CLAS12 Techniques of Detection

Author: Daniel Terrero

Duquesne University, Department of Physics May 3, 2024

Abstract

In the realm of particle physics, the ability to detect the unseen plays a crucial role in the field. This paper delves into the detection techniques employed at Jefferson Lab. Specifically the CLAS12 detector. It provides an overview of the principles being these techniques as well as use cases such as the Heavy Proton Search (HPS) and Beam Spin Asymmetries. It highlights advantages and limitations associated with each technique, emphasizing the importance of selecting the most appropriate method for a specific detection task.

The study also explores the intricate mechanisms of the CLAS12 detector, a cutting-edge tool in particle physics research. It discusses the detector's design, functionality, and its significant contributions to the field. The paper further investigates the challenges faced in detecting elusive particles and the innovative solutions implemented to overcome these obstacles. It underscores the importance of continuous advancements in detection technology to expand our understanding of particle physics. The paper serves as a comprehensive guide for researchers and students alike, offering valuable insights into the complex world of particle detection at Jefferson Lab.

Keywords

- CLAS12
- Jefferson Laboratory
- Hall B

Contents

1 Toroidal and Solenoidal Magnet

1.1 Introduction

The CLAS12 detector is a marvel of engineering designed to delve into the secrets of nuclear and hadronic interactions triggered by electrons. At its heart lies a powerful combination of magnets a six-coil toroid and a robust solenoid.

The toroidal magnet generates a strong magnetic field that extends outward, encompassing particles emitted at angles up to 35 degrees from the beam direction. Inside this toroidal field, a powerful solenoid magnet takes over, creating a 5 Tesla field that covers a central region with a polar angle range of roughly 35 to 125 degrees. This combined magnetic field configuration allows CLAS12 to efficiently detect a wide range of charged and neutral particles across a significant portion of the entire solid angle.

This configuration was suggested to enable the precise measurement of charged particles with high momenta and resolution at forward angles, while maintaining high luminosity in the detector systems. To achieve this, it's crucial to shield low-energy leptons generated in the target material via processes like Møller scattering $l^- + l^- \to l^- + l^-$ (where "l" represents a lepton). This shielding is facilitated by a robust longitudinal magnetic field that redirects the electrons towards a shielding conduit crafted from dense tungsten material, where they dissipate their energy. [1]

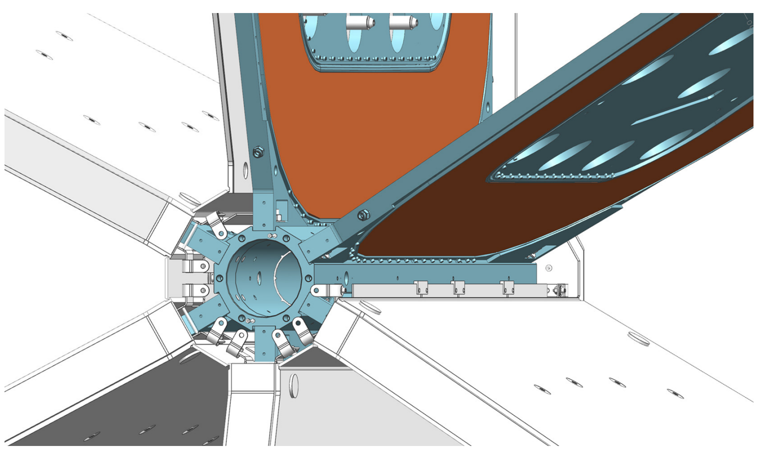

Figure 1: Torus Magnet.

1.2 The Torus Magnet

The magnetic field around the beam line is approximately toroidal, generated by six symmetrically placed magnetic coils. The sextet of coils were mounted onto a shared stainless-steel cylinder within a central cold hub, providing both structural stability and geometric uniformity to align the coils close to the magnet's core (see Fig. 1). This arrangement heightens the accuracy of positioning the coil assemblies in areas where the magnetic field is expected to reach its zenith.

Each superconducting coil consists of a two-coil (double-pancake) encased in an aluminum shell. Each pancake contains 117 windings. The magnet's inductance is 2.0 H, and the stored energy is 14.2 MJ. The magnet is equipped with N_2 cooled heat shields. Upon assembly and cooling, the magnet promptly achieved full field.

