Laboratori Nazionali di Frascati
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INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Spectroscopy with Kaons at CLAS and CLAS12

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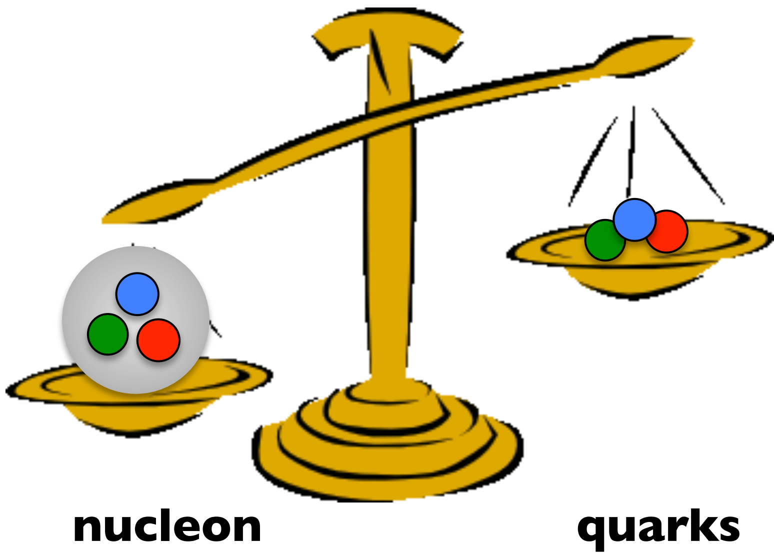
for the CLAS Collaboration

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: known quark configurations are baryons, made of tree quarks and mesons, made of quark-antiquark pairs
- Quark masses account only for a small fraction of the nucleon mass: ~ 1%
  - m_q ~ 10 MeV
  - m_N ~ 1000 MeV

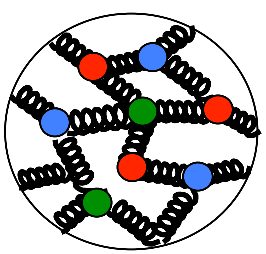
  while the remaining fraction is to to the force that binds the quarks: **QCD**
- QCD with its rules and constraints determines the mass and spectrum of hadrons and makes the world as we know it



Hadrons and QCD

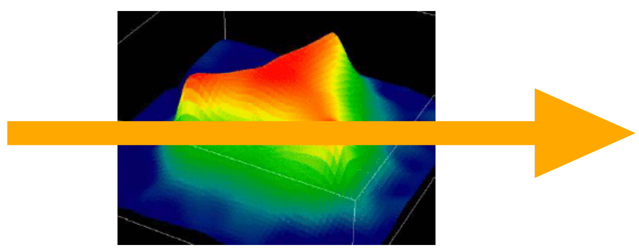
- Studying hadron properties and rules of QCD is crucial to reach a deep understanding of the structure of matter
- Hadrons are color neutral systems made of quarks and gluons but…
  - What is the internal structure and what are the rule that govern hadron production mechanism?
  - What is the role of gluons?
  - What is the origin of quark confinement?
  - Are 3-quarks and quark-antiquark the only possible configurations
- <u>Spectroscopy is a key tool to investigate these issues</u>

<< 0.1 fm



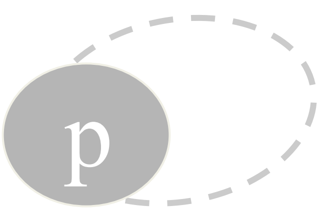
Quarks and Gluons

0.1 – 1 fm



Effective Degrees of Freedom

> 1 fm

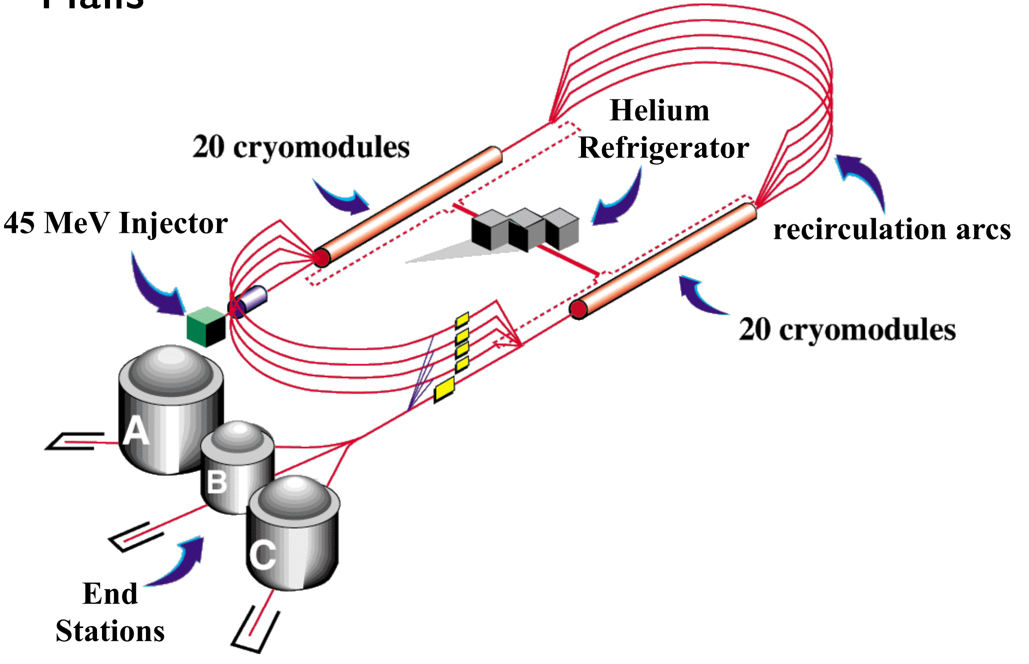


Mesons & Baryons

Jefferson Laboratory

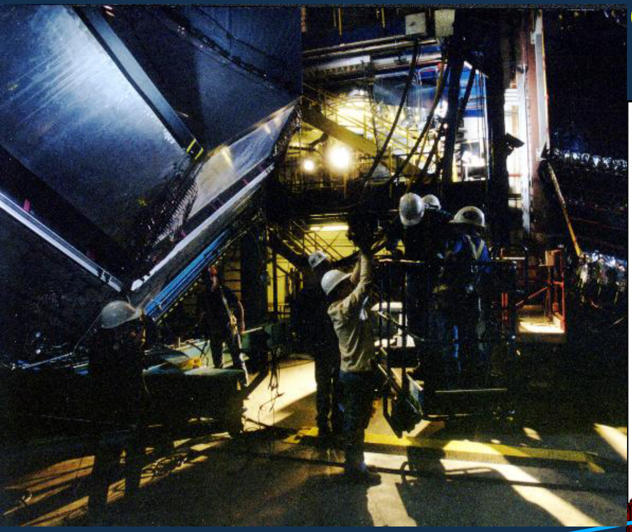
Continuous Electron Beam Accelerator Facility (CEBAF):

- a superconducting electron machine based on two Linacs in racetrack configuration
- Simultaneous distribution to 3 experimental Halls



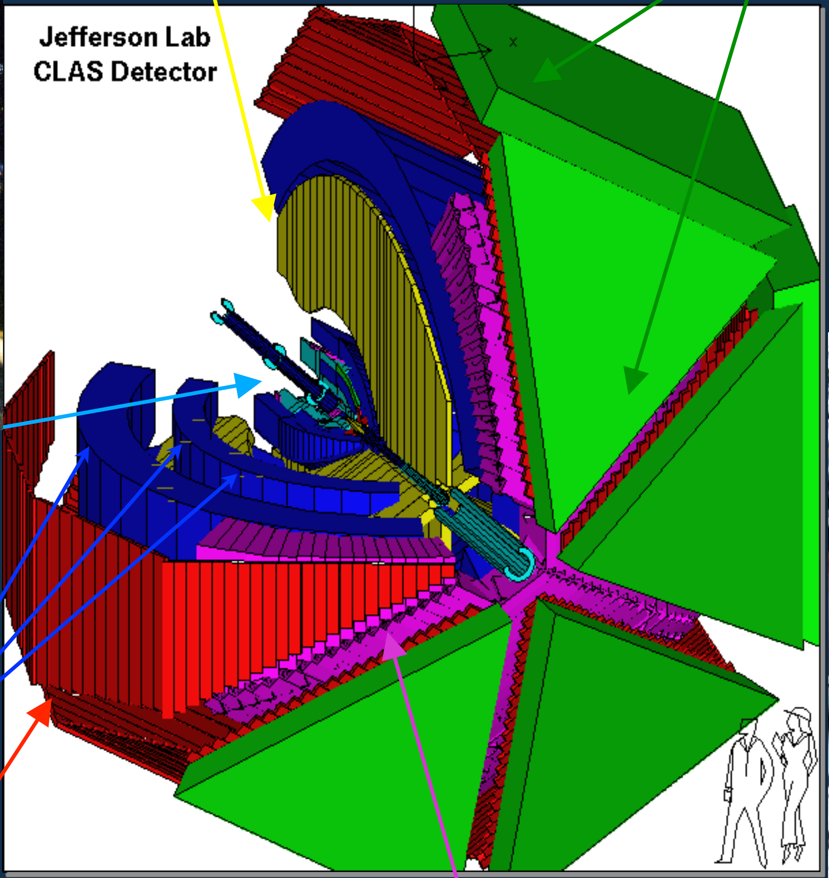
High electron polarization
Beam Power: 1MW
Beam Current: 200 μA
Max Energy: 6 GeV
RF: 1499 MHz

