The Meson Spectroscopy Program Using the Forward Tagger with CLAS12 at Jefferson Lab

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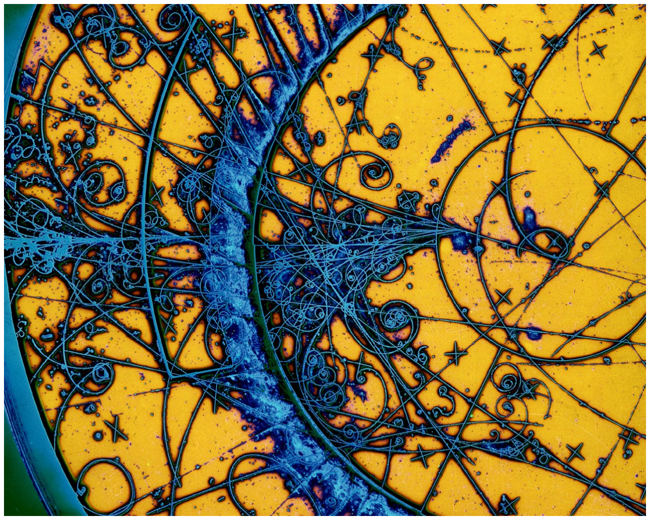
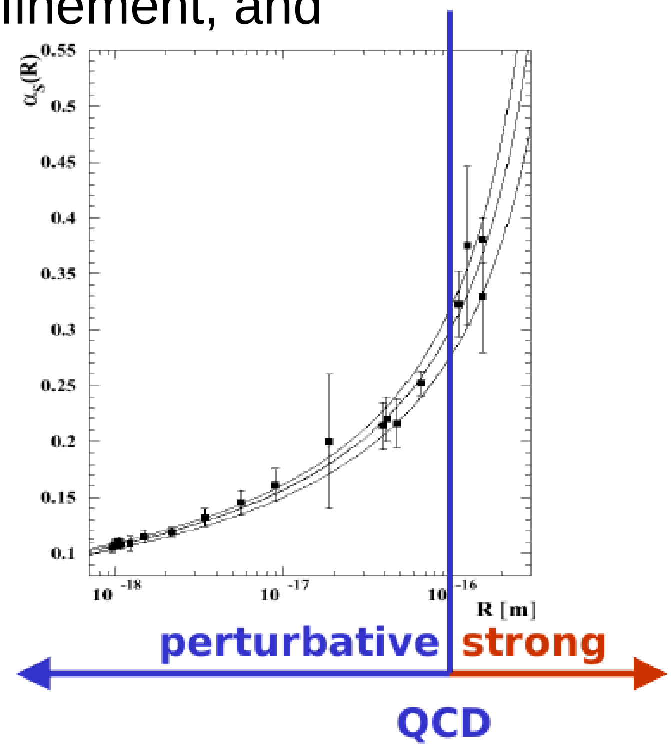
Outline

- Introduction
  - QCD and quark models
- Meson Spectroscopy
  - Mesons, hybrids and exotics, and predictions from Lattice QCD
- Jefferson Lab and the 12 GeV upgrade
- CLAS12 and the Forward Tagger
- Data analysis techniques
  - Partial Wave Analysis
  - The HASPECT collaboration
- Outlook and Summary

Introduction



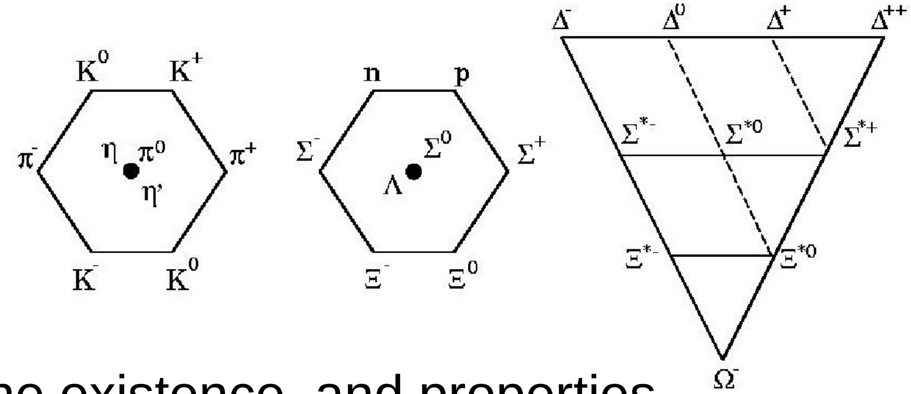
- From its roots in the experimental particle physics of the 1950's and 60's, the development around 40 years ago of the theory of QCD has served as a powerful tool in our understanding of strong force interactions, confinement, and the structure of hadrons



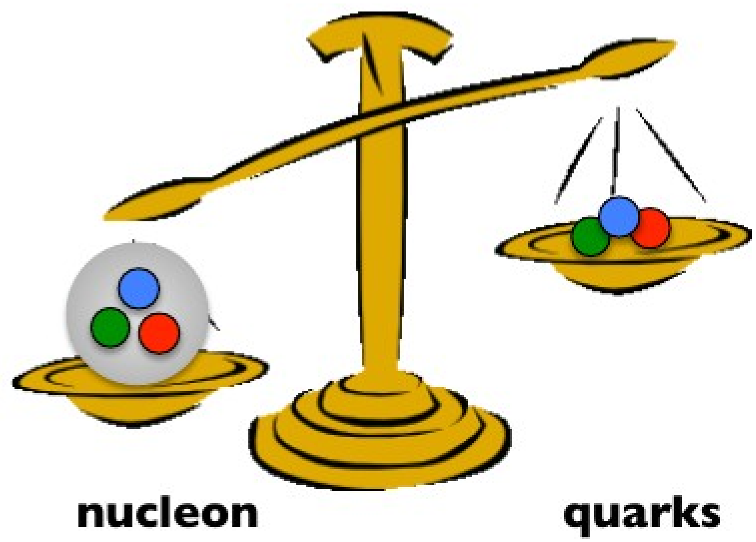
- At high energies, this theory has had great success in describing interactions, as the small QCD coupling constant makes the interaction easier to calculate
- At lower energies, this constant approaches unity and perturbative methods, used in the high energy regime, no longer hold

Introduction (cont.)

