Meson Spectroscopy in the Light Quark Sector

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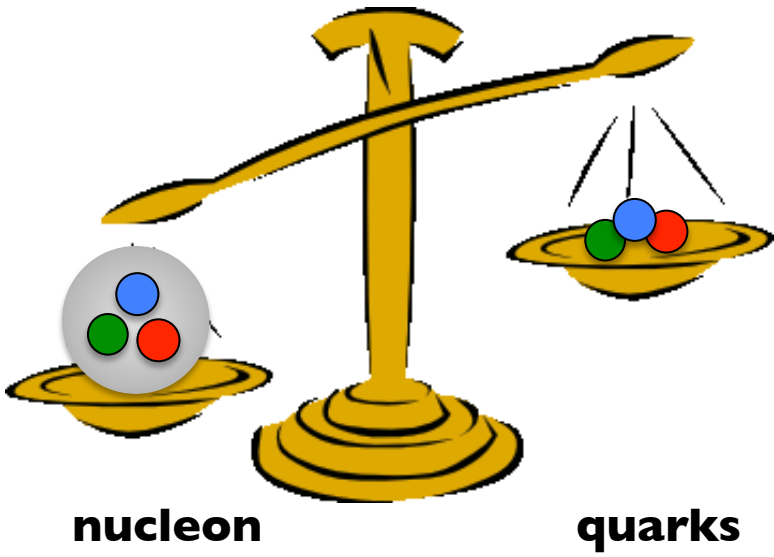
Why Hadron Spectroscopy

- 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

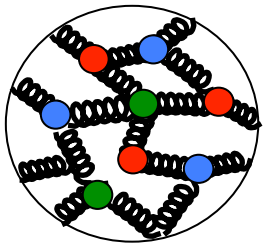
  while the remaining fraction is to to the force that binds the quarks: **QCD**
- QCD with its rules and constraints determines the mass and spectrum of hadrons and makes the world as we know it



Hadrons and QCD

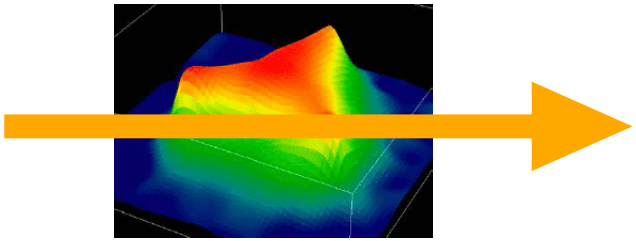
- Studying the hadron properties and the rules of QCD is crucial to reach a deep understanding of the structure of matter
- Hadrons are color neutral systems made of quarks and gluons but…
  - What is the internal structure and what are the internal degrees of freedom of hadrons?
  - What is the role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

<< 0.1 fm



Quarks and Gluons

0.1 – 1 fm



Effective Degrees of Freedom

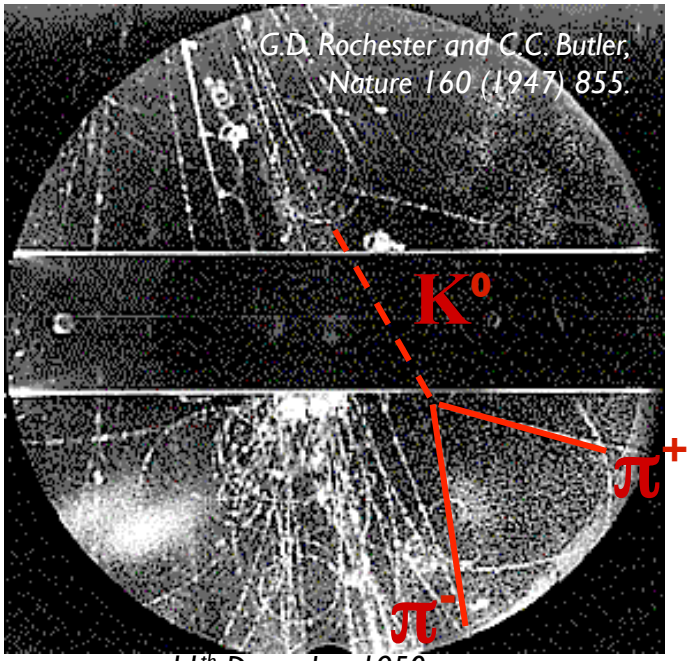
> 1 fm

Mesons & Baryons

Meson Spectroscopy

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

Historically, the study of meson properties led to some of the most relevant discoveries in particles physics



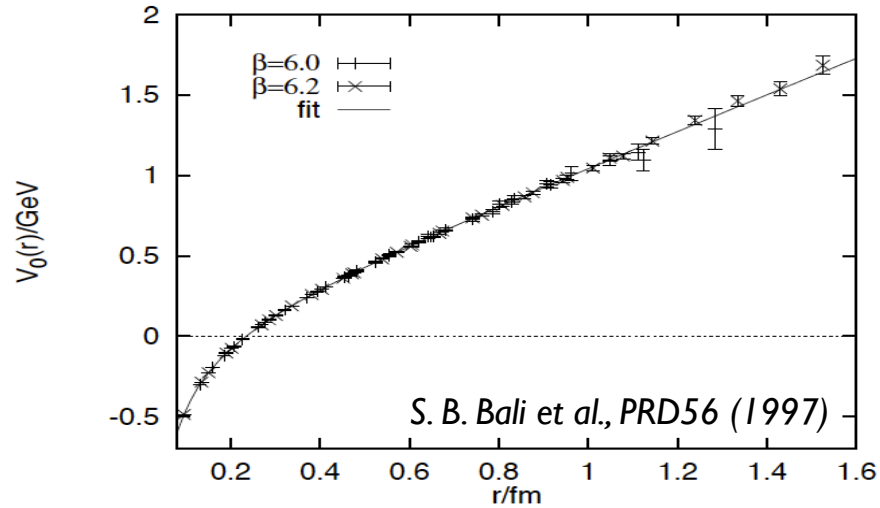
11th December 1950

- in 1947 the discovery of the pion by Powell, Occhialini and Lattes
- in the same year, the discovery of strange particles by Rochester and Butler
- the interpretation of the ϕ decay to KK by Zweig and others in 1963
- the discovery of the J/ψ in 1974
- …

