Meson Spectroscopy at CLAS and CLAS12: the present and the future

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Abstract. Mesons are the simplest quark bound system, being made by a quark and an anti-quark pair. Studying their structure and properties is a fundamental step to reach a deep understanding of QCD. For this purpose both the precise determination of the meson spectrum for conventional states and the search for states beyond the simple $q\bar{q}$ configurations, as hybrids (qqg) or glueballs, are needed. Finding evidence for these unconventional states would help in understanding some of the open issues in hadronic physics, as how the quarks are confined within hadrons and what is the role of gluons. These topics are presently studied with the CLAS detector at Jefferson Lab and will be studied with the novel CLAS12 experiment after the 12 GeV upgrade of the facility. In my talk I will present the physics program that is presently in progress and the future perspectives.

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INTRODUCTION

Understanding the hadron spectrum is one of the fundamental issue in modern particle physics. We know that existing hadron configurations include baryons, made of three quarks, and mesons, made of a quark-antiquark pairs. However most of the mass of the hadrons is not due to the mass of these elementary constituents but to the force that binds them. Studying the hadron spectrum is therefore a tool to explore one of the fundamental forces in nature, i.e. the strong force, and Quantum Chromo Dynamics (QCD), i.e. the theory that describes it. This investigation can provide an answer to fundamental questions as what is the origin of the mass of hadrons, what is the origin of quark confinement, what are the relevant degrees of freedom to describe these complex systems and how the transition between the elementary constituents, quarks and gluons, and baryons and mesons occurs.

In this field a key tool is given by meson spectroscopy. Meson, being made by a quark and an anti-quark, are the simplest quark bound system and therefore the ideal benchmark to study the interaction between quarks and understand what the role of gluons is. In this investigation, it is fundamental to determine precisely the spectrum and properties of mesons but also to search for possible unconventional states beyond the $q\bar{q}$ configuration as tetraquarks ($qqqq$), hybrids (qqg) and glueballs. These unusual states can be distinguished unambiguously from regular mesons when they have exotic quantum numbers, i.e. combinations of total angular momentum, spin and parity that are not allowed for $q\bar{q}$ states. These are called *exotic* quantum numbers and the corresponding states are referred to as *exotics*.

So far, most experiments that have studied the light-quark meson spectrum used hadronic probes and in particular pion beams. A powerful alternative is given by electromagnetic probes and, in particular, photon beams. In fact photons, having spin equal to 1, provide complementary information to pions that have spin equal to 0. The full determination of the initial state that is obtained if the energy of the photon is known allows us to extract information about the meson production mechanism, while the measurement of the meson decay products and in particular of their angular distribution allows us to determine the quantum numbers of the state.

Existing data in photoproduction show that the production cross sections are sizable allowing for a detail study of meson states. In addition it has been suggested that the probability of producing exotics may be higher with photon beams than with pion beams since the presence of a $S = 1$ particle in the initial state may favor the production of quark pairs with aligned spins, which is more likely to result into an exotic configuration. The lowest mass exotics are expected to have masses of about 2 GeV according to lattice QCD calculations as for example the one of Ref. [1]. The existing estimates for exotic meson production also show that the cross sections are expected to be comparable to regular mesons [2].

A thorough study of the meson spectrum and an effective search for exotics states require high intensity beams and large acceptance detectors in order to produce abundantly the resonances to be studied and to measure their decays.

