Hadron Spectroscopy at CLAS12 and Panda

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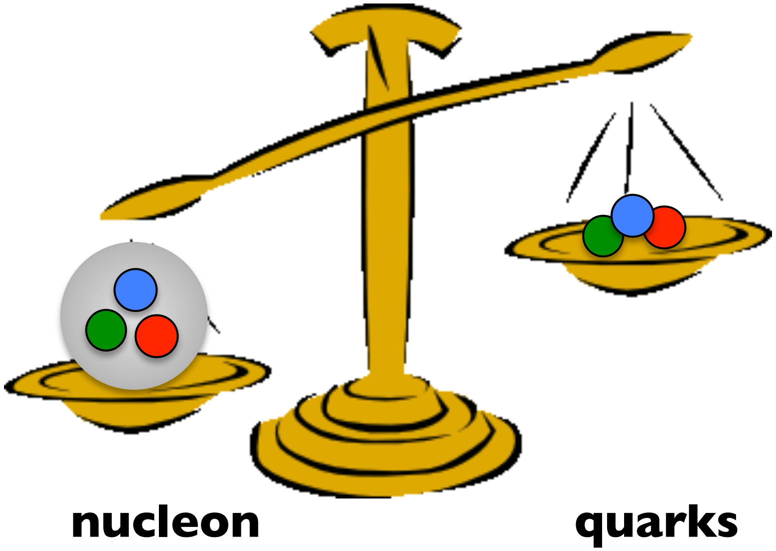
PANDA Collaboration Meeting

Laboratori Nazionali di Frascati 12/9/2014

Why Hadron Spectroscopy

- Most of the visible mass of the universe is due to hadrons, in particular to the protons and neutrons that form the atomic nucleus
- Hadrons have an internal structure being made of quarks but quark masses account only for a small fraction of the nucleon mass: ~ 1%
  - $m_q \sim 10$ MeV
  - $m_N \sim 1000$ MeV

  while the remaining fraction is to to the force that binds the quarks: **QCD**
- Studying the hadron spectrum is a tool to answer fundamental questions as
  - What is the internal structure and what are the internal degrees of freedom of hadrons?
  - What is the role of gluons?
  - What is the origin of quark confinement?
  - Are 3-quarks and quark-antiquark the only possible configurations



A Global Approach to Spectroscopy

Answering these fundamental questions requires is a challenging tasks that requires a **global approach**

Experiments:

- Different reactions in different regimes can provide complementary sensitivity (annihilation, diffraction, photo-production, …)
- New/Critical findings need confirmation from more than one experiment
- Light versus heavy quark

Analysis:

- Sophisticated PWA frameworks to hunt for small signals
- Efficient computing strategies (GPUs, cloud, …) to cope with large statistics and large number of fitting parameters

Theory:

- Critical to provide guidance to experimental studies (Lattice QCD, …)
- Development of sophisticated amplitudes exploiting the world data and fundamental constraints (unitarity, analiticity, …)

Need for a tight collaborations between experiments and between experimentalists and theorists

Spectroscopy in the World: Jlab and Panda

- Many experiments in the world are studying hadron spectroscopy
- **Jlab** and **Panda** are two of the key players in the near future

CLAS12 and GlueX @Jlab:

Technique: *electro- and photo-production on proton and neutron target*

Physics Program:

- ***meson spectroscopy***: *search for hybrids, study of rare states, strangeness-rich resonances, …*
- ***baryon spectroscopy:*** *strangeness-rich states and nucleon resonances*

Panda @ FAIR:

Technique: *proton-antiproton annihilation*

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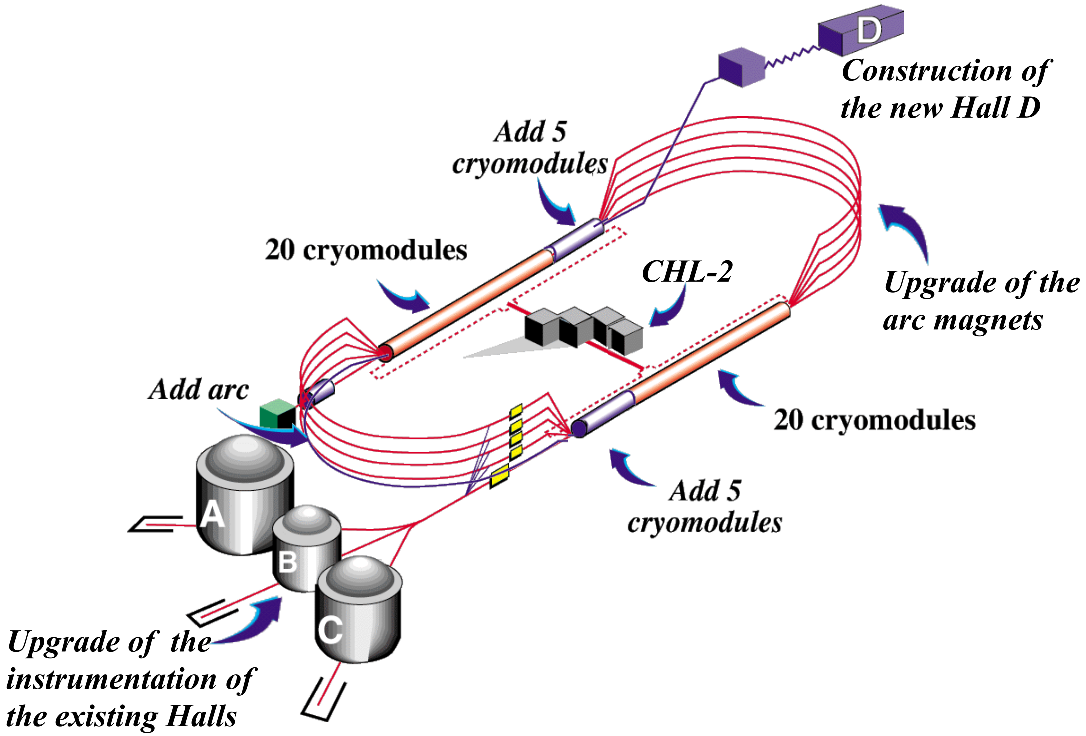
Jefferson Laboratory

Continuous Electron Beam Accelerator Facility (CEBAF):

