Peter Hurck

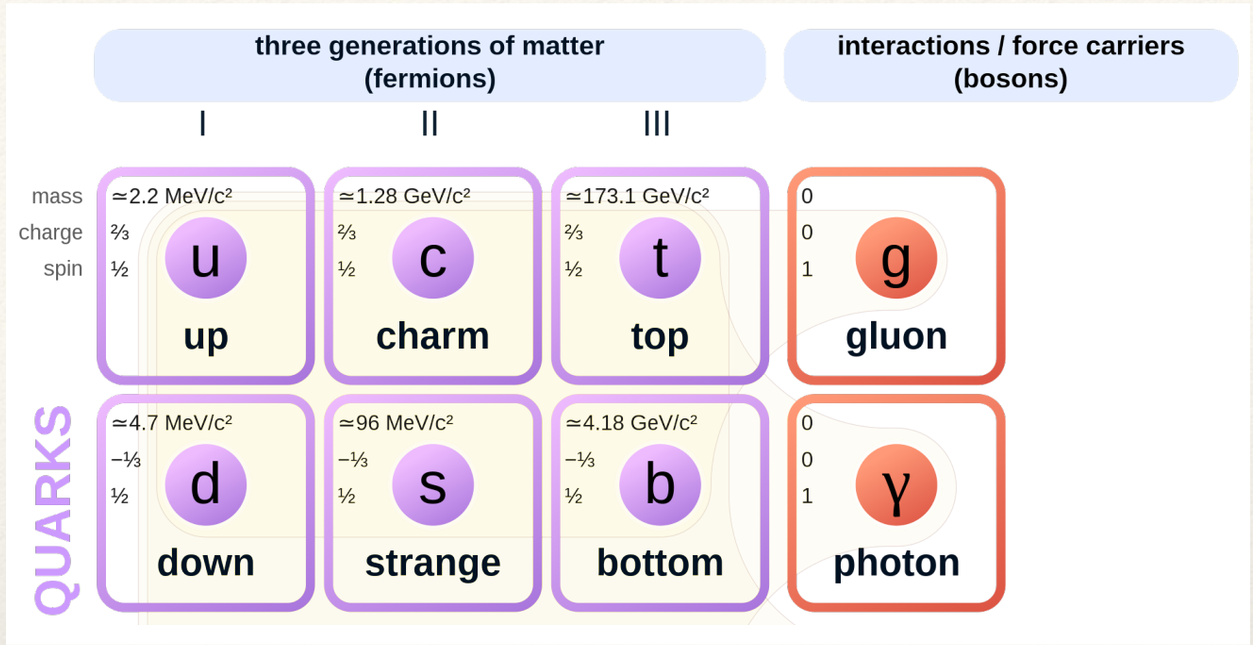
Strange hadron spectroscopy at GlueX and beyond

University of Glasgow

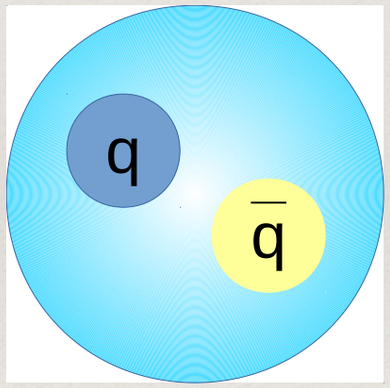
DPG Spring Meeting, Gießen 2024

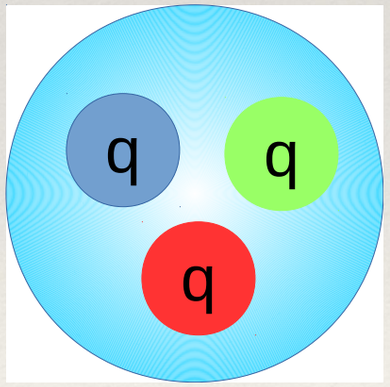
Introduction

- Visible matter in the universe is made from quarks which bind together via the strong interaction to form hadrons
  - Integer spin → meson
  - Half-integer spin → baryon



- Quantum chromodynamics (QCD) is the theory describing the strong interaction
- How does the interaction work that binds almost massless quarks into massive hadrons?





$$\text{proton (uud)} : m(u) + m(u) + m(d) = 2.2\ \text{MeV} + 2.2\ \text{MeV} + 4.7\ \text{MeV} \neq 938\ \text{MeV} = m_p$$

Introduction

- QCD gives rise to spectrum of hadrons
  - Many $q\bar{q}$ and qqq states have been observed
  - $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, … are not forbidden!

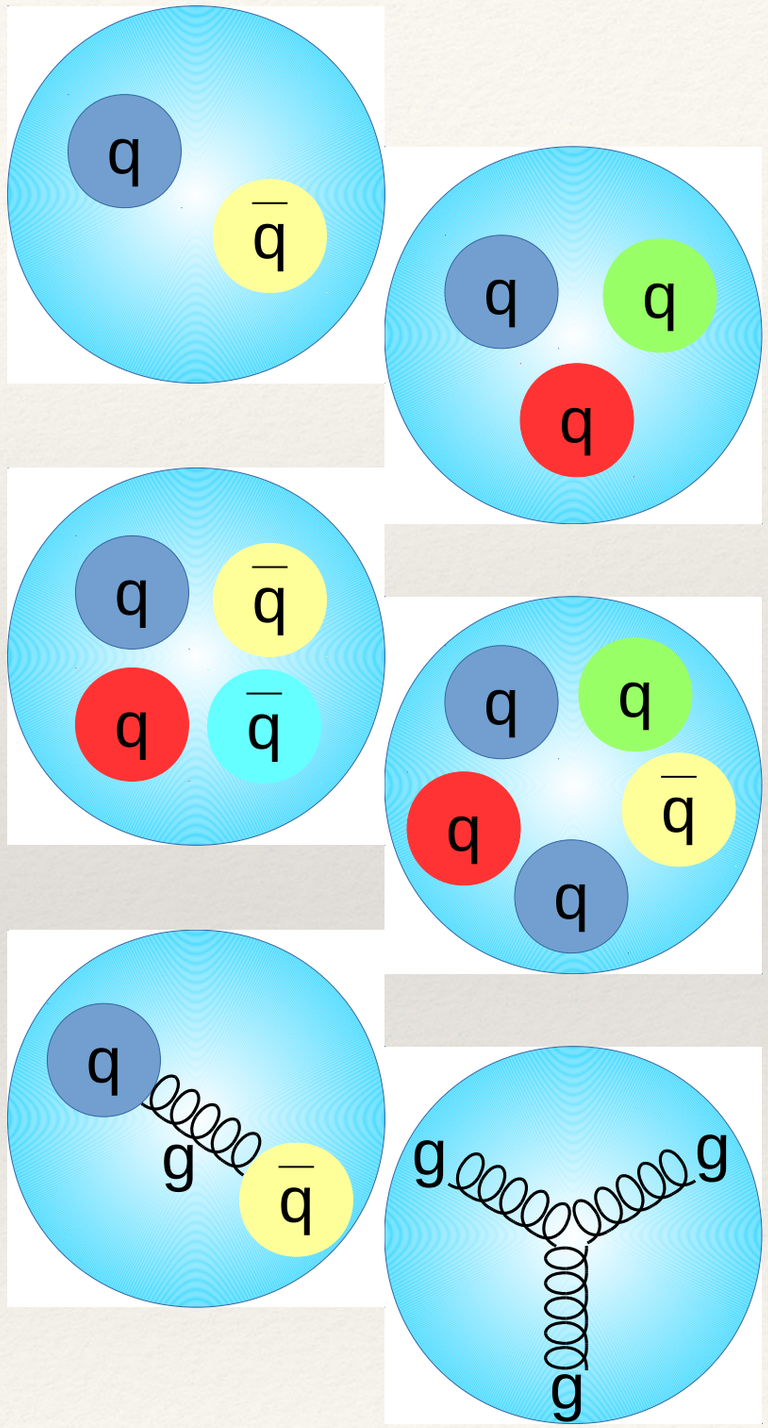
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

. . . Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc. . . .

Phys. Lett. 8 (1964) 214



- $q\bar{q}g$ are also allowed!
- so are g-only states

Current data situation

- Understanding the light baryon spectrum is a long standing quest and much progress has been made in the past decades

- Strange baryons, and especially double strange baryons, are less well studied

> *"For several decades, there has been very little new experimental data bearing on the properties of Λ and Σ resonances. […] the* ***field is starved for data****. Recent analyses (see below) have improved what we know about the properties of the known Λ and Σ resonances, but the* ***established resonances are the same ones that were listed in our 1984 edition*** *[…]"*
>
> — Λ and Σ resonances, PDG (2021)

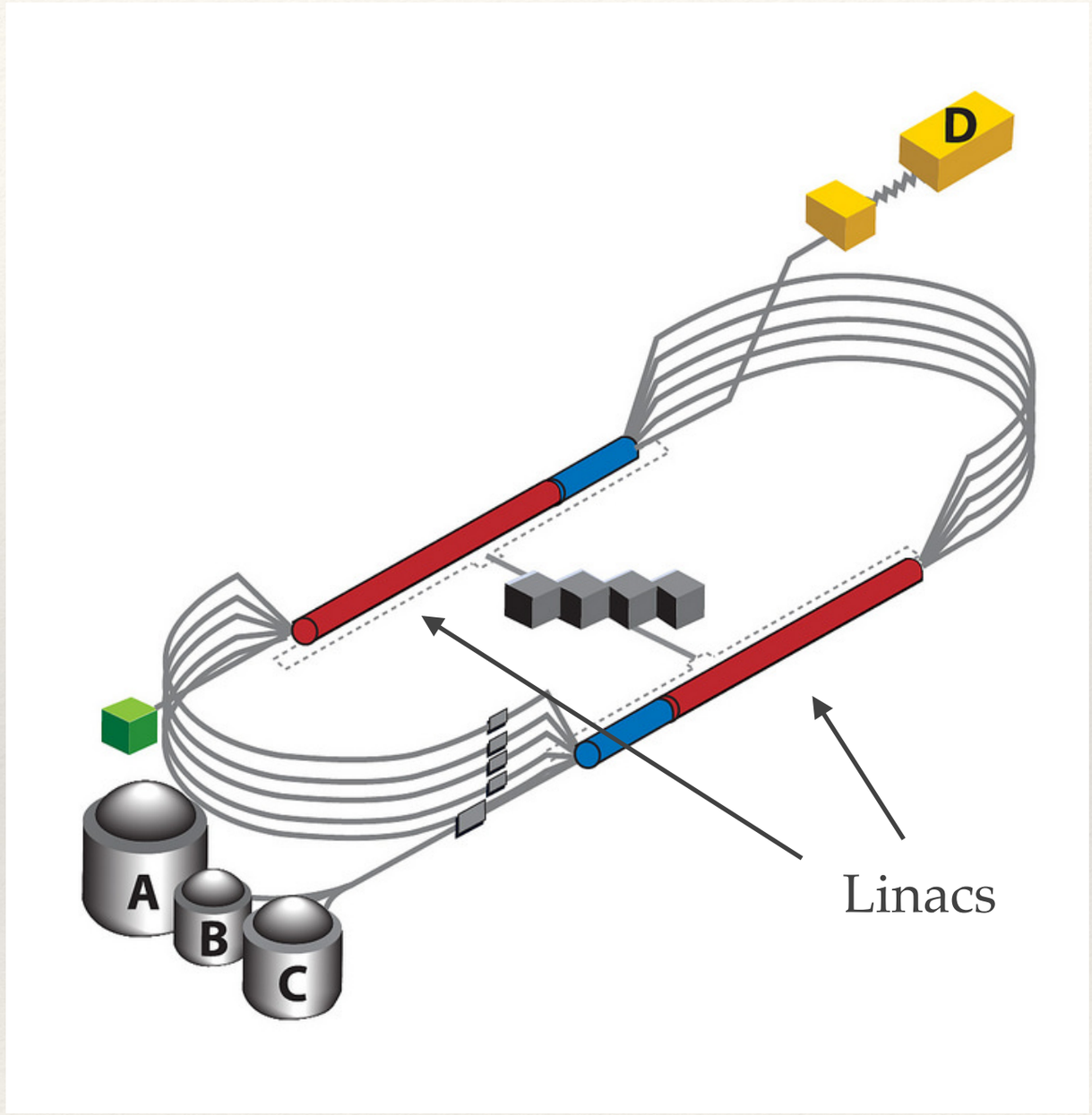
- The situation in the strange meson sector is much the same. Not much has happened since 1990

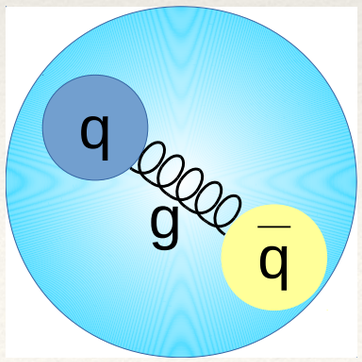
> *"The* ***spectrum of kaon excitations*** *is much less clear cut and therefore* ***deferred to a future edition****, when further data might become available."*
>
> — Spectroscopy of Light Meson Resonances, PDG (2023)

