Meson Spectroscopy with CLAS12 at Jefferson Lab

PWA13/ATHOS8, Williamsburg

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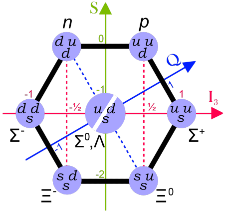
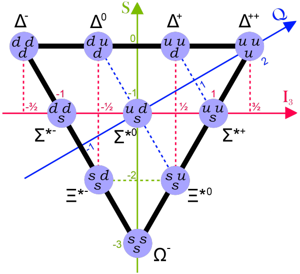
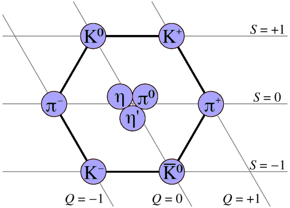
CEBAF Large Acceptance Spectrometer

Introduction

- Quark models play a vital role in the non-perturbative regime of QCD
- Numerous hadronic states predicted from the degrees of freedom associated with coloured quarks
- Experimental data has provided information on many of these states

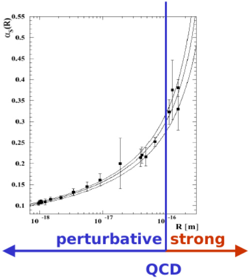






Motivation

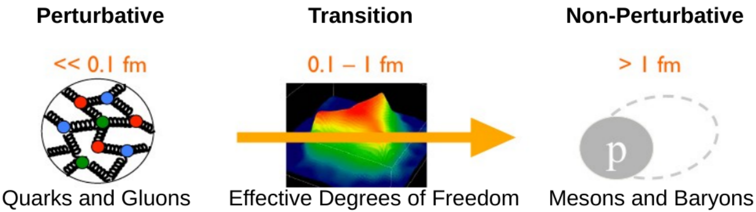
- Despite these successes, models don't tell the whole story
- Experimental data hasn't yet filled in the gaps that remain in our understanding of how quarks and gluons are confined in hadronic states, and the dynamics of the QCD interaction



Exploring Hadronic States

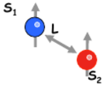
By studying hadronic states, through their production and decays, we can observe QCD in action, and attempt to answer some fundamental questions;

- What is the internal structure and the internal degrees of freedom of hadrons?
- What is the origin of quark confinement?
- What is the role of Gluons?
- Where do properties of hadrons, such as spin and mass, come from?



Meson Spectroscopy

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



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

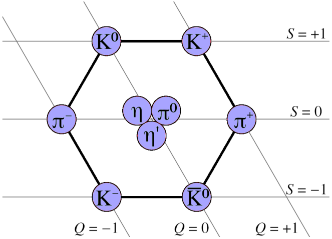
$P = (-1)^{L+1}$ $C = (-1)^{L+S}$

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

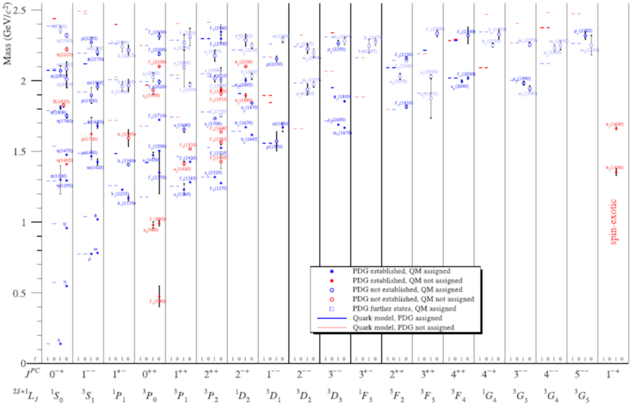
$1^{--} \Rightarrow (\rho, K^*, \omega, \Phi)$

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

...



