Strangeness Analyses with CLAS12 at Jefferson Lab

Hadron Spectroscopy With Strangeness, Glasgow

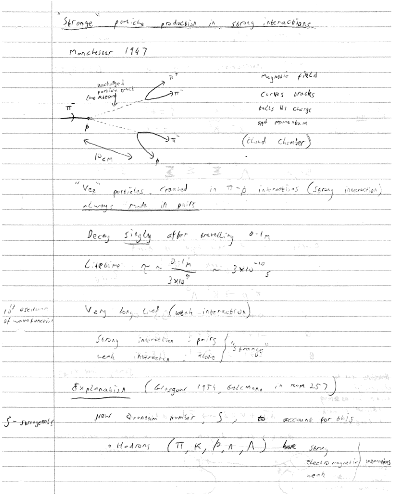
Stuart Fegan

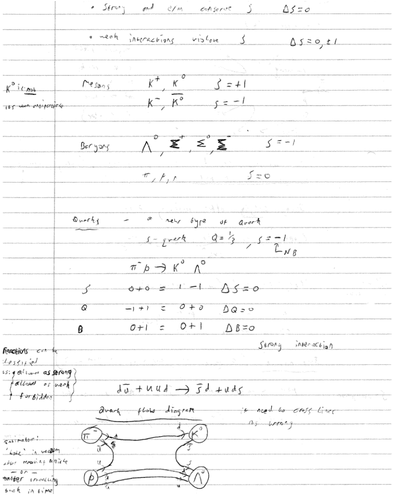
University of York

April 4th, 2024

CEBAF Large Acceptance Spectrometer

Strangeness - A Personal Anecdote





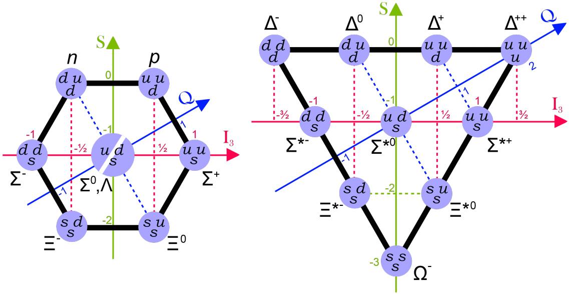
Strangeness - A Personal Anecdote

<u>Explanation</u> (Glasgow 1954, Gell-Mann in room 257)

S - strangeness New Quantum number, S, to account for this

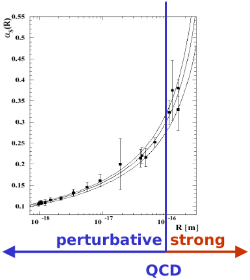
Strangeness

- Introducing the strangeness quantum number greatly aided development of the quark model
- Categorising the known hadrons into multiplets emphasised connection to symmetry groups
- Lead to the prediction, and discovery, of the Ω^{-}, a triumph of the quark model approach



Motivation

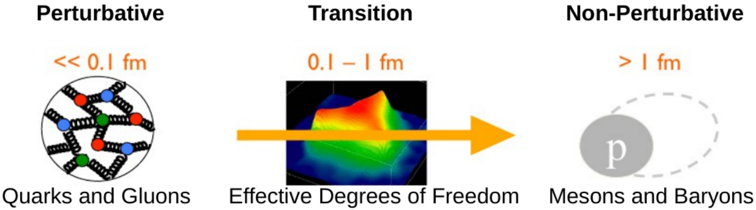
- Quark models have played a vital role in the non-perturbative regime of QCD, predicting numerous states
- As with the Ω^-, many of these states have been confirmed experimentally
- However, Constituent Quark Models don't tell the full story



Exploring Hadronic States

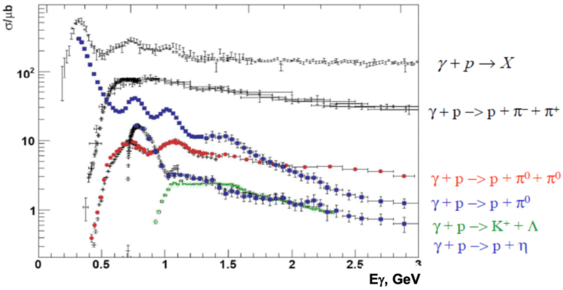
By studying hadronic states, through their production and decays, we can observe QCD in action, and attempt to answer some fundamental questions;

- 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?



