# Track and vertex reconstruction in the BGO-OD experiment using the central MWPC 

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I hereby declare that this thesis was formulated by myself and that no sources or tools other than those cited were used.

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## Introduction

In the last century particle physics was able to contribute significantly to our understanding on the structure of matter surrounding us. The resarches performed in scattering experiments lead to the development of the standard model, which is a huge success and reinforced once again a few years ago by the discovery of the higgs boson. By this discovery the validity of the mechanism, used to assign the elementary particles a non-vanishing rest mass, was proven.

In the standard model matter is composed of leptons and quarks, which can interact with each other. Quarks and leptons are particles called fermions with spin $\frac{1}{2}$. Generally the interactions are mediated by the gauge bosons with integer spins (e.g.. s=1). Each boson couples to a charges of the particles: For example the photon couples to the electric charge. The strong interaction described by $\mathrm{QCD}^{1}$ binds the quarks inside the nucleon (proton/neutron). Furthermore it also plays a major part in the generation of mass and is therefore an important research topic. Particles which can interact strongly carry a quantum number, the colour charge with possible values red, green, blue and the corresponding anti colours. The terminology is chosen such that in analogy to visible colour, the charges can mix to colour neutral (white) objects called hadrons, referring to the confinement observed in QCD. Hadrons with integer spin, composed of antiquark-quark pairs, are called mesons, whereas hadrons with half integer spin, composed of three quarks, are called baryons. Confinement is a consequence of the colour charged gluon, which can couple to other gluons. The gluonic field is strongly localized in a flux tube between the quarks. By trying to split two colour bound quarks, the energy between the quarks exceeds the threshold to create a quark-antiquark pair, resulting again in two colour neutral objects. In this way, in nature, only colour neutral objects can be observed.
As composed objects, hadrons can be excited by introducing energy, and subsequently they decay via the strong interaction under the emission of mesons. Therefore, to access information on the structure of nucleons and strong interaction, the study of meson production off the nucleon, as it is performed at the BGO-OD-experiment (sec.3.2), is very well suited. In photo-production experiments, as performed at the BGO-OD experiment, the target is probed by a real photon beam. The massless photon is used to introduce energy into the probed system without disturbing the system by large momentum transfers.
The BGO-OD-experiment is specifically designed to measure low momentum transfer processes, where the meson is emitted in the very forward direction. The meson can then be measured by the forward spectrometer 3.2.4 and the excited baryons or the hyperons from associated production decay in the central detectors (sec. 3.2.2) into multi-particle final states. As such it is ideally suited for the investigation of associated strangeness production and potential (vector-)meson baryon interactions involving very lightly bound hadronic molecules of baryons and mesons,

[^0]which is discussed in more detail in section (sec. 2).
An important part of the BGO-OD-setup is the newly commissioned MWPC ${ }^{2}$, which allows the tracking of charged particles close to the point where the photons interact with the nucleons and the final state particles are produced. This detector is crucial to the reconstruction of interaction and decay vertices. As the momentum reconstruction in the central region of the experiment relies on the angular resolution of the detectors, it will also profit from the improved resolution by the new detector. This is particularly important for associated strangeness photoproduction reactions, such as the intended $K_{S}^{0}$ cross section measurements on the proton and on the neutron, the reconstruction of the detached decay vertex is essential for background reduction. In this thesis a tracking procedure and vertex reconstruction was developed.
The first part (chapters 2 to 4 ) of this thesis introduces the investigation of hadronic molecular states in the strangeness sector at the BGO-OD. In chapter 2 this research is motivated by examples from the charmed sector and observations in the strangeness sector. The detector setup available for measurements of photo-production is presented in chapter 3 and in chapter 4 limited studies on the reconstruction of strange particles using the existing setup from 2016 are discussed.
In order to improve the reconstruction of reactions including strange particles in the second part of this thesis (chapter 5) track and vertex reconstruction procedures developed for the newly commissioned central MWPC are presented. The final part (chapter 6) presents some preliminary results from the analysis of data taken in April/May 2017.

[^1]
## Motivation for Associated Strangeness Production at the BGO-OD Experiment

As a consequence of confinement due to the strong interaction mentioned in the introduction, quarks, in nature, can only be observed in color-neutral objects composed of multiple quarks, called hadrons. These massive objects posses masses from about hundred MeV , up to some GeV . Considering hadrons composed out of light up and down quarks, like the nucleons or pions, only a negligible part of the hadrons mass originates from the rest mass of the constituent quarks. Most of the energy or mass of the hadron is present in the gluonic-field and sea-quarks generated by the color-interaction between the quarks. Therefore, to understand the generation of mass in matter, it is essential to study the dynamics of the colour interaction inside the hadrons.
Important tools to access information on the structure of hadrons are the investigation of the hadron excitation spectrum and the associated production of particles. In order to perform these investigations, scattering experiments using electron beams induce excitations by transferring energy via virtual photons to the target particle. Similarly in photo-production experiments this is accomplished by the use of real photons.
These experiments, as well as hadron scattering experiments, led to the discovery of numerous new states with different constituent quarks than the initial particle. Depending on the spin and parity these states can be grouped into multiplets as shown for the baryon ground state octet in figure 2.1(a).
To describe the structure of hadrons and their excitation spectrum, different approaches


Figure 2.1: Examples for multiplet structures [Com07]
have been formulated. LQCD ${ }^{1}$ is an approach to describe and understand the quark-gluon dynamics using calculations on a discretized space time lattice. Alternatively models using phenomenological potentials for confinement are quite successful in describing basic features of the excitation spectrum.

(a) Nucleon resonances predicted by the relativistic quark models of Löring et al. (green lines) and the model of Ronniger et al. (blue lines) compared to the observed resonances (red lines)

(b) $\Lambda$ resonances predicted by the relativistic quark model Löring et al. (green lines) and of Ronniger et al., (blue lines) compared to the observed resonances (red lines)

Figure 2.2: Excitation spectrum of nucleons and hyperons [RM11]
In figure 2.2 the spectrum for nucleon and $\Lambda$-hyperon resonances deduced from a relativistic

[^2]quark model from Löring et, al and Ronniger et al. is shown. Both models show reasonable agreements with the observed spectra. Nevertheless there are situations where these models fail to describe the observations. For example two important aspects can be seen in figure 2.2(a). There are a lot more states predicted than can be observed from experiments. Furthermore, the lowest lying excited state of the nucleon has the same parity as the ground state. This is in contrast to what can be expected by increasing the particles angular momentum $(=\mathrm{L})$ by one unit, as a fermions parity is given by: $\mathcal{P}=(-1)^{L+1}$.
Alternative approaches to solve these problems, including models providing additional degrees of freedom by implementing hadronic molecular states, present feasible solutions. In fact recent experimental observations in the charmed quarks sector support the existence of molecular hadronic states composed of two mesons or a baryon and a meson.

### 2.1 Hadronic molecular states and vector meson-baryon interaction

Experimental indications for molecular hadronic states have recently been seen in the hidden charm sector. The charmonium (c̄ meson) excitation spectrum below the threshold for the creation of two open charmed mesons ( $\mathrm{D} \overline{\mathrm{D}}$ ) is well understood and exhibits a comparable structure as it was already observed at the positronium. Unexpected narrow resonances observed at the Belle experiment in 2003 [Cho +03$]$ and at the LHCb experiment in $2016[$ Aai +15$]$ led to speculations about them being more complicated configurations than two or three quark states.

### 2.1.1 Candidates for hadronic molecular states in the charmonium sector

The Belle experiment discovered in 2003 the $\mathrm{X}(3872)$ see figure 2.3(a), which is now confirmed by several other experiments (Belle, Babar, CMS, LHCb, D0[Cho15]). Since the mass of X(3872) is quite close to the $\mathrm{D}^{0} \overline{\mathrm{D}}^{0 *}$ threshold and its quantum numbers poorly fit the charmonium spectrum, the discovery quickly raised speculations about the $\mathrm{X}(3872)$ being a hadronic molecule of $\mathrm{D}^{0}$ and $\overline{\mathrm{D}}^{0 *}$.

(a) Invariant mass of $\pi^{+} \pi^{-} \mathrm{J} / \Psi$ from the decay of B-mesons [Cho+03]

(b) Invariant mass of $J / \Psi K^{-} p$ final state obtained from the $\Lambda^{0}{ }_{b} \rightarrow J / \Psi K^{-} p$. The combined peak of the $\mathrm{P}_{c}(4380)^{+} / \mathrm{P}_{c}(4450)^{+}$is clearly visible above the phase space (red line). [Aai +15$]$

Figure 2.3: Candidates for exotic state in the hidden charm sector
Quite closely related to the $\mathrm{X}(3872)$ state are the $\mathrm{P}_{c}(4380)^{+} / \mathrm{P}_{c}(4450)^{+}$resonances observed in $\Lambda^{0}{ }_{b} \rightarrow J / \Psi K^{-} p$ at the LHCb experiment. These resonances can be interpreted as $\Sigma_{C}{ }^{+} \overline{\mathrm{D}}^{0 *}$ $\left(\Lambda_{C}{ }^{*} \bar{D}^{+}\right)$and $\Sigma_{C}{ }^{+*} \overline{\mathrm{D}}^{0}$ molecules [Fer+]. Since these states could be obtained by replacing the quarks of one of the mesons in the $\mathrm{X}(3872)$ by a charmed baryon, and furthermore that the $\mathrm{X}(3872)$, as well as the $\mathrm{P}_{c}(4380)^{+} / \mathrm{P}_{c}(4450)^{+}$lie in the vicinity of two body thresholds, the resemblance is quite remarkable. Nevertheless, structure of the observed states as molecular or genuine four quark (tetraquark) / five quark (pentaquark) states is still under discussion.
Besides the resonances discussed above, $\mathrm{X}(4140), \mathrm{X}(4274), \mathrm{X}(4500)$ and $\mathrm{X}(4700)$ are also other potential molecular states. These discoveries motivate the search for similar states in other quark sectors, like the strangeness sector, where the $\Lambda(1405)$ exhibits a potential molecular structure.

### 2.1.2 The $\Lambda(1405)$ a potential molecular state in the strangeness sector

In the strangeness sector the $\Lambda(1405)$ is a potential candidate for an unconventional quark configuration since it cannot be explained by the classic three-quark picture [Hyo]. The most striking disagreement is apparently the mass of the $\Lambda(1405)$. By comparing the $\Lambda(1405)$ with its spin-parity partner in the non strange regime, the $\mathrm{S}_{11}(1535)$, the $\Lambda(1405)$ appears to have a too low mass. Due to the larger constituent quark mass of the strange quark ( 486 MeV [Gri08]) compared to the up and down quark constituent quark mass ( $\approx 340 \mathrm{MeV}$ [Gri08]) one would expect the state with strange quark to have a larger mass. In contrast to that expectation the $\mathrm{S}_{11}(1535)$ composed of light quarks is 135 MeV heavier than the $\Lambda(1405)$. Another peculiar feature of the $\Lambda(1405)$ are the line-shapes in the invariant mass spectrum which differs significantly for different $\Sigma \pi$ decay channel as it can be seen in figure 2.4).


Figure 2.4: Line-shapes of the $\Lambda(1405)$, measured by the CLAS experiment [MS11]

Recent LQCD ${ }^{1}$ calculations $[\mathrm{Hal}+15]$ show that by using a realistic pion mass as input parameter, the main component of the $\Lambda(1405)$ exhibits a molecular like structure as shown in figure 2.5.


Figure 2.5: LQCD-calculation showing the different composition of the $\Lambda(1405)$ of a single particle $m_{0}$ or of two particles $(\pi \Sigma)$ or $(\bar{K} N)$ as a function of the pion mass [Hal +15 ]

Another promising candidate for a baryonic molecule in the strangeness sector may be associated with the cusp like structure in $K^{0}$ photo-production off the proton observed at the $\mathrm{K}^{*}$ threshold by the CBELSA experiment in 2012 [Ewa +12 ].

