Experimental studies of the $\Lambda(1405)$

physics654 – Seminar on exotic multi-quark states

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Motivation

What is special about the $\Lambda(1405)$?

- its mass does not fit well into constituent quark models which do predict baryon masses well for other baryons
- invariant mass distribution (line shape) differs significantly from usual Breit-Wigner shapes
- candidate for an exotic multiquark state (bound system of $\overline{K}N$) since its mass lies just below threshold

There are (very) many different theoretical approaches to explain this behavior
$\rightarrow$ There is need for more experimental data!

some plots/pictures?

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Continuous Electron Beam Accelerator Facility (CEBAF)

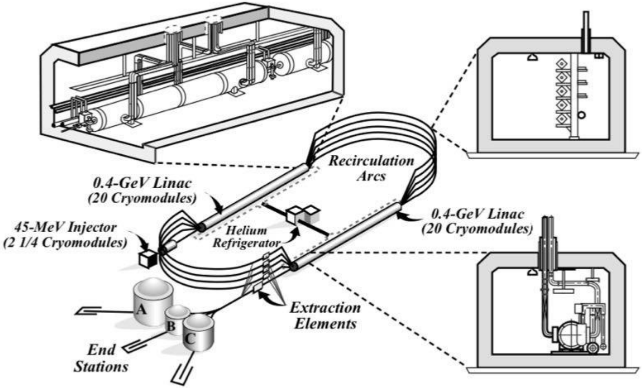


Figure 1: CEBAF layout at Jefferson Lab, [Mecking et al. 2003]

CEBAF Large Acceptance Spectrometer (CLAS)

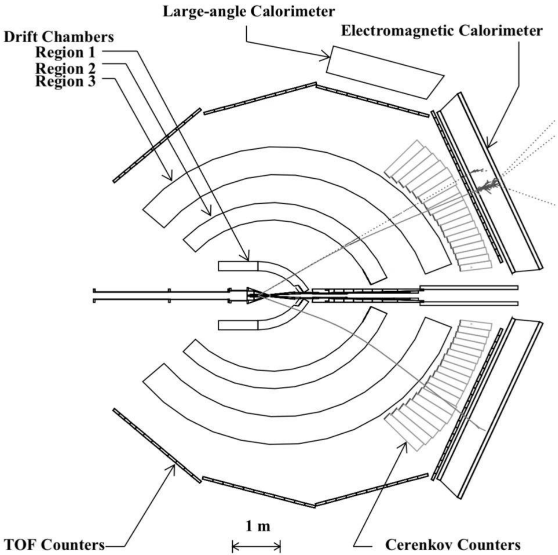
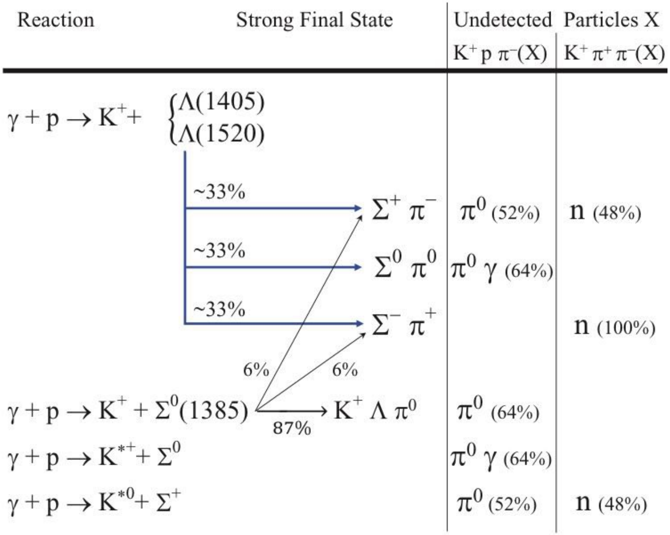


Figure 2: CLAS layout at Jefferson Lab, [Mecking et al. 2003]

Reaction kinematics



$$\Sigma^+ \to p\pi^0$$
$$\Sigma^+ \to n\pi^+$$
$$\Sigma^0 \to \gamma\Lambda \quad \to \gamma p \pi^-$$
$$\Sigma^- \to n\pi^-$$
$$\Lambda \to p\pi^-$$