Spectroscopy with Strangeness

- Reactions involving strangeness offer an additonal lens to probe hadrons
- Some states will have greater coupling strength to strangeness channels
- Kinematics can favour higher mass states, e.g. $N^* \to KY$ versus $N^* \to \pi N$



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

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Polarisation

$$\frac{d\sigma_v}{d\Omega_K^{c.m.}} = \mathcal{K}\sum_{\alpha,\beta} S_\alpha S_\beta \Big[R_T^{\beta\alpha} + \epsilon R_L^{\beta\alpha} + c_+({}^cR_{LT}^{\beta\alpha}\cos\Phi + {}^sR_{LT}^{\beta\alpha}\sin\Phi)$$

$$+ \quad \epsilon({}^cR_{TT}^{\beta\alpha}\cos 2\Phi + {}^sR_{TT}^{\beta\alpha}\sin 2\Phi) + hc_-({}^cR_{LT'}^{\beta\alpha}\cos\Phi + {}^sR_{LT'}^{\beta\alpha}\sin\Phi) + hc_0 R_{TT'}^{\beta\alpha}\Big]$$

Photoproduction and electroproduction of eta mesons

G. Knochlein (Mainz U., Inst. Kernphys.), D. Drechsel (Mainz U., Inst. Kernphys.), L. Tiator (Mainz U., Inst. Kernphys.) (Jun, 1995)

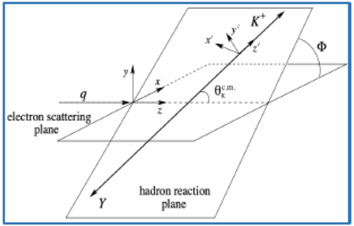
Published in: Z.Phys.A 352 (1995) 327-343 • e-Print: nucl-th/9506029 [nucl-th]

TABLE I. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A.

	Target				Recoil			Target + Recoil								
β	—	—	—	—	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	—	x	y	z	—	—	—	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	*	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	*	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	*	0	*	0	*
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	*	0	${}^cR_{TL}^{x'x}$	0	*	0	*	0	${}^cR_{TL}^{z'x}$	0	*
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTT$	${}^cR_{TT}^{00}$	0	*	0	0	*	0	*	0	*	0	*	0	*	0	*
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	*	0	${}^sR_{TL'}^{x'x}$	0	*	0	*	0	${}^sR_{TL'}^{z'x}$	0	*
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	*	0	*	0	*	0	*	0

Response functions

$R(Q^2, W, \cos\theta_K^{c.m.})$

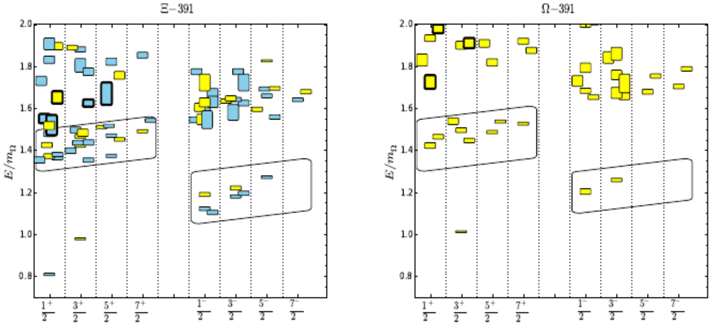


From D.S. Carman (JLab)

Strangeness Spectroscopy

Particle	J^P	Overall status
$\Xi(1320)$	$\frac{1}{2}^+$	****
$\Xi(1530)$	$\frac{3}{2}^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$\frac{3}{2}^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

2022 PDG Listing



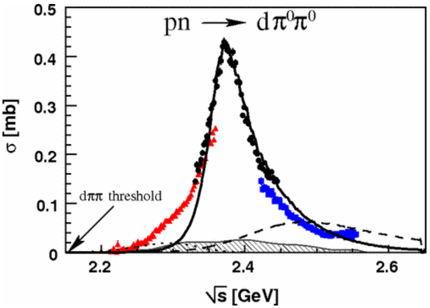
R.G. Edwards,et al. Phys Rev D87 (2013)

