce the available statistics significantly. Because the available statistics is crucial in this analysis and outweighs the PID benefits, it was decided to not use the TRD.

3.2.4 Time-Of-Flight Detector (TOF)

The Time-Of-Flight (TOF) detector [59] is mainly used for PID, i.e. the separation of kaons and pions up to 2.5 GeV/c momentum and the separation of kaons and protons up to 4 GeV/c. This separation is achieved by measuring the TOF of a traversing particle in dependence of its momentum with Multi-gap Resistive-Plate Chamber (MRPC) strips that cover the full azimuthal range and a rapidity of $|\eta| < 0.9$. Nonetheless, the TOF detector was not used in this analysis following the argument of the previous section.

3.2.5 Photon Spectrometer (PHOS)

The Photon Spectrometer (PHOS) [60] is an electromagnetic spectrometer with high granularity and energy resolution, designed for photon measurements especially at low p_T , making it useful e.g. for direct photon measurements. In 2010, when the data used in this analysis was recorded, the PHOS was divided into three units called modules, each segmented into 3584 lead-tungstate (PbWO₄) scintillation crystals that are connected to Avalanche Photo-Diodes (APDs) and a low-noise preamplifier. A schematic of the detector can be seen in Fig. 3.4. Due to the high segmentation of the detector, the three modules only cover a limited azimuthal and pseudorapidity range

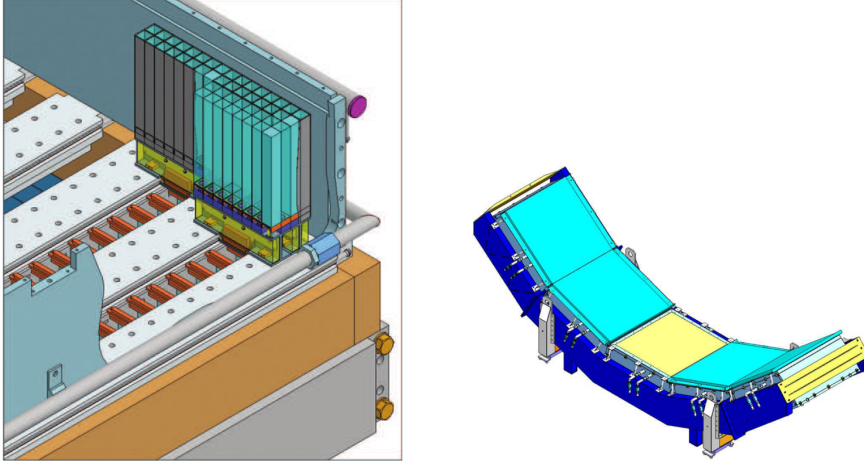


Figure 3.4: Schematics of the Photon Spectrometer (PHOS) [51]. Left: Close-up of a PHOS module showing a few installed lead-tungstate crystals. Each module consists of 3584 crystals. Right: 5 PHOS modules. Note however, that at the time the data for this analysis was taken, only three PHOS modules were installed [61].

of $260^\circ < \phi < 320^\circ$ and $|\eta| < 0.12$ in pseudorapidity. However, the high granularity and the dense scintillation material allow a good energy and spatial resolution [21, 51] of:

$$\frac{\sigma_E}{E[\text{GeV}]} = \frac{1.8\%}{E} \oplus \frac{3.3\%}{\sqrt{E}} \oplus 1.1\% \quad \text{and} \quad \sigma_{x,y}[\text{mm}] = \sqrt{\left(\frac{3.26}{\sqrt{E[\text{GeV}]}}\right)^2 + 0.44^2}. \quad (3.1)$$

Considering e.g. a photon with an energy of 1 GeV, one could measure this energy with an uncertainty of $\sigma_E \approx 40 \text{ MeV}$ and the photons position with $\sigma_{x,y} \approx 3 \text{ mm}$ accuracy.

In this analysis, the PHOS is used as one method to measure the photons needed to reconstruct the neutral pion which will be discussed in detail in Sec. 6.2.

3.2.6 Electromagnetic Calorimeter (EMCal)

The Electromagnetic Calorimeter (EMCal) [62] is a Pb-scintillator sampling calorimeter designed to measure high- p_T objects which is crucial e.g. for photon and jet measurements. Compared to the PHOS it offers a larger acceptance covering (in 2010) an azimuthal range of $\Delta\phi = 40^\circ$ and $|\eta| < 0.7$ in pseudorapidity [63], but with a worse energy resolution. In 2010, four out of $10^{2/3}$ so-called super modules of the EMCal were already in place. Each super module consists of 288 modules where each has a size of about $12 \text{ cm} \times 12 \text{ cm} \times 24.6 \text{ cm}$. The individual modules are divided into $2 \times 2 = 4$ towers, each made up of over 140 alternating lead and scintillator layers which is often referred to as a “Shashlik design”. The lead layers serve as an absorber, where incoming particles produce an electromagnetic shower due to their short radiation length in lead. These showers then produce a signal in the scintillation layers in form of scintillation light which is transported by wavelength-shifting fibres through the stack and then measured by APDs. A schematic of the EMCal and a close-up of one of its modules can be seen in Fig. 3.5.

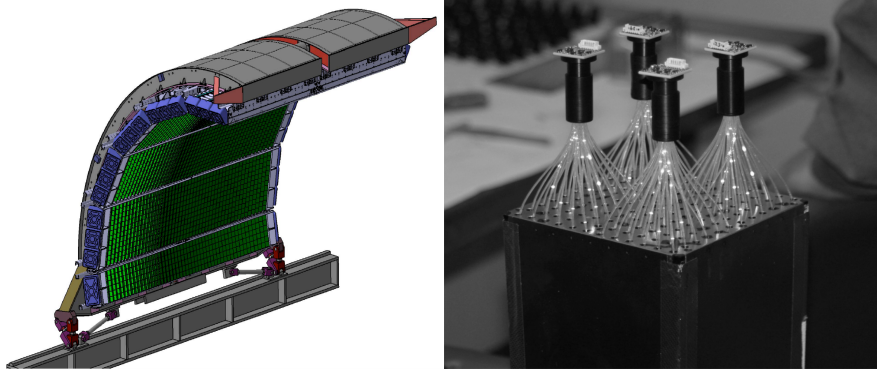


Figure 3.5: Left: Schematic of the [EMCal](#), with the design value of $102/3$ super modules installed [62]. However, during data taking in 2010 only two super modules were already put in place. Right: Close-up of an [EMCal](#) module prototype, where the top has been removed for better visibility [51]. One can see the fibre cables coming from the four towers contained in the module that connect the scintillators to the APDs.

The energy resolution of the [EMCal](#) is optimized for high momenta. It improves with increasing energy of the incident particle and is given by [64]:

$$\frac{\sigma_E}{E[\text{GeV}]} = \frac{4.8\%}{E} \oplus \frac{11.3\%}{\sqrt{E}} \oplus 1.7\%, \quad (3.2)$$

which gives an uncertainty of roughly 2% for incident particle energies above 40 GeV. For rather low energies of 1 GeV, however, the uncertainty is about 12% which is worse than the roughly 4% achieved by the [PHOS](#) at this energy.

Like the [PHOS](#), the [EMCal](#) is used in this analysis as one method to reconstruct the photons coming from the neutral pion.

3.2.7 VZERO Detector

The VZERO detector [65, 66] is located in the forward region of [ALICE](#) and is mainly used as a trigger to distinguish background events such as interactions of the beam with residual gas in the vacuum chamber from actual beam-beam interactions, that one is interested in. Furthermore it allows to measure charged particle multiplicities, which is used to determine the centrality of Pb-Pb collision events. The VZERO system consists of two segmented disks, V0-A and V0-C, which cover pseudorapidity ranges of $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ respectively. Each disk is located at one side of the collision vertex along the beam axis and made up of 32 elementary plastic scintillator counters that are read out by photomultiplier tubes allowing to measure charge and time of a signal produced by incident particles.

In this analysis the VZERO detector is used as a Minimum Bias ([MB](#)) trigger called [MB_{OR}](#) which will be described in Sec. 4.3.

3.3 THE ANALYSIS FRAMEWORK

In this section, a quick overview of the tools used in this analysis to process and visualize the data measured by ALICE is given.

The object oriented data analysis framework ROOT [67] is written in C++ and was designed around the time of the NA49 experiment at CERN in order to deal with the vast amount of data produced by the experiment. The framework consists of a variety of modules that allow to perform tasks such as data fitting, minimization problems and data visualization. One can use the framework either by a graphical interface, the command line or C++ macros and all plotting and fitting in this thesis is done using Version 5.34/30 of ROOT.

The ALIRoot [68] environment is based on ROOT. However it contains an addition of ALICE specific modules that can be used e.g. to conveniently access detector simulations and actual collision data. After a global reconstruction of the raw data collected by ALICE, event properties such as reconstructed tracks and calorimeter clusters are saved as so-called Event Summary Data (ESD) files – a special format provided within the ALIRoot environment. These files are available globally within the collaboration and then used as input for the individual analyses. A more compressed version of ESD files are the Analysis Object Data (AOD) files which only contain the most important feature of an event and are used to decrease the computational resources needed to carry out analyses. However, this further compression of data files was not done for the early 2010 datasets which is why in this analysis ESD files are used as input.

The data is stored and analysed using the LHC's Computing Grid [69] which consists of 170 computing centres around the world that process roughly two million tasks per day and over 500 petabytes of data to date [70].

3.4 TRACK AND VERTEX RECONSTRUCTION

The ITS, which is used to reconstruct the primary vertex, and the TPC, which is ALICE's main tracking detector, have already been covered in Sec. 3.2. This section will outline the algorithms put in place to reconstruct the primary vertex, trajectories of charged particles and secondary vertices from particle decays.

3.4.1 Primary Vertex

A first estimate of the z-coordinate of the primary vertex can be obtained by measuring the z-distribution of reconstructed particle hits in the first pixel layers of the ITS. This distribution is expected to be symmetric and its centroid highly correlated to the true vertex position. However, this is only true for primary vertices within 12 cm distance to the geometrical centre of the ALICE apparatus along the beam axis, because the number of hits that can not be measured increases with displacement of the primary vertex positions from the geometrical centre. This rough estimate of the vertex position is refined by searching for pairs of hits ("tracklets") in the first two layers of the ITS and extrapolating their trajectories to one common primary vertex. The pairs are found by requiring that both of the hits lie in a small azimuthal window

$\Delta\phi$ and the estimate of the primary vertex from the previous step is used to reduce background of uncorrelated hits.

After the z -position of the primary vertex has been reconstructed, the x and y -coordinates are reconstructed in a similar fashion. The radii of the first two layers of the ITS are rather small (4 cm and 7 cm) and consequently the trajectories of tracklets can be approximated by straight lines. By requiring that these trajectories intersect with the z -axis within 4σ of the z -position of the primary vertex obtained in the previous step, one greatly reduces the background of uncorrelated hits and an accurate reconstructed x and y position of the primary vertex can be obtained [71].

3.4.2 Charged Particle Tracking

When a charged particle traverses the ITS and/or the TPC, it deposits energy in the detectors. In an initial step, an algorithm combines these energy depositions to clusters and calculates the cluster's position with a corresponding uncertainty.

In the next step, the search for tracks begins at the outer wall of the TPC starting with the first two clusters and the previously reconstructed primary vertex as "seeds" that are then propagated inwards using a Kalman filter method [72] without further including the primary vertex. The reconstruction improves with each step and added cluster until the inner wall of the TPC is reached. Because there are 159 rows of pads in the TPC, a track can thus contain a maximum of 159 clusters within its volume. However, different reconstructed tracks can share clusters which may result in multiple reconstruction of the same physical track. In order to avoid this, tracks pairs that exceed a certain fraction (25 % to 50 %) of common cluster are rejected.

When the track reconstruction reaches the inner wall of the TPC, the track is further propagated to the outermost layer of the ITS which is then used as a seed for the track reconstruction within the ITS. When a hit is added to the track at each layer it is also used as a new seed, resulting in a variety of possible track candidates in the ITS for each track in the TPC. From all these candidates, the track of highest quality is finally selected taking into account the candidates χ^2 values, missing clusters and clusters shared with other track candidates.

After the best track in the ITS is found, the track are refitted using the Kalman filter method starting from the point of closest approach of each track to the primary vertex and continuing in outward direction. When the outer wall of the TPC is reached, the tracks are matched with the outer detectors, such as e.g. TRD, TOF. Then. they are further propagated and matched with the EMCal and the PHOS. However, at the time the data used in this analysis was recorded, the measurements of these outer detectors were not considered when calculating the kinematics of the tracks and solely used for matching.

Finally, the tracks are yet again refitted in TPC and ITS in an inward direction and important track parameters, such as e.g. position, direction and inverse curvature, are calculated and stored in the ESD file. Furthermore, the final reconstructed tracks are used to improve the determination of the primary vertex that was up to this point determined solely using the ITS.

The reconstruction efficiency of tracks in pp collisions reconstructed using the TPC alone and the combination of TPC and ITS increases with momentum and goes up to about 90 % for high p_T tracks which is mainly limited by the dead zones of the

TPC. The momentum resolution worsens with increasing p_T and the best precision is achieved for low momentum tracks ($p_T \sim 500 \text{ MeV}/c$) of about 0.7 % [51, 61, 71].

3.4.3 Secondary Vertices

Not all particles measured by ALICE originate from the collision itself but rather from other primary particles decaying after travelling a certain distance in the detector. The

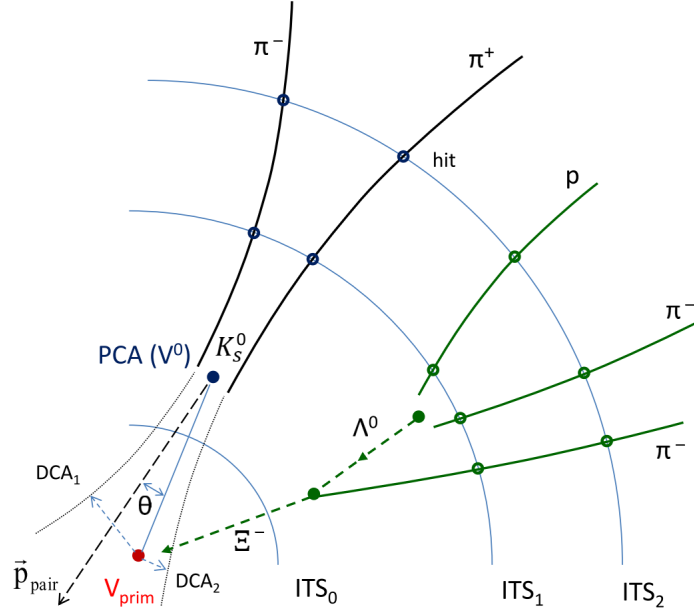


Figure 3.6: Principle of secondary vertex reconstruction shown for the example of K_S^0 and Λ^0 decays, as well as the more complex Ξ^- decay [61].

vertex of this decay is referred to as a secondary vertex to express that it is the origin of a secondary particle, opposed to primary particles originating from the primary vertex of the collision. In order to reconstruct these secondary vertices, a so-called V^0 -finding algorithm [61] is used that will be outlined in this section. It is commonly used for K_S^0 and Λ^0 decays but also to reconstruct the vertex of a photon converting into an electron-positron pair which is the use-case of V^0 -finding in this analysis that will be further elaborated in Sec. 6.3. Here, V^0 refers to an unknown decaying primary particle and the name originates from the distinct 'V' shape seen in the tracking detectors when a neutral particle decays into two particles of opposite charge, as can be seen in Fig. 3.6. Moreover, Fig. 3.6 gives an overview over the principle of secondary vertex reconstruction.

The algorithm begins by selecting tracks with a certain minimum Distance of Closest Approach (DCA) to the primary vertex in order to ensure the selection of tracks that most likely do not originate from the collision point itself. Then, for each pair (referred to as a V^0 candidate) the Point of Closest Approach (PCA) of oppositely charged tracks as well as their DCA is calculated which then can be used to apply further selection criteria: The DCA of the track pair is required to be below a certain threshold rejecting pairs that are not likely to originate from the same vertex. Furthermore, the PCA, which corresponds to the secondary vertex, is required to be closer to the primary vertex than the innermost hit of any of the two tracks ensuring that

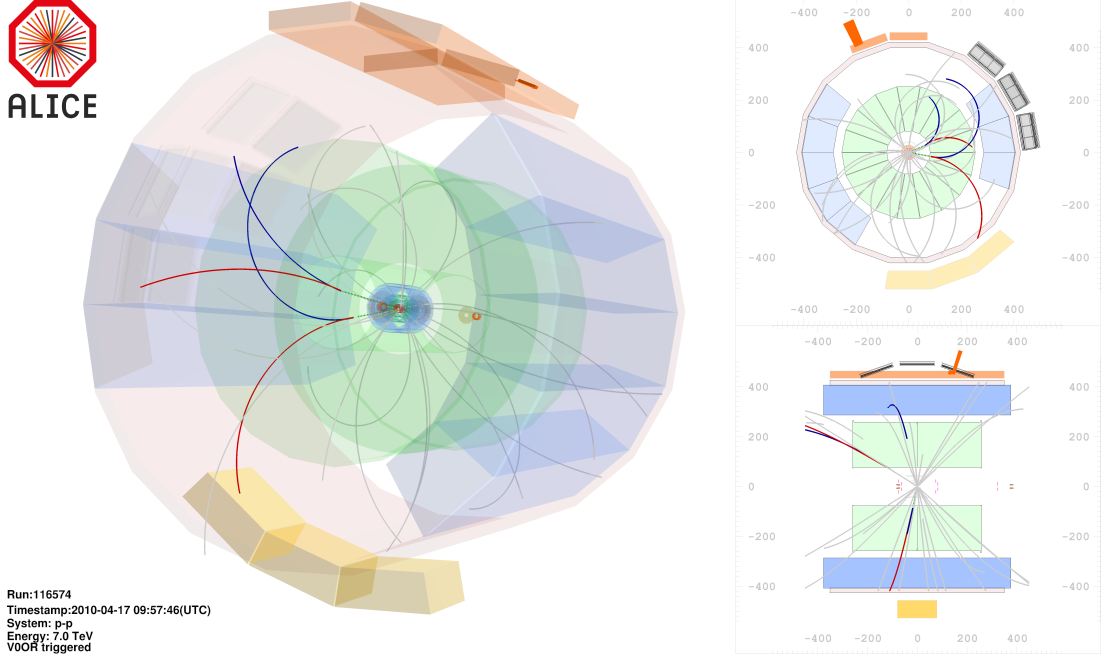


Figure 3.7: Display of a reconstructed pp collision at $\sqrt{s} = 7$ TeV. The left side shows a 3D view of the **ALICE** detector and the panels on the top right and bottom right display the projection onto the xy - and zR -plane respectively. The tracks of primary charged particles (mostly charged pions) are represented by grey lines and the orange boxes show energy depositions in the **EMCal**. The two oppositely charged track pairs highlighted in blue and red are photon conversion candidates found by the on-the-fly Vo finder. The green dotted line represents the corresponding primary particle (e.g. a photon).

the secondary decay particles were indeed present after the expected decay of the primary particle. Finally, the momentum $\vec{p}_{\text{pair}}$ of the V^0 candidate is calculated by summing the momenta of the track pair at the **PCA**. Momentum vectors not pointing toward the primary vertex are rejected by requiring a certain $\cos \vartheta_{\text{PA}}$, where the pointing angle ϑ_{PA} corresponds to the angle between $\vec{p}_{\text{pair}}$ and the direct line connecting primary and secondary vertex, as it can be deduced from Fig. 3.6.

In **ALICE**, one can distinguish between two types of V^0 -finding algorithms: the on-the-fly and the offline V^0 -finding algorithm [73]. The on-the-fly V^0 -finding algorithm, which is the one used in this analysis, is running during global event reconstruction. When a secondary vertex is found, the algorithm allows to refit the according track pairs taking into the vertex as their point of origin which improves the position- and momentum resolution of the respective tracks. The offline V^0 -finding algorithm, on the other hand, is run on the stored **ESD** files after global event reconstruction. Even though this means tracks cannot be refitted using this algorithm, it has the advantage of offering secondary vertex finding independent of the global event reconstruction that allows to include possible recalculations and improvements of previously found secondary vertices.

A display of a fully reconstructed event is presented in Fig. 3.7. For a more detailed account of the V^0 -finding algorithm itself as well as its performance please refer to Ref. [71] and Ref. [61].

In fall 2009 data taking of [ALICE](#) started with pp collisions at a centre-of-mass energy of $\sqrt{s} = 0.9$ TeV. Since then [ALICE](#) measured a variety of collision systems at different centre-of-mass energies, in particular pp collisions at $\sqrt{s} = 0.9, 2.76, 5, 7, 8$ and 13 TeV, p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 8 TeV as well as Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV [61]. In addition, a short period of data taking 2017 was dedicated to Xe-Xe collisions at $\sqrt{s_{NN}} = 5.02$ TeV. After a long shutdown of the [LHC](#) in 2019 and 2020, during which several of [ALICE](#) sub detectors will be upgraded [74], measurements of pp collisions and Pb-Pb collisions at high interaction rates and centre-of-mass energies of $\sqrt{s} = 14$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV respectively are planned until the next shutdown in 2024.

In this thesis, pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV are analysed, which were recorded by [ALICE](#) in 2010 during Run 1 of [LHC](#) operation. Data taking is split into so-called periods, where each period corresponds to about one month of data taking. In this analysis, all five available periods of this collision system LHC10b, LHC10c, LHC10d, LHC10e and LHC10f are used, which from now on will simply be referred to as LHC10bcdef. The recorded raw data goes through a variety of global event reconstruction steps, recovering more and more statistics and fixing possible misbehaviour of a detector, such as e.g. wrong calibration or alignment, with each step. The reconstruction of the dataset used in this analysis is finished and the dataset is consequently referred to as a “pass 4” dataset, indicating that it went through four stages of global reconstruction. The 2010 pp collision data at $\sqrt{s} = 7$ TeV is chosen for this analysis because it offers good minimum bias statistics and is very well understood, i.e. the sub detectors used in this thesis have been used before in other analyses (see e.g. Ref. [20]) and therefore already went through a detailed Quality Assurance (QA) process.

4.1 RUN SELECTION

Each period is furthermore divided into several runs, where each run in general corresponds to a couple of hours of data taking. However, not all runs are suitable to be used in an analysis, because e.g. some of the detectors might be switched off or are not working properly during some runs. Therefore the conditions present in each run need to be carefully checked using the so-called Run Condition Table (RCT) and runs suited for the particular analysis are chosen accordingly.

Because in this thesis different reconstruction methods are used to measure the photons needed to reconstruct the neutral pions, a different set of runs has to be selected, depending on the detectors involved: The [ITS](#) and [TPC](#) are required to be turned on and working properly for all runs used in this analysis, because their tracking capabilities are needed regardless of the method used to reconstruct photons. When the [EMCal](#) or the [PHOS](#) is used to measure at least one of the photons coming from the neutral pion, the respective detector is required to be working un-

der nominal conditions in addition to [ALICE](#)'s tracking detectors. In some cases, runs have been globally flagged as "bad" in the [RCT](#), in which case the run was rejected for the analysis as well. In total three different run lists are used in this analysis: one for photon measurements using only the [PCM](#), one for [EMCal](#) and [PCM-EMCal](#) and one list for [PHOS](#) and [PCM-PHOS](#). The full lists of runs used in this analysis are given in Tab. [B.1](#), [B.2](#) and [B.3](#).

4.2 MONTE CARLO SIMULATIONS

In order to estimate the efficiency and acceptance of the ω and η reconstruction, which are used to apply corrections as discussed in Sec. [8.2](#), information from [MC](#) event generators is needed. In this thesis, [PYTHIA 6.4](#) [[75](#)] is used to simulate the pp collisions and their final state particles which are then further propagated through a full simulation of the [ALICE](#) detector by [GEANT 3](#) [[76](#)].

[PYTHIA](#) is a general purpose event generator which includes a variety of models and theory that allow to simulate the various physics aspects of a high-energy-physics event. It calculates the hard scattering of initial states, given by a [PDF](#), including over 300 different leading order processes, but also has phenomenological models in place to account for soft interactions that can not be treated perturbatively. Furthermore, [PYTHIA](#) accounts for initial- and final-state parton showers, fragmentation and the further decay of the hadrons produced, with the aim to represent the properties of a real collision event as good as possible.

[GEANT](#) is used to simulate the transport of the final state particles of the collision through the [ALICE](#) detector. The geometry of [ALICE](#) is modelled in great detail within the [ALIRoot](#) framework and then passed through an interface to [GEANT](#), which then tracks the propagation of the particles through the detector material taking into account energy loss due to a variety of possible interactions. When the particle loses energy in a 'sensitive' part of the detector, such as e.g. the scintillation crystals of [PHOS](#), the time and position of this interaction is stored as a hit which is then used to simulate the response of the detector.

Like measured data, the events produced by [PYTHIA](#) and [GEANT](#) are reconstructed and then stored in the [ESD](#) format including additional [MC](#) information that can be accessed by the analysis task. The [MC](#) datasets follow the same period- and run structure and are named LHC14j4bcdef accordingly. Furthermore, the [MC](#) datasets are 'anchored' to the real datasets, meaning that they are simulated taking into account the conditions present in each actual run, e.g. same number of events, detector setup and calibration.

4.3 EVENT SELECTION

Each collision event used in this analysis fulfils a Minimum Bias ([MB](#)) trigger condition, referred to as MB_{OR} or INT_1 , requiring for each bunch crossing at least one hit in the [SPD](#), the innermost layer of the [ITS](#), or a hit above a certain threshold in either of the two segmented disks of the [VZERO](#) detector. It is the most basic trigger logic available in [ALICE](#), ensuring that only events where an interaction occurred are recorded. The condition imposed by the MB_{OR} trigger corresponds to the requirement of at least one charged particle anywhere in 8 units of pseudorapidity [[66](#)].

In order to determine the invariant cross section of the ω and η meson, the total cross section of the MB_{OR} trigger is needed. However, this cross section cannot be measured directly and needs to be derived from the total inelastic cross section of the pp collision σ_{INEL} which can be determined using:

$$\frac{dN}{dt} = A \cdot \sigma_{\text{INEL}} \cdot \mathcal{L}, \quad (4.1)$$

where A is the acceptance and efficiency of the trigger, $\frac{dN}{dt}$ the collision rate and $\mathcal{L}$ the luminosity. The trigger efficiency A can be determined using MC simulations which allows to determine σ_{INEL} by simultaneously measuring interaction rate $\frac{dN}{dt}$ and luminosity $\mathcal{L}$, which is given by:

$$\mathcal{L} = f N_1 N_2 / h_x h_y. \quad (4.2)$$

Here f is the accelerators revolution frequency ($f_{\text{LHC}} = 11\,245.5\text{ Hz}$) [30], N_1, N_2 denote the number of protons in each bunch and h_x, h_y describe the effective transverse width of the interaction region. The luminosity can be determined in van der Meer scans [77] and the total inelastic cross section in pp collisions at $\sqrt{s} = 7\text{ TeV}$ was found to be $\sigma_{\text{INEL}} = 73.2^{+2.0}_{-4.6}(\text{model}) \pm 2.6(\text{lumi})\text{ mb}$ [30]. The MB_{OR} trigger efficiency is $85.2^{+6.2}_{-3.0}\%$ and the triggers total cross section $\sigma_{\text{MB}_{\text{OR}}}$ amounts to $(62.4 \pm 2.2)\text{ mb}$ [30]. Furthermore, one can quantify the available statistics for a given dataset, by calculating the integrated luminosity $\mathcal{L}_{\text{int}}$, which is obtained by integrating Eq. 4.1:

$$\mathcal{L}_{\text{int}} = \int \mathcal{L} dt = \frac{N_{\text{events}}}{A \cdot \sigma_{\text{INEL}}} = \frac{N_{\text{events}}}{\sigma_{\text{MB}_{\text{OR}}}} \quad (4.3)$$

Fig. 4.1 shows the number of events N_{MinBias} for each run used in the PHOS related measurements after the MB_{OR} trigger condition was applied. The filled stars

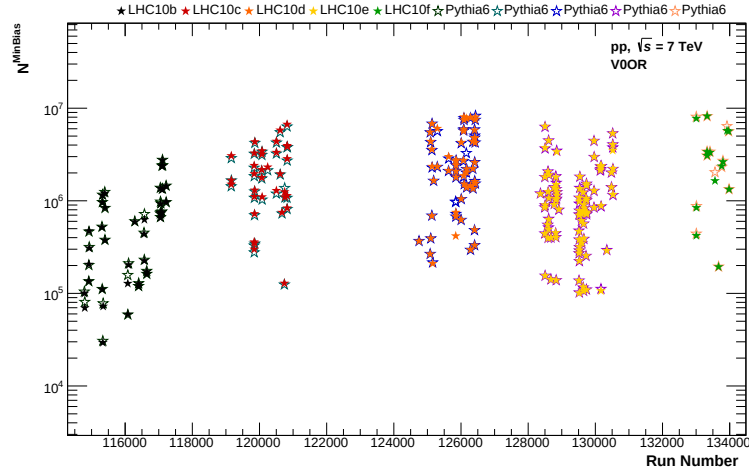


Figure 4.1: Number of MB events N_{MinBias} per run shown for data and MC . The trigger used is the MB_{OR} trigger and the shown runs are used for the PCM-PHOS and stand-alone PHOS measurement.

represent the LHC10bcdef datasets, whereas the open stars show the MC datasets LHC14j4bcdef, using the same colour scheme. One can see that the number of MC events vary from run to run, averaging around one million events per run. Further-

more, the MC simulation manages to reproduce this run dependence. The number of MB events for each reconstruction method can be found in Tab. 4.1.

In addition to the trigger condition, which is enforced “online” during data taking, several other criteria have to be fulfilled “offline” in order for an event to be accepted for this analysis: The primary vertex of an event – reconstructed using the global tracks or only SPD tracklets – is required to lie within $|z_{\text{vtx}}| < 10$ cm to the geometrical centre of the ALICE detector. If no primary vertex could be reconstructed at all, the event is rejected as well. The fraction of MB events that is rejected due to these selection criteria is shown in Tab. 4.1: In data, roughly 9 % of MB events get rejected due to a reconstructed primary vertex that lies more than 10 cm away from the geometrical centre of ALICE in z-direction (B) and furthermore for 8 % of the events no primary vertex could be reconstructed at all (A). Comparing data and simulations, one finds that these fractions are very similar. However, they are slightly overestimated by the MC.

Table 4.1: Overview of the datasets used in this thesis. Because the runs used differ depending on the method used to reconstruct the two photons originating from the neutral pion, the table was split in three row for data and simulation respectively. The abbreviations used are: $A = N_{\text{MB,no vtx}}^{\text{evt}} / N_{\text{MB}}^{\text{evt}}$, $B = N_{\text{MB},|z_{\text{vtx}}|>10\text{ cm}}^{\text{evt}} / N_{\text{MB}}^{\text{evt}}$, $C = N_{\text{MB,pileup}}^{\text{evt}} / N_{\text{MB}}^{\text{evt}}$ and $D = N_{\text{MB,used}}^{\text{evt}} / N_{\text{MB}}^{\text{evt}}$.

DATASET	PHOTON REC. METHOD	$\mathcal{L}_{\text{int}}$ (nb ⁻¹)	$N_{\text{evt,MB}}$ (10 ⁶)	$N_{\text{evt,norm}}$ (10 ⁶)	A (%)	B (%)	C (%)	D (%)
LHC10bcdef	PCM	7.00	486.9	436.5	8.7	8.3	1.2	81.8
	PCM-EMCal	6.03	420.0	376.6	8.6	8.3	1.2	81.9
	EMCal							
	PCM-PHOS	4.59	324.6	286.7	8.8	9.6	1.1	80.4
LHC14j4bcdef	PHOS							
	PCM	7.11	490.5	443.9	9.5	8.6	0	81.9
	PCM-EMCal	6.21	427.3	387.4	9.5	8.5	0	82.0
	EMCal							
	PCM-PHOS	5.78	397.2	360.9	9.5	8.2	0	82.2
	PHOS							

The rejection of events due to these criteria has to be accounted for when normalizing spectra in this analysis, and the number of events $N_{\text{norm,evt}}$ used for normalization is hence calculated using:

$$N_{\text{norm,evt}} = N_{\text{MB},|z_{\text{vtx}}|<10\text{ cm}} + \frac{N_{\text{MB},|z_{\text{vtx}}|<10\text{ cm}}}{N_{\text{MB},|z_{\text{vtx}}|<10\text{ cm}} + N_{\text{MB},|z_{\text{vtx}}|>10\text{ cm}}} N_{\text{MB,no vtx}}, \quad (4.4)$$

which considers a fraction of the events without reconstructed primary vertex that are expected to lie within $|z_{\text{vtx}}| < 10$ cm. For each reconstruction method, the number of events used for normalization $N_{\text{norm,evt}}$ can be found in Tab. 4.1 as well.

Due to the high instantaneous luminosities delivered by the LHC and ALICE’s limited data taking rate, it can happen that multiple primary interactions are recorded in a single event which is called ‘pileup’ and should be avoided in the analysis. One

distinguishes between ‘in-bunch’ pileup, which occurs when more than one interaction takes place during the same bunch crossing, and ‘out-of-bunch’ pileup, which is caused by multiple interactions from different bunch crossings that are attributed to the same event. Even though the interaction rate is reduced in ALICE by displacing the colliding beams [61], this is not enough to avoid pile-up completely. In this analysis, in-bunch pileup is rejected with about 90 % efficiency by requiring that only a single primary vertex is reconstructed using only SPD tracklets, which corresponds to a rejection of about 1.2 % of MB events in data (see Tab. 4.1 C). Because only single collision events are simulated with PYTHIA, the corresponding pileup ratio is zero. ‘Out-of-bunch’ pileup is expected whenever the readout time of a detector involved in the analysis is longer than the time between two bunch crossings. The readout of the EMCal and the PHOS is fairly fast and in addition with the imposed cluster requirements discussed in Chap. 6 this is enough to ensure that no out-of-bunch pileup is present in these measurements. However, due to the long drift time of the TPC ($\sim 92 \mu\text{s}$ [56]), multiple interactions from different bunches are almost always present in the TPC drift region. This usually has to be accounted for by a statistical correction method when the PCM is used to measure photon conversion candidates, where a considerable fraction of the conversion pair tracks are reconstructed using solely TPC information. Nonetheless, no significant out-of-bunch pileup is expected in this analysis due to the additional use of charged pion primary tracks. A substantial amount of these tracks contain information from the ITS which has a very good timing resolution and therefore an adequate distinction between collision events from different bunches is ensured.

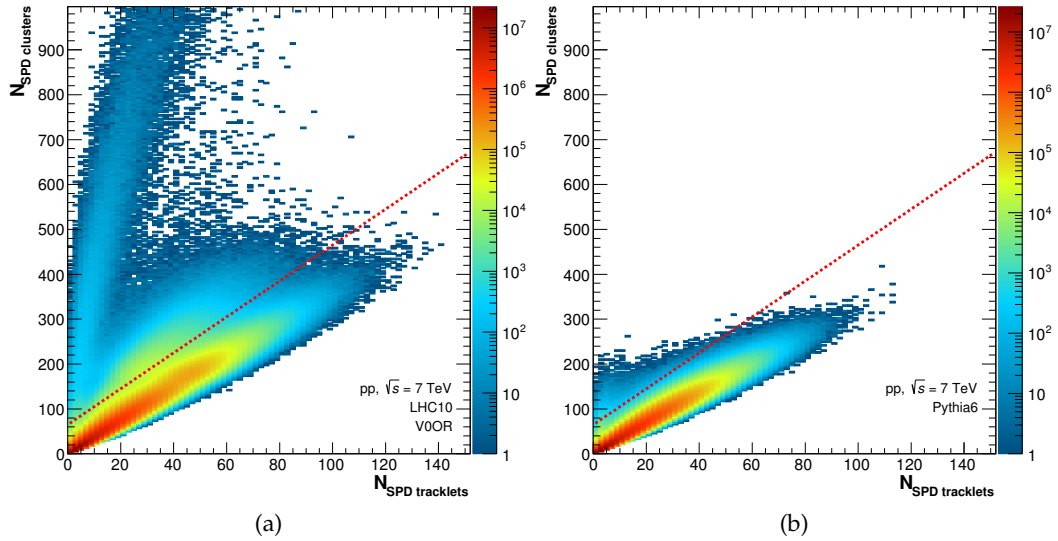


Figure 4.2: Number of clusters in the SPD in dependence of the number of SPD tracklets shown for data (a) and simulation (b). The red dotted line represents the requirement imposed by Eq. 4.5 and events not fulfilling this condition are considered background and rejected from the analysis.

In order to further reject background events mainly occurring due to beam-gas interactions, a cut on the correlation of clusters and tracklets in the SPD is applied: Random hits in the SPD usually originate from particles travelling parallel to the beam axis. A falsely reconstructed track from these random hits that points to the

primary vertex is only probable for a large number of clusters and, consequently, an event with many cluster but not many tracklets in the SPD will be rejected [61]. In this analysis the condition:

$$N_{\text{Clusters}} > 4 \times N_{\text{Tracklets}} + 65 \quad (4.5)$$

is used to reject such background events and it is shown as a red dotted line in Fig. 4.2 together with the number of SPD clusters $N_{\text{SPD clusters}}$ in dependence of the number of SPD tracklets $N_{\text{SPD tracklets}}$ for data and MC simulation. As expected, one finds a strong correlation between the number of SPD clusters and tracklets in data and simulation respectively. However one can see in data, that a fraction of the events contains significantly more clusters than tracklets which is rejected by the applied cut. This excess of clusters is not found in simulations, where background events are not expected which illustrates the validity of the cut used.

CHARGED PION MEASUREMENT

In order to reconstruct the ω and η meson via their $\pi^+\pi^-\pi^0$ decay channel, charged pions $\pi^\pm$ need to be measured which will be elaborated in this chapter. The charged pions have a lifetime of about 2.6×10^{-8} s [14]. Therefore, they can be measured by ALICE detectors before further decaying, allowing to reconstruct tracks from the pions energy deposition in ITS and TPC, as described in Sec. 3.4.2. Before these tracks can be used in the analysis, several selection criteria ('cuts') are applied to ensure a good track quality and furthermore to identify tracks originating from charged pions. An overview of the cuts used can be found in Tab. 5.1.

Table 5.1: Track and PID cuts applied to tracks found in ITS and TPC.

	CUT	SETTING
Track	Pseudorapidity	$ \eta_{\pi^\pm} < 0.9$
	TPC Cluster	$N_{\text{cls,TPC}} > 80$
	χ^2 of TPC track	$\chi^2 / N_{\text{cls,TPC}} < 36$
	require refit in ITS and TPC	no
	Transverse Momentum	$p_T > 100 \text{ MeV}/c$
PID	Energy loss $\frac{dE}{dx}$ in TPC	$-3 < n\sigma_{\pi^\pm} < 3$

When applying cuts on any property, a good balance between the increase of signal purity and the decrease in statistics has to be found. Because good statistics is crucial for this analysis, it was decided to focus on a large track sample rather than one of high track quality. Furthermore, the influence of track quality loss on the analysis is not expected to be statistically significant due to the many combinations of tracks with the neutral pions, performed in a later stage of this analysis to calculate the invariant mass of the ω and η meson (see Chap. 8).

