Proposal to PAC 37

Meson Spectroscopy with low Q^2 electronscattering in CLAS12

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Abstract

Understanding quark and gluon confinement in Quantum Chromo Dynamics is one of the main issues in hadronic physics. Spectroscopy of mesons and baryons with electromagnetic probes is a powerful tool to investigate how the QCD partons manifest themselves in strong interaction at the energy scale of the nucleon mass (GeV). We are proposing to extend the Hall-B CLAS12 capability to run experiments with quasi-real photons to study conventional and unconventional (hybrids and exotics) hadrons. The proposed technique, electroscattering at very low Q^2, providing a high photon flux and a high degree of linear polarization represents a competitive and complementary way to study the hadron spectrum and the production mechanisms with respect to standard real photo-production experiments with bremsstrahlung beams. A forward tagger made by a calorimeter and a tracking device will be added to the standard equipment to detect the scattered electrons in the angular range $\theta_{e'} = 2^\circ - 5^\circ$ and energy range $E_{e'} = 0.5 - 4$ GeV, with an effective quasi-real photon flux of $10^7 - 10^8\ \gamma/s$. The operations of the new device will be compatible with standard electron scattering experiments planned for Hall-B, allowing the proposed measurements to be run in parallel to the already approved program. The unique combination of CLAS12 and the new forward tagger facility will give access to an extensive physics program, which belongs to the main physics focus of the Jefferson Lab upgrade.

Contents

1 Introduction

Spectroscopy of hadrons (mesons and baryons) is one of the key tools for studying the theory of strong interactions, Quantum Chromodynamics (QCD), in the non-perturbative regime (*i.e.*, confinement). Hadron spectroscopy has been an essential component of the physics program with CLAS [1, 2, 3, 4, 5, 6]. To date, a large amount of experimental data on electromagnetic production of mesons and baryons has been collected by CLAS. However, more data will be necessary to guide improvements in hadronic phenomenology and to compare with lattice QCD calculations. The major part of the data obtained so far with CLAS are restricted to the lowest mass states formed with the lightest quarks: up, down and strange. A complete picture of QCD in the strong-coupling (non-perturbative) regime requires an extension of hadron spectroscopy studies to higher masses and/or higher transferred momenta.

The planned energy upgrade of Jefferson Lab to 12 GeV, together with the upgraded detector package in Hall-B (CLAS12) makes this facility the obvious choice for studies of multi-particle final states. Electron scattering at finite Q^2 is very powerful for detailed studies of hadronic structures but, due to the lower cross sections compared to the real photon experiments (Q^2=0), is not the ideal tool for exploratory searches. For this reason, many fundamental topics in hadron spectroscopy are not yet included in the 12 GeV Hall-B physics program. Experiments with tagged real photons would be the natural extension of the proposed physics program as already proved by 15 years of real photon runs with CLAS at 6 GeV.

We are proposing to add to the standard electron scattering operations of CLAS12 the capability of running (quasi−)real photon scattering experiments in parallel.

Some of the measurements that will be possible with the CLAS12 detector and the new (*quasi*−)real photon tagging facility are reported below.
They include:

- Photoproduction of high-mass mesonic states (consisting of ordinary mesons, hybrids, and mesons with exotic J^{PC}) using H_2 and light nuclear targets;
- Photoproduction of charm near threshold on hydrogen and light nuclei;
- Higher mass baryon production, *e.g.*, Ξ and Ω baryons.

The proposed technique for obtaining tagged, linearly polarized, real photons is different from the coherent bremsstrahlung presently used in Hall-B and planned for the GlueX [7] experiment in Hall-D. We are planning to use virtual photons produced when electrons are scattered at very forward angles (*i.e.*, scattering angles between $2^\circ - 5^\circ$). In this kinematics the four-momentum transfer, Q^2, associated to the virtual photon is less than 10^{-1} GeV^2 and consequently the virtual photon can be considered as quasi-real. The equivalent photon flux ($10^7 - 10^8$ γ/s), for a nominal luminosity of 10^{35} cm^{-2} s^{-1}, and the degree of linear polarization ($\sim 40\%$) obtained with this technique is comparable to what is obtained by using the coherent bremsstrahlung.

The low energy scattered electron (0.5 GeV - 4.0 GeV) will be detected in a forward tagger (a calorimeter plus a position-sensitive device), in coincidence with the detection of multi-particle final states with the CLAS12 detector.
Electroproduction at these small values of Q^2 using unpolarized electrons is equivalent to photoproduction using partially linearly polarized photons [8].

The forward tagger will be designed as a part of the CLAS12 standard equipment and in particular, the tagger operations will be possible in parallel to the detection of the electron at larger angles as required in the standard CLAS12 runs. In that respect, the new proposed facility can be viewed as an extension of the CLAS12 Electromagnetic Calorimeter (EC) allowing not only the measurement of electrons scattered at small angles but also providing an excellent coverage for π^0 and γ emitted in the forward direction (e.g. as required in the leading DVCS experiment at 11 GeV).

The physics program using the very small angle electron scattering facility will take advantage of polarized photons with relatively high photon fluxes. Since electrons are tagged after their interaction in the target, no limitations associated to the operation of a standard real photon tagger will be present. The the use of high beam currents to achieve required luminosities on very thin targets (*i.e.*, gas targets) will be possible without jeopardizing signal to accidental ratio. In turn, this will allow detection of low energy recoils (*e.g.*, coherent scattering experiments) and spectators (*e.g.*, scattering off of the neutron in the deuteron).

Knowledge of the photon linear polarization, high fluxes, together with the use of the nearly 4π coverage for hadronic final states in CLAS12, will allow the study of hadron spectroscopy in a competitive and complementary experimental environment to the planned coherent bremsstrahlung photoproduction experiment in Hall-D. Furthermore, the two experimental halls, hosting very different spectrometers (a toroidal-based versus a solenoidal-based detector) with different particle identification capability, angular coverage and resolution, will provide the way to perform independent checks of any possible findings. In the field of hadron spectroscopy, this unique capability will give additional strength to the whole Laboratory.

In the following sections, we present some key experiments that will be feasible using the CLAS12 detector together with the proposed forward tagger and we will discuss the main features of the new facility.

2 Physics motivation

One of the most fundamental interest to hadron physicists is the understanding of the mechanism of confinement. It has been more than thirty years since QCD was postulated as the theory of strong interactions. While much progress has been made in understanding perturbative phenomena, the non-perturbative regime, the regime of hadrons, their excitations, and their couplings, has remained quite obscure. Only recently, with improvements to calculations of lattice QCD, predictions of the spectrum of hadrons [9, 10] directly from theory using only few parameters (such as the bare quark masses) have become possible. New experimental efforts to determine the hadron spectra are timely and are important for theoretical progress in non-perturbative QCD.

