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J/Ψ – ՖՈՏՈԾՆՄԱՆ ՈՒՍՈՒՄՆԱՍԻՐՈՒՄԸ CLAS12 ՍԱՐՔԱՎՈՐՄԱՆ ՎՐԱ

Ա. 04.16. – “Միջուկի, տարրական մասնիկների և տիեզերական ճառագայթների ֆիզիկա” մասնագիտությամբ ֆիզիկամաթեմատիկական գիտությունների թեկնածուի գիտական աստիճանի հայցման ատենախոսության

Ս Ե Ղ Մ Ա Գ Ի Ր

ԵՐԵՎԱՆ 2021

A.I. ALIKHANYAN NATIONAL SCIENCE LABORATORY
(YEREVAN PHYSICS INSTITUTE)

MARTIRYAN DAVIT

STUDY OF J/Ψ PHOTOPRODUCTION USING CLAS12 DETECTOR

SYNOPSIS

of Dissertation in 01.04.16 – "Nuclear, elementary particles and cosmic ray physics"
for the degree of candidate
in physical and mathematical sciences

YEREVAN 2021

Ատենախոսության թեման հաստատվել է Ա.Ի. Ալիխանյանի անվան Ազգային Գիտական Լաբորատորիայի (ԵրՖի) գիտական խորհրդում:

Գիտական ղեկավար՝
Ֆիզմաթ. գիտ. թեկնածու Նատալյա Բախշիի Դաշյան (ԱԱԳԼ)

Պաշտոնական ընդդիմախոսներ՝
Ֆիզմաթ. գիտ. թեկնածու Հրանտ Ռուբենի Գուլկանյան (ԱԱԳԼ)
Ֆիզմաթ. գիտ. դոկտոր Բրայան ՄակԿիննոն (Գլազգոյի համ., ՄԹ)

Առաջատար կազմակերպություն՝
Երևանի պետական համալսարան, Երևան, Հայաստան:

Ատենախոսության պաշտպանությունը կայանալու է 2022թ. Հունվարի 25-ին ժամը 14:00-ին ԱԱԳԼ-ում գործող ԲՈԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Երևան-0036, Ալիխանյան Եղբայրների փ. 2):
Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է 2021թ. Դեկտեմբերի 13-ին:

Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզմաթ. գիտ. դոկտոր Հրաչյա Հովհաննեսի Մարուքյան

The subject of the dissertation is approved by the scientific council of the A.Alikhanyan National Science Laboratory (AANL).

Scientific supervisor:
Candidate of physical-mathematical sciences Natalya Dashyan (AANL)

Official opponents:
Candidate of physical-mathematical sciences Hrant Gulkanyan (AANL)
Dr. of physical-mathematical sciences Bryan McKinnon (University of Glasgow, UK)

Leading organization:
Yerevan State University

The defense will take place on 25th January 2022, 14:00 during the “Physics” professional council’s session of SCC 024 of acting within AANL (2 Alikhanyan Brothers str., 0036 - Yerevan).
The dissertation is available at the AANL library.
The synopsis is delivered on 13th December 2021.

Scientific secretary of the professional council:
Dr. of physical-mathematical sciences Hrachya Marukyan

In dissertation work the analysis of near-threshold photoproduction of the J/ψ meson on a proton is presented. The work is a part of the studies of the near-threshold photoproduction of J/ψ mesons begun at the CLAS12 (Cebaf Large Acceptance Spectrometer) setup installed in the hall B of the Jlab (Jefferson Laboratory, USA). The experimental data obtained during the first stage of the experiment, when a 10.6 GeV electron beam scattered off a liquid hydrogen target (Run group A, project E12-12-001), had been used in the analysis. The first stage of the experiment was carried out in the fall of 2018 and was one of the first experiments carried out on the upgraded, - in connection with the 12 GeV reconstruction of the CEBAF, - magnetic spectrometer CLAS12. The use of the modernized setup and the specificity of the analysis presented in the dissertation, require a particularly careful approach to research methods.

The work consists of two parts, which describe the analysis using different mechanisms of photoproduction. The first part provides an overview of the analysis using the untagged photoproduction. The main task of this part of the analysis was to choose the most efficient way of selecting events for quasi-real near-threshold photoproduction of J/ψ mesons. On the basis of a comparative analysis, the efficiency of various approaches is shown and quantitative estimates of the J/ψ meson yield are given when testing an individual method of analysis. The second part describes the analysis using the tagged photoproduction.

Relevance of the topic (scientific research): While today there is a significant amount of data of J/ψ meson photoproduction at high energies, W> 10 GeV, in good agreement with the mechanism of 2-gluon exchange, the near-threshold energy region remains poorly studied.

Heavy quarkonium production probes the local color (gluon) fields in the nucleon, and can reveal properties such as their response to momentum transfer, their spatial distribution, and their correlation with valence quarks. In exclusive J/ψ production near threshold, the minimum invariant momentum transfer to the nucleon becomes large: $|t_{min}| = 2.23\ GeV^2$ at threshold, and $|t_{min}| = 1.3 - 0.4\ GeV^2$ in the $E_\gamma\ =\ 8.5\ -\ 11$ GeV range. Thus, this process is similar to elastic eN scattering at large $|t|$, only the "probe" interacts with the gluon field in the target. ***Exclusive J/ψ production near threshold thus measures the nucleon form factor of a gluonic operator and can provide unique information on the non-perturbative gluon fields in the nucleon.***

Purpose of work: The main goal of the work presented in the dissertation was to study the possibility of extracting the events of near-threshold photo-production of J/ψ mesons from the data of electroproduction, obtained on CLAS12 detector, as well as the development and research of the most effective methods of analysis that will allow collecting sufficient statistics to study J/ψ photoproduction in a poorly studied and hard-to-reach region of near-threshold energies.

To achieve this goal, two mechanisms of photo production were considered: tagged and untagged. A number of studies were carried out, which made it possible to observe positive dynamics in the set of statistics, as well as a comparative analysis of the results of studies carried out using different software packages and approaches, which made it possible to choose the most suitable constraints on the kinematic parameters used in the study process, and positively influenced the effectiveness of the analysis.

Practical value: The work describes methods of research in the process of analyzing experimental data on electroproduction in order to extract and analyze events of quasi-real near-threshold photoproduction of J/ψ mesons. Considering a number of methodological approaches and data compression technics, a positive dynamic was demonstrated in the process of collecting the statistics necessary for the analysis, which is undoubtedly important in the analysis of the poorly studied and hard-to-reach region of near-threshold photoproduction of heavy quarkonia on nuclei. The results of this work will help to improve event selection for near-threshold J/ψ photoproduction, improve the method of particle identification and encourage to study other J/ψ photoproduction methods near-threshold.