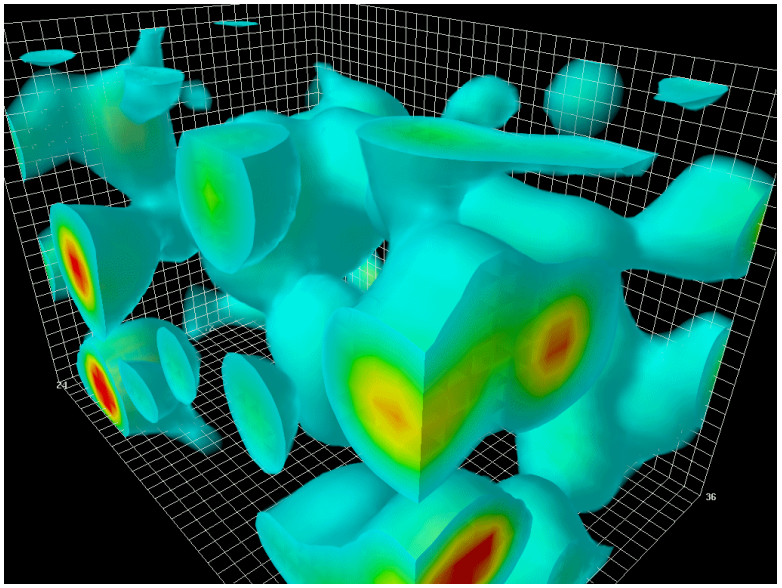
After many years, meson spectroscopy remains a very active field and a precious source of information for the understanding of quark-gluon interaction

Meson Spectroscopy

Goal of modern meson spectroscopy is to answer these fundamental questions of QCD, studying the spectrum of mesons and searching for exotic states



D. Leinweber: LQCD visualization of the QCD vacuum



Light quark mesons (uds):

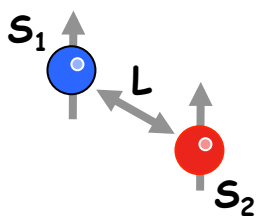
- sensitive to chiral symmetry breaking and vacuum condensate effects
- probe the strong force at larger distances (confinement)

Heavy quark mesons (cbt):

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

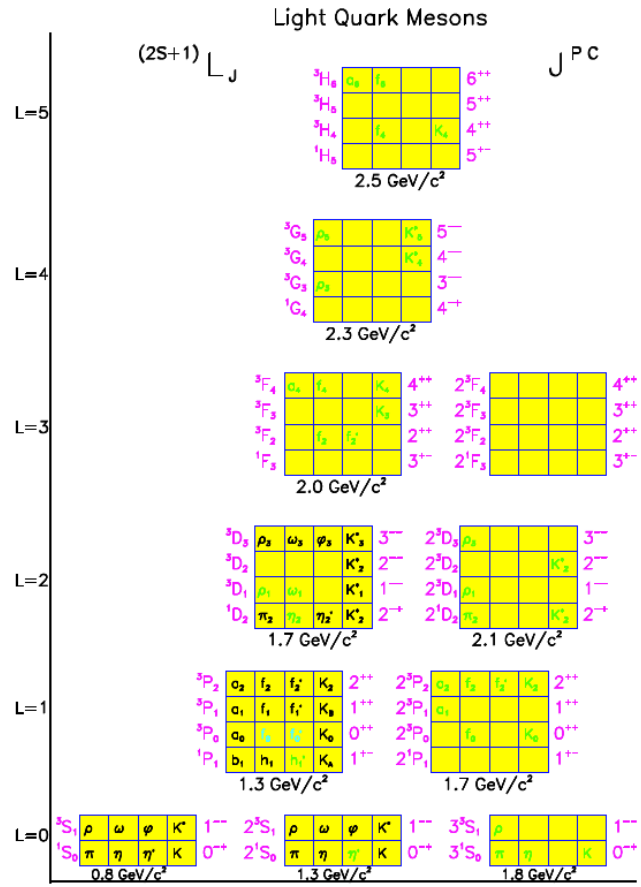
Light Quark Mesons

First indications on the meson spectrum are given by the Constituent Quark Model:



- Quark-antiquark pairs with total spin S=0,1 and orbital angular momentum L
- SU(3) flavor symmetry
- A nonet of states with the same quantum numbers, J^{PC}, for each value of L and S

- Great success in describing the lower mass states
- A number of predicted states is not experimentally observed and assignments are uncertain:
  - failure of the model?
  - limitations in the experimental techniques?
  - …



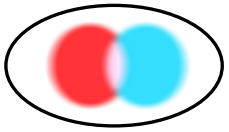
Yellow: expected meson states
Black: established states
Green: tentative assignments

Beyond the quark model…Exotics

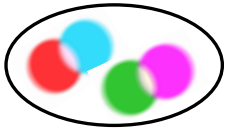
QCD tells us that bound states have to be color neutral but does not prohibit the existence of state with unconventional quark-gluon configurations as tetraquarks, glueballs or hybrids

- Several phenomenological models predict the existence of such states and give indications of masses and decays
- Supporting evidence is provided by Lattice QCD calculations
- Experimental evidence has been searched in many laboratories
  - X(3872) observed at B-factories interpreted as tetraquark
  - Indication of hybrids below 2 GeV reported by several experiments
  - …

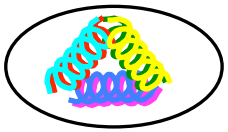
- If unambiguously confirmed, these state would provide the mean to further investigates aspects of QCD as confinement and gluonic excitations