- Quark models play a vital role in the non-perturbative regime; predicting numerous hadronic states from the degrees of freedom associated with the coloured quarks of QCD



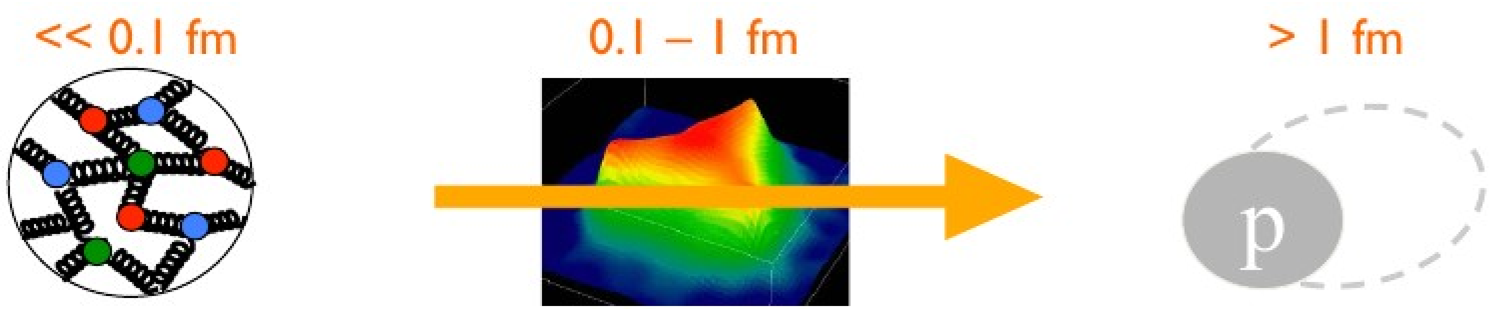
- Experimental data has verified the existence, and properties of, many of these states, however, these models are unable to tell the full story
- Quark mass accounts for only around 1% of the observed nucleon mass
- Our understanding of how quarks and gluons are confined in hadronic states, and the dynamics of the QCD interaction, still has gaps



Why Hadron Spectroscopy?

- To understand these issues, we must study the properties of hadrons and the rules of QCD
- Hadron spectroscopy is one such tool for observing QCD in action and attempts to answer some fundamental questions;
  - What is the internal structure and what are internal degrees of freedom of the hadrons?
  - What is the role of Gluons?
  - What is the origin of quark confinement?
  - Are 3-quark and quark-antiquark the only possible configurations?

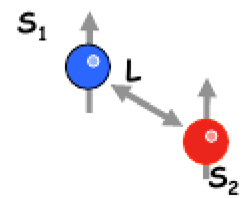
Perturbative **Transition** **Non-Perturbative**



Quarks and Gluons Effective Degrees of Freedom Mesons and Baryons

Meson Spectroscopy

- Mesons, being composed of a quark and antiquark, are the simplest bound quark system, making them an obvious choice for studies of how quarks combine to form hadrons
- The Constituent Quark Model, has had success predicting meson spectrum at low mass
  - CQM describes mesons as quark-antiquark pairs, of spin S=0,1 and orbital angular momentum L
  - SU(3) flavour symmetry implies a nonet of states with the same quantum numbers, J^{PC}, for each value of L and S



$S=S_1+S_2 \qquad J= L+S$

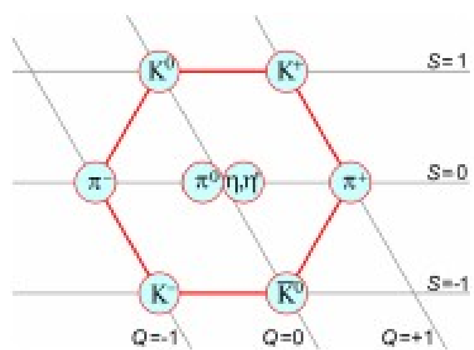
$P = (-1)^{L+1} \quad C= (-1)^{L+S}$

$J^{PC}= 0^{-+} \Rightarrow (\pi,K,\eta,\eta')$

$1^{--} \Rightarrow (\rho,K^*,\omega,\Phi)$

$1^{+-} \Rightarrow (b_1,K_1,h_1,h_1')$

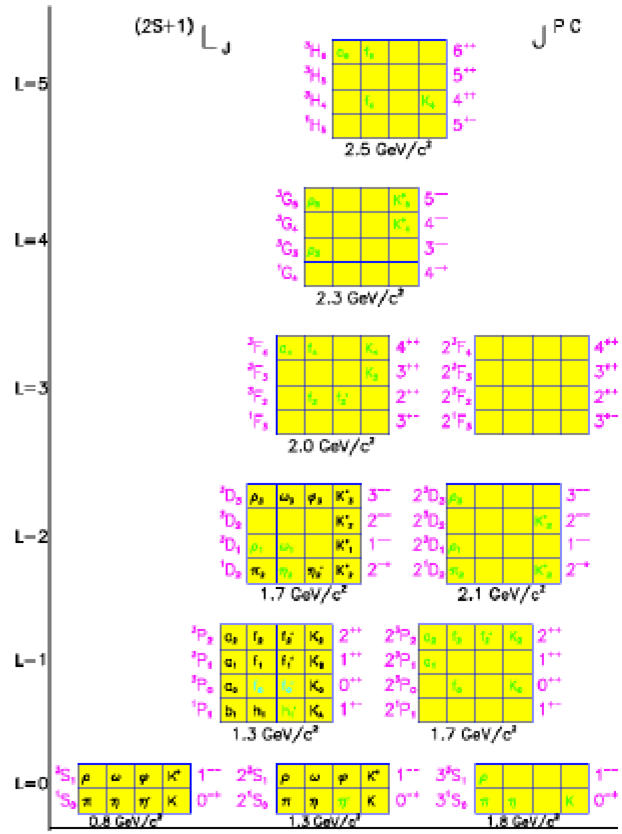
...



Meson Spectroscopy

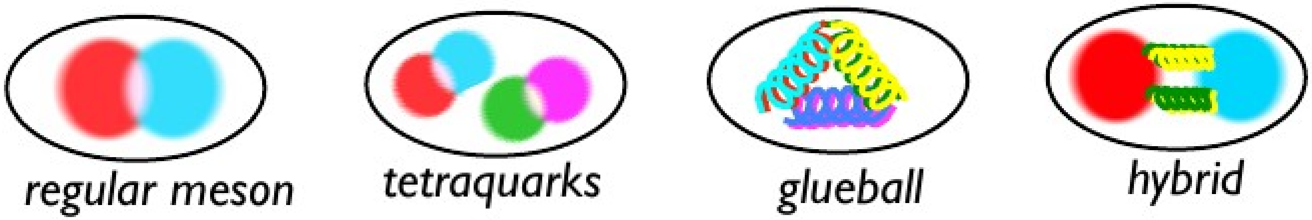
- However, despite this success at predicting low mass states, many of the states predicted by quark models at higher masses have yet to be observed
- Even the assignment of some observed states in terms of quark models is uncertain
- This could be down to problems with the model, limitations of experimental techniques, or perhaps something more... exotic?