- Spectrum of strange baryons is still relatively unknown
- Just a handful of the Ξ and Ω states are considered to be well established
- Quark model approaches, and lattice calculations, suggest a far richer spectrum of $S = -2$ and -3 baryons

Hexaquarks

- QCD allows many states beyond the familiar $q\bar{q}$ of mesons and qqq of baryons
- Hexaquarks are a category of objects consisting of either six valence quarks ($6q$) or three quarks and three antiquarks ($3q3\bar{q}$)

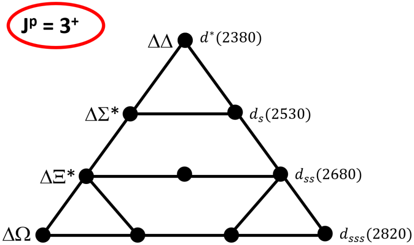
- Initial experimental evidence for the d*(2380) came from the WASA at COSY collaboration in 2011
- Prompted follow up work in York at other facilities (A2@MAMI, JLab)

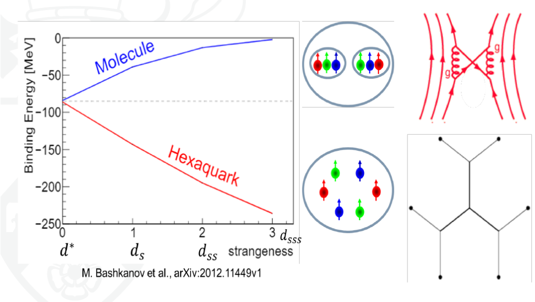


P.Adlarson et al., Phys Rev Lett 106 (2011) 242302

Hexaquarks at CLAS

- Looking to find and establish the nature of hexaquark states
- Exploit strangeness to determine possible structure





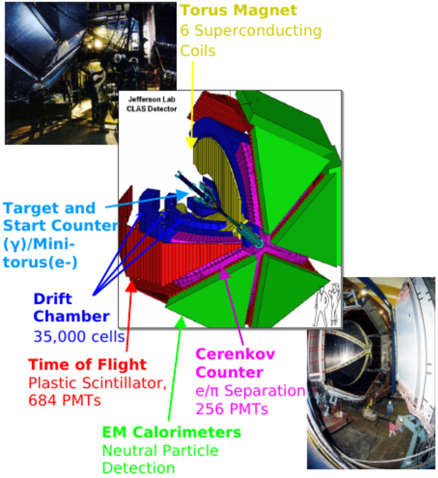
Jefferson Lab

- 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

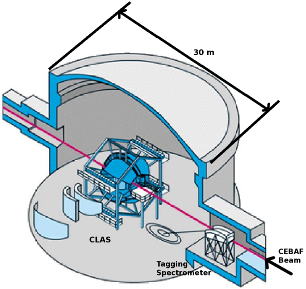
- **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility
- Superconducting RF accelerator
- Anti-parallel double linac, 7/8 of a mile in circumference
- Electron beam energies up to 12 GeV
- Diverse experimental program in four halls
- High-current Electron beams in Halls A and C
- Large acceptance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

Hall B and CLAS

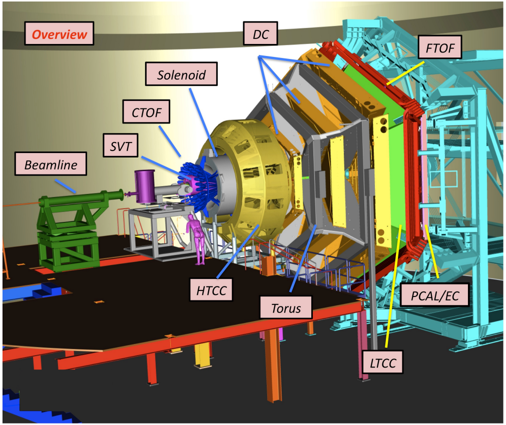


NIM A, 503(3), 2003

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



CLAS12

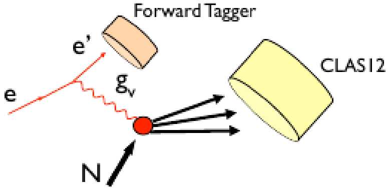


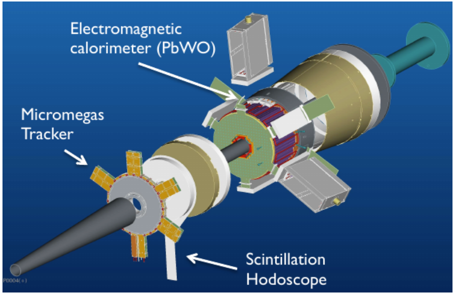
NIM A, 967, 163898 (2020)

