Kaons, Kaons, I Like Kaons

EIC UG ECR, University of Glasgow

Stuart Fegan

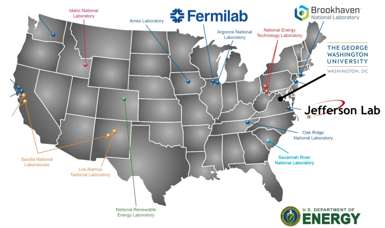
University of York

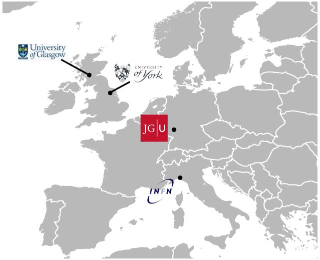
July 11th, 2026

It's Kaons, Kaons, I *Love* Kaons

"Keep it down please sir"

Who Am I?





Participated in experimental programs at Jefferson Lab, A2@MAMI and BESIII, with some Jefferson Lab work overlapping with SLAC, FermiLab and Brookhaven

- PhD, University of Glasgow, 2012
- Postdoc, INFN Genova, 2012-14
- Postdoc, JGU Mainz, 2015-17
- Postdoc, GWU, 2017-19
- Postdoc, University of York, 2019-present

Who, Am I?

This is just an analogy

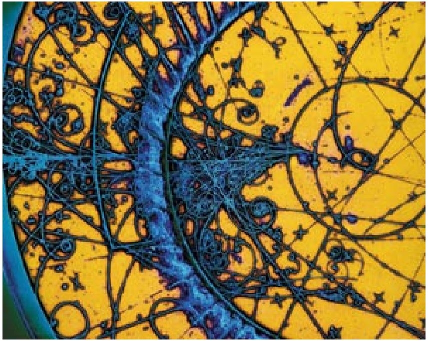


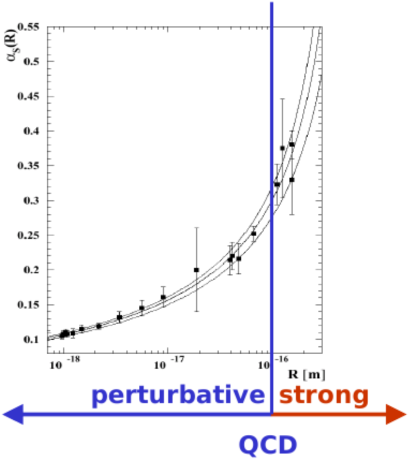



- PhD, University of Glasgow, 2012
- Postdoc, INFN Genova, 2012-14
- Postdoc, JGU Mainz, 2015-17
- Postdoc, GWU, 2017-19
- Postdoc, University of York, 2019-present

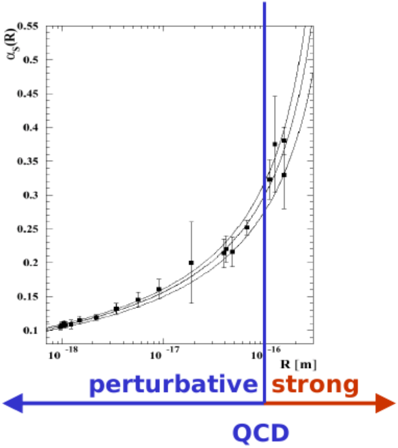
Introduction - QCD

- Quantumchromodynamics - QCD - describes Strong force interactions in the Standard Model





Quantum Chromodynamics

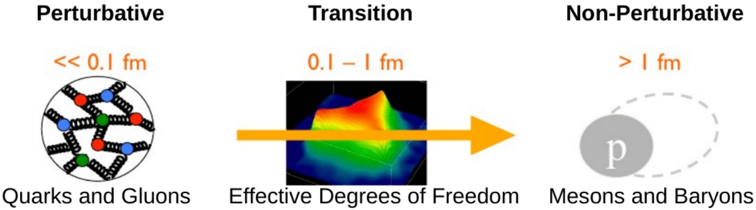


- Hugely successful describing high energy interations as the small coupling constant in this regime makes calculations straigtforward
- However, gaps remain in our understanding of QCD in the lower energy, or non-perturbative, regime
- At these scales, coupling constant approaches unity and pertubative approaches no longer accurately describe the underlying processes
- This is a problem in understanding how quarks combine to form hadrons

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?