Light Quark Mesons



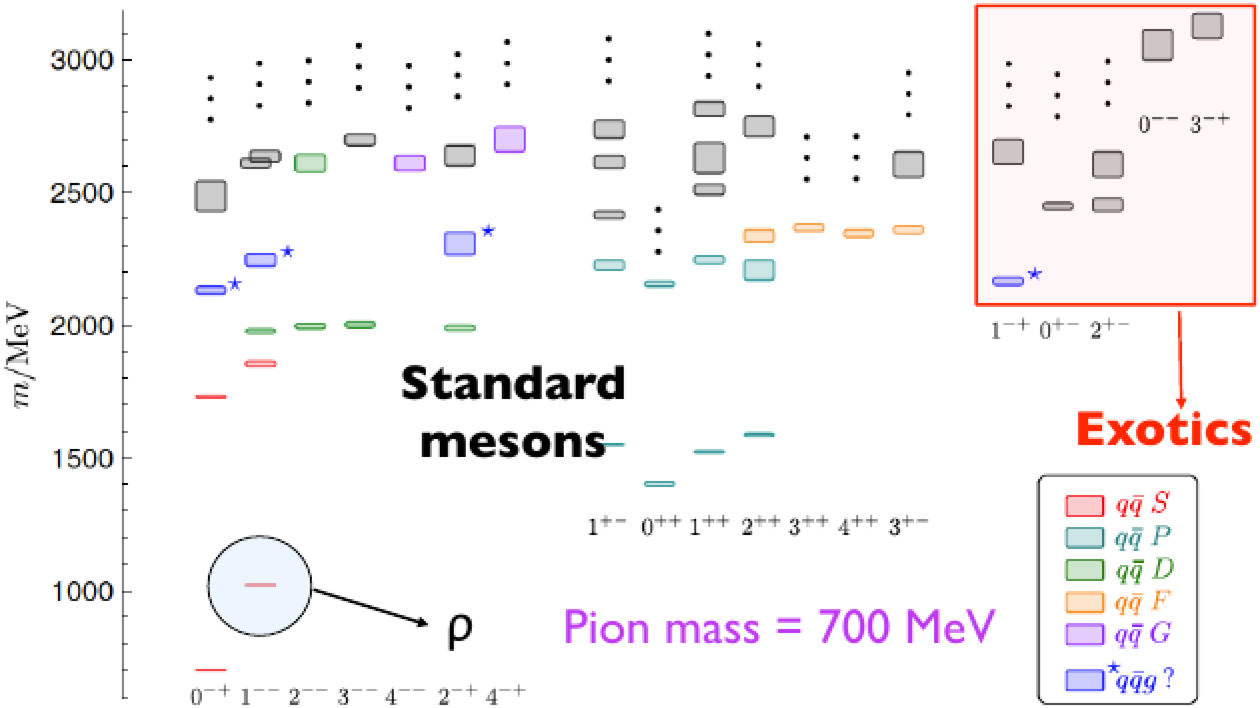
Yellow: expected meson states
Black: established states
Green: tentative assignments

Hybrids and Exotics



- QCD requires that bound states are colour neutral
- This does not mean that unconventional quark-gluon configurations do not exist
- These potential states include tetraquarks ($qq\bar{q}\bar{q}$), glueballs and hybrid mesons (qqg)
- Spectroscopy of these states, if unambiguously confirmed, would enable exploration of gluonic degrees of freedom
- Some phenomenological models predict such states, and make suggestions for masses and decay modes

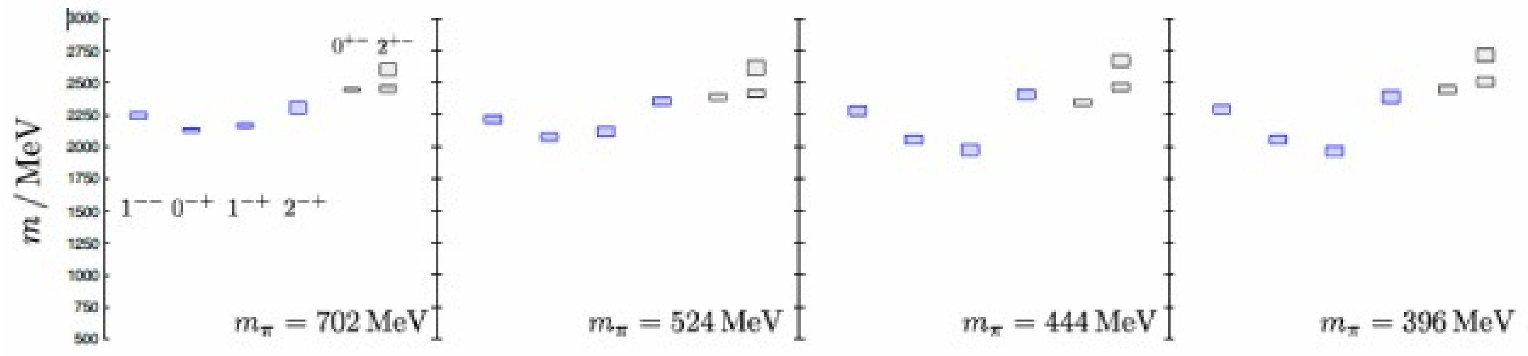
- Lattice QCD calculations are now starting to make predictions of the meson spectrum, including exotic states



J. Dudek, et. al., Phys. Rev. D82 (2010) 034508

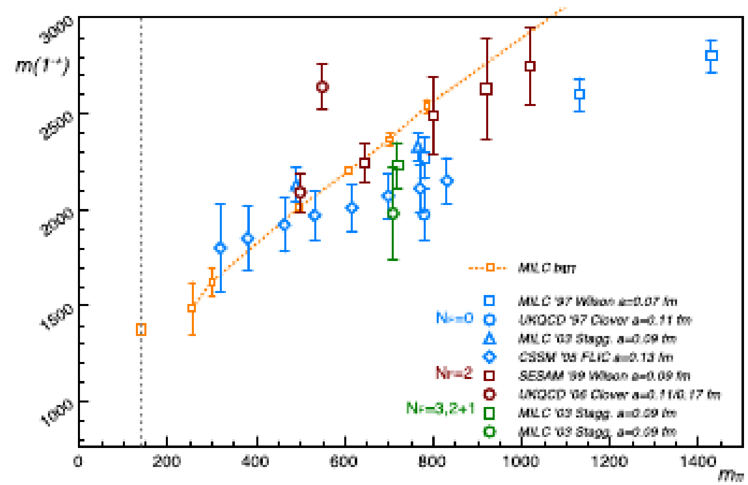
- Limitations remain due to unrealistic quark masses and computational limits on lattice size