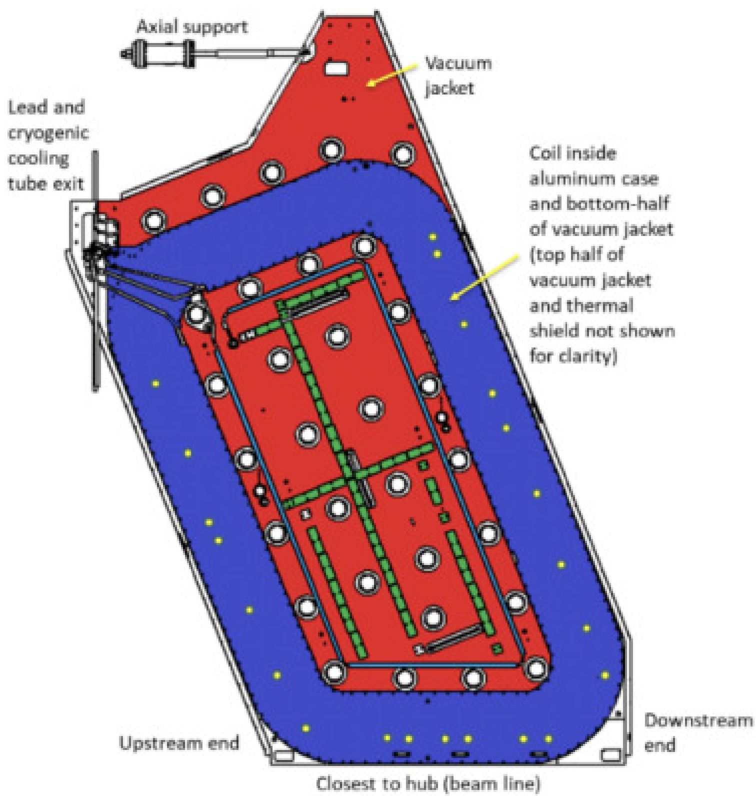

Figure 2: Magnet Line

This design presents several benefits as it permits a robust magnetic field within a compact volume. The potting material offers structural support for the superconducting coils, and the aluminum case aids in conducting heat away from the coils, which is crucial for preserving their superconductivity.

1.3 Solenoid

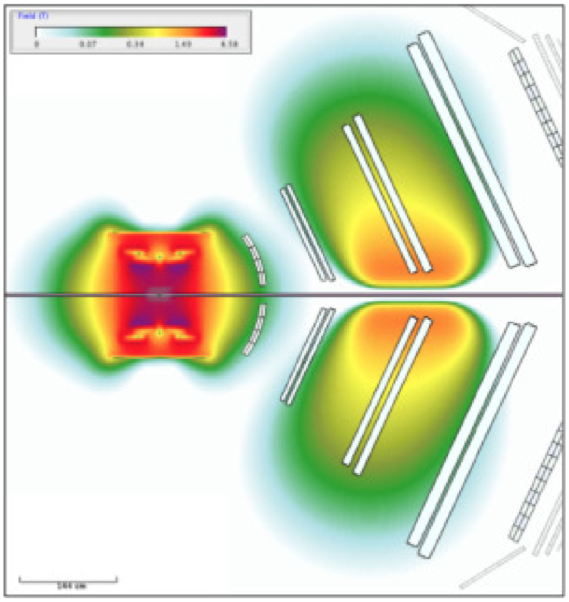

Figure 3: Magnetic fields due to the solenoid and torus

Figure 4: CLAS12 Magnets. Left: Solenoid. Right: Torus Magnet

The solenoid magnet is a self-shielded superconducting magnet positioned around the beam trajectory, designed to produce a magnetic field along the beam direction. The design is motivated by the physics requirement to safeguard the detectors in CLAS12 from scattered electrons due to the Møller effect and to ensure a uniform field.

The magnet is composed of four cylindrical coils arranged in pairs at varying radial distances along the beamline. The fifth coil is situated outside the four inner coils and creates a magnetic field in the opposite direction of the inner coils' field, thereby functioning as an active magnetic shield. At peak current, the solenoid produces a magnetic field of 5 Tesla at its core.

