Structure of the Λ(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
- Pole positions and branchings of the two resonances

Recall the 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 two $I=0$ states in $\Lambda(1405)$ mass range.
- GlueX has the best data set making it cleanly in photoproduction: $\gamma\, p \rightarrow K^+\, \Lambda(1405) \rightarrow K^+ \{\Sigma^0\, \pi^0\}$

  $\rightarrow K^+ \{p\;\; K^-\}$ (> $N\bar{K}$ threshold)

Chiral Unitary Models

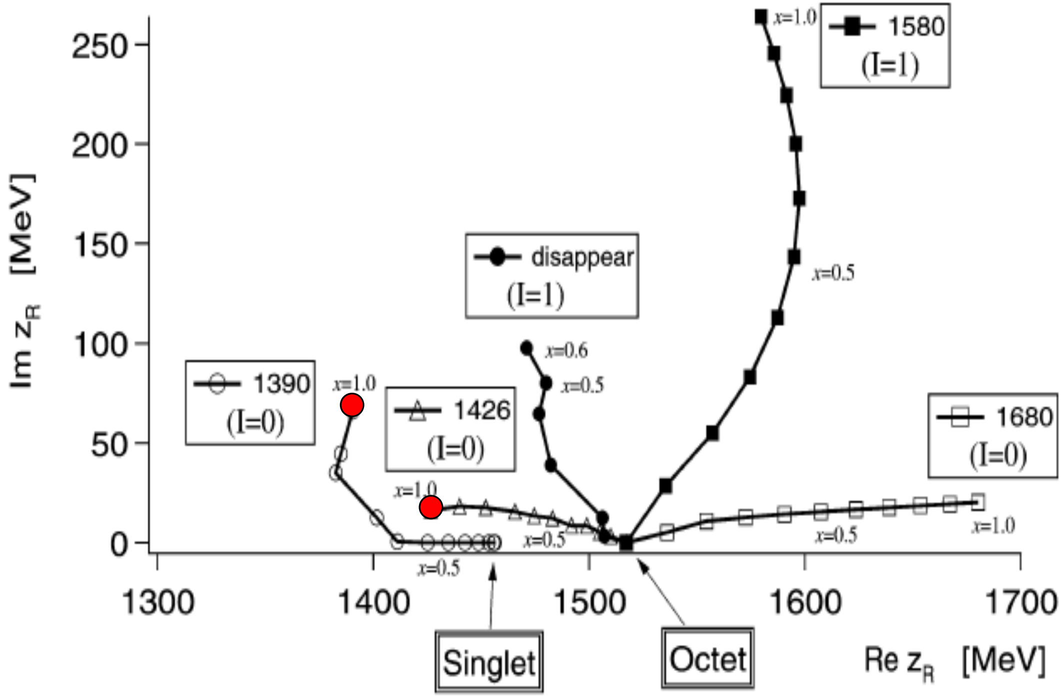
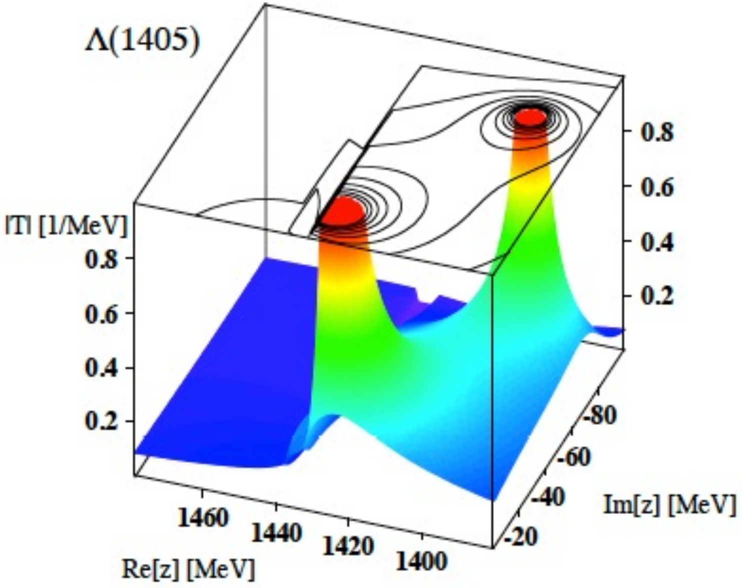


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

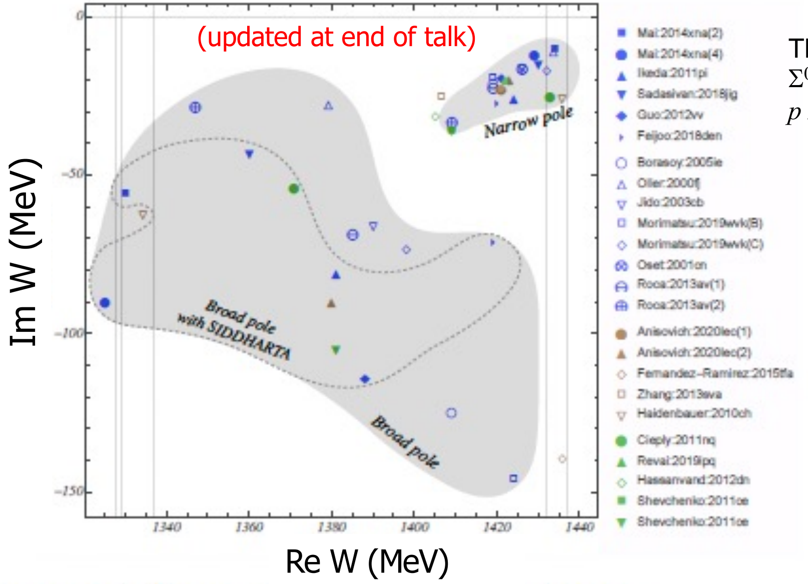
- SU(3) baryons irreps $1+8_s+8_a$ combine with 0^- Goldstone bosons to generate:
  - Two octets and a singlet of ½⁻ baryons dynamically generated in the SU(3) limit
  - SU(3) breaking leads to two $S = -1,\ \ I = 0$ poles near 1405 MeV
    - ~1420 mostly $N\bar{K}$
    - ~1390 mostly $\Sigma\ \pi$
  - Possible weak I=1 pole also predicted