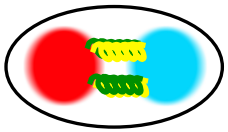
regular meson



tetraquarks



glueball

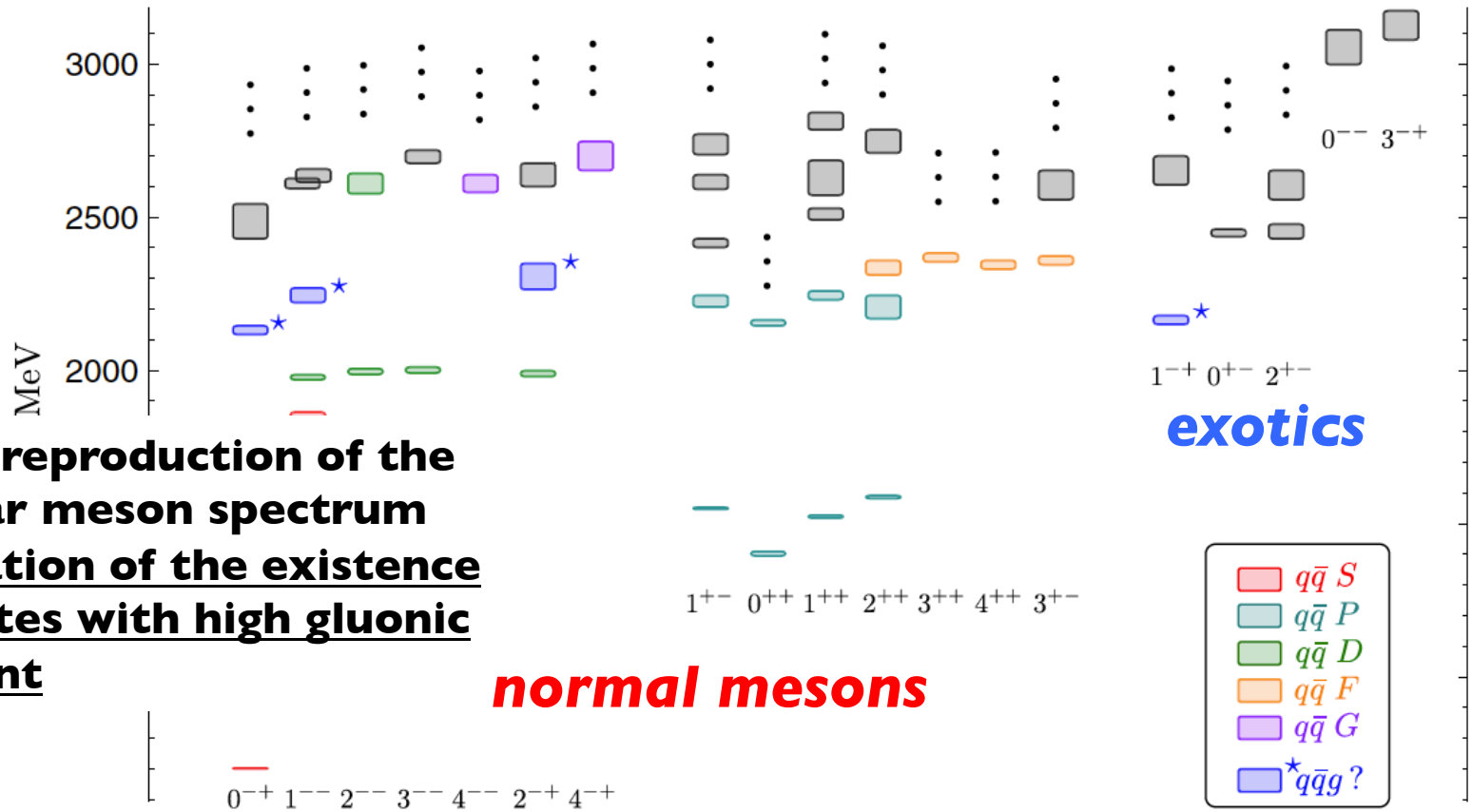


hybrid

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

Lattice QCD

Predictions of the meson spectrum from Lattice QCD are now available



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

isovector mesons, m_π~700 MeV

Meson Spectroscopy in the World

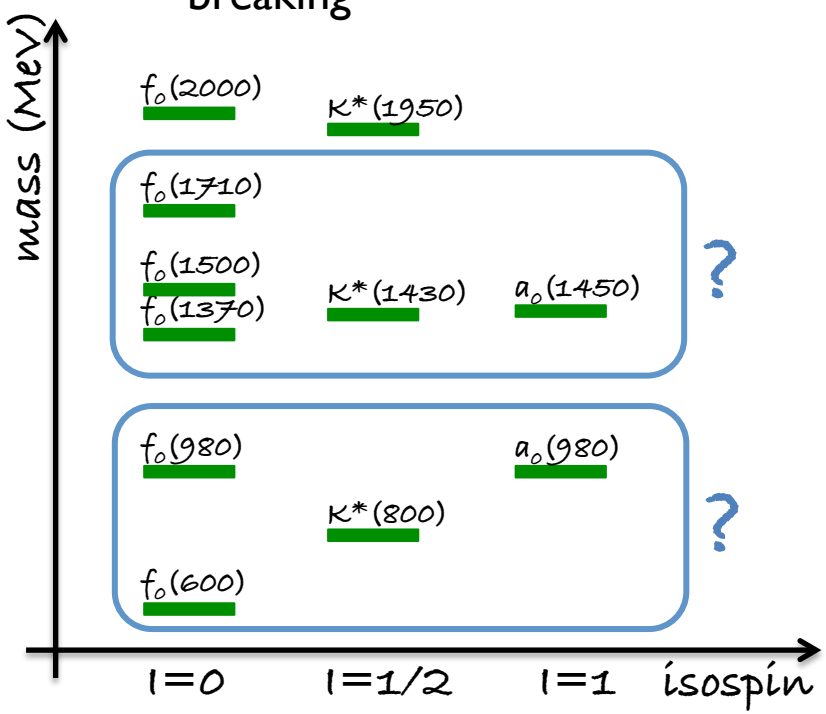
- Many experiments in the world have studied and are studying the meson spectrum in the light-quark sector using different production processes

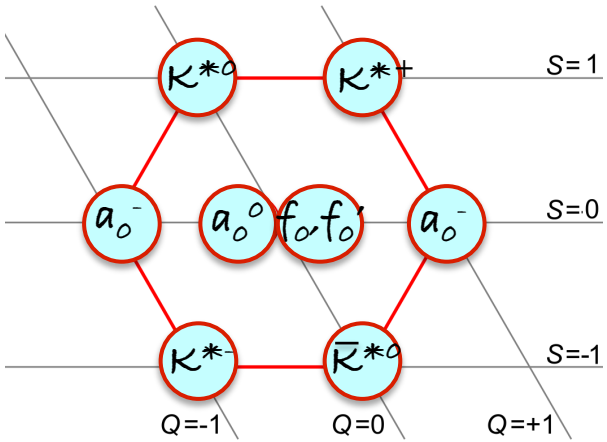
- proton-antiproton annihilation:
  Crystal Barrel at CERN, Panda at GSI, ...
- $e^+ e^-$ annihilation:
  LEP, Babar at SLAC, Belle at KEK, KLOE at Frascati, CLEO at Cornell, BES at Beijing, KLOE-II, Belle II at SuperKEKB, …
- proton-proton scattering:
  WA experiments at CERN, GAMS at Protvino, LHC, …
- pion beams on fixed target:
  E852 at BNL, VES at Protvino, COMPASS at Cern, …
- photoproduction experiments:
  CLAS at Jefferson Lab, GlueX and CLAS12 at Jefferson Lab

