Light Cone 2015

The Hadron Spectroscopy Program at Jefferson Lab

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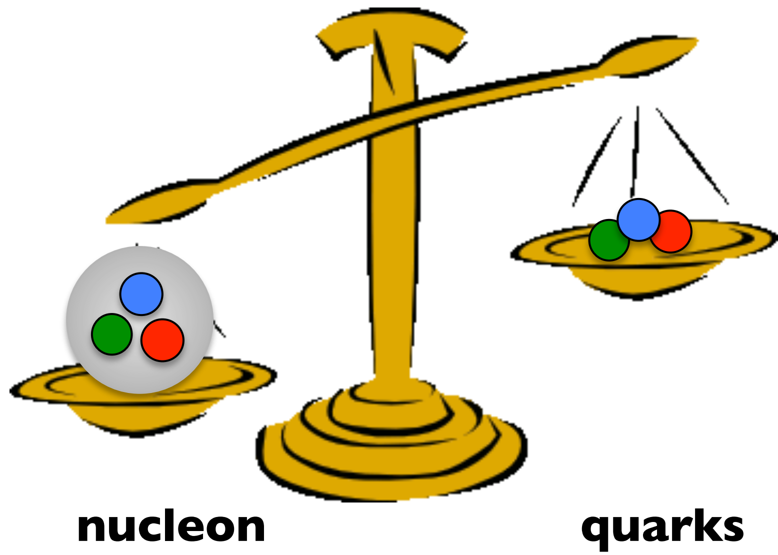
QCD and Spectroscopy

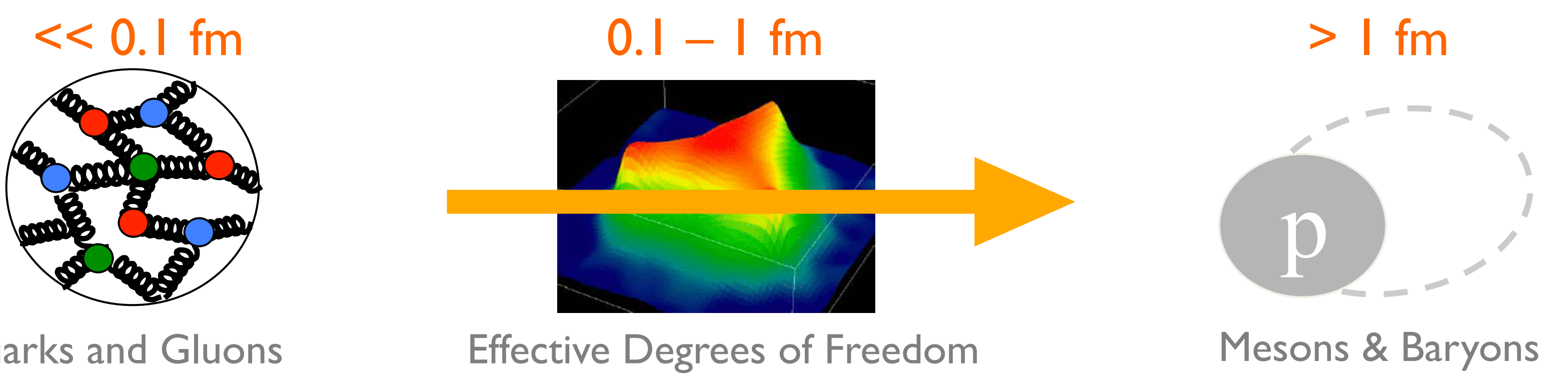
- Hadrons are one of the most relevant manifestations of the works of QCD
- Hadrons have an internal structure being made of quarks: known quark configurations are baryons, made of tree quarks and mesons, made of quark-antiquark pairs
- Quark masses account only for a small fraction of the nucleon mass: ~ 1%
  - $m_q \sim 10$ MeV
  - $m_N \sim 1000$ MeV

  while the remaining fraction is to to the force that binds the quarks: **QCD**
- Hadron spectroscopy is a "portal" to Quantum Chromo Dynamics



Hadrons and QCD

- Hadrons are color neutral systems made of quarks and gluons but…
  - 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?
- <u>Spectroscopy is a key tool to investigate these issues</u>



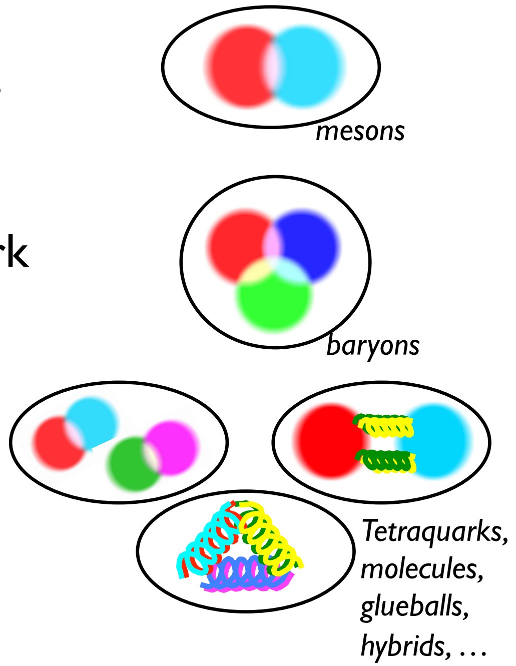
Spectroscopy and QCD

How can we exploit spectroscopy to probe QCD?

Baryons: building blocks of ordinary matter, baryon structure is most obviously related to color degrees of freedom

Mesons: the simplest quark bound states, i.e. the best benchmark to understand how quarks interact to form hadrons

Exotics: unconventional quark-gluon configuration can reveal hidden aspects of QCD



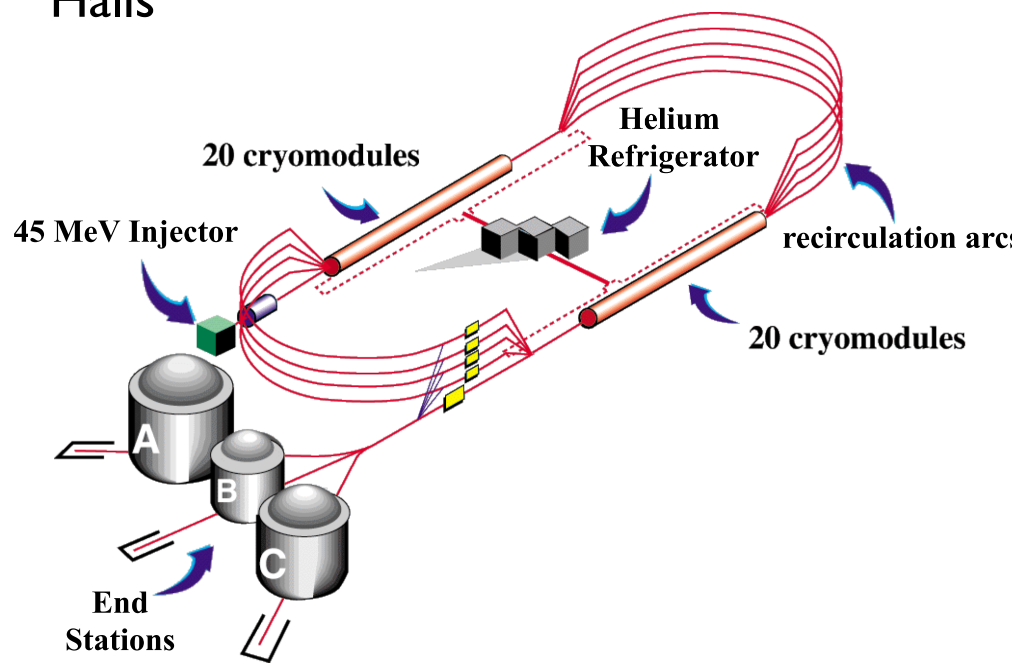
Global effort involving experimentalists and theorists from all over the world…

- different reaction processes
- from low to high energy physics
- electro- and photo-production at Jefferson Lab

Jefferson Laboratory

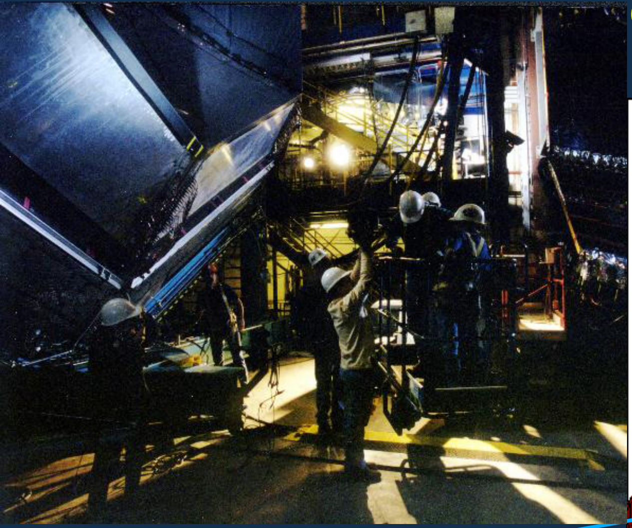
Continuous Electron Beam Accelerator Facility (CEBAF):