CEBAF at Jefferson Lab

CEBAF at Jefferson Lab

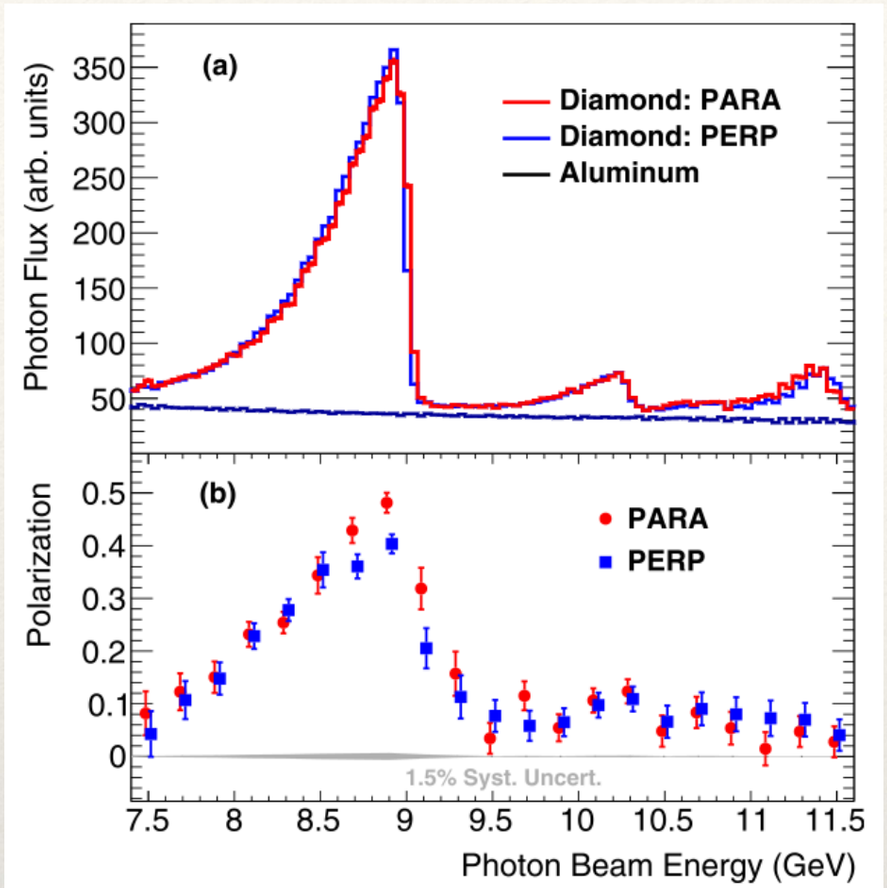
- up to 12 GeV electron beam
- high luminosities for Hall A/C (high resolution spectrometer)
- CLAS12 in Hall B
  - Large acceptance spectrometer
- GlueX in Hall D
  - Focus on exotic hybrid mesons
    BUT:
    Large data set available to study wide range of reactions





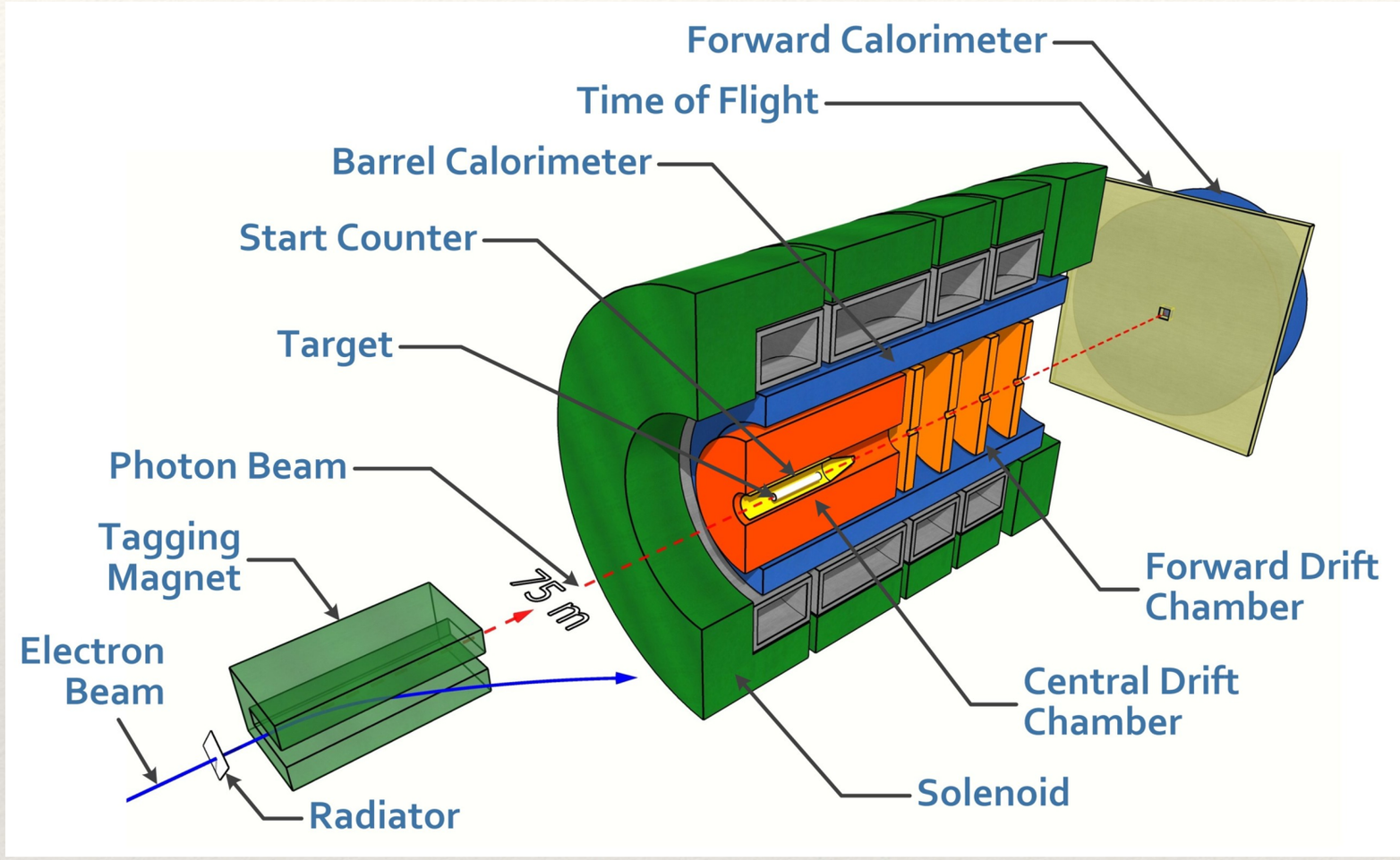
GlueX in Hall D

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



GlueX, Nucl. Instrum. Meth. A 987 (2021) 164807

- produce linearly polarized photon beam via coherent bremsstrahlung on thin diamond