While mesons and baryons may be viewed differently, their phenomenology reflects common aspects of strong interaction dynamics. Searching for mesons with exotic quantum numbers gives us an opportunity to capture gluons as constituent particles that have their own identity along with quarks in forming hadronic bound states. On the other hand, considering interactions between three quarks in a baryon, one finds that the presence of meson-type quark correlations may be crucial in describing baryon properties, reflecting fundamental features of the QCD vacuum. In addition, multi-quark configurations in baryons are possible.

Many experiments have already addressed some of the issues discussed here, however, the experimental coverage is still incomplete. In particular, many individual experiments have been carried out with the aim of addressing single aspects of hadron phenomenology, but the picture of hadrons that has emerged so far is incomplete in some areas and inconsistent in others. The goal of further experiments in this field is to continue our efforts to arrive at a clear, complete and consistent description of hadrons and of their properties. A comprehensive experimental program aimed at describing the hadron properties (mass, width, decay branches, *etc.*) is not trivial. In order to understand the dynamics of QCD in the confinement region, a systematic study of many states and many decay modes is needed.

It has been widely accepted that lattice simulations provide the only *ab initio* calculations of QCD. Early lattice efforts have been aimed mainly at high energy physics. In particular, calculations sought primarily to control hadronic *uncertainties* in the extraction of fundamental quantities (such as the CKM matrix elements) from experimental data. More recently, some lattice efforts have been focused towards *understanding* QCD rather than eliminating it. In other words, some portion of the lattice effort is now aimed at understanding the mechanism of confinement. In order for this lattice effort to make significant progress in addressing confinement, lattice calculations for the masses and couplings of baryons and mesons must be compared with information extracted from precision experiments. Some of the precision experiments needed have been, and are being, carried out at Jefferson Lab, and at other facilities around the world.

The investigations proposed in this Letter of Intent are part of this wide experimental program.

2.1 Meson spectroscopy

A complete mapping of meson resonances in the mass region of 1 to 3 GeV will be particularly important for a better understanding of the QCD confinement mechanism. QCD predicts the existence of several new types of states beyond the naive quark model: glueballs, hybrids, multi-quark $q\overline{q}q\overline{q}$ states [11, 12]. Gluons play a central role in strongly interacting matter – quark confinement is due to gluonic forces. The clearest and most fundamental experimental signature for the presence of dynamics of gluon degrees of freedom is the spectrum of gluonic excitations of hadrons. In a particular model, self interacting gluons form a string-like flux tube between the interacting pair: while normal mesons have quantum numbers compatible with a flux tube in the ground state, in hybrid mesons, gluon degrees of freedom of the excited flux tube add explicitly to the quark quantum numbers resulting in exotic combination of total angular momentum, parity, and C-parity. The identification of states with particular J^{PC} combinations, as 0^{--},0^{+-}, 1^{-+},2^{+-} ..., is an unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states. Determining the properties of such states would shed light on the underlying dynamics of quark confinement. The flux tube excitation will be induced by using a photon beam. Photoproduction of exotics has many advantages compared to traditional hadro-production (pion or kaon beams): there are some theoretical arguments predicting that exotics are more likely produced by the interaction with a photon, a spin 1 probe, and that the expected production rate should be comparable to that of regular mesons.

The identification of these states has been difficult, as high mass resonances are generally broad and overlapping, and often have similar quantum numbers (mixing). Ideally, for a complete mapping of the mesons in this mass region, we will need to study each resonance through as many decay channels and production mechanisms as possible in order to disentangle mixing. To determine meson quantum numbers, we use partial wave analysis (PWA) (in a broad sense, fits to the angular distributions of final states). A complete PWA requires high event statistics, as well as high resolution and geometrical acceptance of the detector. Meson spectroscopy at CLAS12, using the forward tagger, will fulfill many of these stipulations.

2.2 Partial Wave Analysis

The general idea of PWA is to parametrize the intensity distribution in the space of quantum numbers available to the observed final states. The intensity distribution is written as a sum of interfering and non-interfering amplitudes (partial waves), for example in the reflectivity basis [13]: $I(\tau) = \sum_{\epsilon,k} |\sum_b^{\epsilon} V_{bk}^{\epsilon} A_b(\tau)|^2$. The variable k is the rank of the fit, related to the set of partial waves from the production vertex, τ describes the set of angular distributions that define the decays, and b is an index for the set of quantum number accessible to the final state system. The spin density matrix will define the rank of the production waves, entering the production amplitude V_{bk}. The decay amplitudes, $A_b(\tau)$, are given by geometrical terms of combinations of Clebsch-Gordan coefficients (D functions). A maximum likelihood fit is done to the intensity distribution by a set of given partial waves and reasonable assumptions of the production mechanisms. The goodness of the fit is related to the statistics (number of events per binned data) and the rank of the matrix (number of parameters to be fitted). The fit could then be improved by using higher statistics or (equivalently) by reducing the rank of the fit by having more information about the production mechanisms.

The knowledge of photon polarization simplifies the PWA by giving direct information on the production mechanisms and therefore reducing the rank of the fit. Electroproduction at these very small values of Q^2 using unpolarized electrons *is equivalent to photoproduction using partially linearly polarized photons.* The matrix element for the electron scattering process in the one-photon exchange is:

$$|\mathcal{M}|^2 = (2e^4/Q^2)T_{\mu\nu}L^{\mu\nu}$$

where $T_{\mu\nu}$ is the hadronic tensor (expressed in terms of nucleon structure functions) and $L^{\mu\nu}$ is the virtual photon polarization density matrix. Defining the photon polarization as:

$$\epsilon = [1 + 2\frac{(Q^2+\nu^2)}{Q^2}\tan^2(\theta/2)]^{-1},$$

and the longitudinal polarization $\epsilon_L = \frac{Q^2}{\nu^2}\epsilon$, the polarization density matrix can be written as [8]:

$$\begin{pmatrix} \frac{1}{2}(1+\epsilon) & 0 & -[\frac{1}{2}\epsilon_L(1+\epsilon)]^{1/2} \\ 0 & \frac{1}{2}(1-\epsilon) & 0 \\ -[\frac{1}{2}\epsilon_L(1+\epsilon)]^{1/2} & 0 & \epsilon_L \end{pmatrix}$$

At very low values of Q^2 the virtual photon beam becomes, for all practical purposes, almost a real photon beam, since

$$\epsilon_L = \frac{Q^2}{\nu^2}\epsilon = 10^{-3}\epsilon \approx 0.$$

Since there is no longitudinal contribution, the matrix represents the spin density matrix of real (transverse) photons.

The photon polarization produced by an 11 GeV electron beam ranges between 65% (7 GeV photons) to 20% (10 GeV photons) and can be calculated from the electron kinematic for each event.

