Λ(1405) and Λ(1520) Line Shape Studies using GlueX Phase I Data

Sean Dobbs

Florida State University

On behalf of Nilanga Wickramaarachchi (Catholic Univ.)
& Reinhard Schumacher (Carnegie Mellon Univ.) & Peter Hurck (Univ. Glasgow)
& Greg Kalicy (Catholic Univ.) & other GlueX Collaborators

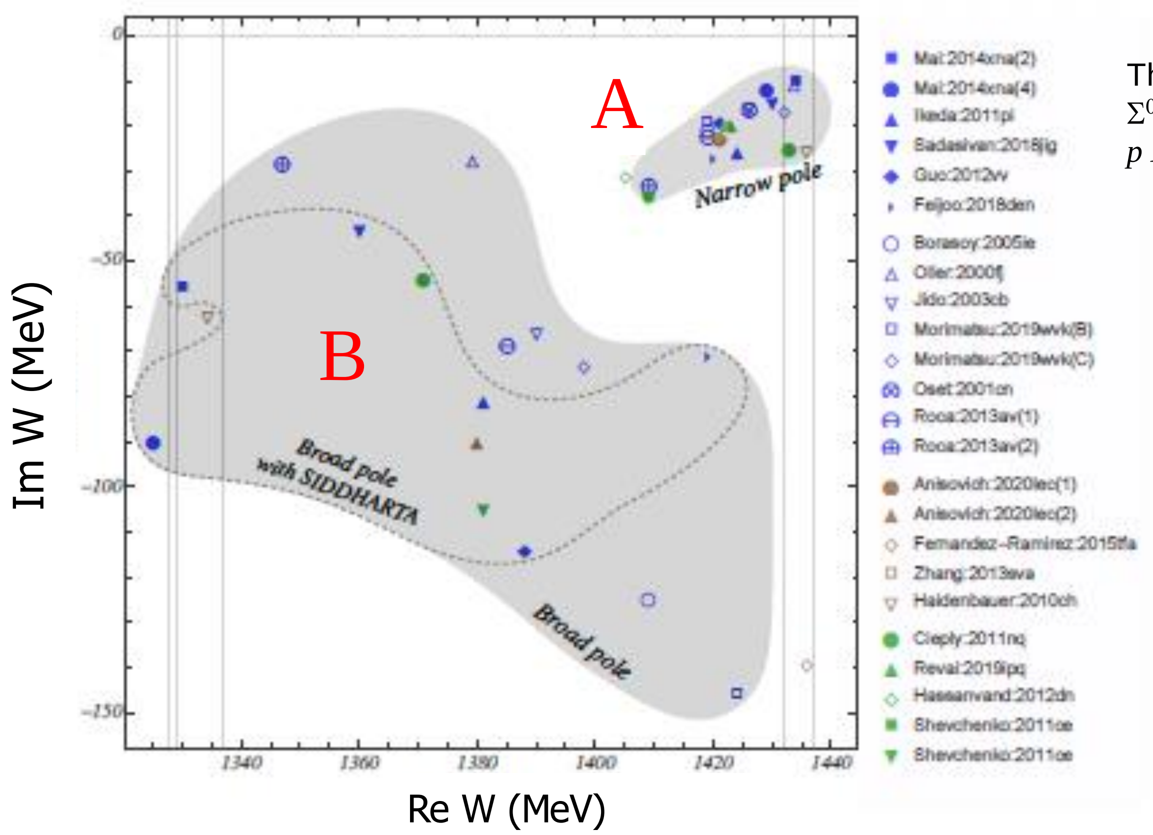
Overview

- 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 of mass spectrum

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 – 1432 MeV
  - 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: γ p→ K^+ $\Lambda(1405)$ → K^+ {Σ^0 π^0}
  → 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 ≥ 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