- a superconducting electron machine based on two linacs in racetrack configuration
- presently being upgraded to 12 GeV



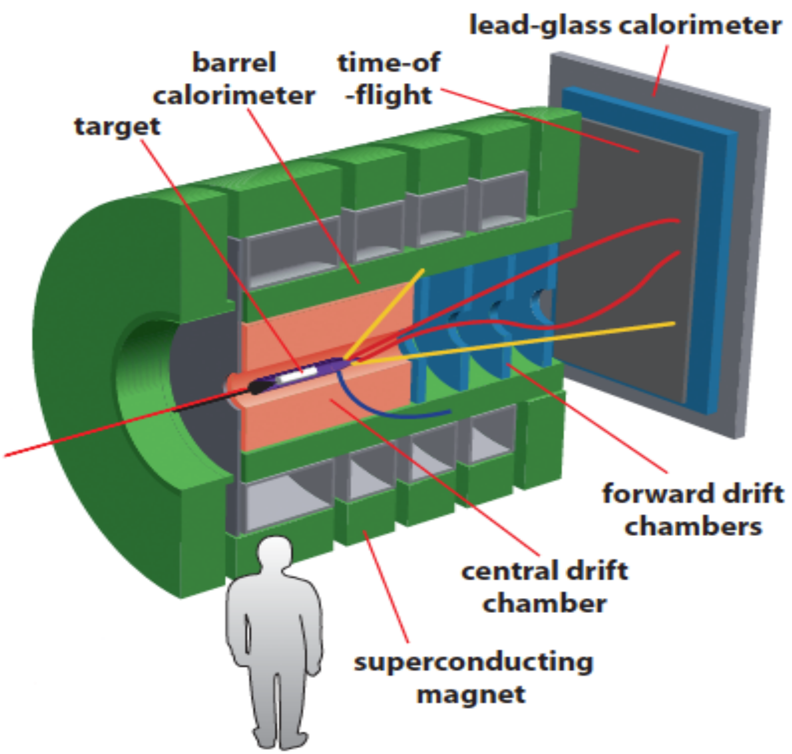
High electron polarization
Beam Power: 1MW
Beam Current: 90 μA
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

CLAS12 and GLUEX

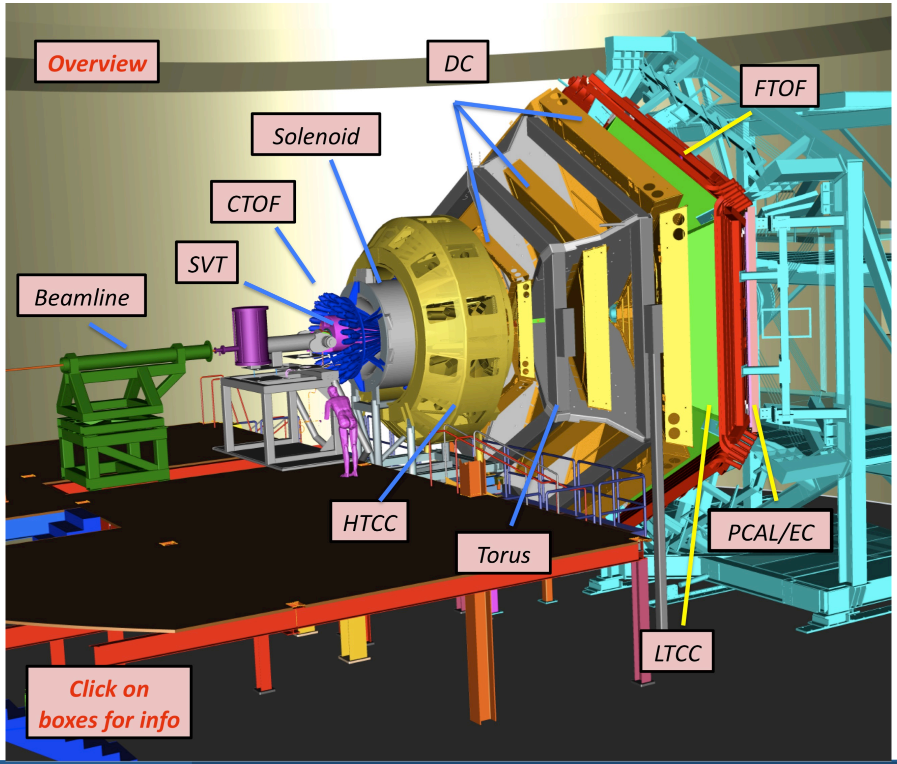
Spectroscopy is one of the main topics that will be studied with the Jlab 12 GeV upgrade. Key elements are:

- High intensity electron and tagged photon beams
- Detectors with large acceptance and good particle identification capabilities