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



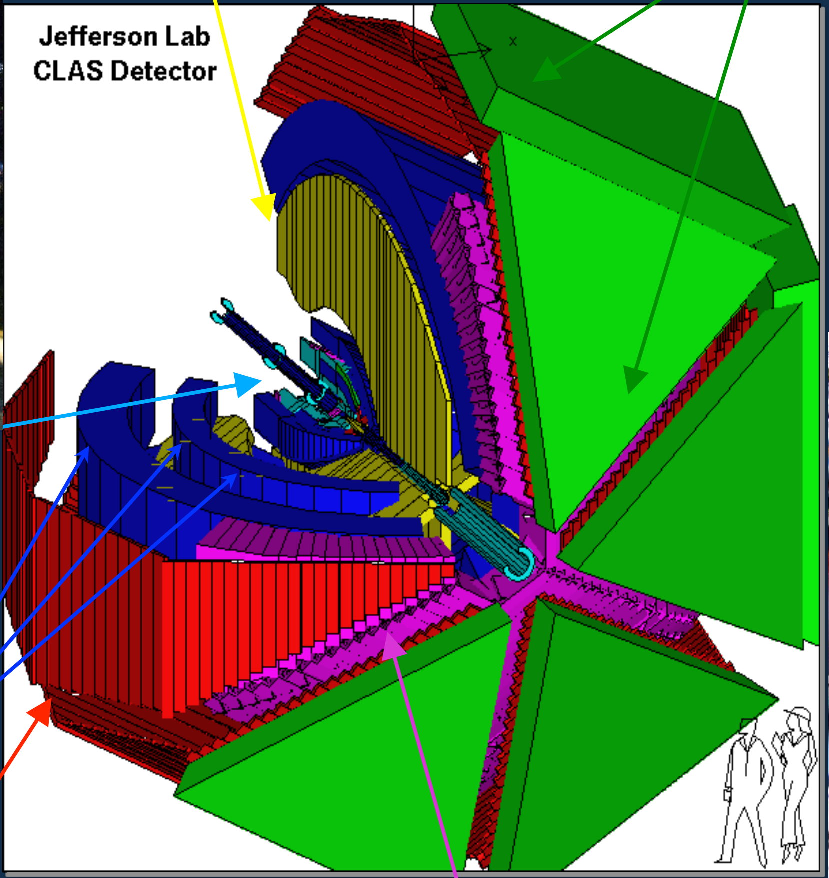
High electron polarization
Beam Power: 1MW
Beam Current: 200 μA
Max Energy: 6 GeV
RF: 1499 MHz

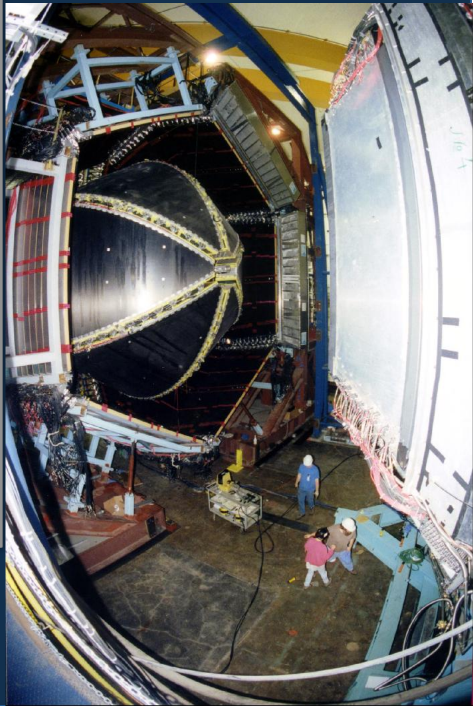
CEBAF Large Acceptance Spectrometer



Torus Magnet
6 Superconductive Coils

Electromagnetic Calorimeter
lead/plastic scintillator, 1296 PMTs





Target + γ
start counter
e mini-torus

Drift Chamber
35,000 cells

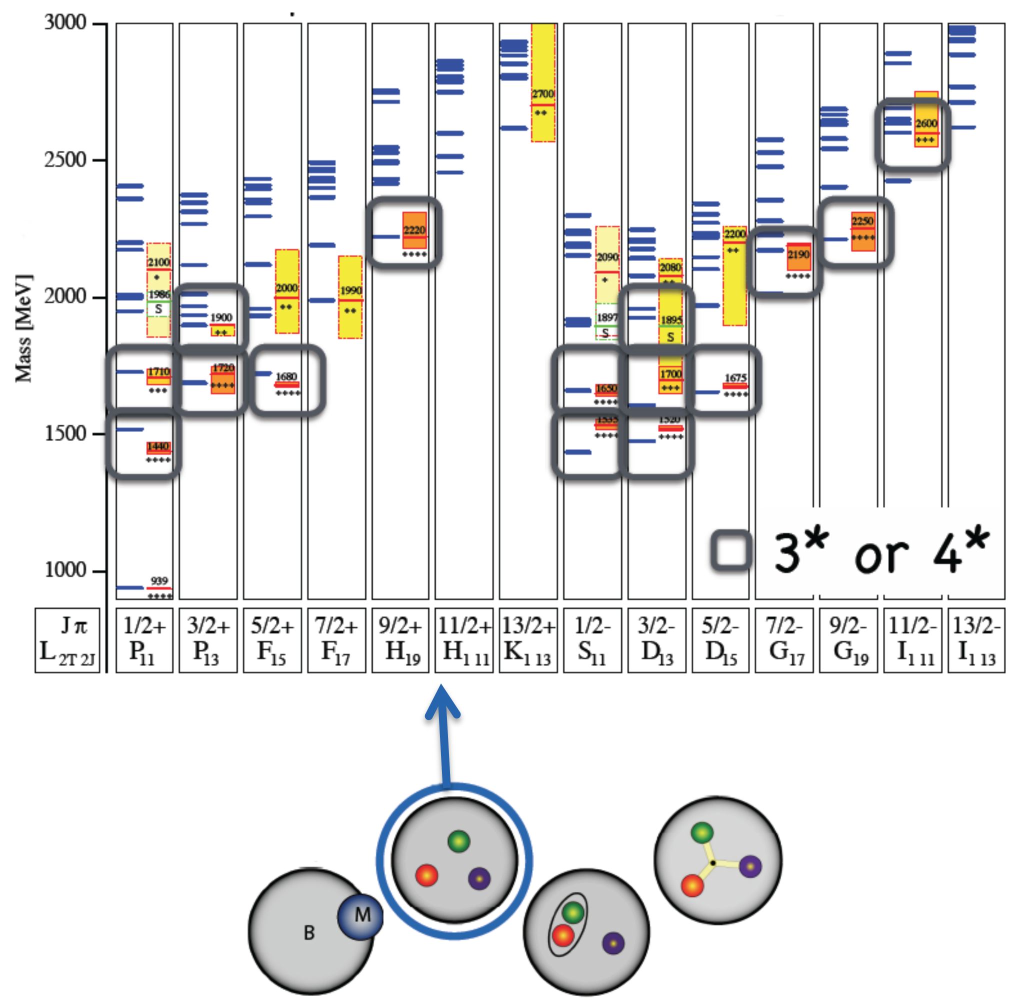
Time of Flight
Plastic Scintillator,
684 PMTs

Cherenkov Counter
e/π separation, 256 PMTs

Baryon Spectroscopy

The baryon spectrum has been crucial for the development of QCD:

- Multiplet structure led to the proposal of the quark model
- The discovery of the Ω^- confirmed the path was correct
- Inner structure connected to number of colors



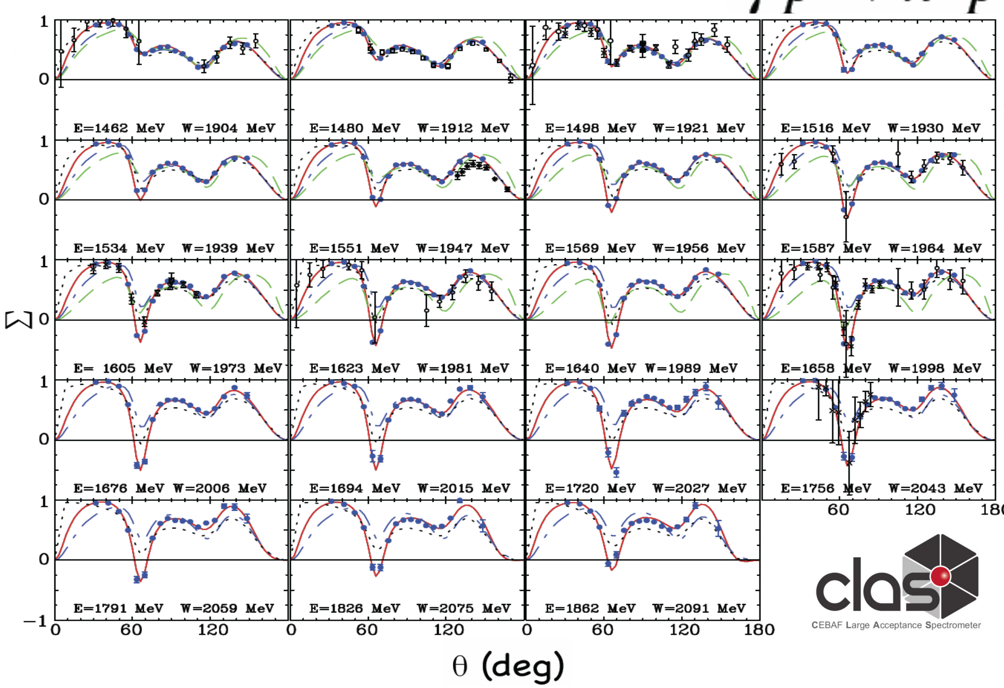
Many open questions (light quarks):

- Nucleon resonance spectrum and missing states
- Effective degrees of freedom and transition from partonic to hadronic description
- Hyperon spectroscopy

Search for Missing Resonances

- High precision measurement of multiple polarization observables in photoproduction off nucleons (“complete” experiments)
- Evidence of new states found in coupled-channel analyses
- Large impact of new data expected!