5.1 TRACK SELECTION

Each reconstructed track is required to lie within the pseudorapidity range of the ITS ($|\eta| < 0.9$) and to contain at least 80 out of 159 possible clusters in the TPC. Tracks that only consist of a few clusters have a very large uncertainty on the calculated p_T . Furthermore they are more likely to be 'fake' tracks, meaning that they do not originate from a particles produced in the collision. They are therefore rejected in this analysis. The χ^2 value of each track is calculated between track helix and its clusters in the TPC, where a low χ^2 value corresponds to a good conformity of track and clusters. Fake tracks usually have a high χ^2 value compared to tracks originating from actual charged particles and therefore this value is required to be below 34. As explained in Sec. 3.4.2, all tracks are refitted in TPC and ITS during the last stage of the tracking algorithm in order to improve the calculation of important track properties. However, this refitting fails in some cases and the tracks are flagged accordingly. These tracks

are usually excluded, in order to ensure a good momentum resolution of the tracks used, however, in this analysis, a successful refitting in ITS and TPC is not required. Furthermore, the calculated transverse momentum of a track is required to be above 100 MeV/c which corresponds to the minimum momentum, where tracking with the TPC is still possible. Tracks with lower momentum are bend too much in the magnetic field and begin to curl in the ITS before reaching the TPC.

5.2 PION IDENTIFICATION

In order to select tracks originating from charged pions, the energy loss dE/dx along the track in the TPC is used, which is required to be within $-3 < n\sigma_{\pi^\pm} < 3$ of the expected average energy loss $\langle dE/dx \rangle_{\pi^\pm}$ of charged pions in the TPC. Here, $\sigma_{\pi^\pm}$ is the energy loss resolution for charged pions and $n\sigma_{\pi^\pm}$ is defined via:

$$n\sigma_{\pi^\pm} = \frac{\frac{dE}{dx} - \left\langle \frac{dE}{dx} \right\rangle_{\pi^\pm}}{\sigma_{\pi^\pm}}. \quad (5.1)$$

The expected energy loss of the charged particles can be described by Bethe-Bloch equation as outlined in Sec. 2.4, which only depends on the particles mass and momentum for a given detection gas.

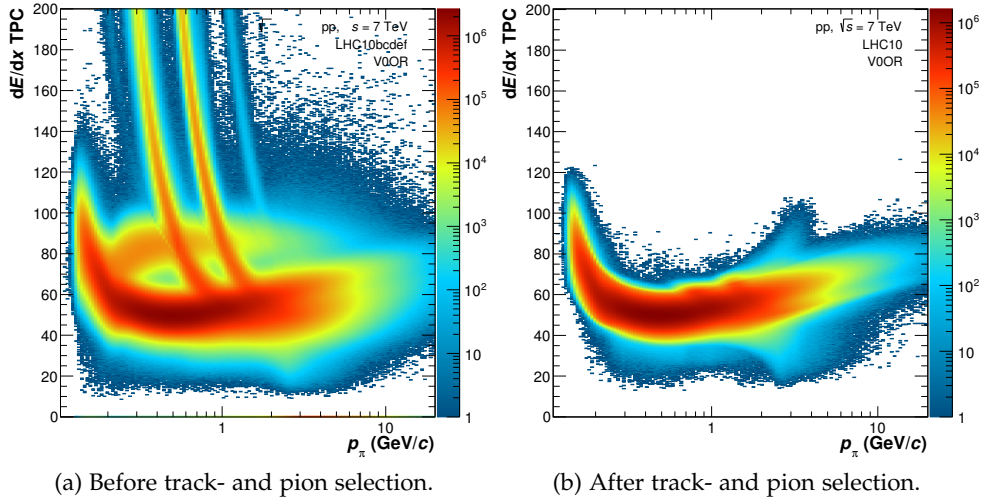


Figure 5.1: dE/dx distribution as a function of momenta, normalized to the number of events, measured with the TPC for the LHC10 datasets. Fig. 5.1a shows the distribution before any track or PID cuts have been used, whereas Fig. 5.1b shows the distribution after all track and pion selection cuts have been applied.

Fig. 5.1 shows the dE/dx distributions measured in the TPC as a function of momentum normalized by number of events, before and after the track and PID cuts described in this section are applied. Looking at Fig. 5.1a, one can see five distinct bands, originating from the specific energy loss of kaons, protons, deuterons, electrons and pions. At low momenta, the electron band merges with the pion band due to the limited dE/dx resolution of the TPC and the similar energy loss of both particles. Furthermore, the specific energy loss of kaons and protons is similar to the pion energy loss at high momenta, making a distinction in this regime difficult as well.

Fig. 5.1b shows the dE/dx distribution after track and PID cuts have been applied. The used cuts manage to suppress contributions from electrons, kaons, protons and deuterons, resulting in a single band around the expected energy loss of charged pions. Even though the selected sample still contains contaminations from electrons, kaons and protons, no further selection criteria, e.g. using the PID capabilities of TOF or TRD, were applied, that would allow to further purify the sample, in order to maintain a high enough reconstruction efficiency.

Using MC information, the p_T integrated purity of the charged pion sample is calculated to be about 92 %, meaning that this fraction of reconstructed pions can be attributed to actual charged pions. Furthermore, the p_T integrated validated efficiency $\epsilon_{\pi^\pm}$ is determined to be about 75 %, which is defined via

$$\epsilon_{\pi^\pm} = \frac{N_{\pi^\pm, \text{rec.,val.}}}{N_{\pi^\pm, \text{MC}, |\eta| < 0.9}}, \quad (5.2)$$

where $N_{\pi^\pm, \text{rec.,val.}}$ denotes the number of reconstructed pions that were validated with true MC information to be actual charged pions and $N_{\pi^\pm, \text{MC}, |\eta| < 0.9}$ stands for the number of charged pions that were produced within the acceptance of the TPC.

PHOTON MEASUREMENT

Unlike the charged pion, the neutral pion has a very short mean lifetime of about 8.5×10^{-17} s [14] and consequently can not be detected directly by ALICE. Instead, the neutral pion needs to be reconstructed via its decay to two photons ($\Gamma_{\gamma\gamma}/\Gamma \approx 98.8\%$ [14]), which will be discussed in Chap. 7.

In this chapter, the methods used in this analysis to measure the photons that are needed for the neutral pion reconstruction will be elaborated: The first two sections discuss the measurement of photons using ALICE's two calorimeters the EMCal and the PHOS. In the last section, the so-called Photon Conversion Method (PCM) is introduced which allows to reconstruct photons down to low momenta via their pair conversion within the detector material.

6.1 PHOTON MEASUREMENT WITH THE EMCAL

The EMCal, which was introduced in Sec. 3.2.6, allows to measure photons, electrons and other hadrons, via the electromagnetic shower they produce within the detector. This shower usually leads to energy depositions in multiple adjacent cells of the calorimeter, which necessitates the combination of the energy deposition in the individual cells to 'clusters' in order to measure the full energy of the incident particle. This combination of cells to clusters is done by a clusterization algorithm, that starts by selecting a seed cell with the highest energy deposition in an event, where the cell furthermore needs to exceed a certain energy threshold E_{seed} . The algorithm then continues to add neighbouring cells exceeding an energy threshold E_{min} to the cluster, as long as their energy is lower than the energy of the cell previously added to it. The process continues until no neighbouring cells are left that fulfil the requirements, and the energy of each cluster is then calculated as the sum of the energies of the individual cells within it [21].

An overview of the clusterizer settings, as well as the cuts used to select clusters originating from photons, which will be discussed later in this section, can be found in Tab. 6.1. The energy E_{seed} of the seed cell, which is used as a starting point by the algorithm, is required to be above 500 MeV and the energy of each neighbouring cell added to a cluster is required to be above 100 MeV. These thresholds correspond to the standard settings used for the EMCal clusterizer and were chosen considering the energy resolution as well as the amount of noise produced by the front-end electronics [21]. Furthermore, the given cell time range corresponds to the readout time of the EMCal of about 1 μ s and therefore no cut is applied at all. It was decided to use no cut, taking into account the cell time distribution, which can be found in Fig. 6.1. One can see the energy dependence of the timing information of cells that were included in a cluster, which shows a bad timing resolution for cell energies below a few hundred MeV. Choosing a strict cell timing cut would therefore reject many low energy cells that surround the seed cell, reducing the number of real clusters reconstructed in data. This should be avoided, especially because no proper timing

Table 6.1: Overview of settings used for the clusterizer algorithm (algo.) and cluster selection criteria used to identify [EMCal](#) clusters originating from a photon.

	CUT	SETTING
algo.	min. seed energy	$E_{\text{seed}} > 0.5 \text{ GeV}$
	min. cell energy	$E_{\text{min}} > 0.1 \text{ GeV}$
	cell time	$-500 \text{ ns} \leq t_{\text{cell}} \leq 500 \text{ ns}$
cluster selection	η position	$ \eta < 0.67$
	ϕ position	$1.40 \text{ rad} < \phi < 3.15 \text{ rad}$
	cluster timing	$-100 \text{ ns} \leq t_{\text{cluster}} \leq 100 \text{ ns}$
	track matching	$ \Delta\eta \leq 0.010 + (p_{\text{T}} + 3.62)^{-2.5}$ $ \Delta\phi \leq 0.015 + (p_{\text{T}} + 4.09)^{-1.75}$
	min. cluster energy	$E_{\text{cluster}} > 0.7 \text{ GeV}$
	nmb. cells per cluster	$N_{\text{cells}} \geq 2$
	cluster shape	$0.1 \leq \sigma_{\text{long}}^2 \leq 0.5$

information exists for [MC](#) and consequently clusters not reconstructed in data due to the timing cut would still be reconstructed in [MC](#).

After cluster reconstruction, several cuts are applied to select clusters suitable for this analysis. Each cluster is required to lie within the [EMCal](#)'s acceptance¹ and furthermore its energy is required to be $E_{\text{clus}} > 0.7 \text{ GeV}$ in order to reduce contributions from minimum-ionizing particles ($\lesssim 300 \text{ MeV}$) [61]. A cluster has to consist of at least two cells in order to remove contributions from detector noise in single cells and to guarantee a minimum size of the cluster. Furthermore, a cut on the cluster time of $|t_{\text{cluster}}| < 100 \text{ ns}$ is applied, which is put in place to reduce possible contaminations from clusters originating from different bunch crossings (see Sec. 4.3).

One important property of a cluster, which can be used to identify clusters originating from photons, is the cluster shape: The shape of a shower can be described via the parameters σ_{long}^2 and σ_{short}^2 that correspond to the long and short axis of an ellipsoidal shower surface. In this analysis, only σ_{long}^2 is used for cutting, which is defined via

$$\sigma_{\text{long}}^2 = 0.5 \left(\sigma_{\phi\phi}^2 + \sigma_{\eta\eta}^2 + \sqrt{(\sigma_{\phi\phi}^2 - \sigma_{\eta\eta}^2) + 4\sigma_{\phi\eta}^2} \right), \quad (6.1)$$

where $\sigma_{\phi\phi}^2$, $\sigma_{\eta\eta}^2$ and $\sigma_{\phi\eta}^2$ are coefficients weighted over all cell energies in the cluster, defined via

$$\sigma_{ab}^2 = \langle ab \rangle - \langle a \rangle \langle b \rangle \quad \text{with} \quad \langle a \rangle = \frac{1}{w_{\text{tot}}} \sum w_i a_i. \quad (6.2)$$

The weights $w_i = \max(0, 4.5 + \log E_i/E)$ account for the fraction of energy E_i deposited in a cell compared to the energy E deposited in the whole cluster and $w_{\text{tot}} = \sum w_i$ expresses the sum of all weights [78]. Neutrons hitting the readout electronics create an abnormal signal that is usually localized in one high energy cell,

¹ Note that the η - ϕ region selected in Tab. 6.1 is a bit smaller than the acceptance stated in Sec. 3.2.6. This is the case, because the coverage in Sec. 3.2.6 is defined for the whole [EMCal](#), whereas for cutting only material sensitive to measurements is selected.

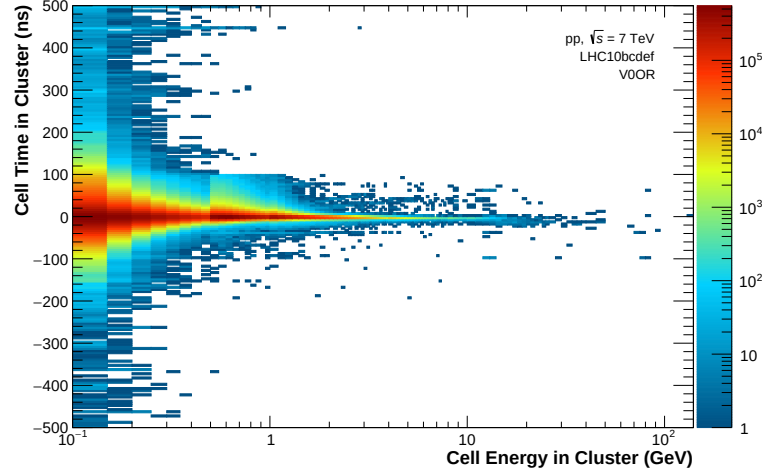


Figure 6.1: Cell time in dependence of cell energy for all cells contained in accepted clusters, where a cell time of zero corresponds to the time of the initial collision. One can see a bad timing resolution for cells with low energy. Because no proper cell timing information exists for [MC](#), no strict cuts on the cell time were applied to avoid a mismatch between data and [MC](#).

surrounded by a few cells of lower energy. These clusters have a small σ_{long}^2 value and therefore can be rejected by requiring $\sigma_{\text{long}}^2 \geq 0.1$. Even though the showers produced by electrons and photons are similar, the shape of the clusters produced by low- p_T electrons are elongated compared to photon clusters, because the electron trajectory gets significantly bend due to the magnetic field of the tracking system, and therefore hits the surface of the [EMCal](#) in an angle. This elongation corresponds to a high σ_{long}^2 value, and low- p_T electron clusters are consequently rejected by requiring $\sigma_{\text{long}}^2 \leq 0.5$. Furthermore, this requirement rejects merged clusters, which are expected at high transverse momenta $p_T \gtrsim 10 \text{ GeV}/c$ when two photons originating from a neutral pion are measured as a single cluster due to their small opening angle [19].

Another method used in this analysis to distinguish photon clusters from clusters originating from charged particles is the so-called track matching, which takes into account information provided by [ALICE](#)'s tracking detectors: In contrast to charged particles, photons do not carry charge and consequently will not leave a track in the tracking system. Charged particle clusters therefore can be rejected by propagating the charged particles tracks to the surface of the [EMCal](#) and then checking for clusters within a certain region around the expected hit on the [EMCal](#). In this analysis, a cluster is rejected if an expected hit of a propagated trajectory is found within a $\Delta\phi$ and $\Delta\eta$ range that is given in Tab. 6.1 and depends on the tracks transverse momentum.

After applying the cluster selection criteria, one finds roughly 0.03 clusters per event, which have a mean energy of about 1.27 GeV. Fig. 6.2a shows the η - ϕ distribution of selected clusters for LHC10bcdef which is normalized by number of events as well as the global average number of clusters per bin. One can see [EMCal](#)'s four super-modules installed at the time of measurement (two super modules join gaplessly at $\eta = 0$), and furthermore finds an increase of cluster density with greater pseudorapidity $|\eta|$, due to the increase of the amount of material, that particles cre-

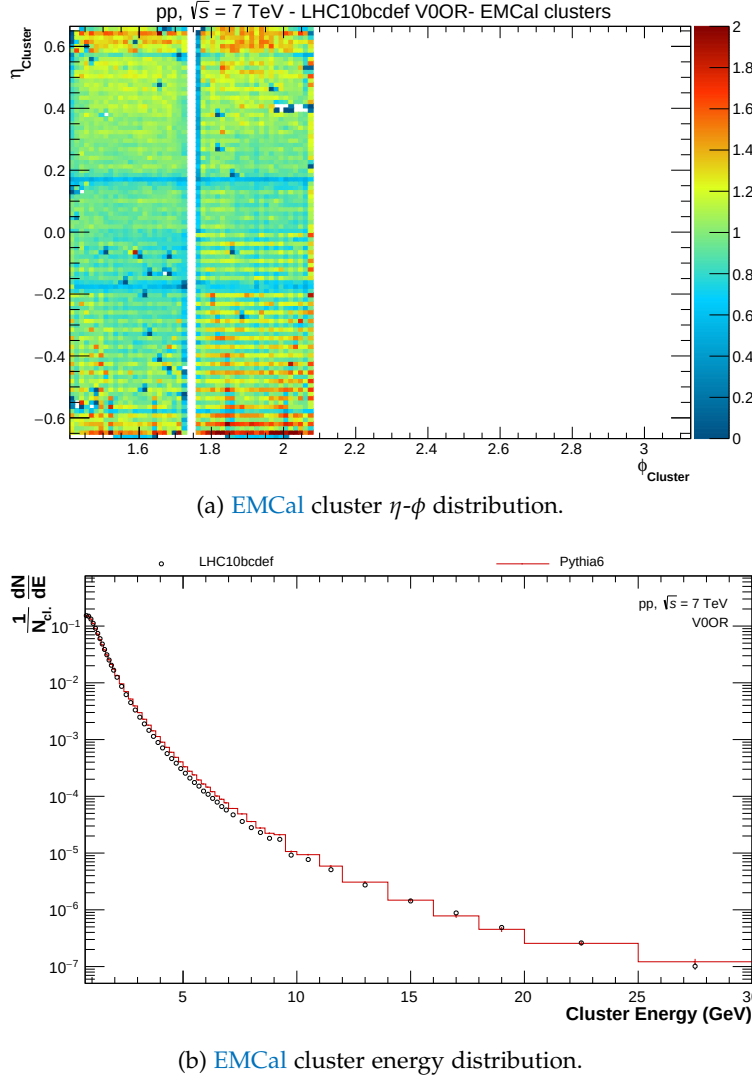


Figure 6.2: Fig. 6.2a: η - ϕ distribution of EMCal clusters, after the cuts found in Tab. 6.1 were applied. The distribution is normalized by the number of events, as well as cluster density per bin. Fig. 6.2b Energy distribution of selected clusters shown for MC and data.

ated in the collision have to traverse. Fig. 6.2b, which shows the energy distribution of selected cluster, illustrates the good agreement between MC and data, which is crucial when estimating reconstruction efficiencies in this analysis. The agreement between data and MC has been checked for a variety of different EMCal cluster properties during a QA process that was carried out as part of different analysis that can be found in Ref. [42].

6.2 PHOTON MEASUREMENT WITH THE PHOS

Analogue to the EMCal, photons can be measured with the PHOS via the electromagnetic shower they produce in the detector. The energy deposited in adjacent cells are grouped into clusters and then clusters that most likely originate from photons are selected using the same selection criteria used for EMCal clusters, as discussed in

the previous section. However, the clusterization algorithm as well as the values used for the cluster selection cuts with the **PHOS** differ from those used with the **EMCal**. Therefore, they will be briefly discussed in the following subsection. Furthermore, the **QA** of **PHOS** clusters has been carried out as part of this thesis, including the identification of bad detector cells as well as the correction of **MC** cluster energies, which will be elaborated in Sec. 6.2.2.

6.2.1 Cluster Selection

The clusterization algorithm used for the **PHOS** begins by selecting all cells with a signal above a certain threshold E_{cell} , which are then sorted according to their amplitude in decreasing order. A cluster is then formed around the first cell exceeding a threshold E_{seed} by adding adjacent cells that share a common side or corner with the initial cell. Once finished, the next unused cell is used as a cluster centre and so on. Within a cluster, a cell is marked as a local maximum if its signal is above the threshold E_{seed} and furthermore exceeds the signal of all adjacent cells by E_{diff} . If more than one local maximum is found the cluster is considered to be originating from the overlap of multiple showers which requires to perform a cluster unfolding. For more details on cluster unfolding, as well as the algorithm used for cluster reconstruction with **PHOS** please refer to Ref. [60].

Table 6.2: Overview of settings used for the clusterizer algorithm and cluster selection criteria used to identify **PHOS** clusters originating from a photon.

	CUT	SETTING
algo.	min. seed energy	$E_{\text{seed}} > 0.200 \text{ GeV}$
	min. cell energy	$E_{\text{min}} > 0.015 \text{ GeV}$
	cell time	$-500 \text{ ns} \leq t_{\text{cell}} \leq 500 \text{ ns}$
cluster selection	η position	$ \eta < 0.12$
	ϕ position	$4.54 \text{ rad} < \phi < 5.59 \text{ rad}$
	cluster timing	$-100 \text{ ns} \leq t_{\text{cluster}} \leq 100 \text{ ns}$
		$ \Delta\eta \leq 0.016$
	track matching	$-0.09 \text{ rad} \leq \Delta\phi \leq 0.06 \text{ rad}$ for pos. tracks
		$-0.06 \text{ rad} \leq \Delta\phi \leq 0.09 \text{ rad}$ for neg. tracks
	min. cluster energy	$E_{\text{cluster}} > 0.5 \text{ GeV}$
	nmb. cells per cluster	$N_{\text{cells}} \geq 3$
	cluster shape	$0.2 \leq \sigma_{\text{long}}^2$

An overview of the selection criteria applied to clusters found by the algorithm, that were already introduced in Sec. 6.1, can be found in Tab. 6.2. The set values are very similar to those used for **EMCal** clusters. However, there are some slight differences: Apart from the obvious change of the η and ϕ cut to match the **PHOS**'s acceptance, the minimum cluster energy is slightly lowered to $E_{\text{cluster}} > 0.5 \text{ GeV}$ and furthermore, the minimum number of cells required per cluster is increased to $N_{\text{cells}} \geq 3$ in order to account for the higher granularity of the **PHOS** detector. No cut on the maximum of σ_{long}^2 is applied because of the algorithm's capabilities to unfold

clusters with multiple maxima. Lastly, a track matching cut which is independent of p_T is chosen which proved to be sufficient for the PHOS analysis.

6.2.2 Quality Assurance

As stated several times throughout this thesis, agreement between MC and data is crucial for efficiency corrections performed in an analysis and furthermore, one needs to make sure that a given detector worked properly during data taking before using its data. Ensuring agreement between MC and data as well as nominal performance of the detector is part of a QA procedure that was carried out for the PHOS detector in the LHC10bcdef dataset as part of this thesis.

6.2.2.1 Identification of Faulty Cells

Before any of the detectors cells can be used and grouped into clusters, one needs to make sure that all cells are working properly which is not always the case, e.g. due to a defect in either the cell itself or the read-out electronics. Even though many cells that are known to be defect beforehand are not processed during global event reconstruction and are therefore automatically excluded from the analysis, one still needs to check the remaining cells and flag those where a defect is present in order to manually exclude them from the analysis. Checking for faulty cells is done by comparing the response of each cell in data with the one from MC. Here, one distinguishes between cold- or dead cells that record less hits than expected or none at all, and hot cells that record more hits than expected from MC. A preselection of candidates for hot/dead/cold cells is performed by looking at the cells energy fraction E_{frac} of the full cluster energy summed over all events in a run and comparing it to the fraction found for the neighbouring cells. A cell carrying much more (less) energy of the cluster, compared to its neighbours, is therefore likely to be a hot (cold) cell. Because an increased E_{frac} value could also arise due to statistical fluctuations, it is furthermore checked that a cell is dead/hot in a given number of consecutive runs and a certain percentage of all analysed runs. After a few more preselection steps that wont be discussed in more detail here, the energy distribution of all faulty cell candidates found during the preselection is compared to the corresponding distribution in MC in order to determine if a faulty cell is actually present. Moreover the timing distribution is checked as well to identify a cell firing at seemingly random times after the initial collision.

As an example, Fig. 6.3a shows the energy- and time distribution of a cell that was classified as faulty. One can see that even though the cell's energy distribution is mostly described by the MC, more than an order of magnitude higher counts than expected from MC are found for two particular energies. Furthermore, looking at the cell time distribution, one finds that these counts are recorded at random times after the initial collision which indicates that this increase is due to noise rather than an actual signal. Other cases of rejected cells include obvious dead cells, where no counts at all can be found in data and cells that record an energy distribution with overall counts several orders of magnitude above MC expectations. Fig. 6.3b, on the other hand, shows an example of a cell that is included in this analysis. The energy distribution found in data agrees with the MC energy distribution and furthermore the cell timing distribution is located close to 0s after the initial collision, as expected.

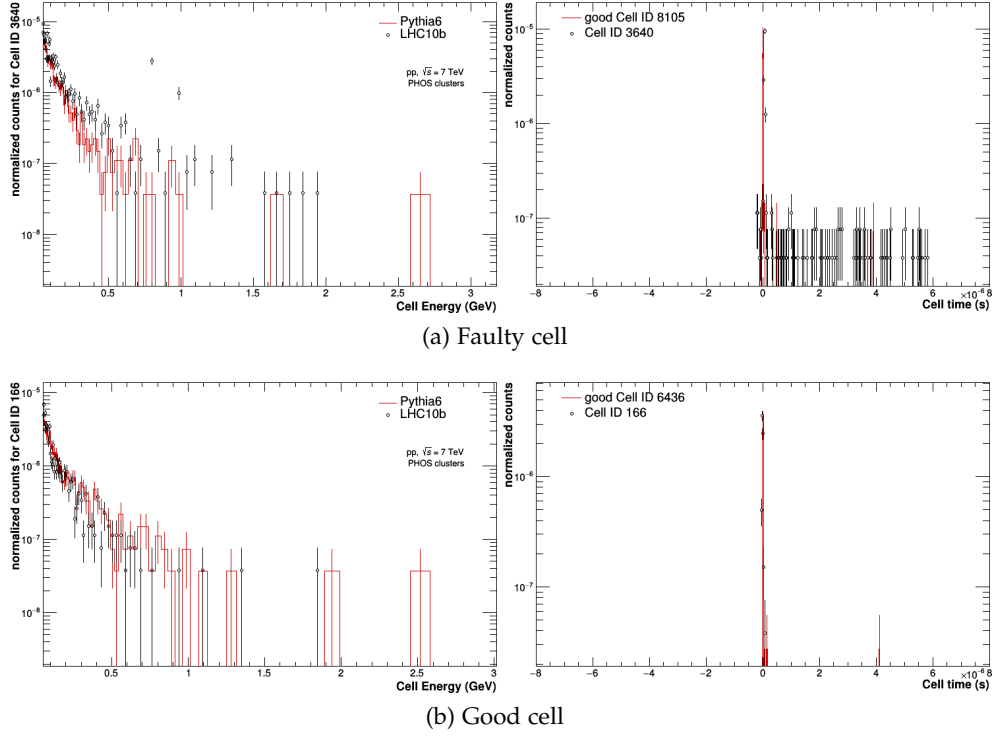


Figure 6.3: Cell energy- and time distributions of two different PHOS cells. The cell energy distribution (left) is shown together with MC predictions, whereas the cell timing distribution is shown together with the distribution of a cell that was accepted for the analysis. Fig. 6.3a shows an example of a faulty cell that is firing at two distinct energies more than expected from MC at random times and is thus rejected for the analysis. Fig. 6.3b shows an example of an accepted cell, where the energy distribution is nicely described by the MC and the timing is close to 0s after the initial collision, as expected.

For period LHC10bcde roughly 400 PHOS cells are flagged as faulty during the cell QA. However, during the LHC10f period of data taking the PHOS performance worsened, resulting in about 1200 cells being flagged as bad. Fig. 6.4 shows the η - ϕ distribution of clusters reconstructed in period LHC10b and LHC10f after the bad cell mapping is applied. One can see PHOS's three super modules installed at the time, each

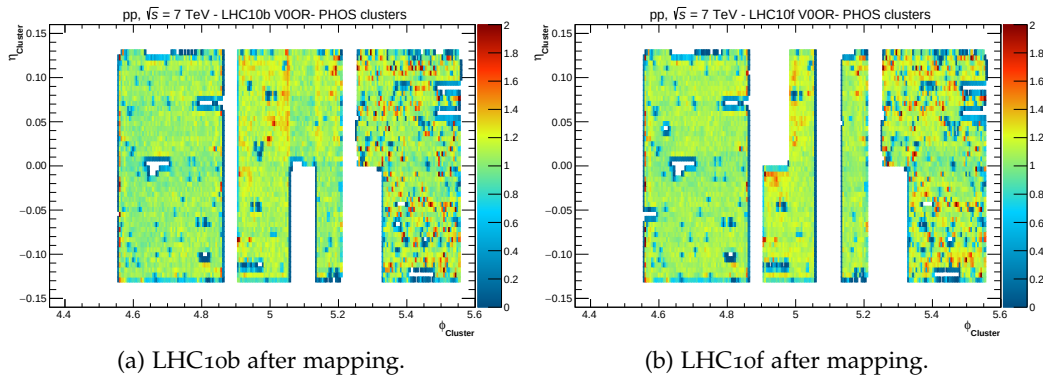


Figure 6.4: η - ϕ distribution of PHOS clusters found in dataset LHC10b (a) and LHC10f (b), after the cuts found in Tab. 6.2 have been applied. The distribution is normalized with number of events, as well as cluster density per bin.

with white areas resulting mainly from cells that were flagged as broken/switched off during data taking. Most of the cells flagged during the QA procedure are single broken cells surrounded by working cells, resulting in only small white spots in the η - ϕ distribution that are not clearly visible here. Comparing the distributions for LHC10b and LHC10f, one can clearly see that large parts of the second super module are not working properly during the last period of data taking. However, no explanation of the cause of this problem could be found when doing research for this thesis. Looking at the last module, one can see red spots, indicating clusters where an especially high energy deposition is registered. These local fluctuations should not be present after the bad channel map found during the QA procedure is applied. Instead, one expects a smooth distribution, comparable to the one seen for the EMCal in Fig. 6.2. This indicates that even though a few hundred cells have already been flagged as faulty, there are still noisy cells that fire more often than expected in the data sample. Nonetheless the quality of the PHOS clusters is for now considered sufficient for this analysis, because the contribution of faulty cells in clusters, that are then combined in pairs to possible π^0 candidates (see Chap. 7), is expected to be negligible for the π^0 reconstruction due to its statistical nature. This assumption is supported when looking at relevant cluster properties, such as the cluster energy distribution and cluster shape, which are well described by the MC, as can be seen in Fig. 6.5.

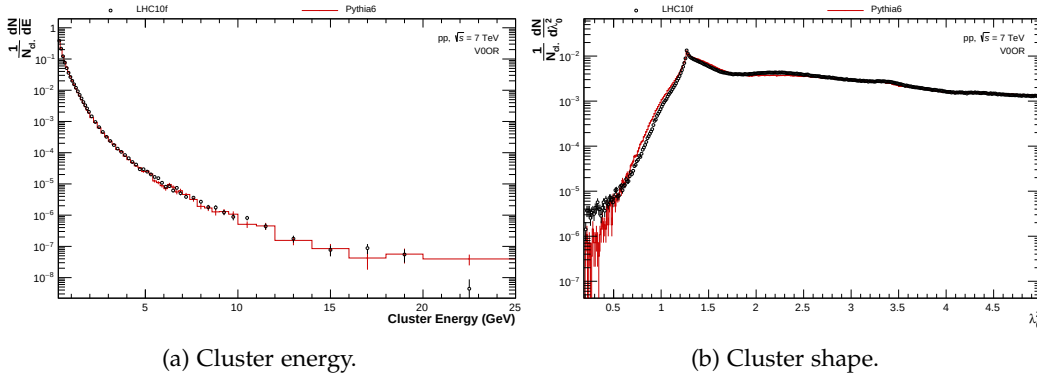


Figure 6.5: Fig. 6.5a: Energy distribution of reconstructed clusters before cluster selection criteria have been applied, shown for data and MC in the LHC10f and LHC14j4f datasets respectively. Fig. 6.5b: Distribution of the cluster shape parameter σ_{long}^2 (by convention labelled as λ_0^2 on the axis instead) shown for data and MC in the LHC10f and LHC14j4f datasets respectively.

6.2.2.2 Correction of Monte Carlo Cluster Energy

When measuring energy depositions with calorimeters, the response of the detector, meaning the signal induced by energy depositions, is mainly linear, i.e. an increase in energy produces a signal proportional to the energy deposition. However, certain detector effects such as e.g. leakage or saturation cause a non-linear detector response that needs to be accounted for and requires a so-called non-linearity correction. This is usually done using data obtained during test-beam measurement [60]. However, an independent calibration approach that includes an overall calibrations as well as non-linearity corrections, is used in this analysis. This approach is in accordance with the

calibration strategy used in existing publications of π^0 and η meson measurements with the PHOS, such as e.g. Ref. [21]. It works by reconstructing the neutral pion in data and MC using the invariant mass method, which is discussed in Sec. 7.1, and then parametrising the peak position ratios to correct the energy of the MC clusters.

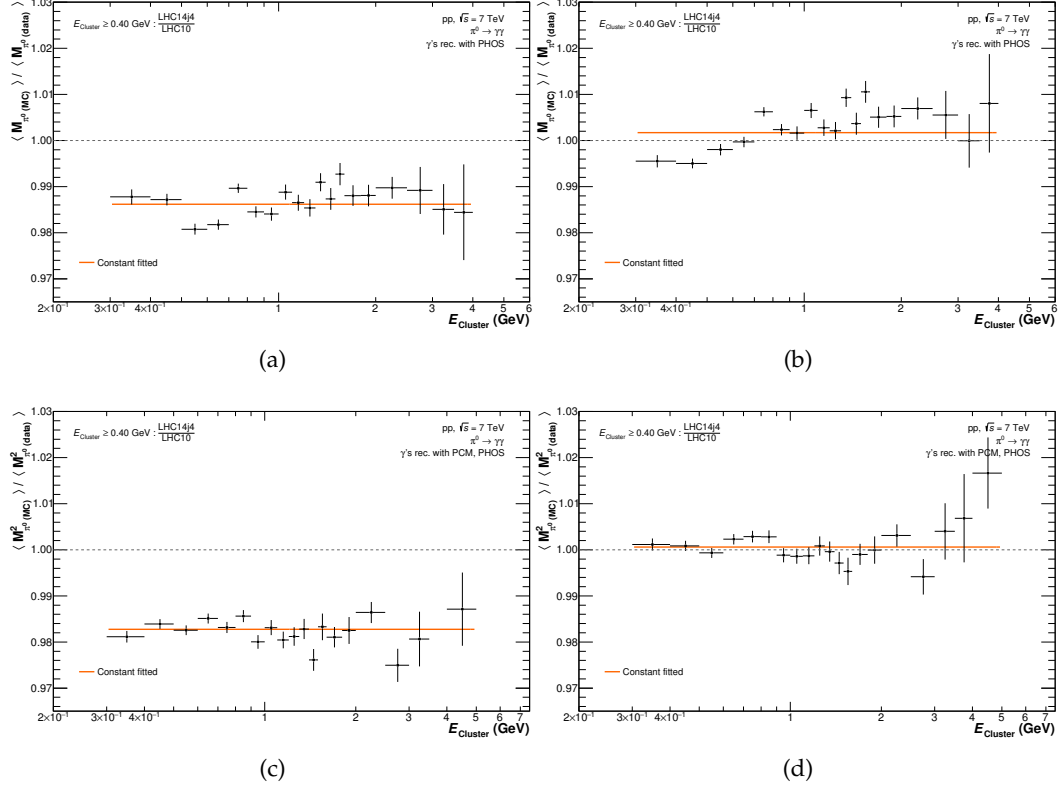


Figure 6.6: Calculated ratios of mass peak positions obtained in data and MC with respect to PHOS cluster energy E_{cluster} . The mass peak positions are obtained by calculating the two photon invariant mass distribution $M_{\gamma\gamma}$ and extracting the peak position as a mean of a Gaussian fit with an exponential tail, where the photons are measured as given in the respective legend. No non-linearity correction has been applied for the figures on the left, whereas the MC cluster energies have been corrected in the figures on the right, as described in this section.

After a basic cell by cell energy calibration that is performed prior to this analysis, the invariant mass distribution $M_{\gamma\gamma}$ of all PHOS cluster pairs is calculated for different cluster energy ranges in data and MC. The resulting invariant mass distributions show peaks roughly at the nominal π^0 mass and after a background subtraction the peaks are fitted with a Gaussian with an exponential tail. In each cluster energy-bin, the ratio between the mass peak position found in data $M_{\pi^0(\text{data})}$ and the position obtained from MC simulations $M_{\pi^0(\text{MC})}$ is calculated, which is shown in Fig. 6.6a. One can clearly see a constant mismatch between data and MC of about 1.5 %, which is visualized by a constant fit shown in orange. Another approach to reconstruct the neutral pion is to use one photon that is measured with the PHOS and combining it with another photon that has been measured using PCM, a technique which will be elaborated in Sec. 6.3. This so-called ‘hybrid’ approach profits from the good energy resolution of the PCM and therefore can be used to improve the precision of the PHOS energy calibration. Fig. 6.6c shows the mass ratios obtained using PCM and

PHOS for the photon measurements as a function of **PHOS** cluster energy E_{cluster} . The mismatch between data and **MC** is fitted with a constant which is then used to correct the **PHOS** cluster energies in **MC** simulations. This hybrid correction approach is used as the standard non-linearity correction procedure in this analysis due to its improved precision resting upon the **PCM** photon. Fig. 6.6b and Fig. 6.6d show the mass peak ratios obtained using **PHOS** and **PCM-PHOS** respectively, where in both cases the correction obtained using the hybrid approach is applied for the **PHOS** cluster energies in **MC**. One finds reasonable agreement between the peak positions in data and **MC** after the non-linearity correction is applied. However, a slight overestimation of the mass peak position in **MC** can be observed for the stand-alone **PHOS** measurement. The uncertainty arising due to a remaining mismatch between data and **MC** is accounted for by studying the effect of different non-linearity corrections on the final measurement, as briefly discussed in Sec. 8.3. For an in depth discussion of different non-linearity correction techniques, please also refer to Ref. [42] and Ref. [73].

6.3 PHOTON RECONSTRUCTION WITH THE PCM

As outlined in Sec. 2.4, highly energetic photons mainly interact with an absorber via the creation of e^+e^- pairs in the field of the absorbers nucleus. Exploiting this pair creation within the detector material, i.e. the **ITS** and **TPC**, one can measure photons that converted within 180 cm of the beam axis by using the V^0 finder elaborated in Sec. 3.4.3. This technique is known as the Photon Conversion Method (**PCM**) [20, 61] and is used as one method in this analysis to measure photons. In order to purify the photon sample, several selection criteria have to be applied to identify tracks originating from electrons/positrons, as well as V^0 candidates corresponding to a photon. These criteria were chosen following the selection strategy used in previous π^0 and η measurements that utilize the **PCM** (e.g. Ref. [20] and Ref. [21]) and will be discussed in this section.

An overview of the selection criteria, that are applied when using **PCM** related photon measurements in this analysis, can be found in Tab. 6.3. The top part of Tab. 6.3 shows the basic selection criteria applied to select suitable tracks and V^0 candidates. In this analysis, the on-the-fly V^0 -finding algorithm (see Sec. 3.4.3) is used, which is chosen due to its good conversion point resolution and the larger photon reconstruction efficiency compared to the offline algorithm, especially at low transverse momenta [73]. The oppositely charged tracks that are taken into account are required to have a minimum momentum of 50 MeV/ c and a fraction of the theoretically findable **TPC** clusters exceeding 60 %. In this case a fraction of **TPC** clusters is required rather than an absolute number of clusters, in order to account for the fact that tracks belonging to secondary particles differ in length depending on their point of origin and inclination. Furthermore, the tracks and the reconstructed V^0 candidates are required to be within the geometrical azimuthal and pseudorapidity coverage of **ITS** and **TPC**, where the pseudorapidity of a candidate is calculated using the angle between its 3-momentum vector and the beam-axis in the zR -plane. However, this calculation does not consider the starting point of the track, which can lead to accepted V^0 candidates outside the angular dimensions of the detector. To avoid this, an additional condition

$$R_{\text{conv}} > |z_{\text{conv}}|S_{\text{ZR}} - 7 \text{ cm} \quad (6.3)$$

Table 6.3: Overview of the selection criteria used for photon measurements with PCM.

