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BOLU ABANT İZZET BAYSAL UNIVERSITY
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**FEASIBILITY STUDY OF Z(4430) EXOTIC STATE AT
PANDA EXPERIMENT**

DOCTOR OF PHILOSOPHY

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ABSTRACT

FEASIBILITY STUDY OF $Z(4430)$ EXOTIC STATE AT $\bar{P}$ ANDA EXPERIMENT

PHD THESIS

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Up until now, elementary particles and their interactions have been satisfactorily characterised by the Standard Model (SM) of particle physics. But a lot of difficult questions remain unanswered. At high energy frontiers like the LHC at CERN, some of these are being researched. The high precision/high intensity frontier made possible by exclusive observations of hadronic reactions at intermediate energies offers an alternative strategy. The upcoming antiProton ANnihilation at DArmstadt ($\bar{P}$ ANDA) experiment at FAIR will utilise antiproton-nucleus and antiproton-proton interactions as diagnostic tools. The $\bar{P}$ ANDA experiment may be used to analyse the spectra of many different particles. $Z(4430)$ is among the most significant of the many XYZ states and they are being examined in numerous global experiments, such as BESIII, Belle, BaBar, and LHCb. Therefore, integrating this research into the $\bar{P}$ ANDA framework and utilising $\bar{P}$ ANDA software to work with this subject is a crucial challenge for the $\bar{P}$ ANDA experiment pertaining to charmonium and exotics. $Z(4430)$ can potentially provide more precise information on mass, width, and other parameters in the $\bar{P}$ ANDA detector spectrum when the entire simulation offered by the $\bar{P}$ ANDA software chain is utilised. To test this, the thesis study titled "Feasibility Study of $Z(4430)$ Exotic State at $\bar{P}$ ANDA Experiment" was designed with the aim of determine whether $Z(4430)$ is feasible in the $\bar{P}$ ANDA detector spectrum. Consequently, according to the results of this study, $Z(4430)$ is shown to be observable in the framework of the $\bar{P}$ ANDA experiment.

KEYWORDS: Charmonium, Exotic Hadrons, $Z(4430)$, $\bar{P}$ ANDA, Accelerator, Detector Simulation, Particle Physics

ÖZET

**Z(4430) EGZOTİK DURUMUNUN $\bar{P}$ ANDA DENEYİNDE FİZİBİLİTE
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Şimdiye kadar, temel parçacıklar ve etkileşimleri parçacık fiziğinin Standart Modeli (SM) tarafından tatmin edici bir şekilde karakterize edilmiştir. Ancak pek çok zor soru cevapsız kalmıştır. CERN'deki LHC gibi yüksek enerji sınırlarında bunlardan bazıları araştırılmaktadır. Orta enerjilerde hadronik reaksiyonların özel gözlemleri ile mümkün kılınan yüksek hassasiyet/yüksek yoğunluk sınırı alternatif bir strateji sunmaktadır. FAIR'de yapılacak olan “anti Proton ANnihilation at DArmstadt” ($\bar{P}$ ANDA) deneyi, antiproton-çekirdek ve antiproton-proton etkileşimlerini teşhis araçları olarak kullanacaktır. $\bar{P}$ ANDA deneyi birçok farklı parçacığın spektrumunu analiz etmek için kullanılabilir. Z(4430), XYZ durumları bunların en önemlileri arasındadır ve BESIII, Belle, BaBar ve LHCb gibi çok sayıda küresel deneyde incelenmektedir. Bu nedenle, bu araştırmayı $\bar{P}$ ANDA çerçevesine entegre etmek ve bu durumu çalışmak için $\bar{P}$ ANDA yazılımını kullanmak, çarmonyum ve egzotiklerle ilgili $\bar{P}$ ANDA deneyi için çok önemli bir konudur. Z(4430) , $\bar{P}$ ANDA yazılım zincirinin sunduğu tüm simülasyon kullanıldığında, $\bar{P}$ ANDA dedektör spektrumundaki kütle, genişlik ve diğer parametreler hakkında potansiyel olarak daha kesin bilgiler sağlayabilir. Bunu test etmek için, “ Z(4430) Egzotik Durumunun $\bar{P}$ ANDA Deneyinde Fizibilite Çalışması” başlıklı tez çalışması, Z(4430)'un $\bar{P}$ ANDA dedektör spektrumunda görülebilir olup olmadığını belirlemek amacıyla tasarlanmıştır. Sonuç olarak, bu çalışmanın sonuçlarına göre, Z(4430) 'un $\bar{P}$ ANDA deneyi çerçevesinde gözlemlenebilir olduğu gösterilmiştir.

ANAHTAR KELİMELEER: Çarmonyum, Egzotik Hadronlar, Z(4430) , $\bar{P}$ ANDA, Hızlandırıcı, Dedektör Simülasyonu, Parçacık Fiziği

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LIST OF ABBREVIATIONS AND SYMBOLS

AIC	: Akaike Information Criterion
AICc	: Akaike Information Criterion Correction
BESIII	: Beijing Spectrometer III
BIC	: Bayesian Information Criterion
CAD	: Computer Aided Design
CDF	: Collider Detector at Fermilab
CERN	: European Organization for Nuclear Research
CM	: Center of Mass, Center-of-Mass
CQM	: Constituent Quark Model
CR	: Collector Ring
DIRC	: Detection of Internal Cherenkov Light
DPM	: Dual Parton Model
EMC	: Electromagnetic Calorimeter
FAIR	: Facility for Antiproton and Ion Research
FS	: Forward Spectrometer
FT	: Forward Tracker
FToF	: Forward Time of Flight
GEM	: Gas Electron Multiplier
GPD	: Generalized Parton Distribution
GSI	: Gesellschaft für Schwerionenforschung, GSI Helmholtzzentrum für Schwerionenforschung
HESR	: High Energy Storage Ring
HV-MAPS	: High Voltage Monolithic Active Pixel Sensors
INP	: Institute of Nuclear Physics in Novosibirsk
LEAR	: Low Energy Antiproton Ring
LHCb	: Large Hadron Collider Beauty Experiment

LMD	: Luminosity Detector
MC	: Monte Carlo
MDS	: Muon Detector System
MDT	: Mini-Drift Tube
MSV	: Modularized Start Version
MVD	: Micro-Vertex Detector
$\bar{\text{P}}\text{ANDA}$	: antiProton ANnihilation at DArmstadt
PAWIAN	: PArtial Wave Interactive ANalysis
PDG	: Particle Data Group
PID	: Particle Identification
PWG	: Physics Working Group
QCD	: Quantum Chromodynamics
QED	: Quantum Electrodynamics
QGP	: Quark-Gluon Plasma
RESR	: Recuperated Experimental Storage Ring
RICH	: Ring Imaging Cherenkov
SM	: Standart Model
STT	: Straw Tube Tracker
ToF	: Time of Flight
TS	: Target Spectrometer
UrQMD	: Ultra Relativistic Quantum Molecular Dynamics
VMC	: Virtual Monte Carlo

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1. INTRODUCTION

1.1 The Standard Model (SM)

According to our current understanding, quarks and leptons are the fundamental building components of matter. In the Standard Model (SM) of particle physics, these particles are described together with the fundamental forces that control their interactions. Collaboration between experimental and theoretical physicists led to the main development of the SM in the second half of the 20th century. Even in cases when the SM accurately describes the observed world, there are still mysteries and some phenomena to be explained. In order to possibly develop and evaluate new models that can improve our understanding of strong interaction, it is crucial to carry out comprehensive measurements of particle attributes.

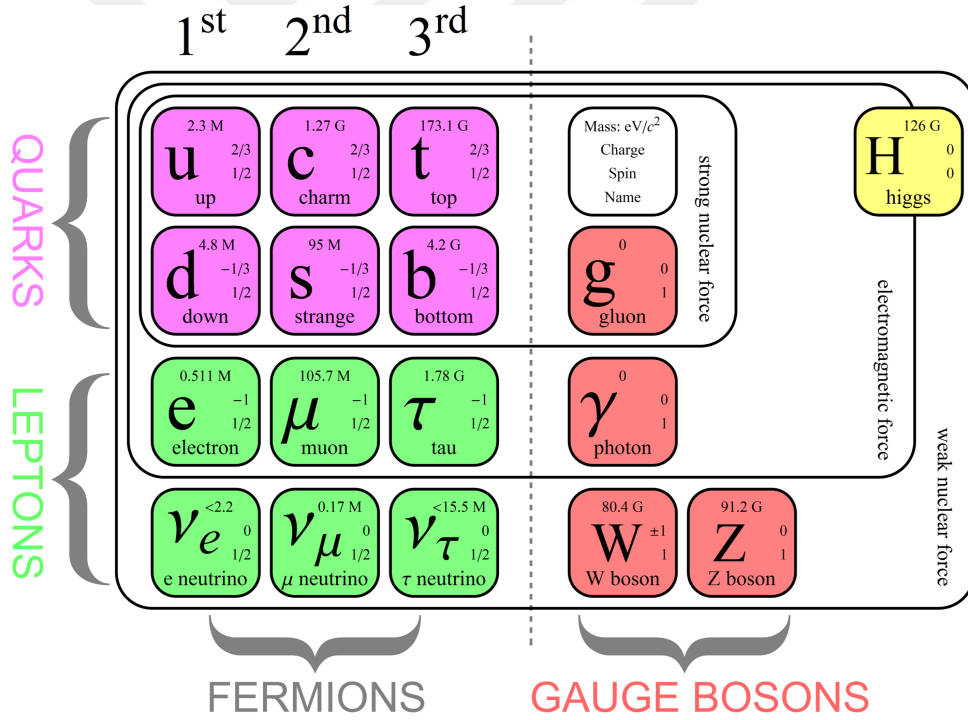


Figure 1.1. The elementary particles which defined by the SM (1).

As in Figure 1.1, SM of particles divided into two groups which are fermions and bosons. According to SM, fermions also divided into two sub-groups which called leptons and quarks. Leptons interact through electromagnetic and weak interactions as well as quarks interact through weak, strong and electromagnetic interactions.

Here, gauge bosons have the spin value of 1, consequently they are vector bosons and the force carriers that mediate electromagnetic, weak as well as strong interactions between particles. Recently, a scalar elementary particle with spin value of zero called the Higgs boson was found. It fundamentally explains why the photon has no mass as well as why fermions with mass are present in the model. It also clarifies the mass of the Z and W bosons. It took several years for experiments to uncover any evidence supporting the notion that the Higgs boson had been discovered, despite years of scientific pursuit. This was not the case until the late 1990s (2, 3).

1.2 The Quark Model

The strong interaction confines quarks within composite particles known as hadrons. Although a complete and quantitative knowledge of the strong dynamics underlying quark-quark interactions in hadrons is still lacking, Gell-Mann (4) and Zweig (5) independently proposed a successful classification scheme for hadrons in the 1960s that is based on the valence quarks of the particles and the underlying symmetries: the Constituent Quark Model (CQM).

In accordance with CQM classification, hadrons are arranged into mass multiplets that are roughly symmetric. The three light flavours (u , d , and s) were considered in the original Gell-Mann (4) scheme because those were the only ones that had been proposed at the time. In these three states, distinct combinations of quarks were said to generate hadrons. This is consistent with the $SU(3)$ symmetry mathematically. Multiplets of one, eight, or ten members are the most basic representations of this symmetry, and they correspond to particles with integer charge. These families must include both mesons, which are bosons made up of a quark-antiquark pair, and baryons, which are fermions made up of three quarks. This description of $SU(3)$ symmetry refers to the light flavour of quarks (u , d , s). The other flavors (c , b , t) were later discovered. Due to their heavier mass, they are difficult to accommodate in an $SU(n)$ symmetry expansion when n is larger than 3. The light hadrons can still be classified and their properties described using the approximate flavour $SU(3)$ symmetry.

A distinct SU(3) symmetry, linked to a quantum degree of freedom named *color*, is the foundation of the strong interaction that bounds quarks in hadrons, as demonstrated by the advent of Quantum Chromodynamics (QCD).

1.3 The Quantum Numbers and Symmetries

According to the current explanation of hadrons, quarks and gluons contain a third quantum number, known as color charge, which classifies three states as red, green, and blue (r, g, b). The strong interaction is caused by the color charge. Whereas an antiquark accepts an anticolor, a quark can only accept one of the three colors. Both a color and an anticolor are carried by gluons. Colorlessness of hadrons is a prerequisite for the color confinement principle. Although there are countless ways to meet this requirement, only mesons and baryons (the two most basic types of hadrons) have been taken into consideration so far (6).

Discrete symmetries also play a very crucial role in the quark model. Charge symmetry (C) replaces each particle by its antiparticle, Time symmetry (T) inverses the direction of time and Parity symmetry (P) represents the simultaneous change in the sign of all three spatial coordinates.

Table 1.1. The quantum numbers and some relations between.

q	Electric charge
B	Baryon number
S	Spin
I_z	Isospin
L	Orbital angular momentum
J	Total angular momentum
C	Charge conjugation
P	Parity

Quantum numbers, which indicate the values of conserved quantities, describe particles. I_z is a quantum number due to the strong interaction and depends on the up and down quark content of the hadron, thus $I_z = 1/2 (N_u - N_d)$, where N_u and N_d are the up and down quark numbers, respectively. The total angular momentum J of a hadron is the orbital angular momentum L between quarks and the total spin

S , which is the combination of the spins of the quarks. S is equal to integer for mesons and half-integer for baryons. Since the charge and parity symmetries are unitary operators, their eigenvalues can only take ± 1 . In mesonic states, the orbital angular momentum and the parity eigenvalue relate via $P = (-1)^{L+1}$. Furthermore, one has $C = (-1)^{L+S}$ for quarkonia, which are eigenstates of the charge conjugation.

1.4 History of Charmonium States and Their Properties

The Quark Model, which was developed in 1964 by scientists Gell-Mann (4) and Zweig (5), a model that provides a convenient framework for the classification of hadrons and a highly successful phenomenological explanation of the observed meson and baryon spectrum. On the other hand, the BaBar Collaboration's 2003 discovery of the $D_s(2317)$ particle (7) is just as intriguing as the 1974 discovery of the J/ψ ($c\bar{c}$) particle (8). Particle physics now has a new direction thanks to this finding. Belle, BESIII, CDF, and LHCb have subsequently investigated a large number of particles with various interior configurations (9-12). A new category was established since these resonant states' spectra and decay models differ greatly from those of regular hadrons. These particles, which do not fit the particle structures known in the Standard Model, are called "exotic particles". These particle structures include XYZ, gluonballs, meson molecules, hybrids, tetraquarks, pentaquarks and hexaquarks. Most of these particles, which are outside the Quark Model of the Standard Model, need to be experimentally verified in laboratories using particle physics collider experiments by analyzing the collision data while searching new physics beyond SM. At the same time, it is thought that research on these particles may provide a new perspective on various topics such as dark matter, dark energy, matter-antimatter asymmetry and the formation of the universe, which have so far remained unexplained in the Standard Model.

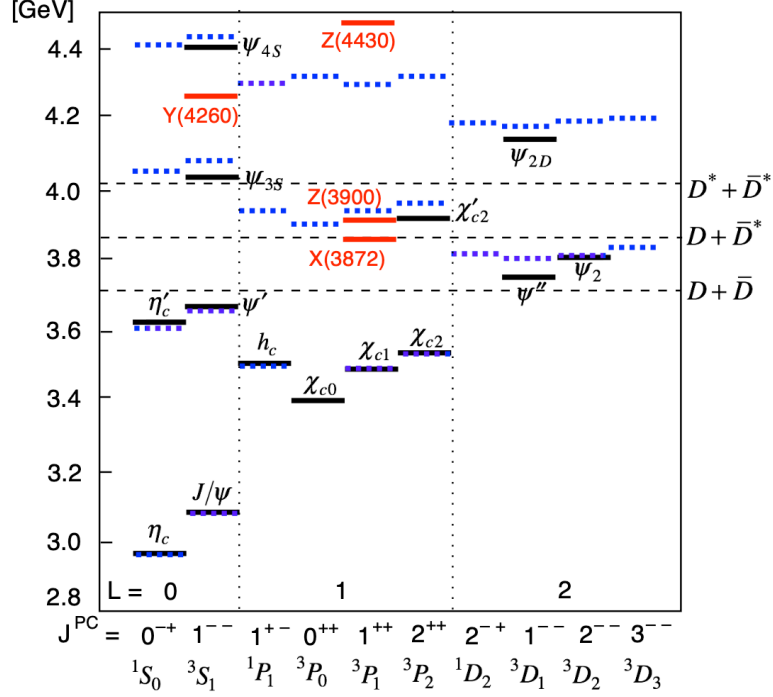


Figure 1.2. Charmonium spectrum sketch (black horizontal lines) with some X, Y, Z states (red horizontal lines) in comparison with a conventional quark model results for $c\bar{c}$ states (blue horizontal dashed lines) (13, 14).

Charmonium and charmonium-like states may specifically point to the non-perturbative behaviour of QCD in the low energy region and have attracted great interest from the hadron physics community (15). A large number of new charmonium and charmonium-like states, also known as XYZ particles, have recently been discovered. Here, XYZ particles represent neutral, hybrid and charged particles, respectively. The Belle experiment (9) first analysed the $B^\pm \rightarrow J/\psi K^\pm \pi^+ \pi^-$ decay in 2003 and discovered an unexpected development in the invariant mass spectrum at 3872 MeV. The particle, named $X(3872)$, was analysed in the CDF (11), D0 (16) and BaBar (17) experiments, and its quantum numbers, mass and decay models were confirmed to have become a candidate for a non-traditional candidate for a harmonium in the years after its discovery. Despite the large number of experimental studies investigating this exotic state, the unusual properties of this particle are mysterious in meson spectroscopy and no agreement has yet been reached on its structure (18). About two years later, the Belle experiment observed a new $B^+ \rightarrow K^+ \omega J/\psi$ decay, $Y(3940)$ (19), which was later confirmed by the BaBar experiment (20). In 2005, the BaBar experiment found the exotic state $Y(4260)$ (21) in the $\pi^+ \pi^- J/\psi$ invariant mass spectrum. The Belle and

CLEO experiments later confirmed the same particle (22). In 2007, the Belle study not only confirmed the existence of the $Y(4260)$ particle, but also discovered the existence of the $Y(4360)$ and $Y(4660)$ states with the same quantum numbers (23). In 2009, the $X(4350)$ state was observed by the Belle collaboration from a two-photon process which is $\gamma\gamma \rightarrow \psi\phi$ (24). These resonance-like structures seen in the $J/\psi\phi$ mass spectrum is very interesting as they can contain both $c\bar{c}$ and $s\bar{s}$ pairs (25). By 2011, the CDF collaboration first found the $Y(4140)$ state in the $J/\psi\phi$ invariant mass distribution from $B^\pm \rightarrow KJ/\psi\phi$ decays (26). In the following years, the CMS and D0 collaborations confirmed the presence of the $Y(4140)$ particle in B decays (27-29). In the last few years, the Belle and BESIII experimental collaborations have observed a charged charmonium-like Z_c^+ family such as $Z_c^+(4430)$ (30), $Z_1^+(4050)$ (31), $Z_2^+(4250)$ (31), $Z_c^+(3900)$ (32), $Z_c^+(3885)$ (33), $Z_c^+(3930)$ (34), $Z_c^+(4020)$ (35), $Z_c^+(4025)$ (36), $Z_c^+(4475)$ (30) and $Z_c^+(4200)$ (37). These charged charmonium-like states go beyond the traditional $c\bar{c}$ -meson picture and include $c\bar{c}u\bar{d}$ tetraquark systems, as they carry a charge. Therefore, they provide a suitable setting for evaluating various phenomenological research methods of hadron physics (38). Additionally, the main characteristics of some the XYZ states are summarized in Table 1.2.

Table 1.2. Summary of the main properties of some of the XYZ states (39, 40).

State	M (MeV/c ²)	Γ (MeV/c ²)	Decay Modes	Production Modes	Seen by
$Y_s(2175)$	2175 ± 8	58 ± 26	$\phi f_0(980)$	$e^+e^-, J/\psi$ decay	BaBar, BES
$X(3872)$	3871.4 ± 0.6	< 2.3	$\pi^+\pi^-J/\psi$, $\gamma J/\psi$	$B \rightarrow X(3872) K, p\bar{p}$	Belle, BaBar, CDF, D0
$X(3875)$	3875.5 ± 1.5	$3.0^{+2.1}_{-1.7}$	$D^0\bar{D}^0\pi^0, D\bar{D}^*$	$B \rightarrow X(3875) K$	Belle, BaBar
$Z(3940)$	3929 ± 5	29 ± 10	$D\bar{D}$	$\gamma\gamma$	Belle
$X(3940)$	3942 ± 9	37 ± 17	$D\bar{D}^*$	$e^+e^- \rightarrow X(3940)J/\psi$	Belle
$Y(3940)$	3943 ± 17	87 ± 34	$\omega J/\psi$	$B \rightarrow Y(3940) K$	Belle, BaBar
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$D^*\bar{D}^*$	$e^+e^- \rightarrow X(4160)J/\psi$	Belle
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	$\pi^+\pi^-J/\psi$	e^+e^-	Belle
$Y(4260)$	4264 ± 12	83 ± 22	$\pi^+\pi^-J/\psi$	e^+e^-	BaBar, Belle, CLEO
$Y(4350)$	4361 ± 13	74 ± 18	$\pi^+\pi^-\psi(2S)$	e^+e^-	BaBar, Belle
$Y(4660)$	4664 ± 12	48 ± 15	$\pi^+\pi^-\psi(2S)$	e^+e^-	Belle
$Z_1^+(4050)$	4051 ± 14	82^{+21}_{-17}	$\pi^+\chi_{c1}$	$B^0 \rightarrow Z_1^+(4050) K^-$	Belle
$Z_2^+(4250)$	4248^{+44}_{-29}	177^{+54}_{-39}	$\pi^+\chi_{c1}$	$B^0 \rightarrow Z_2^+(4250) K^-$	Belle
$Z^\pm(4430)$	4433 ± 5	45^{+35}_{-18}	$\pi^\pm\psi(2S)$	$B \rightarrow Z^\pm(4430) K$	Belle

1.5 $Z(4430)$ Exotic State

As Gell-Mann put it in the original work when he presented the Quark Model (4), mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc., while baryons can now be constructed from quarks using the combinations (qqq) , $(qqqq\bar{q})$, etc. to generate the representations describing the known meson and baryon states, he selected the lowest configurations. Higher configurations were not, however, automatically ruled out, and ever since, researchers and theoretical physicist have been looking for proof that these states exist.

Over the years, the $a_0(980)$ and $f_0(980)$ scalar mesons have received the most interest in the meson sector as potential four-quark states. However, the observation of numerous new charmonium-like states above the threshold for decay to open charm, along with the discovery of the $D_{s0}^*(2317)$ and the $D_{s1}(2460)$, with their unexpectedly low mass values, have given rise to speculation that some of these may be four-quark states (see e.g. (41)), though this has never been definitively established. This is why the Belle Collaboration work (30) that describes the detection of a resonance-like structure, the $Z(4430)^-$, in the

$\psi(2S)\pi^-$ system created in the decays $B^{-,0} \rightarrow \psi(2S)\pi^- K^{0,+}$ (42) has attracted a lot of attention. This kind of state would be the most evident example (first detrminate evidence for the existence of mesons beyond traditional $q\bar{q}$ model) of a four-quark meson state which must have a minimum quark content ($c\bar{c}d\bar{u}$) (Figure 1.3).

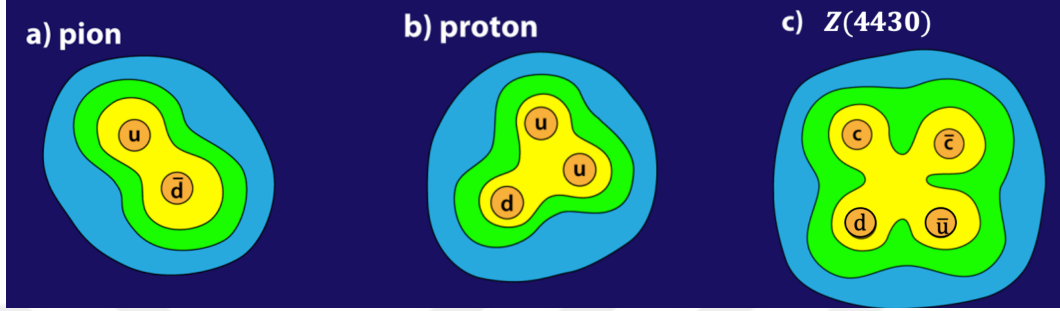


Figure 1.3. Some illustrations and explanations for the quark contents for example traditional particles and $Z(4430)$.

The Belle Collaboration reported a distinct peak in the $\pi^\pm\psi'$ invariant mass distribution in $B \rightarrow K\pi^\pm\psi'$ decay in 2007 (published in 2008). The measured mass and width were $M = 4433 \pm 4(\text{stat})2(\text{syst})$ MeV and $\Gamma = 45^{+18}_{-13}(\text{stat})^{30}_{-13}(\text{syst})$ MeV, respectively (30). Then, the Belle Collaboration discovered evidence for $Z^+(4430) \rightarrow J/\psi \pi^+$ while observing the new charmonium-like state $Z_c^+(4200)$ (37).

For the $Z(4430)^-$ state, the BaBar results (42) did not conflict with the Belle evidence. Subsequently, the Belle collaboration updated their results for $Z(4430)^-$ using a two-dimensional (43, 44) and later a four-dimensional (4D) amplitude analysis (43, 45). This led to $Z(4430)^-$ significance of 5.2σ , a mass of $M_{Z(4430)^-} = 4485 \pm 22^{+28}_{-11}$ MeV, a large width of $\Gamma_{Z(4430)^-} = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV.

The LHCb Collaboration ascribed a spin-parity of 1^+ for the first independent confirmation. The mass of the resonance, $4475 \pm 7^{+15}_{-25}$ MeV, and its width, $172 \pm 13^{+37}_{-34}$ MeV, were measured (44).

According to Particle Data Group (PDG), mass and width of $Z(4430)$ are shown in Figure 1.4 below.

$Z_c(4430)$ $I^G(J^{PC}) = 1^+(1^{+-})$ G, C need confirmation.			
was $X(4430)^\pm$ Properties incompatible with a $q\bar{q}$ structure (exotic state). See the review on non- $q\bar{q}$ states. First seen by CHOI 2008 in $B \rightarrow K\pi^+\psi(2S)$ decays, confirmed by AAIJ 2014AG , and confirmed in a model-independent way by AAIJ 2015BH . Also seen by CHILIKIN 2014 in $B \rightarrow K^+\pi J/\psi$ decays. J^P was determined by CHILIKIN 2013 and AAIJ 2014AG .			
$Z_c(4430)$ MASS	4478⁺¹⁵₋₁₈ MeV		▼
$Z_c(4430)$ WIDTH	181 ± 31 MeV		▼
$Z_c(4430)$ DECAY MODES			
Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1 $\pi^+\psi(2S)$	seen		711 ▼
Γ_2 π^+J/ψ	seen		1162 ▼

Figure 1.4. Mass and width of Z(4430) according to PDG (values shown with blue font are their average values for mass and width) (46).