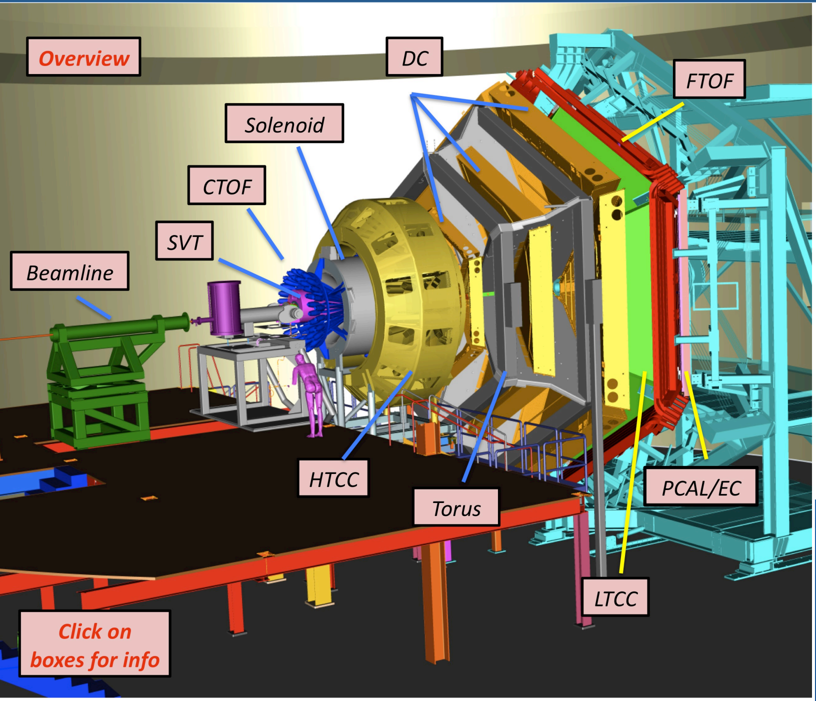
GlueX in Hall D



CLAS12 in Hall B



The CLAS12 Experiment



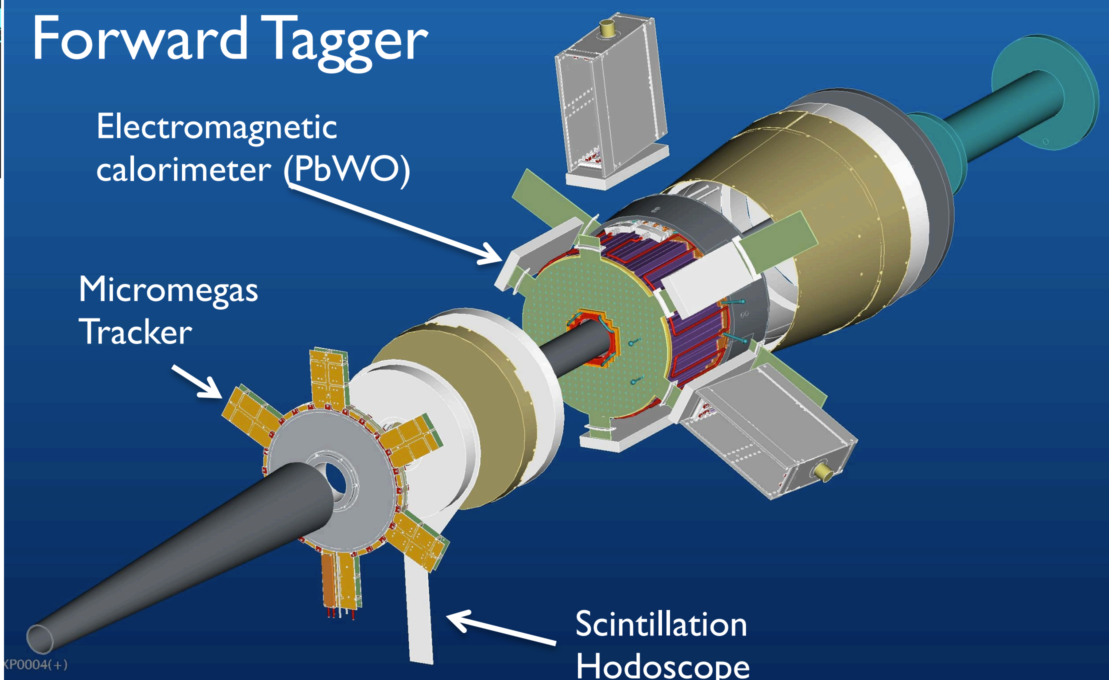
Experimental Technique:

- Detection of multiparticle final state from hadron decay in the large acceptance spectrometer CLAS12
- **Quasi-real photo-production**: Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger
- **Electro-production**: Detection of the scattered electron in CLAS12 to measure the Q^2 evolution of nucleon resonance form factors

Physics goals:

- Detailed mapping of the meson spectrum up to 2.5 GeV, study of strangeness rich states and search for exotics
- Spectroscopy of (very) strange baryons ($\Lambda^*\Sigma^*$, Ξ^* and Ω^-)
- Study of nucleon resonances with the search for missing states and the investigation of form factors

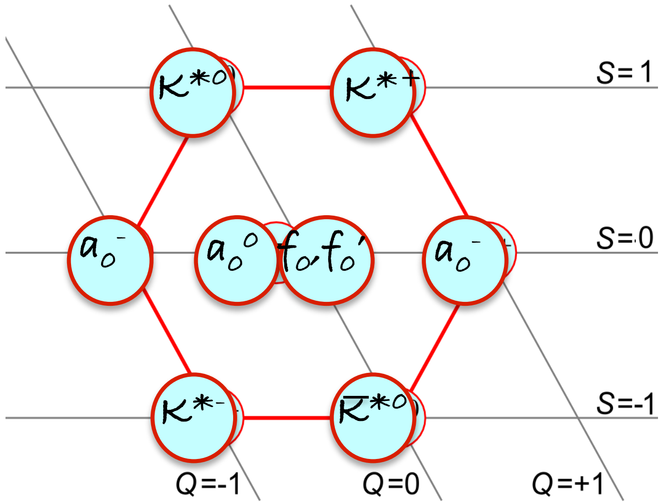
Forward Tagger

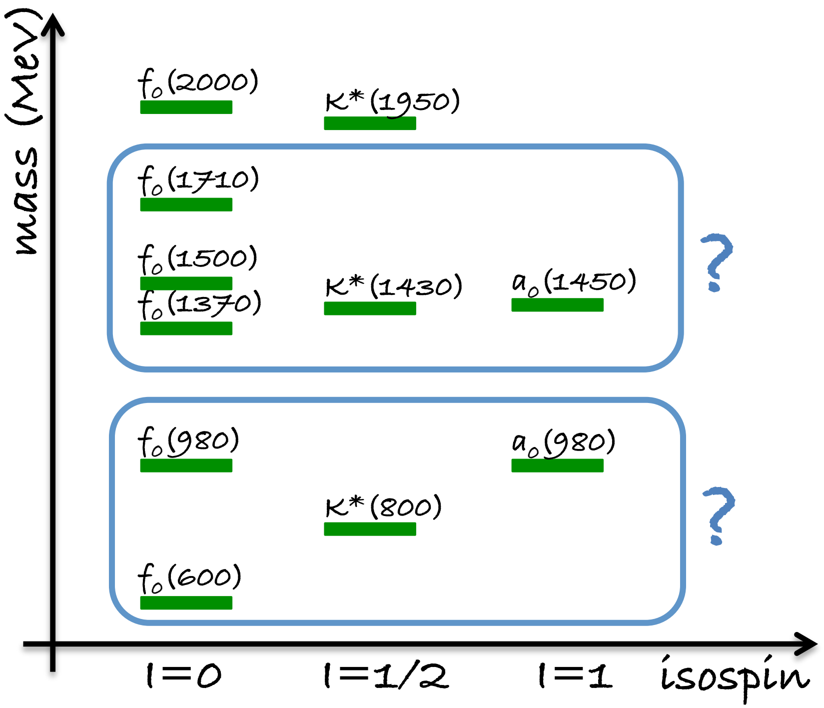


Scalar Mesons

Scalars are fundamental states because they represent the Higgs sector of strong interaction:

- same quantum numbers of the QCD vacuum
- responsible for chiral symmetry breaking



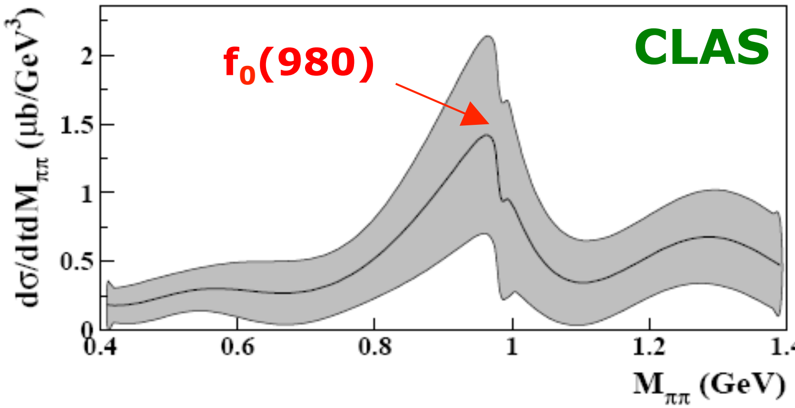


- The scalar meson nonet should be composed by a_0(I=1),K* (I=1/2), f_0 and f_0'(I=0), with the a_0 as lightest state and the f_0' showing a large strange content
- At present, given the I=1 and I=1/2 states that have been identified, there is an excess of I=0 states

The $f_0(980)$ meson

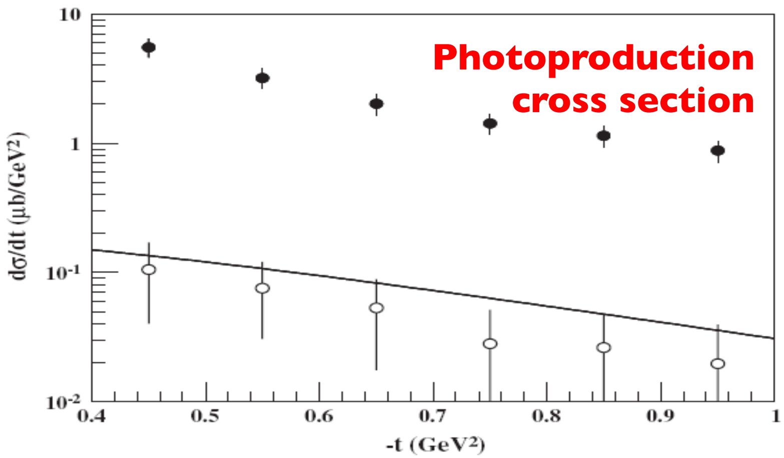
The $f_0(980)$ is one of the lowest mass scalar and isosinglet candidate of the first nonet:

➔ Unusual mas hierarchy of the multiplet ($f_0(980)$ almost degenerate with $a_0(980)$) and decays led to propose these states as TETRAQUARKs



CLAS, PRL 102, 102001 (2009)

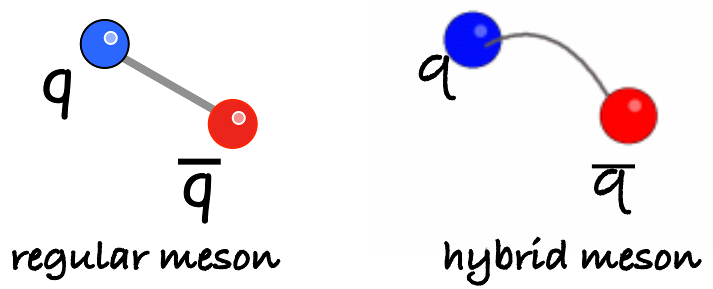
- Studied at CLAS analyzing the photo-production of pion pairs on proton target
- Full PWA analysis of $M(\pi^+\pi^-)$ spectrum below 1.5 GeV:
  - P-wave: ρ meson
  - D-wave: $f_2(1270)$
  - S-wave: σ, $f_0(980)$ and $f_0(1320)$
- Known states well reproduced, e.g. ρ(770)
- First observation of the $f_0(980)$ in photo-production

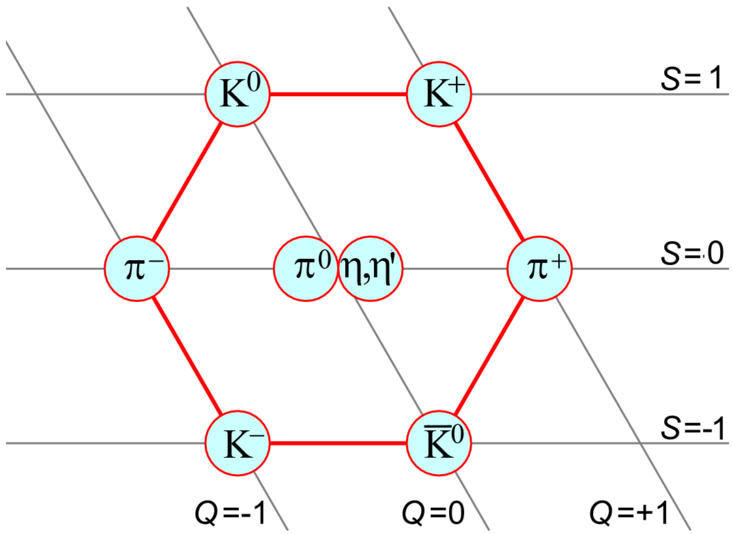


Investigation of scalar mesons will continue with CLAS12

Hybrids and Exotics

- Hybrids ($q\bar{q}g$) are the ideal system to study $q\bar{q}$ interaction and the role of gluons
- Existence is not prohibited by QCD but not yet firmly established.
- A possibility to identify unambiguously a meson as an hybrid state is to look for *exotic quantum numbers*





