Decay of the $\Lambda(1405)$ to $\Sigma^0\pi^0$ measured at GlueX

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Introduction

- $\Lambda(1405)$ - just below $\bar{K}N$ threshold (1.432 GeV)
- In quark model $\Lambda(1405)$ can be considered as spin-orbit partner of $\Lambda(1520)$
- Invariant mass ("line shape") of $\Lambda(1405)$ from experiments distorted from Breit-Wigner form

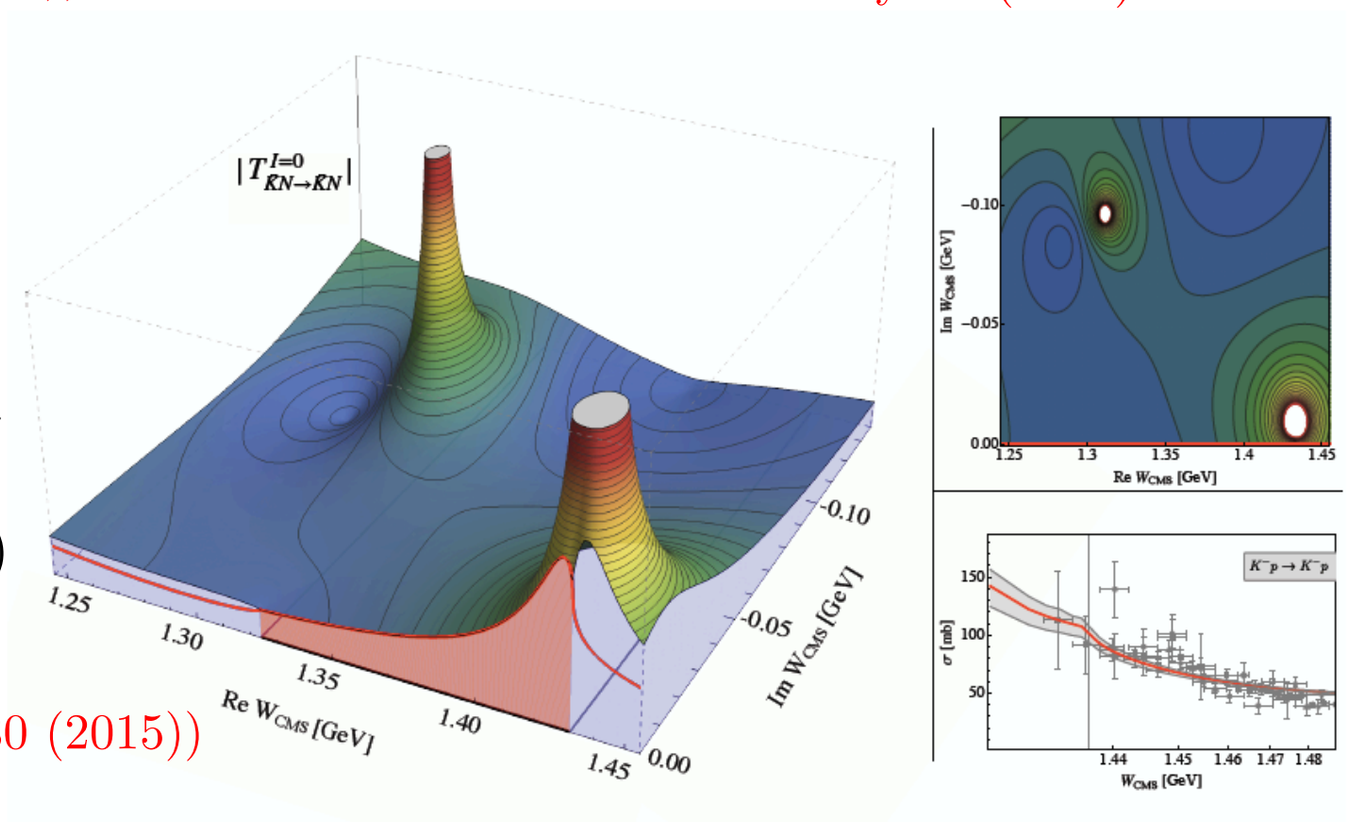
(E.g. K. Moriya, et al, Phys. Rev. C 87, 035206 (2013))

Particle	J^P	Overall status	Status as seen in — $N\bar{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$

V.D. Burkert et al., "Λ and Σ Resonances", The Review of Particle Physics (2022)

- $\Lambda(1405)$ decays 100% into $\Sigma\pi$
- Assumed to couple strongly to $\bar{K}N$ channel
- Some chiral unitary models suggest $\Lambda(1405)$ to be composed of two I=0 poles

(E.g. M. Mai, U.-G. Meissner, Eur. Phys. J. A 51, 30 (2015))



Maxim Mai, arXiv:2010.00056 (2020)

- Recent PDG has $\Lambda(1380)$ added as a two-star resonance

Introduction

- $\Lambda(1405) \to \Sigma^0\pi^0$ decay is pure I=0 (no contamination from $\Sigma^0(1385)$) and data is very limited

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2 + \frac{1}{2}|T^{(1)}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^{(1)*})$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}|T^{(0)}|^2$$

J. C. Nacher, E. Oset, H. Toki, A. Ramos, Phys. Lett. B455, 55 (1999)

- $\Sigma^0\pi^0$ decay is very useful to study the $\Lambda(1405)$ line shape

- GlueX can reconstruct neutral showers well $\Longrightarrow$ ideal to reconstruct $\Sigma^0\pi^0$ decay mode

- Study of the $\Lambda(1405)$ line shape would provide more information on how the $\Sigma\pi$ and $N\bar{K}$ channels contribute to its production

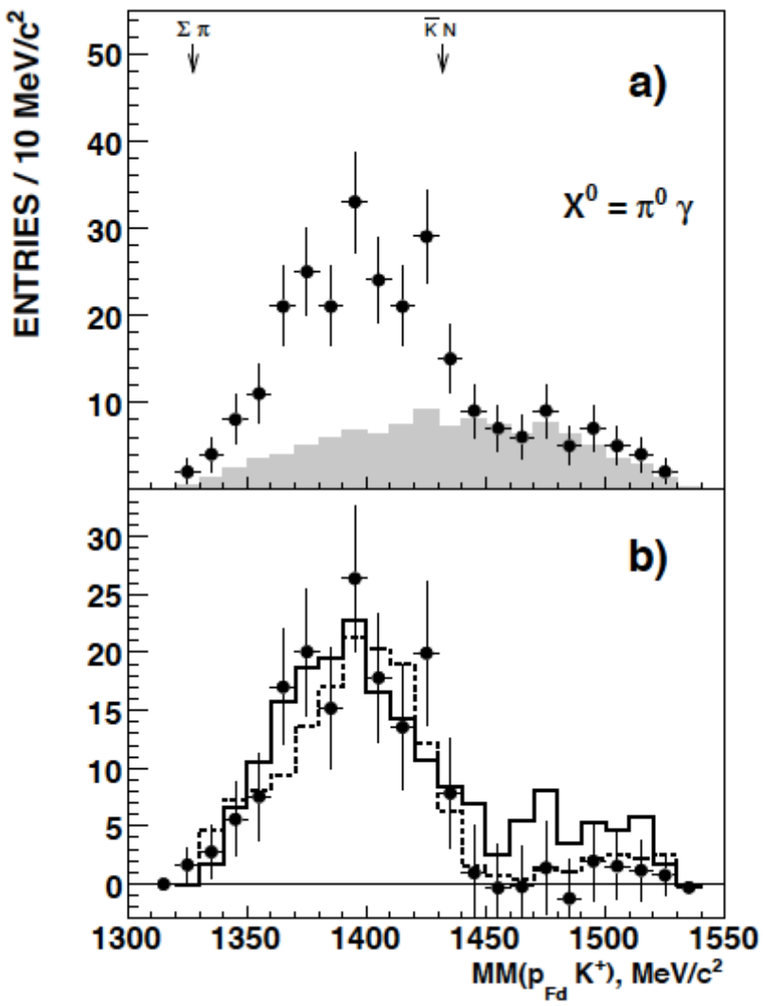
Previous measurements for $\Lambda(1405) \to \Sigma^0\pi^0$

- Early observation in bubble chamber experiments in 1961 **(M. Alston et al., Phys. Rev. Lett. 6, 698 (1961))**