- Although unphysical (m_π = 700 MeV), the quark masses employed in the calculations are beginning to approach reality
- As the quark mass is decreased, the spectra produced continue to show qualitative agreement with each other, and with known states



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

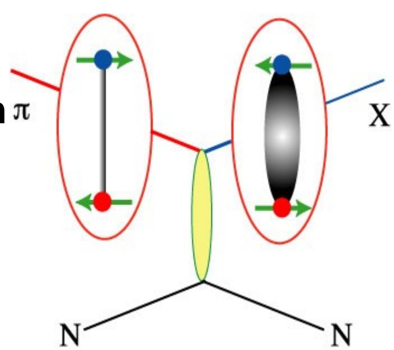
- Strong theoretical and phenomenological evidence for the existence of a rich spectrum of unconventional states
- Hybrids and exotics may be more effectively produced by photon beams
- A photon can fluctuate into a $q\bar{q}$ pair with aligned spins, accessing exotic quantum numbers that pion beams cannot



- It is here that the JLab meson spectroscopy program will contribute

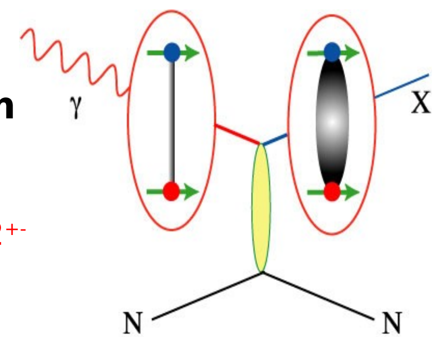
Pion Beam

Quark spins anti-aligned
$J^{PC} = 1^{--}, 1^{++}$



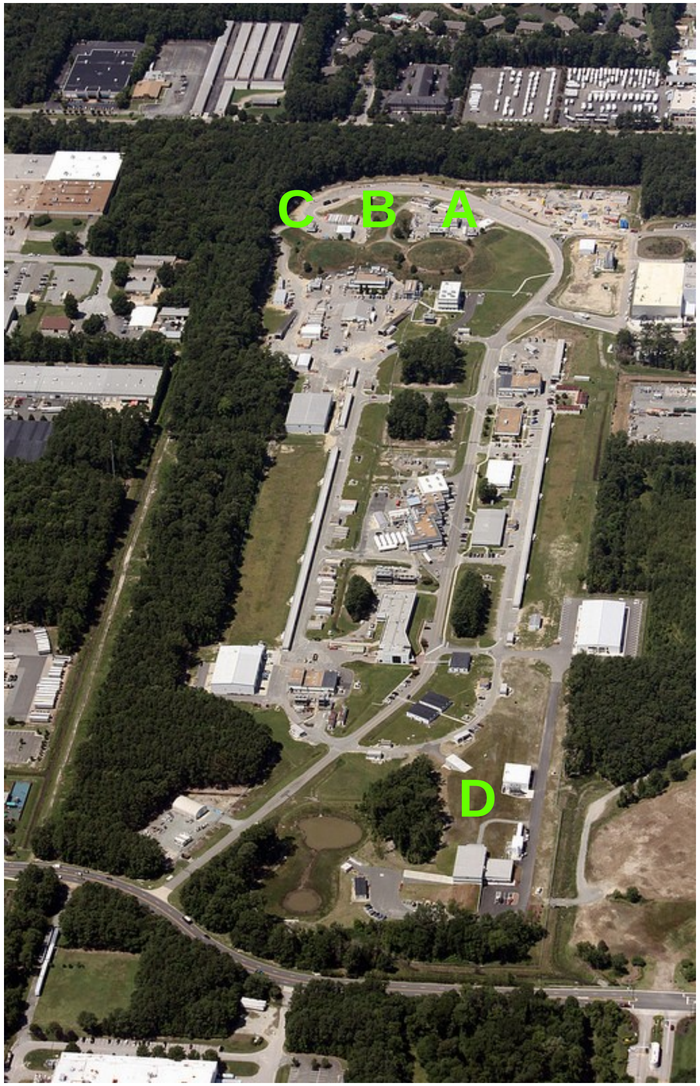
Photon Beam

Quark spins already aligned
$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$