D. Jido, J.A Oller, E. Oset, A. Ramos, U-G Meissner Nucl. Phys. A 725 181 (2003)

Pole positions from the literature



Hyodo, Jido - Prog. Part. Nucl. Phys. 67 (2012) 55



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

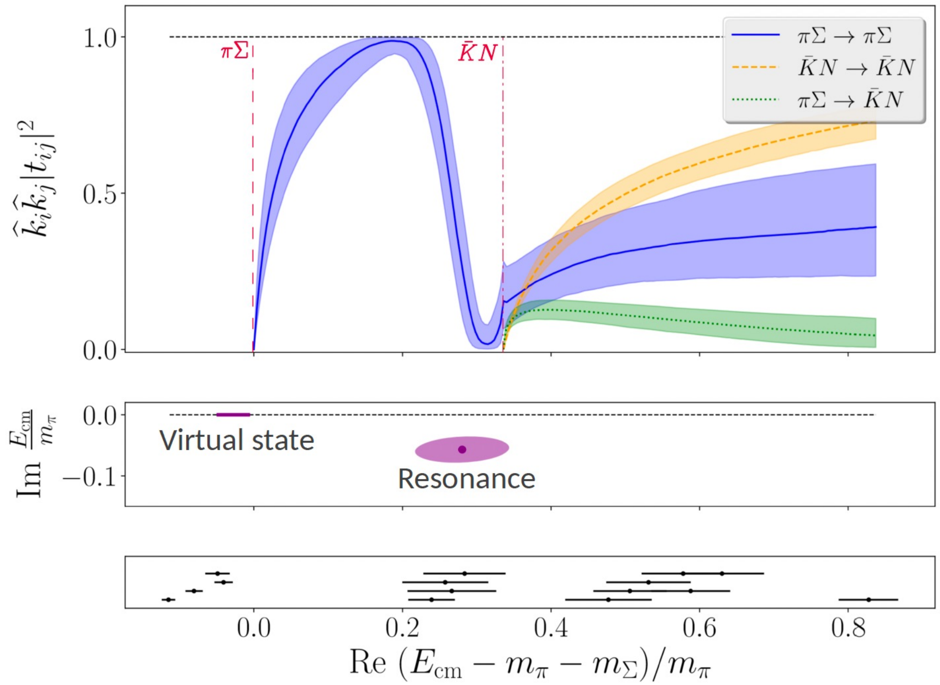
- Higher pole ~1430 MeV couples more strongly to $N\bar{K}$, lower pole ~1390 MeV couples more to $\Sigma\pi$
- Many theorists believe: $N\bar{K}$ quasi-bound state submerged in $\Sigma\pi$ continuum: coupled-channel dynamics
- Most data from low-energy NK scattering, kaonic atoms – not very sensitive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

GlueX approach is new and different

Pole positions from the literature

B. Cid-Mora, HIM Mainz, MENU 2023
Lattice QCD Theory

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



Virtual bound state

$$E_1 = 1392(9)_{\mathrm{stat}}(2)_{\mathrm{model}}(16)_{\mathrm{a}}\mathrm{MeV}$$

$$\left|\frac{c^{(1)}_{\pi\Sigma}}{c^{(1)}_{\bar{K}N}}\right| = 1.9(4)_{\mathrm{stat}}(6)_{\mathrm{model}}$$

Resonance

$$E_2 = \left[1455(13)_{\mathrm{stat}}(2)_{\mathrm{model}}(17)_{\mathrm{a}} - i11.5(4.4)_{\mathrm{stat}}(4.0)_{\mathrm{model}}(0.1)_{\mathrm{a}}\right]\mathrm{MeV}$$

$$\left|\frac{c^{(2)}_{\pi\Sigma}}{c^{(2}_{\bar{K}N}}\right| = 0.53(9)_{\mathrm{stat}}(10)_{\mathrm{model}}$$