2. OUTLINE OF FAIR

The Facility for Antiproton and Ion Research (FAIR) is a worldwide accelerator for ion and antiproton research which located in Europe. In Darmstadt, Germany, FAIR is currently under construction. FAIR's scientific research program is built around four experiments. These experiments address fundamental problems concerning the structure of matter and the development of the cosmos, also including baryonic matter, nuclear structure, atomic and plasma physics, antiproton-induced hadron physics, astrophysics and nuclear structure. $\bar{\text{P}}\text{ANDA}$ expected to be one of these experiments. More information about accelerators at FAIR and technical data can be found in technical report (47).

2.1 antiProton ANnihilation at DArmstadt ($\bar{\text{P}}\text{ANDA}$)

One of the most important experiments at FAIR is $\bar{\text{P}}\text{ANDA}$. Its aim is to study the dynamics as well as structure of hadrons. The experiment explores fundamental physical topics such as strong and weak forces, exotic states of matter and the structure of hadrons. The $\bar{\text{P}}\text{ANDA}$ detector includes a number of sub-detectors for trajectory reconstruction, energy and momentum measurement, and efficient identification of charged particles (48).

Chapter 3 contains a more detailed description of the detector and the physical layout of $\bar{\text{P}}\text{ANDA}$ which is also one of the main topics and motivations of this thesis study.

2.2 FAIR Accelerator Facility

2.2.1 High Energy Storage Ring (HESR)

HESR, a key component of FAIR's physics program, is designed and optimized for high energy antiprotons. Charmonium, hadronic structure and quark-gluon dynamics are the main research topics planned at the HESR.

The storage ring has an elliptical shape which is like a racetrack with a circumference of 574 m (49). There are two 132 m long straight sections. One of the flat sections is dedicated to the kicker of the stochastic cooling and the electron cooling system. The second straight section contains the stochastic collection (pick-

up) and the $\bar{\text{PANDA}}$ experiment. The design uses 48 dipole magnets to achieve a peak rigidity of 50 T·m.

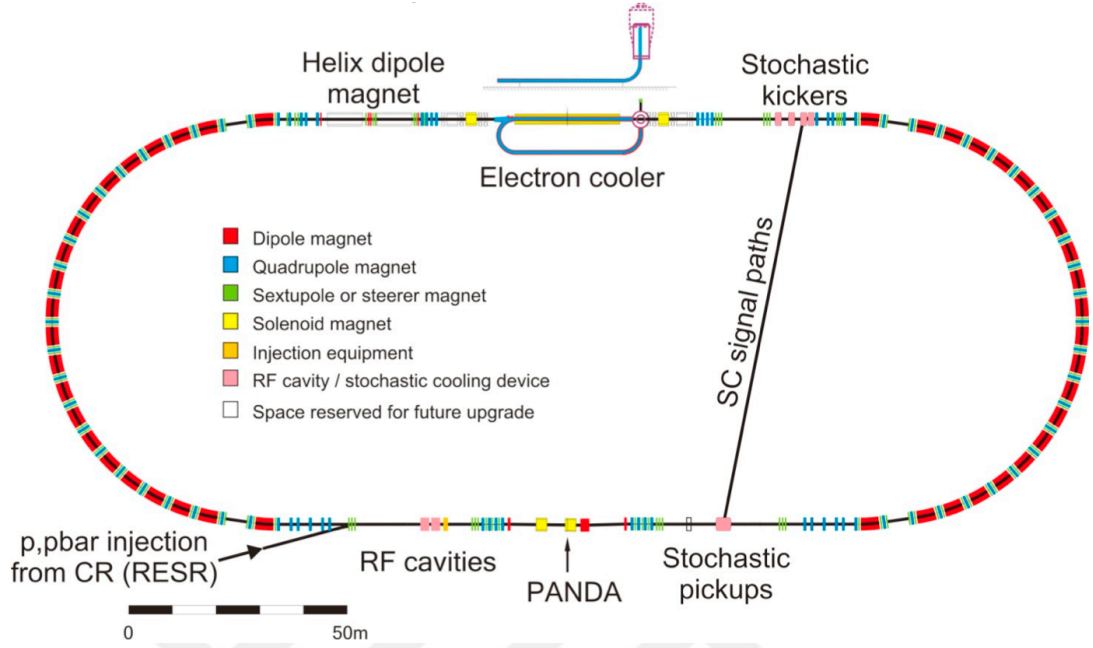


Figure 2.1. HESR illustration (49).

Two different cooling techniques for HESR are used to ensure high beam luminosity and quality. First method is the electron cooling which is to shrink the six-dimensional phase space (Spatial Volume x Volume in Momentum Space) of a charged particle beam while keeping the number of particles the same. In 1966, at the Institute of Nuclear Physics in Novosibirsk (INP), Gersh Budker developed the electron cooling method (50). This method involves combining a beam of quasi-monoenergetic electrons with the beam to be cooled. Here, the average velocity of the particles inside the beam is equal to the average velocity of the electrons. The velocity distribution of the electrons is represented by a delta-function on the scale of both the longitudinal and transverse velocity distribution of the beam. If we use a thermodynamical explanation, beams of ions or hadrons are hot and beams of electrons are cold. Due to the Coulomb scattering of electrons in a gas-like environment, the momentum interchanged until a thermodynamic equilibrium is reached. This thermodynamic equilibrium occurs when the average electron and ion velocities are equal. As a result, the energy spread for ions is reduced and the engaged six-dimensional phase space shrinks due to the previously described interactions. The magnetic hardness for electrons is lower than for ions with the

same velocity by a factor of m_e/M because of the lighter mass of the electrons, where M here is the mass of the particle to be cooled. Afterwards, a dipole magnet can easily separate and bend the electron beam from the antiproton beam (49).

The particle's dispersal in position and momentum phase space is driven by stochastic cooling which is the second cooling technique. Simon van der Meer developed this technique at CERN in 1972 (51), primarily for the purpose of gathering and cooling antiprotons. In this beam damping (cooling) method, an electrical signal is sent across the storage ring by a device called as a "pick-up system," which evaluates the momentum of the particles in the beam and corrects the momentum with a device known as a "kicker." Independent pick-up and kicker systems are employed for each coordinate, transverse and longitudinal (51).

For the HESR, two operation modes are expected: High resolution and high luminosity (52). In high resolution mode, luminosities up to $2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ and a momentum spread of $\Delta p/p = 4 \cdot 10^{-5}$ can be provided. On the other hand, in high luminosity mode, peak luminosity of $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and a momentum spread of $\Delta p/p = 10^{-4}$ also be provided (52).

The operation of HESR in the high luminosity mode is not supported since the Recuperated Experimental Storage Ring (RESR) is not available at the start of the gradual realization of FAIR, it is requiring a change in the injection and accumulation for the antiprotons (53). The antiprotons in the Modularized Start Version (MSV) are gathered and cooled in the Collector Ring (CR). Then, HESR is injected with an antiproton packet containing roughly 10^8 antiprotons for accumulation. Since the antiprotons cannot be employed for experiments during the accumulation, the accumulation inside the HESR results in an additional loss factor for the previously injected antiprotons. Measurements, acceleration, and accumulation occur roughly about every 30 minutes (53). As soon as it becomes available, the antiprotons will be accumulated in the RESR in the latter stage which will allows the injection of antiprotons up to 10^{11} in the HESR.

3. $\bar{\text{P}}\text{ANDA}$ EXPERIMENT AT FAIR

$\bar{\text{P}}\text{ANDA}$ is intended to be used as an internal detector for High Energy Storage Ring (HESR) and is also currently under development. The broad physics program looks at fundamental issues in hadron and nuclear physics with the goal of learning more about strong interactions and hadron structure. By examining observations of unusual states like glueballs and hybrids as well as the spectra of charmonium, D meson, and baryons, $\bar{\text{P}}\text{ANDA}$ will considerably contribute to the resolution of these unanswered puzzles. Furthermore, new paths for studying the dynamics of the forces between nucleons and hyperons will be made possible (48).

The theory of the strong interaction between quarks and gluons, known as QCD is still one of the most intricate and successful parts of the Standard Model of particle physics. However, it is not without its unresolved mysteries. Despite our understanding of quarks' asymptotic freedom at high energy, the mechanism responsible for binding quarks into color-neutral states at low energies remains unclear. Furthermore, the system by which quarks acquire their masses, either via the Higgs mechanism or other variables, and how important of chiral symmetry breaking in mass creation are critical topics of research. While gluons are massless in QCD theory, they are never seen as free particles, prompting issues regarding why this is the case and what gluon self-interactions mean for understanding QCD features. Another major challenge is the strong CP problem, which explains why CP symmetry violation in strong interactions is substantially lower than theoretically predicted. The development and evolution of Quark-Gluon Plasma (QGP) during the early phases of heavy-ion collisions, as well as its transport characteristics including viscosity and thermal conductivity, are other important subjects. Understanding how non-perturbative processes in QCD, such as instantons and topological excitations, fit into the theoretical framework and their impacts on confinement and mass creation is critical. Furthermore, hadronization, the process by which quarks and gluons combine to generate color-neutral hadrons in high-energy collisions, demands more detailed explanations based on QCD principles. Finally, enhancing the precision of QCD predictions for high-energy and high-momentum transfers, as well as understanding the limitations of perturbative vs non-perturbative approaches across various energy regimes, are critical for

progressing both theoretical and experimental physics in this field. These questions highlight the ongoing complexities and current research in QCD (54).

In this chapter of this thesis study, the $\bar{\text{PANDA}}$ physics program, detector and sub-detector systems as well as the software structure of the experiment will be briefly explained.

3.1 Overview of the Physics Program at $\bar{\text{PANDA}}$

The $\bar{\text{PANDA}}$ detector is located at HESR and the researches of interactions between the antiproton beam and the fixed target protons and nuclei practiced here. The antiprotons will have momenta of 1.5 GeV/c and 15 GeV/c (interrelated to energies between $\sqrt{s} = 2.25$ GeV and $\sqrt{s} = 5.47$ GeV). The research program focuses mostly on the non-perturbative domain and seeks answers to fundamental questions in QCD. The high cross-section of antiproton driven reactions will be advantageous for the intended measurements. $\bar{p}p$ collisions, in addition to e^+e^- driven processes, permit all non-exotic quantum number combinations for states that are directly produced. Production reactions will also reveal states with exotic quantum numbers. Only the modest energy spread of the cooled antiproton beam limits the great precision that may be attained in the direct generation of resonant states. The states with narrow widths can also be measured thanks to this high precision (48).

3.1.1 Exotics Excitations

The results of a Monte Carlo (MC) research for energy scan measurements, including a specific example of the charmonium-like $X(3872)$ state, were published in 2019 by the $\bar{\text{PANDA}}$ Collaboration (55). The Belle Collaboration discovered the $X(3872)$ state in 2003 (9), and because of its quantum numbers, it does not fit into the convenient quark model which makes it a distinguished candidate for an exotic state. The study has demonstrated that measuring $X(3872)$'s natural width and line form using $\bar{\text{PANDA}}$ is feasible.

Glueballs

According to the model description, glueballs only contain constituent gluons, not constituent quarks. For the mass region of HESR, theoretical evaluations predict 15 glueball states (56). It is anticipated that a few of these states would have exotic quantum numbers and if they have non-exotic quantum numbers, they will mix with ordinary mesons.

Either directly in antiproton-proton annihilations or in conjunction with another particle, glueball states can be formed. Thus far, two experiments (JetSet and Obelix Collaborations) at the Low Energy Antiproton Ring (LEAR) have detected indications of glueball existence (57, 58). Analogous investigations with statistics two orders of magnitude greater than those of earlier trials will be feasible under the $\bar{\text{P}}\text{ANDA}$ experiment (48).

Hybrids

Hybrid states are $q\bar{q}$ states that excited by one or more constituent gluons. The extra degrees of freedom, such as vibrations, contribute to the quantum numbers that are not probable for ordinary mesons. It is expected that charmonium hybrids will have masses between 3 GeV/c² and 5 GeV/c² region. $\bar{\text{P}}\text{ANDA}$ aims to cover both exotic and non-exotic states by employing charmonium hybrids at high antiproton energies of 15 GeV (48).

Multiquarks

The quark pattern of hadrons has not any specific limitation by QCD. Nonetheless, traditional attire as well as settings that are foreign should be color-neutral. Hadrons consisting of four, five, or six quarks and antiquarks are possible they are called “multiquarks”. As previously mentioned before at Section 1.4, tetraquarks are hadrons with $qq\bar{q}\bar{q}$ content that are tightly bound states with a diquark-antidiquark structure. For the mesons $a(980)$ and $f(980)$, a bound state consisting of two mesons was first proposed by (59). As observed by Belle (9), this concept was also used for $X(3872)$ by (41). More recently, Belle (60) and BESIII (32) have separately observed the $Z_c(3900)$ which is another potential tetraquark.

Numerous measurements attempt to access multi-quark states, but the statistical significance is too low to provide a definitive answer. More precise data will be possible to gathered at $\bar{P}$ ANDA for further understanding of multi-quarks, especially in the meson sector (48).

3.1.2 Heavy-Light Systems

D meson is made up of a light quark and a charm quark as heavy quark. D mesons are gripping because they have the heavy quark as a static color source which helps to understand the strong interaction. For instance, D meson with strange content, also named D_s is different while the experimentally observed D meson spectrum is compatible with the theoretical predictions. The new observed D_s states are not consistent with the quark-model predictions for heavy-light mesons, as demonstrated in Figure 3.1 below.

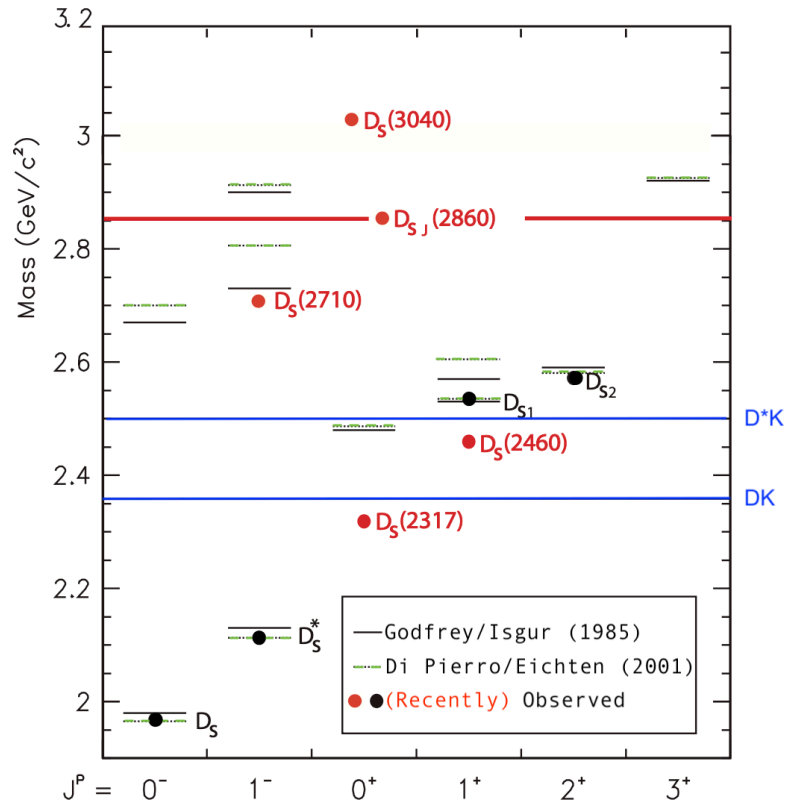


Figure 3.1. The D_s meson spectrum as predicted by Godfrey and Isgur (13) (black solid lines) and by Di Pierro and Eichten (61) (black and green dotted lines). Experimental values are shown by points; red ones to newly discovered ones and black points refer to old measured states. The blue solid lines refer the thresholds for the decays into D^*K and DK pairs. Image taken and adapted from (62).

At $\bar{\text{PANDA}}$, the D_s width in a threshold scan with high energy resolution in the order of 100 keV will be possible due to the low momentum spread in the HESR (63, 64). Here, this referred energy scan will gain importance after the RESR has been added into FAIR because of the narrow cross-sections.

3.1.3 Hypernuclei

Systems called hypernuclei have hyperons instead of nucleons and this results in the strangeness being introduced into the nucleus as a new quantum number. Single and double Λ hypernuclei have been found thus far (65). In practical terms, it is possible to produce hypernuclei efficiently using a $\bar{p}$ beam. The possibility of exact multi-strange hypernucleus spectroscopy at $\bar{\text{PANDA}}$ will allow one to investigate hyperon-hyperon interactions. Consequently, to generate double Λ hypernuclei, a two-step production procedure is performed, as shown in Figure 3.2 below, using a bound Ξ hypernuclear state as the gateway for this production mechanism (66). This process requires a highly adaptable and modular configuration of the central $\bar{\text{PANDA}}$ detector and also specialized runs for studies of hypernuclei (Figure 3.2).

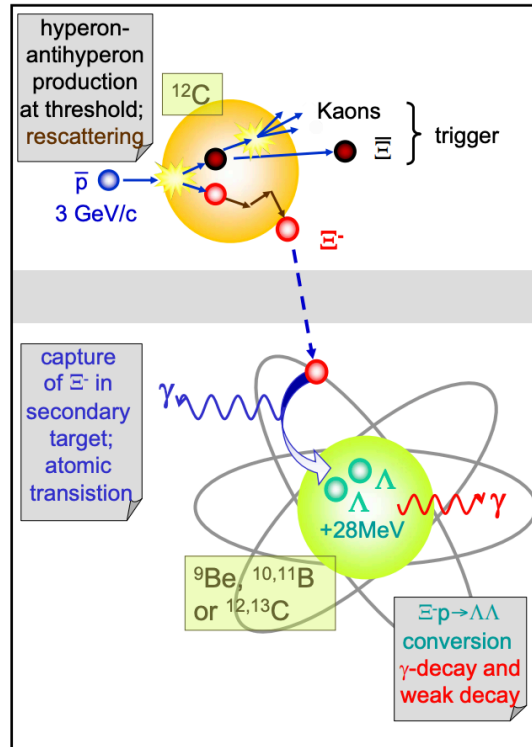


Figure 3.2. Double hypernucleus production steps in $\bar{\text{PANDA}}$ (48).

3.1.4 Nucleon Structure

Studies that involve QCD's perturbative elements will also be performed at $\bar{\text{P}}\text{ANDA}$. These investigations will provide the chance to examine the class of hard exclusive processes, enabling understanding of the intermediate region (48).

Electromagnetic Form Factors of the Proton in the time-like Region

Electromagnetic form factors show the electromagnetic charge distribution of hadrons. As a result, they are very good surveys to investigate how the nucleon structure is formed. In general, particles with $1/2$ spin have two form factors: the electric (G_E) and the magnetic (G_M). Measurements have been made using $\bar{p}p$ and e^+e^- collisions in various experiments such as BaBar (67), LEAR (68) and BESIII (69). However, the findings are not consistent or have large uncertainties. Here, the $\bar{\text{P}}\text{ANDA}$ detector will bring possibilities to detect electromagnetic form factors in a time-like region with high accuracy (48). High luminosity and strong particle identification of $\bar{\text{P}}\text{ANDA}$ enable precise measurements of form factors up to $q^2 = 14 (\text{GeV})^2$ (70).

Generalized Parton Distribution

In order to handle hard exclusive processes in lepton scattering studies, a theoretical framework for Generalized Parton Distributions (GPDs) (71) has recently been developed. The processes are difficult to measure because of the narrow cross-sections. At $\bar{\text{P}}\text{ANDA}$ it is foreseen to study the reaction $\bar{p}p \rightarrow \gamma\gamma$ and with $\bar{\text{P}}\text{ANDA}$'s 4π electromagnetic calorimeter and high luminosity features should allow for the separation of this process from the hadronic background (72).

3.1.5 Charmed and Strange Baryons

Uncovering the baryon excitation spectrum is one of the primary objectives of non-perturbative QCD. The nucleon sector has been the main focus of experiments so far, however there is small agreement with the quark model. While higher states are not seen in experiments, the energy of low-lying states do not pair with the predictions (73). "Missing resonances" refers to this absence of higher states (74).

Strange Baryons

Understanding the spectrum of every weird baryon species, such as Λ , Σ , Ξ , and Ω is vital to answer the question of whether the excited spectra of baryons with light quark content (u , d , and s quarks) follow $SU(3)$ symmetry. In inclusive experiments, Ξ and Ω baryon excited states have been observed as bumps, primarily from bubble chamber experiments. There are no assignments for Ω baryons, however one assignment was reached on $\Xi(1530)^0$ and conducted some theoretical research on the Ξ and Ω spectrum has been done by (75, 76). However, additional experimental evidence is required to validate these calculations.

Given that channels producing baryon and antibaryon pairs account for a significant portion of the inelastic cross-section in $\bar{p}p$ collisions, the $\bar{P}$ ANDA detector is ideally suited for an extensive baryon spectroscopy program. Strange, multi-strange and charm baryons can be characterized by their displaced vertices or the displaced vertices of their daughter particles. It is possible to specify the characteristic displaced vertices because of the $\bar{P}$ ANDA tracking detectors' good capabilities (see Section 3.2.3) and the yields for Ξ^* and $\bar{\Xi}^*$ will be enough for gathering high statistical data samples (48).

3.1.6 Charmonium

Charmonium is a $c\bar{c}$ pair which has similar characteristics with positronium. A Coulomb potential plus extra terms for spin-spin, spin-orbit and Quantum Electrodynamics (QED) effects describe the interaction inside the positronium, while a Coulomb-like potential plus a linear component can be used to describe the charmonium interaction. An illustration of detailed charmonium spectrum is shown in Figure 3.3 below.

3.3. Detailed charmonium spectrum illustration. Blue dashed lines represent the $1S$, $1D$, $1D'$, $1F$, $1F'$, $1G$, $1G'$, $1H$, $1H'$, $1I$, $1I'$, $1J$, $1J'$, $1K$, $1K'$, $1L$, $1L'$, $1M$, $1M'$, $1N$, $1N'$, $1O$, $1O'$, $1P$, $1P'$, $1Q$, $1Q'$, $1R$, $1R'$, $1S$, $1S'$, $1T$, $1T'$, $1U$, $1U'$, $1V$, $1V'$, $1W$, $1W'$, $1X$, $1X'$, $1Y$, $1Y'$, $1Z$, $1Z'$, $1AA$, $1AA'$, $1AB$, $1AB'$, $1AC$, $1AC'$, $1AD$, $1AD'$, $1AE$, $1AE'$, $1AF$, $1AF'$, $1AG$, $1AG'$, $1AH$, $1AH'$, $1AI$, $1AI'$, $1AJ$, $1AJ'$, $1AK$, $1AK'$, $1AL$, $1AL'$, $1AM$, $1AM'$, $1AN$, $1AN'$, $1AO$, $1AO'$, $1AP$, $1AP'$, $1AQ$, $1AQ'$, $1AR$, $1AR'$, $1AS$, $1AS'$, $1AT$, $1AT'$, $1AU$, $1AU'$, $1AV$, $1AV'$, $1AW$, $1AW'$, $1AX$, $1AX'$, $1AY$, $1AY'$, $1AZ$, $1AZ'$, $1BA$, $1BA'$, $1BB$, $1BB'$, $1BC$, $1BC'$, $1BD$, $1BD'$, $1BE$, $1BE'$, $1BF$, $1BF'$, $1BG$, $1BG'$, $1BH$, $1BH'$, $1BI$, $1BI'$, $1BJ$, $1BJ'$, $1BK$, $1BK'$, $1BL$, $1BL'$, $1BM$, $1BM'$, $1BN$, $1BN'$, $1BO$, $1BO'$, $1BP$, $1BP'$, $1BQ$, $1BQ'$, $1BR$, $1BR'$, $1BS$, $1BS'$, $1BT$, $1BT'$, $1BU$, $1BU'$, $1BV$, $1BV'$, $1BW$, $1BW'$, $1BX$, $1BX'$, $1BY$, $1BY'$, $1BZ$, $1BZ'$, $1CA$, $1CA'$, $1CB$, $1CB'$, $1CC$, $1CC'$, $1CD$, $1CD'$, $1CE$, $1CE'$, $1CF$, $1CF'$, $1CG$, $1CG'$, $1CH$, $1CH'$, $1CI$, $1CI'$, $1CJ$, $1CJ'$, $1CK$, $1CK'$, $1CL$, $1CL'$, $1CM$, $1CM'$, $1CN$, $1CN'$, $1CO$, $1CO'$, $1CP$, $1CP'$, $1CQ$, $1CQ'$, $1CR$, $1CR'$, $1CS$, $1CS'$, $1CT$, $1CT'$, $1CU$, $1CU'$, $1CV$, $1CV'$, $1CW$, $1CW'$, $1CX$, $1CX'$, $1CY$, $1CY'$, $1CZ$, $1CZ'$, $1DA$, $1DA'$, $1DB$, $1DB'$, $1DC$, $1DC'$, $1DD$, $1DD'$, $1DE$, $1DE'$, $1DF$, $1DF'$, $1DG$, $1DG'$, $1DH$, $1DH'$, $1DI$, $1DI'$, $1DJ$, $1DJ'$, $1DK$, $1DK'$, $1DL$, $1DL'$, $1DM$, $1DM'$, $1DN$, $1DN'$, $1DO$, $1DO'$, $1DP$, $1DP'$, $1DQ$, $1DQ'$, $1DR$, $1DR'$, $1DS$, $1DS'$, $1DT$, $1DT'$, $1DU$, $1DU'$, $1DV$, $1DV'$, $1DW$, $1DW'$, $1DX$, $1DX'$, $1DY$, $1DY'$, $1DZ$, $1DZ'$, $1EA$, $1EA'$, $1EB$, $1EB'$, $1EC$, $1EC'$, $1ED$, $1ED'$, $1EE$, $1EE'$, $1EF$, $1EF'$, $1EG$, $1EG'$, $1EH$, $1EH'$, $1EI$, $1EI'$, $1EJ$, $1EJ'$, $1EK$, $1EK'$, $1EL$, $1EL'$, $1EM$, $1EM'$, $1EN$, $1EN'$, $1EO$, $1EO'$, $1EP$, $1EP'$, $1EQ$, $1EQ'$, $1ER$, $1ER'$, $1ES$, $1ES'$, $1ET$, $1ET'$, $1EU$, $1EU'$, $1EV$, $1EV'$, $1EW$, $1EW'$, $1EX$, $1EX'$, $1EY$, $1EY'$, $1EZ$, $1EZ'$, $1FA$, $1FA'$, $1FB$, $1FB'$, $1FC$, $1FC'$, $1FD$, $1FD'$, $1FE$, $1FE'$, $1FF$, $1FF'$, $1FG$, $1FG'$, $1FH$, $1FH'$, $1FI$, $1FI'$, $1FJ$, $1FJ'$, $1FK$, $1FK'$, $1FL$, $1FL'$, $1FM$, $1FM'$, $1FN$, $1FN'$, $1FO$, $1FO'$, $1FP$, $1FP'$, $1FQ$, $1FQ'$, $1FR$, $1FR'$, $1FS$, $1FS'$, $1FT$, $1FT'$, $1FU$, $1FU'$, $1FV$, $1FV'$, $1FW$, $1FW'$, $1FX$, $1FX'$, $1FY$, $1FY'$, $1FZ$, $1FZ'$, $1GA$, $1GA'$, $1GB$, $1GB'$, $1GC$, $1GC'$, $1GD$, $1GD'$, $1GE$, $1GE'$, $1GF$, $1GF'$, $1GG$, $1GG'$, $1GH$, $1GH'$, $1GI$, $1GI'$, $1GJ$, $1GJ'$, $1GK$, $1GK'$, $1GL$, $1GL'$, $1GM$, $1GM'$, $1GN$, $1GN'$, $1GO$, $1GO'$, $1GP$, $1GP'$, $1GQ$, $1GQ'$, $1GR$, $1GR'$, $1GS$, $1GS'$, $1GT$, $1GT'$, $1GU$, $1GU'$, $1GV$, $1GV'$, $1GW$, $1GW'$, $1GX$, $1GX'$, $1GY$, $1GY'$, $1GZ$, $1GZ'$, $1HA$, $1HA'$, $1HB$, $1HB'$, $1HC$, $1HC'$, $1HD$, $1HD'$, $1HE$, $1HE'$, $1HF$, $1HF'$, $1HG$, $1HG'$, $1HH$, $1HH'$, $1HI$, $1HI'$, $1HJ$, $1HJ'$, $1HK$, $1HK'$, $1HL$, $1HL'$, $1HM$, $1HM'$, $1HN$, $1HN'$, $1HO$, $1HO'$, $1HP$, $1HP'$, $1HQ$, $1HQ'$, $1HR$, $1HR'$, $1HS$, $1HS'$, $1HT$, $1HT'$, $1HU$, $1HU'$, $1HV$, $1HV'$, $1HW$, $1HW'$, $1HX$, $1HX'$, $1HY$, $1HY'$, $1HZ$, $1HZ'$, $1IA$, $1IA'$, $1IB$, $1IB'$, $1IC$, $1IC'$, $1ID$, $1ID'$, $1IE$, $1IE'$, $1IF$, $1IF'$, $1IG$, $1IG'$, $1IH$, $1IH'$, $1II$, $1II'$, $1IJ$, $1IJ'$, $1IK$, $1IK'$, $1IL$, $1IL'$, $1IM$, $1IM'$, $1IN$, $1IN'$, $1IO$, $1IO'$, $1IP$, $1IP'$, $1IQ$, $1IQ'$, $1IR$, $1IR'$, $1IS$, $1IS'$, $1IT$, $1IT'$, $1IU$, $1IU'$, $1IV$, $1IV'$, <

Hybrids are the charmonium states which have excited gluonic degree of freedom. Molecular states mean if two mesons are loosely bound by two mechanisms which are quark/color exchange for short-distance interactions and pion exchange for larger distances. Here, expected dominative mechanism is the pion exchange. Tetraquarks are tightly bound four-quark states that have distinct characteristics from molecular states. Their diquark-antidiquark contexture grouped in color-triplet scalar and vector clusters where spin-spin interactions are the prepotent interactions.