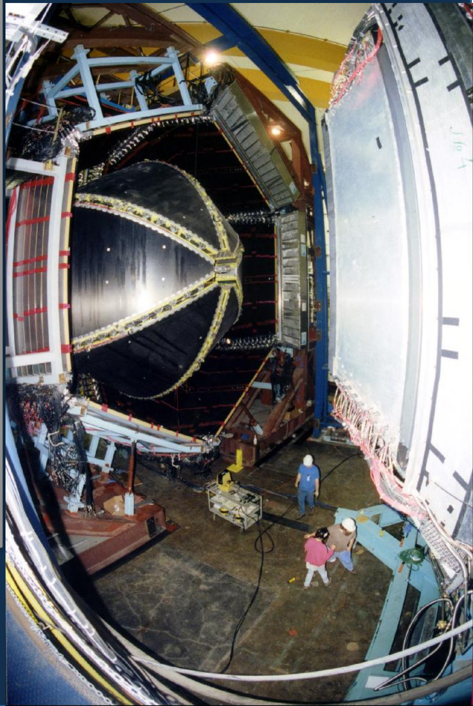
CEBAF Large Acceptance Spectrometer



Torus Magnet
6 Superconductive Coils

Electromagnetic Calorimeter
lead/plastic scintillator, 1296 PMTs





Target + γ
start counter
e mini-torus

Drift Chamber
35,000 cells

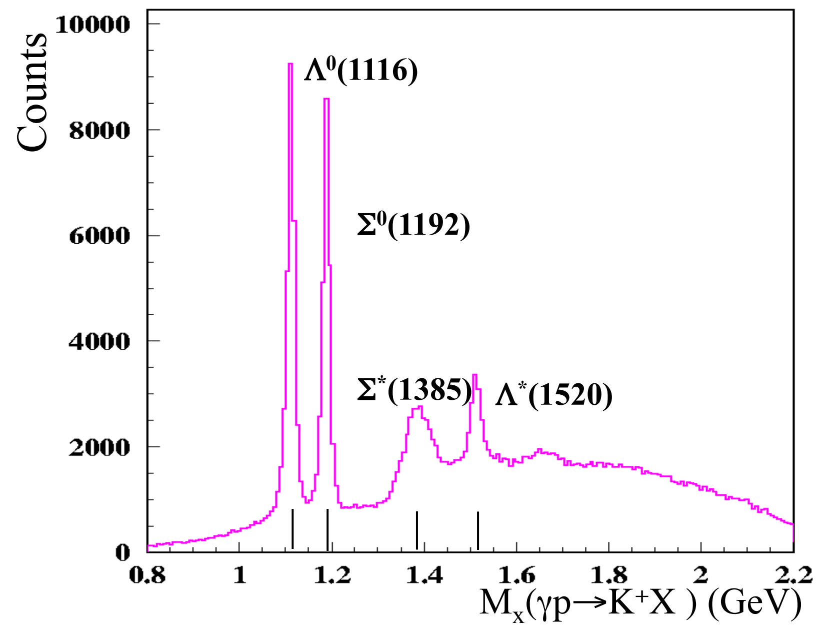
Time of Flight
Plastic Scintillator,
684 PMTs

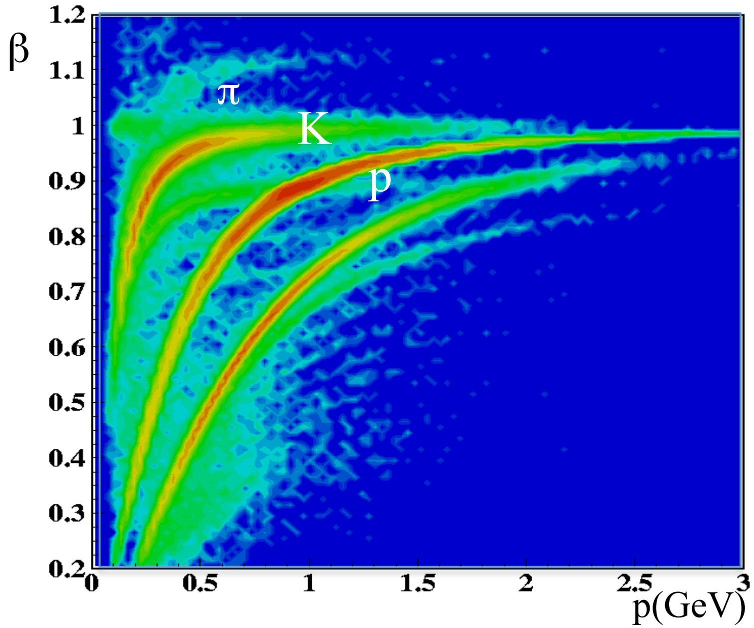
Cherenkov Counter
e/π separation, 256 PMTs

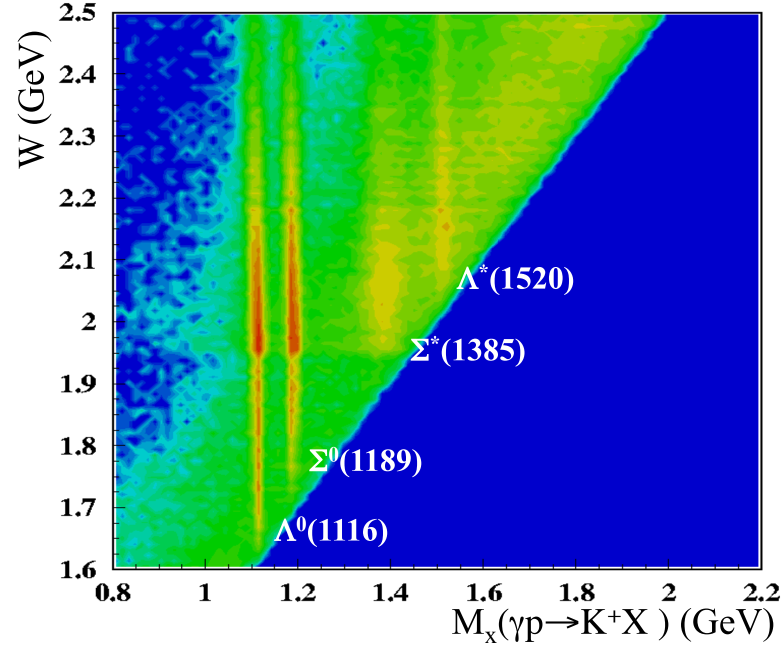
Kaons in CLAS

Kaon ID based on time of flight technique:

- 200 ps average TOF resolution
- pion-kaon separation up to 2.5 GeV
- good match to CLAS energy range and large angular coverage





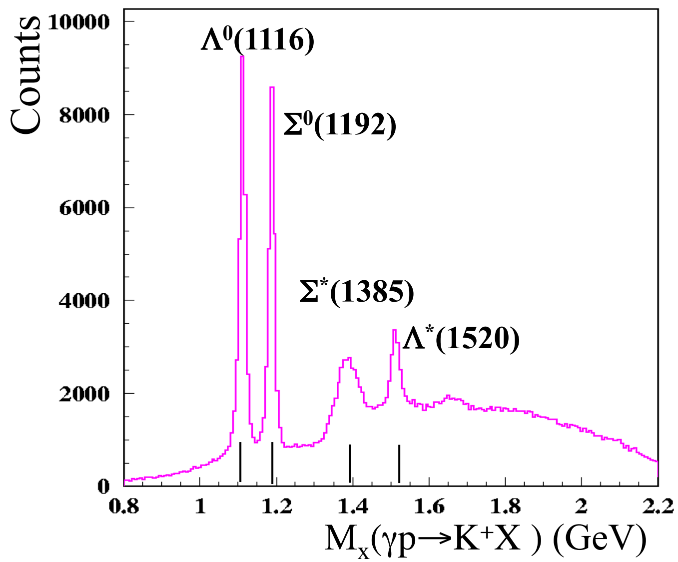


Hadrons and Strangeness

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

- **Spectroscopy of mesons with open and hidden strangeness**:
  - ϕ and $f_0(980)$ production
  - K* spectrum and production

