# Hyperon Program in Hall D

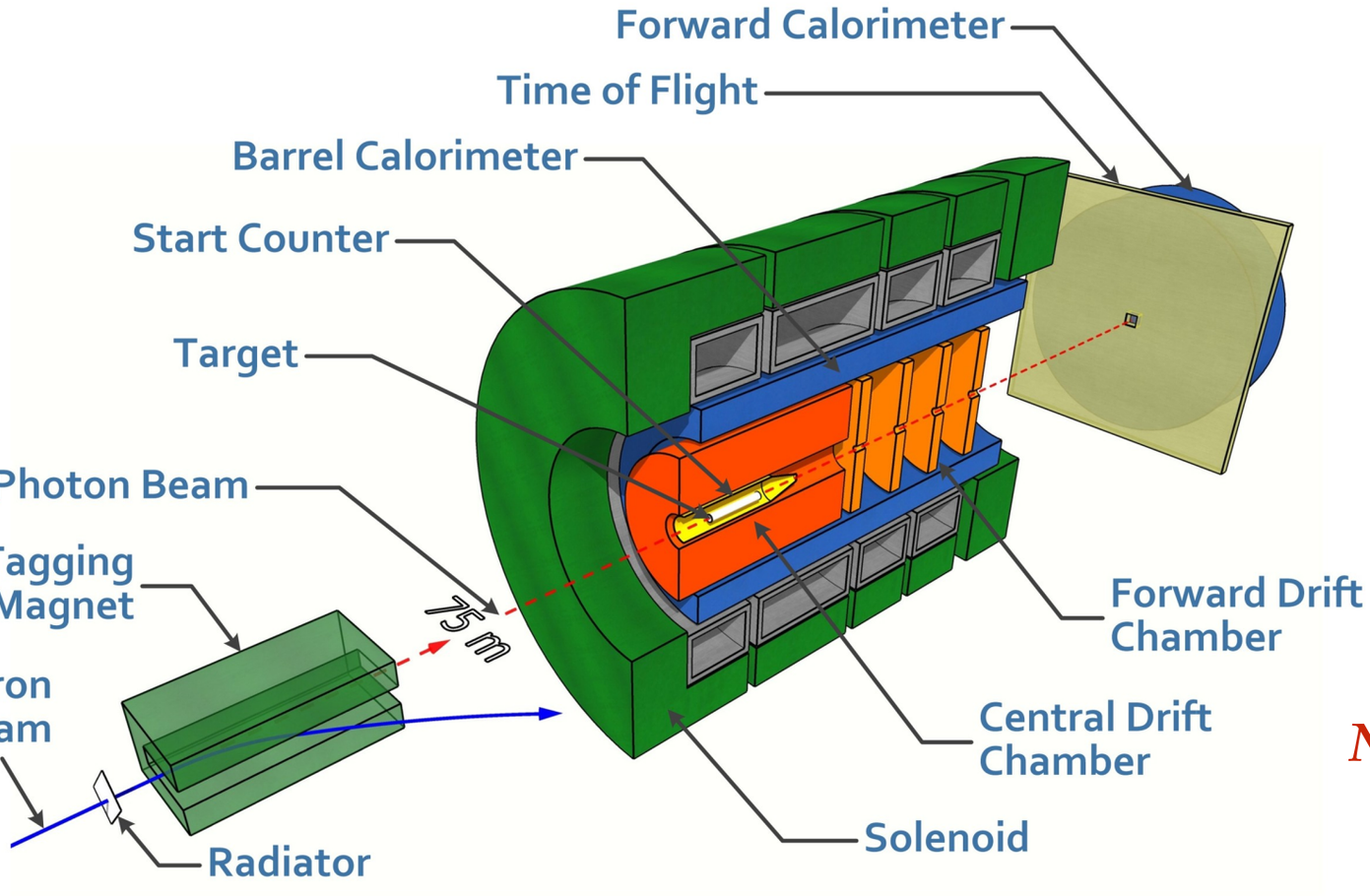
**Nilanga Wickramaarachchi**

**On behalf of the GlueX Collaboration**

**JLUO Meeting 2023**

**06/26/2023**

# GlueX experiment



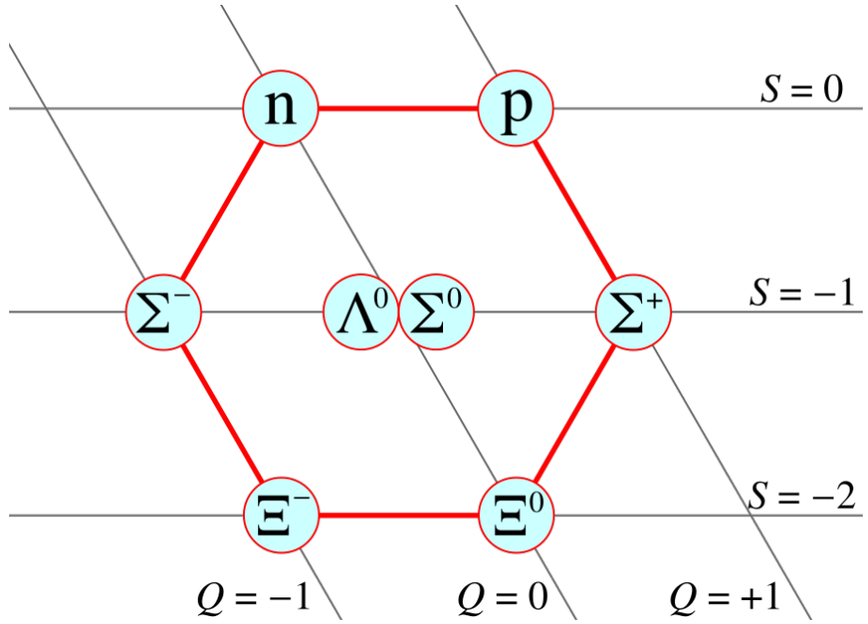

- Located in Hall D
- Photoproduction experiment
- GlueX-I: 2017-2018
  Luminosity $= 439.6$ pb$^{-1}$
  ($E_\gamma > 6.0$ GeV)

***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 $4\pi$ angular coverage
- Detection of charged tracks and photons leads to exclusively reconstruct final state of a reaction
- GlueX phase II started in 2019 with DIRC detector installed

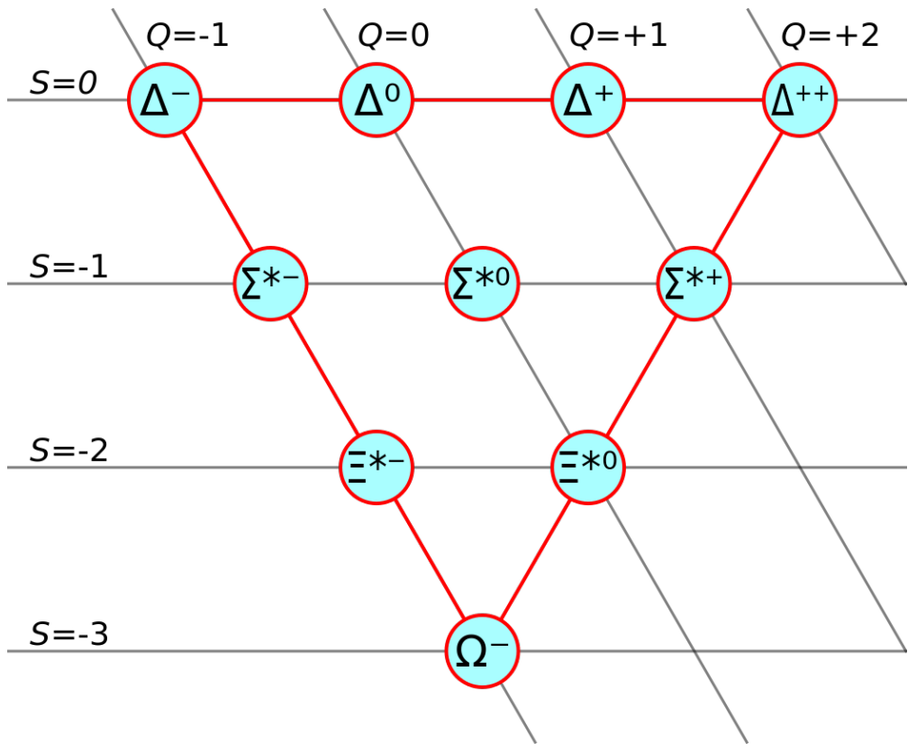
# Hyperons studied

- $\Lambda(1405) \to \Sigma^0\pi^0$
- $Y, Y^*$ production mechanisms ($Y = \Lambda, \Sigma$)
  - $\Sigma^0 \to \Lambda\gamma$
  - $\Lambda(1520) \to K^- p$
  - $\Lambda\bar{\Lambda}$




$J = \frac{1}{2}$

- Ground and excited states of Cascades
  - $\Xi^-(1320)$
  - $\Xi^{*-}(1530)$
  - $\Xi^{*-}(1820)$




$J = \frac{3}{2}$

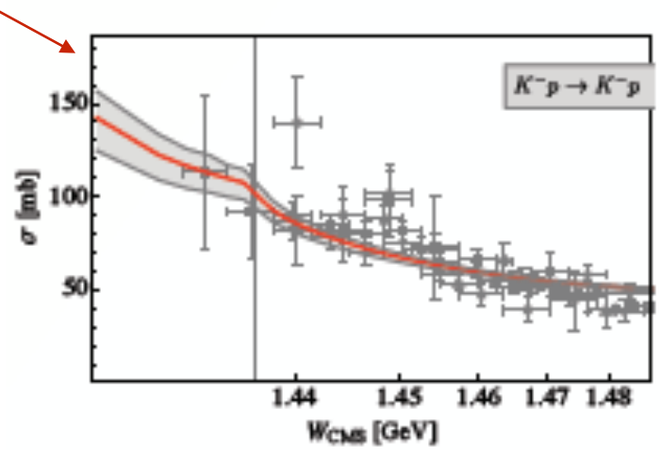
# $\Lambda(1405)$ – Introduction

- $\Lambda(1405)$ - 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 — $N\overline{K}$ | $\Sigma\pi$ | Other channels |
|---|---|---|---|---|---|
| $\Lambda(1116)$ | $1/2^+$ | **** | | | $N\pi$ (weak decay) |
| $\Lambda(1380)$ | $1/2^-$ | ** | ** | ** | |
| $\Lambda(1405)$ | $1/2^-$ | **** | **** | **** | |
| $\Lambda(1520)$ | $3/2^-$ | **** | **** | **** | $\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$ |
| $\Lambda(1600)$ | $1/2^+$ | **** | *** | **** | $\Lambda\pi\pi, \Sigma(1385)\pi$ |
| $\Lambda(1670)$ | $1/2^-$ | **** | **** | **** | $\Lambda\eta$ |
| $\Lambda(1690)$ | $3/2^-$ | **** | **** | *** | $\Lambda\pi\pi, \Sigma(1385)\pi$ |

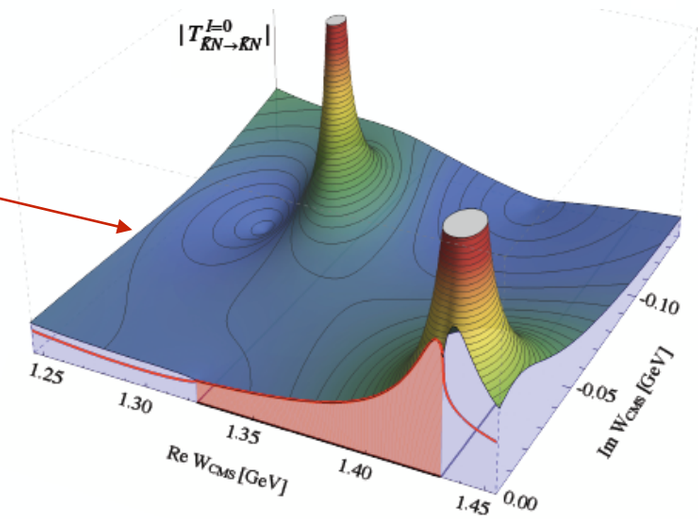
V.D. Burkert et al., "$\Lambda$ and $\Sigma$ Resonances", The Review of Particle Physics (2022)




- $\Lambda(1405)$ 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))

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




Maxim Mai, arXiv:2010.00056 (2020)

- $\Lambda(1405) \to \Sigma^0\pi^0$ 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 $\implies$ 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

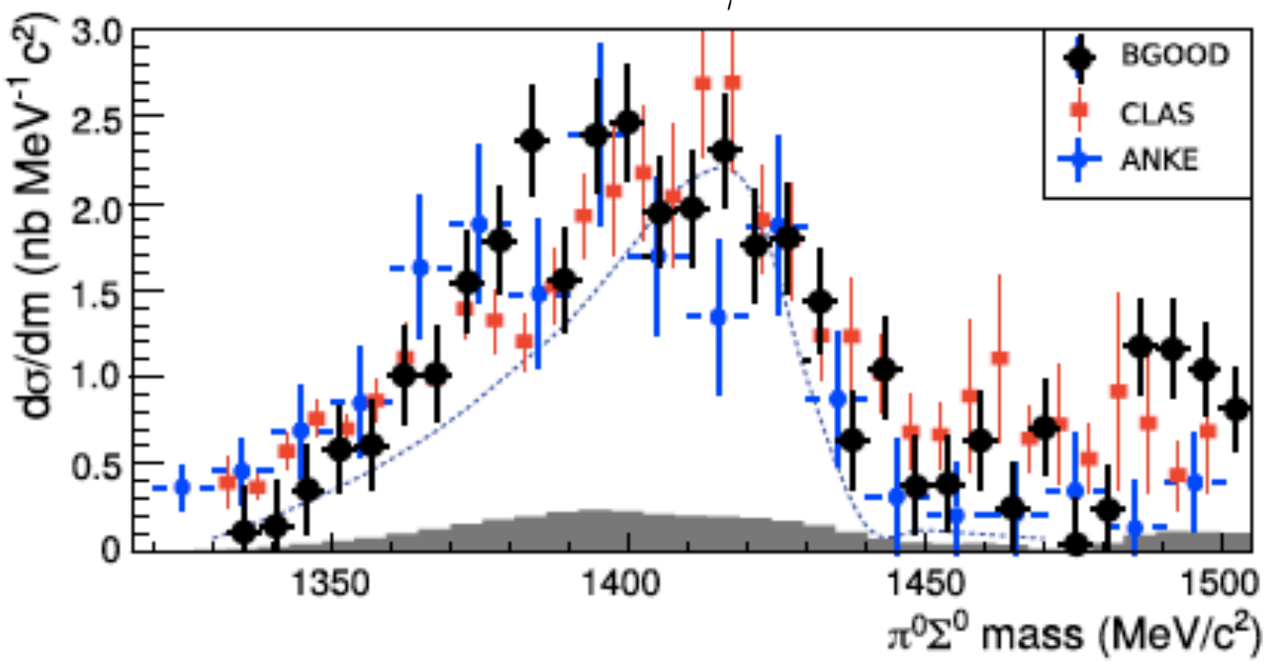
# Previous measurements for $\Lambda(1405) \to \Sigma^0\pi^0$

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

  $K^-p$ interactions at 1.15 GeV/c

| Experiment | Beam momentum / energy | Reaction |
|---|---|---|
| ANKE | 3.65 GeV/$c$ proton beam | $pp \to pK^+Y^0$ |
| CLAS | $1.95 < W < 2.85$ GeV | $\gamma p \to K^+\Sigma\pi$ |
| BGOOD | $1.55 < E_\gamma < 2.9$ GeV | $\gamma p \to K^+\Sigma^0\pi^0$ |