[^3]
### 2.1.3 Potential unconventional state at the $\mathrm{K}^{*}$-threshold

Part of the strangeness program at the BGO-OD experiment aims at the investigation of possible molecular states, that are generated by (vector-)meson baryon interactions at the $K^{*}$ threshold. First indications for such a state came from measurements of the $\mathrm{K}_{S}^{0} \Sigma^{+}$photo-production cross section on the proton at the CBELSA-experiment[Ewa +12 ]. The experiment revealed an unexpected cusp structure in the cross section at the $\mathrm{K}^{*}$ threshold. Moreover, it was observed that the cross section developed from threshold on a significant forward peaking. This hints to

(a) t-channel production of meson (m) associated with a baryon (B)

(b) s-channel production of meson (m) via an excited state $\left(\mathrm{N}^{*}\right)$ off a nucleon $(\mathrm{N})$, decay into a baryon (B)

Figure 2.6: Feynman like graphs illustrating t-channel and s-channel production of mesons
a t-channel (figure: 2.6(a)) production mechanism in which the photon couples directly to a virtual meson in the vicinity of the nucleon and an on-shell meson is produced taking over most of the photon's momentum. In contrast to s-channel (figure: 2.6(b)) production where the whole system takes over the momentum creating an excited state and, in the subsequent decay, the meson is emitted isotropically in the centre of mass frame.

As the incoming photon couples to the electric charge or magnetic momentum of particles, and the neutral Kaon in its ground state $K^{0}$ has neither, one would expect mainly s-channel contribution where the photon couples to the charge of the proton. The significant t -channel contribution which was observed, could be explained by interactions involving a $\mathrm{K}^{*}$ as pictured in figure 2.7(b).
However, to reproduce the cusp structure contributions, a dynamically generated $\mathrm{K}^{*} \Sigma / \Lambda$ states

(a) $\gamma p \rightarrow \mathrm{~K}^{0} \Sigma^{+}$cross section measured by CBELSA in comparison with different partial wave analysis $[$ Ewa +12$]$

(b) t-channel contribution
to $\mathrm{K}^{0}$ photo-production via $\mathrm{K}^{*}$

Figure 2.7: Anomaly in the $\mathrm{K}^{0}$ cross section and possible t-channel contribution via $\mathrm{K}^{*}$
at the $K^{*}$ threshold was suggested. Below the threshold an off shell $K^{*}$ is created. Subsequently, the $\mathrm{K}^{*}$ re-scatters with the baryon and a $\mathrm{K}^{0}$ is emitted as pictured in figure 2.8.
Above the $\mathrm{K}^{*}$-threshold, the $\mathrm{K}^{*}$ can be created as a real particle and no longer contributes to
the $\mathrm{K}^{0}$ production.
This observations led to a model, proposed by A.Ramos and E.Oset [RO13]. In this model


Figure 2.8: Contribution to $\mathrm{K}^{0}$ via re-scattering
the vector meson-baryon interactions lead to a dynamically generated resonance in the mass region of the $\mathrm{K}^{*} \Lambda / \mathrm{K}^{*} \Sigma$ final state. The authors show, that it is possible to reproduce the observed drop off in the $\mathrm{K}^{0}$ cross section by implementing $\mathrm{K}^{*} \Lambda / \mathrm{K}^{*} \Sigma$ intermediate states. By investigating the contribution of the different possible amplitudes in the vector meson-baryon interaction, they found a remarkably interference pattern dependant on the initial nucleon. On the proton the amplitudes of $\mathrm{K}^{*+} \Lambda, \mathrm{K}^{*+} \Sigma^{0}$ and the $\mathrm{K}^{* 0} \Sigma^{+}$contribute. At the neutron only the $\mathrm{K}^{*+} \Sigma^{-}$and $\mathrm{K}^{* 0} \Lambda$ contributes, resulting in a lack of destructive interference on the neutron compared to the proton.


Figure 2.9: Cross section extracted from vector meson-baryon model


Figure 2.10: Feynman like diagram illustrating production mechanism of $\gamma \mathrm{N} \rightarrow \mathrm{K}^{0} \Sigma$ via (vector-)meson baryon interaction.
$\mathrm{V}^{\prime}=\mathrm{K}^{0 /+}, \mathrm{B}^{\prime}=\Sigma^{+/ 0}, \Lambda$ for $\mathrm{N}=\mathrm{p}$ and $\mathrm{V}^{\prime}=\mathrm{K}^{0 /+}, \mathrm{B}^{\prime}=\Sigma^{-}, \Lambda$ for $\mathrm{N}=\mathrm{n}$

A peak is predicted in the $\mathrm{K}^{0}$ photo-production cross section at the neutron in the energy range where the cusp was observed at the proton. If this prediction can be validated or falsified by measurements of the $\mathrm{K}^{0}$ cross section on the neutron, it would significantly improve our understanding of the associated dynamics. It could possibly also explain the absence of some expected nucleon excitations. If vector meson-baryon interactions exist, it would be energetically more favourable for the probed system to de-excite via such an interaction.
As discussed in this chapter there are numerous promising opportunities for investigations on baryonic molecules at the BGO-OD experiment. The next chapter will present the detector setup available to perform the necessary measurements.

## BGO-OD Experiment

Photo-production experiments are very well suited for the investigation of molecular states in the strangeness sector, as mentioned in chapter 2.1.3 and 2.1.2, as well as any research in hadron spectroscopy and meson production. In photo-production experiments real photons are used to excite a nucleon via electromagnetic interaction. Subsequently the excited state can de-excite by strong interaction via the emission of mesons. Alternatively strange quarks can be created via associated (pair-) production. Recombining with the quarks from the baryon, the strange quarks lead to the generation of strange mesons and baryons. The baryons containing strange quarks are called hyperons.
The BGO-OD experiment is a fixed target experiment, run by an international collaboration, at the ELSA ${ }^{1}$ electron accelerator facility of the Physikalisches Institut in Bonn. It aims at the investigation of mechanisms of mesons photo-production on the nucleon. To perform this investigations, the electron beam from the accelerator is converted via bremsstrahlung into a real photon beam, which impinges on the target cell filled with liquid hydrogen or deuterium. The target cell is placed inside an electromagnetic BGO-calorimeter. If a photo-production reaction takes place the produced particles, or their decay products are detected in the BGO-OD setup. The detector setup is divided into several regions corresponding to the polar angular ranges covered. There is the central region defined by the polar acceptance of the BGO-calorimeter ( $\Theta$ $\left.=(25 \text { to } 155)^{\circ}\right)$, the intermediate region $\left(\Theta=(10 \text { to } 25)^{\circ}\right)$ and forward region with the forward spectrometer at polar angles below $10^{\circ}$.
The combination of the calorimeter, covering a large solid angle, with a high resolution forward magnetic spectrometer provides unique capabilities for forward particle identification and detection of decay photons from the decay of neutral particles. Furthermore the experimental setup is equipped with a set of two cylindrical Multi Wire Proportional Chambers inside the electromagnetic calorimeter. These chambers allow the tracking of charged decay particles close to the interaction point. The high angular resolution of the MWPCs enables the reconstruction of interaction and decay vertices.
During thesis procedures for track reconstruction with MWPC are developed.

[^4]
### 3.1 The ELSA-accelerator



Figure 3.1: Overview plan of the accelerator facility

The ELSA accelerator can provide, apart from a microscopic bunch-structure, an almost continuous beam of polarized or unpolarized electrons up to an energy of 3.2 GeV .
As source for unpolarized electrons a thermic gun is used. The polarized source described in [Hil00] can be used to produce polarized electrons.
In a linear accelerator the electrons are accelerated to an energy of 20 MeV and injected in a fast ramping booster synchrotron. Inside the booster synchrotron they can be further accelerated to energies between 500 MeV and 1.2 GeV . The electron bunches, extracted from the synchrotron, are accumulated and further accelerated to energies up to 3.2 GeV inside the stretcher ring. An almost continuous electron beam is then sent to the BGO-OD or the Crystal Barrel experiment, via resonance extraction.

### 3.2 The BGO-OD-Setup

The BGO-OD setup consists of a Photon-Tagging-Apparatus (sec.:3.2.1), to generate an energy tagged photon beam and a detector setup to detect the final state particles of a reaction.
The detector setup itself consists of three subsets of detectors, which are grouped by the polar angle they cover. These subsets are the Central-Detectors (sec.: 3.2.2) surrounding the target cell, the Intermediate Detectors (sec.: 3.2.3) covering the acceptance gap between the central and the forward region and the forward region covered by the Forward-Spectrometer (sec.: 3.2.4).


Figure 3.2: Overview of the BGO-OD detector setup

### 3.2.1 The Photon-Tagging-Apparatus

In front of the experimental area a bremsstrahlung target is used to convert the incoming electron beam in a real photon beam. As radiation media several copper foils or a diamond crystal can be selected by a goniometer. The copper foils produce an unpolarized photon beam. The diamond crystal is used to generate linearly polarized photons via coherent bremsstrahlung. Circularly polarized photons can be produced via bremsstrahlung of linearly polarized electrons. The linear polarization degree of the electrons can be monitored by a Møller polarimeter [Sch13]. After the electrons interacted with the bremsstrahlung target, they enter the field of a dipole magnet and get deflected by the Lorentz force. The resulting deflection, after passing the magnetic field, depends on the momentum of the electrons. The energy of the produced photon corresponds to the energy loss of the electron during the bremsstrahlung process. Since all electrons from the accelerator have the same energy and momentum, the energy loss of the electron can be determined from the deflection in the magnetic field. To estimate the deflection, the positions of the electrons are measured after passing the magnetic field by a segmented hodoscope, the Tagger. The Tagger consists of 120 plastic scintillator bars behind the magnet. For background reduction the bars are partially overlapping, so that the passage of an electron has to be detected by (at least) two adjacent bars. The Tagger covers an energy range from (10 to 90$) \%$ of the incoming beam energy $\left(\mathrm{E}_{0}\right)$ with an energy resolution of ( 0.55 to 2.1 ) \% $\mathrm{E}_{0}$ [Bel16].
To increase energy resolution in the energy range of stronger interest, where the photon beam is polarized via coherent bremsstrahlung, the tagging setup is complemented by the $A R G U S$ detector. This scintillating fibre detector with 480 channels, arranged in three layers, improves the energy resolution to ( 0.08 to 0.45 ) $\% \mathrm{E}_{0}$, inside a range of (30 to 66) \% $\mathrm{E}_{0}$ [Ale15; Rei15]. For photon flux determination the FluMo ${ }^{2}$ detector, consisting of five plastic scintillator pedals,

[^5]is installed at end of the setup [Koh16]. The FluMo is calibrated by a total absorption lead glas detector, the $\mathrm{GIM}^{3}$.
After passing a collimator, the photon beam enters the central part of the setup, where the target cell is placed, surrounded by multiple detectors.

### 3.2.2 The Central-Detectors



Figure 3.3: Detectors surrounding the target in the central region with spectrum of two $\gamma \mathrm{s}$ in the BGO-calorimeter

In the central region of the setup, the energy tagged photon beam impinges on a target cell filled with liquid hydrogen or deuterium. Particles may be produced over the whole angular range, therefore it is important to cover a large solid angle with detectors. The main detector of the central region is an electromagnetic calorimeter, the BGO-calorimeter, covering a polar angle from $\Theta=(25 \text { to } 155)^{\circ}$ and the full azimuthal angle $\phi$.
The main purpose of this detector is the reconstruction of particles decaying into photons, like the $\pi_{0}$ or the $\eta$, as shown in the plot (fig.: 3.3(b)), where the invariant mass reconstructed from two $\gamma$ 's against the missing mass is shown.
The calorimeter consists of 480 bismuth germanate $\left(\mathrm{Bi}_{4} \mathrm{Ge}_{3} \mathrm{O}_{12}\right.$ : BGO $)$ crystals, which are segmented into 15 crowns in $\Theta$ and 32 elements in $\phi$. This detector is very well suited for the detection of photons, since incident photons develop an electromagnetic shower inside the crystals. Consequently they deposit all their energy inside the 21 radiation lengths of the crystals. Usually the lateral expansion of the shower produced by a photon is not contained in one crystal. In such cases the angular resolution can be improved by clustering algorithms, using the deposited energy in the neighbouring crystals to calculate an averaged cluster position.

Charged particles can be detected by the BGO, but since they do not produce an electromagnetic shower they mainly deposit energy in one single crystal. Therefore the angular resolution

[^6]is limited by the granularity of the detector to $11.25^{\circ}$ in $\phi$ and (6 to 10$)^{\circ}$ in $\Theta$. The energy measurement for charged particles in the BGO is also only valid for particles with low momentum, which can be stopped inside the detector. Particles with high enough momenta eventually punch through the crystal, and deposit only a fraction of their energy in the detector. Protons detected in the central region generally do not have enough momentum to punch through the crystals therefore their energy will be measured reasonably well.
Neutral particles can be distinguished from charged particles by a plastic scintillator barrel placed between the target and the calorimeter. This barrel also allows for $\frac{d E}{d x}$ energy deposition measurements, which can be used, by combining it with the total energy deposited in the BGO, to separate minimum ionizing particles from slow protons.
To improve the angular resolution for charged particles and in order to reconstruct tracks of charged particles close to the target cell, a set of two MWPCs is placed between target cell and BGO. This detector is discussed in more detail in chapter 5 .