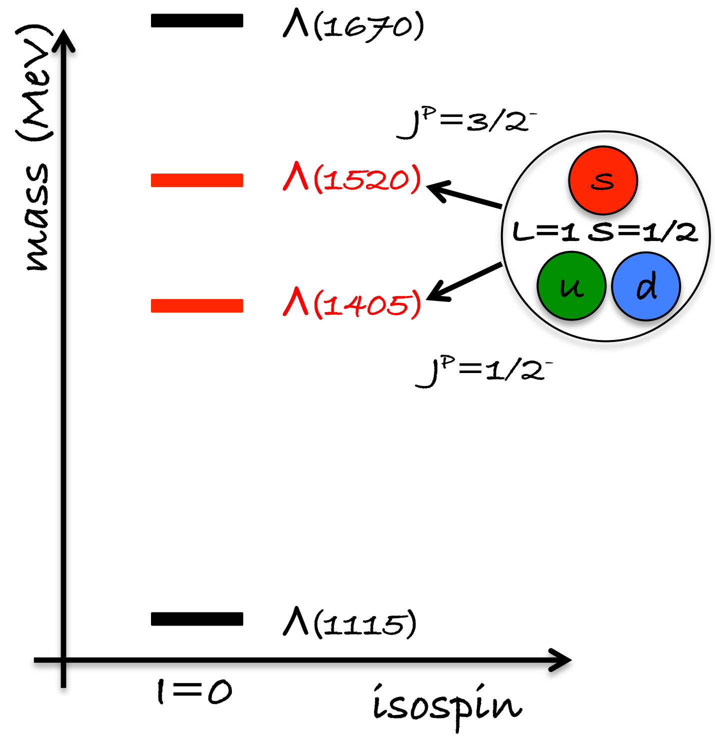


The largest data set in hyperon photo-production and more than 25 publications in journals

Study of the Λ(1405)

First excited state of the Λ baryon:

- State known since 1950's
- PDG:
  - M=(1405±1) MeV
  - Γ=(50±2) MeV
  - $J^P=1/2^-$ based on CQM assignment
- Mass inconsistent with CQM expectations
- Complex line shape
- Mass is below NK threshold but state has a strong coupling to NK
- Different interpretations:
  - Standard 3 quark state
  - Molecule or hybrid
  - Dynamically generated state with two overlapping poles (χUT)



PDG: "The nature of the Λ(1405) has been a puzzle for decades: three-quark state or hybrid; two poles or one. We cannot here survey the rather extensive literature…"

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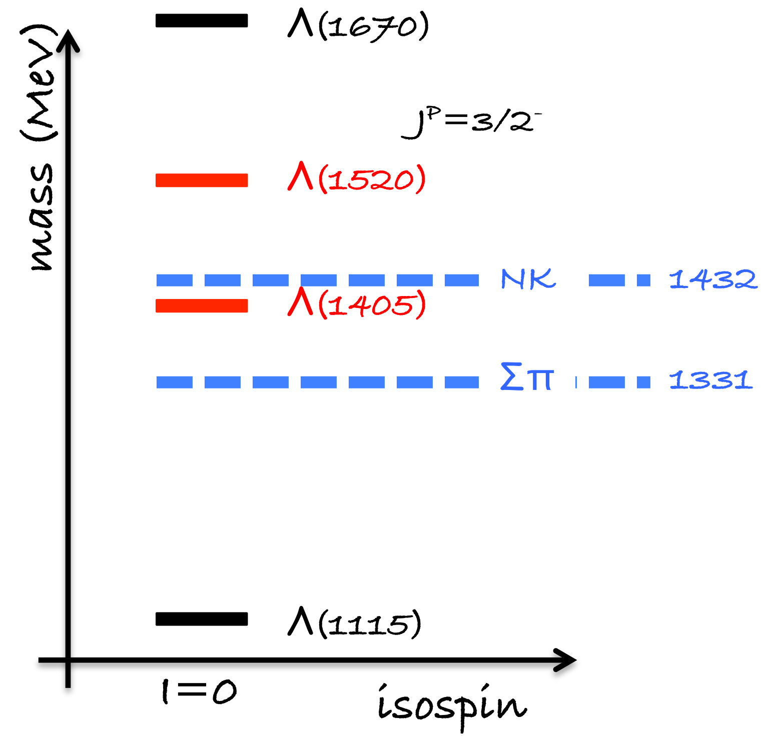

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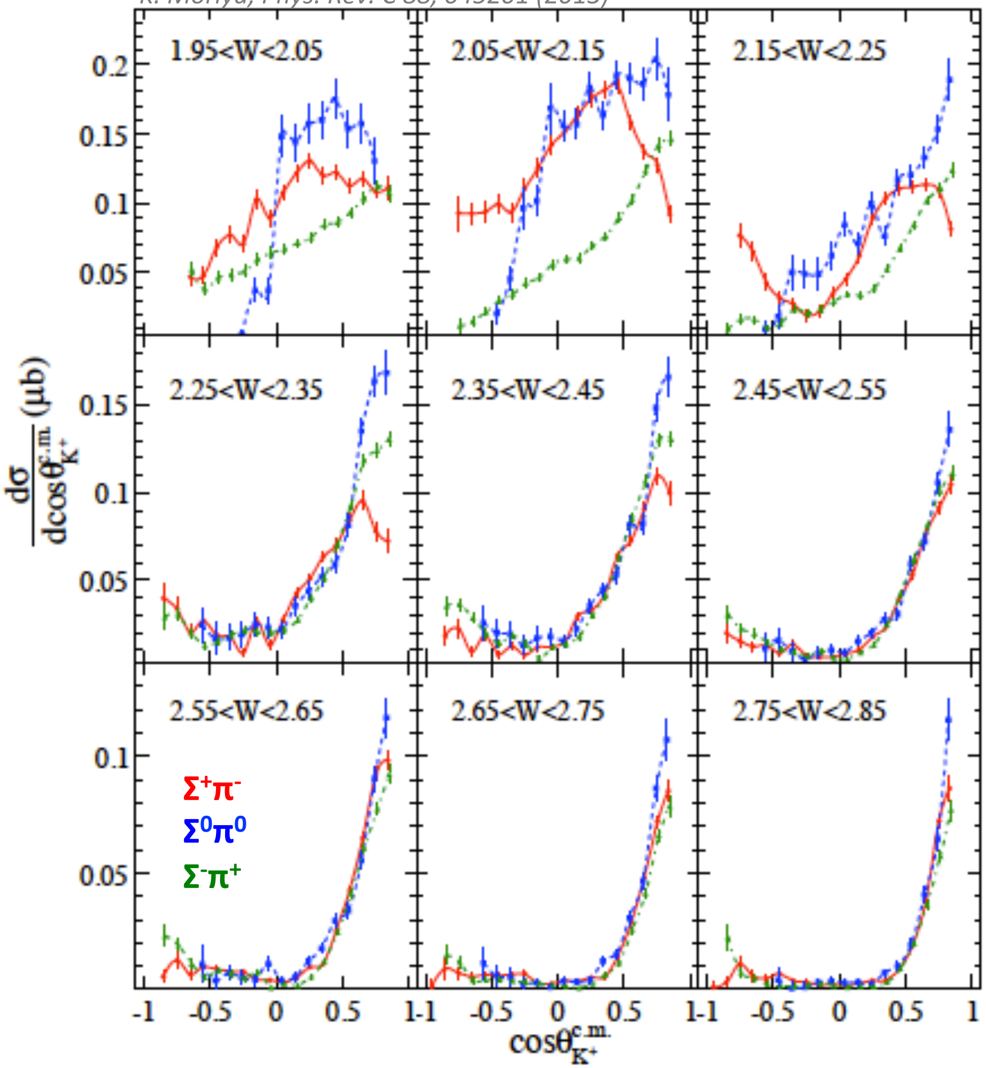
Λ(1405) cross section

K. Moriya, Phys. Rev. C 88, 045201 (2013)



$\gamma p \rightarrow K^+\Lambda(1405)$

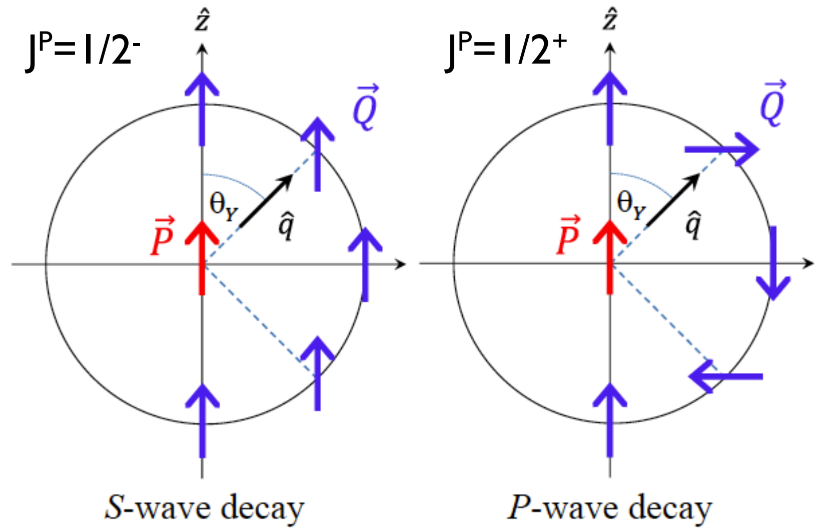
- Experiment: first-ever measurements
- High W: See t-channel like forward peaking & u-channel backward rise at high W
- Low W: See strong isospin dependence
  - Charge channels differ
  - WHY?!?
- Channels merge together at high W