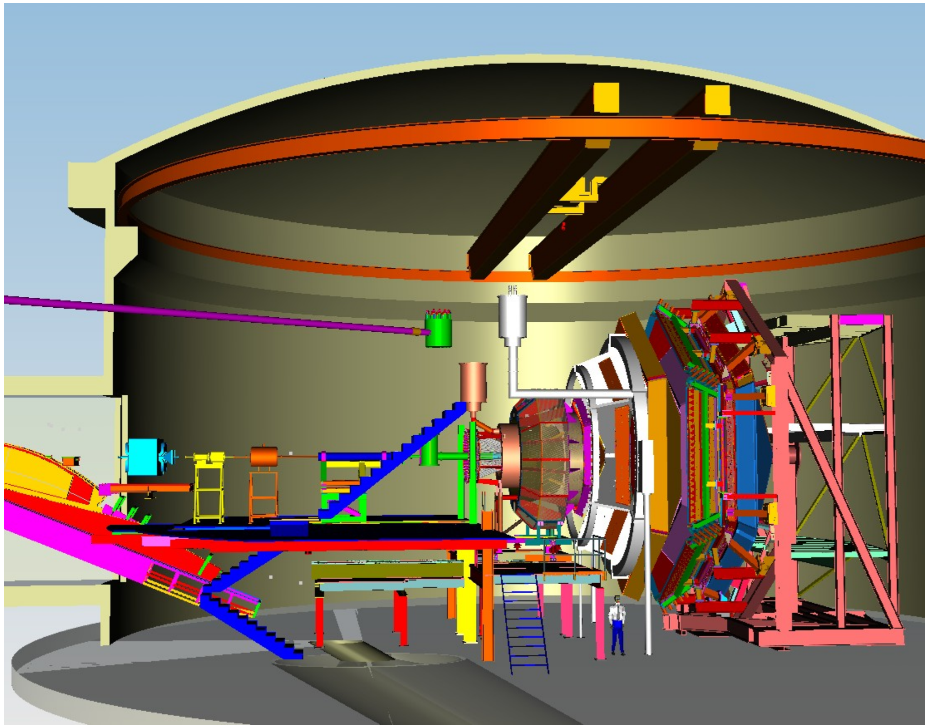


Jeffeson Lab, CEBAF and 12 GeV

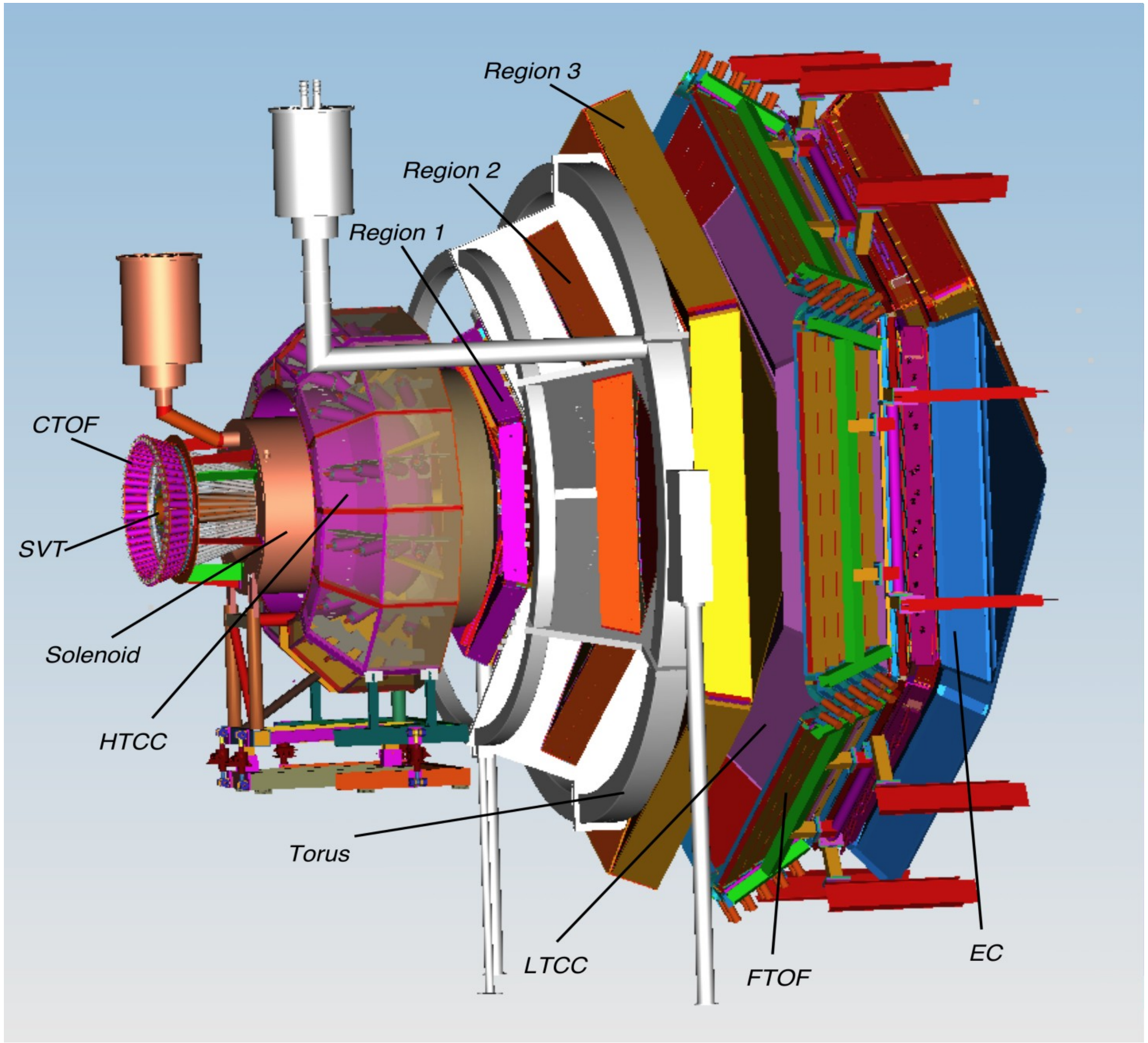
- Jefferson Lab is a US Department of Energy national facility, located in Newport News, Virginia
- The lab's centrepiece accelerator, CEBAF, uses superconducting radio-frequency technology in an anti-parallel, double linac configuration
- An upgrade to 12 GeV is nearing completion, with commissioning of the accelerator now underway
- Commissioning of new and upgraded detector systems also in progress, with staggered start dates for the lab's four halls
- This process should finish in 2016, by which time 12 GeV beam will be simultaneously available to multiple halls, at varying energy and current



- In the 12 GeV era, Experimental Hall B will be home to CLAS12, the CEBAF Large Acceptance Spectrometer
- CLAS12 follows on from the successful CLAS detector, and will comprise two new detector systems working together; a forward detector based upon a toroidal magnetic field, and a central detector based around a solenoid
- The forward detector will re-use some existing CLAS hardware, including the electromagnetic (EM) calorimeter, part of the forward time of flight (TOF) wall and the existing Cerenkov detector
- CLAS12 will be able to operate at ten times the luminosity of CLAS, with large acceptance for the kinematics of the upgraded CEBAF beam