2 Beam

2.1 Beam Introduction

The CLAS12 physics program at Jefferson Lab's Hall B relies on a versatile electron beam to probe targets ranging from simple hydrogen to complex lead nuclei. To maximize the scientific output, the beam needs to be precisely controlled and monitored in terms of energy, current, size, and polarization. We address the challenges posed by the detector's large acceptance and proximity to the target, drawing on successful solutions implemented in previous Hall B experiments. We present the key modifications made to the existing beam line and the additional components introduced to achieve high-quality beams and enable CLAS12 to operate at its design luminosity.[2]

2.2 Beam Parameters

The Hall B beamline is meticulously designed to meet the specific needs of CLAS12 experiments. It offers the necessary tools to maintain precise control and ensure the safety of personnel and equipment during operation.

The following table will detail the key parameters crucial for conducting experiments with CLAS12.

Parameter	Requirement	Unit
Beam energies	≤ 11	GeV
Beam currents	< 500	nA
Current instability	≈ 10	%
Accuracy of current measurement	≈ 1	%
Beam widths (σ_x, σ_y)	< 300	µm
Position stability	< 200	µm
Divergence	< 100	µrad
Beam halo ($> 5\ \sigma_x$)	$< 10^{-4}$	
Beam polarization	> 80	%
Accuracy of polarization	< 3	%

Table 1: Specifications of Beam Parameters

2.3 Hall B Segments

The Hall B beamline acts as the delivery system for CLAS12 experiments. It consists of two main sections: the 2C line and the 2H line.

The 2C line, nicknamed the "beam switch yard delivery line," transports the beam extracted from CEBAF to the upstream end of the Hall B experimental hall. The 2H line then takes over, guiding the beam to its destination - the beam dump located in the downstream tunnel.

For high-energy CLAS12 operations, some upgrades were made to the beamline. The 2C line now houses a new resident: the Møller polarimeter. This instrument precisely measures the beam's longitudinal polarization, a key factor in certain experiments. Additionally, an intermediate beam dump was installed just before the hall to provide more control over the beam.[3]

Downstream in the 2H line, another modification was made. A cryogenic target was introduced, capable of withstanding the intense beams used in CLAS12 experiments. Further along the line, a tungsten shield was placed inside the CLAS12 torus magnet bore to absorb any stray particles.

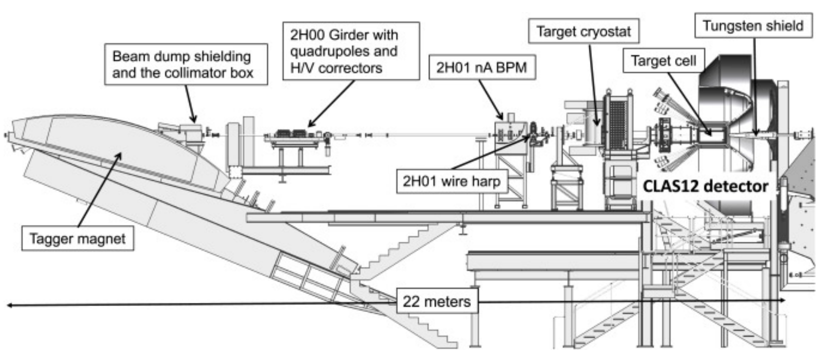

Figure 5: Beamline.

2.4 Instrumentation

The instrumentation of the beamline comprises beam current monitors, beam viewers, collimators, beam profile scanners, and beam halo monitors. Beam current monitors assist in regulating the energy flow to the beam. The beam viewer enables us to see the beam, as it is not visible to the naked eye. Collimators limit the beam's direction. The beam profile scanner manages its intensity, and halo monitors keep track of the particles that have deviated slightly.

On the left of Fig. 31 5, the tagger magnet remains unenergized during production data acquisition. When activated, the yoke of this magnet functions as a beam dump, utilized during beam adjustment prior to directing the beam onto the Hall B production target. Furthermore, it is employed during specific runs, such as polarization measurements in the upstream beamline, to prevent sensitive CLAS12 detectors from exposure to high background loads.

The status of the electron beam and every diagnostic element, including the beamline vacuum and superconducting magnets, was displayed on a monitor accessible to the shift team. More details in Fig 6.