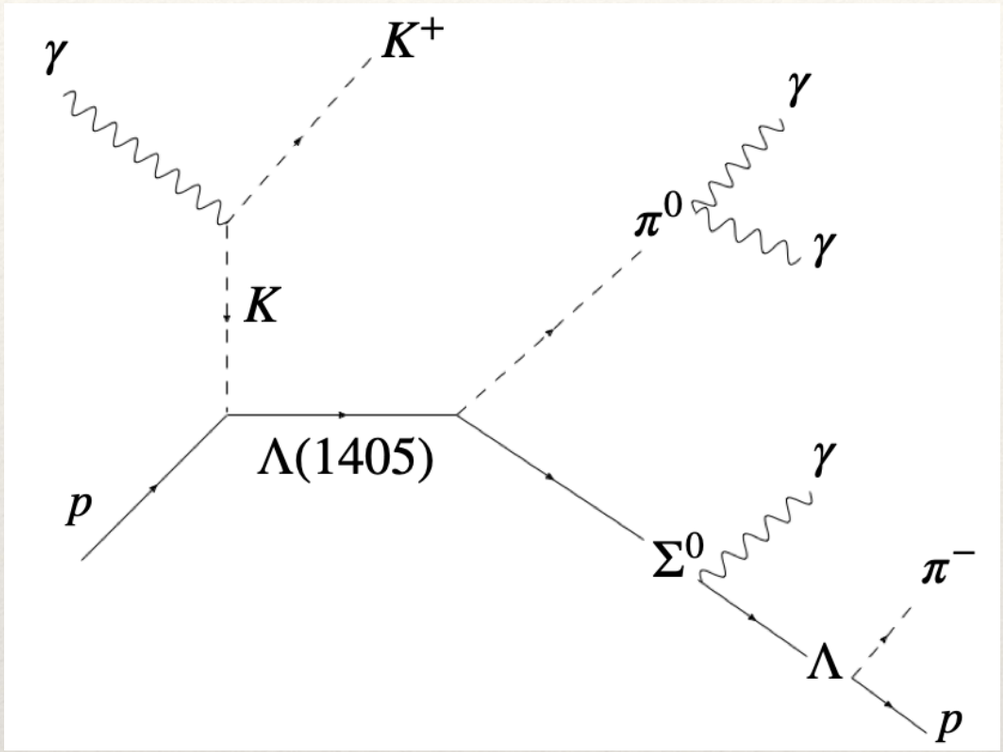


- tag electrons to determine photon energy

GlueX-I (2017-18): $\mathscr{L} = 305\ \text{pb}^{-1}$ $(E_\gamma > 8\ \text{GeV})$
GlueX-II (2020-25): $\mathscr{L} = 320\ \text{pb}^{-1}$, so far
ultimately 3-4x GlueX-I expected

- Acceptance: $\theta_{lab} \approx 1^\circ - 120^\circ$
- Charged particles: $\sigma_p/p \approx 1\% - 3\,\%$
  $(8\% - 9\,\%$ very-forward high-momentum tracks)
- Photons: $\sigma_E/E = 6\,\%/\sqrt{E} \oplus 2\,\%$

$\Lambda(1405)$ line shape measurement

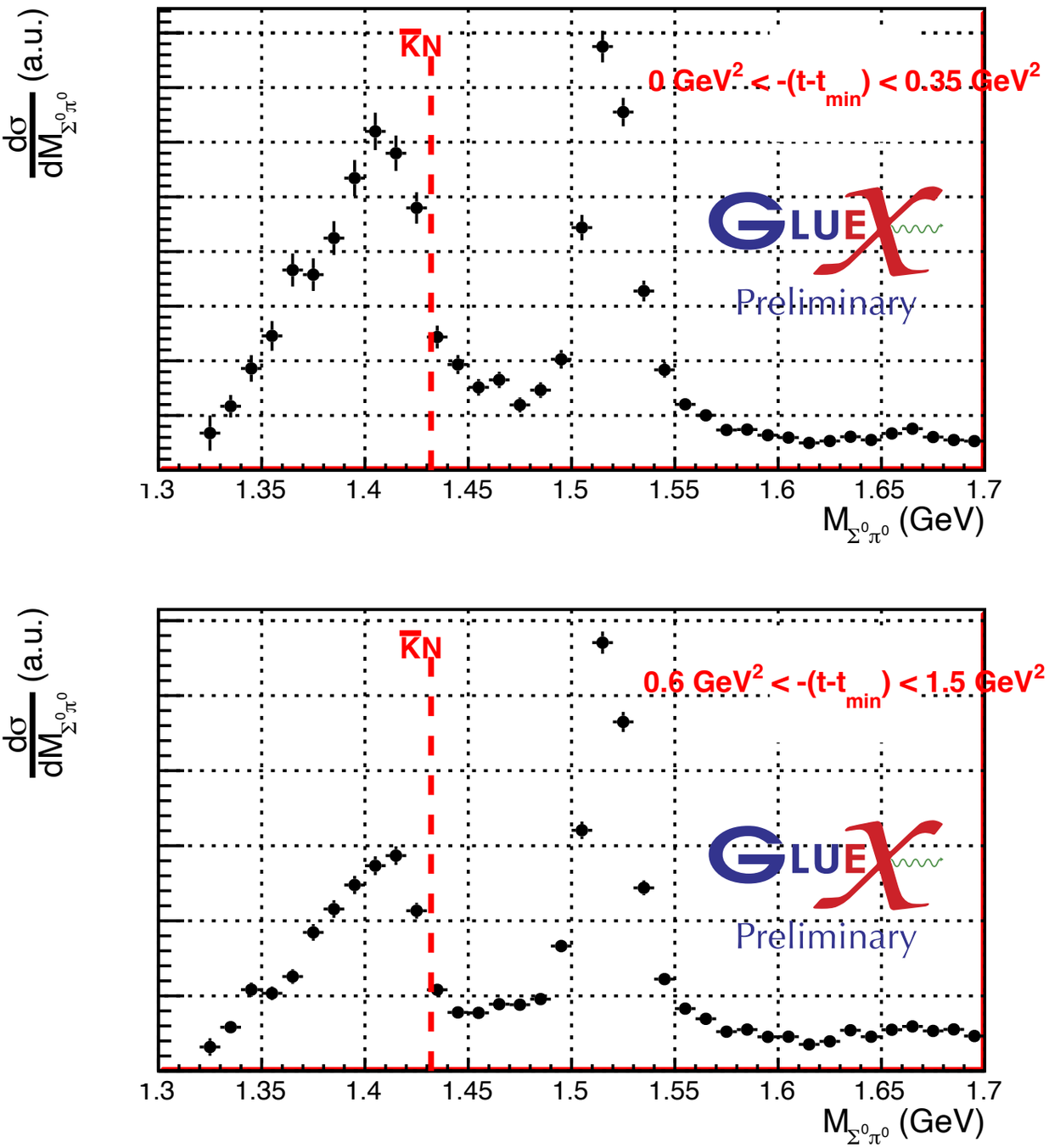


$\Lambda(1405) \to \Sigma^0\pi^0$ ($I = 0$) is free from $\Sigma(1385)$ background