The novelty of the work: A technique was applied to select near-threshold J/ψ photoproduction events from electroproduction data. The developed method of the most efficient highlighting of near-threshold quasi-real J/ψ photoproduction events is given. The method of selection of tagged photoproduction was developed. The tagged photoproduction of J/ψ near-threshold was studied for the first time. There are no other experimental data of near-threshold tagged photoproduction. A new method for detection and accurate reconstruction of the scattered electron momentum in Forward Tagger [4] was developed. For the first time it is shown that there are tagged J/ψ photoproduction events gained from electroproduction data in CLAS12. The distribution of invariant mass and W (total hadronic mass) of tagged photoproduction events are obtained.

Results submitted for defense: The possibility of studying the quasi-real near-threshold J/ψ photoproduction by using the data of electroproduction, applying on both, tagged and untagged, photoproduction mechanisms. The developed method for efficient highlighting of near-threshold quasi-real J/ψ photoproduction events is presented. Improvement of particle identification and mis-identified particles purifying is shown. Comparison of RGA (Run Group A – group that analyzed E12-12-001 data) in-group data and estimation of exclusive variables is presented, it was found, that for the untagged analysis the best variables for the J/ψ event selection are the missing mass squared of the undetected electron and the Q^2. Tagged J/ψ photoproduction events gained from electroproduction data are extracted for the first time. The possibility of estimation of invariant mass and W distribution for tagged photoproduction is shown.

Publications: On the topic of the dissertation work, 4 works have been published, a list of which is given at the end.

Structure of Dissertation: This work consists of 7 chapters including the introduction, conclusion, and references.

Content of the work

Introduction (Chapter 1) described the historical physical background and motivation of this thesis. In this work the experimental data are analyzed on the subject of the near-threshold quasi-real photoproduction of J/ψ - meson. The experimental data obtained in the scattering of electrons with an energy of 10.6 GeV on a liquid hydrogen target are considered. At small angles, scattering occurs due to the exchange of a quasi-real photon (Q^2 ~ 0).

Chapter 2 described theoretical background including Standard model and QCD introduction, as well as introduced Vector Meson Dominance Model [1] and J/ψ particle (discovery, properties and production).

Chapter 3 described the experimental setup, Jefferson laboratory (JLab), CEBAF accelerator and CLAS12 detector in details, with its subsystems. Describing a software system that was used during the analysis to receive and organize data coming from different detectors in a very short time period (decoding process). Then methods of particle identification, gained from the event builder, and parameters on which the cuts were set for sampling events are described.

The Continuous Electron Beam Accelerator Facility (CEBAF) is an electron accelerator located on the campus of Jefferson Lab. CEBAF is a unique and state-of-the-art facility that utilizes superconducting radiofrequency (SRF) technology to transfer RF energy to electrons, while the electron beam bunches are forced along oscillating electric fields. It relies on various aspects of accelerator technology to achieve its physics goals. The entire accelerator is shaped in the form of a race track with two arcs containing re-circulating magnets. The two straight sections of the accelerator

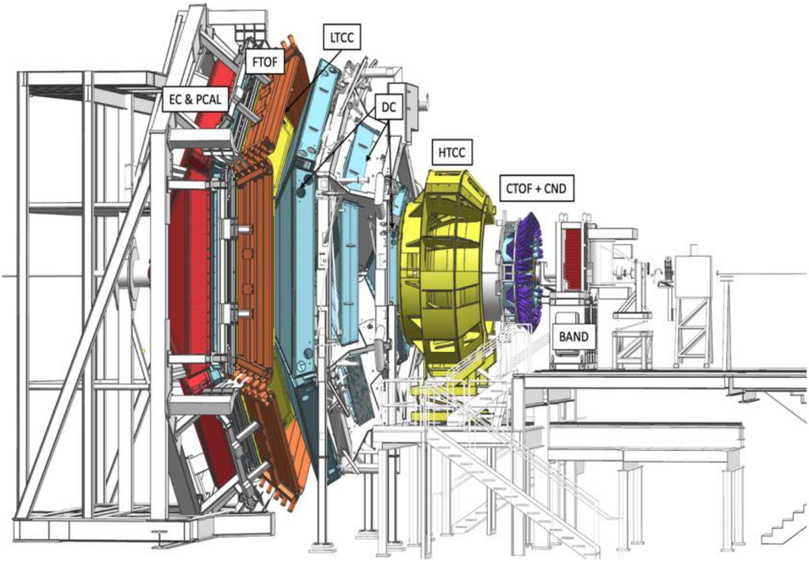

Figure 1. A diagram of CLAS12 showing both the Forward and Central detectors and their subsystems.

provide SRF cavity boosts to pump RF energy for the purpose of accelerating the electron beam bunches. The injector is the source of the beam and is the starting point of the accelerator [2].

In Fig.1 a schematic view of the CLAS12 [3] magnetic spectrometer located in Experimental Hall B of Jefferson's laboratory is presented. This is a complex setup designed for a wide range of experiments to study the structure and interaction of nucleons, nuclei and mesons, using polarized and unpolarized electron beams and targets, for beams with energies up to 11 GeV. CLAS12 consists of two main subgroups of detectors: central detector (CD) and forward detector (FD) and is based on a dual system of magnets, consisting of a solenoidal magnet with a central field of 5 T and a superconducting toroidal magnet with 0.5 - 2.7 Tm, allowing to measure momenta of charged particles, respectively, in CD and FD. The central detector is designed to register particles in the polar angle range from 35 ° to 125 °, has the shape of a cylinder with an azimuthal coverage of almost 2π and is located between the target and the inner wall of the solenoidal magnet. The CD includes a vertex detector CVT (Central Vertex Tracker) and two time-of-flight detectors - CTOF (Central Time of Flight) and CND (Central Neutron Detector) designed to identify charged and neutral particles, respectively. The forward detector registers and identifies charged and neutral particles in the polar angle range from 5 ° to 35 ° in the entire momentum range and consists of six functionally equivalent magnetic spectrometers based on a six-coil superconducting toroidal magnet. Each FD sector is equipped with a High Threshold Cherenkov Counter (HTCC), a set of DC drift cameras (Drift Chambers), a low threshold Cherenkov counter LTCC (Low Threshold Cherenkov Counter), FTOF (Forward Time of Flight) and a complex electromagnetic calorimeter ECAL (EC & PCAL, - Electromagnetic Calorimeter and Pre-shower Calorimeter). The detectors included in the FD are located downstream of the target in the sequence shown in Fig. 1 In addition to CD and FD for identification of electrons and photons emitted very close to the beam line (from 2 ° to 5 °), in close proximity to the beam, after the target, a composite detector "Forward Tagger" (FT) consisting of a calorimeter, a scintillation hodoscope and two two-layer micromega trackers, is installed. Particles in CLAS12 are detected and identified by measuring their momenta, time of flight, the number of photons produced in threshold Cherenkov counters, and energy losses in calorimeters and scintillation counters. Reconstruction of the trajectory in the forward direction, using drift chambers, and in the central part, using the vertex detector, gives a momentum resolution of <1% and <5%, respectively. Cherenkov counters, time-of-flight scintillators and electromagnetic calorimeters provide good particle identification. The fast trigger system and high data collection rate allow operation at a luminosity of 10^{35} cm^{-2} s^{-1}.