### 3.2.3 The Intermediate detectors

The acceptance gap in polar angles between the BGO- calorimeter (25 to 155$)^{\circ}$ and the forward spectrometer $\left(\Theta \lesssim 10^{\circ}\right)$ is at present covered by the $\operatorname{SciRi}^{4}$ [Sch15] detector, composed of 96 segments of plastic scintillator in the same angular division as the BGO.
The original detector foreseen for this region, a MRPC ${ }^{5}$ is still under commissioning and will be providing an angular resolution better than $2^{\circ}$ in $\Theta$ and $\phi$ and time resolution up to 60 ps .

### 3.2.4 The Forward-Spectrometer



Figure 3.4: Forward spectrometer for particle identification
The key feature of the BGO-OD experiment is the forward spectrometer, which allows momentum measurement and particle identification, for charged particles emitted with polar angles smaller than $8^{\circ}$ vertically and $12^{\circ}$ [Fre17] horizontally to the beam axis.
The track is measured between the target and the magnet by two scintillating fibre detectors. The fibre detector closest to the target is the MOMO detector, which consists of 6 modules of

[^7]112 fibres. Directly in front of the magnet the SciFi2 detector[Bös16], with 288 horizontal and 352 vertical fibres, is mounted. After passing the field of the open dipole magnet, a series of eight double layered drift chambers measure the tracks deflected by the magnetic field. By comparing the track before and after the magnet, the deflection angle of the track can be calculated, and for a known field strength of the magnet the momentum of the particles can be determined.
In order to perform particle identification the momentum information is combined with the particle velocity $\beta$, obtained by time of flight measurement. Therefore three ToF ${ }^{6}$-walls with a time resolution up to 250 ps [Bau14] are installed about 6 m downstream from the target. In figure 3.4(b) the momentum $\beta$ correlation is shown for charged particles in the forward spectrometer in coincidence with $\pi_{0}$ detected in the BGO-calorimeter. The curves can be associated with pions, electrons or positrons at the top, charged kaons in the middle and protons in the lower band.

[^8]
# CHAPTER 

# Initial studies on $\Sigma^{0} K^{0}$ and $\Sigma^{+} K^{0}$ reconstruction 

As discussed in chapter 2, measurements of the cross section of neutral kaon production on the proton and the neutron are crucial to validate or reject the hypothesis of the generation of molecular states via vector meson-baryon interaction below the $\mathrm{K}^{*}$ threshold.
The BGO-OD experiment has already taken photo-production data on the proton target and measurements on the neutron, in a deuterium target, are planned for the near future. In advance of the data taking, it is important to develop reconstruction procedures, and to verify that the existing detector setup meets the requirements needed to identify the desired final state.
In the first part of this chapter, a reconstruction procedure of $\Sigma^{0} \mathrm{~K}^{0}$ photo-production on the neutron is presented using simulation. After a quick discussion of the reconstruction efficiency, the obtained signal is compared with two main expected background contributions: The production of uncorrelated pions and the $\rho^{0}$ photo-production on the proton of the deuterium. To get an idea about the background contamination to be expected in real data, the second part of this chapter illustrates the results of the comparable analysis performed for $\Sigma^{+} \mathrm{K}^{0}$ photo-production on the existing proton data.

## $4.1 \Sigma^{0} \mathrm{~K}^{0}$ reconstruction using simulation

In order to determine the feasibility of the measurement of the cross-section of $\mathrm{K}^{0}$ photoproduction on the neutron at BGO-OD simulation studies have been performed with Geant4 [Ago +03$]$. These studies are focused on the reconstruction of $\Sigma^{0} \mathrm{~K}_{s}^{0}$ final states, since final states involving a $K_{L}^{0}$ cannot be observed by the setup. The $\Sigma^{0}$ decays almost exclusively to $\gamma \Lambda$. The $\Lambda$ mainly decays in $\pi^{-} p$, with a branching ratio of $60 \%$. The dominating decay channel for the $\mathrm{K}_{S}^{0}$ is into two charged pions ( $\mathrm{K}_{S}^{0} \rightarrow \pi^{+} \pi^{-}$), with a branching ratio of $66 \%$. Considering the branching ratios of the $\mathrm{K}_{s}{ }^{0}$ and the $\Lambda$, for the reconstruction of the $\Sigma^{0} \mathrm{~K}^{0}$ the most populated decay channel is $\Sigma^{0} \mathrm{~K}^{0} \rightarrow \gamma \Lambda \mathrm{~K}_{s}{ }^{0} \rightarrow \gamma\left(p \pi^{-}\right)\left(\pi^{+} \pi^{-}\right)$with a total branching ratio of $20 \%$.
The reconstruction was performed within the ExPlORA ${ }^{1}$ [Sch +11 ] framework, by using existing plugins for event selection and kinematic fitting.
The first step in the analysis is to select events, where exactly five particles have been detected in the full acceptance region of the BGO-OD setup. Each of these particles can be interpreted as one of the final state particles, therefore each track or hit gets assigned to a particle hypothesis. Finally all possible permutations of particle hypothesis are created. Each particle hypothesis is assigned an individual probability of being correct. The probability for one hypothesis is

[^9]determined by measured properties of the corresponding track or hit. These properties are called probability items in the analysis. An example for such an item is the central chargedness for the separation of charged and neutral particles, based on signals from the plastic scintillator barrel. Photons, as neutral particles, are generally detected only in the BGO and not in the scintillator barrel. This can be interpreted as $94 \%$ probability in favour of the hypothesis the particle being a photon. The remaining $6 \%$ represents the possibility of misidentification of a charged particle as a neutral particle due to inefficiencies in the barrel, which are determined in [Jud16]. The other way around, a photon may also be detected as a charged particle by producing an electron positron pair in the barrel.
In this way a probability based analysis takes into consideration multiple effects, when applying cuts on the individual probability items of the particle candidates to select the correct particle hypothesises. A more detailed description on probability based analysis and the probability items can be found in [Fre17].
As already discussed, applying a cut on central chargedness allows to discriminate between charged particles, e.g. charged pions, and neutral particles, e.g. photons, in the region covered by the plastic scintillator barrel. Due to the electromagnetic shower of the photon the clusters of photons in the BGO usually extend to several crystals, whereas the cluster produced by pions or protons usually contain just one or few elements. This is used by probability item BGO cluster size to select the hypothesises compatible with the observed signal from the BGO. In the analysis the cut on central chargedness and BGO cluster size are applied $3 \sigma$ around the most probable value for each particle hypothesis.
The SciRi detector in the intermediate region does not provide any energy information. Furthermore the energy measured for charged particles, especially for minimum ionizing pions, in the BGO can be incorrect, since the particles may not deposit all of their energy inside the detector, as they are not stopped inside the scintillator crystals. Therefore momentum conservation is used to calculate the momenta from the measured angular distribution for charged particles in the central and intermediate region. Given the momenta are conserved in three spacial dimensions, the unknown momenta of three particles can be calculated. As the final state of the reaction consists of four charged particles a further restriction is needed.
In order to reduce the number of unknown kinematical variables, the proton is required to be detected in the forward detector region, including the $\mathrm{ToF}^{2}$ walls, so that both the momentum and its energy are measured. As the proton has to be seen by the ToF detector, a cut on events where the measured time of flight is compatible with proton hypothesis is applied. Compatible means, that the measured time of flight is within $3 \sigma$ around the expected value for a particle of the proton mass with the measured momentum.
By measuring the proton in forward spectrometer and the decay photon of the $\Sigma^{0}$ in the calorimeter, the number of particles with unknown momenta reduces to the three pions. Neglecting contributions from the fermi momentum of the deuteron and the spectator proton, the initial state is given by the mass of the neutron and the energy of incoming photon, measured by the photon tagging apparatus (chapter 3.2.1). In this way the momenta of the pions can be calculated, after fixing their nominal masses, by momentum conservation from the direction of their tracks as explained in [Sch15].
As seen in figure 4.1(a) no bump structure, which is clearly related to the $\mathrm{K}^{0} \Sigma^{0}$ is visible after the recalculation of the momenta. Aside from false combination of track particle hypothesises, the main reason for this is the limited detector resolution for charged particles in the central region. The recalculation of the particles momenta using momentum conservation as mentioned above, is highly dependent on the angular resolution of the detector used to measure the track of the particle.

[^10]
(a) Reconstructed $\mathrm{K}^{0}$ mass vs $\Sigma^{0}$ mass after recalculating the momenta of the detected particles from their angles

(b) Reconstructed $\mathrm{K}^{0}$ mass vs $\Sigma^{0}$ mass after kinematic fitting

Figure 4.1: Inv. Mass of $\left(\gamma \pi^{-} p\right)$ vs. inv. mass of the $\left(\pi^{-} \pi^{+}\right)$after recalculating the particles momenta and after kinematical fit


Figure 4.2: Reconstructed $\gamma n \rightarrow \mathrm{~K}^{0} \Sigma^{0} \rightarrow\left(\gamma \pi^{-} p\right)\left(\pi^{-} \pi^{+}\right)$event after cut on best confidence in kinematic fit for each event

In order to overcome the eventual limitations in resolution of the experimental setup, a kinematic fitting procedure is performed. The kinematic fit recalculates the angles and momenta of charged particles within the detector resolutions, under the constraints that energy and momentum conservations are fulfilled. The masses of the particles, including the one of the $\Lambda$, are fixed to their nominal value, as listed in the particle data booklet [Pat+16].
The correlation between the $\Sigma^{0}$ and the $\mathrm{K}_{S}^{0}$ mass after the kinematic fit is shown in figure 4.1(b). It should be noted, that what is visible is the result of fitting the masses of the $\left(\pi^{+} \pi^{-}\right)$system and $\left(\gamma \pi^{-} p\right)$ system to the $\mathrm{K}^{0}$ and the $\Sigma^{0}$ mass, whereas the $\left(\gamma \pi^{-} p\right)$ system is already constrained by fixing the mass of the $\left(\pi^{-} p\right)$ to the $\Lambda$ mass. Furthermore there are still multiple combinations per event inside the plot.

Selecting the reaction candidate with the highest confidence level from the kinematic fit for each event leaves the $\Sigma^{0}-\mathrm{K}_{s}^{0}$ mass correlations shown in figure 4.2. The projection of the $\left(\pi^{-} \pi^{+}\right)$ invariant mass in the region a of $\Sigma^{0}$ mass, in a range of (1152 to 1232$) \mathrm{MeV}$, shows a significant peak at 482 MeV with a width of 44 MeV . The rather large width and the shifted position with respect to the nominal value of the $\mathrm{K}^{0}$ mass $(492 \mathrm{MeV})$ are not overall unexpected. The MWPCs
were at that time not integrated in the analysis, and the tracks in the central region were created under the assumption, that they were originating from the target centre. Decay vertices of the $\mathrm{K}_{S}^{0}$ cannot be determined from these tracks. Consequently the reconstructed angles and masses depend on the displacement between the decay vertex and the centre of the target.
To obtain this result, one million $\mathrm{K}^{0} \Sigma^{0}$ events were generated, resulting in about six thousand reconstructed events and a reconstruction efficiency of $\approx 0.6 \%$. It has to be taken into account that about $50 \%$ of generated events involves a $\mathrm{K}_{L}^{0}$, which cannot be detected by the BGO-OD setup. Furthermore, by requiring the generated proton to be in the forward direction, we limit the sample to about thirty thousand events in investigated decay channel. Taking these limitations into consideration, $20 \%$ of the targeted events are reconstructed.