- Excited Λ with $J^P = \frac{1}{2}^-$
- $\Lambda(1405) \to \Sigma\pi$
- Previous measurements (e.g. COSY-Jülich or CLAS) show very clear non-Breit-Wigner line shape
- Interpretation under active investigation
- Many theory models find two-pole structure:
  not just one state
- Recent PDG addition: ** $\Lambda(1380)$

Λ(1405) line shape measurement

N. Wickramaarachchi
(HYP2022)

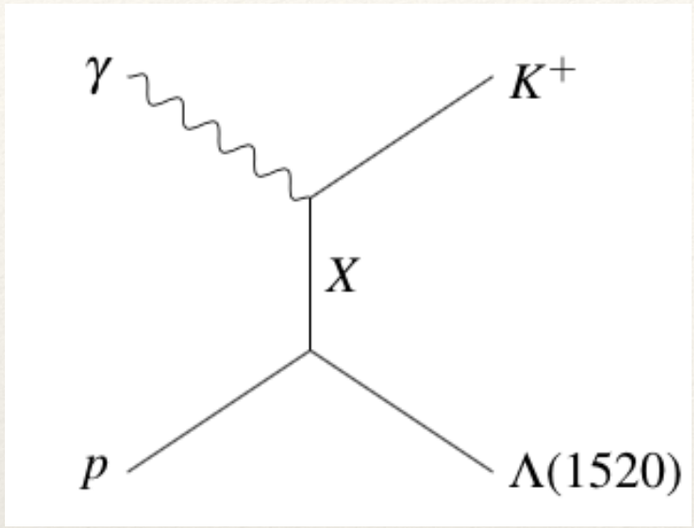


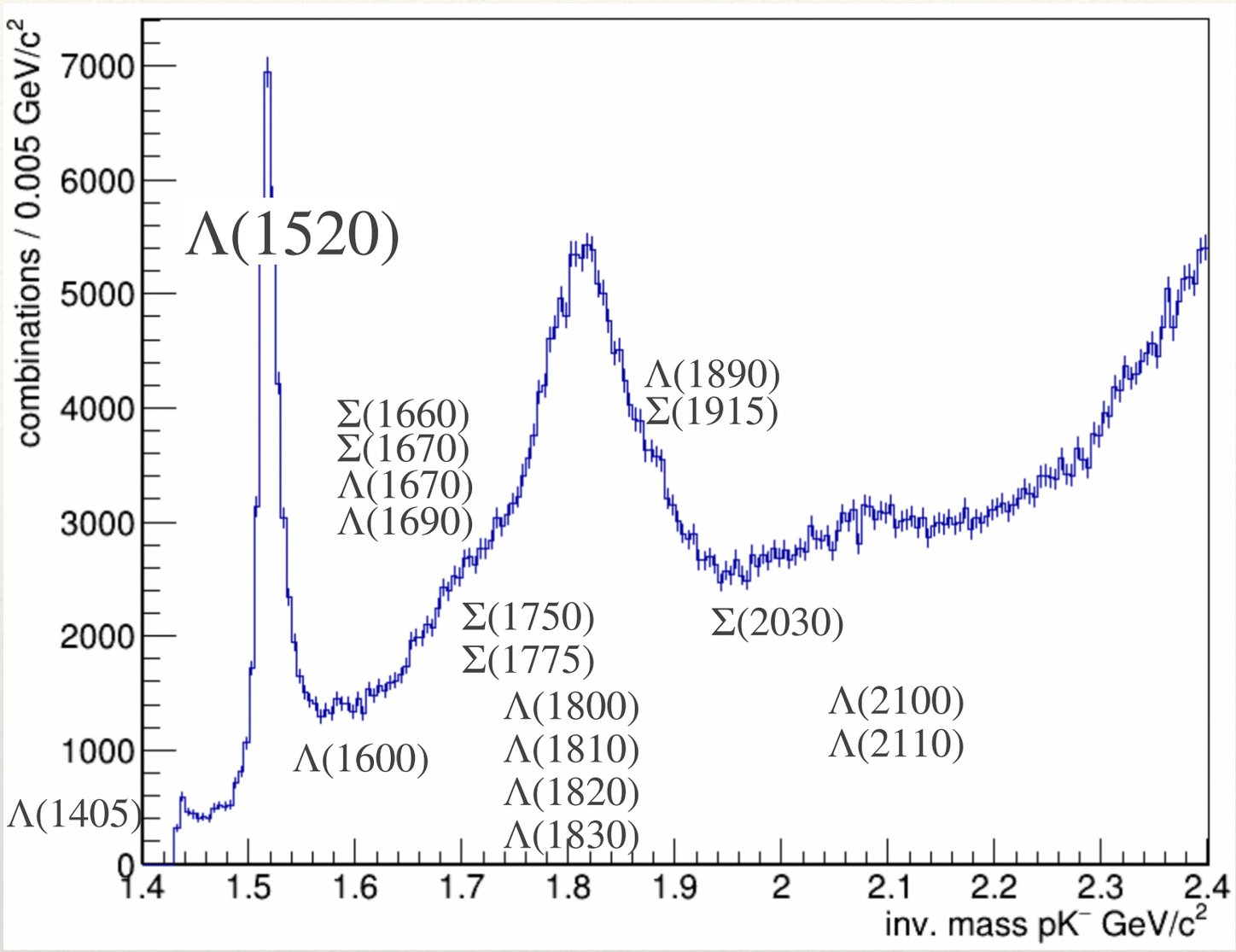
- Λ(1405) t-dependent line shape?
- Could support two-pole structure