CLAS12

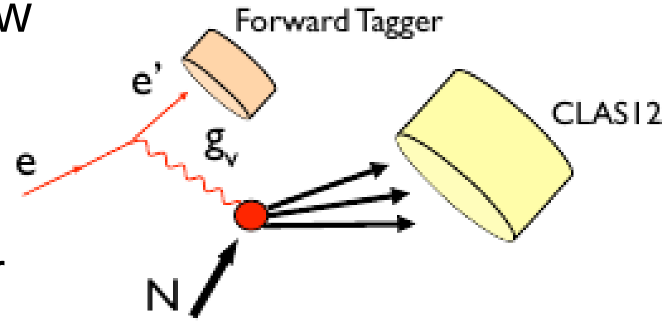


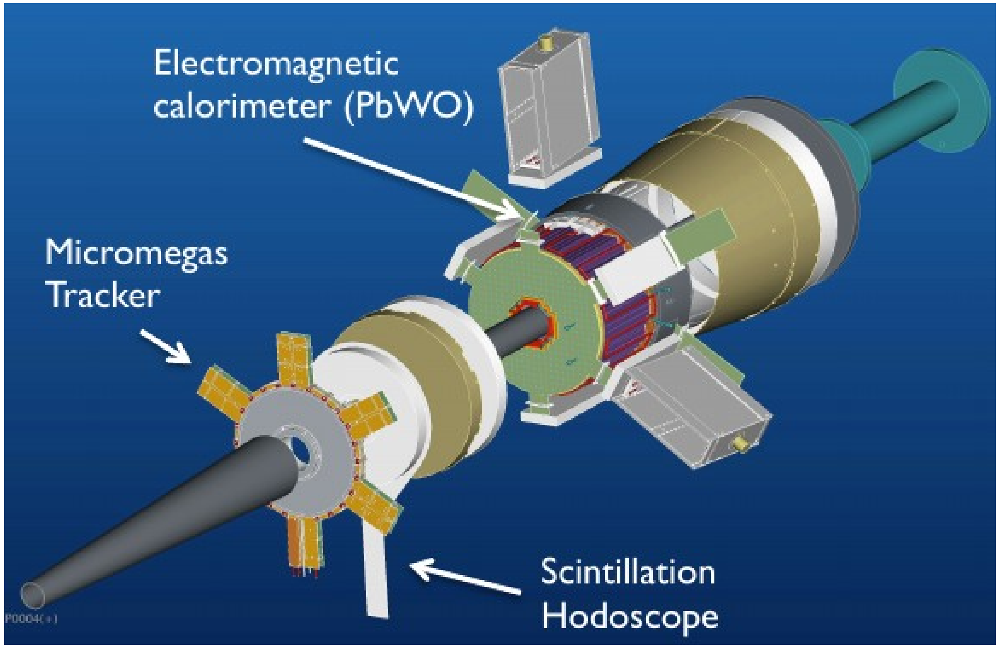
- An extensive program of experiments has been proposed for CLAS12
- These will build on the successes at 6 GeV and exploit the new capabilities of CEBAF and CLAS12
- CLAS12 designed with a new generation of experiments in DVCS and DIS in mind
- However, its capabilities are also useful for experiments in spectroscopy and nuclear physics

INFN Jefferson Lab clas CEBAF Large Acceptance Spectrometer

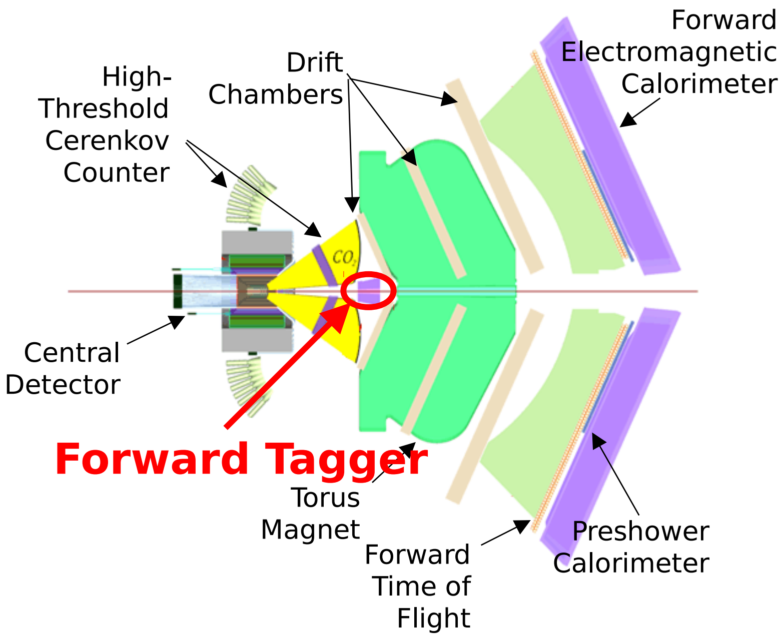
The Forward Tagger

- When an electron scatters with very low Q^2, i.e. at very small angles, quasi-real photons are produced
- Low Q^2 electron detection has been identified as an attractive technique for meson spectroscopy





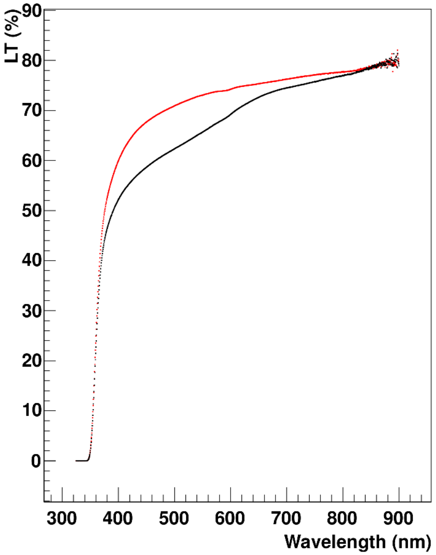
- The Forward Tagger combines a calorimeter, tracker and scintillating hodoscope, extending the forward coverage of CLAS12 down to polar angles of 2.5°
- Quasi-real photons can be reconstructed from the scattered electron



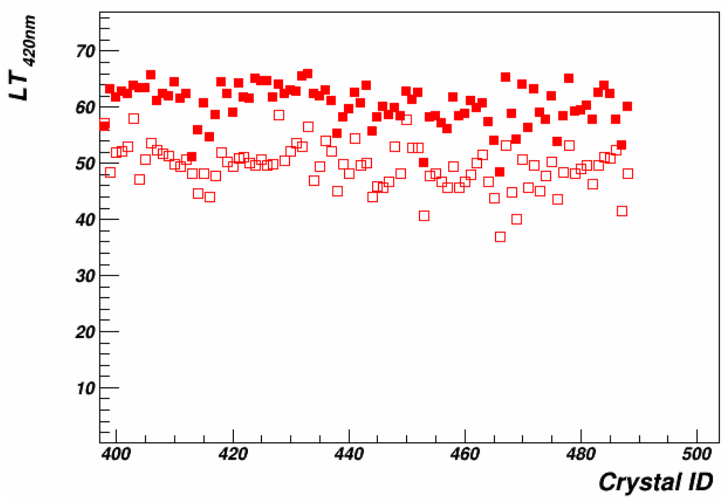
- Photons produced are linearly polarised, with polarisation determinable on an event-by-event basis from the kinematics of the scattered electron
- The Forward Tagger will enable spectroscopy experiments with CLAS12 using quasi-real photons up to 10 GeV