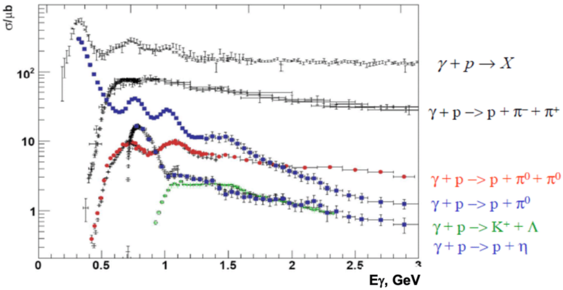


Hadron Spectroscopy

Hadron spectroscopy has two main goals:

- Precision measurements of the properties of observed states
- Searches for unseen, (un)predicted or unconventional states

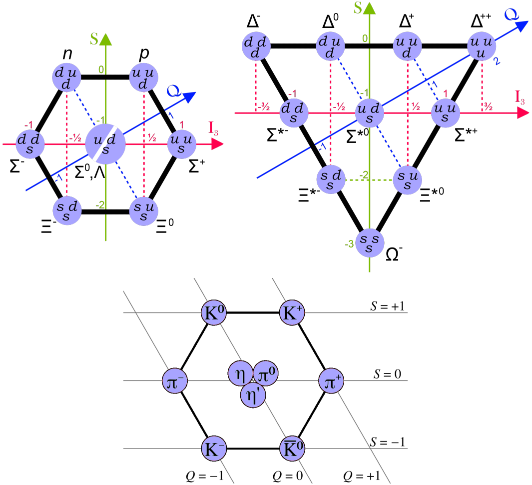
Finding some states can be difficult in a simple "bump hunt"; many are wide and overlap



R. Beck and U. Thoma, EPJ Web Conf 134, 04003 (2017)

Quark Models

- Quark models also play a vital role exploring the spectrum of hadrons
- Numerous hadronic states predicted from the degrees of freedom associated with coloured quarks
- Experimental data has provided information on many of these states



Experimental Facilities

Hadron beam facilities

Electromagnetic beam facilities

Bulk of hadron spectroscopy data from hadron beam facilities

- Dominance of πN scattering data limits sensitivity to resonances that weakly couple to this channel

Electromagnetic beams can provide more information, but cross sections are smaller

Jefferson Lab

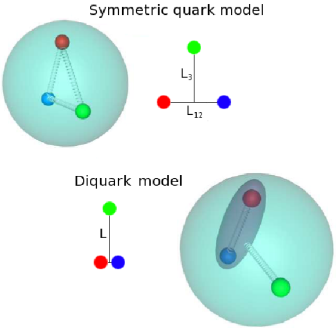
- Jefferson Lab - at the forefront of intermediate energy physics since 1984
- More than 1500 users, from over 230 institutions and 30 countries
- One third of US nuclear physics PhDs come from JLab research

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 6 GeV, now 12 GeV
- Diverse experimental program in three, now 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})

Missing Resonances?

Many more baryon states predicted than currently observed

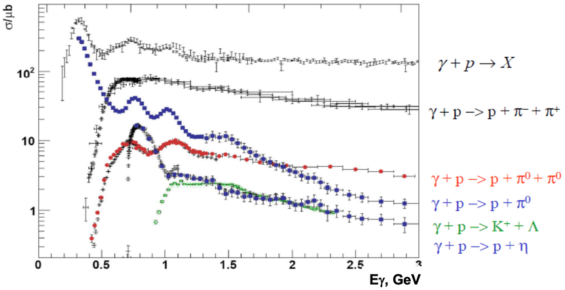


	Predicted	Observed
N^*	62	21
Δ^*	38	12
Λ^*	71	14
Σ^*	66	9
Ξ^*	73	6
Ω^*	36	2

R.G. Edwards et al. Phys Rev D87 (2013) 054506

Differenent models predict different spectra - the *missing resonance* problem

A World of Polarisation (Observables)

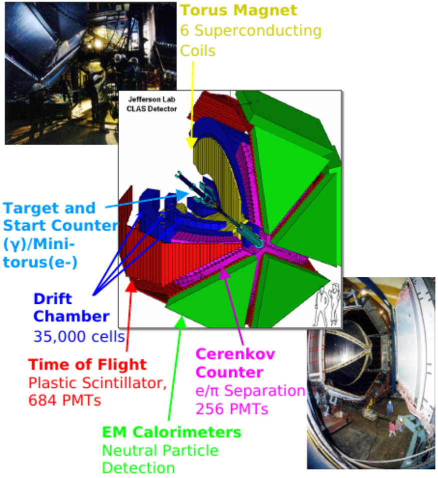


R. Beck and U. Thoma, EPJ Web Conf 134, 04003 (2017)

- Even high quality, high statistics data is insufficient to resolve the full resonance spectrum purely from cross-section measurements
- Use alternative means; coupling strength to a reaction channel, manifestation in experimental observables, etc. to aid searches