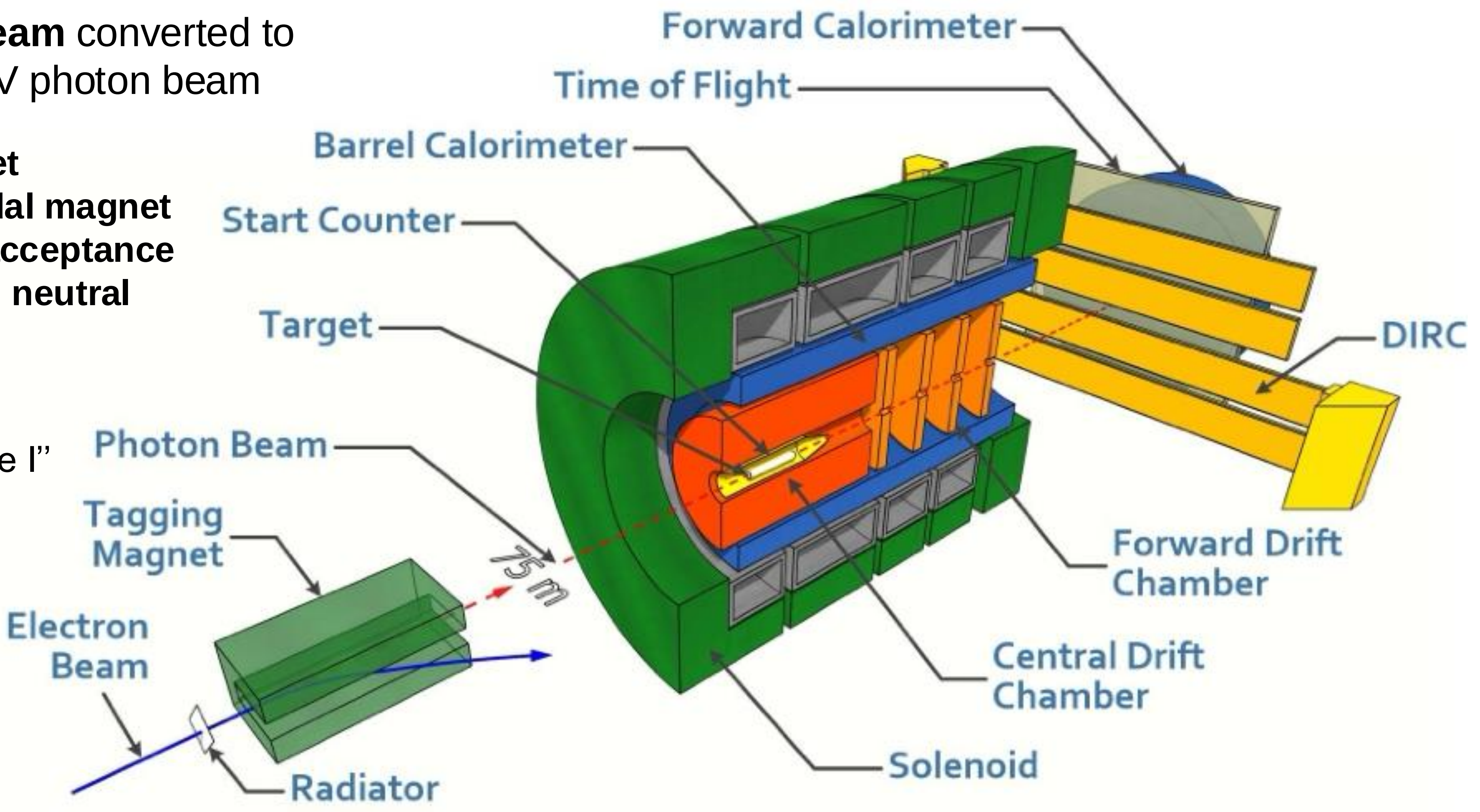
GlueX Experiment at JLab

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**
- **Near hermetic acceptance for charged and neutral particles**

- **This analysis:** Data from “Phase I” runs



GlueX Competitive Advantages

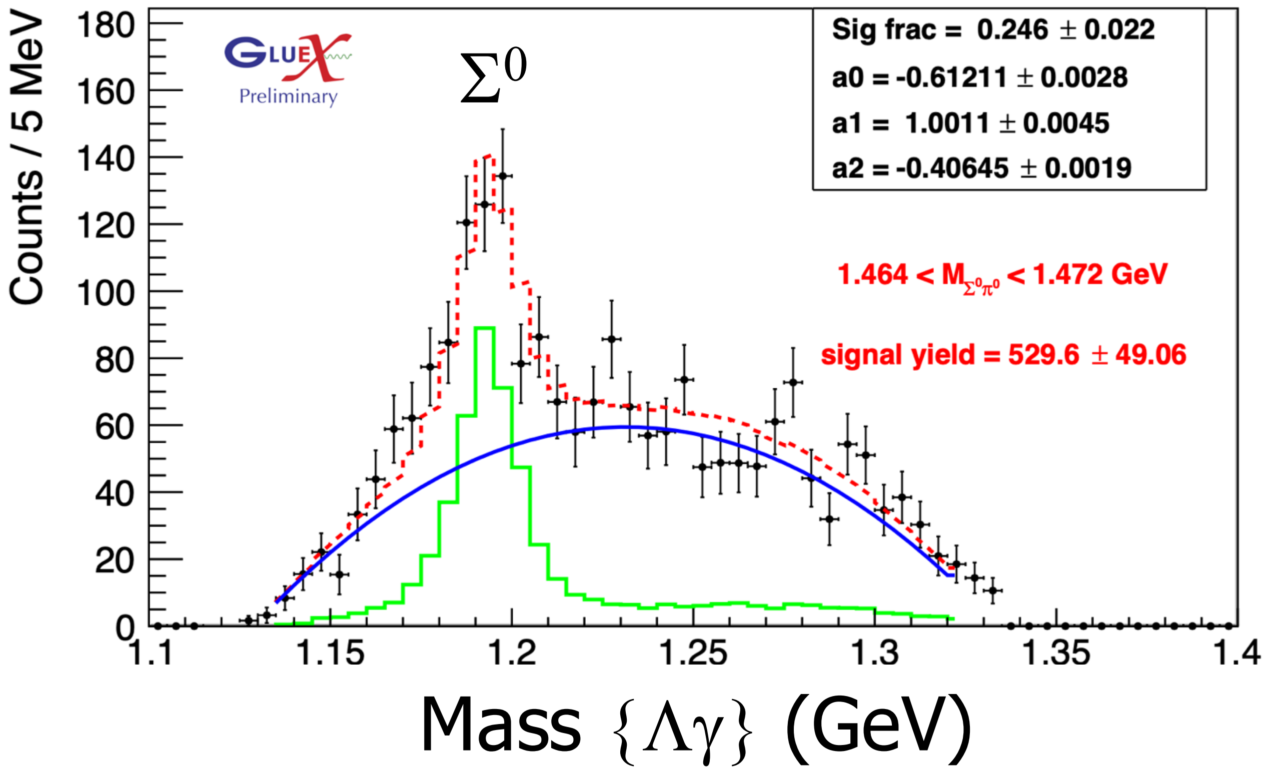
- GlueX has world's best data set producing $\Lambda(1405)$ cleanly in photoproduction: $\gamma\, p \rightarrow K^+\, \Lambda(1405)$

  $\rightarrow K^+\, \{\Sigma^0\ \pi^0\}$ (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…