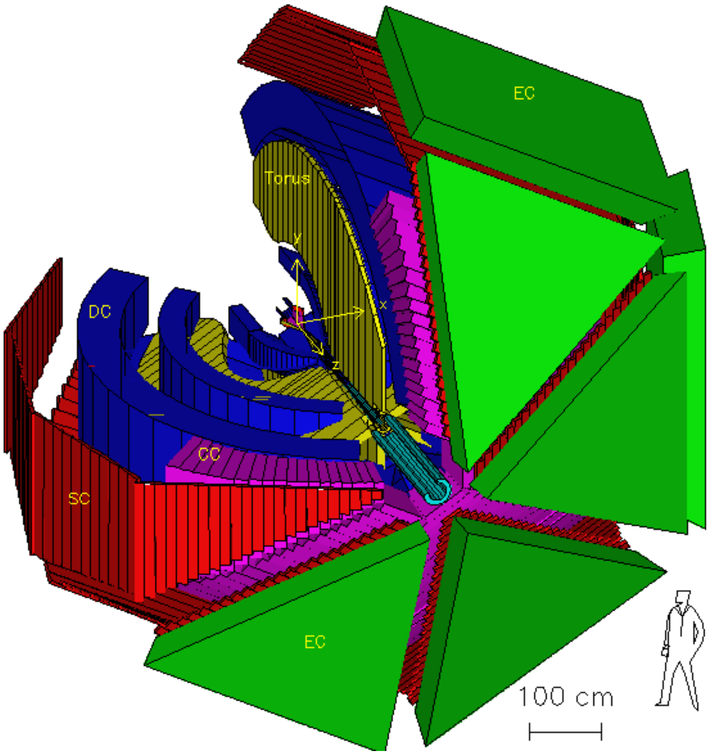

FIGURE 1. Schematic of the CLAS detector. The toroidal magnet, shown in yellow, divides the spectrometer into 6 identical sector, equipped with Drift Chambers (DC), Cerenkov Counters (CC), Scintillator time of flight (SC) and Electromagnetic Calorimeter (EC).

Both this elements are available at Jefferson Laboratory and have motivated the broad physics program that will be described in the next sections.

THE CLAS DETECTOR AT JEFFERSON LABORATORY

The core of Jefferson Lab is the Continuous Electron Beam Accelerator Facility (CEBAF), which delivers simultaneously a low emittance, 100% duty-cycle electron beam to the three different experimental Halls (A, B and C). The maximum energy is presently 6 GeV (with 80% polarization available) with a maximum current of 180 μA. The experimental Hall B is mainly devoted to measurements that require the detection of several particles in the final state, as baryon and meson spectroscopy. It hosts the CEBAF Large Acceptance Spectrometer (CLAS) [3], which is a large acceptance detector capable of measuring multi-particle final states with both charge and neutral particles over a large portion of the solid angle. A schematic of the detector is shown in Figure 1. The spectrometer is made of six identical sectors, placed in between the six superconducting coils of a toroidal magnet. Each sector is equipped with three layers of drift chambers (DC) for track reconstruction, one layer of scintillators (SC) for time-of-flight measurements and hadron identification, forward Cerenkov counters (CC) for electron-pion discrimination, and electromagnetic calorimeters (EC) to identify electrons and neutral particles.

Hall B is also equipped with a Bremsstrahlung photon tagger. The electron beam scatters over a gold radiator producing photons by Bremsstrahlung. The scattered electron is deflected by a dipole magnet toward a scintillator hodoscope, which determines the electron energy and therefore the corresponding photon energy on an event-by-event basis. The produced photon beam is therefore *tagged*. The energy and time resolution of the photon tagger are of the order of 10^{-3} and 100 ps respectively. The maximum photon energy achievable for 6 GeV electrons is of about 5.7 GeV, corresponding to a maximum invariant mass on proton target of $W \sim 3.4$ GeV and meson resonance mass of about 2.5 GeV.