In real data there will be, besides the signal, a large contribution from background events, from reactions with cross sections even orders of magnitude higher then the $\mathrm{K}^{0} \Sigma^{0}$ photo-production cross section. In order to study the background contamination 5 million events of $\gamma p \rightarrow \rho^{0} p$ and of $\gamma n \rightarrow \pi^{-} \pi^{+} \pi^{-} p$ as expected background on the deuterium target are generated and processed. The $\rho^{0}$ is chosen as resonant contribution decaying in a comparable final state. In order to mimic the relative cross-section ratios, the background reactions are further scaled relative to the 1 million $\gamma n \rightarrow \Sigma^{0} \mathrm{~K}^{0}$ events. The total number of $\gamma n \rightarrow \pi^{-} \pi^{+} \pi^{-} p$ events are scaled by a factor of 10 resulting total 10 million events, the total number of $\gamma p \rightarrow \rho^{0} p$ by a factor of 40 resulting in 40 millions events. As it can be seen in figure $4.3(\mathrm{a})$ the signal of the $\mathrm{K}_{S}^{0}$ is still clearly visible above background. By scaling the uncorrelated pion contribution by a factor of 30 relative to the signal the peak corresponding to $\mathrm{K}_{s}^{0}$ mass vanishes 4.3(b).

(a) Projection of the kaon mass in the mass region of the $\Sigma^{0}$ with background of 10 mio. uncor. $\pi^{-} \pi^{+} \pi^{-} p$ and 40 mio. $\rho^{0} p$.

(b) Projection of the kaon mass in the mass region of the $\Sigma^{0}$ with background of 30 mio. uncor. $\pi^{-} \pi^{+} \pi^{-} p$ and 40 mio. $\rho^{0} p$.

Figure 4.3: Reconstructed final state for $\gamma n \rightarrow \mathrm{~K}^{0} \Sigma^{0}$ events: Signal and scaled background contributions
A distinct feature of the investigated reaction is the decay photon of the $\Sigma^{0}$. In the rest-frame of the mother particle, the energy of the photon corresponds to the 77 MeV mass difference between the $\Sigma^{0}$ and the $\Lambda$. To use this for the identification of the reaction within this thesis a feature has been implemented in the analysis framework, allowing to boost the reaction in the rest frame of any particle present in the reaction. The energy distribution of the photon in the rest-frame of the $\Sigma^{0}$ is shown in figure 4.4(a). The mass spectrum of the events, whose decay photon energy ranges between 50 MeV and 100 MeV , is shown in the plot 4.4(b).
As it can be seen in the energy-distribution of the decay photon (fig. 4.4(a)) the peak is within 2 MeV at the correct position. The entries outside of the peak in figure 4.4(a) may be associated with photons from the neutral decay channels, where one photon of the decay $\pi^{0} \rightarrow \gamma \gamma$ is misidentified as a charged particle. The cut on the decay photon energy mainly removes


Figure 4.4: Identification of the decay photon from the $\Sigma^{0}$
misidentified events where the reconstructed mass of the $\Sigma^{0}$ is far from realistic values. The effect of the cut is therefore the same as a cut on the invariant mass of the $\Sigma^{0}$ and no improvement regarding the background rejection in the mass-region of the $\Sigma^{0}$ is achieved.

### 4.2 Background studies on real data reconstructing $\Sigma^{+} \mathrm{K}^{0}$ final states

In order to get a more realistic estimation on the background situation in real data, tests with a comparable analysis of the reaction $\gamma p \rightarrow \Sigma^{+} \mathrm{K}_{s}^{0} \rightarrow \pi^{0} p \pi^{+} \pi^{-}$on proton data taken in June and October 2015 were performed.
While in the $\pi^{+} \pi^{-}$invariant mass no bump is observed that would agree with the $\mathrm{K}^{0}$ mass, a pronounced peak in the $\pi^{+} \pi^{-} \pi^{0}$ invariant mass consistent with the $\omega$ meson mass at about 800 MeV is visible in figure $4.5(\mathrm{a})$. Contributions from the $\omega$ photo-production events are not


Figure 4.5: Inv. mass reconstructed from $\pi^{+} \pi^{-}\left(\mathrm{K}^{0}\right)$ against inv. mass reconstructed from $\pi^{+} \pi^{-} \pi^{0}(\omega)$
unexpected, since the $\omega p$ and the $\Sigma^{+} \mathrm{K}_{s}^{0}$ decay into the same final state. The possibility of removing $\omega$ photo-production events by rejection events with a $\pi^{+} \pi^{-} \pi^{0}$ mass close to the $\omega$ mass is rejected in this thesis since the same cut would also reject a huge amount of $\mathrm{K}^{0} \Sigma^{+}$events. For example a cut to reject events with $\mathrm{M}_{\pi^{+} \pi^{-} \pi^{0}}=\mathrm{M}_{\omega} \pm 15 \mathrm{MeV}$, would also reject $60 \%$ of the simulated $\mathrm{K}^{0} \Sigma^{+}$events, after selecting the reactions with highest confidence level from the kinematic fit. As it can be seen in figure $4.5(\mathrm{~b})$ the signal of simulated $\mathrm{K}^{0} \Sigma^{+}$events has a large overlap with the mass of the $\omega$ meson reconstructed from the $\pi^{+} \pi^{-} \pi^{0}$ system.

It seems to be quite complicated to disentangle the $\Sigma^{+} \mathrm{K}_{s}^{0}$ from the $\omega p$ background. The most striking difference between both reactions, is the displaced decay vertex of the strange particles due to their rather long lifetime, as they have to decay via the weak interaction. For the identification of the displaced vertices a functional tracking of charged particles close to the interaction point using the MWPC is crucial. The vertex reconstruction can also help to separate the signal of the $\Sigma^{0} \mathrm{~K}_{s}^{0}$ from the background of uncorrelated pion production. Because of the importance of a correct vertex reconstruction, the main focus of this thesis is the development and implementation of the tracking algorithms of the MWPCs detector for general use at the BGO-OD experiment.

## The multi wire proportional chambers of the BGO-OD experiment

In the analysis of reactions including strange particles, it can be really difficult to disentangle the signal from background reactions with much higher cross sections. It can be very useful to be able to identify the displaced decay vertex of strange particles, which may decay a few centimetres outside the beam spot or even outside the target cell 5.1(a). To make this identification possible, the BGO-OD experiment has to be complemented with a set of two MWPCs improving the angular resolution for charged particles in the central region of the BGO-OD setup.
In fact the new detector will also improve reconstruction of non strange reactions involving charged decay particles. It will remove artefacts introduced by crystal sizes of the BGO and allows a more reliable track reconstruction in the central region. At present, without the chambers the tracks of charged particles are constructed by using the cluster position inside the BGO, under the assumption that all tracks are originating from the centre of the target. This assumption is not valid for the decay products of strange particles, but also in non strange reactions where the tracks may be originated for any point inside the 6 cm long target cell as pictured in 5.1 (b). Consequently, also in non strange reactions, the measured angles for the particles are off by an error depending on the position of the interaction vertex.
By detecting a particle in the inner and outer chamber, its absolute track can be reconstructed.


Figure 5.1: Illustration of vertices in non strange and strange reactions
The vertex of the reaction can be reconstructed either by determination of a vertex, using two tracks measured by the MWPC, or by extrapolation of the intersection of the reconstructed track and the beam axis, if only one track is measured by the chambers. The vertex illustrated in figure 5.2, determined by only one measured track is referred to from now on as pseudo vertex.


Figure 5.2: Illustration of a pseudo vertex
The momentum reconstruction in the central and intermediate region strongly relies on precise measurement of polar and azimuthal angles as discussed in chapter 4. Therefore the significant improvement on the angular resolution by the MWPC is expected to increase the quality of the recalculating momenta procedure and finally show up in a better invariant-mass distributions.

In this chapter the MWPCs of the BGO-OD experiment are presented and track and vertex reconstruction procedures are explained, beginning with a general introduction on gaseous detectors. In the second part of this chapter the chambers used in the experiment are described. The following part discusses in details how the position of a hit on the chamber can be reconstructed. An important aspect thereby is the implementation of complementary methods to compensate for eventual inefficiencies of detector components. The next step is the association of tracks, obtained from the hit in the two chambers, with other detectors namely the BGO calorimeter and the SciRi detector, and the integration in the analysis framework of the experiment. The final part of this chapter explains the vertex and pseudo vertex reconstruction and shows the expected resolution for the vertex position determined via simulation.

### 5.1 Hardware of the multi wire proportional chambers

### 5.1.1 General functional principle of gaseous detectors

Gaseous detectors, such as the MWPCs, are used to detect charged particles. Commonly they consist of anode wires inside a gas volume surrounded by either multiple cathode wires or by cathode planes. As a charged particle passes the gas volume, it deposits energy, as described by the Bethe-Bloch formula [Pov08]. This energy deposition can occur via the creation of ion-electron pairs, this process being called primary ionisation. Due to the electric field between the anode wire and the cathode, the pair drifts apart along the field lines. Since potential difference inside the detectors is rather large ( $\approx 2.5 \mathrm{kV}$ ) the ion and the electron are accelerated along their path. By the acceleration they gain enough energy to produce additional electron-ion pairs. This process is called secondary ionisation. Especially close to the anode wires, where the field strength increases proportional to $\frac{1}{r}$, the secondary electrons will be able, after a minimal drift, to create new ionisations themselves. This leads to an avalanche effect close to the wires, called gas amplification. The effect of gas amplification is localized only about $100 \mu \mathrm{~m}$ around the anode wire but amplifies the number of electrons by a factor $10^{5}$ to $10^{6}$. In addition to the avalanche effect created by collisions of electrons with the gas atoms, ultraviolet photons emitted by excited gas atoms can lead to a secondary avalanche due to the photo-effect. The amplification per unit length is quantified by material-dependant Townsend coefficients. As nearly all electrons are almost instantaneously absorbed into the anode wire, the main
contribution to the signal in the wire is generated by the induced mirror charge due to the ions created by the gas amplification drifting away from the anode.
Usually gaseous detectors are operated with a mixture of different gases, where each component of the mixture serves a special purpose. For the ionization process it is preferable to use gases which provide no excitation levels and where only ionization takes place. Therefore noble gases are most feasible as the main component of the gas mixture. In order to prevent damaging the detector by continuous discharges due to ultraviolet photons, a molecular quenching gas can be added. The molecules of the quenching gas provide additional rotation and vibration degrees of freedom for the absorption of ultraviolet photons. In this way higher amplifications can by achieved.

### 5.1.2 Cylindrical MWPC at the BGO-OD-Experiment

At the BGO-OD experiment a set of two coaxial cylindrical MWPCs, for used high resolution tracking of charged particles and vertex reconstruction, are installed inside the gap between the plastic scintillator barrel attached to the inner part of the BGO calorimeter and the target cell, as it can be seen in picture $5.3(\mathrm{a})$.
To ensure best angular coverage under the given geometrical constraints, a cylindrical geometry for the chambers is chosen. Based on experiences with comparable chambers at the Crystal Ball experiment in Mainz, the chambers were built by INFN ${ }^{1}$ Pavia with front end electronics provided by the Russian Academy of Science Moscow.

(a) Two chambers mounted inside the BGO

(b) Design of the one chamber

Figure 5.3: Pictures of the chamber

Each chamber consists of two cylindrical cathodes segmented into 4.5 mm wide copper strips helically wound around the cylinder surface. The orientation of the strip to the z-axis defined by the beam is about $+45^{\circ}$ for the inner cathodes and $-45^{\circ}$ for the outer cathode (exact numbers in table 5.1) of the chambers. This means the strips of the inner cathode are wound clockwise and the strips of the outer are wound counter clock wise from the front to the back of the chamber. In the inner chamber, after a distance of about 30 cm in z from the front of the detector, the strip has circumnavigated the cylinder surface. Given the length of the chamber of 52 cm it takes approximately 1.7 turns for the strip to cover the whole length of the inner chamber. The geometry of the chambers allows to determine the z position of a hit in the chambers by

[^11]identifying the intersection of the strips, discussed more in detail in chapter 5.2.
In the middle of the 8 mm gas gap between the two cathode surfaces, an array of equally spaced anode wires is placed parallel to the z axis. The pitch of the wire is 2 mm resulting in an expected azimuthal angular resolution $\Delta \phi \approx 2^{\circ}$.
The gas mixture flooding in the gas gap between the two cathodes of the chamber is called "magic gas". It contains $75 \%$ argon (used as ionization gas) and $24.5 \%$ methane $\left(\mathrm{CH}_{4}\right)$ (used as quencher). To ensure stable operation without damaging the chambers, an additional $0.5 \%$ freon $\left(\mathrm{CF}_{3} \mathrm{Br}\right)$ and methylal $\left(\mathrm{C}_{3} \mathrm{H}_{8} \mathrm{O}_{2}\right)$ are added. The freon absorbs secondary electrons ejected from the cathode due to photo effect. The methylal prevents the accumulation of the recombination products of methane on the surface of the cathode.
To bypass noise picked up along the readout cables and dampening of the signals, pre-amplifier boards are mounted close to the chambers. As it turned out especially the boards for the wires were very sensitive to noise and sometimes generated noise themselves. The boards needed multiple modifications to bring them into operation, which delayed the commissioning of the chambers.
The amplified signals of the wires are read out via TDC ${ }^{2}$ providing only time and no energy information. The signals of the strips are read out by SADC ${ }^{3}$, which enables the use of energy weighted clustering procedures to improve the spacial resolution of strips. The SADC samples the incoming analogue signal with a sample rate of 160 MHz [WIE] providing energy information via the baseline subtracted integral of the signal. The start of the signal is determined from the intersection of the baseline with the leading edge of the signal itself.
By using energy weighted clustering for the strips the resolution in z direction along the beam axis is expected to be about $300 \mu \mathrm{~m}$ resulting in a polar angular resolution of $\Delta \Omega \approx 1^{\circ}$.

| Parameter | Chamber | Inner Cath. | Outer Cath. | wires |
| :---: | :---: | :---: | :---: | :---: |
| \# elements | In | 48 | 56 | 160 |
|  | Out | 80 | 88 | 256 |
| radius /cm | In | 4.82 | 5.62 | 5.22 |
|  | Out | 7.95 | 8.75 | 8.35 |

Table 5.1: Structural parameters of the chambers

[^12]
### 5.2 MWPC-Track Reconstruction

To perform the track reconstruction for the MWPCs two, major tasks have to be accomplished. First the position of the hit in the chambers has to be determined from the signals of the strips and wires. Then the tracks obtained from the hits in the two chambers have to be associated with the other detectors. The general approach to extract the position of a hit in the chamber is to determine the multiple intersections of the strips from the outer and inner cathode of each chamber, and then identify the correct intersection with the information from the wires.