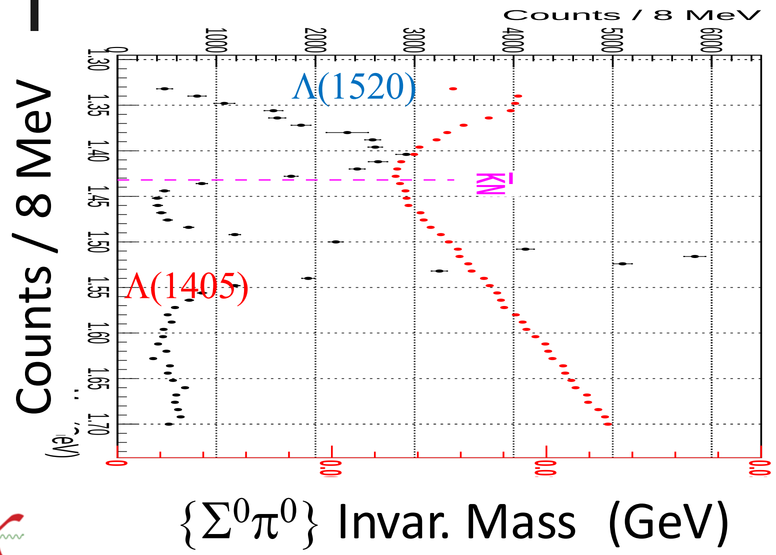
Experimental Method I



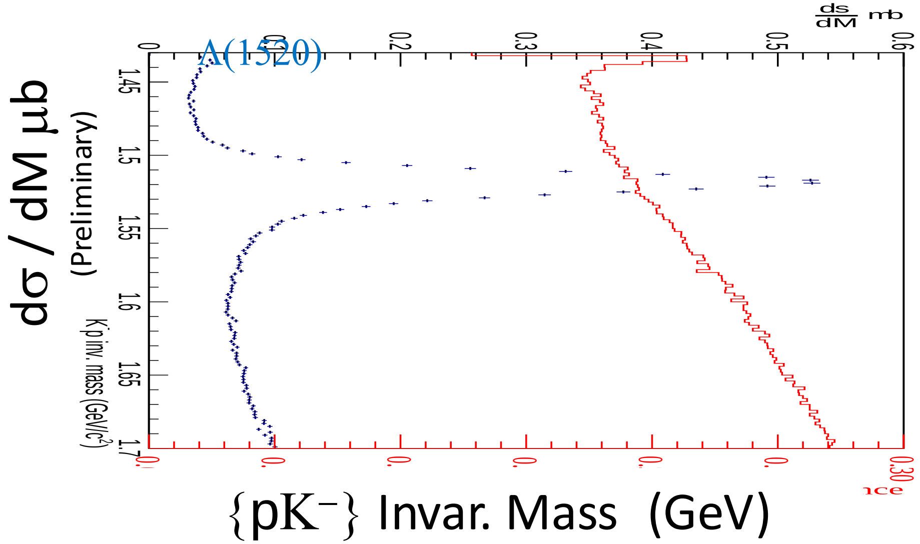
$\Sigma^0\pi^0$ channel

- 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

Experimental Method II

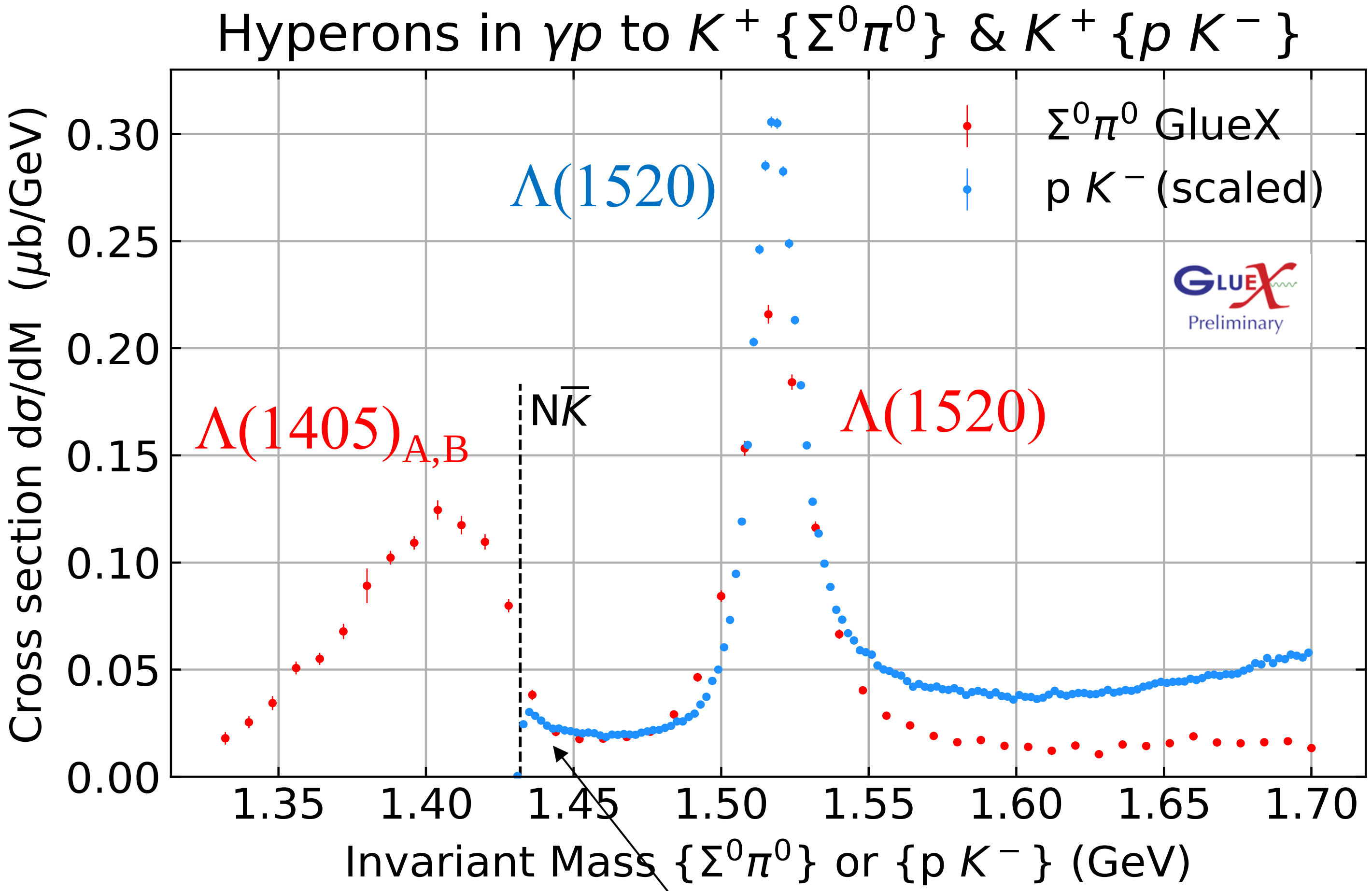


Preliminary



- $\Sigma^0\pi^0$ 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

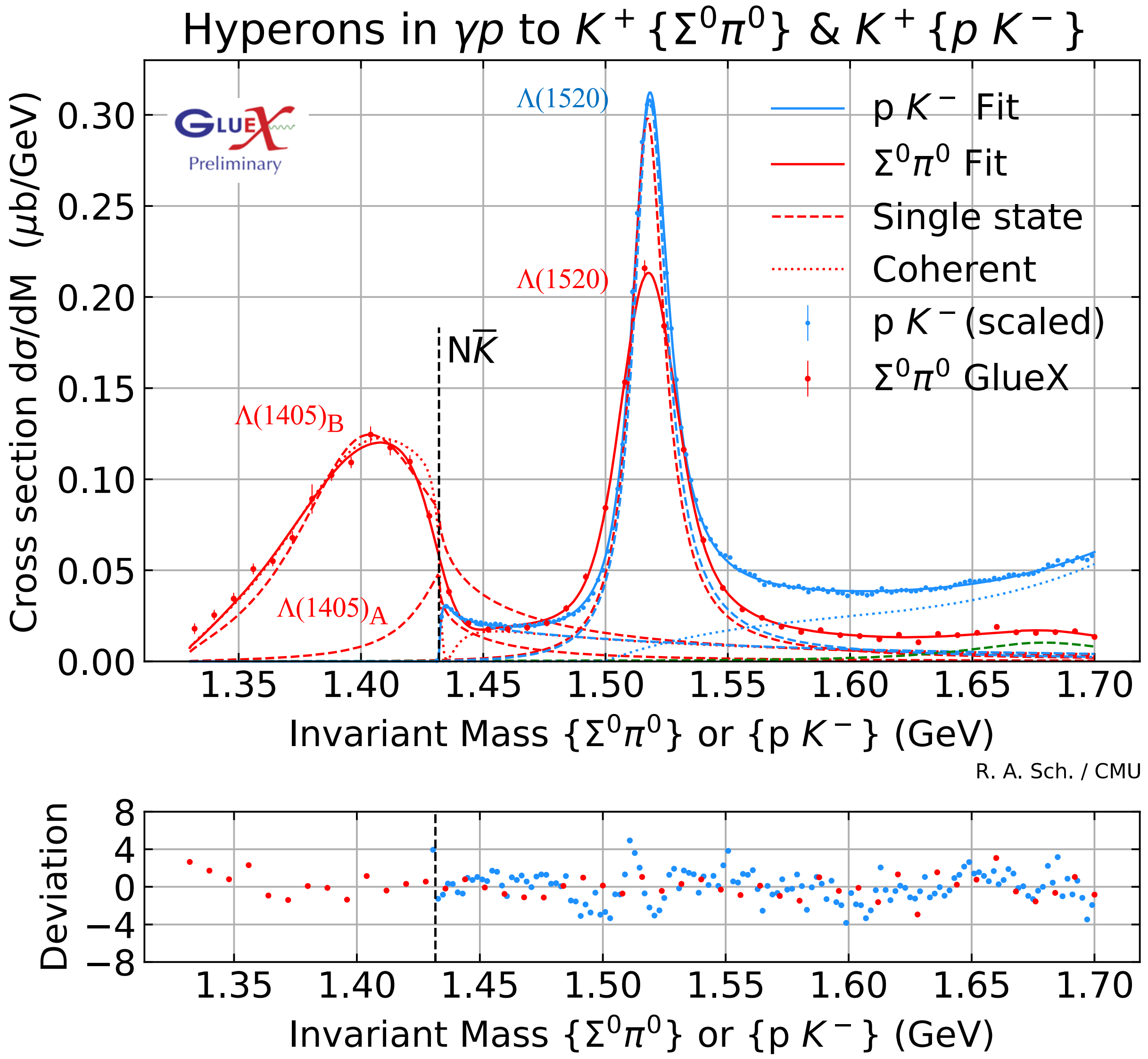
Thresholds:
$\Sigma^0\pi^0$ 1327.62 MeV