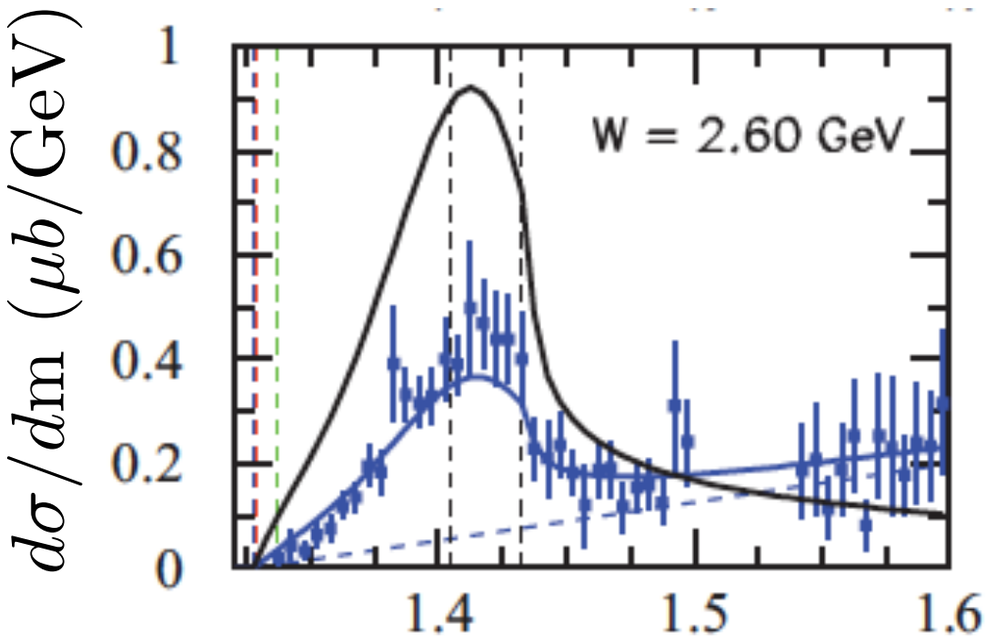
BGOOD results for $E_\gamma = 1550 - 2300$ MeV




**Phys. Lett. B 833 137375 (2022)**
**Phys. Lett. B 660 167 (2008)**

**CLAS**

**Phys. Rev. C 87, 035206 (2013)**




**Phys. Rev. C 87, 035206 (2013)**
**Phys. Lett. B455, 55 (1999)**

——— I = 0 line shape

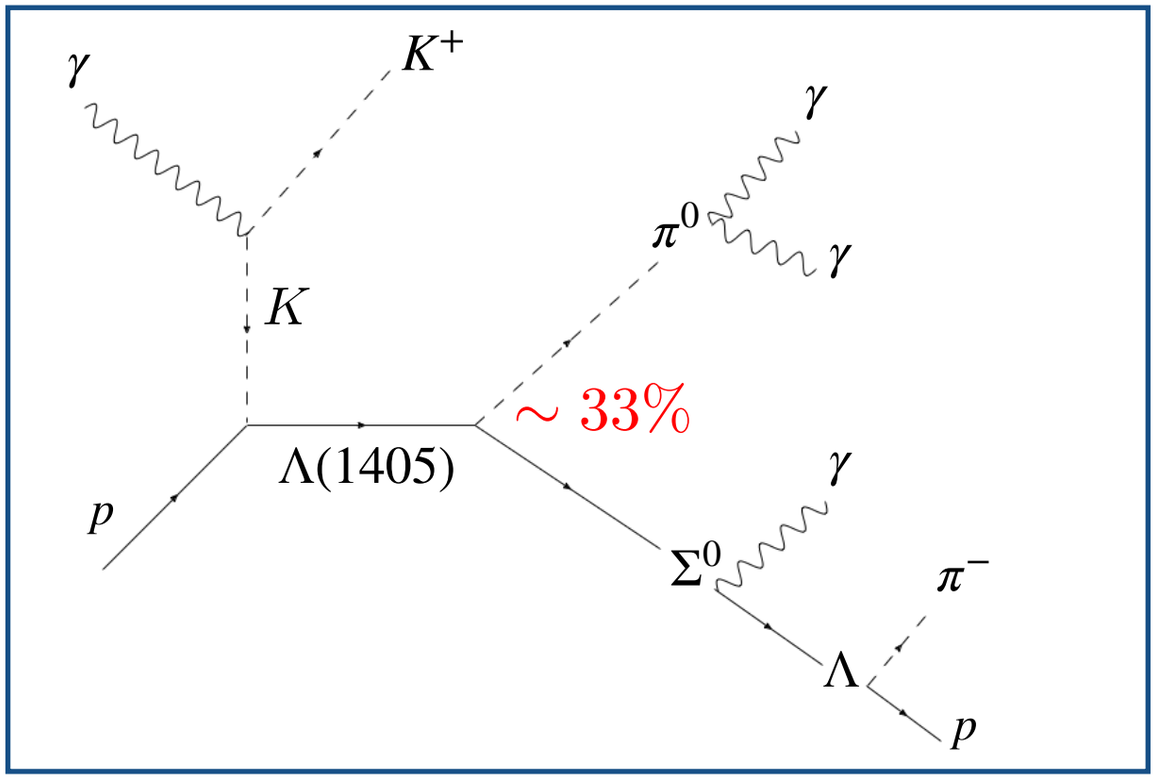
– – – – Incoherent background

——— Fit to data

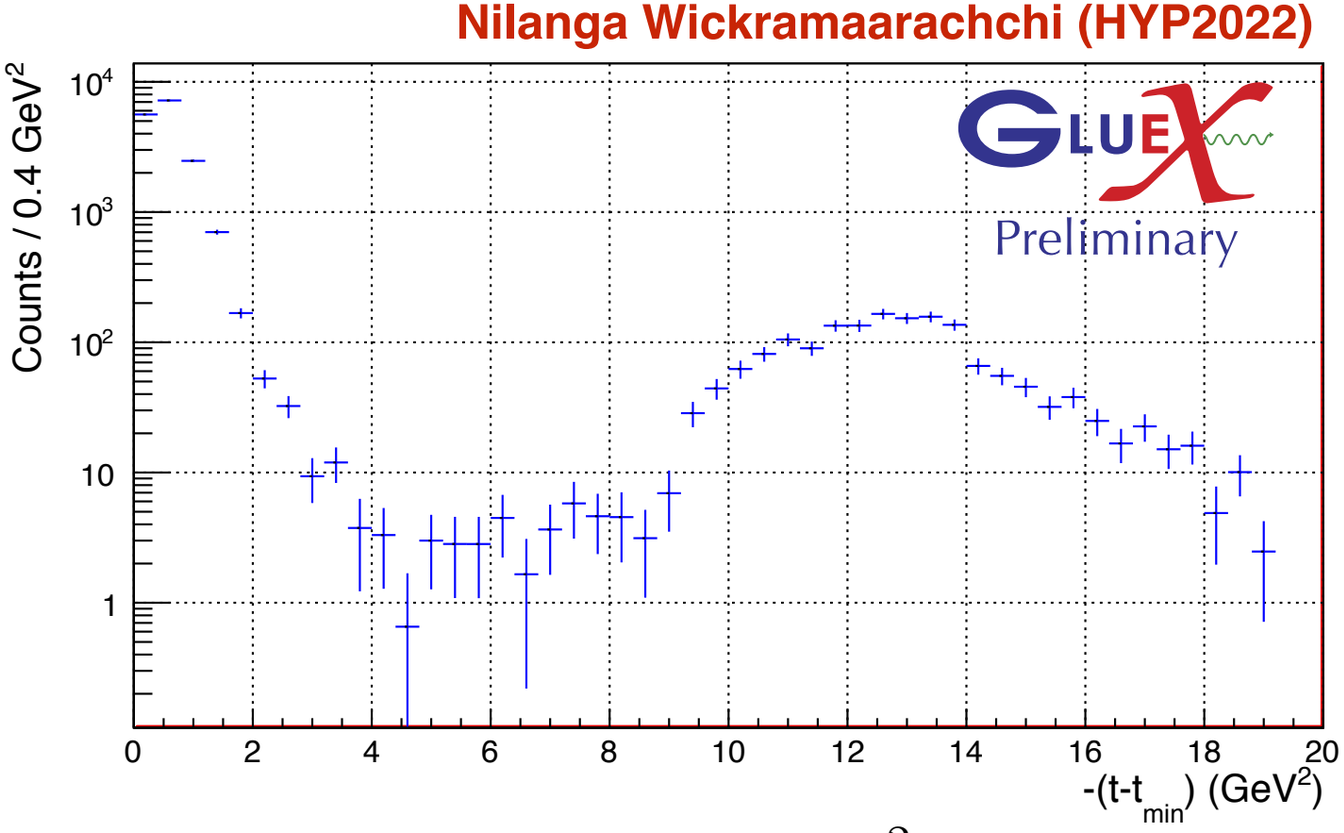
GlueX can exclusively reconstruct $\Lambda(1405) \to \Sigma^0\pi^0$ with use of kinematic fitting to reduce background and optimize mass resolution

# Event selection

- GlueX Phase-I data
- Photon beam energy = 6.5 - 11.6 GeV
  - Luminosity $\sim$ 423 pb$^{-1}$
- Exclusive reconstruction of $\gamma p \to K^+\pi^- p\gamma\gamma\gamma$
- Kinematic fit conserving 4-momentum and constraining event vertex
  - $\pi^0$ and $\Sigma^0$ masses constrained to improve $\Sigma^0\pi^0$ mass resolution




Nilanga Wickramaarachchi (HYP2022)

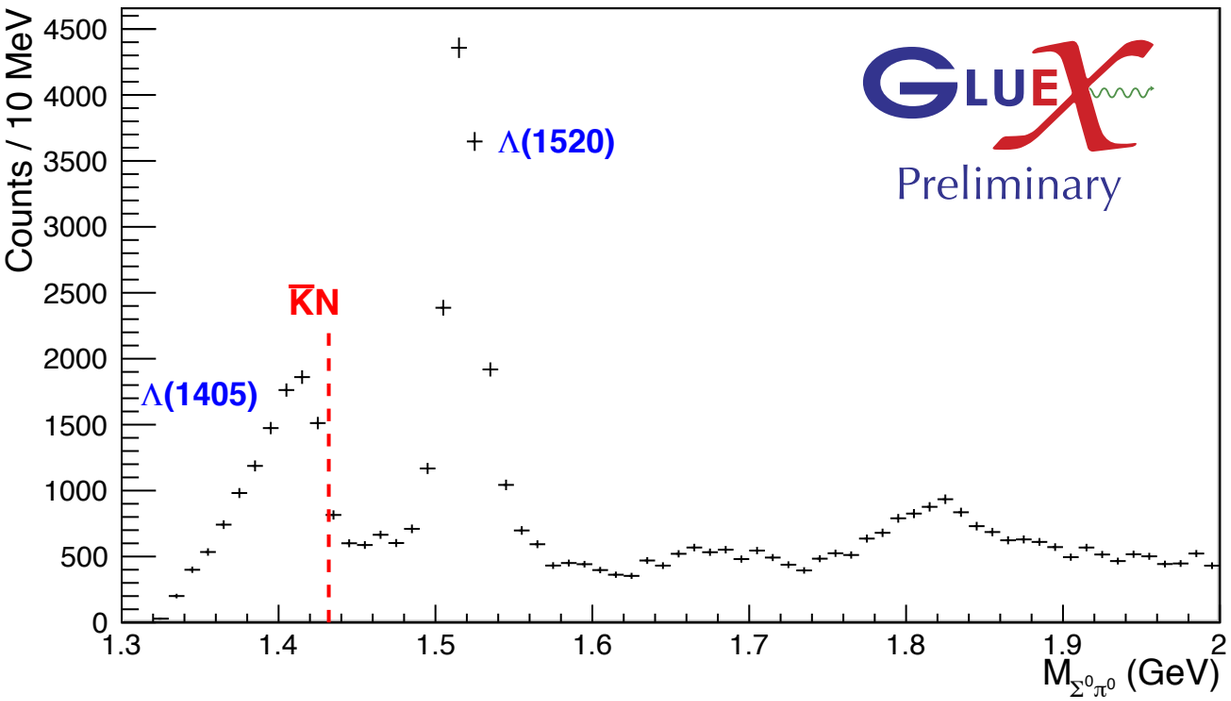



- $t = (p_{\gamma(\text{beam})} - p_{K^+})^2$

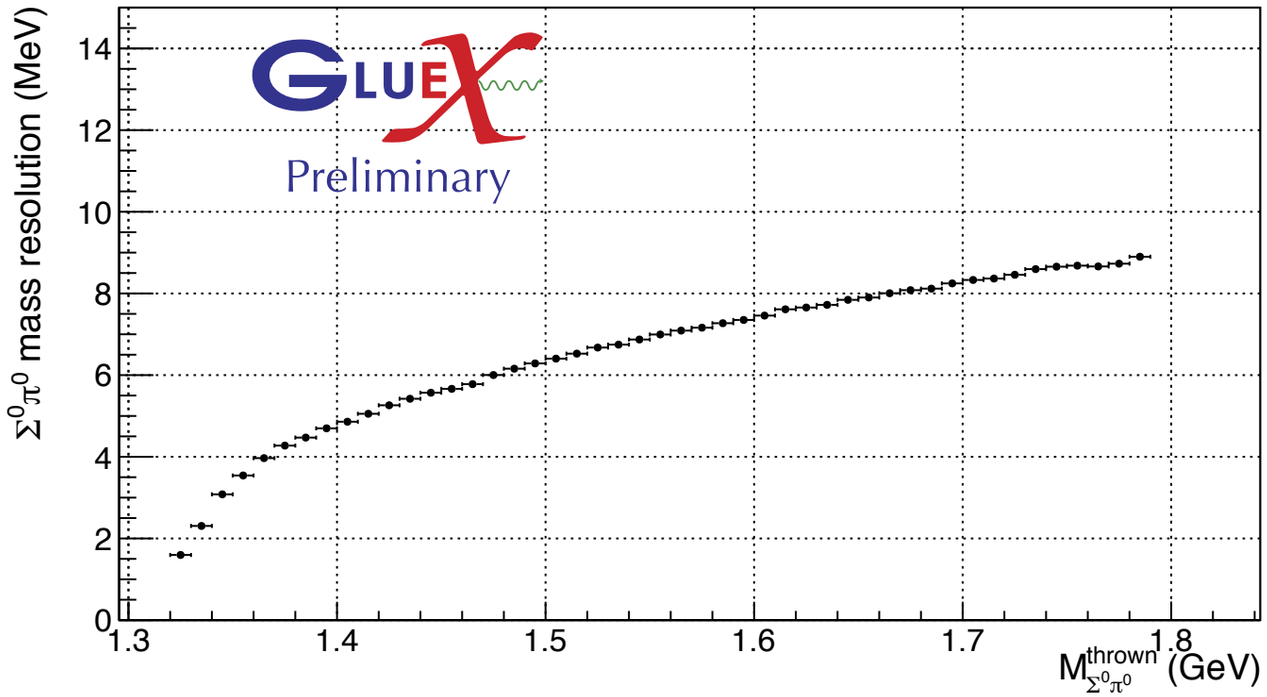
- Focus on t-channel production of $\Lambda(1405)$