Figure 3: Possible and studied reactions in the analysis of the lineshapes of $\Lambda(1405)$, taken from [Moriya, Schumacher, Adhikari et al. 2013]

Event selection

There are two sets of reactions that the detector sees

1. $K^+ p \pi^-$
2. $K^+ \pi^+ \pi^-$

There are many cuts that can be made that apply to both

Initial selection of particles

- Initial final state Kaon selection
- fiducial cuts
- remove false K^+ due to π^+ or p
- Loose ΔTOF cut ($\Delta\mathrm{TOF} = t_{\mathrm{meas}} - t_{\mathrm{calc}} = t_{\mathrm{meas}} - \frac{l\sqrt{p^2+m_0^2}}{cp}$)
- vertex z cut
- minimum $|\mathbf{p}|$ cuts
- Precise ΔTOF cuts

Event selection

In all channels, the data was divided into 10 bins of energy spanning 100 MeV in the CMS energy $W = \sqrt{s}$ and 20 angle bins in the CMS kaon angle.
$\rightarrow$ the following analysis was performed independently in every bin of energy and angle!

Event selection

extracting $\Lambda\pi^0$ and $\Sigma^+\pi^-$

- reminder: $\Lambda \to p\pi^-, \Sigma^+ \to p\pi^0$
- final state particles: $K^+p\pi^-(\pi^0)$
- determine p_π via missing mass fit
- apply cuts based on fits to the invariant masses $M_{p\pi^-}$ and $M_{p\pi^0}$

extracting $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$

- reminder: $\Sigma^\pm \to n\pi^\pm$
- final state particles: $K^+\pi^+\pi^-(n)$
- determine p_n via missing mass fit
- apply cuts based on fits to the invariant masses $M_{n\pi^\pm}$

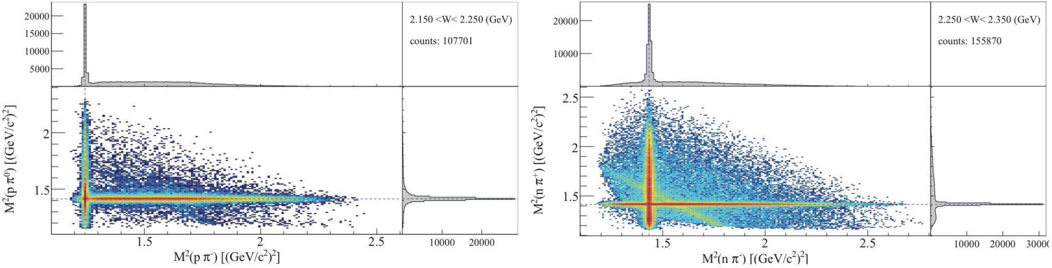


Figure 4: Dalitz-like plots of the above mentioned invariant masses, taken from [Moriya, Schumacher, Adhikari et al. 2013]

Event selection

extracting $\Sigma^0\pi^0$

- reminder: $\Sigma^0 \to \gamma\Lambda \to \gamma p\pi^-$
- final state particles: $K^+p\pi^-(\gamma\pi^0)$ - missing mass fit is not applicable here: demand the missing mass is sufficiently greater than m_π
- make cuts based on the invariant mass $M_{p\pi^-}$
- now the missing mass ($\gamma p \to K^+X$) gives the $\Sigma^0\pi^0$ lineshape

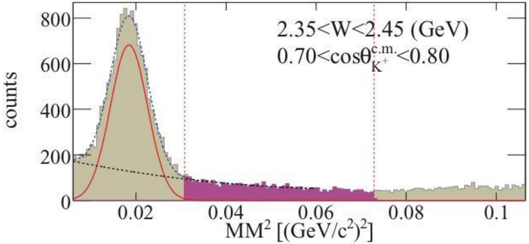


Figure 5: Invariant mass of the $\gamma\pi$ system, selection range in magenta. Taken from [Moriya, Schumacher, Adhikari et al. 2013]

Measurements and analysis

- Now the signal regions have been established
- he true lineshape of the $\Lambda(1405)$ has to be extracted from the vast of reactions $\rightarrow$ any other contributions have to be excluded
- Strategy: use of MONTE-CARLO fits to the data, simulating the contribution of other resonances

I will not really go into detail here...(??)