	CUT	SETTING
track & V^0 sel.	V^0 -finding algorithm	on-the-fly
	pseudorapidity	$ \eta_{\text{track}, V^0} < 0.9$
	azimuthal angle	$0 < \phi_{\text{track}, V^0} < 2\pi$
	min. track p_T	$p_{T,\text{track}} > 0.05 \text{ GeV}/c$
	min. clusters in TPC	$\frac{N_{\text{cls. TPC}}}{N_{\text{findable cls. TPC}}} > 60 \%$
	conversion radius	$5 \text{ cm} < R_{\text{conv.}} < 180 \text{ cm}$
PID	electron identification	$-3 < n\sigma_{e,\text{TPC}} < 5$
	pion rejection	$n\sigma_{\pi,\text{TPC}} < 1$ for $p > 0.4 \text{ GeV}/c$
photon sel.	photon quality	$\chi_\gamma/\text{ndf} < 30$ $ \psi_{\text{pair}} < 0.1$
	Armenteros-Podolanski	$q_{T,\text{max}} = 0.05 \text{ GeV}/c$ $ \alpha_{\text{max}} = 0.95$
	pointing angle	$\cos \vartheta_{\text{PA}} > 0.85$

is imposed, where $S_{\text{ZR}} = \tan(2 \arctan(\exp(-\eta_{\text{cut}})))$ and the coordinates R_{conv} and z_{conv} are determined with respect to the nominal centre of the detector [21]. Moreover, the conversion radius R_{conv} of the secondary vertex is required to be within $5 \text{ cm} < R_{\text{conv}} < 180 \text{ cm}$, where the lower limit is chosen to reduce contributions of π^0 and η Dalitz decays, and the upper limit ensures secondary track reconstruction within the TPC.

In order to identify tracks belonging to electrons and reject those originating from pions, cuts on the energy loss per unit length dE/dx in the TPC are applied: An inclusion cut on the expected electron energy loss in the TPC of $-3 < n\sigma_{e,\text{TPC}} < 5$ is used, removing track candidates with an energy loss too far away from the expected electron energy loss. Moreover, a pion exclusion cut is applied to further reduce pion contamination in the sample by excluding all tracks with $n\sigma_{\pi,\text{TPC}} < 1$. This cut can be restricted to a certain track momentum range, e.g. to only apply the pion exclusion cut for low momenta tracks. However, no momentum distinction is done in this analysis, and all secondary tracks with $0.4 \text{ GeV}/c < p < 100 \text{ GeV}/c$ are used for the pion dE/dx exclusion. Fig. 6.7a shows the dE/dx distribution of secondary tracks after only the track selection criteria have been applied. Even though one can still see contributions from pions, protons and kaons, comparing this distribution to the primary track sample shown in Fig. 5.1a, one can observe an enhancement of electrons in the secondary track sample. Fig. 6.7b shows the dE/dx distribution after the PID cuts as well as the photons cuts, which will be described in the course of this section, have been applied, and a suppression of non-electron contributions is clearly visible.

The last part of Tab. 6.3 shows the selection criteria that were applied to increase the photon purity in the V^0 sample. First, a triangular two-dimensional cut on χ^2/ndf and ψ_{pair} is applied to increase the overall quality of the reconstructed photons. Here, χ^2 refers to the reduced χ^2 of the Kalman-Filter hypothesis for the e^+e^- pair, and ψ_{pair}

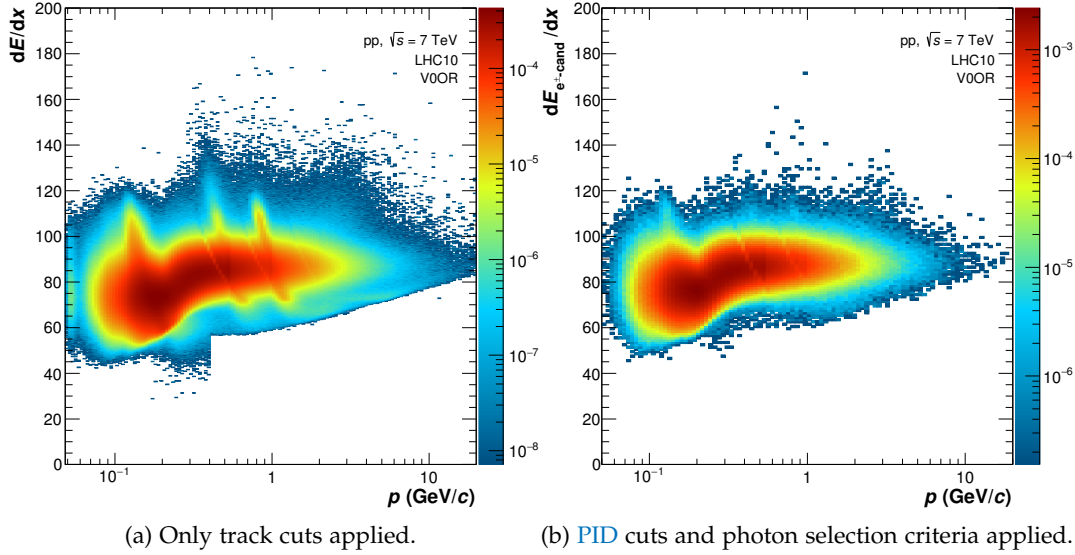


Figure 6.7: TPC dE/dx distribution after application of different selection criteria: Fig. 6.7a shows the distribution after only track selection criteria have been applied. After the application of electron PID cuts, as well as photon selection criteria, a rather clean electron sample is obtained, which is shown in Fig. 6.7b

is the angle between the plane spanned by the e^+e^- pair and the plane perpendicular to the magnetic field of ALICE [20]. Requiring ψ_{pair} to not exceed 0.1 allows to reduce remaining background by exploiting the fact that e^+e^- tracks are only marginally bend in the magnetic field. In addition, a cut on the pointing angle ϑ_{PA} (see Sec. 3.4.3) is applied by requiring that $\cos \vartheta_{\text{PA}} > 0.85$ which corresponds to the requirement that the momentum vector of the V^0 points towards the primary vertex. In order to remove remaining contributions from K_S^0 , Λ and $\bar{\Lambda}$ particles, one can apply selection criteria based on the momenta and opening angles expected for the specific two-body decays. A convenient way to display two-body decay regularities is an Armenteros-Podolanski plot [79] which is shown in Fig. 6.8. This plot displays the distribution of e^+e^- pairs as a function of two quantities: The longitudinal momentum asymmetry (α) and the projection of the daughter (e^+e^-) particles combined momentum with respect to the mother particle (V^0) in the transverse direction q_T . The longitudinal momentum asymmetry α is defined via:

$$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}, \quad (6.4)$$

where p_L^+ and p_L^- are the longitudinal momenta of the electron- and positron track respectively. This quantity is sensitive to the masses of the decay products, and one expects a symmetric distribution in α if their masses are identical. The projection q_T is defined as:

$$q_T = p \cdot \sin \vartheta_{\text{mother-daughter}}, \quad (6.5)$$

where p is the momentum of the daughter particle and $\vartheta_{\text{mother-daughter}}$ the opening angle between daughter and mother particle. Fig. 6.8a shows the Armenteros-Podolanski plot after only the basic track cuts have been applied to the V^0 candidates. Four characteristic contributions from K_S^0 , Λ , $\bar{\Lambda}$ and photon conversions are

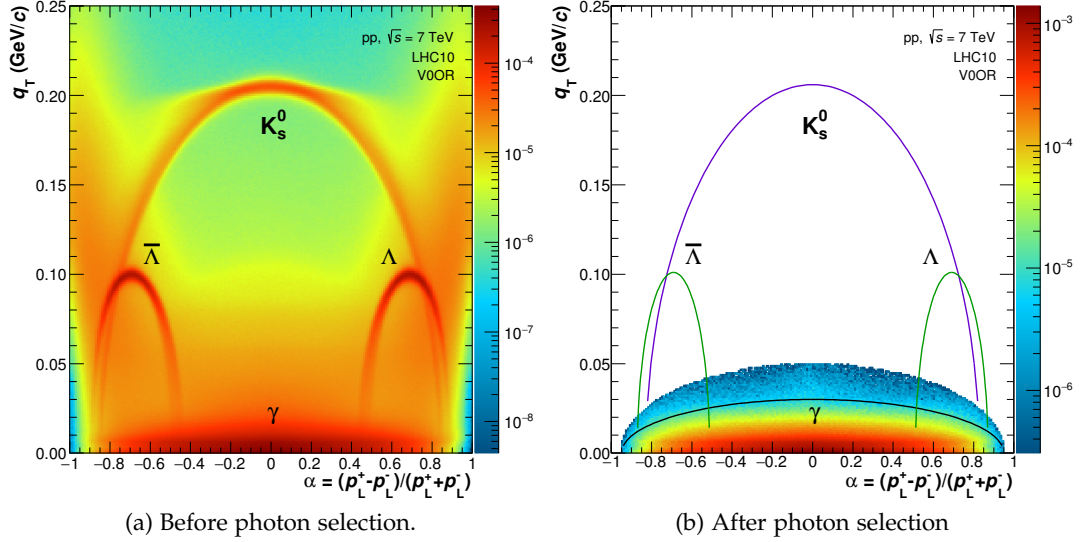


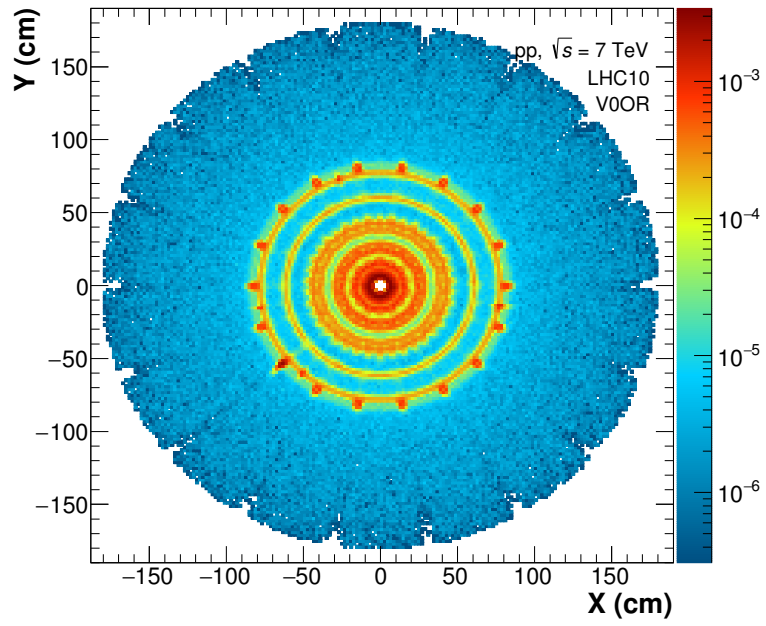
Figure 6.8: Armenteros-Podolanski plot before (a) and after (b) the photon selection criteria elaborated in this section have been applied. The photons are visible as a symmetric distribution with q_T close to zero and are therefore selected according to Eq. 6.6.

clearly visible. The photons contribute with a symmetric distribution and a q_T close to zero due to the identical mass of the decay products and the photons negligible mass respectively. Another symmetric contribution can be seen for $0.1 \text{ GeV}/c \lesssim q_T \lesssim 0.2 \text{ GeV}/c$ originating from K_S^0 decays. The distribution originating from Λ and $\bar{\Lambda}$ baryons is visible for $0.04 \text{ GeV}/c \lesssim q_T \lesssim 0.1 \text{ GeV}/c$. In contrast to the other contributions, it is asymmetric due to the Λ 's decay to a proton and a charged pion which differ significantly in mass. In order to isolate the photon contribution an asymmetry dependent cut:

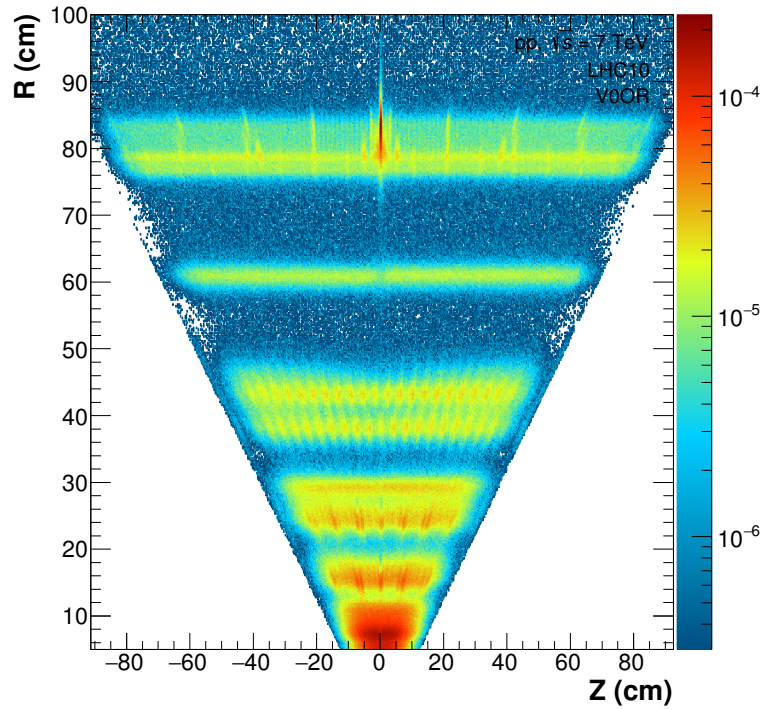
$$q_T < q_{T,\text{max}} \sqrt{1 - \alpha^2 / \alpha_{\text{max}}^2} \quad (6.6)$$

is applied, where $q_{T,\text{max}} = 0.05 \text{ GeV}$ and $\alpha_{\text{max}} = 0.95$. The Armenteros-Podolanski plot, after application of all photon selection cuts, can be seen in Fig. 6.8b. Only very few Λ and $\bar{\Lambda}$ with low q_T survive the applied cut, leading to a photon sample of high purity.

Finally, the conversion points of all selected photon candidates are shown in Fig. 6.9 in the xy , as well as the zR -plane. Most of the conversions happen within the layers of the ITS as well as the inner containment vessel and inner field cage of the TPC (two outermost visible 'rings'). Only a fraction of the conversions happens inside the TPC gas (outer blue area). The material sensitivity of the photon conversions allows a detector tomography that can be e.g. used to estimate the material budget of the detector [61, 80].



(a)



(b)

Figure 6.9: Conversion points of selected photon candidates shown in the xy - and zR -plane, where the z -axis corresponds to the beam axis.

NEUTRAL PION RECONSTRUCTION

Following the discussion of photon measurements in the previous chapter, this chapter is dedicated to the reconstruction of neutral pions via their decay to two photons. In this analysis, five different techniques are used to reconstruct the neutral pion, which are referred to by the following naming scheme:

PCM	Both photons used to reconstruct the neutral pion are measured using the PCM .
PCM-EMCAL	A hybrid method using one photon measured with the PCM and combining it with a photon measured with the EMCal to reconstruct the neutral pion.
PCM-PHOS	A hybrid method using one photon measured with the PCM and combining it with a photon measured with the PHOS to reconstruct the neutral pion.
EMCAL	Both photons used to reconstruct the neutral pion are measured with the EMCal .
PHOS	Both photons used to reconstruct the neutral pion are measured with the PHOS .

Different approaches for the neutral pion reconstruction are used in order to exploit the advantages offered by the individual methods to measure photons: Measurements with [PCM](#) profit from its capabilities to measure photons with good momentum resolution down to low transverse momenta ($p_T \sim 0.2 \text{ GeV}/c$) allowing π^0 measurements down to $p_T = 0.4 \text{ GeV}/c$ [20]. Photon measurements with the [EMCal](#) benefit from its large acceptance. However for π^0 measurements its upper p_T -reach ($p_T \sim 20 \text{ GeV}/c$) is limited by cluster merging which was briefly mentioned in Sec. 6.1. The [PHOS](#), on the other hand, offers a higher granularity than the [EMCal](#) which reduces cluster merging and allows π^0 reconstruction up to $p_T = 25 \text{ GeV}/c$ [20]. However, even though the [PHOS](#) is designed for low- p_T photon measurements ($p_T \sim 0.5 \text{ GeV}/c$) and offers a better momentum resolution than [EMCal](#), its smaller acceptance results in less statistics available for π^0 reconstruction, considering that two photons need to be detected within the detector's acceptance. Lastly, the hybrid methods [PCM-EMCal](#) and [PCM-PHOS](#) allow to combine the good momentum resolution and p_T -coverage of [PCM](#) with the capabilities of each calorimeter. Hybrid methods have already been used for π^0 and η measurements at different centre-of-mass energies (e.g. $\sqrt{s} = 8 \text{ TeV}$ [21] and 2.76 TeV [19]), demonstrating their advantages for neutral meson reconstruction.

7.1 INVARIANT MASS METHOD

The neutral pions are reconstructed using the invariant mass method which exploits the fact the invariant mass M of a particle is conserved during its decay to daughter

particles. Therefore, the invariant mass of a mother particle can be obtained by adding up the four-vector momenta of its decay particles and calculating the invariant mass of the resulting four-vector. However, in a real event it is neither known which of the detected particles belong to a particular decay nor if they even belong to a decay at all. Information about the mother particle consequently has to be extracted statistically by looking at an invariant mass distribution which is calculated taking into account all possible combinations of the respective daughter particles in an event. In this distribution a peak around the mother particles mass is expected, which then can be used to extract properties, e.g. the mother particle's mass and yield.

Because the four-vector momentum of the individual photons is not known, the invariant mass of a photon pair $M_{\gamma\gamma}$ is calculated using the relation:

$$M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1 - \cos \vartheta_{12})}, \quad (7.1)$$

where E_{γ} is the energy of the respective photon and ϑ_{12} the angle between the photon pair in the laboratory frame. The invariant mass $M_{\gamma\gamma}$ is calculated for all possible photon pairs in a given event, where the photons are selected as described in Chap. 6.

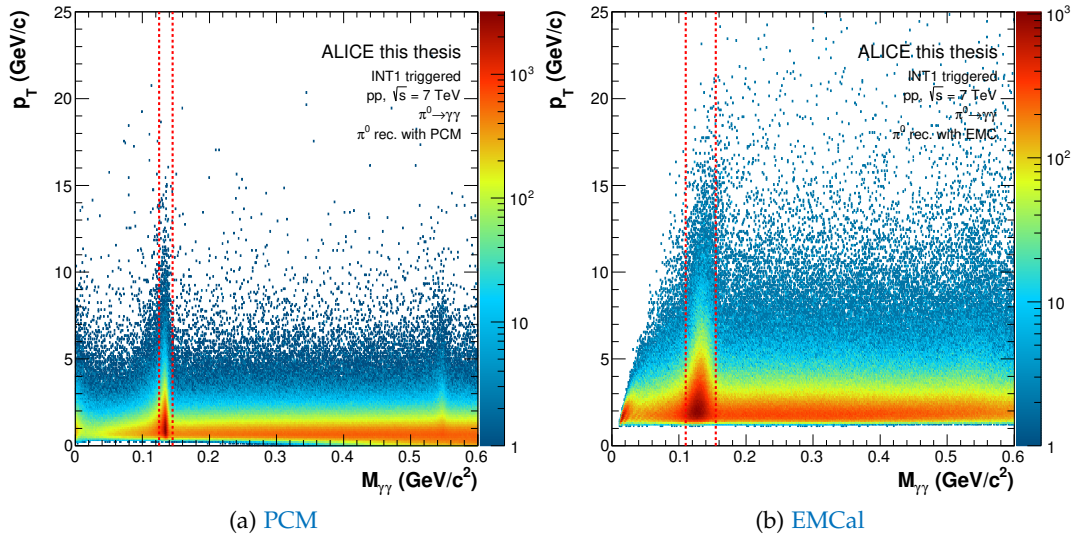


Figure 7.1: Invariant mass distributions of all photon pairs plotted as a function of their transverse momentum before the application of any meson selection criteria. In these examples, both photons are measured with **PCM** (a) and **EMCal** (b) respectively and the photons are selected as described in Chap. 6. The dotted lines represent the cut on the invariant mass, which is applied as part of the neutral pion selection that is described later in this section. No contributions below transverse momenta of about 1 GeV are visible in Fig. 7.1b due to the required minimum **EMCal** cluster energy $E_{\min} > 0.7$ GeV.

Fig. 7.1 shows the resulting invariant mass distribution of all photon pairs as a function of their transverse momentum. In the shown examples the photons are measured with the **PCM** and the **EMCal** respectively. As expected, one can clearly see an excess of combinations in the vicinity of the nominal neutral pion mass ($m_{\pi^0} \approx 135 \text{ MeV}/c^2$ [14]) on top of a combinatorial background which arises due to random photon combinations that do not belong to a decay. Moreover, a small excess is visible around

550 MeV originating from the $\eta \rightarrow \gamma\gamma$ decay. Comparing the distributions obtained using the PCM and the EMCAL, one observes a broadening of the neutral pion peak for the EMCAL measurement due to its limited energy resolution. The width of the neutral pion peak depends on the pions transverse momentum, as well as the reconstruction technique. This dependence is well understood, and has been studied in previously performed π^0 and η analyses [19–21].

7.2 NEUTRAL PION SELECTION

After obtaining the sample of photon pairs, as described in the previous section, neutral pion candidates have to be identified. This is done by applying several selection criteria that can be found in Tab. 7.1.

Table 7.1: Overview of neutral pion selection criteria, that are applied for the respective reconstruction techniques.

REC. METHOD	CUT		
	RAPIDITY	OPENING ANGLE (mrad)	MASS RANGE (MeV/c ²)
PCM	$ \eta < 0.85$	5	$125 < M_{\gamma\gamma} < 145$
PCM-EMCAL	$ \eta < 0.85$	5	$125 < M_{\gamma\gamma} < 145$
EMCAL	$ \eta < 0.85$	17	$110 < M_{\gamma\gamma} < 155$
PCM-PHOS	$ \eta < 0.85$	5	$120 < M_{\gamma\gamma} < 150$
PHOS	$ \eta < 0.85$	5	$110 < M_{\gamma\gamma} < 145$

Each reconstructed photon pair is required to lie within a pseudorapidity range of $|\eta| < 0.85$ which is chosen a bit smaller than the coverage $|\eta| < 0.9$ of the central-barrel in order to avoid edge effects. For all reconstruction techniques except EMCAL, a cut on the opening angle between the two photon momentum vectors of $\vartheta > 5$ mrad is applied to remove contamination of double counted photons, which can e.g. occur if multiple V^0 's are falsely attributed to the same e^+e^- conversion pair. A characteristic feature of the double counted photons is their small separation in space, i.e. a small opening angle, and consequently their contribution to the sample can be greatly reduced by applying this criterium. A greater constraint of $\vartheta > 17$ mrad is chosen for photon pairs that are reconstructed solely with the EMCAL. Due to its limited segmentation, clusters from photon pairs with a smaller opening angle can no longer be separated. Finally, a cut on the invariant mass $M_{\gamma\gamma}$ of a photon pair is applied in order to exclude purely combinatorial photon pairs outside the vicinity of the nominal neutral pion mass. As illustrated in Fig. 7.1, the peak width varies depending on the reconstruction technique and therefore the invariant mass cut has to be adapted accordingly. In this thesis, only photon candidates within an invariant mass window approximately 2σ around the nominal π^0 mass are accepted for the respective reconstruction techniques, which is represented by the red dotted lines shown in Fig. 7.1.

NEUTRAL MESON ANALYSIS

This chapter is dedicated to the reconstruction of the ω and η meson via their $\pi^+\pi^-\pi^0$ decay using all five techniques to reconstruct neutral pions that were elaborated in the previous chapter. The first section of this chapter describes the reconstruction procedure itself, i.e. how underlying background is described and how the neutral meson signal is extracted. Then the obtained neutral meson raw yields are corrected for geometrical detector acceptance and reconstruction efficiency which will be covered in Sec. 8.2. After an evaluation of systematic uncertainty sources and their influence on the measurement in Sec. 8.3, the invariant cross sections for the ω and η mesons are finally presented in Sec. 8.4 together with a description the procedure used to combine the cross sections of the individual measurements.

8.1 NEUTRAL MESON RECONSTRUCTION

Analogous to the procedure described in the previous chapter for neutral pions, the ω and η mesons are reconstructed using the invariant mass method: Taking into account all possible $\pi^+\pi^-\pi^0$ combinations in an event, where the charged- and neutral pions are selected according to Chap. 5 and 7, the four-vector momentum of a neutral meson candidate is calculated by summing over all four-vector momenta of the respective pions in a combination. From the resulting sample, neutral meson candidates are selected by a few loose requirements, that can be found in Tab. 8.1.

Table 8.1: Overview of the neutral meson selection criteria.

CUT	SETTING
rapidity	$ \eta < 0.85$
charged pion mass	$M_{\pi^+\pi^-} < 850 \text{ MeV}/c^2$

Following the reasoning in Sec. 7.2, a requirement on the rapidity of $|\eta| < 0.85$ is applied to avoid edge effects. Moreover, a loose cut on the invariant mass of the charged pion pair is applied, in order to exclude candidates with invariant masses way above the respective nominal mass of the ω and η meson of $M_\omega \approx 782 \text{ MeV}/c^2$ and $M_\eta \approx 547 \text{ MeV}/c^2$.

Because the ω and η mesons both decay into three pions, they can be reconstructed simultaneously and one expects accumulations in the vicinity of their respective nominal masses in the invariant mass distribution. In order to reduce the influence of the neutral pion reconstruction, the invariant mass $M_{\pi^+\pi^-\pi^0,\text{rec.}}$ of a neutral meson candidate is corrected using:

$$M_{\pi^+\pi^-\pi^0} = M_{\pi^+\pi^-\pi^0,\text{rec.}} - (M_{\pi^0,\text{rec.}} - M_{\pi^0,\text{PDG}}), \quad (8.1)$$

where $M_{\pi^0,\text{rec.}}$ is the invariant mass of the respective reconstructed neutral pion and $M_{\pi^0,\text{PDG}}$ the nominal π^0 mass.

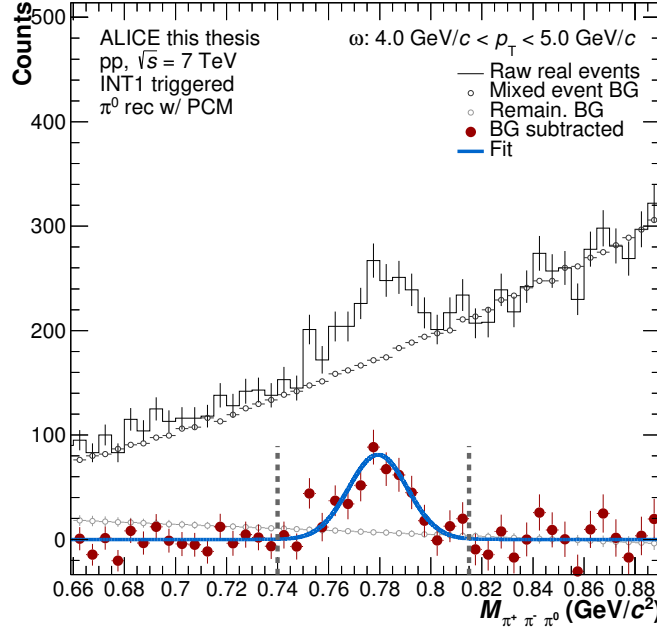


Figure 8.1: Invariant mass distribution shown in the vicinity of the ω meson’s nominal mass for an exemplary p_T -interval. The neutral pion is reconstructed using the PCM and the background description is obtained using the event-mixing technique. The signal is fitted with a Gaussian with an exponential tail, after any residual background has been subtracted. The vertical grey lines indicate the integration range used to obtain the raw yield.

Fig. 8.1 shows an exemplary invariant mass distribution $M_{\pi^+\pi^-\pi^0}$ in the vicinity of the ω nominal mass for transverse momenta within $4 \text{ GeV}/c < p_T < 5 \text{ GeV}/c$, which is calculated using the four-vector momenta of the neutral meson candidates. A peak is clearly visible on top of an underlying combinatorial background arising due to mostly uncorrelated $\pi^+\pi^-\pi^0$ combinations that do not stem from the same particle. In order to obtain the neutral meson signal, an accurate description of this background is needed which is represented in Fig. 8.1 by open dark grey markers. In this analysis an event-mixing approach is used for background description among two other methods, which are used to evaluate the systematic uncertainty of the background description procedure in Sec. 8.3. The different background description techniques, as well as the composition of the underlying background, will be discussed in Sec. 8.1.1. After subtracting the combinatorial- as well as any residual background (light grey), one finally obtains the neutral meson signal (red) which then can be fitted by a Gaussian with an exponential tail (blue). This signal extraction is elaborated in more detail in Sec. 8.1.2, where moreover invariant mass distributions obtained with the different neutral pion reconstruction techniques are presented.

8.1.1 Background Description

As previously stated, the background is expected to be mostly of combinatorial nature. In order to confirm this assumption, the different contributions to the invariant mass distribution are studied as part of this thesis, by performing the full reconstruc-

tion procedure on the LHC14j4 dataset, which incorporates simulations of pp collision events with **MC** generator PYTHIA 6 and a full detector response using GEANT 3.

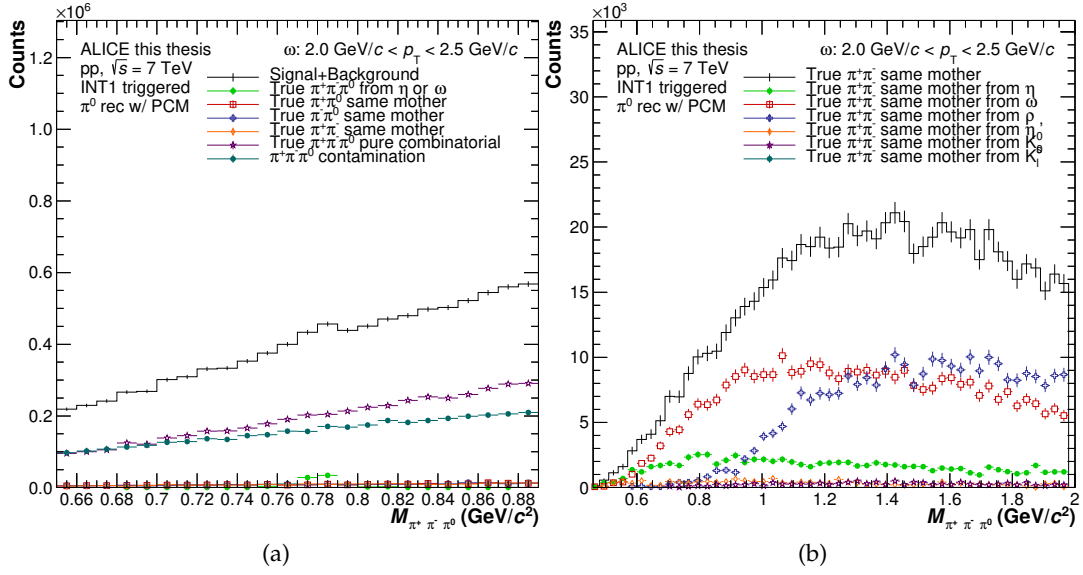


Figure 8.2: Fig. 8.2a: Invariant mass distribution for an exemplary momentum range of $2.0 \text{ GeV}/c < p_T < 2.5 \text{ GeV}/c$, where the different contributions are obtained using **MC** simulations with full detector response. The background is mainly composed of purely combinatorial combinations and combinations, where one of the pions (mostly π^0) was wrongly identified as such. The contributions due two two-pion correlations are found to be negligible. Fig. 8.2b: Invariant mass distribution for all $\pi^+\pi^-\pi^0$ combinations where the π^+ and π^- originate from the same mother particle. Below $1.2 \text{ GeV}/c^2$ most of the pairs originate from ω and η mesons and an increasing contribution from ρ mesons can be found that dominates the contributions above $1.2 \text{ GeV}/c^2$.

Fig. 8.2a shows the invariant mass distribution (black) for an exemplary transverse momentum range $2.0 \text{ GeV}/c < p_T < 2.5 \text{ GeV}/c$. The neutral pion is reconstructed using **PCM** and the different contributions to the total invariant mass distribution, which were extracted using true **MC** information, are shown in different colours. The distribution is dominated by contributions from purely combinatorial $\pi^+\pi^-\pi^0$ combinations, which are defined as pion triplets where none of the pions originate from the same mother particle. Furthermore a big contribution of ‘contaminated’ $\pi^+\pi^-\pi^0$ combinations is visible, where at least one of the three pions was wrongly identified as such. The performed studies indicate, that a majority of this contribution arises due to wrongly identified neutral pions, i.e. neutral pions originating from the combinatorial $\gamma\gamma$ background of the π^0 reconstruction. Moreover, the background studies show that contributions originating from two pion correlations, where two out of three pions originate from the same mother particle, have a negligible contribution to the total invariant mass distribution, supporting the assumption of a mostly uncorrelated background.

Nonetheless the origins of two pion correlations were investigated and one of the results is shown in Fig. 8.2b. Here, the total invariant mass distribution of three pion combinations, where the π^+ and π^- originate from the same mother particle, is shown in black, and the contributions from different mother particles are repre-

sented by coloured distributions. For invariant masses below $1.2 \text{ GeV}/c^2$, most of the pairs originate from the an ω or η meson. Furthermore, a contribution from ρ^0 mesons can be observed which starts at roughly $0.8 \text{ GeV}/c^2$ and is the dominant source of $\pi^+\pi^-$ decay correlations above roughly $1.4 \text{ GeV}/c^2$. Similar contributions are observed when studying the $\pi^+\pi^0$ and $\pi^-\pi^0$ contributions, originating from the ρ^+ and ρ^- , as shown in Fig. A.1.

It should be noted, that the studies carried out as part of this thesis only studied possible correlations originating from particle decays. In the future, other possible correlations, e.g. originating from underlying jet structures, could be studied. Nonetheless the assumption of a mostly uncorrelated background, which is supported by studies up to this point, will be considered as valid and the methods used in this thesis to describe the background by exploiting the lack of correlation, are described in the following:

EVENT-MIXING METHOD This method [81] describes the underlying background by performing the invariant mass method on pions originating from different collision events, which thus can not be correlated. This method is the standard technique used for neutral meson analyses [19–21] and is also used as the main method of background description in this analysis. Because previous studies found that the shape of the combinatorial $\gamma\gamma$ background is dependent on event properties such as primary vertex position and multiplicity, this dependency is also assumed for the three pion background and consequently the pions are grouped into different ‘pools’ according to the event multiplicity and z-position of the primary vertex [42]. The event mixing is performed with a pion from the current event and pions from the corresponding pool, each containing a maximum of 50 previous events. Once the pool is full, its oldest entry is deleted and the pions of the current event are added to the pool’s buffer.

Table 8.2: Illustration of the different event-mixing groups, where ‘X’ indicates that the respective pion is taken from the current event.

GROUP	π^+	π^-	π^0
1	X	X	-
2	X	-	X
3	-	X	X
4	-	-	-

Even though no significant two-pion correlations were found during the background studies (see above), four different groups are implemented for the event-mixing method in order to account for possible unknown two-pion correlations by performing the event mixing with two out of three pions from the same event. The different groups are illustrated in Tab. 8.2, where ‘X’ indicates that the respective pion is taken from the current event. The background is finally described by taking the sum of the normalized distributions obtained using the four different event-mixing groups. However, the distributions of the different groups are found to not significantly differ in shape.

LIKE-SIGN MIXING Using this method, underlying correlations are destroyed by only considering three pion combinations, where the two charged pions are of same charge, i.e. the combinations $\pi^+\pi^+\pi^0$ and $\pi^-\pi^-\pi^0$, and therefore can not originate from any decay of interest. Compared to the event-mixing method, like-sign mixing has the advantage that the three pion combinations are taken from the same event and therefore differences in the underlying event structure do not have to be considered. However, the sample size in the same event is limited and consequently the distributions obtained with the like-sign mixing method have larger statistical uncertainties than the ones obtained with the event-mixing method. Even though the like-sign mixing method was found to describe the background shape as good as the event-mixing method, its limited statistics are problematic especially for neutral meson signal extraction at high transverse momenta. Therefore event-mixing is preferred in this analysis and like-sign mixing is only used to determine systematic uncertainties of the background description (see Sec. 8.3).

SIDEBAND MIXING This method works by performing the invariant mass method on $\pi^+\pi^-\pi^0$ combinations, but instead of selecting the respective neutral pions candidates with an invariant mass according to Tab. 7.1, only π^0 candidates outside of the invariant mass range where a π^0 signal is expected are selected. Thus, the selected π^0 candidates most likely originate from the uncorrelated combinatorial $\gamma\gamma$ background and consequently are also not correlated to the charged pion pair. In this analysis, the side-band mixing is performed in three different variations, considering π^0 candidates only in an invariant mass range below the nominal π^0 mass ($50 \text{ MeV}/c^2 < M_{\gamma\gamma} < 100 \text{ MeV}/c^2$) and above ($180 \text{ MeV}/c^2 < M_{\gamma\gamma} < 220 \text{ MeV}/c^2$), as well as below and above. Comparing this method to like-sign mixing, the increase of statistical uncertainty is found to be less prominent and the shape of the background is nicely described. However, compared to event mixing, no improvements could be observed and this method is therefore only used for the systematic uncertainty estimation as well.

BACKGROUND FITTING Another approach to background description that has been studied as part of this analysis is fitting of a second order polynomial to the underlying background, where the invariant mass region of the neutral meson peak is excluded from the fitting procedure. However, this method of background description is not used in this analysis for two main reasons: 1. This method is ‘unphysical’ or at least less physical than the other background description methods, in the sense that the choice of fitting function is arbitrary and not physically motivated. 2. This method was found to be insufficient to describe the background for high transverse momenta, due to the lack of statistics.