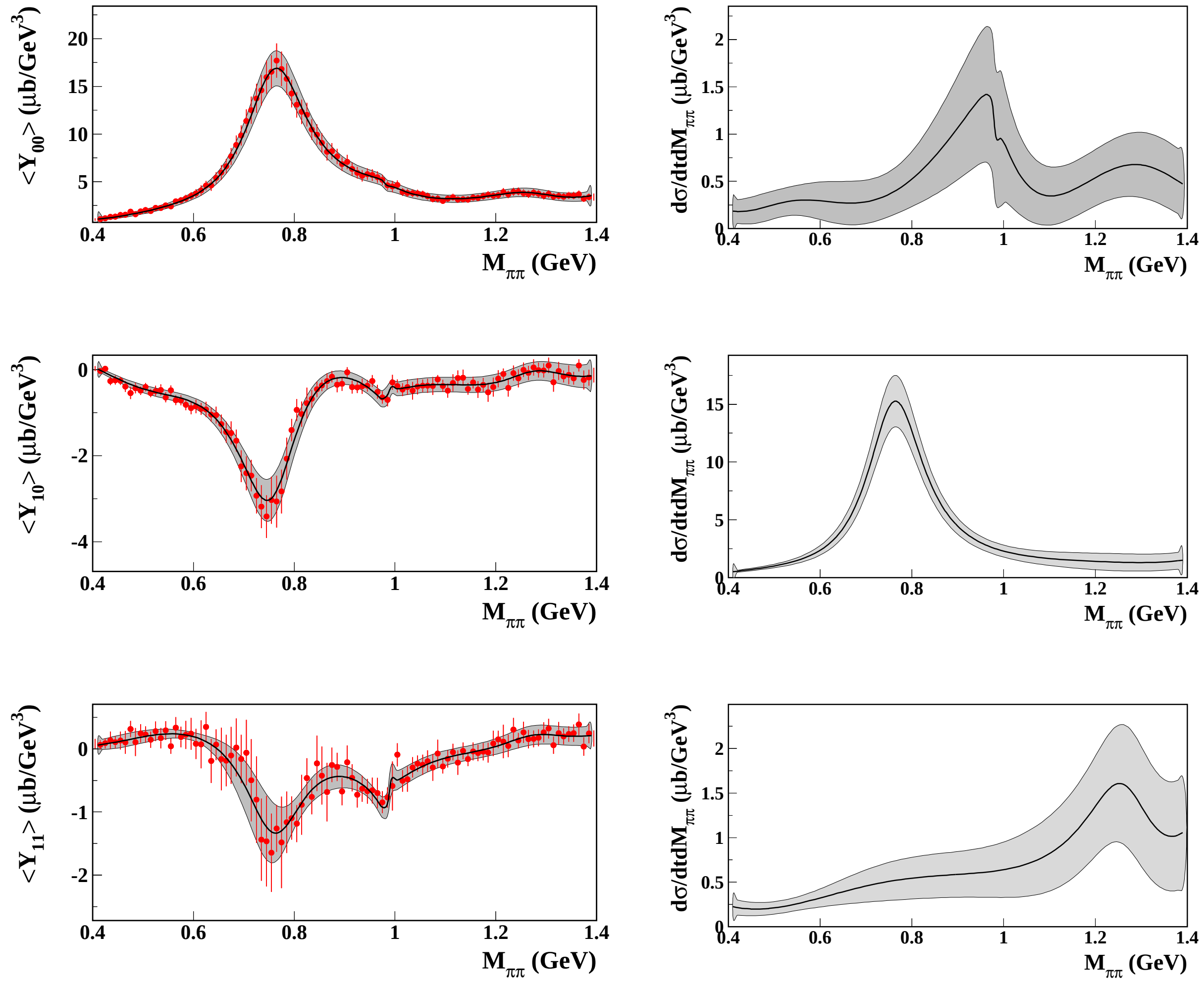

FIGURE 2. Left: Y_{00}, Y_{10}, Y_{11} moments of the di-pion decay angular distribution in the photon energy range $E_\gamma = 3.2-3.4$GeV and momentum transfer range $-t = 0.5-0.6$ GeV^2 as a function of the di-pion mass; all moments are dominated by the contribution of the $\rho(770)$ meson in the $p-$wave, while a structure associated to the $f_0(980)$ becomes evident in the Y_{10}, Y_{11} because of the interference between the S and P waves. Right: differential cross section associated to the S (top), P (middle) and D (bottom) waves.

MESON SPECTROSCOPY AT CLAS

Meson spectroscopy represents a significant part of the physics program of the CLAS Collaboration. Several exclusive final states have been measured looking for contribution of specific resonances. Since meson resonances are numerous, broad and often overlapping, the extraction of a single state requires sophisticated Partial Wave Analysis (PWA) techniques. Two different approaches have been applied to the analysis of the CLAS data. The first is based on the so-called *isobar model*, where the amplitudes that are fitted to the data are built assuming the decay of the resonance to the multi-particle final state occurs through a series of subsequent two-body decays. This approach has been widely adopted in meson spectroscopy studies as it allows to construct amplitudes for a number of complex final states starting from well known two-body decays. The second approach is based on the extraction of angular moments that are then analyzed in terms of partial waves using dispersion relations.

The isobar model approach was applied to CLAS data of three pion photoproduction on proton target [4]. This reaction channel is particularly interesting for the search for exotics. Evidence for the exotic $\pi_1(1600)$ was in fact reported from the analysis of three pion data recorded by the E852 Collaboration at BNL [5]. This first result was not confirmed by a later re-analysis of the same data with a PWA that includes a larger number of of waves [6], leaving an open question about the existence of this state. The results of the analysis of the CLAS data showed clear evidence for know resonances as the $a_2(1320)$ but no indication for the exotic π_1, setting an upper limit on the production cross section for the state of about 13.5 nb at 95% CL. Recently, new evidence for the same exotic state was reported by the COMPASS Collaboration [7], opening once more the debate on the real existence of this resonance.