- MesonEx is an approved experiment for CLAS12, and will use the FT with CLAS12 to explore the spectrum of mesons
- Preparations for this program are well underway, constructing the FT, as well as development of the necessary analysis tools to exploit the coming data

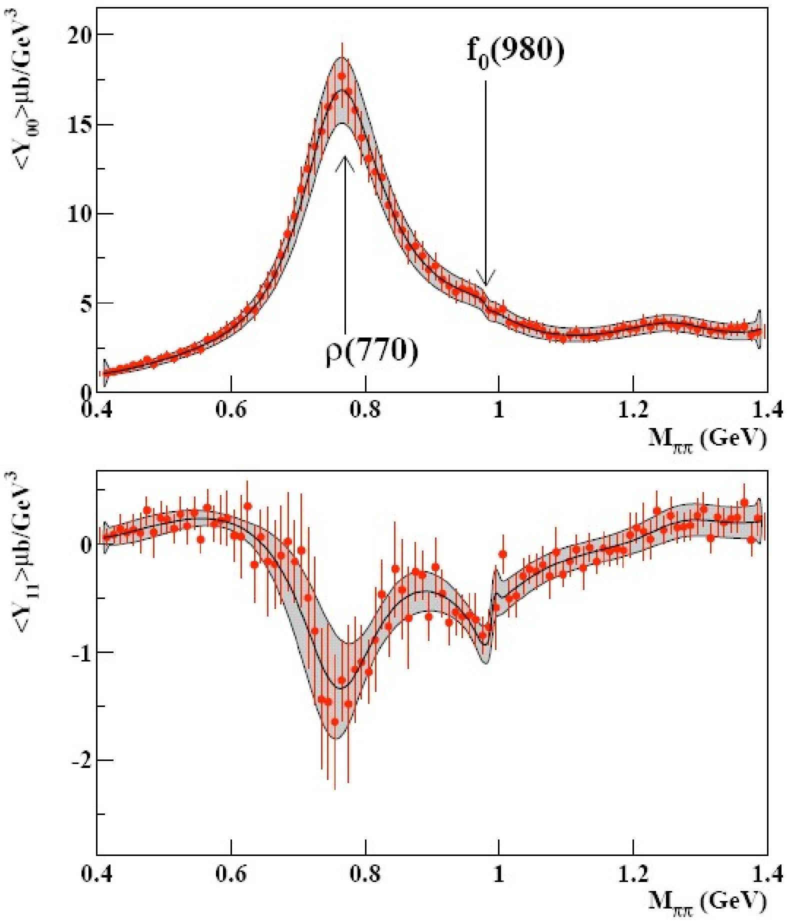
Crystal Tests for FT-Cal



- The FT calorimeter will use 332 lead tungstate crystals to detect scattered electrons and measure EM shower energies
- Position close to beamline means FT is subject to high radiation doses
- Assessing radiation hardness of crystals to select crystals from a larger sample, and determine positioning in FT Cal of those chosen
  - Third phase of tests, on replacements for those crystals rejected in previous tests, completed yesterday in Giessen
  - Crystals arriving in Genova today for assembly of FT

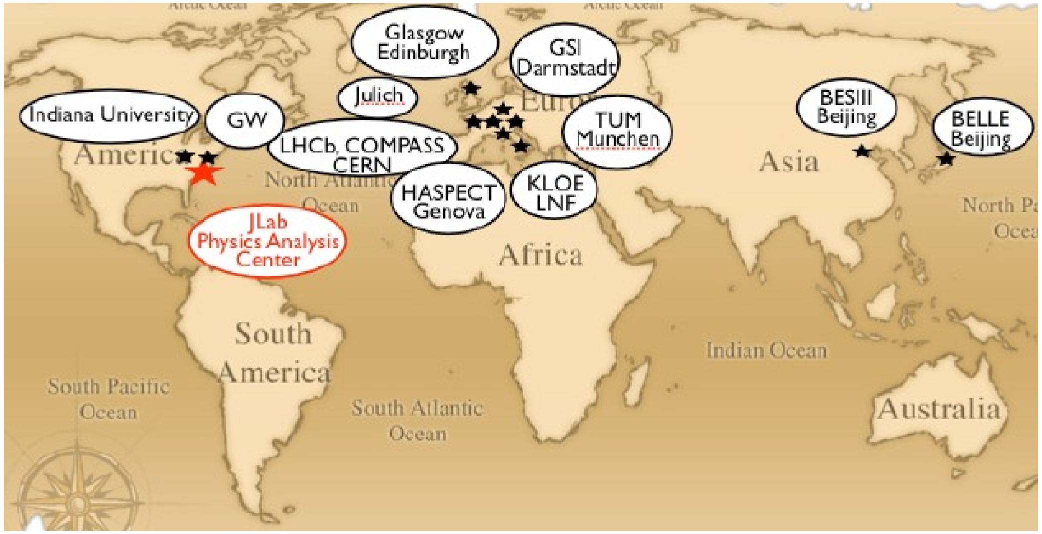


- Promising work has already been done measuring scalar mesons in photoproduction reactions at 6 GeV with CLAS
- Evidence for the observation of the $f_0(980)$ state has been seen in partial wave analysis of the $\gamma p \rightarrow p\pi^+\pi^-$ reaction
- Distributions of measured particles in the final state are interpreted in terms contributing partial wave amplitudes
- At 12 GeV, detailed study of states at higher masses will be possible



M. Battaglieri et al. (CLAS Collaboration), "Photoproduction of π+π- Meson Pairs on the Proton", Phys. Rev. D 80, 072005 (2009)

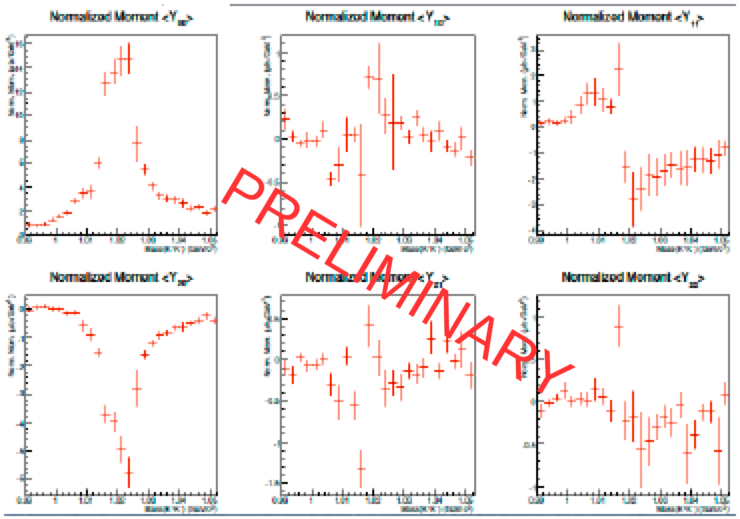
- The 12 GeV data at JLab will provide high-quality, high-statistics data, requiring a robust analysis framework
- Partial Wave Analysis lies on the boundary between theory and experiment, with scattering theory used to define contributing waves
- Resonant and non-resonant contributions included, and fits to data used to find states
- Feedback required to fine-tune waves in terms of the properties of contributing states