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

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

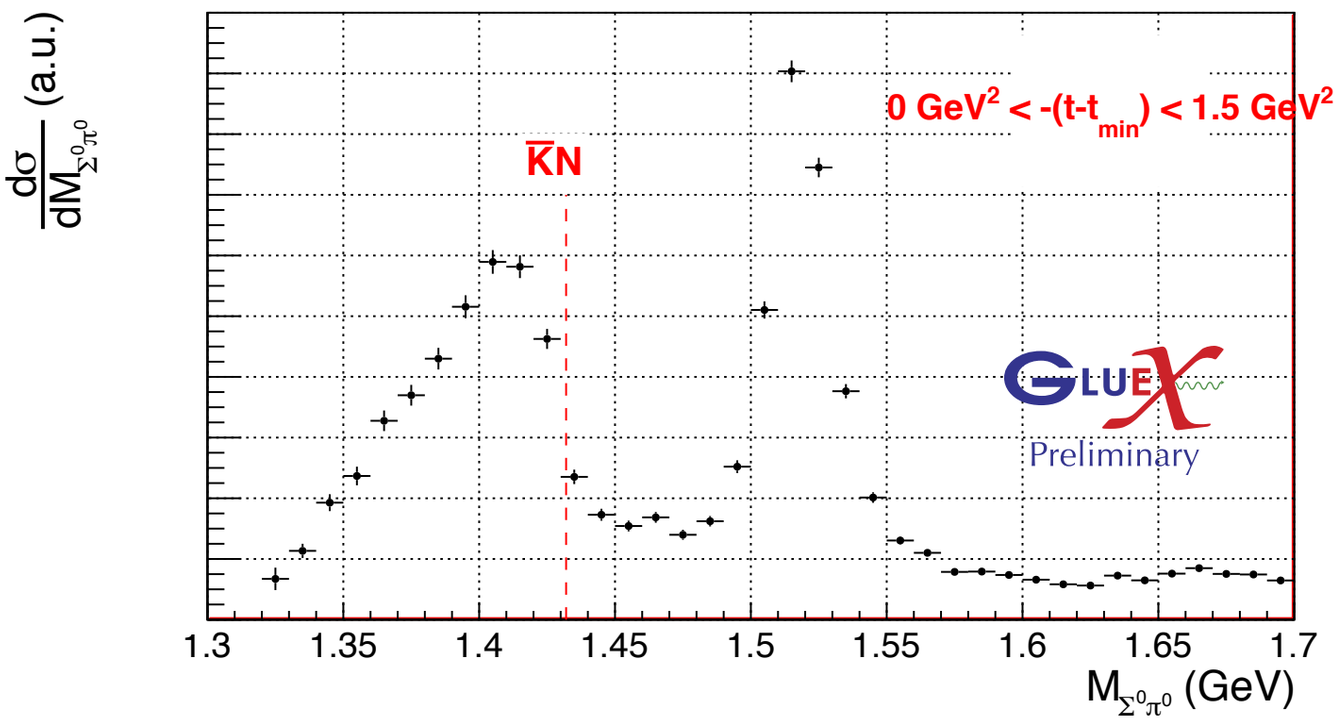


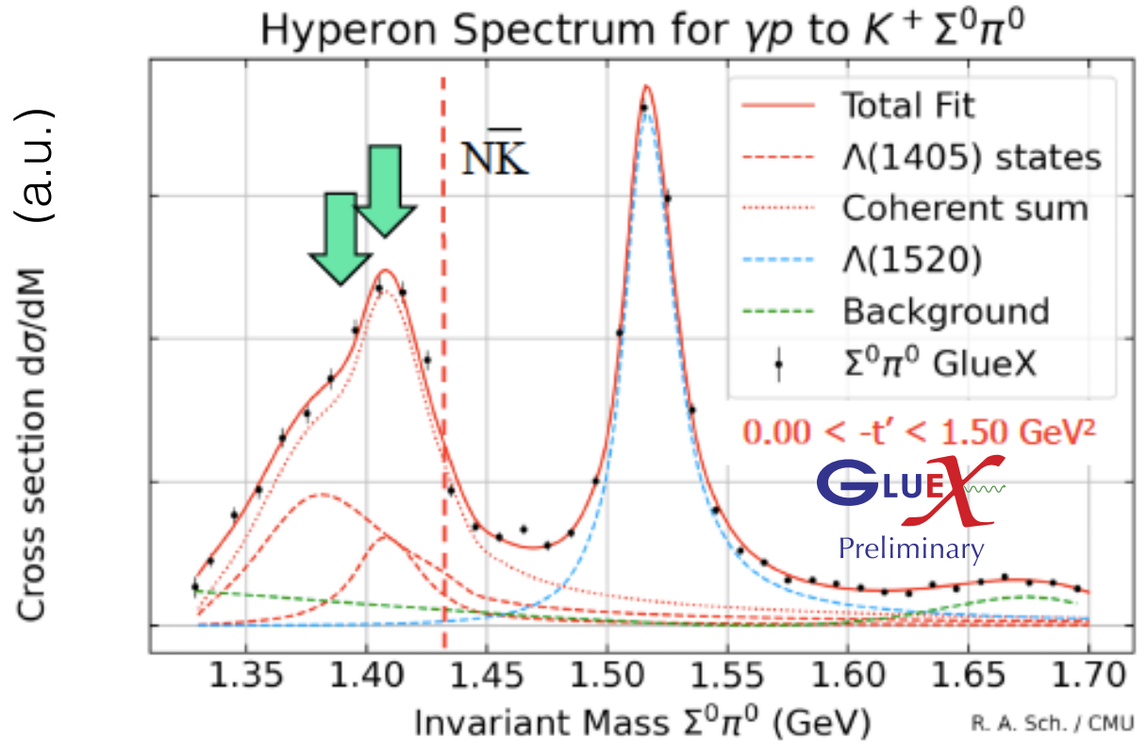

$\Sigma^0\pi^0$ mass resolution from MC




- Clear peaks of $\Lambda(1405)$ and $\Lambda(1520)$
- $13351 \pm 139$ 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 - $\frac{d\sigma}{dM_{\Sigma^0\pi^0}}$



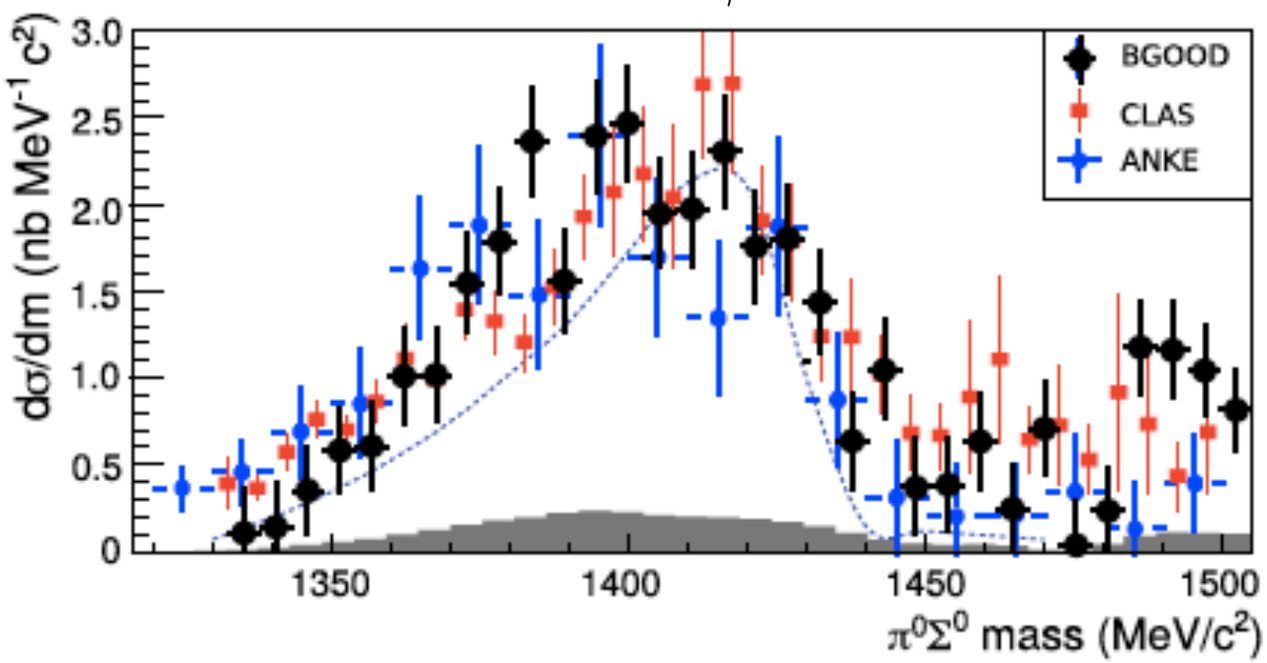



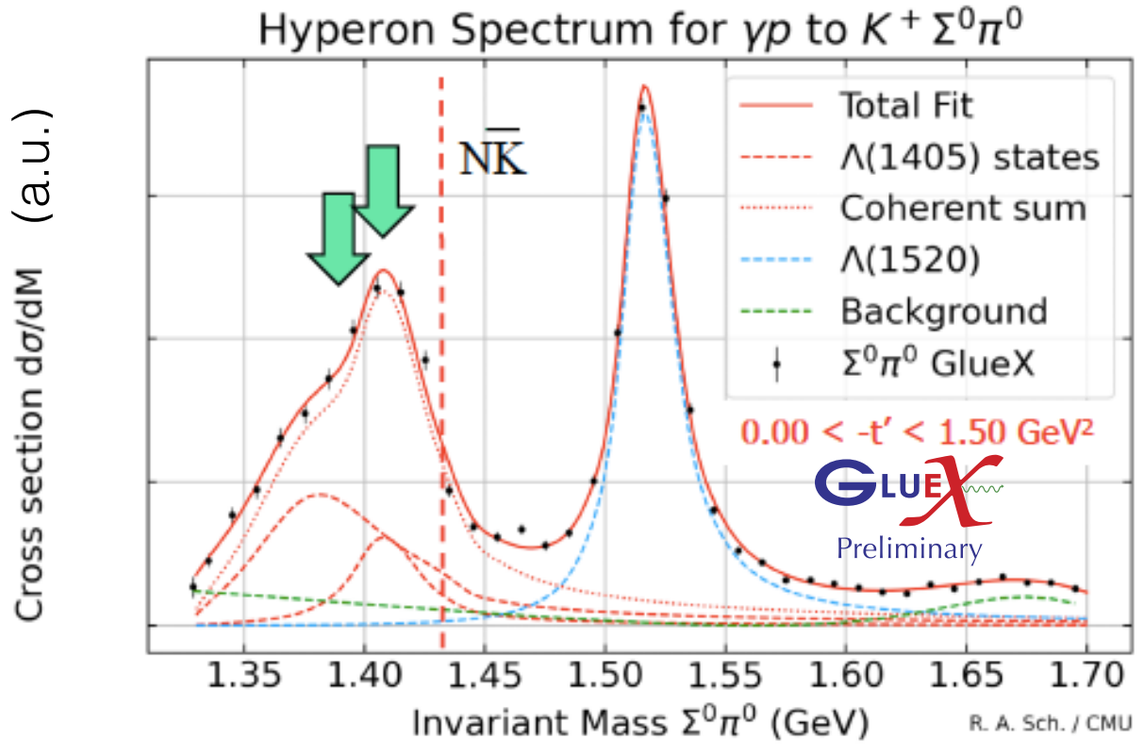

- Normalization yet to be finalized
- Uncertainties are only statistical
- $\Lambda(1405)$ line shape deviates from a Breit-Wigner form

- Compound coherent $\Lambda(1405)$'s
- Flatte-type amplitude
- Incoherent $\Lambda(1520)$ and backgrounds
- $\Lambda(1405)$ is split into two centroids at $\sim 1387$ MeV and $\sim 1409$ MeV
- K-matrix fits in progress

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

BGOOD results for $E_\gamma = 1550 - 2300$ MeV



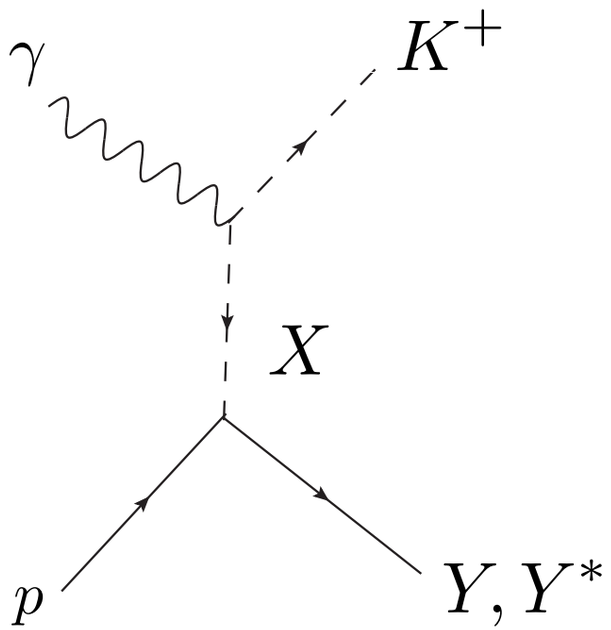




**Phys. Lett. B 833 137375 (2022)** **Phys. Rev. C 87, 035206 (2013)**
**Phys. Lett. B 660 167 (2008)** **Phys. Lett. B455, 55 (1999)**

- $\Lambda(1405)$ line shape deviates from a Breit-Wigner form
- High statistics in GlueX to study $\Lambda(1405)$ line shape

- Compound coherent $\Lambda(1405)$'s
- Flatte-type amplitude
- Incoherent $\Lambda(1520)$ and backgrounds
- $\Lambda(1405)$ is split into two centroids at $\sim 1387$ MeV and $\sim 1409$ MeV
- K-matrix fits in progress

# $Y, Y^*$ production mechanisms




$X$ – Exchanged particle in $t$-channel
(Regge trajectory)

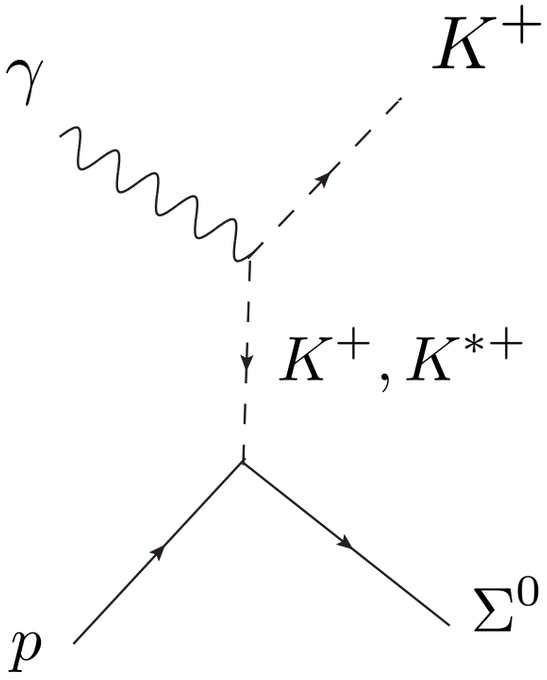
$Y$ – $\Lambda, \Sigma$

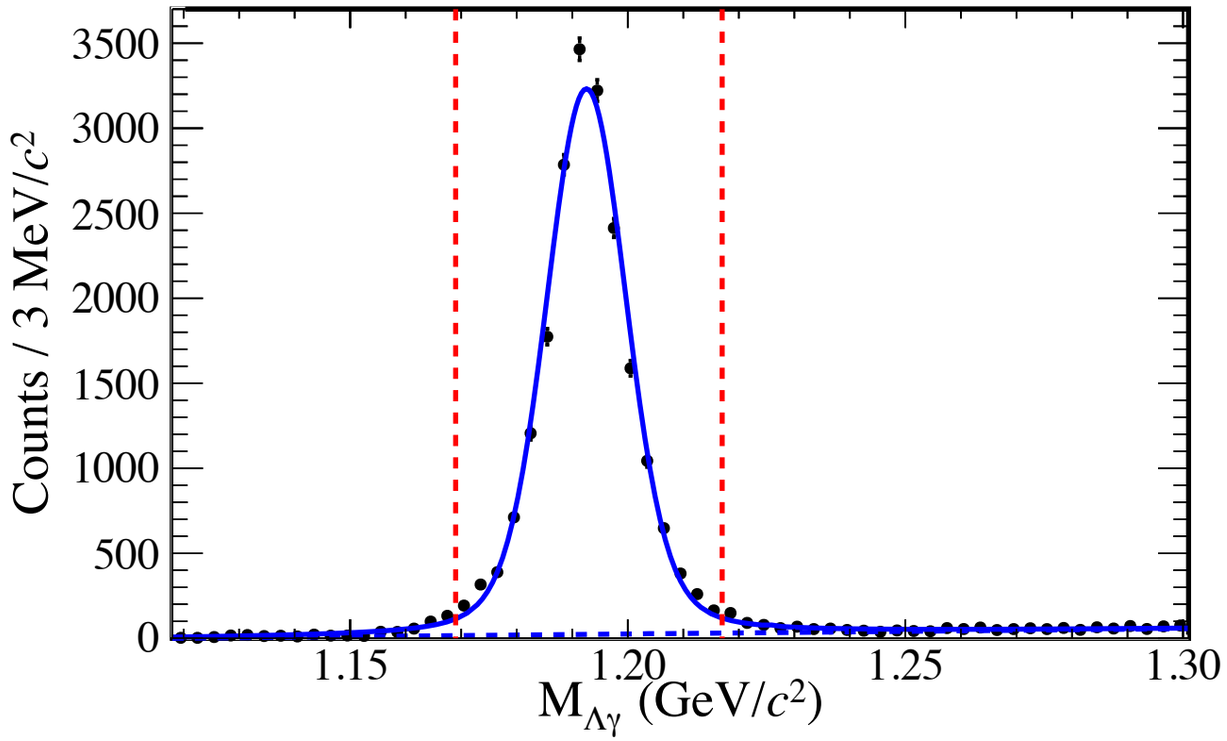
- $t$-channel exchange expected to dominate at GlueX photon beam energies
  $t = (p_\gamma - p_{K^+})^2$

- For exchanged particle with parity $P$ and spin $J$, naturality $\eta = P(-1)^J$
  - $\eta = +1 \implies$ natural parity
  - $\eta = -1 \implies$ unnatural parity

- Study type of parity exchanged by measuring beam asymmetry ($\Sigma$) and spin density matrix elements (SDME)
  - $K^+\Sigma^0$ beam asymmetry
  - $\Lambda(1520)$ SDMEs

