Structure of the $\Lambda(1405)$ from Photoproduction at GlueX

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Jefferson Lab

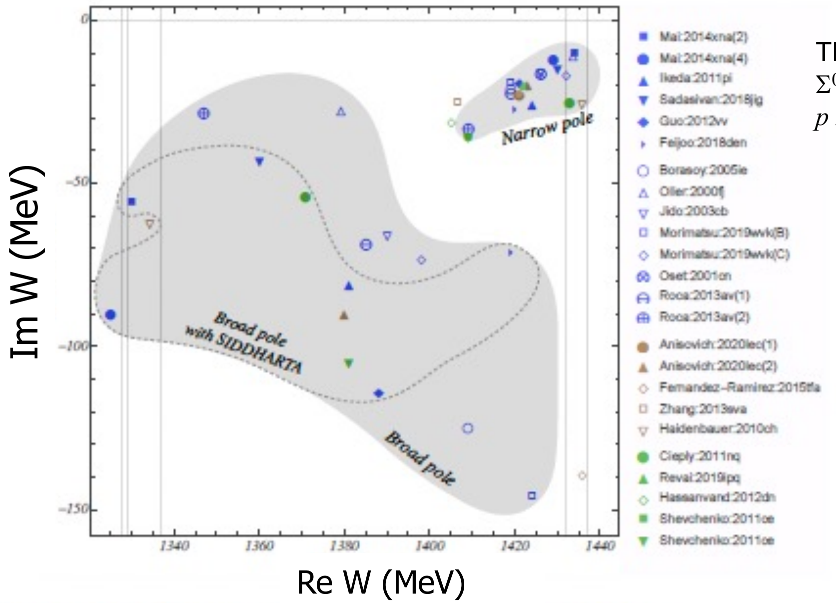
Overview

- Place of the $\Lambda(1405)$ in the world
- GlueX measurement for two final states
- K-matrix fits with one or two $\Lambda(1405)$ resonances & two scattering states
- 2-Pole nature and branching fractions of both resonances

Motivation

- What is the place of the $\Lambda(1405)$ in baryonic physics?
  - It's too light, compared to $\Lambda(1520)$, in the quark model.
  - Close to the $N\bar{K}$ mass threshold – molecular/penta aspect.
  - Decays to $\Sigma\pi$, but MUST also decay to $N\bar{K}$.
- Chiral unitary models, CPT, LQCD (& others) predict <u>two</u> I=0 states in $\Lambda(1405)$ mass range.
- GlueX has the best data set, generating it cleanly in photoproduction: $\gamma\, p \rightarrow K^+\, \Lambda(1405) \rightarrow K^+ \{\Sigma^0\ \pi^0\}$
  $\rightarrow K^+ \{p\ \ K^-\}$ (> $N\bar{K}$ threshold)