### 5.2.1 Reconstruction of Hits in the chambers

A cylindrical chamber, as used in the BGO-OD experiment essentially provides three measured parameters, namely the azimuthal angle of the wire $\varphi_{w}$ and indices of cathode strips $\varphi_{I} / \varphi_{E}$. The indices $\varphi_{I} / \varphi_{E}$ of the strips correspond to the azimuthal angle of the strips at the front of the detector, where they are read out. From the measured parameters only the $\varphi_{w}$ of the wires corresponds to the azimuthal angle of the particle hitting the chamber. The angles retrieved from the strips indices depend not only on the $\varphi$ angle but also on the z position of the hit on the chamber. In order to extract the physical position of the hit from the strips, the relation between the z position of the hit and the azimuthal angle $\varphi_{I, E}$ provided by the strips has to be established. This leads to a system of two linear equations, one equation for each cathode, with two unknown parameters $(\varphi, z)$. The solutions of the system correspond to the intersections of both strips. To select the correct intersection of strips, the signals from the wires, or from the BGO or from the SciRi detector can be used.


Figure 5.4: Sketch illustrating the orientation of the strips on the inner and outer cathode

The strips are wound around the chamber on a cylindrical surface as illustrated in the sketch 5.4. Due to the orientation of the strips, particles hitting the chamber at the same azimuthal angle $\varphi$ but in different z positions will activate strips with different indices. To illustrate the dependency of the z position and the $\varphi$ from the detector parameters, figure 5.8 shows a flat projection of the cathodes surface. The vertical axis represents the arc length of the radial detector segment spanned between $\varphi_{I, E}$ of the strip readout and the $\varphi$ of a potential hit. As $\varphi$ runs from 0 to $2 \pi$ per turn of strip, after $2 \pi$ the full circumference of the cathode $\left(=2 \pi R_{I, E}\right)$ is reached. Since generally the cathode is longer than its circumference, multiple turns of a strip are possible, corresponding to a shift of the $\varphi$ angle via a $2 \pi$ offset.

From the illustration above the z distance from the front of the detector per unit angle (in radian) can be deduced, in equation 5.1, by trigonometry and by using the linear dependence of z and $\varphi$ visible in the figures. In order to get the shift in positive z -direction, on the outer cathode, the $\varphi$ angle has be considered in the range of ( 0 to $-2 \pi$ ) resulting in an maximal arc length of $-2 \pi R_{E}$.

(a) $\mathrm{z}-\varphi_{I}$ relation for the inner cathode in orange. The strip tilted by an angle $\beta_{I}=45^{\circ}$ to the zdirection, $\mathrm{R}_{I}$ is the radius of the inner cathode

(b) $\mathrm{z}-\varphi_{E}$ relation for the outer cathode, in green. The strip tilted by an angle $\beta_{E}=-45^{\circ}$ to the z -direction, $\mathrm{R}_{E}$ is the radius of the inner cathode

Figure 5.5: Illustration of the dependence of z position and $\varphi$

$$
\begin{align*}
\tan \left(\beta_{I}\right) & =\frac{Z(\varphi=-2 \pi)}{-2 \pi R_{I}} \rightarrow Z(\varphi=-2 \pi)=\frac{-2 \pi R_{I}}{\tan \left(\beta_{I}\right)} \\
& \Rightarrow \tilde{Z}_{I}^{r a d}=\frac{Z(\varphi=-2 \pi)}{2 \pi}=-\frac{R_{I}}{\tan \left(\beta_{I}\right)}:=-Z_{I}^{r a d} \\
\tan \left(\beta_{E}\right) & =\frac{Z(\varphi=2 \pi)}{2 \pi R_{E}} \rightarrow Z(\varphi=2 \pi)=\frac{2 \pi R_{E}}{\tan \left(\beta_{E}\right)} \\
& \Rightarrow Z_{E}^{r a d}=\frac{Z(\varphi=2 \pi)}{2 \pi}=\frac{R_{E}}{\tan \left(\beta_{E}\right)} \tag{5.1}
\end{align*}
$$

To determine the z position of a hit on the cathode, the azimuthal angle $\delta$ spanned by the strip between the read out position of the strip and the $\varphi$ angle of the hit is needed. This angle corresponds to angles in figure 5.6 and is solely induced by the distance in z between readout and hit. It has to be considered, that strips of the inner cathode are wound clockwise and the strip of the outer cathode counter clockwise, affecting the orientation of the angle called $\delta$ in figure 5.6. In figure $5.6(\mathrm{a})$ it is shown which angles have to be considered, as a particle hits the chamber at the azimuthal angle $\varphi$ and a strip readout of the inner cathode gives a signal at $\varphi_{I}$. The corresponding situation for the outer cathode is given in figure $5.6(\mathrm{~b})$. By the pictures 5.6 it can


Figure 5.6: Relation of the angles on the cathodes, where $\varphi$ is the azimuthal angle of the hit, $\varphi_{I, E}$ is angle given by the strip and $\delta$ the angle spanned by the strip between hit and read out
be concluded that angle $\delta_{I, E}$ is given by equation 5.2 :

$$
\begin{align*}
\delta_{I} & =\left(2 \pi-\varphi_{I}\right)+\varphi \\
\delta_{E} & =\varphi_{E}-\varphi \tag{5.2}
\end{align*}
$$

The parameter $Z_{I, E}^{r a d}$ can now be used to relate the angle $\delta$ to the z position of the hit measured relative to the readout position of the strips. Given the length of the chambers of 52 cm and z shift for one turnaround of the strips in the inner chamber of about 32 cm , multiple turnarounds also have to be implemented. This means the angle $\delta$ can be shifted by integers of $2 \pi$.
Since $\delta$ is only unique up to multiples of $2 \pi$ and the chambers have to be aligned with the rest of the setup at a later stage anyway, the read out of the strips can set to be at $\mathrm{z}=0$ meaning the target centre. The actual physical read out at the front end of the chamber corresponds to a z position associated with $\delta=-2 \pi$ plus some constant offsets in z and $\varphi_{I, E}$, that can be determined from data.
Making use of the $\delta_{I, E}$ in equation 5.2 and of the parameter $Z_{I, E}^{r a d}$ determined in equation 5.1, the $z$ position of the hit on the cathodes can be written as in the equations (5.3)/ (5.4). Each of the equations (5.3), (5.4) still contain the parameter $\varphi$, which is not measured by the strips.

$$
\begin{align*}
& z=\left(\varphi_{I}-\varphi+2 \pi k\right) \cdot Z_{I}^{r a d}  \tag{5.3}\\
& z=\left(\varphi_{E}+\varphi+2 \pi l\right) \cdot Z_{E}^{r a d} \tag{5.4}
\end{align*}
$$

By requiring the same hit to be seen on both cathodes of the same chamber at the same position, the two equations can be combined and two equations containing only known or measured parameters (5.5) and (5.6) are obtained:

$$
\begin{align*}
& \Rightarrow \quad z=\frac{Z_{I}^{r a d} Z_{E}^{r a d}}{Z_{E}^{\text {rad }}-Z_{I}^{\text {rad }}}\left(\varphi_{I}-\varphi_{E}+2 \pi(k-l)\right)  \tag{5.5}\\
& \Rightarrow \quad \varphi=\frac{1}{Z_{I}^{r a d}-Z_{E}^{\text {rad }}}\left(\left(\varphi_{I}+2 \pi k\right) \cdot Z_{I}^{\text {rad }}-\left(\varphi_{E}+2 \pi l\right) \cdot Z_{E}^{r a d}\right) \tag{5.6}
\end{align*}
$$

The z and $\varphi$ from the above equations correspond to the intersections of the strips on the two cathodes. Since the strips are crossing twice per turn and the strips turn around more than once over the complete length of the chambers, the intersection points are universally determined. The equations also yield to multiple solutions depending on the free parameters k and l associated with different orders of $2 \pi$.


Figure 5.7: Sketch illustrating the selection of the correct intersection of two strips by using the signal from a wire

The ambiguity in the intersections can be resolved by comparing the azimuthal angle obtained by equation 5.6 with the azimuthal angle measured by the wires. To do that the $\varphi$ from equation
5.6 has to be projected into the angular range from $-\pi$ to $\pi$ used for azimuthal angles in the BGO-OD setup. Non-physical solutions associated with z positions outside the detector volume are rejected. Combining the strips of the inner and of the outer cathode, plot 5.8 shows three intersection points in figure 5.8(a). In figure 5.8(b) the vertical axis is scaled, so that the z position on both cathodes depends solely on $\varphi$ and corresponds to the solutions of the equations 5.5 and 5.6.

(a) $\mathrm{z}-\varphi_{I}$ relation for the inner cathode, in orange the strip tilted by an angle $\beta_{I}$ to the z-direction, $\mathrm{R}_{I}$ is the radius of the inner cathode

(b) $\mathrm{z}-\varphi_{E}$ relation for the outer cathode, in green the strip tilted by an angle $\beta_{E}$ to the z -direction, $\mathrm{R}_{E}$ is the radius of the inner cathode

Figure 5.8: Illustration of the dependence of z position and $\varphi$
In order to produce distributions comparable to real data, for the spectra in figure 5.9(a) simulated $\gamma p \rightarrow \pi^{0} p$ events were used. Figure 5.9(a) shoes the difference in azimuthal angles of the intersections $\left(\varphi_{\text {strip }}\right)$ compared to the $\varphi_{\text {wire }}$ measured by the wires $\left(\Delta \varphi=\varphi_{\text {wire }}-\varphi_{\text {strip }}\right)$. The remaining solutions after selecting the smallest $\Delta \varphi$ is shown in the right panel 5.9.
In the distribution of the difference between the $\varphi_{\text {wire }}$ and the $\varphi_{\text {strip }}$ from the intersections


Figure 5.9: Distribution of the difference between the azimuthal angle $\left(\varphi_{w}\right)$ measured by the wires and the azimuthal angle calculated from the intersection.
there are multiple peaks visible. The correct wire-strips associations are the ones for which the difference in the azimuthal angle is centred at $0^{\circ}$. The peaks at around $\Delta \varphi \approx \pm 180^{\circ}$ correlate to the second crossing of the strips in the same turn of the real hit at the opposite side of the chamber. In figure 5.8(b) this would correspond to the the angular difference between the intersections 1,3 to intersection 2 . These intersections are slightly shifted to $\pm 180^{\circ}$ due to the different radii of the two cylindrical cathodes. The peak right to the centre at about $30^{\circ}$ belongs to the intersections of strips in different orders of $2 \pi$ ( $k=l \pm 1$ in eq. 5.6). These intersections would correspond in figure $5.8(\mathrm{~b})$ to the crossing 1 at $\Delta \varphi=0^{\circ}$ and 3 at $\Delta \varphi=30^{\circ}$ or vice versa.