J. Bulava et al., Phys Rev Lett 132, 051901 (2024)
J. Bulava et al., Phys Rev D 109, 014511 (2024)

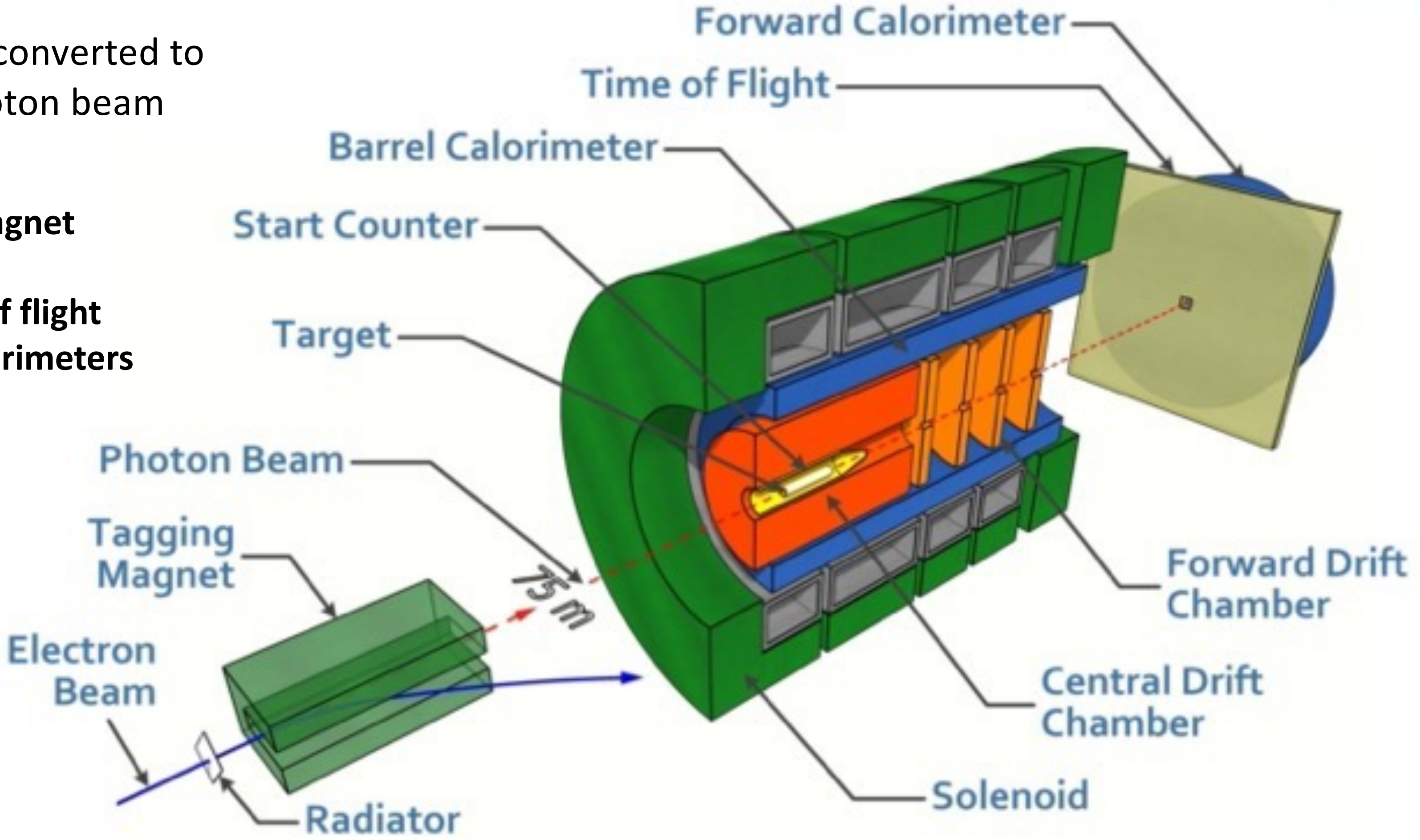
GlueX System at JLab

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:

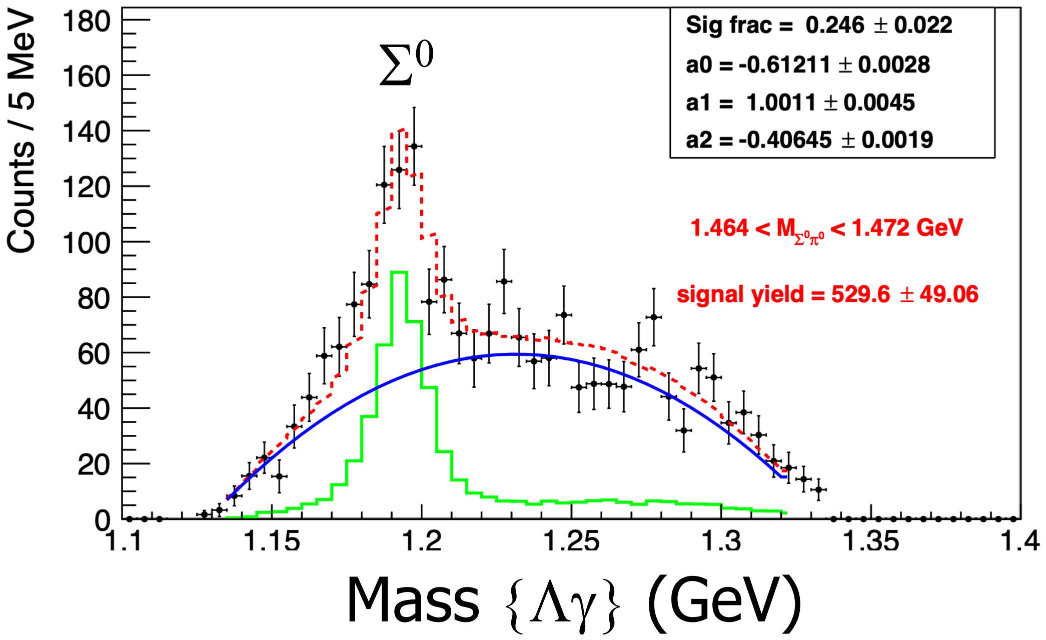
- GlueX has world's best data set making $\Lambda(1405)$ cleanly in photoproduction: $\gamma\, p \rightarrow K^+\, \Lambda(1405)$

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

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

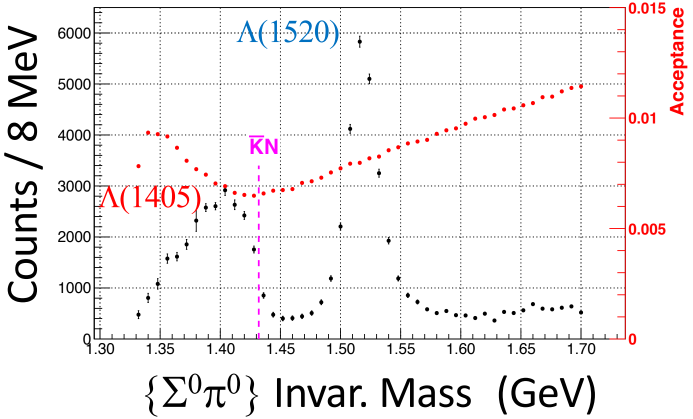
  $\rightarrow K^+\ \{p\ \ K^-\}$ (when above $N\bar{K}$ threshold)
- Do K-matrix fit to both final states together
  - Never done before…