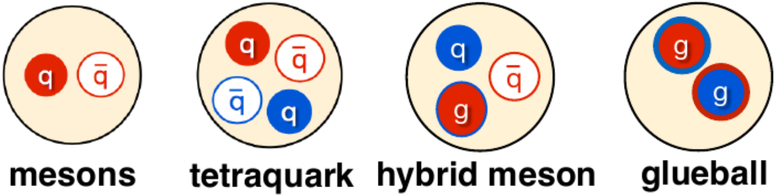
Meson Spectroscopy



B. Ketzer, et. al., Prog. Part Nucl. Phys 113 (2020) 103755

- At higher masses, the Quark Model picture less clear
- Many higher mass states remain unobserved
- Observed states are uncertain in assignment
- Limitations of experiments? Problems with the model? Something more (pun intended) exotic?

Hybrids and Exotics



- QCD requires that bound states are colour neutral
- This does not mean that unconventional quark-gluon configurations do not exist
- Potential states include tetraquarks ($qq\bar{q}\bar{q}$), glueballs and hybrid mesons (qqg)
- Spectroscopy of these states would enable exploration of gluonic degrees of freedom

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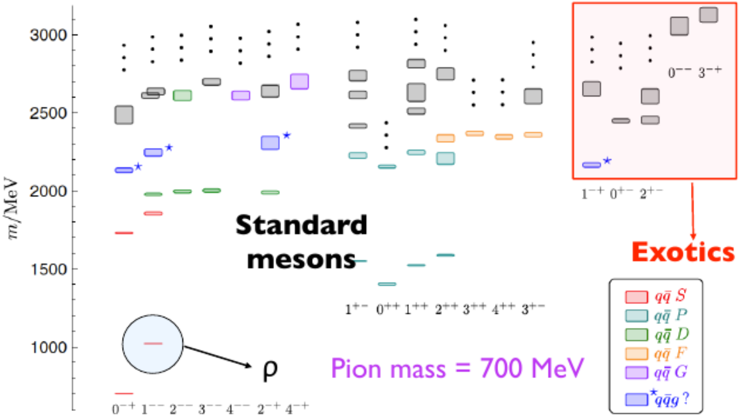
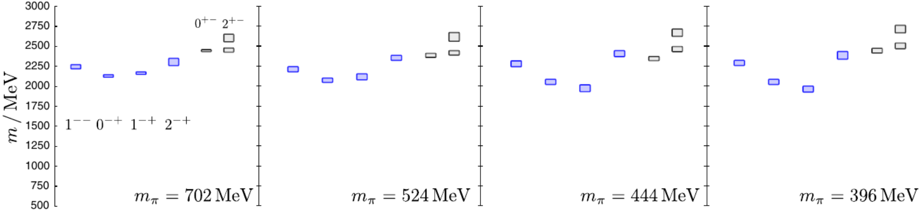
On the Lattice

- Lattice QCD calculations hint at exotic states



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

On the Lattice

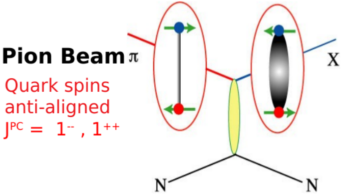


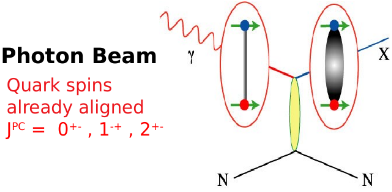
J. Dudek, et. al., Phys. Rev. D84 (2011) 074023

- Even as quark mass is decreased, lattice-produced spectra show qualitative agreement with each other, and with known states