$p\ K^-$ 1431.95 MeV

Application of K-Matrix Method*

- Resonances included (all coupled to $\Sigma^0 \pi^0$ and p K^-):
  - $\Lambda(1405)_A$ (J=1/2 L=0)
  - $\Lambda(1405)_B$ (J=1/2 L=0)
  - $\Lambda(1520)$ (J=3/2 L=2)
- Assume J=1/2 L=0 states do not interfere with J=3/2 L=2 state
- 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

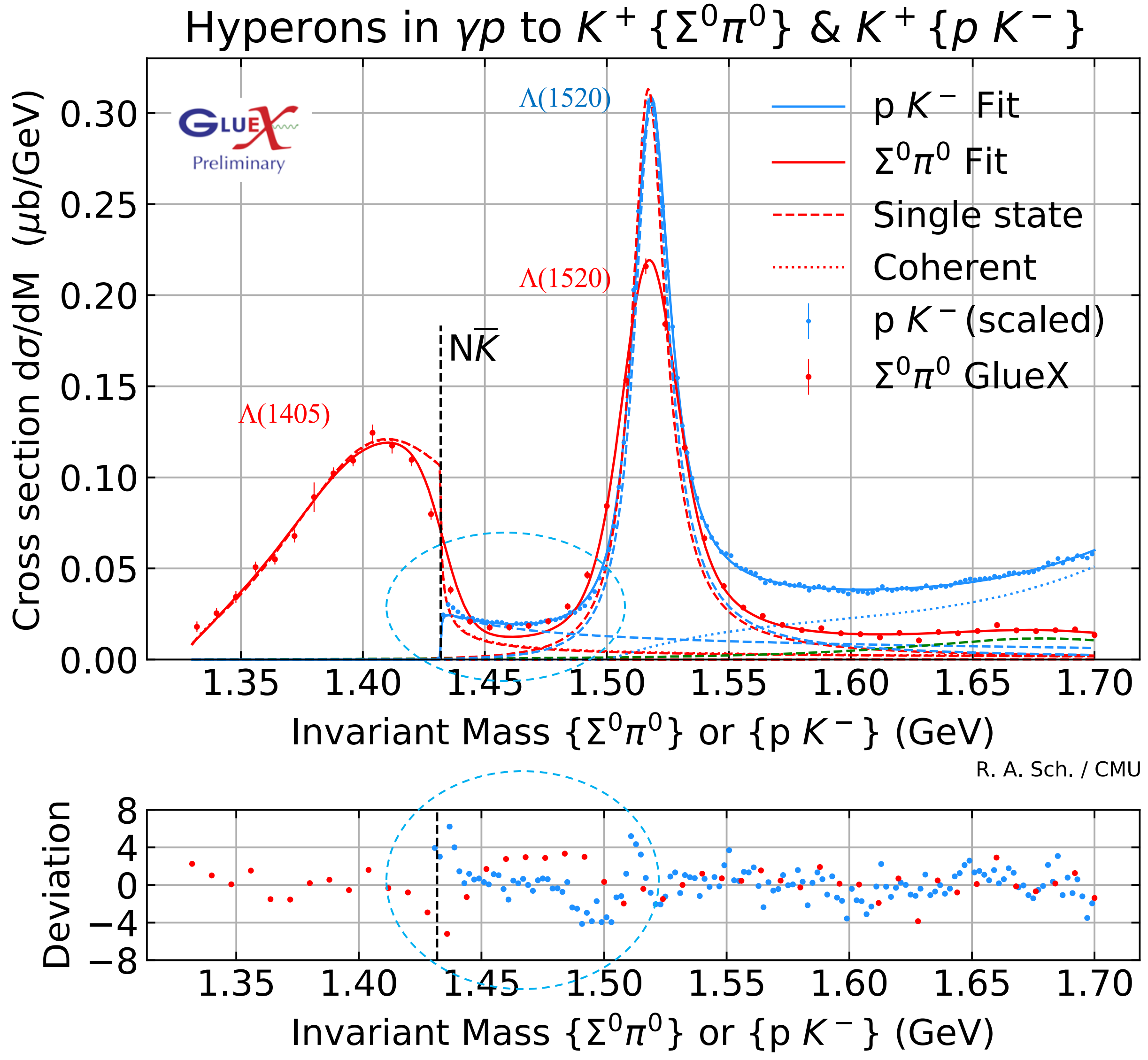
* à la S.U. Chung *et al.*, Ann. Physik 4, 404 (1995).