8.1.2 Signal Extraction

In order to extract the signal of ω and η mesons, the invariant mass distribution $M_{\pi^+\pi^-\pi^0}$, as well as the event-mixing background, is calculated in different p_T -slices. The chosen slices are identical with the ones presented in the neutral meson cross sections (see Sec. 8.4), taking into account the statistical uncertainties of the respective neutral pion reconstruction technique. In each p_T -slice the event-mixing distribution

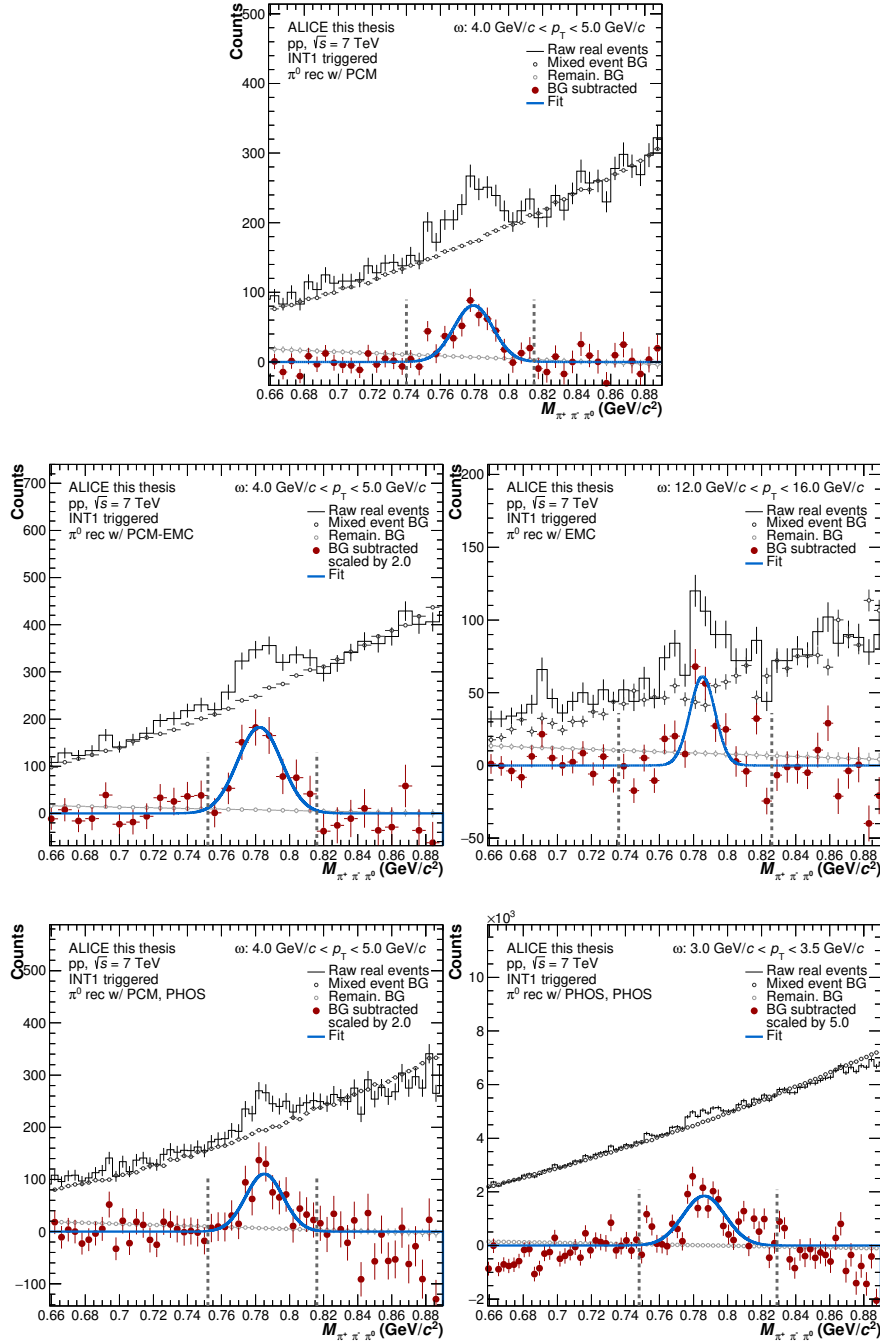


Figure 8.3: Invariant mass distributions shown in the vicinity of the nominal mass of the ω meson for exemplary p_T -ranges. The technique used to reconstruct the neutral pion is stated in each plot and the background is obtained using the event-mixing method. The signal is fitted with a Gaussian with an exponential tail after any residual background has been subtracted. The vertical grey lines indicate the integration range used to obtain the raw yield.

is normalized to the total¹ invariant mass distribution, by calculating their respective integrals in a given invariant mass range. This normalization range should be close enough to the meson peak to describe the background in the peak region prop-

¹ When talking about the 'total' invariant mass distribution, what is meant is the invariant mass distribution containing the signal and background.

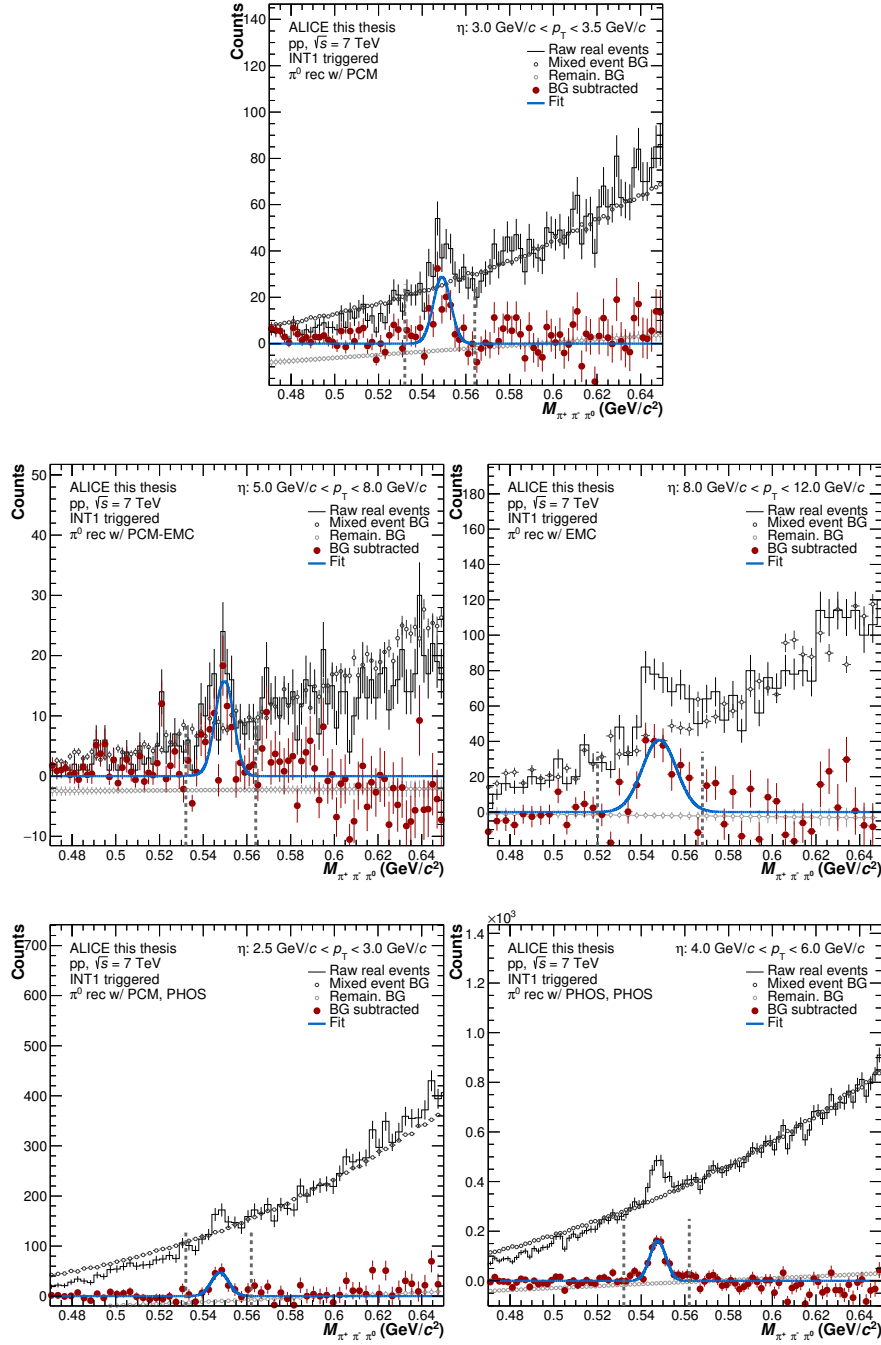


Figure 8.4: Example invariant mass distributions shown in the vicinity of the nominal mass of the η meson for exemplary p_T -ranges. The technique used to reconstruct the neutral pion is stated in each plot and the background is obtained using the event-mixing method. The signal is fitted with a Gaussian with an exponential tail after any residual background has been subtracted. The vertical grey lines indicate the integration range used to obtain the raw yield.

erly but not too close, in order to avoid that actual neutral meson signal is used for normalization. In this analysis, the normalization is carried out in a range on the right side of the neutral meson peak and the normalization ranges are adapted to the peak widths of each reconstruction method. An overview of all invariant mass distributions as well as the corresponding normalized event-mixing background, can

be found in Sec. A.2. Moreover, the normalization ranges used in this analysis are presented in Tab. 8.3. In addition, normalization on the left side of the peak can be

Table 8.3: Overview of the standard invariant mass ranges used to normalize the event-mixing distribution to the total invariant mass distribution.

METHOD	NORMALIZATION RANGE (MeV/c ²)	
	ω	η
PCM	830 – 880	557 – 570
PCM-EMCal	825 – 865	557 – 570
PCM-PHOS	815 – 850	560 – 590
EMCal	830 – 890	570 – 640
PHOS	810 – 850	557 – 570

performed, which is used to evaluate the systematic uncertainty of the signal extraction, which will be elaborated in Sec. 8.3.

After the normalization step, the event-mixing background is subtracted from the total invariant mass distribution and one obtains the neutral meson signal on top of residual background. This background is found to be fairly small for the ω meson over the whole analysed p_T -range for all reconstruction techniques. However, when extracting the η meson signal the residual background is more significant, especially at low transverse momenta ($p_T \lesssim 4 \text{ GeV}/c$), where the event-mixing background is found to increasingly overestimate the actual background with decreasing momentum.

After the background subtraction the distribution is fitted with a function consisting of a Gaussian on top of a linear function to describe any residual background and an additional exponential tail to account for Bremsstrahlung. The fitting function [82] is given by:

$$\begin{aligned}
 f(M) = A \cdot & \left(G(M) \right. \\
 & + \exp\left(\frac{M - M_{\omega(\eta)}}{\lambda}\right) \cdot (1 - G(M)) \cdot \Theta(M - M_{\omega(\eta)}) \Bigg) \\
 & + B + C \cdot M,
 \end{aligned} \tag{8.2}$$

where $G(M)$ is the Gaussian function defined as:

$$G(M) = \exp\left(-0.5 \left(\frac{M - M_{\omega(\eta)}}{\sigma_M}\right)^2\right). \tag{8.3}$$

The Gaussian is characterized by the Amplitude A , the width σ_M and its mean $M_{\omega(\eta)}$, which from now on will be referred to as the reconstructed mass of the respective neutral meson. The exponential tail with an inverse slope λ is only applied below $M_{\omega(\eta)}$, by using the heavy-side function $\Theta(M - M_{\omega(\eta)})$. The implementation of an exponential tail is motivated by previous $\pi^0(\eta) \rightarrow \gamma\gamma$ measurements [20], where a very pronounced tail can be seen due to Bremsstrahlung and late photon conversions.

However, no such tail could be observed in this analysis using the three pion decay channel, which is why the slope parameter is fixed to $\lambda = 0.0007$, practically disabling the exponential tail feature in this analysis. As previously mentioned, more significant residual background is observed for the η measurement at low p_T and a linear description is found to be insufficient for $p_T < 2.5 \text{ GeV}/c$. Therefore a second order polynomial is used to describe residual background in this regime, resulting in an additional term $D \cdot M^2$ in Eq. 8.2.

Fig. 8.3 and 8.4 show the invariant mass distributions in selected p_T -slices for the ω and η meson respectively, where the individual panels represent the different techniques used for the neutral pion reconstruction. In addition, the invariant mass distributions in all used p_T -slices and for all five reconstruction techniques can be found in Sec. A.2. The invariant mass distribution of the ω meson using PCM was already presented in Fig. 8.1 at the beginning of this section and is shown here as well for better comparability with the other π^0 reconstruction techniques. Clear peaks are visible around the ω and η nominal masses for all five reconstruction techniques on top of a combinatorial background, showcasing the capability of all five methods to measure ω and η mesons in the three pion decay channel at $\sqrt{s} = 7 \text{ TeV}$. Looking at the invariant mass distribution of the extracted signal (red), no significant remaining background is visible and the distribution outside the peak range is flat and in agreement with zero showing that the use of event-mixing together with linear fitting is indeed sufficient to remove underlying background.

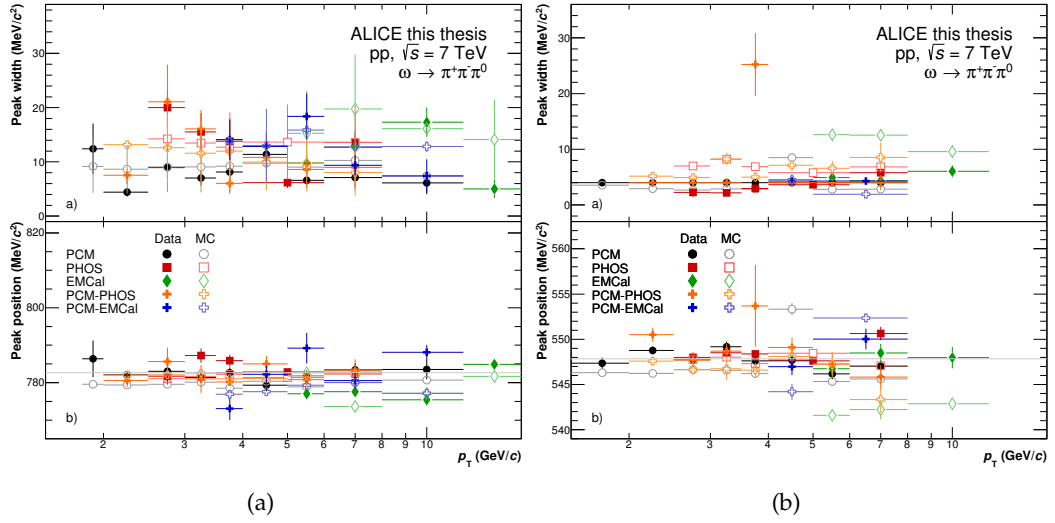


Figure 8.5: Peak width $\sigma_{\omega(\eta)}$ (top) and peak position $M_{\omega(\eta)}$ (bottom) of the individual ω (a) and η (b) measurements, that are obtained via the fitting procedure described in this section. The full markers indicate the values extracted from the signal extraction carried out on data, whereas the open markers represent the peak position and width taken from the signal extraction performed on MC simulations that are treated as data. The grey line shown in the peak position plots indicates the nominal mass of the respective meson.

Comparing the different reconstruction techniques, a difference in peak width can be observed which is a consequence of the differing energy resolutions of the detection methods involved. Comparisons of the peak positions and widths are shown in Fig. 8.5a and Fig. 8.5b for the ω and η signal extraction respectively, where data

is shown as full markers and MC as open markers. The MC peak widths and positions are obtained by carrying out the analysis on the LHC14j4 datasets which are treated as real data, i.e. not considering any information only available on a MC level. Neutral pion studies [20, 42] show a peak width ordering of $\sigma_{\pi^0, \text{PCM}} < \sigma_{\pi^0, \text{PHOS}} < \sigma_{\pi^0, \text{PCM-EMCal}} < \sigma_{\pi^0, \text{EMCal}}$, which is expected to propagate to the ω and η measurement carried out in this thesis. For ω reconstruction with PCM, peak widths of $\sigma_{\omega, \text{PCM}} \sim 8 \text{ MeV}/c^2$ are observed, whereas width up to $\sigma_{\omega, \text{EMCal}} \sim 18 \text{ MeV}/c^2$ and $\sigma_{\omega, \text{PHOS}} \sim 12 \text{ MeV}/c^2$ are obtained when using EMCal and PHOS respectively, which is compatible with the width ordering observed for neutral pions. Comparing the EMCal and the PHOS measurements with their corresponding hybrid methods, no significant difference in peak width can be observed due to the large statistical uncertainties of the used fits. The obtained mass peak positions are centred around the nominal ω (η) mass, which is indicated by a grey line, and agree within the statistical uncertainties with the peak positions observed for MC. Comparing the ω and η measurement, one observes overall smaller peak widths ($\sigma_\eta \sim 5 \text{ MeV}/c^2$) for the η meson, which is expected due to its much smaller decay width. However, a comparison of the different reconstruction techniques is not yet feasible with the available statistics.

Table 8.4: Overview of the integration ranges $[M_{\omega(\eta)} - \Delta M, M_{\omega(\eta)} + \Delta M]$ used to obtain the meson raw yield for each reconstruction method. The reconstructed meson mass $M_{\omega(\eta)}$ is obtained from the Gaussian fit in each p_T -slice and the range ΔM is chosen taking into account the signal peak width.

METHOD	INTEGRATION RANGE	
	$\Delta M (\text{MeV}/c^2)$	
	ω	η
PCM	35	15
PCM-EMCal	30	20
PCM-PHOS	30	13
EMCal	40	-26/ + 17
PHOS	40	14

Following the fitting procedure, the raw yield of the ω and η meson is calculated in each p_T -slice by integrating the full background subtracted distribution in different ranges ΔM around the reconstructed mass of the corresponding meson $M_{\omega(\eta)}$, which is the peak position of the respective fit (see. Fig. 8.5). The integration is performed by counting the bin entries of the signal distributions within the integration ranges, which are given in Tab. 8.4. As a clarification it should be noted that this means that the fitting procedure itself is only used to subtract the residual background and to determine the centre of the integration range, but not for the actual calculation of the raw yields. After the signal has been extracted in form of raw yields, several corrections need to be applied to this quantity, which will be covered in the following section.

8.2 SPECTRA CORRECTIONS

Due the limited geometrical coverage of the detectors involved in the measurement, naturally not all particles created in a collision can be measured which is described by the acceptance of the detector. The acceptance $A_{\omega(\eta)}$ is calculated using MC event

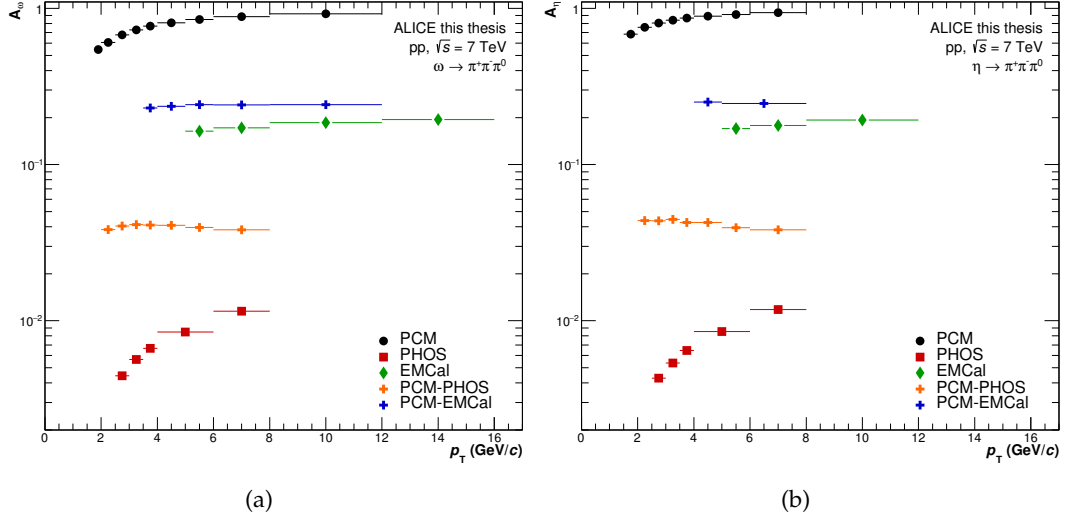


Figure 8.6: Acceptance A as a function of p_T shown for the ω (a) and η meson (b) measurement, where the different techniques used to reconstruct the neutral pion are shown in different colours.

generator PYTHIA 6 and is defined as:

$$A_{\omega(\eta)} = \frac{N_{\omega(\eta), |y| < 0.85} \text{ with daughter particles within } |\eta_{\pi^\pm}| < 0.9 \ \& \ |\eta_{\gamma_1, \gamma_2}| < \eta_{\text{conv}} (\text{calo})}{N_{\omega(\eta), |y| < 0.85}}, \quad (8.4)$$

which is the fraction of all ω (η) generated by PYTHIA within a rapidity of $|y| < 0.85$ that have daughter particles within the pseudorapidity coverage of the respective detector used with respect to all ω (η) mesons present within $|y| < 0.85$. More specifically, the two oppositely charged pions are required to be within $|\eta_{\pi^\pm}| < 0.9$ and the two photons originating from the neutral pion, are required to be within the coverage of the PCM ($|\eta_{\text{conv}}| < 0.9$), the EMCAL ($|\eta_{\text{EMCAL}}| < 0.67$) or the PHOS ($|\eta_{\text{PHOS}}| < 0.12$), depending on which methods are used to measure each photon.

Apart from the geometrical limitations of the detectors, the reconstruction technique itself is expected to be limited. This is expressed by the validated reconstruction efficiency ϵ_{true} which is defined as:

$$\epsilon_{\text{true}} = \frac{N_{\text{rec.,val. } \omega(\eta)}}{N_{\omega(\eta), |y| < 0.85} \text{ with daughter particles within } |\eta_{\pi^\pm}| < 0.9 \ \& \ |\eta_{\gamma_1, \gamma_2}| < \eta_{\text{conv}} (\text{calo})}. \quad (8.5)$$

The number of validated reconstructed ω (η) mesons $N_{\text{rec.,val. } \omega(\eta)}$ is obtained by carrying out the analysis on the anchored MC dataset and validating that the found $\pi^+ \pi^- \pi^0$ combinations indeed originate from a ω (η) meson. The number of ω (η) mesons $N_{\omega(\eta), |y| < 0.85}$ present in the given rapidity is determined using only true MC information. In addition, the normal reconstruction efficiency $\epsilon_{\text{rec.}}$ is calculated,

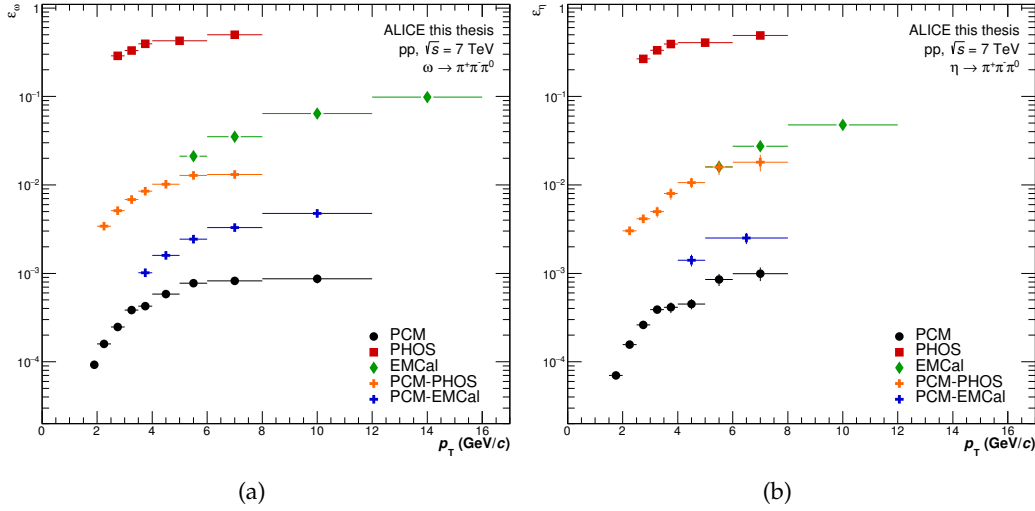


Figure 8.7: True validated reconstruction efficiency $\varepsilon_{\text{true}}$ as a function of p_T shown for the ω (a) and η (b) meson measurement, where the different techniques used to reconstruct the neutral pion are shown in different colours.

where no additional validation of the pion combinations is required. Both efficiencies agree within the statistical uncertainties and the normal reconstruction efficiency is used as a cross-check in this analysis.

The determined acceptance of the five neutral pion reconstruction techniques as a function of p_T can be found in Fig. 8.6a and Fig. 8.6b for the ω and η meson respectively. For all methods, an increasing acceptance can be observed for rising p_T due to the decreasing angles between the decay products of the boosted neutral meson. Comparing the different methods, the highest acceptance is observed for PCM measurements, due to the large coverage of the ITS and TPC. Analogously, the acceptance for EMCal and PHOS is lower due to their much smaller geometrical coverage. The hybrid method acceptances lie in between the PCM and calorimeter measurements due to the fact that only one of the two photons has to point towards a calorimeter.

In addition, the validated reconstruction efficiencies for the respective mesons and reconstruction techniques are shown in Fig. 8.7a and Fig. 8.7b. In contrast to its large acceptance, the PCM has the lowest reconstruction efficiency due to the photon conversion probability of about 8.5%. The slope arises due to the p_T dependence of electron reconstruction as well as the photon conversion probability, which declines with decreasing transverse momentum [20]. Measurements with PHOS and EMCal have an efficiency a few orders of magnitude higher than PCM and as expected the hybrid methods lie in between the PCM and stand-alone calorimeter method.

Finally, the total correction factor $\varepsilon = 2\pi \cdot \Delta y \cdot A \cdot \varepsilon_{\text{rec}}$ is presented for the ω and η meson in Fig. 8.8a and Fig. 8.8b respectively, which is used to correct the extracted raw yields. Comparing the coverage of the different methods, it can be seen that the EMCal stand-alone measurement works best at high transverse momenta allowing measurements up to $p_T = 16 \text{ GeV}/c$ ($12 \text{ GeV}/c$ for η). The PHOS measurement covers the intermediate p_T -range, whereas the PCM measurements allow to measure the ω (η) down to low momenta of $1.8 \text{ GeV}/c$ ($1.5 \text{ GeV}/c$). The two hybrid methods extend the p_T -reach of the corresponding stand-alone calorimeter measurements to lower transverse momenta which nicely illustrates how one can profit from the ad-

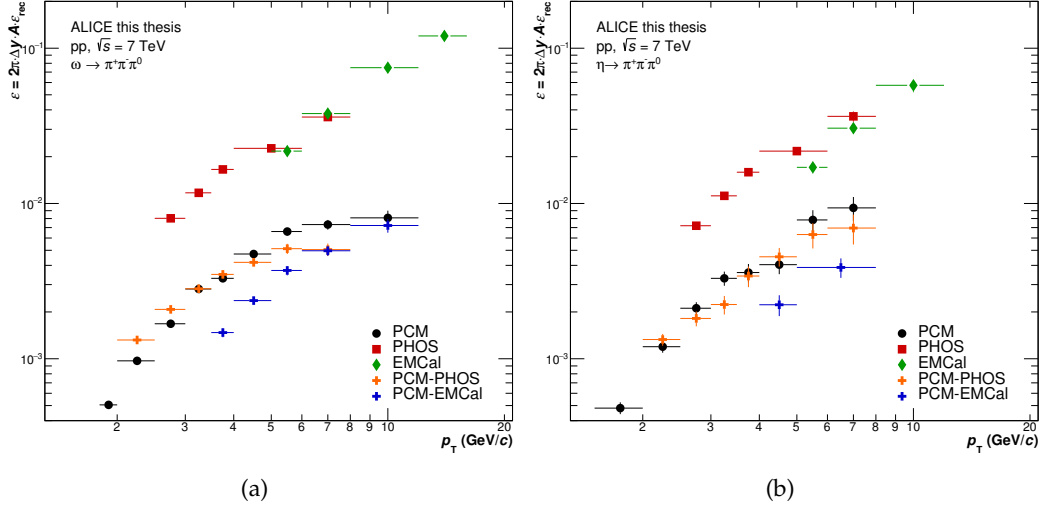


Figure 8.8: Correction factors shown for ω (Fig. 8.8a) and η (Fig. 8.8b) mesons for the respective reconstruction techniques.

advantages of both neutral pion reconstruction methods when using a hybrid approach. The correction factors express the combination of effects found for the acceptance and efficiency: Regardless of its limited geometrical acceptance, the correction factor is largest for the **EMCal** method followed by the π^0 reconstruction with **PHOS**. Correction factors about a magnitude smaller are found for **PCM**, where the large geometrical acceptance is compensated by the low reconstruction efficiency. The obtained correction factors have been compared to those used in the $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ analyses, as presented in Ref. [42], and the ordering of the different methods, as well as their shapes were found to be compatible with this analysis. Moreover, the correction factors in this analysis are smaller compared to the ones of the π^0 (η) analysis in the $\gamma\gamma$ channel which is expected due to the additional reconstruction of a charged pion pair.

8.3 EVALUATION OF SYSTEMATIC UNCERTAINTIES

Statistical uncertainties arise due to random fluctuations and can be explored by repeated measurements. Depending on the type of experiment, there are different ways to obtain these uncertainties and in this analysis the statistical uncertainty of any counted number N can simply be estimated by its square root $\sqrt{N}$. Systematic uncertainties, on the other hand, arise consistently due to an effect inherent in the measurement setup itself and thus can not be estimated using statistical methods [83]. Instead, one has to identify possible sources of systematic uncertainties and carefully study their influence on the measurement – a process which will be elaborated in this section.

In this thesis, systematic uncertainties are evaluated for the ω measurements with **PCM**, **PCM-EMCal** and **EMCal** by varying the different selection criteria used throughout this analysis and studying their effect on the fully corrected meson spectra following the strategy outlined by Barlow [84]. The selection criteria are varied one at a time and the differences in the resulting corrected spectra are calculated in each

p_T -bin. However, due to the limited statistics of the measurements presented in this thesis, discrimination of statistical- and systematic uncertainties is challenging, and significant differences² can often not be observed in the corrected spectra. In these cases, background information, such as the systematic uncertainty evaluations from previous π^0 and η analyses [20, 21] as well as the information from different reconstruction methods is taken into account to find a good estimate of the systematic uncertainties in this analysis. Furthermore, a smoothing of the obtained systematic uncertainties is performed for all contributions except the signal extraction by fitting their p_T dependence to account for remaining statistical fluctuations that do not originate from systematic effects.

An overview of the different systematic uncertainty sources for the ω measurement with PCM, PCM-EMCal and EMCal can be found in Tab. 8.5 for two exemplary p_T -bins. The values are given as relative uncertainties in percent, expressing 1σ deviations. Moreover the individual uncertainties are added in quadrature to obtain the total systematic uncertainty in each p_T bin. No full systematic uncertainty evaluation has yet been performed for the PCM-PHOS and PHOS method as well as all η measurements. For now, almost all systematic uncertainties for these measurements are borrowed from the PCM-EMCal and EMCal evaluation. However, the systematic uncertainty arising due to the signal extraction is still properly evaluated as described in more detail later in this section.

The different sources of systematic uncertainties can be summarized in several groups as stated in Tab. 8.5, which will be briefly elaborated in the following:

SIGNAL EXTRACTION This category includes the yield extraction itself, the background description as well as the cut on the invariant mass of the charged pion pair. The uncertainty of the yield extraction is estimated by varying the integration range used to obtain the raw yield. This variation consists of two integration ranges, one wider and one narrower than the standard integration range. Furthermore, the signal is extracted for all three integration windows, after the normalization of the background is performed on the left side of the peak instead of the right side, which is the standard in this analysis. In order to estimate the uncertainty arising due to the background description, side-band mixing as well as like-sign mixing is used alongside the standard event-mixing approach. The systematic uncertainty of the signal extraction is the largest contribution to the overall systematic uncertainty and is calculated to be about 7 – 11 % for the PCM and EMCal measurement. A greater conservative uncertainty of roughly 17% is estimated for the hybrid PCM-EMCal measurement, where a disentanglement of systematic and statistical influences was found to be especially challenging.

CHARGED PION RECONSTRUCTION The systematic uncertainty arising due to the charged pion reconstruction are evaluated by variation of the charged pion cuts given in Tab. 5.1. The thus estimated uncertainty is about 9 %, where the individual contributions are flat in p_T and contribute roughly equally to this group. No significant dependence on reconstruction method could be observed for this uncertainty group.

² Significant in the sense of Barlow, as outlined in Ref. [84].

Table 8.5: Systematic uncertainty sources for the ω measurement, where [PCM](#), [PCM-EMCal](#) and [EMCal](#) are used to reconstruct the neutral pion. For each source, the relative uncertainty is given in percent for two exemplary p_T -bins. The values given at the very bottom of this table for each p_T -bin and reconstruction method represent the quadratic sums of the individual systematic uncertainties, which are used as the systematic uncertainty of the respective measurement in that bin. The systematic uncertainty sources are grouped according to the different analysis steps, which is stated on the far left of this table. The normalization efficiency entering the determined cross sections is not shown here and can be obtained from the results presented in Chap. 9.

SOURCE	5 – 6 GeV/ c			8 – 12 GeV/ c		
	PCM	PCM-EMC	EMC	PCM	PCM-EMC	EMC
pileup	0.5	0.5	0.5	0.5	0.5	0.5
material	9.0	4.7	3.0	9.0	4.7	3.0
$\gamma_{\text{conv. rec.}}$	min. track p_T	0.5	0.7	-	0.5	0.7
	min. cluster in TPC	2.0	3.0	-	2.0	3.0
	electron PID	1.0	1.5	-	1.0	1.5
	pion rejection	0.2	1.2	-	0.2	1.2
	q_T cut	1.8	4.0	-	1.8	4.0
	χ^2/ndf cut	1.5	2.0	-	1.5	2.0
	ψ_{pair} cut	1.5	2.0	-	1.5	2.0
	pointing angle	0.2	1.0	-	0.2	1.0
	non-linearity	-	1.5	1.0	-	1.5
$\gamma_{\text{calo. rec.}}$	cluster timing	-	1.0	0.5	-	1.0
	track matching	-	0.5	2.5	-	1.5
	min. cluster energy	-	1.5	2.9	-	1.5
	nmb. cells per cls.	-	1.0	1.0	-	1.0
	cluster shape	-	0.7	0.8	-	1.2
	clusterizer	-	2.7	3.0	-	4.9
$\pi^\pm$ rec.	min. cluster in TPC	2.3	5.5	5.5	2.3	5.5
	DCA cut	4.5	4.5	4.5	4.5	4.5
	$\pi^\pm$ min. p_T	4.0	4.0	4.0	4.0	4.0
	charged pion PID	3.0	4.0	3.0	3.0	4.0
π^0	π^0 min. p_T	1.5	1.5	1.5	1.5	1.5
	$M_{\gamma\gamma}$ cut	9.0	9.0	9.0	9.0	9.0
signal	$M_{\pi^+\pi^-}$ cut	4.0	9.0	4.0	4.0	9.0
	yield extraction	9.4	8.1	6.0	3.9	12.1
	background description	5.2	13.0	9.4	5.2	13.0
quad. sum		18.9	23.6	18.3	16.9	25.3
					12.1	6.4

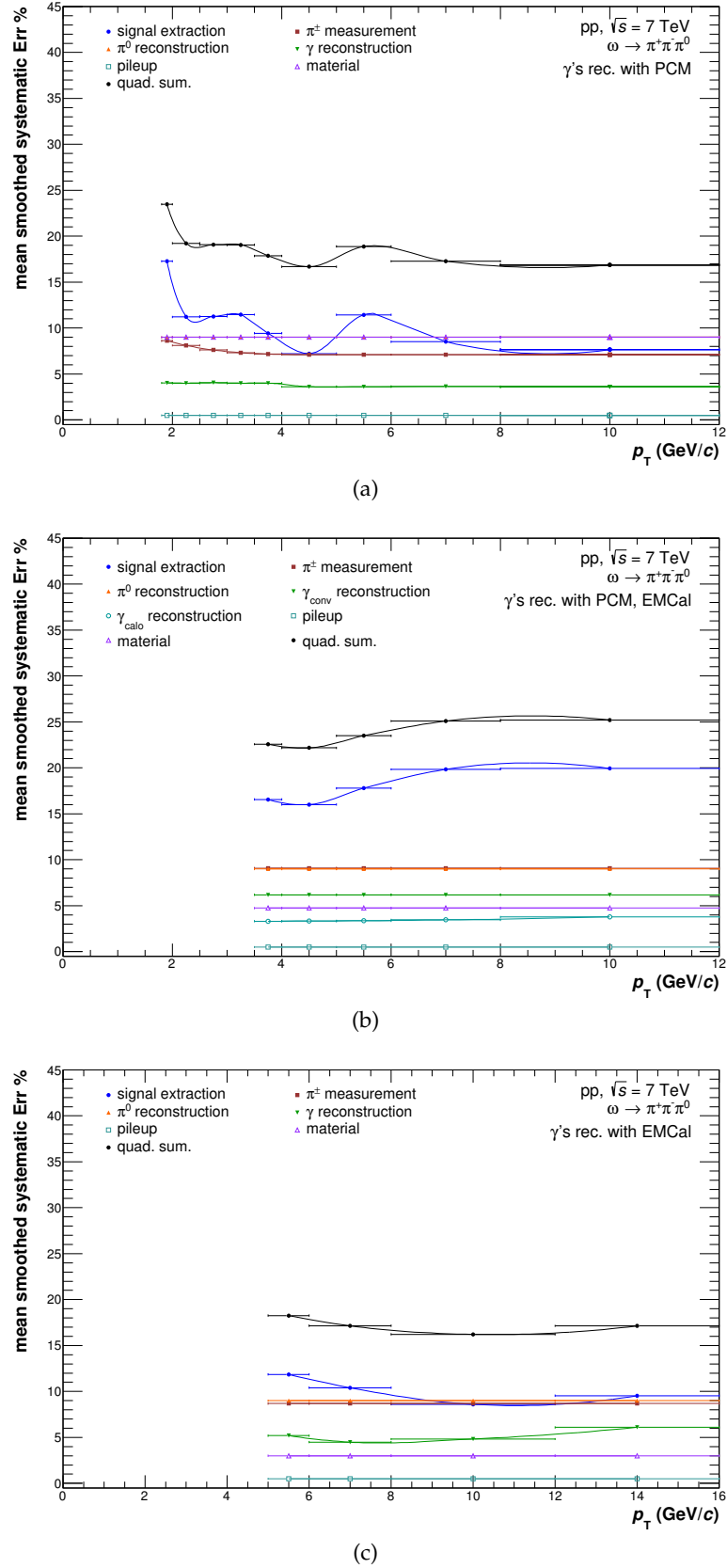


Figure 8.9: Overview of the smoothed total systematic uncertainties of the ω measurements as a function of transverse momentum where the neutral pion is reconstructed using PCM (a), PCM-EMCal (b) or EMCal (c). In addition, the different contributions to the total uncertainty are shown, which are grouped according to different analysis aspects, as shown in Tab. 8.5.

CONVERSION PHOTON RECONSTRUCTION The systematic uncertainty of conversion photon reconstruction is calculated to be about 4 % for **PCM** and 6 % for **PCM-EMCal**. The biggest contribution to this category are the dE/dx cuts applied to identify electrons as well as the q_t and α requirements used to select photon candidates.

CLUSTER RECONSTRUCTION Uncertainties of about 4 – 6 % are obtained for the cluster related selection criteria which are used in the **PCM-EMCal** and stand-alone **EMCal** measurements. The source which is stated as ‘clusterizer’ in Tab. 8.5 accounts for systematic uncertainties arising from the clusterization algorithm that was previously discussed in Sec. 6.1. This systematic uncertainty is estimated to coincide with the uncertainty obtained for the π^0 analysis presented in Ref. [42] which was carried out at the same centre-of-mass energy as this analysis. The cut variations used in Ref. [42] to estimate the uncertainty of the clusterization algorithm are applied to the energy thresholds E_{seed} and E_{min} as well as the timing selection applied on cell level. The uncertainty of the non-linearity correction is evaluated by using different calibration techniques, e.g. only taking into account clusters instead of using a hybrid approach with **PCM** to determine the correction as discussed in Sec. 6.2.2.2.

NEUTRAL PION RECONSTRUCTION No significant influence of the opening angle cut as well as the rapidity cut could be observed and therefore the invariant mass cut applied to the photon pair is the only contribution to this category. For each evaluated reconstruction method the corrected yield is extracted for four additional cut variations, including wider and narrower $M_{\gamma\gamma}$ windows than the standard choice for the respective method. Evaluating these cut variations turned out to be especially challenging, due to a significant loss in statistics for the narrower cuts as well as a reduction of the signal to background ratio for the wider invariant mass windows. By comparing the variations for all three reconstruction methods, the systematic uncertainty was estimated to be about 9 % for all methods.