$$\vec{\gamma} p \rightarrow \pi^0 p$$



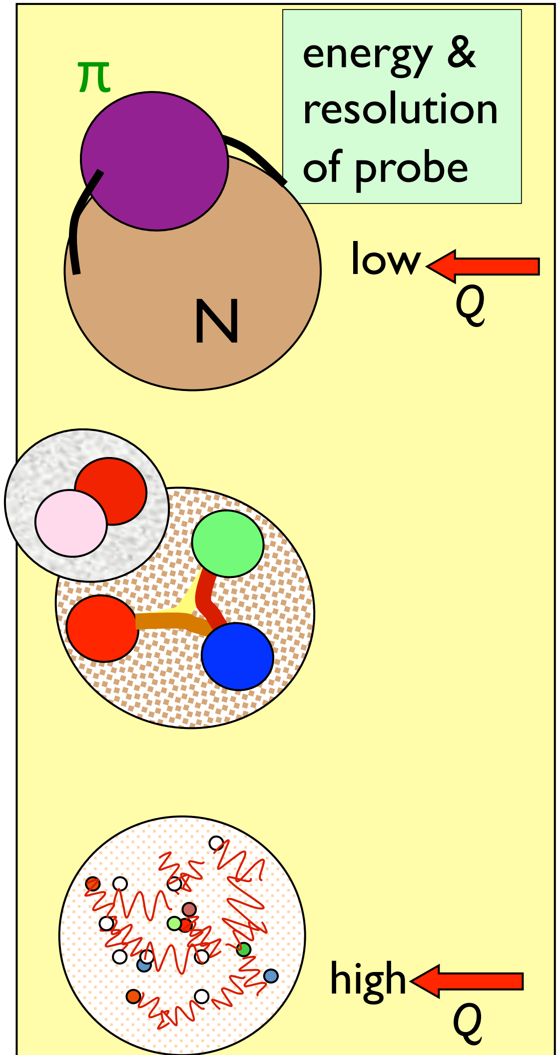
M. Dugger et. al, Phys. Rev. C88, 065203 (2013)

PDG baryon summary table for N* resonances

N^*	J^P $(L_{2I,2J})$	2010	2012	future
p	$1/2^+$ (P_{11})	****	****	
n	$1/2^+$ (P_{11})	****	****	
$N(1440)$	$1/2^+$ (P_{11})	****	****	
$N(1520)$	$3/2^-$ (D_{13})	****	****	
$N(1535)$	$1/2^-$ (S_{11})	****	****	
$N(1650)$	$1/2^-$ (S_{11})	****	****	
$N(1675)$	$5/2^-$ (D_{15})	****	****	
$N(1680)$	$5/2^+$ (F_{15})	****	****	
$N(1685)$			*	
$N(1700)$	$3/2^-$ (D_{13})	***	***	
$N(1710)$	$1/2^+$ (P_{11})	***	***	
$N(1720)$	$3/2^+$ (P_{13})	****	****	
$N(1860)$	$5/2^+$		**	
$N(1875)$	$3/2^-$		***	
$N(1880)$	$1/2^+$		**	
$N(1895)$	$1/2^-$		**	
$N(1900)$	$3/2^+$ (P_{13})	**	***	
$N(1990)$	$7/2^+$ (F_{17})	**	**	
$N(2000)$	$5/2^+$ (F_{15})	**	**	
~~$N(2080)$~~	D_{13}	**		
~~$N(2090)$~~	S_{11}	*		
$N(2040)$	$3/2^+$		*	
$N(2060)$	$5/2^-$		**	
$N(2100)$	$1/2^+$ (P_{11})	*	*	
$N(2120)$	$3/2^-$		**	
$N(2190)$	$7/2^-$ (G_{17})	****	****	
~~$N(2200)$~~	D_{15}	**		
$N(2220)$	$9/2^+$ (H_{19})	****	****	
$N(2250)$	$9/2^-$ (G_{19})	****	****	
$N(2600)$	$11/2^-$ $(I_{1,11})$	***	***	
$N(2700)$	$13/2^+$ $(K_{1,13})$	**	**	

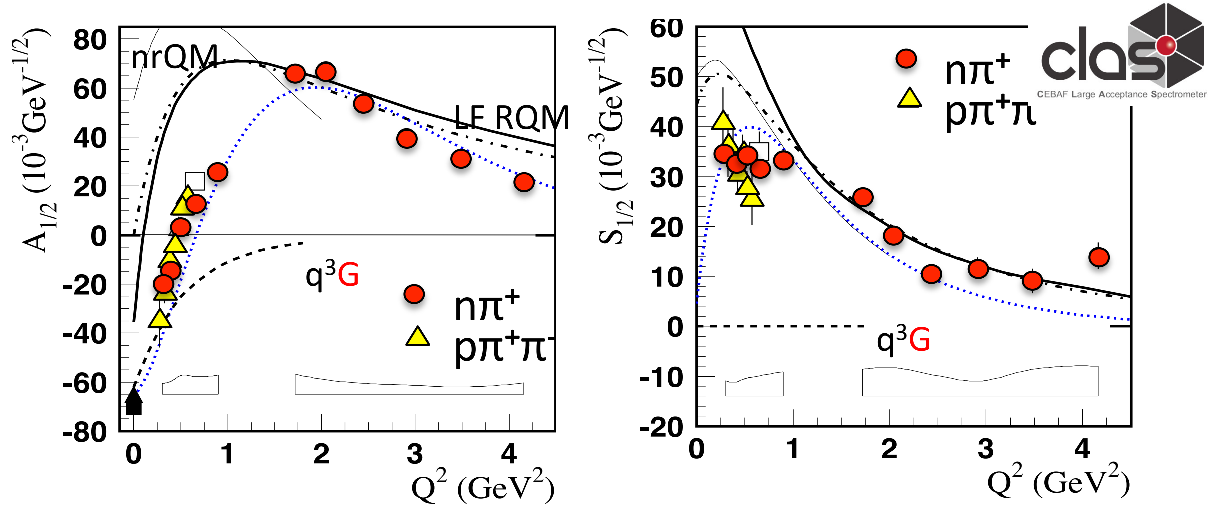
... upcoming updates ...

Transition Form Factors



Electro-production can be used to explore the hadron structure at different wavelengths (Q^2)

Electro-couplings of "Roper" N(1440)1/2+

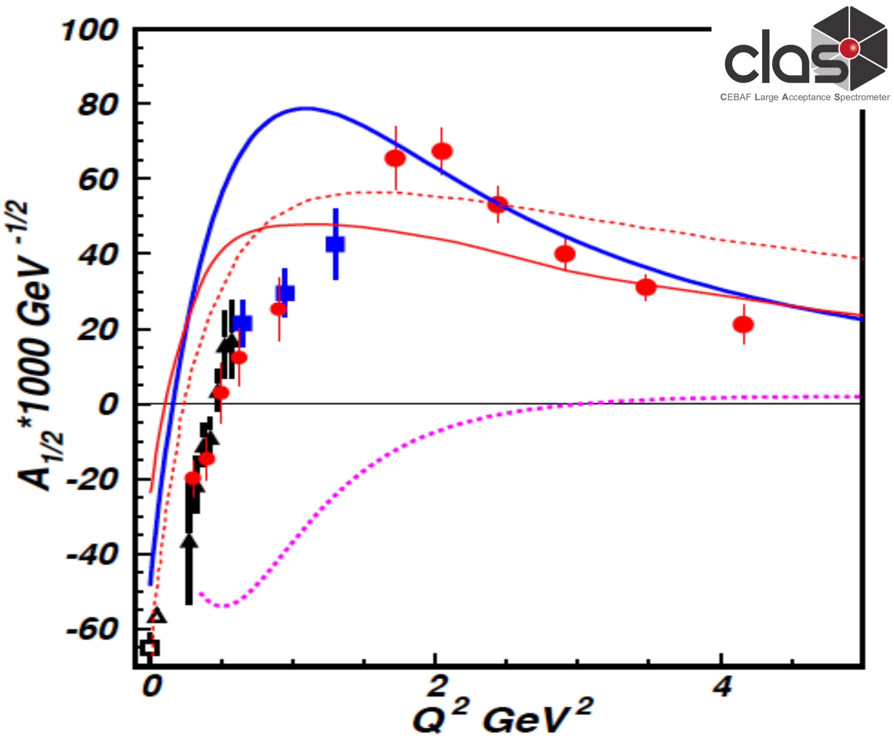


- $N\pi$ and $N\pi\pi$ give consistent results
- $A_{1/2}$ changes sign and has large magnitude at high Q^2
- QM fails to reproduce low Q^2 behavior, LFQM better at large Q^2
- Both $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ inconsistent with hybrid model prediction

The “Roper” resonance in 2015

Description of the N(1440)1/2$^+$ $A_{1/2}$ electro-coupling in LF QM that incorporate the inner core of three dressed quarks in the first radial excitation and outer meson-baryon (MB) cloud:

- (red solid line) Nπ loops to model MB cloud; **running quark mass**, in LF RQM. I.G. Aznauryan, V.B., Phys. Rev. C85, 055202 (2012)
- (red dashed line) Nσ loops to model MB cloud**; frozen constituent quark mass**. I.T. Obukhovsky, et al., Phys. Rev. D89, 014032 (2014).
- (blue line) **Quark core** contributions from DSE/QCD (2015), J. Segovia et al., arXiv: 1504.04386
- (magenta line) MB cloud **inferred from the CLAS data** as the difference between the data and quark core evaluated in DSE/QCD