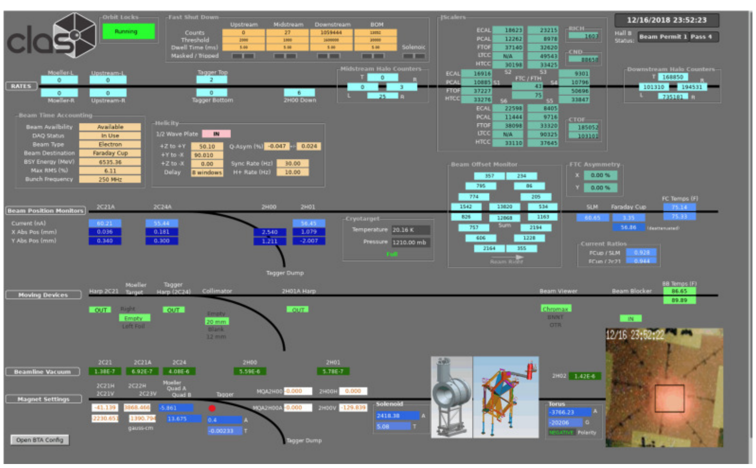

Figure 6: Beamline monitoring systems

3 Data Acquisition Simulation

Understanding the intricacies of nuclear and hadronic reactions within CLAS12 hinges on a powerful interplay between data acquisition and simulation techniques. A complex detector system, comprised of multiple subsystems like drift chambers, scintillators, and calorimeters (detailed in Section 1), captures the interactions triggered by the electron beam. This data, exceeding 100,000 channels, forms the raw material for scientific discovery.[4]

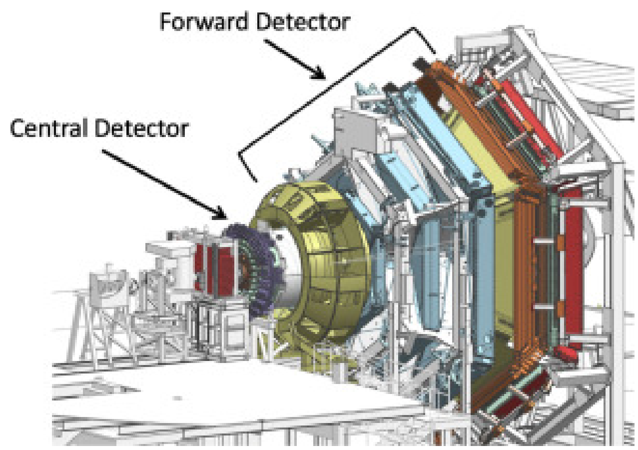

Figure 7: CLAS12.

3.1 Generated Events

The CLAS12 data-acquisition system was conceptualized as a network-based system operating on a pipeline principle. The data gathering process initiated from the front-end elements of CLAS12. These elements, despite their varying hardware and software configurations, were designed to be harmonious with the overall system. These front-end elements are known as Readout Controllers (ROCs). All ROC components were linked via TCP sockets over Ethernet to the Event Builder component. The TCP protocol guarantees that the data-sending component is linked to the data-receiving component before data transmission, unlike UCP, which transmits data before confirming the receiver's connection.

The Event Builder (EB) is a multithreaded C application that operates on a multicore Linux server. Once the events were gathered, they were forwarded to the Event Transfer (ET) system. This multithreaded C application is engineered to facilitate data-processing programs to filter, monitor, and store data in shared memory. Typically, EB is executed on the same server as ET, but it can also be spread across a series of ET servers. The final component in this series is the Event Recorder (ER), which receives data from the ET and logs them on a disk.

3.2 Reconstructed Events

The Event Reconstruction software, which aids in event simulation, was conceived and cultivated within the CLARA framework. CLARA assists in designing and developing scientific data processing applications without the need for actual coding.

The data reader functionalities extract the deciphered detector data archived in the database. Each deciphered detector hit entry forms a database entry, containing identifiers for detector elements and data of the detector, such as current, signal and time tailored to the particular system. Comparable database frameworks are produced during the decoding phase for different parameters necessary for simulation. It's at this juncture that we deploy reconstruction algorithms to populate these databases.

CLARA acts as the engine for reconstructing particle interactions within our experiment. It takes data from existing databases as its raw material and generates new databases containing reconstructed information. These outputs are then fed back into the reconstruction process, leading to a more complete picture of the event.

The reconstruction process itself mirrors a larger framework called CLAS12. It starts with reconstructing individual particles within specific detector systems, like the Central and Forward Detectors. This initial step, called hit-based tracking, relies on the spatial information from sensor readings. Simultaneously, other detectors process data to reconstruct the energy and timing of particle interactions.