- 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
- Photons produced are linearly polarised, with polarisation determinable from electron kinematics

Run Groups

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

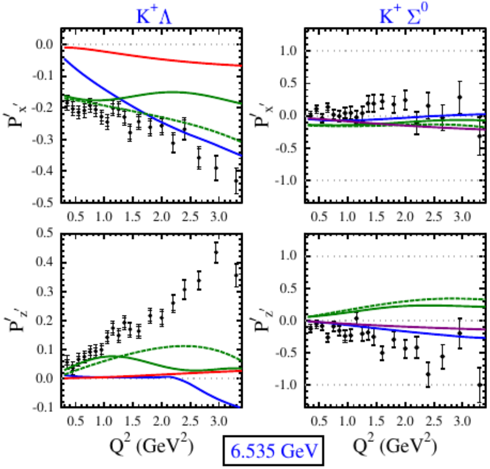
Proposal	Physics	Contact	Rating	Days	PAC
E12-07-104	Neutron magnetic form factor	Gilfoyle	A-	30	32 J:48
E12-07-104A	Quasi-real photoproduction on deuterium	Phelps			47 J:48
E12-09-007(a)	Study of partonic distributions in SIDIS kaon production	Hafidi	A-	110	38 J:48
E12-09-008	Boer-Mulders asymmetry in 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

- Proposals with similar experimental conditions collected as *Run Groups*
- The strangeness analyses described mainly use data at 11 GeV beam energy from Run Groups A (LH_2 target) and B (LD_2 target)
- Also a lower energy run group on LD_2, Run Group K

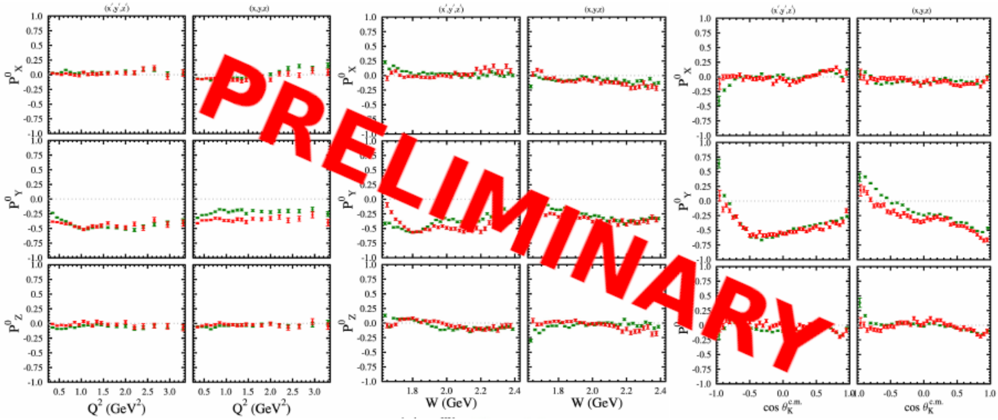
Polarisation Transfer in KY Electroproduction

- 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



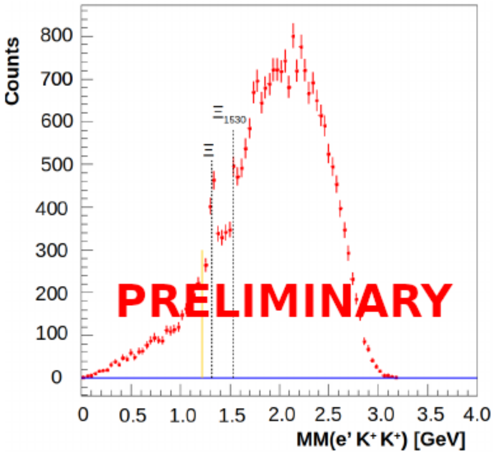
D.S. Carman et al., Phys Rev C 105 (2022)