MATERIAL BUDGET Knowledge of the geometry and amount of material present in the **ALICE** detector as well as its chemical composition, is limited. One therefore has to account for possible mismatch between the material present in the **ALICE** detector and its implementation in **GEANT 3**, which is used in the **MC** simulations. This is especially important for photon measurements, which are very sensitive to the material they traverse. Depending on the kind of photon measurements used to reconstruct the neutral pion, one distinguishes between two sources of systematic uncertainty, that arise due to a mismatch in material description of the inner- or outer detector:

If a conversion photon is used to reconstruct the neutral pion the inner material up to $R = 180$ cm (midpoint of **TPC**) has to be considered, which is the region in which photon conversion candidates are accepted. The conversion probability of a photon depends on the material it traverses and therefore an uncertainty of the material distribution leads to an uncertainty of the R -distribution of photon conversion candidates. This systematic uncertainty has been extensively studied in Ref. [80], and was found to be 4.5 % per conversion photon.

For photon measurements using **EMCal** one has to account for the outer material, which refers to the region from the midpoint of the **TPC** to the **EMCal**. The main contribution to material in front of the **EMCal** are the outer wall of the **TPC** and the

TOF detector. No TRD modules were yet installed in front of the EMCal during data taking in 2010, which therefore do not have to be considered in the outer material budget. When a photon traverses through the material in front of the calorimeter, its conversion probability increases with increasing radius and therefore it might not be detected by the calorimeter if a conversion occurred, or only partly, if only one of the two conversion electrons is measured, worsening the resolution of the π^0 measurement. The systematic uncertainty arising from TRD material has been studied in Ref. [42] and was found to be 3 % for the stand-alone EMCal measurement, and 1.5 % for PCM-EMCal measurements. Due to the similar material budget present in TRD and TOF, equal uncertainties were assigned for the TOF material, which are used in this analysis as the sole uncertainties of the outer material, given the fact that no TRD modules are present in front of the EMCal.

The inner- and outer material uncertainties are added in quadrature for each reconstruction method, yielding an overall material uncertainty of $9\% = 2 \cdot 4.5\%$ for the PCM measurement, $4.7\% \approx 1.5\% \oplus 4.5\%$ for PCM-EMCal and 3 % for the stand-alone EMCal measurement.

PILEUP CORRECTION To account for the systematic uncertainties arising due to the requirements imposed to reject in-bunch pileup, as discussed in Sec. 4.3, the analysis is carried out without this requirement, resulting in an increase of the corrected yield of about 5 %. Previous studies [42] show an efficiency of the in-bunch pileup rejection of about 92 %, which is also assumed for this analysis. Consequently, about 8 % of in-bunch pileup events remain in the data sample and the corresponding uncertainty is thus estimated to be $0.5\% \approx 5\% \cdot 8\%$.

Fig. 8.9 shows the the systematic uncertainties of the previously discussed groups, as well as the overall systematic uncertainty in dependence of transverse momentum for PCM, PCM-EMCal and EMCal for the ω measurement. The uncertainties assumed for PCM-PHOS and PHOS, all of which have been borrowed from the respective EMCal measurements, except the signal extraction uncertainty, can be found in Sec. A.3. Moreover the overviews of systematic uncertainties of the η meson measurements can be found in Sec. A.3, which for now have been assumed to be mostly equal to the ones obtained for the ω measurements as well.

8.4 INVARIANT MESON CROSS SECTIONS & COMBINATION OF MEASUREMENTS

The fully corrected invariant cross sections of the ω and η meson are calculated individually for each reconstruction technique using:

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi} \frac{1}{p_T} \cdot \frac{\sigma_{\text{MBOR}}}{N_{\text{evt,MB}}} \cdot \frac{1}{A \cdot \epsilon_{\text{rec.}}} \cdot \frac{1}{\text{BR}} \cdot \frac{N^{\omega(\eta)}}{\Delta y \Delta p_T}. \quad (8.6)$$

Here $N_{\text{evt,MB}}$ is the number of MB events, $\sigma_{\text{MBOR}} = (62.4 \pm 2.2) \text{ mb}$ [30] denotes the MB cross section, $\epsilon_{\text{rec.}}$ and A are the reconstruction efficiency and acceptance of the respective method and BR is the branching ratio of the $\pi^+ \pi^- \pi^0$ decay for each meson as given in Ref. [14]. Moreover, $N^{\omega(\eta)}$ stands for the number of ω (η) mesons, which is normalized by the transverse momentum bin width Δp_T and the rapidity range $\Delta y = 1.7$. For the individual measurements the transverse momentum p_T at the centre

of the respective bin is used to calculate the invariant cross section, whereas for the combined measurements a corrected p_T value is used which accounts for the finite width of the respective p_T bin – a procedure which will be further elaborated in the course of this section.

The obtained invariant cross sections of ω and η meson production in pp collisions at $\sqrt{s} = 7$ TeV are presented in Fig. 8.10a and Fig. 8.10b respectively. For each meson, five different reconstruction methods are used to reconstruct the neutral pion. The obtained cross sections agree with each other within the statistical and systematic uncertainties. Furthermore, Fig. 8.10 illustrates the p_T -coverage of each method which is given in Tab. 8.6 as well.

Table 8.6: Transverse momentum coverage of the individual cross sections shown in Fig. 8.10.

METHOD	MOMENTUM COVERAGE p_T (GeV/c)	
	ω	η
PCM	1.8–12.0	1.5–8.0
PCM-EMCal	3.5–12.0	4.0–8.0
PCM-PHOS	2.0–8.0	2.0–8.0
EMCal	5.0–16.0	5.0–12.0
PHOS	2.5–8.0	2.5–8.0

COMBINATION OF MEASUREMENTS The individual cross sections obtained for the different reconstruction techniques are combined using the Best Linear Unbiased Estimate (BLUE) method [85–87], where the p_T -binning of the combined cross section is chosen to include bins where most of the p_T -bins of the individual measurements coincide. In each p_T -bin the available measurements are combined, taking into account their statistical and systematic uncertainties. No correlations of the statistical uncertainties are expected [21], whereas the systematic uncertainties are found to be largely correlated among the different measurements. Thus, these correlations have to be accounted for in the combination procedure. The degree of correlation between measurement i and measurement j is expressed in a 5×5 matrix:

$$C(p_T) = \begin{pmatrix} \text{PCM} & \text{PCM-EMC} & \text{EMC} & \text{PCM-PHOS} & \text{PHOS} \\ \begin{pmatrix} 1 & \mathcal{C}_{12} & \mathcal{C}_{13} & \mathcal{C}_{14} & \mathcal{C}_{15} \\ \mathcal{C}_{21} & 1 & \mathcal{C}_{23} & \mathcal{C}_{24} & \mathcal{C}_{25} \\ \mathcal{C}_{31} & \mathcal{C}_{32} & 1 & \mathcal{C}_{34} & \mathcal{C}_{35} \\ \mathcal{C}_{41} & \mathcal{C}_{42} & \mathcal{C}_{43} & 1 & \mathcal{C}_{45} \\ \mathcal{C}_{51} & \mathcal{C}_{52} & \mathcal{C}_{53} & \mathcal{C}_{54} & 1 \end{pmatrix} & \begin{pmatrix} \text{PCM} \\ \text{PCM-EMC} \\ \text{EMC} \\ \text{PCM-PHOS} \\ \text{PHOS} \end{pmatrix} \end{pmatrix} \quad (8.7)$$

where each element is a p_T -dependent correlation coefficient $\mathcal{C}_{ij}(p_T)$ defined as:

$$\mathcal{C}_{ij}(p_T) = \frac{q_{ij}S_i(p_T)q_{ji}S_j(p_T)}{T_i(p_T)T_j(p_T)}. \quad (8.8)$$

The total systematic uncertainty $T_i(p_T)$ is calculated as the quadratic sum of the statistical $D_i(p_T)$ and systematic uncertainty $S_i(p_T)$ of the respective measurement. The

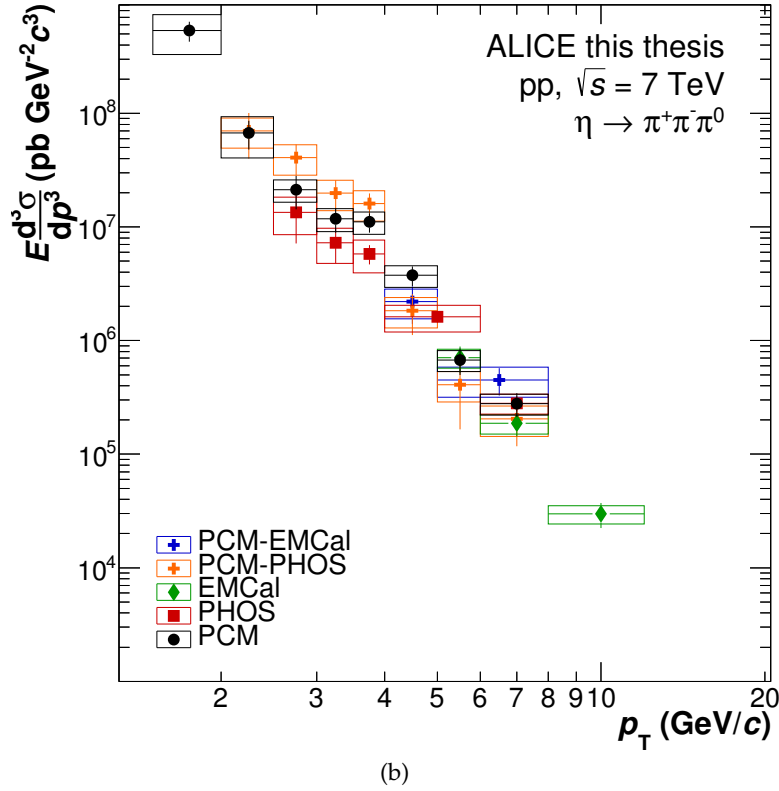
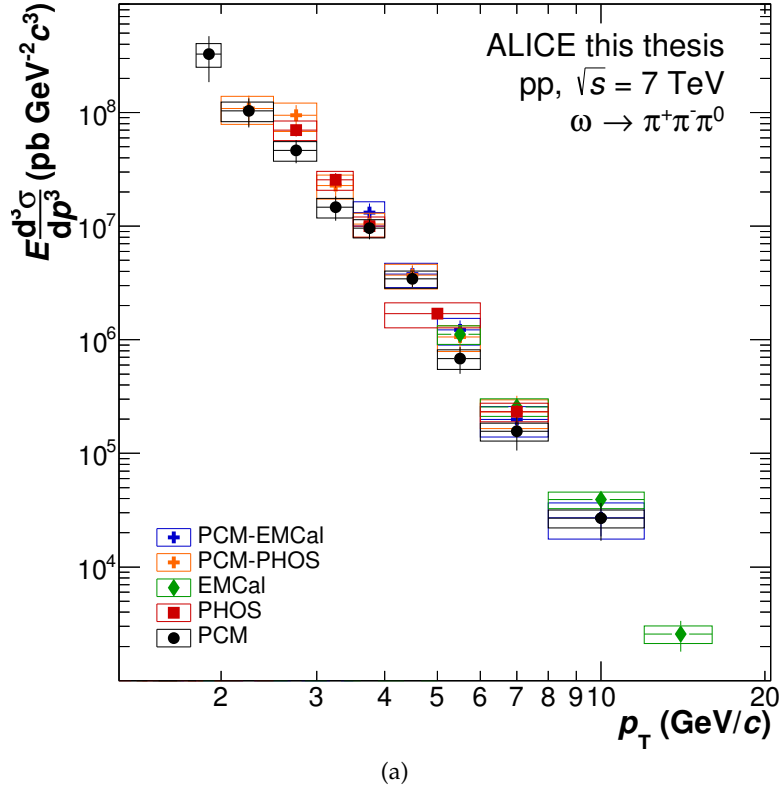


Figure 8.10: Invariant cross sections of the ω (a) and η (b) meson which are measured in pp collisions at $\sqrt{s} = 7$ TeV using five different reconstruction techniques to measure the neutral meson, further elaborated in Chap. 7.

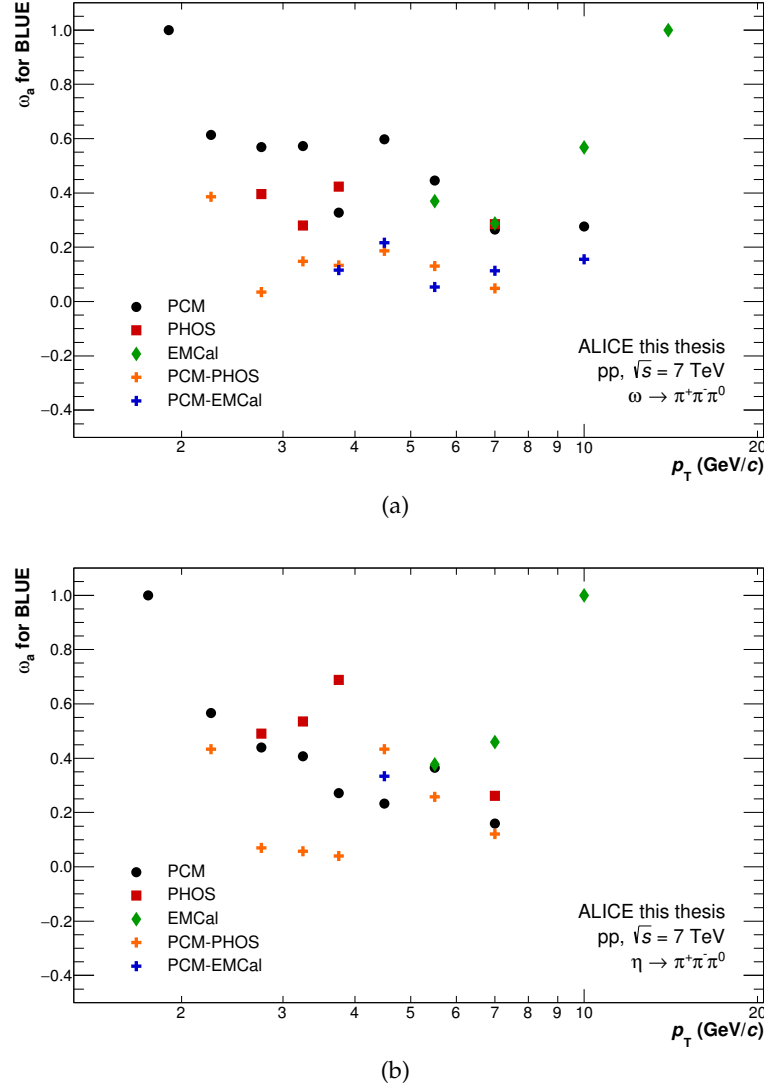


Figure 8.11: Weights $\omega_a(p_T)$ obtained for the individual ω (a) and η (b) measurements using the **BLUE** method, which are applied when combining the individual cross sections presented in Fig. 8.10.

correlation factor $\varrho_{ij}(p_T)$ expresses the fraction of systematic uncertainty that is correlated and is thus given as:

$$\varrho_{ij}(p_T) = \frac{\sqrt{S_i^2(p_T) - U_{ij}^2(p_T)}}{S_i(p_T)}, \quad (8.9)$$

where $U_{ij}(p_T)$ denotes the uncorrelated uncertainty of measurement i and j . The correlation factors ϱ_{ij} are obtained by carefully studying the different uncertainties sources shared by the individual measurement (as given in Tab. 8.5) and estimating the degree of correlation between them. As an example, looking at the material uncertainty of the **PCM** measurement and its correlation with respect to the **PCM-EMCal** measurement, about 50 % of this uncertainty is found to correlated which arises due to the shared inner material uncertainty of a single photon. On the other hand, only a fraction of 32 % is correlated vice versa because the material uncertainty of the **PCM-**

EMCal measurement is dominated by the outer material uncertainty. The obtained correlation coefficients $\rho_{ij}(p_T)$ are presented in Fig. A.16 for the ω and η measurement. Taking into account these correlations, weighting factors $\omega_a(p_T)$ are calculated for each measurement according to the BLUE method which are shown in Fig. 8.11. The determined weights are then used to obtain the combined cross sections of the ω and η measurements which are presented in Chap. 9.

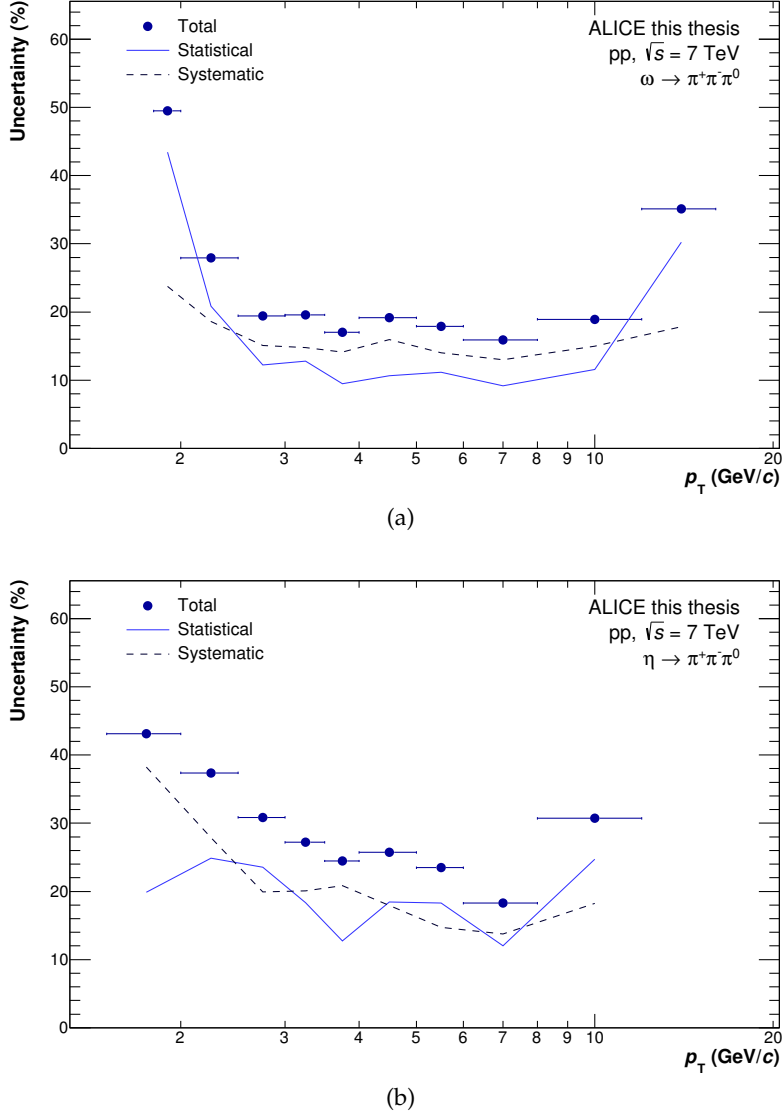


Figure 8.12: Overview of the relative total, systematic and statistical uncertainties of the combined ω (a) and η (b) cross sections as a function of transverse momentum p_T .

The relative total, systematic and statistical uncertainties of the combined cross sections are shown in Fig. 8.12 as a function of p_T . For the ω measurement the systematic uncertainties dominate the total uncertainties at mid- p_T , whereas they are of similar magnitude for the η measurement. The total uncertainty rises at the low and high p_T end of the spectrum, which is consistent with the aggravated signal extraction in these regions.

CORRECTION FOR FINITE BIN WIDTH Up to this point, the invariant cross sections were evaluated at the centre of each p_T -bin. However, the underlying spectra are falling within each bin and thus an evaluation at the centre of the bin is incorrect [88]. Consequently, a correction is applied by approximating the underlying spectrum with a Tsallis [89] fit function and shifting the data point horizontally in p_T direction, so that the data point lies on the curve of the fit. The Tsallis fit function is given by:

$$E \frac{d^3\sigma}{dp^3} = \frac{C}{2\pi nT(nT + m_0(n-2))} \left(1 + \frac{m_T - m_0}{nT}\right)^{-n}, \quad (8.10)$$

where T , c and n are free parameters of the fit and m_0 and $m_T = \sqrt{p_T^2 + m_0^2}$ correspond to the rest- and transverse mass of the given particle respectively. The relative shift performed in each p_T -bin for the ω and η cross section is shown in Fig. 8.13. The corrections are in the order of a few percent and depend on the bin-width as well as the shape of the underlying spectrum.

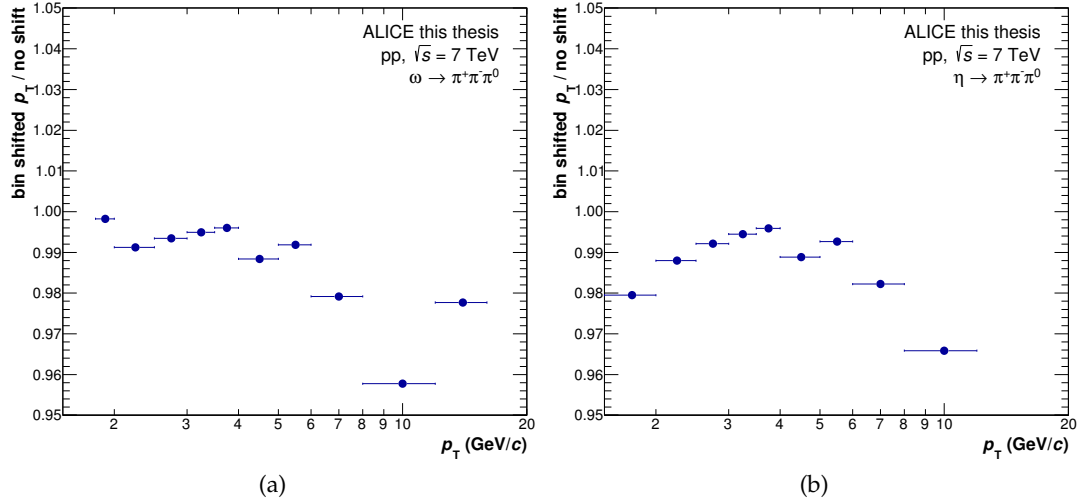


Figure 8.13: Overview of the shift in p_T -direction applied for each data point of the combined ω (a) and η (b) cross section. This correction is applied to account for the finite p_T -bin width by approximating the underlying spectra with a Tsallis [89] fit function as defined in Eq. 8.10 and shifting the data points accordingly in p_T -direction.

The combined invariant cross sections of the ω and η meson are presented in the following chapter, where a correction accounting for the finite p_T -bin width has been applied if not stated otherwise.

RESULTS

The differential invariant cross sections of ω and η meson production are measured at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV, covering a transverse momentum range of $1.8 \text{ GeV}/c < p_T < 16 \text{ GeV}/c$ and $1.5 \text{ GeV}/c < p_T < 12 \text{ GeV}/c$ respectively. The cross sections are presented in Fig. 9.1 together with theory predictions as well as other measurements [18, 20].

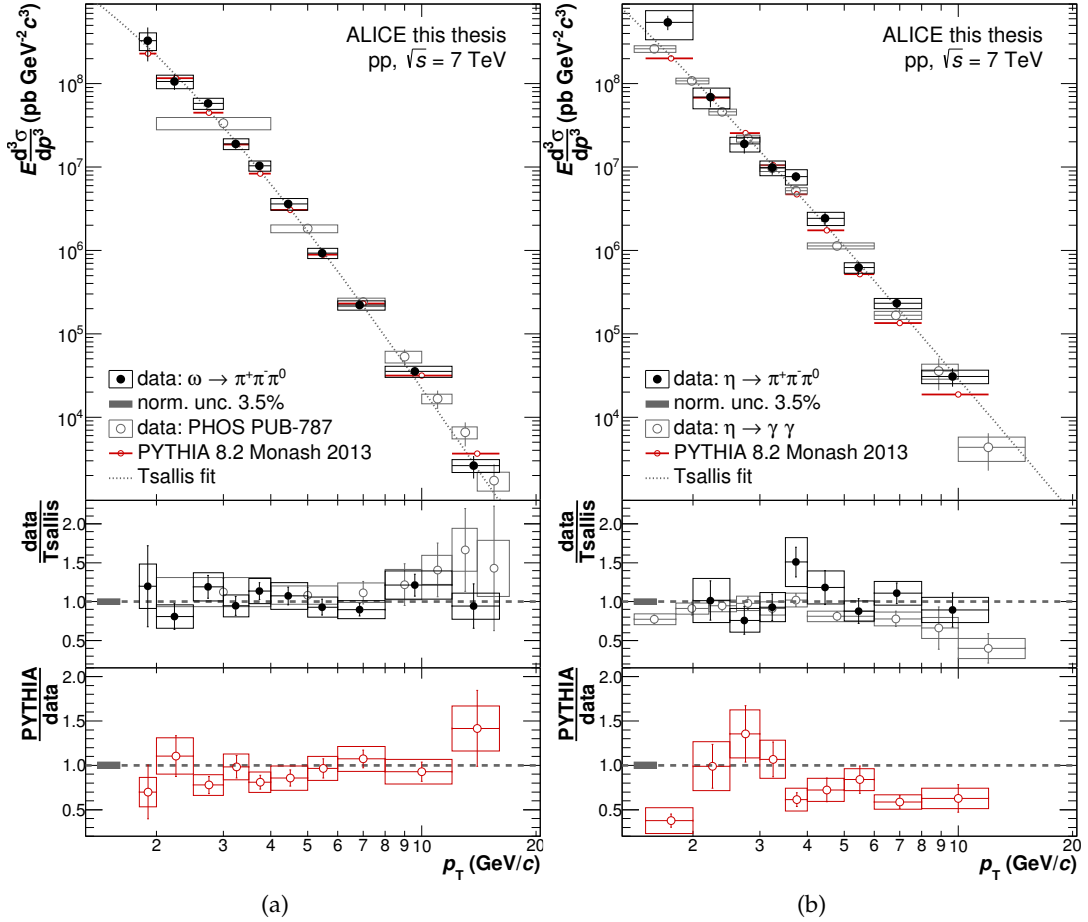


Figure 9.1: Combined invariant cross sections of the ω (a) and η (b) meson, shown together with a comparison to theory predictions as well as other measurements [18, 20]. The statistical and systematic uncertainties are represented by vertical bars and boxes respectively. A Tsallis function [89] is used to parametrize the spectra, which is shown as a grey dotted line. The theory predictions are shown as red markers and are provided by the event generator PYTHIA 8.2 [75] using the Monash 2013 tune [90]. The middle panel shows the ratio of the combined spectra over its Tsallis fit (black) as well as the ratio of the comparison measurements (grey) over the same function. The ratio shown in the bottom panel is calculated between the unshifted combined cross section and the theory prediction in each p_T -bin.

The cross sections are obtained following the combination procedure outlined in Sec. 8.4, taking into account five different reconstruction techniques for each meson. The statistical and systematic uncertainties were evaluated as discussed in Sec. 8.3 and are represented by vertical bars and boxes respectively. Furthermore, the normalization uncertainty of 3.5 % is shown as a grey box, arising due to the uncertainty of the MB cross section [30]. The meson spectra are fitted with a Tsallis function [89], which is given by Eq. 8.10, and the ratio of the cross section over this fit is shown in the middle panel of Fig. 9.1, showcasing that the chosen parametrization manages to describe the neutral meson spectra.

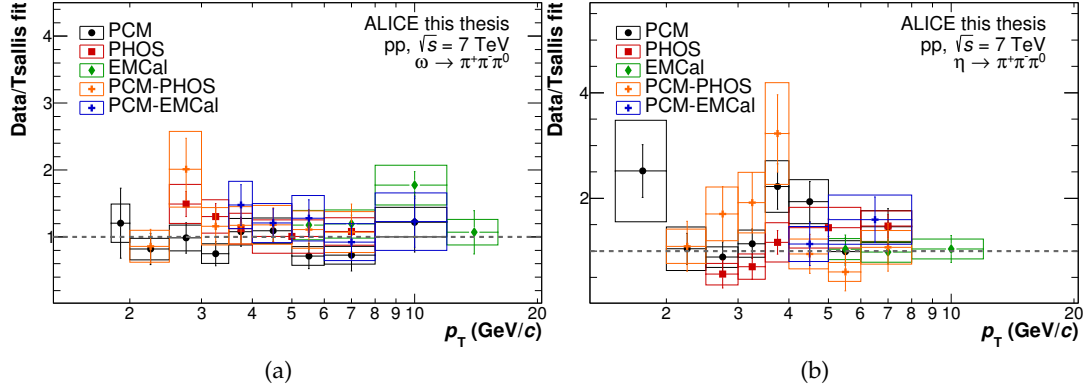


Figure 9.2: Ratio of the individual ω (a) and η (b) cross sections over the Tsallis fit of the combined cross section shown in Fig. 8.4. The individual cross sections are obtained using different techniques to reconstruct the neutral pion and are presented in Fig. 8.10.

The individual reconstruction methods entering the combination procedure are compared by calculating their ratios with respect to the Tsallis fit of the fully combined cross section, which are shown in Fig. 9.2. The ω measurements agree with each other within the statistical and systematic uncertainties over the whole p_T -range and a reasonable agreement is observed for the individual η measurements as well. However, rather large fluctuations can be seen for the η cross sections in some p_T -bins, especially for the PCM-PHOS measurement, but also for the PCM measurement in the lowest p_T -bin. This is attributed to the challenging signal extraction that has been previously mentioned in this thesis. Furthermore, no complete evaluation of the systematic uncertainties has yet been performed for the η measurement as part of this thesis and the assumed uncertainties hence seem to underestimate the uncertainties that are actually present for this measurement.

Moreover, the ω and η cross sections obtained in this thesis are compared to measurements from other analyses that have been carried out at the same centre-of-mass energy, which are represented in Fig. 9.1 by grey markers. The ω cross section is compared to the results presented in Ref. [18], where the ω is reconstructed via its three pion decay solely using the PHOS to reconstruct the neutral pion. Looking at the ratio of this reference measurement and the Tsallis fit of the ω cross section presented in this thesis, it can be seen that both measurements nicely agree within the systematic and statistical uncertainties. Furthermore, a comparison of the p_T -bin width of both measurements illustrates the advantages of using multiple methods to reconstruct the neutral pion: At low transverse momentum, especially the use of the PCM allows

to achieve a much higher granularity in p_T as well as an extension of the p_T -reach down to $1.8 \text{ GeV}/c$. The η cross section obtained in this thesis is compared to the one presented in Ref. [20]. In this analysis, the η is reconstructed via its decay to two photons, which are both measured using PCM and PHOS. The shown cross section is a result of the combination of those two measurements, following the same procedure presented in this thesis. Looking at the ratio of the combined $\eta \rightarrow \gamma\gamma$ cross section and the Tsallis fit of the $\eta \rightarrow \pi^+\pi^-\pi^0$ cross section, one can see that both measurements are in good agreement within the statistical and systematic uncertainties. The slight divergence of the $\eta \rightarrow \gamma\gamma$ measurement from the Tsallis fit observed at low and high- p_T is attributed to the Tsallis fit, which is not very well constrained in these regions, given the substantial uncertainties of the $\eta \rightarrow \pi^+\pi^-\pi^0$ measurement.

Furthermore, the differential cross sections are compared to PYTHIA 8.2 [75] MC simulations, where refined parameters provided by the well-established Monash 2013 tune [90] are used. The cross sections obtained from PYTHIA are shown in Fig. 9.1a and Fig. 9.1b by red markers and have uncertainties below 2%, which are not visible in the logarithmic representation. The PYTHIA cross sections are provided in the same p_T -binning as the cross sections presented in this thesis which allows to calculate the ratio of the PYTHIA prediction and the unshifted measured cross section in each p_T bin. Thus, the obtained ratios are presented in the bottom panel of Fig. 9.1a and Fig. 9.1b for the ω and η meson respectively. Good agreement between data and the MC prediction is found over the whole p_T -range for the ω meson, indicating that PYTHIA 8.2 together with the Monash 2013 tune manages to sufficiently describe ω production in this regime. Looking at the same comparison for the η meson in Fig. 9.1b, an underestimation of the measured cross section by PYTHIA can be observed as well as substantial fluctuations. However, this is attributed to the fluctuations observed for the individual measurements, shown in Fig. 9.2b, as well as the differences between the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ measurement at the low and high p_T of the spectrum that have been previously mentioned. This is further exemplified, when looking at the region $2.0 \text{ GeV}/c < p_T < 3.5 \text{ GeV}/c$, where especially good agreement between both η measurements is observed, as well as good agreement between data and the PYTHIA predictions.

The cross section ratios ω/π^0 and η/π^0 are presented in Fig. 9.3a and Fig. 9.3b together with PYTHIA predictions and other measurements [18, 20], analogue to the previous comparisons. In this thesis, the ω/π^0 and η/π^0 ratios are obtained by calculating the ratios of the measured ω (η) cross sections and the Tsallis fit of the π^0 cross section which is taken from Ref. [20]. The ratios of the comparison measurements are calculated using the respective cross sections presented in Fig. 9.1, where the same π^0 cross section is used as the denominator. The PYTHIA predictions slightly underestimate the ω/π^0 ratio measured as part of this thesis, yet it can still be concluded that data and PYTHIA predictions are consistent within the statistical and systematic uncertainties of the measurement. A more substantial underestimation is observed for the η/π^0 ratio, especially at high p_T , whereas reasonable agreement is observed between $2.0 \text{ GeV}/c < p_T < 3.5 \text{ GeV}/c$. Furthermore, the comparison to the other measurements of the ω/π^0 and η/π^0 shows that the results presented as part of this thesis are consistent with those presented Ref. [18] and Ref. [20]. Nonetheless, the η/π^0 ratio measured as part of this thesis is slightly higher than the one measured in the two photon decay channel, especially at high p_T .

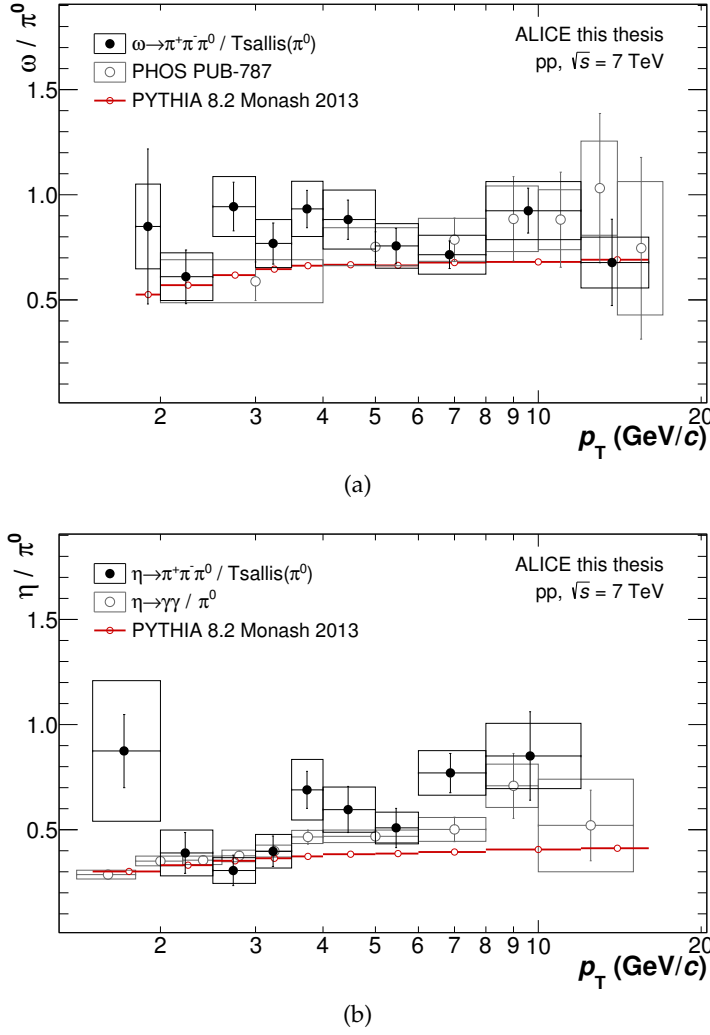


Figure 9.3: ω/π^0 and η/π^0 ratio calculated as part of this thesis (black) shown together with theory predictions (red) and reference measurements (grey) [18, 20]. The ratios in this analysis are calculated as the ratio of the respective combined cross section and the Tsallis fit of the π^0 spectrum which is provided by Ref. [20].

Measuring cross section ratios like the ones previously presented is motivated by transverse mass scaling (m_T -scaling), which is an empirical scaling rule stating that the cross sections of different mesons can be described by a single universal function $f(m_T)$ of transverse mass, only differing by a constant normalization factor C^h [91]:

$$E \frac{d^3\sigma}{dp^3} = C^h f(m_T) \quad \text{with} \quad m_T = \sqrt{p_T^2 + m_0^2}. \quad (9.1)$$

This allows to estimate meson cross sections by scaling the well measured cross sections of light mesons, such as pions and kaons. Even though this scaling relation is not expected to hold in general, this method is e.g. used in direct photon [3] or di-electron analyses [4] to describe those contributions to the hadronic background for which no measurements are available. The scaling relation has been observed to hold in pp collisions for various mesons over a variety of collision energies ranging from $\sqrt{s} = 6$ GeV to 200 GeV [92–94]. However, recent measurements at higher LHC

energies ($\sqrt{s} \geq 900$ GeV) indicate that m_T -scaling is already broken at higher p_T than previously observed [91].

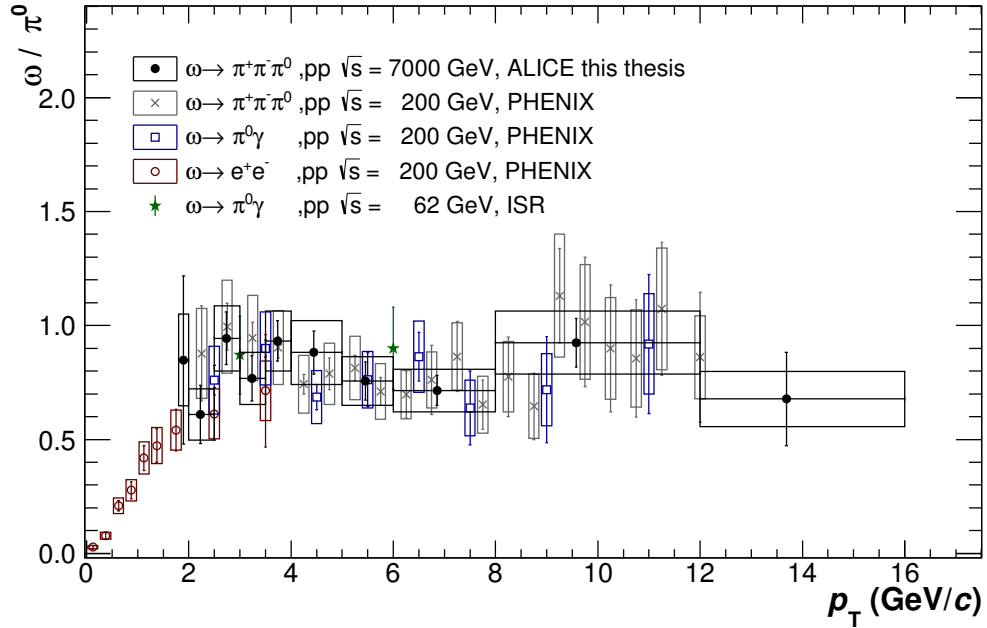


Figure 9.4: ω/π^0 ratio shown as a function of p_T for pp collisions at various centre-of-mass energies ranging from $\sqrt{s} = 62$ GeV – 7000 GeV [15–17]. The ratios obtained as part of this thesis are measured at $\sqrt{s} = 7$ TeV and represented by black markers. The statistical uncertainties are shown as vertical error bars, whereas the systematic uncertainties are shown as boxes, if available. The decay channel used to reconstruct the ω meson as well as the centre-of-mass energy and the experiment responsible for the measurement are given in the legend.