Until now, the best resolution $\delta p/p = 10^{-4}$ and the best luminosity $2 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ were achieved in the Fermilab experiments which are E760 (77) and E835 (78). The design of the $\bar{\text{P}}\text{ANDA}$ detector is intended for charmonium physics and utilizes the entire mass region above and below the open-charm threshold. The momentum resolution of $\bar{\text{P}}\text{ANDA}$ will be $4 \cdot 10^{-5}$ in high-resolution mode as well as the high luminosity mode will be ten times higher than the luminosity achieved by Fermilab (48). During a working day of the detector, it will be possible to collect a large number of $c\bar{c}$ states at full luminosity mode.

3.2 The $\bar{\text{P}}\text{ANDA}$ Detector

To achieve the full physics potential of $\bar{\text{P}}\text{ANDA}$ which briefly explained in previous Section 3.1, different requirements for various detector parts are needed. In general terms, you need a modular and adaptable architecture, comprehensive angular coverage, high resolution in a wide range of energies, good particle identification, and the capability to detect charged and neutral particles.

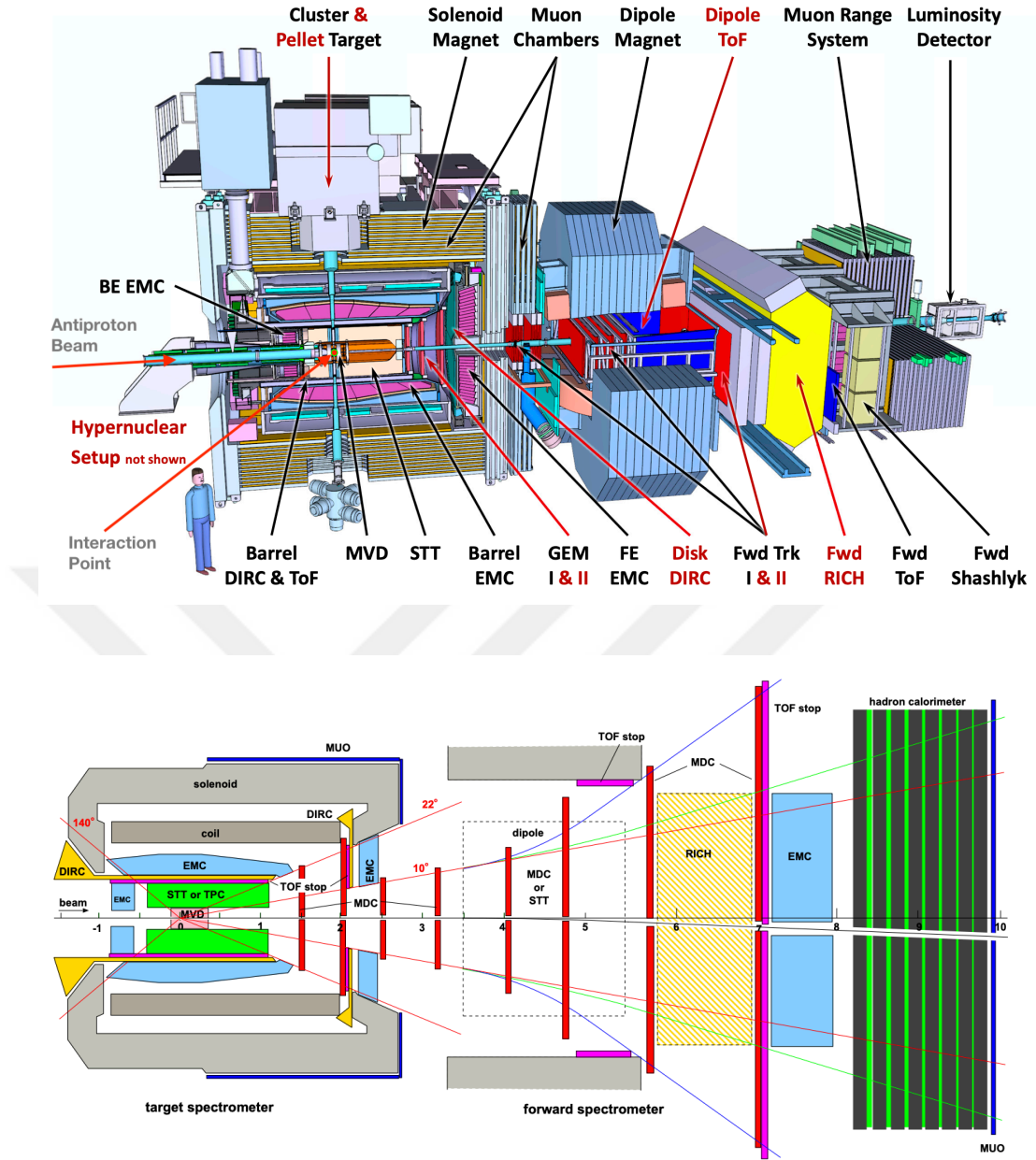


Figure 3.4. Side (at top) and top view (at bottom) of $\bar{\text{P}}\text{ANDA}$ detector illustrations. The Forward Spectrometer (FS) beginning at the center of the dipole magnet on the right, and the Target Spectrometer (TS) on the left. From the left, the antiproton beam enters.

As shown in Figure 3.4, there are two primary components to the $\bar{\text{P}}\text{ANDA}$ detector:

- The *Target Spectrometer* (TS) is utilized to identify particles at significant scattering angles ($> 10^\circ$). The superconducting solenoid magnet, which has a field

strength of 2 T, serves as the source for the momentum measurement of charged particles.

- The *Forward Spectrometer* (FS) is for particles emitted in the forward direction ($< 10^\circ$ in the horizontal direction and less than $< 5^\circ$ in the vertical direction). A dipole magnet with a bending power of up to 2 T·m provides the basis for the momentum measurement (79).

3.2.1 Target Spectrometer

The requirements for the target are specified by the scheduled measurements in $\bar{\text{P}}\text{ANDA}$. A tiny, localized piece of matter in ultra-high vacuum must be the target in order to prevent multiple scattering. Condensed matter particles of various sizes, such as clusters, drops, or pellets may achieve this by passing the antiproton beam in the transverse direction. The majority of the physics program's measurements need a very high purity pure proton target (any impurities or pollution would produce a disturbing background). Hydrogen or deuterium in gaseous or solid state are the possible greatest targets and the noble gases Ne, Ar, Kr, and Xe as well as heavier target material like N_2 would be ideal for the planned studies of $\bar{p}p$ annihilation in nuclear matter. The installation of a cluster-jet or pellet target can fulfill a significant portion of the specified requirements. While the cluster-jet target will be a component of the start configuration, both target types are planned to be included in $\bar{\text{P}}\text{ANDA}$ (80).

Cluster-Jet Target

For internal storage ring experiments, cluster-jet beams are often created by expanding pre-cooled gases in convergent-divergent Laval-style nozzles equipped with micron-sized throats into vacuum. The size of the cluster, which usually has $10^3 - 10^5 \frac{\text{atoms}}{\text{cluster}}$, is on the nanoscale and is dependent on the experimental conditions. The planned use of cluster at $\bar{\text{P}}\text{ANDA}$ called as Münster-Type cluster-jet target, which operates in the domain where hydrogen is already liquid before entering the nozzle and this results in higher target beam densities. For the prototype cluster-jet target for $\bar{\text{P}}\text{ANDA}$, the target density achieved was about $2 \cdot 10^{15} \frac{\text{atoms}}{\text{cm}^2}$ (80).

Pellet Target

The ability to determine the position of the pellets during interaction and the very high effective target thickness are the two main benefits of using pellet targets. However, because of the characteristics of the pellets, there might be wide variations in thickness (80). The triple-point chamber serves as the production hub for pellets. A cryogenic liquid is injected into a gas close to the triple-point within the chamber gas type may differ or remain the same). Next, a periodic excitation is produced by a piezoelectric transducer. When the jet radius equal to the perturbation amplitude, the gas breaks up into drops and this technique guarantees that the drops fall steadily. Consequently, a consistent flow of frozen pellets is produced when the surface of these drops evaporates after passing through a thin tube (81).

Pellet target operation modes comes in two different varieties: pellet tracking and pellet high luminosity. Optical detection techniques are used in the pellet tracking mode. $\bar{\text{P}}\text{ANDA}$ requires high-accuracy in pellet tracking in order to perform measurements on charmonium and hyperon decays. However, the target thickness is greater in the high luminosity mode compared to the tracking mode, but the timeline is smoother (80).

3.2.2 Magnets

The momentum and energy loss of charged particles will be measured in both $\bar{\text{P}}\text{ANDA}$ spectrometers. The fact that charged particles travel in a curved trajectory in a magnetic field is used here. Also, in a homogeneous solenoid field, the radius of the projection to a plane perpendicular to the field direction is directly proportional to the momentum of the particle. Hence, two different kinds of magnets are aforesought for the $\bar{\text{P}}\text{ANDA}$ detector: A superconducting solenoid magnet for the Target Spectrometer and a dipole magnet for the Forward Spectrometer (82).

The solenoid magnet will have 2.5 m magnetic length and the main goal of it is to deliver a 2 T magnetic field which must be not only parallel but also uniform over the entire tracking detector zone (82).

To extend the solenoid in the forward region, the Forward Spectrometer will use a dipole magnet with a 2 T·m bending power. The dipole magnet planned to be a part of the accelerator lattice of the HESR and it will be 2.5 meters along the beamline (total size of the dipole magnet is 3.9 meters in height and 5.3 meters in width) in order to balance the needs of the magnet and detector (82).

3.2.3 Tracking Detectors

Micro Vertex Detector

Silicon detectors as sensitive elements are used in the Micro Vertex Detector (MVD), which is the innermost component of the Target Spectrometer's central tracking system. There will be two distinct types of detectors used: hybrid pixel detectors and double-sided microstrip detectors. In close proximity to the interaction point, the MVD will provide 3D hit data. It will also be probable to offer time of the track which is critical for reconstruction of the events. For outer detector systems, it might serve as time reference for particle detection times whereas the track information inside the solenoid field will provide particle momentum and event topology data. The identification of open charm and strangeness is the main objective of MVD along with an additional effort which is the measurement of the energy loss for slow protons, pions, and kaons. That will provide more information for identification of global particles (83, 84).

The following fundamental prerequisites are imposed by the physics goals and the experimental setup in which the detector will operate:

- For displaced vertices, it is required to detect the first track point that is extremely close to the decay point.
- The MVD must cover the region from $\Theta = 3^\circ$ to 150° since the whole $\bar{\text{PANDA}}$ detector will cover almost the entire solid angle (83).
- A good spatial resolution of $\sim 10 \mu\text{m}$ in the x and y directions and at least $100 \mu\text{m}$ in the z direction is required in the forward region (83).
- A minimum material budget is required to prevent low-energy particles from scattering many times inside the silicon layers. In terms of radiation

length, the total material budget for the STT and the MVD is estimated to be $\frac{X}{X_0} = 10\%$ (83).

- Since the interaction point is close to the MVD, a high radiation hardness is necessary. The desired radiation tolerance in terms of 1 MeV neutron equivalent is $10^{14} n_{\text{eq}} \text{ cm}^{-2}$, assuming a ten-year overall lifetime for $\bar{\text{PANDA}}$ with a duty cycle of 50% (85).
- The desired temporal resolution is around 10 ns, necessitating a quick and adaptable read-out mechanism (83).
- More information on global particle identification for low-energy particles.

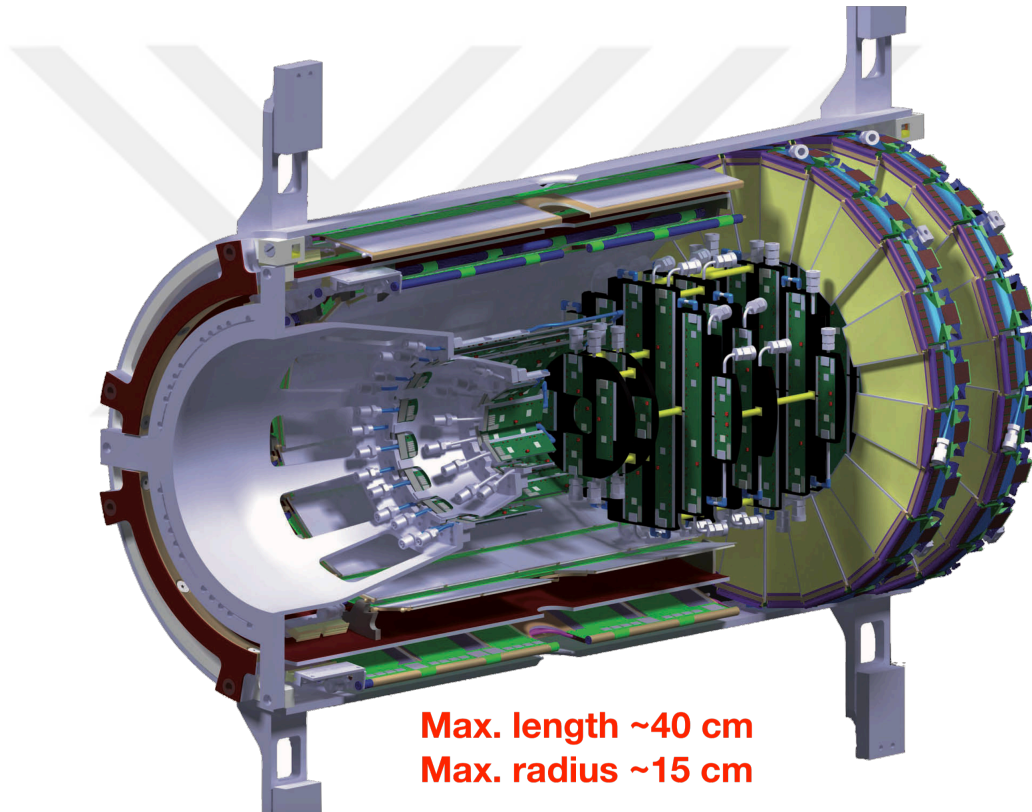


Figure 3.5. Computer Aided Design (CAD) drawing of the MVD, seen from upstream. Some elements are hidden, thus allowing to see the inner components (86).

The MVD design's CAD drawing is shown in Figure 3.5 which has been optimized to meet the mentioned physics goal requirements. The MVD will consist of two pieces, a barrel and a disc section, and will have a maximum radius of 15 cm as well as maximum length of 40 cm. The active volume differs from -17 cm to 23 cm in z direction with regard to the interaction point (83, 84, 86).

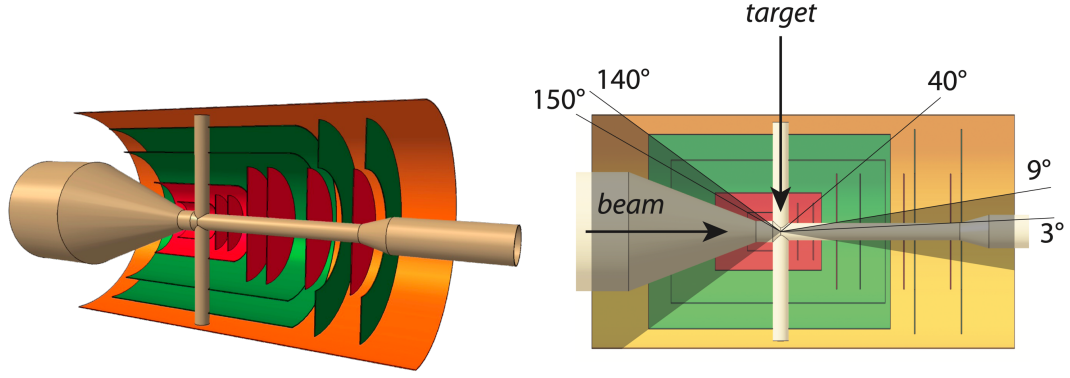


Figure 3.6. Basic layout of the MVD (left). Double-sided silicon micro-strip detectors are shown in green and the silicon hybrid pixel sensors are shown in red. MVD's polar angle coverage illustration (right). The shaded gray regions indicate the region that is not covered inside the polar angle coverage range which is from 3° up to 150° . Images adapted from (83, 84) and (86), respectively.

The barrel part is made up of four layers: two outside layers have double-sided silicon micro-strip detectors, while the two interior layers have silicon hybrid pixel detectors that shown in Figure 3.6 (left). The barrel section will cover polar angles ranging from 40° to 150° that also shown in Figure 3.6 (right). The forward section will encompass the region of the polar angle between 3° and 40° (83, 84, 86).

Straw Tube Tracker

The straw tubes are gas-filled cylindrical shaped tubes with an anode wire through the cylinder axis and a conductive cathode as inner layer. The electric field between the inner layer and the wire separates electrons and ions which are generated along the trajectory of a charged particle in the gas volume of the tube. Positioned around the interaction point, which also covers the MVD, are 4224 single straw tubes organized in a cylindrical body that make up the Straw Tube Tracker (STT) of $\bar{\text{P}}\text{ANDA}$, the primary tracking detector for charged particles in the $\bar{\text{P}}\text{ANDA}$ target spectrometer. Also, the Gas Electron Multiplier (GEM) planes follow the STT along the beamline (87).

With STT, the helical track of charged particles with momentum ranging from $100 \text{ MeV}/c$ to $6 \text{ GeV}/c$ may be precisely reconstructed spatially. Also, reconstructing the trajectory of charged particles in a solenoidal magnetic field

allows one to calculate particle momentum. The other task is to separate protons, kaons, and pions with the momentum below 1 GeV/c using specific energy-loss measurements. On the other hand, the drift-time of the electrons arriving earlier may also be found and which allows the evaluation of smallest distance for the particle track from the wire (87).

Using the straws in the tube is advantageous because of their strong electrostatic configuration, strong mechanical stability (when they are organized in closely packed multi-layers), minimal dead zones at the end of the tubes (millimeter order), a small radiation length of $X/X_0 \sim 0.05\%$ per tube (if straws with $\sim 30 \mu\text{m}$ film tubes are used) and high detection efficiency (about 99.5%). The $\bar{\text{PANDA}}$ STT's straw tubes are made up of two $12 \mu\text{m}$ thin aluminized Mylar film layers and about 1400 mm in length, 10 mm in inner diameter, and $27 \mu\text{m}$ in wall thickness. The anode is a $20 \mu\text{m}$ -diameter tungsten-rhenium wire that has been gold-plated and studies on appropriate gas mixtures lead to the selection of an Ar + 10% CO₂ mixture for the tube (87).

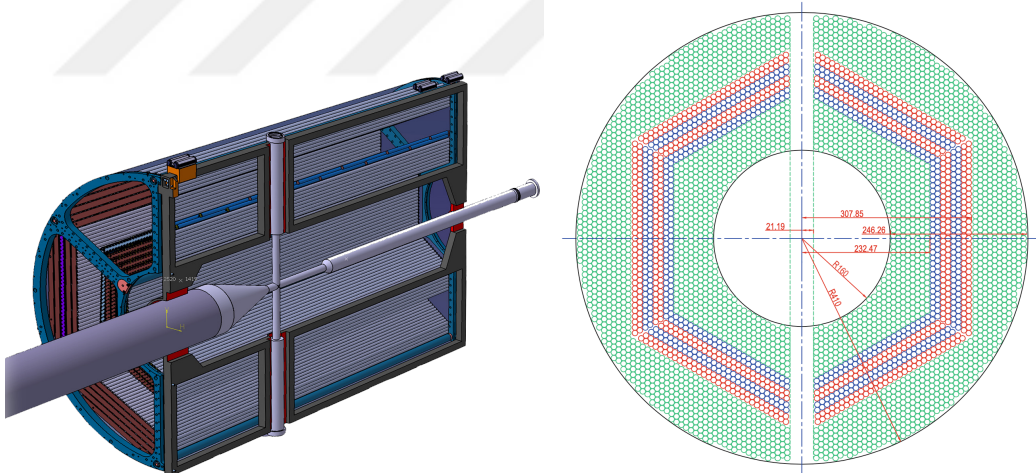


Figure 3.7. CAD drawing of the $\bar{\text{PANDA}}$ STT (left) (outer radius of 420 mm, total length of 1650 mm). The layout of the STT showing straws tube inside in 2D-view (xy-plane view). The green, blue and red marked straw layers are tilted by -2.9° and 2.9° , respectively. Images from (88) and (87) from left to right.

A CAD drawing (left) and an illustration of the straw tube layout (right) are shown in Figure 3.7. Here, pressurized straw tubes were glued to one another to create planar multi-layer modules with a hexagonal arrangement which were also closely packed (gap less than $20 \mu\text{m}$). Eight straw layers parallel to the beam line,

four stereo double layers with tubes skewed by $\pm 2.9^\circ$, four more parallel layers, and seven more parallel layers with reduced straws per layer make up each hexagonal sector. With a 42 mm gap, the STT is split into two semi-cylinders (a semi-cylinder is made up from three hexagonal parts) to maintain access to the target and the MVD. The azimuthal coverage is only restricted by the gap between two semi-cylinders for the target pipe at $\varphi = \pm 90^\circ$, while the $\bar{\text{P}}\text{ANDA}$ STT will cover particle detection at a polar angle between $10^\circ - 140^\circ$. An isochrone resolution of less than $150\ \mu\text{m}$ and a momentum resolution of $\sigma_p/p \sim 1 - 2\%$ for charged particles are obtained in simulation studies and the determined energy resolution is better than 8% (87).

Gas Electron Multiplier

To extend the acceptance of the STT into forward directions, three stations of Gas Electron Multiplier (GEM) (follows STT directly) detectors which are parts of the tracking detector in TS positioned between 1.1 m and 1.9 m downstream of the interaction point. The GEMs detect charged particle tracks at polar angles between 5° and 22° (89). Each station will have two planes with two projections which equipped with gaseous micro-pattern detectors that are based on Gas Electron Multipliers foils as amplification phase. The $50\ \mu\text{m}$ kapton is made up of a foil that has a $5\ \mu\text{m}$ copper layer on both sides and is typically punched with a high hole rate of 100 holes/ mm^2 (90-92).

In between a drift and a charge collection electron, the GEM foil is inserted and a potential of a few keV/cm is usually applied to form field lines surrounding the holes. As incoming particles produce electrons, they will accelerate along the field lines, multiplying the primary charge in avalanche until it collected at the readout anode. It is expected that the spatial resolution of the GEM detector at $\bar{\text{P}}\text{ANDA}$ will be perform better than $100\ \mu\text{m}$ (91).

Forward Tracker

As a fixed-target experiment, $\bar{\text{P}}\text{ANDA}$ should cover solid angle of 4π and offer great momentum resolution for charged particles. The Forward Spectrometer will cover the region below $\pm 5^\circ$ in the vertical and $\pm 10^\circ$ in the horizontal plane, as previously described. The Forward Tracker (FT) will monitor the charged particles

within the Forward Spectrometer and, for example, finding low momentum pions from Λ decays is one of its missions (93).

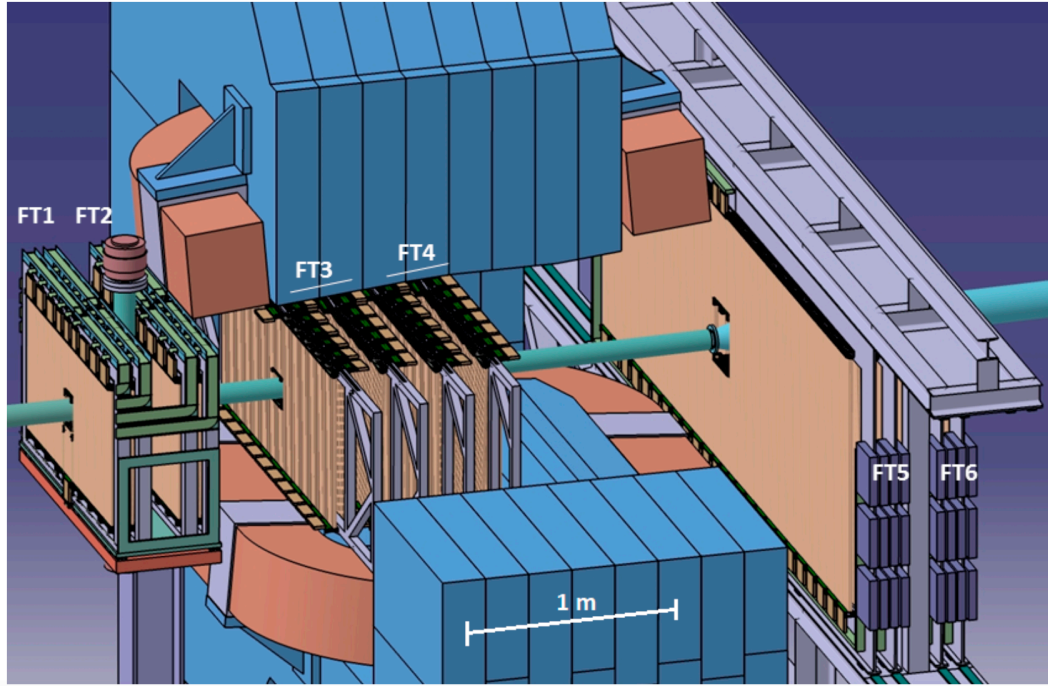


Figure 3.8. CAD drawing of the Forward Tracker (FT) which shows three pairs of tracking stations (FT1 & FT2, FT3 & FT4, FT5 & FT6) as well as a section of the dipole magnet. Image taken from (93).