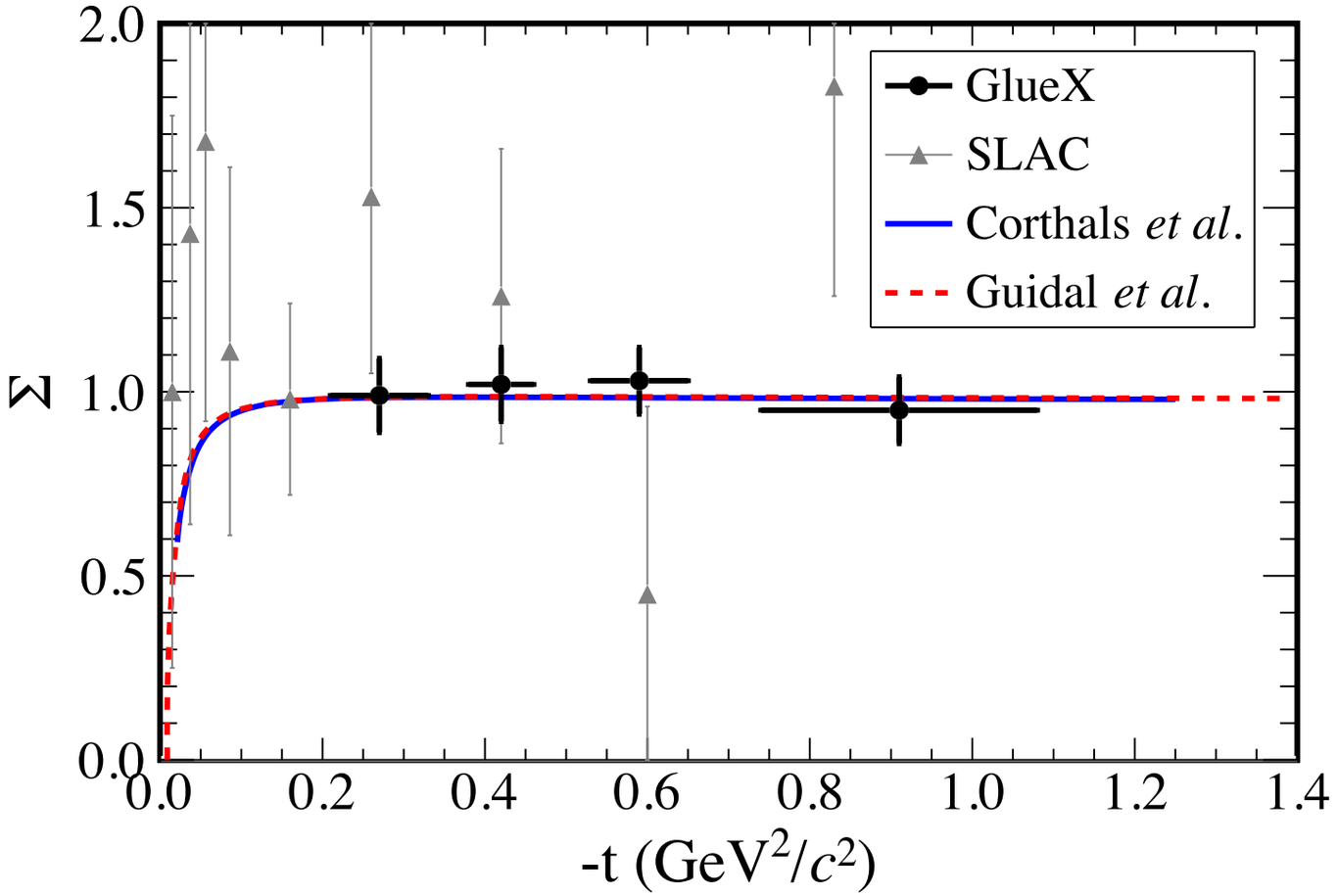
# $K^+\Sigma^0$ beam asymmetry




**Phys. Rev. C 101, 065206 (2020)**
**(GlueX Collaboration)**

- $\sim 20\%$ of GlueX-I data
- Photon beam energy = 8.2 - 8.8 GeV
- Measure beam asymmetry $\Sigma$
  - Difference between cross sections for photon polarized perpendicular and parallel to reaction plane




**Phys. Rev. C 101, 065206 (2020)**
**(GlueX Collaboration)**

- Natural parity exchange dominates in $t$-channel

  Average $\Sigma = 1.00 \pm 0.05$

- Consistent with theoretical predictions

  **Phys. Rev. C 75, 045204 (2007)**
  **Nucl. Phys. A 627, 645 (1997)**

- SLAC results at $E_\gamma = 16$ GeV

  **Phys. Rev. D 20 1553 (1979)**

- Higher statistical precision from GlueX compared to SLAC

# $\Lambda(1520)$ SDMEs

- Polarization transfer to $\Lambda^*$ with $J^P = \frac{3}{2}^-$

- $\gamma p \to K^+\Lambda(1520)$

  $\Lambda(1520) \to K^- p$

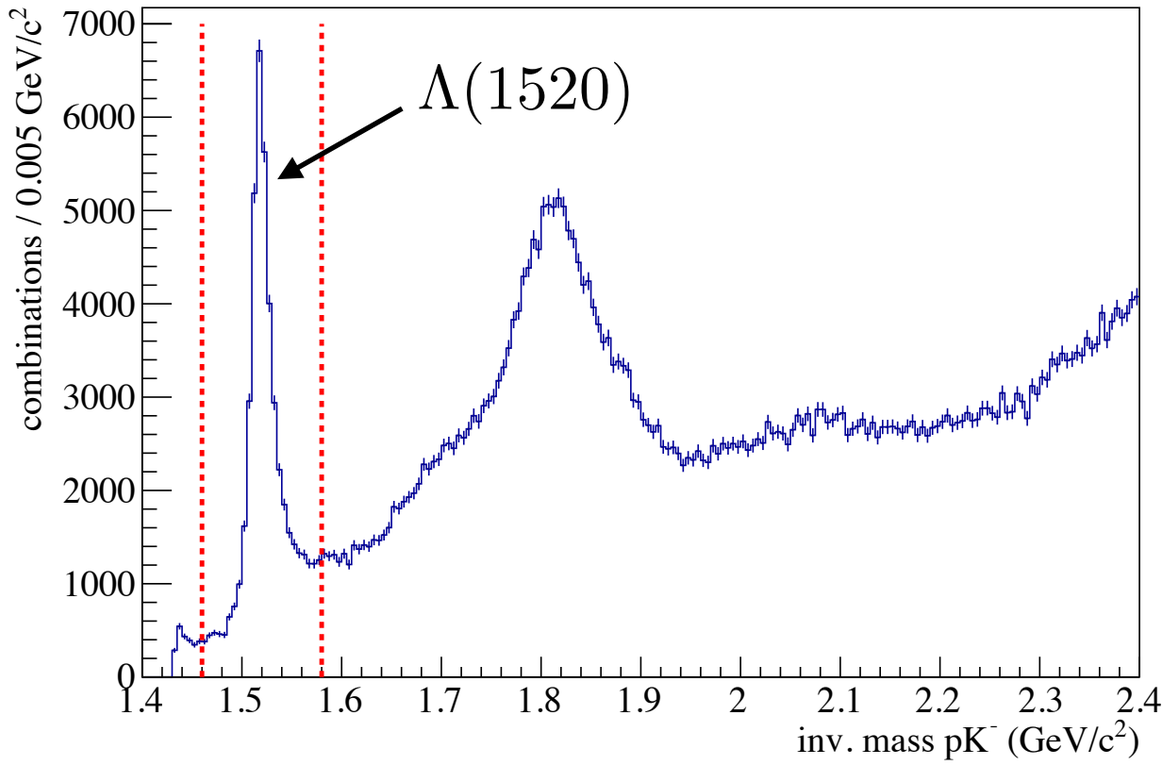
  (Branching fraction = 22.5%)

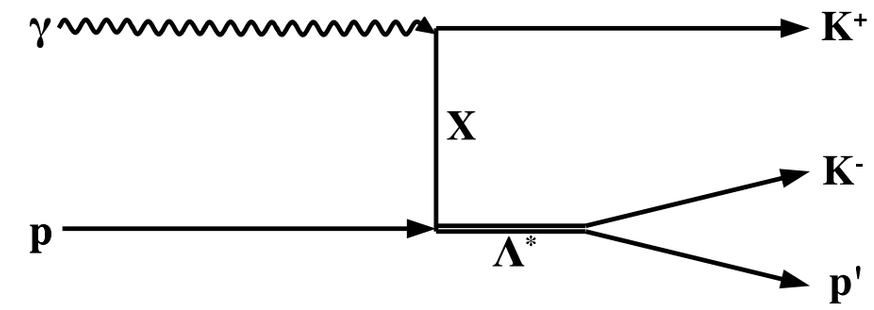
- $\sim$ 20% of GlueX-I data

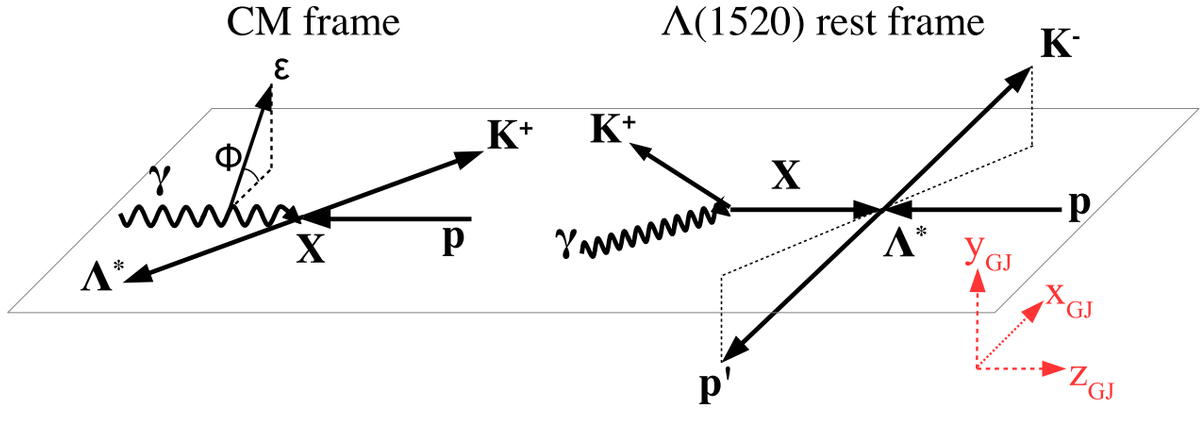
- Photon beam energy = 8.2 - 8.8 GeV

- Study $t$-channel exchange in Gottfried-Jackson frame

**Phys. Rev. C 105, 035201 (2022)**
**(GlueX Collaboration)**



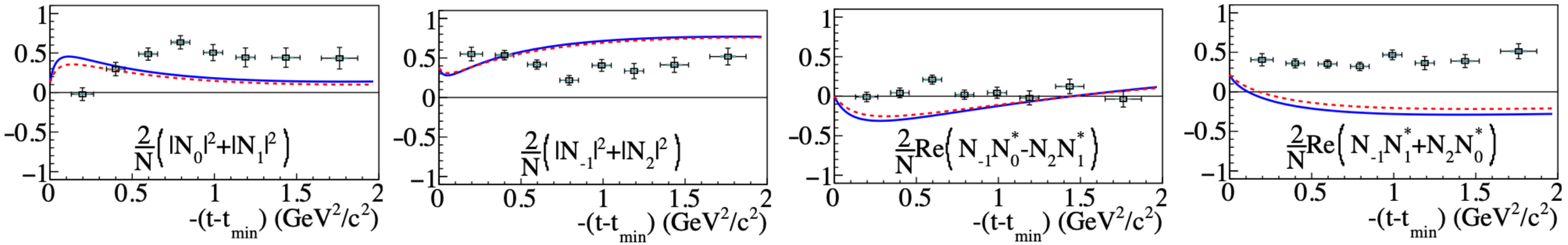
- Combinations of SDMEs can be expressed as linear combinations of purely natural or purely unnatural exchange amplitudes

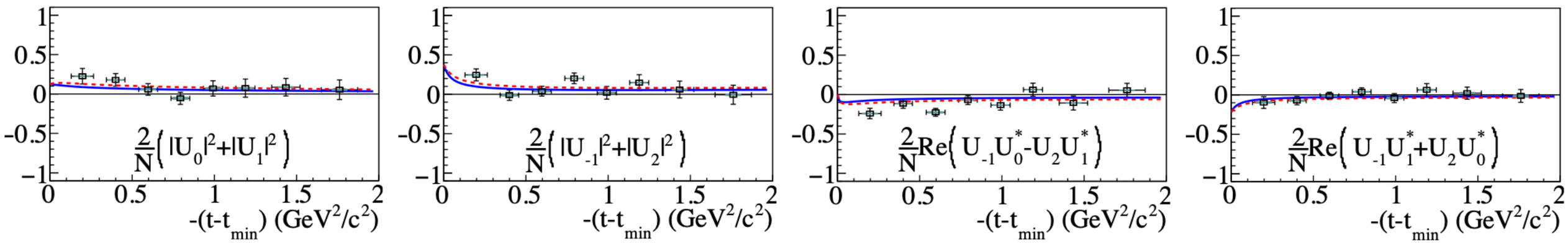
  Natural - e.g. $K^*(892), K_2^*(1430)$

  Unnatural - e.g. $K(492), K_1(1270)$

**Phys. Rev. C 105, 035201 (2022)**
**(GlueX Collaboration)**

Natural




Unnatural

- Natural amplitudes exchange dominates

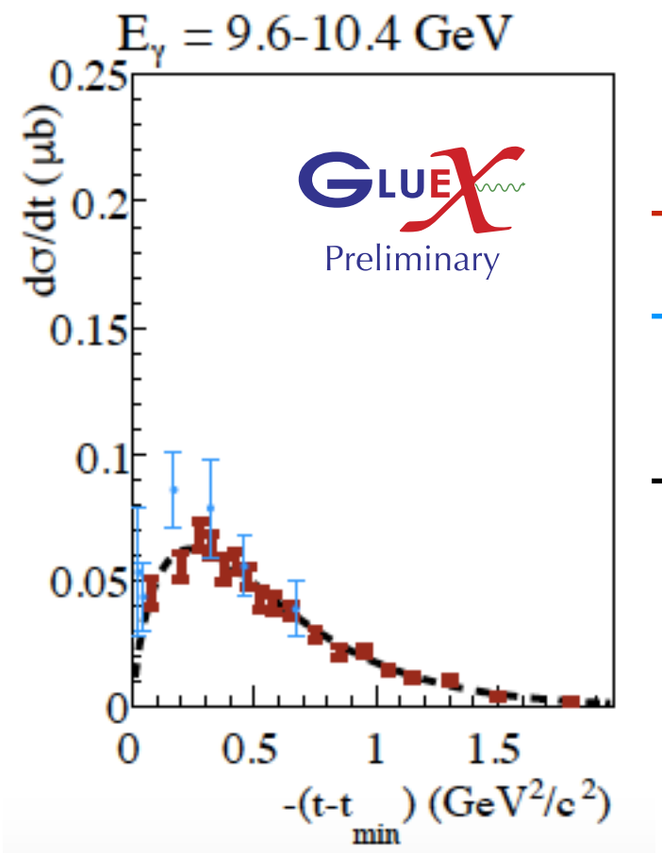
---------- Model predictions in

———— Reggeized framework

Byung-Geel Yu and Kook-Jin Kong,

Phys. Rev. C **96**, 025208 (2017)