  K^-p interactions at 1.15 GeV/c

I. Zychor, et al., Phys. Lett. B660 167-171 (2008)

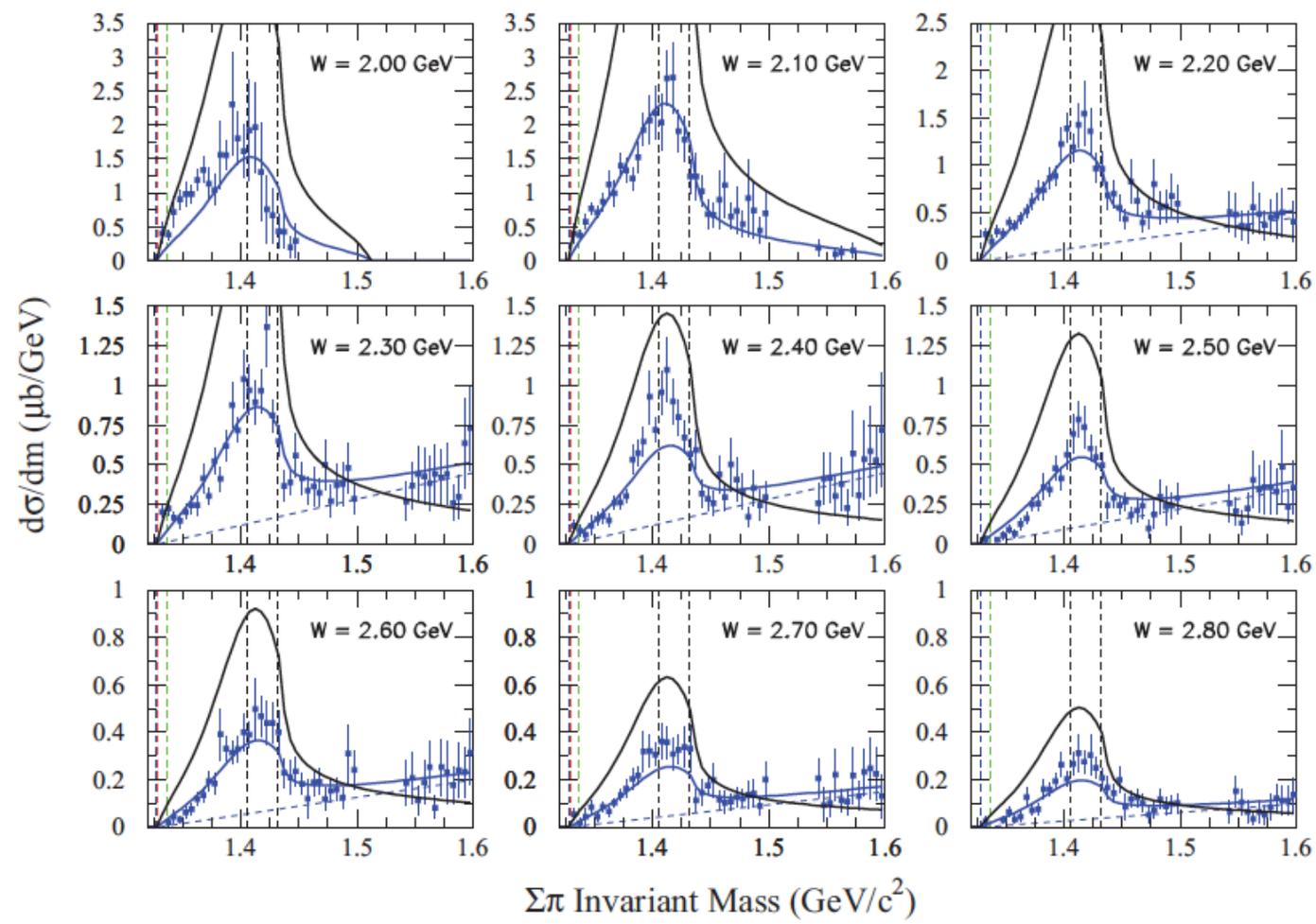
ANKE



Nucl. Phys. B 56 (1973) 15

Nucl. Phys. B 253 (1984) 742

K. Moriya, et al, Phys. Rev. C 87, 035206 (2013)

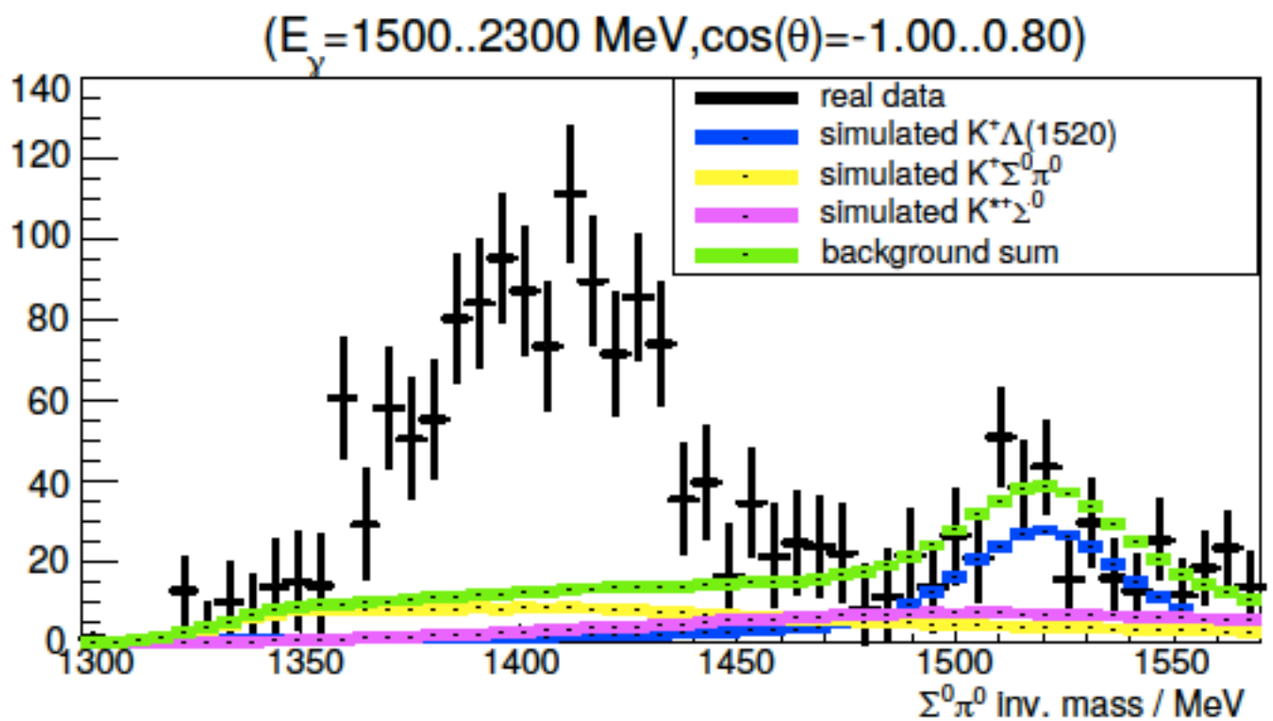


- $pp \to pK^+Y^0$
- 3.65 GeV/c proton beam at COSY-Jülich
- $\sigma_{tot}(pp \to pK^+\Lambda(1405)) = (4.5 \pm 0.9_{stat} \pm 1.8_{syst})\,\mu\text{b}$