2-Pole K-matrix Fit to Λ(1405)A,B



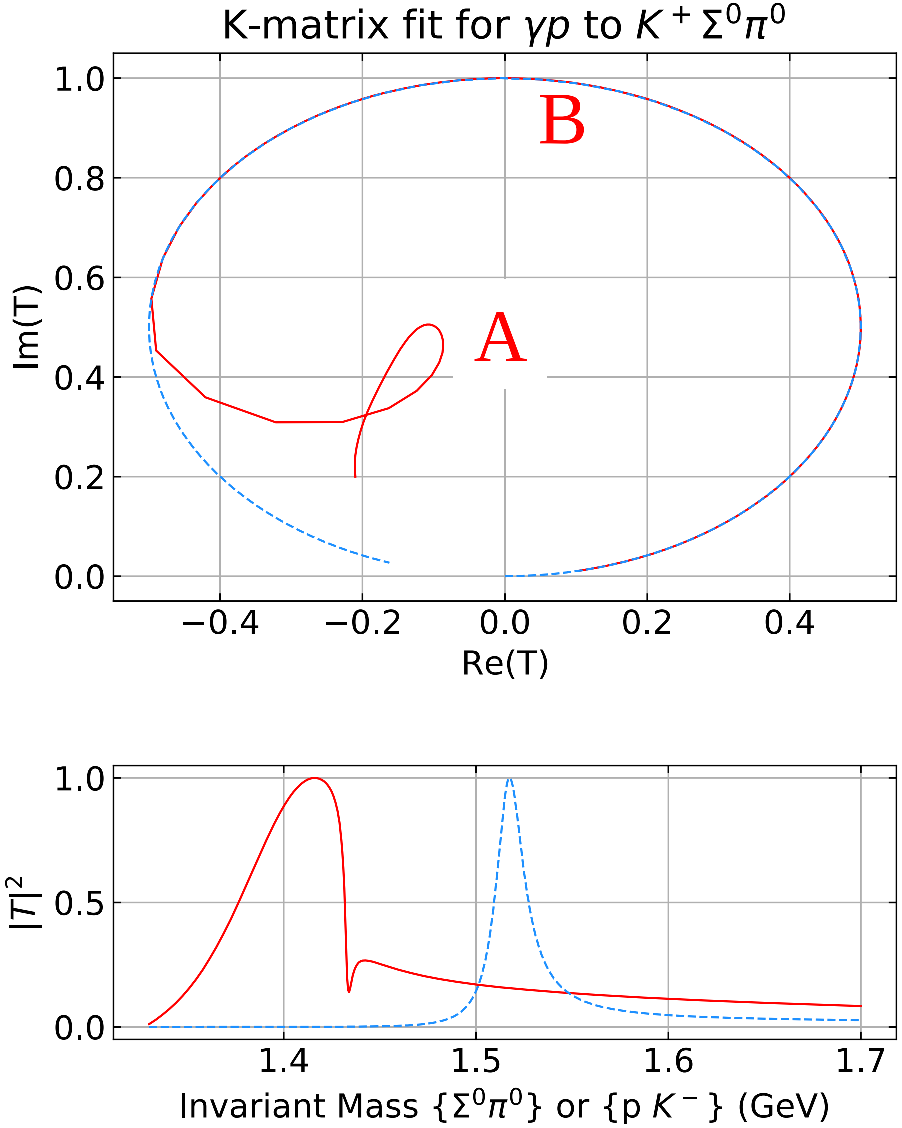
- $\Sigma^0\pi^0$ channel
  - Solid – fit to data
  - Dashed – each A,B resonance separately
  - Dotted – fit to data:
    - full K-matrix fit with coherent Λ(1405)A,B states
    - prior to convolving 7.8 MeV GlueX mass resolution
- pK^- channel
  - Solid – fit to data:
    - 2.0 MeV GlueX mass resolution
  - 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

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)

R. A. Sch./ CMU

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
- Final pole positions and branching ratio/fractions being determined
- Systematics to be finalized

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

Supplemental Slides

Λ(1520) Pole Position Compared to 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):