To illustrate the importance of linear polarization, a simulation of meson photoproduction was performed for the current experimental configuration: the CLAS detector and an electron beam energy of 6 GeV. Events were generated according to t channel phase space with a $\frac{\partial\sigma}{\partial t} \propto e^{5t}$. These events were weighted according to a photoproduction cross-section as a function of polarization and with a one pion exchange production (OPE) mechanism. Included in the description of the cross-section were 4 resonances: $a_1(1260), a_2(1320), \pi_1(1600)$ and $\pi_2(1670)$. Events were then filtered through a GEANT-3 simulation of the detector *(GSIM)*. The events were simulated for $\nu = 4\ GeV$, so the polarization of the virtual photon was $\approx 60\%$, similar to the one expected at CLAS12 running with an 11 GeV electron beam.

The effects related to the polarization can be directly seen in Figure 1. Because pion exchange corresponds to unnatural parity exchange the ϕ dependence of the produced 3π system will flip depending on the naturality of the state [14]. These two figures differ only in the direction of the photon polarization and correspond to the two eigenstates of reflectivity. In Figure 1 (a) are those events where the photon polarization is normal to the production plane, and (b) are those events where the photon polarization is in the production plane. Due to parity conservation in the production process, states of the same reflectivity but opposite naturality will have opposite ϕ distributions, which may be observed in the figure. It is most clearly seen for the band at the $a_2(1320)$ mass. This distribution is $cos^2(\phi)$ in one figure and $sin^2(\phi)$ in the other. Another band at a mass near 1.7 GeV has the opposite ϕ behavior of the $a_2(1320)$. It corresponds to the $\pi_2(1670)$ which has a naturality opposite that of the $a_2(1320)$.

In practice, the spin-parity, and therefore the naturality, of a resonance is measured via a partial wave analysis. Using this and the known beam polarization information, the naturality of the unknown exchange particle can be determined thus providing key insight into the production mechanism.

The study of the meson spectrum already started by using data collected with CLAS and now progresses in developing the analysis tools necessary to identify exotic mesons by testing them on both well and poorly known meson states, such as the ρ and the $f_0(980)$ respectively [15]. As an example, Fig. 2 shows the results of a partial wave analysis of the $\gamma p \to p\pi^+\pi^-$ channel. In the upper panel the prominent peak of the ρ-meson dominates the $\pi - \pi$ P-wave differential cross section. In the lower panel, the S-wave shows a clear variation in the vicinity of the $f_0(980)$. It has to be noted that this is the first time that the $f_0(980)$ meson has been measured in a photo-production experiment. The evidence of the $f_0(980)$ signal in the S-wave is a sign that photo-production may indeed be a good tool for accessing meson resonances other than vector meson states.

CLAS12 will be able to measure multi-charged and multi-photon particle final states with good acceptances for up to four or five final state particles. PWA of more than four or five final particles becomes difficult and increasingly unreliable, limiting the possible number of decay channels to be analyzed. We plan to obtain the high statistics that will be needed to access channels with four observed particles in the final state by running high beam currents. As a comparison, current CLAS

Figure 1: The ϕ/π vs. Mass[3π] for those events with the polarization perpendicular to the production plane (left) and in the production plane (right). The simulated polarization was set to 60%.

Figure 2: Partial wave cross sections $d\sigma/dtdM_{\pi\pi}$ for the reaction $\gamma p \rightarrow p\pi^+\pi^-$ in the photon energy bin $3.2 < E_\gamma < 3.4$ GeV and momentum transfer $0.5 < -t < 0.6$ GeV^2. The top and bottom panels show the P- and the S-wave, respectively.

experiments using CLAS bremsstrahlung beams at DAQ rates of 2 KHz were able to achieve comparable statistics (in three particles final states) to previous π beam experiments in about one or two months (*real time*) of running.

Details related to CLAS12 kinematic, resolution and acceptance for some benchmark reaction channels are presented in the Section 5.1.

The reliability of the Partial Wave Analysis technique and, in particular, of the necessary approximations involved in the application of such technique to practical cases are one of the crucial points in this type of research. Most of the analysis of multiparticle final states have relied so far on the Isobar Model, where the many-body decay of resonances are assumed to occur through a sequence of two-body decays. While this approach has been found to be rather effective in the analysis of many resonance decays, it is known to violate basic principles as unitarity. A more theoretically sound technique for the construction of resonance decay amplitudes would be highly desirable in particular for the search of the small signals associated to exotics or hybrids, not observed so far. To address these very important issues, a working group involving both theorists and experimentalist has been formed and a proposal to form a five-year collaboration on the topic of the Analysis of the Hadron

Spectrum has been submitted in response to the announcement by the Department of Energy, Office of Science, Division of Nuclear Physics Funding Opportunity, Topical Collaborations in Nuclear Theory FAPN09-24 [16]. The idea is to develop novel PWA tools that will take advantage of recent developments in effective field theory together with old methods based on the S-matrix theory to explore the analytical properties of the amplitudes. The collaboration aims in developing a set of tools for analysis of CLAS12, GluEX, BESII and PANDA light hadron spectroscopy data. The meson spectroscopy we are presenting here is perfectly inserted in this stream.

3 Electroproduction at very small Q^2

The current photoproduction setup of CLAS, producing real bremsstrahlung photons tagged by a magnetic spectrometer, can not be operated at 11 GeV energies because of the limitation of the existing magnet.

Instead, we are planning to use quasi-real photons produced when electrons are scattered at very forward angles (*i.e.*, scattering angles of few degrees). Electron detection at very small angles, (Q^2 values of about 10^{-1} GeV^2 or lower) with the coincidence detection of the hadronic final states in CLAS12, is a very attractive alternative to photoproduction experiments [8]. We plan to use a small angle forward electron tagger extending the CLAS12 acceptance for electrons in the range $2^\circ - 5^\circ$, not covered by the standard equipment. This technique was used in the past to produce high energy (~ 100 GeV) photon beams at CERN (Omega Collaboration) and DESY (ZEUS experiment). At our knowledge no attempts were made with a ~ 10 GeV electron beam. First tests were performed in the actual configuration of the CLAS experiments with the 6 GeV electron beam, by looking for hadronic events with no electron detected in the CLAS calorimeters acceptance ($> 5^\circ$), and final state compatible with the assumption of a forward-going electron. The reconstructed mass spectra of $\pi^0\pi^0$ and $\pi^0\eta$ show clear evidence of rare mesons expected in these channels ($f_0(980)$, $f_2(1270)$, $a_0(980)$) demonstrating that this technique works quite well (see Fig. 3). Presently, the eg6 run is using this technique to study coherent meson production on ^4He [18].

The degree of polarization (up to 60%) and the quasi-real photon flux (up to 0.5 10^8 γ/s) achievable with the CLAS12 nominal luminosity of 10^{35} cm$^{-2}s^{-1}$, are similar to what expected by using the coherent bremsstrahlung technique planned by GLUEX experiment in Hall-D. Additionally, the photon linear polarization can be defined on an event-by-event basis measuring the electron scattering plane. Furthermore, since electrons are tagged after their target interactions, this technique allows the use of high electron currents, permitting to achieve high luminosity on thin (gas) targets not operable with photon Bremsstrahlung beams as discussed in Section **??**.