The separation of the two crossings is again induced by the different radii of the cathodes. A peak at $-30^{\circ}$ is suppressed since due to the phase space used to generate the $\pi^{0} p$ events there are almost no protons present at large polar angles $\left(\Theta \geq 80^{\circ}\right)$. All peaks are clearly separated and the correct solution for 5.6 and 5.5 can be selected.

This procedure requires a hit in all three detector components of the chamber to identify the correct position of the hit. If one component (e.g. the wires) is missing only a set of possible solutions including the physical hit position can be determined. Nevertheless other detectors like the BGO or SciRi can be used to select the correct position. This will be shown in the next section 5.2.2.
At this point we have already the set of intersections from two strips derived in 5.5 and 5.6. The intersections of a wire and one strip can be reconstructed by the equations 5.3 and 5.4 using the $\varphi$ measured by the wire.

### 5.2.2 Association with BGO and SciRi

In the BGO-OD setup the MWPC is placed around the target cell, surrounded by other detectors which are also sensitive to charged particles, as the BGO calorimeter or the SciRi detector. In the analysis framework of the BGO-OD experiment, the tracking algorithm foreseen at present defines a track by connecting the centre of the target cell to a hit or a cluster position in the BGO or SciRi. The tracking is now implemented by using the MWPCs. This can be done after building a track from the hits in the outer and inner chamber and then associating a signal coming from the BGO or SciRi.
Depending on the polar angular region and on the detectors involved, the tracks are created as Central tracks in the region from $\Theta=(25 \text { to } 155)^{\circ}$ covered by the BGO or Intermediate tracks for $\Theta=(10 \text { to } 25)^{\circ}$ covered by the SciRi detector. The tracks in forward direction with $\Theta \leq 10^{\circ}$ do not overlap with the acceptance of the MWPC and are therefore ignored in this chapter. The selection strategy for the central tracks containing clusters from the BGO is pictured in 5.10. After building a track from the hits in the two chambers, the minimal distance of the track


Figure 5.10: Schematic to associate track from MWPC with Central tracks using BGO clusters
to the cluster in the BGO is calculated. If the minimal distance to the cluster is closer than the width of the BGO crystals (about 5 cm ) the cluster is associated with the track. In the plot 5.10 (a) the distribution of distances cluster to track for simulated $\gamma p \rightarrow \pi^{0} p$ is presented. In the plot the correlated clusters peaking below 5 cm are clearly separated from the uncorrelated ones beginning to rise at about 10 cm . By using the distance from track to cluster, rather than angular cuts, misalignments due to the different origin of the tracks are circumvented. The procedure for
the intermediate tracks is exactly the same as the one for the central tracks, just using SciRi hits instead of BGO clusters.

The effect of the selection can be seen by comparing the obtained track with the position of the BGO cluster or hit in SciRi. The histograms shown in figure 5.11 and figure 5.12 show the correlation of the tracks, constructed from the hits in the MWPC, to the cluster positions in BGO respectively the SciRi detector. The simulated $\gamma p \rightarrow \pi^{0} p$ events are generated at a vertex fixed to the target centre. Therefore the track and the position measured by BGO/SciRi should agree within resolution of the detectors, and it can be expected that the entries are centred around zero. This is exactly what can be seen in the histograms, where it is also clearly visible that the cut on the distance to the cluster improves the correlation. The improvement of the correlation in the plots is partly achieved by removing hits from the photons in the BGO which are in the left plot still inside but not correlated to the track from the MWPCs.


Figure 5.11: Tracks constructed from MWPC for simulated $\gamma p \rightarrow \pi^{0} p$ compared to the BGO. Before and after cutting.


Figure 5.12: Tracks constructed from MWPC for simulated $\gamma p \rightarrow \pi^{0} p$ compared to the SciRi. Before and after cutting

As already mentioned in the section before, the information from the other detectors can also be used to remove the ambiguities in intersections where one sub-detector of one MWPC
is inefficient. In this case the intersection closest in $\Theta$ and $\varphi$ to the BGO or SciRi cluster is chosen. This is done for the intersections of the inner and the outer chamber separately. If the intersections are closer than $15^{\circ}$ in $\Theta$ and $\varphi$ to a cluster in the BGO, a track is created.
The following figures show the evolvement of the tracks constructed from the intersection of two strips in the central region using again simulated $\gamma p \rightarrow \pi^{0} p$ events. In the first plot 5.13(a) the angular correlation between the intersections on the inner chamber and the BGO is shown. Besides some hits uncorrelated to the proton, two pronounced peaks are visible. The peak corresponding to the correct intersection is clearly centred around zero on both axes, showing good agreement between the reconstructed angles in the MWPC and the measurement of the BGO. In the lower left corner a bump is visible, which is associated with the crossing of the strips opposite to the hit position ( $\Delta \varphi \approx 180^{\circ}$ ).
After requesting the angular difference in $\Theta$ and $\varphi$ to be smaller than $15^{\circ}$, the intersections in figure $5.13(\mathrm{~b})$ are used to create a track $5.13(\mathrm{c})$ with the hits in the outer chamber. Finally selecting the tracks pointing to a cluster in the BGO again leads to a clean signal as seen in figure 5.13(d).


Figure 5.13: Tracks constructed from MWPC without signals from the wires for simulated $\gamma p \rightarrow \pi^{0} p$ compared to the BGO.

Since the software for hit and track reconstruction for the MWPC detector is now integrated in the general software framework of BGO-OD, the effect on the angular resolution of the detector setup can be studied. This is done in the next section with simulation studies by comparing the deviation of the reconstructed track from the momentum direction of a simulated proton.

### 5.2.3 Impact on detector resolution

The impact of the improved angular resolution due to the MWPC is studied in this chapter via the simulation of isotropically distributed protons.
Figure 5.14 shows the difference between the azimuthal angle of the generated proton and the azimuthal angle measured by the BGO (left panel) or the MWPC (right panel) according to the simulation.


Figure 5.14: Determination of the detector resolution in $\varphi$ using simulated protons
Clearly visible is the effect induced by the granularity of the BGO detector. To be able to quantify this effect on the top-right corner of each panel the difference $\Delta \varphi$ is shown for a small azimuthal region corresponding to the width of the BGO-crystals installed at $\varphi=0$.
For the BGO detector the distribution results from the superimposition of a Gaussian profile and rectangular distribution. The attempt to fit a Gaussian function leads to an extraction of a width of the distribution of about $4^{\circ}$.
In contrast, in the case of the MWPCs the azimuthal distribution shows a real Gaussian behaviour with a width of $\sigma=1.715^{\circ}$.

The situation for the intermediate tracks is almost the same as for central tracks due to the analogous problem of the granularity of the SciRi detector. The main difference is a consequence of the thickness of the plastic scintillator of the SciRi detector $(1 \mathrm{~cm})$ and therefore particles will not be able to enter neighbouring segments as they pass the active detector material.
In the intermediate region the improvement expected by the installation of the MWPC detector is even stronger than the one expected for the central region, as it can be seen in figure 5.15. The granularity of the SciRi detector limits its resolution to $\Delta \varphi \approx 6^{\circ}$, while with the MWPC a resolution better than $2^{\circ}$ can be achieved. The resulting resolution of the MWPC is slightly worse than in the central region but still comparable.
As it was done for the azimuthal angle $\varphi$, figure 5.16 shows the deviation between the reconstructed $\Theta$ angle and the generated one. The left plot shows again the distribution obtained by using tracks reconstructed from the position of the cluster in the BGO, whereas in the right plot tracks from the MWPC are used.
Both distributions are wider in the centre around $90^{\circ}$ than the ones at the edges. This is due to the cylindrical geometry of the chambers, where the effective surface facing the target depends


Figure 5.15: Determination of the azimuthal detector resolution using simulated protons


Figure 5.16: Resolutions of the BGO and the MWPCs in polar angle
on the z coordinate of the track. For the BGO the use of smaller crystals in first and last two $\Theta$ segments influence the resolution at the verge of the detector acceptance. The resolution for the BGO is limited to the size of the crystals, ranging from $6^{\circ}$ to $10^{\circ}$. Compared to tracks from the BGO (figure: 5.16(a)), the resolution is significantly improved by the MWPCs to $1.3^{\circ}$ at the edges of the central detector region and to $3.4^{\circ}$ in the middle sector.
In both plots the influence of detector segmentation is clearly visible as agglomeration of hits in tilted bands. The plot constructed from the MWPC tracks shows a much finer division of the bands, since the width of the cathode strips is 4.5 mm , much smaller than the ( 2 to 3 ) cm of the BGO crystals. Another reason for the improved resolution is the measurement of the track in two places, namely on the outer and the inner chamber.

In order to extract the relation between the position of a hit and the resolution of the detector in figure 5.17, the resolution is averaged over all entries in one $1^{\circ}$ wide section. The distribution for the MWPCs can be approximated quite well by the function given in equation 5.7.


Figure 5.17: Distribution of the $\Theta$ resolution in the central region using MWPC tracks where the resolution in each $1^{\circ}$ bin is averaged over all entries in the bin

$$
\begin{equation*}
\Delta \theta=1.672+1.463 \cdot \sin (x)^{2} \tag{5.7}
\end{equation*}
$$

In the intermediate region the tracks from the MWPCs are compared with tracks constructed

from the hits in SciRi which have the same granularity in $\varphi$ as the BGO. Concerning the resolution in polar angles for the SciRi detector, the segmentation into three rings is clearly visible where the resolution of the MWPCs are almost constant over the covered polar region.


Figure 5.18: Distribution of the $\Theta$ resolution in the intermediate region using MWPC tracks where the resolution in each $1^{\circ}$ bin is averaged over all entries in the bin

The constant resolution of about $1.5^{\circ}$ is also clearly visible in the plot 5.18 where the averaged resolution for each $1^{\circ}$ sector is shown. The limit of the detector acceptance can also be seen at $15^{\circ}$.

After developing a track reconstruction for the MWPC and estimating the resolutions, which can be expected from these tracks, the tracks can used to reconstruct vertices. In the next chapter vertex reconstruction techniques are presented and the accuracy of the reconstructed vertices is determined from simulation.

### 5.3 Vertex Reconstruction

In the ideal case the reconstructed tracks of two particles originating from the decay of a mother particle meet at the position where the decay took place. In reality the accuracy of the tracks, measured by the detector, are limited by the resolution and the precision of the alignment of the detector. Therefore, the reconstructed tracks are generally skewed lines and in order to determine the common vertex of two tracks the points of closest approach have to be determined.


Figure 5.19: Illustration of vertex determination by point of closest approach of two skewed lines. $V_{1,2}$ are points of closest approach, $\mathrm{D}_{1,2}$ are the direction of the tracks, $\mathrm{P}_{1,2}$ is the position where the tracks hit the outer chamber. (Angles are distorted by perspective view)

Translated in a mathematical expression these are the points $V_{1,2}$ (figure 5.19 ) on the skewed lines defined by the tracks, where the vector connecting these points is simultaneously perpendicular to the directions of both tracks. Using the positions where the tracks hit the outer chamber of the MWPCs ( $\mathrm{P}_{1,2}$ ) and the measured direction of the tracks $\left(D_{1,2}\right)$ we can deduce the vertex position as follows.

$$
\begin{align*}
\vec{V}_{1}-\vec{V}_{2}=\vec{w}_{\text {vertex }} \perp \vec{D}_{1,2} \quad \Rightarrow & \vec{w}_{\text {vertex }} \cdot \vec{D}_{1}=0 \\
& \vec{w}_{\text {vertex }} \cdot \vec{D}_{2}=0 \tag{5.8}
\end{align*}
$$

The line describing the measured track can be expressed in terms of the direction, a fixed point ( $\mathrm{P}_{1,2}$ ) on the track and the free parameter t or s as:

$$
\begin{array}{ll}
\vec{P}(t)=\vec{P}_{1}+\vec{D}_{1} \cdot t & \Rightarrow \vec{V}_{1}=\vec{P}_{1}+\vec{D}_{1} \cdot t_{c a} \\
\vec{Q}(t)=\vec{P}_{2}+\vec{D}_{2} \cdot s & \Rightarrow \vec{V}_{2}=\vec{P}_{2}+\vec{D}_{2} \cdot s_{c a}
\end{array}
$$