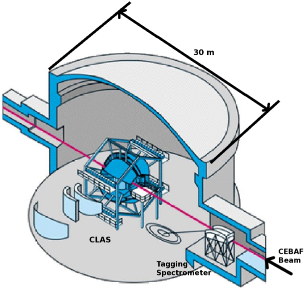
- Polarisation of the reaction particles can be exploited to probe resonances in more detail by measuring *Polarisation Observables*

Hall B and CLAS

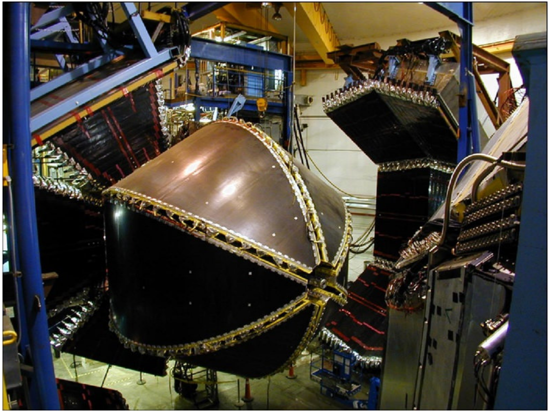


NIM A, 503(3), 2003

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



Hall B and CLAS

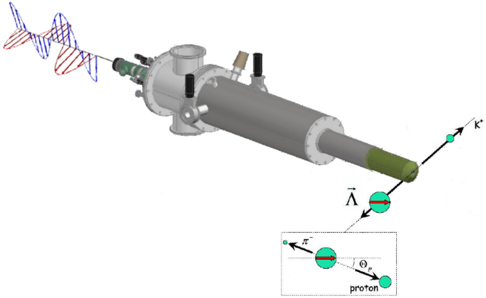


The CLAS design offered;

- Large acceptance coverage
- Good momentum resolution
- Operation at high luminosity wrt other large acceptance facilities
- Polarised photon and electron beams
- Operation with polarised targets

A World of Polarisation (Observables)

- Polarisation observables are experimentally measurable quantities, associated with the polarised particles in an interation
- For example, in $K^{+}\Lambda$ photoproduction (right), polarisation can be carried by
  - The photon beam
  - The target nucleon
  - The recoiling hyperon



These observables are directly relatable to the scattering amplitudes describing the interaction

A World of Polarisation (Observables)

- Single pseudoscalar meson photoproduction, such as $K^+\Lambda$, is described by four complex, parity conserving, amplitudes
- These give rise to 16 polarisation observables, arising from the spin states of the beam, the target and the baryon recoil

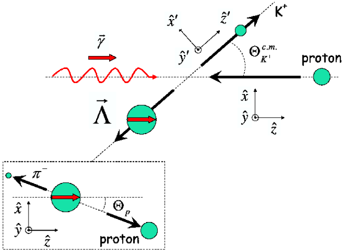
		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
Beam (P^γ)		x	y	z	x'	y'	z'	x' x	x' y	x' z	y' x	y' y	y' z	z' x	z' y	z' z
Unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\underline{\hat{\Sigma}}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{\mathbf{C}}_{\mathbf{z'}}$		$\hat{\mathbf{E}}$		$\hat{\mathbf{F}}$		$-\hat{\mathbf{C}}_{\mathbf{x'}}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$\underline{-\hat{P}}$			$\underline{-\hat{T}}$		$-\hat{\mathbf{L}}_{\mathbf{z'}}$		$\hat{\mathbf{T}}_{\mathbf{z'}}$		$-\mathrm{d}\sigma_0$		$\hat{\mathbf{L}}_{\mathbf{x'}}$		$-\hat{\mathbf{T}}_{\mathbf{x'}}$
Circular P_c^γ		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{\mathbf{O}}_{\mathbf{z'}}$		$\hat{\mathbf{G}}$		$-\hat{\mathbf{H}}$		$\hat{\mathbf{O}}_{\mathbf{x'}}$	

A. M. Sandorfi et. al J. Phys. G: Nucl. Part. Phys. 38 053001 (2011)

- Theoretical predictions of these observables vary depenging on the resonances included in the underlying model

A World of Polarisation (Observables)

- "Single": σ, Σ, P, T
- Beam-Target: E, F, G, H
- Beam-Recoil: O_X, O_Z, C_X, C_Z
- Target-Recoil: T_X, T_Z, L_X, L_Z



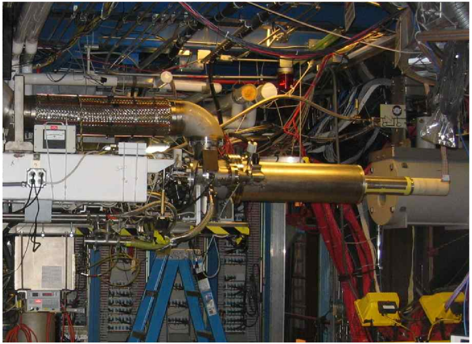
- With a polarised beam and target, can access the single and beam-target observables;

$$\sigma, \Sigma, P, T, E, F, G, H$$

- And in strangeness reactions, such as $\gamma p \rightarrow K^+\Lambda$, recoil observables can be measured (i.e. hyperon is self-analysing)