The presented experiment uses an unpolarized cryogenic target LH_2 [4]. The target material is placed in a 5 cm Kapton cone, on each end of which there are inlet and outlet aluminum windows with a diameter of 23.66 mm and 15.08 mm, respectively, and a thickness of 30 μm. The target cell is positioned in the scattering chamber installed at the nominal center of the CLAS12 spectrometer.

The experimental data set is carried out and controlled by the Trigger system and Data Acquisition System (DAQ). The main function of a trigger is to provide the data acquisition system with a trigger signal for recording data. The main purpose of DAQ is to organize the information coming from the detectors and transfer this information to tape storage. In general, the CLAS12 trigger depends on seven detectors: HTCC, DC, FTOF, ECAL, CTOF, CND, FT and is carried out in three stages, during which in the online mode it is determined whether it is worth recording an event for subsequent offline analysis, - the events in which the electron effectively interacted with the target, are saved. Data collection comes from interface components of the DAQ system called read controllers (ROCs [5]).

At the first stage of offline processing of the collected experimental data, the so-called decoding, during which EVIO format files are converted to HIPO (High Performance Output) format are performed. The CLAS12 reconstruction environment is based on the CLARA (CLAS Analysis and

Reconstruction Architecture) service-oriented software architecture [6], in which event reconstruction is divided into microservices that perform data processing algorithms. Each CLAS12 sub-detector has its own reconstruction service. The output of each subsystem service is connected into the input of the Event Builder (EB), which links all subsystem responses and performs particle identification.

The primary banks that are utilized for data analysis are from the CLAS12 Event Builder (EB). The EB banks consist of four-vector and vertex information as well as the associated detector hits for each of the charged tracks and neutral tracks. An additional post-processing step is necessary after the reconstruction.

For this work, several programs were written and combined to analyze data, including data-merging to dispose of unnecessary events and for more fast analysis. There are several conditions that the algorithms accept in the data merging:

- <u>an electron, positron and a positive particle.</u>
- a positive muon, a negative muon, and 1 proton from FD.
- <u>an electron-positron pair with momentum greater than 2 GeV.</u>
- an di-muon pair with momentum more than 2 GeV
- <u>minimum ionizing particle PCAL (>0.11 GeV), ECIN (>0.1 GeV), and ECOUT (>0.2 GeV) energy cuts.</u>

In this work, underlined conditions were used in the analysis.

One of the important steps in data reconstruction is particle identification. At this step, a list of particles is formed using the values of the momentums, the vertex coordinates of the formation, as well as the corresponding list of detectors of the CLAS12 setup. Particle identification is based on various combinations of measured physical quantities, and constraints have been added to the event generation algorithm to account for the calibration constants of various detectors that can affect identification.

Due to their low mass, leptons can most likely be registered in the forward detector (FD). Here, particle identification is based on a combination of information from DC, ECAL, HTCC and FTOF. The FTOF time resolution does not allow the separation of leptons and pions in CLAS12 kinematics. The efficiency and method of identifying leptons depends on their energy, such as for energies below 4.9 GeV/c EB-identification of electrons and positrons is quite effective, since it is less prone to pions contamination, the HTCC threshold is in effect. Above this threshold, HTCC generates a signal for both leptons and pions and, therefore, cannot participate in their separation; as a consequence, in the high momentum region, the identification of leptons is based solely on the "Sampling Fraction" value in the electromagnetic calorimeter:

$$SF = \frac{E_{tot}}{p} \tag{1}$$

where E_{tot} is the total energy (total energy of clusters of three layers of the calorimeter) deposited in ECAL, and p is the momentum measured in DC. The SF value of each particle is unique. Variables determining the identifier of a particle with a given measured SF value are the mean and standard deviation values obtained by parameterizing the dependence of the total sample fraction on the total energy deposited in the calorimeter. For electrons and positrons, the measured SF_{meas} must be within five standard deviations of the calculated mean SF_{calc}.

The Event builder identifies a particle as an electron or a positron (the particle charge is determined by the curvature of the track in the magnetic field of the torus) if the following conditions are met:

- DC track detection and corresponding shower in ECAL.
- The minimum number of photoelectrons in the HTCC should be more than two: $n_{phel} > 2$, at P <4.9 GeV
- Minimum PCAL energy is 60 MeV;
- If $|SF_{meas}(E_{tot}) - SF_{calc}(E_{tot})| < 5\sigma_p$ (The energy-dependent ECAL sampling fraction falls within 5σ of the expected mean).

Hadrons (particularly protons) are identified by their time of flight (TOF) from the production vertex to the point of interaction with time-of-flight detectors. The CLAS12 setup has two time-of-flight detectors, the central one (CTOF) and the forward one (FTOF). In both cases, the procedure for identifying hadrons is similar: the difference between the measured and calculated time of flight is considered. The identification of charged hadrons is performed by comparing the expected and measured vertex times based on the values when the mass of those particles is assigned in those calculations.

The measured time of flight, $t_{tof} = t_{TOF} - t_s$ is the time interval between the time of collision (hit) of the particle with the time-of-flight detector, in which it was registered, t_{TOF}, and the start time of the event t_s^*. The time of flight is calculated based on the readings of track detectors $t_{track} = P_L\sqrt{(p^2 + m^2)}/pc$, where p is the momentum, P_L is the path length from the production vertex to the point of interaction with the time-of-flight detector, m is the particle mass , determined on the basis of a sample of given possible values - the particle is assigned a mass (and, therefore, the corresponding identifier, PID) at which the difference $(t_{TOF} - t_{track})$ is minimal.