- Excitation of the glue leads to a new spectrum of hadrons that can have *exotic quantum numbers*

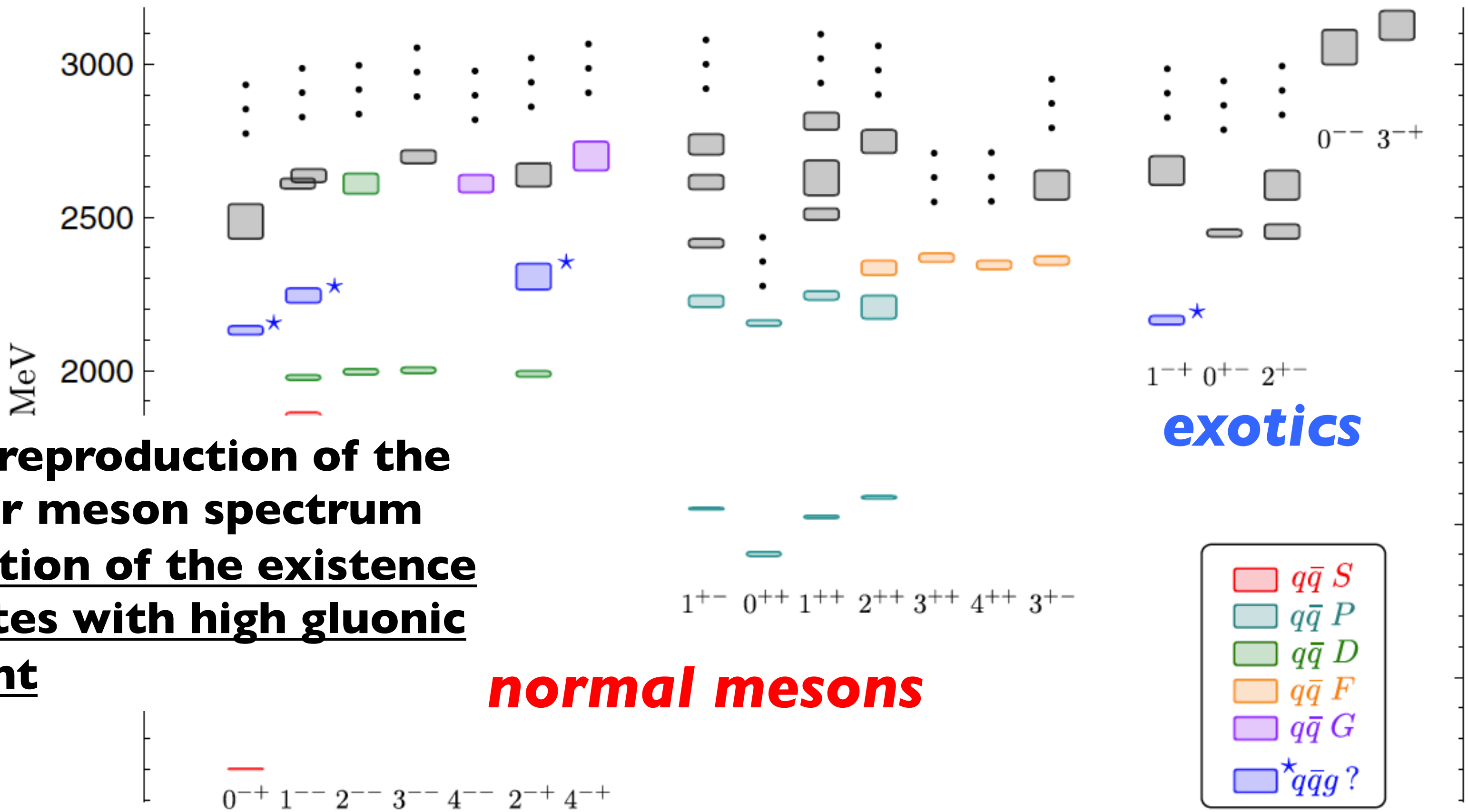
$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} \ldots$$

- For each exotic quantum number combination, a nonet of state should exist, including states with open or hidden strangeness
- Lattice QCD calculations predict masses around 2 GeV, a range that can be explored at JLab

Lattice QCD

J. Dudek et al., Phys. Rev. D84, 074023 (2011)

Predictions of the meson spectrum from Lattice QCD are now available



- **Good reproduction of the regular meson spectrum**
- **Indication of the existence of states with high gluonic content**

isovector mesons, m_π~700 MeV

Strangeonia in CLAS12

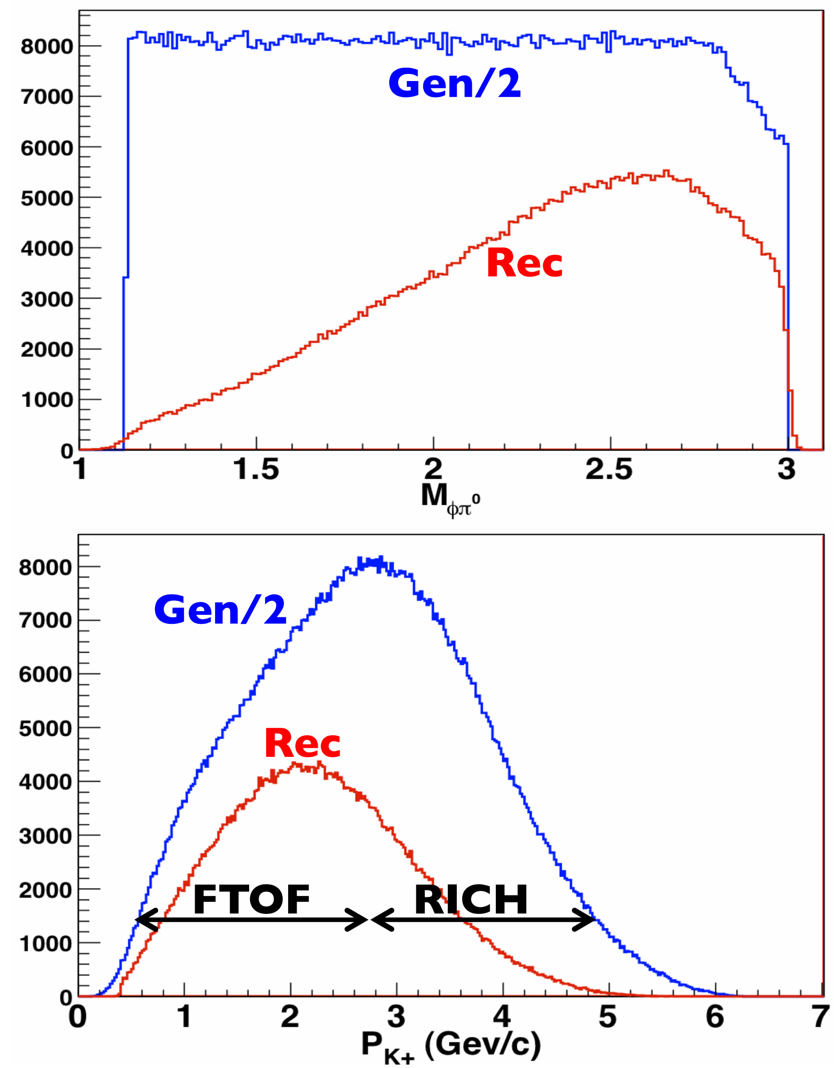
- The φπ final state is one of the best candidate for the search of hybrids:
  - $s\bar{s}$ meson decay is prohibited by isotopic spin conservation
  - $n\bar{n}$ meson decay is suppressed because of the OZI rule
  - Strong coupling is expected for hybrids and tetraquarks