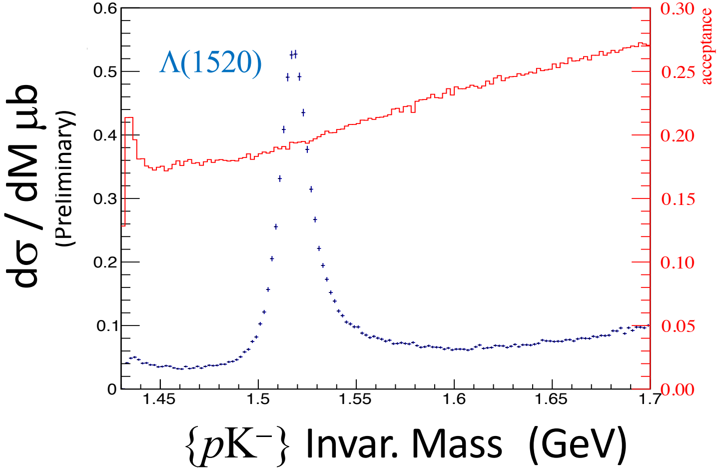
Experimental Method I



- $\Sigma^0\pi^0$ 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

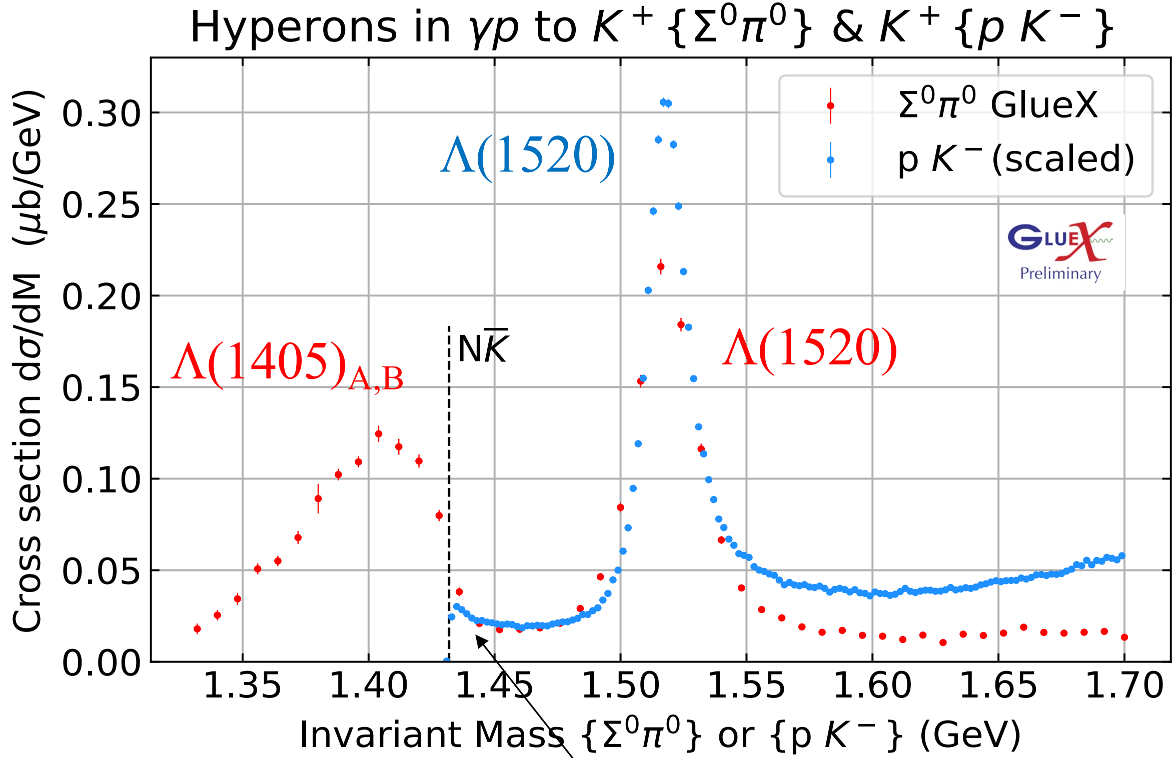
Experimental Method II





- $\Sigma^0\pi^0$ 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

K-matrix formalism* (outline sketch)

- 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 $J=\frac{1}{2}\ \ L=0$ states do no interfere with $J=3/2\ \ L=2$ state

$$\widehat{T} = \left(I - i\widehat{K}\rho\right)^{-1}\widehat{K}$$

Lorentz-invariant T-matrix (2 in x 2 out)

$$K = \sum_{\alpha} \frac{m_\alpha \Gamma_\alpha(m)}{m_\alpha^2 - m^2}$$

Sum over resonances A & B ;
real function, preserves unitarity of T

$$\widehat{K_{ij}} = \sum_{\alpha} \frac{\gamma_{\alpha i}\gamma_{\alpha j} m_\alpha \Gamma_\alpha^0}{m_\alpha^2 - m^2} B_{\alpha i}^l B_{\alpha j}^l$$

Invariant K-matrix for available decay modes i, j = $\{\Sigma^0\pi^0, p\,K^-\}$

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

K-matrix formalism* (outline sketch)

$$\widehat{P}_i = \sum_\alpha \frac{\beta_\alpha \gamma_{\alpha i} m_\alpha \Gamma^0_\alpha}{m_\alpha^2 - m^2}$$

Photoproduction vector for decay modes i ; same sum over poles as K matrix

$$\widehat{F}_i = \left(I - i\widehat{K}\rho \right)^{-1} \widehat{P}_i$$

Production exp't replacement of T matrix "formation exp't" for decay mode i

$$\frac{d\sigma_i(m)}{dm} \sim \rho_i \left| \widehat{F}_i(m) \right|^2$$

Fit to experimental data for decay mode i

$$T_{11}(m) = \rho_{\Sigma^0\pi^0}(m)\widehat{T}_{11}(m)$$

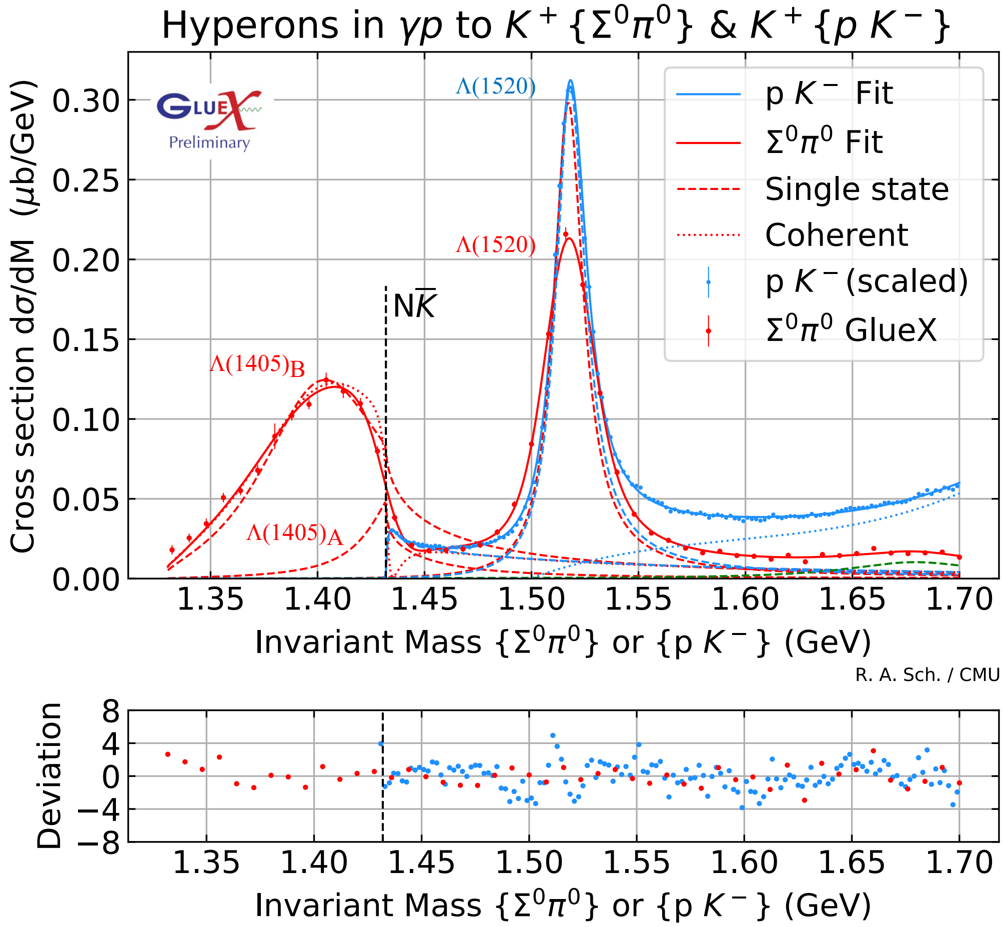
Compute T-matrix to be tested for unitarity and to find "T-matrix poles"