Hybrids and Exotics

- 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 contributes





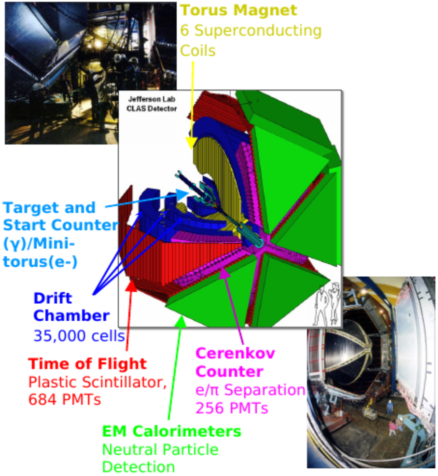
Jefferson Lab

- Jefferson Lab - at the forefront of intermediate energy physics since 1984
- More than 1500 users, from over 230 institutions and 30 countries
- One third of US nuclear physics PhDs come from JLab research

CEBAF

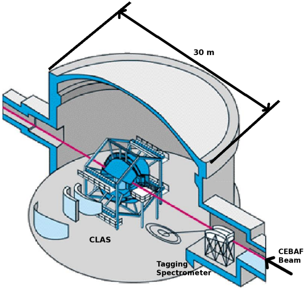
- **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility
- Superconducting RF accelerator
- Anti-parallel double linac, 7/8 of a mile in circumference
- Electron beam energies up to 12 GeV
- Diverse experimental program in four halls
- High-current Electron beams in Halls A and C
- Large acceptance detectors in Halls B and D
- Secondary beams available (real photons) and proposed (K_{Long})

Hall B and CLAS

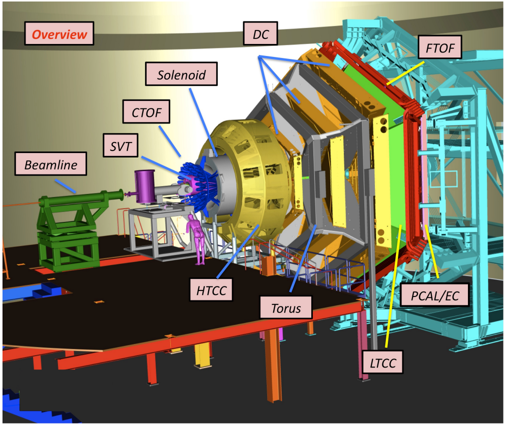


NIM A, 503(3), 2003

- CEBAF Large Acceptance Spectrometer (1995-2012)
- Multi layered and segmented
- Toroidal magnetic field



CLAS12

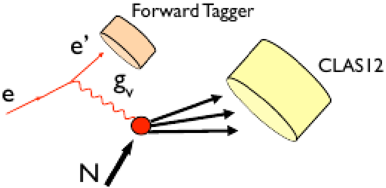


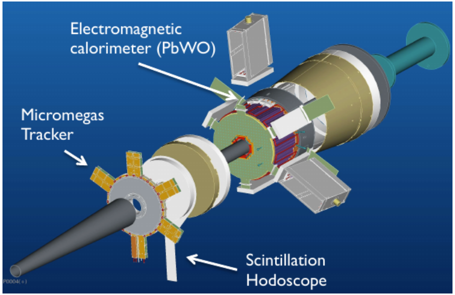
NIM A, 967, 163898 (2020)

- CLAS 12 GeV Upgrade (2012-Present)
- Essentially a new detector, optimised for 12 GeV kinematics
- Forward detector based around a toroidal magnetic field, and a central detector utilising a solenoidal field

The CLAS12 Forward Tagger

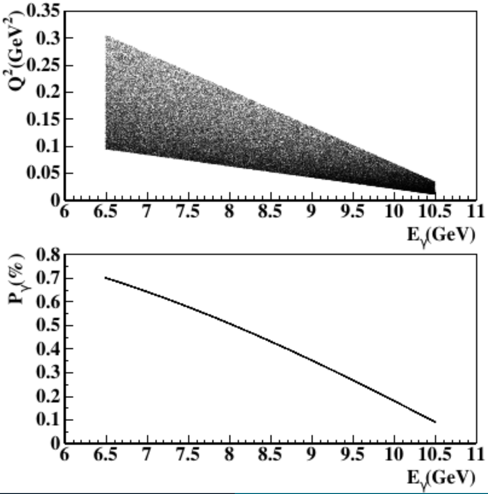
- The Forward Tagger enables spectroscopy experiments with CLAS12 using quasi-real photons up to 10 GeV
- When an electron scatters with very low Q^2, i.e. at very small angles, quasi-real photons are produced