KY Polarisation



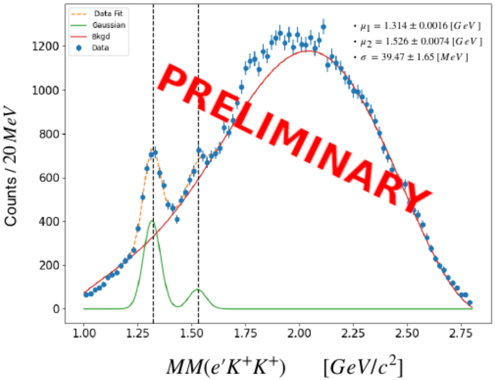
D.S. Carman (JLab), L. Lanza (INFN Rome)

Cascade Spectroscopy



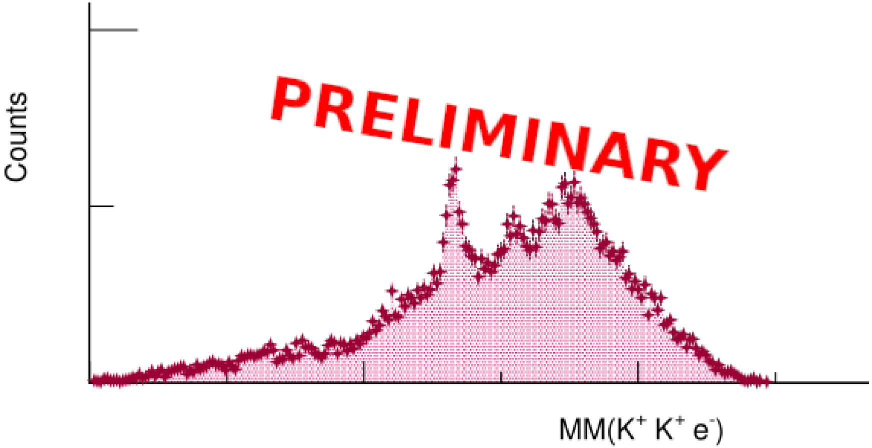
- M. Nicol, York, 2022 PhD
- Survey of eK^+K^+ missing mass shows clear Ξ sigmals
- First observation in CLAS12 data

Cascade Spectroscopy



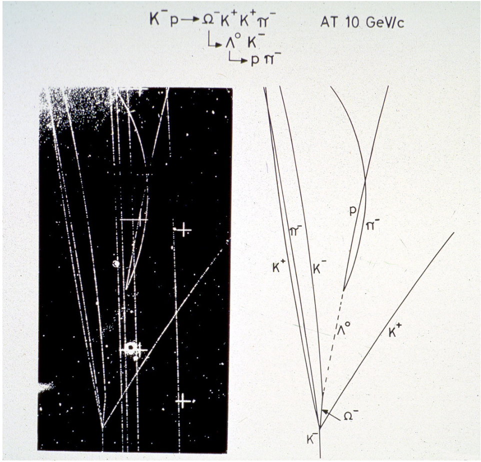
- PhD of J. Carvajal (FIU), defended last week
- More detailed study of the eK^+K^+ final state
- Cross section measurement of Ξ^- in low and high Q^2 regions
- Q^2 evolution will allow exploration of production methods

Cascade Spectroscopy



- Photoproduction (i.e. low Q^2) studies of higher mass Ξ states (A. Acar, York)

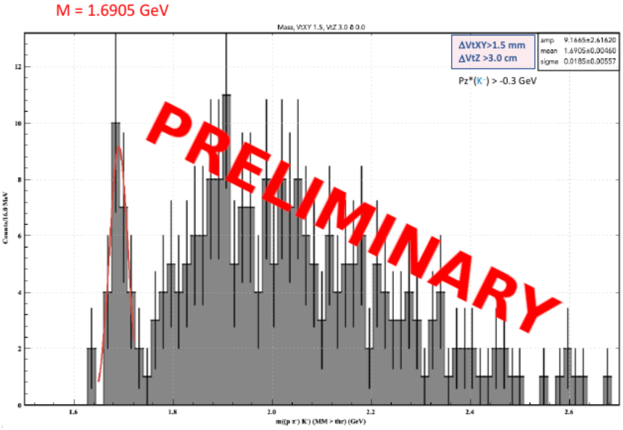
Omega Searches



CERN-EX-41769

- The Ω^- has yet to be seen in electroproduction, CLAS12 would be a first measurement
- This single bubble chamber event was a PRL, and the previously mentioned triumph of the quark model
- With low Q^2 photoproduction, we hope to make first measurements of the Ω^- cross section
- Ω^- has no quarks inherited from the target proton, what can data tell us about the reaction mechanism?