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



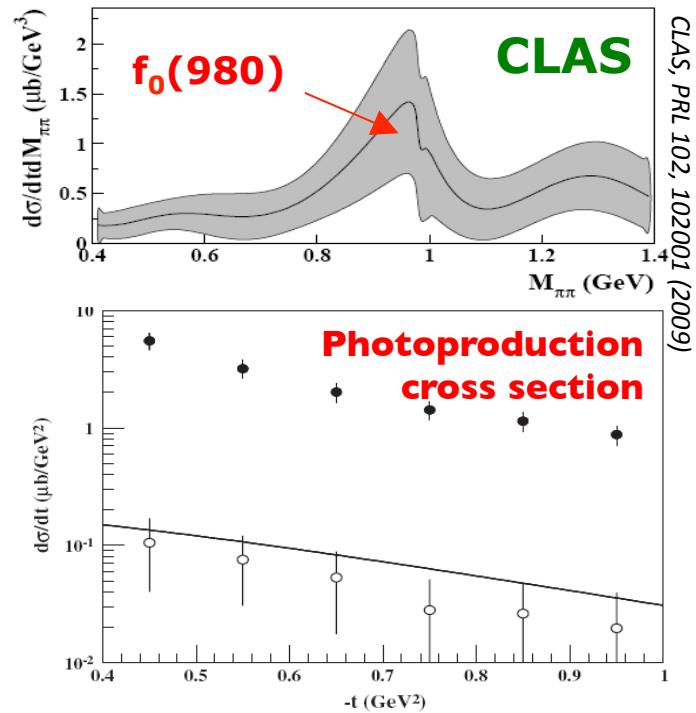


- The scalar meson nonet should be composed by a_0(I=1),K* (I=1/2), f_0 and f_0'(I=0), with the a_0 as lightest state and the f_0' showing a large strange content
- At present, given the I=1 and I=1/2 states that have been identified, there is an excess of I=0 states

The $f_0(980)$ meson

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

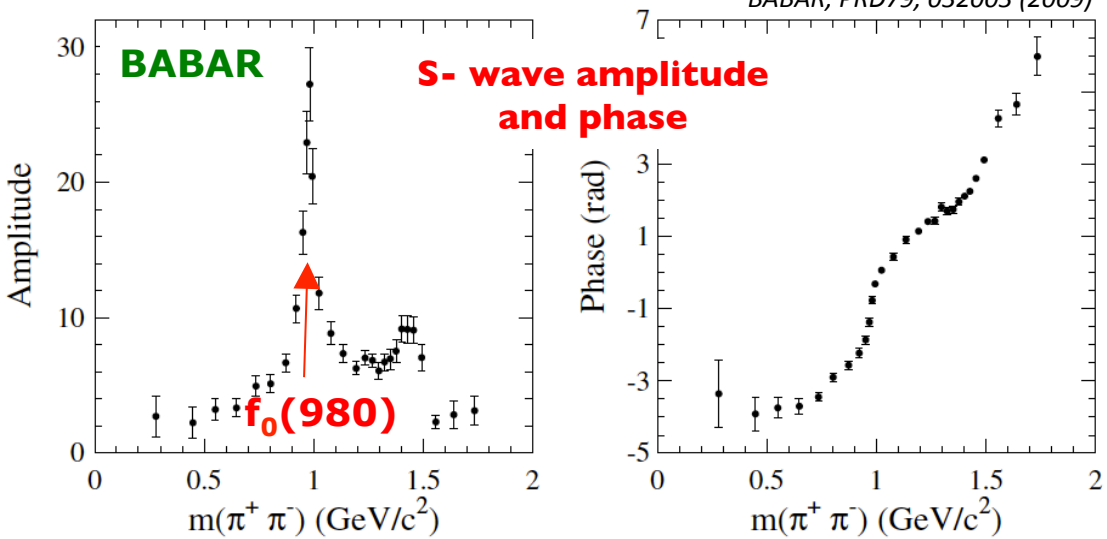
➔ Unusual mas hierarchy of the multiplet ($f_0(980)$ almost degenerate with $a_0(980)$) and decays led to propose these states as TETRAQUARKs



CLAS, PRL 102, 102001 (2009)

Detailed measurement of the **S wave** around the resonance mass needed to determine the nature of this state

BABAR, PRD79, 032003 (2009)



High precision data from BES, KLOE, BABAR, CLAS and others now available can shed light on this puzzle

Higher mass scalars

Abundance of I=0 states with unexpected decay patterns between 1.3 and 2 GeV led to speculate about the presence of a glueball in this sector

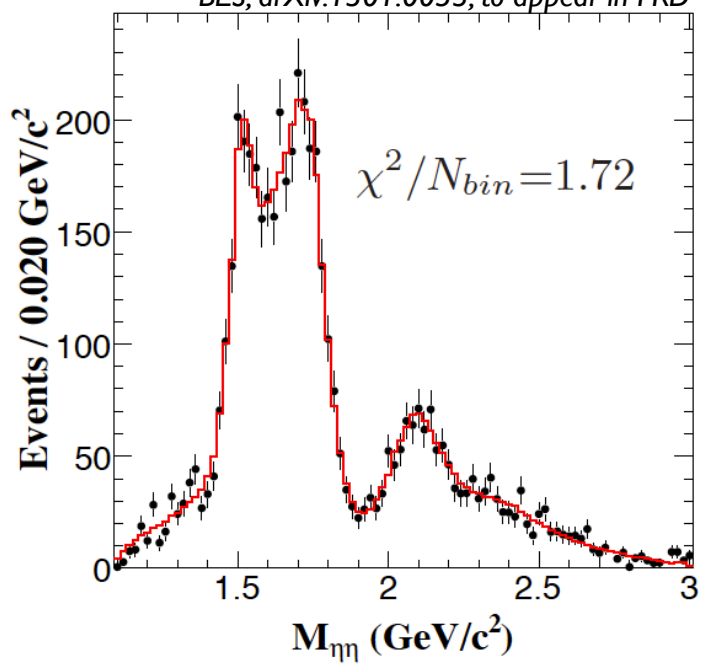
$f_0(1370)$
$f_0(1500)$
$f_0(1710)$
$f_0(2100)$
…

- Lower two states seen first by Crystal Barrel
- Higher mass states seen by WA102 and BES
- Discrepancies between different experimental observations
- *High statistics/high precision data needed!*

New high statistics data set from BESIII in Beijing:

- clear structures in the ηη mass spectrum from J/ψ radiative decays
- full partial wave analysis to isolate S wave contribution
- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2 σ)
- $f_0(1710)$ and $f_0(2100)$ strength ~10x larger than $f_0(1500)$