The forward tagger facility will be designed as an extension of the CLAS12 standard equipment such that the low angle electron tagging will be possible in parallel

Figure 3: Invariant mass distribution for $\pi^0\pi^0$ (left) and $\pi^0\eta$ (right) for the reactions $ep \rightarrow p\pi^0\pi^0(e)$ and $ep \rightarrow p\pi^0\eta(e)$, respectively. In both cases, the protons and 4 photons from the meson decays were detected while the final state electron was unmeasured, being emitted at $0°$.

to the standard electroproduction experiments running in Hall-B. In this way no dedicated run-time will be requested to accomplish the physics program outlined in the previous Section (as far as the torus field and the target requirements will be compatible). Moreover, the new device will extend the π^0 and photons acceptance of CLAS12 to very small angles.

Virtual ('quasi-real') photoproduction presents several advantages over photon bremsstrahlung beams. Only electrons corresponding to photons that have produced hadronic interactions are registered by the tagger, thus allowing a higher beam flux for a comparable accidental rates. This is a major advantage for using thin (gas) targets. For "post-tagged", very low Q^2, beams the tagged electron flux is proportional to the hadronic rate and not to the incoming photon flux, so that the photon flux is not limited by the electron tagging rate. It is, therefore, possible to run higher beam currents into thin targets without an increase in accidental rates. As a consequence, higher luminosities can be achieved using thin (in gm/cm^2) targets than in case of a tagged bremsstrahlung beam.

The combination of polarized photons with relatively high photon fluxes and the excellent performance expected by CLAS12 (good momentum resolution, down to 0.1%, good particle identification, in particular kaon separation up to $p_K \sim 4$ GeV/c, and nearly 4π coverage for hadronic final states) will make Hall-B a competitive and complementary experimental environment to the already planned coherent bremsstrahlung production experiments at Jefferson Lab at 12 GeV.

4 Experimental setup

Kinematics, rates, and backgrounds for this facility are briefly described in the next sections.

4.1 CLAS12 configuration

4.2 Electron detection: the Forward Tagger

To reconstruct the the quasi-real photon variables is necessary to measure the scattered electron three momentum. The relevant quantities are:

- the energy $E_{e'}$: since the photon energy is given by $E_\gamma=\nu=E_{Beam}-E_{e'}$ and its linear polarization by $P_\gamma = \epsilon^{-1} = 1 + \frac{\nu^2}{2E_{Beam}E_{e'}}$
- the polar angle $\phi_{e'}$ to determine the polarization plane
- the azimuthal angle angle $\theta_{e'}$: since $Q^2 = 4E_{Beam}E_{e'}\sin^2\theta/2$

Due to the small scattering angles ($2^\circ < \theta_{e'} < 5^\circ$), the standard tracking of charged particles of CLAS12 can not be applied. Therefore a new detector component has to be added. The forward tagger will be made of a calorimeter to reconstruct the scattered electron energy ($E_{e'}$) and of a position sensitive device that will measure the scattering angles ($\theta_{e'}$ and $\phi_{e'}$) with good accuracy. The device will be placed between the high threshold Cerenkov Counter (HTCC) and the torus support, at about 2m downstream of the target (nominal) position. The location very close to the beam line (2° corresponds to $\sim$8 cm distance) and the available clearance (at most $\sim$40 cm along the beam axes), requires a compact calorimeter with a small radiation length and a very good radiation hardness. Figure 4 shows a cut of the CLAS12 area (from the target to the torus support) where the forward tagger would be installed. The existing CLAS Inner Calorimeter (IC) is shown in the same position as the forward tagger.

The position sensitive detector will be placed in front of the calorimeter. A resolution of $\pm 300\mu$m on X and Y could be achieved by using two layers of 1mm quartz fibers that have a very high radiation hardness, a good timing and a simple readout based on multianod photomultipliers. Magnetic shields may be necessary for the operation of such sensors. This device will also be used to discriminate forward going photons from electrons. Other options as well as a second tracking plane close to the target are under study.

Figure 4: The forward tagger position in CLAS12. The new device will replace the Inner Calorimeter located between the HTCC and the torus support.

Due to the expected high rate from Møller scattering, the calorimeter should be segmented transversely as much as possible in order to maintain each channel at a sustainable readout-rate. The (minimum) size of each pixel should be comparable with the characteristic electromagnetic shower transverse size in order to contain the shower associated to each incident electron. The calorimeter Moliere radius has to be as small as possible to reduce pile-up.

The electron energy resolution is not a crucial issue since the relative error on the photon energy determination takes advantage of the large value of E_γ at the denominator reducing by almost an order of magnitude the experimental energy resolution:

$$\frac{\Delta E_\gamma}{E_\gamma} = \frac{\Delta E'_e}{E_{Beam} - E'_e} \tag{1}$$

An electron energy resolution of few percent (at 1 GeV) would result in an energy resolution of $\sim 0.1\%$ for the corresponding 10 GeV photon and would be functional to the use the missing mass technique for the most part of the reactions studied (see also the discussion in the benchmark channels Section).

The forward tagger has to be fast ($\sim$ 10 ns) providing the scattered electron interaction time with good accuracy (<1 ns). As previously mentioned, a good timing is necessary to reject the background in the off-line analysis. In fact a time coincidence of few ns between the hadrons detected in CLAS12 and the scattered electron measured in the forward tagger is crucial to identify the hit associated with the scattered electron among the background hits due to Møller or elastic radiated electrons lying in the same energy range.

A last issue that worth to mention concerns the light read-out: the photodetector will be placed in a sizable magnetic field and have to be small in size to fit the available clearance. The standard photomultiplier readout seems to be excluded while photodetectors based on semiconductors, e.g. Avalanche Photo Diode (APD) or Silicon Photo Multipliers (SiPM) should guarantee the requested performance.

There are different colorimetric options that could fulfill the requirements in terms of:

- radiation hardness,
- light yield,
- radiation length and Moliere radius,
- energy and timing resolution.

In the following paragraphs will briefly review review the possible hardware options.

4.2.1 The calorimeter

Electromagnetic calorimeters based on homogeneous crystals give the best performance in term of energy and time resolution. In fact if the shower is longitudinally and transversely contained, the photoelectron fluctuations is the only sizable contribution to $\sigma(E)/E$ and $\sigma(T)/T$.

In the latest years materials as $PbWO_4$ have been extensively studied showing to be very resistant to the radiation damage and were used in large scale detectors involving hundred thousands of crystals, in leading experiments at CERN (CMS-ECal [41], ALICE-PHOS [42]), GSI (PANDA-EMC [43]) and Jefferson Lab (CLAS-IC [44]). Against a very fast scintillation decay time (6.5 ns), a very small radiation length (0.9 cm) and one of the smaller Moliere radius (2.1 cm), the main disadvantage of the $PbWO_4$ is the poor light yield (only 0.3% of NaI(Tl)). According to the PANDA-EMC study, the new crystal manufacturing procedures (PbWO-II from BTCP) and the reduction of the working temperature to -25° should ensure a better performance with a gain of a factor of 8 in light. With this design an energy resolution of $(2\%/\sqrt{E(GeV)} \oplus 1\%)$ is expected. A $\sim$5% at 1 GeV energy resolution has already been achieved by the existing CLAS-IC with an APD-based readout.