The Event Builder service then takes center stage. It matches the reconstructed tracks with energy and timing information, essentially creating a profile for each particle. Any leftover unmatched data points could indicate the presence of neutral particles. At this point, the Event Builder can pinpoint the exact moment of interaction between the beam and the target, effectively setting the event's "start time." With this crucial information, a more refined tracking process, called time-based tracking, can be initiated.[5]

The improved tracks are then fed back into the Event Builder, leading to a final, comprehensive reconstruction of the entire event. Importantly, some reconstruction steps can happen concurrently, while others require the completion of previous steps before they can begin.

To streamline this complex process, we've developed a service-oriented architecture specifically designed for CLAS12 data reconstruction and analysis. This framework utilizes various libraries to manage data input/output, detector geometry, databases, and magnetic field configurations, ensuring the smooth operation of the entire reconstruction pipeline.

4 CLAS12 Experiments

First, we embark on a journey with the Heavy Photon Search (HPS) experiment [6]. Here, CLAS12 serves as a vital component in the hunt for a new particle, the elusive "heavy photon."

Secondly, we shift focus to the realm of hadron interactions, where CLAS12 plays a key role in unraveling the mysteries of beam spin asymmetries in pion production (See Figure 4). This experiment sheds light on the intricate dance between gluons and quarks within protons [7].

4.1 Heavy Photon Search

4.1.1 Objective

In order for scientists to search for the dark photon in fixed target electro-production, they design the Heavy Photon Search at Thomas Jefferson National Accelerator Facility. Their purpose is to detect $e^{-}e^{+}$ decay of the dark photon.

For them to sense the decay a silicon vertex tracker and a fragmented electromagnetic calorimeter is used to measure the bump on the data.

4.1.2 Beamline Characteristics

The layout consists of our target inside a vacuum chamber with our silicon vertex trackers. This is inside the center our our dipole magnets core, behind the magnets is our calorimeter. The entirety of this setup is located in a compartment of the CLAS12.

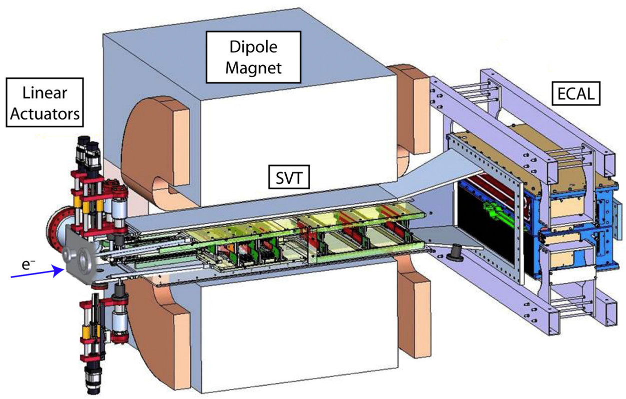

Figure 8: Cross-section of HPS setup

The experiment runs using beam energies that range from 1 to 6.6 GeV and beam currents fluctuating from 1 to 500nA. A table with the beam parameters is below.

Parameter	Requirement	Unit
Beam energies	$\leq 1 - 6.6$	GeV
Beam currents	< 500	nA
Current instability	≈ 5	%
Beam widths (σ_x, σ_y)	$<$ (300, 50)	µm
Position stability	< 30	µm
Divergence	< 100	µrad
Beam halo ($> 5\ \sigma_x$)	$< 10^{-5}$	

Table 2: Beam Parameters HPS

This parameters for the beam have been established by running a variety of simulations.

The two segments of the Hall B are use for this experiment. The 2C segment redirects and elevates our beam to the Hall B elevation after its extracted from the Beam Switch Yard (BSY). In the 2H segment, specifically near the end of the beamline, the target is located. The target being tungsten foil. The devices located in the 2H segment are enough to monitor the beam properties.

4.1.3 Performance

Before starting production is necessary to evaluate the quality of the beam. So a first tuning is done to correct the beam profile in the 2C segment. After, the beam is sent to the beam dump on Hall B to fix the profile of the downstream beam.

After the beam profile is perfected the orbit lock system is displayed. This system helps control and monitored the beam width to regulate the motion with respect to the target. Succeeding the verification of the beam profile the HPS target is inserted. Following the target, the halo counters of the FSD are inserted. This helps control the profile and width because if the beam halo moves closer to the collimator walls or the detectors in the edges the halo rates would increase.