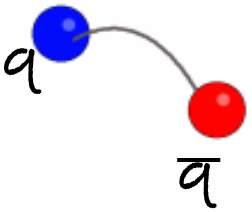
BES, arXiv:1301.0053, to appear in PRD

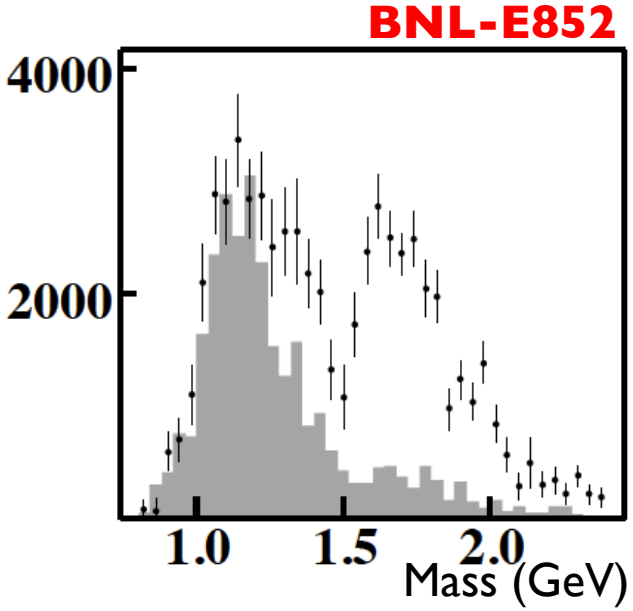


Additional data expected in the near future from this and other experiments can lead to a full understanding of the scalar sector

Search for Hybrids

- Ideal benchmark to study quark-quark interaction and excitations of the glue
- Existence of hybrids states is supported by several theoretical models and by lattice QCD calculations
- Recent studies indicate the lightest states could have mass below 2 GeV and "exotic" quantum numbers $J^{PC}=1^{-+}$

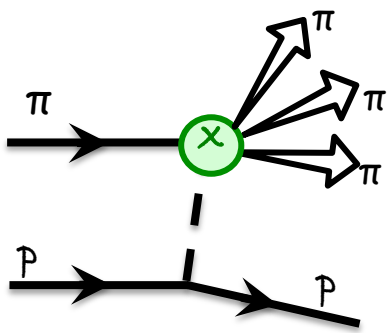




Most debated experimental evidence is related to the so-called $\pi_1(1600)$:

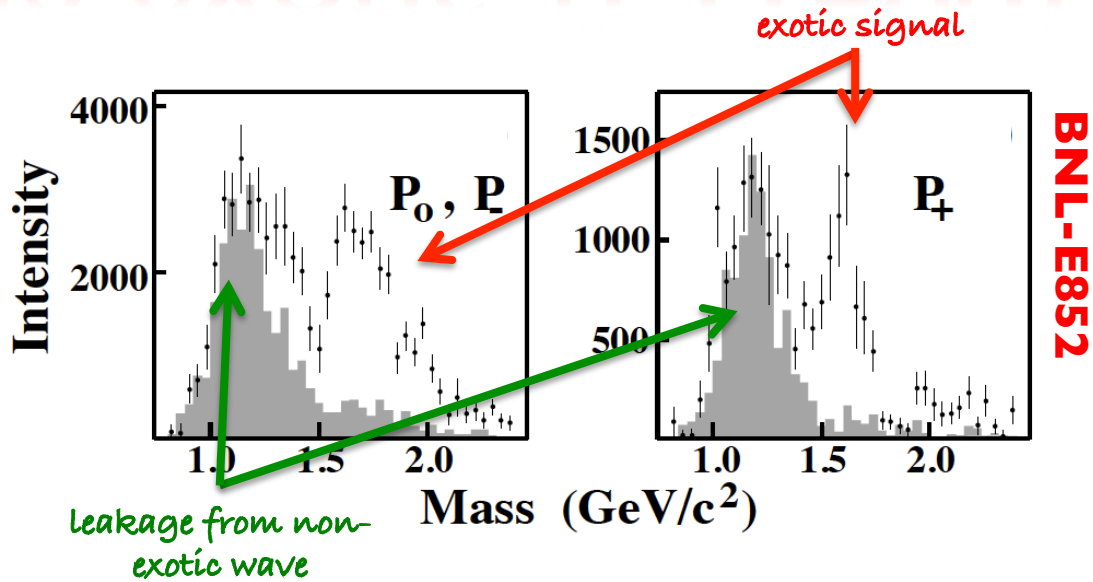
- observed in several decay modes ($\rho\pi$, $\eta'\pi$, $f_1\pi$, $b_1\pi$) including decays to L=1-L=0 meson pairs as predicted by the flux tube model
- observations reported by different experiments (E852,VES,COMPASS) but with different production mechanisms
- presence of resonant signal still requires confirmation

The exotic $\pi_1(1600)$



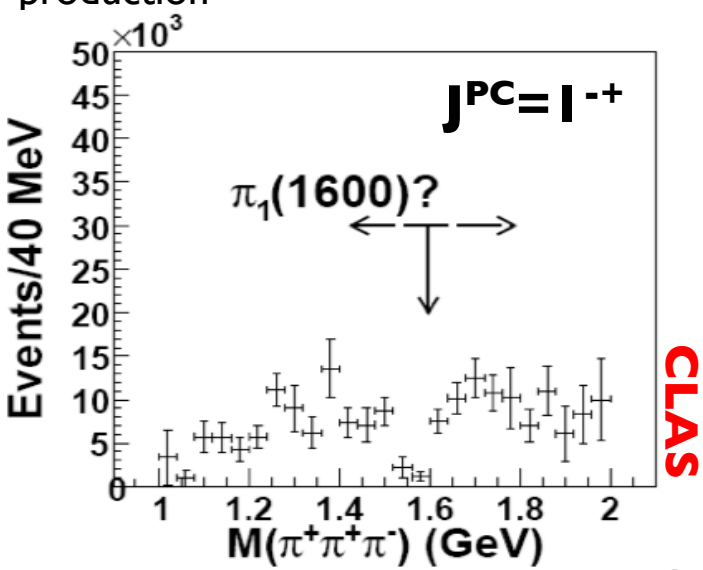
Exotic signal reported by BNL-E852 experiment in the analysis of the 3 pion final state