# $\Lambda(1520)$ cross section




20% of GlueX-I

SLAC@11GeV scaled by $E_\gamma^2$

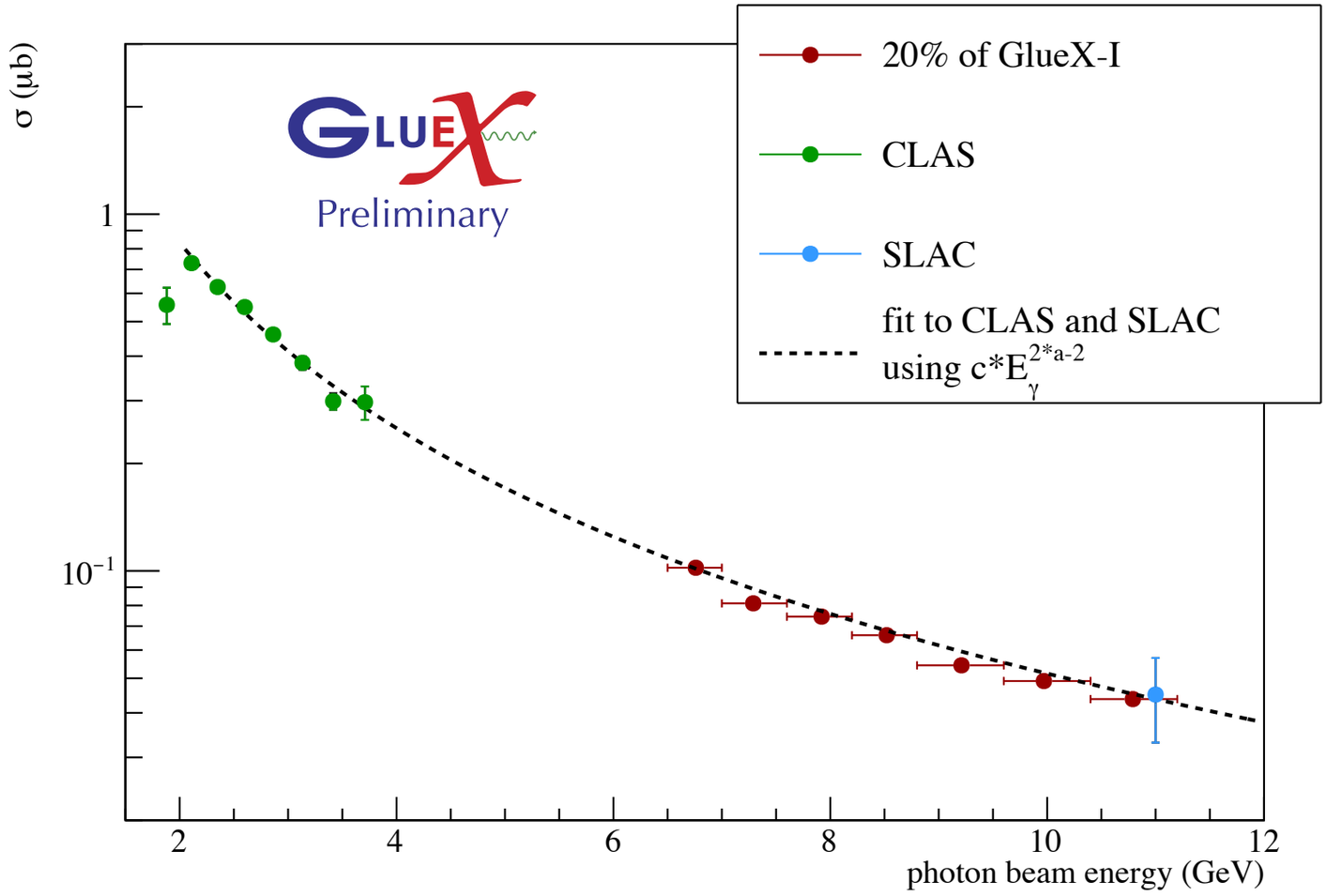
$c * t^a * e^{bt}$

**Peter Hurck (HYP2022)**

- Differential cross sections $\frac{d\sigma}{dt}$ for $\Lambda(1520)$ photoproduction
- Compared to SLAC measurements at $E_\gamma = 11$ GeV

  **Phys. Lett. B 34 , 547 (1971)**

- Good agreement with SLAC data particularly at higher beam energies



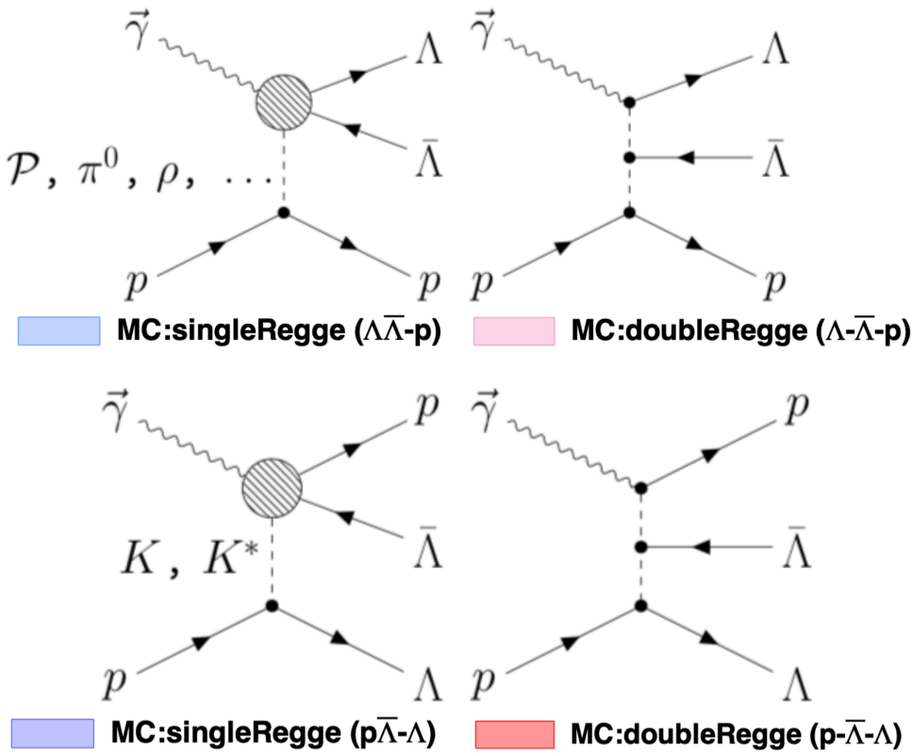

- Fit $\frac{d\sigma}{dt}$ results with function $ct^a e^{bt}$ and integrate to get total cross sectio
- CLAS and SLAC data are fit using function $cE_\gamma^{2a-2}$

  **Phys. Rev. C 88 , 045201 (2013)**

  **Phys. Lett. B 34 , 547 (1971)**

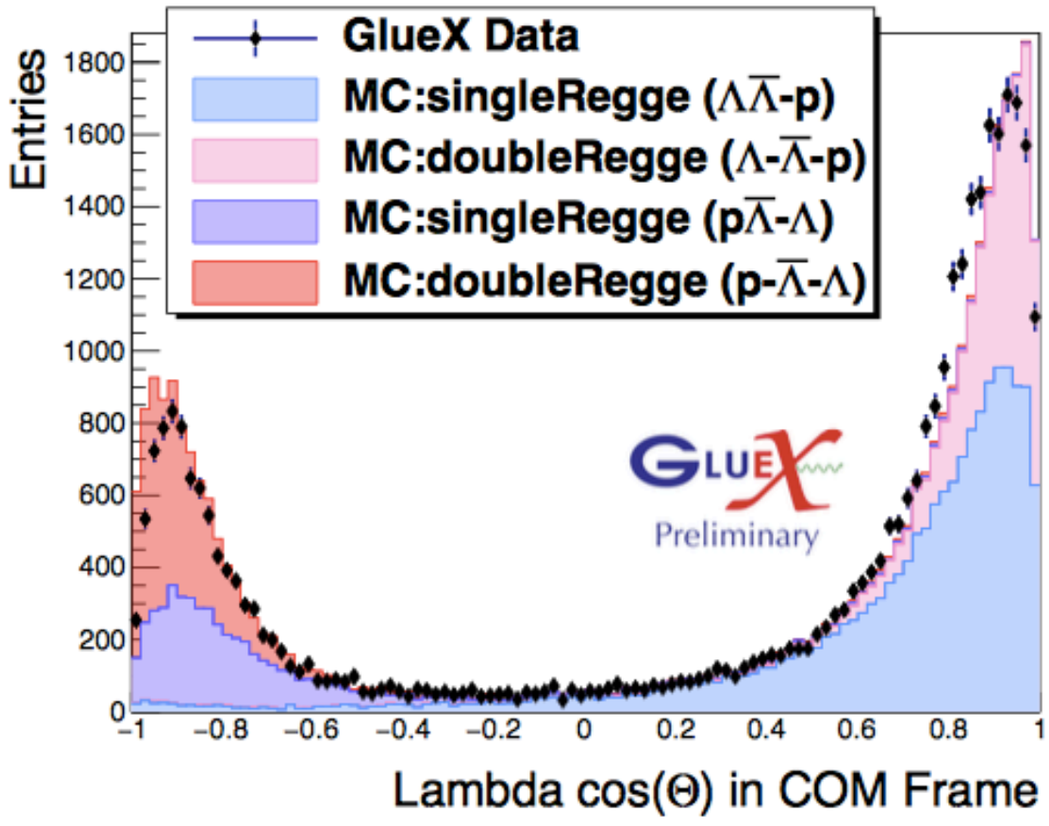
- GlueX results agree very well with the fit

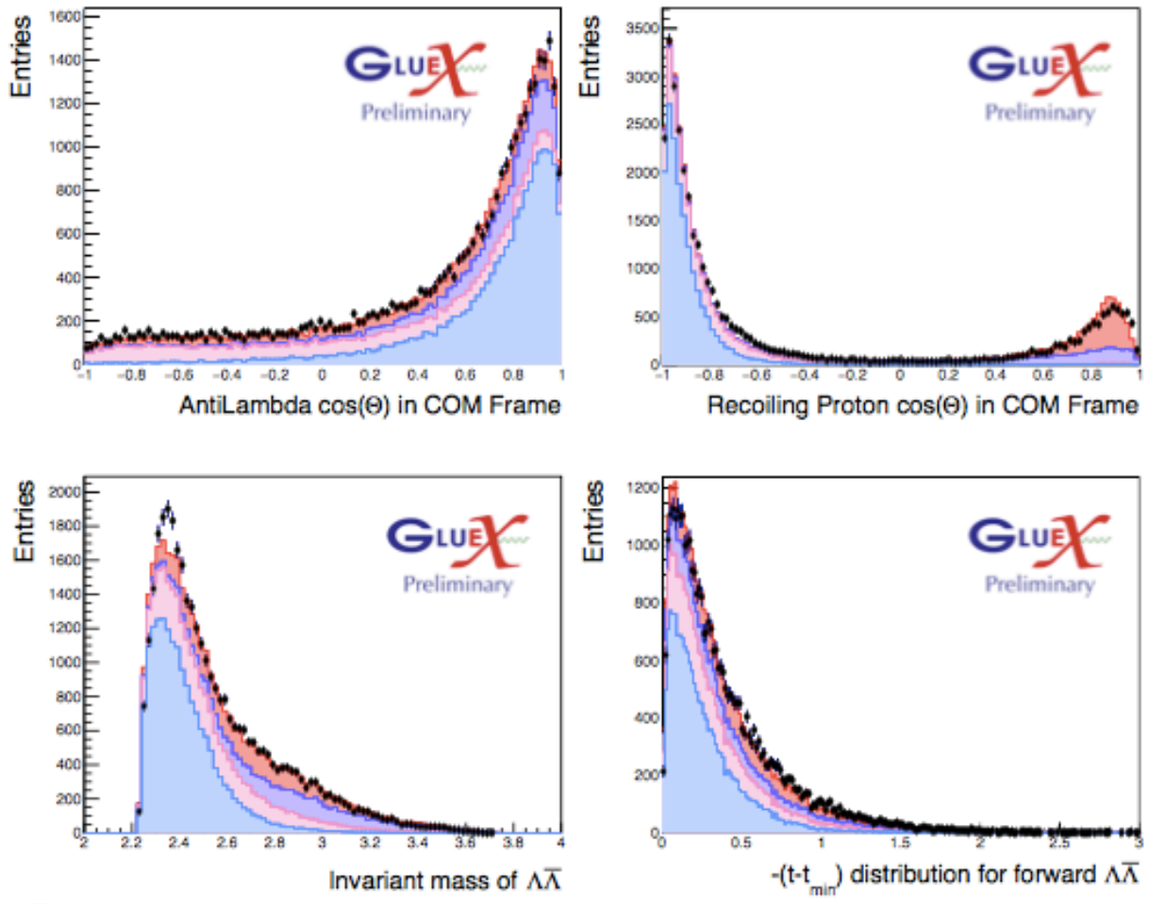
# $\Lambda\bar{\Lambda}$ photoproduction