A CAD drawing of the FT is shown in Figure 3.8. It shows three pairs of tracking stations which consist of the FT and also include a section of the dipole magnet. One tracking station consists of four double-layers of two straw tube modules. The modules usually consist of 32 straw tube detectors placed in two phased layers glued together. However, only 24 straw tubes will be contained in the narrower modules near to the beam pipe of the tracking stations on either side of the dipole magnet. The first pair is planned to be placed upstream of the dipole magnet, the second pair in the magnetic gap and the third pair downstream of the dipole magnet. The first two pairs of tracking stations upstream of the dipole contain straws skewed by $\pm 5^\circ$, respectively and this arrangement made three-dimensional track reconstruction at each station possible which is useful for the reconstruction of multi-track events (93).

Considering the material budget, straw tube detectors used for STT will also be planning to use for the FT. Also, the momentum resolution of the FT must be at

least comparable to the 1.5% of momentum resolution for the Target Spectrometer in order to guarantee a high invariant mass resolution. The position resolution and momentum of the FT were estimated by the simulations of benchmark channels and background reactions. Therefore, for position, the predicted resolution is about in the order of $100\ \mu\text{m}$, and for momentum, it is greater than 1%. Furthermore, the information about track parameters at the forward RICH and the forward ToF wall, which are situated downstream of the dipole magnet, will be supplied by the FT. Due to the total high counting rates of $5 \cdot 10^7$ tracks/s, the FT ought to withstand aging effects as well as fast front-end and digitization electronics are necessary (93).

3.2.4 Particle Identification Detectors

Particle identification (PID) is crucial for event reconstruction in addition to charged particle tracking. Thus, sub-detectors for PID, such as Cherenkov detectors; Detection of Internal Cherenkov Light (DIRC) and Ring Imaging Cherenkov (RICH) detector, the Barrel Time of Flight detector, Forward Time of Flight (FToF) detector, and Muon Detector System (MDS), are also included in the conceptional design of the $\bar{\text{P}}\text{ANDA}$ detector.

DIRC and RICH

Photons are collected by Cherenkov detectors which are produced when a charged particle traveling through a dielectric environment. Photons are emitted on a cone with half the aperture angle is given by $\cos \Theta_c = 1/\beta_n$ if the particle velocity v is larger than the speed of light in a material with refractive index n , $v > c/n$. With data assessed in terms of the particle's production angle and momentum information obtained from tracking detectors, the mass of the particle can be determined with a certain accuracy. In $\bar{\text{P}}\text{ANDA}$, it is planned to use two DIRC systems for the Target Spectrometer which using the same detection technique as well as a RICH detector will be placed in the Forward Spectrometer (94).

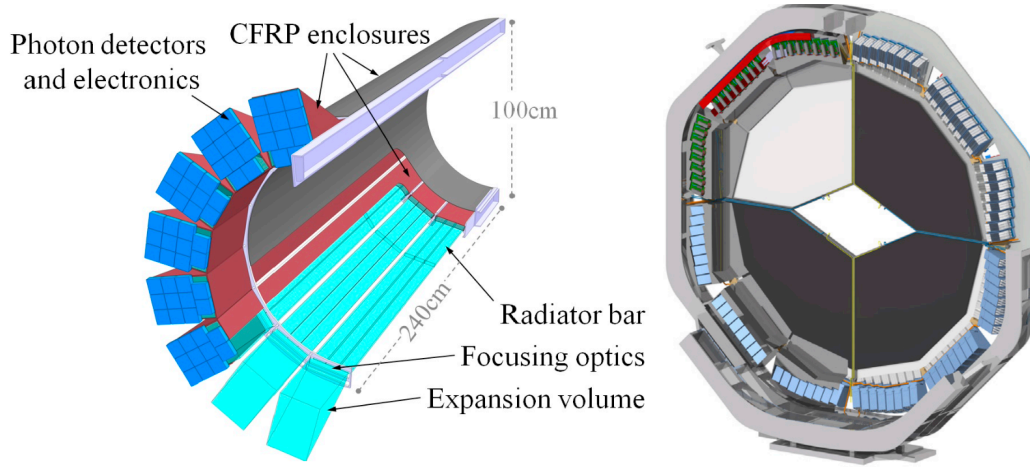


Figure 3.9. Drawing of the Barrel DIRC detector (left) and the partial section of the Disc DIRC detector (right). Images taken from (94) and (95), respectively.

The concept of DIRC detectors is the detection of internally reflected Cherenkov light. Positioned at a radial distance of 47.6 cm and stretching 240 cm down the beam line, the barrel DIRC is placed in the TS which shown schematically in the left side of Figure 3.9 (94). There are 16 optically insulated sectors in the detector and every sector made up from three fused silica bars, each 17 mm thick and with a refractive index of $n = 1.473$. A flat mirror is fixed to the forward end surface of every bar to reflect photons in the direction of the read-out mechanism at the upstream. Here, the arrival time and the location of the photons are measured using an array of 11 life-time improved Microchannel Plate PhotoMultiplier Tubes (MCP-PMTs) with a time and position resolution of 100 ps and 2 mm, respectively. For momenta up to 4.2 GeV/c, the barrel DIRC can separate pions and kaons over the polar angle range of 22° to 140° (94).

The disc DIRC is the second Cherenkov detector in the TS, as shown in the right side of Figure 3.9. It is composed of 2 cm thick active fields made of fused silica organized in a dodecagonal arrangement. Located upstream of the forward endcap calorimeter, the 110 cm diameter disc DIRC covers polar angles ranging from 10° to 22° (96).

On the other hand, an aerogel RICH detector as the Cherenkov detector will be located between the dipole magnet and the Forward Spectrometer. It covers polar angles up to 5° in the vertical plane and up to 10° in the horizontal plane. The main

goal of the RICH detector is the identification of hadrons with high momenta. The Cherenkov light, produced in a double-layer radiator made of aerogel and gas, is focused by a mirror to an array of PMTs placed outside the detector acceptance. It is possible to separate hadrons in the range from 2 GeV/c up to 4 GeV/c using the RICH (94).

Barrel Time of Flight (ToF) Detector

The interaction point is surrounded by the Barrel Time of Flight detector, which is situated approximately 50 cm away and covers the polar angles between 22° and 140° . Identifying low momentum particles at large polar angles and providing a reference time t_0 for the event is one of the primary objectives (97).

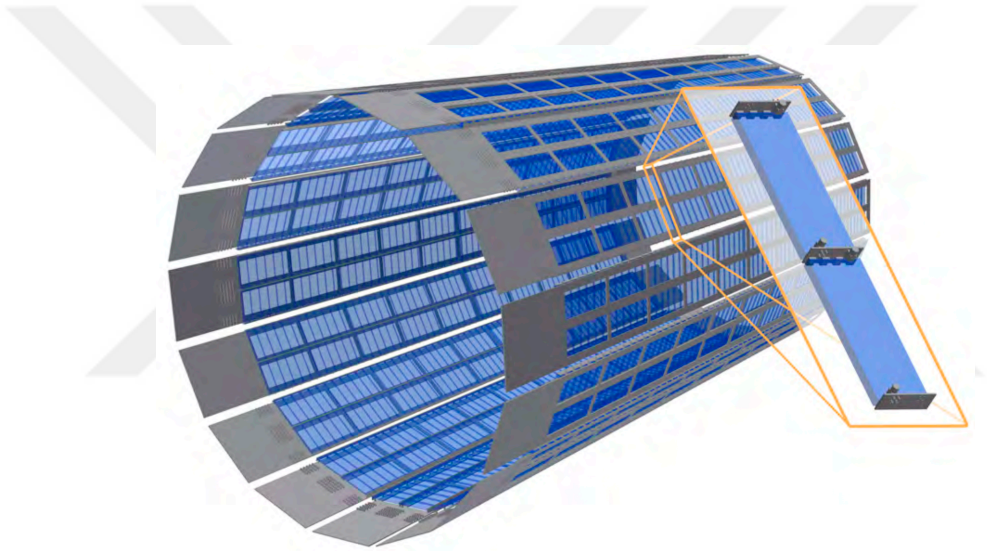


Figure 3.10. CAD Drawing of the whole Barrel Time of Flight (ToF) detector featuring an enlarged drawing of two scintillator tiles. PCB boards are depicted in gray, and scintillator tiles in blue. It has an external radius of 538 mm, a length of 2460 mm, weighing about 400 kg, is made up of 16 segments and covers about 5 m² Illustration from (97).

A CAD drawing of the Barrel ToF is displayed in Figure 3.10 above, along with an expanded drawing of two scintillator tiles. Due to the fact that the Barrel ToF shares its mechanical support with the previously discussed Barrel DIRC, the segmentation structure is again composed of 16 independently moving segments. The segments, which are called as super-modules, are 87 mm long and 20 mm thick. They are made up of 120 scintillation tiles that are organized in two columns of 60 scintillators apiece. Four Silicon Photo Multipliers (SiPMs) integrated into one unit

used as readout elements at each end. A time resolution of $\sigma_t < 60$ ps is obtained for a single tile, which is better than the original design objective of 100 ps, because the scintillator tiles are composed of fast-response materials (97).

Forward Time of Flight Wall (FToF wall) Detector

In the Forward Spectrometer (FS), the Forward Time of Flight (FToF wall) is used exclusively for hadron identification (98). The FToF wall will provide the PID information at particle momenta below 4 GeV/c, while the RICH will provide an effective hadron separation in the momentum region between 2 GeV/c and 4 GeV/c. One of the FToF wall's primary objectives, in addition to the PID, is the detection of event time stamps in one or more scintillation slabs. For relativistic particles, the collected data will provide the opportunity to reconstruct the event start time and the time resolution must therefore be greater than 100 ps (98).

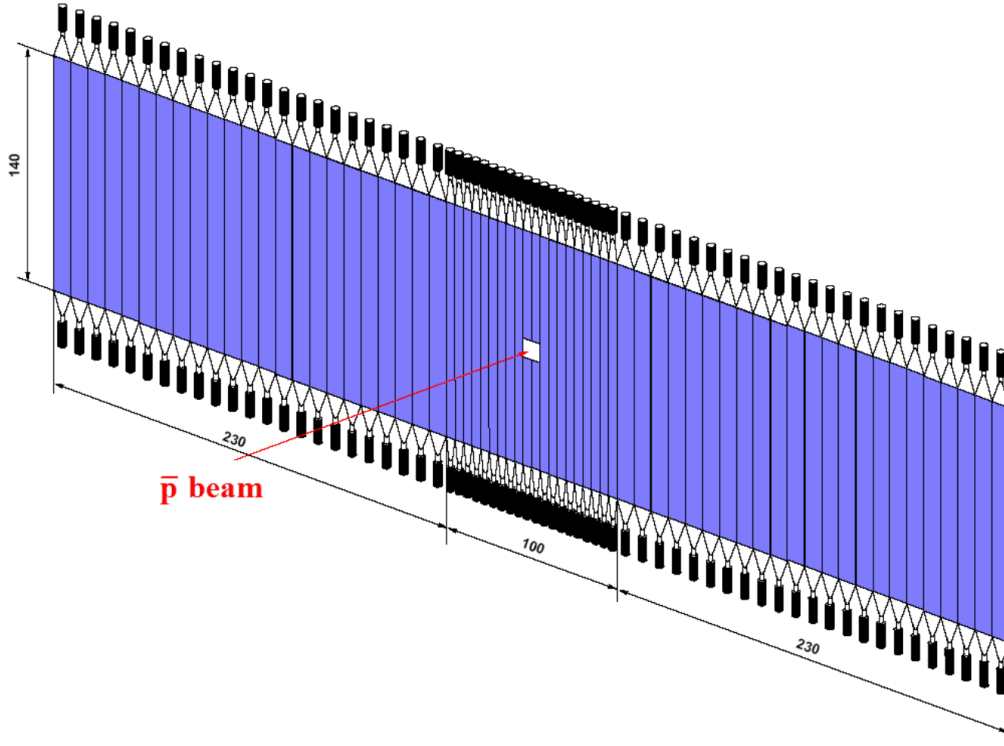


Figure 3.11. CAD drawing of the FToF wall (showing scintillation slabs in blue). Image taken from (98).

The FToF wall, which is situated 7.5 meters downstream of the interaction point, will be a part of the FS. Figure 3.11 shows the FToF wall detector in general with its scintillation blocks/slabs. The FToF wall is made up of 23 scintillator slabs

on each side that are 10 cm wide in the outside region and 20 scintillator slabs that are 5 cm wide in the center. Hence, which makes the entire sensitive area arranged in a scintillation wall is 5.6 m wide, 1.4 m tall and has a thickness of 2.5 cm. In the center, 1 inch PMTs are used for the read-out, while in the wider outer regions, 2 inches PMTs are used and all PMTs were arranged vertically with its axes parallel to the $\bar{\text{PANDA}}$ detector's y-axis. An online time resolution about 200 - 250 ps can be obtained, but in the offline analysis a better time resolution about 60 - 80 ps would be achieved by hit location and amplitude corrections (98).

Muon Detectors

In $\bar{\text{PANDA}}$, a good muon identification is required to measure muons with a momentum up to 10 GeV/c. In the $\bar{\text{PANDA}}$ spectrometer, muons can be identified using a variety of detectors; including the muon filter, the scintillator detectors, the calorimeters and Cherenkov detectors whereas the primary detector for muon identification is the muon filter. By associating the signals from all the specified systems will lead to reach the desired purity of signal. The muon system detectors' main objective is to identify muons by matching-up the track segments with the detectors' tracks inside the magnets and by applying pattern identification technologies (99).

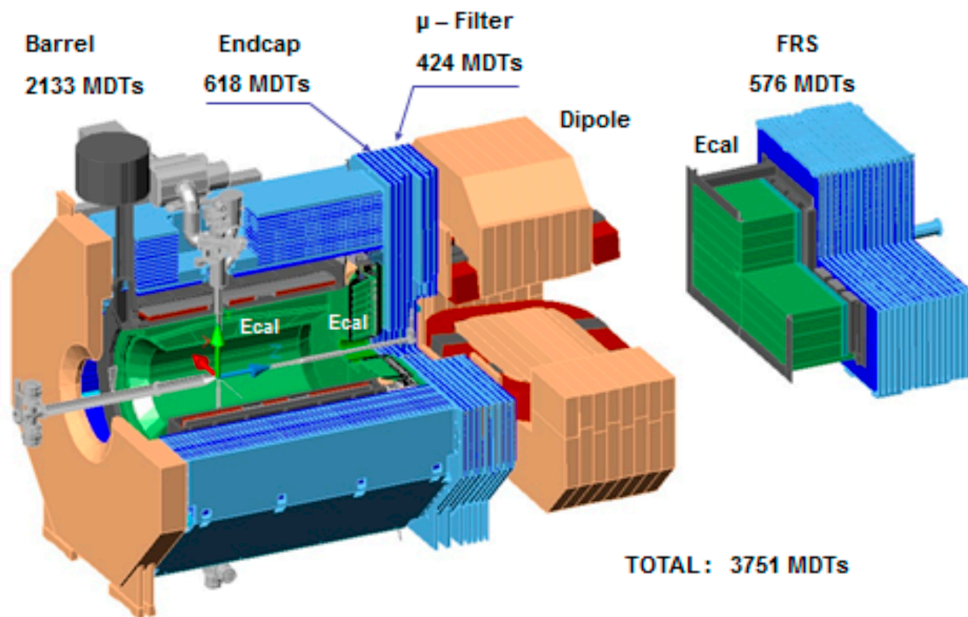


Figure 3.12. The layout of Muon Detectors (components shown in blue) with the number of Mini-Drift Tubes (MDTs) for each sub-system Image from (99).

The muon detector system that shown in Figure 3.12 is made up of a barrel section and an End-Cap in the Target Spectrometer (TS) as well as a range system in the Forward Spectrometer (FS). 13 sensitive layers with 3 cm of thickness, substituting with iron absorber layers with a thickness of 3 cm (the first and last iron absorber layers are 6 cm thick due to mechanical reasons) are planned for the muon detector systems' barrel section. Here, one sensitive layer is formed by the Mini-Drift Tubes (MDTs) and strip boards that are attached together and the full muon detector system were included about 4000 MDTs in total (99).

The End-Cap consists of 6 sensitive layers with 5 iron absorber layers in between. The iron absorber in the End-Cap needs to be thicker than the barrel part in order to provide better muon detection, as a result, 6 cm thickness was chosen. Additionally, a muon filter is planned for the End-Cap section. Although the number of layers differs, the mechanical structure of the muon filter is selected based on the End-Cap's structure. 5 sensitive layers with 4 iron absorber layers in between to be positioned in the space between the solenoid and the dipole magnet. (99).

3.2.5 Electromagnetic Calorimeter (EMC)

Within the extensive $\bar{\text{P}}\text{ANDA}$ physics program, many channels include photons or electron-positron couples in their final state (89, 100). While suppressing the background efficiently, Electromagnetic Calorimeter (EMC) offers an effective reconstruction of photons, electrons and positrons. Apart from calculating the total energy, EMC will also give time data to provide separation between the closely timed events. Because of its compact layout and high-count rates, the Target Spectrometer needs a fast scintillator material with a short radiation length for the structure of the EMC. Adjusted for large-scale productions, lead tungstate (PbWO_4) inorganic scintillator material offers decent energy and time resolution to detect hadrons, electrons and photons (89, 100).

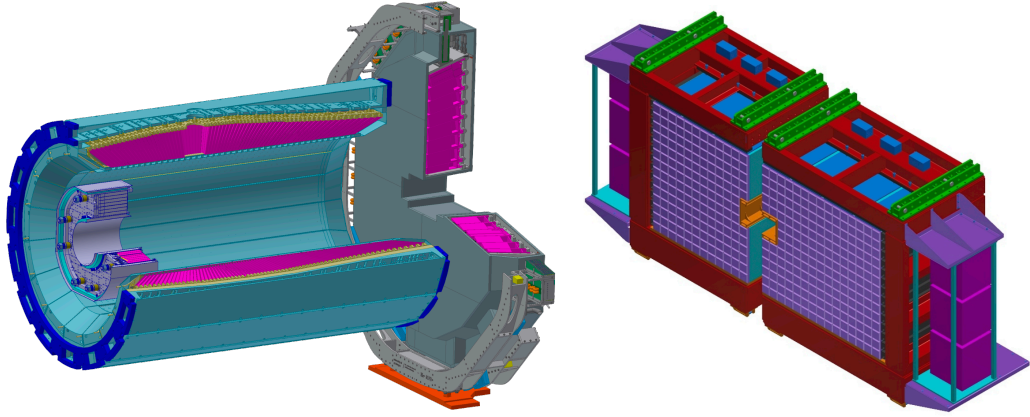


Figure 3.13. CAD drawing of the 2.5 m long (inner radius 0.57 m) EMC barrel with the forward endcap (2 m diameter) (left). Front side illustration of the Forward Spectrometer Electromagnetic Calorimeter (FSC) (right) (3.6 m in width and 2.2 m in height). Images taken from (100) and (101), respectively.

To reach energy resolution of more than 2% at 1 GeV, $\bar{\text{P}}\text{ANDA}$ EMC crystals, illustrated in Figure 3.13 (left), are 20 cm long and that corresponds to a radiation length of $22 X_0$. The $2.1 \times 2.1 \text{ cm}^2$ front sized conical crystals will be placed with an inner radius of 57 cm. Hence, in order to boost the light yield by a factor of 4 by operating at -25°C compared to operation at $+25^\circ\text{C}$, more than 15.000 PbWO_4 scintillator crystals will be mounted to the barrel EMC. Nearly the whole polar angle region and the energy range from 10 MeV to 15 GeV should be covered by the EMC. As a result, the barrel section and two endcaps sections (forward and backward) made up the EMC in the Target Spectrometer (89, 100). The forward endcap covers the polar angles between 5° and 22° and in the barrel section, particles with angles ranging from 22° to 140° will be measured. The backward endcap will cover the backward region, which corresponds to polar angles between 140° and 150° with respect to the beam direction. Thus, roughly 99% of the full solid angle is covered. In addition to their angular coverage, the various EMC components also cover various energy ranges (89). The energy and angular coverage for each of the three EMC components in the Target Spectrometer are compiled in Table 3.1 below.

Table 3.1. The different EMC parts' dynamic energy range and polar angle coverage (89).

	Polar Angle Range	Energy Range
Backward Endcap	5° - 22°	10 MeV – 0.7 GeV
Barrel EMC	22° - 140°	10 MeV – 7.3 GeV
Forward Endcap	140° - 150°	10 MeV – 14.6 GeV

A shashlyk-type calorimeter is planned in the Forward Spectrometer, and it is situated roughly 7 m downstream from the interaction point. A sketch of the Forward Spectrometer Electromagnetic Calorimeter (FSC) is shown in Figure 3.13 (right). The overall depth is constrained by the Forward Spectrometer's length because it will be positioned between the FToF and the Muon Detector System and this leads to $20 X_0$ radiation length in terms of its depth (101). 378 modules with 4 cells of $55 \times 55 \text{ mm}^2$ apiece, the calorimeter will have an overall active area of $3 \text{ m} \times 1.5 \text{ m}$. The FSC at $\bar{\text{P}}\text{ANDA}$ covers a polar angle region up to 5° and its design purpose is to detect electrons and photons within an energy range of 10 MeV – 15 GeV. Here, for FSC, the expected energy resolution is $\sigma_E/E \approx (2 - 3)\% / \sqrt{E/\text{GeV}}$ (101).

3.2.6 Luminosity Detector (LMD)

Hadron production mechanisms are the subject of a significant portion of spectroscopy research. For example, the formation of a resonant state can be observed by altering the beam energy. The physical form of the resonance can be revealed through an accurate measurement of the beam energy and luminosity (102). An accurate measurement of luminosity is required, since the measurement must be normalized with the time integrated luminosity for each beam energy. In order to prevent non-interacting beam particles from masking the interacting particles, the distance to the interaction must be sufficiently large for the LMD at $\bar{\text{P}}\text{ANDA}$ to monitor elastically forward scattered antiprotons at small momentum transfers. Consequently, mounting the LMD 11 m downstream of the interaction point is planned because it was only possible to measure elastically scattered antiprotons at small angles approximately 11 m downstream of the interaction point (102). Elastically scattered particles in the angular range of 3 mrad to 8 mrad can

be measured with the LMD. The planned LMD is shown as a CAD drawing in Figure 3.14. It will have 400 actively cooled High Voltage Monolithic Active Pixel Sensors (HV-MAPS) lowered inside a vacuum box, arranged in four detector planes with a radius of 15 cm. The HV-MAPS are generated as $2 \times 2 \text{ cm}^2$ individual squares and the sensors are overlapping to cover a 2π acceptance around the beam pipe (102).

Particle tracks reconstructed in the LMD will be back-propagated to the interaction point in order to identify the t-dependence of the cross-section. Time integrated luminosity will then be determined by fitting the expected cross-section to the angular distribution. It is expected that the precision for the relative time-integrated luminosity will be better than 1% and for the absolute time-integrated luminosity will also be better than 5% (102).

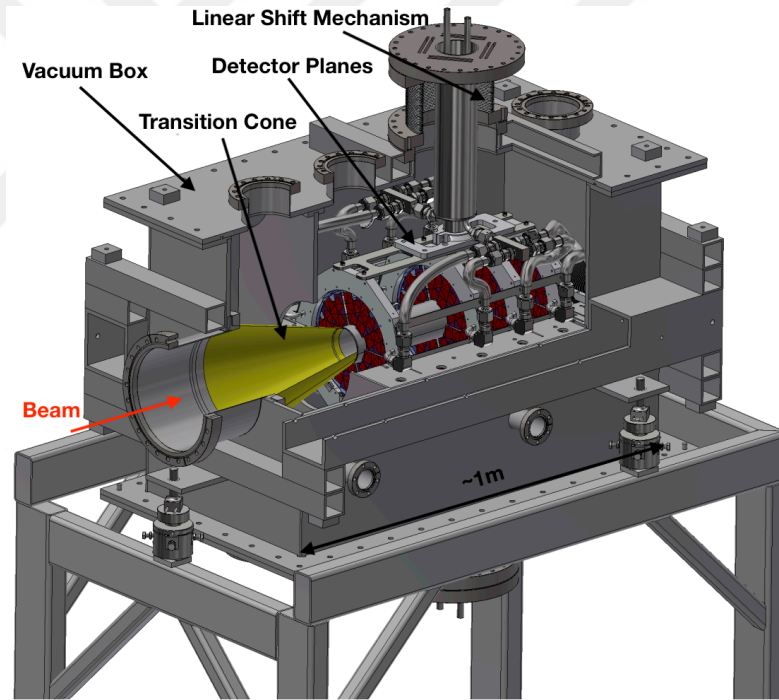


Figure 3.14. CAD drawing of the $\bar{\text{P}}$ ANDA Luminosity Detector (LMD). The radius of the detector planes displayed here is 15 cm. Image adapted from (103).

3.3 $\bar{\text{P}}\text{ANDA}$ Software

The $\bar{\text{P}}\text{ANDA}$ experiment's software framework, known as PandaRoot, is on the basis of the ROOT (104) and the Virtual Monte Carlo (VMC) packages (105). The reconstruction and $\bar{\text{P}}\text{ANDA}$ detector simulation codes are implemented within the FairRoot software framework (106), which was created by the GSI (Gesellschaft für Schwerionenforschung, GSI Helmholtzzentrum für Schwerionenforschung) FAIR-IT with the intention of providing a standard computational system for all upcoming FAIR experiments (107). Additionally built on top of the ROOT package, FairRoot offers dynamic data structures. The transport models Geant3 and GEANT4 can be used with the same detector code since VMC manages the detector simulation. PandaRoot uses a number of event generators, including Dual Parton Model (DPM), PYHTIA, Fluka, EvtGen, Ultra Relativistic Quantum Molecular Dynamics (UrQMD) to produce physics background events. VMC then forwards these events to the transport model. ROOT objects or ASCII files can be used to describe the geometry of the detector (CAD drawings can also be converted into ROOT geometry using an additional application). Digitizers simulate the detector response after simulating the events which passed through the detector geometries.

In short, in order to perform a full analysis with PandaRoot; event generation by VMC simulation, digitization (by using realistic detector geometries with Geant3 and GEANT4), PID, reconstruction and the offline analysis are the required steps. The framework structure and the data flow scheme for PandaRoot is given in Figure 3.15 and Figure 3.16, respectively.