- Candidate C(1480) observed by the LEPTON-F experiment:

  M=(1480±40) MeV

  Γ =(130±60) MeV

- Can be studied in CLAS12 via the final state $\gamma p \rightarrow pK^+(K^-)\gamma\gamma$
  - acceptance ~10%
  - exp. cross section ~10nb
  - **π/K separation up to 4-5 GeV needed: FTOF+RICH**



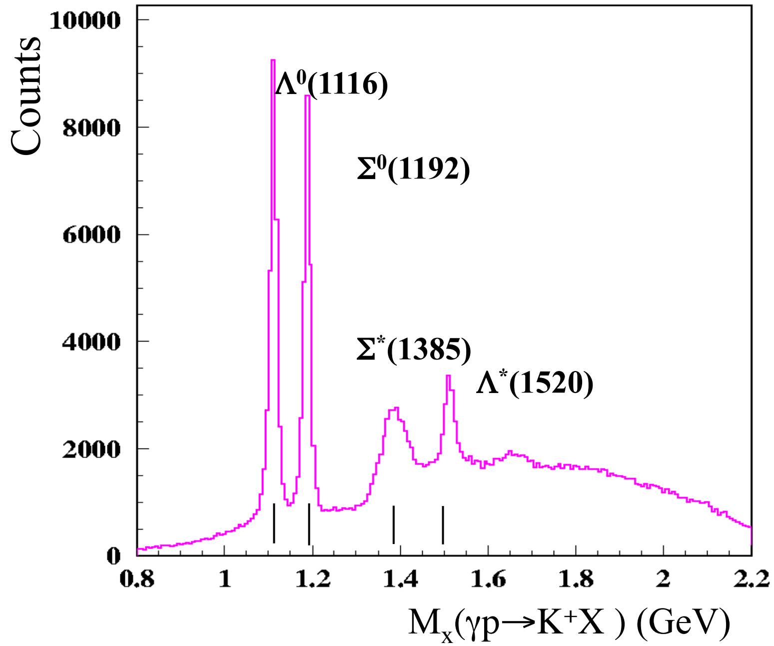
Hadrons and Strangeness

Rich physics program focused on understanding the hadron spectrum and hadron production mechanisms via strangeness tagging in photo and electro-production:

Program started with CLAS…

- **Spectroscopy of mesons with open and hidden strangeness**:
  - φ and $f_0(980)$ production
  - K* spectrum and production
- **Hyperon spectroscopy**:
  - Lambda, Sigma and Cascade ground and excited states
  - Measurement of total cross sections, differential cross sections and polarization observables to investigate internal structure and strangeness formation

…will be extended in scope and precision with CLAS12

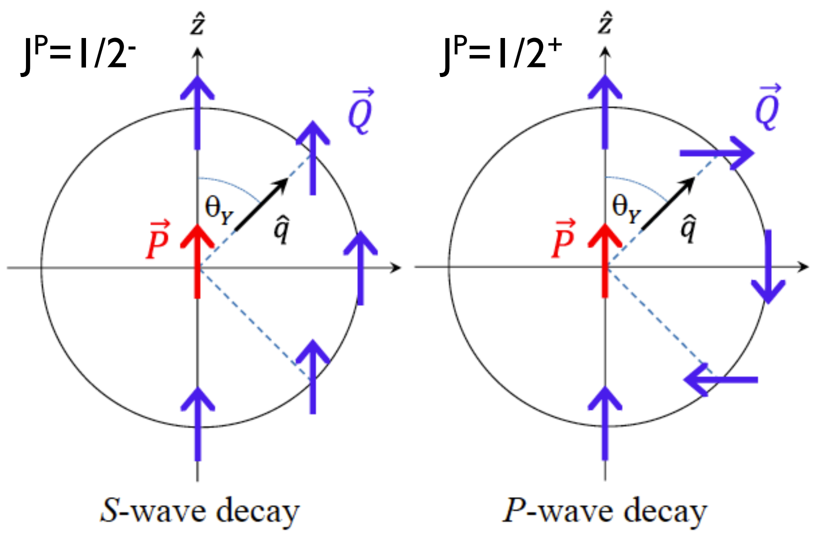


CLAS has the largest data set in hyperon photo-production and more than 25 publications in journals