Opposite findings reported by the CLAS Collaboration in photo-production



P_+ or $M^\varepsilon = 1^+$ natural-parity exchange

$P_{0,-}$ or $M^\varepsilon = 0^-, 1^-$ unnatural-parity exchange



Significant intensity in the 1^{-+} wave with clear phase motion with respect to the 2^{-+}

$$M = \left(1.593 \pm 0.080^{+0.029}_{-0.047}\right) GeV$$

$$\Gamma = \left(0.168 \pm 0.020^{+0.150}_{-0.012}\right) GeV$$

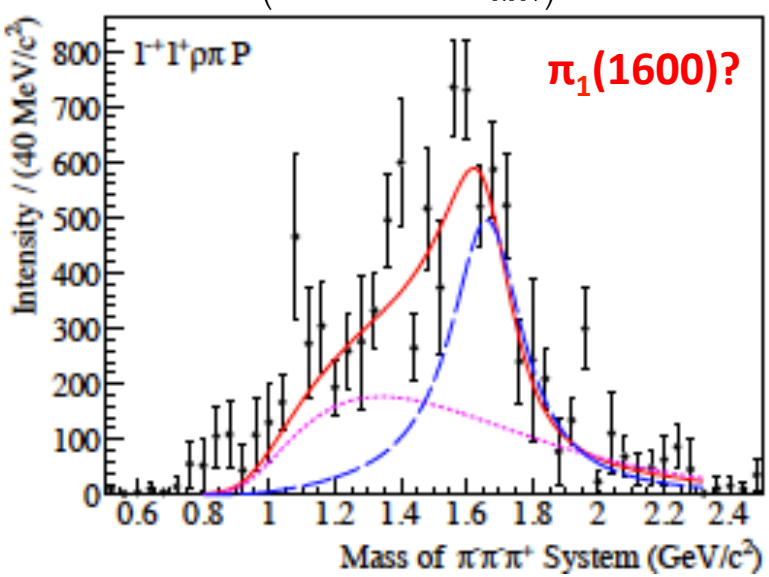
Ongoing searches

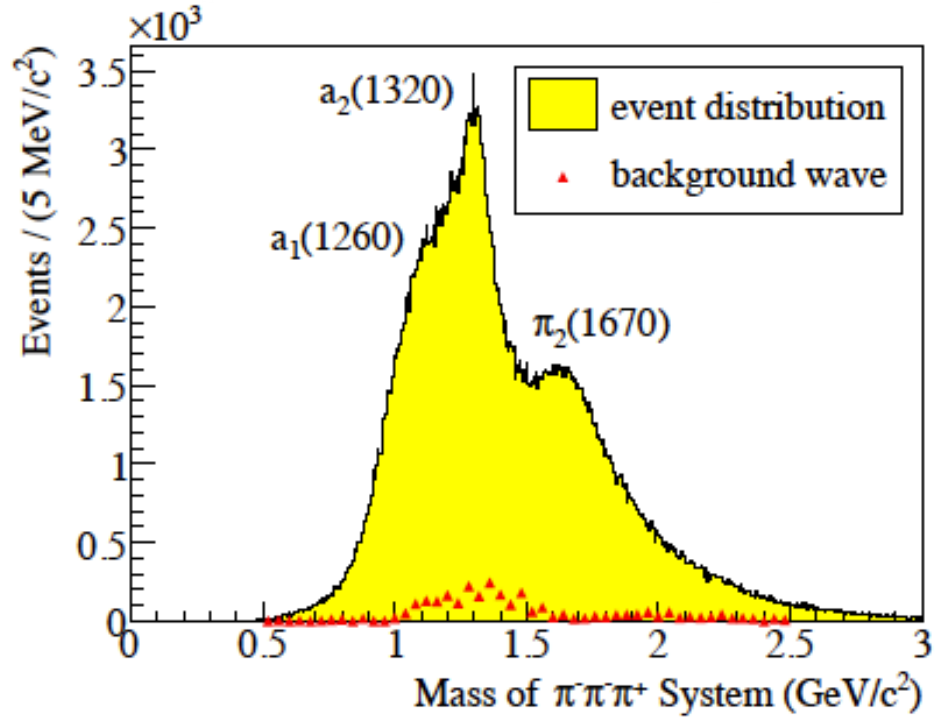
Experimental investigation continues at COMPASS at CERN SPS with 192 GeV pion beam on nuclear targets

- Positive observation reported from the analysis of 2004 pilot run on lead

$$M = \left(1.660 \pm 0.010^{+0}_{-0.064}\right) GeV$$

$$\Gamma = \left(0.269 \pm 0.021^{+0.042}_{-0.064}\right) GeV$$





- Analysis of 2008 run (96 M events) will allow better control of background processes
- High quality results expected

Meson Spectroscopy in the World

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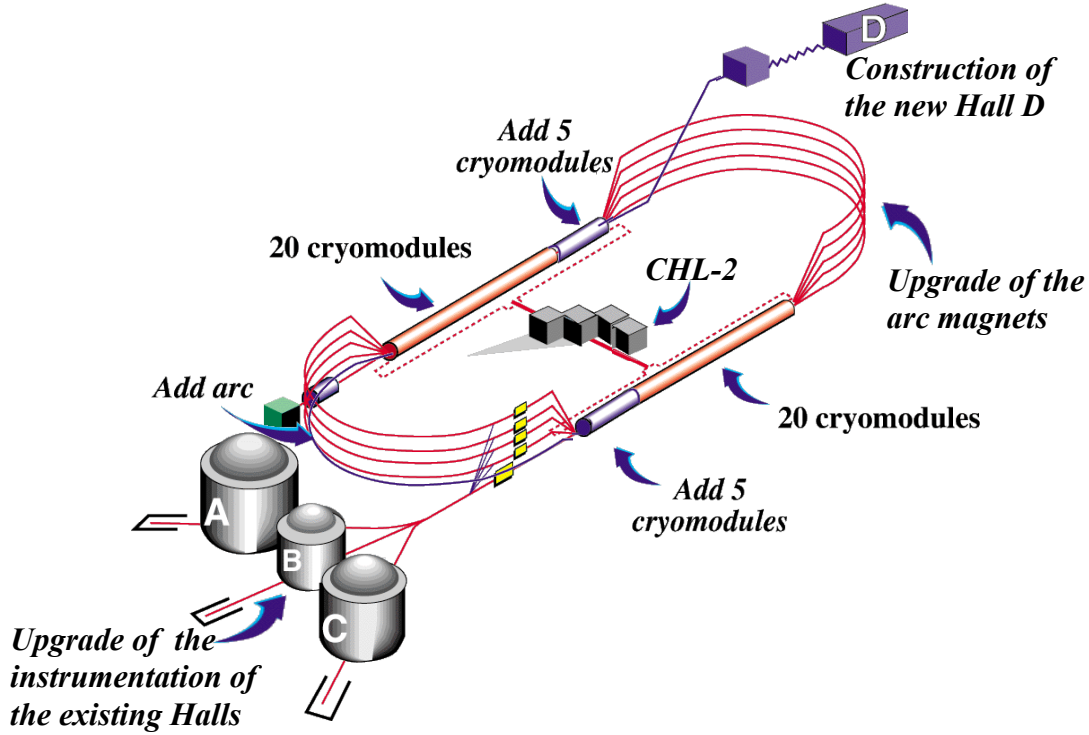
- proton-proton scattering:
  WA experiments at CERN, GAMS at Protvino, LHC, …
- pion beams on fixed target:
  E852 at BNL, VES at Protvino, COMPASS at Cern, …
- photoproduction experiments:
  CLAS at Jefferson Lab, GlueX and CLAS12 at Jefferson Lab