Fig. 9.4 shows the ω/π^0 ratio determined in the context of this thesis in pp collisions at $\sqrt{s} = 7$ TeV with ALICE together with previous ω/π^0 measurements that have been carried out at different centre-of-mass energies and in various decay channels [15–17]. The measurements are in good agreement with each other, supporting the previous observations that the ω/π^0 ratio is independent of collision energy, at least at high p_T . Looking at the overall shape of the distribution, one can see a quick rise of the ω/π^0 ratio before reaching a plateau above about 3.5 GeV/c. The measurement carried out as part of this thesis starts to contribute just before this plateau is reached, up to transverse momenta of 16 GeV/c, which could not be reached at previous experiments.

Finally, the constant normalization factors C^{ω/π^0} and C^{η/π^0} are determined, which can be used to obtain a parametrization of the ω and η meson respectively, according to the m_T scaling relation given in Eq. 9.1. The factors are evaluated by fitting the determined ω/π^0 and η/π^0 ratios (see Fig. 9.3) each with a constant above $p_T = 3.5$ GeV/c, yielding the following normalization factors C^h :

$$C^{\omega/\pi^0} = 0.804 \pm 0.037 \text{ (stat)} \pm 0.050 \text{ (sys)} \quad (9.2)$$

$$C^{\eta/\pi^0} = 0.641 \pm 0.046 \text{ (stat)} \pm 0.051 \text{ (sys)}$$

A selection of normalization factors C^h obtained in pp collisions at different centre-of-mass energies can be found in Tab. 9.1, which are used as a comparison for the

Table 9.1: Overview of normalization factors C^h which are obtained by fitting the ω/π^0 and η/π^0 ratios in the high p_T region. Results from selected previous measurements are presented, where the centre-of-mass energy $\sqrt{s}$ of the pp collision is given, as well as the method used to reconstruct the numerator meson.

RATIO	$\sqrt{s}(\text{GeV})$	DECAY	C^h	REFERENCE
ω/π^0	62	$\pi^0\gamma$	0.89 ± 0.22	[15]
ω/π^0	200	various	0.85 ± 0.05 (stat) ± 0.09 (sys)	[17]
ω/π^0	7000	$\pi^+\pi^-\pi^0$	0.804 ± 0.037 (stat) ± 0.050 (sys)	this thesis
η/π^0	62	$\gamma\gamma$	0.53 ± 0.07	[95]
η/π^0	200	various	0.48 ± 0.02 (stat) ± 0.02 (sys)	[96]
η/π^0	7000	$\gamma\gamma$	0.468 ± 0.011 (stat) ± 0.009 (sys)	[42]
η/π^0	7000	$\pi^+\pi^-\pi^0$	0.641 ± 0.046 (stat) ± 0.051 (sys)	this thesis

factors calculated as part of this thesis. Even though both η/π^0 measurements compared in Fig. 9.3b are consistent with each other, the obtained factor C^{η/π^0} is substantially above the ones measured as previous experiments. This is due to the fact, that the earlier mentioned slight deviation of both ratios observed at high p_T enters the fit significantly, which is only performed at $p_T \geq 3.5 \text{ GeV}/c$. The C^{ω/π^0} ratio, on the other hand, is in good agreement with previous experiments within the statistical and systematic uncertainties.

SUMMARY & OUTLOOK

In this thesis, the production cross sections of ω and η mesons has been measured at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV with [ALICE](#). Measurements of neutral meson cross sections allow to test and constrain theory predictions, which is especially interesting for ω production, due to the mesons heavy mass given its light flavour content. Moreover, neutral meson cross sections are needed for other analyses, such as direct photon [\[3\]](#) and di-electron [\[4\]](#) measurements, when estimating the background of hadronic decays.

Both mesons were reconstructed with the invariant mass method via their decay to $\pi^+\pi^-\pi^0$, where the charged pions were measured using the [ITS](#) and [TPC](#) and the neutral pion was reconstructed via its decay to two photons. Three different methods are available to detect photons within [ALICE](#) at mid-rapidity, all of which were exploited in this thesis: Photons can be either reconstructed via their energy depositions in one of [ALICE](#)'s calorimeters, the [PHOS](#) and the [EMCal](#), or by using the Photon Conversion Method ([PCM](#)), which allows to reconstruct photons which converted to an e^+e^- pair within the [ITS](#) and [TPC](#). The latter method profits from an excellent momentum resolution, whereas the calorimeter measurements are more efficient at measuring photons, thus providing a bigger photon sample. Five different approaches have been used to reconstruct the ω and η meson, where the π^0 decay photons are measured using the [EMCal](#), [PHOS](#), [PCM](#) and two hybrid techniques. The latter use a calorimeter photon as well as a conversion photon for the π^0 reconstruction, hence combining the advantages of each approach. The hybrid [PCM-PHOS](#) approach was furthermore used to obtain a new cluster energy correction for the [MC](#) description of [PHOS](#) clusters, ensuring agreement of π^0 peak positions in [MC](#) and data.

Using these approaches, five invariant cross sections were obtained for each meson, taking into account geometrical acceptances as well as reconstruction efficiencies. The reconstruction carried out using [PCM](#) allowed to measure the ω (η) cross section down to low transverse momenta p_T of 1.8 GeV/c (1.5 GeV/c), whereas the use of the [EMCal](#) extended the p_T -reach up to 16 GeV/c (12 GeV/c). Furthermore, the systematic uncertainties of three ω measurements have been evaluated, which were found to be in the order of about 20%. All cross sections were found to agree with each other within the statistical and systematic uncertainties.

By combination of the five individual measurements, the differential cross sections of ω and η meson production were measured at mid-rapidity over a transverse momentum range of $1.8 \text{ GeV}/c < p_T < 16 \text{ GeV}/c$ and $1.5 \text{ GeV}/c < p_T < 12 \text{ GeV}/c$ respectively. A Tsallis [\[89\]](#) fit function is used as parametrization, which was found to sufficiently describe the measured cross sections. Furthermore, the cross sections were compared to other measurements: The ω cross section was found to be in good agreement with the results presented in Ref. [\[18\]](#) and moreover a greatly improved momentum resolution was achieved at low- p_T compared to the existing measurement due to the additional use of the [PCM](#). Moreover, a measurement of the η meson [\[20\]](#) via its decay to two photons was compared to the measurements performed in the

three pion decay channel as part of this thesis and reasonable agreement was observed as well, which underlines the validity of the methods used in this thesis.

Additionally, the cross sections were compared to predictions of MC event generator PYTHIA 8.2 [75], where refined parameters provided by the well-established Monash 2013 tune [90] were used. The PYTHIA predictions manage to describe ω production over the whole measured p_T -range, whereas the η cross section was found to be underestimated by the prediction.

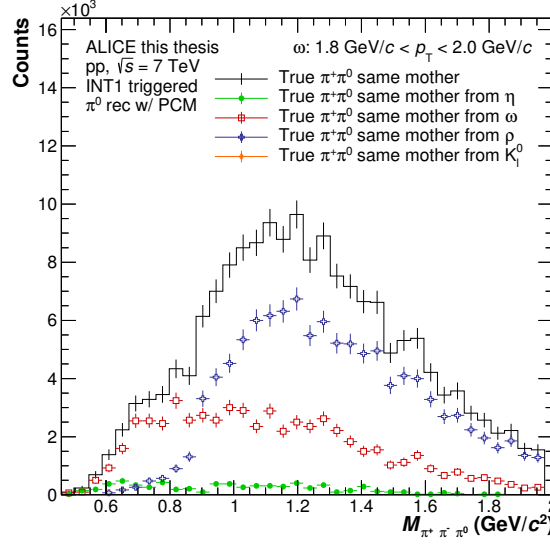
Moreover, the ω/π^0 and η/π^0 ratios were calculated using the Tsallis parametrization of the π^0 cross section presented in Ref. [20] as the denominator. Both measurements were compared to PYTHIA predictions as well as other measurements [18, 20]. The ratios are consistent with the results presented in Ref. [18] and Ref. [20], however the η/π^0 ratio is found to be slightly above the one presented as part of the $\eta \rightarrow \gamma\gamma$ publication [20]. The comparison to PYTHIA shows that it generally underestimates the ratios, especially η/π^0 measurement. However, the prediction of the ω/π^0 ratio is still consistent with the measurement within the uncertainties.

Finally, the ω/π^0 ratio was compared to previous measurements at lower centre-of-mass energies [15–17] and good agreement could be observed over the whole p_T -range, indicating that the ω/π^0 ratio is independent of collisions energy for high p_T . Moreover constant normalization factors were obtained by fitting the ω/π^0 and η/π^0 ratios with a constant for $p_T \geq 3.5 \text{ GeV}/c$, which can be used to calculate parametrizations of the respective meson using m_T scaling [91]. The η/π^0 normalization factor is substantially above the ones obtained in other measurements [42, 95, 96], whereas the ω/π^0 normalization factor is in good agreement with previous measurements [15, 17].

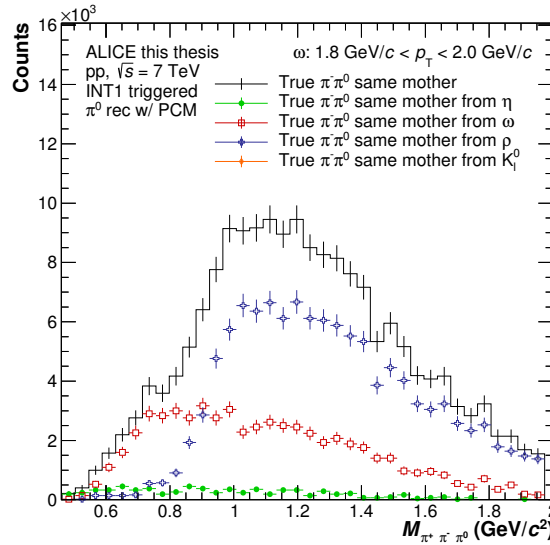
Overall, this thesis demonstrated the capability of five different reconstruction methods to measure ω and η mesons in the three pion decay channel in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ and furthermore showed the consistency of the results with other measurements as well as PYTHIA predictions. The η differential cross section has been measured for the first time at $\sqrt{s} = 7 \text{ TeV}$ in this decay channel and can serve as a supplement and cross check for the well established $\eta \rightarrow \gamma\gamma$ analyses in the future, especially when more statistics is available. The ω measurement was carried out for the first time using all available photon detection methods at mid-rapidity within ALICE and the agreement with the PHOS measurement presented in Ref. [18] supports the validity of the methods used. In the future, a measurement carried out, e.g. in pp collisions at $\sqrt{s} = 13 \text{ TeV}$, where twice as much MB statistics is available, should allow to further probe the low- p_T region of ω meson production with PCM as well as extending the upper p_T -reach with the calorimeters, especially given the possibility of using triggered data.

ADDITIONAL FIGURES

A.1 BACKGROUND STUDIES



(a)



(b)

Figure A.1: Invariant mass distributions in an exemplary p_T -slice, which are obtained by carrying out the reconstruction on the MC datasets. The true MC information is used to show contributions of $\pi^+ \pi^- \pi^0$ combinations where a π^+ and π^0 (a) or π^- and π^0 (b) originate from the same mother particle.

A.2 SIGNAL EXTRACTION

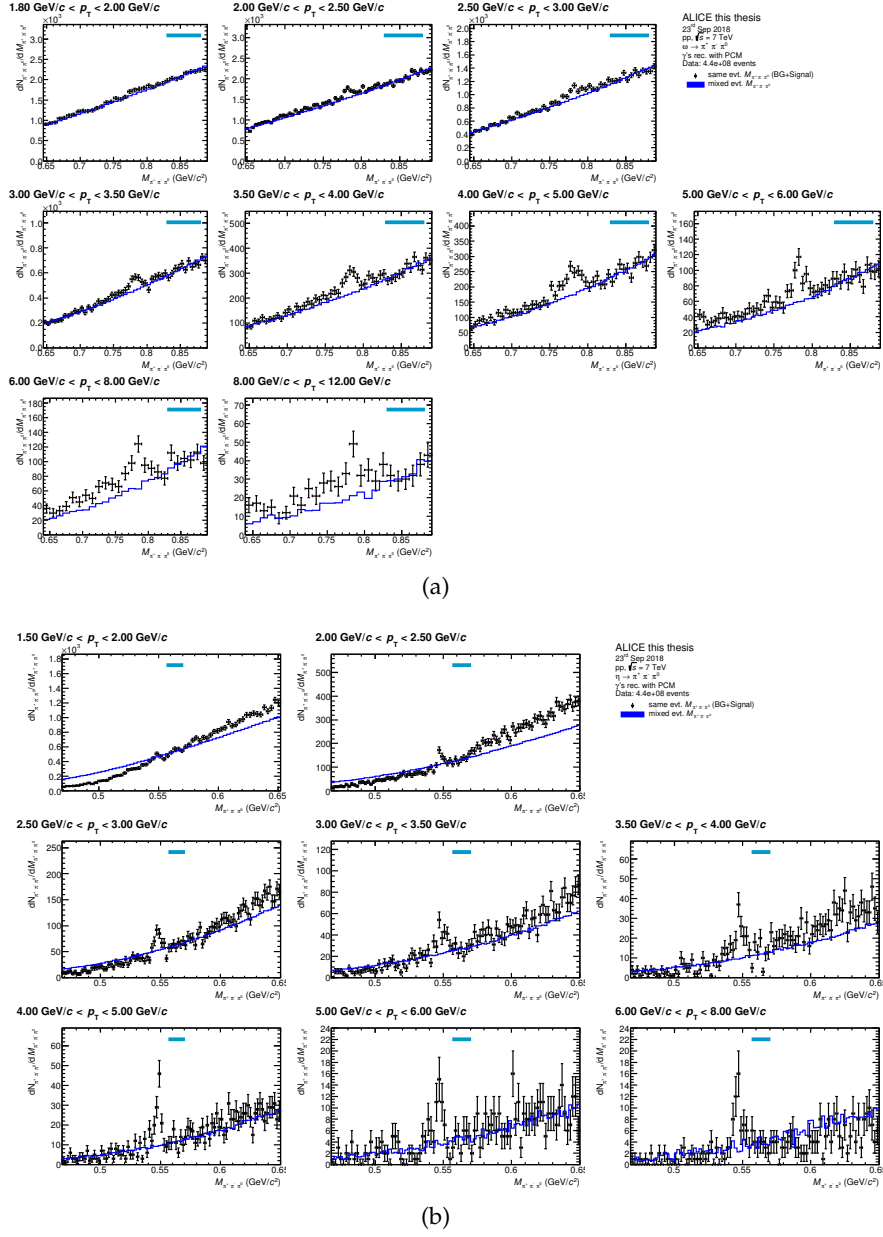


Figure A.2: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices. The neutral pion is reconstructed using the [PCM](#) for both photons. The scaled event-mixing background is shown in dark blue and a light blue box indicates the normalization range used.

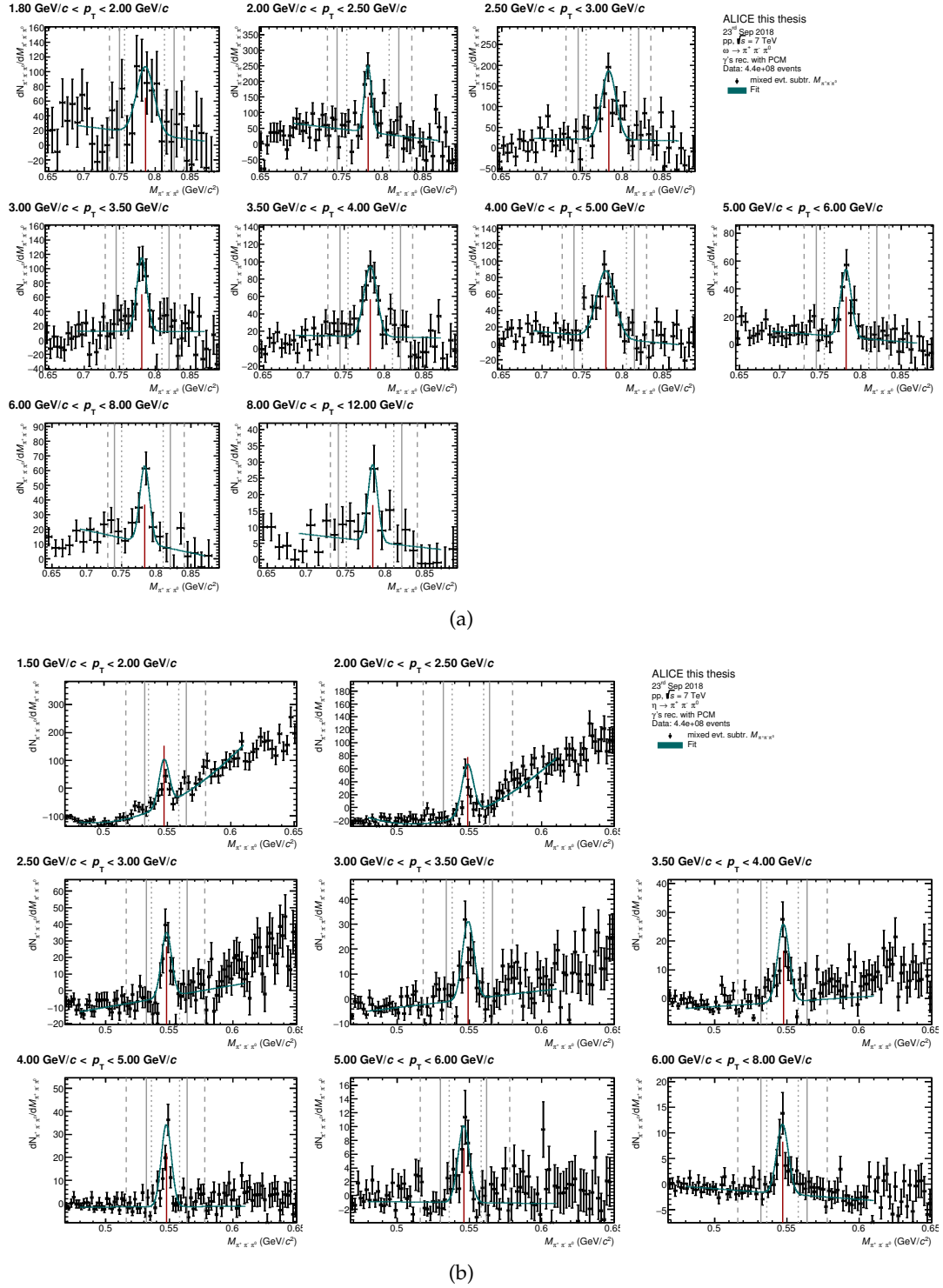


Figure A.3: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PCM for both photons. A fit according to Eq. 8.2 is performed (blue) and the grey lines represent the different integration ranges. Moreover, a red line indicates the reconstructed mass.

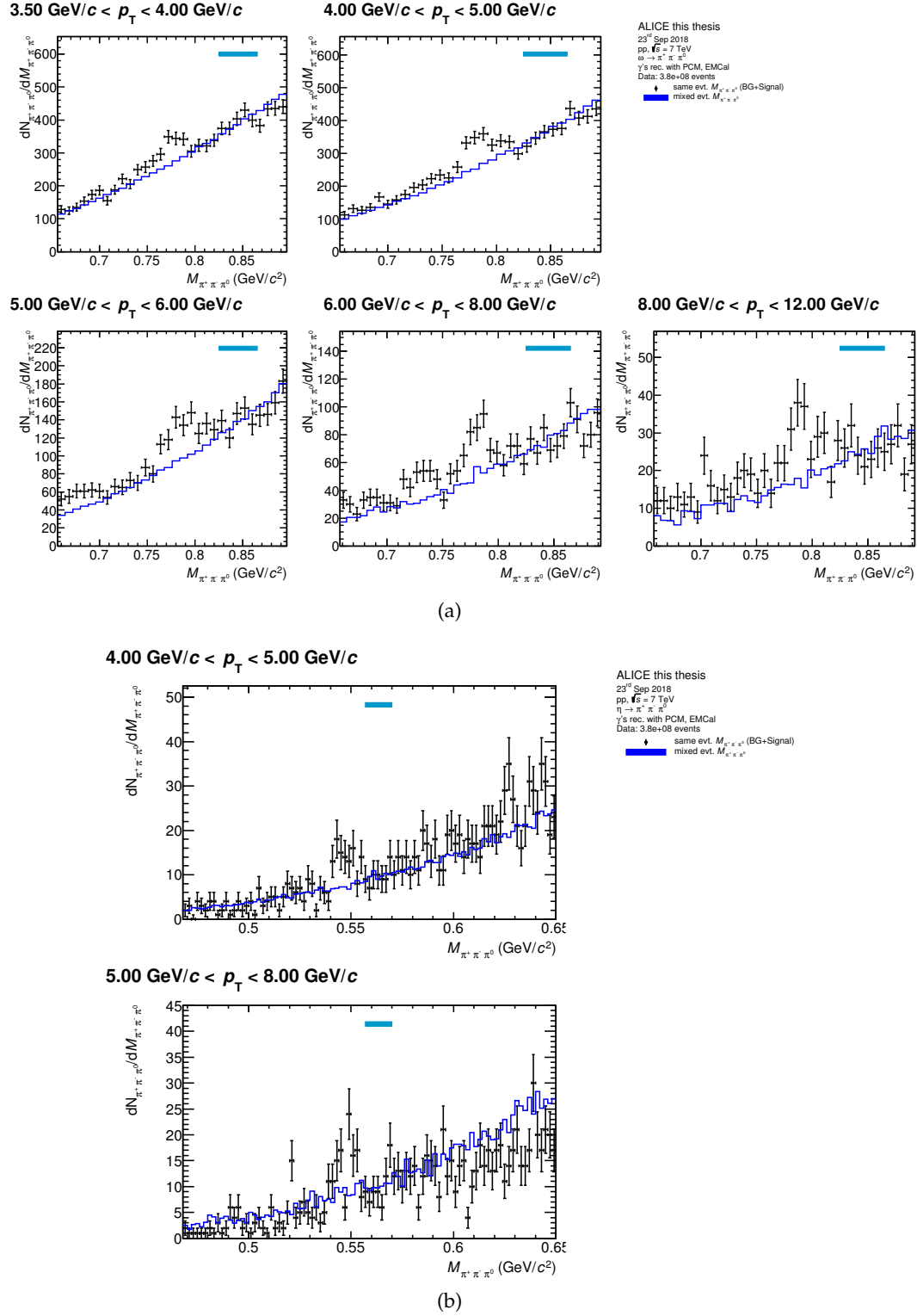


Figure A.4: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices. The neutral pion is reconstructed using the PCM-EMCal. The scaled event-mixing background is shown in dark blue and a light blue box indicates the normalization range used.

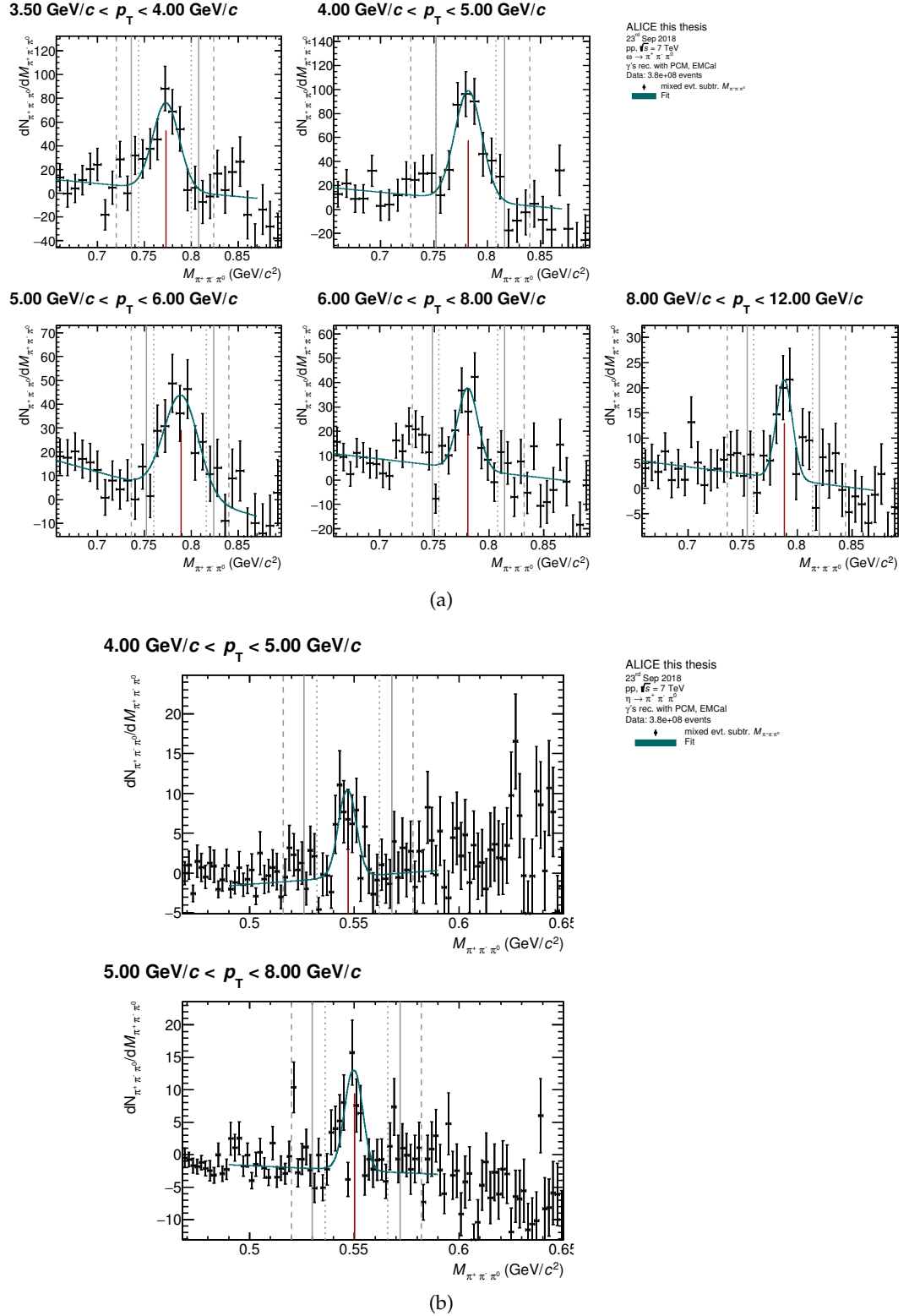


Figure A.5: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PCM-EMCal. A fit according to Eq. 8.2 is performed (blue) and the grey lines represent the different integration ranges. Moreover, a red line indicates the reconstructed mass.

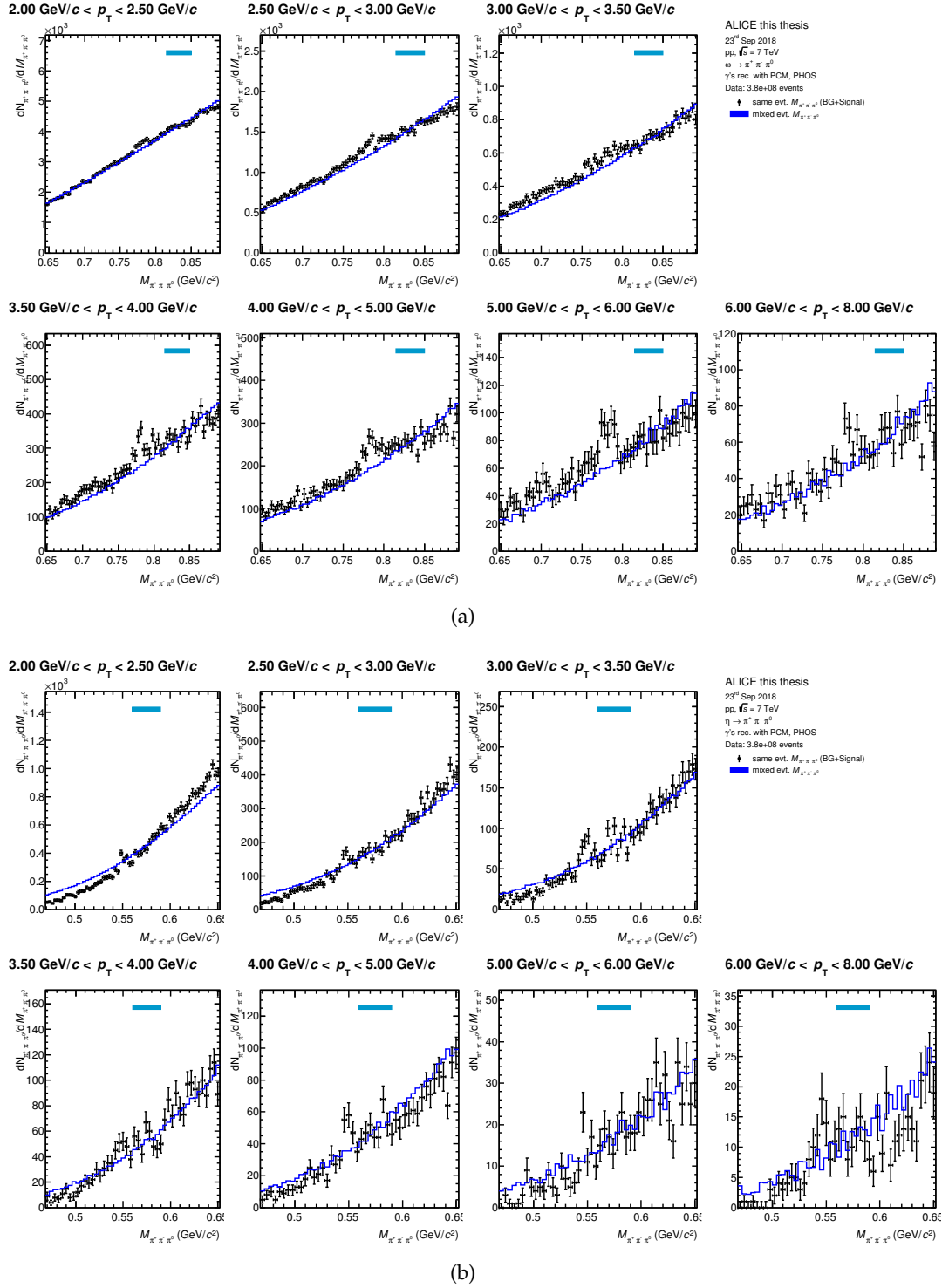


Figure A.6: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices. The neutral pion is reconstructed using PCM-PHOS. The scaled event-mixing background is shown in dark blue and a light blue box indicates the normalization range used.

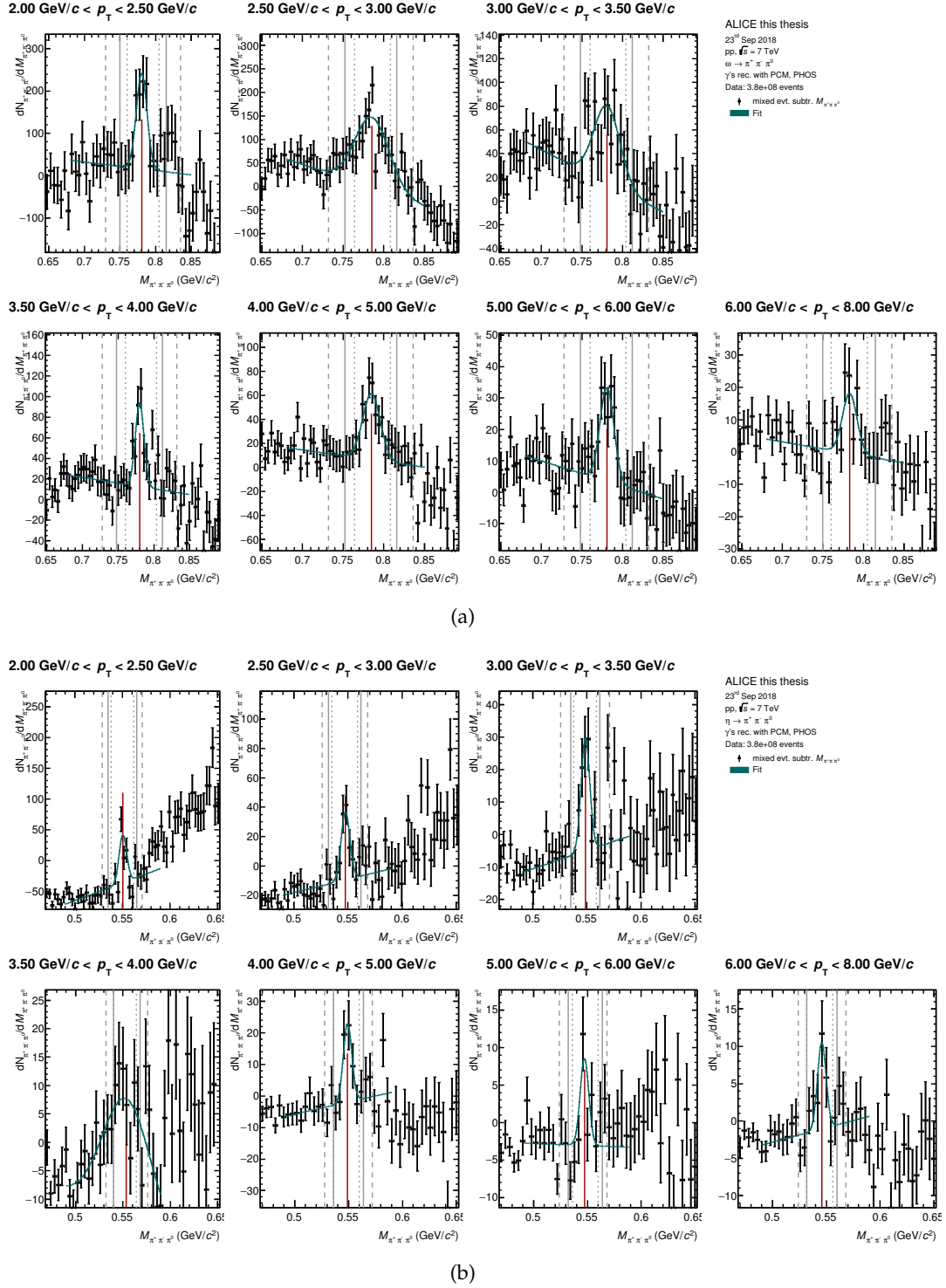


Figure A.7: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using PCM-PHOS. A fit according to Eq. 8.2 is performed (blue) and the grey lines represent the different integration ranges. Moreover, a red line indicates the reconstructed mass.

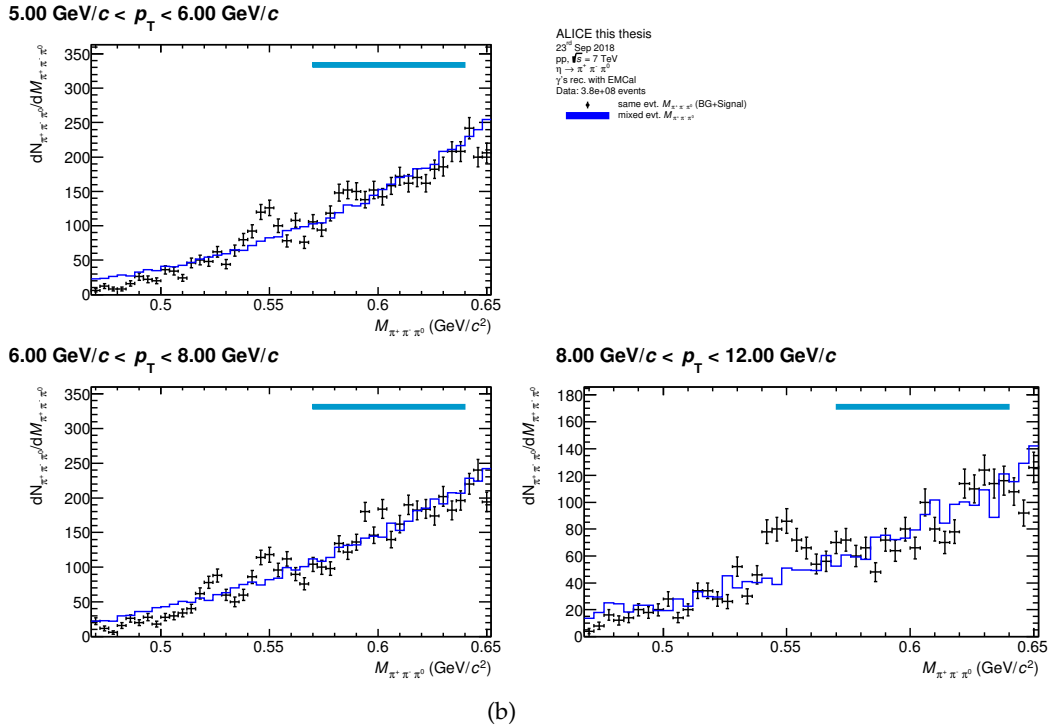
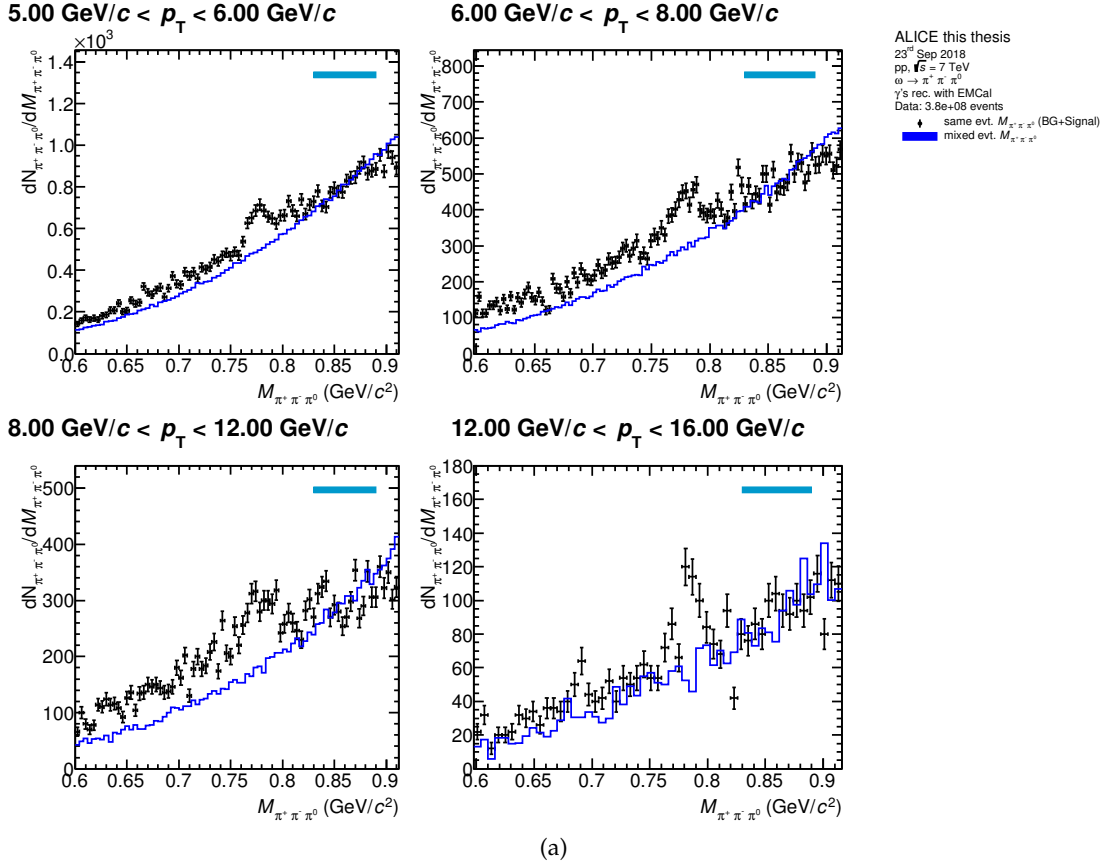


Figure A.8: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices. The neutral pion is reconstructed using the **EMCal** for both photons. The scaled event-mixing background is shown in dark blue and a light blue box indicates the normalization range used.