The FROST Experiment

- FROST - **FRO**zen **S**pin **T**arget
- g9a (Nov 2007 - Feb 2008): Linearly and circularly polarised photon beams on a longitudinally polarised target
- g9b (Mar - Apr 2010): Transversely polarised target
- Polarisation direction regularly flipped during runs
- Nine energy settings in linear polarisation, spanning range 0.7 to 2.3 GeV

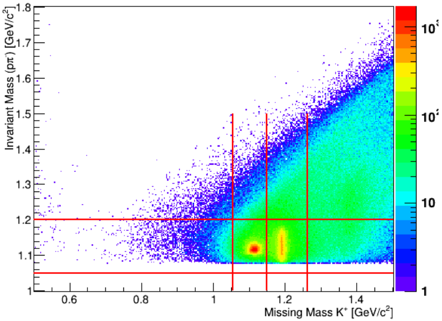


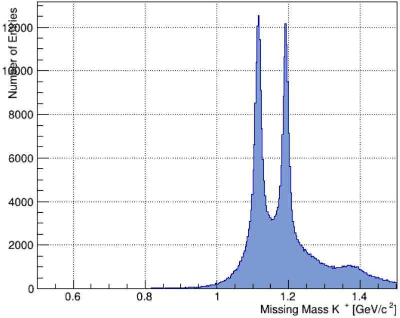
Channel Identification

- Select channels of interest:

$$\gamma p \to K^+\Lambda \to K^+ p\pi^- \text{ and } \gamma p \to K^+\Lambda \to K^+ p\pi^-$$

- Non exclusive selection - reconstruct pion from detected proton and kaon
- Hyperons identified via kaon missing mass and proton pion invariant mass





Extracting Observables

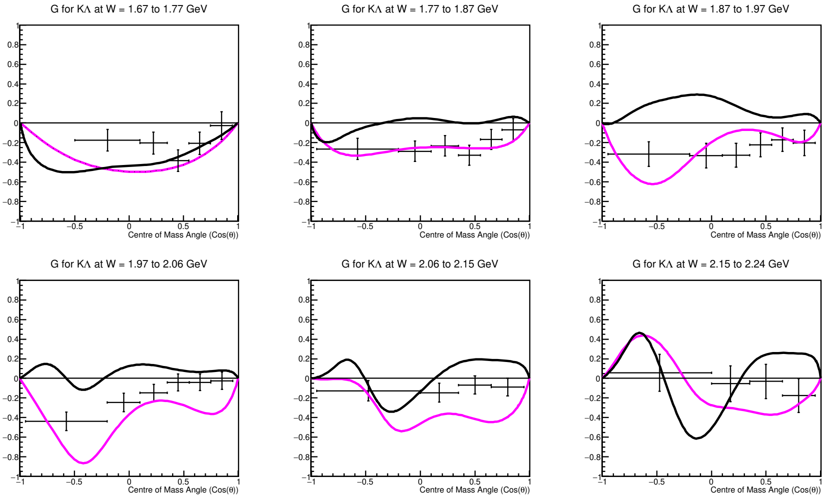
- Using a maximum likelihood approach, which extracts observables event-by-event
- Can better account for variation between polarisation states wrt. other approaches such as binned asymmetry fitting
- We define the likelihood function for each event as:

$$L_i = c_i[1 - P_{lin,i}\Sigma cos(2\phi_i) + P_{z,i}(P_{lin,i}Gsin(2\phi_i))]A$$

- And extract observables by maximising the log-likelihood function:

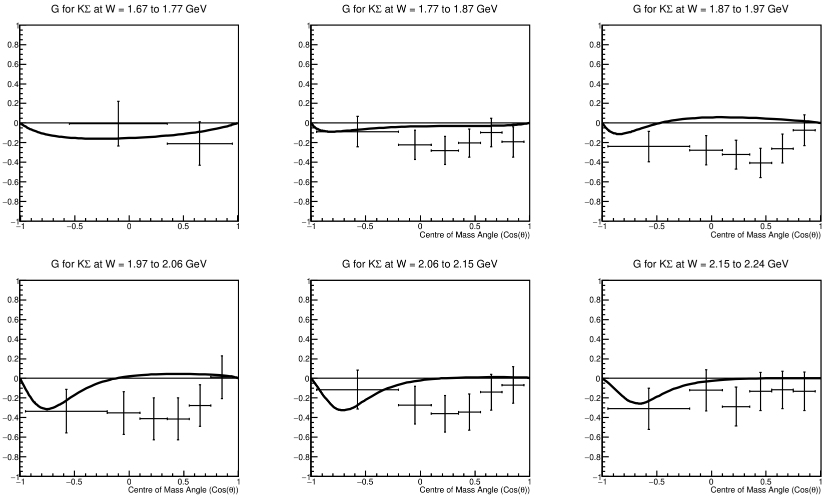
$$\log L = b + \sum_i \log[1 - P_{lin,i}\Sigma cos(2\phi_i) + P_{z,i}(P_{lin,i}Gsin(2\phi_i))]$$