Interpretation of the results

Theoretical basics

The $\Lambda(1405)$ is so far (mostly) assumed to have $J^P = \frac{1}{2}^-$, but this has not been determined experimentally

Measuring spin

- consider the strong decay $Y^* \to Y\pi$, with J^P the spin and parity of Y^*
- the $Y\pi$ angular distribution will only depend on J

$$I(\theta_Y) = \text{const.} \qquad J = 1/2$$

$$I(\theta_Y) \propto 1 + \frac{3(1-2p)}{2p+1}\cos^2\theta_Y \qquad J = 3/2,$$

  where θ_Y is the polar angle of the decay direction of Y in the Y^* rest frame, p describes the fraction of spin projections along the z axis
- uniform decay pattern is best evidence for spin $J = 1/2$

[Moriya, Schumacher, Aghasyan et al. 2014]

Theoretical basics

Measuring parity

- the key to accessing the parity lies in determining the Polarization transfer to the decay product Y which we will denote $\mathbf{Q}$
- the angular distribution of $\mathbf{Q}$ will only depend on $\mathbf{P}$

$$\mathbf{Q}(\theta_Y) = \text{const.} \qquad J^P = 1/2^-$$
$$\mathbf{Q}(\theta_Y) = -\mathbf{P} + 2(\mathbf{P}\cdot\mathbf{q})\mathbf{q} \qquad J^P = 1/2^+$$

- $\mathbf{Q}$ can be measured from weak decay angular distribution of Y

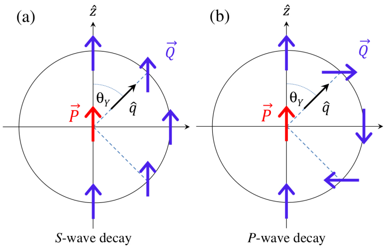


Figure 6: Polarization transfer in the strong decay $Y^* \to Y\pi$, taken from [Moriya, Schumacher, Aghasyan et al. 2014]

[Moriya, Schumacher, Aghasyan et al. 2014 and Ref. therein]

Measurements and analysis

Event selection

- select kinematic region where the $\Sigma\pi$ invariant mass is dominated by the $\Lambda(1405) \to M_{\Sigma\pi} \in 1.30\,\text{GeV to } 1.45\,\text{GeV}$
- inspect nine bins in energy and angle, namely with CM energy at $2.6, 2.7$ and 2.8 GeV and the three forwardmost kaon angle bins each

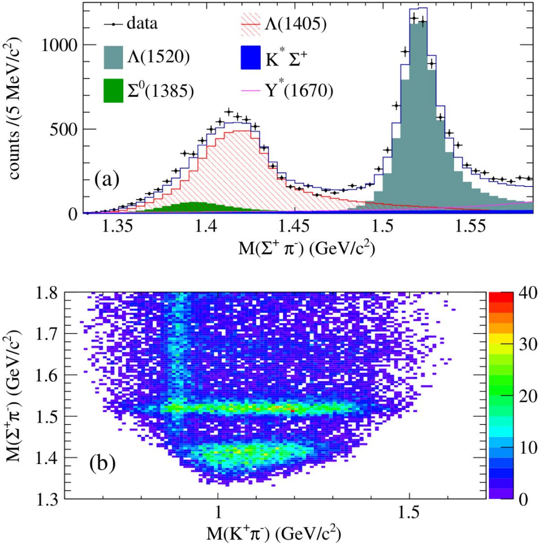


Figure 7: $\Sigma\pi$ and $K\pi$ invariant mass in the vicinity of the $\Lambda(1405)$, taken from [Moriya, Schumacher, Aghasyan et al. 2014]

Measurements and analysis

Analysis procedure

- plot the angular distribution of the projections $\cos\theta_\Sigma$ and $\cos\theta_p$ for each bin
- test each spin hypothesis using Monte-Carlo maximum likelihood fits, which employ angular decay probability distributions according to each hypothesis for $\Sigma\pi$ and $p\pi$. From the fit Q_z will be determined
- test parity hypotheses by determining $Q_z(\cos\theta_\Sigma)$
- compare each hypothesis by calculating a χ^2 probability

Result: data is consistent with $J^P = 1/2^-$ but does in principle not rule out $J^P = 3/2^+$. $1/2^+$ and $3/2^-$ can be discarded.

Measurements and analysis

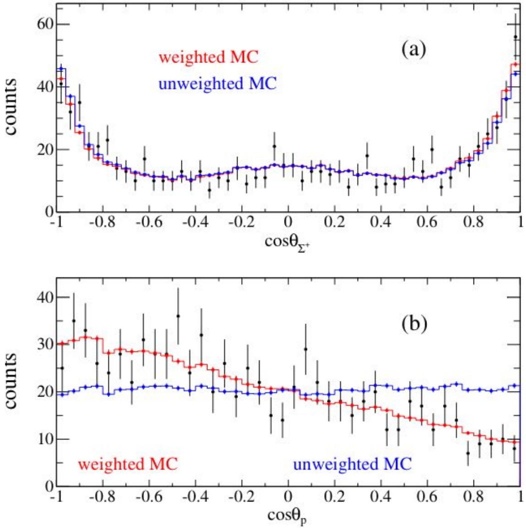


Figure 8: Distributions of the projections of (a)$\cos\theta_\Sigma$ and (b) $\cos\theta_p$ @ $2.65 < W < 2.75\,\mathrm{GeV}$ and $0.70 < \cos\theta < 0.80$, taken from [Moriya, Schumacher, Aghasyan et al. 2014]

Measurements and analysis

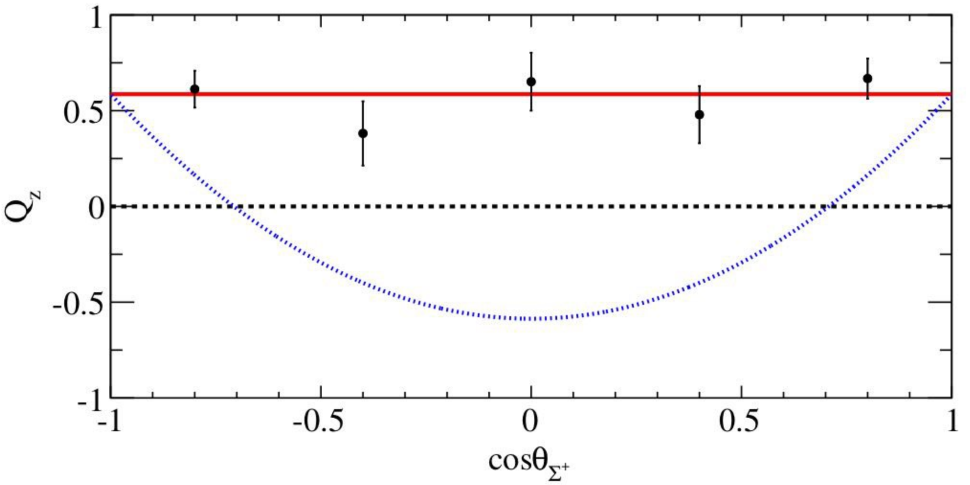


Figure 9: angular distribution of the polarization Q_z @ $2.65 < W < 2.75\,\mathrm{GeV}$ and $0.70 < \cos\theta < 0.80$. Red: average, blue: expectation for P-wave decay. Taken from [Moriya, Schumacher, Aghasyan et al. 2014]

Conclusion

References

- Mecking, B.A. et al. (2003). 'The CEBAF large acceptance spectrometer (CLAS)'. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 503.3, pp. 513–553. ISSN: 0168-9002. DOI: https://doi.org/10.1016/S0168-9002(03)01001-5. URL: https://www.sciencedirect.com/science/article/pii/S0168900203010015.
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- Moriya, K., R. A. Schumacher, M. Aghasyan et al. (Feb. 2014). 'Spin and parity measurement of the $\Lambda(1405)$ baryon'. In: *Phys. Rev. Lett.* 112 (8), p. 082004. DOI: 10.1103/PhysRevLett.112.082004. URL: https://link.aps.org/doi/10.1103/PhysRevLett.112.082004.