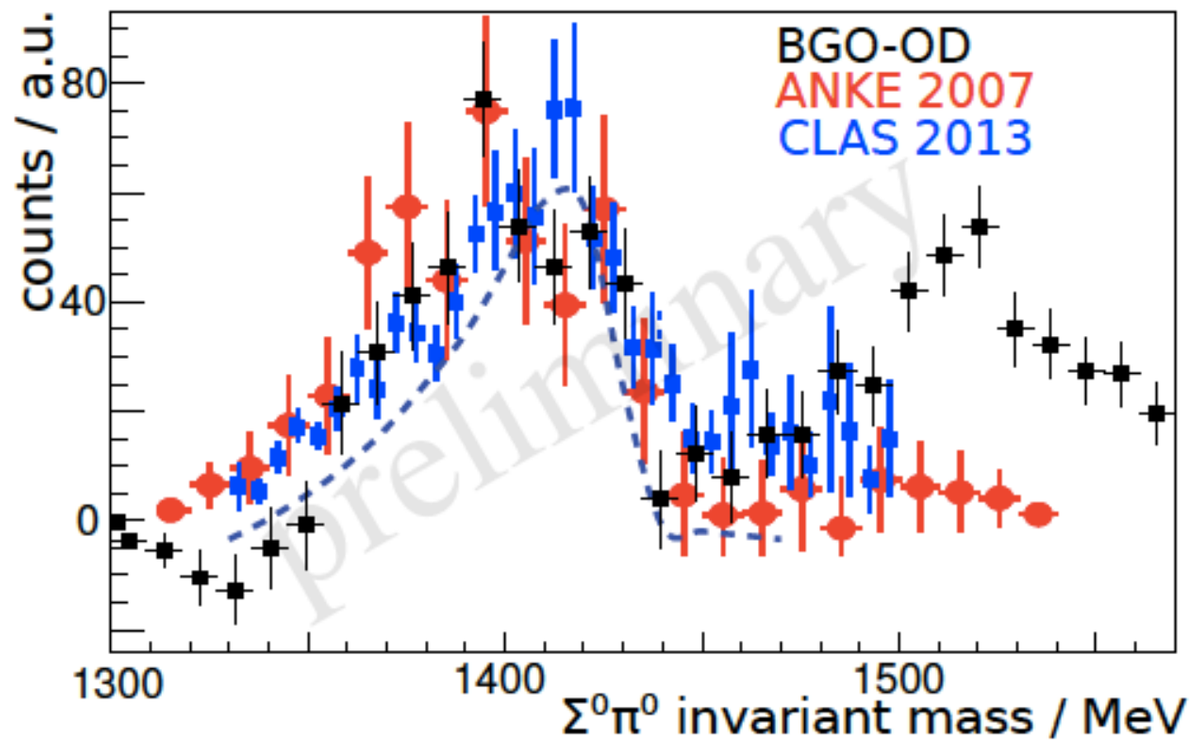
- $\gamma p \to K^+\Sigma\pi$ at **CLAS**
- $1.95 < W < 2.85$ GeV

Previous measurements for $\Lambda(1405) \to \Sigma^0\pi^0$

BGO-OD at ELSA



Comparison



arXiv:2007.08898v3 (2020)

Phys. Rev. C 88, 045201 (2013)
Phys. Lett. B660 167-171 (2008)
Phys. Lett. B455, 55 (1999)

- Exclusive reconstruction of $\gamma p \to K^+\pi^- p\gamma\gamma\gamma$ final state
  - Large background under the Σ^0 peak
  - Limited statistics

GlueX can exclusively reconstruct this state with use of kinematic fitting to reduce background and optimize mass resolution

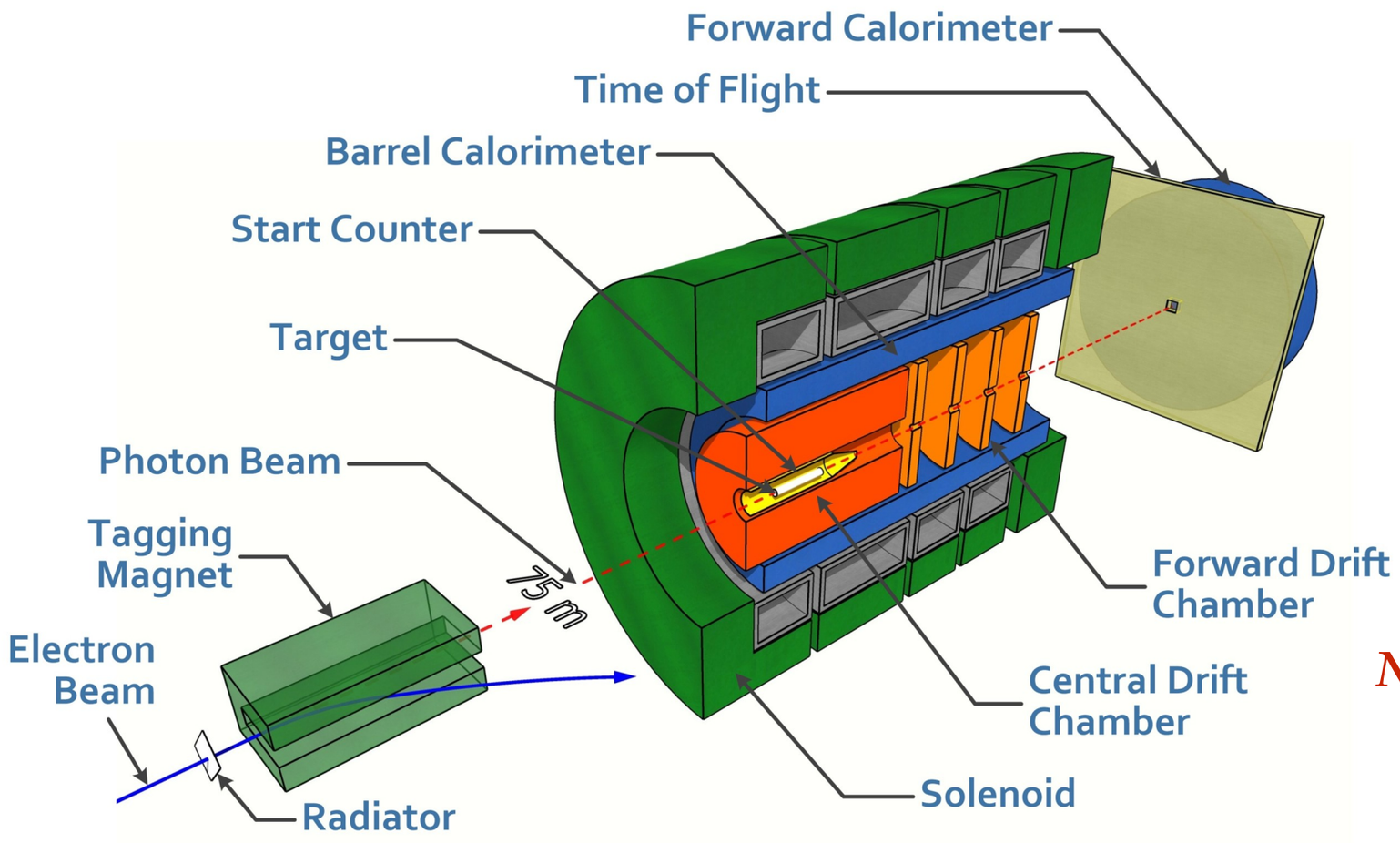
GlueX Experiment

- Located in Hall D at Jefferson Lab, USA
- Photoproduction experiment

Main goals

- Search for hybrid mesons
- Study light quark meson spectrum
- Hyperon spectroscopy

GlueX spectrometer



More info -> M. Khachatryan (Tue)

Nucl. Instrum. Meth. A **987 (2021) 164807**

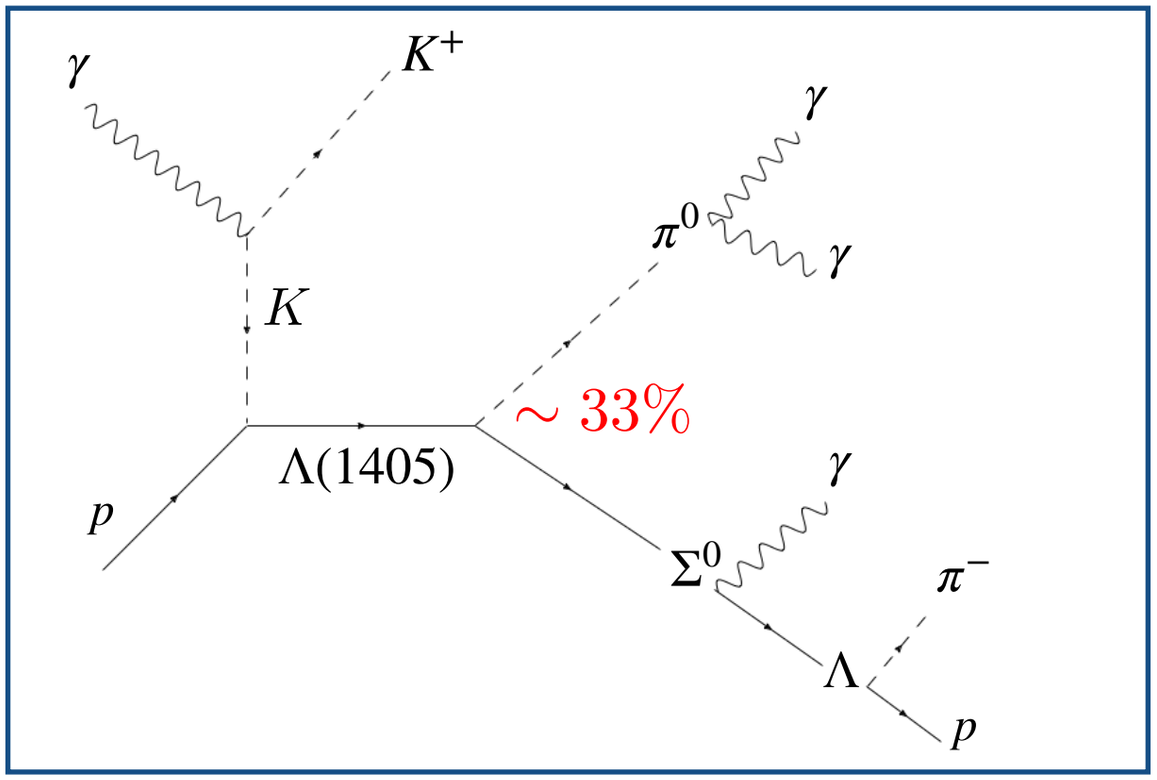
- Liquid hydrogen target
- Bremsstrahlung photons tagged in the energy range 3.0 - 11.6 GeV
  - Linearly polarized tagged photons $\sim$ 9 GeV produced by coherent bremsstrahlung
- Nearly 4π angular coverage
- Detection of charged tracks and photons leads to exclusively reconstruct final state of a reaction