$K^+\Lambda$ Results, G



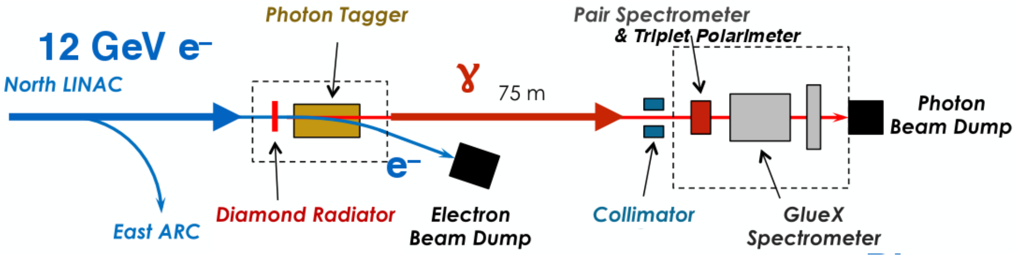
CLAS Approved, currently drafting paper

$K^+\Sigma$ Results, G



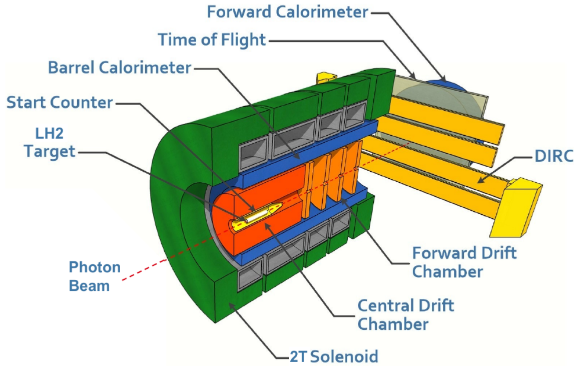
CLAS Approved, currently drafting paper

GlueX Beamline



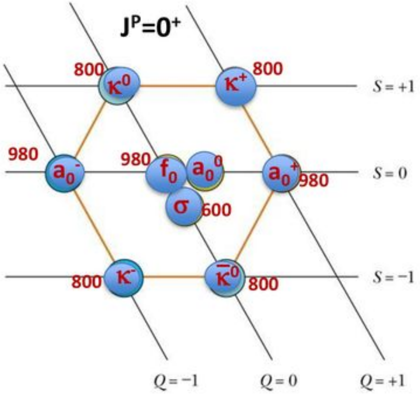
- 12 GeV electron beam produces real photon beams via bremsstrahulng radiation off a radiator
- Polarised photon beams from coherent bremsstrahlung off diamond radiators
- Photon energy tagged by detecting energy-degraded electron in one of two devices in the tagger focal plane
- Ancillary devices to determine flux and polarisation

The GlueX Detector in Hall D



- Charged and neutral particle detection in a hermetic solenoid-based detector
- Uniform acceptance
- GlueX is a meson spectrosopy experiment, but hall and equipment used for other experiments, including KLF

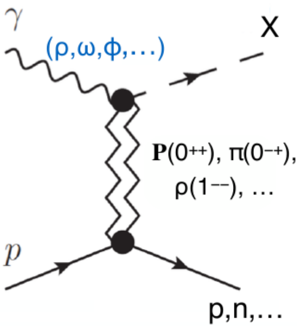
Light Scalar Mesons



- The structure of light scalar meson states (spin 0, even parity) is poorly understood
- Large widths mean states have significant overlap with background
- Further complicated by proximity to $K\bar{K}$ and $\eta\eta$ thresholds

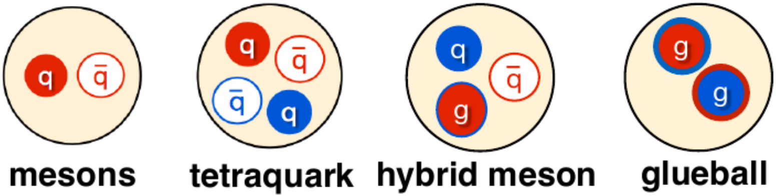
Observables

- At sufficiently high beam energies, t-channel processes are dominant, and the t-dependence of observables can be studied free from lower energy backgrounds