Pole Positions from the Literature



Thresholds:
$\Sigma^0\pi^0$ 1327.62 MeV
$p\,K^-$ 1431.95 MeV

all recent (year $\geq$ 2000) predictions

M. Mai - Eur. Phys. J. Spec. Top. 230 (2021) 6, 1593

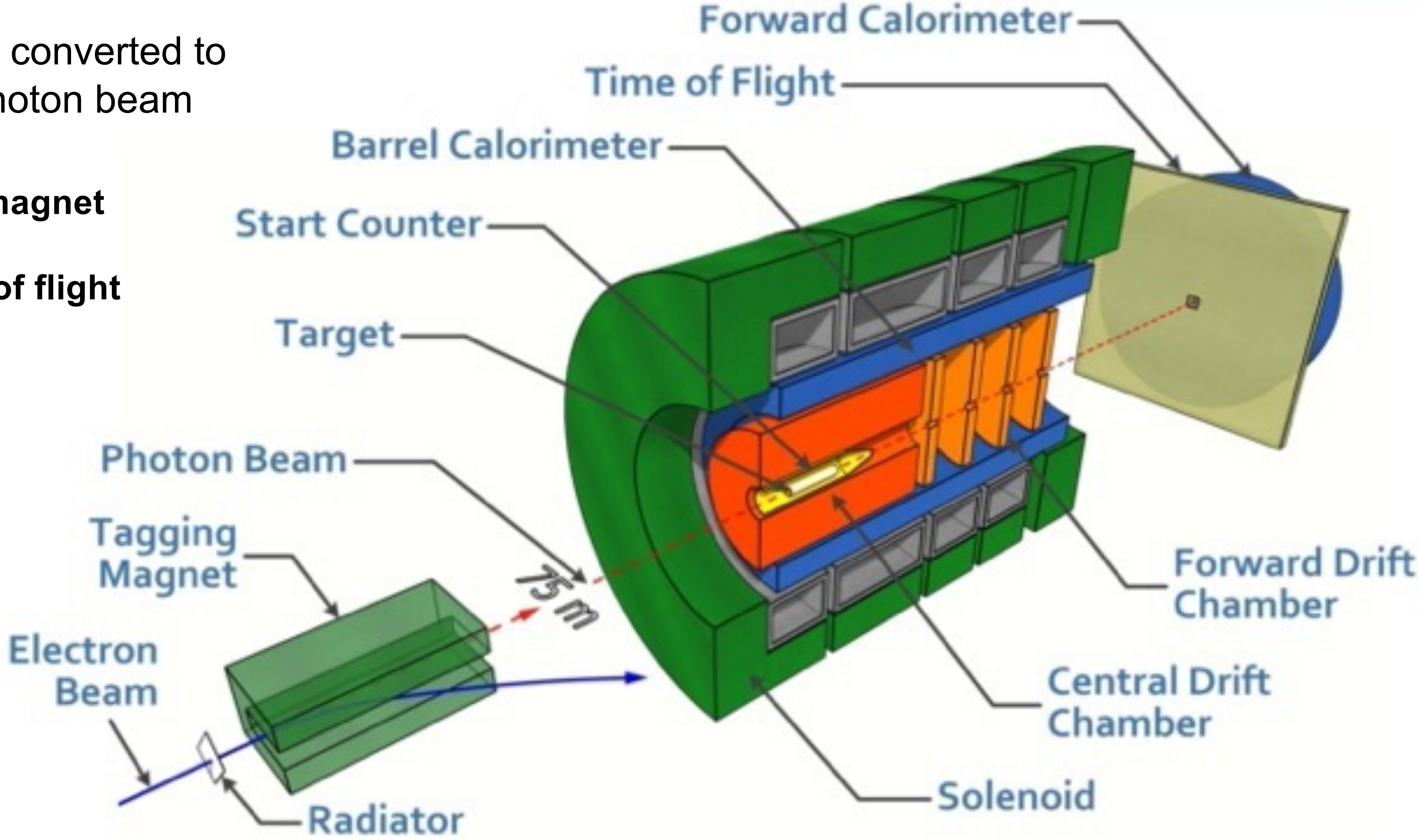
- Higher pole ~1430 MeV couples more strongly to $N\bar{K}$, lower pole ~1390 MeV couples more to $\Sigma\pi$
- Many theorists believe: $N\bar{K}$ quasi-bound state submerged in $\Sigma\pi$ continuum: coupled-channel dynamics
- Most data from low-energy *NK* scattering, kaonic atoms – not very sensitive to $\Sigma\pi$ pole position

GlueX approach is new and different

GlueX System at JLab

The GlueX Beamline and Detector
NIM A 987, 164807 (2021)

- **~ 12 GeV e⁻ beam** converted to 6.5 – 11.6 GeV photon beam
- **30 cm LH2 target**
- **~ 1.5 T Solenoidal magnet**
- **Drift chambers**
- **Start counter/Time of flight**
- **Electromagnetic Calorimeters**
- **This analysis:** Data from “Phase I” runs 2017, 2018



GlueX Competitive Advantages:

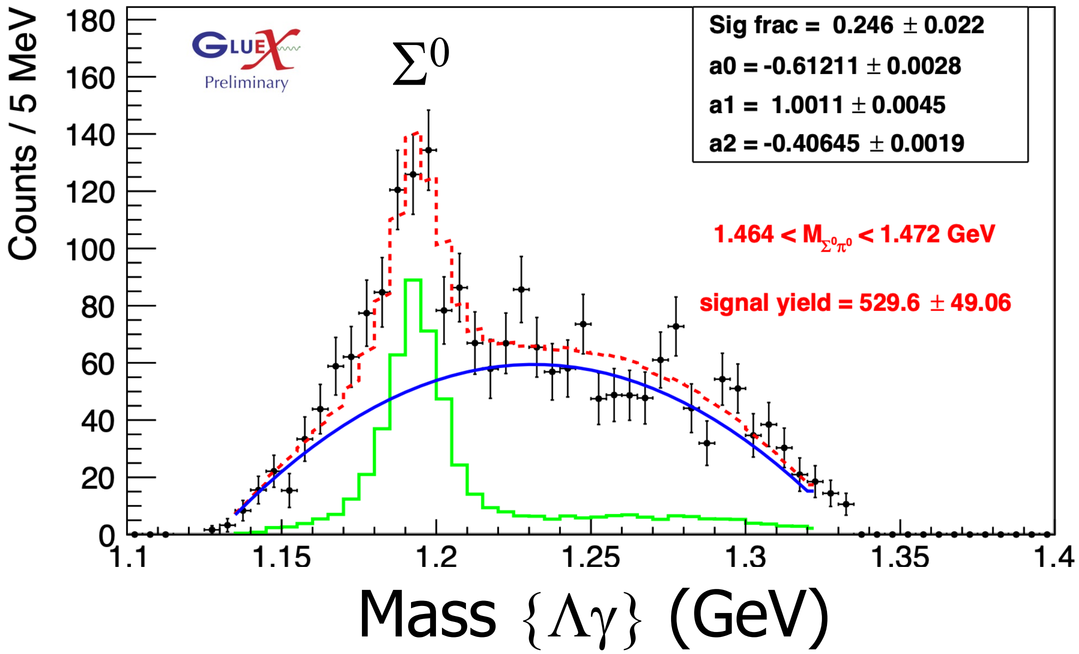
- GlueX has world's best data set making $\Lambda(1405)$ cleanly in photoproduction: $\gamma\, p \rightarrow K^+\, \Lambda(1405)$

  $\rightarrow K^+\, \{\Sigma^0\ \ \pi^0\}$ (pure I = 0, no I = 1 contamination)

  $\rightarrow K^+\ \ \{\{\gamma\, \Lambda\}\, \pi^0\} \rightarrow K^+\, \gamma\ \ p\, \pi^-\ \ \gamma\, \gamma$
- GlueX also has: $\gamma\, p \rightarrow K^+\, \Lambda(1405)$

  $\rightarrow K^+\ \ \{p\ \ K^-\}$ (when above $N\bar{K}$ threshold)
- Do K-matrix fit to both final states together
  - Never done before…

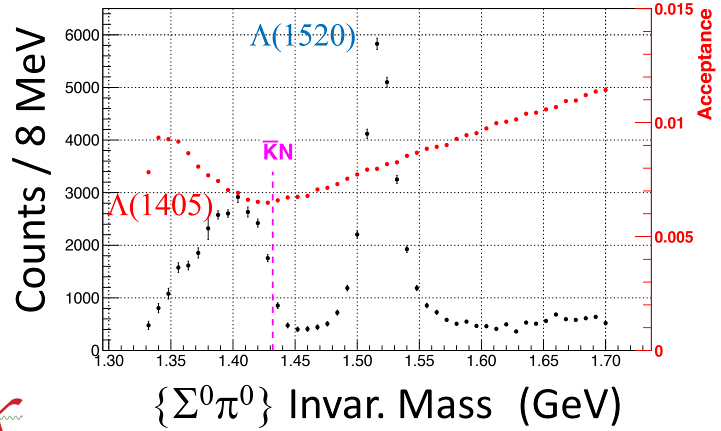
Experimental Method I



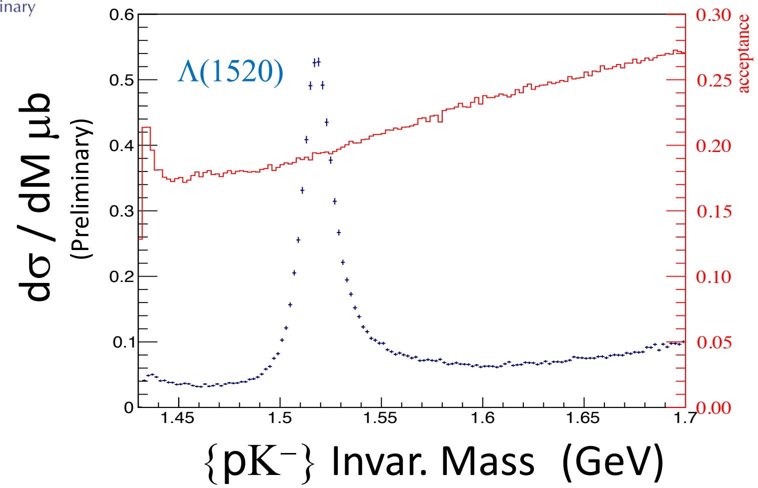
$\Sigma^0\pi^0$ channel

- Exclusive kinematic fit to beam photon & final state $\{K^+ \gamma\ \ p\ \pi^-\ \ \gamma\ \gamma\}$ particles
- Constrain Λ and π^0 masses, but not Σ^0 mass, in each $\Sigma^0\pi^0$ mass bin
- Background removal fit under Σ^0 in each $\Sigma^0\pi^0$ mass bin
- Use common GlueX acceptance & photon flux normalizations