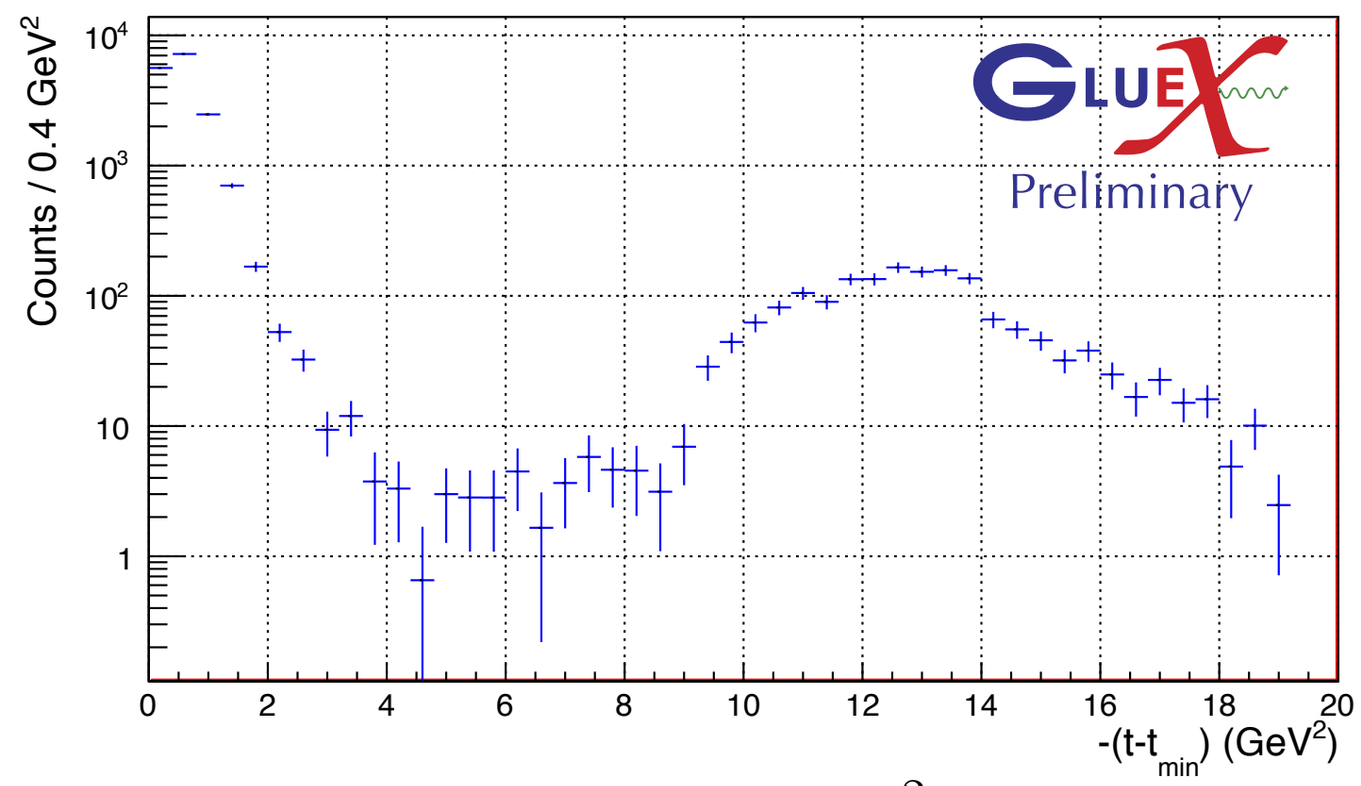
Event selection

- GlueX Phase-I data

- Photon beam energy = 6.5 - 11.6 GeV
  - Luminosity $\sim$ 423 pb^{-1}

- Kinematic fit conserving 4-momentum and constraining event vertex
  - π^0 and Σ^0 masses constrained to improve $\Sigma^0\pi^0$ mass resolution