The start time of the event is determined using the FTOF response to the trigger particle. The trigger particle is considered to be the most energetic lepton or, the pion with the highest momentum, if there is no lepton. According to the $t_v = t - P_L/c$ formula, so called uncorrected trigger particle vertex time is calculated, where t is the trigger particle time measured in FTOF, and P_L is the path length from the vertex to the detection point in FTOF. Next, the vertex time is then corrected for the z_v vertex position (to account for the time required for the beam bunch to propagate from the CLAS12 origin, defined as the target center z_0, to the vertex), and provided by the accelerator the radio frequency time, t_{RF}:

$$\Delta t_{RF} = t_v + \frac{z_0 - z_v}{c} - t_{RF} - \frac{N + 1/2}{f_{RF}} \quad (2)$$

where f_{RF} is the accelerator frequency and N is a large integer (usually 800). This allows to find from which bunch the event was originated, and precisely match the vertex time with the time interval between two bunches using the expression:

$$\Delta t'_{RF} = mod\left(\Delta t_{RF}, \frac{1}{f_{RF}}\right) - \frac{1}{2f_{RF}} \quad (3)$$

Finally, the starting time is defined as:

$$t_s = t_v - \Delta t'_{RF} \quad (4)$$

The particle identifiers assigned by the event builder coincide with the designations in the Particle Data Group (PDG), as an example, according to this designation, the electron and positron indices are

11 and -11, respectively, the proton index is 2212. The reliability of the identifiers is estimated by the "chi2pid" value specified for each particle, and is defined as the deviation of the identifying value (SF for leptons, TOF for a proton) from the expected value.

During the analysis, applying a stricter cut to the "chi2pid" value, more than default inputs, can improve the identification quality.

Chapter 4 is describing stages and methodology of the analysis. The analysis presented in the work was carried out on the data of experiment E12-12-001 [7], obtained on CLAS12 spectrometer in Hall B of Jefferson's laboratory. This is one of the first experiments carried out at the CLAS12 setup after the 12 GeV CEBAF upgrade. The subject of interest was fully exclusive electroproduction reaction:

$$ep \rightarrow e'e^+e^-p' \quad (5)$$

where e and p are incident electron and target proton, respectively, e′ - is the scattered electron, (e^+e^-) - is the produced lepton pair and p′ - is the recoil proton.

The analysis is carried out in the environment of the ROOT package (a multifunctional package of object-oriented programs and libraries for data analysis in high energy physics [8]). The input data is data that has been preprocessed and recorded in accordance with the standard software developed for the CLAS12. The analysis is carried out using the technique of constructing the invariant and missing masses, as well as evaluating a number of kinematic quantities based on the energy conservation law and the requirements due to the specificity of the reaction under consideration.

The analysis was carried out in two stages using two different photoproduction mechanisms: tagged and untagged. In the case of tagged production, the scattered electron is detected in the CLAS12 Forward Tagger (FT), while the leptons from the J/ψ decay are detected in the CLAS12 forward detector (FD). In the untagged production case, the recoil proton and both decay leptons are detected in FD, the initial electron (e′) scatters at a small angle (∼ 0°), and escapes detection in CLAS12. As in tagged as well in untagged cases 3 out of 4 final state particles in reaction $ep \rightarrow e'J/\psi p' \rightarrow e'e^+e^-p'$ are detected in the final state, with a difference that in untagged case the missing system X is the scattered electron e', and in tagged case the missing system is the recoil proton, p′.

Method for extracting quasi-real photoproduction events from electroproduction data is described. The particle selection and identification methods, with restrictions applied during analysis are presented. As well as research for the detection and disposal of incorrectly identified pions are considered. The procedure for taking into account the energy losses of leptons when passing through the material of the CLAS12 is described in detail.

To detect the J/ψ - resonance, the distribution of the invariant mass of the e^+e^- pair is investigated. Information of the missing mass, $(m^2_{miss} = E^2_{miss} - p^2_{miss})$ and the transverse components of the missing momentum $\frac{p_x}{p_{miss}}$ and $\frac{p_y}{p_{miss}}$ is necessary for the "exclusivity" constraints [9] applied to select completely exclusive final states $e^+e^-p'(e')$ and separating quasi-real photoproduction from the electroproduction reaction:

$$ep \rightarrow (e')\gamma p \rightarrow (e')e^+e^-p' \quad (6)$$

The corresponding equation for the conservation of 4-dimensional momentum:

$$p_{beam} + p_{target} = p_{scat} + p_{\gamma} + p_{target} = p_{scat} + p_{e^+} + p_{e^-} + p_p \quad (7)$$

Two exclusivity cuts applied to the missing particle (X) of the pe^+e^-X system. The mass and fraction of the transverse momentum of the missing particle X should be close to zero. The cuts on mass ensures that the missing particle is an electron. The cuts on the transverse momentum ensures low virtuality of the photon, which corresponds to the quasi-real photoproduction of an e^+e^- pair. The virtuality of the intermediate photon can be written as follows:

$$Q^2 = 2E_{beam}E_X(1 - cos\theta_z) \quad (8)$$

where E_{beam} is the energy of the electron beam, E_X is the energy of an untagged scattered electron, θ_x is its scattering angle in the laboratory frame of reference,

So, for $\left|\frac{P_{tr}}{P_X}\right| < 0.05$, $|M^2_{miss}| < 0.4 \left(\frac{GeV}{c^2}\right)^2$, virtuality of the intermediate photon is $Q^2 < 0.02$ (GeV/c)^2.

During the J/ψ photoproduction analysis, good identification of the final state leptons is very

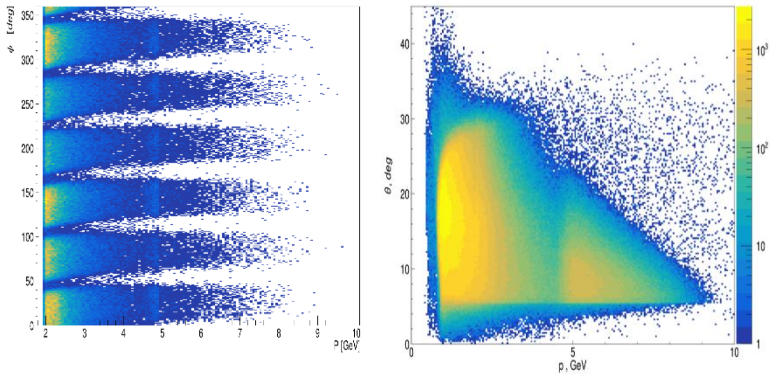

Figure 2. The positron scattering angle as a function of the momentum was analyzed and a visible cluster of events above 5 GeV indicate pion contamination at that energy range. 2D distribution for electron's angular dependance of momentum: Azimuthal angle vs momentum (left) and Polar angle vs momentum(right).

important. If in the energy range up to 4.9 GeV HTCC CLAS12 provides good separation of pions and leptons, where the efficiency of selection of leptons by HTCC is approximately 99% [10], then for momentum above the HTCC threshold (4.9 GeV) for pions, both experimental data and simulation show the presence of a large amount of contamination of π+ mesons in the positron samples. To reduce the likelihood that a high energy pion will pass through the positron ID, additional constraints are needed, which is especially important for the photoproduction of the J/ψ meson, since the momentum of electrons and positrons in the final state usually can reach 9 GeV. There is clear qualitative evidence of pion contamination for the dataset used in this analysis.