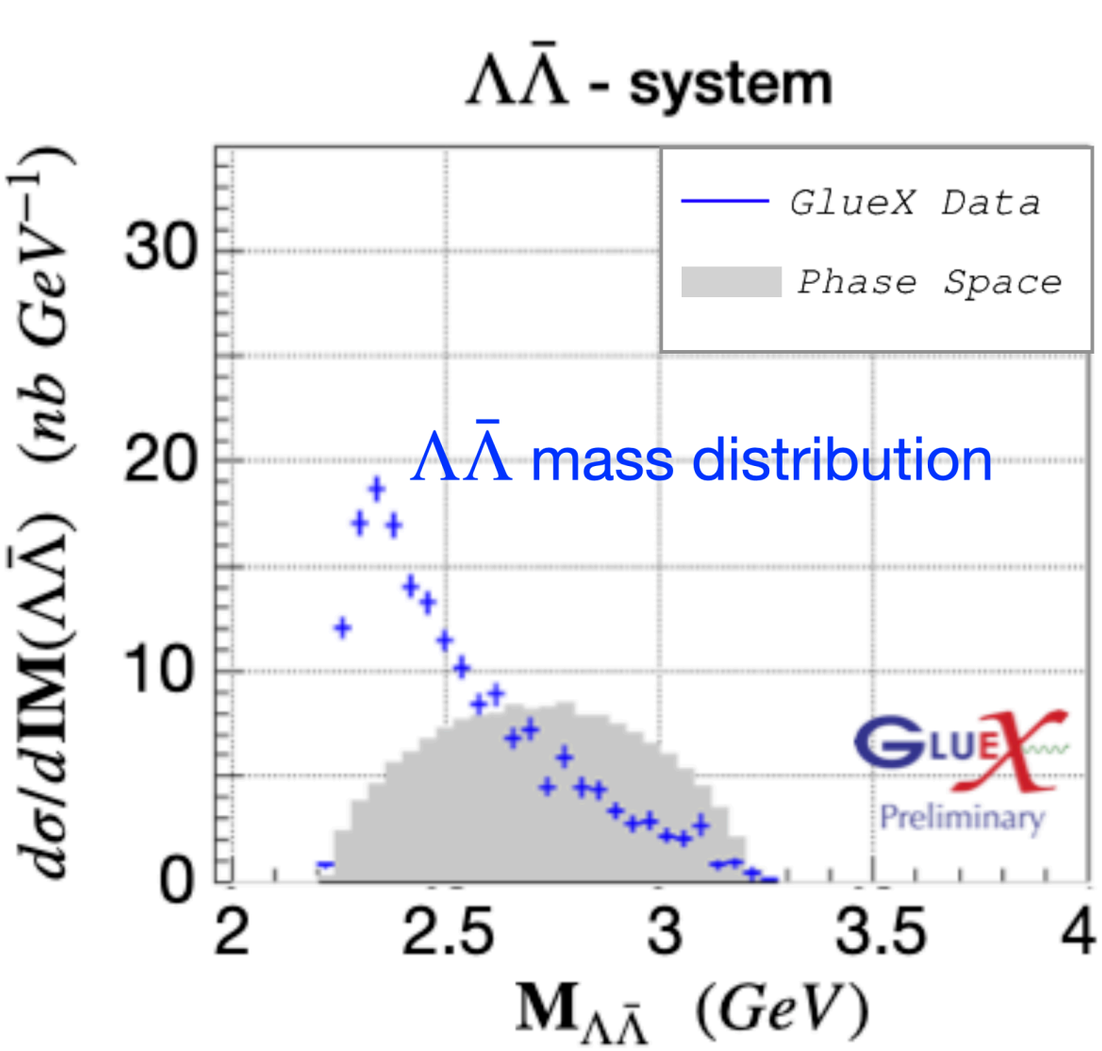


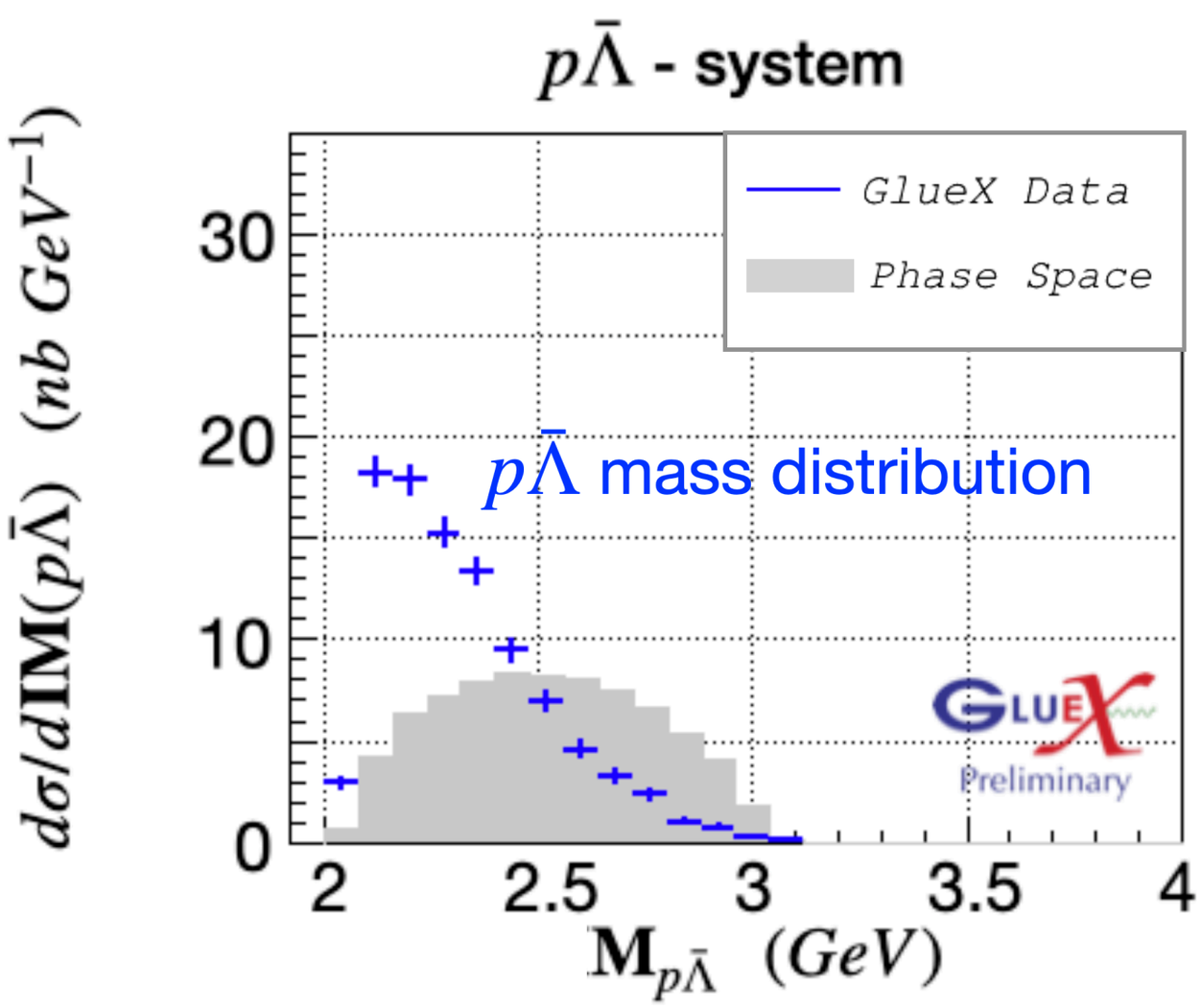

- $\gamma p \to \Lambda\bar{\Lambda}p \to p\pi^-\bar{p}\pi^+p$
- GlueX-I data
- Photon beam energy = 6.4 - 11.6 GeV
  Luminosity $\sim$ 439.6 pb$^{-1}$
- Model reaction kinematics using single and double Regge processes
- Good agreement between data and MC

**Hao Li (DNP2022)**



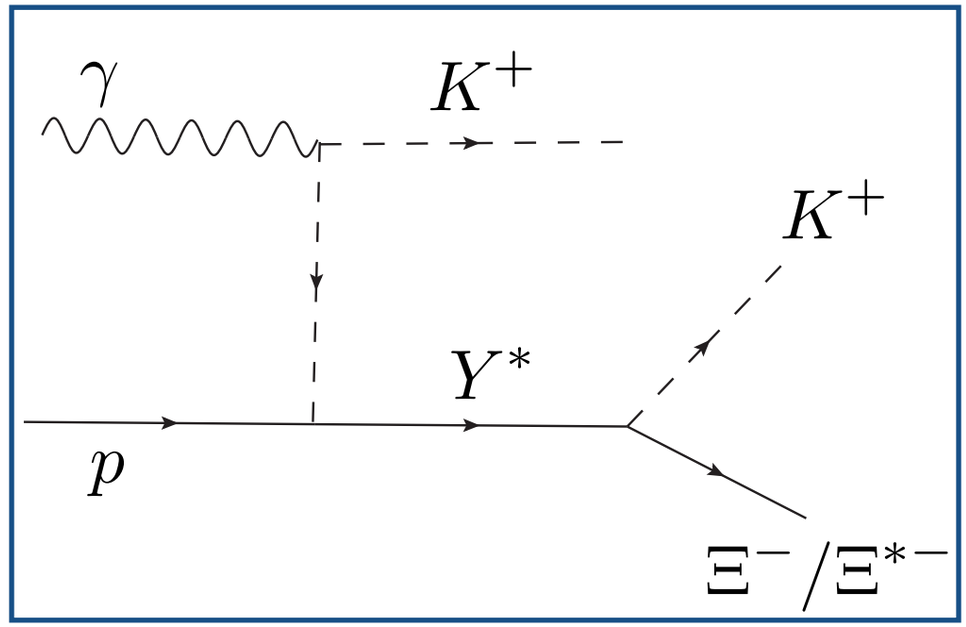



- Measure cross sections to study reaction mechanisms
- Investigating enhancements at threshold
- Also studying polarization of $\Lambda\bar{\Lambda}$ pair

# Cascades

- Hyperons with strangeness S = -2
- Data for Ξ resonances is very limited
  - Production cross sections are small
  - Final states are complicated to analyze



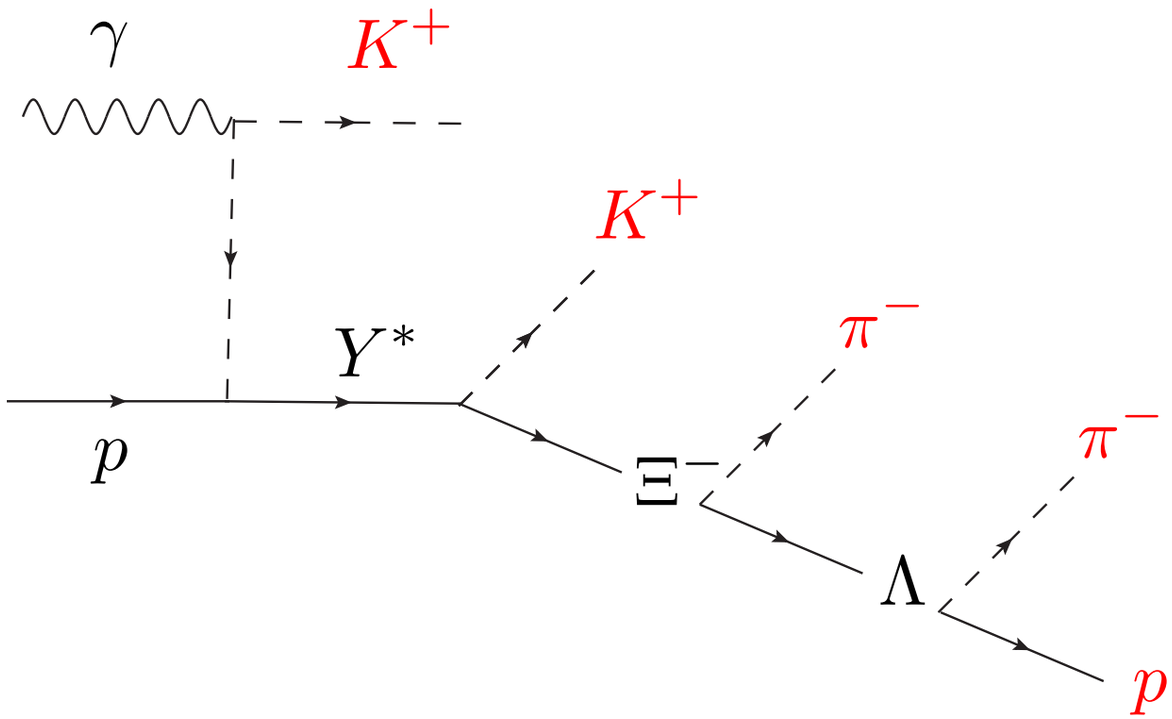

| Particle | $J^P$ | Overall status | Status as seen in — $\Xi\pi$ | $\Lambda K$ | $\Sigma K$ | $\Xi(1530)\pi$ | Other channels |
|---|---|---|---|---|---|---|---|
| Ξ(1318) | 1/2+ | **** | | | | | Decays weakly |
| Ξ(1530) | 3/2+ | **** | **** | | | | |
| Ξ(1620) | | * | * | | | | |
| Ξ(1690) | | *** | | *** | ** | | |
| Ξ(1820) | 3/2− | *** | ** | *** | ** | ** | |
| Ξ(1950) | | *** | ** | ** | | * | |
| Ξ(2030) | | *** | | ** | *** | | |
| Ξ(2120) | | * | | * | | | |
| Ξ(2250) | | ** | | | | | 3-body decays |
| Ξ(2370) | | ** | | | | | 3-body decays |
| Ξ(2500) | | * | | * | * | | 3-body decays |

C.G. Wohl, "Ξ Resonances", The Review of Particle Physics (2022)

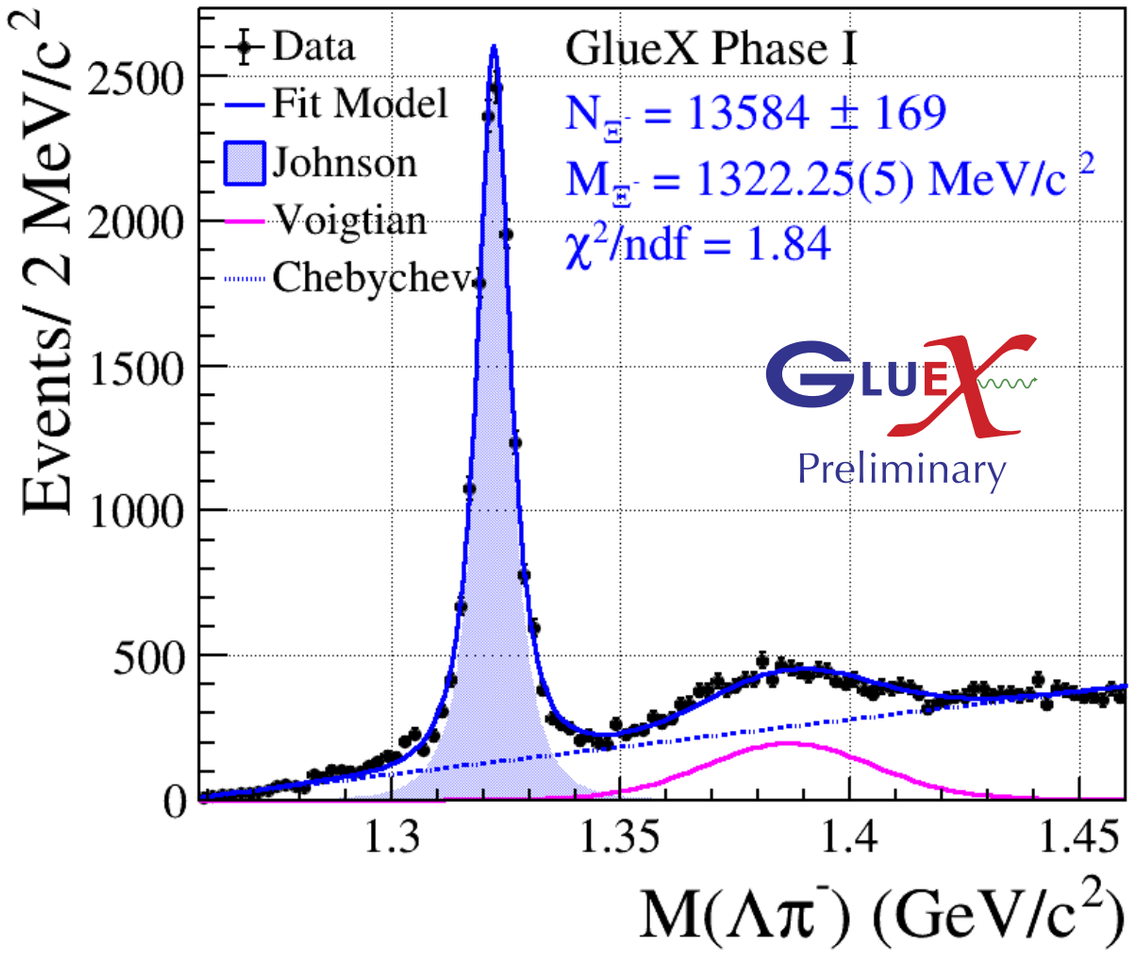
- GlueX is able to reconstruct final states exclusively and will provide more data on Ξ resonances

# $\Xi^-(1320)$

- Ground state Cascade

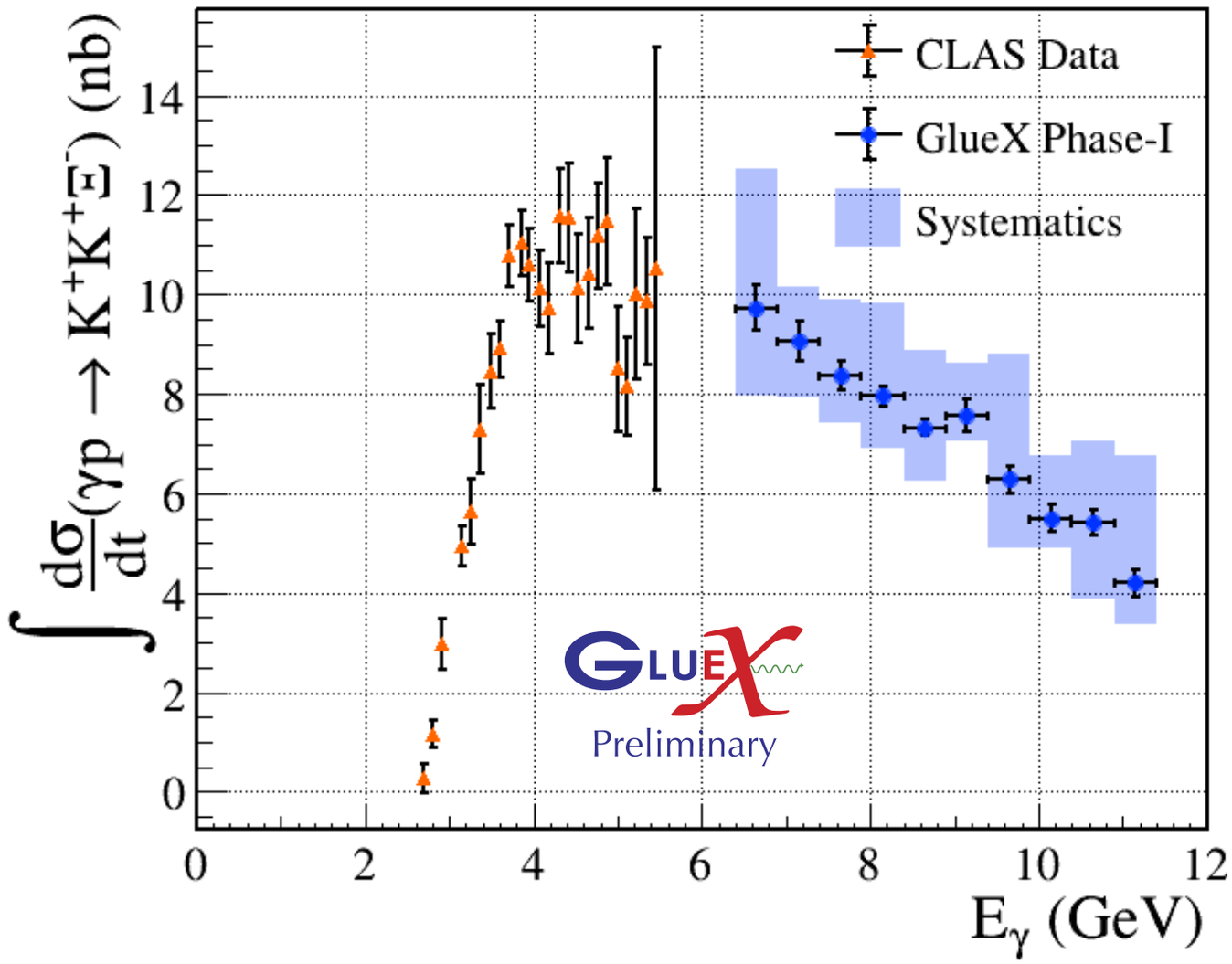



Jesse Hernandez (Baryons 2022)




- Final state particles: $K^+K^+\pi^-\pi^-p$
- GlueX-I data
- Clear peak of $\Xi^-$ in the $\Lambda\pi^-$ mass spectrum