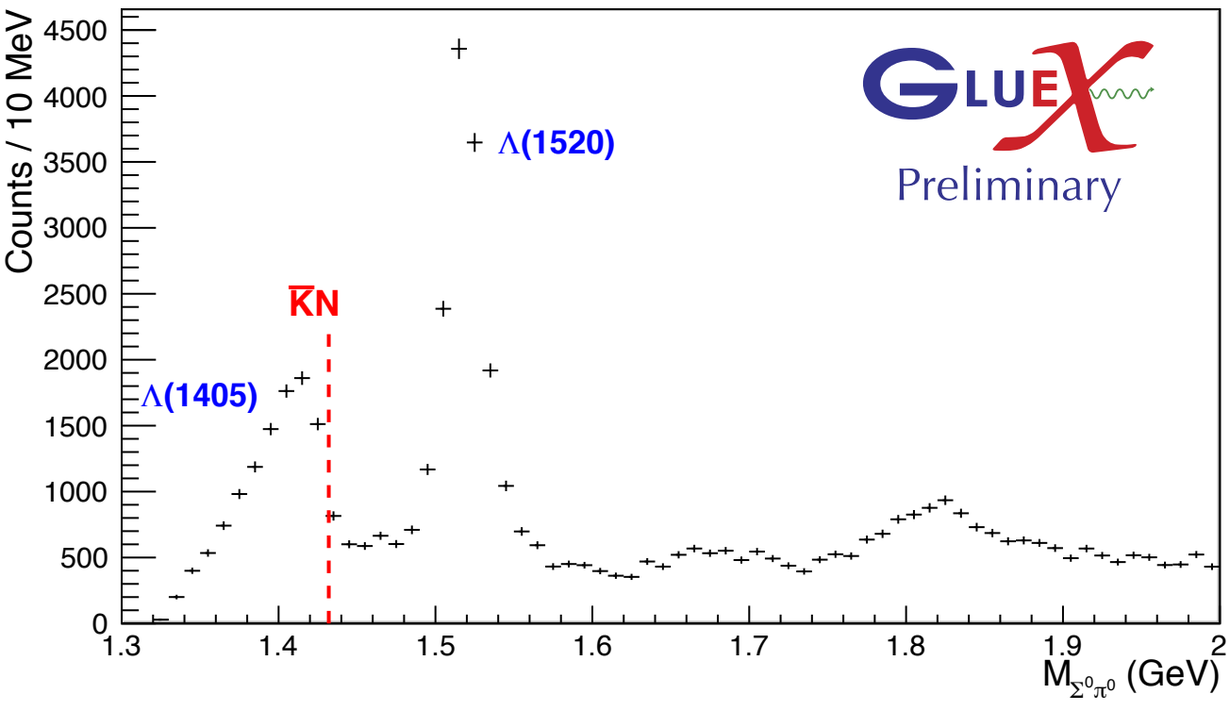


- $t = (p_{\gamma(\mathrm{beam})} - p_{K^+})^2$

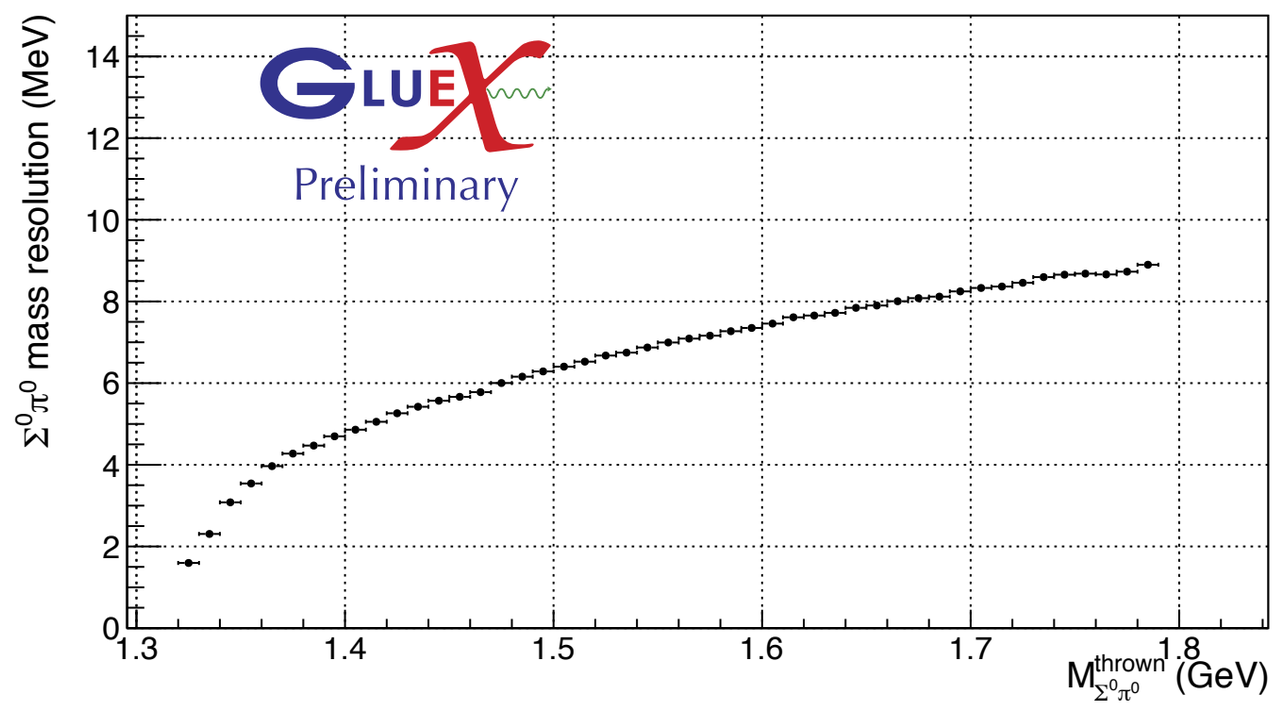
- Focus on t-channel production of $\Lambda(1405)$