Experimental Method II

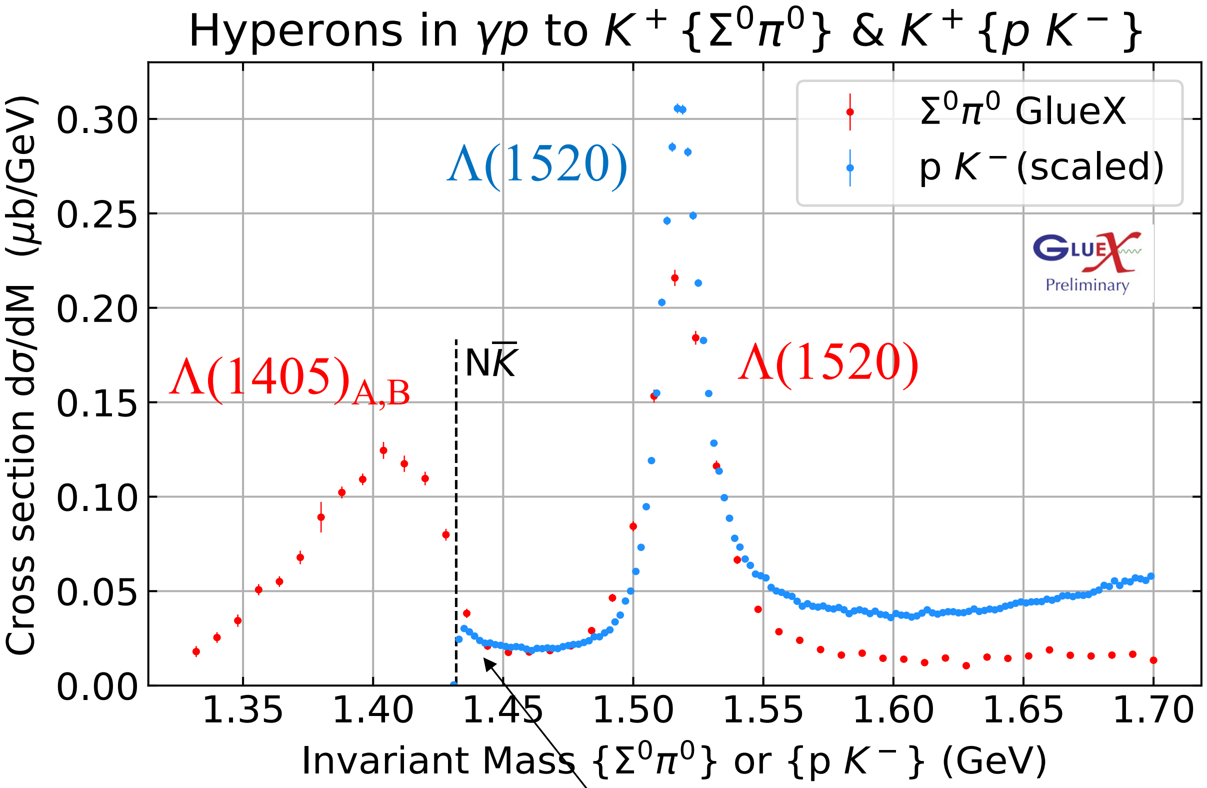


GlueX Preliminary



- $\Sigma^0\pi^0$ channel
  - Clean detection of Λ(1405) & Λ(1520)
  - Evident pK$^-$ threshold effect
  - Smooth acceptance
- pK$^-$ channel
  - Λ(1520) sits on top of Λ(1405) tails
  - Good, smooth acceptance