- Low Q^2 electron detection is a competitive technique for meson spectroscopy
- This is the basis of the *MesonEx* experiment

MesonEx



- The low Q^2 photons produced are linearly polarised
- Polarisation can be determined event-by-event from electron kinematics
- A competitive technique for meson spectroscopy

Data Mining (CLAS6)

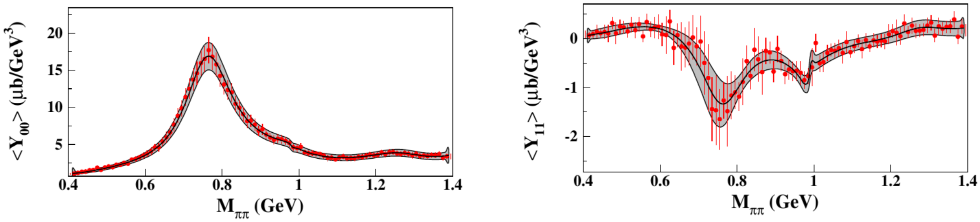
- A wealth of real photon beam data available from the CLAS6 era

Run Period Titles

g1	N* and Mesons
g2	Deuterium Target
g3	Few Body and Nuclei
g5	Photoabsorption and Photofission of Nuclei
g6	N^* and Meson Properties
g7	Vector Mesons in Nuclei
g8	Vector Mesons with Polarized Photons
g9-Frost	Mesons with polarized target and photon beams
g10	Search for Θ^+ Pentaquark on Deuterium
g11	Search for Θ^+ and excited states on hydrogen
g12	Hybrid Mesons and Exotic Baryon Search
g13	Kaon Production on the Deuteron Using Polarized Photons
g14	Search for neutron resonances in hyperon production from polarized HD target

- g12 was the immediate precursor for meson spectroscopy in the 12 GeV era
- g10 and g11 also used for pathfinder analyses in the development of MesonEx

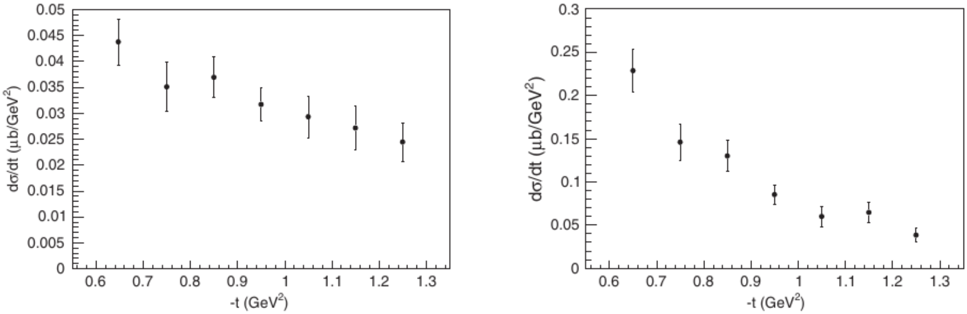
CLAS6 Analyses



M. Battaglieri, et. al., Phys. Rev. D80 (2009) 072005

- Observation of the $f_0(980)$ in $\pi^+\pi^-$ photoproduction on the proton in CLAS6
- Moments extracted from experimental data, and differential cross sections derived for S, P, and D-waves, allowing a partial wave expansion

