Project submitted for the base funding of Artem Alikhanyan National Laboratory (ANL)

Principal Investigator: Prof. N. Akopov

TITLE: "Studies of hadron physics based on the data accumulated at HERMES experiment"

Division, group: Experimental physics/Computing center, HERMES-OLYMPUS group

The ANL group participating in this project is a full member of the HERMES Collaboration starting 1993, and also full member of the OLYMPUS Collaboration starting 2009. In many HERMES papers official acknowledgment to the Armenian Government is expressed. In according with the HERMES constitution the ANL group has a full right to use any data accumulated on HERA accelerator by the HERMES experiment (as well the OLYMPUS experiment, which will be performed on DORIS accelerator during the 2012) for physics analyses and future publications.

DURATION: Three years

Estimated Project Costs (± 20%) ***(эта часть заполняется по согласованию с дирекцией Национальной Лаборатории)***

Estimated total cost of the project (US $)

Including:

Payments to Individual Participants	
Equipment	
Materials	
Other Direct Costs	
Travel	

PROBLEM:

The hadron physics is the most interesting area in modern high energy physics due to lack of theory of the strong interactions and ultimate necessity to check many theoretical models pretending to describe the spin and hadronization phenomena.

The proposed project is devoted to the important aspects of hadron physics. The first one is related to the problem of the nucleon spin structure via the investigation of azimuthal asymmetries in exclusive electroproduction of real photons in Deeply Virtual Compton Scattering (DVCS) reactions. Another aspect is related to the problem of hadronization mechanism via the study of electroproduction of various identified hadrons on different nuclear targets. The experimental data associated with both aspects are extremely important to complete our knowledge and approach to the adequate theory of the strong interactions similar to Quantum Electro Dynamics (QED) for electromagnetic interactions.

Exclusive reactions are intensively investigated at different high energy laboratories like HERMES [1-12], Jlab [13-17], CERN (COMPASS). The HERMES based results together with the Jlab and COMPAS results will allow to perform a global fit to adjust the differnt GPD based structure functions and make a big step towards to the clarification of famous old problem which is called the “spin crisis” [26,27].

Also the hadronization in nuclear medium is a matter of high interest at HERMES [19-22] and Jlab [23-25], the results on hadronization in nuclear medium will allow to make essential progress with the understanding of the hadronization phenomenon. Within the proposed project also the models describing the phenomenology of the nuclear attenuation based on obtained HERMES data (see already published [28]), are supposed to be developed. The data to be analyzed are collected at HERMES experiment [29] on HERA accelerator at DESY during more than ten years.

Within the present project also methodic works with the Time of Flight (TOF) system and Monte Carlo simulations for a new OLYMPUS experiment at DESY on DORIS accelerator are planned. The main goal of this experiment is the study of the cross sections asymmetry in the elastic elctron-proton and positron-proton scattering in order to check the possible contribution of the two-photon exchange diagramm in the interpretation of well known essential difference in the ratio of electric to magnetic form factors observed by using the Rosenblut separation method and measurements of the recoil proton polarization [30-40].

OBJECTIVES:

To achieve the planning goals the full set of the modern high energy physics analysis methods and approaches will be used. Based on well known systems like PAW and ROOT all subject related data accumulated at HERMES will be analyzed as multidimensional histograms (Ntuples) with applying of different complicated sets of kinematical and geometrical conditions. Also the full information on data quality available at HERMES and related to all detectors/components performance, as well as to the quality and stability of the beam and target during the data taking, will be used to discriminate different types of false (non physical) effects. In order to provide high quality of the analyses the detailed Monte Carlo studies based on different types of physics generators like PYTHIA, PEPSI, GEANT etc. will be preformed.

Such studies are necessary to make the realistic estimations for possible systematic uncertainties, as well to take into account things like the acceptance effect, radiative corrections and smearing effects due to finite bin sizes and detector resolutions.

In order to provide high statistics for Monte Carlo samples needed to perform the physics analysis related to the mentioned above items a modern GRID technologies will be used to organize the massive Monte Carlo production with the GRID servers installed at ANL.

TASK 1: Studies of the nucleon spin structure (based on GPDs structure functions) via the exclusively produced photons in deep inelastic scattering of electrons and positrons off polarized (unpolarized) hydrogen and unpolarized deuterium targets.

Task 1.1 To complete the analysis and publish separately the results of beam-charge and helicity asymmetry amplitudes from the hydrogen data collected at HERMES during the years 2006 and 2007 with the standard procedure of using the exclusivity window for the missing mass, developed at HERMES [5, 6], without using of additional information from the Recoil Detector (RD).

Task 1.2 To reanalyze the DVCS data off a transversely polarized target. This will allow in addition to the previously published results of imaginary parts of the corresponding asymmetry amplitudes [3], to obtain also the real parts of the same amplitudes. These results will be included in another publication on DVCS subject at HERMES. The analysis includes the extraction of asymmetries, corrections on background mainly from the semi-inclusive processes and the Monte Carlo (MC) simulations, which serves for the calculation of fractional contributions from different processes to the DVCS signal as well as for the estimation of systematic uncertainty of the measurement. The results of the MC simulations, based on the VGG model [41] are supposed to be published in one of the Armenian physics journals.

Task 1.3 To continue the DVCS analysis from the hydrogen data of the years 2006-2007 using the information from RD. This enables to extract the corresponding asymmetry amplitudes in a clean way, without the contribution from the "so-called" associated processes, i.e. when the nucleon is excited to resonances in the final state, as well to obtain the asymmetry amplitudes for the latter process.

TASK 2. Studies of the hadronization in nuclear medium.

Task 2.1 Based on the data saved up at HERMES experiment , to study the multiplicity ratio R_A^h

for all charged hadrons final states separately for neon, krypton and xenon targets, using a detailed binning in one variable and three slices in another one (two-dimensional dependences). It is planned to conduct investigation of the R_A^h for such combinations of the kinematic variables ν, z, Q^2 and p_t^2 for six hadron types: π^+, K^+, p, π^-, K^- and pbar. These results will provide the input needed to further constrain of hadronization models.

Task 2.2 To study the quasi-real photoproduction of charged identified hadrons on different nuclei (D, Ne, Kr, Xe). In such a kinematic regime $(Q^2 \approx 0)$ photon reveals the partonic structure and behaves often like hadron. The "struck" quark in γA interaction can be produced in hard scattering of two partons, from photon and nuclei. In this stage the nuclear effects should be expected in the modification of partonic distributions of the nuclear target. In subsequent stages: the hard process, where a number of outgoing partons are produced; the outgoing partons branching; to build up final-state gluon showers; the fragmentation of the outgoing quarks and gluons, the nuclear effects are also natural, especially in the latter processes.

Task 2.3 To investigate R_A^h in addition to the identified hadrons, also for resonances like K_s, ρ^0-meson, Λ^0 hyperon. Since the detection of the scattered positron is not required for the hadrons used in this analysis and the final data sample is dominated by the $Q^2 \approx 0$ limit where the cross-section and hence statistics are largest, this allowed to have significant less experimental uncertainty than in electroproduction.

Task 2.4 Studies of the charged hadrons production asymmetry in quasi-real photoproduction regime on different targets as a function of x_F and p_t^2 at two values of beam energy : 27.6 and 12 GeV, available at HERMES.

Task 2.5 Based on precise set of the HERMES data related to the attenuation phenomena in electroproduction of identified hadrons on different nuclear targets : ^{4}He, ^{20}Ne, ^{84}Kr and ^{132}Xe to construct the physics generator using well known standard generator like PYTHIA for deuterium target, as well to develop phenomenological models to describe the nuclear physics in semi-inclusive deep inelastic scattering.

Task 2.6 To develop the models describing the nuclear attenuation of high energy multi-hadron systems in the framework of the string model, as well to provide the calculations for the proton electroproduction on nuclei, which has some specific features in sense of the production mechanisms.

TASK 3 Methodic studies with the Time of Light (TOF) system and Monte Carlo studies of possible systematic uncertainties for the OLYMPUS experiment.

Task 3.1 Investigation of TOF counters efficiency using cosmic ray. R&D of Gain Monitoring System (GMS) based on the LED, design of distributors for optical fibers and their connection to TOF counters. Participation in TOF counters mounting in the experimental area, testing and tuning. Equalization of timing information, measurement of TOF counters real time resolution, monitoring of time parameters during data taking, maintenance and system control. The online and offline data analysis using TOF data will be performed.

Task 3.2 Monte Carlo studies based on GEANT4 oriented generator simulating the real conditions of the OLYMPUS experiment in order to estimate possible systematic uncertainties.

Description of deliverables

The results related to the Tasks 1.1 – 1.3 will be reported (released) on HERMES, ANL seminars/meetings. Expected publications: 1 paper till the end of 2011 in journal like JHEP, PL or NP is expected for the Task 1.1, 1-2 papers during the 2011-2012 in mentioned above journals and/or one of Armenian journals are expected for the Task 1.2 , as well as 1-2 papers are expected to be published for the Task 1.3 during 2012 2013.

The results related to the Tasks 2.1 – 2.6 will be reported (released) on HERMES, ANL seminars/meetings. Expected publications: 1 paper during the 2011 in journal like EPJ C is expected for the Task 2.1; 2-3 papers are expected to be published in journals e.g. Nucl. Phys. B, PRC or EPJ C during 2011- 2013 for the Tasks 2.2 - 2.4. Concerning the Task 2.5 the expected result is the written code for mentioned above physics generator, as well 1-2 papers in journals like NIM, EPJ C, PRC during the years 2012-2013. The results related to the Task 2.6 (1-2 papers) are supposed to be published the EPJ C or Phys. Rev. C.

The results of the Tasks 3.1, 3.2 (1-2 papers) reflected the methodic works done for the OLYMPUS experiment are supposed to be published in NIM and/or in Eur.Phys.J.C .

IMPACT: One of the main challenges of today's modern physics is to understand the confinement phenomenon of the strong forces, which govern the interaction between partons (quarks and gluons) and its associated theory, namely Quantum Chromo-Dynamics (QCD). Even more than forty years after the discovery of partons inside the nucleon, the precise way they compose the nucleon and give rise to its properties remains a large mystery. In last decade, a powerful concept of Generalized Parton Distributions (GPDs) [42-50], which allows a more comprehensive multidimensional description of the nucleon structure, has emerged. For instance, nucleon GPDs embody parton distribution functions, the longitudinal momentum distributions of quarks and gluons in the “infinite momentum frame”, as limiting cases and elastic form factors, i.e. one dimensional transverse special distribution of charge and magnetization in the nucleon, appearing as certain moments. GPDs contain also correlations between longitudinal momentum and transverse spatial distributions of quarks and gluons [51], which are currently unknown, thereby allowing for image tomography of the nucleon. Besides imaging of special distributions in momentum slices, strong interest to GPDs is motivated by the fact that they are related, through the Ji’s sum rule [43], to the total angular momentum carried by partons in the nucleon. The latter is of great importance due to the fact that according to most recent HERMES, Jefferson Lab and Compass measurements, in the decomposition of the z-component of the nucleons spin through spins and orbital angular momentum of quarks and total angular momentum of gluons only 30% of the proton spin is accounted by quarks, so called parton spin puzzle [26,27], and that the quark contribution is dominated by the valence component. Current efforts, both in theory and experiment, are therefore directed toward determining the contributions of orbital angular momentum of quarks, as well as of the spin and orbital angular momentum of the gluons.

The measurements on different cross section asymmetries in DVCS process at HERMES, Jefferson Lab and coming experiment at COMPASS as well the measurement of DVCS cross section at H1 and ZEUS will serve for the fitting of these results and extraction of information on certain CFFs [52, 53].

The investigation of the hadronization process at present time is one of the actual problems of hadronic physics. To uncover its nature, hadronic reactions in a nuclear medium, either cold or hot, are studied [54-61]. In this case the hadrons yields are observed to be different from those observed in the corresponding reactions on free nucleons.

The process that leads from the partons produced in the elementary interaction to the hadrons observed experimentally is commonly referred to as hadronization or fragmentation. Semi-inclusive production of hadrons in deep inelastic scattering (DIS) of leptons from nuclei provides a way to investigate quark propagation and hadronization. Moreover, the relatively clean nuclear environment of lepton-induced reactions allows the investigation of the space-time evolution of the hadronization process already in the early stage of hadron production.

The results of investigation of these processes will provide the new information on the mechanism of a production of hadrons in the nuclear environment, and also can be useful to check the assumption of the universal nature of fragmentation functions in the cold and hot nuclear medium [62].

Brief survey of the worldwide researches made on the project topic, the competitiveness of the project, and achievements of the group (not more than 2 pages):

From the experimental point of view, the GPDs can be accessed through hard exclusive processes, where the target stays intact after the scattering. One of the most favorable hard exclusive processes is Deeply Virtual Compton Scattering (DVCS), i.e. hard leptoproduction of a real photon, where the quark absorbs a hard virtual photon, emits a real one and rejoins the target. Beside DVCS, there is another process with the same initial and final state, Bethe-Heitler (BH), where the final photon is radiated by the incoming or outgoing lepton. These processes are experimentally indistinguishable, and due to the same final state they interfere. Although in the kinematic conditions of HERMES experiments the cross section of DVCS process is much smaller than that of BH, the presence of interference allows the access of DVCS amplitude through the measurement of cross section asymmetries with respect to the beam charge/helicity or the target polarization.

Presently, a number of experimental measurements of DVCS are available. The first measurement of beam-helicity asymmetry on a proton target were reported in 2001 by HERMES [1] and CLASS [13] collaborations. Later asymmetries with respect to longitudinal [2,14] and transverse [3] target polarization, as well as beam charge [4] and, with greater precision, beam helicity [5,15-17], were also measured on the proton. HERMES collaboration also has measured the beam-charge, beam-helicity asymmetries from unpolarized deuterium or heavier targets [6, 7], as well as plenty of asymmetries including the tensor ones from the polarized deuterium target [8]. The results on beam-charge asymmetries obtained at HERMES are unique, also the advantage of the HERMES data related to the DVCS is quite wide kinematics, different targets used, as well as many constrains for the future global GPDs fit provided by many different asymmetries available with the HERMES data.

As to the investigations of the hadronization in nuclear medium, the only data available in the most interesting kinematics, which is the range of medium virtual photon energies, are the HERMES collected data. The old studies [55,56] were done at very high energy (ν~200 GeV), where the attenuation phenomenon is not prominent. The recent studies performed at JLab [24,25] are limited with very low values of the virtual photon energy ν~5 GeV, which makes quite limited the information about the hadronization process in scale of the hadron formation time (length). Also concerning the planned studies on hadronization of different identified hadrons in the regime of quasi-real photoproduction in nuclear medium, one can mention, that such data will be unique and will allow to make very interesting comparison with the photoproduction data obtained before.

Also very interesting data will be collected with the OLYMPUS detector in 2012, attempting to make clear one of the most intriguing recently recognized puzzle, which is huge difference in the results for so classic value as the ratio of electric to magnetic formfactors, measured with Rosenblut separation method and measurements of the recoil proton polarization [30-40].

The ANL team being the full member of the HERMES collaboration was actively participating on all stages of the HERMES experiment starting the detectors installations, tuning, data taking and data analysis. The participants of this project have a rich experience in the presenting field, they were the main authors and analyzers of many HERMES published papers, actively presenting the results on various international conferences and meetings during past 10 years.

The head of presented Project Prof. N. Akopov was awarded in 2003 (for GDH Sum RULE) and in 2007 (for g_1 spin structure function) by the First and Second International Scientific Prizes of JINR (Dubna). During the last 5 years 4 PhD (supervisors N. Akopov, R. Avagyan and H. Marukyan) theses directly related to the subjects of presenting project were successfully defended. Also we are expecting two more PhD theses will be defended during the next 2 years.

Below are listed the journal publications and conferences proceedings, done by members of scientific group in the framework of poposed project during the last five years:

A1. L. Grigoryan, Phys.Rev., C83:014904, 2011.

A2. A. Airapetian, N. Akopov, Z. Akopov et al., Nucl. Phys. B842 (2011) 265.

A3. H. Marukyan, Proceedings of the 18th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2010) Florence, Italy.

A4. A. Airapetian, N. Akopov, Z. Akopov et al., JHEP 06 (2010) 019.

A5. N. Akopov, L Grigoryan, Z. Akopov, Eur. Phys. J. C70 (2010) 5.

A6. L. Grigoryan, Phys. Rev. C81 (2010) 045207.

A7. A. Airapetian, N. Akopov, Z. Akopov et al., Nucl. Phys. B829 (2010) 1.

A8. A. Airapetian, N. Akopov, Z. Akopov et al., Phys. Rev. C81 (2010) 035202.

A9. A. Airapetian, N. Akopov, Z. Akopov et al., JHEP 11 (2009) 083.

A10. L. Grigoryan, Phys. Rev. C80 (2009) 055209.

A11. A. Movsisyan, Proceedings of the 17th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2009) Madrid, Spain .

A12. H. Marukyan, Proceedings of the conference Spin 2008, 4 pp. Published in AIP conf. Proc. 1149 (2008) 619.

A13. G. Elbakian, Proceedings of the conference Spin 2008, 4 pp. Published in AIP conf. Proc. 1149 (2008) 690.

A14. N. Akopov, L Grigoryan, Z. Akopov, arXiv: 0810.4841 [hep-ph].

A15. L. Grigoryan, arXiv: 0809.0281 [hep-ph].

A16. L. Grigoryan, Phys. Lett. B666 (2008) 173.

A17. N. Akopov, Z. Akopov, G. Aslanyan and L Grigoryan, arXiv: 0707.3530 [hep-ph].

A18. N. Akopov, L Grigoryan, Z. Akopov, Eur. Phys. J. C52 (2007) 893.

A19. N. Akopov, L Grigoryan, Z. Akopov, Phys. Rev. C76 (2007) 065203.
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A21. A. Airapetian, N. Akopov, Z. Akopov et al., Phys. Rev. D75 (2007) 011103(R).
A22. H. Marukyan, Nucl. Phys. B (Proc. Suppl.) 174, 2007, p. 19.
A23 G. Elbakian, 9th International Workshop on Meson Production, Properties and Interaction (MESON 2006), Cracow, Poland.

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4. A. Airapetian, N. Akopov, Z. Akopov et al., Phys. Rev. D 75 011103 (2007).
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Personnel Commitments (chart, total number of project participants, responsibilities of each).

To provide the effective realization of the proposed programm during the 2011-2013 years it is planned to have the regular visits to DESY to discuss the investigated items with the HERMES/OLYMPUS and DESY experts.

The list of the scientific group members to realize this project is the following:

1. N. Akopov   Prof. Scientific supervisor of the project
2. A. Avetisyan   senior scientist, PhD, main activities is related to the Task 3
3. G.Elbakyan   ----------"--------   Tasks 2,3
4. L. Grigoryan   ----------"--------   Tasks 2
5. H. Marukyan   ----------"---------   Tasks 1,3
6. A. Movsisyan   PhD   (< 35) ,   Tasks 1,3
7. G. Karyan   PhD student   (< 35),   Tasks 2,3
8. A. Petrosyan   PhD student   (< 35),   Task 2

We need mainly the adequate salaries (not less than 150000 dram/month) to provide the effective work at Yerevan, particularly to save our young personell. Untill the 2011 we still have financial support from DESY for the equipment and materials, after 2011 we will need also financial support for this items.

The estimated average age of the Projec partcipants is 49 years.

[x] - *сведения носят информационный характер*

Equipment

Equipment description	Cost (US $)
Total	

Подробное описание заказываемого оборудования, указание сайта фирмы.

Materials

Materials description	Cost (US $)

Other Direct Costs

Direct cost description	Cost (US $)

Travel costs (US $)

CIS travel	International travel	Total

Technical Approach and Methodology

The measurement of an exclusive process requires exact determination of the final state, which in the case of DVCS/BH consists of three particles. Even though by detection of only scattered lepton and emitted photon, it is still possible to achieve exclusivity by means of restriction of the squared missing mass of the reaction ep(d)->eγX to certain kinematic range. Note that using the missing mass technique in the case, when the process is considered on a deuteron target, it becomes impossible to separate contributions to the yield of coherent process when the deuteron stays intact (ed -> edγ), from that of incoherent process when it breaks up (ed -> epnγ). In addition, there is a large contribution from the associated incoherent processes when one of the target nucleons excites to a resonance in the final state, and from a decay of neutral mesons in DIS fragmentation processes.

The event selection is considered in three steps. As a first step the events containing exactly one electron/positron that satisfies all the DIS requirements are selected. These events are referred to as DIS events in the following. In a second step, within the DIS events those with exactly one photon are selected (referred to as single photon events in the following). Finally, in a third step the exclusive DVCS/BH events (exclusive events or sample) are selected by means of missing mass technique. All the steps of event selection require a sufficient Monte Carlo based investigations to ensure the exclusivity of the final selected event sample.

The events that contain at least one reconstructed charged track from the signals in both front and rear tracking chambers, and with certain energy deposition in the calorimeter, are selected. To be sure that the charged track did not hit the frames of the tracking chambers and also the septum plate or the field clamps, the fiducial volume cuts were applied on the x-coordinate of the track at the front field clamp, y-coordinate of the track at the beginning of the septum plate and on the x and y-coordinates of the track at the rear field clamp. In addition the requirements were applied on the impact x and y positions of the track at the surface of the calorimeter. This assures that the tracks are not incident in the outermost two-third of the outer row/column of the calorimeter blocks and the shower produced by them is entirely contained in the lead glass blocks. Further the charged track had to be identified as a lepton. For the identification of the particles, the information based on the likelihood of the combined PID detector responses of the pre-shower, calorimeter and the TRD was used. It was also required that the track possesses the same charge as the charge of the beam in the considered data taking year.

The hard leptoproduction regime of the DVCS/BH processes needs to be ensured. That was achieved with the applying of the requirement on the photon virtuality $Q^2 > 1$ GeV^2 The squared invariant mass W^2 was required to be above 9 GeV^2, which excludes the data from a resonance region. For the case of DVCS process this cut does not affect the exclusive sample, as all the exclusive events satisfy to that requirement. The lower cut on W^2 is essential for the selection of inclusive DIS and semi-inclusive DIS processes. The choice of the cut on W^2 was motivated by a comparison of data collected in different time periods (years) with Monte Carlo simulations. A sufficient agreement between data and Monte Carlo is achieved started from the value of 9 GeV^2. It is important to choose an appropriate kinematic range for the investigation of various background processes, mainly the production of semi-inclusive neutral pions, which is one of the main background processes. For the same data consistency reasons, the energy transfer from the incoming lepton to the virtual photon ν was restricted to the values below 22 GeV.

Like in the case of DIS leptons, also for photons the fiducial volume cuts were applied. In addition, the photons were required to have an energy larger than 5 GeV. This cut is applied in order to improve the exclusivity of the measurement. In the left side of Fig.1 the squared missing mass distributions, that will be defined below, are shown, corresponding to different cuts on photon energy. As can be seen this cut has a very small impact on the events from the exclusive region ($M_X \approx m_P$), while it significantly reduces the yield in a non-exclusive region. The nonexclusive region originates mainly from the photons of a π^0 and η decay with a typically low cluster energies.

As it was mentioned above, various processes contribute in the sample of single photon events. Beside the elastic DVCS/BH events which are referred in the following as a signal of interest, also the associated incoherent processes with resonance excitation and semi-inclusive production of neutral mesons contribute in the single photon event sample. The latter two are referred to as a background processes. In order to maximally assure exclusivity of data sample, e.g. to select an event sample where the signal of interest will significantly dominate the contribution from the background processes, a number of requirements need to be applied on the `exclusive' kinematic variables. One of such a variables is the opening angle between virtual and real photons $\theta_{\gamma\gamma^*}$. It was required to be in a region between 5-45 mrad. Monte Carlo simulations indicate a strong increase of smearing effects at the region below 5 mrad, while an upper cut was chosen from a comparison of fractional contributions of signal and background processes versus opening angle. For the same reasons, an upper cut was applied on the squared four momentum transferred to the target. Direct definition of variable $t=(q-q')^2$ is sensitive to photon energy, which leads to a large uncertainties in the reconstruction of t. Due to the small magnitude of t compared with Q^2 and the photon energy E_γ, the resolution of E_γ, which is about few percents, leads to a large resolution in t. This can be eliminated considering the constrained variable t_c instead of t. Within the assumption that the process is elastic ($M_x = m_p$) the constraint four-momentum transfer t_c can be calculated without using the photon energy

$$t_c = \frac{-Q^2 - 2\nu(\nu - \sqrt{\nu^2 + Q^2}\cos\theta_{\gamma\gamma^*})}{1 + \frac{1}{m_P}(\nu - \sqrt{\nu^2 + Q^2}\cos\theta_{\gamma\gamma^*})}.$$

Such a definition improves the resolution of t by one order of magnitude. Nevertheless, the dependence on photon energy remains in the definition of missing mass

$$M_X^2 = (q + p - q')^2 = m_P^2 + 2m_P(\nu - E_\gamma) + t,$$

therefore, the distributions of missing mass can reach a negative values. The final choice of the exclusive event sample is achieved by means of restriction the missing mass window in the region -2.25 GeV^2<M_X^2<2.89 GeV^2, where the fractional contributions of the signal of interest is larger than that from a background process. The fractional contributions obtained from Monte Carlo simulations of signal and background processes are shown on the right plot of Fig. 1 versus the squared missing mass.

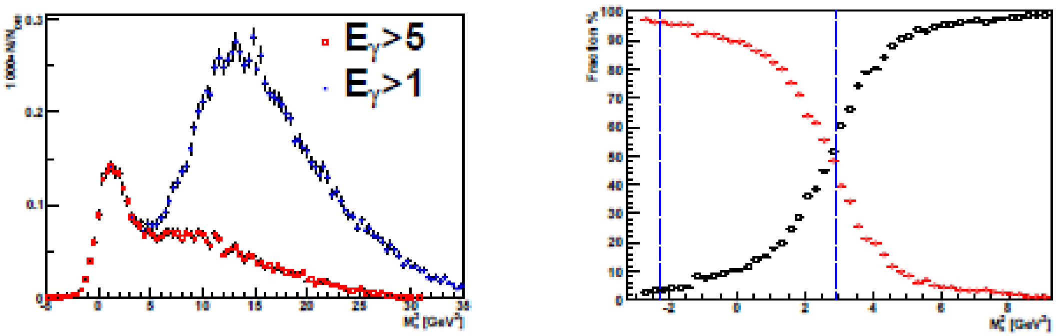


Figure1: Distributions of M_X^2 for different cuts on photon energy (left) and the fractional

contributions of the signal and background processes versus M_X^2.

The obtained exclusive event sample is further used for the extractions of azimuthal asymmetry amplitudes. These asymmetries originate in the azimuthal distributions of real photons. Using data collected with both beam helicities, both beam charges and both target polarization states (data with longitudinally or transversely polarized targets) one can define asymmetries with respect to beam charge, beam helicity or target spin, together with different combinations of charge, beam and target polarizations. As an example, in the case of the unpolarized target three asymmetries can be defined

$$A_C(\varphi) = \frac{\left[\vec{\sigma}^+(\varphi) + \overleftarrow{\sigma}^+(\varphi)\right] - \left[\vec{\sigma}^-(\varphi) + \overleftarrow{\sigma}^-(\varphi)\right]}{\vec{\sigma}^+(\varphi) + \overleftarrow{\sigma}^+(\varphi) + \vec{\sigma}^-(\varphi) + \overleftarrow{\sigma}^-(\varphi)},$$

$$A_{LU}^{DVCS}(\varphi) = \frac{\left[\vec{\sigma}^+(\varphi) + \vec{\sigma}^-(\varphi)\right] - \left[\overleftarrow{\sigma}^+(\varphi) + \overleftarrow{\sigma}^-(\varphi)\right]}{\vec{\sigma}^+(\varphi) + \overleftarrow{\sigma}^+(\varphi) + \vec{\sigma}^-(\varphi) + \overleftarrow{\sigma}^-(\varphi)},$$

$$A_{LU}^{I}(\varphi) = \frac{\left[\vec{\sigma}^+(\varphi) + \overleftarrow{\sigma}^-(\varphi)\right] - \left[\overleftarrow{\sigma}^+(\varphi) + \vec{\sigma}^-(\varphi)\right]}{\vec{\sigma}^+(\varphi) + \overleftarrow{\sigma}^+(\varphi) + \vec{\sigma}^-(\varphi) + \overleftarrow{\sigma}^-(\varphi)}.$$

Here, the + (-) sign denotes the lepton beam charge and left (right) arrows - the beam helicity. Such a definition of asymmetries is possible only in the case when data collected with both beam charges are available, which enable to separate these two beam-helicity asymmetries, i.e., contributions of interference term of the BH/DVCS cross section from that of squared DVCS term in the numerator of given asymmetries.

Similarly, it is possible to consider combined double asymmetries with respect to beam charge and target polarization (longitudinal or transverse) together with double spin asymmetries. A typical distribution of the asymmetry A_{LU}^{I} in bins of azimuthal angle φ is shown in Fig. 2 .

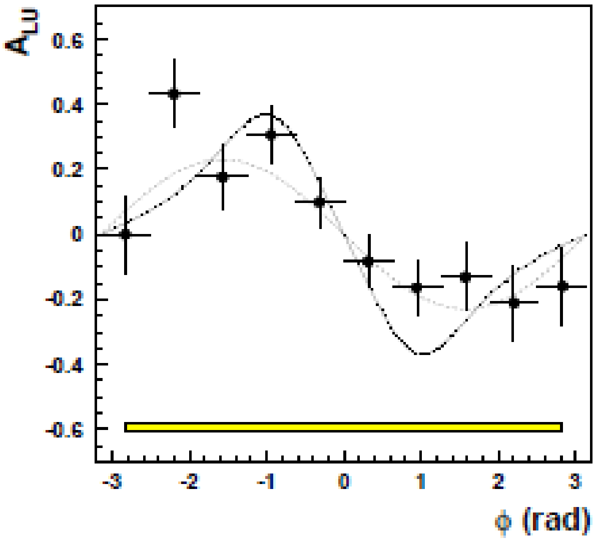


Fig 2: An example of the azimuthal distribution of the asymmetry.

From the azimuthal distributions trigonometric moments or the asymmetry amplitudes can be extracted by a fit method. Presently the maximum likelihood fit method is used for the extraction of asymmetry amplitudes. As an example, the expected value of the measured yield of events for scattering a polarized lepton beam from an unpolarized target can be parameterized according to

$$\langle N \rangle (P_l, e_l, \varphi) = L(P_l, e_l)\varepsilon(e_l, \varphi)\sigma_{UU}(\varphi)\left[\mathbf{1} + e_l A_C(\varphi) + P_l A_{LU}^{DVCS}(\varphi) + P_l, e_l A_{LU}^{I}(\varphi)\right]$$

Here, L denotes the integrated luminosity, ε is the detection efficiency, P_l and e_l are the beam polarization and elementary charge. The σ_{UU} is the cross section for “unpolarized” target averaged over both beam charges and both beam helicities. The given parameterization of the yield can be used as a probability distribution function (p.d.f.) for the maximum likelihood fit method. The asymmetries given in the above equation are expanded into harmonic functions in azimuthal angle φ

$$A_C(\varphi) = \sum_{i=\mathbf{0}}^{\mathbf{3}} A_C^{\cos(n\varphi)} \cos(n\varphi)\,,$$

$$A_{LU}^{DVCS}(\varphi) = A_{LU,DVCS}^{\cos(\mathbf{0}\varphi)} + A_{LU,DVCS}^{\sin(\varphi)} \sin(\varphi)\,,$$

$$A_{LU}^{I}(\varphi) = \sum_{i=\mathbf{1}}^{\mathbf{2}} A_{LU,I}^{\sin(n\varphi)} \sin(n\varphi) + A_{LU,I}^{\cos(\mathbf{0}\varphi)}\,.$$

The amplitudes from the expansion are extracted from the fit. Hence, the maximum likelihood method allows the simultaneous extraction of the asymmetry amplitudes for all three asymmetries. The normalization of maximum likelihood function, which is needed in case of extended maximum likelihood fit method is used, provides a possibility to account for the possible luminosity averaged imbalances in the beam polarization for different states.

The process of quark fragmentation and hadronization can be studied by measuring hadron production in semi-inclusive deep-inelastic scattering (SIDIS) on nuclei of various sizes. As typical hadronization lengths are of order of the nucleus' size, the nuclei act as scale probes of the underlying hadronization mechanism, cross sections are expected to be sensitive to whether the hadronization occurs within or outside the nucleus. A clean way to study SIDIS is to use leptonic probes, when the initial state interactions can be neglected and, the energy and momentum transferred to the struck parton are well determined by the measured kinematic properties of the scattered lepton in the final state.

The studies of the hadronization phenomena in nuclear medium are usually performed based on the extracted multiplicities ratio:

$$R_A^h(\nu, z, Q^2, p_t^2) = \left(\frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)}\right)_A \Bigg/ \left(\frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)}\right)_D$$

It is the ratio of the number of hadrons N^h produced normalized to deep-inelastic scattering events N^e on a given nucleus A compared to the same ratio on the deuteron D. The dependence of this ratio on four kinematic variables was studied, while integrating over the azimuthal angle φ: the photon energy ν and its virtuality Q^2, the fraction z of the virtual-photon energy carried by the hadron, and the square of the hadron momentum component p_t^2 transverse to the direction of the virtual photon, all of which have been measured in the target rest system.

Experiments at large values of ν [53, 54] give values $R_A^h \approx 1.0$ within the experimental uncertainty. This is interpreted as in indication that nuclear effects are negligible in that region. At lower values of ν the value of R_A^h has been found to be well bellow unity [19-21]. The last results of HERMES collaboration [19] obtained on different nuclear targets (helium, neon, krypton and xenon) show the prominent features of the data. The attenuation increases (decrease of R_A^h below unity) with increasing value of the atomic mass number A of the nucleus and becomes smaller (larger) with increasing values of ν (z). At low values of z, especially for heavier targets and for protons and K^+ mesons, a strong rise of R_A^h, even to above of unity, is observed. In total a very extensive data set to guide modelling hadronization in nuclear matter has been collected. Note that from the theoretical side there is significant interest in hadron-multiplicity ratios, as exemplified by the diversity of model calculations [60÷65].

To date, the available experimental data with leptonic probes [19-21,53-54] are presented in most cases as a function of one variable, integrating over the other variables within the experimental acceptance (one-dimensional dependences), due to limited statistics. Only in one case was a two-dimensional dependence extracted, for a combined sample of charged pions [19]. In the proposed analysis the data of Ref. [19] will be used to study R_A^h for charged pions, kaons, protons and antiprotons for neon (Ne), krypton (Kr), and xenon (Xe) targets, using a two-dimensional representation consisting of a fine binning in one variable and three slices in another one. This will allow to study the dependences in more detail, while keeping the statistical uncertainties at moderate levels, at least for pions, positive kaons and protons.

The wealth of theoretical model calculations and studies [68,69] reflect the strong interest of the community in hadron-multiplicities. It is expected that the results with 2D slices will provide the input needed to further constrain hadronization models.

The measurements were performed with the HERMES spectrometer [27] using 27.6 GeV positron and electron beams stored in HERA at DESY. Data were collected during 1999, 2000, 2004 and 2005 with gaseous targets of D, Ne, Kr, and Xe. The identification of charged hadrons was accomplished using information from the dual-radiator ring-imaging Cerenkov detector (RICH) [56], which provided separation of pions, kaons and (anti)protons in the momentum range between 2 and 15 GeV. In contrast to the analysis described in Ref. [19], a different hadron identification algorithm will be used, which is based on a collective assignment of a set of identities to all particles detected in the event, accounting for the correlations among their probabilities .

The kinematic constraints supposed to be imposed on the scattered leptons are: $4.0 < \nu < 23.5$ GeV, $Q^2 > 1$ GeV^2, $W^2 > 4$GeV^2 and $y = \nu / E < 0.85$, where E is the beam energy. The constraints on W^2 and y will be applied in order to exclude events originating from nucleon resonances and to limit the magnitude of radiative corrections, respectively. The kinematic constraints will be imposed on the selected hadrons: $2 < p_h <15$GeV, $z > 0.2$ and $x_F > 0$, where p_h is the hadron momentum, $z = E_h/\nu$ with the hadron's energy E_h, and the Feynman variable x_F is defined as the ratio of the momentum transferred to the hadron in the direction of the incident photon in the photon-nucleon centre-of-mass system to its maximum possible value. Together, the two latter constraints reduce possible contributions from target fragmentation. The constraints on W and y are applied in order to exclude nucleon resonances and to limit the magnitude of the radiative corrections to R_A^h, respectively.

From the data the ratio of hadron multiplicities R_A^h is determined for each hadron type and target. The data for the multiplicity ratios have to be corrected for radiative processes in the manner described in [66]. The code of Ref. [67] was modified to include the measured SIDIS cross sections. The radiative corrections (RC) are applied to both the inclusive N^e and the semi-inclusive N^h parts (see definition for R_A^h). For the inclusive cross sections elastic, quasi-elastic, and inelastic processes need to be taken into account, whereas for the semi-inclusive ones only inelastic radiative processes contribute. The correction for the ratio of the latter was taken to be independent of z. Since the inelastic radiative effects are almost the same for the nuclei A and D, the size of the radiative corrections applied to R_A^h was small over most of the kinematic range. Only in kinematic regions of DIS where the elastic and quasi-elastic tails are non-negligible, i.e., at the highest value of ν and lowest value of Q^2 (low x_{Bj}), there is a noticeable effect on R_A^h, with a maximum (increase) of R_A^h of about 7% for xenon and krypton, 4.5% for neon, and 1% for helium.

For two-dimensional representation the radiative corrections will be applied following the scheme described above, using average values of ν and Q^2 for each kinematic bin in the analysis. Two types of systematic uncertainties have to be distinguished: *scale uncertainties*, which are constant over all kinematic bins for each hadron type, and *bin-to-bin uncertainties*, which differ for each bin. The identification efficiencies and contaminations for pions, kaons, protons and antiprotons have been determined in a Monte Carlo simulation as a function of the hadron momentum and multiplicity in the relevant detector half. These performance parameters were verified in a limited kinematical domain using known particle species from identified resonance decays. They are used in a matrix method to unfold the true hadron distributions from the measured ones. Systematic uncertainties in the unfolding are estimated by using matrices determined in different ways.

The studies of hadronization in nuclear medim in quasi-real photoproduction regime is supposed to be performed via two available variables, first one is the transverse hadron momentum in respect to the lepton beam direction p_t^b, and second one is the x_F^b variable, which in this case is also defined in respect to the lepton beam direction. Such analysis will provide the unique opportunity to compare three different scales over the Q^2 to test the hadronization mechanism in nuclear medium:

1. almost real photon case: $Q^2 \approx 0$
2. low Q^2 region: $0.3 < Q^2 < 1.\ GeV$
3. high Q^2 (DIS) region: $Q^2 > 1.\ GeV$

Also the atomic mass dependence based on HERMES data collected in this regime on hydrogen, deuterium and four different nuclea: Helium4, Neon, Krypton and Xenon, will be extracted as a function of p_t^b , x_F^b and Q^2. As to the available similar data, there are measurements performed with hydrogen target [57] and also data with the real photon beam done at low energy about 1 GeV (see [70] and references there) on different nuclear targets, also some data is available at high energies [71]. The results will be extracted based on HERMES data related to the charged hadrons production asymmetries are quite interesting and will provide essential information on hadronization mechanism on free nucleon, as well in nuclear medium. Also they will be very useful to perform the tuning of different Monte Carlo generators.

Nuclear attenuation of the multi-hadron systems will be considered in the string model. The improved two-scale model with set of parameters obtained recently for the single hadron attenuation will be used for comparison of the features of the one-, two- and three-hadron systems. The predictions of the model for nuclear attenuation of multi-hadron systems will be presented also. In this work we will continue the study of the electroproduction of multi-hadron states in cold nuclear matter. This is the main goal of the present invsetigation to consider the mutual screening of the prehadrons and hadrons in string (jet). We will compare one-, two- and three-hadron systems because we think that mutual screening of prehadrons and hadrons plays essential role and can be measured experimentally. For instance such data can be obtained by HERMES Experiment, SKAT Experiment, and JLab after upgrade to the energy 12 GeV. We suppose that investigation of the mutual screening of prehadrons and hadrons in cold nuclear matter can help to establish initial conditions for the study of similar processes in hot nuclear matter appearing in high energy hadron-nucleus and nucleus-nucleus interactions at RHIC and LHC.

The electroproduction of protons on the nuclei has some features in comparison with the production of other particles. This is due to the fact that in nuclei there are ready protons, which in the process are not produced, but just knocked out from the nucleus. If the diquark is compact enough object, it can be knocked out by the virtual photon as a whole. As a result, on a fast end of the string will be produced a proton. String-flip mechanism [72] also plays essential role in case of production of protons. As a result we have in the case of electroproduction of the protons four instead of one mechanism in the case of mesons. This is the reason that the production of protons is still relatively little studied. In framework of this project we will study the relative contribution of these mechanisms in different kinematic regions and compare it with available experimental data.

During more than 50 years the separation of the proton's electric and magnetic form factors $G_E^p(Q^2)$ and $G_M^p(Q^2)$ has been of particular interest. Until 1990's the experimental method to separate $G_E^p(Q^2)$ and $G_M^p(Q^2)$ was based on the procedure by Rosenbluth [73] measuring the unpolarized elastic cross section at fixed four-momentum transfer Q^2, but with different electron scattering angles and incident beam energies. It was found that the dipole form factor $(1+ Q^2/0.71)^{-2}$ is a good approximation for Q^2 dependences of $G_E^p(Q^2)$ and $G_M^p(Q^2)$. The Rosenbluth separation becomes rather difficult at high momentum transfer as the weight of G_E in the cross section becomes less at higher Q^2, due to the nature of the Rosenbluth formula

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = \frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2} = \frac{\varepsilon G_M^2(Q^2)+\tau G_M^2(Q^2)}{\varepsilon(1+\tau)}$$

with

$$\tau = \frac{Q^2}{4M_P^2},\ \frac{1}{\varepsilon} = 1+2(1+\tau)\tan^2\frac{\theta}{2},\ \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2}\frac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}\frac{E'}{E}$$

where θ is defined as laboratory scattering angle of the lepton and ε can be identified with the transverse virtual photon polarization. The world data for elastic *e-p* scattering has been recently compiled by [74], also the most recent Rosenbluth-type measurements have again confirmed the scaling behavior like $\mu G_E/G_M \approx 1$ of the proton form factor ratio [31,32].

In the late 1990's, development of polarized beams, targets and polarimeters allowed to measure the form factor ratio more directly through the interference of G_E and G_M in the spin-dependent elastic cross section asymmetry [35-38]. It came as a **big surprise** when the high precision polarization transfer measurements at JLab at higher momentum transfer (up to 5.5 GeV^2) gave striking evidence that the proton form factor ratio $\mu G_E/G_M$ was monotonically falling with Q^2 [33]. The generally accepted explanation for the discrepancy between the recoil polarization and Rosenbluth determinations of the elastic proton form factor ratio is the exchange of multiple (>1) photons during the electron-proton elastic scattering process [75,76]. The effect of multiple-photon exchange on the electromagnetic elastic form factors involves the real part of the multiple-photon exchange amplitude. The observable most sensitive to this amplitude is the ratio of the elastic cross section for electron-proton to positron-proton scattering. In the presence of multiple-photon exchange, the cross section for unpolarized lepton-proton scattering contains an interference term between the one- and two-photon amplitudes, where this interference is odd under time reversal, and hence has the opposite sign for elastic positron-proton and electron-proton scattering. Figure 1 shows the ratio of the two cross sections as a function of the virtual photon polarization ε. This ratio would be unity in case of pure single photon exchange, i.e. the Born approximation. The sensitivity is enhanced at low ε, exceeding 4% for $\varepsilon \leq 0.4$, provided $Q^2 \geq 2$ GeV^2.

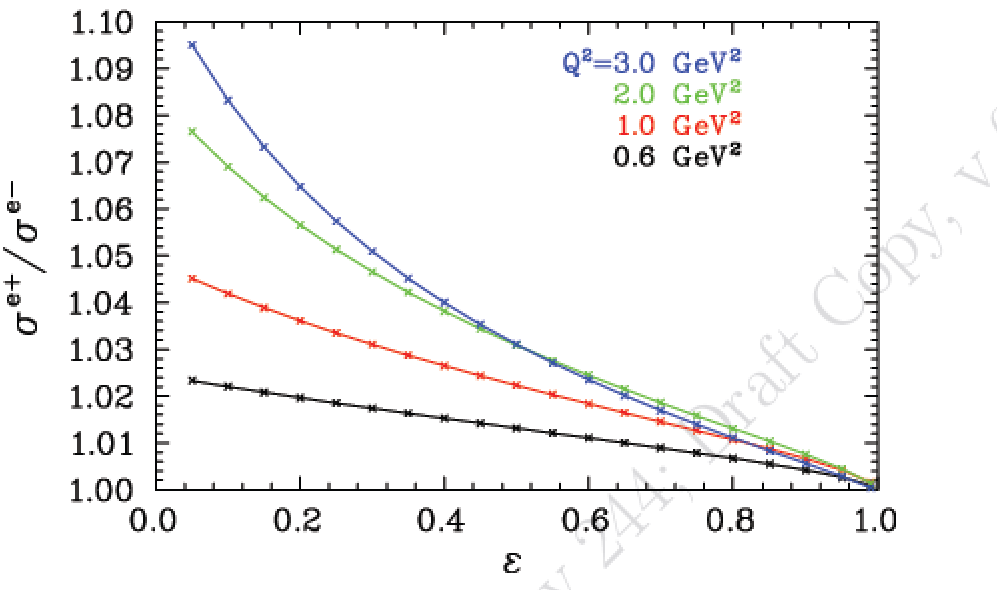


Figure 1. *Ratio of elastic positron-proton to electron-proton cross section versus virtual photon polarization ε for given Q^2[76]*

The use of the intense, multi-GeV stored electron and positron beams at the storage ring DORIS at DESY, Hamburg, Germany in combination with the BLAST detector can produce the most definitive data to determine the effect of multiple-photon exchange in elastic lepton-proton scattering and verify the recent theoretical predictions. The OLYMPUS experiment will measure the ratio of electron-proton to positron-proton elastic cross sections over a range of ε with the BLAST detector using an internal unpolarized hydrogen target and intense stored beams of unpolarized positrons and electrons at an energy of 2.0 GeV at the site of the ARGUS experiment on the storage ring DORIS at DESY in Hamburg. Figure 2 shows the expected number of counts in any given angle bin and for various beam energies for a canonical run of 500 h at a luminosity of $2*10^{33}/(cm^2s)$ as a function of Q^2. Hohler form factor [77] based cross sections were used for this estimate, good to within 10% for both e^+ and e^- up to $Q^2 \approx 3$ GeV^2.

The primary observable of the OLYMPUS experiment is the ratio of the electron-proton to positron-proton elastic cross sections. The redundant control measurements of the luminosity will allow the $e^+p/\,e^-p$ cross section ratio to be determined with high precision. The differential number of counts dN between times t and $t + dt$ and in the detector volume element $d^n x$, using generalized detector coordinates x_k, is a function of efficiencies for proton and lepton detection, luminosity, differential cross section and acceptance and is given by

$$dN = k^p(t)k^l(t)\dot{L}(t)dt\,\frac{d\sigma}{d\Omega}(\theta_e)a(x_k)d^n x,$$

where k^p and k^l denote the proton and lepton detection efficiencies, which could generally vary with time, and $L(t)$ is the instantaneous luminosity. The elastic differential cross section is denoted by $d\sigma/d\Omega$ and is only function of one variable, e.g. the lepton scattering angle. The acceptance function $a(x_k)$ depends on all detector-related coordinates x_k, which can be lepton and proton angles and momneta, or reconstructed vertices, etc., i.e. all degree of freedom of a coincident lepton-proton event. For any given event, $a(x_k)$ describes whether or not it would be accepted by the detector, i.e. the acceptance function's value is either 0 or 1. It is the task of a Monte Carlo simulation to determine the bin-averaged acceptance or phasespace integral. For a given bin, the number of events is hence given by

$$N_{ij} = L_{ij}\sigma_i k_{ij}^p k_{ij}^l A_{ij}$$

where $i= e^+$ (e^-) for positrons (electrons) and $j= +$ $(-)$ for positive (negative) OLYMPUS magnetic field polarity, L is the integrated luminosity, and the integrated acceptance or phasespace integral is given by A. With a given polarity of the OLYMPUS magnetic filed, the efficiency for detecting the recoil protons in the same kinematics will be identical for both electron and positron scattering, namely: $k_{e^+ +}^p = k_{e^- +}^p$ and $k_{e^+ -}^p = k_{e^- -}^p$. Hence, for a given field polarity j, the proton efficiencies k_{ij}^p cancel in the ratio

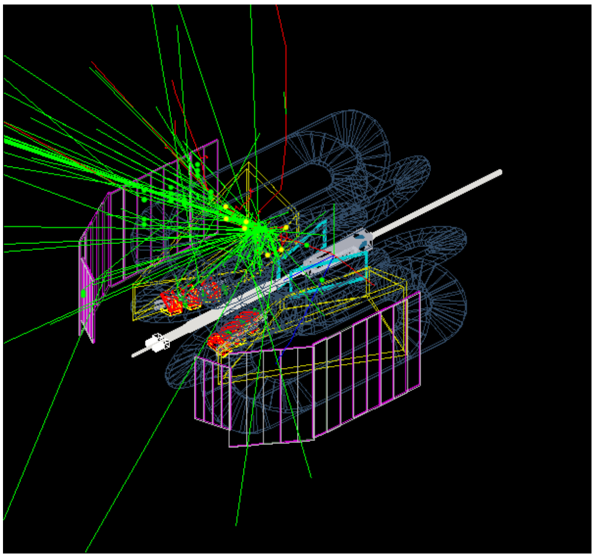
$$\frac{N_{e^+j} / L_{e^+j}}{N_{e^-j} / L_{e^-j}} = \frac{\sigma_{e^+}}{\sigma_{e^-}} \frac{k_{e^+j}^l}{k_{e^-j}^l} \frac{A_{e^+j}}{A_{e^-j}}$$

However, the efficiencies for detecting the scattering electron or positron may differ for a given OLYMPUS polarity but will be the same for opposite polarities, namely: $k_{e^+ +}^l = k_{e^- -}^l$ and $k_{e^+ -}^l = k_{e^- +}^l$. By taking the product of the above ratio for opposite magnetic filed polarities yields

$$\frac{\sigma_{e^+}}{\sigma_{e^-}} = \left[\frac{N_{e^+ +}N_{e^+ -}}{N_{e^- +}N_{e^- -}} \Bigg/ \left(\frac{L_{e^+ +}L_{e^+ -}}{L_{e^- +}L_{e^- -}} \cdot \frac{A_{e^+ +}A_{e^+ -}}{A_{e^- +}A_{e^- -}} \right) \right]^{\frac{1}{2}}$$

which measures the cross section ratio directly, where all lepton and proton efficiencies cancel out if they do not change during the length of the cycle of four combined states and if the reversal of the magnet polarity exactly reproduces the field amplitude. This equation contains the super ratio of four phases-space integrals A_{ij}, which has to be determined with dedicated Monte Carlo simulations. The quality and precision of such Monte Carlo simulations should be quite high to provide the estimation of possible systematic uncertainties expected to be on the order of 1% with enough precision.

The OLYMPUS Monte Carlo is based on GEANT4 simulation package. It provides lepton (electron, positron)-proton elastic scattering in OLYMPUS spectrometer designed by GEANT4 toolkit including detector subsets and constructing materials. The MC program integrated with ROOT libraries which allow to accumulate simulated data in `.root` file for later analysis. The single interaction act looks like



Necessary detailed MC studies to provide the estimation of possible systematic uncertainties, to estimate the angular and momentum resolutions for the OLYMPUS experiment will be performed in framework of this project.

Дополнения и разъяснения, если они не были указаны ранее и в них есть необходимость. *(желательно не более 1.0-1.5 страницы)*