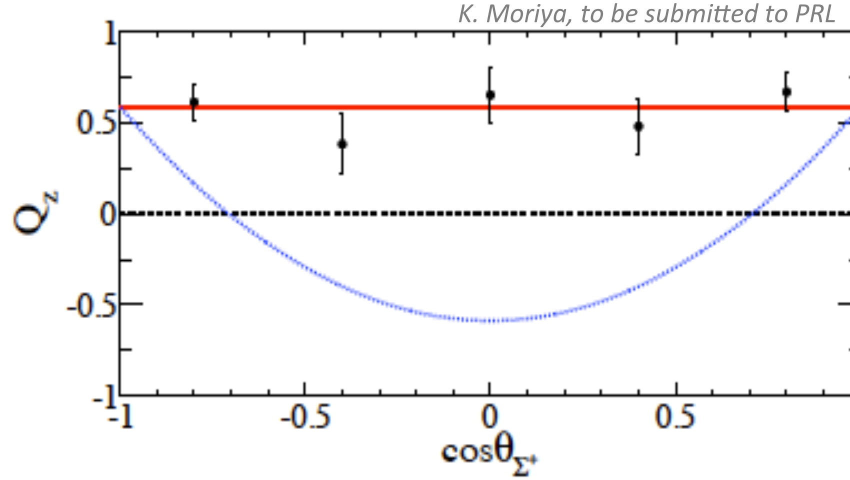
Possible interference of I=0 and I=1 amplitudes in the mass range of the Λ(1405)

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





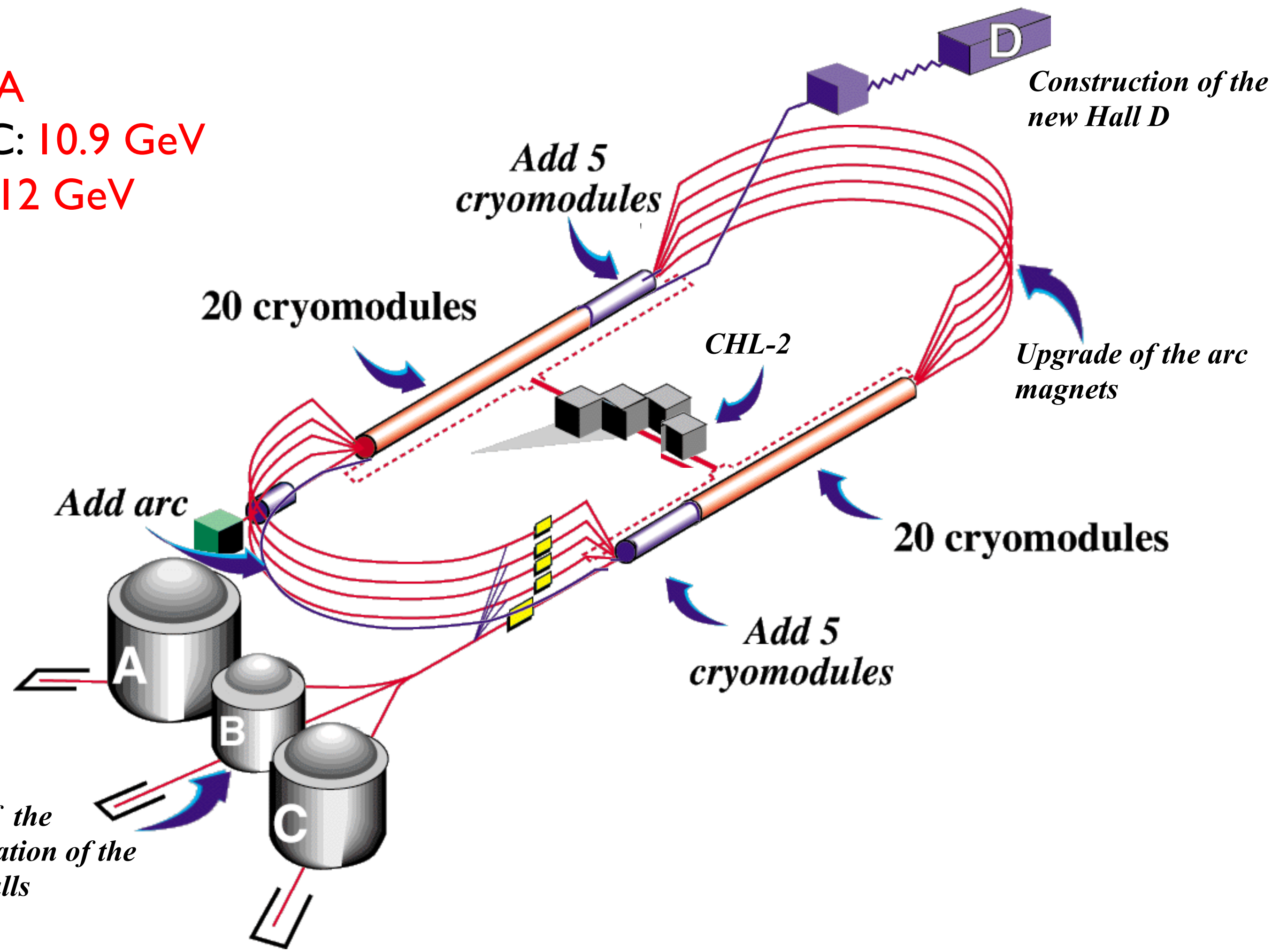
Analysis of decay angular distribution indicate an isotropic decay in S-wave

$J^P=1/2^-$

experimentally determined for the first time

Jefferson Lab Upgrade

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



CLAS12

Forward Detector:

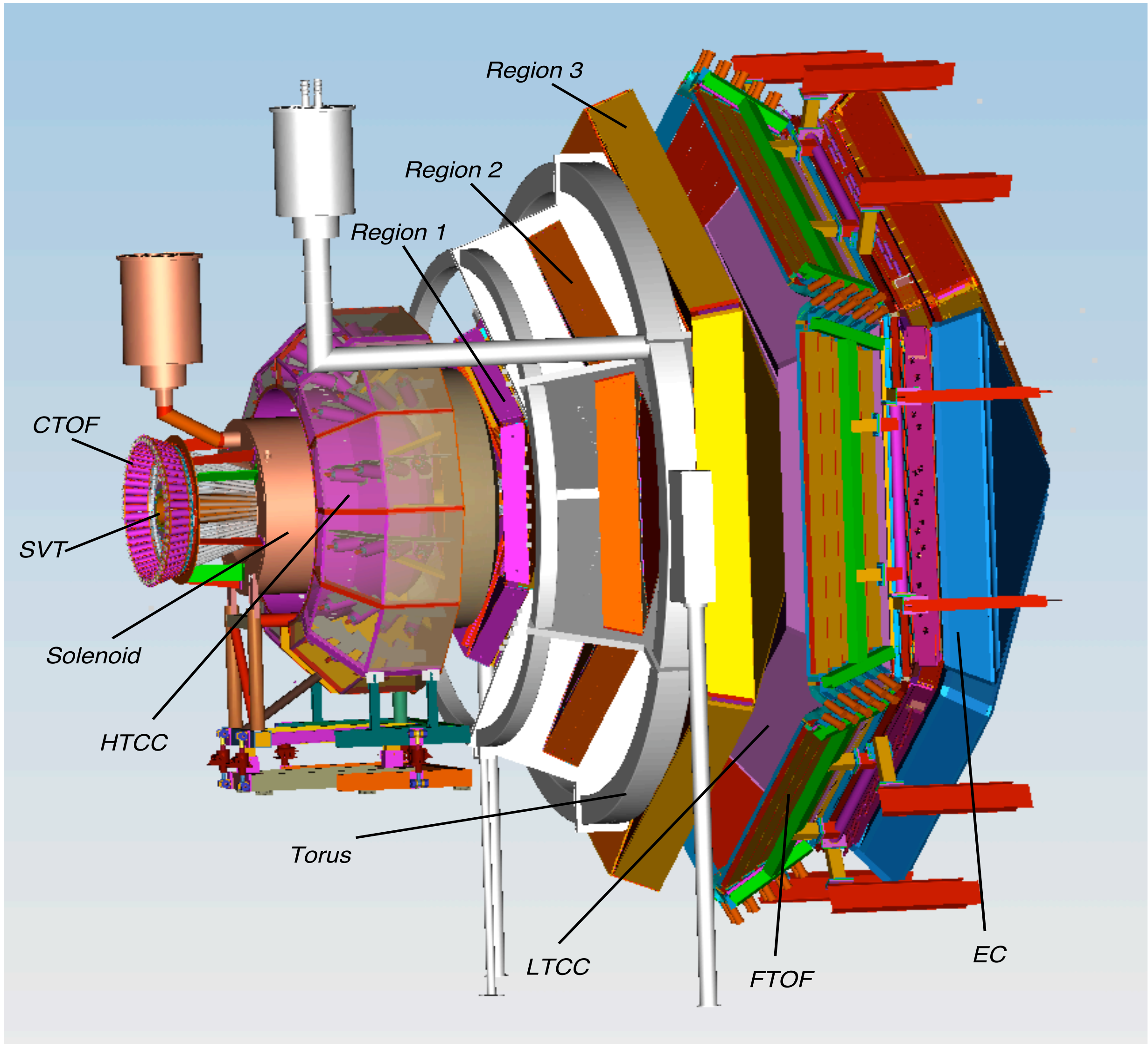
- *TORUS magnet*
- *Forward SVT tracker*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