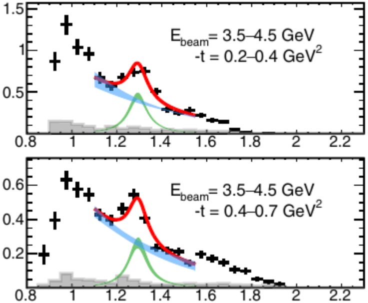
CLAS6 Analyses

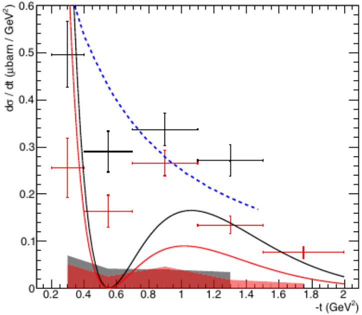


S. Lombardo, et. al., Phys. Rev. D98 (2018) 052009

- Study of the K^+K^- system in photoproduction on the proton in CLAS6
- Like the $\pi^+\pi^-$ analysis, moments extracted from experimental data
- S (left) and P-wave (right) contributons to cross section extracted

CLAS6 Analyses





A. Celentano, et. al., Phys. Rev. C102 (2020) 032201

- Observation of the $a_2(1320)^0$ in $\eta\pi^0$ photoproduction on the proton in CLAS6
- Differential cross sections measured over a range of $-t$ bins at $E_\gamma = 3.5 - 4.5$GeV and $E_\gamma = 4.5 - 5.5$GeV

CLAS12 Data

Proposal	Physics	Contact	Rating	Days	PAC
E12-06-108	Hard exclusive electro-production of π^0, η	Stoler	B	80	38 J:48
E12-06-108A	Exclusive N* to KY studies with CLAS12	Carman			42 J:48
E12-06-108B	Transition form factor of the η' Meson with CLAS12	Kunkel			44 J:48
E12-06-112	Proton's quark dynamics in SIDIS pion production	Avakian	A	60	38 J:48
E12-06-112A	Semi-inclusive Λ productiuon in target fragmentation region	Mirazita			42 J:48
E12-06-112B	Colinear nucleon structure at twist-3	Pisano			42 J:48
E12-06-119(a)	Deeply Virtual Compton scattering	Sabatie	A	80	30 J:48
E12-09-003	Excitation of nucleon resonances at high Q^2	Gothe	B+	40	34 J:48
E12-11-005	Hadron spectroscopy with forward tagger	Battaglieri	A-	119	37 J:48
E12-11-005A	Photoproduction of the very strangest baryon	Guo			40 J:48
E12-12-001	Timelike Compton scatt. & J/ψ production in e+e-	Nadel-Turonski	A-	120	39 J:48
E12-12-001A	Near threshold J/ψ photoproduction and study of LHCb pentaquarks	Stepanyan			45 J:48
E12-12-007	Exclusive ϕ meson electroproduction with CLAS12	Stoler, Weiss	B+	60	39 J:48

Proposal	Physics	Contact	Rating	Days	PAC
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30	32 J:48
E12-07-104A	Quasi-real photoproduction on deuterium	Phelps			47 J:48
E12-09-007(a)	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	110	38 J:48
E12-09-008	Boer-Mulders asymmetry in K SIDIS w/ H and D targets	Contalbrigo	A-	56	38 J:48
E12-09-008A	Hadron production in target fragmentation region	Mirazita			42 J:48
E12-09-008B	Colinear nucleon structuer at twist-3	Pisano			42 J:48
E12-11-003	DVCS on neutron target	Niccolai	A	90	38 J:48
E12-11-003A	In medium structure functions, SRC, and the EMC effect	Hen			43 J:48
E12-11-003B	Study of J/ψ photoproduction from the deuteron	Ilieva			46 J:48
E12-16-010	A search for Hybrid Baryons in Hall B with CLAS12	D'Angelo	A-	100	44 J:48
E12-16-010A	Nucleon Resonances in exclusive KY electroproduction	Carman			44 J:48
E12-16-010B	DVCS with CLAS12 at 6.6 and 8.8 GeV	Elouadrhiri			44 J:48
E12-16-010C	Separation of the σL and σT contributions to hadron production	Avakian			51