The PbWO option is the leading option for the forward tagger calorimeter.

Other crystals as LSO/LYSO (or the very recent LaBr) shares almost all the good specifications of the PbWO with a light yield $>$ 100 times bigger. A shortage of extensive studies of radiation hardness and a reduced experience in the manufacturing procedures prevent them to be considered as the main option. Nevertheless we are planning to test in parallel some samples of these new crystals and of different light sensor to establish the ultimate performance in terms of time and energy resolution.

4.2.2 The tracker

4.2.3 The veto counter

All these different hardware options will be investigated in the $R\&D$ phase before the submission of a full proposal.

4.3 GEMC Simulations

First simulations of the forward tagger facility to understand kinematics, backgrounds and the detector response have been done with GEMC, the GEANT4-based Monte Carlo code for CLAS12 [21]. The forward tagger geometry was implemented in GEMC starting from the existing description of the CLAS Inner Calorimeter [44]. A $PbWO_4$ calorimeter consisting of 425 crystals was placed at a distance of 178 cm from the CLAS12 center. The crystal have a trapezoidal shape with a front face of 13×13 mm^2, a rear face of 16×16 mm^2, and a length of 16 cm, corresponding to about 20 radiation lengths . With the chosen geometry, the calorimeter provides and angular coverage from 2 to 5 degrees. The detector is shielded from Møller electrons produced by the interaction of the beam in the target by a tungsten cone covering polar angles up to 1.95 degrees. The location and shape of the shield was based on the most recent drawing of the CLAS12 beamline and will be finalized with further simulation studies. A schematic of the setup implements in GEMC is shown in Fig. 5. A second tungsten cone, which is not shown in the figure, surrounds the first cone blocking polar angles from 5 to 5.5 deg., to prevent low energy electrons emitted at larger angles to enter in the acceptance of the forward tagger because of the effect of the magnetic field which bends them toward the beamline. For these simulation a 5 cm-long, liquid-hydrogen target was used.

The GEMC simulations were first used to understand the electron kinematics and the forward tagger acceptance. For this purpose electrons with momentum from 0.05 to 4 GeV and polar angle from 1 to 35 degrees were generated uniformly at the target location. The trajectory of the electrons is affected by the solenoidal field, which mainly bends the particle in ϕ while leaving the polar angle, θ, almost unchanged. This is shown in Fig. 6 where the difference between the polar and azimuthal angles measured at the detector (θ_{FT}, ϕ_{FT}) and at the target (θ, ϕ) as a function of the particle momentum and of the vertex polar angle θ, are shown respectively. As expected the polar angle is affected by the magnetic field only for very small electron momenta, while the azimuthal angle has a strong shift, which depends mainly on the momentum and only marginally on the polar angle. In more details, as shown by Fig. 7, a significant shift of the polar angle is observed only for electron momentum of the order of 500 MeV, while no clear dependence of the ϕ shift, $(\phi_{FT} - \phi)$, from θ is

Figure 5: Schematic of the forward tagger facility as implemented in GEMC. The lead tungsten calorimeter, shown in green, is located at 178 cm from the target (red) and the center of the CLAS12 detector. A tungsten cone, shown in blue, shields the detector from Møller electrons generated at the target by the interaction of the beam. The right panel shows how Møller electrons, represented by the red tracks, are focused in the forward direction by the 5 Tesla solenoidal field and contained in the shield. This event was generated at a luminosity of 10^{34} cm $^{-2}$s^{-1}, for graphical reason.

observed. Because of these effect, the actual angular acceptance varies as a function of the particle momentum as shown by the bottom panels of Fig. 6.

The interaction of the electron in the $PbWO_4$ calorimeter were fully simulated, up to the generation of the ADC and TDC signal measurable from each crystal. The conversion from energy to light and from light to the digital signal was based on the specifications of the scintillator crystals and of the readout system used for the existing IC. Fig. 8 shows the deposited energy as a function of the electron momentum, their difference and the longitudinal distribution of the electromagnetic shower. Fig. 9 shows the cluster multiplicity as a function of the electron energy, the simulated ADC spectrum, the calorimeter occupancy for the simulated events and an example of the signal generated by one electron.

The electromagnetic background produced by the interaction of the electron beam in the target was also simulated. For this purpose, for each primary electron generated in the kinematic of interest, about 58k, 11 GeV electrons were generated 10 cm upstream with respect to the target. The electrons were generated randomly with the 2 ns radiofrequency structure of the CEBAF beam in a 124 ns window, which corresponds to the data acquisition window that will be used in CLAS12. The number

Figure 6: GEMC simulation results. Top: difference between the polar and azimuthal angles measured at the detector (θ_{FT}, ϕ_{FT}) and at the target (θ, ϕ) as a function of the particle momentum and of the vertex polar angle θ, respectively. Bottom: θ versus p distribution for events with deposited energy in the forward tagger calorimeter greater than zero. All plots are based on simulation of electrons generated uniformly in the momentum range 0.05-4 GeV and polar angle range 1-35 degrees.

Figure 7: GEMC simulation results. Difference between the polar and azimuthal angles measured at the detector (θ_{FT}, ϕ_{FT}) and at the target (θ, ϕ) as a function of θ. The top, middle and bottom row correspond to electron momenta of 0.5, 1.5 and 2.5 GeV. A significant shift of the polar angle is observed only for electron momentum of the order of 500 MeV, while no clear dependence of the ϕ shift, $(\phi_{FT} - \phi)$, from θ is observed.

Figure 8: GEMC simulation results. Top: deposited energy in the lead-tungsten calorimeter (left) and their difference (right) as a function of the electron momentum. Bottom: energy deposited as a function of the hit depth in the calorimeter and distribution of the hit positions.

Figure 9: GEMC simulation results. Top: Number of crystal with energy deposited above 5 MeV as a function of the electron momentum (left) and ADC distribution (right). Bottom: calorimeter occupancy for the simulated events (left) and for one specific case (right). Note that the electron were generated uniformly in θ with $\phi = 0$: for this reason the corresponding hits are on the right side of the calorimeter, in proximity of the horizontal axis.

Figure 10: Simulation of the electromagnetic background with GEMC. The plots show the total energy deposited in the forward tagger calorimeter in a 124 ns window (top-left), the number of crystals with energy deposited greater than 5 MeV (top-right), the energy deposited in the calorimeter for unit of time considering all the hits in the 124 ns window (bottom-left) and only the ones within a ± 1 ns windows from the primary electron (bottom-right). The unit on the z-axis for the latter two plots are MeV/ns.