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

Good agreement with PDG:
suggests the GlueX method is sound

Chiral Unitary Models

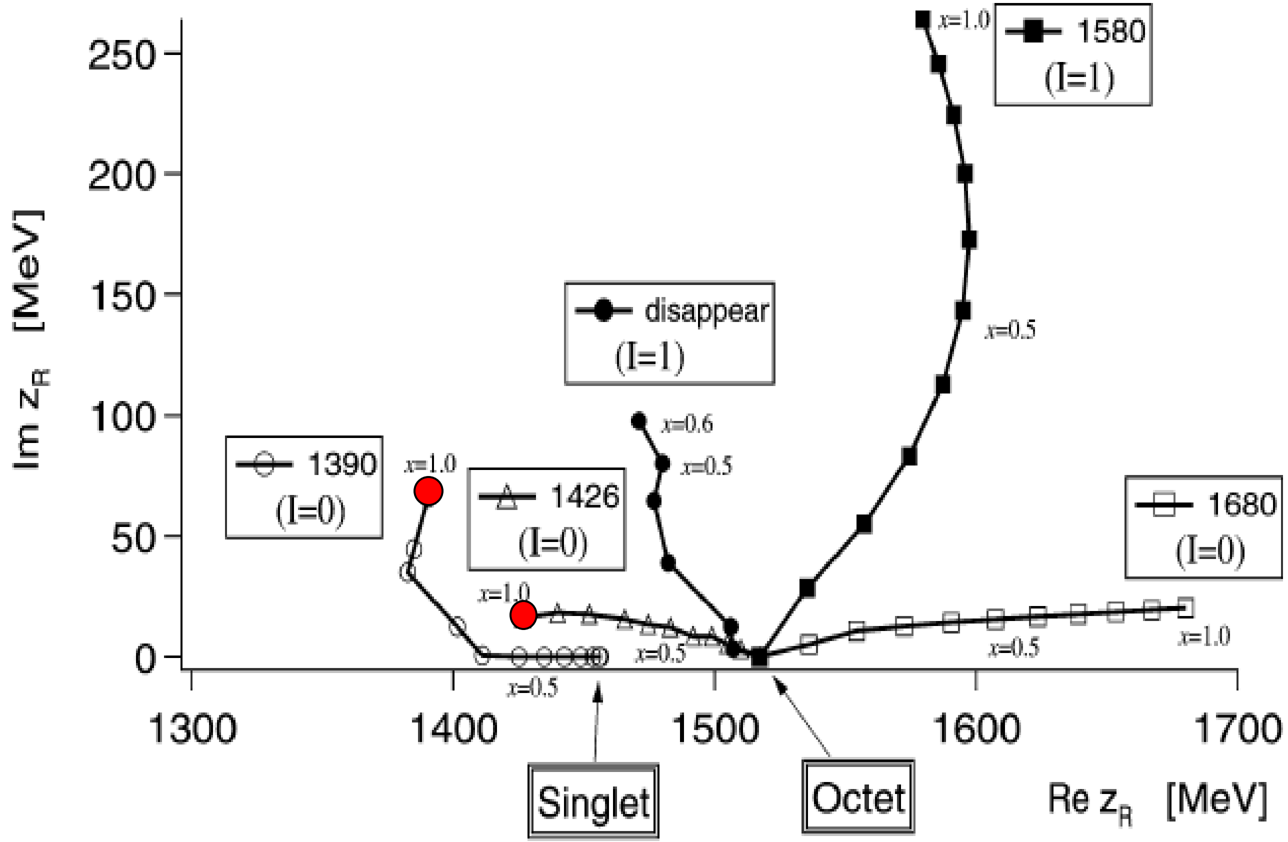
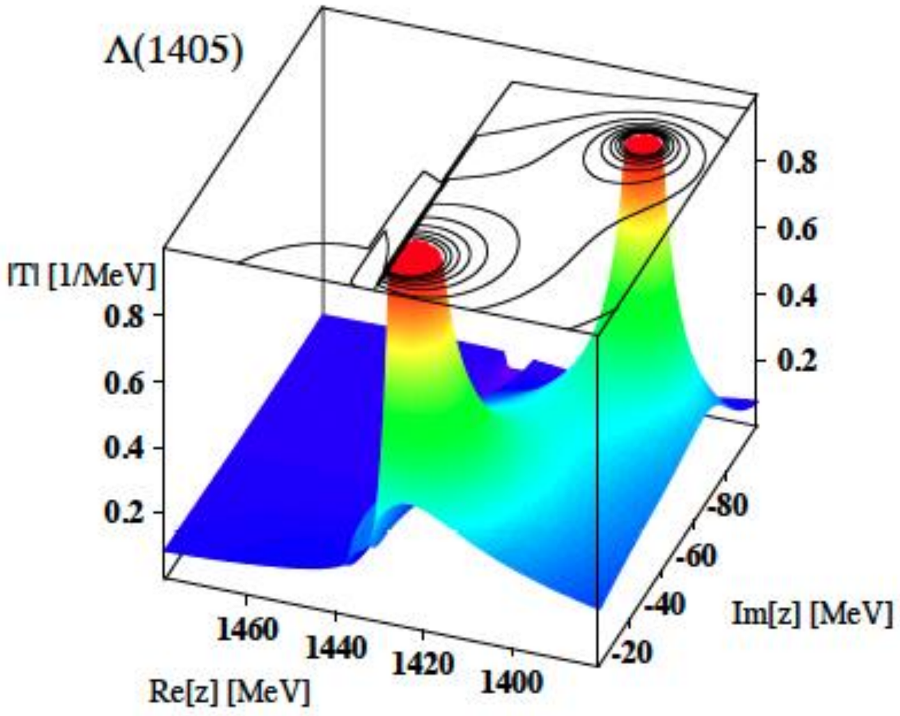


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size $\delta x = 0.1$.

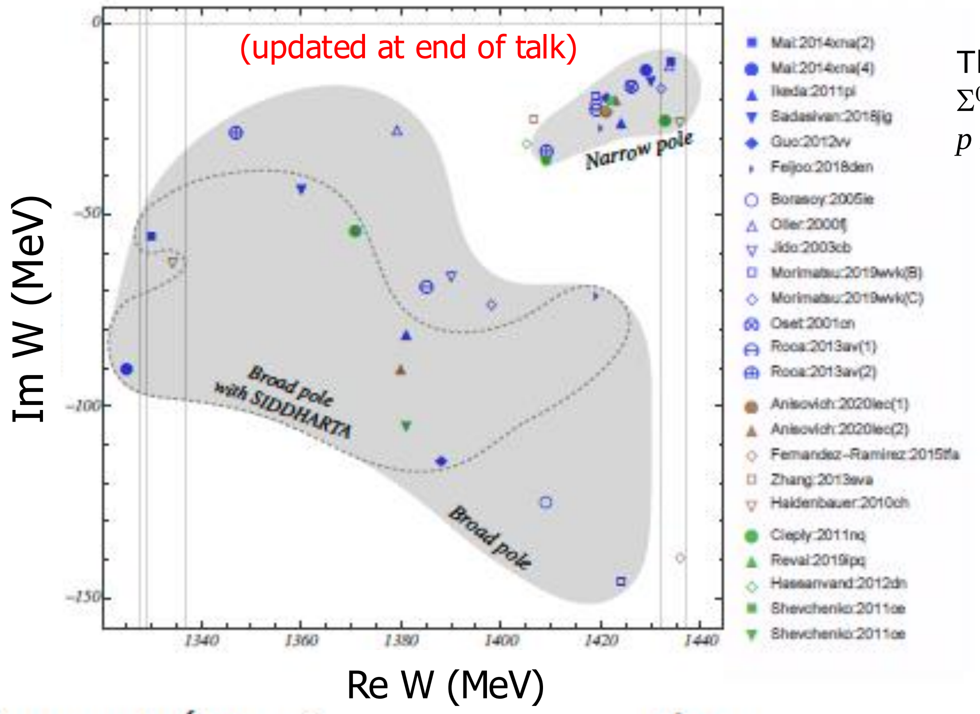
- SU(3) baryons irreps $1+8_s+8_a$ combine with 0^- Goldstone bosons to generate:
  - Two octets and a singlet of ½⁻ baryons dynamically generated in the SU(3) limit
  - SU(3) breaking leads to two $S = -1,\ I = 0$ poles near 1405 MeV
    - ~1420 mostly $N\bar{K}$
    - ~1390 mostly $\Sigma\,\pi$
  -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