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

K-matrix formalism - issues

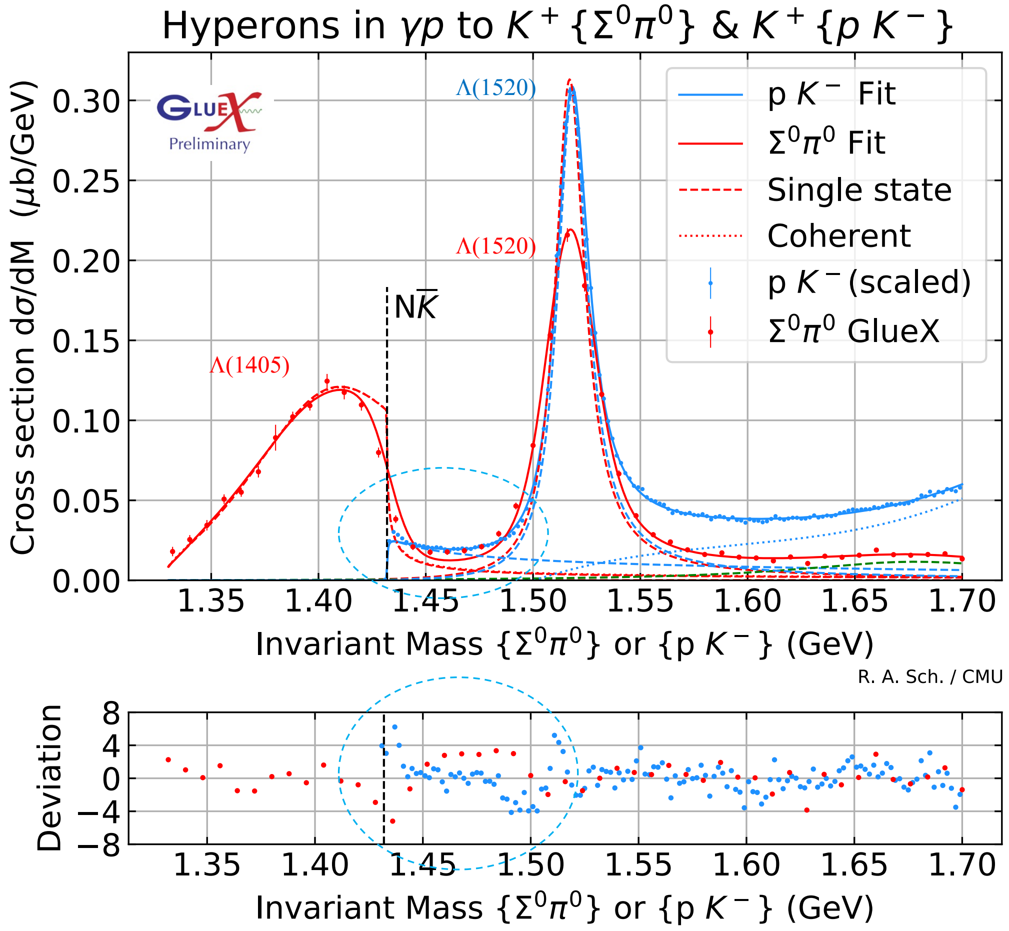
- Ignore the possibility of $\eta\Lambda$ and $K\Xi$ decays
- Poles "A" & "B" are below threshold for pK^- channel
- Define "branching ratio" & "branching fractions" in terms of fitted $\Sigma\pi$ and $N\bar{K}$ final states
  - Calculate using mass-integrated cross sections to each final state computed for each resonance separately
  - Not computed in terms of pole residues
    - (threshold issues make this difficult)

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
- $0.00 < t < 1.50\ \mathrm{GeV}^2$ (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

Pole positions from the literature

$\Lambda(1520)$ PDG

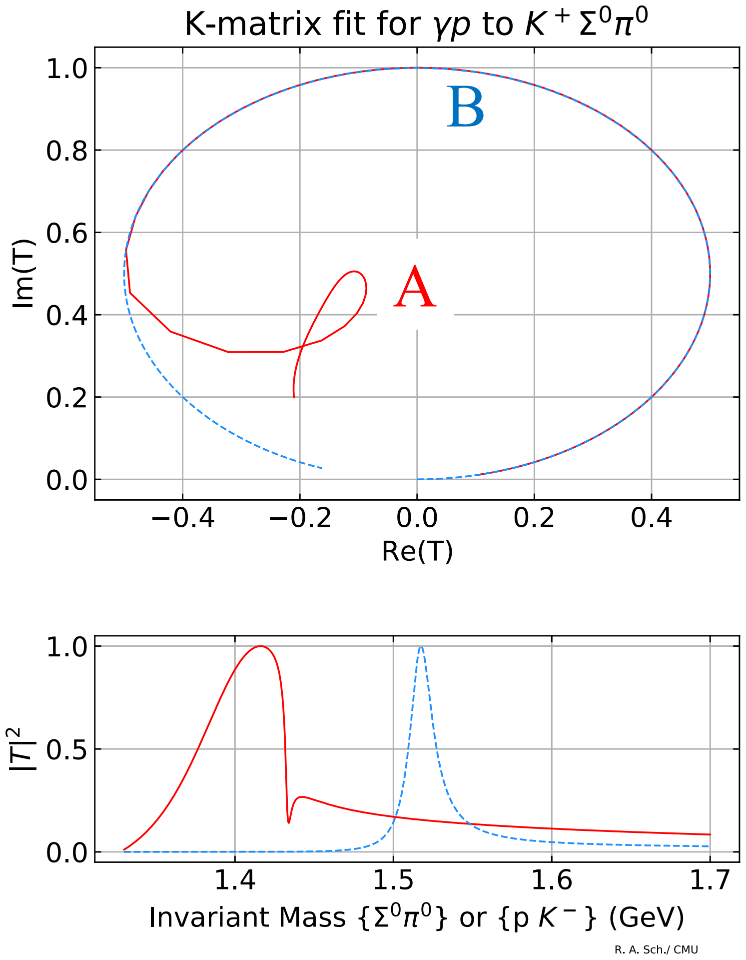
$\Lambda(1520)$ **POLE POSITION**	
REAL PART	1517 to 1518 (≈ 1517.5) MeV
$-2\times$IMAGINARY PART	14 to 18 (≈ 16) MeV (→ ~ 2 x 8 MeV)