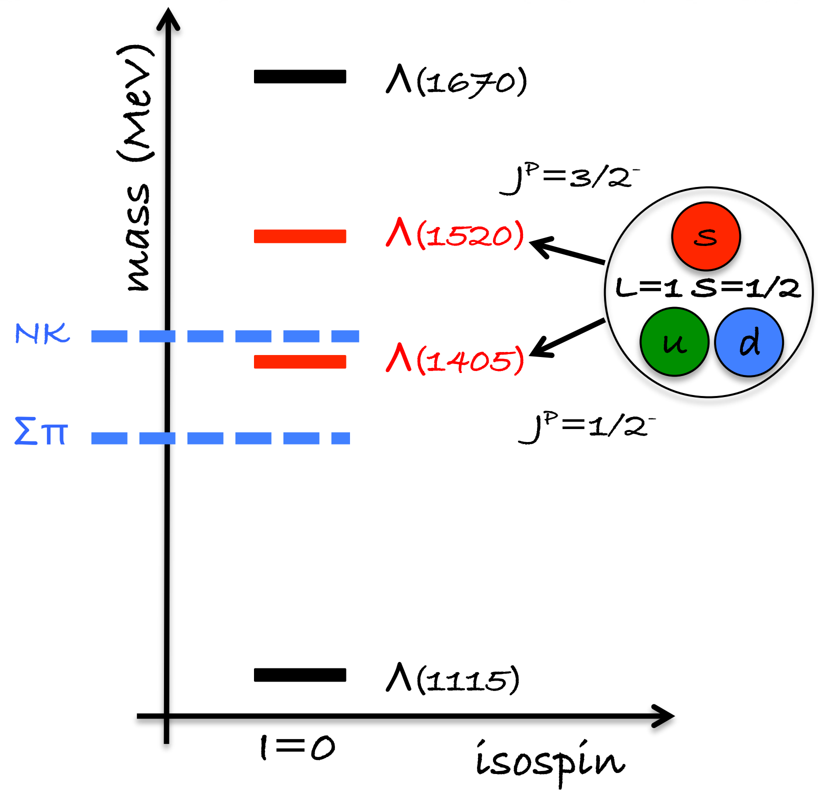


The structure of N(1440)1/2$^+$ resonance is determined by the interplay between a core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud

The Puzzling 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…"

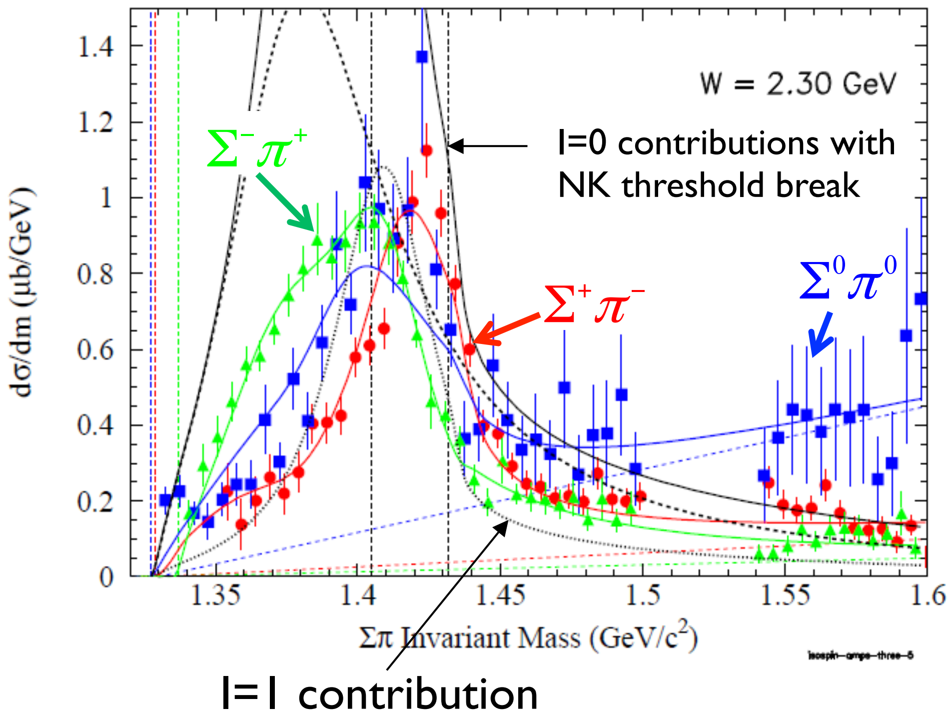
The Puzzling Λ(1405)

An issue since its prediction/discovery:

- CQM: SU(3) singlet 3q state, I=0, $J^P = ½^-$
- Unusual mass, line shape and couplings
- Proposed as dynamically generated state, molecule, …

CLAS at JLAB:

- Measured in photoproduction off proton
- Analysis of lines shape from Σπ decay consistent with I=1 contribution (resonance or continuum?)
- $J^P=1/2^-$ experimentally determined for the first time from decay angular distribution

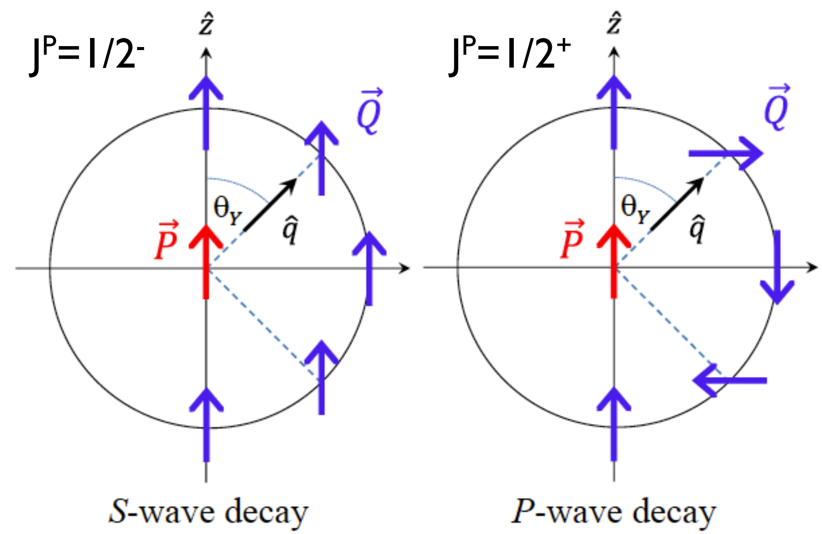


Phys. Rev. C 87, 035206 (2013)
Nucl. Phys A 914, 51 (2013)
Phys. Rev. Lett. 112, 082004 (2014)

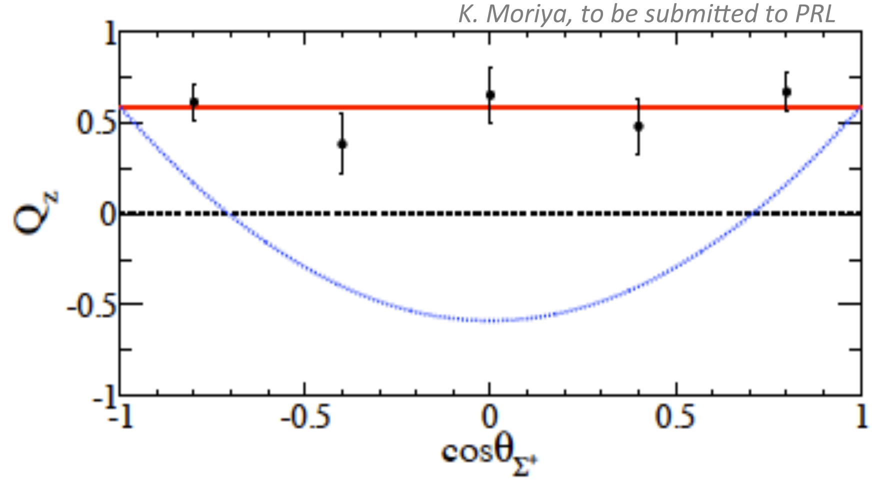
Λ(1405) Spin and Parity

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:
  $\Lambda(1405) \to \Sigma\,\pi$
- 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, to be submitted to PRL



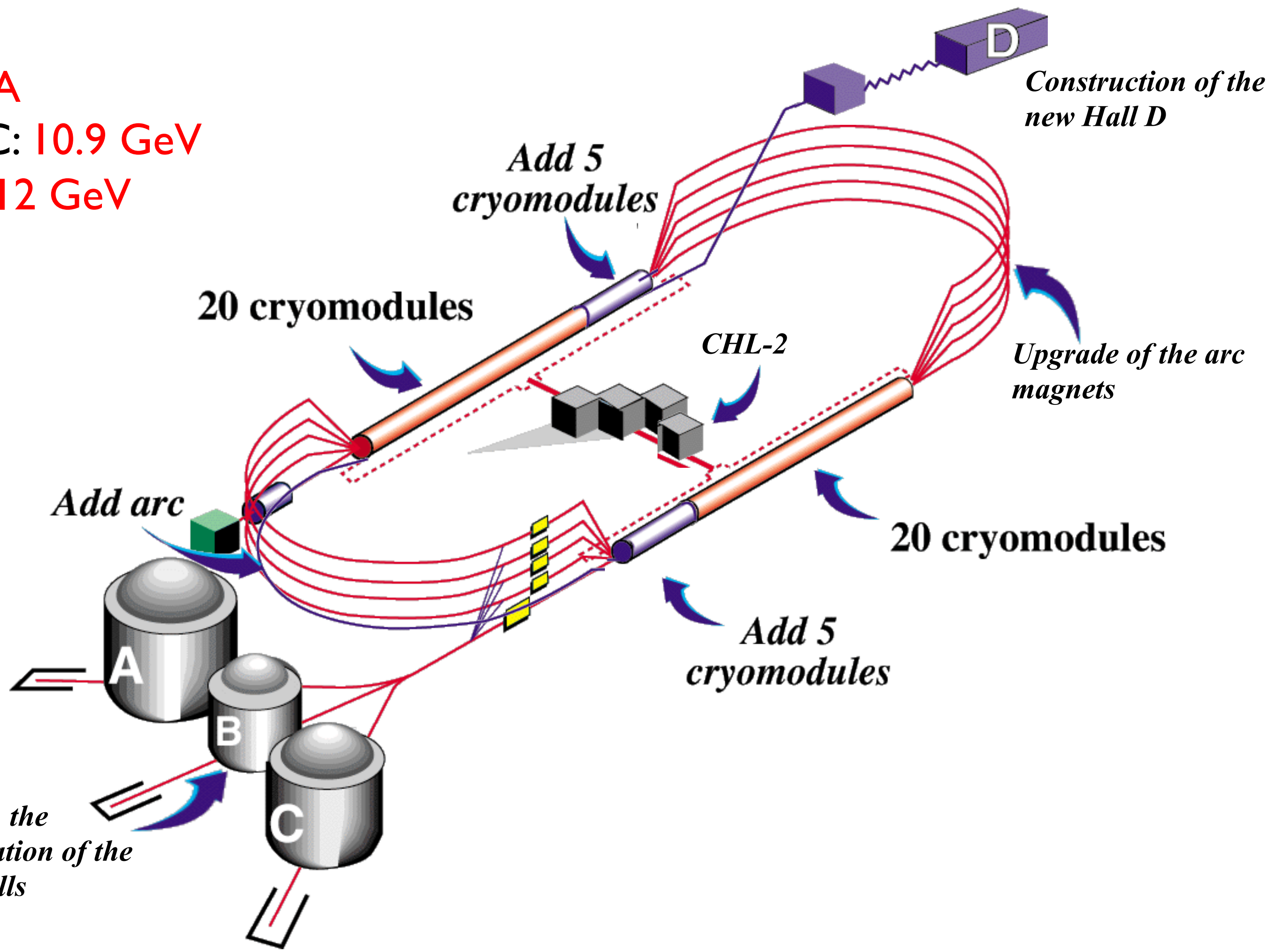
Analysis of decay angular distribution indicate an isotropic decay in S-wave