Cross Sections Differential in Mass



Ansatz: $\Lambda(1405)$ tails cause pK^- turn-on at threshold

- $\Sigma^0\ \pi^0$
  - $N\bar{K}$ threshold break visible
  - Average mass resolution ~7.8 MeV
- p K$^-$
  - Scaled by PDG branching and isospin factors of $\Lambda(1520)$ to "match" $\Sigma^0\ \pi^0$ scale
  - N.B.: instant turn-on at $N\bar{K}$ threshold
  - Average mass resolution ~2.0 MeV
- *0.00 < t < 1.50* GeV^2

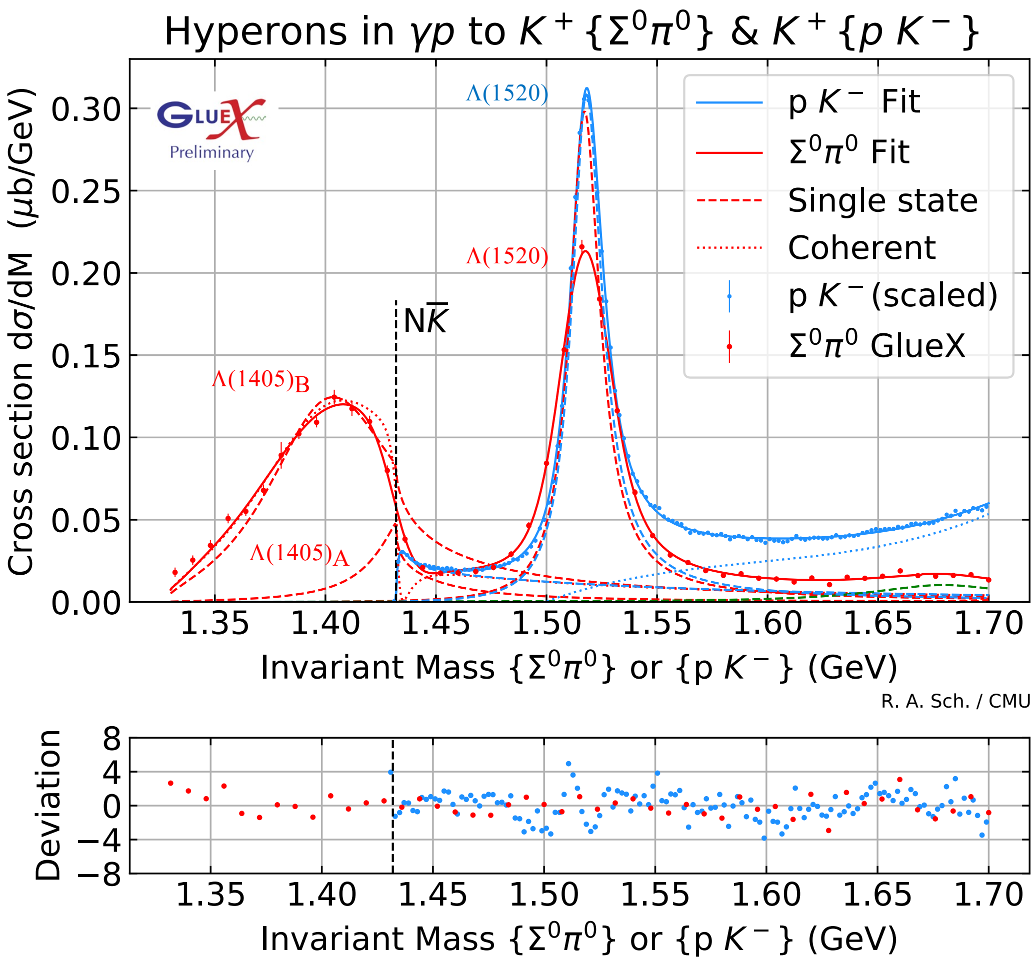
Thresholds:
$\Sigma^0\pi^0$ 1327.62 MeV
$p\ K^-$ 1431.95 MeV

Application of K-Matrix Method*

- We have two resonances, $\Lambda(1405)_A$ and $\Lambda(1405)_B$, each coupled to $\Sigma^0\,\pi^0$ and p K^-. The $\Lambda(1520)$ also decays to the same final states.
- Assume J= ½ L=0 states do not interfere with J=3/2 L=2 state
- Ignore the possibility of $\eta\Lambda$ and $K\Xi$ decays
- Poles "A" & "B" are below threshold for pK^- channel
- Define "branching ratio" & "branching fractions" in terms of fitted $\Sigma\pi$ and $N\bar{K}$ final states