GlueX (preliminary):

$$(1516.5 \pm 0.3) - i\,(8.3 \pm 0.1)\ \text{MeV}$$

Good agreement with PDG:
suggests the GlueX method is sound

Check Unitarity of the Amplitudes



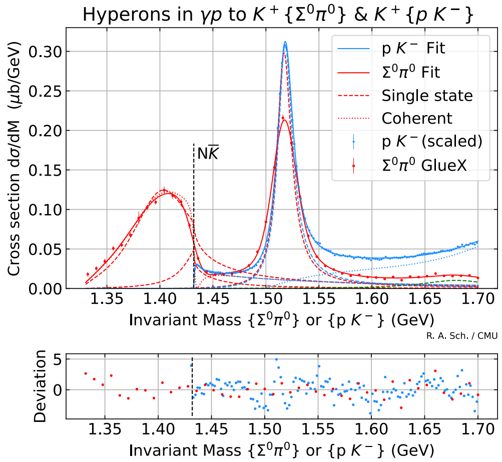
- Argand diagram and squared-magnitude for the $\Sigma^0\pi^0$ amplitude (red)
  - Two $\Lambda(1405)$ resonances with $\Sigma^0\pi^0$ and pK^- initial/final states.
  - Each amplitude stays properly bounded.
- Separately, $\Lambda(1520)$ is a single pK^- amplitude (blue)

Cross Sections & Branching Fractions

Full $-t$ range:

$0.00 < t < 1.50$ GeV^2

Preliminary



- $\Sigma^0\pi^0$ channel
- pK^- channel
- Bootstrap statistical uncertainties only
- Nominal benchmark fit

```
Cross_section_of_Lambda(1520)_from_Sigma_pi   23.11 +- 0.26 nanobarns
Cross_section_of_Lambda(1520)_from_NK         24.27 +- 0.05 nanobarns
```

	sigma(Sigma pi) (nb)	sigma(N K) (nb)	sigma(Total) (nb)	BR(NK/Sigma pi)	BF(Sig.pi/Total)	BF(NK/Total)
Lambda(1405)A	5.50 +- 0.37	3.58 +- 0.21	9.07 +- 0.57	0.651 +- 0.010	0.606 +- 0.004	0.394 +- 0.004
Lambda(1405)B	32.90 +- 0.54	5.39 +- 0.20	38.29 +- 0.45	0.164 +- 0.008	0.859 +- 0.006	0.141 +- 0.006

```
T-matrix pole positions for Lambda hyperons, R.A.Sch., Carnegie Mellon Univ.  May 29, 2024 14:11:32

Lambda(1405)_A_Sigpi: Real 1432.01 +-   0.05 ; Imaginary  -2.85 +/-   0.73
Lambda(1405)_B_Sigpi: Real 1398.60 +-   1.21 ; Imaginary -50.20 +/-   2.21
Lambda(1520)________: Real 1516.96 +-   0.21 ; Imaginary  -8.34 +/-   0.03
```