One of the indications of pion contamination is illustrated in Fig. 2, where for the events under study there is a two-dimensional dependence of the scattering angle of positrons on their momentum. Kinematic calculations have shown that a statistically significant cluster above 5 GeV can be caused by pions that have passed the constraints specified in the event builder. Further evidence of pion contamination of a positron sample can be observed when examining an exclusive reaction with a pion (misidentified as a positron), an electron and a missing neutron in the final state.

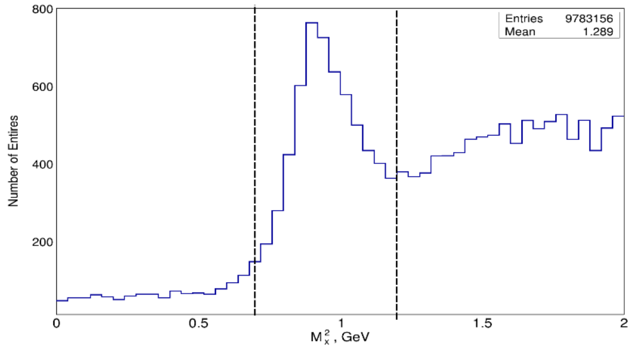

Figure 3. Missing neutron peak, which is used to estimate mis-identified positrons. All pion candidates are from PID = -11 data set and are under the observed neutron peak.

From the CLAS12 dataset, events are selected in which particles with index -11 (positron ID) and momentum above 4.5 GeV and an electron with momentum below 4.5 GeV are present. Both particles must be detected in the forward detector. The cuts on the momentum of the electron ensures that it is a real electron. The missing mass is calculated by assigning the mass of a pion to the positron. The resulting spectrum of missing masses is shown in Fig. 3. A clear peak is seen in the neutron mass region. This peak is the result of the reaction $ep \rightarrow e\pi^+n$, where π^+ was misidentified as a positron.

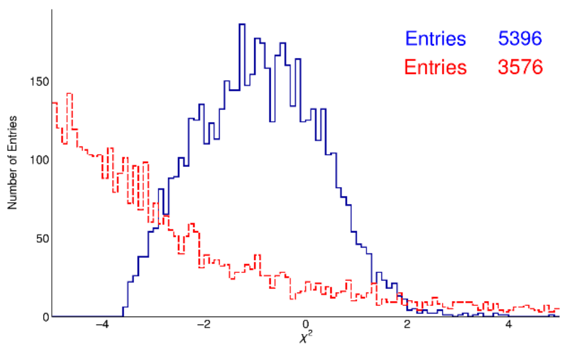

Figure 4. $\chi2$ (chi2pid) distribution for real high-energy positrons (blue) and incorrectly identified pions (red, dashed).

A measure of the quality of the lepton indices assigned by the event builder is the "chi2pid" quantity. In fig. 4 shows the distributions of this quantity for true positrons and misidentified pions. As it can be seen that the misidentified pions mainly populate the region with low "chi2pid" - the fraction of the sample of these pions turned out to be quite large, as a result of which they were identified as positrons. There are two possible strategies for tightening the cuts on the value of “chi2pid”, which are checked during the analysis: cutting off modulo (|“chi2pid”| <c) or at low values (“chi2pid” > c).

Longitudinal ECAL segmentation is proving useful for positron recognition. Positrons are more likely to deposit all their energy in the first layers of the calorimeter (PCAL and ECIN). On the other hand, pions, being minimally ionizing particles (MIP), are more likely to store energy in all layers of the electromagnetic calorimeter. The efficiency of rejecting false events can be increased by examining the two-dimensional dependence of the ECIN sample rate on the PCAL sample rate. As can be seen from fig. 5, the constraint given by the $SF_{ECIN} = 0.2 - SF_{PCAL}$ expression can reject a significant portion of the pions, while preserving the positrons [11].

In this analysis of J/ψ photoproduction, additional constraints were applied only to positrons for which the momentum in the final state of the reaction exceeded 5 GeV. For electrons the constraints set by the event builder (EB) was used, - π^- contamination is not significant in the phase space, which is analyzed in this work. In addition, the conservation of the lepton number imposes restrictions on the final reaction. When there are well-identified lower-energy positrons, the corresponding higher-energy negative particles must be electrons and the likelihood of π^- contamination is very small.

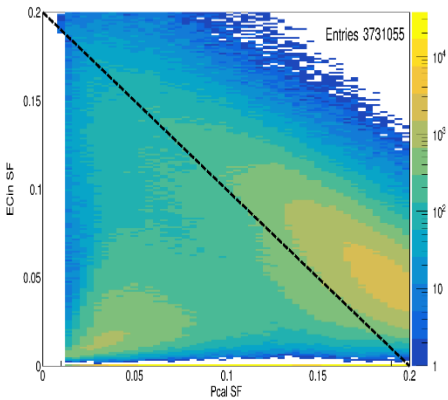

Figure 5. PCAL sampling fraction vs. ECIN sampling fraction

Parameters recommended by the event builder for proton identification are satisfying for this analysis (the past developed proton identification techniques and used in the work [12] are now contained in EB).

Fig. 6 shows the distribution of the invariant mass of the $e^+ e^-$ pair after the correction of the particles specified by the event builder. The yield of J/ψ - mesons at this stage of the analysis is equal to 120.