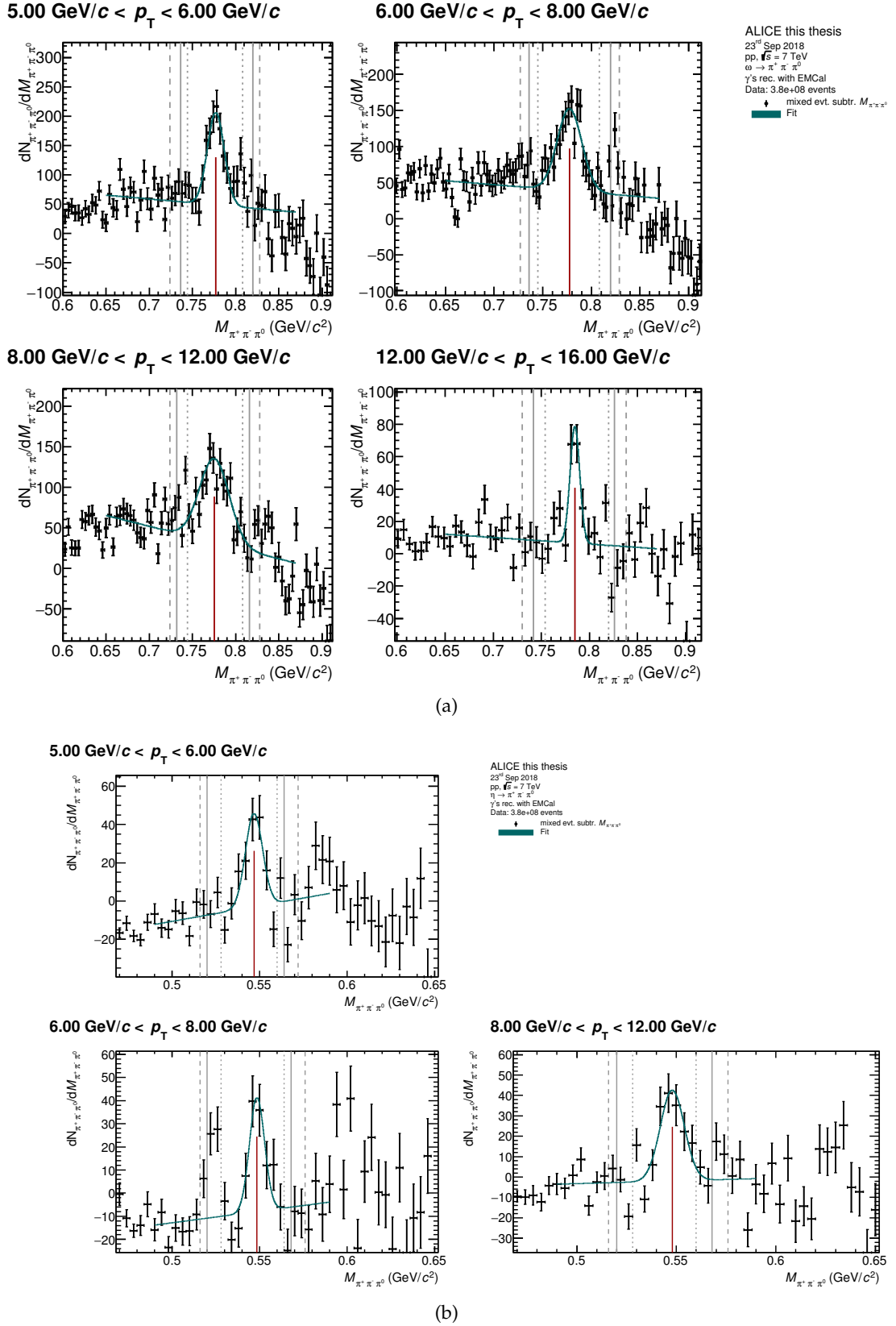


Figure A.9: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the [EMCal](#) for both photons. A fit according to Eq. 8.2 is performed (blue) and the grey lines represent the different integration ranges. Moreover, a red line indicates the reconstructed mass.

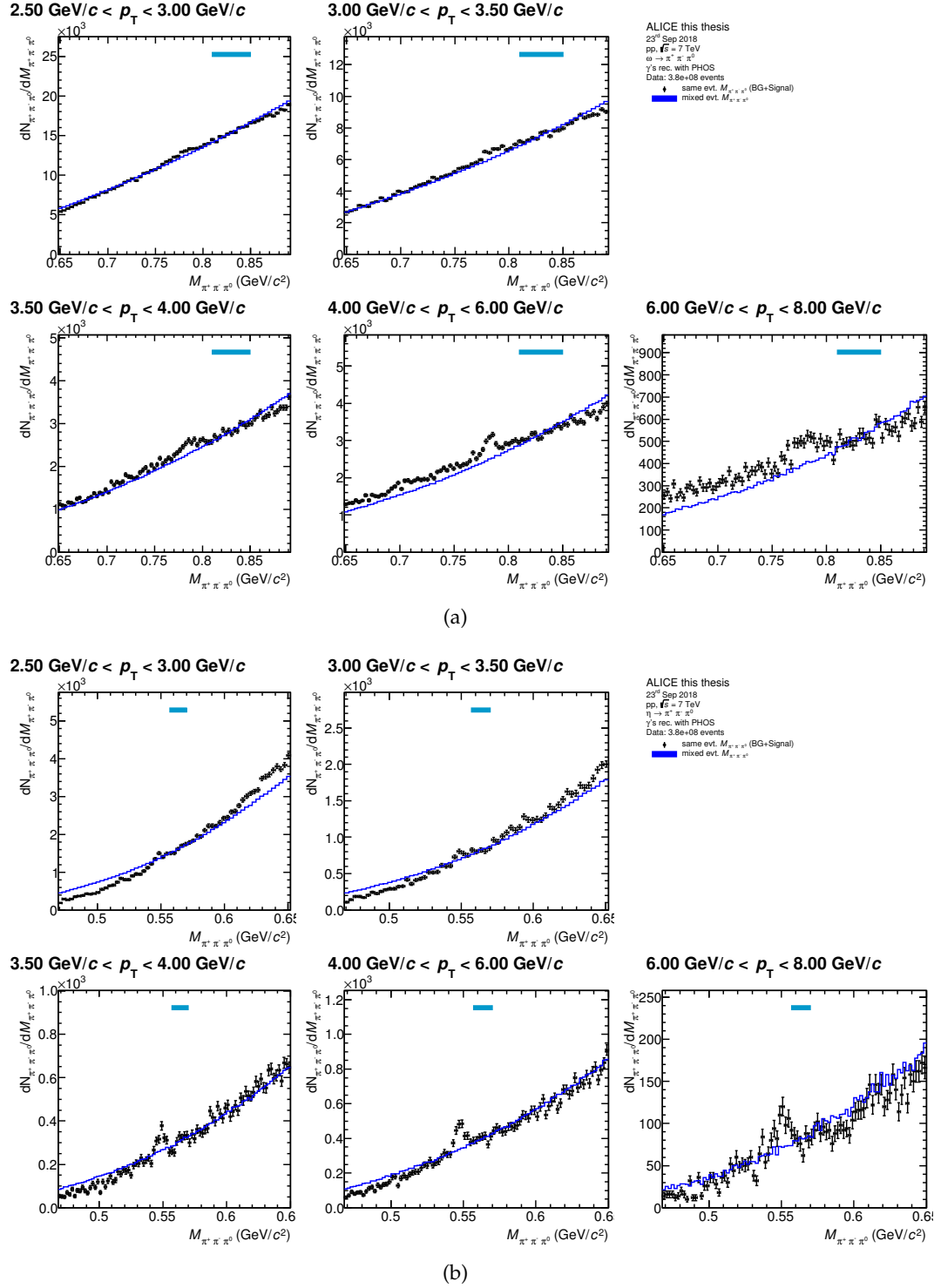


Figure A.10: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices. The neutral pion is reconstructed using the PHOS for both photons. The scaled event-mixing background is shown in dark blue and a light blue box indicates the normalization range used.

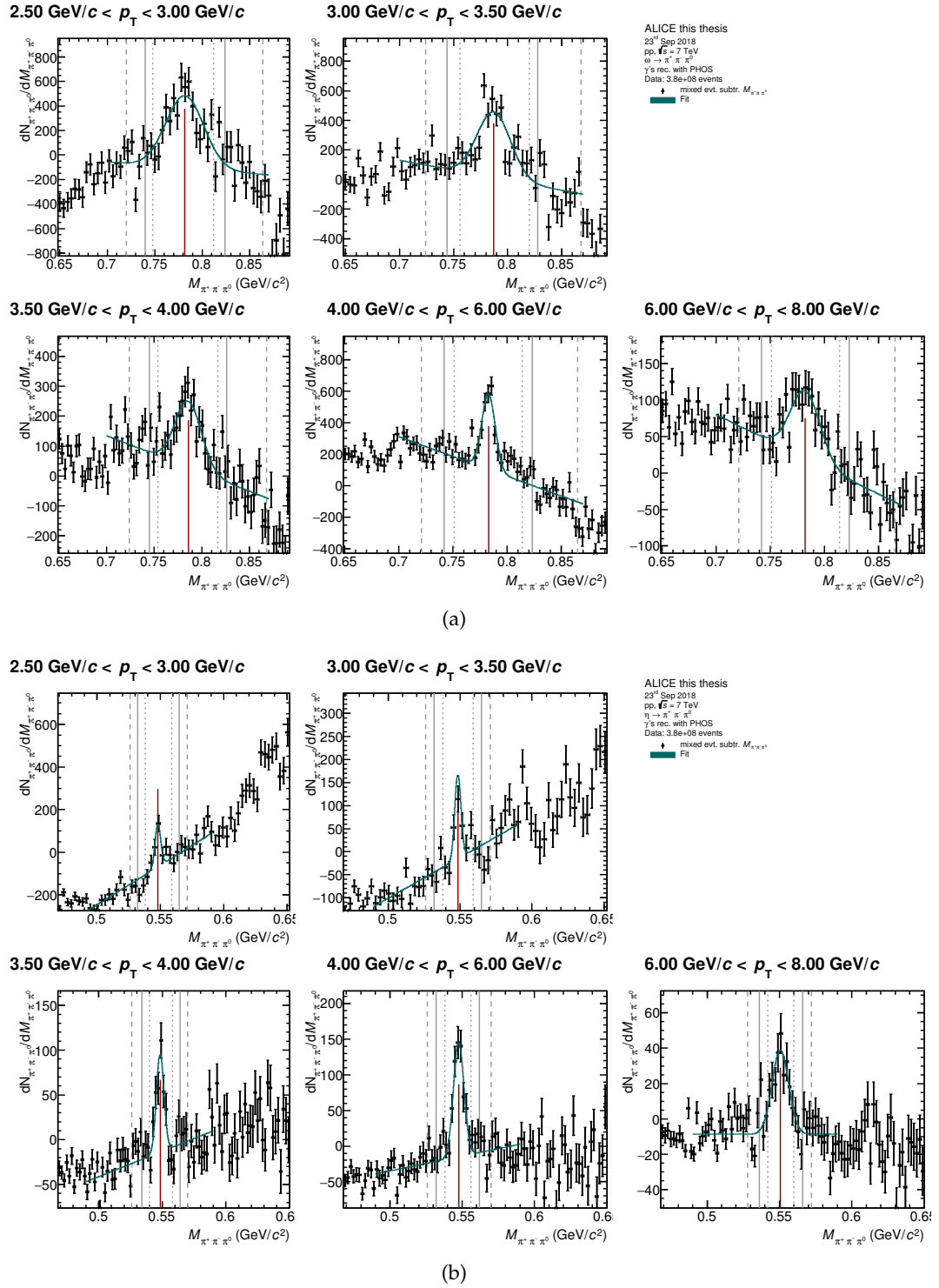


Figure A.11: Invariant distributions in the vicinity of the nominal ω (a) and η (b) mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PHOS for both photons. A fit according to Eq. 8.2 is performed (blue) and the grey lines represent the different integration ranges. Moreover, a red line indicates the reconstructed mass.

A.3 SYSTEMATIC UNCERTAINTIES

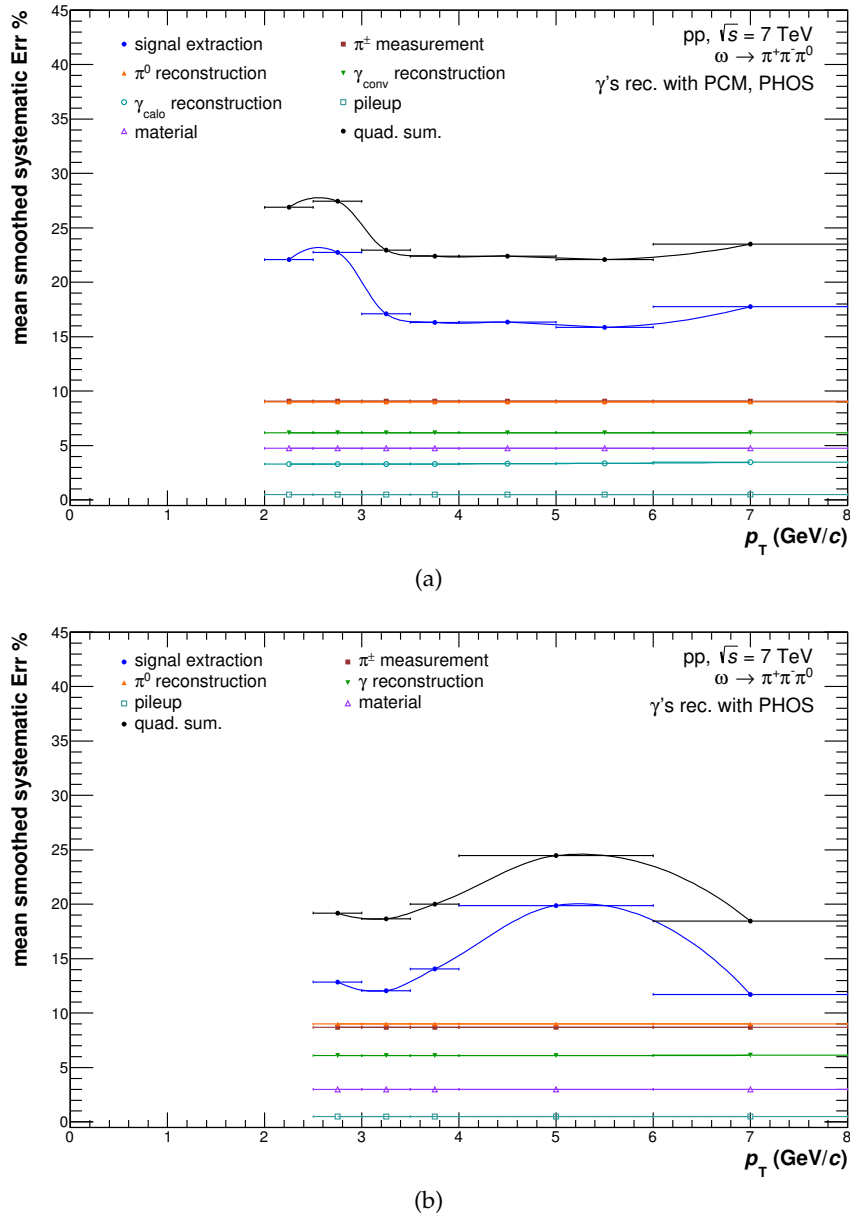
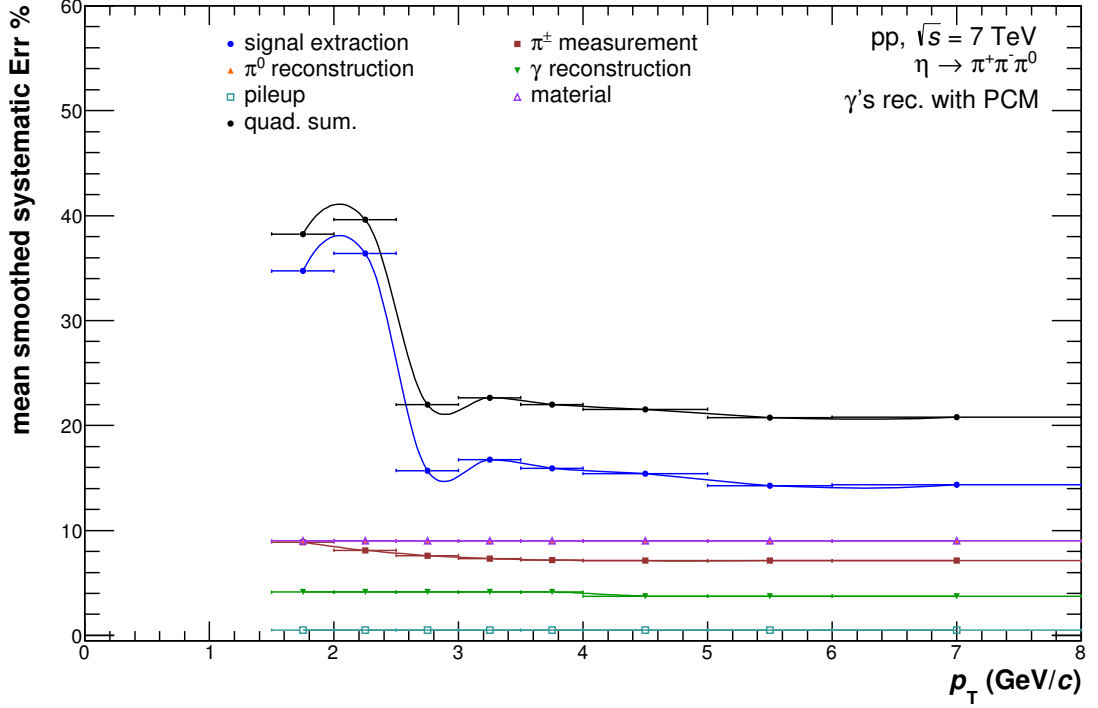
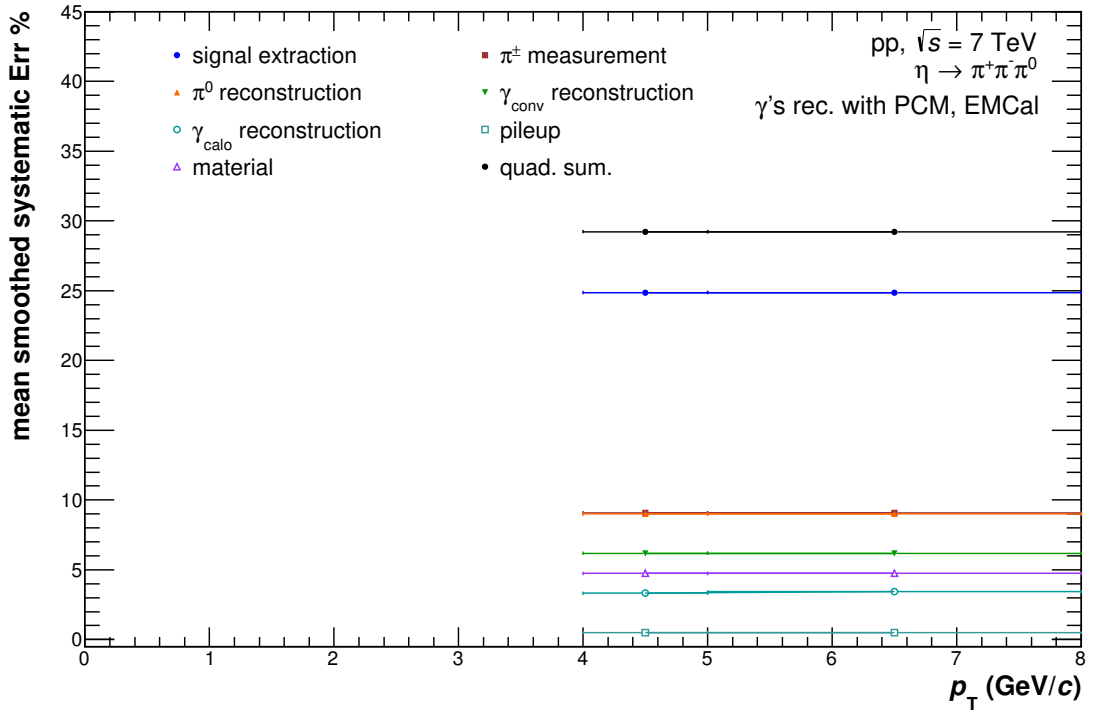


Figure A.12: Overview of the smoothed total systematic uncertainties of the ω measurements as a function of transverse momentum where the neutral pion is reconstructed using **PCM-PHOS** (a) and **PHOS** (b). In addition, the different contributions to the total uncertainty are shown, which are grouped according to different analysis aspects, as shown in Tab. 8.5.

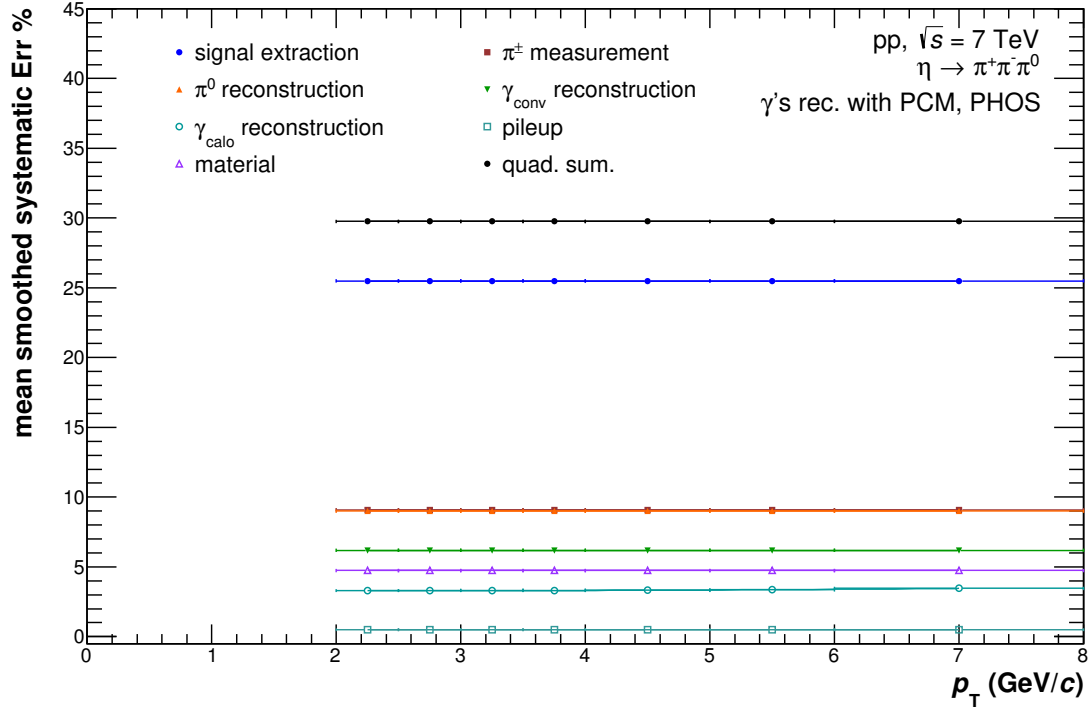


(a)

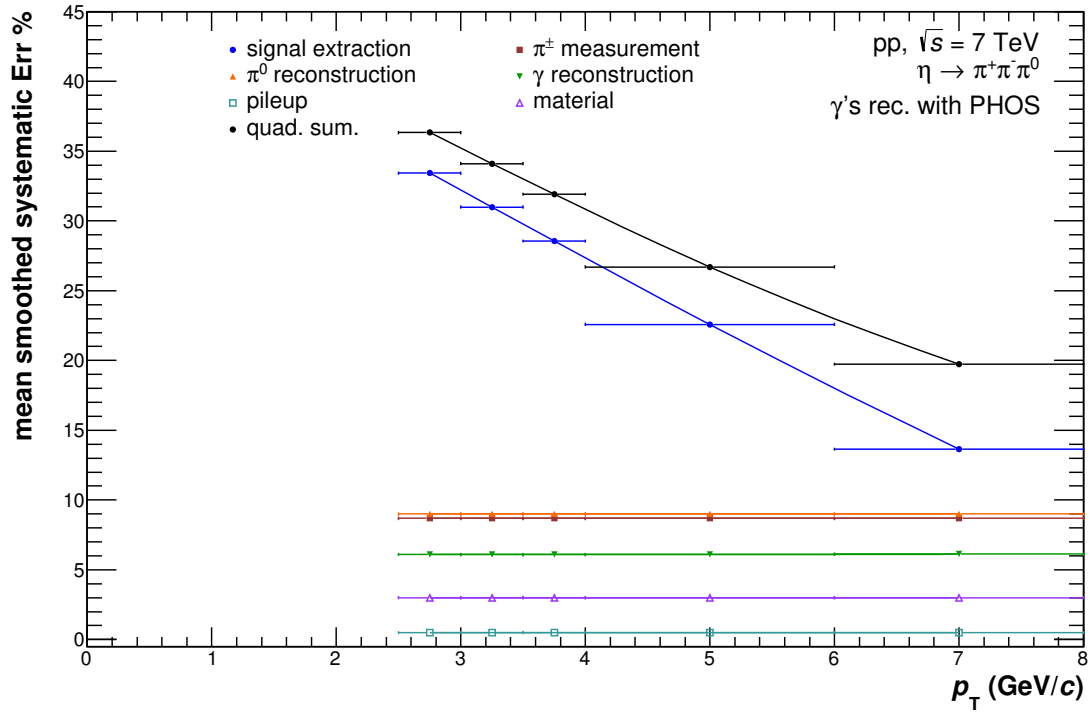


(b)

Figure A.13: Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using PCM (a) and PCM-EMCal (b). In addition, the different contributions to the total uncertainty are shown, which are grouped according to different analysis aspects, as shown in Tab. 8.5. For now, all systematic uncertainties are borrowed from the ω measurements, except the signal extraction uncertainties.



(a)



(b)

Figure A.14: Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using [PCM-PHOS](#) (a) and [PHOS](#) (b). In addition, the different contributions to the total uncertainty are shown, which are grouped according to different analysis aspects, as shown in Tab. 8.5. For now, all systematic uncertainties are borrowed from the ω measurements, except the signal extraction uncertainties.

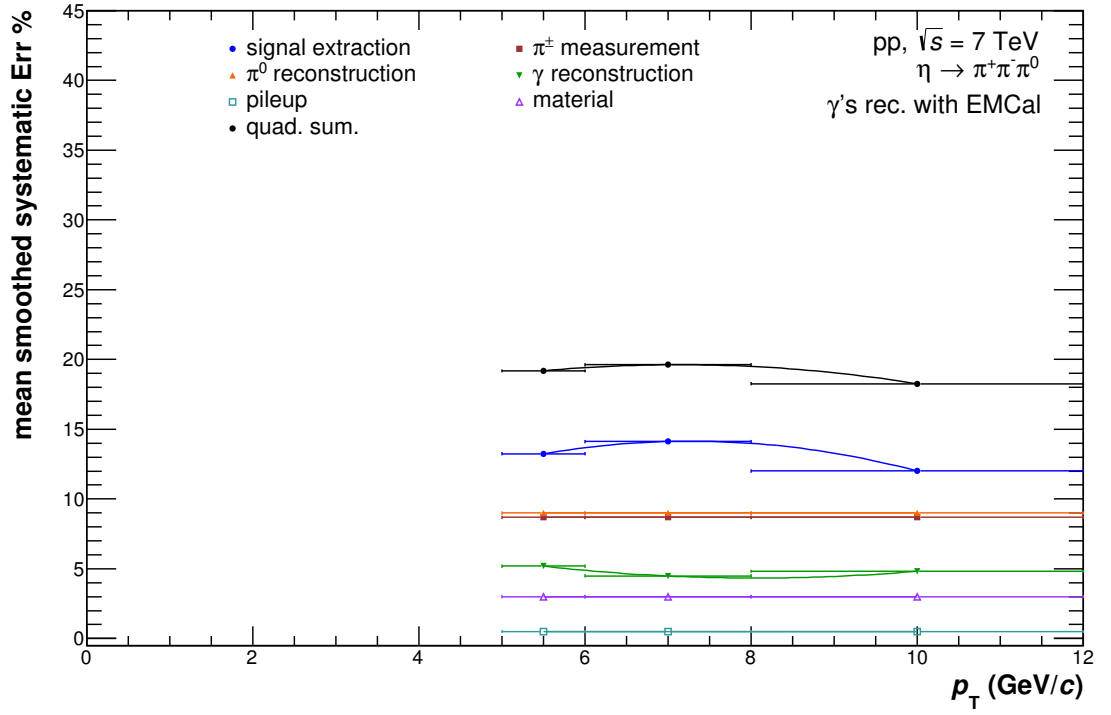


Figure A.15: Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using the [EMCAL](#). In addition, the different contributions to the total uncertainty are shown, which are grouped according to different analysis aspects, as shown in Tab. 8.5. For now, all systematic uncertainties are borrowed from the ω measurements, except the signal extraction uncertainties.

A.4 COMBINATION OF MEASUREMENTS

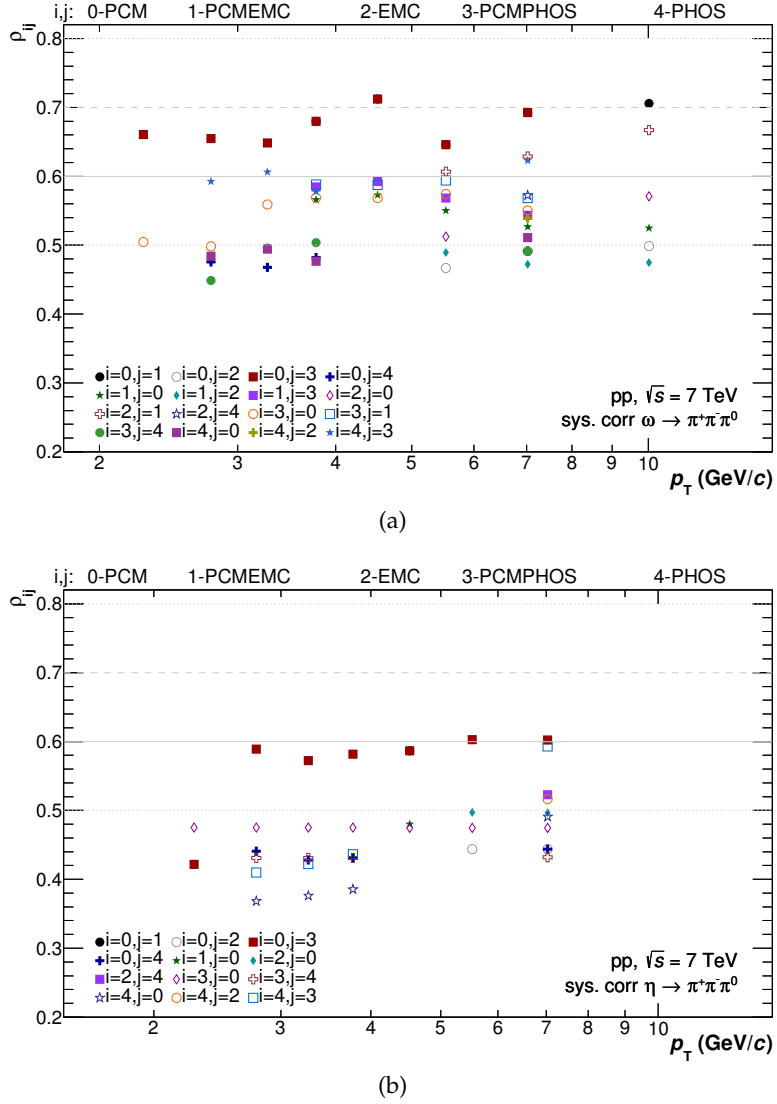


Figure A.16: Correlation factor ρ_{ij} of measurement i with respect to measurement j , as defined in Eq. 8.9. The factors are shown for the ω (a) and η (b) and are taken into account in the combination procedure described in this section.

ADDITIONAL TABLES

Table B.1: List of [LHC](#) runs that are used for all measurements using only the [PCM](#) for photon measurement.

PERIOD	RUN NUMBERS
LHC10b	114786, 114798, 114918, 114920, 114924, 114931, 115186, 115193, 115310, 115318, 115322, 115328, 115335, 115345, 115393, 115399, 115401, 116079, 116081, 116102, 116288, 116402, 116403, 116562, 116571, 116574, 116643, 116645, 117048, 117050, 117052, 117053, 117059, 117060, 117063, 117092, 117099, 117109, 117112, 117116, 117220, 117222
LHC10c	119159, 119161, 119163, 119841, 119842, 119844, 119845, 119846, 119849, 119853, 119856, 119859, 119862, 120067, 120069, 120072, 120076, 120079, 120505, 120616, 120617, 120671, 120741, 120750, 120758, 120820, 120821, 120822, 120823, 120824, 120825, 120829
LHC10d	122374, 122375, 124751, 125083, 125085, 125097, 125100, 125133, 125134, 125139, 125140, 125156, 125186, 125295, 125296, 125630, 125632, 125842, 125843, 125847, 125848, 125849, 125850, 125851, 125855, 126004, 126007, 126008, 126073, 126078, 126081, 126082, 126088, 126090, 126097, 126158, 126160, 126167, 126168, 126283, 126284, 126285, 126351, 126352, 126359, 126403, 126404, 126405, 126406, 126407, 126408, 126409, 126422, 126424, 126425, 126432
LHC10e	128366, 128494, 128495, 128498, 128503, 128504, 128505, 128506, 128582, 128590, 128592, 128594, 128596, 128605, 128609, 128611, 128615, 128621, 128677, 128678, 128777, 128778, 128819, 128820, 128823, 128824, 128833, 128834, 128835, 128836, 128843, 128850, 128853, 128855, 128913, 129042, 129512, 129513, 129514, 129515, 129516, 129519, 129520, 129521, 129523, 129524, 129525, 129527, 129528, 129536, 129540, 129586, 129587, 129599, 129639, 129641, 129647, 129650, 129651, 129652, 129653, 129659, 129666, 129723, 129726, 129729, 129734, 129735, 129736, 129738, 129742, 129744, 129959, 129960, 129961, 129962, 129966, 130149, 130151, 130157, 130158, 130168, 130172, 130178, 130342, 130343, 130354, 130356, 130358, 130360, 130375, 130480, 130481, 130517, 130519, 130520, 130524, 130526, 130601, 130608, 130609, 130620, 130621, 130623, 130628, 130696, 130704, 130793, 130795, 130798, 130799, 130834, 130840, 130842, 130844, 130847, 130848, 130850
LHC10f	133006, 133007, 133010, 133327, 133329, 133330, 133414, 133563, 133670, 133762, 133800, 133920, 133969, 133982

Table B.2: List of [LHC](#) runs that are used for all measurements involving the [EMCal](#).

PERIOD	RUN NUMBERS
LHC10b	115393, 115399, 115401, 116102, 116288, 116402, 116403, 116643, 116645, 117050, 117052, 117053, 117059, 117060, 117063, 117099, 117109, 117112, 117116, 117220, 117222
LHC10c	119159, 119161, 119163, 119841, 119842, 119844, 119845, 119846, 119853, 119856, 119859, 119862, 120067, 120069, 120072, 120076, 120079, 120244, 120503, 120504, 120505, 120616, 120617, 120671, 120741, 120820, 120821, 120822, 120823, 120824, 120825, 120829
LHC10d	122374, 122375, 125630, 125632, 125633, 125842, 125843, 125844, 125847, 125848, 125849, 125850, 125851, 125855, 126004, 126007, 126008, 126073, 126078, 126081, 126082, 126088, 126090, 126097, 126158, 126160, 126167, 126168, 126284, 126285, 126351, 126352, 126359, 126403, 126404, 126405, 126406, 126407, 126408, 126409, 126422, 126424, 126425, 126432
LHC10e	128486, 128494, 128495, 128498, 128503, 128504, 128505, 128506, 128582, 128590, 128592, 128594, 128596, 128605, 128609, 128611, 128615, 128621, 128677, 128678, 128777, 128778, 128819, 128820, 128823, 128824, 128833, 128834, 128835, 128836, 128843, 128850, 128853, 128855, 128913, 129042, 129512, 129513, 129514, 129515, 129516, 129519, 129520, 129521, 129523, 129524, 129525, 129527, 129528, 129536, 129540, 129586, 129587, 129599, 129639, 129641, 129647, 129650, 129651, 129652, 129653, 129659, 129666, 129723, 129726, 129729, 129734, 129735, 129736, 129738, 129742, 129744, 129959, 129960, 129961, 129962, 129966, 129983, 130149, 130151, 130157, 130158, 130168, 130172, 130178, 130343, 130354, 130356, 130358, 130360, 130375, 130480, 130481, 130517, 130519, 130696, 130704, 130793, 130795, 130798, 130799, 130834, 130840, 130842, 130844, 130847, 130848
LHC10f	133006, 133007, 133010, 133327, 133329, 133330, 133414, 133670, 133762, 133800, 133920, 133969, 133982

Table B.3: List of LHC runs that are used for all measurements involving the PHOS.