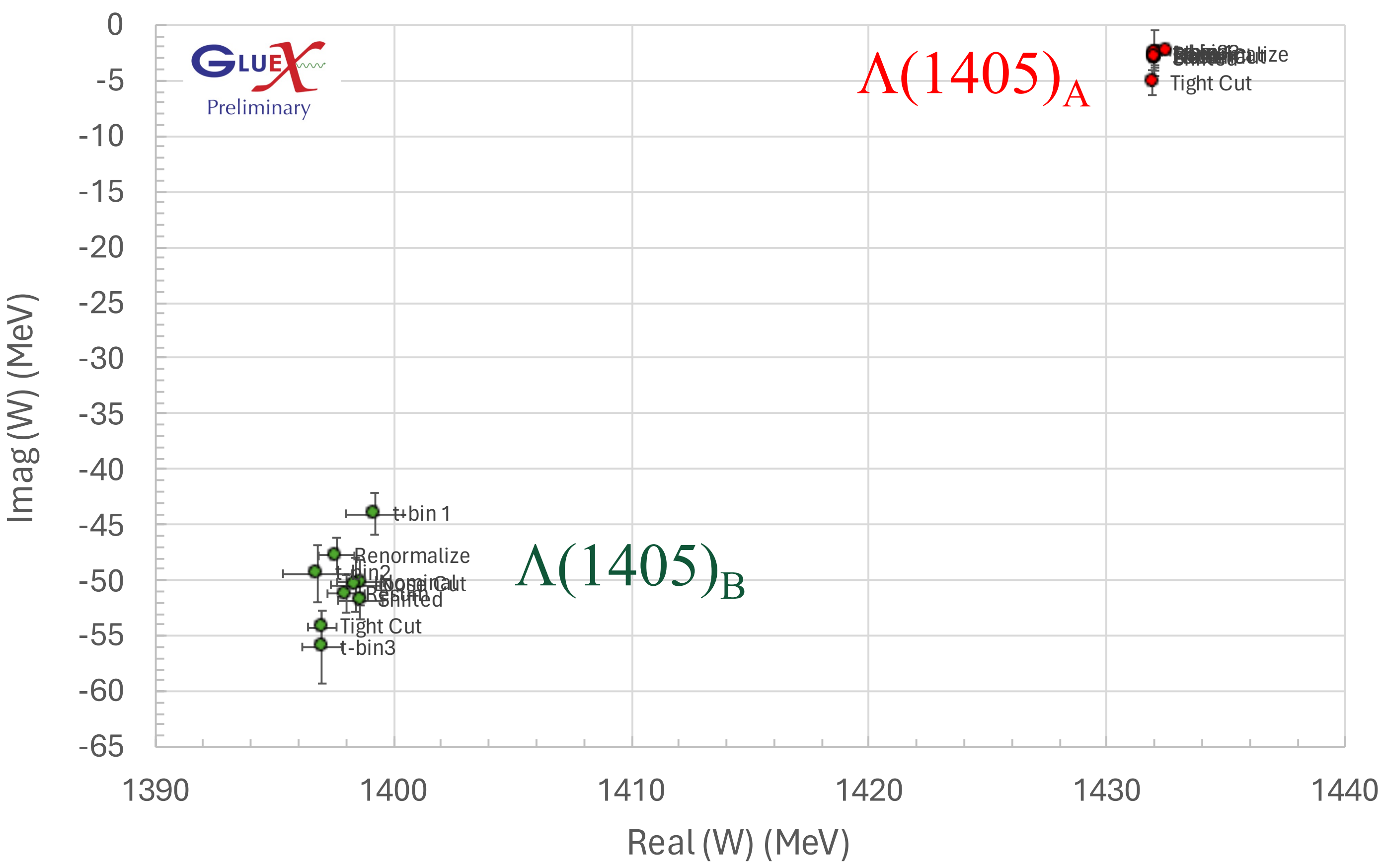
Detector-independent quantities

Systematic Uncertainty in Pole Locations

- Variations on the procedures:
  - Nominal fit – defines central values
  - Shift mass bins by 4 MeV and redo the fits: sensitive to pK^- threshold
  - Tighter kinematic fit cut: sensitive to any backgrounds between Λ's
  - Looser kinematic fit cut: " " " " "
  - Slice data by t-bin: $0.00 < t < 0.35$ GeV^2
  - " " " : $0.35 < t < 0.60$ GeV^2
  - " " " : $0.60 < t < 1.50$ GeV^2
  - Resum t-bins to total: sensitive to acceptance modeling
  - Rescale $\Lambda(1520)$ cross section to exactly match in both channels

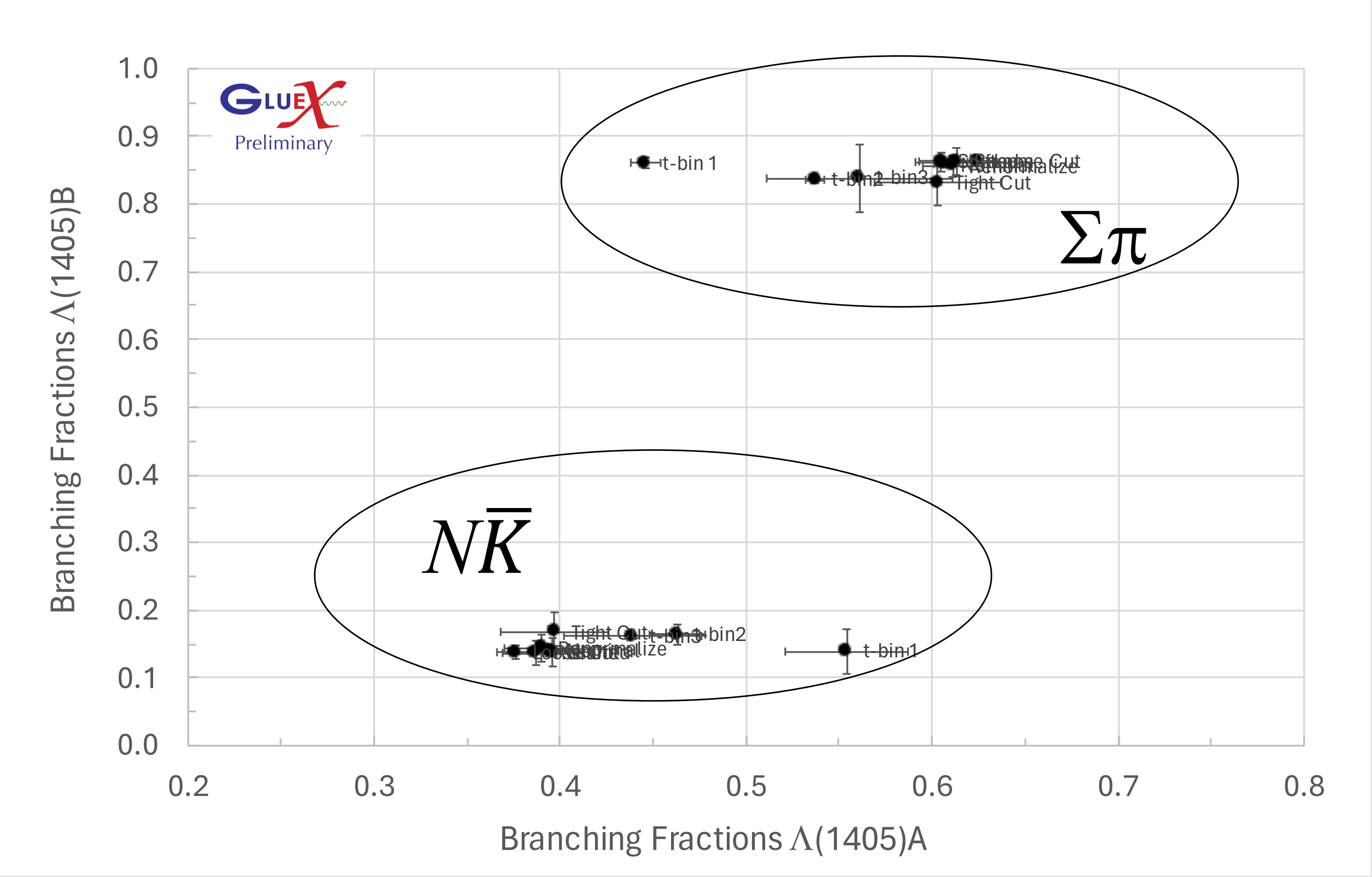
- How to combine all this information ?
  - Use "Nominal" fit for central values…
  - Use standard deviations of all fits to define systematic spreads

Systematic Tests Summary I



- Pole Positions
  - Nominal
  - Shifted bins
  - Tighter KINFIT
  - Looser KINFIT
  - t-bin 1
  - t-bin 2
  - t-bin 3
  - Resum t-bins
  - Rescale Λ(1520) cross section

Systematic Tests Summary II



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

The Landscape Including GlueX Data/Fit

GlueX (preliminary):

Red dot positions and error bars to be finalized…

Recent (year ≥ 2000) predictions:
M. Mai – Eur. Phys. J. Spec. Top. 230 6, 1593, (2021)