The equation above on the right apply in the points of closest approach (ca) are fixing the parameters $t_{c a}$ and $s_{c a}$. From (5.8) it follows:

$$
\begin{aligned}
& 0=\left(\vec{P}_{1}+\vec{D}_{1} \cdot t_{c a}-\vec{P}_{2}-\vec{D}_{2} \cdot s_{c a}\right) \cdot \vec{D}_{1} \\
& 0=\left(\vec{P}_{1}+\vec{D}_{1} \cdot t_{c a}-\vec{P}_{2}-\vec{D}_{2} \cdot s_{c a}\right) \cdot \vec{D}_{2}
\end{aligned}
$$

It is then possible to extract the parameters $s_{c a}$ and $t_{c a}$ :

$$
\begin{aligned}
& s_{c a}=\frac{\left(D_{1} D_{2}\right)\left(D_{2}\left(P_{1}-P_{2}\right)\right)-D_{2}^{2}\left(D_{1}\left(P_{1}-P_{2}\right)\right)}{D_{1}^{2} D_{2}^{2}-\left(D_{1} D_{2}\right)^{2}} \\
& t_{c a}=\frac{D_{1}^{2}\left(D_{2}\left(P_{1}-P_{2}\right)\right)-\left(D_{1} D_{2}\right)\left(D_{1}\left(P_{1}-P_{2}\right)\right)}{D_{1}^{2} D_{2}^{2}-\left(D_{1} D_{2}\right)^{2}}
\end{aligned}
$$

The most realistic estimation of the common vertex is given by the central point on the line connecting the two points of closest approach:

$$
\text { vertex }=0.5 \cdot\left(\vec{V}_{1}-\vec{V}_{2}\right)=0.5 \cdot\left(\vec{P}_{1}+\vec{D}_{1} \cdot t_{c a}-\vec{P}_{2}-\vec{D}_{2} \cdot s_{c a}\right)
$$

For the analysis used at the BGO-OD experiment in this thesis three slightly differing implementations for vertex determination were developed. Two implementations are performed within the software plugin BTVertexFromTrack at the pre-analysis stage directly after the tracks have been reconstructed. At this stage the tracks from the central region of the experiment and the intermediate region are separated, which would make the construction of vertices for tracks from different regions very time consuming during data processing. Therefore the reconstruction in these implementations is restricted to tracks from the central region covering most of the acceptance of the MWPCs.


Figure 5.20: Vertex resolution for pseudo vertex constructed from central tracks during tracking determined from simulated $\gamma p \rightarrow \pi^{0} p$

The third implementation within the BTReactionVertex plugin can be used after a reaction
hypothesis has been created for events meeting the restrictions of the hypothesis (e.g. number of particles).
The implementation on the reaction level is very well suited for specific analysis, whereas the vertices created in the pre-analysis provide high statistics, which can be used e.g. for detector alignment.
The BTVertexFromTrack can be called with two options to select the reconstruction procedure. The first option (getreactionvertex) starts a reconstruction of a pseudo vertex for each track measured by the MWPCs, where it is assumed that the track originates around the beam axis and the point of closest approach to the beam axis is determined. If the distance to the beam axis at this point is below a threshold parameter (e.g. 0.5 cm ), the vertex is considered valid and saved as track parameter. This reduces the uncertainty on the z position of non strange reactions from the size of the target cell $\Delta z \approx \pm 3 \mathrm{~cm}$ to $\Delta z \approx \pm 1 \mathrm{~cm}$ as can be seen in figure 5.20 (c) and therefore increasing the mass resolution in the central region.

The second option (getdecayvertex) requires at least two tracks to be measured by the MWPCs. For these two tracks the point of closest approach is determined as described in the introduction of this chapter. If more than two tracks are measured by the MWPCs, all combinations of subsets containing two tracks are taken into consideration and sorted by their distance in the points of closest approach. The tracks closest to each other are paired and their common vertex is stored.


Figure 5.21: Vertex resolution for vertices of $\Lambda$ constructed from all from central tracks during tracking determined from simulated $\gamma p \rightarrow \Lambda \mathrm{~K}^{+}$

Both procedures show reasonable agreement of the reconstructed vertices with generated ones. In the distributions of vertices created from two tracks (figure:5.21), an influence of false
associations is visible. The spectra probably can be improved by more restrictive cuts. For the comparison of the achieved resolutions of the vertex and pseudo vertex reconstruction some important points have to be considered. For the vertex reconstruction reactions including strange particles are used, as they are of main interest of the research program at the BGO-OD. These reactions lead to multiple particle final states, therefore the possibility for false combinations is not negligible. For pseudo vertex reconstruction strange particles are not suited due to their displaced decay vertex, therefore for the pseudo vertex reconstruction $\gamma p \rightarrow \pi^{0} p$ events are used. For the pseudo vertex therefore only one charged particle, the proton, is present in the final state and no false combinations are possible.
To use the reconstruction within the BTReactionVertex plugin a reaction hypothesis including unstable particles has has to be created in the analysis. The plugin calculates the decay vertex of unstable particle types given to the plugin as parameters (e.g. $\mathrm{K}_{s}^{0}, \Lambda^{0}, \omega \ldots$ ). The figures 5.22


(c) Vertex resolution in Z direction

Figure 5.22: Vertex resolution for vertices of $\mathrm{K}^{0}$ candidates reconstructed during the analysis process using central an intermediate tracks determined from simulated $\Sigma^{0} K^{0}$
show much cleaner spectra, the false combinations are significantly reduced and the resolutions improved. The resolutions for the reconstructed vertices summarized in table 5.2 are of the order of a few mm

$$
\begin{array}{llll}
\text { Track vertices } & \sigma_{x} \approx 0.7 \mathrm{~cm} & \sigma_{y} \approx 0.7 \mathrm{~cm} & \sigma_{x} \approx 0.8 \mathrm{~cm} \\
\text { Reaction vertices } & \sigma_{x} \approx 0.4 \mathrm{~cm} & \sigma_{y} \approx 0.4 \mathrm{~cm} & \sigma_{z} \approx 0.5 \mathrm{~cm} \\
\text { Pseudo vertices } & \sigma_{x} \approx 0.5 \mathrm{~cm} & \sigma_{y} \approx 0.5 \mathrm{~cm} & \sigma_{z} \approx 1.1 \mathrm{~cm}
\end{array}
$$

Table 5.2: Resolutions of the different vertex reconstructions

## CHAPTER 6

## Commissioning and First Data taking with MWPC

After some tests, using data from cosmic radiation, and a short test with beam in February 2017, in April/May 2017 three weeks of data with beam could be taken with working MWPCs.
Based on the data taken in this beamtime, the tracking procedure and its performances can be tested. This chapter will first discuss the correction of the strips and wires in each chamber. Afterwards the results of the track reconstruction will be presented using BGO and SciRi as references. For the reconstructed tracks an efficiency can be estimated, using reconstructed $\gamma p \rightarrow \pi^{0} p$ events, where the proton has to be detected in SciRi or BGO. Finally the reconstructed vertices are presented and compared to the expected origin of most of the tracks within the target cell and the beam profile.

### 6.1 Azimuthal correction of strips and wires

In order to check the correlation between the azimuthal angles measured by the wires and the angle calculated for the intersections of the strips, the distribution of $\Delta \varphi$ is plotted in figures 6.1 and 6.2. To reduce combinatorial background in the plot only events with one cluster in each of the cathodes and the wires are used. The correlation generally shows the same distribution as


Figure 6.1: Azimuthal angular correlation between wires and strip intersections in the inner chamber for all intersections (left panel) and selected intersections after cuts (right panel)
obtained by the simulations in chapter 5.2. At $\Delta \varphi=0$ the peak corresponding to the correct


Figure 6.2: Azimuthal angular correlation between wires and strip intersections for all intersections in the outer chamber (left panel) and selected intersections after cuts (right panel)
intersections associated with the hit in the wires is clearly visible. To the left and right of the central peak there are the peaks corresponding to the intersections of two strips which are not associated with the hit measured by the wires. A more detailed discussion of the spectrum is given in chapter 5.2.
The widths of the distributions for selected intersections are increased due to a cross-talk problem in the read out of the wires, causing signals in neighbouring wires which were not hit. In the outer chamber the influence of the cross-talk is also visible as a double peak structure in the distribution of the selected intersections (fig. 6.2(b)).
The validity of the selected intersections can be checked by comparing the position of the selected intersection with hits in the detectors surrounding the MWPCs.

### 6.2 Angular correlations of hits and tracks from the MWPC to BGO and SciRi

The BGO and the SciRi detector provide additional information by the measured polar angle $\Theta$ and can therefore be used to align the MWPCs along the beam (z) axis with rest of the setup. Figure 6.3 shows the polar $(\Delta \Theta)$ and azimuthal $(\Delta \varphi)$ angular correlation of all possible intersections of strips within the acceptance of the BGO and all clusters in the BGO.
Without any further cuts, the correct intersections associated with the hit in the BGO are already visible at $\Delta \Theta \approx 0$ and $\Delta \varphi \approx 0$ and can be used to align the detector. The distribution for the inner chamber looks a bit smeared out, this may be caused by the worse resolution compared to the outer chamber due to the smaller circumference of the inner chamber by same strips widths. Furthermore, there may be misalignments relative to the beam axis to which the inner chamber is more sensitive than the outer chamber.


Figure 6.3: Angular correlation of all possible intersections in the MWPCs and all hits in the BGO


Figure 6.4: Angular correlation of all possible intersections in the MWPCs and all hits in the SciRi

In the intermediate region the peaks at zero are also visible for both chambers. For the inner chamber the correct intersections however seem to be not as well separated from the background as they are compared to the BGO. The resolution of the SciRi detector is the same as the BGO and the polar resolution of the MWPC is even better in this region than in the central region. Therefore the separation should be equal or even better than in the central region. The comparatively worse separation may be caused by an inaccuracy in the polar alignment of the SciRi detector, since the MWPCs with a better resolution than SciRi are aligned to the BGO. To check whether the correct intersections are selected by choosing the smallest azimuthal angular difference between the wires and the intersection point of the strips, the figures 6.5 and 6.6 show the correlations of the selected intersections to the hits in the BGO and the SciRi detector.

The correlations with the BGO show only one bump in the centre, indicating that, apart from some even distributed background, nearly all selected intersections are correct. The comparison of the intersections with the hits in SciRi shows also reasonable agreement. However, besides the bump at $\Delta \Theta=0, \Delta \varphi=0$, there is a second agglomeration of intersections which would agree in $\varphi$ with the hits in SciRi but are shifted by approximately 150 degrees in $\Theta$ to the position of the hit in SciRi. This may result from a misalignment of the MWPC along the beam axis. The correct intersection may then be rejected since, by using the not correct detector position in software, the intersection would have been outside of the detector. In this case the strip

(a) Angular correlation of hit in inner chamber to $\mathrm{BGO}(\mathrm{b})$ Angular correlation of hit in outer chamber to BGO

Figure 6.5: Angular correlations of strip-strip intersections to clusters in the BGO


(a) Angular correlation of hit in inner chamber to $\operatorname{SciRi}(\mathrm{b})$ Angular correlation of hit in outer chamber to SciRi

Figure 6.6: Angular correlations of strip-strip intersections to hits in the SciRi detector
intersection of a different order of $2 \pi$ with the second best agreement to the wires may haven been selected, if the azimuthal angular difference between the wire and the intersection is still inside the cut.
Using the intersections selected by the wires in both chambers, tracks can be reconstructed. Figure 6.7 shows the correlation between the constructed tracks and the position of the hit in the BGO.


Figure 6.7: Correlation of tracks constructed from intersections of two strips and one wire in both chambers

Selecting the intersections with the best correlation to a hit in the BGO, by cutting on the bump at $(\Delta \Theta=0, \Delta \varphi=0)$ in the distributions visible in figure 6.3 , tracks can be reconstructed where one detector element (e.g. the anode or one cathode) of the chamber is missing. The correlations of the track without anode signals can be seen in figure 6.8(a). Figure 6.8(b) shows the correlations for tracks where the strip of one cathode is missing. Both distributions agree well


Figure 6.8: Angular correlation of tracks from intersections of two detector elements of the MWPCs in each chamber to the BGO
for $\Theta$, but are distorted in $\varphi$ direction. The structure in $\varphi$ may be the result of a $\varphi$-dependant offset in $\varphi$, caused by a shift in the x or y direction perpendicular to the beam axis. Despite the distortion in the $\varphi$, the agreement of the tracks and the hit positions in the hit in the BGO still visible.