When the beam evaluation is being done in the 2H segment for the first time a silicon vertex tracker scan is executed in order to control the profile and to check the beam alignment with respect to the silicon vertex tracker coordinate system. In Fig. 9 the first peak shows the halo rate with respect to the SVTs coordinates. If it was not center it would be adjusted.[6]

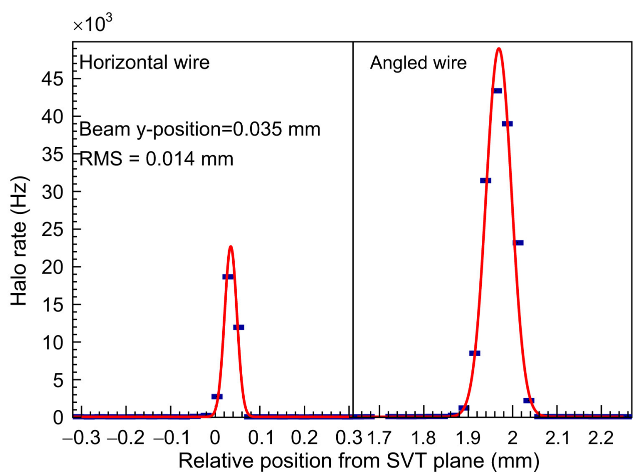

Figure 9: SVT Scan

4.2 Beam Spin Asymmetries

4.2.1 Objective

Parton distribution functions "PDF" and Fragmentation Functions "FF" are of high importance to particle physicists because they contain information of the momentum distribution of the quarks and of the formation of hadrons. For the purpose of accessing them, semi-inclusive deep inelastic scattering "SIDIS" is considered. Specifically the high energy of the electron collision with the proton allows us to analyze the interaction as if it were a one-on-one encounter with a single fundamental particle within the proton. This is why the single spin asymmetries for the production of two pions was studied at JLab. [7]

$e(l) + p(P) \to e'(l') + \pi^+(P_1) + \pi^-(P_2) + X$

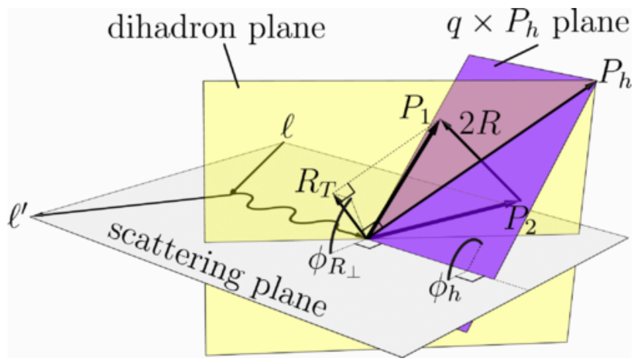

Figure 10: Reaction Plane

In the figure above we have the plane of our reaction. The scattering plane is mainly defined by l, which can be visualized as the incoming electron beam and the dihadron plane is created by P_1 and P_2, the initial being the hadron momentum.

4.2.2 Detectors and Data Extraction

Experimental data was acquire using the spectrometer located in the CLAS12. The beam was longitudinally polarized with an energy of 10.6 GeV and with a frequency of 30 Hz it was inverted in order to diminish systematic errors. The beam was acquired through CEBAF (Continuous Electron Beam Accelerator Facility), subsequently it enter the 2C segment of Hall B where the beam profile was tuned before entering the 2H segment.

After the tuning was performed on the 2H segment the target, which consisted of liquid hydrogen, was placed before the CLAS12 detector.

For the purpose of identifying the scattered electrons and pions the Forward Detector is used. The Forward Detector is composed of a tracking subsystem which identifies the electrons and pions through a set of Cherenkov counters and drift chambers inside a toroid.

This method coupled with an supplementary identification by an electromagnetic calorimeter for electrons and plastic scintillators for pions ensures identification of them.