Thresholds:
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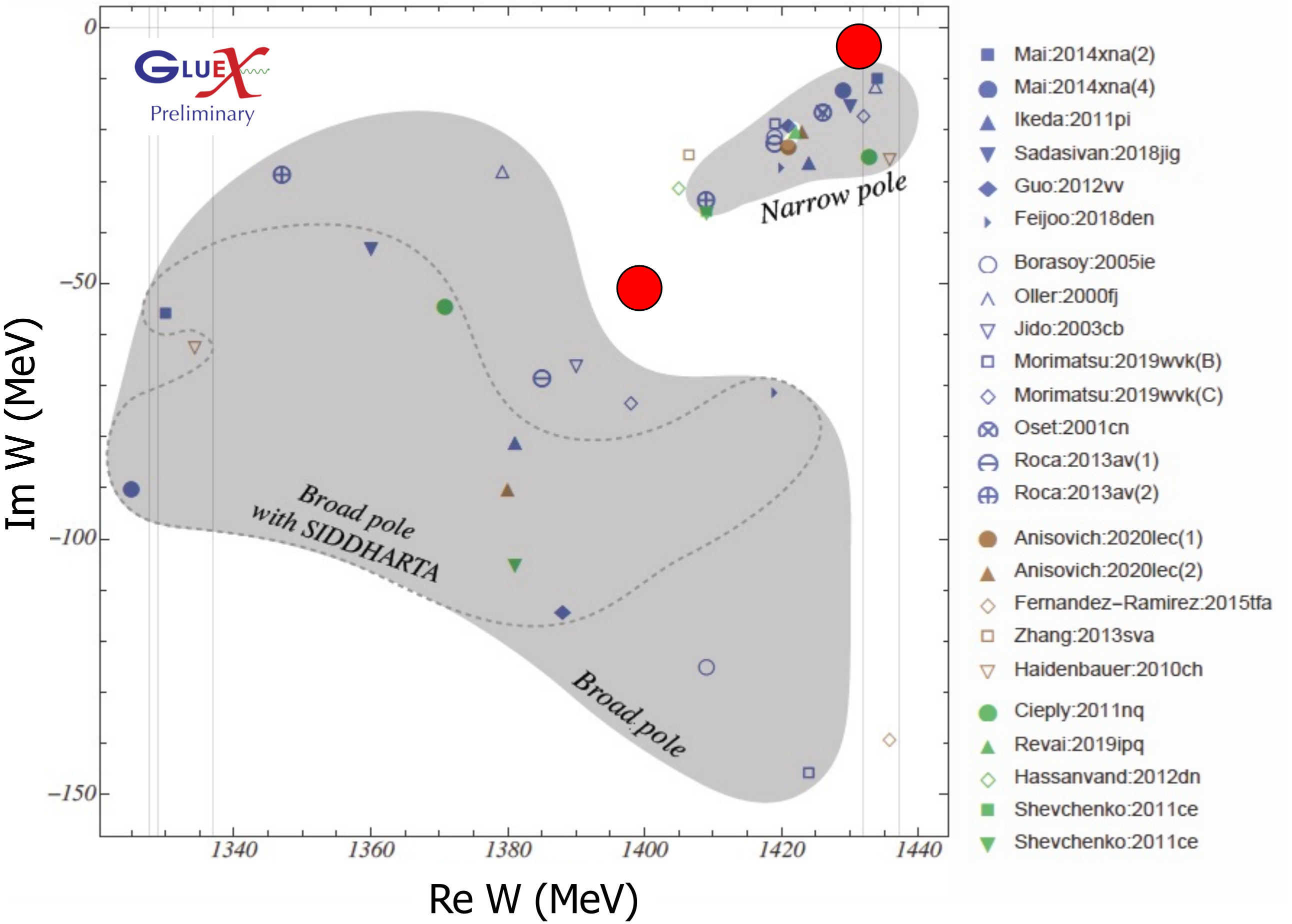

RESULTS OF THE EXPERIMENT

Branching Ratio/Fractions

Preliminary

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	T.B.D.	0.859	0.005	T.B.D.	0.141	0.005	T.B.D.

- 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 $\sigma_{\Sigma0\pi0}$ / σ_{pK-} , etc.

Summary/Conclusions

- First measurement of the $\Lambda(1405)$s decaying two separate ways: $\Sigma^0\pi^0$ & 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

GlueX acknowledges the support of several funding agencies and computing facilities (http://gluex.org/thanks)

Supplemental Slides

Rescaling of pK^- and $\Sigma^0\pi^0$ Data

- Trust that isospin holds exactly
- Trust that PDG branching fractions are all OK
- Part I: Scale (Peter's) $\Lambda(1520) \rightarrow p\,K^-$ cross section to match (Nilanga's) $\Lambda(1520) \rightarrow \Sigma^0\,\pi^0$ cross section
  - $p\,K^-$ branch to $\Lambda(1520)$ total: x 1/(0.45/2) (scale up)
  - Total $\Lambda(1520)$ to $\Sigma^0\,\pi^0$: x 0.42 / 3 (scale down)
  - Net $p\,K^-$ rescaling factor = 0.6222

Rescaling of pK^- and $\Sigma^0\pi^0$ Data

- The $p\,K^-$ "background" gets rescaled, too… so…
- Part II: Scale (Reinhard's) computed model $\Lambda(1405) \rightarrow p\,K^-$ tail to match rescaled $\Lambda(1520) \rightarrow \Sigma^0\pi^0$
  - We see only $\Sigma^0\pi^0$ but not $\Sigma^+\pi^-$ & $\Sigma^-\pi^+$: x 3.0 (scale up)
    - (this is the total strength of $\Lambda(1405)$ production)
  - Equal $\Lambda(1405)$ decay to nK^0 and pK^- : x 0.5 (scale down)
  - Adjust for the pK^- data rescaling: x 0.622
  - Net pK^- calculated tail curve rescaling = 0.9333

Rescaling of pK^- and $\Sigma^0\pi^0$ Data

- Our quoted $\Lambda(1405)$ branching ratio/fractions are for isospin-corrected $\Sigma\pi$ and $N\bar{K}$
- Part III: Scale measured cross sections to account for isospin
  - We measure (Nilanga) $\Lambda(1405) \rightarrow \Sigma^0\pi^0$, not $\Sigma^+\pi^-$ & $\Sigma^-\pi^+$, so correct for isospin: × 3 (scale up)
  - Computed $N\bar{K}$ tail (Reinhard) from $\Lambda(1405) \rightarrow \Sigma^0\pi^0$, again correct for isospin: × 3 (scale up)
    - (K-matrix fit does not, in itself, distinguish NK modes)