The second PWA approach was applied to the analysis of the photoproduction of pion pairs [9, 10]. In this case moments of the di-pion angular distribution were evaluated from the data using an unbinned likelihood fit. Angular moments $\langle Y_{LM} \rangle$ are projection of the di-pion differential cross section onto specific spherical harmonics with total angular moment L and z-projection M. Different moments have different sensitivity to specific partial waves, depending on the values of L and M. For example, the $\langle Y_{10} \rangle$ and $\langle Y_{11} \rangle$ are particularly sensitive to the waves with lower angular momentum and specifically to the S, P and D waves. As an example, the first three moments of the di-pion angular distribution are shown in the left panels of Fig. 2. The dominant contribution of the $\rho(770)$ is clearly observed in all three moments, while a narrow structure below 1 GeV is found in the $\langle Y_{10} \rangle$ and $\langle Y_{11} \rangle$ moments. This structure is interpreted as evidence for the scaler $f_0(980)$ meson. This conclusion is supported by the partial waves that were evaluated from the experimental moments using dispersion relations and in particular by the structure observed in the S-wave shown in the top-right panel of Fig. 2. The strength of the S-wave in the mass region of the $f_0(1980)$ is found to be a factor of about 50 lower than the strength of the dominant P-wave.

Presently, other large statistics samples are being analyzed. Among these, data are being analyzed looking for coherent meson production on ^4He [11]. The final states that are being studied are the $\pi\eta$ and $\pi\eta'$ channels, where the strongest evidence for the exotic $J^{PC} = 1^{-+}$ $\pi_1(1400)$ was reported by the E852 Collaboration [8]. These final states are produced by scattering the electrons of the primary Jefferson Lab beam on an 7 atm. ^4He gas target. The electron is scattered at “0” degrees, corresponding to very low four-momentum transfer and therefore quasi-real photons. The coherence of the reactions is ensured by detecting the recoiling ^4He in a radial TPC, which surrounds the high-pressure target. In this type of reactions, the excitation of nucleon resonances, which constitutes a major source of background, is significantly suppressed. In addition ^4He, being a spin and isospin zero object, acts as a spin and parity filter for the final state mesons. Data in this configuration were taken in the fall of 2009 and results are expected in the near future.

THE JEFFERSON LAB UPGRADE AND THE CLAS12 DETECTOR

Jefferson Lab is in the process of upgrading the energy of the accelerator from the 6 GeV, presently available, to 12 GeV. The upgrade plan includes the installation of new superconductive cavities to increase the energy of the two LINACs to 1.1 GeV and the upgrade of the magnets of the re-circulation arcs. This will lead the accelerator to deliver 11 GeV electron beam to the three existing experimental Halls and 12 GeV beam the new Hall D that is being built as part of the upgrade scope. The equipment of the Halls A,B and C will also be upgraded as part of the project. Hall B will hosts the newly designed CLAS12 detector. This spectrometer will retain the most significant features of the existing CLAS detector with enhanced capabilities in terms of kinematic coverage, resolution, particle identification and operating luminosity ($10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$). CLAS12 will consist of a forward spectrometer and a central spectrometer, based respectively on a toroidal and solenoidal magnet. The forward spectrometer, including new drift chambers, time of flight scintillators, Cerenkov counter and electromagnetic calorimeter, will provide the detection capability for the scattered electron and forward-going hadrons. The central spectrometer is designed to detect large-angle recoiling hadrons, using a silicon tracker, time of flight detector and a neutron detector. Most of these elements are part of the basic equipment that is part of the Jefferson Lab upgrade project, funded by the US Department of Energy for a total of 310 million dollars.

While the construction of the new detector components has already started to be ready for the beginning of operation planned for 2013-2014, upgrades to the approved equipment have already been proposed by several participating institutions and are being designed. These include a RICH detector to extend the particle identification in the kaon sector, the above-mentioned neutron detector, the micromegas central tracker which will complement the silicon tracker and the *forward photon tagger* that will allow to continue the photoproduction program at 12 GeV.

QUASI-REAL PHOTOPRODUCTION WITH CLAS12

The existing Hall B photon tagger will not be upgraded to operate at 12 GeV, both because of cost consideration and space constraints. An alternative possibility to continue measuring photoproduction reactions at higher energy is to use