Invariant mass of $\Sigma^0\pi^0$

- $0\,\mathrm{GeV}^2 < -(t - t_{min}) < 1.5\,\mathrm{GeV}^2$

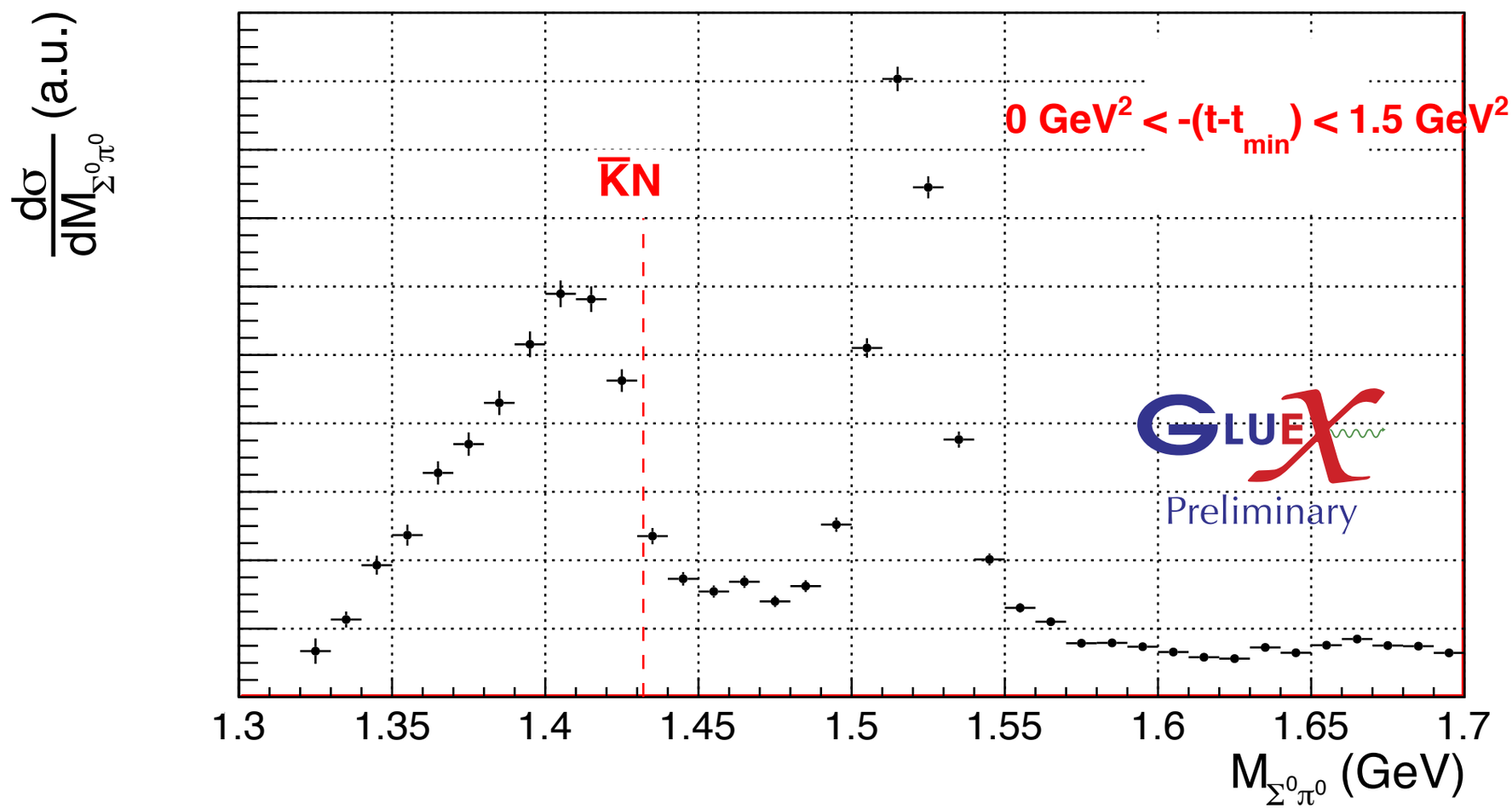


$\Sigma^0\pi^0$ mass resolution from MC



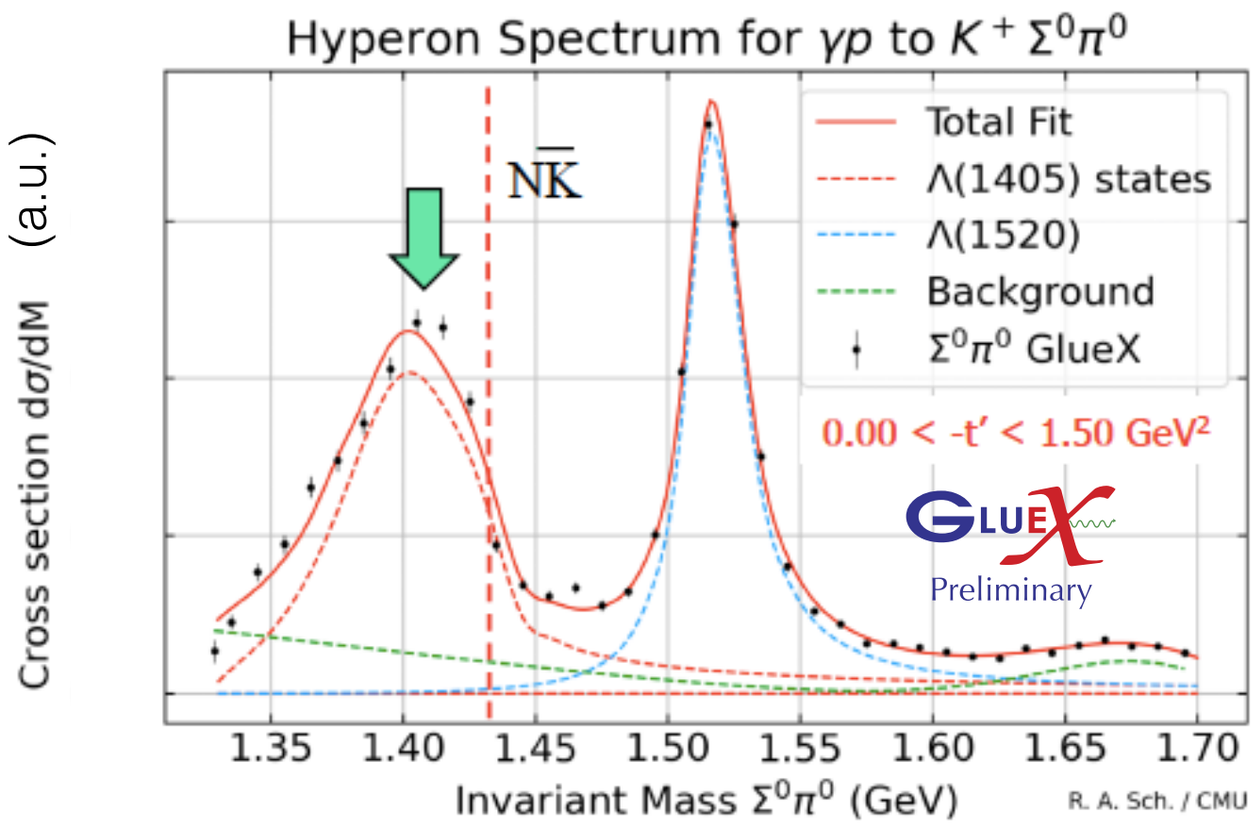
- Clear peaks of $\Lambda(1405)$ and $\Lambda(1520)$
- 13351 ± 139 counts in the $\Lambda(1405)$ region ($M_{\Sigma^0\pi^0} < 1.47$ GeV) (Assumed background free)
- A sharp drop of yield at $\bar{K}N$ threshold seen for $\Lambda(1405)$
- Simulations indicate good resolution for $\Sigma^0\pi^0$ mass in $\Lambda(1405)$ region

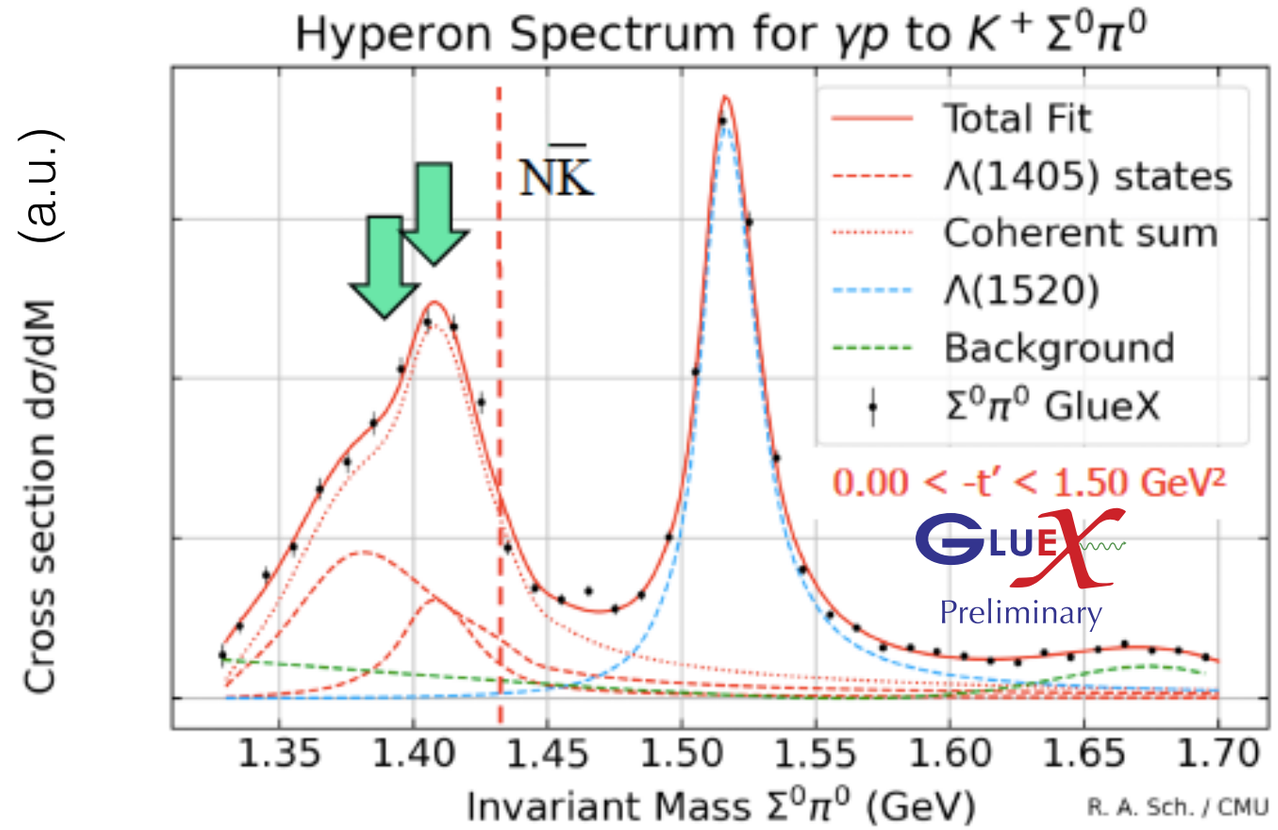
$\Lambda(1405)$ line shape - $\frac{d\sigma}{dM_{\Sigma^0\pi^0}}$



- Normalization yet to be finalized
- Uncertainties are only statistical
- $\Lambda(1405)$ line shape deviates from a Breit-Wigner form
- Test two hypotheses for fitting $\Lambda(1405)$ line shape (next slide)