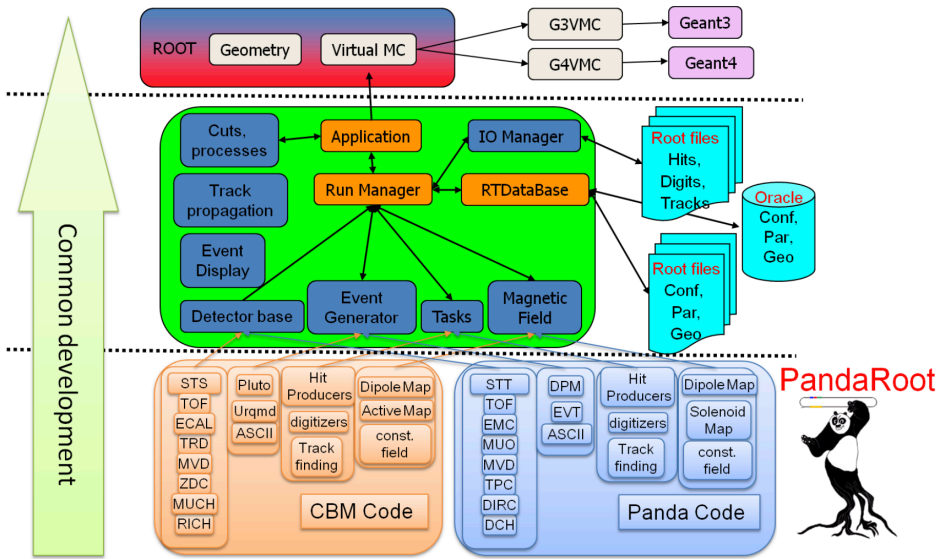


Figure 3.15. The framework's structure. Both the Virtual Montecarlo and ROOT remain at the top level. The general infrastructure is managed by the FairRoot framework using tasks and simulation on a lower stage. Reconstruction and detector details remain at the bottom level. Image adapted from (108) and (109).

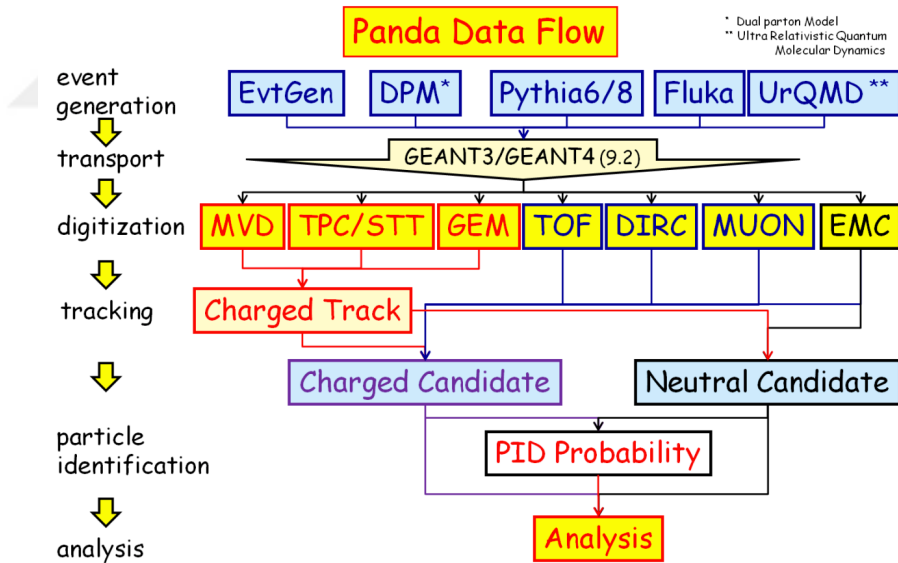


Figure 3.16. PandaRoot data flow scheme. Image from (108).

3.3.1 Particle Tracking and Reconstruction

Hits on the tracking detectors are combined to form charged particle tracks. Reconstruction codes are thus used to merge the data gathered from the several tracking detectors. Helical trajectories for charged tracks and a steady magnetic

field are assumed during tracking for the target detector. Magnetic field inhomogeneities, energy loss, various data structures, and error estimations for the detectors must all be taken into consideration in order to obtain high momentum resolution for the reconstruction. Thus, GENFIT (110) which contains a validated Kalman filter and GEANE (111) as track follower were used. The GENFIT algorithm is commonly used for track fitting in particle spectrometers (110). The GEANE, which is used to extrapolate the track parameters and their associated errors due to magnetic field, straggling in energy loss, and Coulomb multiple scattering, is crucial in studying a detector's reconstruction capabilities (111).

Based on the generated particle information, the ideal tracking algorithms group the hit spots along a particle track. On the other hand, this causes one of the tracking detectors to reconstruct particle tracks with just one hit point.

3.3.2 Particle Identification (PID)

The information coming from the PID detectors (Cherenkov angle, energy deposition in the EMC, etc.) and from the reconstructed particle tracks on the tracking detectors are combined to create charged particle candidates. Neutral particle candidates are the EMC clusters that do not correlate with charged clusters.

For every candidate, a number of PID algorithms compute probability density functions. There are two steps for the PID algorithm. The first step provides the final probability for each of the five particle hypotheses (e , μ , π , K , and p) by performing recognition for each detector independently. With the assumption that all particle types have the same fluxes, the probabilities are uniquely normalized. In the second step, by using a conventional probabilistic approach, the global PID gathers data from each sub-detector (EMC, STT, Barrel DIRC, Disc DIRC and MVD).

3.3.3 Analysis

PandaRoot integrated a modified version of the Rho package (112) in order to do a high-level analysis. This software offers the ability to choose particle candidates based on kinematic limitations and predefined PID selection criteria. It is possible to combine the chosen particles with ROOT macros while using various

kinematic algorithms and vertex fitting algorithms inside the macro codes. The use of the different algorithms and fits will lead a better selection of combined particles in the analysis.



4. SIMULATION AND RECONSTRUCTION OF $Z(4430)$ AT $\bar{P}$ ANDA

$\bar{P}$ ANDA experiment setup will have great particle identification over a broad momentum range as well as vertex reconstruction. The technology of $\bar{P}$ ANDA collider experiment will also include a barrier bucket cavity which compensates the mean energy loss in the thick target and also does a fine-tuning for the absolute beam energy. This enables precise energy scans around hadronic resonances and kinematic thresholds. Hence, the center-of-mass resolution will be about 50 keV, which to date is unreachable by other accelerators using different probes (79). This means that the $\bar{P}$ ANDA detector will have a great separation while tracking and reconstructing the particles thanks to low center-of-mass (CM) resolution interspace. That will bring us bright opportunities to work on specific resonances for deserving particles like in this thesis study for $Z(4430)$. For XYZ states, $Z(4430)$ is one of the most important of the many. It can be seen as studied in many experiments throughout the world including Belle, BaBar, LHCb etc. Thus, bringing this study to $\bar{P}$ ANDA frame and working this particle by using $\bar{P}$ ANDA software is an important task for the $\bar{P}$ ANDA experiment in the charmonium/exotics aspect. By using full simulation provided by PandaRoot software chain, $Z(4430)$ can be unfolded about mass, width etc. in the the $\bar{P}$ ANDA detector's spectrum may be with more precision.

4.1 Event Generation

Before the event generation for the $Z(4430)$, a reaction channel for that must be selected. There are two intermediate resonances in the reaction chain we selected, and the secondary decays from those resonances are important for producing data for this study.

Table 4.1. $Z(4430)$ decay modes (73).

$Z_c(4430)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\pi^+ \psi(2S)$	seen
Γ_2	$\pi^+ J/\psi$	seen

Table 4.2. $\psi(2S)$ decay modes (73).

$\psi(2S)$ DECAY MODES		
Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1 hadrons	(97.85 $\pm$ 0.13) %	S=1.5
Γ_2 virtual $\gamma \rightarrow$ hadrons	(1.73 $\pm$ 0.14) %	
Γ_3 $g g g$	(10.6 $\pm$ 1.6) %	
Γ_4 $\gamma g g$	(1.03 $\pm$ 0.29) %	
Γ_5 light hadrons	(15.4 $\pm$ 1.5) %	
Γ_6 $e^+ e^-$	(7.93 $\pm$ 0.17) $\times 10^{-3}$	
Γ_7 $\mu^+ \mu^-$	(8.0 $\pm$ 0.6) $\times 10^{-3}$	
Γ_8 $\tau^+ \tau^-$	(3.1 $\pm$ 0.4) $\times 10^{-3}$	

According to Table 4.1 and Table 4.2, decay modes of $Z(4430)$ and $\psi(2S)$ have been selected. For $Z(4430)$, decay mode Γ_1 selected because it was the dominant decay mode in the experiments which were seen the $Z(4430)$ signal previously. Consequently, using this prominent decay mode was the ideal selection. $\psi(2S)$, on the other hand, have much more previously seen decay channels. Following discussions with the $\bar{P}$ ANDA Physics Working Group ($\bar{P}$ ANDA PWG) after the first presentations, Γ_6 and Γ_7 selected, because reconstructing the $Z(4430)^\mp$ by using $\pi^\pm, \pi^\mp, e^+, e^-$ or $\pi^\pm, \pi^\mp, \mu^+, \mu^-$ as final state particles have a very low fraction according to Tanabashi et al. (73) which makes it a bit challenging task to perform.

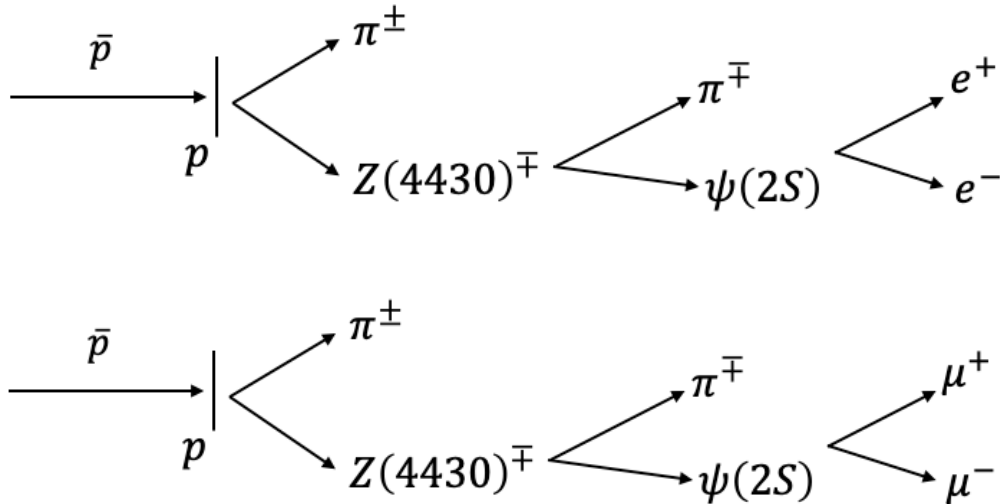


Figure 4.1. Sketch of the selected decay chains for $Z(4430)$.

For the decay chains shown in Figure 4.1, the beam momentum was chosen as 15 GeV/c which also corresponds to a center-of-mass energy about ~ 5.5 GeV (see conversion calculation below). This selection made because the mid-resonances from the decay channel was unknown that the $Z(4430)$ decays from. As a result, the maximum beam momentum value that the $\bar{P}$ ANDA can reach and corresponding center-of-mass energy were selected. $\bar{P}$ ANDA have a spectrum of 1.5 GeV and 15 GeV also corresponds to center-of-mass energies between ~ 2.2 GeV to ~ 5.5 GeV, respectively. To convert this energy range from the lab frame to the CM frame, we perform the following calculation:

$$\text{CM Frame:} \quad \begin{array}{c} \bullet \rightarrow \quad \leftarrow \bullet \\ p \quad \bar{p} \end{array} \quad \text{Lab Frame:} \quad \begin{array}{c} \bullet \rightarrow \quad \bullet \\ \bar{p} \quad p \end{array} \quad (1)$$

$$E_{CM} = \sqrt{S}, \quad S = (P_{\bar{p}} + P_p)^2 = P_{\bar{p}}^2 + P_p^2 + 2 P_{\bar{p}} \cdot P_p \quad (2)$$

$$= m_{\bar{p}}^2 + m_p^2 + 2 E_{\bar{p}} E_p - 2 \vec{P}_{\bar{p}} \cdot \vec{P}_p \quad \begin{array}{l} \nearrow 0 \text{ at lab frame} \\ \nwarrow E_{\bar{p}_{lab}} \quad \searrow E_p = m_p \end{array} \quad (3)$$

which resulting;

$$S = m_{\bar{p}}^2 + m_p^2 + 2 E_{\bar{p}_{lab}} m_p, \quad (4)$$

$$\boxed{E_{CM} = \sqrt{m_{\bar{p}}^2 + m_p^2 + 2 E_{\bar{p}_{lab}} m_p}} \quad (5)$$

where $m_{\bar{p}} = m_p =$ rest mass of proton/antiproton. And checking conversion of $1.5 \text{ GeV} < E_{\bar{p}_{lab}} < 15 \text{ GeV}$ from lab frame to CM frame by using Equation (5);

$$E_{CM} = \sqrt{(0.938 \text{ GeV})^2 + (0.938 \text{ GeV})^2 + 2(1.5 \text{ GeV})(0.938 \text{ GeV})} \quad (6)$$

$$= 2.14 \text{ GeV} \rightarrow \cong \boxed{2.2 \text{ GeV}} \quad (7)$$

$$E_{CM} = \sqrt{(0.938 \text{ GeV})^2 + (0.938 \text{ GeV})^2 + 2(15 \text{ GeV})(0.938 \text{ GeV})} \quad (8)$$

$$= 5.468 \text{ GeV} \rightarrow \cong \boxed{5.5 \text{ GeV}}. \quad (9)$$

Consequently, calculated values of the conversion of $1.5 \text{ GeV} < E_{\bar{p}_{lab}} < 15 \text{ GeV}$ values from lab frame to CM frame are about $2.2 \text{ GeV} < E_{CM} < 5.5 \text{ GeV}$.

The events to be analyzed in the later part for this study were generated by using the event generator EvtGen (113). The chosen momentum for the antiproton beam is 15 GeV/c which corresponds to a center-of-mass energy about 5.5 GeV. Inside the PandaRoot, the program needs to read a script to understand which reaction/decay chain will be used and which EvtGen model to be used. Thus, multiple decay files for that purpose were created for both $Z(4430)^+$ and $Z(4430)^-$ with last state particles using $\pi^\pm, \pi^\mp, e^+, e^-$ or $\pi^\pm, \pi^\mp, \mu^+, \mu^-$ separately.

In addition, for the event generation for this thesis study, we choose to generate events with an offline PandaRoot installation on our own server with 64-core CPU and 128 GB RAM inside our laboratory at Bolu Abant İzzet Baysal University and get familiar with the PandaRoot program and structure.

<pre> 1 noPhotos 2 3 Decay pbarpSystem1 4 1.0 Z_c(4430)- pi+ PHSP; 5 Enddecay 6 7 Decay Z_c(4430)- 8 1.0 psi(2S) pi- PHSP; 9 Enddecay 10 11 Decay psi(2S) 12 1.0 e+ e- VLL; 13 Enddecay 14 15 End </pre> a)	<pre> 1 noPhotos 2 3 Decay pbarpSystem1 4 1.0 Z_c(4430)- pi+ PHSP; 5 Enddecay 6 7 Decay Z_c(4430)- 8 1.0 psi(2S) pi- PHSP; 9 Enddecay 10 11 Decay psi(2S) 12 1.0 mu+ mu- VLL; 13 Enddecay 14 15 End </pre> b)
<pre> 1 noPhotos 2 3 Decay pbarpSystem1 4 1.0 Z_c(4430)+ pi- PHSP; 5 Enddecay 6 7 Decay Z_c(4430)+ 8 1.0 psi(2S) pi+ PHSP; 9 Enddecay 10 11 Decay psi(2S) 12 1.0 e+ e- VLL; 13 Enddecay 14 15 End </pre> c)	<pre> 1 noPhotos 2 3 Decay pbarpSystem1 4 1.0 Z_c(4430)+ pi- PHSP; 5 Enddecay 6 7 Decay Z_c(4430)+ 8 1.0 psi(2S) pi+ PHSP; 9 Enddecay 10 11 Decay psi(2S) 12 1.0 mu+ mu- VLL; 13 Enddecay 14 15 End </pre> d)

Figure 4.2. The "decay" file that PandaRoot reads for the EvtGen package inside to generate events.

As shown in Figure 4.2, the EvtGen takes the needed information from those decay files to generate reaction chains and the raw data itself. (a) and (b) were prepared for $Z(4430)^-$, (c) and (d) were also prepared for $Z(4430)^+$ reactions chains. Here, PHSP and VLL decay models of the EvtGen were used for the decay files. To take everything into consideration, PHSP was used for the $Z(4430)$ and $\psi(2S)$ as well as VLL was used when the last state particles are pair of leptons. The PHSP model is generic phase space to n-bodies and all spins of particles in the initial state and the final state are averaged (114). On the other hand, The VLL model is used when a vector meson decays to a pair of charged leptons (114). Lastly, to incorporate the final state radiation effects (bremsstrahlung) the PHOTOS (114, 115) package inside EvtGen has been introduced. PHOTOS is a package that produces photons in their final state on a generated decay and may be included in each decay, but to simplify analysis, the PHOTOS was turned off.

Table 4.3. The width and mass of the resonances that EvtGen used to generate events.

State	Mass, M	Width, Γ
$Z(4430)$	4478.00 MeV/c ²	181.00 MeV
$\psi(2S)$	3686.09 MeV/c ²	294.00 keV

Table 4.3 above summarizes the resonances' pre-determined mass and width values inside EvtGen. Thus, with this knowledge, EvtGen knows the specifications of the given state and it can recognize them.

Moreover, the data generated was initially discussed in $\bar{\text{P}}\text{ANDA}$ PWG and 10.000 events has been generated and analyzed. After first analysis results, it was agreed that the data consists of at least more than 1.000.000 events to be more statistically significant. Consequently, a script created for the event generation and 2.000.000 events for 4 decay channels ($Z(4430)^\mp$ with $\pi^\pm, \pi^\mp, e^+, e^-$ or $\pi^\pm, \pi^\mp, \mu^+, \mu^-$) were generated as 10.000 x 200 data packages. This makes it 2.000.000 signal events for each different decay channels. In addition, a total of 7.000.000 background events also created with Dual Parton Model (DPM) (116). The DPM model roughly produces cross-sections of proton reactions, including hadronisation. The model takes into account elastic scattering, including Coulomb

and hadronic ones, the annihilation of one or two pairs of quarks and antiquarks. The DPM generator included in the PandaRoot as one of the many generators, and is used to produce background events. While producing the background events, the maximum value for the beam momentum, 15 GeV/c, is also used. The total generation of signal and background events takes around 1 year to complete in our server.

4.2 Event Analysis Studies

In the analysis, the PandaRoot program's own software language based on C++ was used. Using this language, new intermediate resonance or resonant particle candidates can be reconstructed by combining the final state particle candidates obtained/filtered from the data with the help of the commands included in the software package in C++ macros. In this section, the algorithm shown in Figure 4.3 below, which includes certain cut algorithms in order to obtain the best results for the $Z(4430)^{\mp}$ candidates to be reconstructed with C++ macros, is developed.

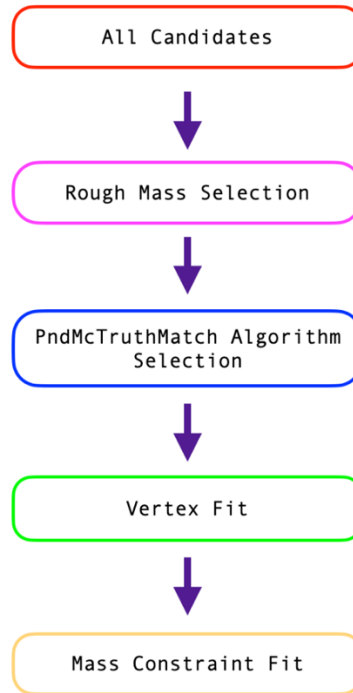


Figure 4.3. Algorithm for particle selection with specific cuts.

The algorithm shown in Figure 4.3 was also presented at the $\bar{\text{P}}\text{ANDA}$ collaboration meetings and optimized for particle selection based on the feedback received (117-119). Here, first of all, all candidates for the desired particle were taken without any cuts, and then the so-called “Rough Mass Selection” was applied as a cut to select particle candidates in a mass window that is on average 2 times the width of the particle in the literature (± 0.25 GeV). In particular, this part was applied at the very beginning of the algorithm and the selection process after the feedbacks to ensure a sharper selection. The second cut “PndMcTruthMatch” is an algorithm in PandaRoot and is a particle identification class for Monte Carlo Truth Matching. This algorithm matches the decaying mother with the intermediate resonance and final state particles, one by one and one-to-one, thus eliminating reconstructed particle candidates with mismatching low mass. The particle candidates are then subjected to a “Vertex Fit” filter that brings the particle tracks in the signal as close as possible to the hypothetical vertex points. When applying this filter, the part with probability greater than 1% is selected. Then, “Mass Constraint Fit” was applied to the remaining particle candidates as the last filter in the algorithm. Again, the ones with probability above 1% were selected and the particle candidates obtained after this estimation were tried to be selected in the best way as the candidates closest to the mass range of the actual particle candidates to be selected. When the selection algorithms and estimations we have described here are considered for the case of $Z(4430)^{\mp}$, firstly, $\psi(2S)$, which is our intermediate resonance in the decay channel, is reconstructed from the final state particles e^+, e^- and μ^+, μ^- , then the candidates obtained after all the filters and cuts applied to $\psi(2S)$ and the final state particle π^+ or π^- are combined to obtain all $Z(4430)^{\mp}$ candidates. As final step, all filter algorithms were applied to $Z(4430)^{\mp}$ again in the same way except “Rough Mass Selection” and the final candidates were obtained. Because $Z(4430)^{\mp}$ is the particle we actually want to obtain, we don't impose a rough mass filter here with first cut in the algorithm scheme in order to improve the number of candidates and statistics we can obtain in this range. This analysis scheme was applied separately for all four different $Z(4430)^{\mp}$ decay channels and the candidates were selected in the best way possible in those scenarios with the applied cut algorithms. The main goal here is to select the best $Z(4430)^{\mp}$ candidates that are closest to the mass range in the literature and to

determine whether this is a situation that can be observed and analyzed when real data is taken in the framework of the $\bar{\text{P}}\text{ANDA}$ experiment.

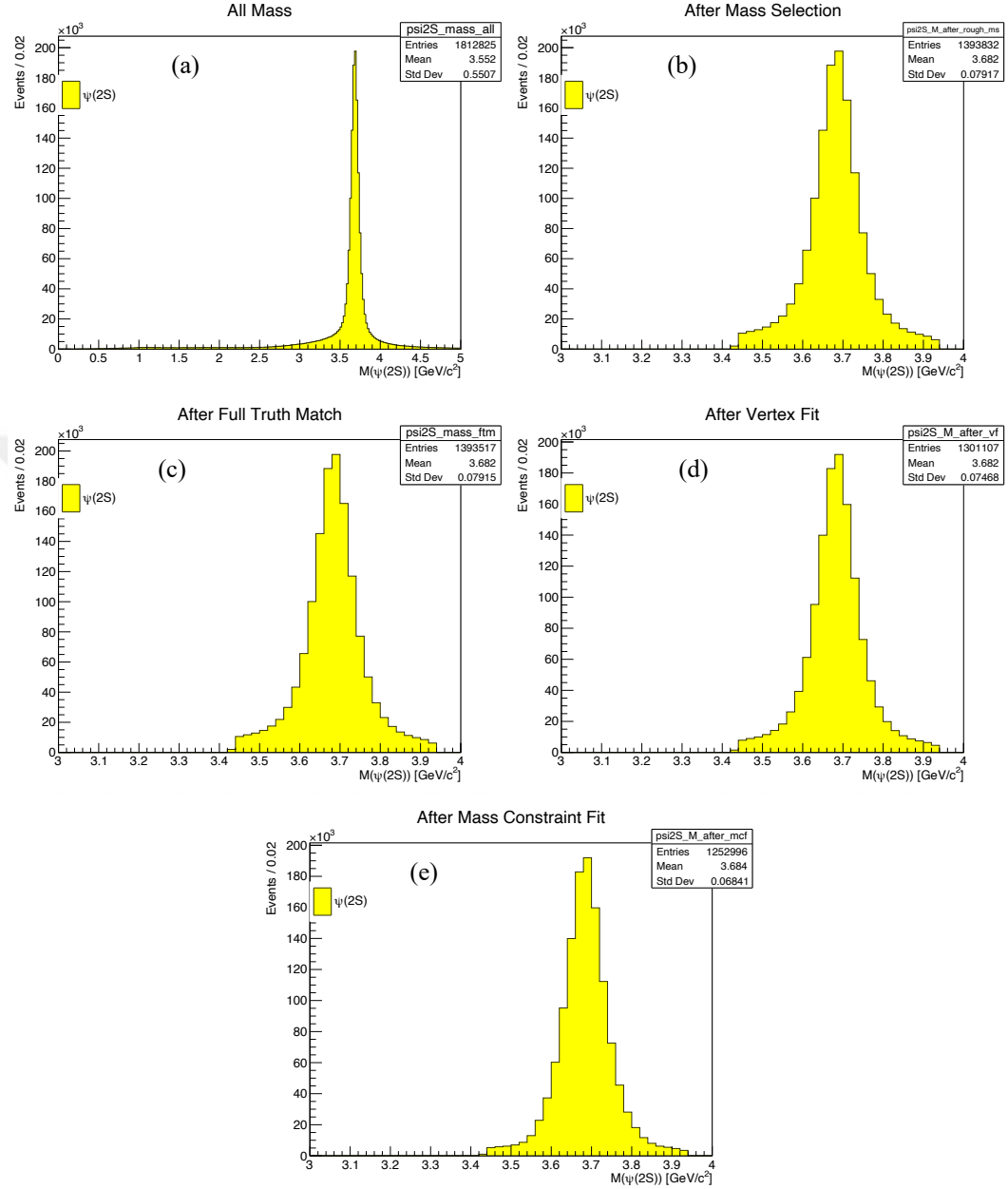


Figure 4.4. Mass distributions of $\psi(2S)$ candidates obtained after going through each of the cuts applied in the algorithm for the analysis study. Candidates after each algorithm applied were shown in (a): “All Candidates without any filters”, (b): “Rough Mass Selection”, (c): “McTruthMatch”, (d): “VertexFit”, (e): “Mass Constraint Fit”. The last graph (e) is the filtered and obtained $\psi(2S)$ candidates for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ channel.