- Models describing the photoproduction process can predict experimentally observable quantities
- Measurements of cross sections and beam asymmetries can provide constraints to models
- For example, the magnitude and sign of the beam asymmetry can indicate the dominance of a particular exchange process

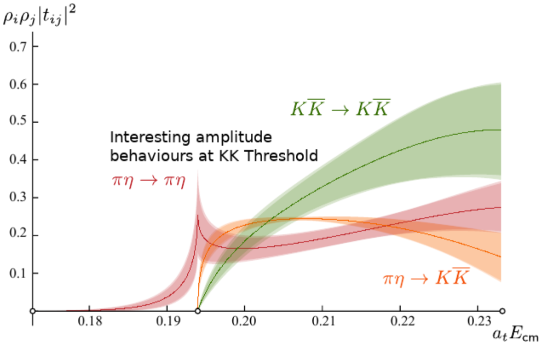
Light Scalar Mesons



- The $\pi\pi$ decay of $f_0(980)$, and the $\eta\pi$ decay of $a_0(980)$ are thought to be a powerful tool to discriminate between models
- Both states lie close to $K\bar{K}$ threshold, which has so far made accurate determination of resonance properties difficult

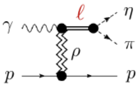
Theoretical Insights (Lattice QCD)

- S-wave scattering amplitude from a coupled-channel lattice calculation
- Usual caveats about unphysical quark masses
- Suggestions that something significant happens at $K\bar{K}$ threshold
- Possibly an $a_0(980)$-like resonance, coupled to $K\bar{K}$ and $\eta\pi$



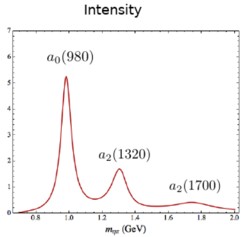
Phys. Rev. D93, 094506 (2016)

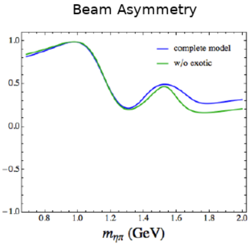
Theoretical Insights (JPAC)



$$R = \{\underbrace{a_0(980)}_{S_0^{(+)}}, \underbrace{\pi_1(1600)}_{P_{0,1}^{(+)}}, \underbrace{a_2(1320), a_2(1700)}_{D_{0,1,2}^{(+)}}\}$$

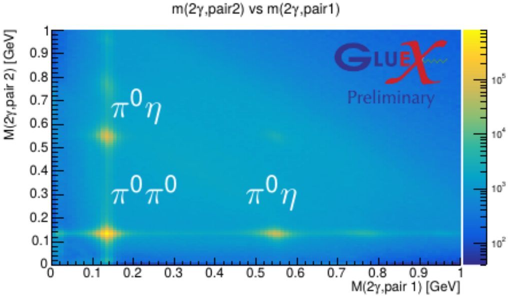
- JPAC model describing $\eta\pi$ in terms of contributing waves from various mesons (arXiv:1906.04841)
- Possible influence of an exotic state in the model can be expressed in terms of the beam asymmetry