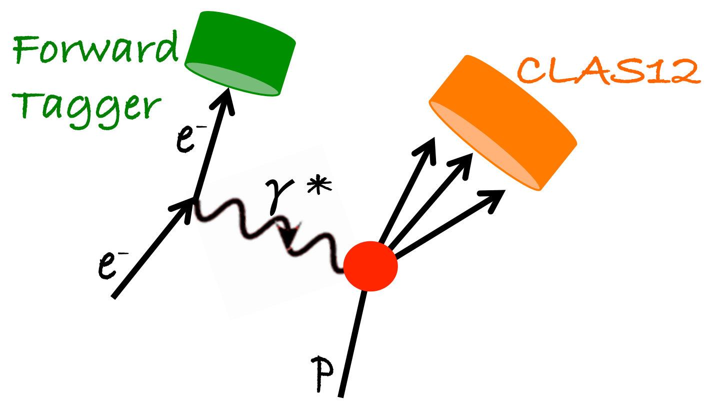
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Proposed upgrades:

- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*



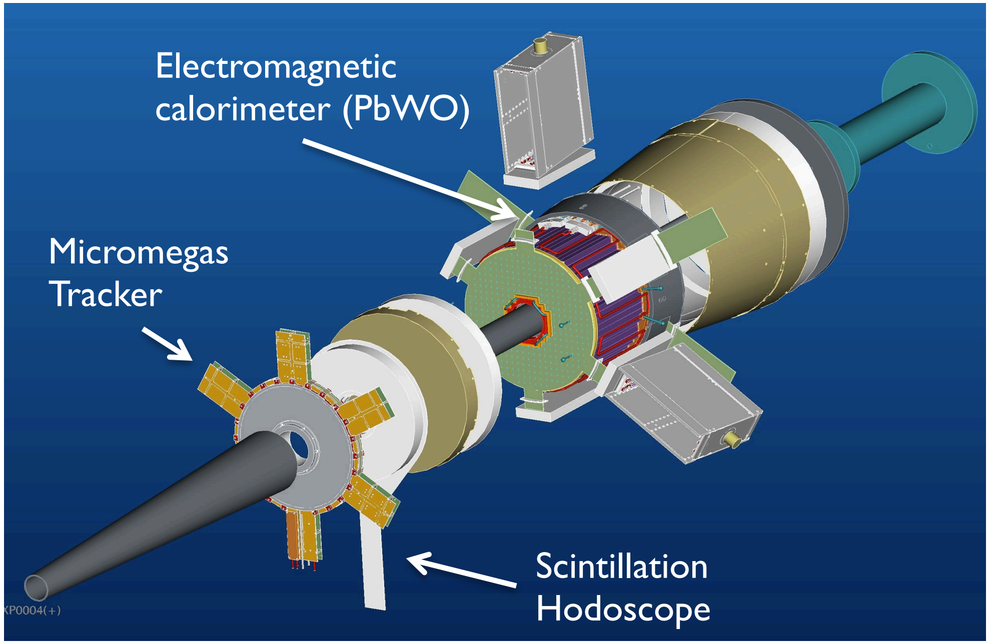
The CLAS12 Forward Tagger



Quasi-real photoproduction on proton target:

- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger

Forward Tagger	
E'	0.5-4.5 GeV
ν	7-10.5 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.6-4.5 GeV
Photon Flux	5×10^7 γ/s @ $L_e=10^{35}$



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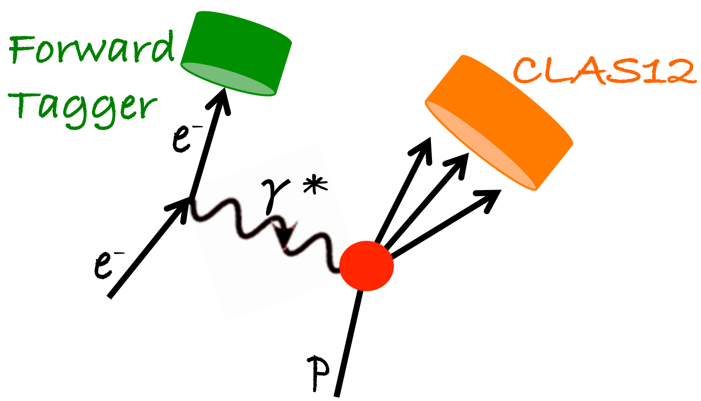

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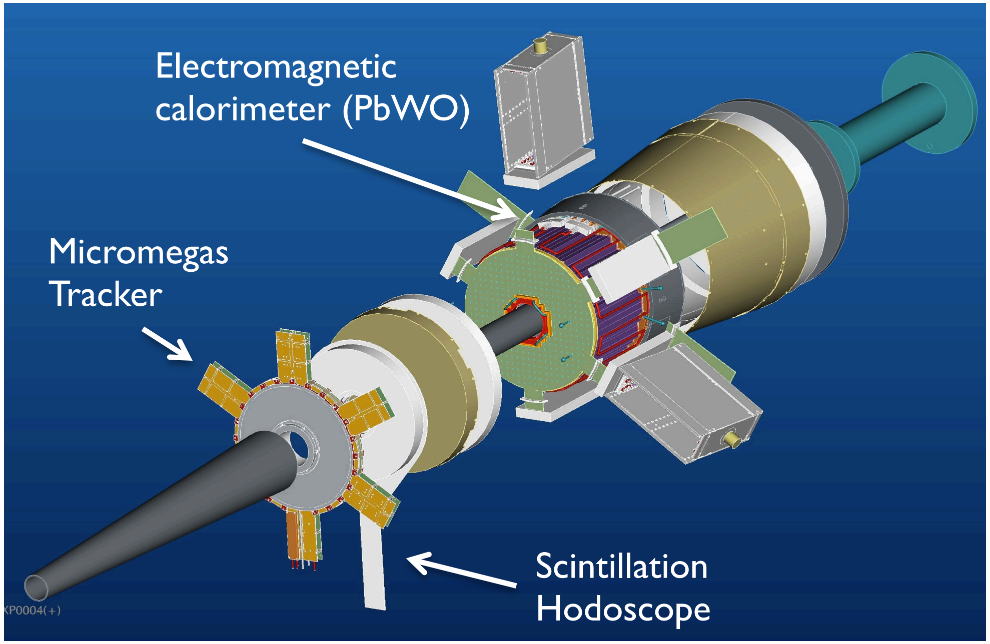


Physics goals

Meson spectroscopy:

- Detailed mapping of the meson spectrum up to 2.5 GeV
- Investigation of strangeonium and strangeness rich states
- Search for exotics

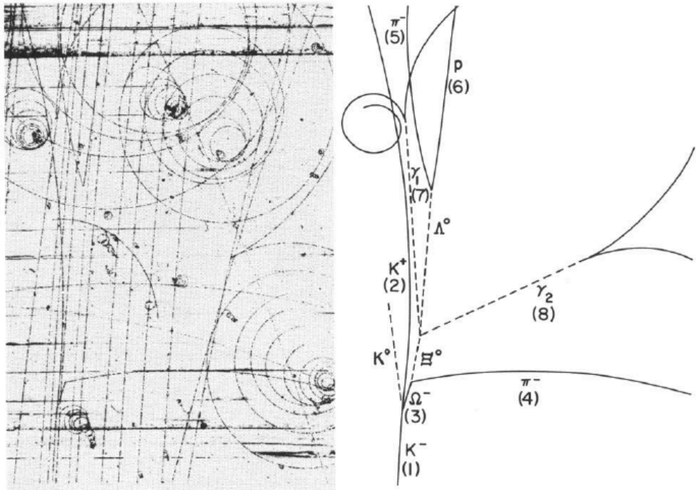
Baryon spectroscopy:

- Study of the Ω^- and Ξ^*
- Study of Ξ^* production and polarization mechanisms

Very Strange Baryons

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

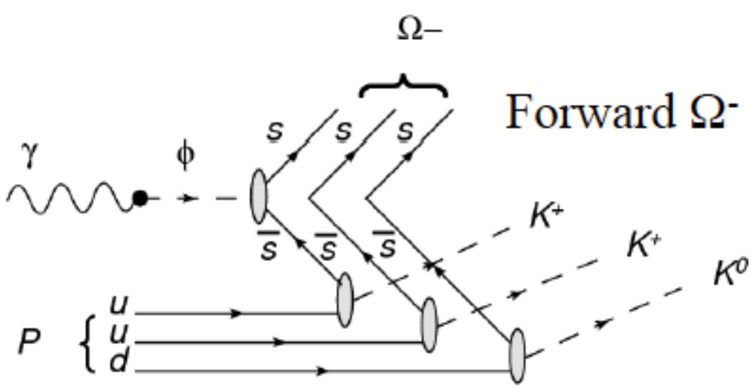
- Ω^- discovered in 1964: after 50 years, indication on J^P from Babar and others but full determination not yet achieved
- Ξ^* spectrum still poorly known: many states missing and spin/parity undetermined