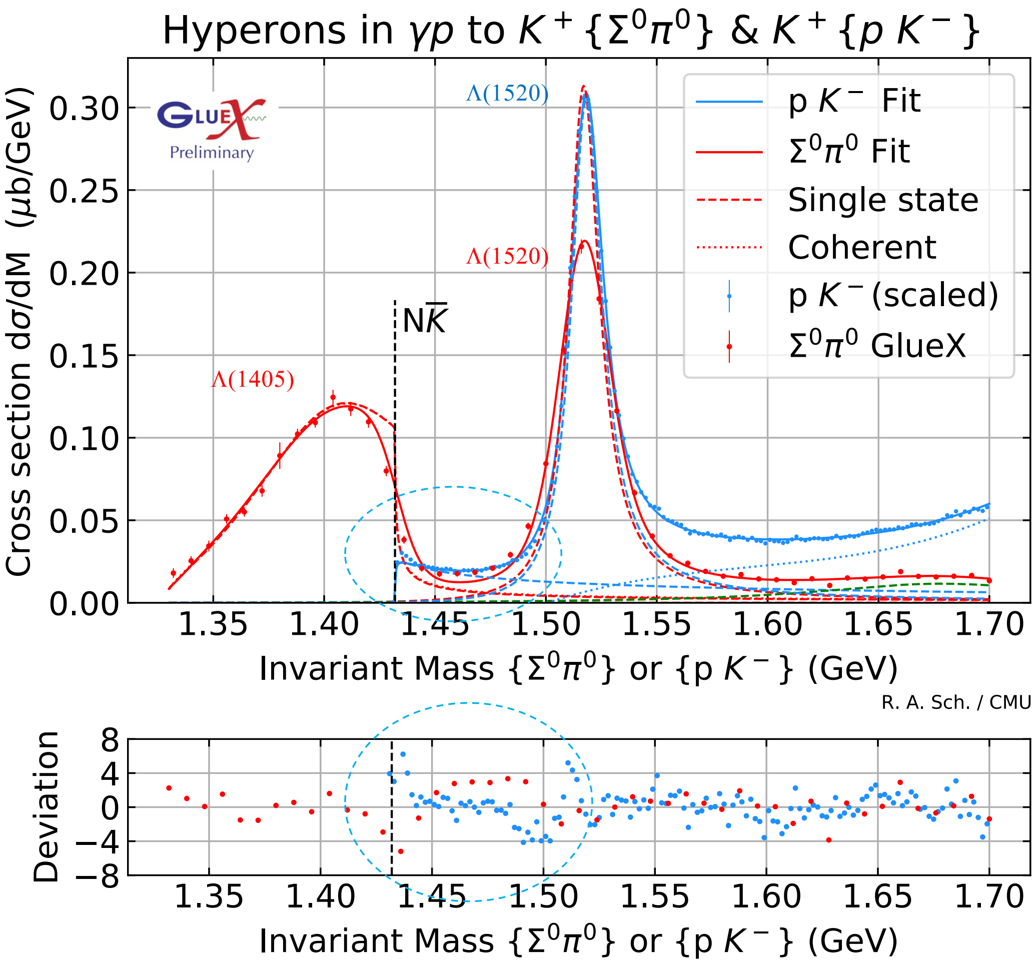
* à la S.U. Chung *et al.*, Ann. Physik 4, 404 (1995).

2-Pole K-matrix Fit to Λ(1405)A,B



- $\Sigma^0\pi^0$ channel
  - Solid – fit to data
  - Dashed – each A,B resonance separately
  - Dotted – fit to data:
    - full K-matrix fit with coherent Λ(1405)A,B states
    - prior to convolving 7.8 MeV GlueX mass resolution
- pK^- channel
  - Solid – fit to data:
    - 2.0 MeV GlueX mass resolution
  - Dashed – coherent tail of Λ(1405)A,B states
  - Dotted – incoherent high-mass background
    - 3rd order polynomial
- *0.00* < *t* < *1.50* GeV^2 (full range)
- Λ(1520) cross section agreement < 5%

1-Pole K-matrix Fit to Λ(1405)B



- $\Sigma^0\pi^0$ channel
  - Solid – fit to data
  - Dashed – single Λ(1405) resonance
- pK^- channel
  - Solid – fit to data
  - Dashed – pK^- tail of Λ(1405) state
  - Dotted – incoherent high-mass background
    - 3rd order polynomial
- *0.00< t < 1.50* GeV^2 (full range)
- **Poorer fit** than 2-pole ansatz: especially in critical threshold region