PERIOD	RUN NUMBERS
LHC10b	117222, 117220, 117116, 117112, 117109, 117099, 117092, 117063, 117059, 117053, 117052, 117050, 117048, 116645, 116643, 116574, 116571, 116562, 116403, 116402, 116288, 116102, 116081, 116079, 115401, 115399, 115393, 115345, 115335, 115328, 115322, 115318, 115310, 114931, 114924, 114920, 114918, 114798, 114786
LHC10c	120829, 120825, 120824, 120823, 120822, 120821, 120758, 120750, 120741, 120671, 120617, 120616, 120505, 120504, 120503, 120244, 120079, 120076, 120072, 120069, 120067, 119862, 119859, 119856, 119853, 119849, 119846, 119845, 119844, 119842, 119841, 119163, 119161, 119159
LHC10d	126432, 126425, 126424, 126422, 126409, 126408, 126407, 126406, 126405, 126404, 126403, 126359, 126352, 126351, 126285, 126284, 126283, 126168, 126167, 126160, 126158, 126097, 126090, 126088, 126082, 126081, 126078, 126073, 126008, 126007, 126004, 125855, 125851, 125850, 125849, 125848, 125847, 125843, 125842, 125632, 125630, 125296, 125295, 125186, 125156, 125140, 125139, 125134, 125133, 125100, 125097, 125085, 125083, 124751
LHC10e	130526, 130524, 130520, 130519, 130517, 130481, 130480, 130342, 130178, 130172, 130168, 130158, 130157, 130149, 129966, 129962, 129961, 129960, 129744, 129742, 129738, 129736, 129735, 129734, 129729, 129726, 129723, 129666, 129659, 129653, 129652, 129651, 129650, 129647, 129641, 129639, 129599, 129587, 129586, 129540, 129536, 129528, 129527, 129525, 129524, 129523, 129521, 129520, 129519, 129516, 129515, 129514, 129513, 128913, 128855, 128853, 128850, 128843, 128836, 128835, 128833, 128824, 128823, 128820, 128819, 128778, 128777, 128678, 128677, 128621, 128615, 128611, 128609, 128605, 128596, 128594, 128592, 128582, 128506, 128505, 128504, 128503, 128498, 128495, 128494, 128366
LHC10f	133982, 133969, 133920, 133800, 133762, 133670, 133563, 133414, 133330, 133329, 133327, 133010, 133007, 133006

LIST OF FIGURES

Figure 2.1	Overview of the fundamental particles of the Standard Model [7].	4
Figure 2.2	The fundamental vertices of QCD [9].	5
Figure 2.3	Different measurements of the coupling constant α_s [14].	5
Figure 2.4	Multiplets of the pseudoscalar and vector mesons, considering the quark flavours u, d, c and s [14].	6
Figure 2.5	Differential yields of a variety of particles produced in pp collisions at $\sqrt{s} = 7$ TeV.	10
Figure 2.6	Sketch of the QCD phase diagram [37].	13
Figure 2.7	Nuclear modification factor R_{AA} calculated from measured neutral pion spectra in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE [40].	14
Figure 2.8	Contributions to decay photons originating from different hadrons as a function of transverse momentum [3].	15
Figure 2.9	Measurement of the double ratio R_γ and direct photon spectra in three different centrality classes [3].	16
Figure 2.10	Mean energy loss rate per unit length of heavy particles at intermediate energies for different absorber materials [14].	17
Figure 2.11	Total cross sections of photons and the different contributions, shown for a lead absorber.	18
Figure 3.1	Overview of CERN's acceleration complex and experiments [44].	20
Figure 3.2	Schematic layout of the ALICE detector [53].	21
Figure 3.3	Schematic 3D view of the TPC [57].	22
Figure 3.4	Schematics of the Photon Spectrometer (PHOS) [51].	24
Figure 3.5	Schematic of the EMCal	25
Figure 3.6	Principle of secondary vertex reconstruction shown for the example of K_S^0 and Λ^0 decays, as well as the more complex Ξ^- decay [61].	28
Figure 3.7	Display of a reconstructed pp collision at $\sqrt{s} = 7$ TeV.	29
Figure 4.1	Number of MB events N^{MinBias} per run shown for data and MC.	33
Figure 4.2	Number of clusters in the SPD in dependence of the number of SPD tracklets.	35
Figure 5.1	dE/dx distribution as a function of momenta, normalized to the number of events, measured with the TPC for the LHC10 datasets.	38
Figure 6.1	Cell time in dependence of cell energy for all cells contained in accepted clusters.	43
Figure 6.2	η - ϕ distribution of EMCal clusters, after the cuts found in Tab. 6.1 were applied.	44
Figure 6.3	Cell energy- and time distributions of two different PHOS cells.	47
Figure 6.4	η - ϕ distribution of PHOS clusters.	47
Figure 6.5	Energy- and cluster shape distribution of reconstructed clusters before cluster selection criteria have been applied.	48

Figure 6.6	Calculated ratios of mass peak positions obtained in data and MC with respect to PHOS cluster energy E_{cluster}	49
Figure 6.7	TPC dE/dx distribution after application of different selection criteria used to identify electrons.	52
Figure 6.8	Armenteros-Podolanski plot before and after photon selection criteria have been applied.	53
Figure 6.9	Conversion points of selected photon candidates shown in the xy - and zR -plane.	54
Figure 7.1	Invariant mass distributions of all photon pairs plotted as a function transverse momentum before the application of any meson selection criteria.	56
Figure 8.1	Invariant mass distribution obtained with the PCM shown in the vicinity of the ω meson's nominal mass for an exemplary p_T -interval.	60
Figure 8.2	Invariant mass distribution for an exemplary momentum range of $2.0 \text{ GeV}/c < p_T < 2.5 \text{ GeV}/c$, where different contributions are obtained using MC simulations with full detector response.	61
Figure 8.3	Invariant mass distributions shown in the vicinity of the nominal mass of the ω meson for exemplary p_T -ranges.	64
Figure 8.4	Example invariant mass distributions shown in the vicinity of the nominal mass of the η meson for exemplary p_T -ranges.	65
Figure 8.5	Peak width $\sigma_{\omega,(\eta)}$ and peak position $M_{\omega(\eta)}$ of the individual ω and η measurements.	67
Figure 8.6	Acceptance A as a function of p_T shown for the ω and η meson measurement.	69
Figure 8.7	True validated reconstruction efficiency $\varepsilon_{\text{true}}$ as a function of p_T shown for the ω and η meson measurement.	70
Figure 8.8	Correction factors shown for ω and η mesons for the respective reconstruction techniques.	71
Figure 8.9	Overview of the smoothed total systematic uncertainties of the ω measurements as a function of transverse momentum.	74
Figure 8.10	Invariant cross sections of the ω and η meson which are measured using five different reconstruction techniques.	78
Figure 8.11	Weights $\omega_a(p_T)$ obtained for the individual ω and η measurements using the BLUE method.	79
Figure 8.12	Overview of the relative total, systematic and statistical uncertainties of the combined ω and η cross sections.	80
Figure 8.13	Overview of the shift in p_T -direction applied for each data point of the combined ω and η cross section.	81
Figure 9.1	Combined invariant cross sections of the ω and η meson, shown together with a comparison to theory predictions as well as other measurements [18, 20].	83
Figure 9.2	Ratio of the individual ω and η cross sections over the Tsallis fit of the combined cross section.	84
Figure 9.3	ω/π^0 and η/π^0 ratio shown together with theory predictions and reference measurements [18, 20].	86

Figure 9.4	ω/π^0 ratio shown as a function of p_T for pp collisions at various centre-of-mass energies ranging from $\sqrt{s} = 62 \text{ GeV} - 7000 \text{ GeV}$ [15–17].	87
Figure A.1	Invariant mass distributions in an exemplary p_T -slice, where true MC information is used to show two-pion correlations. . .	91
Figure A.2	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices. The neutral pion is reconstructed using the PCM for both photons.	92
Figure A.3	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PCM for both photons.	93
Figure A.4	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices. The neutral pion is reconstructed using the PCM-EMCal.	94
Figure A.5	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PCM-EMCal.	95
Figure A.6	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices. The neutral pion is reconstructed using PCM-PHOS.	96
Figure A.7	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using PCM-PHOS.	97
Figure A.8	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices. The neutral pion is reconstructed using the EMCal for both photons.	98
Figure A.9	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the EMCal for both photons.	99
Figure A.10	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices. The neutral pion is reconstructed using the PHOS for both photons.	100
Figure A.11	Invariant distributions in the vicinity of the nominal ω and η mass shown for different p_T -slices after event-mixing background subtraction. The neutral pion is reconstructed using the PHOS for both photons.	101
Figure A.12	Overview of the smoothed total systematic uncertainties of the ω measurements as a function of transverse momentum where the neutral pion is reconstructed using PCM-PHOS and PHOS.	102
Figure A.13	Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using PCM and PCM-EMCal.	103

Figure A.14	Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using PCM-PHOS and PHOS	104
Figure A.15	Overview of the smoothed total systematic uncertainties of the η measurements as a function of transverse momentum where the neutral pion is reconstructed using the EMCal	105
Figure A.16	Correlation factor ρ_{ij} of measurement i with respect to measurement j , as defined in Eq. 8.9	106

LIST OF TABLES

Table 4.1	Overview of the datasets used in this thesis.	34
Table 5.1	Track and PID cuts applied to tracks found in ITS and TPC . . .	37
Table 6.1	Overview of settings used for the clusterizer algorithm and EMCal cluster selection criteria.	42
Table 6.2	Overview of settings used for the clusterizer algorithm (algo.) and the PHOS cluster selection criteria.	45
Table 6.3	Overview of the selection criteria used for photon measurements with PCM	51
Table 7.1	Overview of neutral pion selection criteria, that are applied for the respective reconstruction techniques.	57
Table 8.1	Overview of the neutral meson selection criteria.	59
Table 8.2	Illustration of the different event-mixing groups.	62
Table 8.3	Overview of the standard invariant mass ranges used to normalize the event-mixing distribution to the total invariant mass distribution.	66
Table 8.4	Overview of the integration ranges used to obtain the meson raw yield for each reconstruction method.	68
Table 8.5	Systematic uncertainty sources for the ω measurement, where PCM , PCM-EMCal and EMCal are used to reconstruct the neutral pion.	73
Table 8.6	Transverse momentum coverage of the individual cross sections shown in Fig. 8.10.	77
Table 9.1	Overview of normalization factors C^h which are obtained by fitting the ω/π^0 and η/π^0 ratios in the high p_T region.	88
Table B.1	List of LHC runs that are used for all measurements using only the PCM for photon measurement.	107
Table B.2	List of LHC runs that are used for all measurements involving the EMCal	108
Table B.3	List of LHC runs that are used for all measurements involving the PHOS	109

ACRONYMS

LHC	Large Hadron Collider
ALICE	A Large Ion Collider Experiment
QGP	Quark-Gluon Plasma
QCD	Quantum Chromodynamics
pQCD	perturbative QCD
PDF	Parton Distribution Function
FF	Fragmentation Function
MC	Monte Carlo
PHOS	Photon Spectrometer
EMCal	Electromagnetic Calorimeter
PCM	Photon Conversion Method
QED	Quantum Electrodynamics
QFT	Quantum Field Theory
ISR	CERN Intersecting Storage Rings
RHIC	Relativistic Heavy Ion Collider
BNL	Brookhaven National Laboratory
CERN	Conseil Européen pour la Recherche Nucléaire
LEP	Large Electron-Positron Collider
LINAC 2	Linear Accelerator 2
PS BOOSTER	Proton Synchrotron Booster
PS	Proton Synchrotron
SPS	Super Proton Synchrotron
ATLAS	A Toroidal LHC ApparatuS
CMS	Compact Muon Solenoid
SM	Standard Model
PID	Particle Identification
ITS	Inner Tracking System

SPD	Silicon Pixel Detector
SDD	Silicon Drift Detector
SSD	Silicon Strip Detectors
TPC	Time Projection Chamber
TRD	Transition Radiation Detector
TOF	Time-Of-Flight
MRPC	Multi-gap Resistive-Plate Chamber
MB	Minimum Bias
ESD	Event Summary Data
AOD	Analysis Object Data
QA	Quality Assurance
RCT	Run Condition Table
DCA	Distance of Closest Approach
PCA	Point of Closest Approach
BLUE	Best Linear Unbiased Estimate
APD	Avalanche Photo-Diode

BIBLIOGRAPHY

- [1] S. Berryman. “Ancient Atomism.” In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Winter 2016. Metaphysics Research Lab, Stanford University, 2016.
- [2] K. Aamodt et al. “The ALICE experiment at the CERN LHC.” In: *JINST* 3 (2008), S08002. DOI: [10.1088/1748-0221/3/08/S08002](https://doi.org/10.1088/1748-0221/3/08/S08002).
- [3] J. Adam et al. “Direct photon production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.” In: *Phys. Lett. B* 754 (2016), pp. 235–248. DOI: [10.1016/j.physletb.2016.01.020](https://doi.org/10.1016/j.physletb.2016.01.020). arXiv: [1509.07324](https://arxiv.org/abs/1509.07324) [nucl-ex].
- [4] S. Acharya et al. “Dielectron production in proton-proton collisions at $\sqrt{s} = 7$ TeV.” In: (2018). arXiv: [1805.04391](https://arxiv.org/abs/1805.04391) [hep-ex].
- [5] V. Metag. “Medium Modifications of Mesons in Elementary Reactions and Heavy-Ion Collisions.” In: *Prog. Part. Nucl. Phys.* 61 (2008), pp. 245–252. DOI: [10.1016/j.ppnp.2007.12.041](https://doi.org/10.1016/j.ppnp.2007.12.041). arXiv: [0711.4709](https://arxiv.org/abs/0711.4709) [nucl-ex].
- [6] Y. Tsuchimoto. “In-Medium Modifications of Low-Mass Vector Mesons in PHENIX at RHIC.” In: *Nucl. Phys. A* 830 (2009), pp. 487C–490C. DOI: [10.1016/j.nuclphysa.2009.10.105](https://doi.org/10.1016/j.nuclphysa.2009.10.105). arXiv: [0907.5049](https://arxiv.org/abs/0907.5049) [hep-ex].
- [7] Wikipedia. *Standard Model* — Wikipedia, The Free Encyclopedia. <http://en.wikipedia.org/w/index.php?title=Standard%20Model&oldid=826979209>. [Online; accessed 15-March-2018]. 2018.
- [8] G. Altarelli. “The Standard model of particle physics.” In: (2005). arXiv: [hep-ph/0510281](https://arxiv.org/abs/hep-ph/0510281) [hep-ph].
- [9] C. Klein-Bösing. “Study of the Quark-Gluon Plasma with Hard and Electromagnetic Probes.” Habilitation. Westfälische Wilhelms-Universität, 2013.
- [10] S. F. Novaes. “Standard model: An Introduction.” In: *Particles and fields. Proceedings, 10th Jorge Andre Swieca Summer School, Sao Paulo, Brazil, February 6-12, 1999*. 1999, pp. 5–102. arXiv: [hep-ph/0001283](https://arxiv.org/abs/hep-ph/0001283) [hep-ph].
- [11] M. Thomson. *Modern particle physics*. New York: Cambridge University Press, 2013. ISBN: 9781107034266. URL: <http://www-spires.fnal.gov/spires/find/books/www?cl=QC793.2.T46::2013>.
- [12] P. Skands. “Introduction to QCD.” In: *Proceedings, Theoretical Advanced Study Institute in Elementary Particle Physics: Searching for New Physics at Small and Large Scales (TASI 2012): Boulder, Colorado, June 4-29, 2012*. [63(2107)]. 2013, pp. 341–420. DOI: [10.1142/9789814525220_0008](https://doi.org/10.1142/9789814525220_0008), [10.23730/CYRSP-2017-002.63](https://doi.org/10.23730/CYRSP-2017-002.63). arXiv: [1207.2389](https://arxiv.org/abs/1207.2389) [hep-ph]. URL: <https://inspirehep.net/record/1121892/files/arXiv:1207.2389.pdf>.
- [13] C. Y. Wong. *Introduction to high-energy heavy ion collisions*. 1995. ISBN: 9789810202637.
- [14] C. Patrignani et al. “Review of Particle Physics.” In: *Chin. Phys. C* 40.10 (2016), p. 100001. DOI: [10.1088/1674-1137/40/10/100001](https://doi.org/10.1088/1674-1137/40/10/100001).

- [15] D. Diakonou et al. “Inclusive high- p_T ω^0 and η' production at the ISR.” In: *Physics Letters B* 89.3 (1980), pp. 432–436. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/0370-2693\(80\)90159-8](https://doi.org/10.1016/0370-2693(80)90159-8). URL: <http://www.sciencedirect.com/science/article/pii/0370269380901598>.
- [16] A. Adare et al. “Production of ω mesons in $p + p$, d+Au, Cu+Cu, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.” In: *Phys. Rev. C* 84 (2011), p. 044902. DOI: [10.1103/PhysRevC.84.044902](https://doi.org/10.1103/PhysRevC.84.044902). arXiv: [1105.3467](https://arxiv.org/abs/1105.3467) [nucl-ex].
- [17] S. S. Adler et al. “Production of ω mesons at Large Transverse Momenta in $p + p$ and $d + Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV.” In: *Phys. Rev. C* 75 (2007), p. 051902. DOI: [10.1103/PhysRevC.75.051902](https://doi.org/10.1103/PhysRevC.75.051902). arXiv: [nuc1-ex/0611031](https://arxiv.org/abs/nuc1-ex/0611031) [nucl-ex].
- [18] “Production of $\omega(782)$ in pp collisions at $\sqrt{s} = 7$ TeV.” In: (2018). URL: <http://cds.cern.ch/record/2316785>.
- [19] Shreyasi Acharya et al. “Production of π^0 and η mesons up to high transverse momentum in pp collisions at 2.76 TeV.” In: *Eur. Phys. J. C* 77.5 (2017). [Eur. Phys. J. C 77, no. 9, 586 (2017)], p. 339. DOI: [10.1140/epjc/s10052-017-5144-7](https://doi.org/10.1140/epjc/s10052-017-5144-7), [10.1140/epjc/s10052-017-4890-x](https://doi.org/10.1140/epjc/s10052-017-4890-x). arXiv: [1702.00917](https://arxiv.org/abs/1702.00917) [hep-ex].
- [20] B. Abelev et al. “Neutral pion and η meson production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV.” In: *Phys. Lett. B* 717 (2012), pp. 162–172. DOI: [10.1016/j.physletb.2012.09.015](https://doi.org/10.1016/j.physletb.2012.09.015). arXiv: [1205.5724](https://arxiv.org/abs/1205.5724) [hep-ex].
- [21] Shreyasi Acharya et al. “ π^0 and η meson production in proton-proton collisions at $\sqrt{s} = 8$ TeV.” In: (2017). arXiv: [1708.08745](https://arxiv.org/abs/1708.08745) [hep-ex].
- [22] Shreyasi Acharya et al. “Neutral pion and η meson production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.” In: (2018). arXiv: [1801.07051](https://arxiv.org/abs/1801.07051) [nucl-ex].
- [23] Shreyasi Acharya et al. “Neutral pion and η meson production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.” In: (2018). arXiv: [1803.05490](https://arxiv.org/abs/1803.05490) [nucl-ex].
- [24] R. Aaij et al. “Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays.” In: *Phys. Rev. Lett.* 115 (2015), p. 072001. DOI: [10.1103/PhysRevLett.115.072001](https://doi.org/10.1103/PhysRevLett.115.072001). arXiv: [1507.03414](https://arxiv.org/abs/1507.03414) [hep-ex].
- [25] J. Adam et al. “Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.” In: *Phys. Lett. B* 760 (2016), pp. 720–735. DOI: [10.1016/j.physletb.2016.07.050](https://doi.org/10.1016/j.physletb.2016.07.050). arXiv: [1601.03658](https://arxiv.org/abs/1601.03658) [nucl-ex].
- [26] B. Abelev et al. “Production of $K^*(892)^0$ and $\phi(1020)$ in pp collisions at $\sqrt{s} = 7$ TeV.” In: *Eur. Phys. J. C* 72 (2012), p. 2183. DOI: [10.1140/epjc/s10052-012-2183-y](https://doi.org/10.1140/epjc/s10052-012-2183-y). arXiv: [1208.5717](https://arxiv.org/abs/1208.5717) [hep-ex].
- [27] B. Abelev et al. “Production of $\Sigma(1385)^\pm$ and $\Xi(1530)^0$ in proton-proton collisions at $\sqrt{s} = 7$ TeV.” In: *Eur. Phys. J. C* 75.1 (2015), p. 1. DOI: [10.1140/epjc/s10052-014-3191-x](https://doi.org/10.1140/epjc/s10052-014-3191-x). arXiv: [1406.3206](https://arxiv.org/abs/1406.3206) [nucl-ex].
- [28] B. Abelev et al. “Multi-strange baryon production in pp collisions at $\sqrt{s} = 7$ TeV with ALICE.” In: *Phys. Lett. B* 712 (2012), pp. 309–318. DOI: [10.1016/j.physletb.2012.05.011](https://doi.org/10.1016/j.physletb.2012.05.011). arXiv: [1204.0282](https://arxiv.org/abs/1204.0282) [nucl-ex].
- [29] G. Antchev et al. “Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s} = 7$ TeV.” In: *EPL* 101.2 (2013), p. 21004. DOI: [10.1209/0295-5075/101/21004](https://doi.org/10.1209/0295-5075/101/21004).

- [30] Betty Abelev et al. “Measurement of inelastic, single- and double-diffraction cross sections in proton–proton collisions at the LHC with ALICE.” In: *Eur. Phys. J. C* 73.6 (2013), p. 2456. DOI: [10.1140/epjc/s10052-013-2456-0](https://doi.org/10.1140/epjc/s10052-013-2456-0). arXiv: [1208.4968](https://arxiv.org/abs/1208.4968) [hep-ex].
- [31] C. Klein-Bösing. “Production of Neutral Pions and Direct Photons in Ultra-Relativistic Au + Au Collisions.” PhD. Westfälische Wilhelms-Universität Münster, 2004.
- [32] J. C. Collins, D. E. Soper, and G. F. Sterman. “Factorization of Hard Processes in QCD.” In: *Adv. Ser. Direct. High Energy Phys.* 5 (1989), pp. 1–91. DOI: [10.1142/9789814503266_0001](https://doi.org/10.1142/9789814503266_0001). arXiv: [hep-ph/0409313](https://arxiv.org/abs/hep-ph/0409313) [hep-ph].
- [33] J. C. Collins and M. J. Perry. “Superdense Matter: Neutrons or Asymptotically Free Quarks?” In: *Phys. Rev. Lett.* 34 (21 1975), pp. 1353–1356. DOI: [10.1103/PhysRevLett.34.1353](https://doi.org/10.1103/PhysRevLett.34.1353). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.34.1353>.
- [34] N. Cabibbo and G. Parisi. “Exponential Hadronic Spectrum and Quark Liberation.” In: *Phys. Lett.* 59B (1975), pp. 67–69. DOI: [10.1016/0370-2693\(75\)90158-6](https://doi.org/10.1016/0370-2693(75)90158-6).
- [35] K. Yagi, T. Hatsuda, and Y. Miake. “Quark-gluon plasma: From big bang to little bang.” In: *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* 23 (2005), pp. 1–446.
- [36] R. Pasechnik and M. Šumbera. “Phenomenological Review on Quark–Gluon Plasma: Concepts vs. Observations.” In: *Universe* 3.1 (2017), p. 7. DOI: [10.3390/universe3010007](https://doi.org/10.3390/universe3010007). arXiv: [1611.01533](https://arxiv.org/abs/1611.01533) [hep-ph].
- [37] H. Ding, F. Karsch, and S. Mukherjee. “Thermodynamics of strong-interaction matter from Lattice QCD.” In: *Int. J. Mod. Phys. E* 24.10 (2015), p. 1530007. DOI: [10.1142/S0218301315300076](https://doi.org/10.1142/S0218301315300076). arXiv: [1504.05274](https://arxiv.org/abs/1504.05274) [hep-lat].
- [38] P. Braun-Munzinger and J. Stachel. “The quest for the quark-gluon plasma.” In: *Nature* 448 (2007), pp. 302–309. DOI: [10.1038/nature06080](https://doi.org/10.1038/nature06080).
- [39] J. Adam et al. “Measurement of transverse energy at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.” In: *Phys. Rev. C* 94.3 (2016), p. 034903. DOI: [10.1103/PhysRevC.94.034903](https://doi.org/10.1103/PhysRevC.94.034903). arXiv: [1603.04775](https://arxiv.org/abs/1603.04775) [nucl-ex].
- [40] B. Abelev et al. “Neutral pion production at midrapidity in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.” In: *Eur. Phys. J. C* 74.10 (2014), p. 3108. DOI: [10.1140/epjc/s10052-014-3108-8](https://doi.org/10.1140/epjc/s10052-014-3108-8). arXiv: [1405.3794](https://arxiv.org/abs/1405.3794) [nucl-ex].
- [41] T. Peitzmann. “Direct photon production in high-energy nuclear collisions.” In: *AIP Conf. Proc.* 1701 (2016), p. 060016. DOI: [10.1063/1.4938679](https://doi.org/10.1063/1.4938679).
- [42] D. Mühlheim. “Measurement of Neutral Mesons and Direct Photons in pp Collisions with ALICE.” PhD thesis. University of Münster, 2018.
- [43] L. Evans and P. Bryant. “LHC Machine.” In: *JINST* 3 (2008), So8001. DOI: [10.1088/1748-0221/3/08/S08001](https://doi.org/10.1088/1748-0221/3/08/S08001).
- [44] E. Mobs. “The CERN accelerator complex. Complexe des accélérateurs du CERN.” In: (2016). General Photo. URL: <http://cds.cern.ch/record/2197559>.
- [45] G. Aad et al. “The ATLAS Experiment at the CERN Large Hadron Collider.” In: *JINST* 3 (2008), So8003. DOI: [10.1088/1748-0221/3/08/S08003](https://doi.org/10.1088/1748-0221/3/08/S08003).

- [46] S. Chatrchyan et al. "The CMS Experiment at the CERN LHC." In: *JINST* 3 (2008), So8004. DOI: [10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).
- [47] G. Aad et al. "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC." In: *Phys. Lett. B* 716 (2012), pp. 1–29. DOI: [10.1016/j.physletb.2012.08.020](https://doi.org/10.1016/j.physletb.2012.08.020). arXiv: [1207.7214 \[hep-ex\]](https://arxiv.org/abs/1207.7214).
- [48] S. Chatrchyan et al. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC." In: *Phys. Lett. B* 716 (2012), pp. 30–61. DOI: [10.1016/j.physletb.2012.08.021](https://doi.org/10.1016/j.physletb.2012.08.021). arXiv: [1207.7235 \[hep-ex\]](https://arxiv.org/abs/1207.7235).
- [49] T. Sirunyan et al. "Observation of $t\bar{t}H$ Production." In: *Phys. Rev. Lett.* 120 (23 2018), p. 231801. DOI: [10.1103/PhysRevLett.120.231801](https://doi.org/10.1103/PhysRevLett.120.231801). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.120.231801>.
- [50] A. Augusto Alves Jr. et al. "The LHCb Detector at the LHC." In: *JINST* 3 (2008), So8005. DOI: [10.1088/1748-0221/3/08/S08005](https://doi.org/10.1088/1748-0221/3/08/S08005).
- [51] K. Aamodt et al. "The ALICE experiment at the CERN LHC." In: *JINST* 3 (2008), So8002. DOI: [10.1088/1748-0221/3/08/S08002](https://doi.org/10.1088/1748-0221/3/08/S08002).
- [52] P. Cortese et al. "ALICE: Physics performance report, volume I." In: *J. Phys. G* 30 (2004). Ed. by F Carminati, P Foka, P Giubellino, Andreas Morsch, G Paic, Jean Pierre Charles Revol, K Safarik, Y Schutz, and Urs Achim Wiedemann, pp. 1517–1763. DOI: [10.1088/0954-3899/30/11/001](https://doi.org/10.1088/0954-3899/30/11/001).
- [53] J. Thaeder. *3D ALICE Schematic - with Description*. [accessed July 11, 2018]. URL: <https://aliceinfo.cern.ch/Figure/node/3400>.
- [54] G. Dellacasa et al. "ALICE technical design report of the Inner Tracking System (ITS)." In: (1999).
- [55] G. Dellacasa et al. "ALICE: Technical design report of the Time Projection Chamber." In: (2000).
- [56] C. Lippmann. "Performance of the ALICE Time Projection Chamber." In: *Physics Procedia* 37 (2012). Proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (TIPP 2011), pp. 434 –441. ISSN: 1875-3892. DOI: <https://doi.org/10.1016/j.phpro.2012.02.390>. URL: <http://www.sciencedirect.com/science/article/pii/S187538921201721X>.
- [57] J. Alme et al. "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events." In: *Nucl. Instrum. Meth. A* 622 (2010), pp. 316–367. DOI: [10.1016/j.nima.2010.04.042](https://doi.org/10.1016/j.nima.2010.04.042). arXiv: [1001.1950 \[physics.ins-det\]](https://arxiv.org/abs/1001.1950).
- [58] P. Cortese. "ALICE: Technical design report of the Transition Radiation Detector." In: (2001).
- [59] G. Dellacasa et al. "ALICE technical design report of the time-of-flight system (TOF)." In: (2000).
- [60] G. Dellacasa et al. "ALICE technical design report of the photon spectrometer (PHOS)." In: (1999).
- [61] B. Abelev et al. "Performance of the ALICE Experiment at the CERN LHC." In: *Int. J. Mod. Phys. A* 29 (2014), p. 1430044. DOI: [10.1142/S0217751X14300440](https://doi.org/10.1142/S0217751X14300440). arXiv: [1402.4476 \[nucl-ex\]](https://arxiv.org/abs/1402.4476).

- [62] P. Cortese et al. “ALICE electromagnetic calorimeter technical design report.” In: (2008).
- [63] B. Abelev et al. “Measurement of electrons from semileptonic heavy-flavour hadron decays in pp collisions at $\sqrt{s} = 7\text{TeV}$.” In: *Phys. Rev. D* 86 (2012), p. 112007. DOI: [10.1103/PhysRevD.86.112007](https://doi.org/10.1103/PhysRevD.86.112007). arXiv: [1205.5423 \[hep-ex\]](https://arxiv.org/abs/1205.5423).
- [64] U. Abeysekara et al. “ALICE EMCal Physics Performance Report.” In: (2010). arXiv: [1008.0413 \[physics.ins-det\]](https://arxiv.org/abs/1008.0413).
- [65] P Cortese et al. “ALICE technical design report on forward detectors: FMD, To and Vo.” In: (2004).
- [66] E. Abbas et al. “Performance of the ALICE VZERO system.” In: *JINST* 8 (2013), P10016. DOI: [10.1088/1748-0221/8/10/P10016](https://doi.org/10.1088/1748-0221/8/10/P10016). arXiv: [1306.3130 \[nucl-ex\]](https://arxiv.org/abs/1306.3130).
- [67] Rene Brun and Fons Rademakers. “ROOT — An object oriented data analysis framework.” In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 389.1 (1997). New Computing Techniques in Physics Research V, pp. 81–86. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X). URL: <http://www.sciencedirect.com/science/article/pii/S016890029700048X>.
- [68] *AliRoot Documentation*. URL: <http://alice-offline.web.cern.ch/AliRoot/Manual.html>.
- [69] C. Eck et al. *LHC computing Grid: Technical Design Report. Version 1.06* (20 Jun 2005). Technical Design Report LCG. Geneva: CERN, 2005. URL: <http://cds.cern.ch/record/840543>.
- [70] *Public Webiste Worldwide Computing Grid*. URL: <http://wlcg-public.web.cern.ch>.
- [71] C. W. Fabjan et al. “ALICE: Physics performance report, volume II.” In: *J. Phys. G* 32 (2006). Ed. by B. Alessandro, F. Antinori, J. A. Belikov, C. Blume, A. Dainese, P. Foka, P. Giubellino, B. Hippolyte, C. Kuhn, G. Martínez, et al., pp. 1295–2040. DOI: [10.1088/0954-3899/32/10/001](https://doi.org/10.1088/0954-3899/32/10/001).
- [72] R. Fruhwirth. “Application of Kalman filtering to track and vertex fitting.” In: *Nucl. Instrum. Meth. A* 262 (1987), pp. 444–450. DOI: [10.1016/0168-9002\(87\)90887-4](https://doi.org/10.1016/0168-9002(87)90887-4).
- [73] F. Bock. “Measurement of Direct Photons and Neutral Mesons in Small Collisions Systems with the ALICE Experiment at the LHC.” PhD thesis. University of Heidelberg, 2017.
- [74] L. Valencia Palomo. “The ALICE experiment upgrades for LHC Run 3 and beyond: contributions from mexican groups.” In: *Journal of Physics: Conference Series* 912.1 (2017), p. 012023. URL: <http://stacks.iop.org/1742-6596/912/i=1/a=012023>.
- [75] T. Sjostrand, S. Mrenna, and P. Skands. “PYTHIA 6.4 Physics and Manual.” In: *JHEP* 05 (2006), p. 026. DOI: [10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026). arXiv: [hep-ph/0603175 \[hep-ph\]](https://arxiv.org/abs/hep-ph/0603175).
- [76] R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zancarini. *GEANT 3: user’s guide Geant 3.10, Geant 3.11; rev. version*. Geneva: CERN, 1987. URL: <https://cds.cern.ch/record/1119728>.

- [77] S. van der Meer. "Calibration of the Effective Beam Height in the ISR." In: (1968).
- [78] T. C. Awes, F. E. Obenshain, F. Plasil, S. Saini, S. P. Sorensen, and G. R. Young. "A Simple method of shower localization and identification in laterally segmented calorimeters." In: *Nucl. Instrum. Meth.* A311 (1992), pp. 130–138. DOI: [10.1016/0168-9002\(92\)90858-2](https://doi.org/10.1016/0168-9002(92)90858-2).
- [79] J. Podolanski and R. Armenteros. "Analysis of V-events." In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 45.360 (1954), pp. 13–30. ISSN: 1941-5982. DOI: [10.1080/14786440108520416](https://doi.org/10.1080/14786440108520416). URL: <http://www.tandfonline.com/doi/abs/10.1080/14786440108520416>.
- [80] F. Bock. "Neutral Pion and Eta Meson Production in pp and Pb-Pb Collisions at the LHC with the ALICE Detector." master thesis. University of Heidelberg, 2012.
- [81] G. I. Kopylov. "Like particle correlations as a tool to study the multiple production mechanism." In: *Physics Letters B* 50.4 (1974), pp. 472–474. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/0370-2693\(74\)90263-9](https://doi.org/10.1016/0370-2693(74)90263-9). URL: <http://www.sciencedirect.com/science/article/pii/0370269374902639>.
- [82] T. Matulewicz et al. "Response of BaF₂ detectors to photons of 3–50 MeV energy." In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 289.1 (1990), pp. 194–204. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/0168-9002\(90\)90259-9](https://doi.org/10.1016/0168-9002(90)90259-9). URL: <http://www.sciencedirect.com/science/article/pii/0168900290902599>.
- [83] J.R. Taylor. *An Introduction to Error Analysis*. Sausalito, California: University Science Books, 1997.
- [84] R. Barlow. "Systematic errors: Facts and fictions." In: *Advanced Statistical Techniques in Particle Physics. Proceedings, Conference, Durham, UK, March 18-22, 2002*. 2002, pp. 134–144. arXiv: [hep-ex/0207026](https://arxiv.org/abs/hep-ex/0207026) [hep-ex]. URL: <http://www.ippp.dur.ac.uk/Workshops/02/statistics/proceedings//barlow.pdf>.
- [85] L. Lyons, D. Gibaut, and P. Clifford. "How to Combine Correlated Estimates of a Single Physical Quantity." In: *Nucl. Instrum. Meth.* A270 (1988), p. 110. DOI: [10.1016/0168-9002\(88\)90018-6](https://doi.org/10.1016/0168-9002(88)90018-6).
- [86] A. Valassi. "Combining correlated measurements of several different physical quantities." In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 500.1 (2003). NIMA Vol 500, pp. 391–405. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/S0168-9002\(03\)00329-2](https://doi.org/10.1016/S0168-9002(03)00329-2). URL: <http://www.sciencedirect.com/science/article/pii/S0168900203003292>.
- [87] A. Valassi and R. Chierici. "Information and treatment of unknown correlations in the combination of measurements using the BLUE method." In: *Eur. Phys. J.* C74 (2014), p. 2717. DOI: [10.1140/epjc/s10052-014-2717-6](https://doi.org/10.1140/epjc/s10052-014-2717-6). arXiv: [1307.4003](https://arxiv.org/abs/1307.4003) [physics.data-an].

- [88] G.D. Lafferty and T.R. Wyatt. "Where to stick your data points: The treatment of measurements within wide bins." In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 355.2 (1995), pp. 541–547. ISSN: 0168-9002. DOI: [https://doi.org/10.1016/0168-9002\(94\)01112-5](https://doi.org/10.1016/0168-9002(94)01112-5). URL: <http://www.sciencedirect.com/science/article/pii/0168900294011125>.
- [89] C. Tsallis. "Possible Generalization of Boltzmann-Gibbs Statistics." In: *J. Statist. Phys.* 52 (1988), pp. 479–487. DOI: [10.1007/BF01016429](https://doi.org/10.1007/BF01016429).
- [90] P. Skands, S. Carrazza, and J. Rojo. "Tuning PYTHIA 8.1: the Monash 2013 Tune." In: *Eur. Phys. J. C* 74.8 (2014), p. 3024. DOI: [10.1140/epjc/s10052-014-3024-y](https://doi.org/10.1140/epjc/s10052-014-3024-y). arXiv: [1404.5630](https://arxiv.org/abs/1404.5630) [hep-ph].
- [91] L. Altenkämper, F. Bock, C. Loizides, and N. Schmidt. "Applicability of transverse mass scaling in hadronic collisions at energies available at the CERN Large Hadron Collider." In: *Phys. Rev. C* 96.6 (2017), p. 064907. DOI: [10.1103/PhysRevC.96.064907](https://doi.org/10.1103/PhysRevC.96.064907). arXiv: [1710.01933](https://arxiv.org/abs/1710.01933) [hep-ph].
- [92] B. Alper et al. "The Production of Charged Particles with High Transverse Momentum in Proton-Proton Collisions at the CERN ISR." In: *Nucl. Phys.* B87 (1975), p. 19. DOI: [10.1016/0550-3213\(75\)90248-5](https://doi.org/10.1016/0550-3213(75)90248-5).
- [93] M. Bourquin and J. M. Gaillard. "A Simple Phenomenological Description of Hadron Production." In: *Nucl. Phys.* B114 (1976), pp. 334–364. DOI: [10.1016/0550-3213\(76\)90592-7](https://doi.org/10.1016/0550-3213(76)90592-7).
- [94] A. Adare et al. "Measurement of neutral mesons in p+p collisions at $\sqrt{s}=200$ GeV and scaling properties of hadron production." In: *Phys. Rev. D* 83 (2011), p. 052004. DOI: [10.1103/PhysRevD.83.052004](https://doi.org/10.1103/PhysRevD.83.052004). arXiv: [1005.3674](https://arxiv.org/abs/1005.3674) [hep-ex].
- [95] C. Kourkoumelis et al. "Inclusive eta production at high p_T at the ISR." In: *Phys. Lett. B* 84.CERN-EP-79-30. 2 (1979), 277–280. 12 p. URL: <https://cds.cern.ch/record/133179>.
- [96] S. S. Adler et al. "High transverse momentum η meson production in p^+p , d^+ Au and Au+Au collisions at $S(NN)^{(1/2)} = 200$ -GeV." In: *Phys. Rev. C* 75 (2007), p. 024909. DOI: [10.1103/PhysRevC.75.024909](https://doi.org/10.1103/PhysRevC.75.024909). arXiv: [nuc1-ex/0611006](https://arxiv.org/abs/nuc1-ex/0611006) [nucl-ex].

DECLARATION

Hiermit versichere ich, dass die vorliegende Arbeit über *Measurement of ω and η mesons via their three pion decay with ALICE in pp collisions at $\sqrt{s} = 7$ TeV* selbstständig verfasst worden ist, dass keine anderen Quellen und Hilfsmittel als die angegebenen benutzt worden sind und dass die Stellen der Arbeit, die anderen Werken – auch elektronischen Medien – dem Wortlaut oder Sinn nach entnommenen wurden, auf jeden Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht worden sind.

Münster, September 2018

Florian Jonas

Ich erkläre mich mit einem Abgleich der Arbeit mit anderen Texten zwecks Auffindung von Übereinstimmungen sowie mit einer zu diesem Zweck vorzunehmenden Speicherung der Arbeit in eine Datenbank einverstanden.

Münster, September 2018

Florian Jonas

COLOPHON

This document was typeset using the typographical look-and-feel classicthesis developed by André Miede and Ivo Pletikosić. The style was inspired by Robert Bringhurst's seminal book on typography "*The Elements of Typographic Style*". classicthesis is available for both L^AT_EX and L^yX:

<https://bitbucket.org/amiede/classicthesis/>