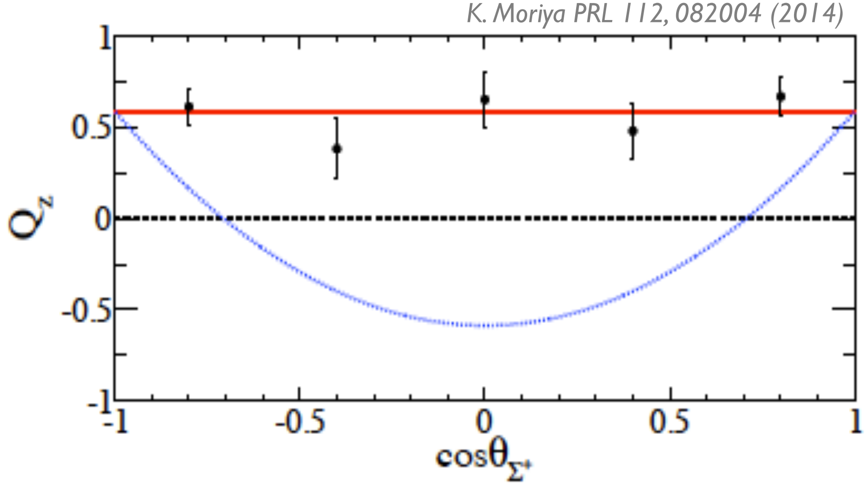
Hyperons: Λ (1405) Spin and Parity

Parity and spin of the state were never measured before and PDG J^P assignment is based on the CQM expectation

- J and P can be inferred finding a reaction where Λ(1405) is created polarized and studying the decay:
  $$\Lambda(1405) \rightarrow \Sigma\,\pi$$
- Decay angular distribution relates to J:
  - J=1/2: flat distribution
  - J=3/2: "smile" or "frown" distribution
- Parity is given by polarization transfer to daughter



K. Moriya PRL 112, 082004 (2014)



Analysis of decay angular distribution indicate an isotropic decay in S-wave

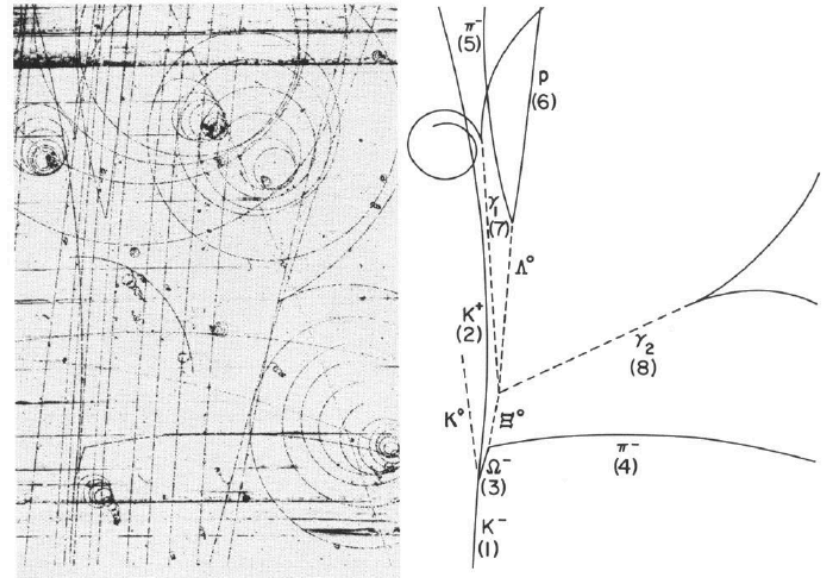
$J^P=1/2^-$

experimentally determined for the first time

Very Strange Baryons

Study of the Ω^- and Ξ^* are among the main goals of the CLAS12 spectroscopy program:

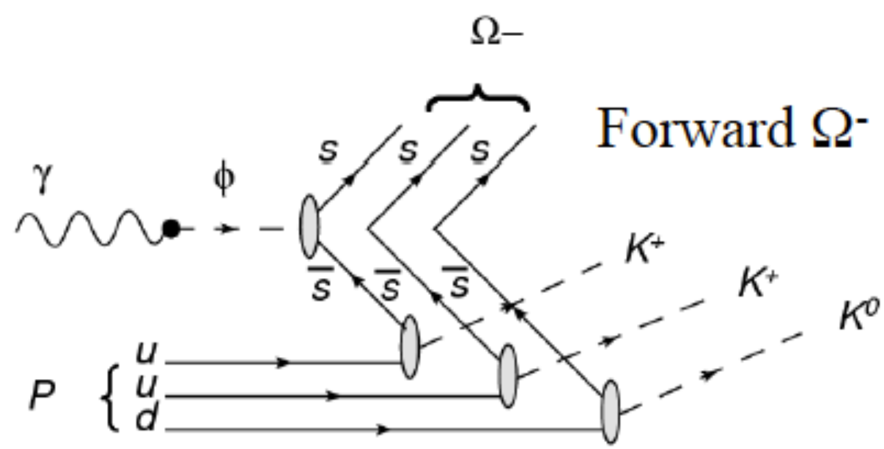
- Ω^- discovered in 1964: after 50 years, indication on J^P from Babar and others but full determination not yet achieved
- Ξ^* spectrum still poorly known: many states missing and spin/parity undetermined



