Strangeness Analyses with CLAS12 at Jefferson Lab

Hadron Spectroscopy With Strangeness, Glasgow

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April 4th, 2024

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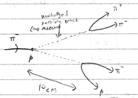
clas

CEBAF Large Acceptance Spectrometer

Strangeness - A Personal Anecdote

"Strange" particle production in strong interactions

Manchester 1947



Magnetic field curves tracks tells us charge and momentum

(Cloud Chamber)

"Vee" particles. Created in $\pi - p$ interactions (strong interaction) always made in pairs

Decay singly after travelling 0.1m

Lifetime $\tau \sim \frac{0.1m}{3\times10^8} \sim 3\times10^{-10}s$

10^{13} oscillations of wavefunction

Very long lived (weak interaction)

Strong interaction : pairs
weak interaction : alone } "strange"

Explanation (Glasgow 1954, Gell-Mann in room 257)

S - strangeness

New Quantum number, S, to account for this

- Hadrons (π, K, p, n, Λ) have strong, electromagnetic, weak } interactions

- Strong and e/m conserve S $\quad \Delta S = 0$
- weak interactions violate S $\quad \Delta S = 0, \pm1$

K^0 is not its own antiparticle

Mesons $\quad K^+, K^0 \quad S = +1$
$\quad K^-, \overline{K^0} \quad S = -1$

Baryons $\quad \Lambda^0, \Sigma^+, \Sigma^0, \Sigma^- \quad S = -1$

$\pi, p, n \quad S = 0$

Quarks - a new type of quark

s-quark $\quad Q = \frac{1}{3}, \quad S = -1$ NB

$\pi^- p \rightarrow K^0 \Lambda^0$

S	$0+0$	$= 1-1$	$\Delta S = 0$
Q	$-1+1$	$= 0+0$	$\Delta Q = 0$
B	$0+1$	$= 0+1$	$\Delta B = 0$

Strong interaction

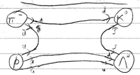
Reactions can be classified as: allowed as strong, allowed as weak, forbidden

$d\bar{u} + uud \rightarrow \bar{s}d + uds$

Quark flow diagram

no need to cross lines as wrong

antimatter: 'hole' in vacuum after removing particle — or — matter travelling back in time



Strangeness - A Personal Anecdote

Explanation (Glasgow 1954, Gell-Mann in room 257)

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

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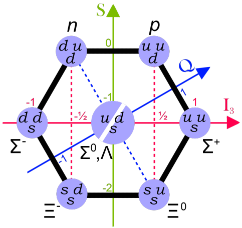
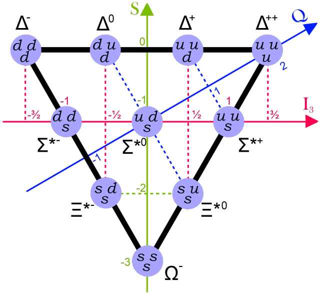
Strangeness

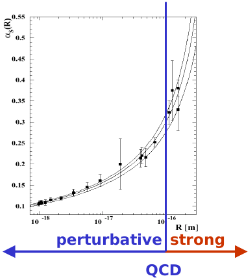
- Introducing the strangeness quantum number greatly aided development of the quark model
- Categorising the known hadrons into multiplets emphasised connection to symmetry groups
- Lead to the prediction, and discovery, of the Ω^-, a triumph of the quark model approach





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



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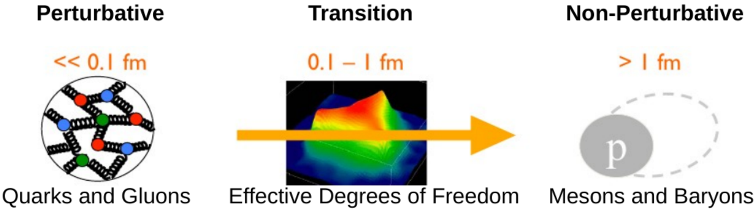
Exploring Hadronic States

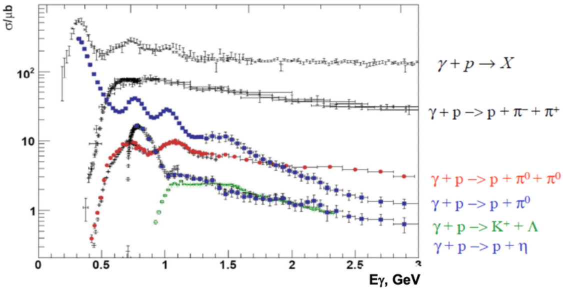
By studying hadronic states, through their production and decays, we can observe QCD in action, and attempt to answer some fundamental questions;

- 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)

Polarisation

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

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

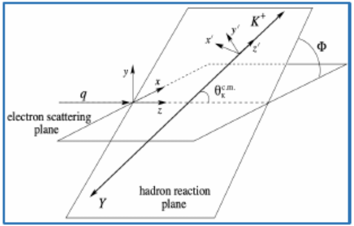
Photoproduction and electroproduction of eta mesons
G. Knochlein (Mainz U., Inst. Kernphys.), D. Drechsel (Mainz U., Inst. Kernphys.), L. Tiator (Mainz U., Inst. Kernphys.) (Jun, 1995)
Published in: Z.Phys.A 352 (1995) 327-343 • e-Print: nucl-th/9506029 [nucl-th]

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

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

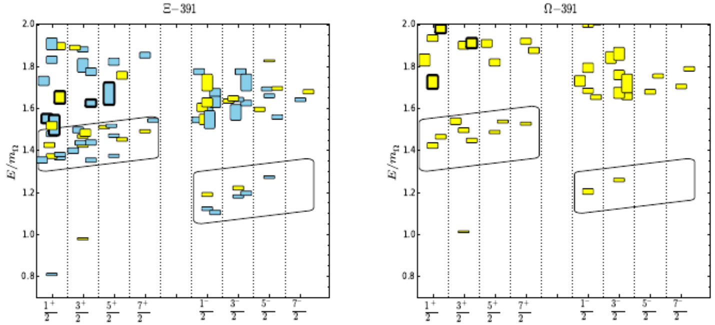


From D.S. Carman (JLab)

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



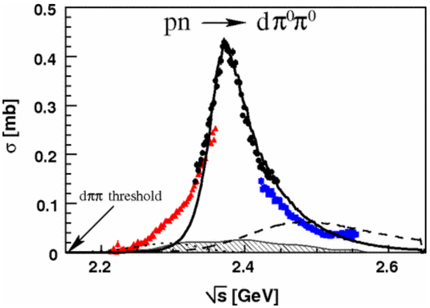
R.G. Edwards,et al. Phys Rev D87 (2013)

- 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 ($3q3\bar{q}$)

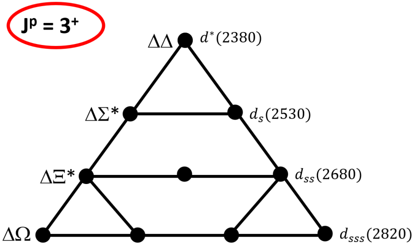
- Initial experimental evidence for the d*(2380) came from the WASA at COSY collaboration in 2011
- Prompted follow up work in York at other facilities (A2@MAMI, JLab)

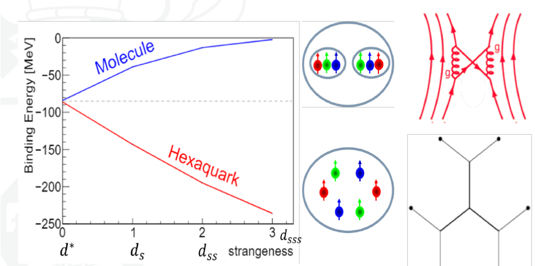


P.Adlarson et al., Phys Rev Lett 106 (2011) 242302

Hexaquarks at CLAS

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





M. Bashkanov et al., arXiv:2012.11449v1

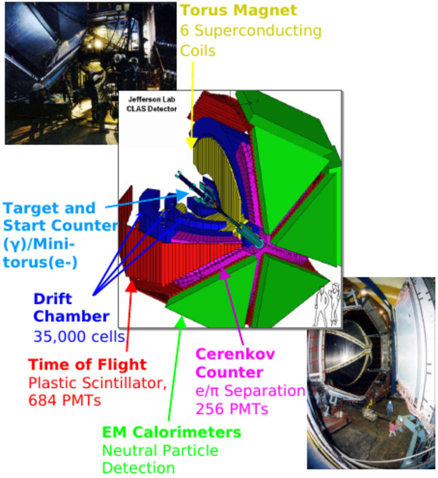
Jefferson Lab

- 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

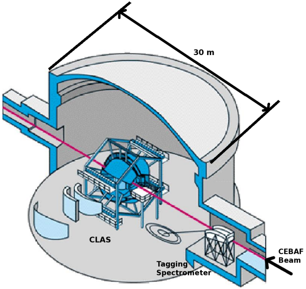
- **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility
- Superconducting RF accelerator
- Anti-parallel double linac, 7/8 of a mile in circumference
- Electron beam energies up to 12 GeV
- Diverse experimental program in four halls
- High-current Electron beams in Halls A and C
- Large acceptance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

Hall B and CLAS

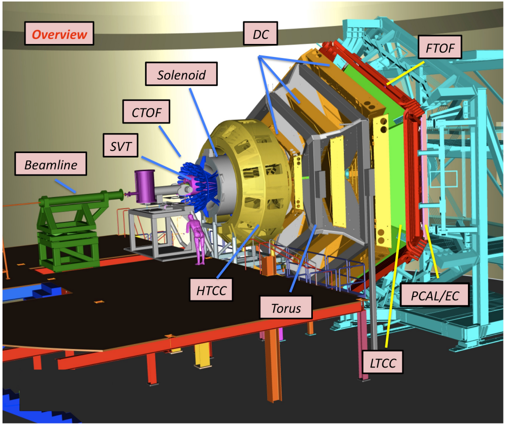


NIM A, 503(3), 2003

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



CLAS12

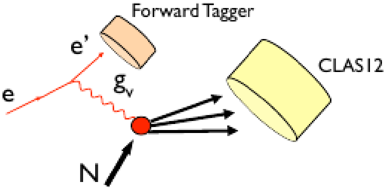


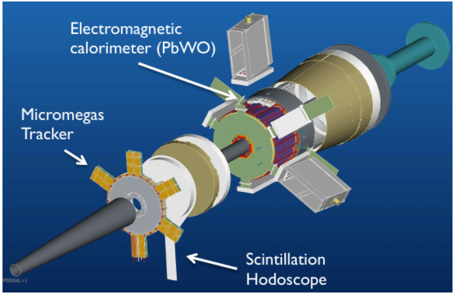
NIM A, 967, 163898 (2020)

- 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

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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 producuon 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

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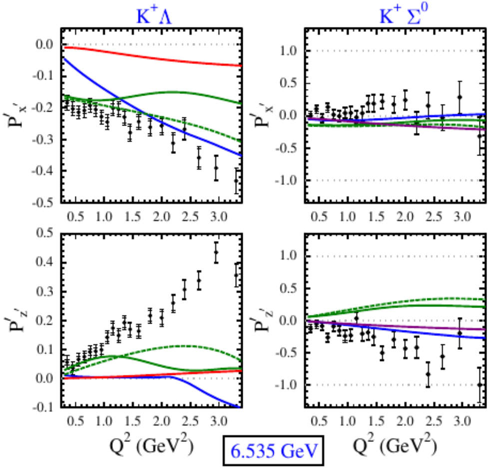
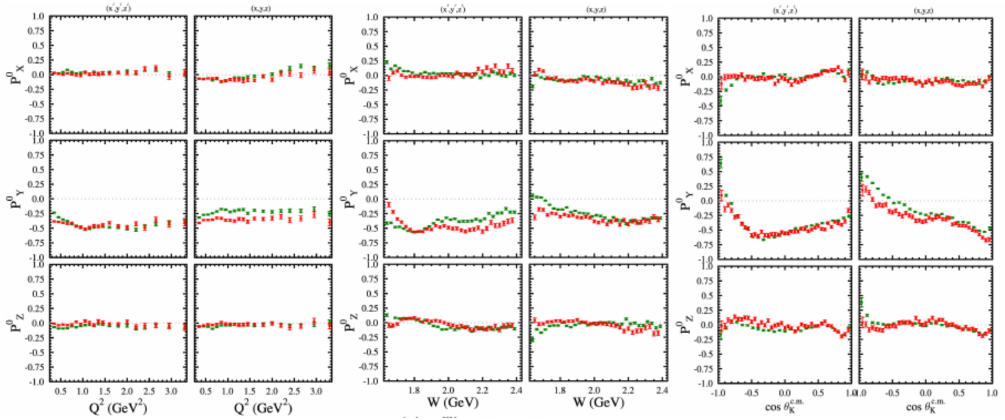
Polarisation Transfer in KY Electroproduction

- 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



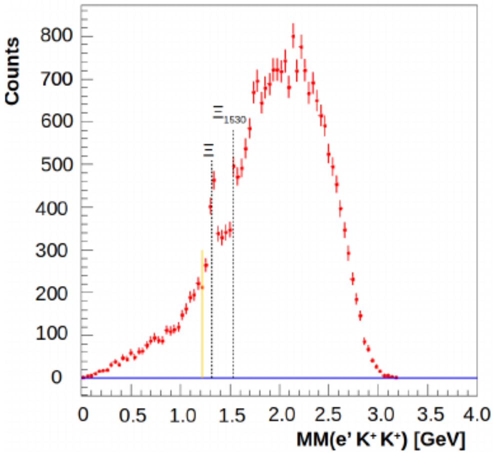
D.S. Carman et al., Phys Rev C 105 (2022)

KY Polarisation



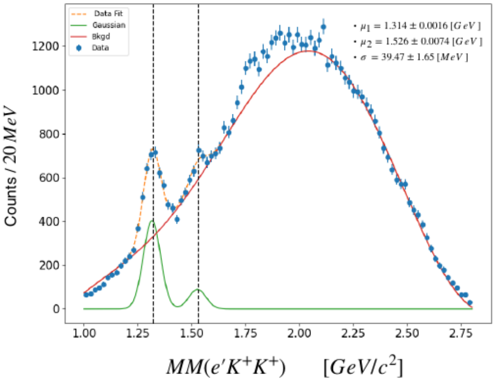
D.S. Carman (JLab), L. Lanza (INFN Rome)

Cascade Spectroscopy



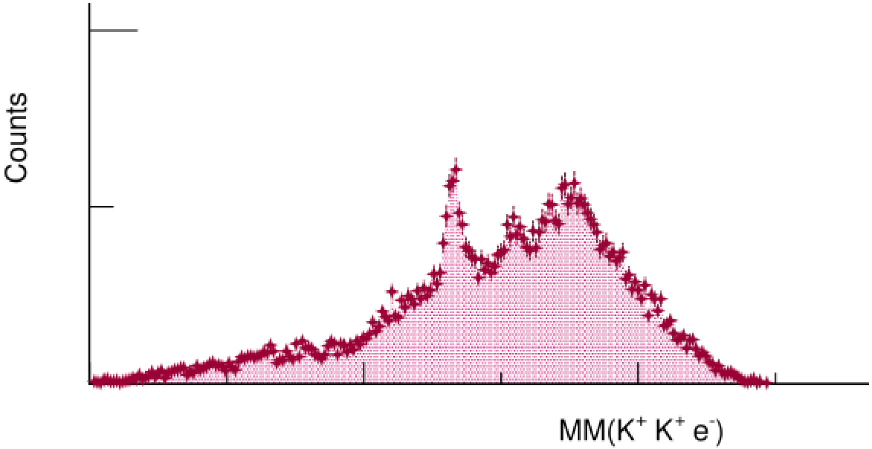
- M. Nicol, York, 2022 PhD
- Survey of eK^+K^+ missing mass shows clear Ξ sigmals
- First observation in CLAS12 data

Cascade Spectroscopy



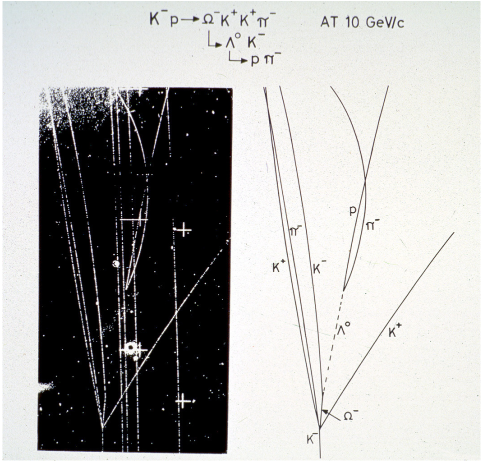
- PhD of J. Carvajal (FIU), defended last week
- More detailed study of the eK^+K^+ final state
- Cross section measurement of Ξ^- in low and high Q^2 regions
- Q^2 evolution will allow exploration of production methods

Cascade Spectroscopy



- placeholder text, add some comment about Asli's analysis

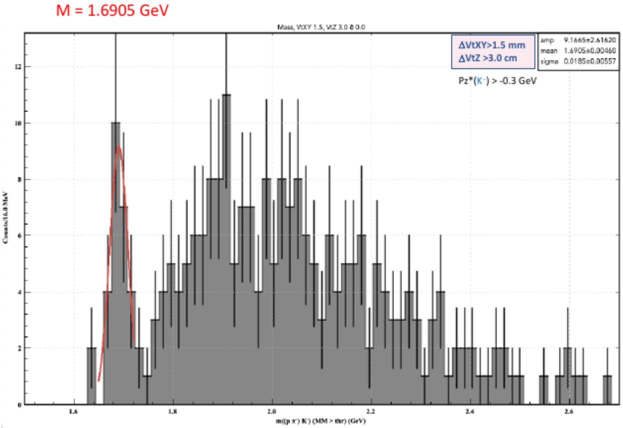
Omega Searches



CERN-EX-41769

- The Ω^- has yet to be seen in electroproduction, CLAS12 would be a first measurement
- 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 data tell us about the reaction mechanism?

Omega Searches

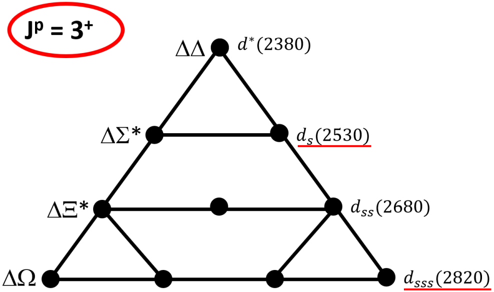


V. Ziegler, JLab

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

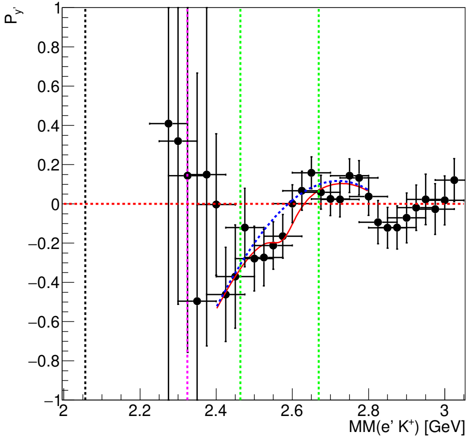
Hexaquarks at CLAS

- 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

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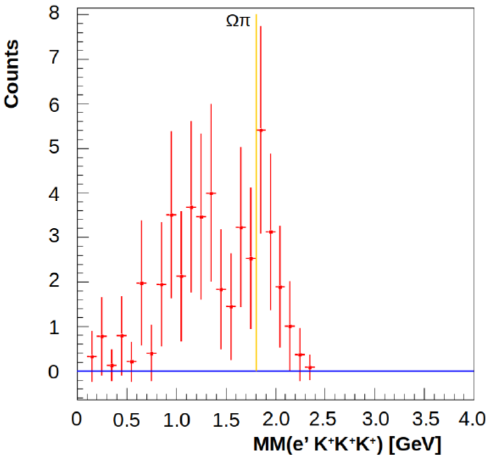
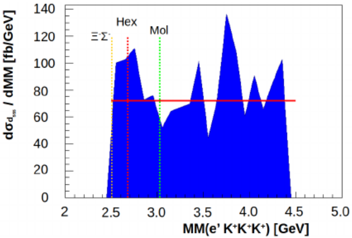
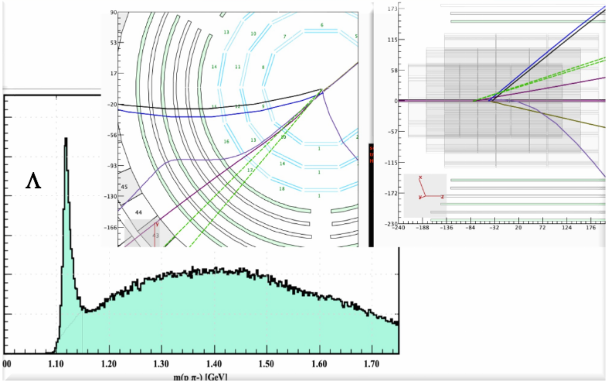
Search for d_{sss} (M. Nicol)



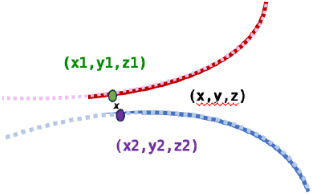
- Also RGB data
- $ed \to e' K^+ K^+ K^+ d_{sss}$
- "Bump hunt" shows no obvious d_{sss} signal
- Cross section upper limit established



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
- This is just a flavour of CLAS12 activities in strangeness; so much more in both our ongoing CLAS6 activities, and our exploitation of CLAS12 data