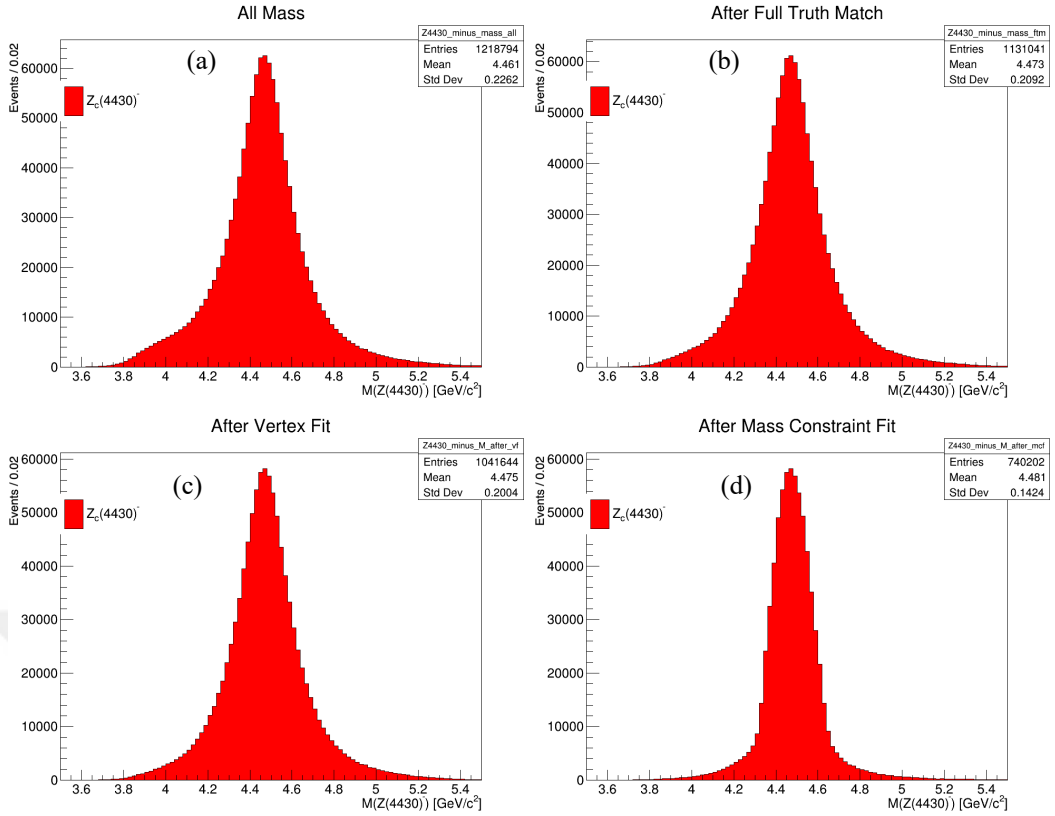


Figure 4.5. Change in the mass distributions of $Z(4430)^-$ candidates after each stage of the applied cut algorithms. Candidates after each algorithm applied were shown in (a); “All Candidates without any filters”, (b): “McTruthMatch”, (c): “VertexFit”, (d): “Mass Constraint Fit”. The last graph (d) is the filtered and obtained $Z(4430)^-$ candidates for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ channel.

As can be seen in Figure 4.4 and Figure 4.5, each step in the selection algorithm led to a sharper reconstruction for both $\psi(2S)$ and $Z(4430)^-$. As can be seen from plots (a) and (e) in Figure 4.4, 1.812.825 $\psi(2S)$ candidates were reconstructed from the data containing 2.000.000 total signal events and 1.252.996 of them were selected to form $Z(4430)^-$ ’s after filtering. As shown in graphs (a) and (e) in Figure 4.5, $Z(4430)^-$ candidates were reconstructed using the obtained $\psi(2S)$ and π^- candidates, and out of the 1.218.794 candidates, 740.202 candidates remained after filtering. After that, Breit-Wigner (120) fit function was applied to the mass distribution of the last remaining candidates of the reconstructed $Z(4430)^-$ candidates and it was tested how close the values in the literature for the particle could be approximated. Figure 4.6 shows the plot of the Breit-Wigner fit function applied to the mass distribution of the $Z(4430)^-$ candidates obtained from the “Mass Constraint Fit” in Figure 4.5(d).

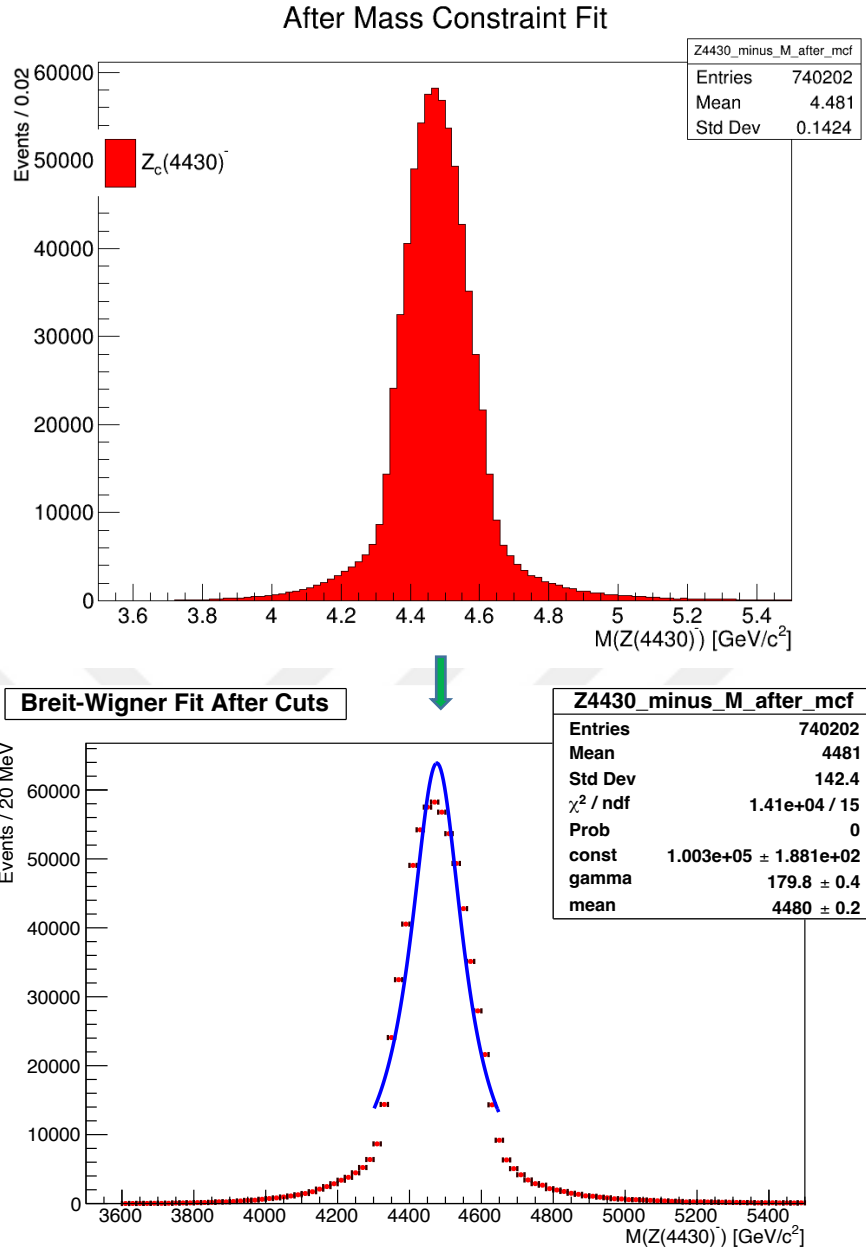


Figure 4.6. Results of the Breit-Wigner fit function applied to the mass distributions of $Z(4430)^-$ candidates obtained after passing through all cuts ($Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$) channel.

According to the Breit-Wigner fit results in Figure 4.6, the mass is 4480 ± 0.2 MeV and the width (Γ) is 179.8 ± 0.4 MeV. In the literature, these values are 4478^{+15}_{-18} MeV mass and 181 ± 31 MeV width, respectively (73). When we compare these values, it is seen that these values are reached with an error of 0.04% in mass and 0.72% in width. Since the analysis was repeated by increasing the number of events from 1M to 2M for the pre-generated data, it can be said that this statistical increase helped to obtain better results.

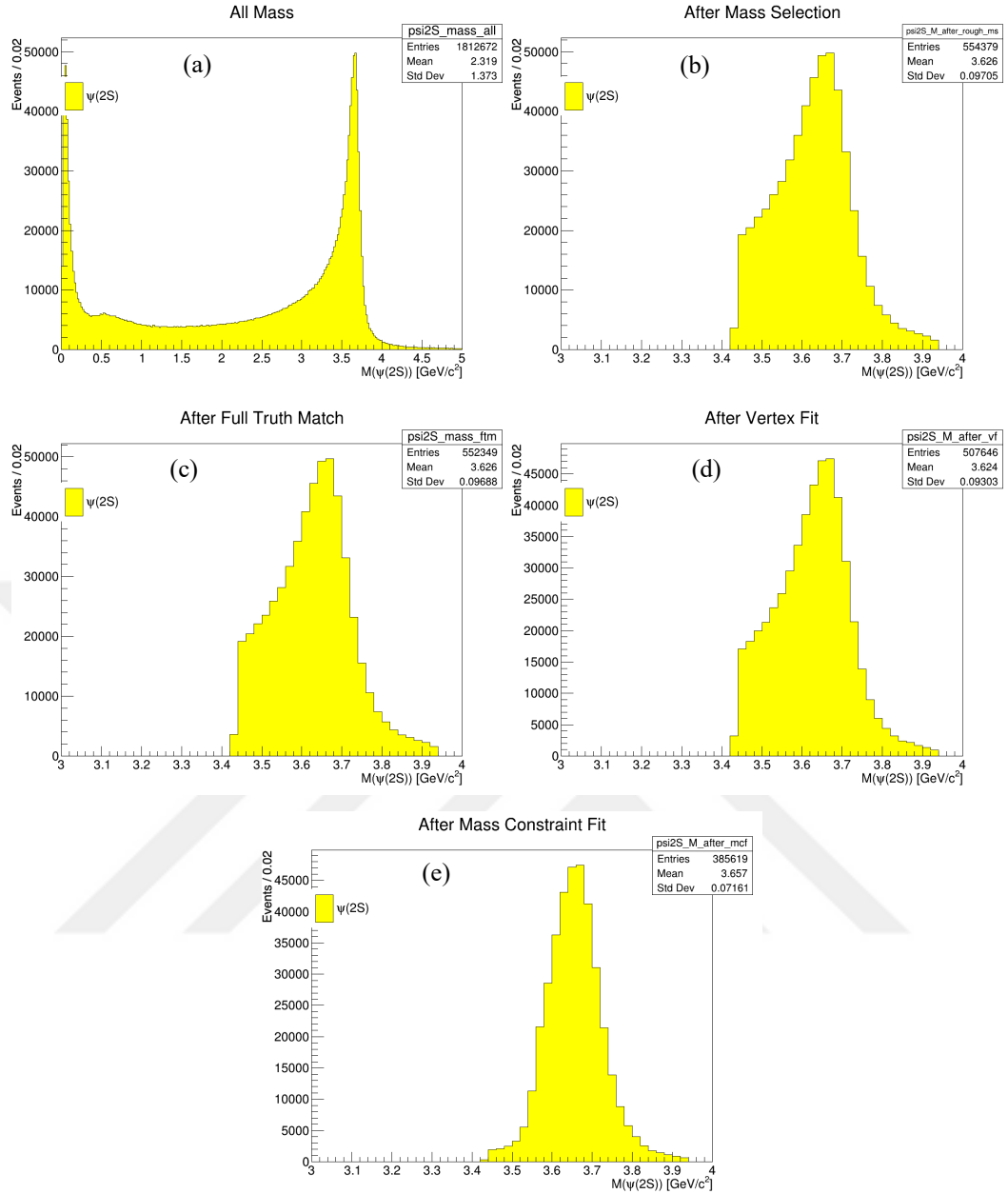


Figure 4.7. Mass distributions of $\psi(2S)$ candidates obtained after going through each of the cuts applied in the algorithm for the analysis study. Candidates after each algorithm applied were shown in (a): “All Candidates without any filters”, (b): “Rough Mass Selection”, (c): “McTruthMatch”, (d): “VertexFit”, (e): “Mass Constraint Fit”. The last graph (e) is the filtered and obtained $\psi(2S)$ candidates for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ channel.

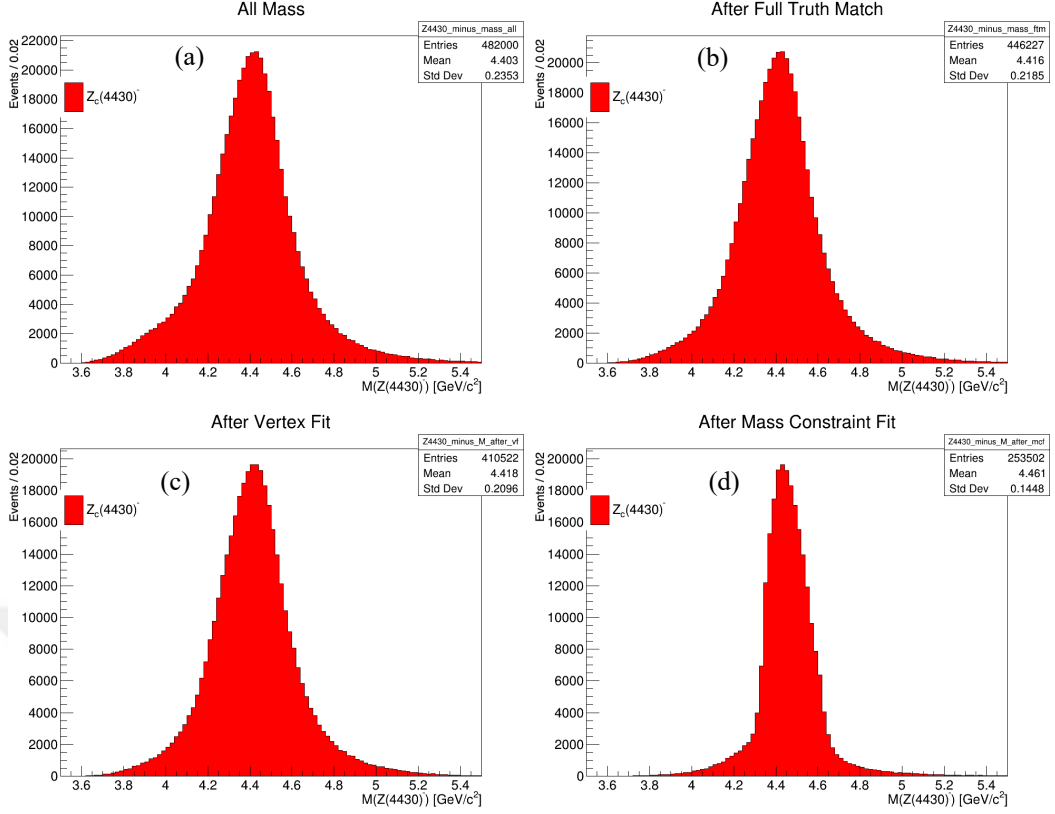


Figure 4.8. Change in the mass distributions of $Z(4430)^-$ candidates after each stage of the applied cut algorithms. Candidates after each algorithm applied were shown in (a); “All Candidates without any filters”, (b): “McTruthMatch”, (c): “VertexFit”, (d): “Mass Constraint Fit”. The last graph (d) is the filtered and obtained $Z(4430)^-$ candidates for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ channel.

In Figure 4.7, as in the previous decay channel, all filters were step by step applied to the reconstructed $\psi(2S)$ candidates and the best candidates were obtained. In Figure 4.7(e), the $Z(4430)^-$ candidates were reconstructed by combining the $\psi(2S)$ candidates with the π^- candidates. These candidates were then subjected to all the cuts and filters in the selection algorithm one by one, again excluding only “Rough Mass Selection”, and the results are shown in Figure 4.8. The Breit-Wigner fit function was applied to the last remaining $Z(4430)^-$ candidates and the results are also given in Figure 4.9 below.

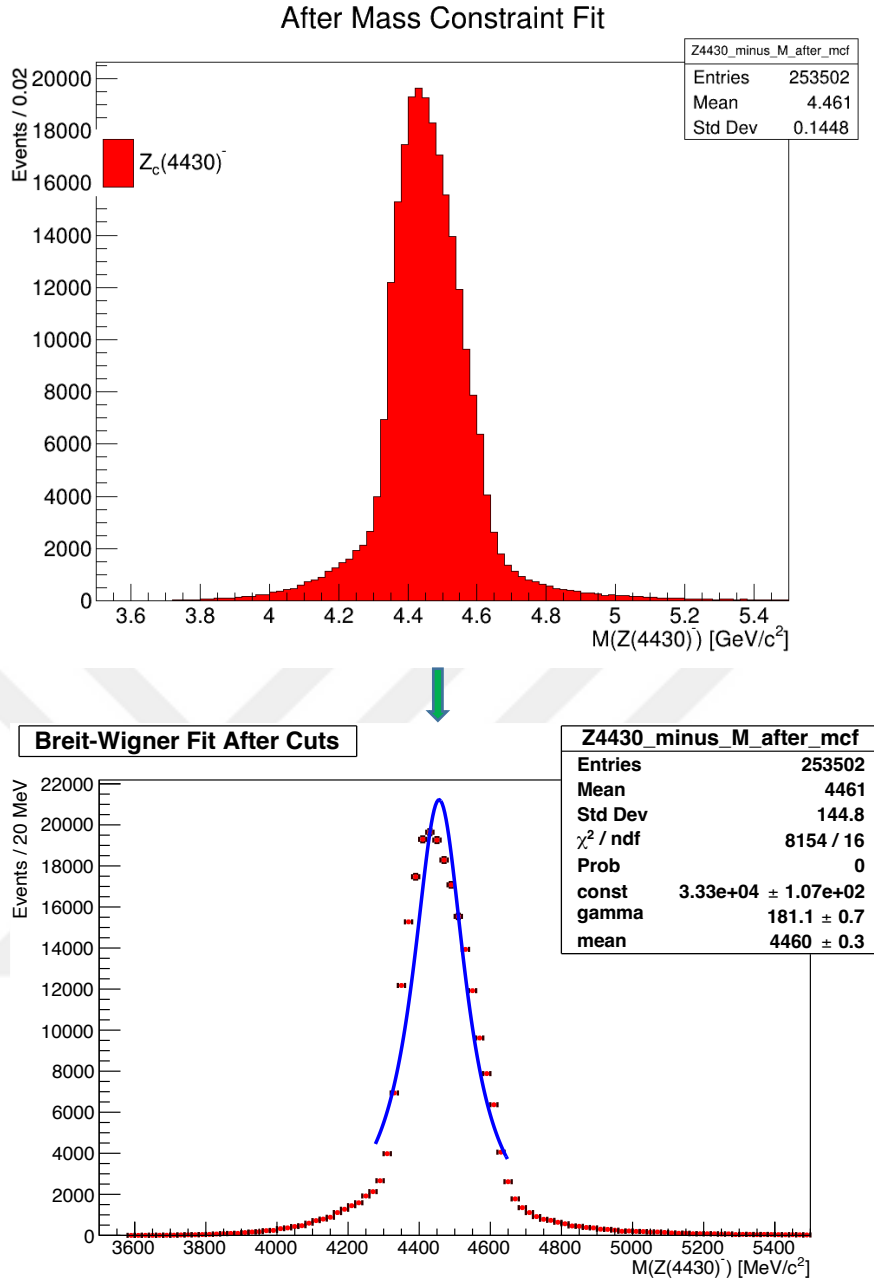


Figure 4.9. Results of the Breit-Wigner fit function applied to the mass distributions of $Z(4430)^-$ candidates obtained after passing through all cuts ($Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$) channel.

Figure 4.9 shows that the mass (from the mean value of the graph) is 4460 ± 0.3 MeV and the width is 181.1 ± 0.7 MeV based on the Breit-Wigner fit results in the graph. When we compare these values with the literature, it is seen that these values are obtained with an error of 0.40% in mass and 0.06% in width.

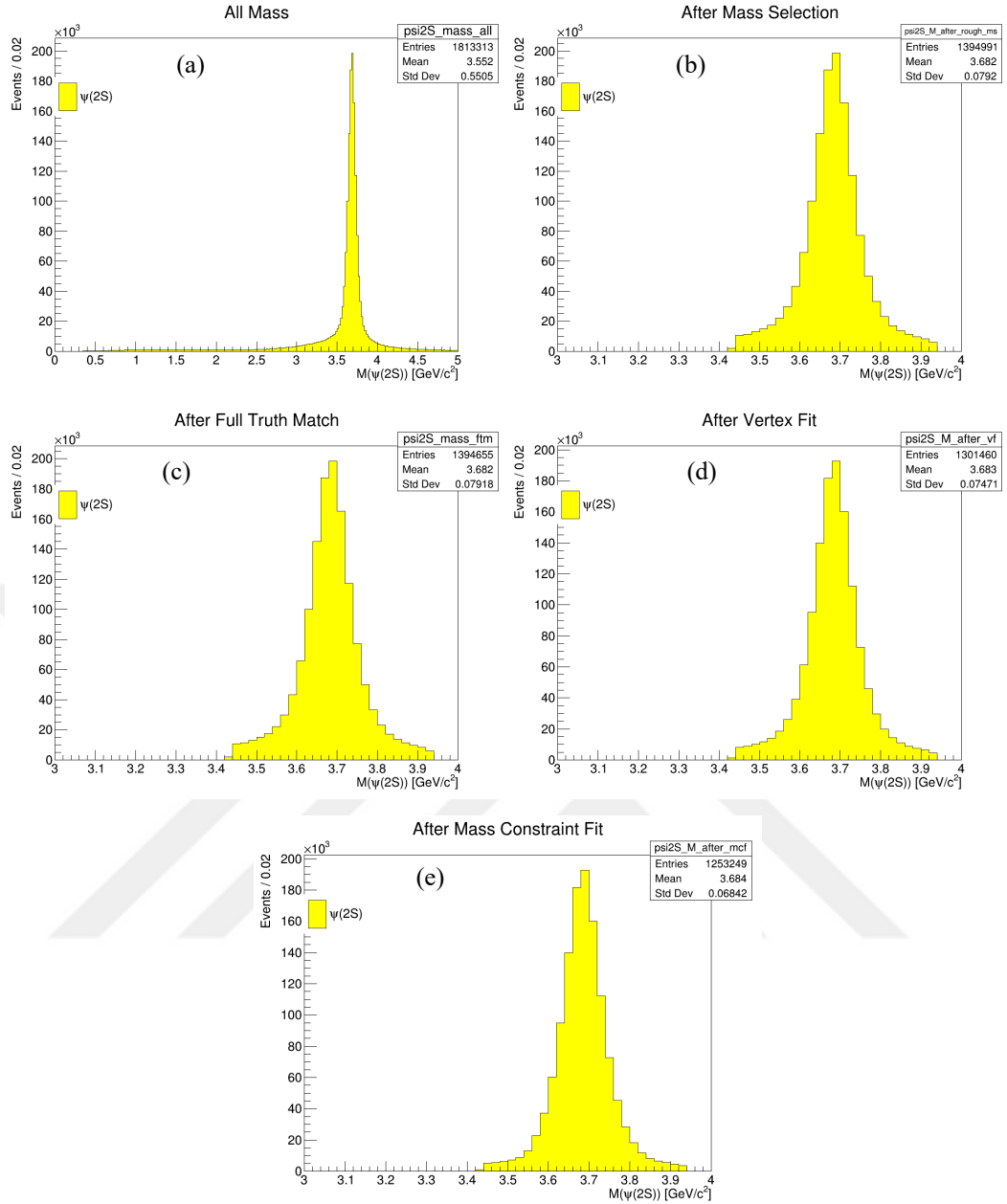


Figure 4.10. Mass distributions of $\psi(2S)$ candidates obtained after going through each of the cuts applied in the algorithm for the analysis study. Candidates after each algorithm applied were shown in (a): “All Candidates without any filters”, (b): “Rough Mass Selection”, (c): “McTruthMatch”, (d): “VertexFit”, (e): “Mass Constraint Fit”. The last graph (e) is the filtered and obtained $\psi(2S)$ candidates for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ channel.

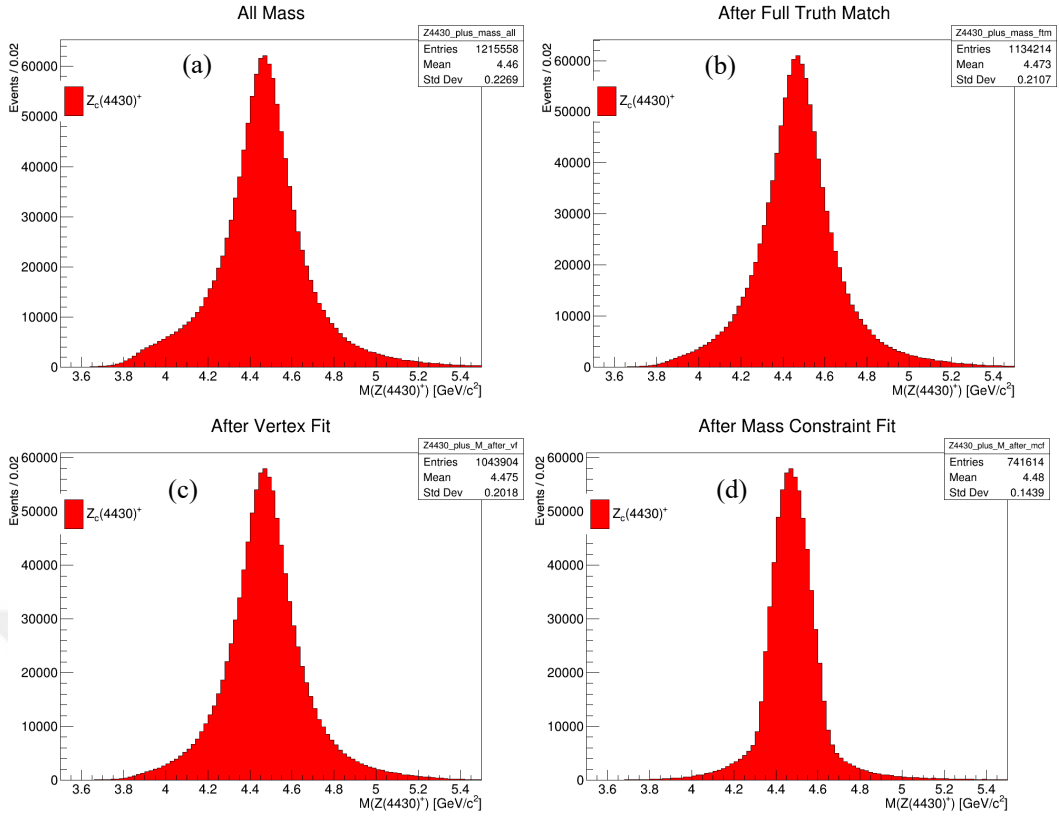


Figure 4.11. Change in the mass distributions of $Z(4430)^+$ candidates after each stage of the applied cut algorithms. Candidates after each algorithm applied were shown in (a); “All Candidates without any filters”, (b): “McTruthMatch”, (c): “VertexFit”, (d): “Mass Constraint Fit”. The last graph (d) is the filtered and obtained $Z(4430)^+$ candidates for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ channel.

For the $Z(4430)^+$, the analysis method used for $Z(4430)^-$ was also applied for both channels of it. The best selection of reconstructed $\psi(2S)$ candidates after all applied cuts and filters were also shown in Figure 4.10(e). These $\psi(2S)$ candidates then taken and combined with π^+ to reconstruct all $Z(4430)^+$ particle candidates. The applied cuts and mass distributions of $Z(4430)^+$ were also shown in Figure 4.11. Here, the plot Figure 4.11(d) is showing best selection of reconstructed $Z(4430)^+$ candidates for this decay channel.