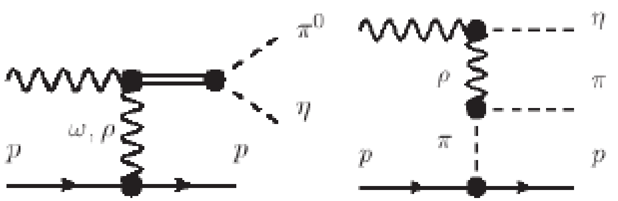


- HASPECT (Hadron SPEctroscopy CenTer) is one proposal for coordinating the efforts of theorists and experimentalists

HASPECT Status

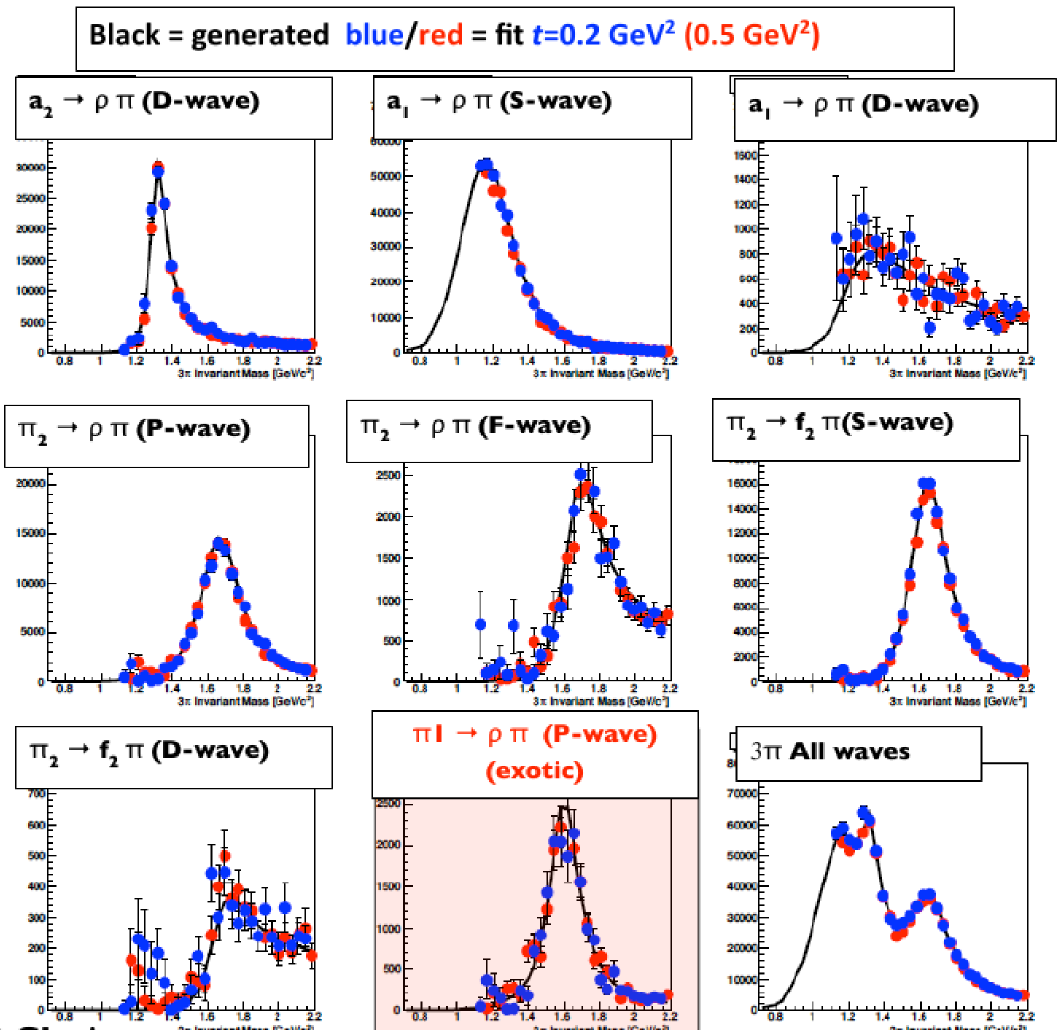
- HASPECT is currently a small (but growing) collaboration, centred on the INFN Genova group
- Regular phone meetings with participants across Italy, Scotland, and the USA
- Collaboration meetings held one or two times a year, most recently in Genova, May 20-22
- Group embarking on meson spectroscopy analysis of CLAS data from 6 GeV era





- Two pathfinder analyses, $\gamma p \rightarrow pK^+K^-$ (S. Lombardo, Indiana University) and $\gamma p \rightarrow \pi^0\eta$ (A. Celentano, INFN Genova)
- The tools and procedures developed in these analyses are being used to inform those being performed by others in the HASPECT group

Meson spectroscopy at 12 GeV



D.Glazier

- Feasibility study of PWA at 12 GeV with CLAS12
- Reference reaction $\gamma p \rightarrow (n)\pi^+\pi^+\pi^-$
- Existing data and its theoretical interpretation used to generate pseudo data in terms of 8 isobar channels (including an exotic P-wave state)
- Projected onto CLAS12 geometry and PWA fit performed
- Fit is stable over CLAS12 acceptance

Summary

- Meson spectroscopy poses a tantalising opportunity to address fundamental questions in our understanding of QCD
- The existence of exotic states, suggested by both quark models and Lattice QCD calculations, would enable exploration of the role of gluons in the QCD interaction at the scale of hadrons
- The MesonEx experiment, planned for the 12 GeV era in Hall B at Jefferson Lab, aims to build on the lab's historical strengths in hadron spectroscopy, and continue this legacy into higher energies
- Developing tools and procedures required to analyse the coming data is a prerequisite for a successful program of next generation experiments both at JLab and across the physics community
- HASPECT is one such effort hoping to meet these challenges, uniting experimentalists and theorists and establishing a roadmap for effective analysis