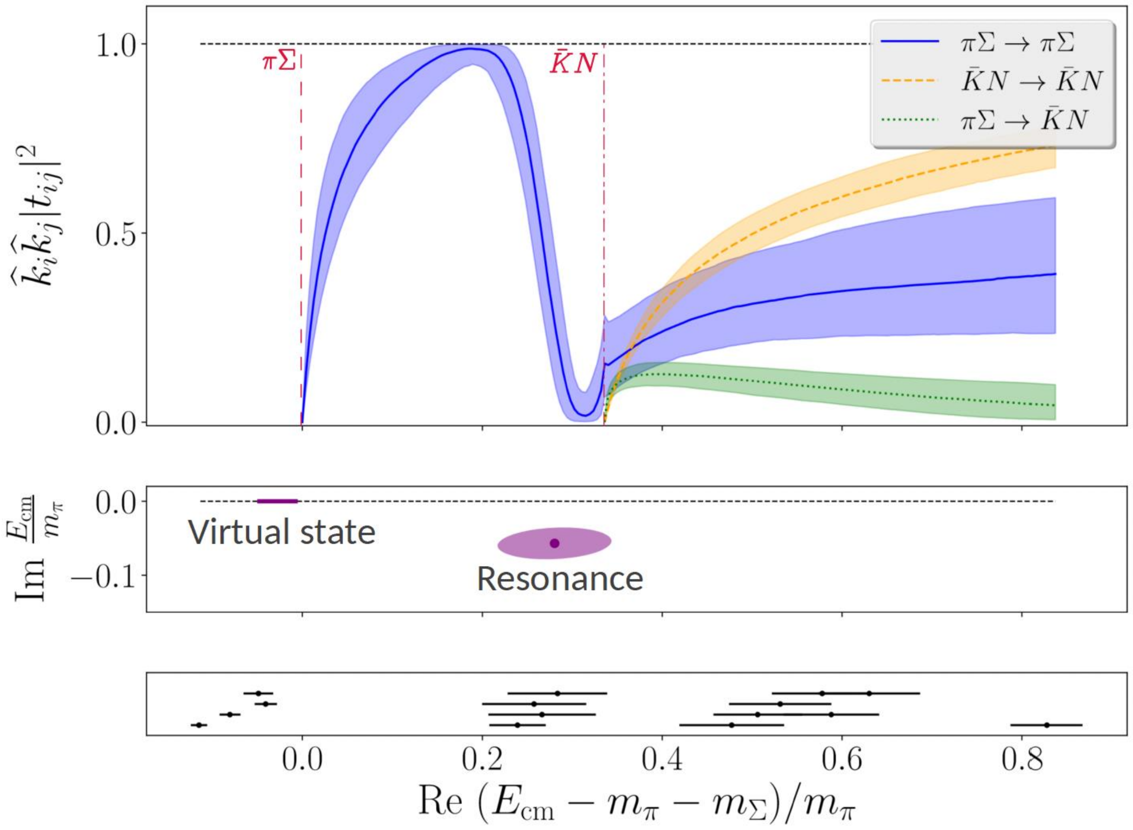
- Higher pole ~1430 MeV couples more strongly to $N\bar{K}$, lower pole ~1390 MeV couples more to $\Sigma\pi$
- Many theorists believe: $N\bar{K}$ quasi-bound state submerged in $\Sigma\pi$ continuum: coupled-channel dynamics
- Most data from low-energy NK scattering, kaonic atoms – not very sensitive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

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= ½ L=0 states do not 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 $i, j = \{\Sigma^0\pi^0, \mathrm{p}\, K^-\}$

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

K-matrix formalism* (outline sketch)

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

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)

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) $\Lambda(1405) \to \Sigma^0\pi^0$, not $\Sigma^+\pi^-$ & $\Sigma^-\pi^+$, so correct for isospin: × 3 (scale up)
  - Computed $N\bar{K}$ tail (Reinhard) from $\Lambda(1405) \to \Sigma^0\pi^0$, again correct for isospin: × 3 (scale up)
    - (K-matrix fit does not, in itself, distinguish NK modes)

Chiral Unitary Models

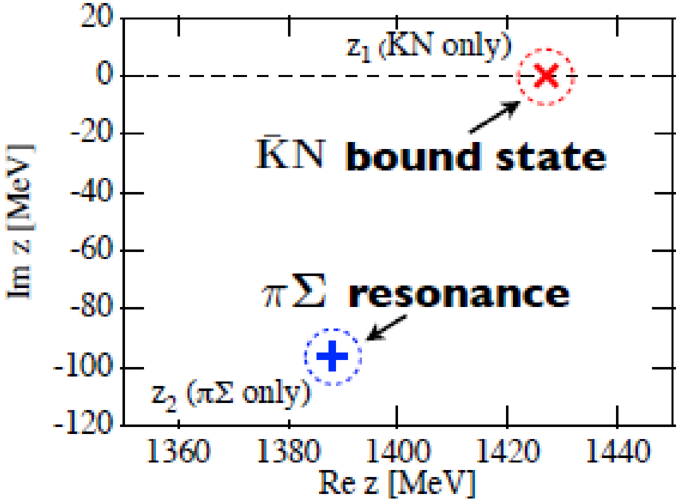
The TWO POLES scenario

D. Jido et al.
Nucl. Phys. A725 (2003) 181

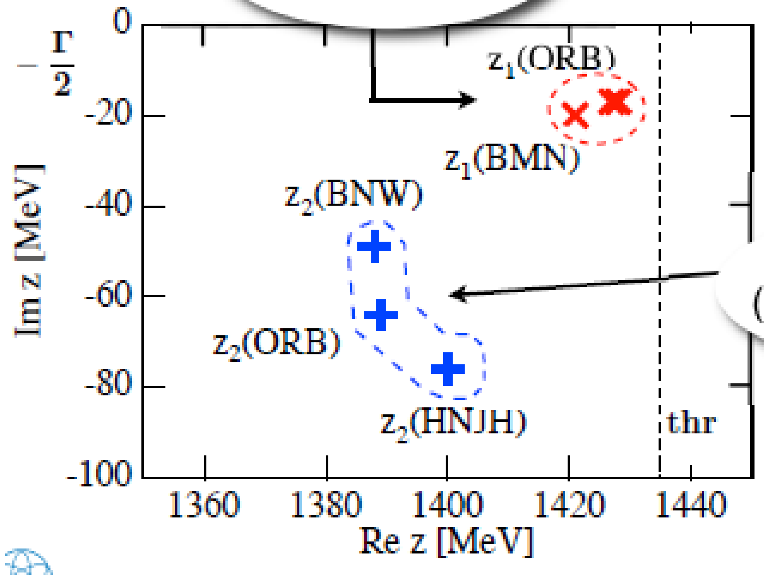
T. Hyodo, W.W., Phys. Rev. C77 (2008) 03524