$J^P=1/2^-$

experimentally determined for the first time

Jefferson Lab Upgrade

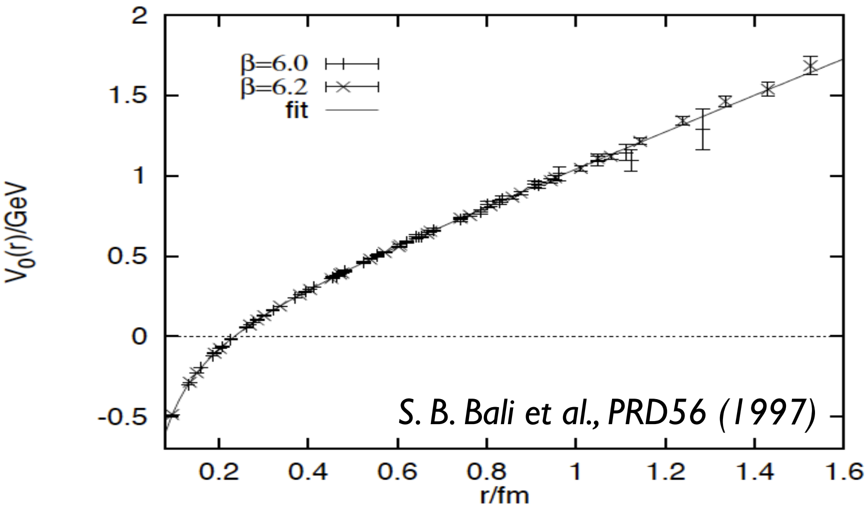
High electron polarization
Beam Power: 1MW
Beam Current: 90 μA
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV



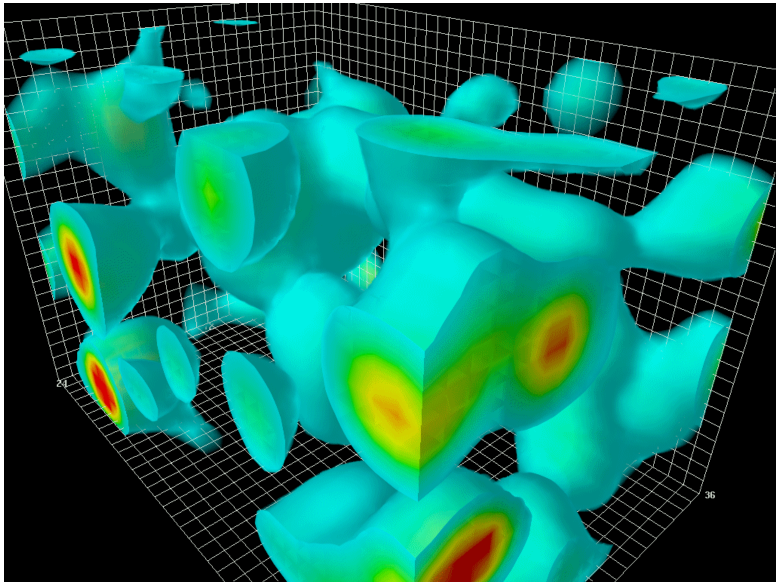
Jefferson Lab Upgrade

Meson Spectroscopy

Goals in meson spectroscopy are to investigate fundamental aspects of QCD, studying meson spectrum and decays and searching for exotic states



D. Leinweber: LQCD visualization of the QCD vacuum



Light quark mesons (uds):

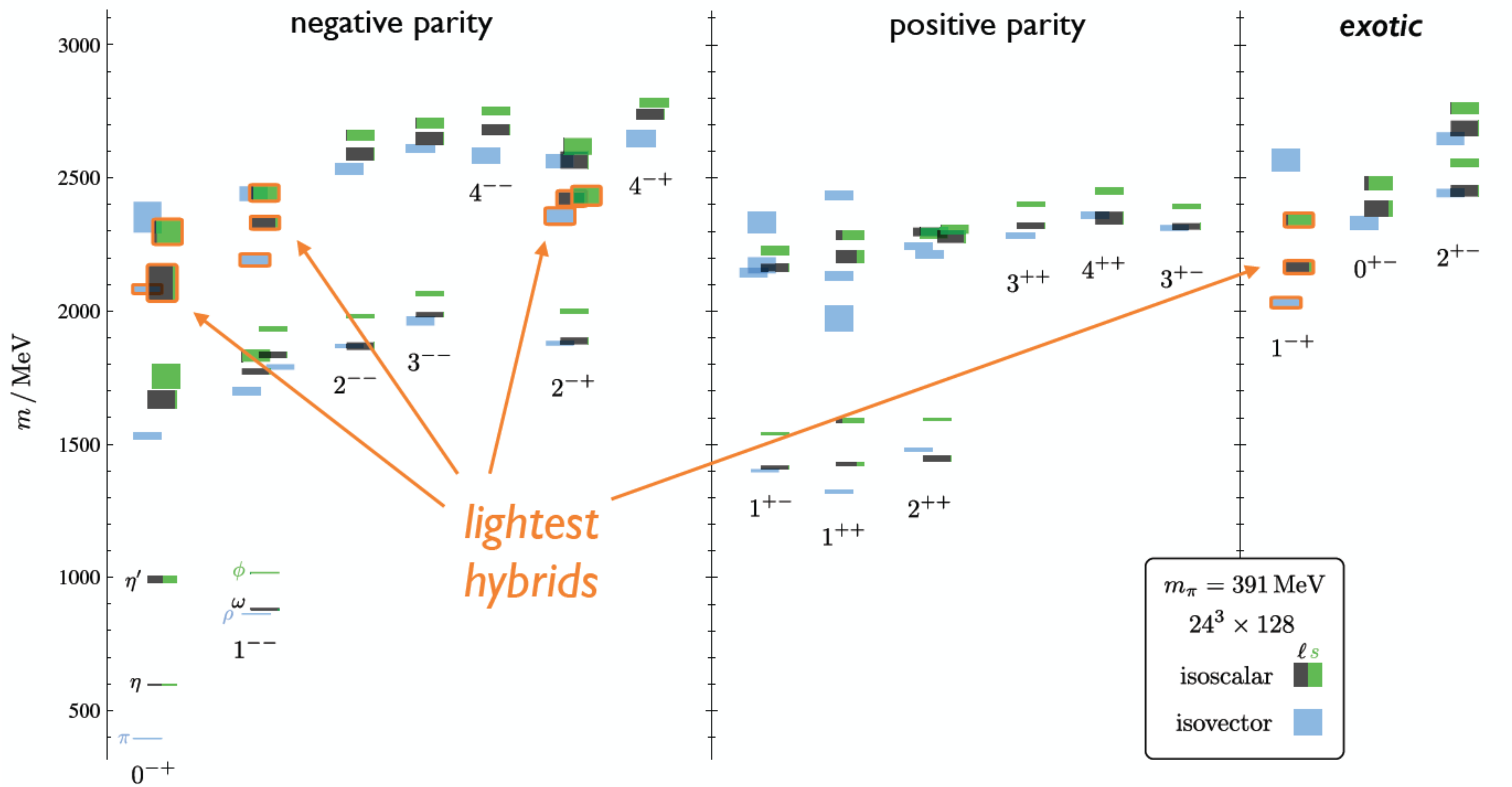
- sensitive to chiral symmetry breaking and vacuum condensate effects
- probe the strong force at larger distances (confinement)

Heavy quark mesons (cbt):

- can be described with non-relativistic potential models
- probe the strong force at smaller distances where short-range color interaction dominates