Excited hyperons

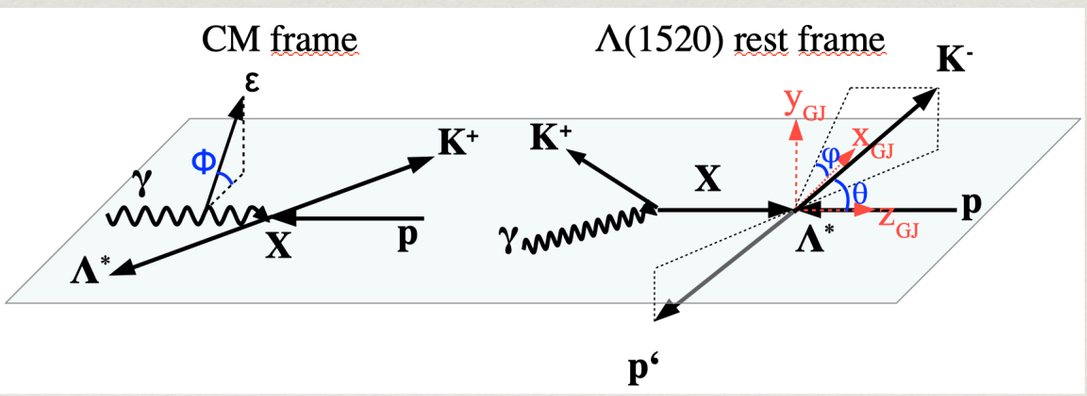
Phys. Rev. C **105**, 035201

$\gamma p \to K^+ Y^* \to K^+ K^- p$





Λ(1520) SDMEs



$$W_0 = \frac{1}{4\pi}\left[3\left(\frac{1}{2} - \rho^0_{11}\right)\sin^2(\theta) + \rho^0_{11}\left(1 + 3\cos^2(\theta)\right) - 2\sqrt{3}\left(\mathrm{Re}(\rho^0_{31})\cos(\varphi)\sin(2\theta) + \mathrm{Re}(\rho^0_{3-1})\cos(2\varphi)\sin^2(\theta)\right)\right]$$

$$W_1 = \frac{1}{4\pi}\left[3\rho^1_{33}\sin^2(\theta) + \rho^1_{11}(1 + 3\cos^2(\theta)) - 2\sqrt{3}\left(\mathrm{Re}(\rho^1_{31})\cos(\varphi)\sin(2\theta) + \mathrm{Re}(\rho^1_{3-1})\cos(2\varphi)\sin^2(\theta)\right)\right]$$

$$W_2 = \frac{1}{4\pi}\left[2\sqrt{3}\left(\mathrm{Im}(\rho^2_{31})\sin(\varphi)\sin(2\theta) + \mathrm{Im}(\rho^2_{3-1})\sin(2\varphi)\sin^2(\theta)\right)\right]$$

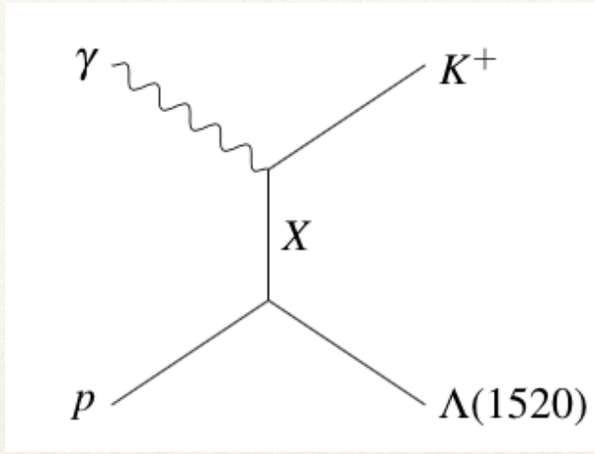
$$W = W_0 - P_\gamma\cos(2\Phi)W_1 - P_\gamma\sin(2\Phi)W_2$$

- Many excited Λ* and Σ* expected in spectrum
- Most prominent: Λ(1520) hyperon with $J^P = 3/2^-$

Λ(1520) SDME combinations

Phys. Rev. C **105**, 035201

- red and blue show model predictions in Reggeized framework (priv. comm. based on [1])
- natural amplitudes dominate
- More work needed to model the reaction accurately

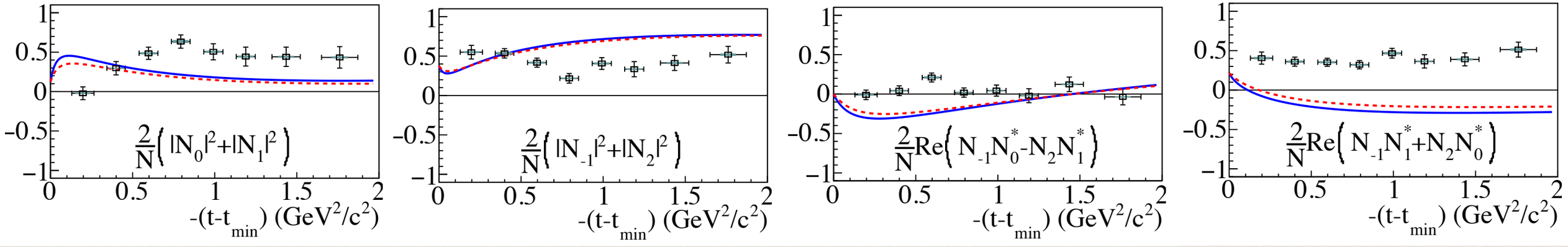


X is exchange particle with spin-parity quantum number J^P and naturality $\eta = P(-1)^J$