4.2.3 Findings

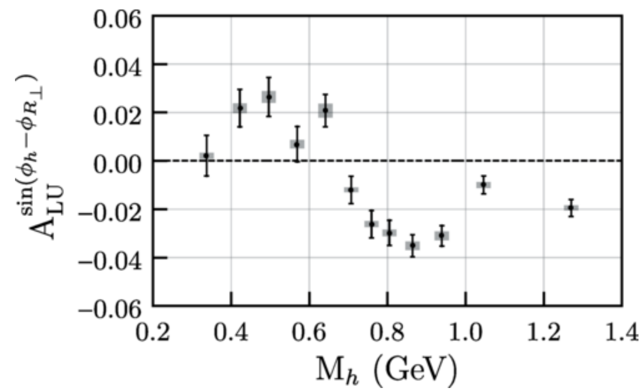

Figure 11: A_{LU} vs M_h (GeV)

The key finding of the experiment was the observation of a clear change in the sign of the beam spin asymmetry around the mass of the rho meson (ρ). The change in sign in Fig.11 indicates a dependence between the helicity (spin) of the fragmenting quark and the produced pions. In simpler terms, the spin orientation of the quark leaving the collision seems to influence the type of pions created. This finding provides the first experimental signal for a specific quantity called the helicity-dependent two-pion fragmentation function. This function offers valuable insights into the interactions between gluons and quarks within protons.

5 Conclusions

The CLAS12 detector stands as a remarkable feat of human ingenuity, a monument to our relentless quest to crack the code of the subatomic world. Its innovative design, a marriage of powerful toroidal and solenoid magnets, shatters the boundaries of particle detection. CLAS12 allows us to capture a stunning array of charged and neutral particles across a significant chunk of this hidden universe. This comprehensive data collection forms the foundation for groundbreaking discoveries in nuclear and hadronic physics, each finding a stepping stone towards a deeper understanding of the cosmos.

The success of CLAS12 experiments is a delicate dance between cutting-edge technology and meticulous control. The precisely tuned beamline components ensure the delivery of electron beams with the desired energy, current, size, and polarization. Sophisticated instruments within the beamline act as guardians, continuously monitoring and maintaining these parameters. Any deviation could introduce noise into the delicate symphony of subatomic interactions, potentially masking the data.

The data acquisition and simulation systems of CLAS12 act as the bridge between the captured data and the secrets it holds. The complex detector system meticulously captures the fleeting interactions, transforming them into raw data. This data then undergoes a sophisticated transformation through advanced software tools. Reconstruction algorithms breathe life into the data, piecing together the fragments of the collision events. Through this process, scientists gain unparalleled access to the fundamental forces and building blocks of matter, the quarks and gluons that reside within protons and neutrons.

The examples presented here; the Heavy Photon Search (HPS) and the study of Beam Spin Asymmetries in pion production showcase just a glimpse of CLAS12's immense potential. The HPS experiment allows scientists to peer beyond the Standard Model of particle physics, searching for entirely new particles that could hold the key to a deeper understanding of the universe. Meanwhile, the studies of beam spin asymmetries shed light on the complex internal dynamics of protons, revealing the intricate interplay between gluons and quarks.

Looking ahead, CLAS12 remains poised to play a pivotal role in the ongoing exploration of the subatomic world. As scientists continue to push the boundaries of this realm, CLAS12 stands ready to capture the fleeting glimpses of these interactions, offering invaluable data for groundbreaking discoveries in the years to come.

References

[1] V. Burkert, L. Elouadrhiri, and K. Adhikari, "The clas12 spectrometer at jefferson laboratory," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 959, 2020.

[2] N. Baltzell, V. Burkert, and J. Carvajal, "The clas12 beamline and its performance," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 959, 2020.

[3] N. Baltzell, H. Egiyan, and M. Ehrhart, "The heavy photon search beamline and its performance," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 859, pp. 69–75, 2017.

[4] M. Ungaro, G. Angelini, and M. Battaglieri, "The clas12 geant4 simulation," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 959, 2020.

[5] V. Ziegler, N. A. Baltzell, F. Bossù, D. S. Carman, P. Chatagnon, M. Contalbrigo, and M. Ungaro, "The clas12 software framework and event reconstruction," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 959, p. 163472, 2020.

[6] N. Baltzell, H. Egiyan, and M. Ehrhart, "The heavy photon search beamline and its performance," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 859, pp. 69–75, 2017.

[7] T. B. Hayward, C. Dilks, and A. Vossen, "Observation of beam spin asymmetries in the process $ep \to e'\pi^+\pi^- x$ with clas12," *Phys. Rev. Lett.*, vol. 126, Apr 2021.