# $\Xi^-$ cross section



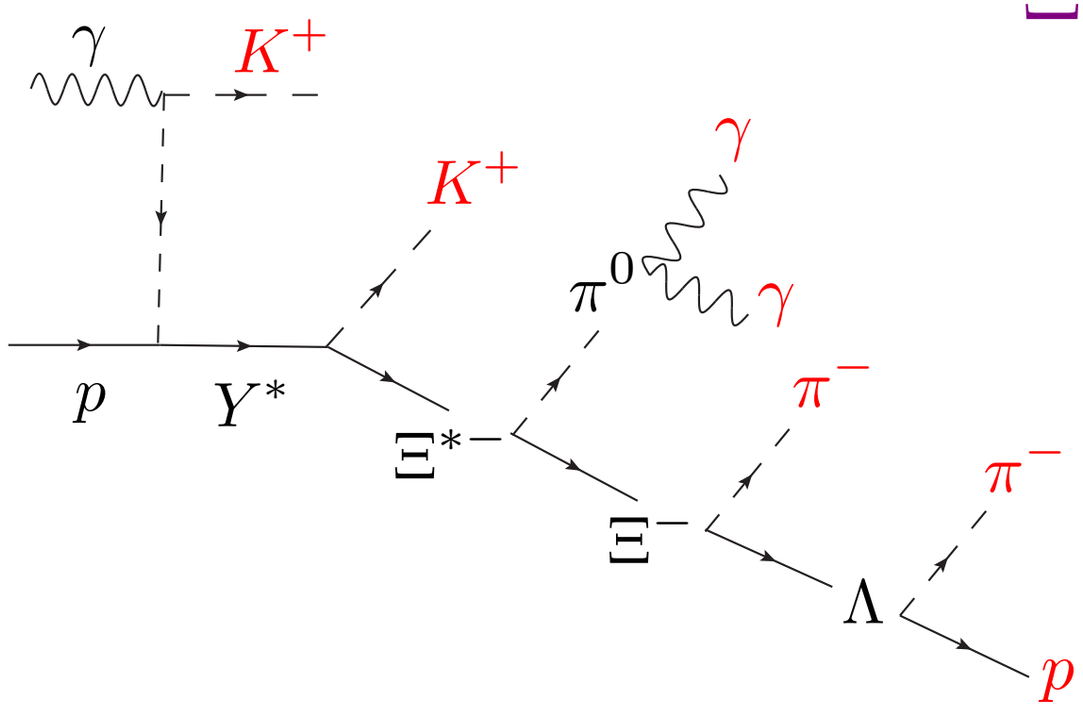

Jesse Hernandez
(Baryons 2022)

- $t$ calculated using high momentum $K^+$

$$t = (p_\gamma - p_{K^+_{high}})^2$$

- Integrated differential cross section compared with CLAS data (Phys. Rev. C 98, 062201(R) (2018))
- Systematics are being evaluated
- Observe cross section falls with energy

# $\Xi^{*-}(1530)$



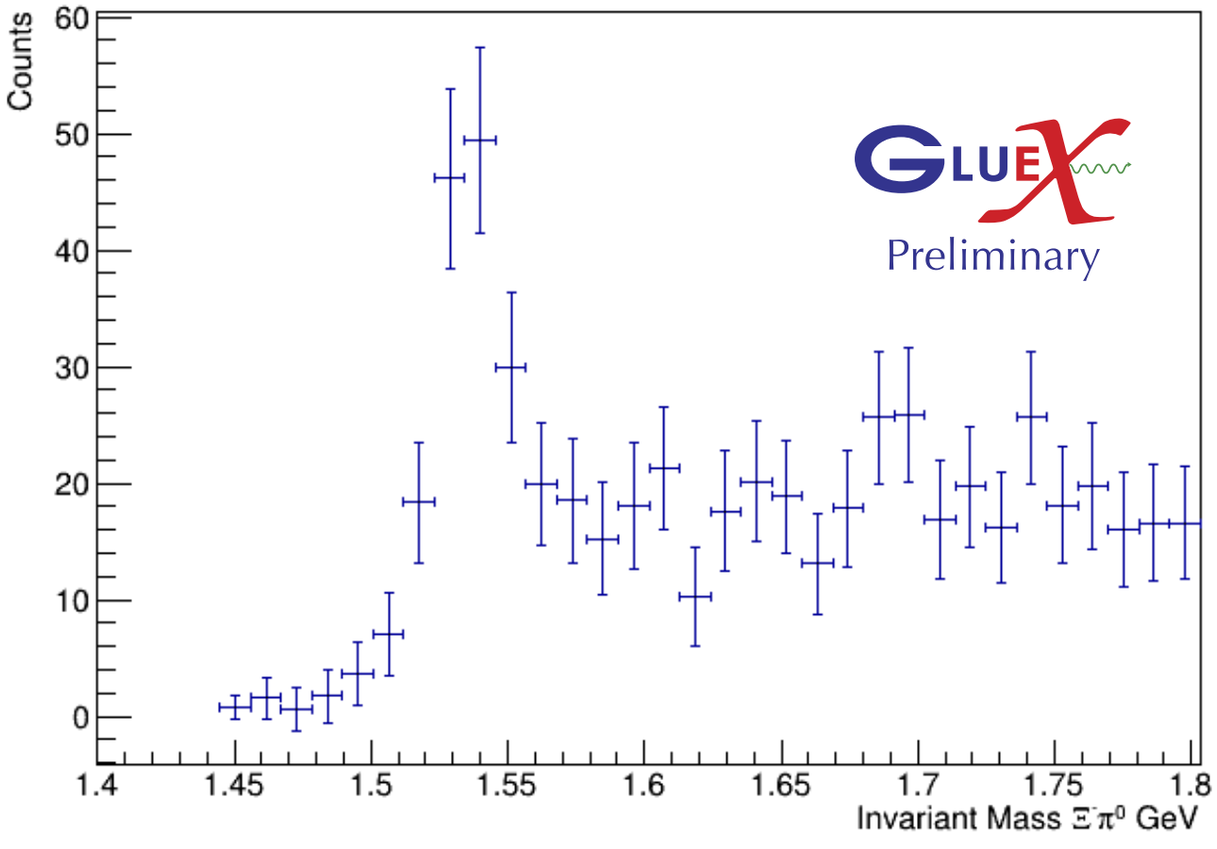

- $\sim 50\%$ of GlueX-I data
- Masses of $\Lambda$ and pions are constrained in the kinematic fit
- $\Xi^{*-}(1530) \rightarrow \Xi^- \pi^0$
- No significant energy dependence for cross section