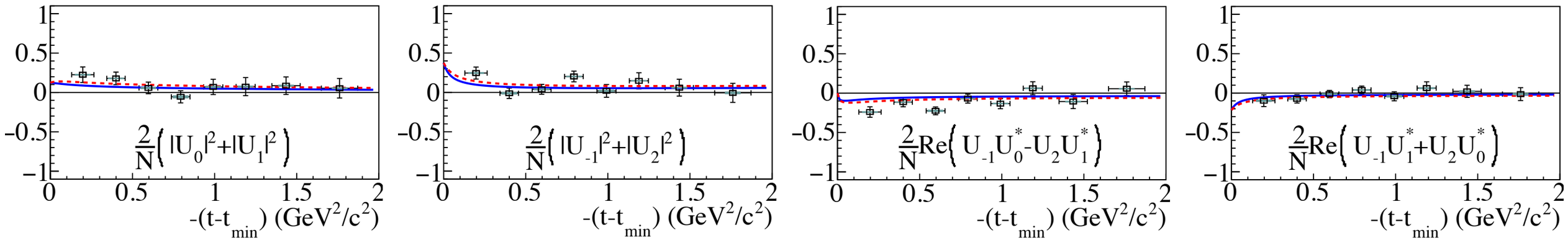
Natural: e.g. $K^*(892)$, $K_2^*(1430)$

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

Natural

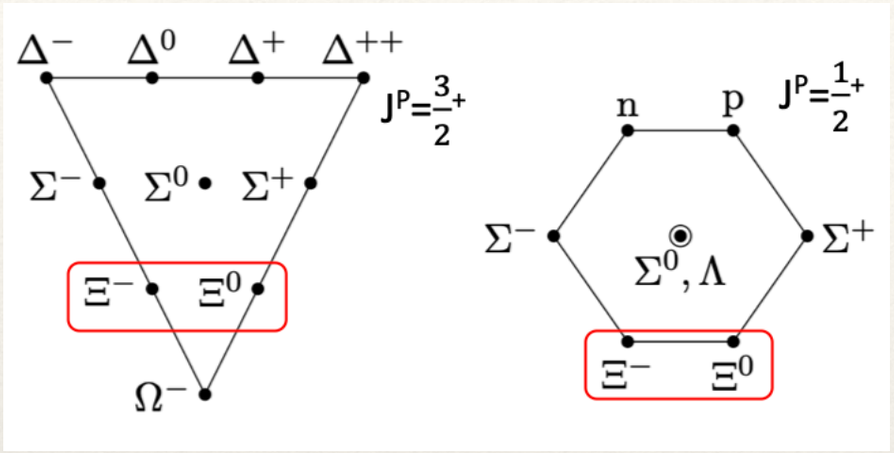


Unnatural



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

Cascades at GlueX

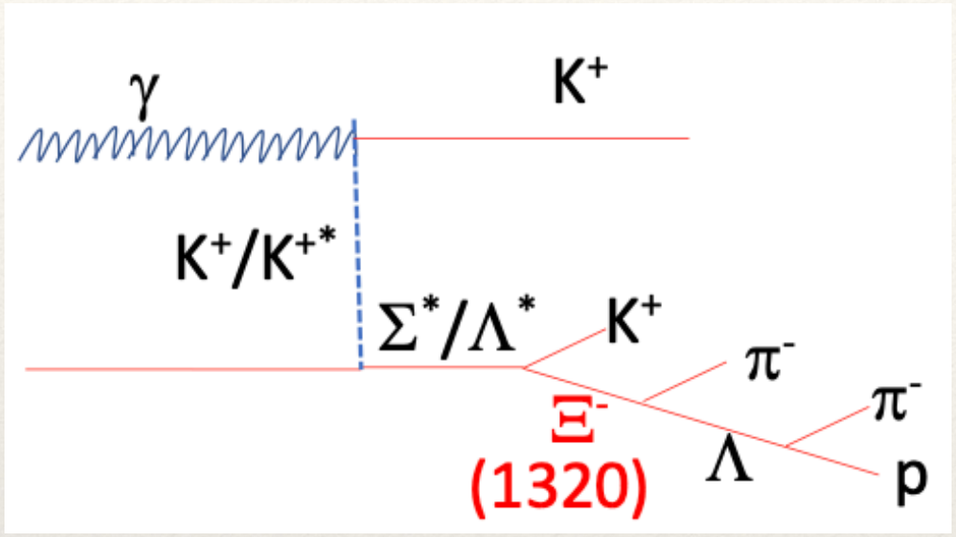


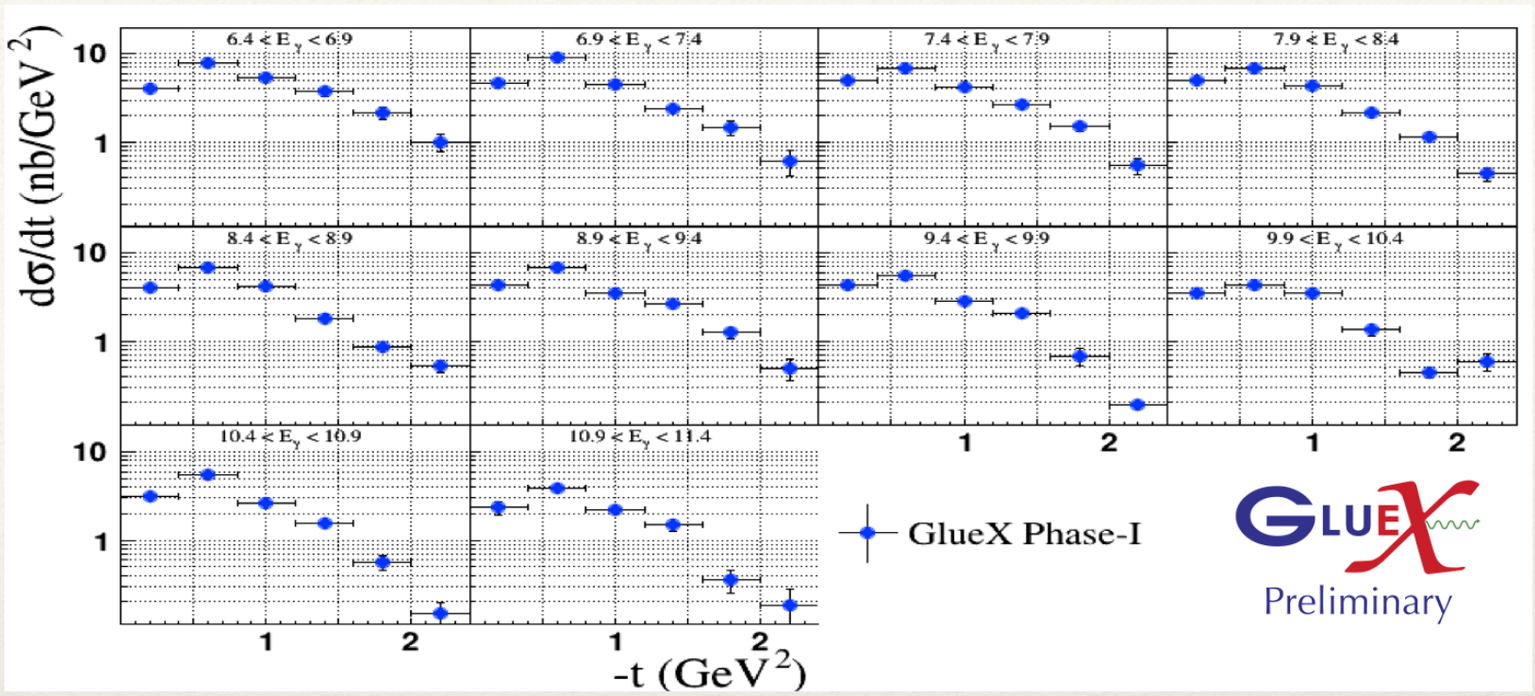
Particle	J^P	Overall Status	Status as seen in: $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$
$\Xi(1318)$	$1/2^+$	****				
$\Xi(1530)$	$3/2^+$	****	****			
$\Xi(1620)$		*	*			
$\Xi(1690)$		***		***	**	
$\Xi(1820)$	$3/2^-$	***	**	***	**	**
$\Xi(1950)$		***	**	**		*
$\Xi(2030)$		***		**	***	
$\Xi(2120)$		*		*		
$\Xi(2250)$		**				
$\Xi(2370)$		**				
$\Xi(2500)$		*		*	*	