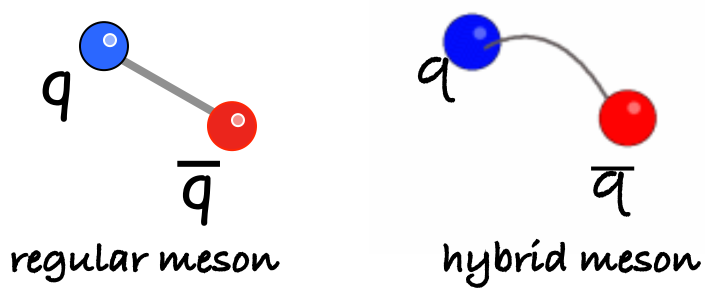
Hadrons on the Lattice

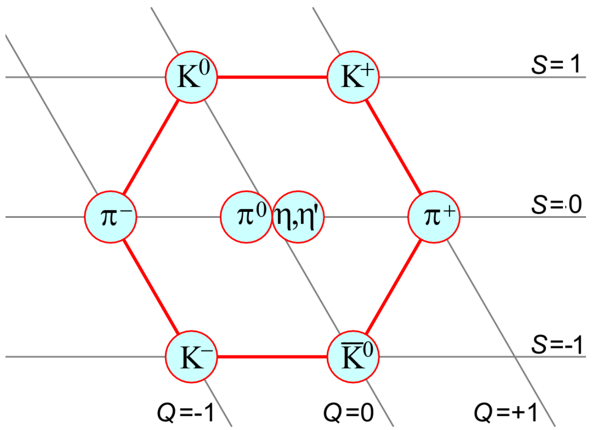
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



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*

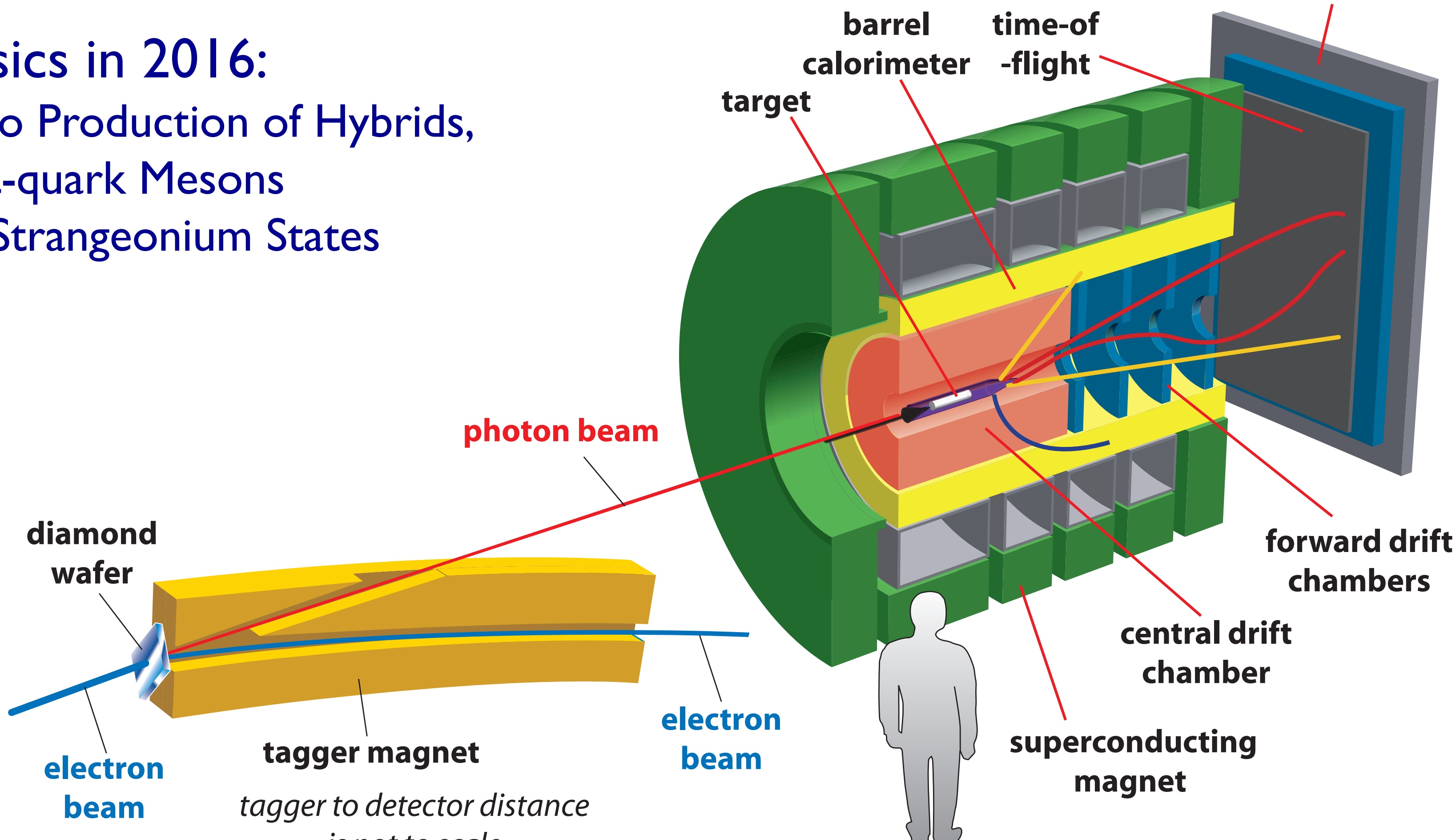




- Excitation of the glue leads to a new spectrum of hadrons that can have *exotic quantum numbers*
  $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} ...$
- For each exotic quantum number combination, a nonet of state should exist
- Lattice QCD predictions indicated the mass of the lowest state to be around 2 GeV, a range that can be explored at JLab

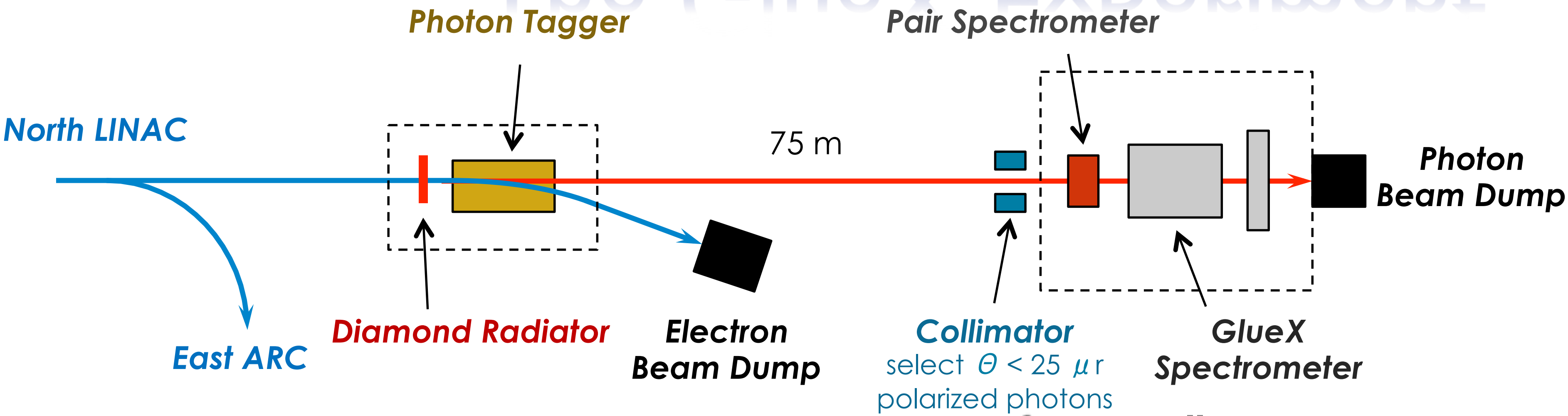
The GlueX Experiment

Physics in 2016:
Photo Production of Hybrids, Light-quark Mesons and Strangeonium States

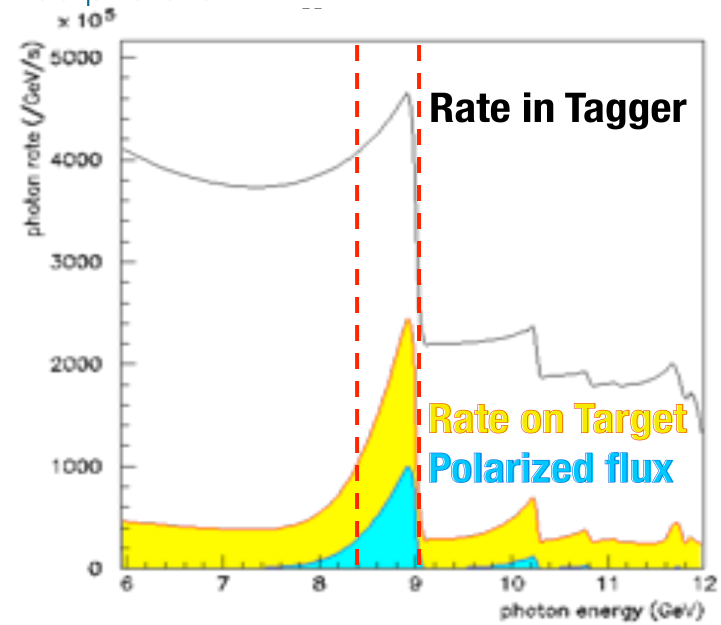


tagger to detector distance is not to scale

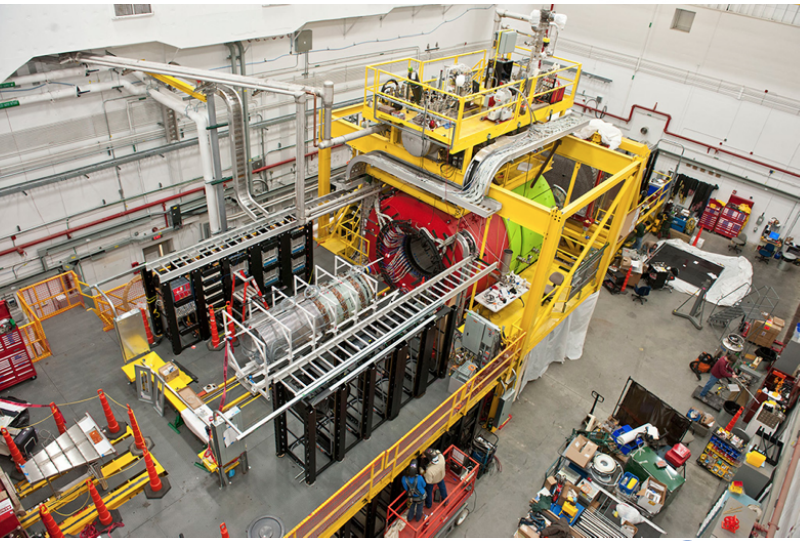
The GlueX Experiment



- 12 GeV e⁻ beam up to 2.2 μA.
- Linearly polarized photons (P_γ≈40%) from coherent bremsstrahlung on diamond radiator
- Design intensity of 10^8 γ/s in coherent peak (E_γ = 8.4-9 GeV)