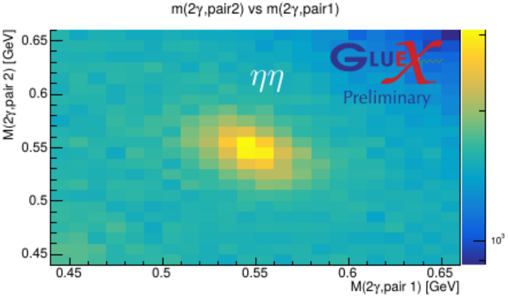




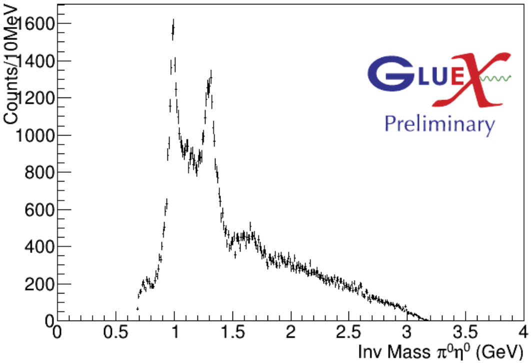
The $\eta\pi^0$ Channel

- π^0 and η distributions from diphoton invariant masses





Invariant Mass Distribution of $\eta\pi$

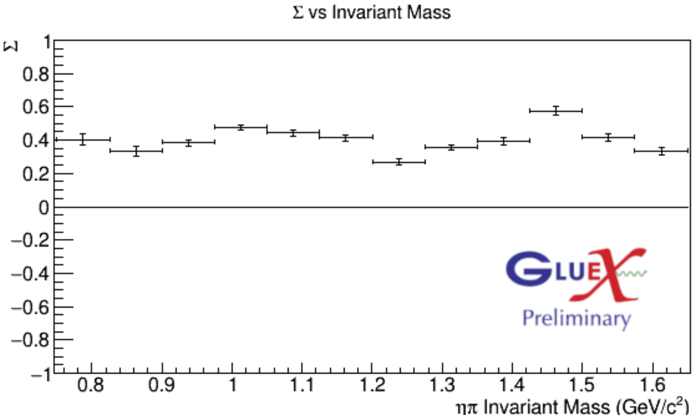


- $a_0(980)$ and $a_2(1320)$ clearly seen in the invariant mass distribution

UNIVERSITY of York

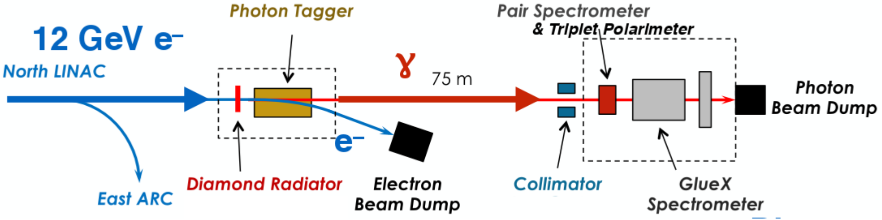
Beam Asymmetry on $\eta\pi$

- Beam Asymmetries with $\eta\pi$ invariant mass, statistical errors only

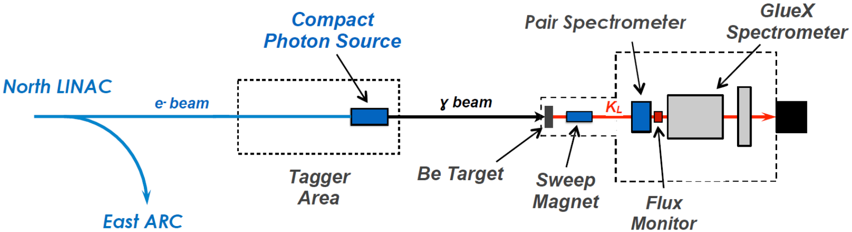


K_{Long} Facility in Hall D

We take this:

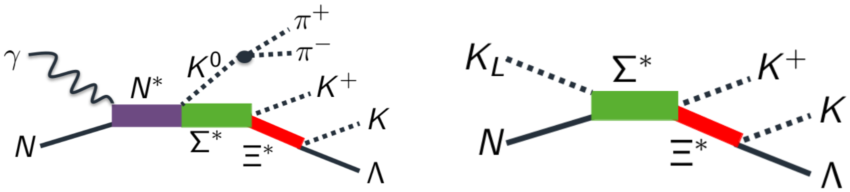


and turn it into this:



Strange Beams

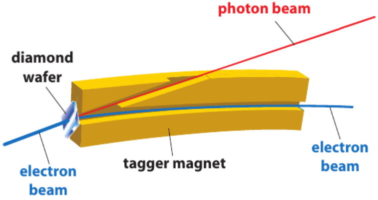
With a unit of Strangeness in the beam, producing hyperon resonances becomes much more straightforward



Compact Photon Source

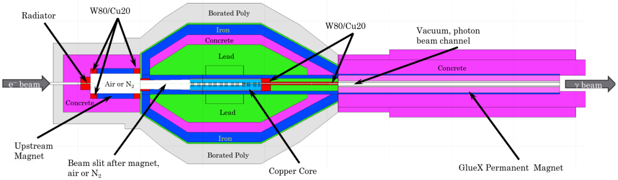
Secondary photon beam in GlueX:

- Thin radiators, minimise rescattering
- Limits photon beam intensity



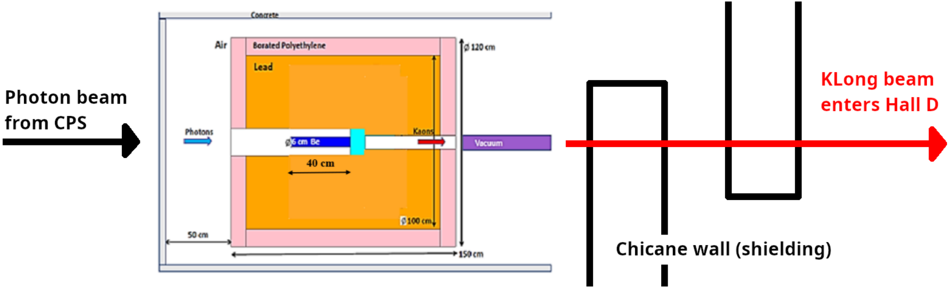
Tertiary K_{Long} beam, first produce photons from CEBAF electrons:

- Compact Photon Source - produces high intensity photon beam
- Thick radiator, heavily shielded to reduce background dose



K_{Long} Production

Beam from Compact Photon Source impinges on Beryllium target, producing K_{Long} beam

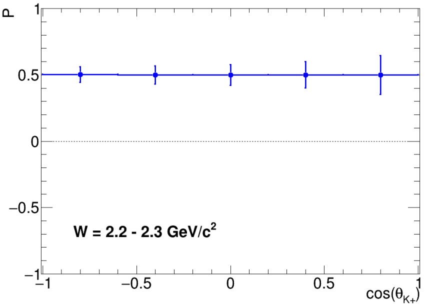


The Future: Let Me Remind You...

The KLong Facility has the potential to make major contributions to hyperon spectroscopy

- Strangeness in the beam makes hyperons much easier to produce, particularly with S = 2 and 3
- No polarisation of beam and no current proposals for a polarised target
- Self analysing property of hyperons will allow measurement of hyperon recoil polarisation, P

$K_L p \to K^+ \Xi^0$

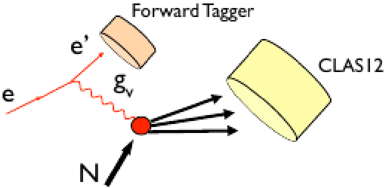


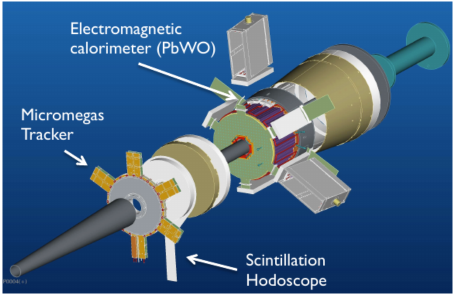
Summary

- Over the course of my regenerations, kaons have never been far from my work
- You could go as far as to say I like kaons. . .

The CLAS12 Forward Tagger

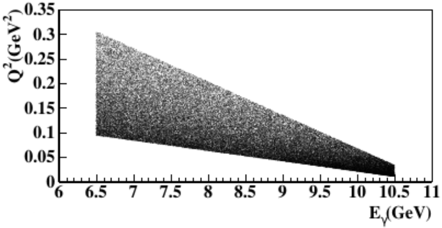
- The Forward Tagger enables spectroscopy experiments with CLAS12 using quasi-real photons up to 10 GeV
- When an electron scatters with very low Q^2, i.e. at very small angles, quasi-real photons are produced

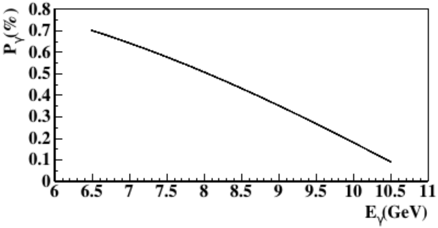




- Low Q^2 electron detection is a competitive technique for spectroscopy
- Used in MesonEx and Hybrid Baryon searches

Forward Tagger

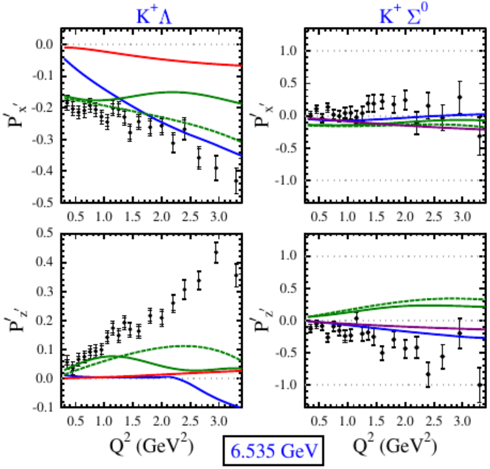




- The low Q^2 photons produced are linearly polarised
- Polarisation can be determined event-by-event from electron kinematics

Polarisation Transfer in KY Electroproduction

- Beam-recoil polarisation transfer in $K^+\Lambda$ and $K^+\Sigma$ electroproduction
- Sensitivity to higher mass N^* and Δ^* states
- CLAS12 statistics sufficient for first-ever multi-dimensional analysis for these observables in Q^2, W and $cos\theta_K^{c.m.}$
- Data will spur further development of reaction models and enable extraction of electrocoupling amplitudes



D.S. Carman et al., Phys Rev C 105 (2022)