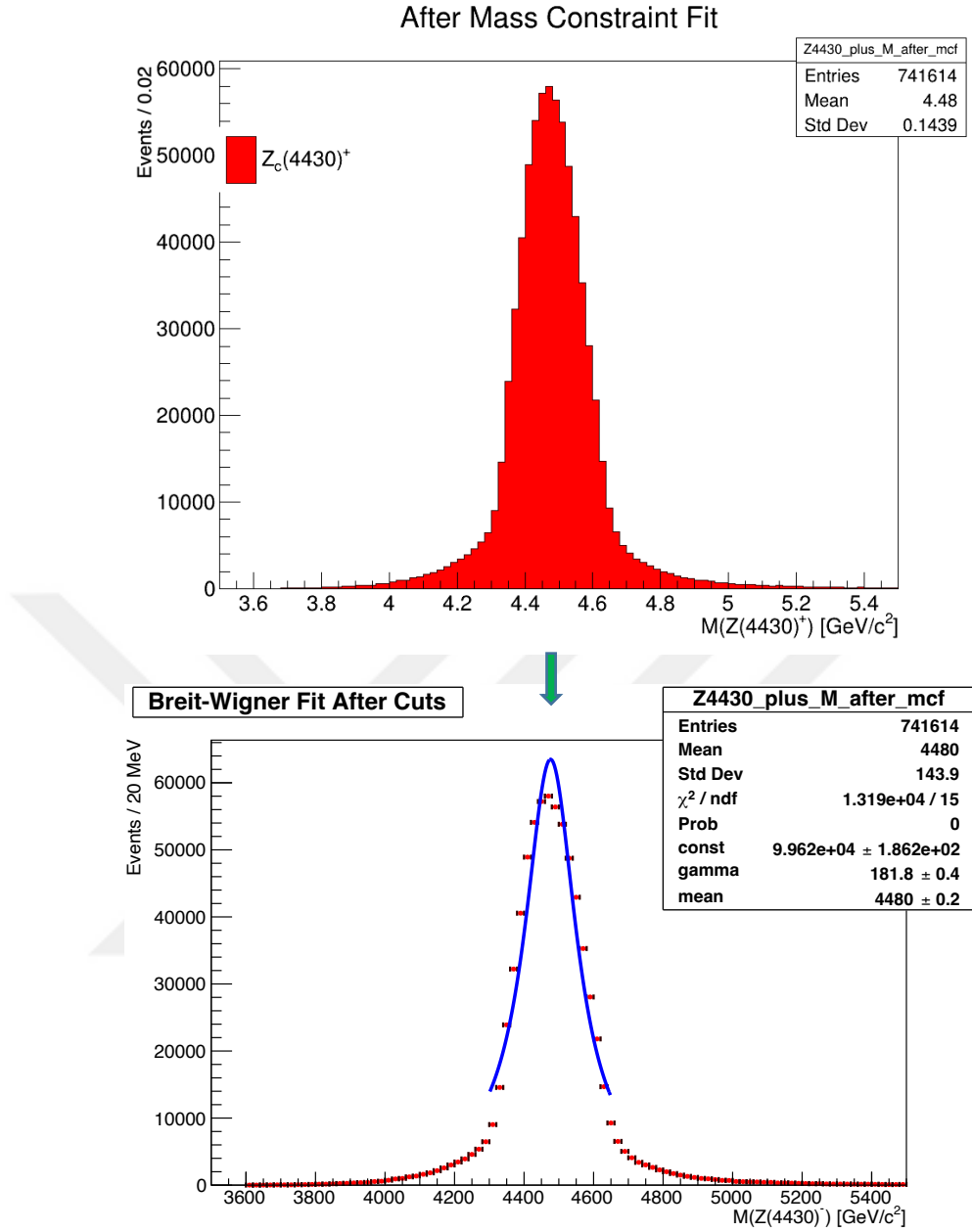


Figure 4.12. Results of the Breit-Wigner fit function applied to the mass distributions of $Z(4430)^+$ candidates obtained after passing through all cuts ($Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$) channel.

According to the applied Breit-Wigner fit function results in Figure 4.12, the mass is 4480 ± 0.2 MeV and width is 181.8 ± 0.4 MeV. When we compare these values with the ones in literature, it is seen that these values were obtained with an error of 0.04% in mass and an error of 0.44% in width.

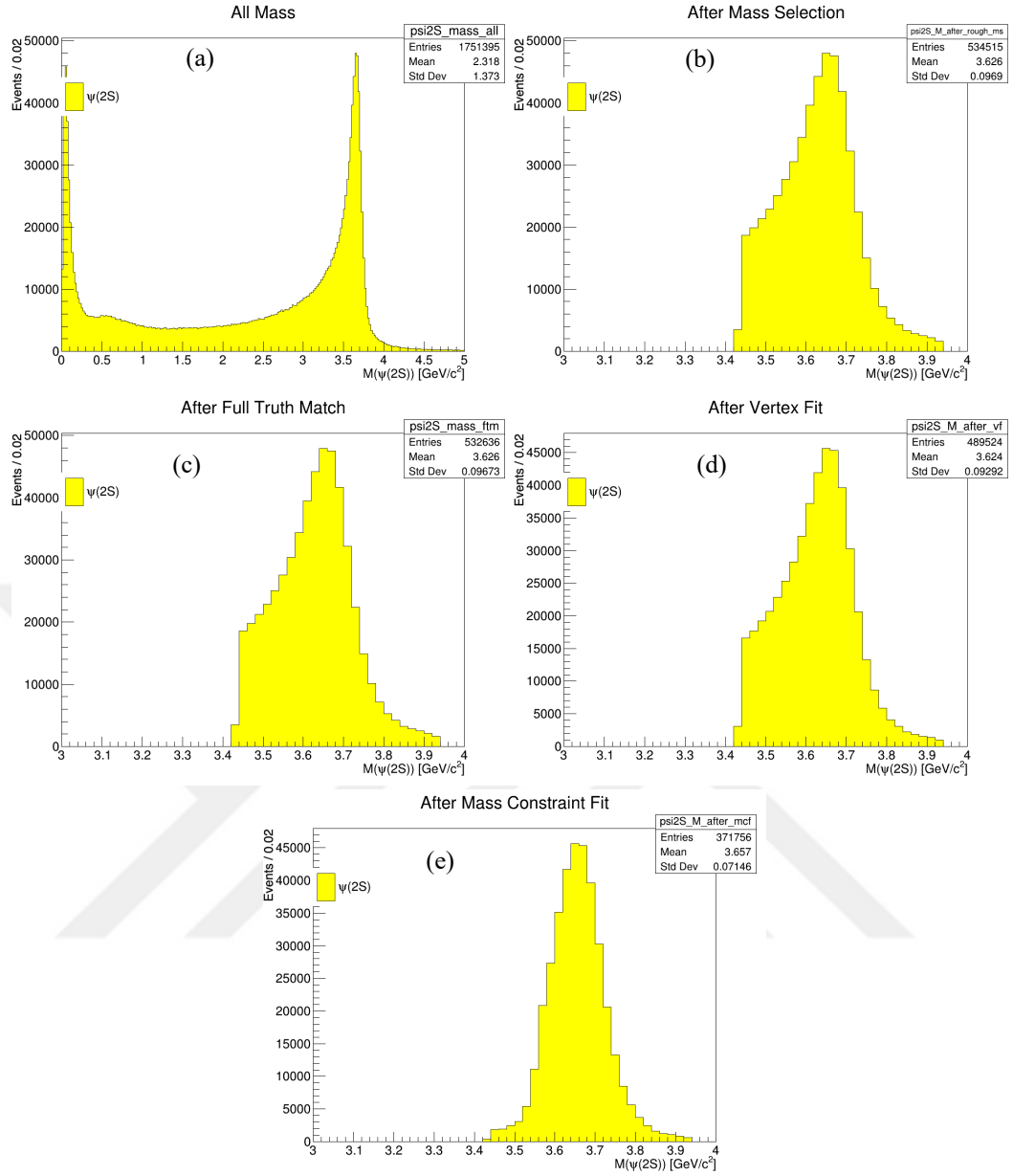


Figure 4.13. Mass distributions of $\psi(2S)$ candidates obtained after going through each of the cuts applied in the algorithm for the analysis study. Candidates after each algorithm applied were shown in (a): “All Candidates without any filters”, (b): “Rough Mass Selection”, (c): “McTruthMatch”, (d): “VertexFit”, (e): “Mass Constraint Fit”. The last graph (e) is the filtered and obtained $\psi(2S)$ candidates for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ channel.

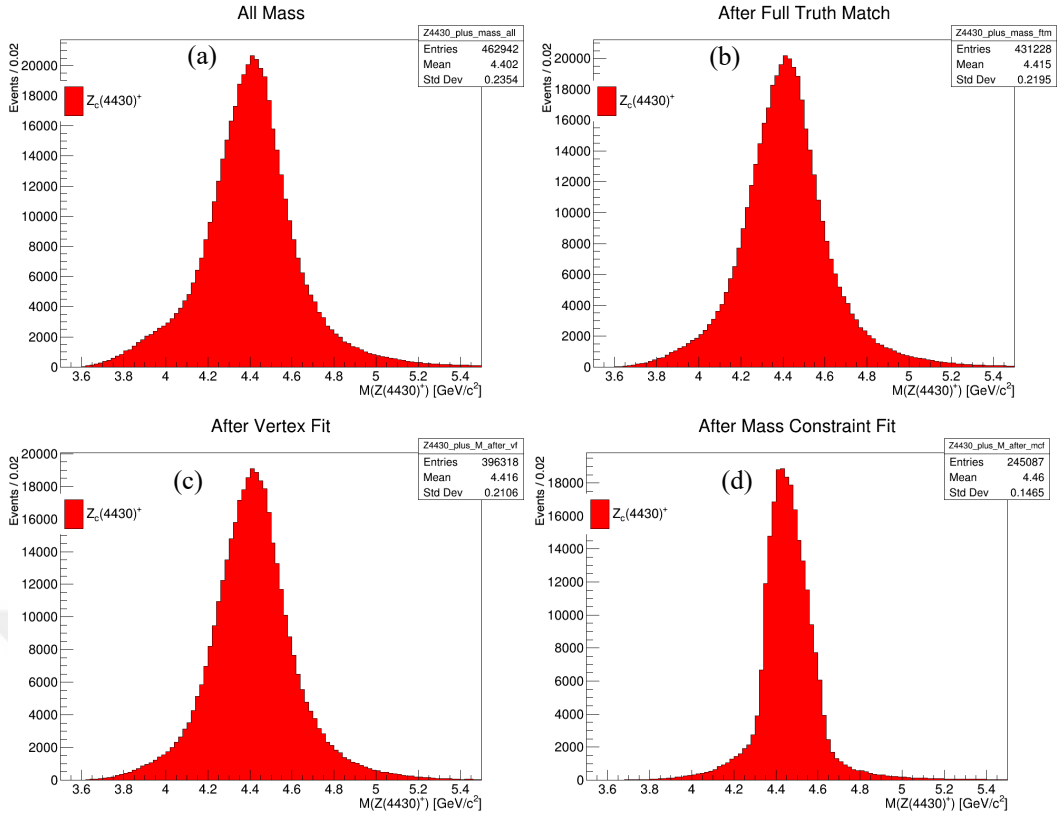


Figure 4.14. Change in the mass distributions of $Z(4430)^+$ candidates after each stage of the applied cut algorithms. Candidates after each algorithm applied were shown in (a); “All Candidates without any filters”, (b): “McTruthMatch”, (c): “VertexFit”, (d): “Mass Constraint Fit”. The last graph (d) is the filtered and obtained $Z(4430)^+$ candidates for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ channel.

As with the other three decay channels, Figure 4.13 shows the mass distributions of the $\psi(2S)$ candidates after applying the filters and cuts in the algorithm scheme. The candidates in plot Figure 4.13(e), which were selected as the best candidates, were again combined with the π^+ candidates and the $Z(4430)^+$ particle was reconstructed in a similar way. The resulting $Z(4430)^+$ candidates for this decay channel were also passed through the selection filters again and the best candidates were obtained which shown in Figure 4.14 above.

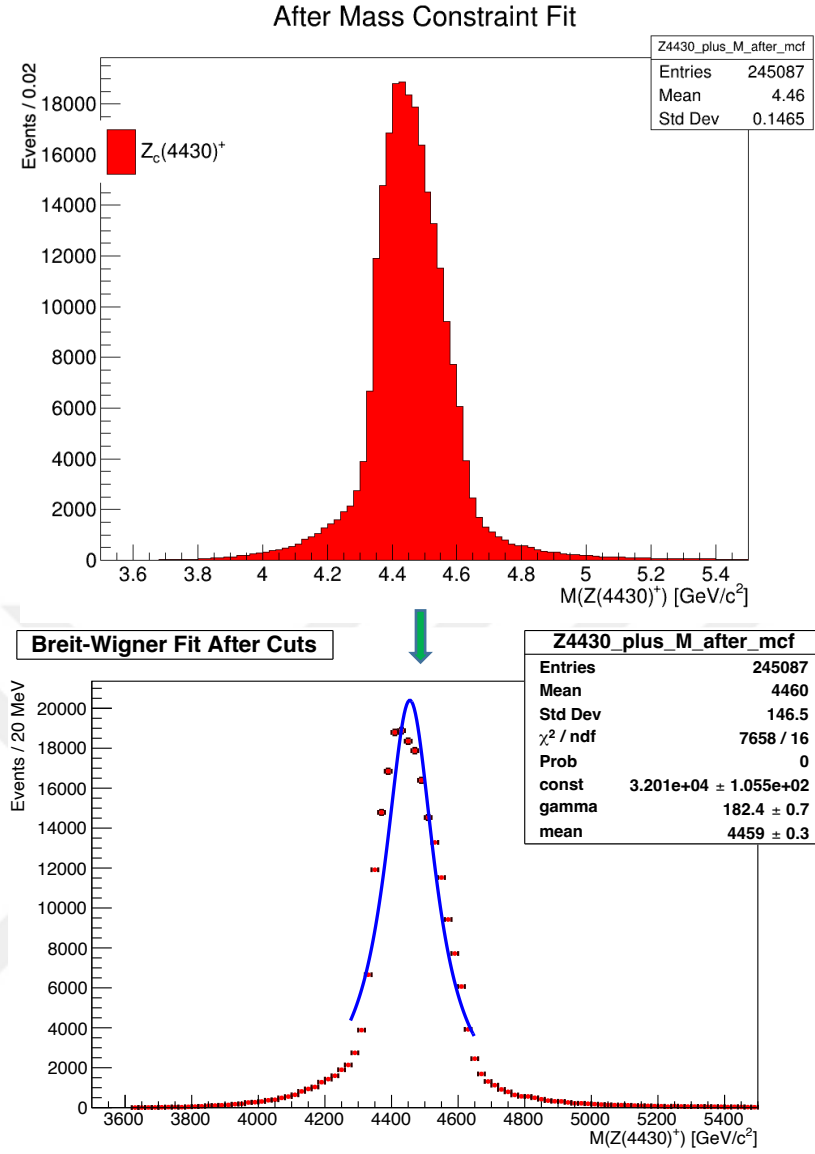


Figure 4.15. Results of the Breit-Wigner fit function applied to the mass distributions of $Z(4430)^+$ candidates obtained after passing through all cuts ($Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$) channel.

The mass is 4459 ± 0.3 MeV and the width is 182.4 ± 0.7 MeV, based on the Breit-Wigner fit findings shown in Figure 4.15. These values were acquired with an error of 0.42% in mass and 0.77% in width, when we compare them to ones in the literature. After the results of the analysis of four different decay channels including $e^+ e^-$ and $\mu^+ \mu^-$ end states for both $Z(4430)^+$ and $Z(4430)^-$, one of the most important aspects of this feasibility study is the efficiency of the final state particles and the reconstructed intermediate resonance and resonance states. In this context, percentage efficiencies were calculated for all the different decay channels and are given in Table 4.4 below. Upper numbers in the table represent the all-

reconstructed candidates and the bottom numbers represent the remaining candidates after PID and applied particle selection algorithm.

Table 4.4. Reconstruction efficiency values (%) for final state particles, intermediate resonance and resonance states.

Decay Channel	$Z(4430)^- \rightarrow \psi(2S) \rightarrow \mu^+ \mu^-$	$Z(4430)^- \rightarrow \psi(2S) \rightarrow e^+ e^-$	$Z(4430)^+ \rightarrow \psi(2S) \rightarrow \mu^+ \mu^-$	$Z(4430)^+ \rightarrow \psi(2S) \rightarrow e^+ e^-$
# of π^+	1.640.810 1.737.202	1.635.884 1.733.618	1.640.939 1.741.706	1.553.386 1.650.439
π^+ efficiency	94.45%	94.36%	94.21%	94.12%
# of π^-	1.635.904 1.738.198	1.629.044 1.733.218	1.649.695 1.748.163	1.561.336 1.656.211
π^- efficiency	94.11%	93.99%	94.37%	94.27%
# of μ^+ or e^+	1.740.519 1.899.100	1.635.022 1.798.656	1.749.626 1.911.903	1.561.368 1.718.026
μ^+ or e^+ efficiency	91.65%	90.90%	91.51%	90.88%
# of μ^- or e^-	1.725.943 1.879.149	1.629.587 1.809.402	1.734.455 1.885.728	1.556.395 1.728.647
μ^- or e^- efficiency	91.85%	90.06%	91.98%	90.04%
$(\mu^+ * \mu^-)$ or $(e^+ * e^-)$	84.18%	81.87%	84.17%	81.83%
# of $\psi(2S)$	1.393.517 1.812.825	552.349 1.812.672	1.394.655 1.813.313	532.636 1.751.395
$\psi(2S)$ efficiency	76.87%	30.47%	76.91%	30.41%
# of $Z(4430)^\mp$	740.202 1.218.794	253.502 482.000	741.614 1.215.558	245.087 462.942
$Z(4430)^\mp$ efficiency	60.73%	52.59%	61.01%	52.94%

In addition to the efficiency study, we finally analyzed the filtered background DPM data (containing at least four charged particles, which eliminates unnecessary events and reduces the data size, but still contains large data) containing 7.000.000 background events, to observe the separability of the signal data from the background data of the final mass distributions obtained for $\psi(2S)$ and $Z(4430)^\mp$ after the background data and the signal data were passed through the same particle selection algorithm in the analysis. These are given in Figure 4.16, Figure 4.17, Figure 4.18 and Figure 4.19 for the four different decay channels (see Table 4.4), respectively.

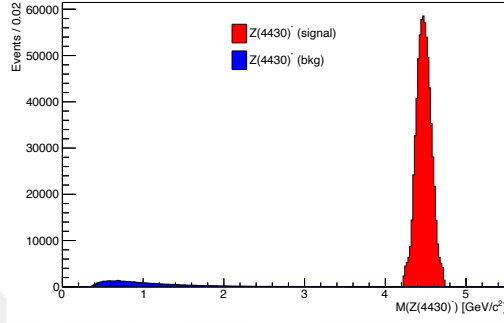
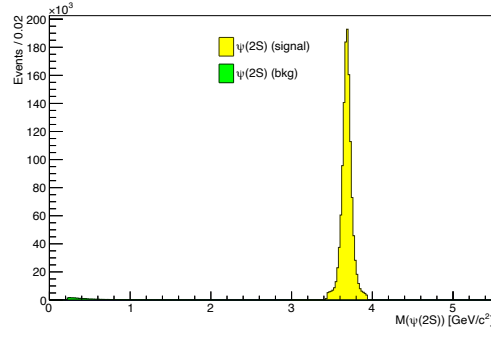


Figure 4.16. $\psi(2S)$ and $Z(4430)^-$ mass distributions obtained after passing through all filters and cuts in the algorithm, using signal and DPM background data ($Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ decay channel).

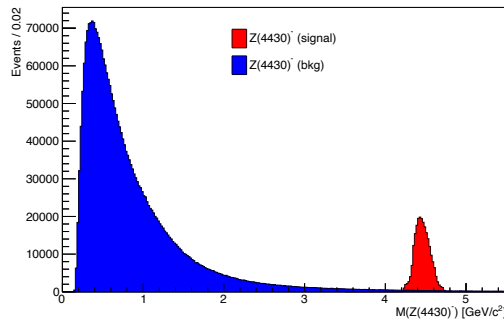
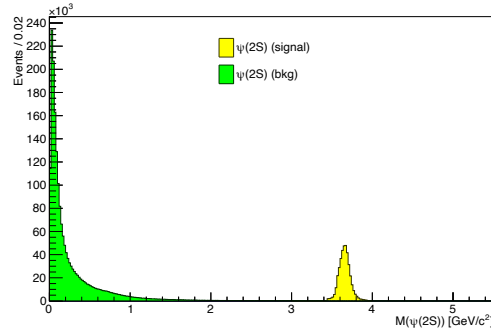


Figure 4.17. $\psi(2S)$ and $Z(4430)^-$ mass distributions obtained after passing through all filters and cuts in the algorithm, using signal and DPM background data ($Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ decay channel).

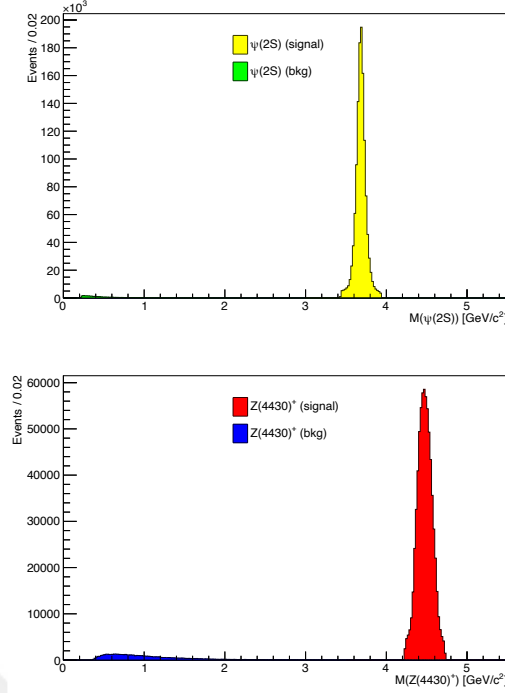


Figure 4.18. $\psi(2S)$ and $Z(4430)^+$ mass distributions obtained after passing through all filters and cuts in the algorithm, using signal and DPM background data ($Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ decay channel).

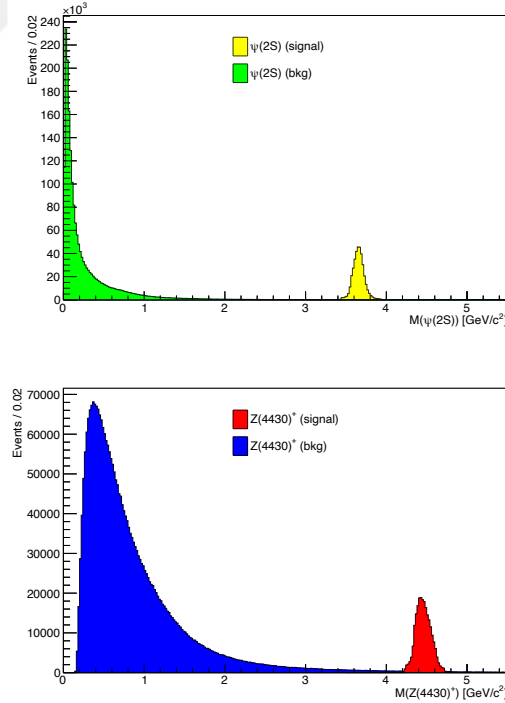


Figure 4.19. $\psi(2S)$ and $Z(4430)^+$ mass distributions obtained after passing through all filters and cuts in the algorithm, using signal and DPM background data ($Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ decay channel).

In the last part of the study, signal-to-background ratio and statistical significance calculations were also performed for 4 different decay channels. As mentioned before, none of the 7 million background events generated for the analysis escaped the particle selection algorithm. Here, the absence of any background event corresponds to a 90% confidence level (C.L.) of 2.3 events. The signal-to-background ratio is calculated as follows:

$$\frac{S}{B} = \frac{\sigma_{sig} \cdot \epsilon_{sig} \cdot Br_{sig}}{\sigma_{bg} \cdot \epsilon_{bg}} \quad (11)$$

where σ_{sig} is the signal cross-section and σ_{bg} is the background cross-section, Br_{sig} is the total branching fraction of the last selected signal events. ϵ_{sig} and ϵ_{bg} are the reconstruction efficiencies for signal and background events, respectively.

In addition, statistical significance (SS) is given by the following calculation:

$$SS = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bg} \cdot F_{bg}}} \quad (12)$$

where N_{sig} and N_{bg} are the number of remaining signal and background events after the analysis, respectively. F_{bg} is a scaling factor to correct the number of background events by the number of signal events, as this ratio does not reflect the cross-sections. The scaling factor F_{bg} is given by the following formula;

$$F_{bg} = \frac{N_{sig}^{gen} \cdot \sigma_{bg}}{N_{bg}^{gen} \cdot \sigma_{sig} \cdot Br_{sig}}. \quad (13)$$

In Equation (13), N_{sig}^{gen} and N_{bg}^{gen} are represent the number of total generated signal and background events, respectively.

In order to make calculations here, the signal and background cross-sections must be known. Since there is no experimental data yet in the $\bar{P}$ ANDA experiment, the signal cross-section data from (121) ($\sigma_{sig} = 5.5 \pm 16.7$ fb), which was previously calculated with real data. Additionally, at 15 GeV/c beam momentum, the inelastic cross-section was taken as $\sigma_{bg} = 40$ mb as shown in Figure 4.20.

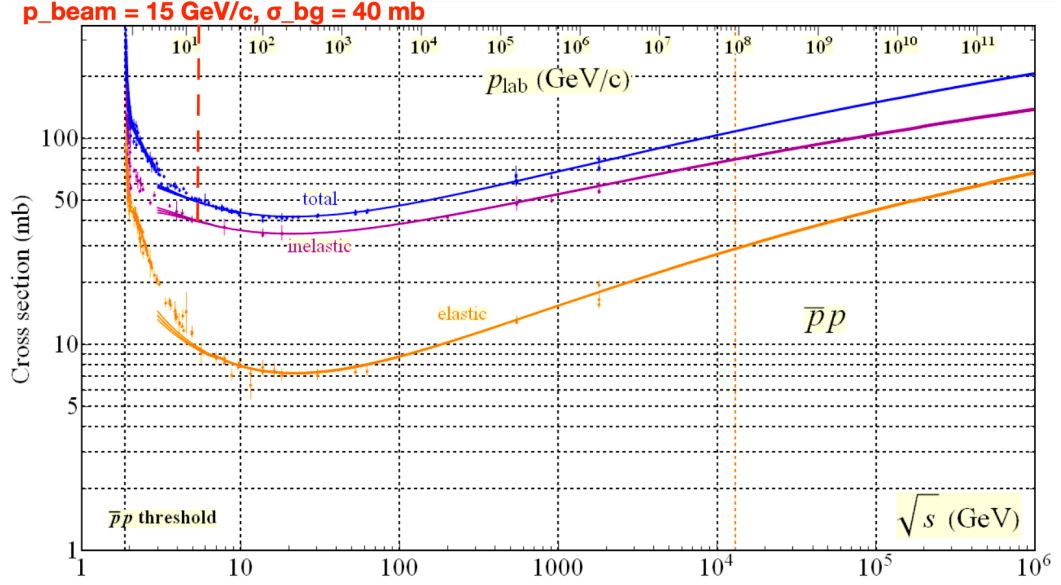


Figure 4.20. Elastic, inelastic and total cross-sections as a function of laboratory beam momentum and total center-of-mass energy and for pp and $\bar{p}p$ collisions (46).