### 6.3 Efficiency estimations

To study the efficiencies of the chambers and of the track reconstruction procedure, $\gamma p \rightarrow \pi^{0} p$ events are used. This sufficiently abundant reaction allows the testing of the tracking of the MWPC with an almost clean signal from the proton by largely suppressed backgrounds.
For the reconstruction of the $\gamma p \rightarrow \pi^{0} p$ reaction events with two neutral hits in the BGO, corresponding to the photons from the decay $\pi^{0} \rightarrow \gamma \gamma$, and one charged hit in BGO or SciRi are used. In order to suppress background and contribution by other reactions, where for example one particle is not detected by the setup, for the reconstruction only events with the energy difference between the initial state and the final state smaller than 150 MeV are used. Further restrictions are that the invariant mass, corresponding to the $\pi^{0}$ reconstructed from the two photons, is larger than 90 MeV and smaller than 180 MeV and the missing mass to the $\pi^{0}$ is within ( 800 to 1000 ) MeV , matching to the mass of the proton.

Figure 6.9 show the invariant mass distributions for the reconstructed mass from the two photons before any cuts are applied and after applying the cuts discussed above. Whereas in the left panel 6.9 (a) the peak associated with the $\pi^{0}$ is visible above a background distribution, in the right panel $6.9(\mathrm{~b})$ almost no background is apparent. The position of the peak in the the mass distribution $6.9(\mathrm{~b})$ is centred at 145 MeV and therefore a bit above the $\pi^{0}$ mass $(\approx$ 135 MeV ). This effect is ascribed to a not yet final calibration of the BGO crystals.
The kinematic of the reaction used, restricts the angular region in which the proton is emitted.


Figure 6.9: Invariant mass distributions of reconstructed $\pi^{0} \mathrm{~s}$ before and after cuts

Outside this region the efficiency can not be reliably estimated. In simulations $\gamma p \rightarrow \pi^{0} p$ events with realistic kinematics can be generated by the event generator implemented in the ExPlORA framework. The resulting polar angular distribution of the protons can be seen in figure 6.10.
From the distribution in figure 6.10 it is apparent that in $\gamma p \rightarrow \pi^{0} p$ reactions no protons are


Figure 6.10: Polar distribution of generated final state protons in simulated $\gamma p \rightarrow \pi^{0} p$ events
emitted in $\Theta$ angles larger than $84^{\circ}$. The efficiency obtained by using the proton of reconstructed $\gamma p \rightarrow \pi^{0} p$ reactions can only reasonably be estimated for $\Theta$ angles below $84^{\circ}$.
The distributions of the reconstructed proton from hits in the BGO or SciRi 6.11(a) and from hits in BGO/SciRi and MWPC shows distributions similar to the ones obtained from simulations (fig. 6.10). There are some hits visible at the very backward angles $\left(\Theta \approx 140^{\circ}\right.$ ), which can not be associated with the proton of the reconstructed reaction. This shows that the reconstruction is still contaminated by background, which has to be investigated further.
The following efficiencies can therefore only be considered as rough estimations to compare different settings. The following efficiency plots show the ratio between all reconstructed proton tracks and the tracks reconstructed with the MWPCs.
The first efficiency estimation in figure 6.12(a) using only tracks reconstructed from intersections of two strips and one wire in both chambers revealed a very low efficiency of the order of (10 to 20) $\%$. To compensate for this low efficiency, in addition, the reconstruction of tracks, using intersections of two strips or one strip and one wire in each chamber, is implemented.


Figure 6.11: Polar angular distribution of the reconstructed protons


(a) Efficiency of the MWPC tracking including detector (b) Efficiency after including tacks created from strip-strip efficiency for protons from reconstructed $\pi^{0} p$ events using and one strip wire intersections selected by BGO and SciRi tracks from strip-strip intersection and wires

Figure 6.12: Polar efficiency distributions for tracks reconstructed from MWPC using $\gamma p \rightarrow \pi^{0} p$ events. Right to the vertical red line no reasonable values can be estimated since no signals associated with the reconstructed reaction are observable

By using these tracks the efficiency distribution in right panel 6.12(b) of the order (50 to 70) \% is achieved. The vertical red line in both plots indicates the $\Theta$ angle above which no protons associated with $\gamma p \rightarrow \pi^{0} p$ reactions are observable. The efficiencies to the right of the red line are obtained by using background events. Therefore influences not correlated to the detector efficiency are very likely and the values should be disregarded. The drop off at $\Theta$ below $20^{\circ}$ indicates the end of the overlap between the outer chamber and the SciRi detector, marking the position of the MWPC along the beam axis.

(a) Efficiency of the MWPC tracking including detector (a) Efficiency of the MWPC tracking including detector
 tracks from strip-strip intersection and wires

Figure 6.13: Azimuthal efficiency distributions for tracks reconstructed from MWPC using $\gamma p \rightarrow \pi^{0} p$ events.

During the beamtime, the dead time of the data acquisition appeared to be dominated by the read out of the MWPCs. In order optimize the data acquisition, different threshold settings for the SADC used to read out the strips were tested. By reducing the amount of noise read out on the strips, without loosing the signals of real hits, a lower dead time and, consequently, a more efficient data taking could be achieved. To ensure that no signal of real events is lost, the tracking efficiency is checked.
In figure 6.14 the the effects of two different threshold settings are presented.

(a) Efficiency of the MWPC tracking using $\pi^{0} p$ events with maximal threshold for the read out of the strips

(b) Efficiency of the MWPC tracking using $\pi^{0} p$ events with the standard threshold,as used during the data taking, for the read out of the strips

Figure 6.14: Effect of different threshold settings for the SADC of the readout of the strips on the MWPCs efficiency

The use of the maximal threshold setting possible at the SADC results in a significant loss of efficiency from approximately $65 \%$ (at about $40^{\circ}$ in figure $6.14(\mathrm{~b})$ ) to $50 \%$ (at about $40^{\circ}$ in figure 6.14(a)). For nearly the complete beamtime the threshold setting from the right panel 6.14(b) was used.

### 6.4 Vertex reconstruction

With the tracks from the MWPCs, using the data taken in 2017, it is for the first time possible to reconstruct vertices at the BGO-OD experiment. In this chapter the reconstructed vertex positions are presented, using the procedure for reaction hypothesises, as shown in chapter 5.3. For the analysis, events with two neutral and three charged final state particles, consistent with the reactions $\gamma p \rightarrow \omega p \rightarrow\left(\gamma \gamma \pi^{+} \pi^{-}\right) p$ or $\gamma p \rightarrow \Sigma^{+} \mathrm{K}^{0} \rightarrow(\gamma \gamma p)\left(\pi^{+} \pi^{-}\right)$, were used. In the following the reconstructed common vertex of the $\pi^{+}$and the $\pi^{-}$are shown.
The position of the vertex in the plane perpendicular to the beam axis is shown in figure $6.15(\mathrm{a})$. The figure $6.15(\mathrm{~b})$ shows the projection of the left plot on the x axis. In the left picture an agglomeration corresponding to the beam spot is visible in the middle. The Gaussian function fitted to the distribution in the right panel reveals that the detector is shifted about 4 mm relative to the beam axis. The 1 cm width of the distribution is, considering the expected vertex resolution of 4 mm (chapter 5.3) and the beam divergence, compatible with the 7 mm collimator installed in front of the target.


Figure 6.15: Reconstructed vertices in the plane perpendicular to the beam axis


Figure 6.16: Reconstructed vertices along the beam axis ( z ), the vertical black lines indicate the position of the target cell, the horizontal red lines indicate the beam profile expected by using a collimator with 7 mm diameter

The positions of the reconstructed vertices in the $\mathrm{X}-\mathrm{Z}$ plane visible in figure 6.16 (a), show again the 4 mm shift relative to the expected beam position in the x direction, in the z direction
the vertex positions agree well with the position of the target. The projection of the vertex positions in the y-z plane (fig.6.16(b)) agrees well with the expected beam position, indicated by the horizontal red lines.
For further physics analysis it is important to correct the x position of the MWPC detector in the software. If the structures visible in the comparison of the tracks to the BGO in figure 6.8 are caused by the same misalignment, this indicates that the chambers are shifted with respect to each other. A shift of both chambers relative to the beam axis would not be visible in the comparison of the angles, since the track measured by the chambers would be parallel to the track of the particle.
The vertex reconstruction performed on the data taken in April/May 2017 nevertheless shows reasonable results. To validate the reconstructed vertices further investigations are necessary.

## CHAPTER

## Outlook and Conclusion

For the investigation of potentially molecular hadronic states in the strangeness sector at the BGO-OD experiment it is essential to reconstruct the charged decay modes of strange particles. Within this thesis important tools for the reconstruction of these decay channels have been implemented. Central for the reconstruction of charged decay modes of strange and non strange particles is the improved tracking capability for charged particles in a large angular region covered by the central MWPC.
Track reconstruction techniques for the central MWPC, and methods for vertex reconstruction at the BGO-OD experiment, were developed and implemented. Simulation studies were performed to estimate the position resolution of the reconstructed tracks and vertices. The tracks obtained from the MWPC showed a significantly enhanced resolution of about $1.7^{\circ}$ for azimuthal angle $\varphi$ and, depending on the polar angle of the hit, from ( 1.3 to 3.4$)^{\circ}$ in $\Theta$. The vertices reconstructed from these tracks exhibited resolutions of 0.4 cm in the directions perpendicular to the beam axis and 0.5 cm along the beam axis.
Analysis performed on the data taken in $04 / 2017$ showed reasonable agreement of the tracks from the MWPC with the hits measured by the BGO calorimeter. Requiring a signal from all three detector components (both cathodes and one wire) results in a very low efficiency ( $\approx 10$ to 20) \%), which can be compensated by requiring a signal in two out of the three components and correlated hit in the BGO. In this way a preliminary efficiency, of ( 55 to 70 ) \% is estimated. For a more reliable efficiency determination, background studies still have to be performed and efficiencies for each wire and strip have to be extracted individually.
Within this thesis it was for the first time possible to reconstruct vertices at the BGO-OD experiment. The reconstructed vertices show good agreement with the target and beam position. In the x direction the distribution of the vertices hints to a 0.4 cm misalignment of the detector with respect to the beam axis or the chambers in respect to each other. To use the MWPC and the vertex reconstruction for further analysis, a correction of this shift has to be implemented into the analysis framework.
The track and vertex reconstruction, using the central MWPC, developed in this thesis, shows promising results. In order to improve the resolution in a larger polar region tracks with signals from only one chamber have to be included. This would increase the acceptance region significantly, since the inner chamber covers an about $10^{\circ}$ larger polar angle than the outer chamber. Additionally in the region covered by both chambers the efficiency should get enhanced by this procedure. To improve the vertex reconstruction the use fitting techniques, which are minimizing the distance of the two tracks of the vertex within the detector resolution, can be investigated. Whether it will be possible to identify strange reactions due to their displaced vertex can't be state at present. This requires more detailed studies taking in to account the beam profile ( $\sigma_{\text {beam }} \approx 0.7 \mathrm{~cm}$ ), length of the target cell $\left(1_{\text {target }}=6.0 \mathrm{~cm}\right)$ and the limited decay
lengths of the particles ( $\mathrm{K}_{S}^{0}: \mathrm{c} \tau \approx 2.7 \mathrm{~cm}, \Lambda: \mathrm{c} \tau \approx 7.9 \mathrm{~cm}$ ).

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[^0]:    ${ }^{1}$ Quantum ChromoDynamics

[^1]:    ${ }^{2}$ Multi Wire Proportional Chamber

[^2]:    ${ }^{1}$ Lattice Quantum Chromodynamic

[^3]:    ${ }^{1}$ Lattice Quantum ChromoDynamic

[^4]:    ${ }^{1}$ ELektronen Stretcher Anlage

[^5]:    ${ }^{2}$ Flux Monitor

[^6]:    ${ }^{3}$ Gamma Intensity Monitor

[^7]:    ${ }^{4}$ Scintillating Ring
    ${ }^{5}$ Multigap Resistive Plate Chamber

[^8]:    ${ }^{6}$ Time Of Flight

[^9]:    ${ }^{1}$ Extended Pluggable Oblectorientated ROOTified Analysis

[^10]:    ${ }^{2}$ Time of Flight

[^11]:    ${ }^{1}$ Istution Nationale di Fisica Nucleare

[^12]:    ${ }^{2}$ Time to Dgital Converter
    ${ }^{3}$ Sampling Analog to Dgital Converter