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

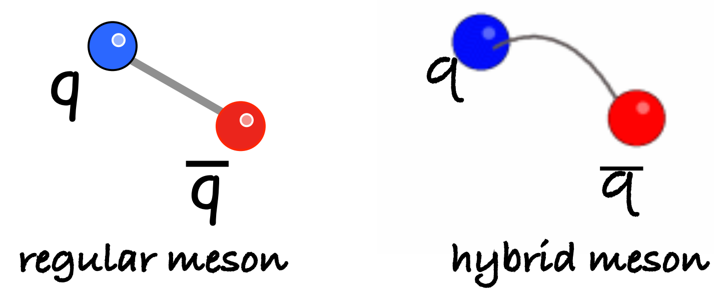
Photoproduction mechanism implies creation of three s quarks

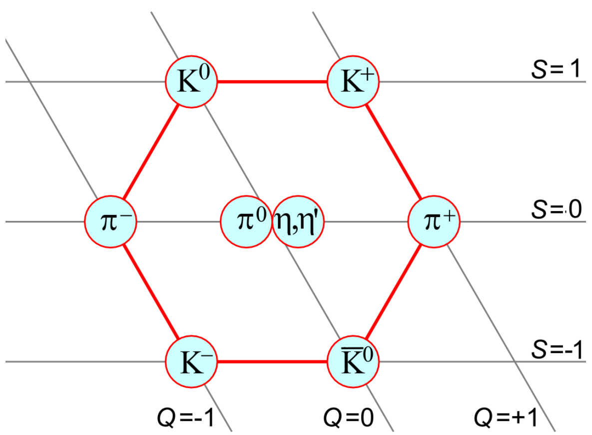
- Models indicate $\sigma(\Omega^-)$ ~0.3-2 nb at E~7GeV
- Expected production rates in CLAS12:
  - Ω^- : 90 /h
  - Ξ-(1690)/Ξ-(1820): 0.2/0.9 k/h
- Ω^- : measurement of the cross section and investigation of production mechanisms
- Ξ^*: spin/parity determination, cross section and production mechanism,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



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*



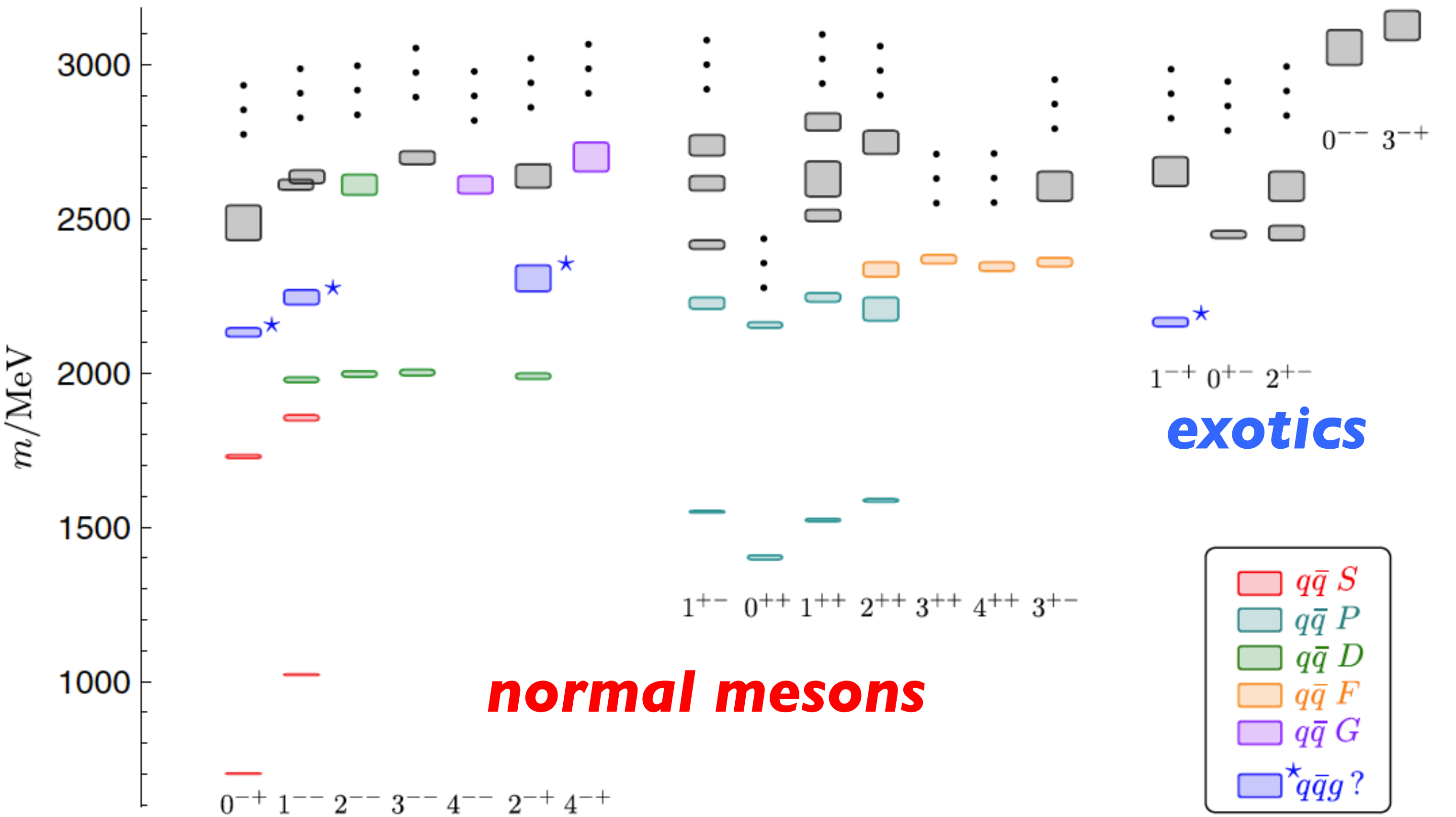


- Excitation of the glue leads to a new spectrum of hadrons that can have *exotic quantum numbers*
  $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} ...$
- For each exotic quantum number combination, a nonet of state should exist, including states with open or hidden strangeness
- Lattice QCD calculations predict masses around 2 GeV, a range that can be explored at JLab

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

Lattice QCD

Predictions of the meson spectrum from Lattice QCD are now available



isovector mesons, m_{π}~700 MeV

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

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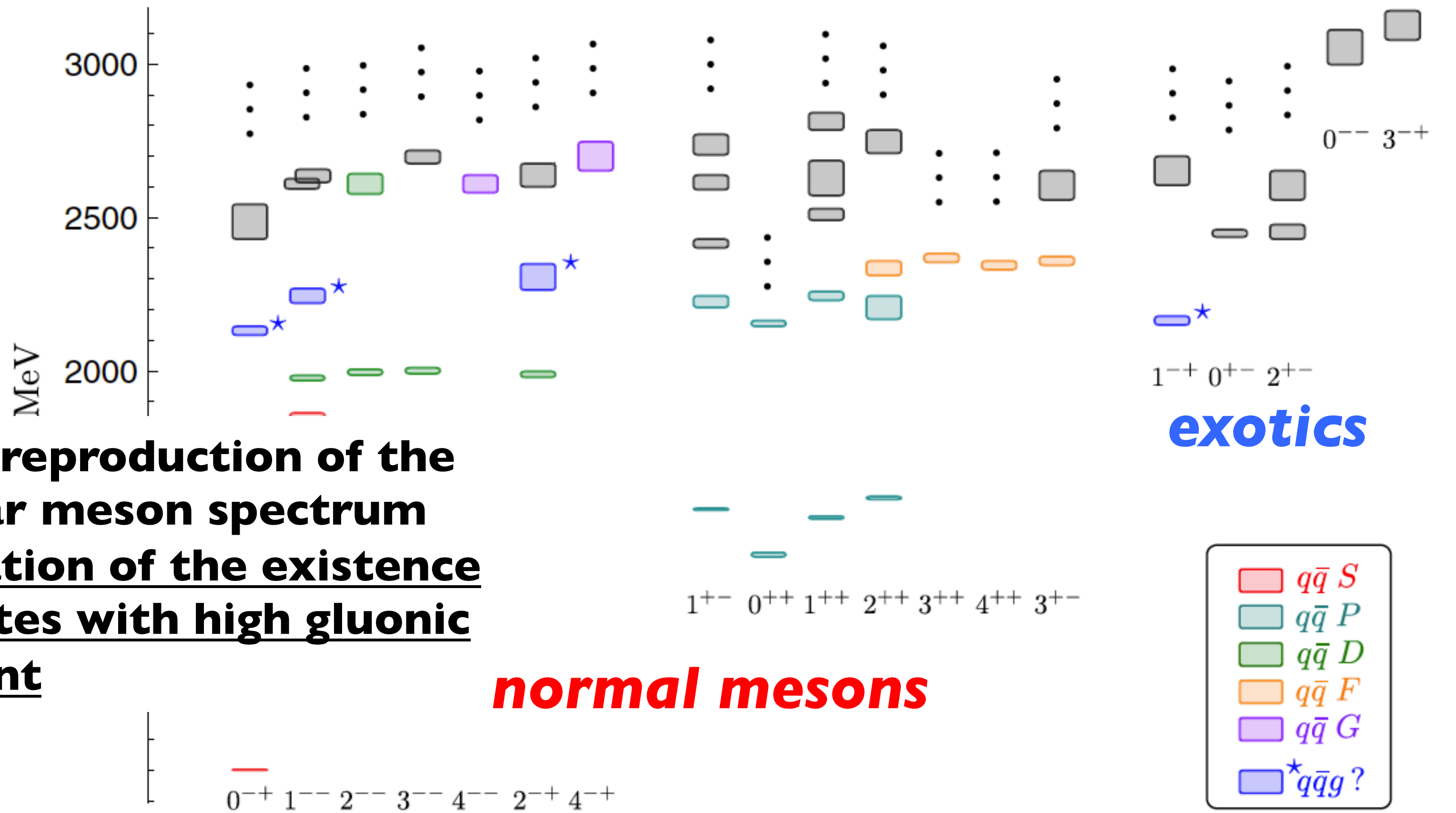