Figure 11: Simulation of events with one electron with $p = 0.5-1$ GeV and $\theta = 2^{\circ}-5^{\circ}$ detected in the forward tagger and the electromagnetic background due to Møller electrons at a luminosity of 10^{35} cm $^{-2}$s^{-1}. The left and right columns show the same distribution without any cuts and using a 50 MeV threshold on the energy deposited in the crystals, respectively. The top rows shows the time distribution of the crystals signal: the peak at 70 ns corresponds to signal associated to the good electron. The middle row shows the calorimeter occupancy weighted with the energy deposited in MeV/ns. The bottom row shows the calorimeter signals in MeV for a single event.

$E_{scattered}$	0.5 - 4 GeV
θ	2.0^o - 5.0^o
ϕ	0^o - 360^o
ν	7 - 10.5 GeV
Q^2	0.005 - 0.3 GeV^2 ($< Q^2 >$ 0.09 GeV^2)
W	3.7 - 4.5 GeV

Table 1: Kinematic range covered by the forward tagger.

of electrons corresponds to a luminosity of 10^{35} cm $^{-2}$s^{-1}. Fig. 10 shows the total energy deposited in the calorimeter in the 124 ns window, the number of crystal with more than 5 MeV of energy deposited, the energy-weighted occupancy of the calorimeter and the same occupancy when only hits within a ± 1 ns window from the primary electron are retained. The normalization for the bottom-right plot was chosen in such a way that the z axis corresponds to the energy absorbed by the calorimeter per ns.

To study the effect of this background on the reconstruction of "good" electrons, events were simulated with one electron in the kinematic of interest, i.e. $p = 0.5 - 4$ GeV and $\theta = 2° - 5°$, background produced by the beam at a luminosity of 10^{35} cm $^{-2}$s^{-1}. As shown in Fig. 11, the signal associated with good electrons are localized in time and can be extracted by knowing the event start time, determined from the hadrons detected in CLAS12. Considering only crystals with a time within a ± 5 ns window around the observed peak and deposited energy greater than 50 MeV, the background is strongly suppressed as shown by the plots in the right column. In particular, the signal associated to the good electrons start to emerge as shown by the yellow band in the middle right plot (to be compared with the bottom left plot of Fig. 9). The effect is even more evident if a single event is considered as shown by the bottom plots of Fig. 11: when the time and energy cuts are applied, the cluster associated to the good electron (4 close crystals on the right of the calorimeter) can be clearly isolated. The time and energy cuts used for this study are a quite rough way to suppress that backgrounds and a better signal-to-noise ratio can be achieved with a more sophisticated analysis and using a complete cluster recognition and reconstruction algorithm.

4.4 Kinematics, rates and backgrounds

The kinematic range covered by the forward tagger facility is shown in Tab. 1 for an incoming electron beam of 11 GeV.

Electron scattering contains contributions from one-photon exchange (Born process), from QED vacuum polarization loops, and from the emission of additional real

Figure 12: Angular and energy distribution of inelastic events within the geometrical and momentum acceptance of the forward tagger.

photons (radiative corrections). The importance of the internal radiative corrections in relation to the Born process depends on the kinematics. Radiative corrections increase with decreasing Q^2 and increasing $\nu = E_{Beam} - E_{e'} = E_\gamma$. We have used the program RADGEN 1.0 [40] to calculate the contributions of internal radiative corrections to the total inclusive cross section. Including such effects, the total inclusive electron rate within the geometrical and momentum acceptance of the forward tagger will be of about 2.5 MHz ($\Delta E_{e'}$=0.3-10.8 GeV and $\Delta\theta_{e'}$=2.0^o-5.0^o). Inelastic processes represent about 1% of the total cross section in our kinematic range. The remaining 99% is due to elastic events where at most one proton will go in the active area of CLAS12. It is, therefore, essential for our measurements to require a tight time coincidence between the forward tagger and the detection of multi-particle final states in the CLAS detector.

The total rate of inelastic events in the forward tagger acceptance with $E_\gamma = \nu$=7-10.5 GeV, is expected to be about 8.5 kHz . The energy and the angular distributions of inelastic events are reported in Fig. 12. Figure 13 shows the Q^2 and the linear polarization for the same events.

Electromagnetic backgrounds to the forward electron tagger include bremsstrahlung and Møller processes. Bremsstrahlung photon production peaks at very forward an-

Figure 13: Q^2 and the linear polarization of inelastic events within the geometrical and momentum acceptance of the forward tagger.

gles (about $\delta\theta \approx m_e/E$), therefore their contribution at angles $\theta > 0.5^o$ is very small. We have calculated the Møller electron rates at forward angles. Figure 14 shows the cross section and the angular rate of Møller as a function of the electron angles in the laboratory for a luminosity of 10^{35} cm^{-2} sec^{-1}. The rates of Møller electrons remains almost flat within the forward tagger acceptance (2.0^o-5.0^o). The low energy electrons produced by the interaction of the beam with the target are focused towards the beam line by the 5T solenoidal field of the CLAS12 central part. Therefore only electrons with $E_e > 250$ MeV can reach the forward tagger acceptance. In addition, a tungsten conic shield around the beam-pipe would be used to stop the low energy electromagnetic background produced by secondary interactions (low energy photons, X-rays, beam halo ...). These backgrounds are being studied using a GEANT4 simulation of CLAS12 (GEMC). More details are reported in the next paragraph. The total expected Møller rate is about 50 MHz. As shown in Fig. 15, most of the Møller electrons have energies lower than 1 GeV: another option to reduce the overall rate on the forward tagger would be to increase the threshold on the total energy up to that value. Anyway, these can be almost totally rejected in the off-line analysis when a time coincidence of few nanosecond with the rest of CLAS12 is required, since no hadrons associated to such events will reach the CLAS12 detector, and the typical

Figure 14: Møller electron rates for L=10^{35} cm^{-2} sec^{-1}. Angles are in the laboratory.

2-body correlation between angle and energy is used.

Due to the high rate in the forward tagger it does not seem possible to use the prompt signal as a on-line trigger for the data acquisition. The DAQ trigger scheme will require 2 or more particles (charged and/or neutrals) within the CLAS12 detector and off-line a tight time coincidence window (few nanosecond) will be applied between the forward tagger and the CLAS12 to identify the right electron.

In the next Section we will briefly discuss the different hardware options for the electron detection at small angles.

4.5 Trigger

5 Expected results

Figure 15: Inelastic (black) and Møller electron (red) kinematics. The second Møller electron is emitted in the range $\Delta\theta = 0.01^o$ - 0.2^o and ΔE=10.1-10.9 GeV, well outside the geometrical acceptance of the forward calorimeter.

Figure 16: FASTMC resolutions for e^- at $\theta = 15°$.

5.1 Benchmark channels

In the following we will discuss in more details some of the reaction channels that we aim at investigating, reporting the first results obtained from Monte Carlo Simulations for the detection of these channels.

The simulations were based on the CLAS12 Fast Monte Carlo (FASTMC) [49], which used parametrization of the detector acceptance and resolutions for different particle types. The parametrization of angular resolutions were updated to agree with the most recent Monte Carlo tracking results [50, 20] and are shown in Fig. 16.