- Singularities of $\bar{K}N$ amplitude in the complex energy plane

starting point:
no channel coupling ▶

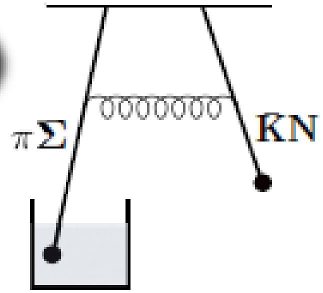


Pole I
(dominantly $\bar{K}N$)



◀ **channel coupling** at work

Pole II
(dominantly $\pi\Sigma$)



Graphic: W. Weise

Pole positions from the literature

Xiu-Lei Ren, HIM Mainz, MENU 2023
Chiral Perturbation Theory

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

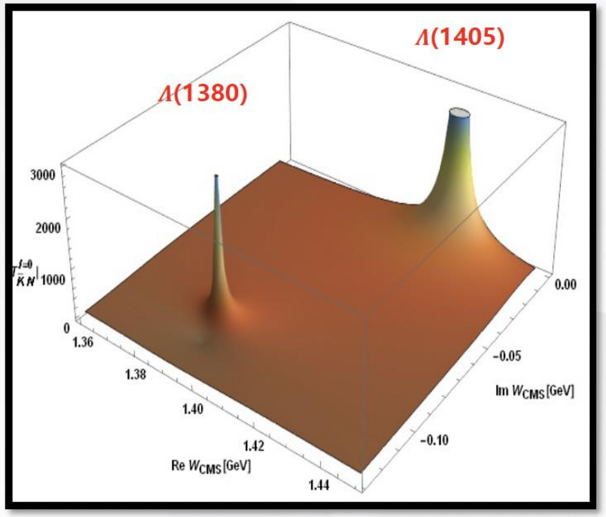
		lower pole	higher pole
This work	$F_0 = F_\pi$	$1337.7 - i\,79.1$	$1430.9 - i\,8.0$
(LO)	$F_0 = 103.4$	$1348.2 - i\,120.2$	$1436.3 - i\,0.7$
NLO	*Y. Ikeda,NPA(2012)*	$1381^{+18}_{-6} - i81^{+19}_{-8}$	$1424^{+7}_{-23} - i26^{+3}_{-14}$
	Z.-H.Guo,PRC(2013)-Fit II	$1388^{+9}_{-9} - i114^{+24}_{-25}$	$1421^{+3}_{-2} - i19^{+8}_{-5}$
	M.Mai,EPJA2015)-sol-2	$1330^{+4}_{-5} - i56^{+17}_{-11}$	$1434^{+2}_{-2} - i10^{+2}_{-1}$
	M.Mai,EPJA2015)-sol-4	$1325^{+15}_{-15} - i90^{+12}_{-18}$	$1429^{+8}_{-7} - i12^{+2}_{-3}$

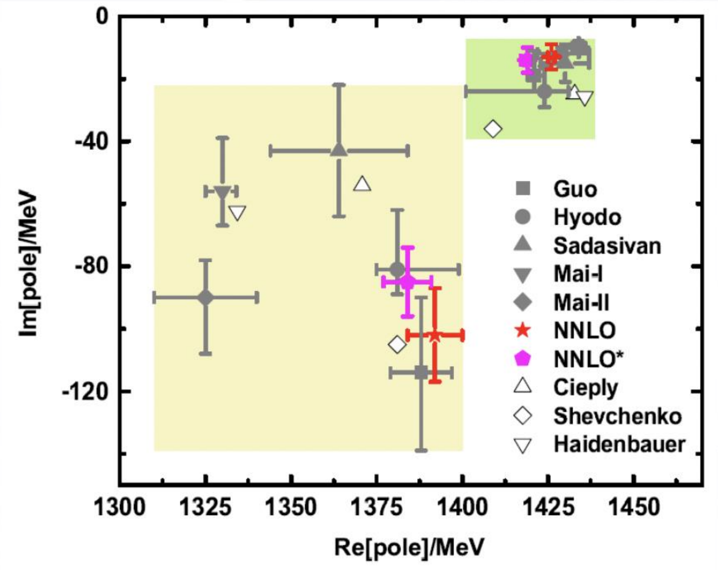
Pole positions from the literature

Li-Sheng Geng, Beihang Univ. MENU 2023

The two-pole structure persists at N2LO

Meson-baryon scattering up to N2LO, Jun-Xu Lu, LSG*, M. Doering and M. Mai, PRL130, 071902(2023)





		Pole positions [MeV]	$\lvert g_{\pi\Sigma}\rvert$ [GeV]	$\lvert g_{\eta\Lambda}\rvert$ [GeV]	$\lvert g_{\bar{K}N}\rvert$ [GeV]	$\lvert g_{K\Xi}\rvert$ [GeV]
NNLO	Λ(1380)	$1392 \pm 8 - i(102 \pm 15)$	6.40 ± 0.10	3.01 ± 0.15	2.31 ± 0.10	0.45 ± 0.01
	Λ(1405)	$1425 \pm 1 - i(13 \pm 4)$	2.15 ± 0.07	5.45 ± 0.24	4.99 ± 0.08	0.58 ± 0.02
NNLO*	Λ(1380)	$1384 \pm 7 - i(85 \pm 11)$	3.26 ± 0.11	0.87 ± 0.02	2.04 ± 0.11	0.61 ± 0.02
	Λ(1405)	$1419 \pm 2 - i(14 \pm 4)$	3.24 ± 0.17	0.42 ± 0.02	6.01 ± 0.12	0.81 ± 0.03