Λ(1520) Pole Position Compared to PDG

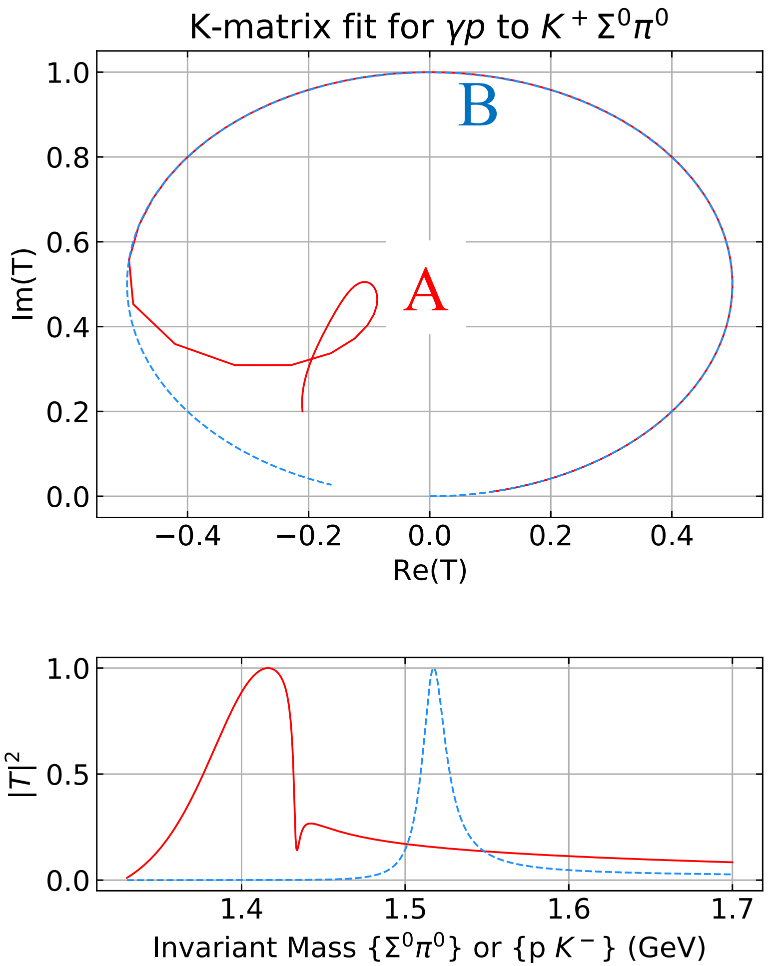
Λ(1520) POLE POSITION	
REAL PART	1517 to 1518 (≈ 1517.5) MeV
−2×IMAGINARY PART	14 to 18 (≈ 16) MeV (→ ~ 2 x 8 MeV)

GlueX (preliminary):

$(1516.5 \pm 0.3) - i\,(8.3 \pm 0.1)$ MeV
(stat errors only)