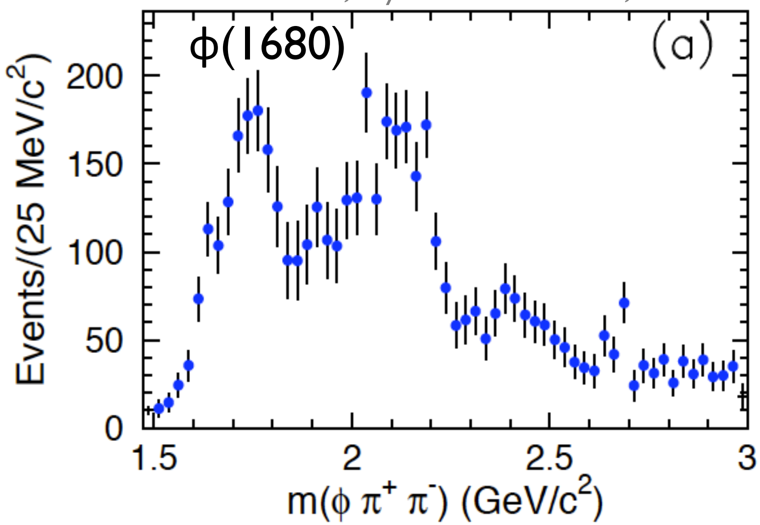
- **Good reproduction of the regular meson spectrum**
- **Indication of the existence of states with high gluonic content**

isovector mesons, m_{π}~700 MeV

Strangeonia

- Mesons containing $s\bar{s}$ pairs
- Regular states in the quark model or hybrids ($s\bar{s}g$) with/without exotic quantum numbers
- Experimental data still quite sparse: only 7 of the 22 states expected below 2.2 GeV are widely accepted
- Model predictions for width and decays available
- Experimental search would require measurement of many different final states

C P. Shen, Phys.Rev.D80:031101,2009



$^3P_0$ model, Barnes, Black and Page (2002)

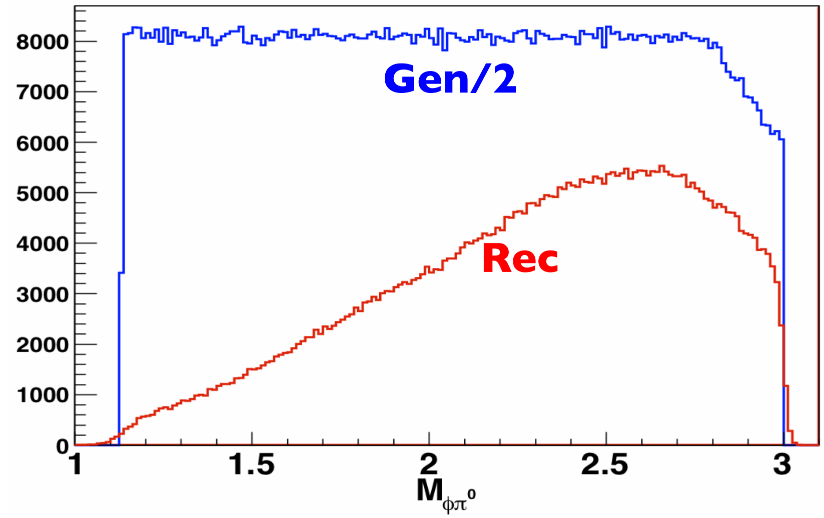
State	Γ_{tot}		Γ_i			
	Γ_{th}	Γ_{exp}	KK	KK*	ηϕ	K*K*, $KK_{1,(2)}$, η'ϕ, …
ϕ(1019)	2.5 MeV	4.26 MeV				
ϕ(1680)	378 MeV	150 MeV	Γ_{th}=89 MeV	Γ_{th}=245 MeV	Γ_{th}=44 MeV	
ϕ(2050)	378 MeV			Γ_{th}=20 MeV	Γ_{th}=21 MeV	Γ_{th}=337 MeV

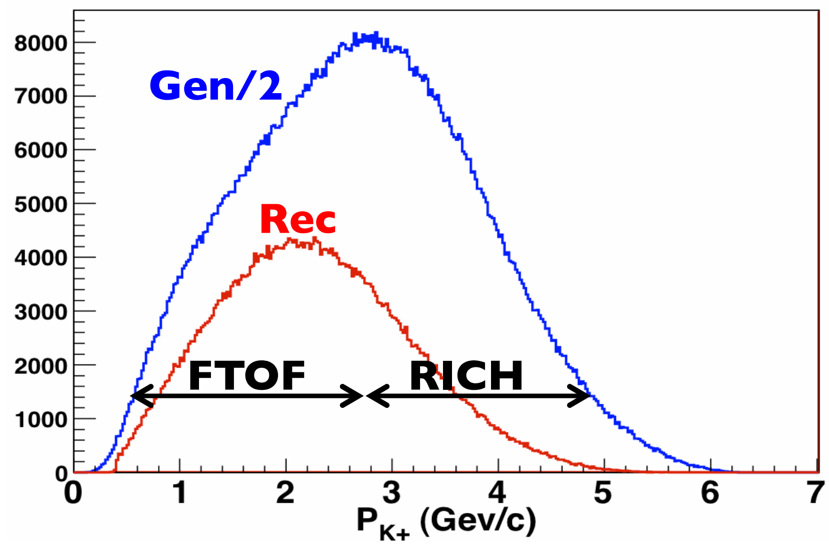
Strangeonia in CLAS12

- 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 $\gamma p \rightarrow p K^{+}(K^{-})\gamma\gamma$
  - acceptance ~10%
  - exp. cross section ~10nb
  - **π/K separation up to 4-5 GeV needed: FTOF+RICH**





Summary

* Spectroscopy is a key field for the understanding of fundamental questions in hadronic physics as what is the origin of the nucleon mass and what is the role of gluons

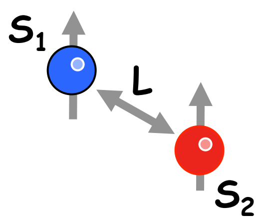
* The study of strangeness production and strangeness-rich states represent an important sector and provide the mean to investigate crucial issues in spectroscopy and hadron production mechanisms

* CLAS has carried out a broad program focused on hyperon spectroscopy and study of meson production with open or hidden strangeness

* This program will be extended with CLAS12 at 12 GeV using quasi-real photo-production, continuing the study of hyperons and opening new research lines focused on the search for exotics and strangeonia

Mesons in the Quark Model

In the quark model meson are quark-antiquark bound states.