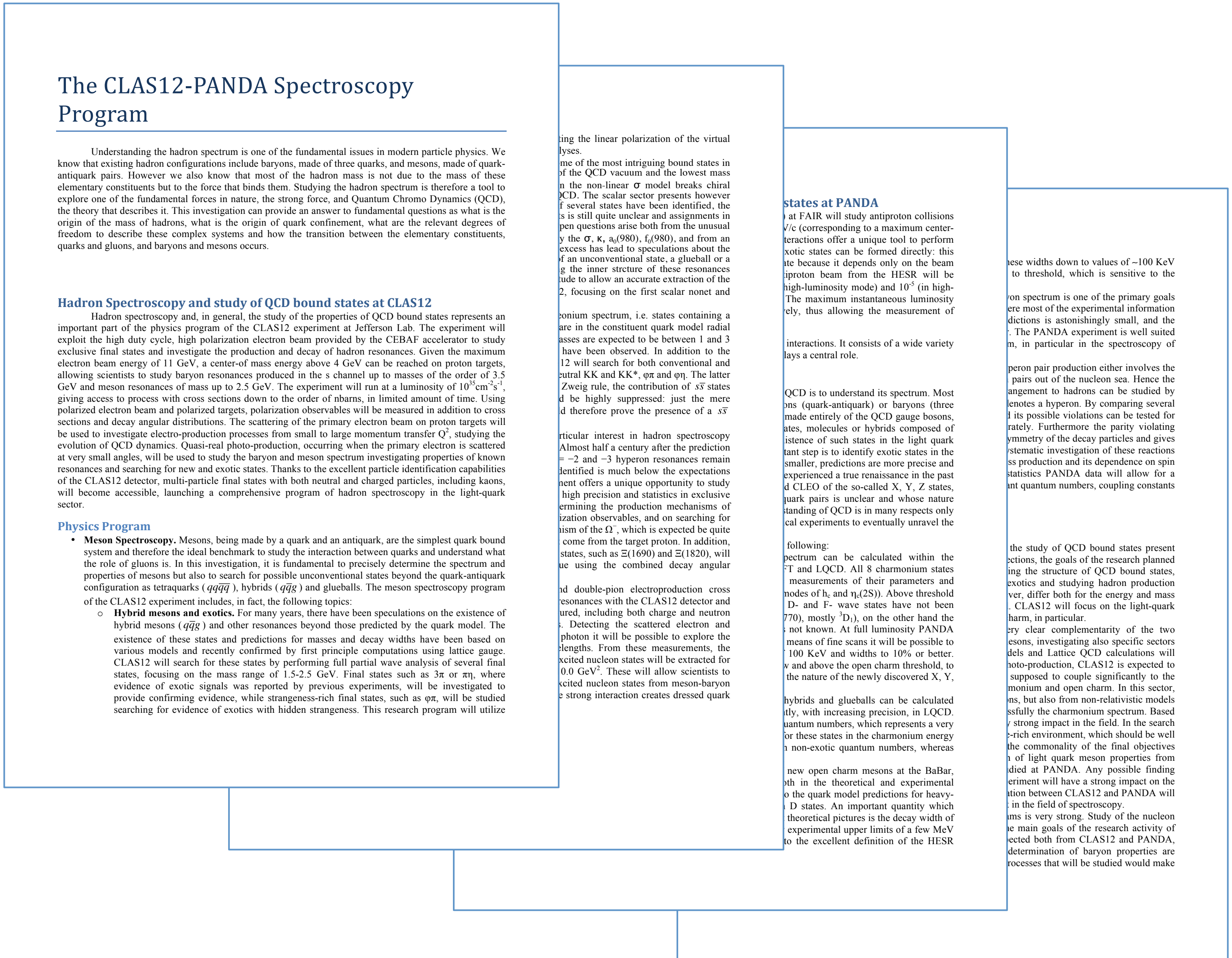
V. E. Barnes et al., Phys. Rev. Let. 12 (1964) 204

Photoproduction mechanism implies creation of three s quarks

- Models indicate $\sigma(\Omega^-) \sim 0.3\text{-}2$ nb at E~7GeV
- Expected production rates in CLAS12:
  - Ω^- : 90 /h
  - Ξ-(1690)/Ξ-(1820): 0.2/0.9 k/h
- Ω^- : measurement of the cross section and investigation of production mechanisms
- Ξ^*: spin/parity determination, cross section and production mechanism, measurement of doublets mass splitting



CLAS12-PANDA Spectroscopy Program



The CLAS12-PANDA Spectroscopy Program

Understanding the hadron spectrum is one of the fundamental issues in modern particle physics. We know that existing hadron configurations include baryons, made of three quarks, and mesons, made of quark-antiquark pairs. However we also know that most of the hadron mass 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, the strong force, and Quantum Chromo Dynamics (QCD), 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.

Hadron Spectroscopy and study of QCD bound states at CLAS12

Hadron spectroscopy and, in general, the study of the properties of QCD bound states represents an important part of the physics program of the CLAS12 experiment at Jefferson Lab. The experiment will exploit the high duty cycle, high polarization electron beam provided by the CEBAF accelerator to study exclusive final states and investigate the production and decay of hadron resonances. Given the maximum electron beam energy of 11 GeV, a center-of mass energy above 4 GeV can be reached on proton targets, allowing scientists to study baryon resonances produced in the s channel up to masses of the order of 3.5 GeV and meson resonances of mass up to 2.5 GeV. The experiment will run at a luminosity of $10^{35}cm^{-2}s^{-1}$, giving access to process with cross sections down to the order of nbarns, in limited amount of time. Using polarized electron beam and polarized targets, polarization observables will be measured in addition to cross sections and decay angular distributions. The scattering of the primary electron beam on proton targets will be used to investigate electro-production processes from small to large momentum transfer Q^2, studying the evolution of QCD dynamics. Quasi-real photo-production, occurring when the primary electron is scattered at very small angles, will be used to study the baryon and meson spectrum investigating properties of known resonances and searching for new and exotic states. Thanks to the excellent particle identification capabilities of the CLAS12 detector, multi-particle final states with both neutral and charged particles, including kaons, will become accessible, launching a comprehensive program of hadron spectroscopy in the light-quark sector.

Physics Program

- **Meson Spectroscopy.** Mesons, being made by a quark and an antiquark, 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 precisely determine the spectrum and properties of mesons but also to search for possible unconventional states beyond the quark-antiquark configuration as tetraquarks ($qq\bar{q}\bar{q}$), hybrids ($q\bar{q}g$) and glueballs. The meson spectroscopy program of the CLAS12 experiment includes, in fact, the following topics:
  - **Hybrid mesons and exotics.** For many years, there have been speculations on the existence of hybrid mesons ($q\bar{q}g$) and other resonances beyond those predicted by the quark model. The existence of these states and predictions for masses and decay widths have been based on various models and recently confirmed by first principle computations using lattice gauge. CLAS12 will search for these states by performing full partial wave analysis of several final states, focusing on the mass range of 1.5-2.5 GeV. Final states such as 3π or πη, where evidence of exotic signals was reported by previous experiments, will be investigated to provide confirming evidence, while strangeness-rich final states, such as φπ, will be studied searching for evidence of exotics with hidden strangeness. This research program will utilize

Summary

- Hadron spectroscopy is a key tool to study fundamental aspects of QCD and reach a deep understanding of strong interaction
- The collaboration of experimentalists and theorists at the worldwide level is critical to overcome the open problems and challenges of hadron spectroscopy
- Panda and CLAS12, as key players in the field, have the possibility to strengthen their potential by establishing a tight collaboration and exploiting their similarities and complementarities
- The CLAS collaboration has started a thorough investigation of the meson and hadron spectrum based on existing data
- These studies will continue with CLAS12 with renewed tools and broader reach