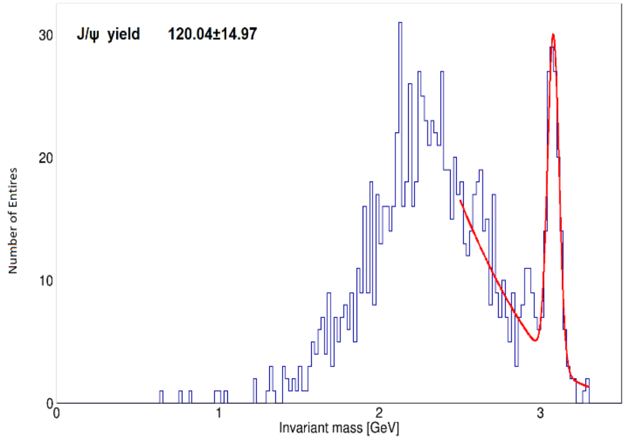

Figure 6. Invariant mass of $e^+ e^-$ pair after identifier correction.

One more type of correction is important to take into account both when calculating invariant mass, and to reduce event loss when the exclusivity cut is applied. This is the energy losses for radiation of electrons and positrons from the decay of the J/ψ -meson when they passing through the material of the CLAS12 setup from the production vertex to the detection place. Energy can be lost due to radiation at the vertex in the target, in the scattering chamber, on the materials of the SVT cover, HTCC windows and mirrors - essentially any material that predates drifting chambers.

Some part of the radiation photons will be detected in EC. The measured energy of the radiation photons can be used to reconstruct the momentum of electrons and positrons at the production vertex. In the longitudinal field of the solenoid at the point of radiation, the polar angle of the electron is the same as at the production vertex. With the azimuthal angle, the situation is more complicated, because there is a dependence on the three-dimensional momentum of the electron and the distance from the production vertex. Radiated photons in EC can be identified by analyzing the differences between the values of the reconstructed electron (or positron) and neutral particle angles: $\Delta\theta = \theta_\gamma - \theta_e^r$; $\Delta\varphi = \varphi_\gamma - \varphi_e^r$. Events with an electron (positron) and at least one neutral particle was selected for analysis. During the selection of radiation photons, a cut was applied on the difference between the polar angle of an electron (or positron) and a photon, detected in EC, since the angle at the point of formation of radiation photons coincides with the angle of the lepton that emitted them, the cut was taken to be rather small $\sim 0{,}7^{\circ}$. The photons that are emitted before the electron reaches the drift chambers can be easily identified - these are photons, detected in EC, that are not associated with a track in DC. The energy of such photons was directly summed up with the energy of the radiated leptons.

Another consideration to be taken into account is that not all radiated photons are identified correctly in the event builder. To distinguish between photons and neutrons, the event builder's algorithm calculates particle velocities β using time information in the calorimeter. Due to imperfect EC timing associations, some photons are misidentified as neutrons. To account for such photons, we analyzed all neutral particles that passed the angle difference cuts, regardless of their indexation. For such photons, which are misidentified as a neutron, the momentum must be recalculated using sampling fraction as a function of photon energy [11,13].

The distribution of the invariant mass of the $e^+ e^-$ pair after taking into account the energy loss corrections is shown in Fig. 7. The number of J/ψ mesons increased to 166.

Table 1 shows estimates of the change in the invariant mass of the e^+e^- pair as a result of taking into account the above corrections.

Table 1. Fitting parameters of the function of approximation of the lepton pairs' invariant mass distribution corresponding to the region of the mass of the J/ψ meson. Const (G), Mean (G) and σ (G) are the parameters of the Gaussian function, with polynomial function. Number of J/ψ calculated with $A = (Const(G)\sigma\sqrt{2\pi})\ /\ b$ where b is the bin size.

Const(G)	Mean(G)	σ(G)	J/ψ yield	growth (%)
26.85±3.35	3.087±0.011	0.0357±0.0003	120.04±14.97	—
36.64±.3.79	3.091±0.019	0.03638±0.003	166.63±17.25	39

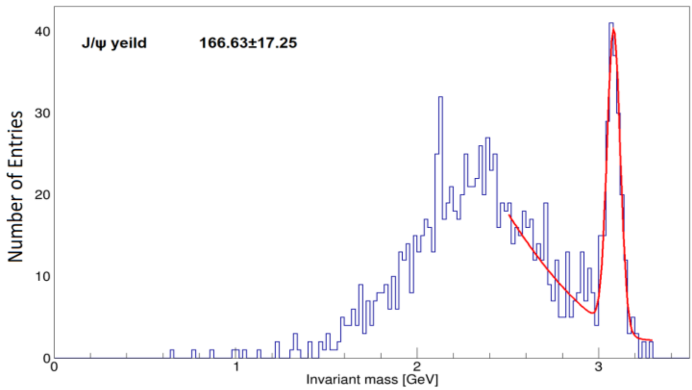

Figure 7. Invariant mass of lepton pair after radiative corrections.

<u>Chapter 5</u> describes the comparison of different experimental methods on J/ψ untagged photoproduction selection, where four different data gathered by different softs compare to each other. The estimation of exclusive variables was given.

The analysis of the data of the experiment conducted by RGA is carried out by different groups involved in this project, with different research directions. However, at the first stage of the analysis, all researchers faced the same challenge - the development of a methodology that ensures the acceptable reliability of the result obtained. One of the interesting aspects of this study is the comparison of the current analysis results with the results of other project participants who use in their analysis various available tools, provided both by the capabilities of modern generally accepted data analysis tools and by the capabilities of the CLAS software. The purpose of cross-checking the results of various analyzes was to get an idea of the effectiveness of various methods for selecting events, to determine the optimal values of the cuts used in the analysis, as well as to find possible inconsistencies, which was very important, since the analyzed data was obtained on an upgraded setup and processed using updated software. The results of analyzes with the same final states of selected events and with using the same selection technique, however, with different software analysis packages, written in different base languages, - PAW ++ (FORTRAN), ROOT (c++ and c++ with AI), JAVA, - as well as using different capabilities of these packages, have been chosen for comparison. In Figure 8 presented the results of the comparisons.

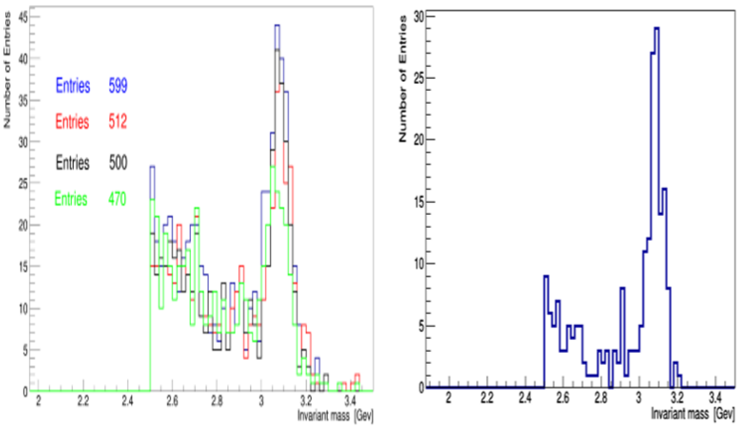

Figure 8. The Invariant mass distributions of the lepton pair from J/ψ decay for different analysis, obtained from the same data and carried out in base of different software packages: ROOT(black, *our data*), JAVA(red), FORTRAN(blue), ROOT(AI) (green) (left) and invariant mass distributions after multiple data comparison (right).