Omega Searches

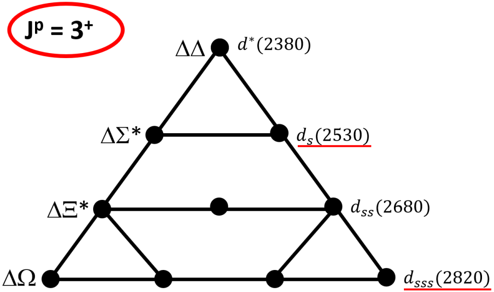


V. Ziegler, JLab

- $p\pi^- K^-$ mass distribution
- Possible Ω^- peak seen
- Background studies ongoing
- Data will also be used to search for excited Ω states

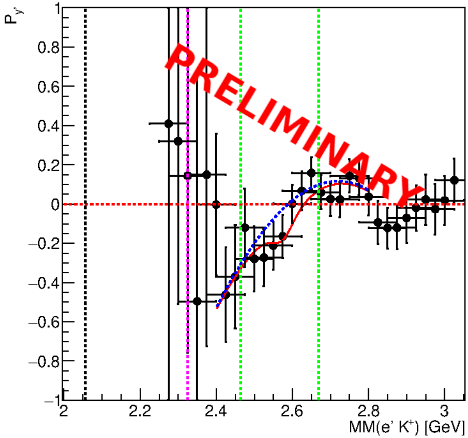
Hexaquarks at CLAS

- Two CLAS12 PhD analyses searching for d^* states so far in York:



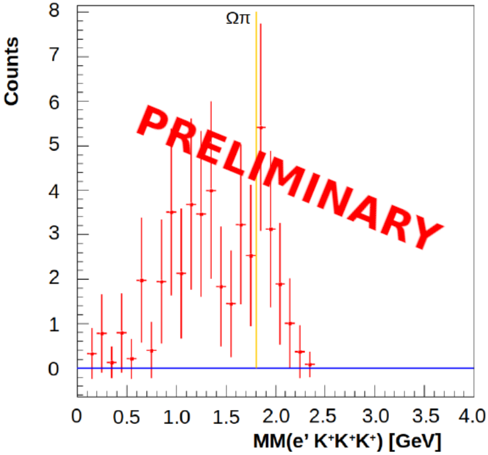
- G. Clash, defended last year, *Search for a Singly Strange Hexaquark Using Polarization Data From CLAS12*
- M. Nicol, defended Autumn 2022, *Exploring The Strong Interaction Through Electroproduction of Exotic Particles*

Search for a Singly Strange Hexaquark (G. Clash)

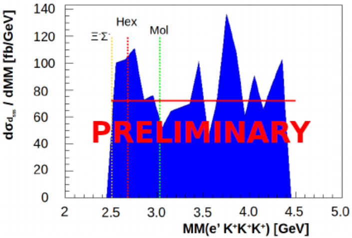


- Looking for signs of a hexaquark state in RGB data
- $ed \rightarrow e' K^+ d_s^0$
- The d_s^0 decays through Λn
- Final state of $e' K^+ p \pi^- n$
- Using polarisation as lens to perform this search
- $P_{y'}$ measurements of the Λ used to establish an upper limit on this state's peak strength

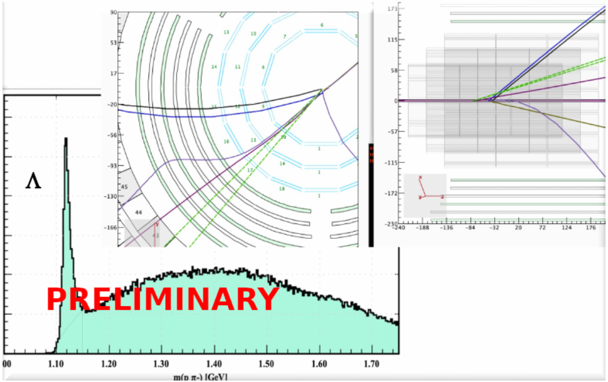
Search for d_{sss} (M. Nicol)