- CLAS12 proposals with similar experimental conditions collected as *Run Groups*
- The MesonEx experiment mainly uses data at 11 GeV beam energy from Run Group A (LH_2 target)
- Run Group B (LD_2 target) and Run Group K (lower energy on LD_2) can also contribute

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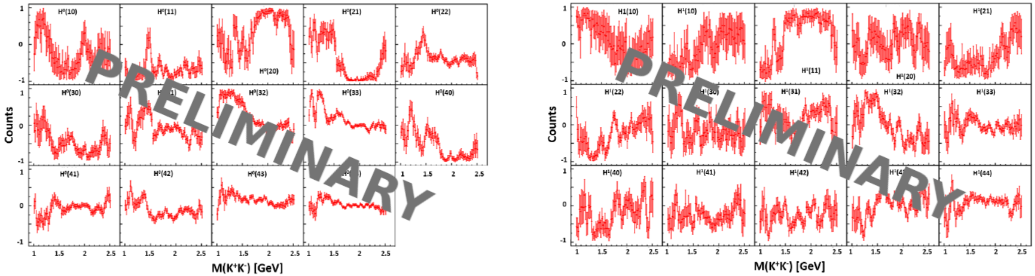
Early Analyses

- Three CLAS12 PhD analyses so far from MexonEx:
    - M. Nicol (University of York), 2023, *Exploring The Strong Interaction Through Electroproduction of Exotic Particles*
    - L. Biondi (University of Messina), 2023, *Investigation on exclusive beam asymmetry measurements of* $e + p \to e + p + \pi^0$ *process at CLAS12*
    - R. Wishart (University of Glasgow), 2023, *Analysis of three body decays in quasi-real photoproduction*
- These early analyses have been invaluable in verifying MesonEx data and paving the way for amplitude analysis

Studies of K^+K^-



- Preliminary moments of the K^+K^- system (M. Nicol, York, PhD)
- Work remains to realise reliable determination of amplitudes

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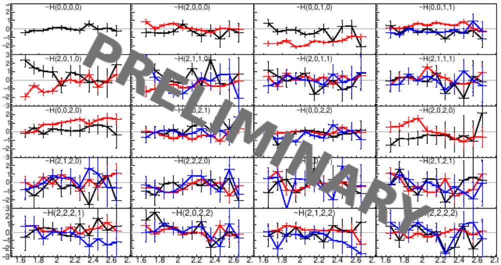
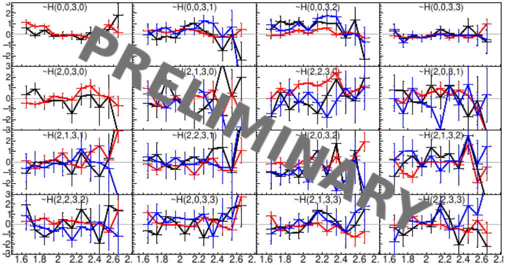
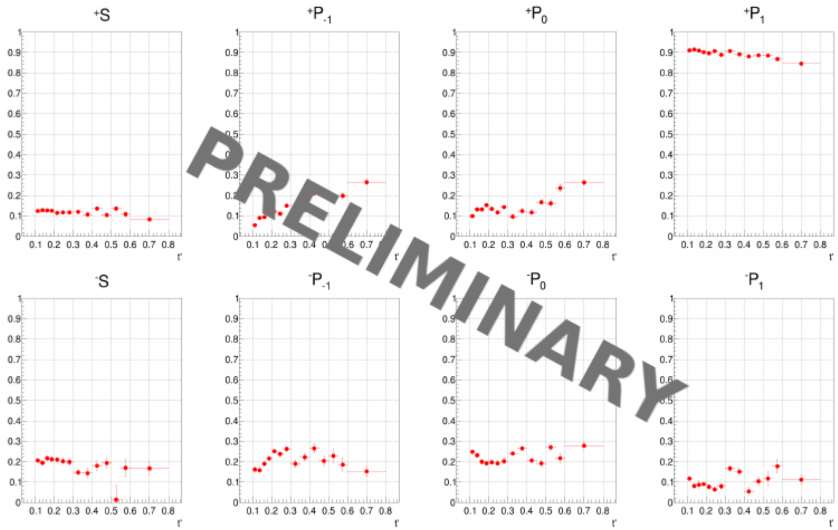
Three Body Decays