Two line shape ansatzes



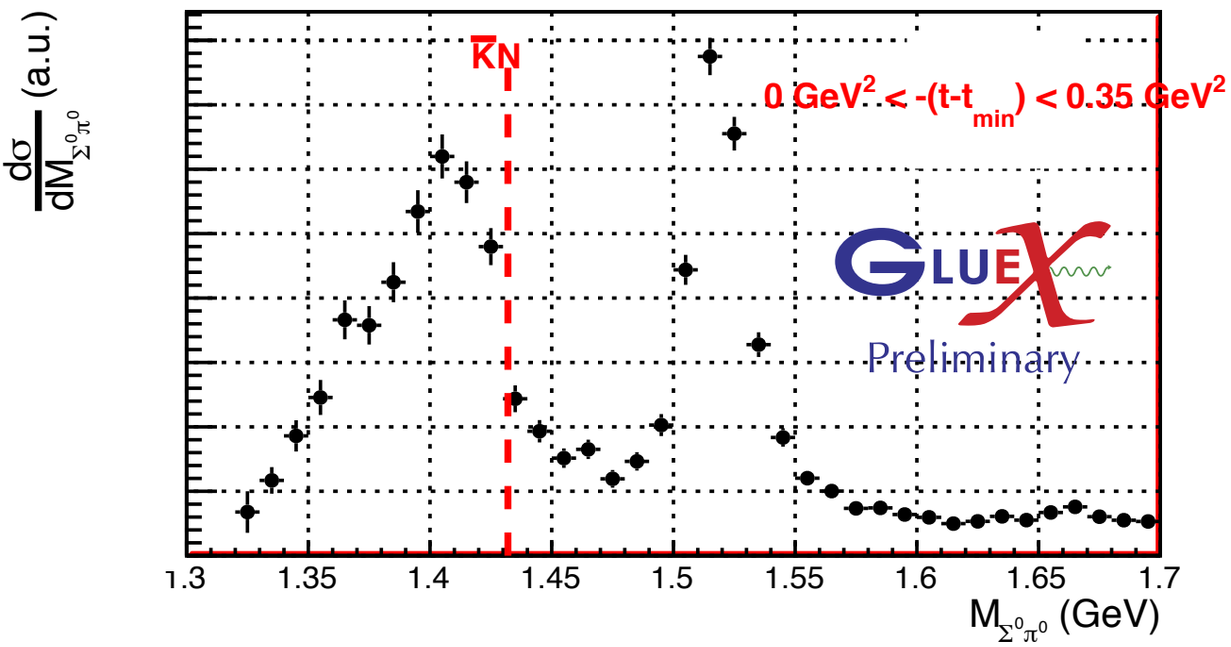


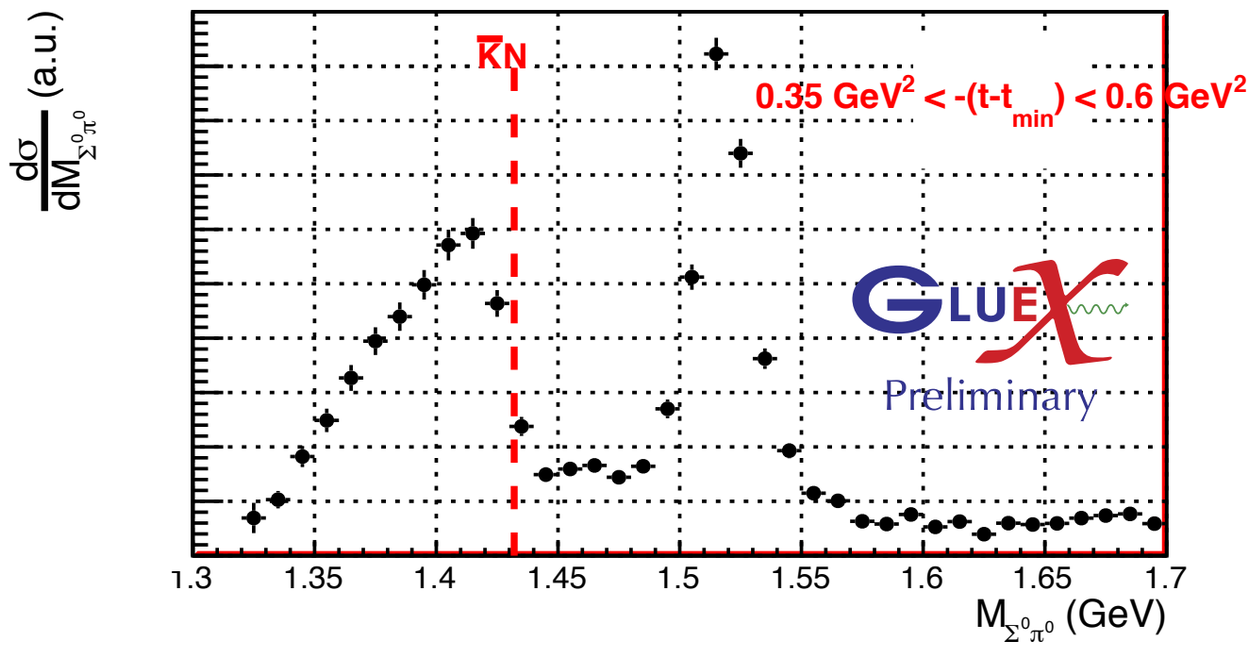
- Single $\Lambda(1405)$
- Parameterized with one Flatté amplitude
- Incoherent $\Lambda(1520)$ and backgrounds
- χ^2/d.o.f of the fit = 5.1
- Centroid at 1407 MeV

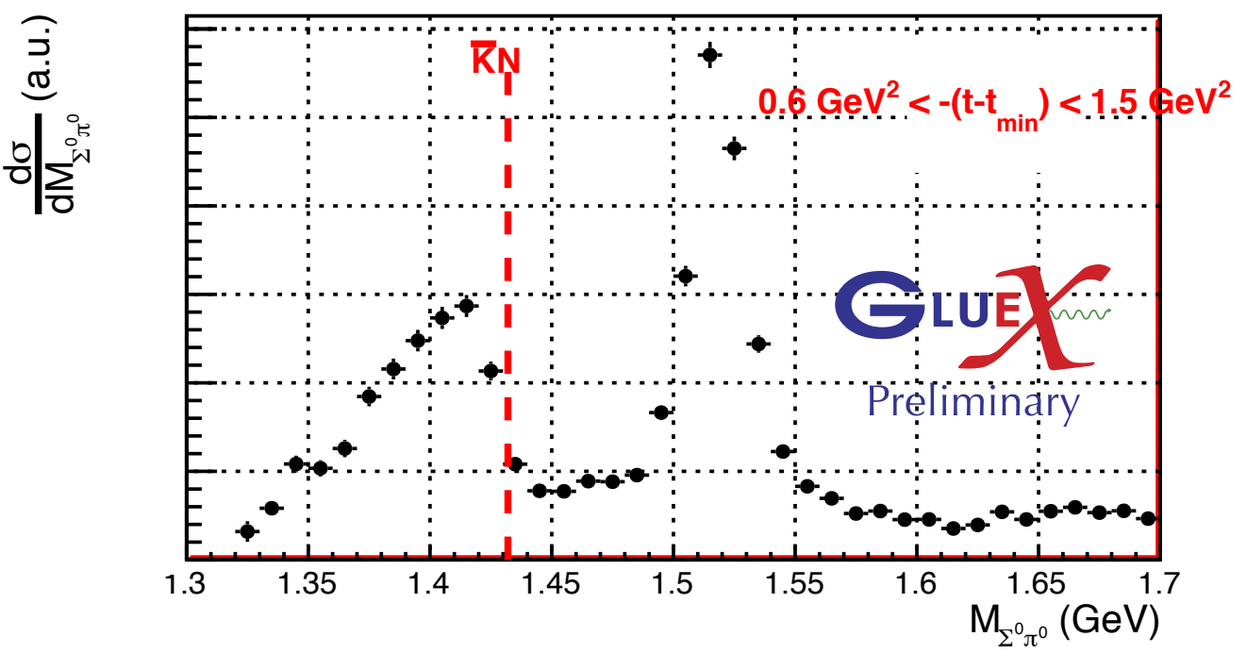
- More detailed fitting is in progress

- Compound coherent $\Lambda(1405)$'s
- Two Flatté amplitudes
  - no strong phase between them
  - a common Flatté factor
- Incoherent $\Lambda(1520)$ and backgrounds
- $\boxed{\chi^2/\text{d.o.f of the fit} = 3.5}$ Better fit !
- $\Lambda(1405)$ is split into two centroids at ~ 1387 MeV and ~ 1409 MeV

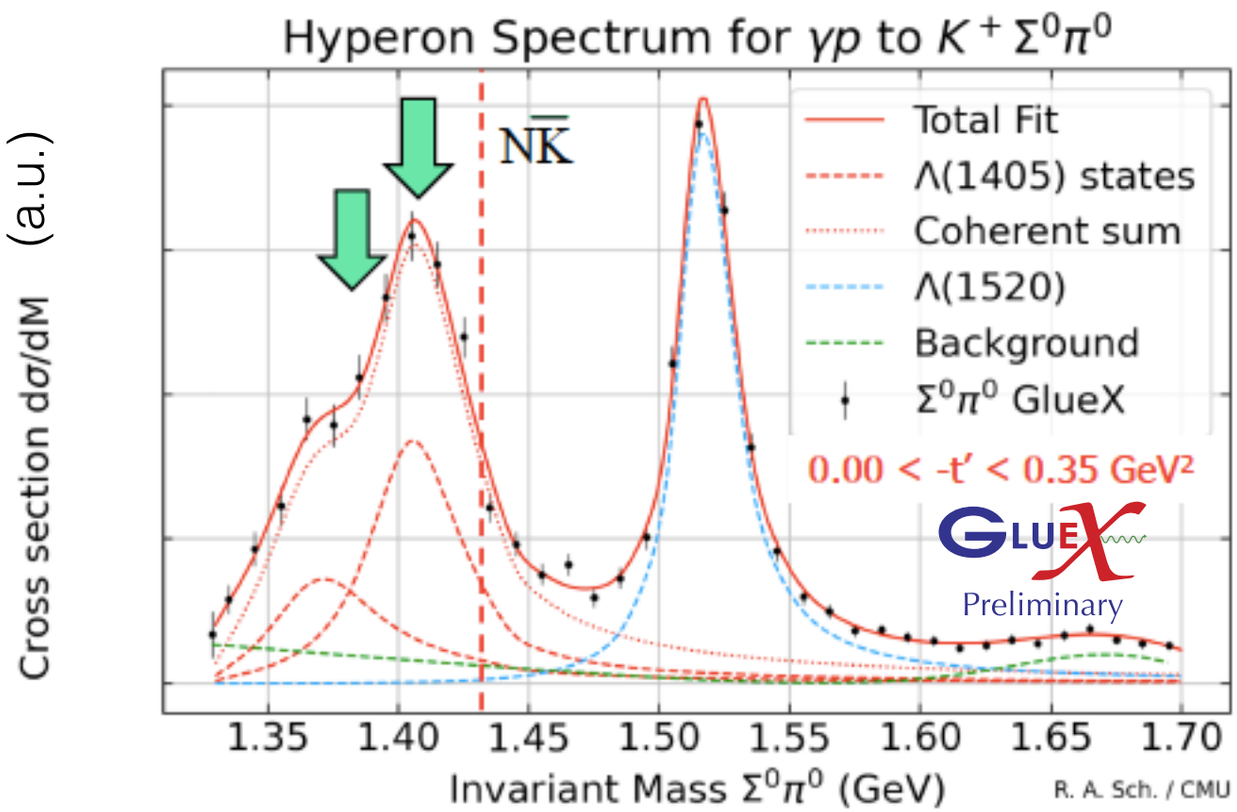
$\frac{d\sigma}{dM_{\Sigma^0\pi^0}}$ for different bins of $-(t-t_{min})$