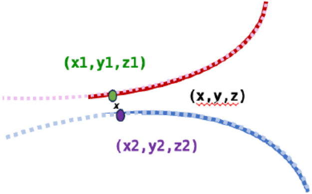
- Also RGB data
- $ed \to e' K^+ K^+ K^+ d_{sss}$
- "Bump hunt" shows no obvious d_{sss} signal
- Cross section upper limit established



Further Analyses



- Recent developments in detached vertex reconstruction (V. Ziegler, JLab)
- Improve resolution in several channels that rely on hyperon reconstruction



Outlook and Plans

- CLAS12 data is making significant contributions to our understanding of the role of strangeness
- Spectroscopy of Ξ and Ω states will enable models of hyperon production to be more fully explored
- Leveraging polarisation provides an additional lens to study the role of strangeness in resonance production
- Searches for unconventional states, e.g. hybrid baryons and hexaquarks, benefit from the study of strangeness channels

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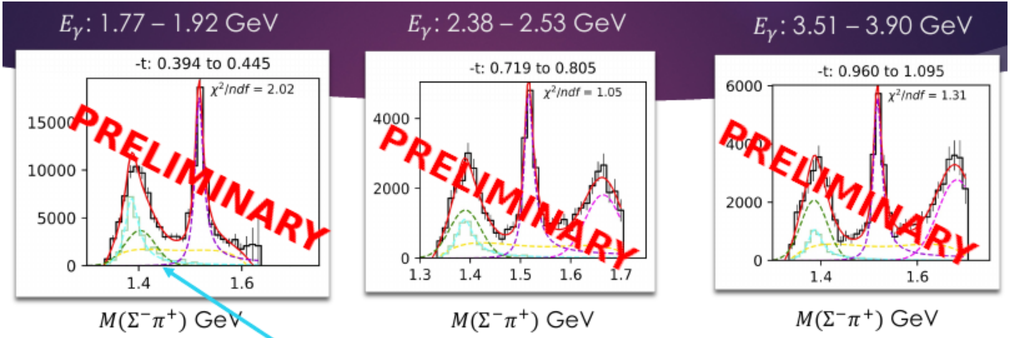
Outlook and Plans

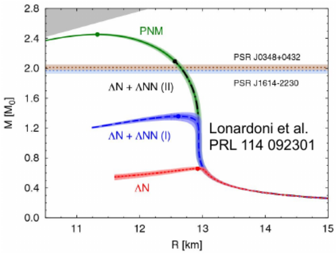
- This is just a flavour of CLAS12 activities in strangeness; so much more in both our ongoing CLAS6 analysis, and our exploitation of CLAS12 data
- To name but some, study of Λ and Σ states, YN interactions, and polarisation observables in photoproduction
- Complementarity with several facilities, and new collaborators are always welcome

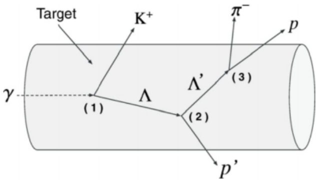
(Backup) Λ(1405) photoproduciton (T. Reed, FIU)

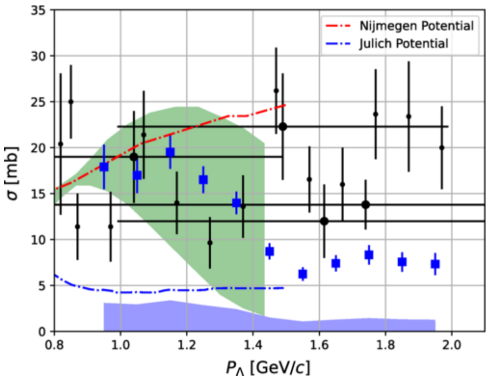


- Total fit function (red): (Gaussian on Λ(1405)) + (Mass-dependent relativistic Breit-Wigner on Λ(1520)) + (Mass-dependent non-relativistic Breit-Wigner on Σ(1385)) + (Gaussian on 1660 peak) + $C * bg$
  - bg is 4th order polynomial with fixed parameters from fits to mixed-angle events
  - C is a scaling factor multiplied by the fixed 4th order polynomial
  - The Breit-Wigner function on Σ(1385) is completely fixed

YN Rescattering (Rowley et al., PRL127, 272303, 2021)







(Backup) G polarisation observable on $K^+\Lambda$ photoproduciton