90% C.L. reconstruction efficiency for background events is about $\epsilon_{bg} = 2.3 \times 10^{-8}$. The branching ratio of $\psi(2S)$ was set to 100% during event generation. In the calculations of S/B and SS , $Br_{sig} = Br_{\psi(2S)} = 7.7 \times 10^{-3}$ for the $\psi(2S) \rightarrow \mu^+ \mu^-$ channels and $Br_{sig} = Br_{\psi(2S)} = 7.72 \times 10^{-3}$ for the $\psi(2S) \rightarrow e^+ e^-$ channels (46). N_{sig}^{gen} and N_{bg}^{gen} are 2.000.000 and 7.000.000, respectively. N_{sig} and N_{bg} were also taken from our results which previously given in Table 4.4. For 4 different decay channels, the calculated signal-to-background ratio and statistical significance values are listed in Table 4.5.

Table 4.5. Calculated signal-to-background ratio and statistical significance values for full decay tree fit.

Decay Channel	$Br_{sig} = Br_{\psi(2S)}$	$S/B \times 10^{-8}$	SS
$Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$	7.70×10^{-3}	2.796	0.0742*
$Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$	7.72×10^{-3}	2.427	0.0294*
$Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$	7.70×10^{-3}	2.808	0.0740*
$Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$	7.72×10^{-3}	2.443	0.0282*

*Assuming at least 1 background event.

The cross-section of the exact process $p\bar{p} \rightarrow Z(4430)^\pm \rightarrow \psi(2S) \pi^\pm \rightarrow \mu(or e)^+ \mu(or e)^- \pi^\pm$ is still unknown. The only related measurement for this type of decay process in the literature is from Jia et al. (121), which is $e^+e^- \rightarrow Z_c^+(4430) Z_c^-(4430)$ and the branching ratio is about $5.5 \pm 16.7 fb = 0.0055 pb$. According to foreseen high luminosity value of $\bar{P}$ ANDA from (52), $2 \times 10^{32} cm^{-2}s^{-1} = 2 \times 10^{-4} pb^{-2}s^{-1}$, and the signal cross-section of $Z(4430)$ from (121), $5.5 \pm 16.7 fb = 0.0055 pb$, one can calculate $N_{evts/sec} = L \cdot \sigma$ and $N_{expected evts/sec} = L \cdot \sigma \cdot \epsilon$ where L is luminosity, σ is cross-section and ϵ is reconstruction efficiency. $N_{evts/sec} = L \cdot \sigma = 2 \times 10^{-4} pb^{-1}s^{-1} \times 0.0055 pb = 1.1 \times 10^{-6} s^{-1}$ which means that 1.1×10^{-6} $Z(4430)$ events per second might be produced. A summary of the $N_{evts/sec}$ and $N_{expected evts/sec}$ calculations are given in Table 4.6 below.

Table 4.6. Estimated calculations of possible number of $Z(4430)$ produced per day and the estimation of possible number of $Z(4430)$ reconstructed per day.

Decay Channel	Reconstruction Efficiency of $Z(4430)$	With Detector Efficiency Reconstructed Per Day (MC Truth)	Total Signal Reconstructed Per Day
$Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$	60.73%	0.0577	0.095
$Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$	52.59%	0.0500	0.095
$Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$	61.01%	0.0580	0.095
$Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$	52.94%	0.0503	0.095

4.3 Analysis Results

While analyzing the signal data, both $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ and $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ decay channels shows a significant drop for the number of reconstructed $Z(4430)$ candidates comparing them with $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ and $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$. This is because of the Bremsstrahlung effects not properly works on the detector software when e^+e^- are included. That issue also shared in the $\bar{P}$ ANDA PWG and Collaboration meetings (117-119) with the authorized people and they sent this consideration to the Software Group of $\bar{P}$ ANDA. The software team then

investigated the issue and gave feedback after that the considered errors in the software is actually existed and they started to prepare some fix for the affected libraries/code strings. Consequently, this work also contributed to reveal some bugs in the $\bar{\text{PANDA}}$ software about Bremsstrahlung and final state radiation effects.

Finally, as a result of the filters and cuts developed for particle selection algorithm as well as due to the continuous increase of the statistics (number of events) of the data with continuous production for 4 different decay channels that we have examined for the $Z(4430)^{\mp}$ state, the mass and width values have been approximated to the values in the literature (4478^{+15}_{-18} MeV for $Z(4430)$'s mass and 181 ± 31 MeV for $Z(4430)$'s width (46)) with very small errors according to our average results of mass and width from 4 different decay channels of $Z(4430)^{\pm}$ ($Z(4430)^{\pm} \rightarrow \psi(2S) \pi^{\pm} \rightarrow \mu^+ \mu^- \pi^{\pm}$ and $Z(4430)^{\pm} \rightarrow \psi(2S) \pi^{\pm} \rightarrow e^+ e^- \pi^{\pm}$) which are 4470 ± 0.25 MeV and 181.3 ± 0.55 MeV, respectively. Thus, these precise results are showing that the $Z(4430)$ state is a feasible state and it can be possible detected and seen in the $\bar{\text{PANDA}}$ detector's spectrum.

According to results from Table 4.5, the statistical significance (p-values) of 0.0742, 0.0294, 0.0740, and 0.0282 observed for the signal events provide a nuanced view of the statistical significance of the findings. The calculated p-values of 0.0294 for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ decay channel and 0.0282 for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ decay channel are notably below the conventional significance threshold of 0.05, suggesting that these results are statistically significant and provide stronger evidence for a potential real signal according to our simulations and analysis. This level of significance indicates a relatively low probability (2.94% and 2.82%, respectively) that the observed effects could be attributed to random fluctuations in the background noise, thus supporting the validity of these signals. In addition, the p-values of 0.0742 for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ decay channel and 0.0740 for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ decay channel exceed the 0.05 threshold, implying that these results are a little less statistically robust. With probabilities of 7.42% and 7.40%, respectively, these values indicate that the observed signals might still be due to random variations with a small chance. Collectively, these p-values suggest that the

observed signals show some promising signs of significance according to their low probabilities to be random fluctuations.

From the signal-to-background calculation results from Table 4.5; for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$ decay channel, S/B is 2.796×10^{-8} , for $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$ decay channel, S/B is 2.427×10^{-8} , for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ decay channel, S/B is 2.808×10^{-8} and for $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ decay channel, calculated S/B is about 2.443×10^{-8} . The values are quite close to each other, indicating that there is little variation in the signal-to-background ratio across the different measurements. This consistency suggests that the signal strength relative to the background is uniformly low, but in the analysis study, this not affected separation of signal events from background events.

Moreover, according to results shown in Table 4.6, from the estimated calculations 1×10^{-6} $Z(4430)$ events per second which equals to 0.095 $Z(4430)$ events per day and ~ 35 $Z(4430)$ events per year can be produced in $\bar{P}$ ANDA detector with a same or close cross-section value used in those calculations. Also, by using reconstruction efficiencies presented in Table 4.4, estimated calculations for possible $Z(4430)$ production per day were also done and for decay channels $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow \mu^+ \mu^- \pi^-$, $Z(4430)^- \rightarrow \psi(2S) \pi^- \rightarrow e^+ e^- \pi^-$, $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow \mu^+ \mu^- \pi^+$ and $Z(4430)^+ \rightarrow \psi(2S) \pi^+ \rightarrow e^+ e^- \pi^+$ these values are 0.0577 per day, 0.0500 per day, 0.0580 per day and 0.0503 per day, respectively.

In the reconstruction efficiency study, the multiplication of the efficiencies of the final state particles $e^+ e^-$ and $\mu^+ \mu^-$ should be approximate to the efficiency of $\psi(2S)$ obtained from these two final state particles included. As can be seen in Table 4.4, those efficiency percentages are close to each other for all four decay channels. For the $e^+ e^-$, $\mu^+ \mu^-$ and $\pi^+ \pi^-$ final state particles, the general agreement is that the efficiency is always above 90% and the values are interpreted as very high and good. For $Z(4430)^-$ and $Z(4430)^+$, the reconstruction efficiency percentages are around 52-61% and the $\bar{P}$ ANDA detector performance in the simulations and analysis is considered to be generally good in that study.

For the DPM background studies, even using the filtered DPM background data, which is about 4 times higher than the number of signal events, the selection algorithm we used in our analysis easily distinguishes between signal and background events, and also very few particles in the DPM data are in the mass range of our intermediate resonance and resonance state. So, separating the signal data from the DPM background data becomes quite easy with that particle selection algorithm we developed.



5. PARTIAL WAVE ANALYSIS OF Z(4430) WITH PAWIAN SOFTWARE

Amplitude analysis and partial wave decomposition of the recorded data are methods we use to do advanced analyses in the field of hadron spectroscopy. Antiproton-proton annihilation data from the Crystal Barrel experiment at LEAR in CERN (122), charmonium decays using data from the BESIII experiment (123), and antiproton-proton simulation studies for the planned $\overline{\text{P}}\text{ANDA}$ experiment at FAIR are among the many analyses that are now ongoing (124).

5.1 Partial Wave Interactive ANalysis (PAWIAN) Software

PAWIAN (124) is a dedicated software package for partial wave analysis which is being developed at Ruhr-Universität Bochum, Institut Für Experimentalphysik, Lehrstuhl I. With the purpose of supporting studies for a wide range of distinct physics scenarios at hadron physics experiments, PAWIAN is a potent, intuitive, and highly adaptable software tool for partial wave analysis. With PAWIAN, actual data from the $\bar{p}p$ annihilation process and from e^+e^- reactions are presently being examined. Without changing or compiling any code, complex decay trees, various spin formalisms, resonance dynamics, and a host of other parameters can be set up using a straightforward plain text configuration file (124).

With PAWIAN:

- Several formalisms can be used to characterise the amplitudes. Thus far, the commonly-used Rarita-Schwinger formalisms that are Lorentz-invariant, canonical, and helicity are supported.
- One can select between several different formulations for the dynamics of resonances, such as the K-matrix formalism, the Flatté formalism, and the Breit-Wigner parametrization with or without barrier factors.
- A maximum likelihood fit based on events is used to achieve the minimising. It utilises the minimising package MINUIT2 (125).

- Applications can be executed in parallel on multi-core CPUs (multithreading) or on computer clusters (networking) to speed up the extremely time-consuming fit method.
- Analyses of coupled channels are also supported.
- Events can be produced using the user-defined decay model or the fit result produced from actual data.
- There are also tools for histogramming, quality control, and extracting data from various goodness-of-fit criteria.

In short, PAWIAN is an object-oriented programming language with a great deal of flexibility, built in C++. As a result, the code may be readily expanded to include additional decay models, full amplitudes, and additional dynamic descriptions (124).

5.2 Analysis Strategy of $Z(4430)$ with PAWIAN

Initially, testing different quantum numbers for $Z(4430)$ with PAWIAN was considered as part of this thesis work. After contacting the PAWIAN working group, the feedback was that these tests were not meaningful for particles whose quantum numbers were already determined in the literature, and instead data was generated for $Z(4430)$ via PAWIAN with the determined quantum numbers in the literature. While generating this data, another particle candidate, $f_2(1270)$, also added to the data as a result of the consultations, and the distinguishability of the $Z(4430)$ candidates generated from the same decay channel as in the $\bar{\text{PANDA}}$ experiment on PAWIAN was checked from this different particle signal. So, in a way, the decay channel we were working at the $\bar{\text{PANDA}}$ for $Z(4430)$ was simply cross-checked on PAWIAN.

As the first step of the analysis, a wrong set of quantum numbers for $Z(4430)$, $I^G(J^{PC}) = 1^-(1^-)$ was initiated and data was created. The data tested with different fits. By using information of the goodness of the fits by looking at the values from MINUIT2 (AIC (Akaike Information Criterion) (126), BIC (Bayesian Information Criterion) (127), AICc (Akaike Information Criterion Correction) (126) (by selecting the best one). On the other hand, by using the data created with $I^G(J^{PC}) = 1^+(1^-)$ quantum numbers for $Z(4430)$, the fit results were obviously way

better than the previous data as expected. This procedure just done for seeing the effects of using wrong quantum numbers for a particle which has pre-determined values for them.

The data was created with the help of PAWIAN working group's head person at the GSI-FAIR IT department's data center. While creating the data with the decay channel we provided, a several criteria have been followed as below:

- To obtain a more realistic data, at least add one particle in $\bar{p}p$ (have $\pi^+\pi^-$ in its decay modes as last state particles, similar to $\psi(2S)$) system was added. In this case, the particle was $f_2(1270)$ and it interferes (shape under $Z(4430)$, they can interfere, see Figure 5.1 and Figure 5.2) with $Z(4430)$, because of the interference effects and the data becomes more realistic.
- In a Dalitz plot, these two particles' overlapping can be seen.
- Why we didn't choose to add a particle like J/ψ (which is also includes $\pi^+\pi^-$ as last state particles in its decays)? Because, they are narrow resonances and there is no overlap between J/ψ and $\psi(2S)$. Therefore, it doesn't make sense because no interference effects can be seen.

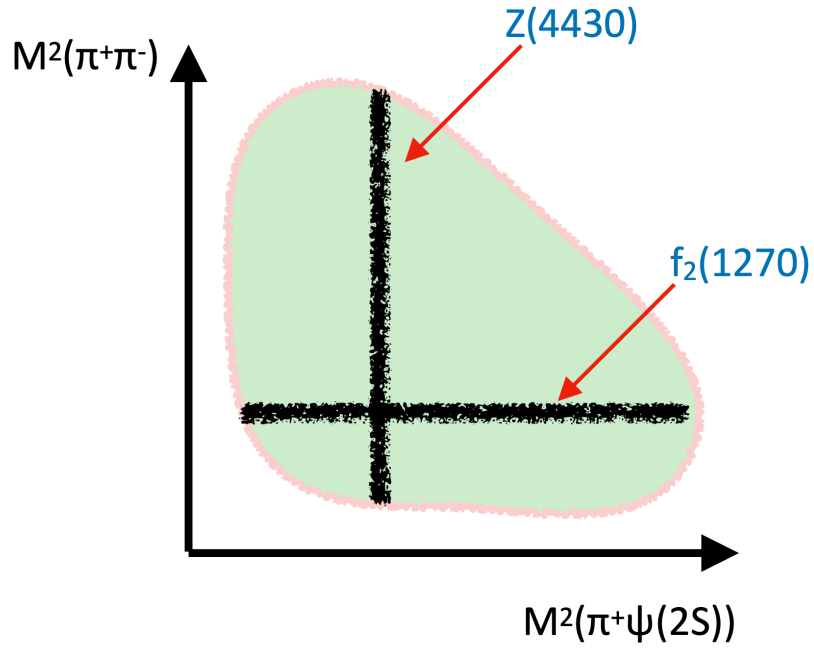


Figure 5.1. Illustration of possible interference of $Z(4430)$ and $f_2(1270)$ with the Dalitz plot.

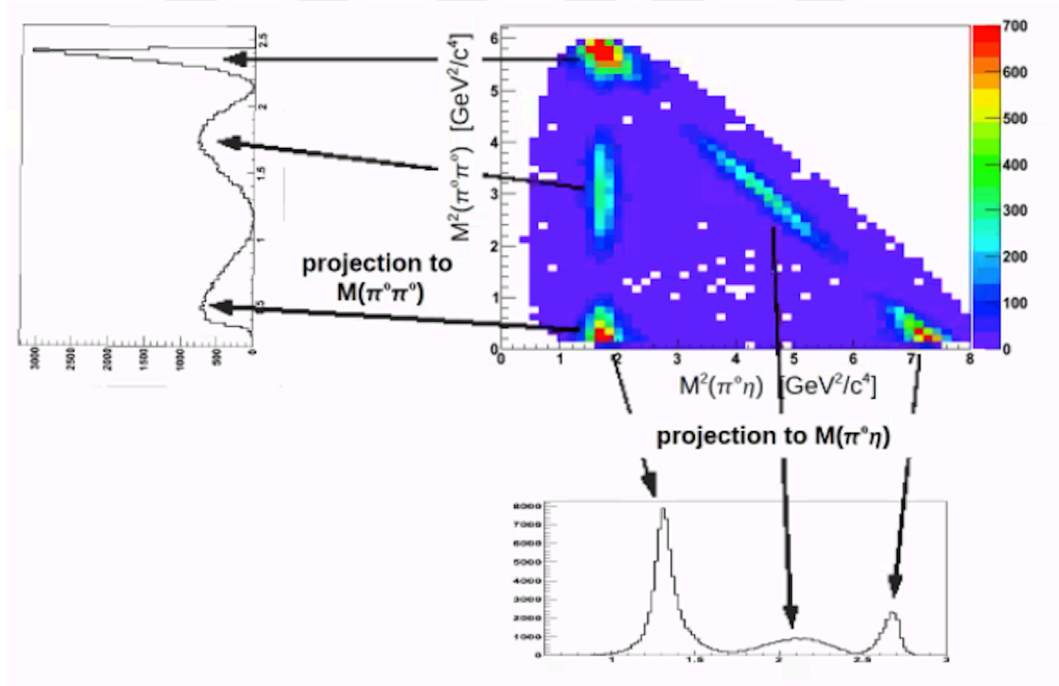


Figure 5.2. Example Dalitz plot that shows decay process of $\eta_c \rightarrow a_2(1320) \pi^0 \rightarrow (\pi^0 \eta) \pi^0$ and the interference.

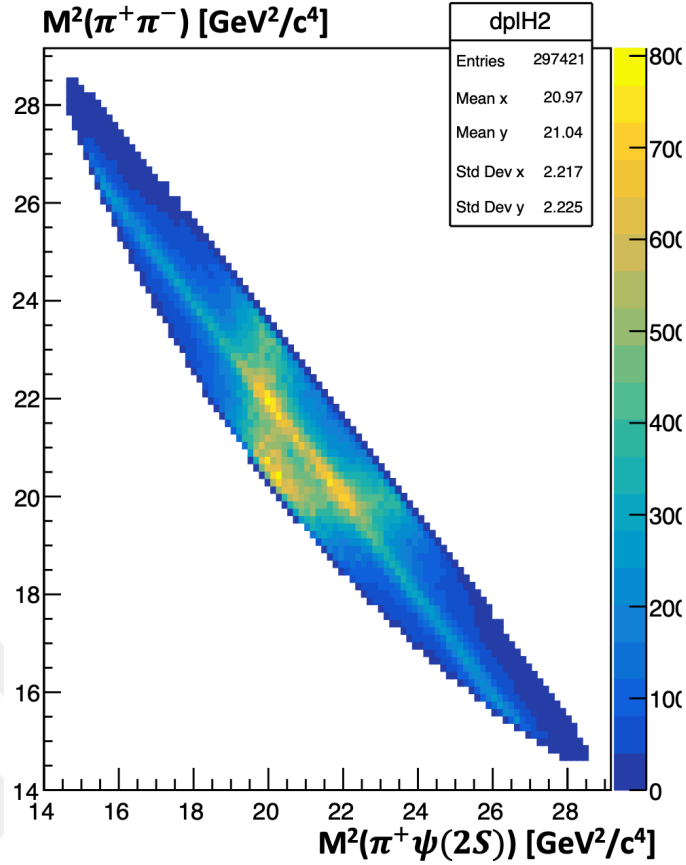


Figure 5.3. Dalitz plot of the $M^2(\pi^+\psi(2S))$ vs $\pi^+\pi^-$ from $f_2(1270)$.

In Figure 5.3, interference of the $Z(4430)$ and $f_2(1270)$ can be seen from the Dalitz plot at the yellow areas in the plot. This indicates that both particles in the same spectrum and needs to be separated from each other when a signal data like this was produced and analyzed. Additionally, if we mention about the data was produced, the decay process of $Z(4430)^{\mp}\pi^{\pm} \rightarrow \psi(2S)\pi^{\mp} \rightarrow \mu^+\mu^-\pi^-$ or $Z(4430)^{\mp}\pi^{\pm} \rightarrow \psi(2S)\pi^{\mp} \rightarrow e^+e^-\pi^-$ has never been introduced to PAWIAN. Thus, just cross-checking if a clear separation of $Z(4430)$ from any other similar spectrum particles by using the same decay process that we used in $\bar{\text{P}}\text{ANDA}$ software is the main goal here and this was also an important task to complete.

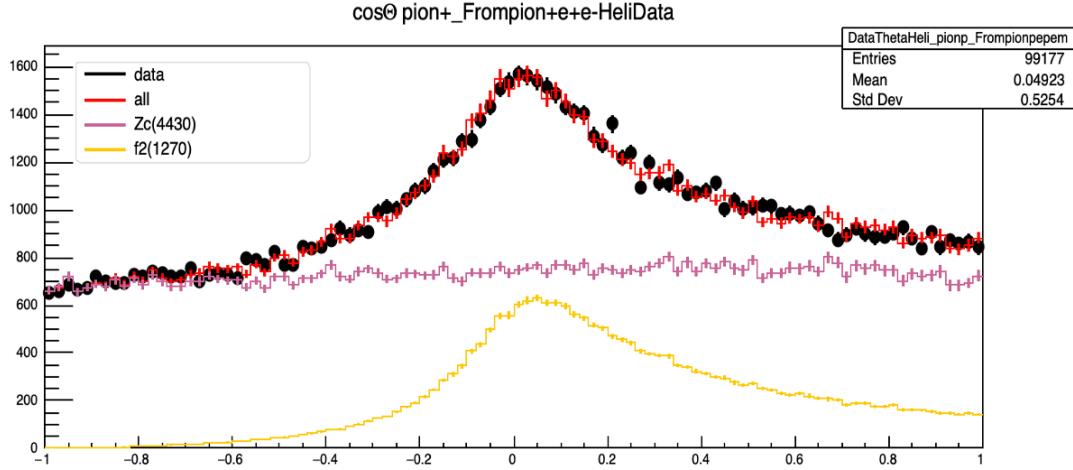


Figure 5.4. $\cos\Theta$ distribution of reconstructed $Z(4430)$.

As can be seen from Figure 5.4, when the $f_2(1270)$ particle is added to the data created with PAWIAN for $Z(4430)$ with 200.000 events by introducing the quantum numbers in the literature to the program by a created input file. Here, black dots are whole data which includes all particles in the spectrum, red line is the fit for that data, magenta line represents $Z(4430)$ and the yellow line represents $f_2(1270)$. When this data is analyzed, we can easily distinguish two different particle signals, for example, from the distributions of $\cos\Theta$. These results are similar to the analysis results for the data we previously created with EvtGen generator inside PandaRoot in terms of distinguishability.

Furthermore, with a different study, the data generated in PAWIAN with the help of 4 different decay channels ($Z(4430)^{\mp}\pi^{\pm} \rightarrow \psi(2S)\pi^{\mp} \rightarrow \mu^+\mu^-\pi^-$ and $Z(4430)^{\mp}\pi^{\pm} \rightarrow \psi(2S)\pi^{\mp} \rightarrow e^+e^-\pi^-$), which we have already identified for $Z(4430)$ and performed a complete analysis study, can be taken and analyzed within the $\bar{\text{PANDA}}$ framework, including the detector effects in PandaRoot, and this study can be given a different dimension. Of course, for this study, the PAWIAN data, which is output in ASCII format, must be converted separately and introduced into the PandaRoot software universe and this work is a bit different task to carry out.

6. CONCLUSIONS AND RECOMMENDATIONS

Many measurements are made in an effort to reach multiquark states, but the statistical significance is insufficient to yield a conclusive result as mentioned before at Section 3.1.1. $\bar{\text{P}}\text{ANDA}$ will enable the collection of more accurate data to further our understanding of multiquarks, particularly in the meson section (48). Consequently The $Z(4430)$ resonance's feasibility investigation in the framework of the $\bar{\text{P}}\text{ANDA}$ experiment falls under the scope of the multiquarks topic to be covered in the $\bar{\text{P}}\text{ANDA}$ physics program, which is the subject and motivation behind this thesis study.

Regarding elementary particles and their interactions, there are still a lot of difficult questions to be answered. A distinct approach is the high precision/high intensity frontier, which is made possible by exclusive observations of hadronic processes at intermediate energies, while some of these are being explored at the high energy frontier. This will be used as a diagnostic tool in the next $\bar{\text{P}}\text{ANDA}$ experiment at FAIR, where antiproton-nucleus and antiproton-proton interactions are involved. $\bar{\text{P}}\text{ANDA}$ will undoubtedly be a successful experiment on this frontier, where the center of mass resolution will be approximately 50 keV, a level of energy that has not yet been reached by other accelerators (79). This is where the $\bar{\text{P}}\text{ANDA}$ experiment is a great candidate to become an experiment that stands out for what it promises. It will undoubtedly become one of the most important experiments in its field such as BESIII and BaBar. Considering all these factors, all the work to be done in the spectrum of the $\bar{\text{P}}\text{ANDA}$ experiment is indeed of great importance (79).

Strong interaction studies are the focus of $\bar{\text{P}}\text{ANDA}$'s antiproton beam's precision, intensity, and momentum range. $\bar{\text{P}}\text{ANDA}$ can analyse the hadron-antihadron formation near their production threshold, measure the line-shape of states with high accuracy, and provide access to the mass regime where new and exciting forms of hadronic matter have recently been identified (XYZ states). $Z(4430)$ is one of the most studied of these, and it is really important to study the feasibility of these and similar charmonium/exotic states within the framework of the $\bar{\text{P}}\text{ANDA}$ experiment and to simulate and prove whether they are observable or not. Therefore, the motivation and goal of this thesis is therefore to prove with high

precision through simulation studies that the $Z(4430)$ resonance is observable within the framework of the $\bar{\text{PANDA}}$ experiment.

In this context, it has been demonstrated that the $Z(4430)$ state can be observed with high precision in the spectrum of the $\bar{\text{PANDA}}$ experiment by particle selection thanks to the analysis codes written using PandaRoot and the particle selection algorithm developed. At the same time, while working with PandaRoot, which is partially in the use of certain users, due to the fact that the parts of the program containing Bremsstrahlung and final state radiation effects could not be properly simulated in the simulations, the errors in these parts were revealed and reported to the authorities and certain contributions were made in this regard within the framework of the $\bar{\text{PANDA}}$ Collaboration. These feasibility studies, which will become even more important when real data starts to be taken in the $\bar{\text{PANDA}}$ detector, can be optimized to work with real data by making certain modifications to the analysis studies. Based on this, real data can be analyzed for a specific case such as $Z(4430)$, and such studies are among the important physics studies for the experiment. Consequently, the data analyzed with the real data in future can be compared in terms of the precision with the simulations done here.

Studies such as this thesis can bridge the gap between theoretical and experimental studies and contribute to various topics such as determining the internal structure of various charmonium-like tetraquarks like $Z(4430)$, fixing quantum numbers, specifying the effects of spin-spin, spin-orbit and QED effects.

On the other hand, in order to ensure that this study is not just a feasibility study, in the future, when the $\bar{\text{PANDA}}$ detector starts to operate and provide real data, and when data similar to the data created and analyzed with the help of PandaRoot in this thesis are tried to be obtained from the detector as real data, it may be possible to determine how many days, at what energy and at what luminosity the $\bar{\text{PANDA}}$ detector will operate. Of course, this will be the result of a completely different study.

7. REFERENCES

Vancouver reference style was used in this thesis.

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