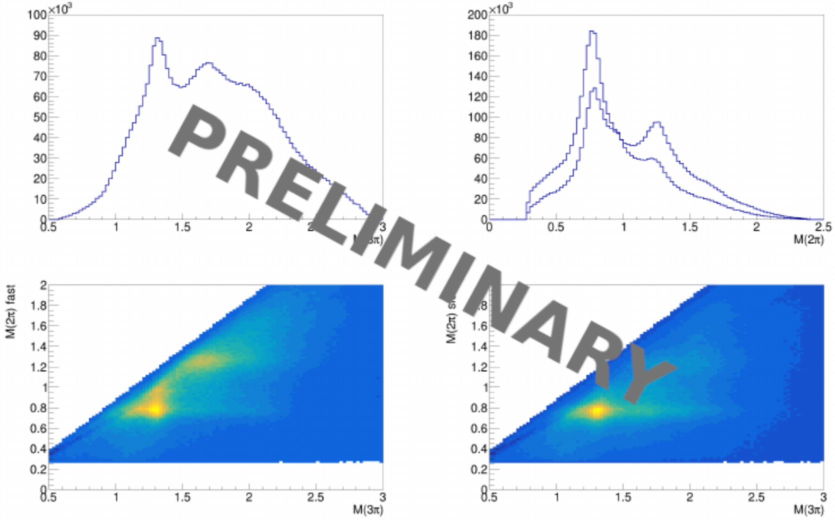



- R. Wishart, Glasgow, PhD
- Studying the K^*K^+ system from $e^-K^+K^-\pi^+$ final state events
- Moments up to $J = 6$ extracted from decay angle distributions ($J = 2$ and $J = 3$ shown)

Preliminary Partial Wave Extraction on ρ



The 3π System

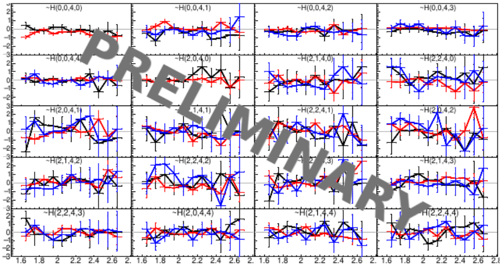


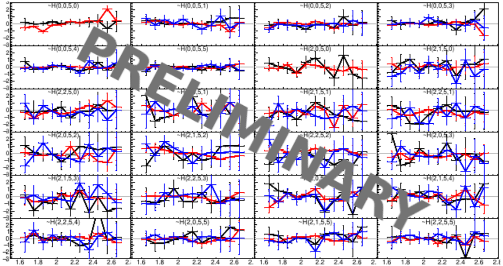
Summary and Outlook

- CLAS12 data is capable of making significant contributions to our understanding of the meson spectrum
- Led by initial analyses, our understanding of Partial Wave Analysis with polarized photoproduction continues to improve
- Recent progress in data reconstruction and calibration is being leveraged to realise the potential of CLAS12 data

Thanks for Listening!

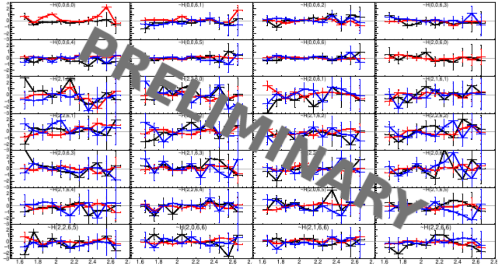
(Backup) Three Body Decays





- K^*K^+ moments for $J = 4$ and $J = 5$

(Backup) Three Body Decays



- K^*K^+ moments for $J = 6$