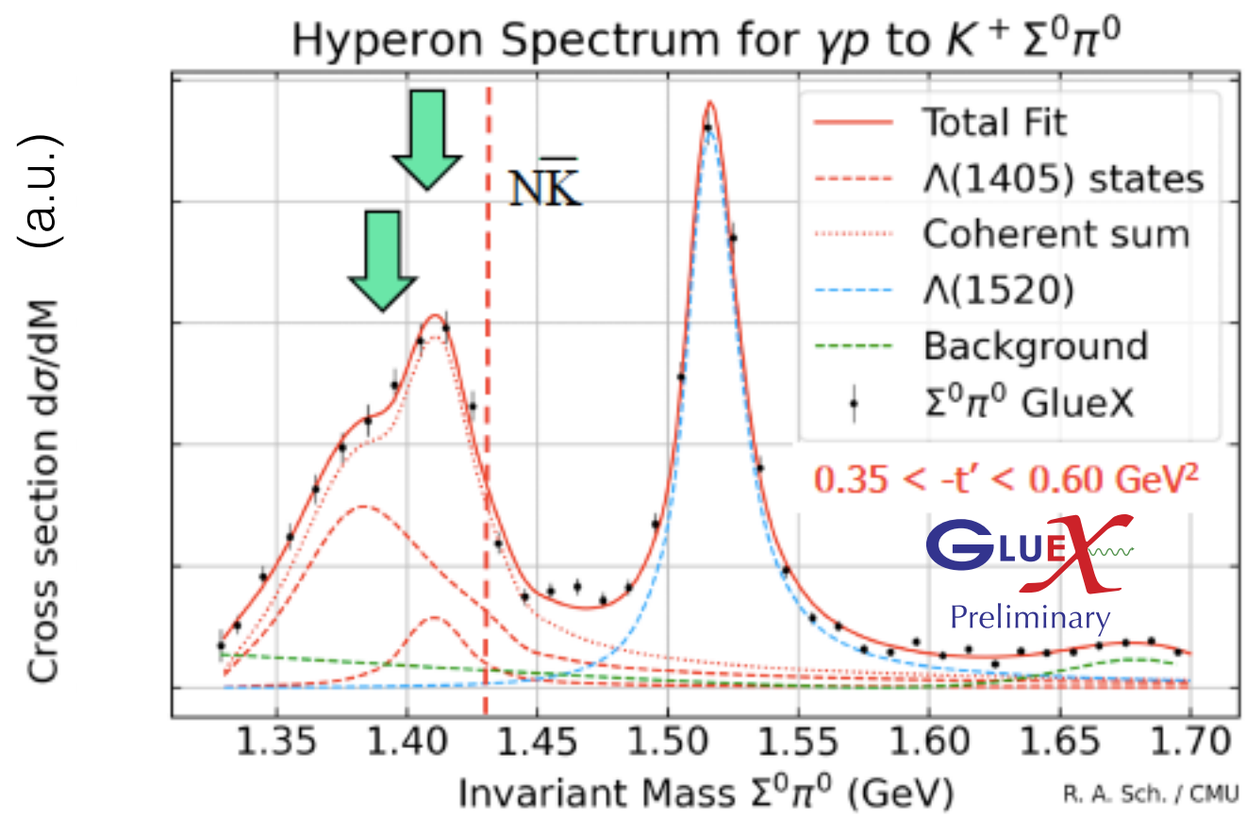


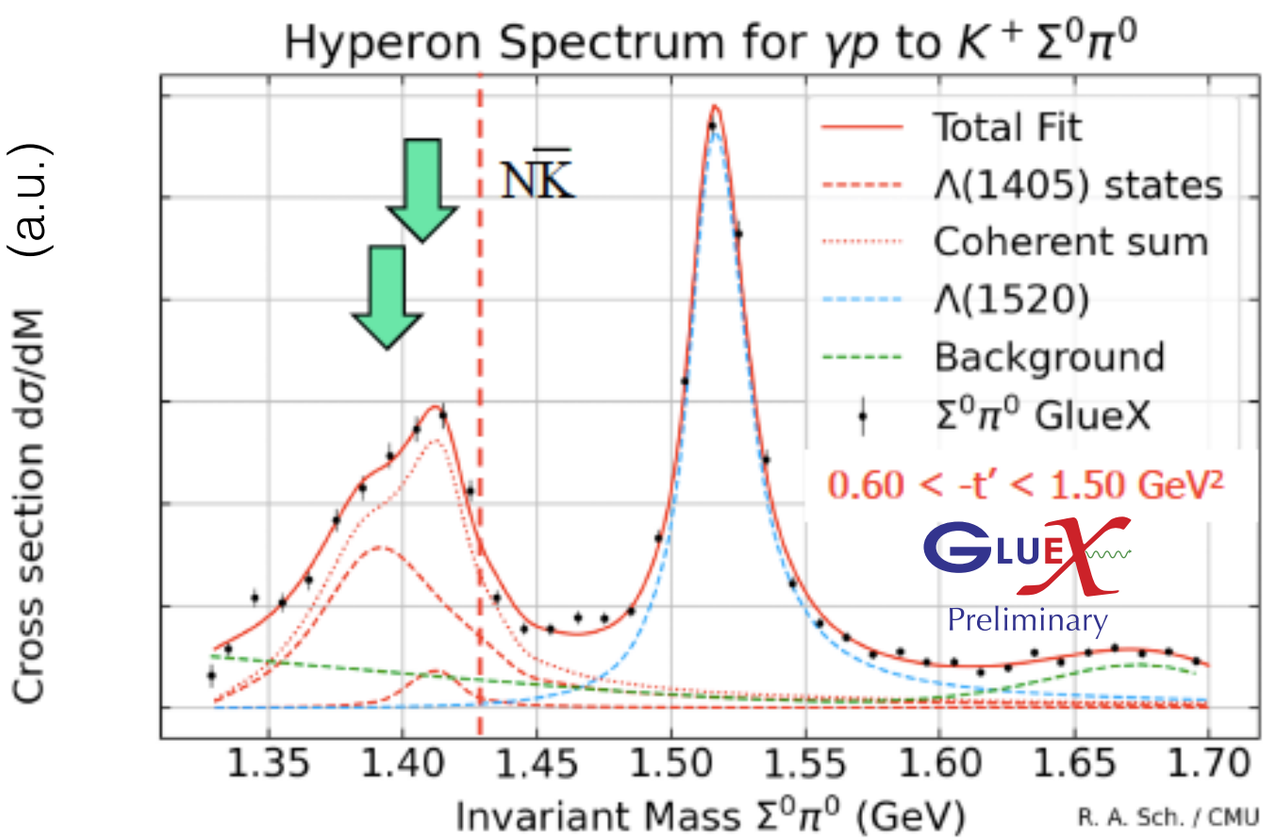




- t-dependence seen in $\Lambda(1405)$ line shape







- Coherent fit to two $\Lambda(1405)$'s
- Incoherent $\Lambda(1520)$ and backgrounds
- Relative intensities of two $\Lambda(1405)$'s change with $-t'$
- Fits describe the data well in all $-t'$ bins

Summary

- GlueX is ideally suited for exclusive reconstruction of $\Lambda(1405) \to \Sigma^0\pi^0$
  - Highest statistics obtained so far
  - $\sim$ 5 MeV resolution in mass for $\Sigma^0\pi^0$ mass near $\Lambda(1405)$
- $\Lambda(1405)$ line shape clearly seems to deviate from a Breit-Wigner form
- Fits to line shape favor a composite (two coherent states) picture for $\Lambda(1405)$
- t-dependence observed for the $\Lambda(1405)$ line shape
- GlueX preliminary result supports previous theory and experiment suggesting the $\Lambda(1405)$ is a composite baryon state

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