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



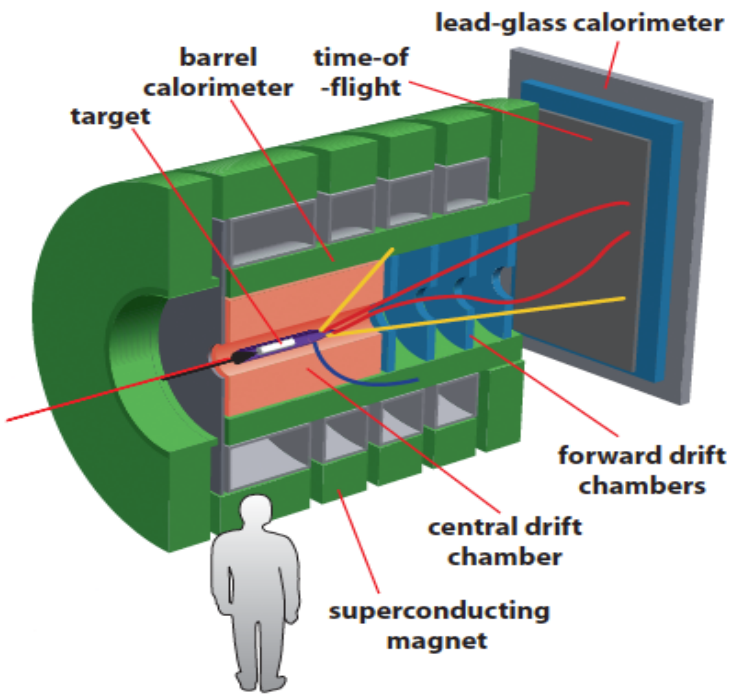
High electron polarization
Beam Power: 1MW
Beam Current: 90 μA
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

CLAS12 and GLUEX

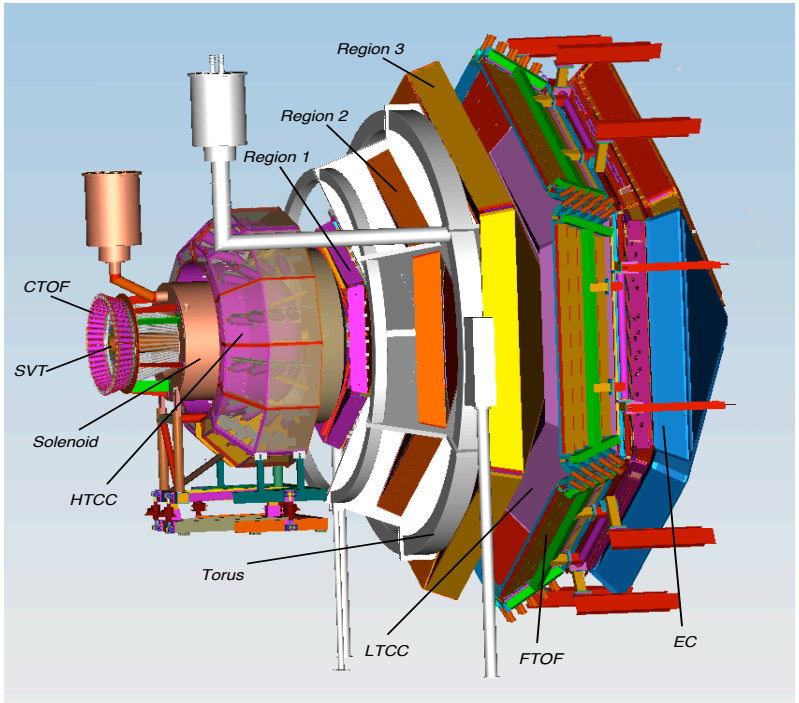
Meson spectroscopy is one of the main topics that will be studied with the Jlab 12 GeV upgrade. Key elements are:

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

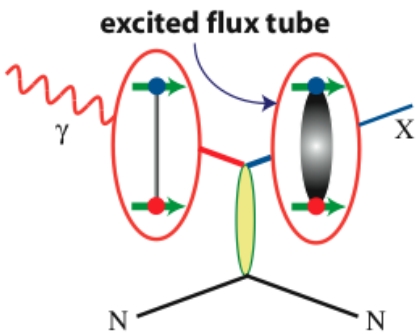
GlueX in Hall D



CLAS12 in Hall B



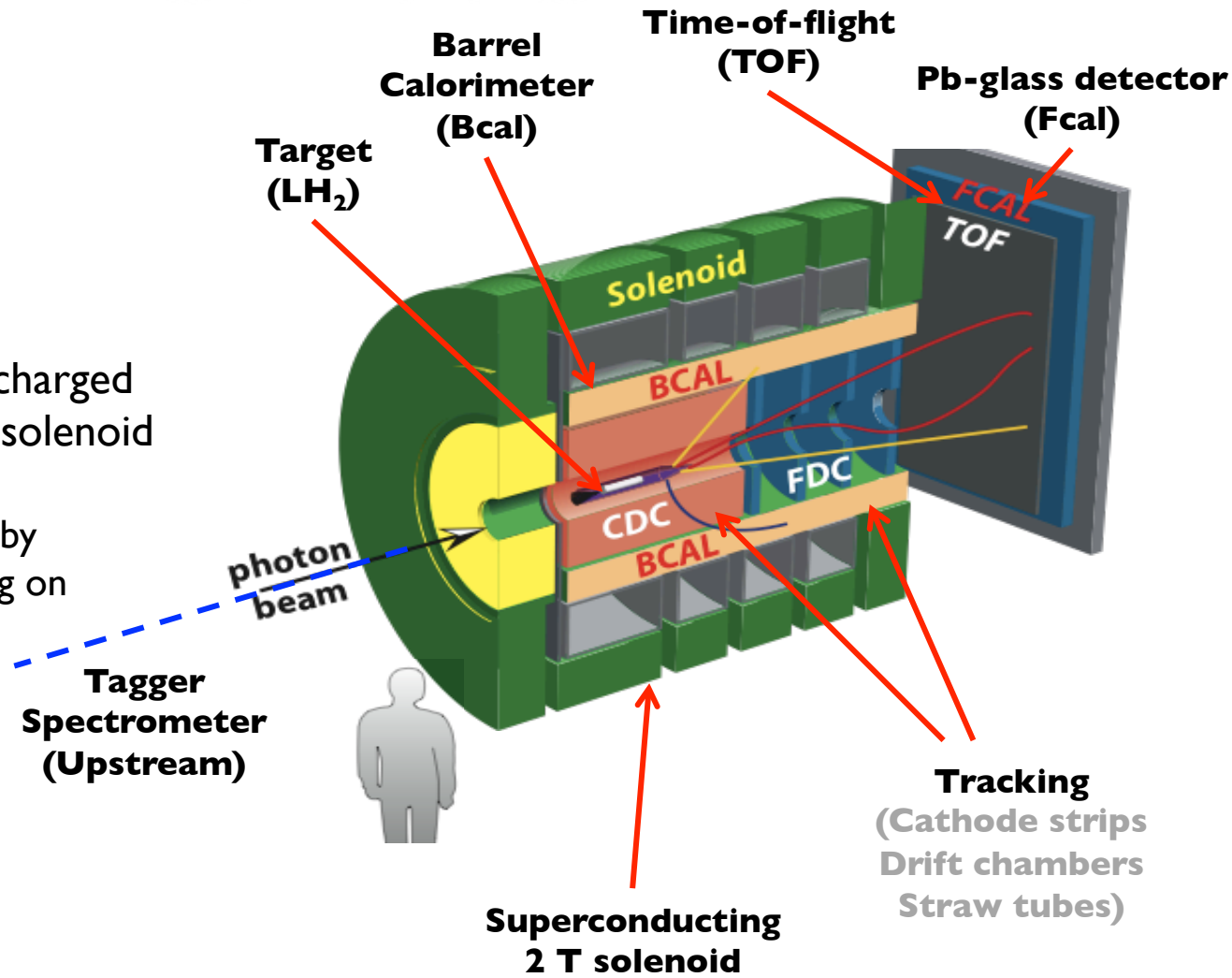
The GlueX Experiment



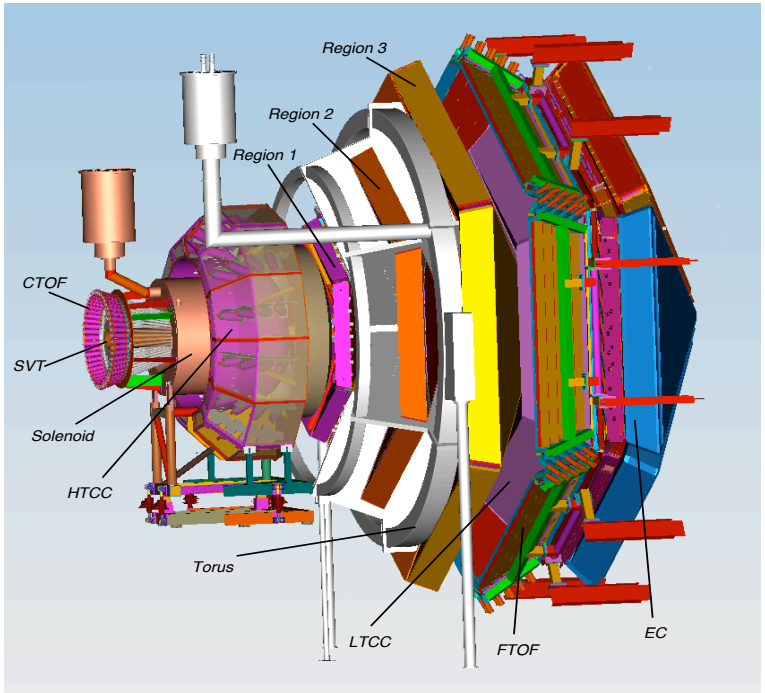
Hermetic detection of charged and neutral particles in solenoid magnet:

- Photon beam produced by coherent Bremsstrahlung on diamond radiator
- Initial Flux 10^7 g/s
- 18,000 FADCs
- 4,000 pipeline TDCs
- 20 KHz L1 trigger
- 300 MB/s to tape

D. Lawrence's talk

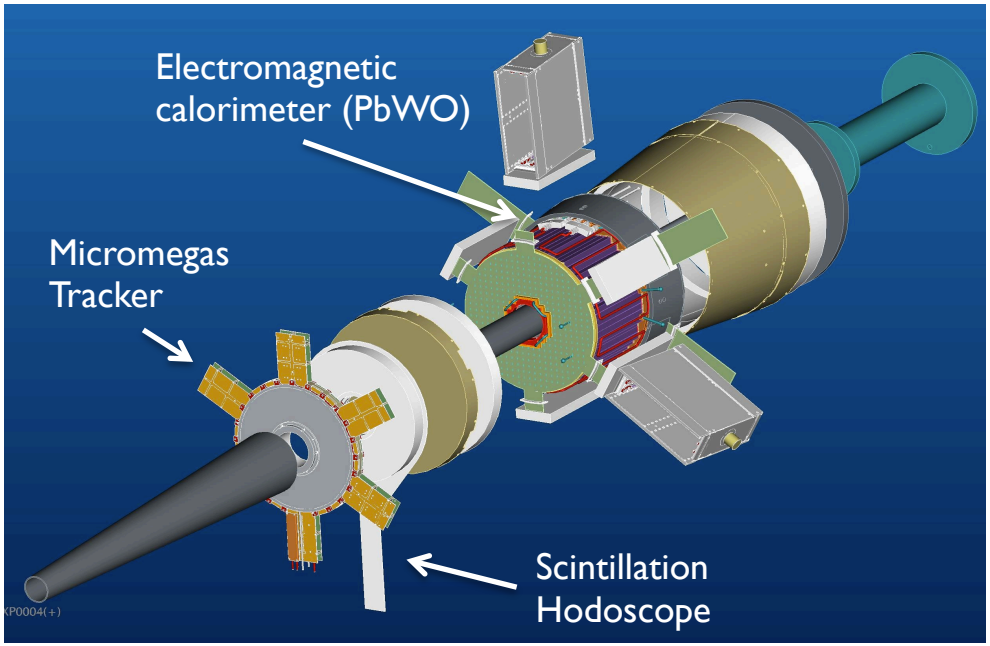


The CLAS12 Experiment



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



Physics goals:

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

Summary

* Meson 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

* Primary focus of the research activity in this field is to establish the quark-antiquark bound state spectrum and search for exotic configurations

* Experiments all over the world are collecting high statistics high precision data, providing new insight in the meson spectrum

* The new experimental data with the support of recent theoretical developments can lead physicists to solve one of the most intriguing puzzles in hadronic physics