Chapter 6 describes tagged photoproduction using the Forward Tagger (FT) to detect the scattered electron. W distribution for different experiment (in-bending, out-bending) was studied.

With CLAL12, meson production was studied in the tagged photoproduction using the Forward Tagger (FT) to detect the scattered electron. Here presented one of the channels from the J/ψ photoproduction reaction: $ep \rightarrow (e')J/\psi X \rightarrow e'e^{+}e^{-}X$, where X identifies in the missing momentum analysis as a recoil proton (p') (fig. 9). As in the untagged case, 3 out 4 final state particles are detected in the final state, with a difference that in untagged missing system X was the scattered electron.

The selection of the lepton pair is done exactly the same way as in untagged analysis, including the radiative energy loss correction. The events with an electron in FT are selected for further analysis. Only 9% of events have electrons in Forward Tagger, where 95% of them have one electron in FT. For analysis of the tagged J/ψ photoproduction, events with one FT electron are selected. To selected FT electron from the same event as the pair in FD and FT electrons time vertex difference (Δt_v) have been studied.

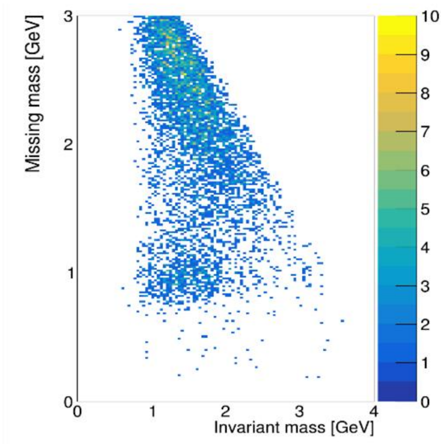

Figure 9. 2D distribution of Missing mass vs invariant mass of lepton pair.

Events with $|\Delta t_v| < 2$ ns are selected as a true $(e'e^+e^-)$ coincidence events. The missing momentum analysis of the tugged photoproduction reaction was done to select events with the missing proton. Before the analysis the momentum of the FT electron was recalculated to account cost difficulties in the calibration of the data. The following correction to the total energy (momentum) is applied:

$$E_{new} = -0.03689 \cdot E_{old} + 1.1412 \cdot E_{old}^2 - 0.007046 \cdot E_{old}^3 + 0.0004055 \cdot E_{old}^4 \quad (9)$$

The J/ψ mass peak is visible in both data sets and distribution of total hadronic mass, W for events under the J/ψ-mass peak is shown.

$$W = \sqrt{M^2 + 2ME' + Q^2} \quad (10)$$

where $Q^2 = 2E_{beam}E_{FTe}(1 - cos\theta_{FTe})$, $E' = E_{beam} - E_{FTe}$ and M is the mass of the proton. In Fig. 10 the invariant mass distribution and the W distribution of events under the J/ψ-mass peak is shown for combined data.

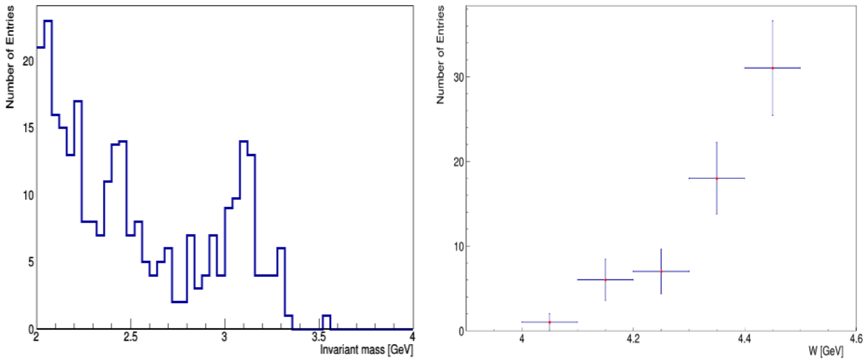

Figure 10. The Invariant mass(left) and W (right) distribution of tagged photoproduction.

Conclusion (Chapter 7) describes summary of taken work, showing obtained results gathered from whole analysis.

Studding various untagged photoproduction methods led us to evaluate kinematic variables such as missing momentum and missing mass, as well as to understand the distributions of exclusivity variables to quantify them dependence on photon energy. Optimized event selection allows for the more efficient disposal of pion contamination or other non-photoproduction events.

In this work, J/ψ production near threshold was studied using two methods, untagged and tagged photoproduction at low Q^2. The J/ψ photoproduction is studied in electron scattering on hydrogen. This reaction, $ep \rightarrow e'p'J/\psi \rightarrow e'p'e^+e^-$ has four final state particles, scattered electron (e'), recoil proton (p') and the decay leptons (e^+e^-) from J/ψ. In the untagged photoproduction case, the scattered electron is not detected. Instead, its kinematic is deduced from the missing momentum analysis of the final state $p'e^+e^-$. Kinematic of the reaction at JLAB energies, near-threshold, is such that all three particles are produced in the very forward region and the ($p'e^+e^-$) will be detected in the CLAS12 forward detector. In the second method, a tagged photoproduction, the scattered electron is detected in the forward tagger. FT detects and identifies electrons in the polar angular range from 2.5 to 4.5 degrees. Only decay leptons of J/ψ decay are detected in the CLAS12 forward detector together with the scattered electron. The kinematic of the proton is determined in the missing momentum analysis of ($e'e^+e^-$). In this method, the interacting photon kinematic is fixed by the scattered electron at very small virtuality's, $Q^2 < 0.2\ GeV^2$.

The untagged method was the precursor of the analysis for the tagged photoproduction at low $Q^2 < 0.2$. This method was used to develop particle identification and event selection methods. The analysis techniques are validated by comparing the results of this analysis with the results of other analyses in the collaboration. It was found, that for the untagged analysis the best variables for the J/ψ event selection are the missing mass squared of the undetected electron and the Q^2. The analysis showed that the detector resolution for these variables is kinematic dependent and must be taken into account when cuts are developed. It was also found that the additional cuts are needed to suppress π^+ background in the positron sample, especially true for momenta <5 GeV/c. The comparison is done in this work help the collaborators and other analyzers to correct their studies of the untagged photoproduction.