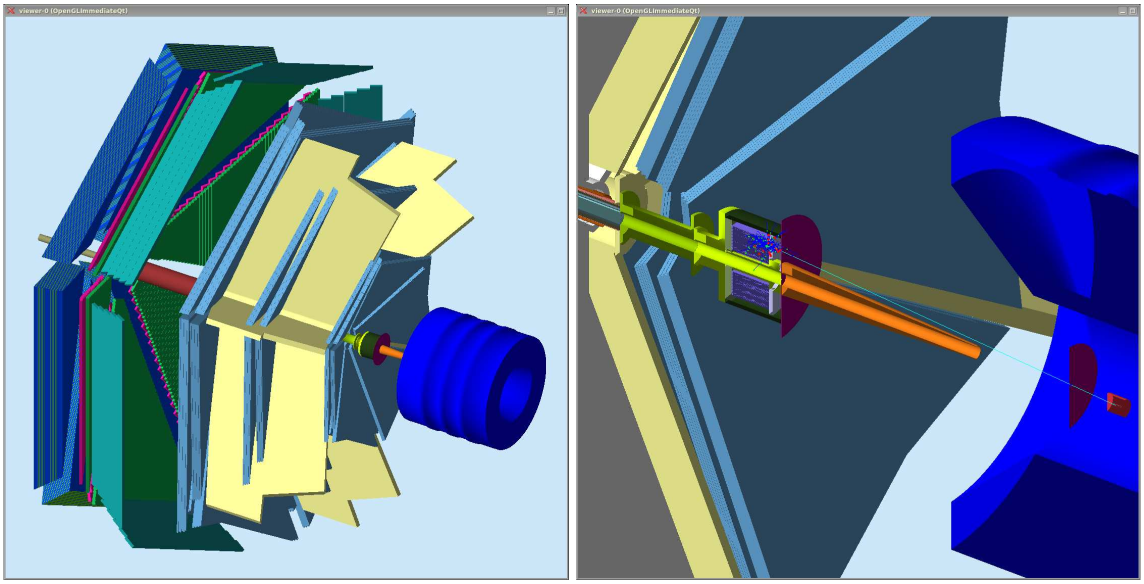

FIGURE 3. GEANT4 visualization of CLAS12 and of the low Q^2 photon tagging facility. The system consist of an electromagnetic calorimeter, shown in green in the left panel, a veto counter and a tracker, shown in magenta, located between the forward and central CLAS12 spectrometer. A tungsten cone, shown in orange, shield the calorimeter by Möller electrons. In the right panel, a longitudinal section of the CLAS12 setup is shown for an event with 2 GeV, 3° electron impinging on the tagging facility.

electro-production at very small electron scattering angles, of the order of few degrees or smaller. In this kinematics, the four-momentum transfer, Q^2, associated to the reaction is very small and the virtual photon which is produced can be considered as quasi-real. This technique has been widely used in high energy experiments as H1 and ZEUS at DESY or COMPASS at CERN and has several advantages with respect to the traditional Bremmstrahlung photon beams. The virtual photons associated with small-angle electrons have an intrinsic and sizeable degree of linear polarization with values that depend on the photon energy. The linear polarization can be established on an-event-by-event basis by measuring the electron energy and scattering plane. This information is crucial to understand the meson production mechanism and provides important constraints in the PWA, reducing therefore ambiguities in the physics analysis. In addition, the usage of electron beams gives the possibility of running with high luminosity on thin targets as for example, the ^{4}He gas target mentioned before.

To exploit this possibility, a low-Q^2 tagging facility or *forward tagger* has been proposed for CLAS12. The facility will be used to detect electrons between 2.5 and 4.5 degrees in the energy range between 500 MeV and 4.5 GeV. The corresponding virtual photons will be in the energy range 6.5-10.5 GeV, which is adequate for the production of mesons with masses around 2 GeV. The Q^2 will be between 0.01 and 0.3 GeV^2 and the degree of linear polarization will vary between 10 and 65%. The forward tagger will consist of an electromagnetic calorimeter to identify the electrons and measure their energy, a veto counter to distinguish electrons from photons and a tracker to measure the electron angles precisely and therefore determine the photon linar polarization. The facility will be located between the CLAS12 forward and central spectrometers and will be designed to be compatible with the detector base equipment.

The use of the *forward tagger* to measure low-Q^2 electrons in conjunction with the detection of multiparticle final states in CLAS12 will open new possibilities for high quality physics beyond the already approved program. The large acceptance for charged and neutral particles, the excellent momentum resolution and the particle-identification capabilities will allow the study of a broad range of exclusive reactions and continue the study of meson and baryon spectroscopy at 12 GeV.

SUMMARY

Meson spectroscopy is a fundamental tool to deepen our understanding of strong interaction. The investigation of meson production and the search for exotics quark-gluon configurations is presently an important part of the physics program that is being carried on with CLAS at 6 GeV. First results from PWA analysis of multiparticle final states have been published, demonstrating the feasibility of these complex analyses in CLAS and contributing to the worldwide effort in this field. New high statistics data sets are already available and are now being analyzed.

The extension of this physics program at 12 GeV is being proposed based on quasi-real photoproduction. For this purpose a new detector component, called *forward tagger*, is being designed to measure electrons scattered at very small angles and therefore tag the corresponding virtual photons. This facility will allow to run high intensity beam on proton and light-nuclei targets, giving access to a rich physics program.

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