The acceptance for the tagger was assumed to be 100% in the range $1 < E_{e'} < 4$ GeV and $2° < \theta_{e'} < 5°$. The resolution of the forward tagger in determining the scattered electron momentum and angles was parametrized for two different assumptions on the detector structure:

1. the existing CLAS-IC $PbWO_4$ calorimeter

- $\sigma_\theta = 0.1^\circ$ and $\sigma_P = \sqrt{0.02^2 + 0.03^2 P + 0.024^2 P^2}$ GeV

2. a poorer resolution sampling calorimeter or equivalent

   - $\sigma_\theta = 0.1^\circ$ and $\sigma_P = 0.2\sqrt{P}$ GeV

Different reactions were studied using reasonable assumptions on productions mechanism. Events were generated via the Monte Carlo technique, projected onto the detector to determine acceptances and the 4-vectors smeared according to the above parametrization. 100,000 events were analyzed for each final state. In the following section we described the results obtained for four specific cases.

5.1.1 $\gamma p \to n\pi^+\pi^+\pi^-$

One of the most interesting final state for the search of exotic mesons is the 3π channel. For example, exotics with $J^{PC} = 1^{-+}$ are expected to contribute to this final state, via their decay to $\rho\pi$. In fact evidence for the exotic $\pi_1(1600)$ in this decay mode was reported first by the VES Collaboration [51], followed by the E852 Collaboration at Brookhaven [52]. The latter results are highly controversial, since the initial observation of an exotic 1^{-+} signal at a mass of $M = (1593 \pm 8)$ MeV with a width of $\Gamma = (168 \pm 20)$ MeV was not confirmed by a later analysis that used more statistics and a larger set of waves in the PWA [53]. More recently, the same reaction channel was investigated by the CLAS Collaboration [54], that found no evidence for the exotic $\pi_1(1600)$ state from the analysis of about 83000 $\gamma p \to \pi^+\pi^+\pi^- n$ events. An upper limit of 13.5 nb on for $\pi_1(1600)$ production cross section, less than 2% of the $a_2(1320)$ production, was set. Finally in September 2009, the Compass Collaboration reported the observation of a resonance with $J^{PC} = 1^{-+}$, a mass of $(1660 \pm 10^{+0}_{-64})$ MeV and a width of $(269 \pm 21^{42}_{64})$ MeV, in diffractive dissociation of negative pions into $\pi^-\pi^-\pi^+$ final state using a 190 GeV/c pion beam hitting a lead target [55].

In spite of the large number of experiments that have investigated the 3π system, no definitive conclusion on the existence of an exotic signal in this final state has been obtained. For this reason further studies of these reactions channel are highly desirable.

The $\gamma p \to n\pi^+\pi^+\pi^-$ reaction can be easily accessed in the CLAS12 experimental setup by detecting the three charged pions in the forward part of the CLAS12 detector. The exclusivity of the reaction can be ensured by using the forward tagger facility to determine the energy of the initial state photon and then applying the missing mass technique to select events with a missing neutron. The exotic wave will be isolated performing a full partial wave analysis of the final state as discussed in Section 2.2. Known mesonic states as the $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ will be used as a benchmark of the analysis procedure.

The capability to identify a resonance in this final state was studied using FASTMC. As well as having a broad mass, the resonance was produced in the t channel with a

Figure 18: Missing mass (top) and invariant mass (bottom) resolutions for the $PbWO_4$ tagger. Left to right show the 3 different torus field settings, 3200A, 2400A and 1600A.

Figure 19: Missing mass (top) and invariant mass (bottom) resolutions for the lower-resolution tagger. Left to right show the 3 different torus field settings, 3200A, 2400A and 1600A.

distribution $\frac{d\sigma}{dt} \propto e^{5t}$. Angular acceptances for π^+ and π^- from the resonance decay are shown in Fig. 17, while the missing and invariant mass resolutions for the two hypothesis on the forward tagger detector are shown in Fig. 18 and 19. The study was repeated for different values of the intensity of the CLAS12 toroidal magnetic field. While the acceptance for negative particles varies strongly depending on the intensity of the field, the resolution both in missing mass and invariant mass remain quite stable. For this reason, it would be more efficient to operate the torus field at low current. For the rest of this study we assumed a torus current of 1600 A, i.e. the lowest value considered in the simulation mentioned above. A stronger effect on the final missing mass resolution is due to the energy resolution of the forward tagger. This is more evident in Fig. 20, where the missing mass of the chosen reaction is compared to that of a possible background containing an additional π^0. This 4π background channel is assumed to have a purely phase space distribution and the π^0 is ignored in the tracking analysis.

These results showed that a good energy resolution in the forward tagger would be necessary to have a clear identification of the final state.

5.1.2 $\gamma p \rightarrow p\eta^0\pi^0$

5.1.3 $\gamma p \rightarrow pK^+K^-\pi^0$ and $\gamma p \rightarrow nK^+K^-\pi^+$

One very attractive method to identify exotic mesons is through the $\phi\pi$ decay mode. Any $s\bar{s}$-meson decay to $\phi\pi$ is forbidden due to the conservation of isotopic spin. This decay mode is forbidden by the Okubo-Zweig-Iizuka (OZI) rule for any $n\bar{n}$-meson (where n is u or d quarks) as well. On the other hand, multiquark or hybrid mesons may have a strong coupling to the $\phi\pi$ system. The discovery of a $\phi\pi$ resonance would indicate a new kind of hadron and suggest a $q\bar{q}g$ or $q\bar{q}q\bar{q}$ state. This is true for $f'\pi$ and $J/\psi\pi$ decay modes as well [56].

There is some experimental evidence for the existence of a resonance with strong $\phi\pi$ coupling. In experiments at the LEPTON-F spectrometer [57, 58], the charge

Figure 20: Missing mass of the three pion system with the $PbWO_4$ tagger (left) and the lower resolution tagger (right). The black line correspondent to the reaction of interest and the red line to the 4π background.

exchange reaction

$$\pi^- p \to (\phi\pi^0)n, \tag{2}$$

has been studied at a π^-–momentum of 32 GeV/c. In the mass spectrum of the $\phi\pi^0$ system a new meson, C(1480), with mass 1480 ± 40 MeV and width 130 ± 60 MeV, was observed. The angular distributions of the sequential decay $C(1480) \to \phi\pi^0, \phi \to K^+K^-$ have been studied, and the quantum numbers for C(1480) meson have been determined: $I^G = 1^+, J^{PC} = 1^{--}$. For this meson an anomalously large value of the ratio

$$BR(C(1480) \to \phi\pi^0)/BR(C(1480) \to \omega\pi^0) > 0.5 \tag{3}$$

at 95% C.L. has been obtained. This value is more than two orders of magnitude higher than the expected ratio for mesons with the standard isovector quark structure. At the present time the only consistent explanation of these properties can be obtained with the assumption that the $C(1480)$ meson is a four quark or hybrid state.

At the Ω–spectrometer [59] the cross section for the reaction $\gamma p \to \phi\pi^0 p$ has been measured. Although the number of events is not large ($\sim$ 25), an excess of events in the mass spectrum of the $\phi\pi^0$ system at $\sim$1.4 GeV is observed. The $\phi\pi^0$ photoproduction cross section was estimated as

$$\sigma(\gamma p \to \phi\pi^0 p) = 6 \pm 3\text{nb} \tag{4}$$

(at 95% C.L.)

The existence of the structure in the same mass range was confirmed with the study of inclusive $\phi\pi^+$ production with a pion beam [60].

Recently the BaBar Collaboration published new data on the cross section for the annihilation $e^+e^- \to \phi\pi^0$. There is a prominent structure in the cross section near the total energy 1.5 GeV [61].

Quasi-real photoproduction is likely to be one of the more promising mechanisms for the production of exotic mesons with hidden strangeness due to the relatively large $s\bar{s}$ content of the photon. Photons are also expected to be efficient in the production of spin-1 hybrids.

The first attempts to explore existing data from CLAS runs g6a and g6b showed that the multiparticle reactions

$$\gamma p \to (\phi\pi^0)p, \quad \phi \to K^+K^-, \quad \pi^0 \to \gamma\gamma \tag{5}$$

$$\gamma p \to (\phi\pi^+)n, \quad \phi \to K^+K^- \tag{6}$$

can be investigated [62].

Figure 21: Reconstructed masses from the $pK^+\gamma\gamma$ final state for the $PbWO_4$ tagger (top) and the lowest resolution tagger (bottom). In all plots, the black line shows the final state of interest, while the red line is for a phase space $\gamma p \to K^+\pi^0\pi^- p$ reaction. The left plot shows the missing mass ($\sim K^-$), the middle the reconstructed ϕ mass and the right plot the missing, mass having fixed the reconstructed ϕ mass to 1.020 GeV.

Figure 22: $\pi^+\pi^0\gamma p$ missing mass for the radiative decay of the a^0 meson to $\omega\gamma$, corresponding to π^- mass. The left plot is for $PbW0_4$ calorimeter while the right one for the lower resolution tagger. The blue line is the standard missing mass while the red line constrains the π^0 mass and the black line also constrains the ω mass.

The CLAS12 spectrometer has excellent momentum and angular resolution and particle identification. These features are extremely important for the mass determination and background reduction.

The acceptance and resolution for an exotic decaying to $\phi\pi^0$ was studied assuming the resonance to be produced and decay via the reaction $\gamma p \to Xp \to \phi\pi^0 p \to K^+K^-\gamma\gamma p$. Again the resonance X was produced with a t distribution, $\frac{d\sigma}{dt} \propto e^{5t}$. In this case, the K^- from the decay of the ϕ meson is mainly produced at very forward angle, i.e. typically below 15 degrees in the lab with an overall detection efficiency of about 2%. The detection of this particle leads therefore to a very strong reduction of the overall acceptance. A more efficient identification of this final state is achieved by detecting the proton, the K^+, the π^0 via its decay to two photons and selecting the K^- in missing mass. In this way the overall acceptance was estimated to be of the order of 9%, to be compared with $\sim 1.2\%$ achieved by detecting proton, K^+ and K^-.

Fig. 21 shows the reconstructed masses from the $pK^+\gamma\gamma$ final state. Also shown is a phase space $\gamma p \to K^+\pi^0\pi^- p$ background. The missing masses have widths of 0.054 and 0.093 GeV for the $PbWO_4$ and low-resolution tagger respectively. The resolution is the same for the reconstructed ϕ mass. Again, the capability to determine the photon energy with a good resolution is crucial to be able to study this reaction channel with a sizable efficiency and a good signal to background ratio.

5.1.4 Conclusions

The results of the study on benchmark reactions presented in the previous sections has clearly shown that the possibility of inferring the energy of the quasi-real photon measuring the scattered low angle electron gives significant advantages for the study of exclusive multiparticle final states. First of all, the complete determination of the initial state makes it possible to use the missing mass technique to ensure the exclusivity of the reaction. Without such information, a full measurement of the final state particles would be necessary, resulting in acceptances of the % level or below for many of the studied reactions. To fully exploit the missing mass technique, a good energy resolution for the tagger is desirable. In cases where full detection of the final state is possible, the determination of the initial state allows to apply further constraints to suppress backgrounds coming from other reactions and extract small cross section signals.

5.2 Beam time request and expected results

6 Summary

We are proposing to add to the CLAS12 equipment a new quasi-real photon tagging facility that will allow to address fundamental questions about hadron spectroscopy and QCD via photoproduction experiments. This facility will detect electrons scattered at very small angles, namely from $2°$ to $5°$, providing the possibility to perform experiments at very small four-momentum transfer Q^2, below 10^{-1} GeV^2. In this kinematics, the virtual photon can be considered as quasi real and low-Q^2 electron production can be treated as photoproduction. The effective photon flux and the degree of linear polarization that can be reached with this technique are of the order of $10^7 - 10^8$ γ/s and $\sim 40\%$, respectively, that are comparable with what is obtained by using coherent bremsstrahlung as planned in the new Hall-D. The device we are proposing will consist of a calorimeter to measure the energy of the scattered electron, and therefore infer the energy of the virtual photon, and of a tracking device to determine precisely the scattering plane, and therefore the photon polarization.

This new facility will allow to continue with CLAS12 the extensive photoproduction program that was started with CLAS. The highest photon energy that will be achieved with the 11 GeV electron beam ($E_\gamma = 7 - 10.5$ GeV) will allow to address several fundamental topics in hadronic physics as the precise determination of the meson spectrum and the search for exotics or hybrids on proton and light-nuclei targets, the study of radiative decays of scalar and vector mesons, the production of high-mass baryons and in particular the Ξ spectroscopy. The use of quasi-real electron scattering will also allow to perform experiments on thin targets to study coherent meson production, that would not be possible with bremsstrahlung photon beams because of the limitation in luminosity. These comprehensive program can provide important information for the understanding of the dynamics of strong interaction and address the origin of confinement, the role of gluons in determine the spectrum of hadrons and the origin of their mass.

The design of the forward tagger will be compatible with the CLAS12 standard running, so that the tagger operation will be possible in parallel to standard electron scattering measurements that are part of the already approved physics program. The proposed detector will therefore extend the CLAS12 detection capabilities for electron down to 2°, also providing an excellent acceptance for photons emitted in the forward direction. The proposed technique gives access to an extensive physics program that is complementary to the program planned in Hall-D by the GLUEX Collaboration. The meson spectroscopy program proposed in Hall-D has been one of the driving forces for the Jefferson Lab 12 GeV upgrade and the additional contribution to this fundamental physics that CLAS12 with the new forward tagging facility would give will strengthen the role of the Laboratory in answering key questions in non-perturbative QCD.

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