The tagged photoproduction of J/ψ near-threshold was studied for the first time. There are no other experimental data for this reaction. The decay leptons are detected and identified the same way as in the untagged method. The recoil proton is not detected, instead, its kinematic is deduced from the missing momentum analysis. A new method for detection and accurate reconstruction of the scattered electron momentum in FT was developed. Since the events of the interest were triggered by electron and/or positron in the CLAS12 FD during data taking, there are a fair number of accidental electrons reconstructed in FT during the same trigger window. Using very good time resolution of FD and FT, which allows separation of the interactions in the target from different electron beam buckets, we were able to select correct scattered electron in FT in coincidence with (e^+e^-) in FD. The main outcome of this study are: (a) for the first time it is shown that there are tagged J/ψ photoproduction events in CLAS12, and (b) the rate of detection of such events is comparable to the estimates [14].

List of articles published for the dissertation topic:

- D. A. Martiryan, N. B. Dashyan, and N. E. Gevorgyan, “The Extraction of the Near-Threshold J/ψ-Meson Photoproduction Reaction from Experimental Electroproduction Data”, Journal of Contemporary Physics (Armenian Academy of Sciences), 2021, Vol. 56, No. 2, pp. 79–84.
- Д.А. Мартирян “Методические Изыскания По Улучшению Извлечения Процесса Околопорогового Квазиреального Фоторождения J/ψ – Мезонов На Нуклонах Из Экспериментальных Данных Электророждения На Ядре Водорода Полученных На Установке CLAS12”, Известия НАН Армении, Физика, T.57, №1, с.3–18 (2022).
- D. A. Martiryan “Selection of Coincidence Electron-Proton Events in Nuclei Interaction” Proceedings of The Yerevan State University, 2019, 53(1), p. 53–59.
- D. A. Martiryan, “The Radiative Corrections Accounting in The Reaction Near-Threshold Of J/Ψ Photoproduction” Proceedings of The Yerevan State University, 2021, 55(2), p. 141–147.

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МАРТИРЯН ДАВИД АРМЕНОВИЧ

ИССЛЕДОВАНИЕ ФОТОРОЖДЕНИЯ J / Ψ С ИСПОЛЬЗОВАНИЕМ ДЕТЕКТОРА CLAS12

Резюме

В диссертационной работе представлен анализ околопорогового фоторождения J/ψ -мезона на протоне. Работа является частью исследований околопорогового фоторождения J/ψ-мезонов, начатых на установке CLAS12 (Cebaf Large Acceptance Spectrometer), установленной в зале B лаборатории Jlab (лаборатория Джефферсона, США). При анализе использовались экспериментальные данные, полученные на первом этапе эксперимента, когда пучок электронов с энергией 10,6 ГэВ рассеивался на мишени из жидкого водорода (RGA, проект E12-12-001). Первый этап эксперимента был проведен осенью 2018 года и был одним из первых экспериментов, проведенных на модернизированном - в связи с реконструкцией CEBAF на 12 ГэВ - магнитном спектрометре CLAS12. Использование модернизированной установки и специфика анализа, представленного в диссертации, требуют особенно внимательного подхода к методам исследования.

Работа состоит из двух частей, в которых описывается анализ с использованием различных методов отбора событий фоторождения. В первой части представлены результаты анализа с использованием непомеченного фоторождения. Основная задача этой части анализа - выбрать наиболее эффективный способ отбора событий для квазиреального околопорогового фоторождения J/ψ -мезонов. На основе сравнительного анализа показана эффективность различных подходов и даны количественные оценки выхода J/ψ-мезонов для каждого из них. Во второй части описан анализ помеченного фоторождения.

ՄԱՐՏԻՐՅԱՆ ԴԱՎԻԹ ԱՐՄԵՆԻ

J/Ψ – ՖՈՏՈԾՆՄԱՆ ՈՒՍՈՒՄՆԱՍԻՐՈՒՄԸ CLAS12 ՍԱՐՔԱՎՈՐՄԱՆ ՎՐԱ

Ամփոփագիր

Ատենախոսական աշխատանքում ներկայացվում է պրոտոնի վրա J/ψ մեզոնի շեմամերձ (շեմին մոտ) ֆոտոծնման ուսումնասիրությունը: Այս աշխատանքը J/ψ մեզոնի շեմամերձ ֆոտոծնման ուսումնասիրությունների մի մասն է, որն սկսվել է CLAS12 (Cebaf Large Acceptance Spectrometer) սարքավորման վրա, որը գտնվում է Jlab լաբորատորիայի B սրահում (Ջեֆերսոնի լաբորատորիա, ԱՄՆ): Մշակումների ժամանակ օգտագործվել են փորձարարական տվյալներ, որոնք ստացվել են գիտափորձի առաջին փուլում, երբ հեղուկ ջրածնային թիրախի վրա ցրվել է 10,6 ԳէՎ էներգիա ունեցող էլեկտրոնային փունջը (RGA, նախագիծ E12-12-001): Գիտափորձի առաջին փուլն իրականացվել է 2018 թվականի աշնանը, այն առաջին գիտափորձերից մեկն էր, որն իրականացվել է արդիականացված CEBAF արագացուցչի՝ մինչև 12 ԳէՎ վերակառուցումից հետո, CLAS12 մագնիսական սպեկտրոմետրի վրա: Արդիականացված սարքավորումը և ատենախոսության մեջ ներկայացված վերլուծության առանձնահատկությունը պահանջում են հատուկ հետազոտական մեթոդների կիրառում:

Աշխատանքը բաղկացած է երկու մասից, որոնցում նկարագրվում են ֆոտոծնման հետազոտման երկու տարբեր մեթոդներ: Առաջին մասում ներկայացված են վերլուծության արդյունքները՝ օգտագործելով չպիտակավորված ֆոտոծնումը: Մշակումների այս մասի հիմնական խնդիրն է որոշել J/ψ-մեզոնի քվազի-ռեալ շեմամերձ ֆոտոծնման դեպքերի ընտրության ամենաարդյունավետ եղանակը: Համեմատական վերլուծության հիման վրա ցույց է տրվում տարբեր մոտեցումների արդյունավետությունը և տրվում են J/ψ - մեզոնի ելքի քանակական գնահատականներ վերլուծության յուրաքանչյուր մեթոդի համար: Երկրորդ մասում ներկայացված են պիտակավորված ֆոտոծնման դեպքերի վերլուծության արդյունքները: