

# Experimental studies of the $\Lambda(1405)$

physics654 – Seminar on exotic multi-quark states

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

- ▶ mass does not fit well into constituent quark models
- ▶ invariant mass distribution (line shape) differs significantly from usual BREIT-WIGNER shape
- ▶ candidate for an exotic multiquark state (bound system of  $\bar{K}N$ ) since its mass lies just below production threshold

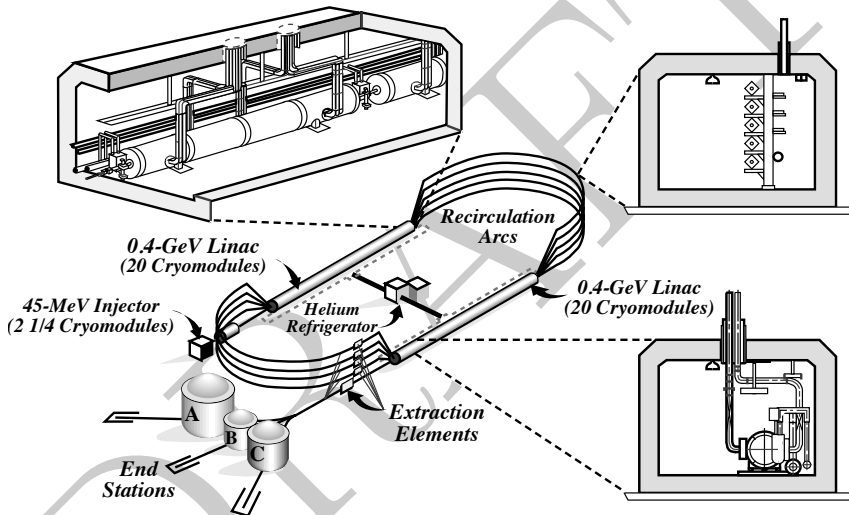
There are many different theoretical approaches to explain this behavior  
→ There is need for more experimental data!

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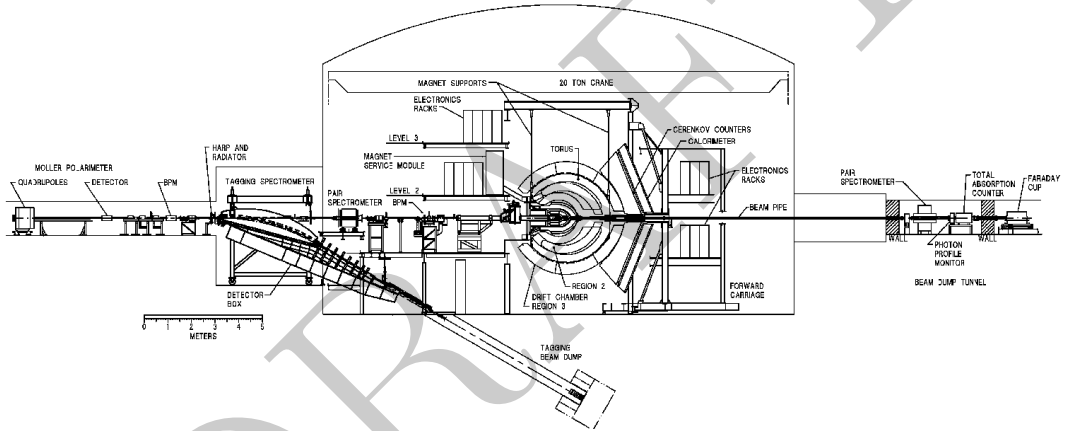
1. Experimental setup
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# Continuous Electron Beam Accelerator Facility (CEBAF)



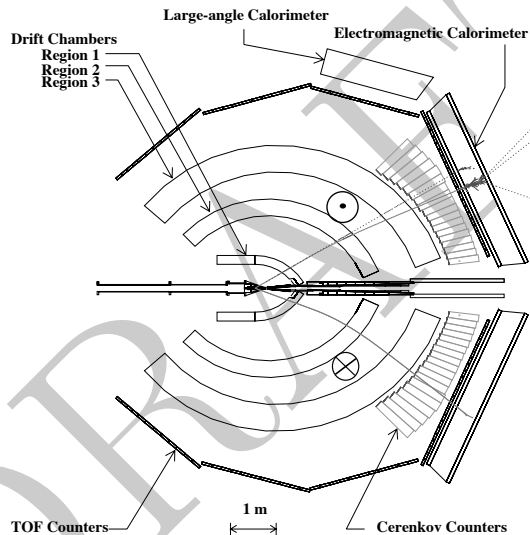
CEBAF layout at Jefferson Lab, [Mecking et al. 2003]

# Continuous Electron Beam Accelerator Facility (CEBAF)



**Figure 1:** Overview of the CLAS detector setup, including the tagger, [Mecking et al. 2003]

# CEBAF Large Acceptance Spectrometer (CLAS)



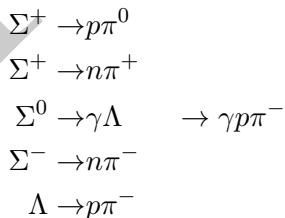
CLAS layout at Jefferson Lab, [Mecking et al. 2003]

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# Reaction kinematics

Reaction	Strong Final State	Undetected	Particles X
		$K^+ p \pi^-(X)$	$K^+ \pi^+ \pi^-(X)$
$\gamma + p \rightarrow K^{++} \begin{cases} \Lambda(1405) \\ \Lambda(1520) \end{cases}$	$\sim 33\% \rightarrow \Sigma^+ \pi^-$ $\sim 33\% \rightarrow \Sigma^0 \pi^0$ $\sim 33\% \rightarrow \Sigma^- \pi^+$	$\pi^0$ (52%) $\pi^0 \gamma$ (64%)	$n$ (48%) $n$ (100%)
	$6\% \rightarrow K^+ \Lambda \pi^0$ $6\% \rightarrow K^+ \Lambda \pi^0$		
	$87\% \rightarrow K^+ \Lambda \pi^0$	$\pi^0$ (64%)	
		$\pi^0 \gamma$ (64%)	
$\gamma + p \rightarrow K^{*+} + \Sigma^0$		$\pi^0$ (52%)	$n$ (48%)
$\gamma + p \rightarrow K^{*0} + \Sigma^+$			



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

## Event selection

two sets of reactions that the detector sees

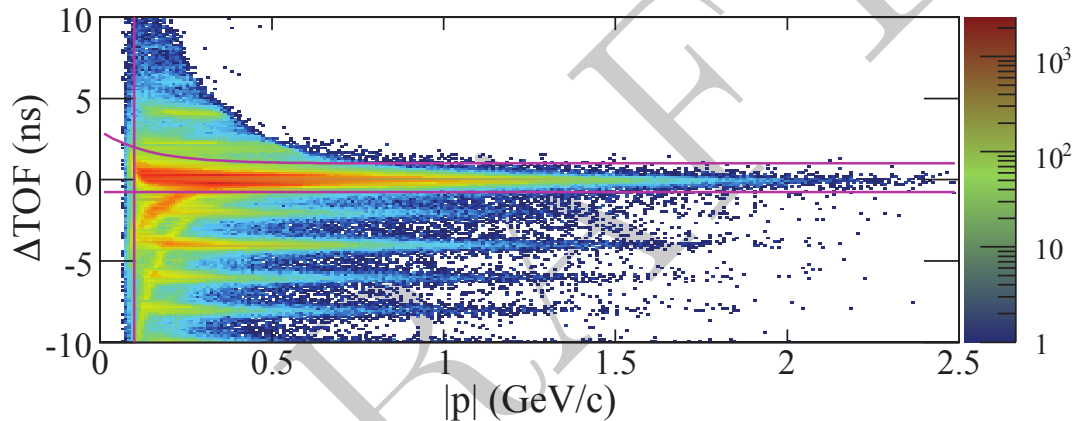
1.  $K^+ p \pi^-(X)$
2.  $K^+ \pi^+ \pi^-(X)$

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

### Initial selection of particles

- ▶ particle identification using TOF counters and momentum measurements
- ▶ kinematic cuts from MONTE CARLO

## Event selection



$\Delta\text{TOF}$  for  $\pi^+$  @  $2.35 < W < 2.45$  GeV, applied cuts are shown in magenta. [Moriya, Schumacher, Adhikari et al. 2013]

## Event selection

data was divided into 10 100 MeV in the CMS energy  $W = \sqrt{s} \in [2, 3]\text{GeV}$  and 20 angle bins of 0.1 in  $\cos \theta_K^{\text{CMS}}$ .

→ the following analysis was performed independently in every bin of energy and angle!

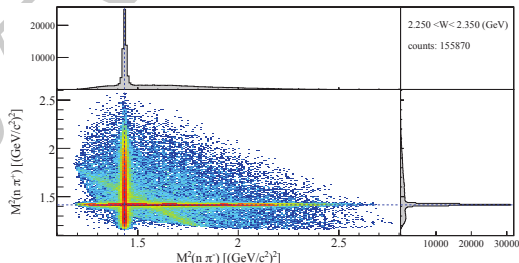
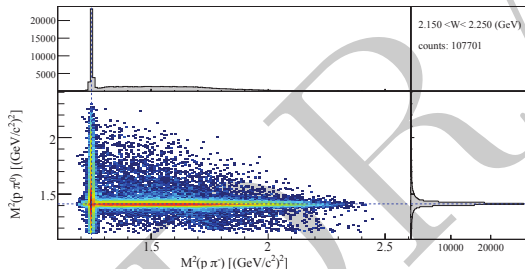
# Event selection

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

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

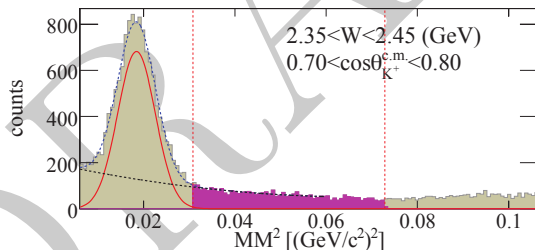


DALITZ-like plots of the above mentioned invariant masses, [Moriya, Schumacher, Adhikari et al. 2013]

## Event selection

extracting  $\Sigma^0\pi^0$

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



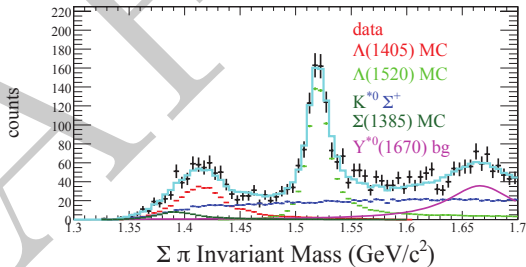
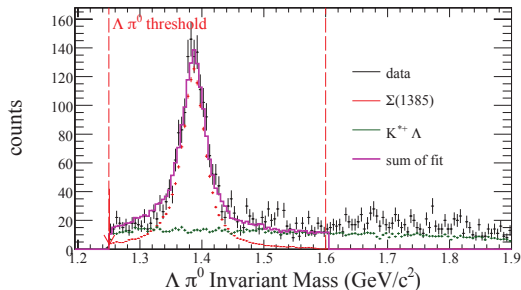
Missing mass of the reaction  $\gamma p \rightarrow K^+p\pi^-(X)$ , selection range in magenta. [Moriya, Schumacher, Adhikari et al. 2013]

# Measurements and analysis

- ▶ Now the signal regions have been established
- ▶ The true lineshape of the  $\Lambda(1405)$  has to be extracted from the vast of reactions  $\rightarrow$  any other contributions have to be subtracted
- ▶ Strategy: use of MONTE-CARLO fits to the data, simulating the contribution of other resonances using the PDG widths and masses

# Measurements and analysis

Some fit results:

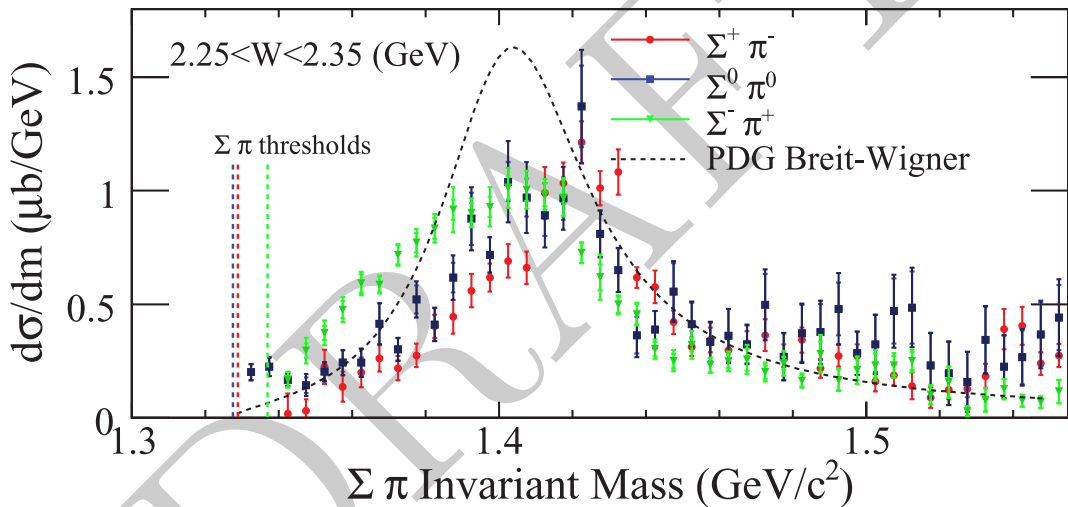


Sample fit results of invariant mass spectra for a single bin in energy and angle, [Moriya, Schumacher, Adhikari et al. 2013]



## Interpretation of the results

Having subtracted all unwanted reactions, one can obtain the true  $\Lambda(1405)$  lineshapes:

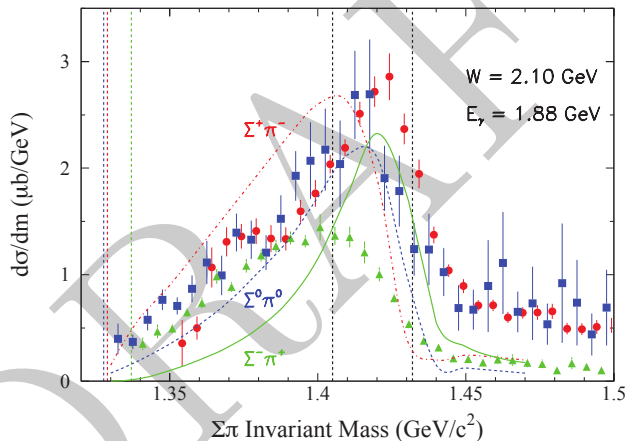


Lineshapes of the  $\Lambda(1405)$  for the 3 different decay channels and the PDG BREIT-WIGNER. The data were summed over all angles for better statistics. [Moriya, Schumacher, Adhikari et al. 2013]

## Interpretation of the results

There are in fact predictions of the lineshapes differing by decay channel [Nacher et al. 1999].

→ main idea: not one amplitude, but two due to isospin decomposition.



Lineshapes of the  $\Lambda(1405)$  for the 3 different decay channels and the prediction of [Nacher et al. 1999], [Moriya, Schumacher, Adhikari et al. 2013]

# Interpretation of the results

MORIYA ET AL. saw two main reasons for the lineshapes differing from a simple BREIT-WIGNER:

1. Isospin decomposition
2. channel coupling between the detected  $\Sigma\pi$  and  $N\bar{K}$  final states

## Isospin decomposition

let

$$|t_I|^2 = |\langle I, 0 | T^{(I)} | \gamma p \rangle|^2,$$

then we can write (neglecting  $I = 2$  using CGK)

$$|T_{\pi^-\Sigma^+}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 - \frac{2}{\sqrt{6}}t_0t_1 \cos \phi_{01}$$

$$|T_{\pi^0\Sigma^0}|^2 = \frac{1}{3}|t_0|^2$$

$$|T_{\pi^+\Sigma^-}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 + \frac{2}{\sqrt{6}}t_0t_1 \cos \phi_{01}$$

## Channel coupling

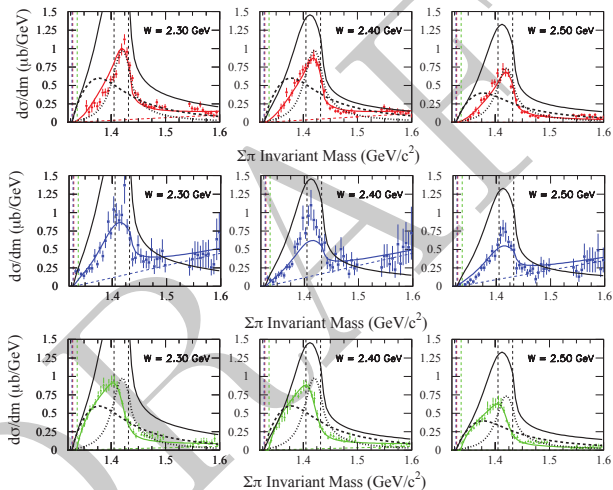
the  $t_I$  are described by one or two BREIT-WIGNER amplitudes with mass dependent widths  $\Gamma$

→ modify the amplitude preserving analyticity [Flatté 1976] including the  $N\bar{K}$  decay channel available at threshold

$$m_K + m_p \approx 1434 \text{ MeV}$$

# Interpretation of results

Fits with two  $I = 1$  and one  $I = 0$  amplitudes lead to best agreement with measured data



Data and fits for  $\Sigma^a\pi^b$ ,  $\{a,b\} \in \{+-, 00, -+\}$  for different bins in  $W$ .  $I = 0$  (solid black), narrow  $I = 1$  (dotted black) and wide  $I = 1$  (dashed black). Background in dashed red. [Moriya, Schumacher, Adhikari et al. 2013]

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## Theoretical basics I

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  $Y^* \rightarrow Y\pi$ , with  $J^P$  the spin and parity of  $Y^*$
- ▶ the  $Y\pi$  angular distribution will only depend on  $J$

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

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

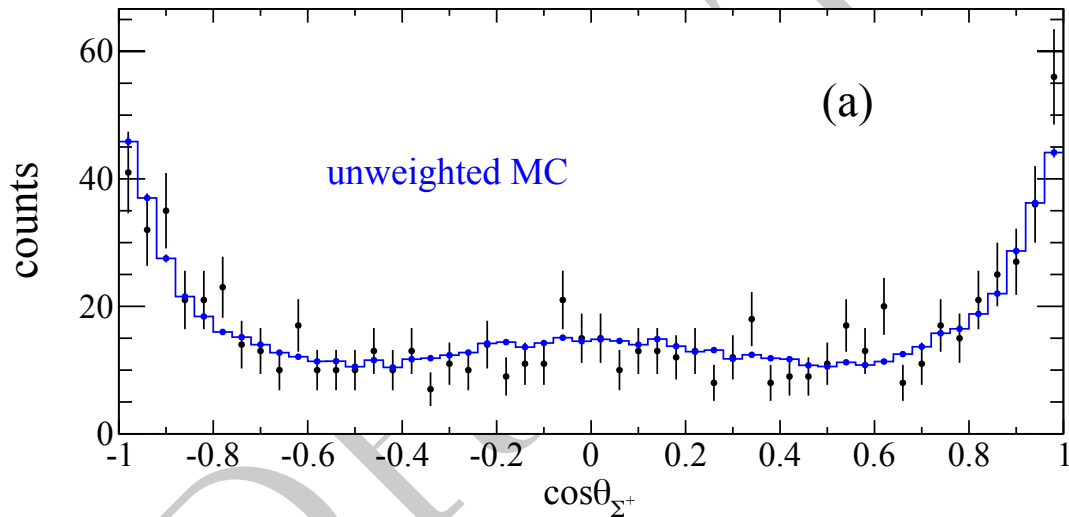
where  $\theta_Y$  is the polar angle of the decay direction of  $Y$  in the  $Y^*$  rest frame,  $p$  describes the fraction of spin projections along the  $z$  axis

- ▶ uniform decay pattern is best evidence for spin  $J = 1/2$

[Moriya, Schumacher, Aghasyan et al. 2014]

## Analysis procedure

- ▶ plot the angular distribution of the projections  $\cos \theta_{\Sigma}$  for each bin
- ▶ test each spin hypothesis using MONTE-CARLO maximum likelihood fits, which employ angular decay probability distributions according to each hypothesis for  $\Sigma\pi$
- ▶ compare each hypothesis by calculating a  $\chi^2$  probability



**Figure 2:** Distribution of decay angle of the  $\sigma^+$  with MONTE-CARLO fit using flat templates [Moriya, Schumacher, Aghasyan et al. 2014]



## Theoretical basics II

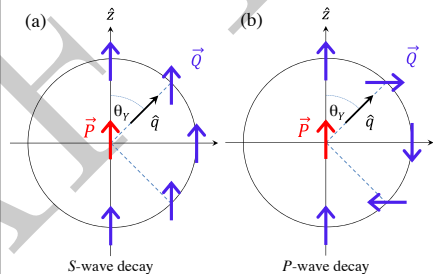
### Measuring parity

- ▶ 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  $\mathbf{P}$

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

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

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



Polarization transfer in the strong decay  $Y^* \rightarrow Y\pi$ , [Moriya, Schumacher, Aghasyan et al. 2014]

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

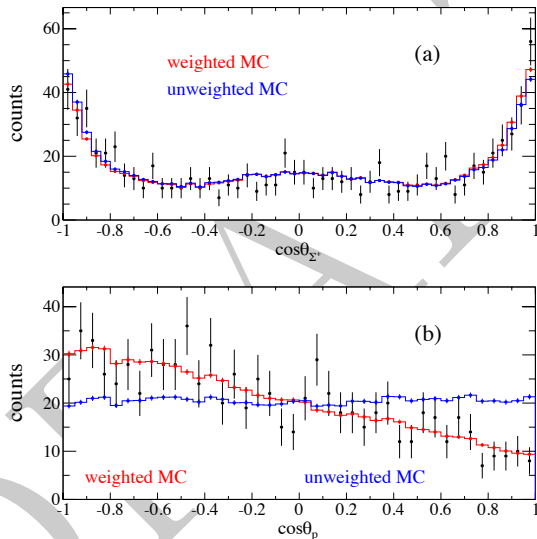
## Measurements and analysis II

### Analysis procedure

- ▶ plot the angular distribution of the projections  $\cos \theta_p$  for each bin
- ▶ determine the polarization using MONTE-CARLO fits
- ▶ determine  $Q_z(\cos \theta_{\Sigma^+})$  to get the parity (const. for  $P = -$  quadratic for  $P = +$ )

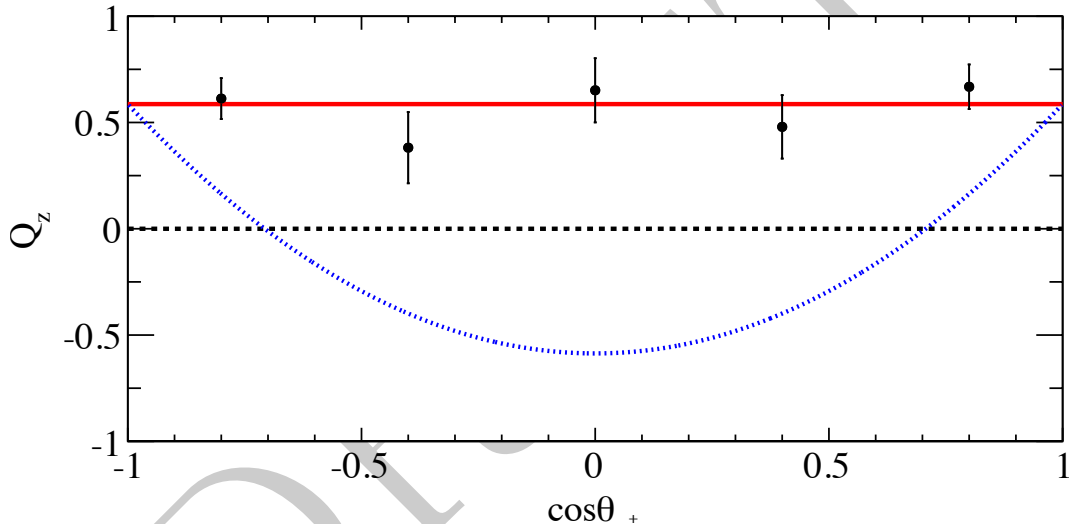
Result: data is consistent with  $J^P = 1/2^-$  but does in principle not rule out  $J^P = 3/2^+$ .  $1/2^+$  and  $3/2^-$  hypotheses can be discarded.

## Measurements and analysis II



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

## Measurements and analysis II



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

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# Conclusion

## Lineshape measurement

- ▶ the CLAS detector was used to study  $\gamma p \rightarrow K^+ \Lambda(1405)$
- ▶ after selecting the correct events the true lineshape was extracted using MONTE-CARLO sim. of the yield of other resonances
- ▶ the lineshapes in different decay channels differ from each other and from a simple BREIT-WIGNER
- ▶ a phenomenological isospin decomposition model was able to describe the data

## Spin parity measurement

- ▶ the angular distribution of the decay  $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$  was studied
- ▶ the angular distributions were tested against various  $J^P$  hypotheses
- ▶ the data is consistent with  $J^P = 1/2^-$  but does not exclude  $J^P = 3/2^+$

## Back-up: Continuous Electron Beam Accelerator Facility (CEBAF)

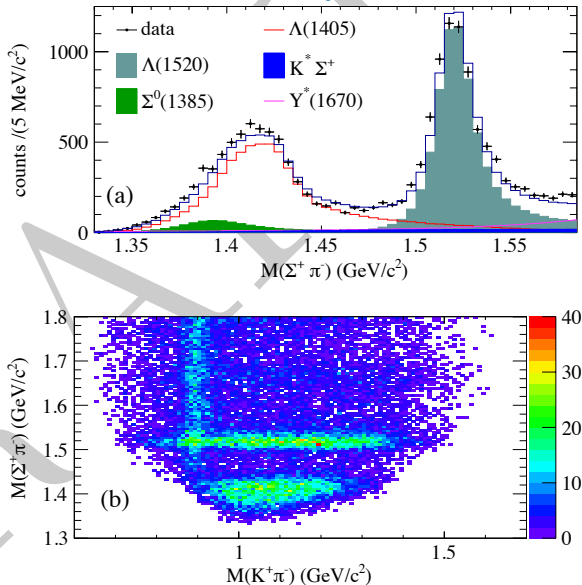
How can we access  $\Lambda(1405)$  with this setup?

- ▶ employ radiator target for the electrons
- ▶ generate high energy photons using the *bremsstrahlung* process
- ▶ shoot high energy photons on proton target (LH2)
- ▶ then we can observe  $\gamma p \rightarrow K^+ \Lambda(1405)$  while knowing  $p_\gamma, p_p$

# Back-up: Spin-Parity – Measurements and analysis

## Event selection





- ▶ select kinematic region where the  $\Sigma\pi$  invariant mass is dominated by the  $\Lambda(1405) \rightarrow M_{\Sigma\pi} \in 1.30 \text{ GeV to } 1.45 \text{ GeV}$
- ▶ 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



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



## References

-  Flatté, S.M. (1976). ‘Coupled-channel analysis of the  $\pi\eta$  and  $K\bar{K}$  systems near  $K\bar{K}$  threshold’. In: *Physics Letters B* 63.2, pp. 224–227. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/0370-2693\(76\)90654-7](https://doi.org/10.1016/0370-2693(76)90654-7). URL: <https://www.sciencedirect.com/science/article/pii/0370269376906547>.
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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](https://doi.org/10.1103/PhysRevLett.112.082004). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.112.082004>.