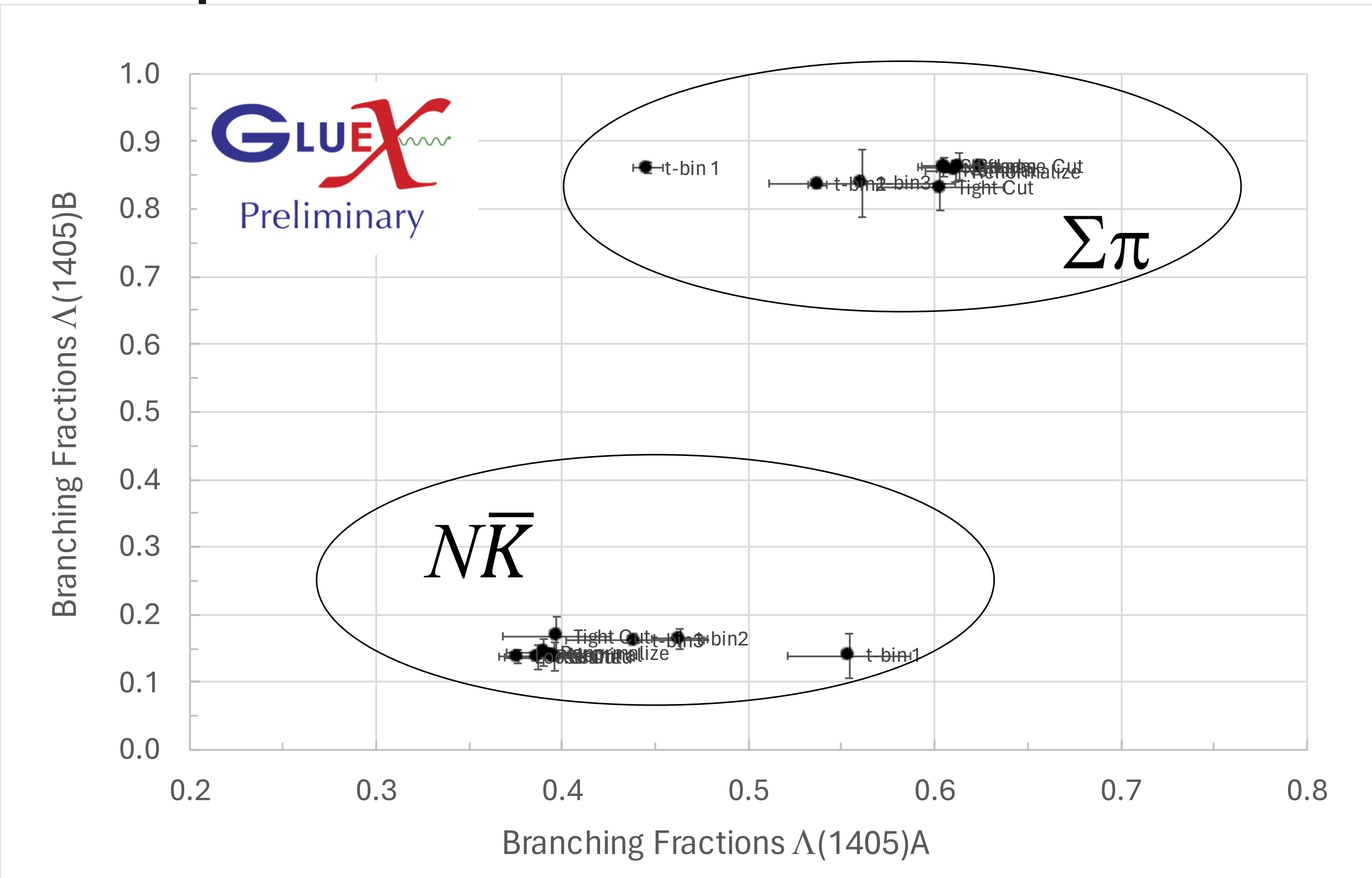
Good agreement with PDG:
suggests the GlueX method is sound

Check Unitarity of the Amplitudes



- Argand diagram and squared-magnitude for the $\Sigma^0\pi^0$ amplitude (red)
  - Two $\Lambda(1405)$ resonances with $\Sigma^0\pi^0$ and pK^- initial/final states.
  - Each amplitude stays properly bounded.
- Separately, $\Lambda(1520)$ is a single pK- amplitude (blue)

Systematic Tests (work in progress)



- Branching Fractions
  - Nominal
  - Shifted bins
  - Tight KINFIT
  - Loose KINFIT
  - t-bin 1
  - t-bin 2
  - t-bin 3
  - Resum t-bins
  - Rescale $\Lambda(1520)$ cross section

Branching Ratios/Fractions

Preliminary

- Project each resonance separately onto the real axis
- Integrate $\Sigma^0\pi^0$ & pK^- modes across full mass range: σ_{ij}
- Define branching ratio as $\sigma_{\Sigma 0\pi 0}$ / σ_{pK-} , etc.

Hyperon	$BR(\frac{NK}{\Sigma\pi})$ (value)	(stat)	(syst)	$BF(\frac{\Sigma\pi}{Total})$ (value)	(stat)	(syst)	$BF(\frac{NK}{Total})$ (value)	(stat)	(syst)
$\Lambda(1405)$ [A]	0.65	0.02	T.B.D.	0.606	0.009	T.B.D.	0.394	0.009	T.B.D.
$\Lambda(1405)$ [B]	0.16	0.01		0.859	0.005		0.141	0.005	

Summary/Conclusions

- First measurement of the $\Lambda(1405)$ decaying into two separate channels: $\Sigma^0\pi^0$ & pK^-
- K-matrix fit to two intermediate resonances: A & B
- Two-pole ansatz is superior to single-pole ansatz
- Branching ratio/fractions defined and presented
- To do: systematics to be finalized

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