The GlueX Experiment

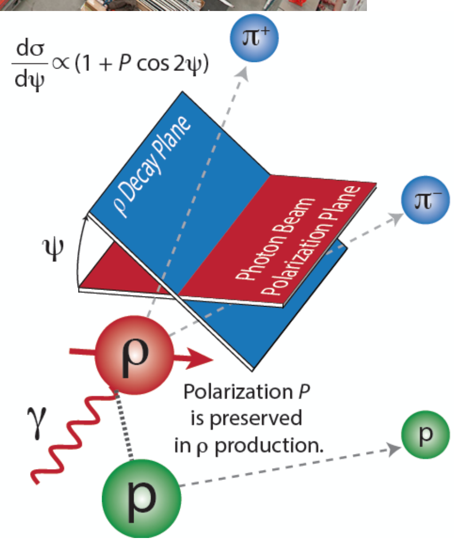


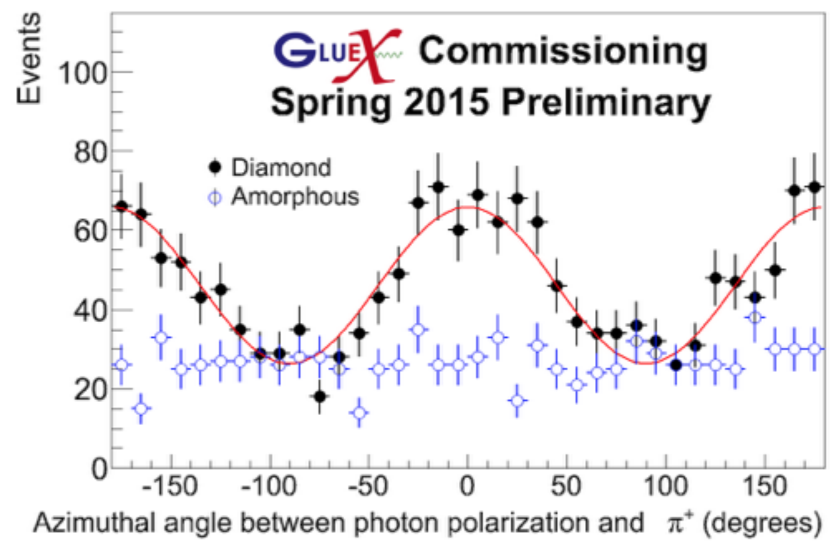
Spring 2014:	Installation mostly complete
Fall 2014:	First commissioning beam (~2 weeks@ 10.5 GeV)
Spring 2015:	Commissioning (~1 week @ 5 GeV) first liquid hydrogen target, first linearly polarized beam

Observations:

- Particles: π^0 η and ϕ ρ ω in exclusive channels
- Polarization asymmetry in physics reactions

First physics with GLUEX!





CLAS12

Forward Detector:

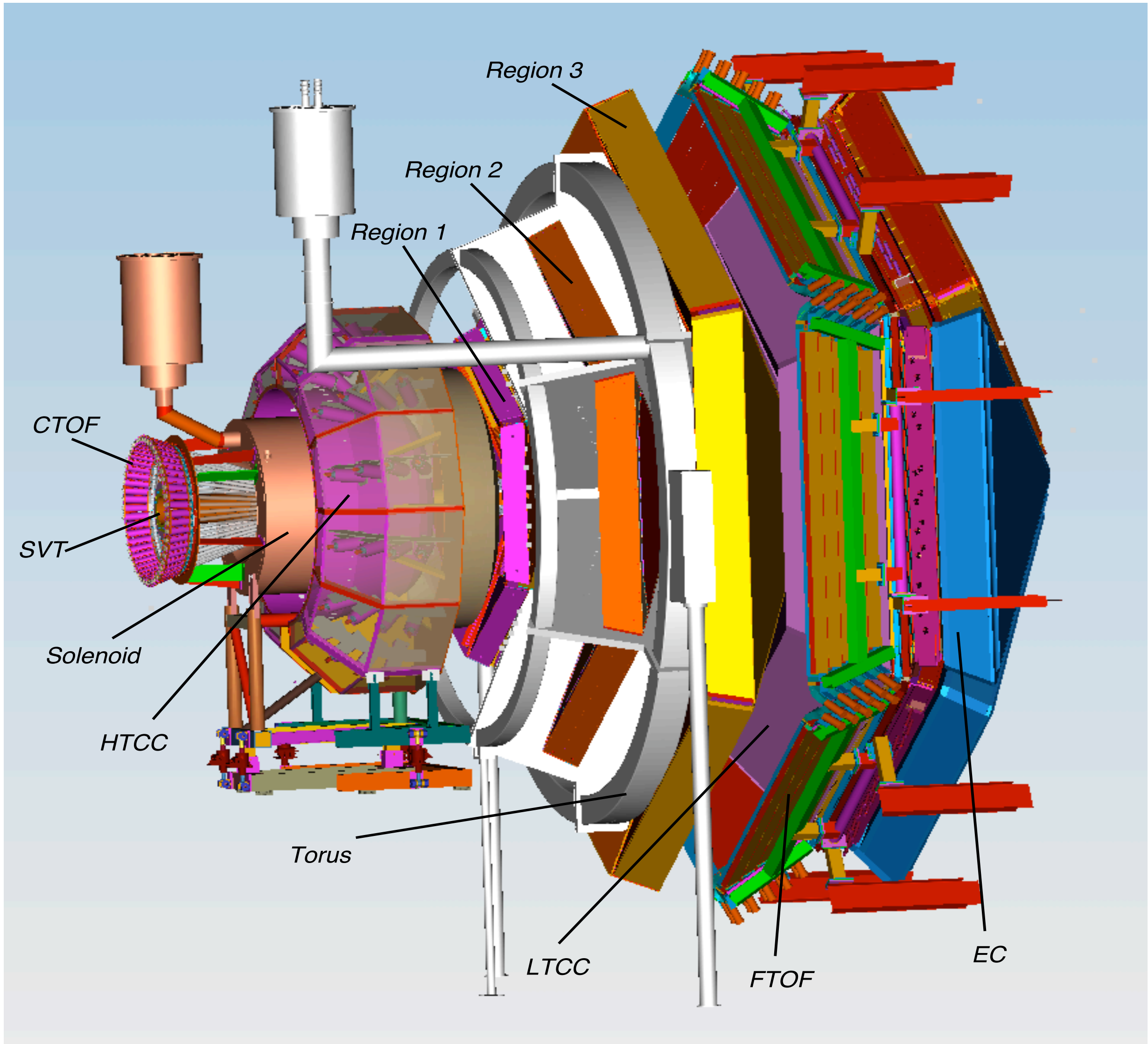
- *TORUS magnet*
- *Forward SVT tracker*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

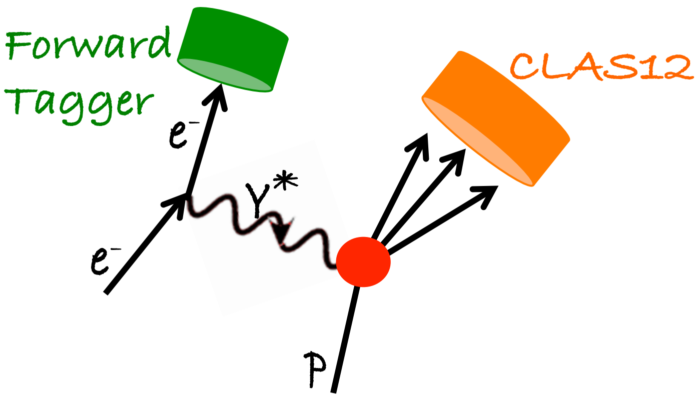
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Proposed upgrades:

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



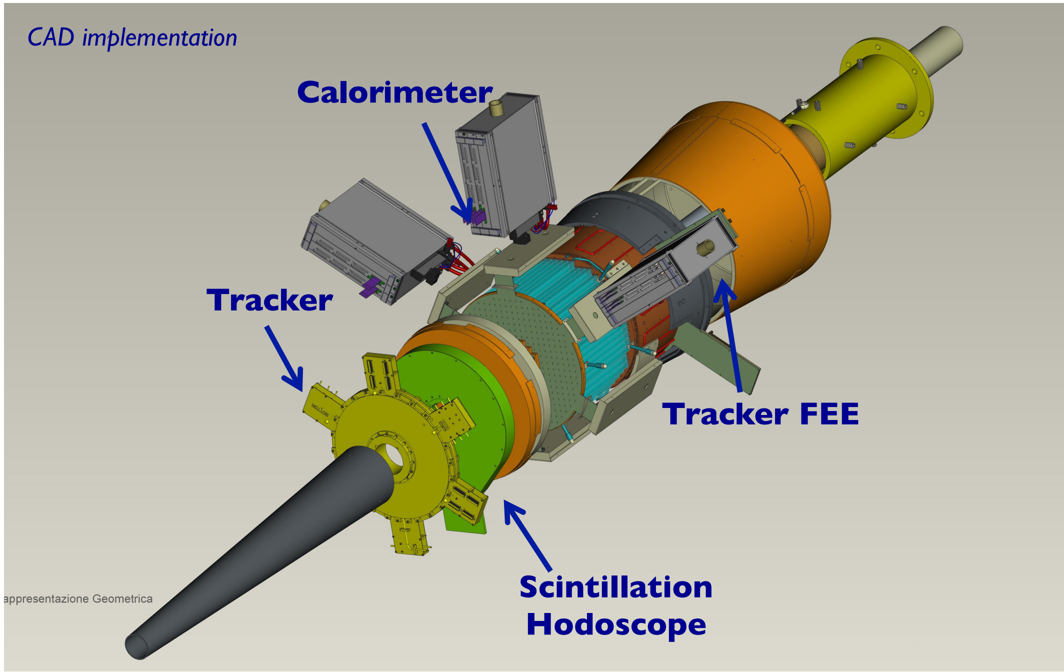
The CLAS12 Forward Tagger



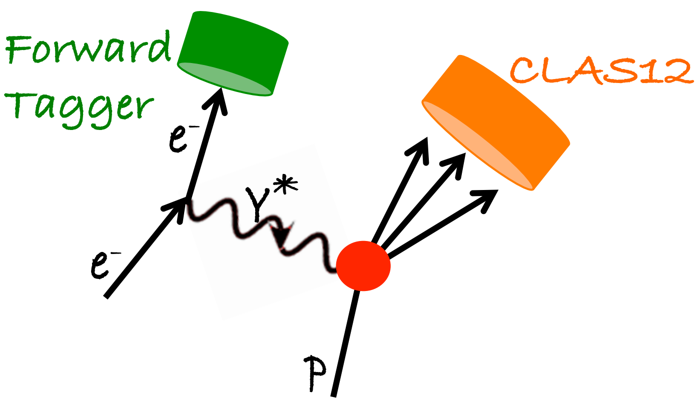
Quasi-real photoproduction on proton target:

- 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 @ $L_e=10^{35}$



The CLAS12 Forward Tagger



Physics goals

Meson spectroscopy:

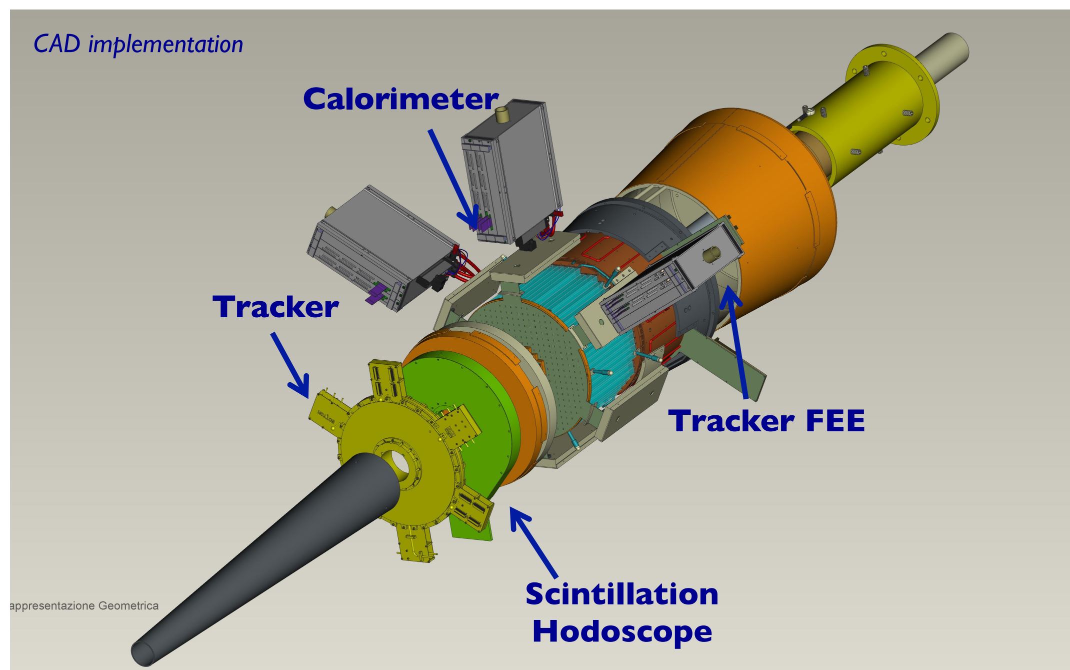
- Detailed mapping of the meson spectrum up to 2.5 GeV
- Investigation of strangeonium and strangeness rich states
- Search for exotics

Baryon spectroscopy:

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

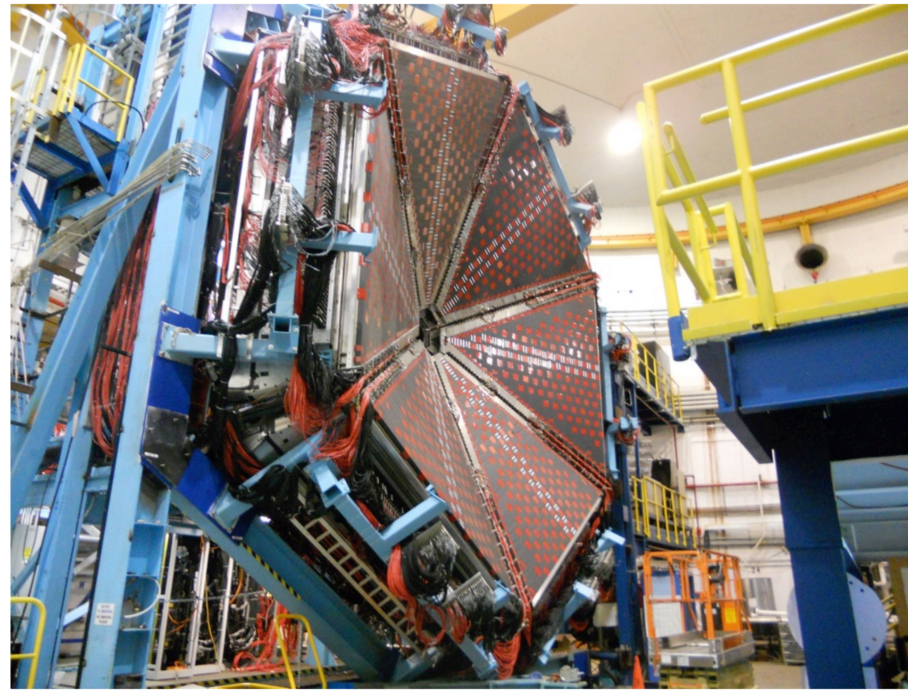
Quasi-real photoproduction on proton target:

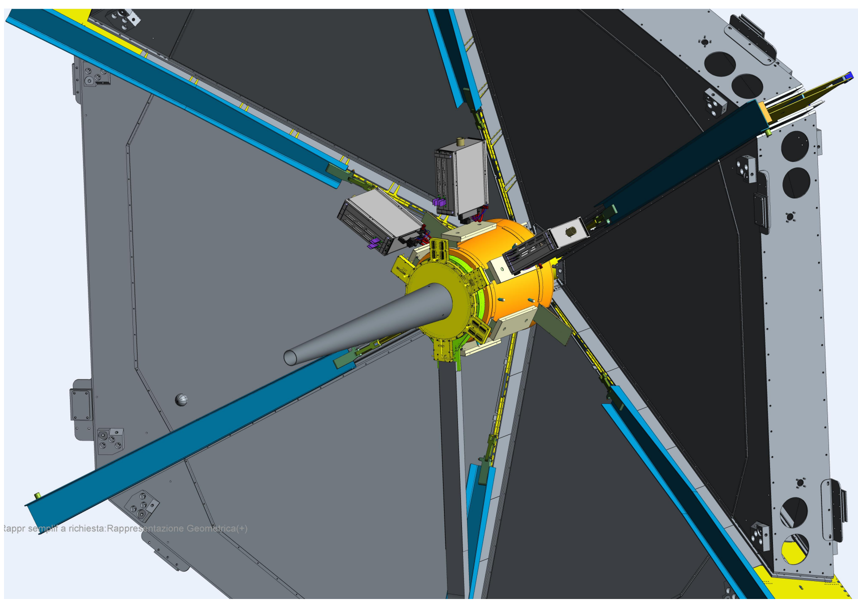
- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the novel Forward Tagger



The CLAS12 Forward Tagger

- FT components in final assembly/test phase at different institutions
- Integration and installation plan defined
- First FT detector (calorimeter) to be transferred at Jefferson Lab in the Fall for full commissioning





- Installation scheduled for late summer 2016
- Commissioning of the full CLAS12 detector in Fall 2016
- First physics run in spring 2017

Summary and Perspectives

- The study of hadron spectroscopy can shed light on fundamental problems in the understanding of strong interaction and QCD
- Hadron spectroscopy is one of the pillars of the Jefferson Lab physics program carried out in the 6 GeV era and planned at 12 GeV
- The CLAS data at 6 GeV have provided important input for the understanding of the hadron spectrum and structure:
  - N* resonances
  - Hyperons
  - Light mesons
- An extensive program is planned at 12 GeV exploiting both real and quasi-real photo-production:
  - GlueX in Hall D starting physics production in 2016
  - CLAS12 in Hall B starting physics production in 2017