The two constituents can pair giving total spin S=0 (singlet) or S=1 (triplet) and have a non zero orbital angular momentum L

The resulting bound states are classified according to their J^{PC} where

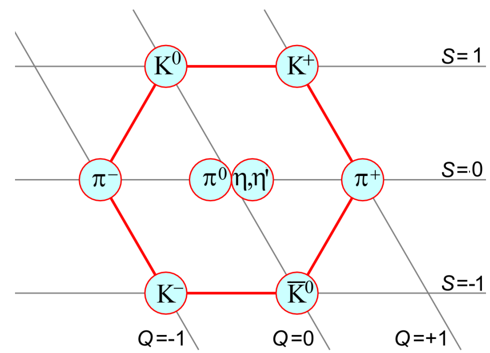
$$P=(-1)^{L+1}$$
$$C=(-1)^{L+S}$$

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} …

For each combination of J^{PC}, SU(3) flavor symmetry predicts the existence of a nonet ($8\oplus1$) of degenerate states

$$J^{PC}= 0^{-+} \Rightarrow (\pi, K, \eta, \eta')$$
$$1^{--} \Rightarrow (\rho, K^*, \omega, \Phi)$$
$$1^{+-} \Rightarrow (b_1, K_1, h_1, h_1')$$
…



Hybrids and Exotics

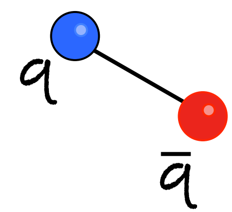
Another category of unconventional mesons are **hybrids**, i.e. states with $q\bar{q}g$ configuration

- In the flux tube model, hybrids arise from **excitations of the flux tube** that connects the quark and antiquark
- The excited flux tube carries **non-zero angular momentum** that contribute to the quantum numbers of the new system
- Excitation of the flux tube leads to a **new spectrum of hadrons** that can have both regular and **exotic quantum numbers**

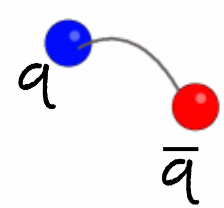
  $J^{PC} = 0^{-+}, 0^{+-}, 1^{++}, 1^{--}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$

- For each J^{PC} combination a **nonet** of states is expected
- Masses of the lower states are predicted to be around 2 GeV

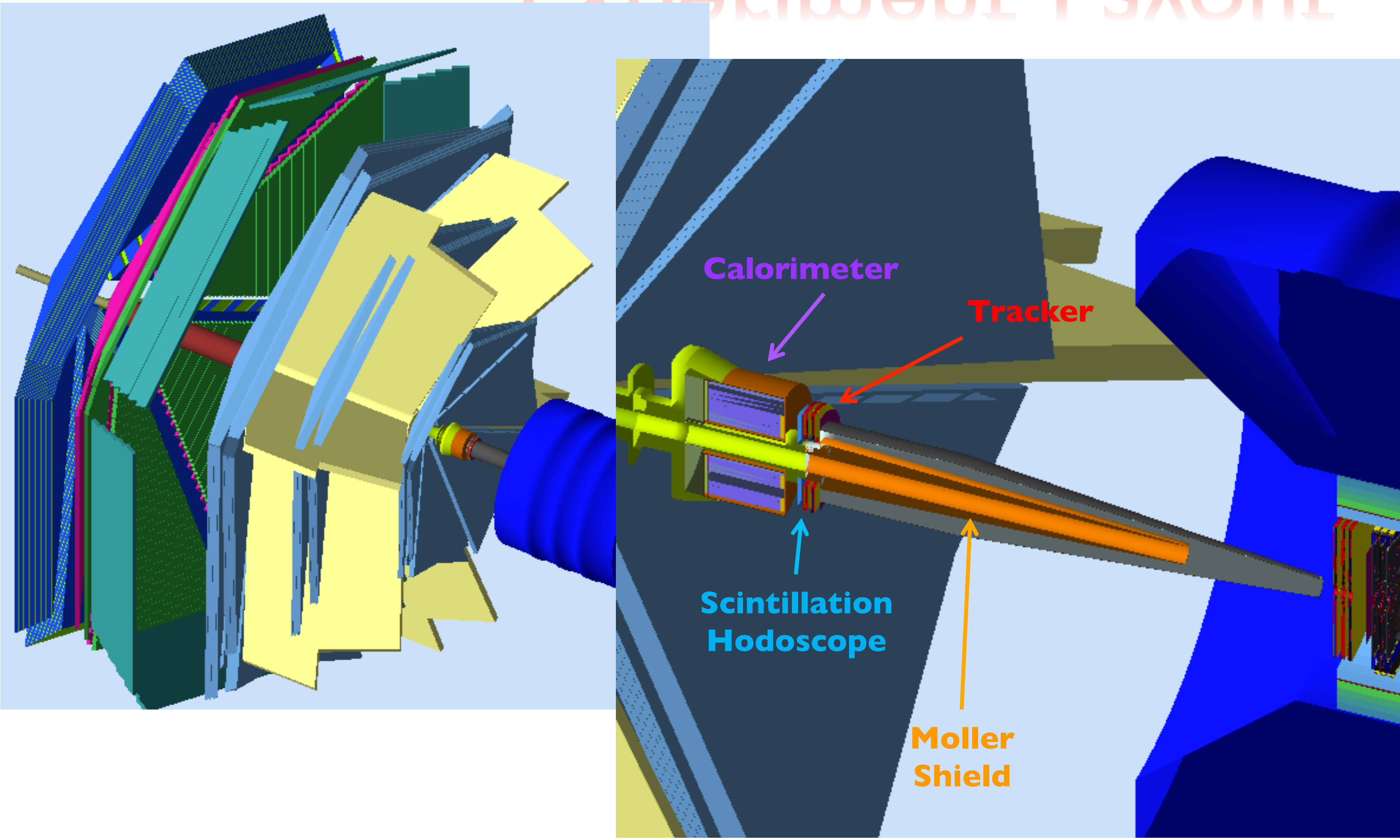
Normal meson:
flux tube in ground state
$m=0$, $PC=(-1)^{S+1}$



Hybrid meson:
flux tube in excited state
$m=1$, $PC=(-1)^{S}$



Experiment Layout



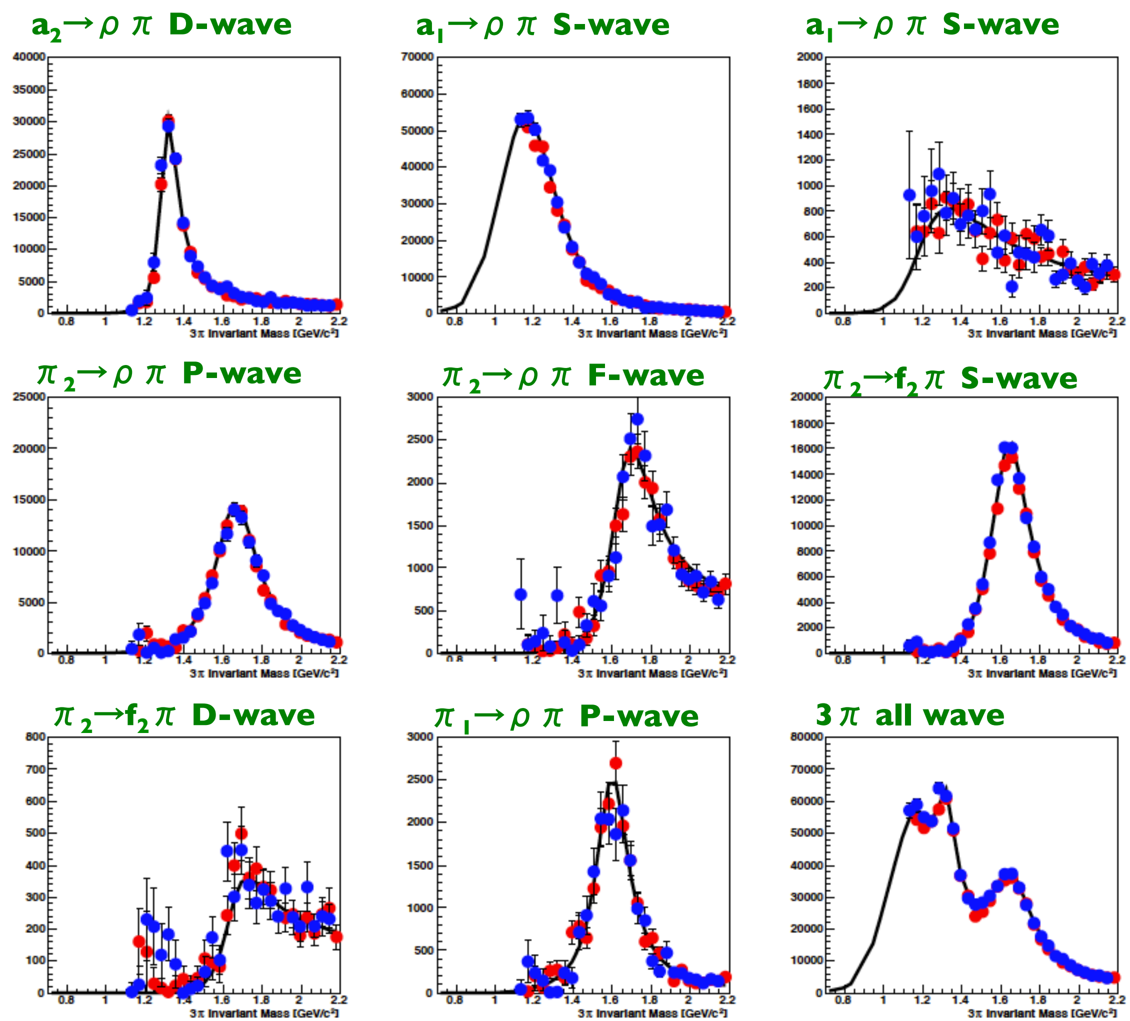
PWA in CLAS12

In preparation for the experiment, **PWA tools** are being developed and tested on pseudo data (Monte Carlo) for different reactions as $\gamma p \rightarrow n\pi^+\pi^+\pi^-$

Test for 2 t bins:

- line: generated wave
- $|t|=0.2\ GeV^2$
- $|t|=0.5\ GeV^2$

As a function of $M_{3\pi}$



The CLAS12 detector system is intrinsically capable of meson spectroscopy measurements