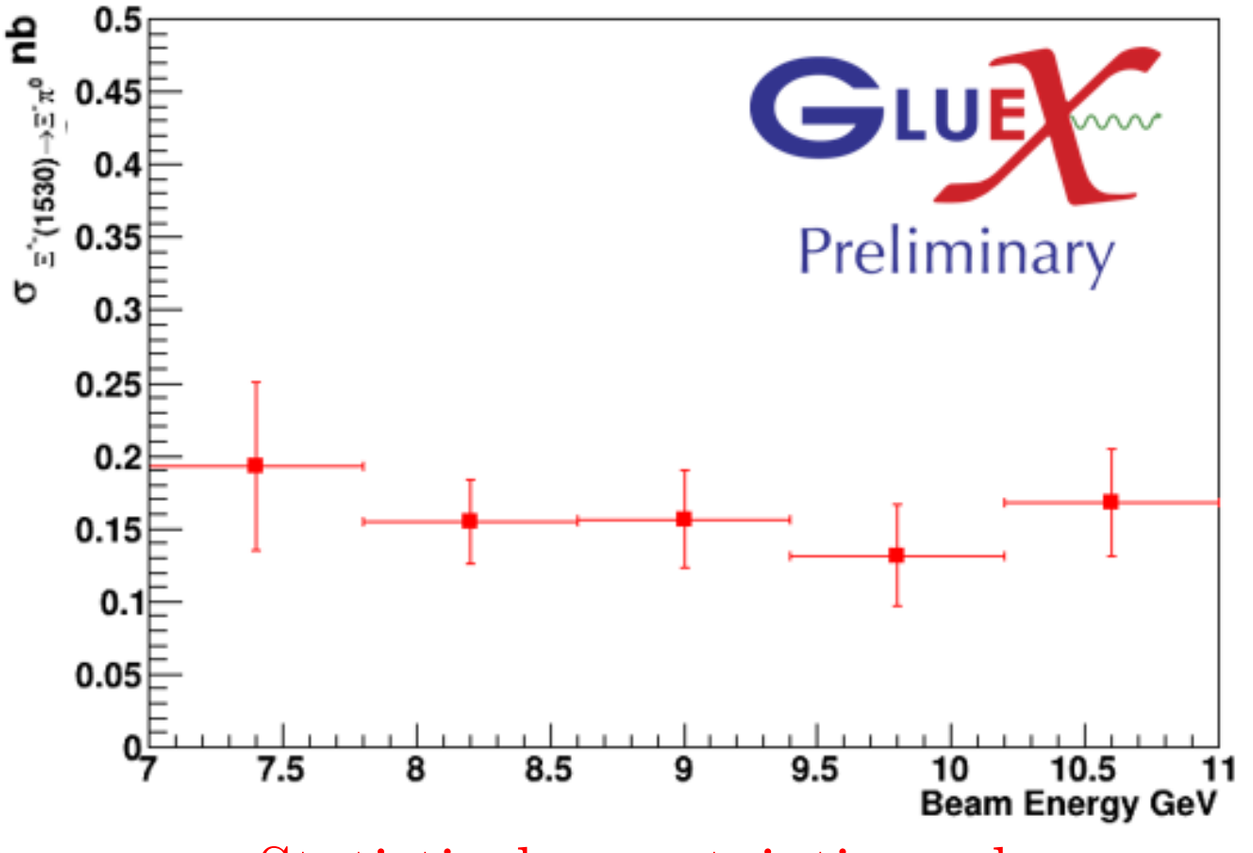
$< \sigma >= 0.16$ nb

standard deviation $= 0.06$ nb

**Brandon Sumner**

**(GHP 2023)**

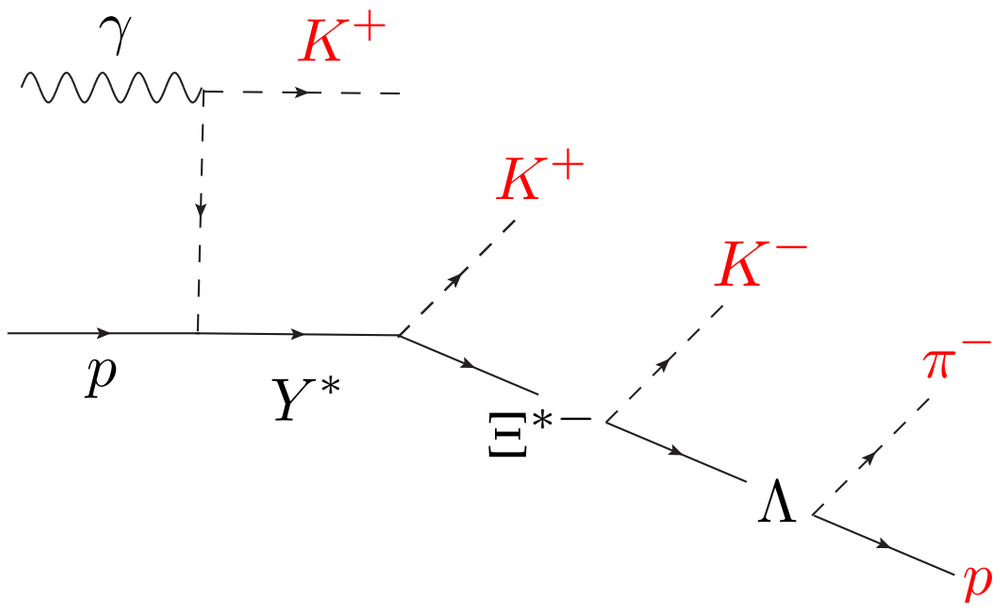


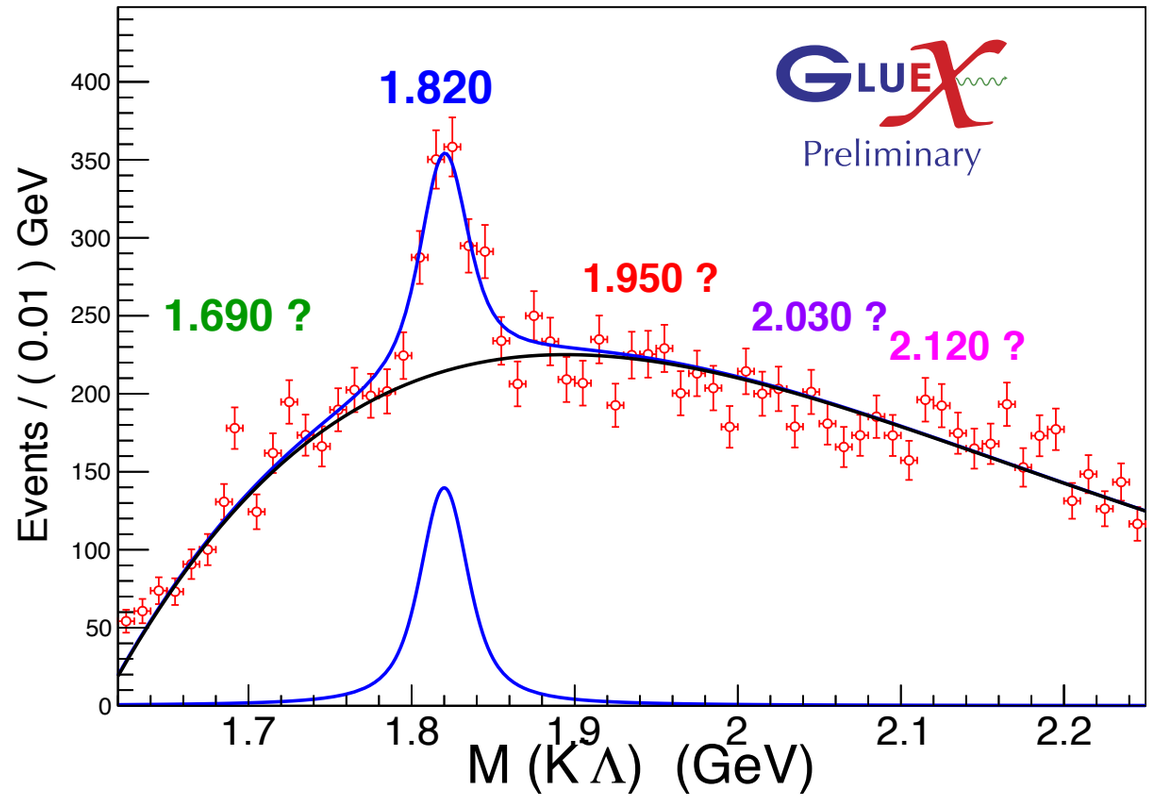



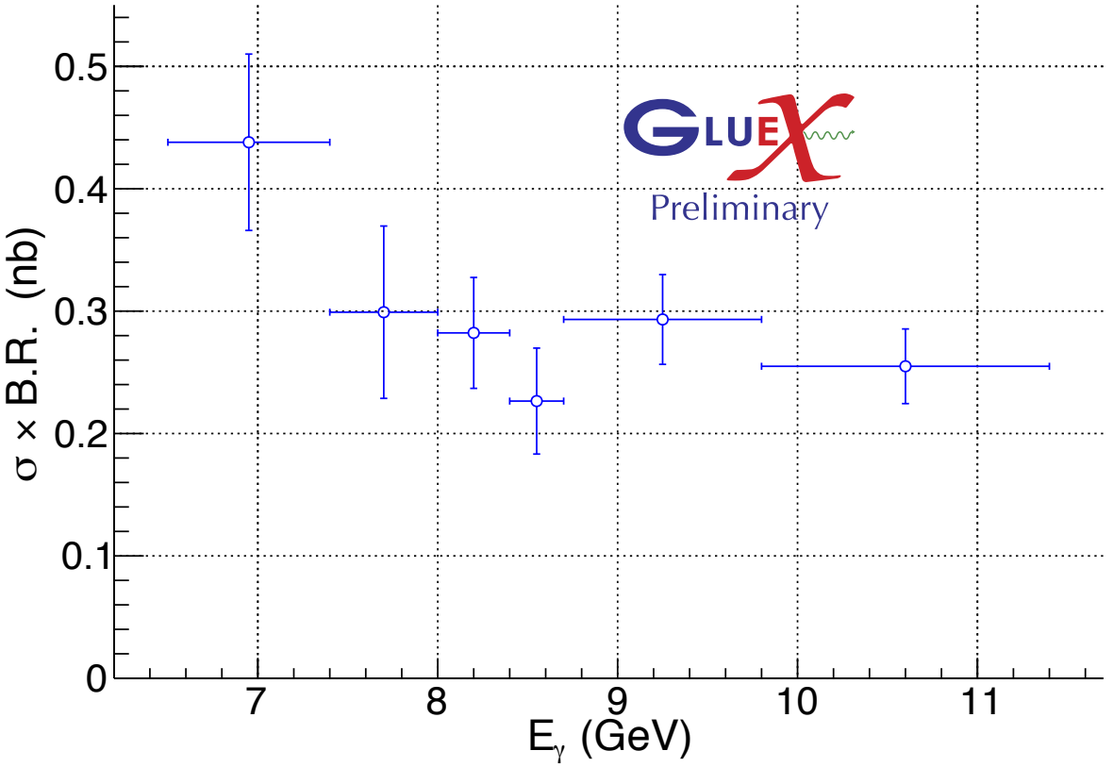

Statistical uncertainties only

# $\Xi^{*-}(1820)$

**Chandrasekhar Akondi (GHP 2023)**




Cross section for $\Xi^{*-}(1820) \to K^-\Lambda$

Statistical uncertainties only

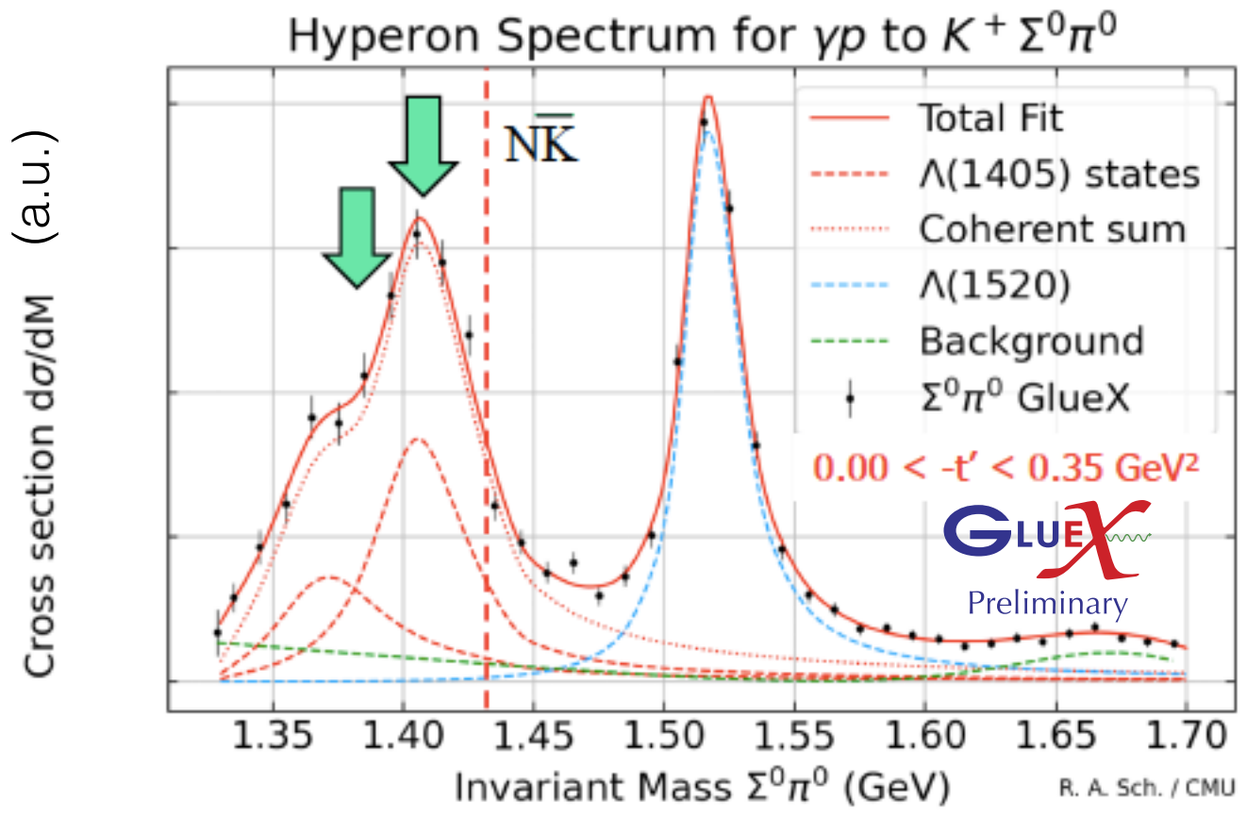
- GlueX-I data
- $\Xi^{*-}(1820) \to K^-\Lambda$
- First cross section results for $\Xi^{*-}(1820) \to K^-\Lambda$ in photoprodutcion
- No significant energy dependence for cross section

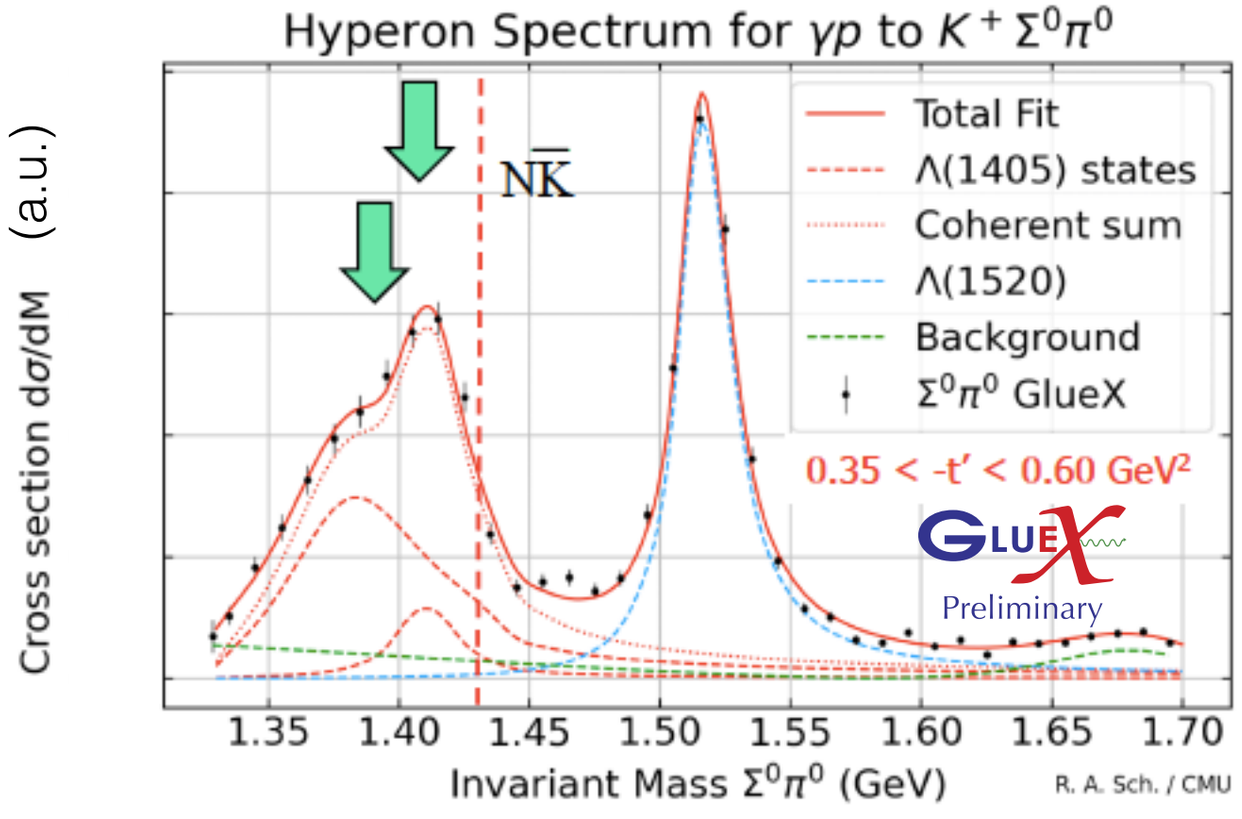
# Summary and Outlook

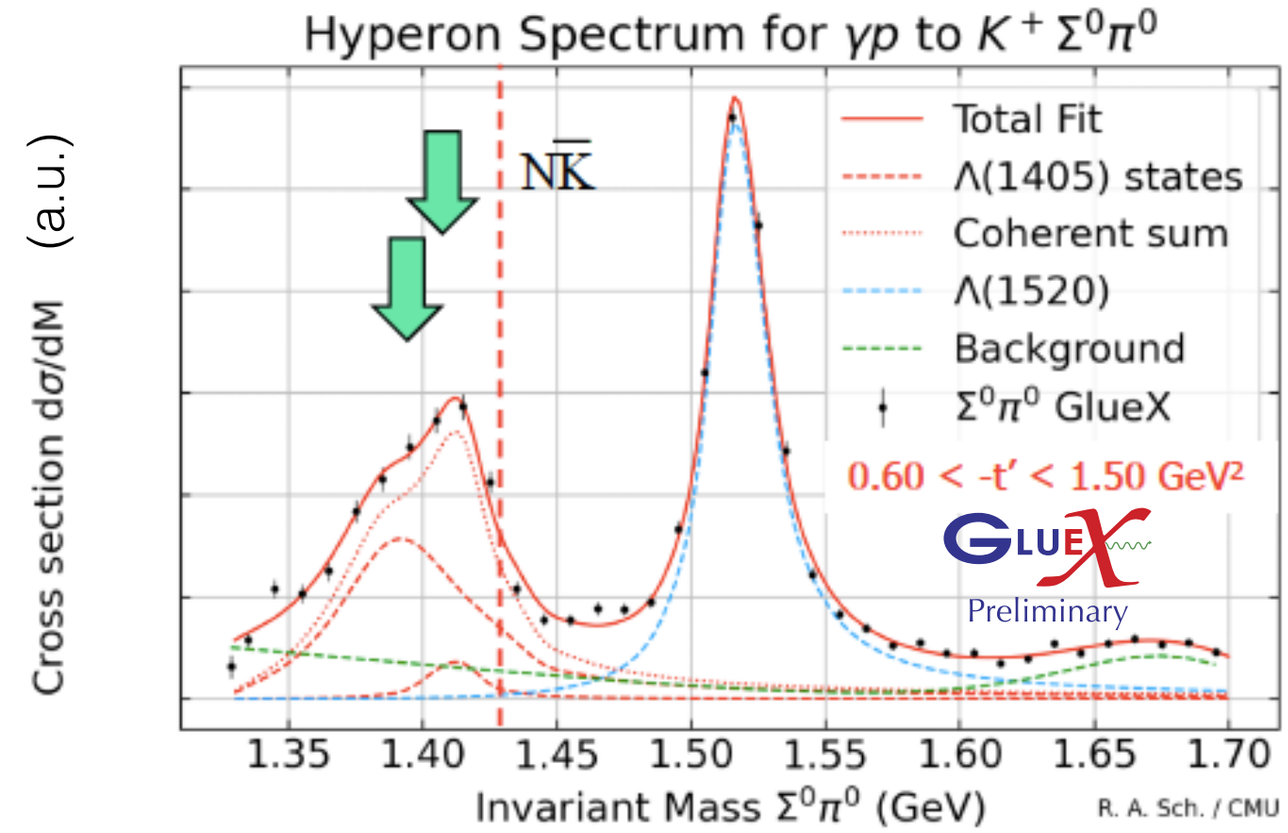
- GlueX is ideally suited for exclusive reconstruction of $\Lambda(1405) \to \Sigma^0\pi^0$
  - Observed $\Lambda(1405)$ line shape clearly deviates from a Breit-Wigner form
  - Preliminary fits support two-pole structure for $\Lambda(1405)$
- Studying $Y, Y^*$ production mechanisms in photoproduction
  - $K^+\Sigma^0$ beam asymmetry
  - $\Lambda(1520)$ SDMEs and cross section
  - $\bar{\Lambda}\Lambda$ photoproduction
- GlueX data will provide valuable information on Cascades
  - $\Xi^-(1320)$
  - $\Xi^{*-}(1530)$
  - $\Xi^{*-}(1820)$

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

# Backup – $\Lambda(1405) \to \Sigma^0\pi^0$



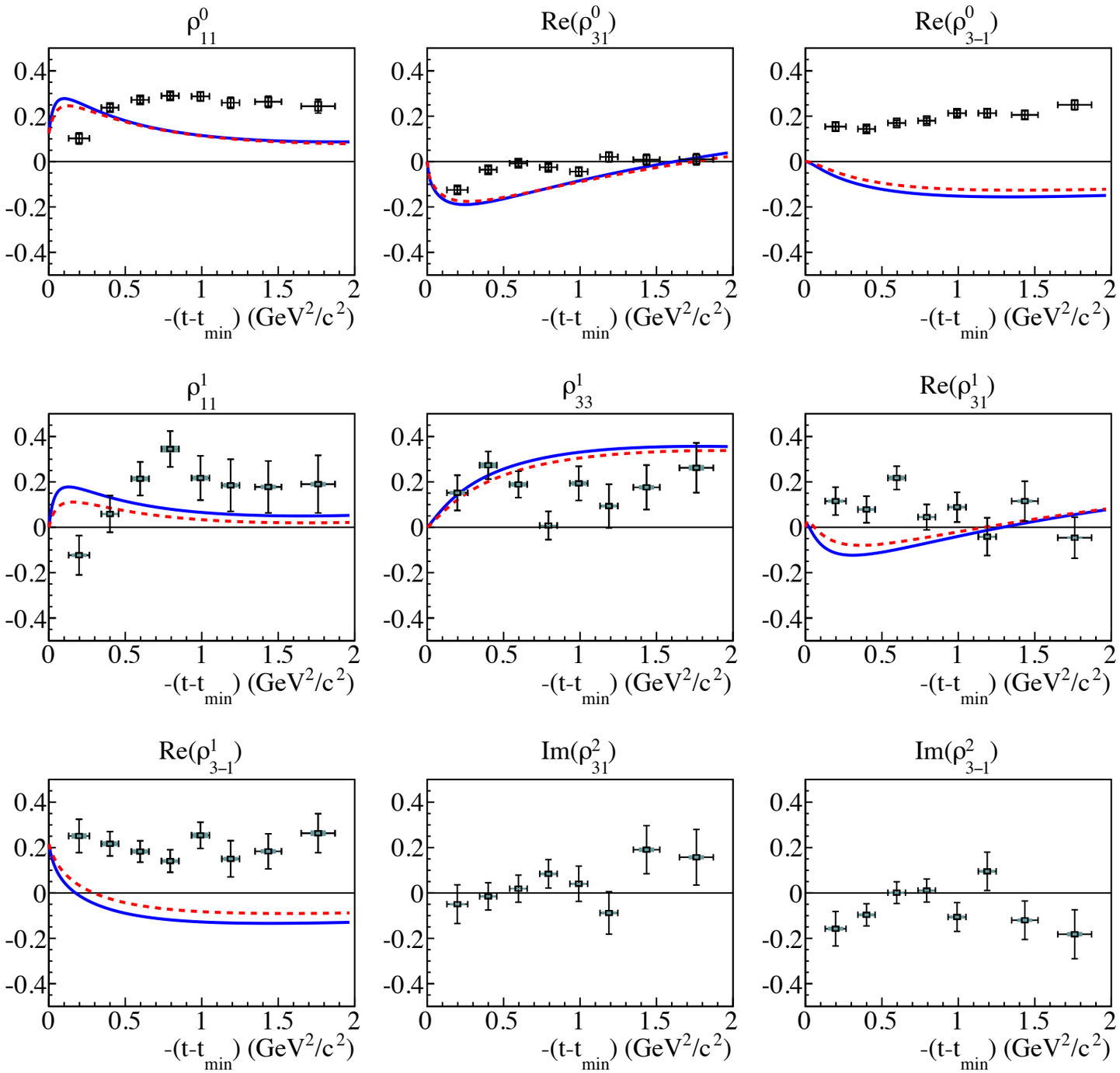




- Coherent fit to two $\Lambda(1405)$'s
- Incoherent $\Lambda(1520)$ and backgrounds
- Relative intensities of two $\Lambda(1405)$'s change with $-t'$
- Fits describe the data well in all $-t'$ bins
- Fits support two-pole structure
- K-matrix fits in progress

# $\Lambda(1520)$ SDMEs

- SDMEs are directly related to helicity amplitudes of the production process

**Phys. Rev. C 105, 035201 (2022)**
**(GlueX Collaboration)**




Model predictions in Reggeized framework

Byung-Geel Yu and Kook-Jin Kong,
Phys. Rev. C **96**, 025208 (2017)