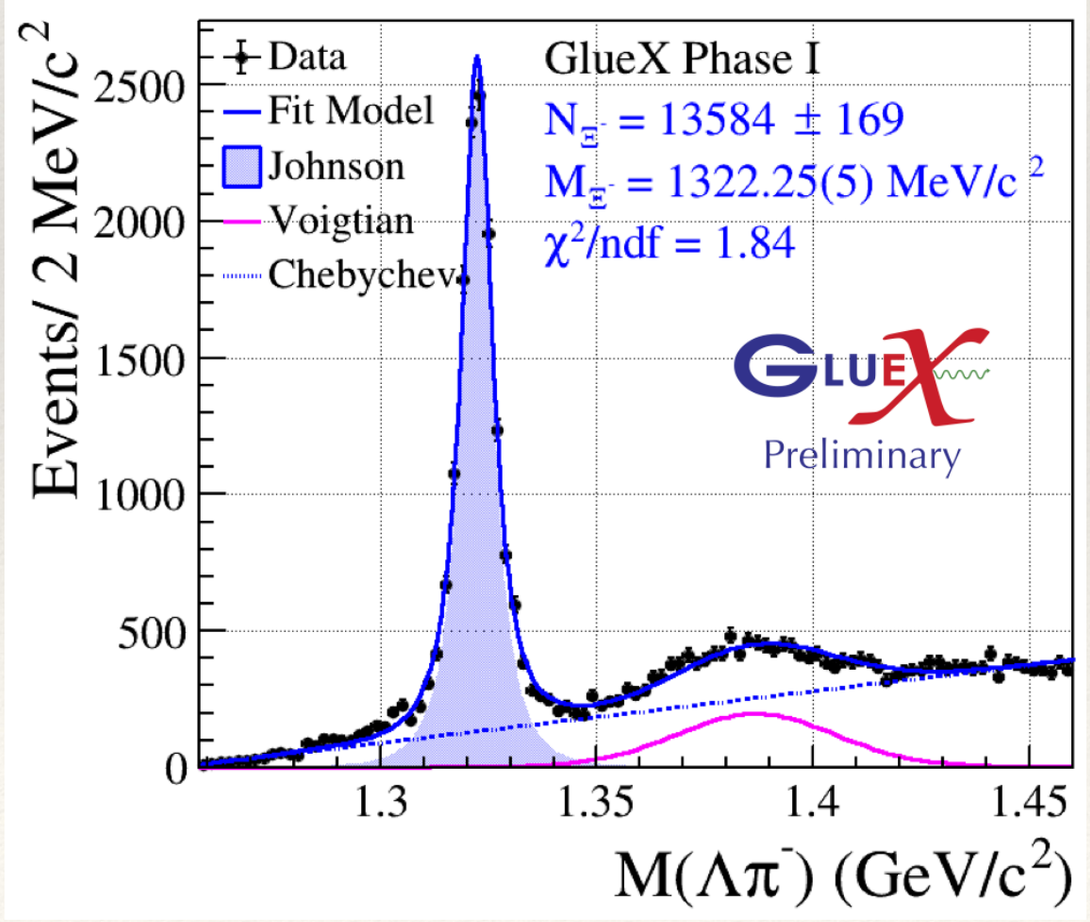
- Only six well known states (>3***)
- Would expect as many Ξs as N*s and Δs
- Not many photoproduction experiments have been performed so far ($S = -2$)
- GlueX with its good charged and neutral final state particle coverage could help here
- Difficult analyses due to many final state particles

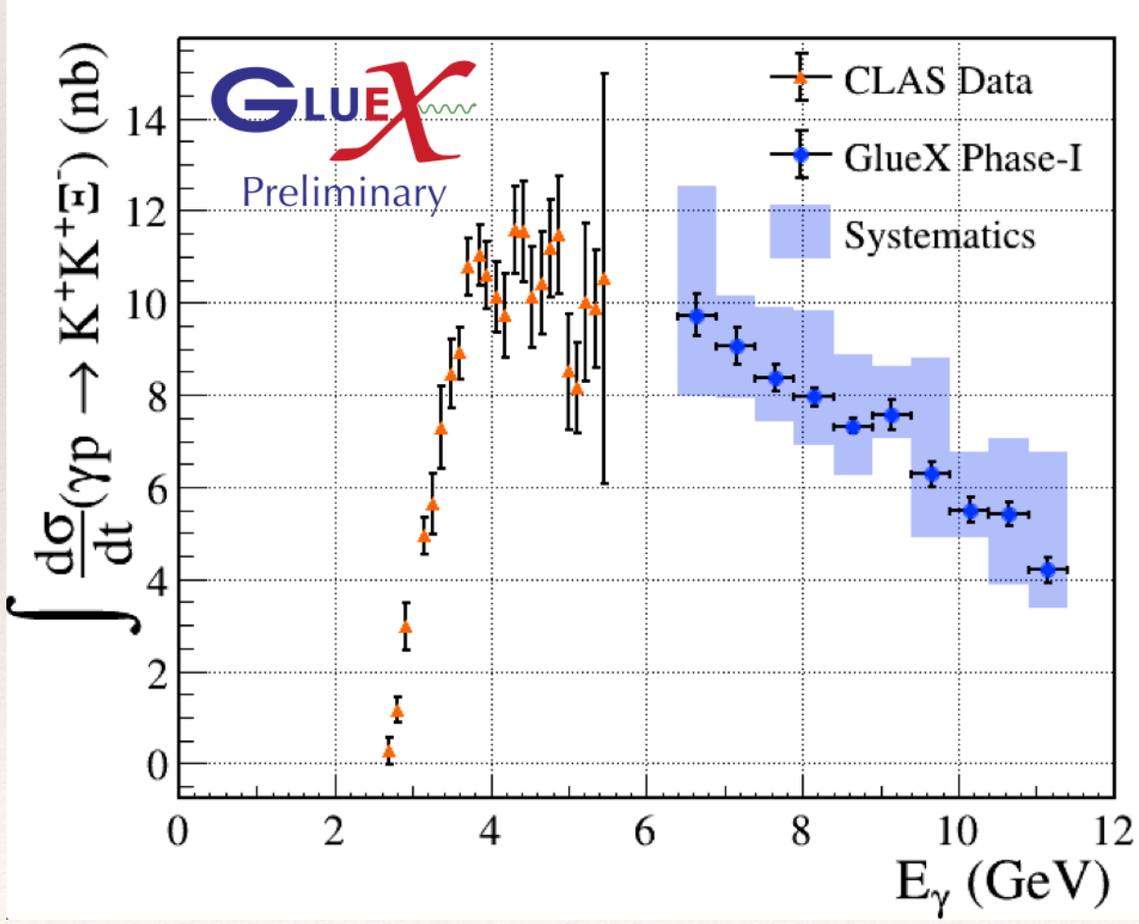
Cascades at GlueX

J. Hernandez (Baryon 2022)



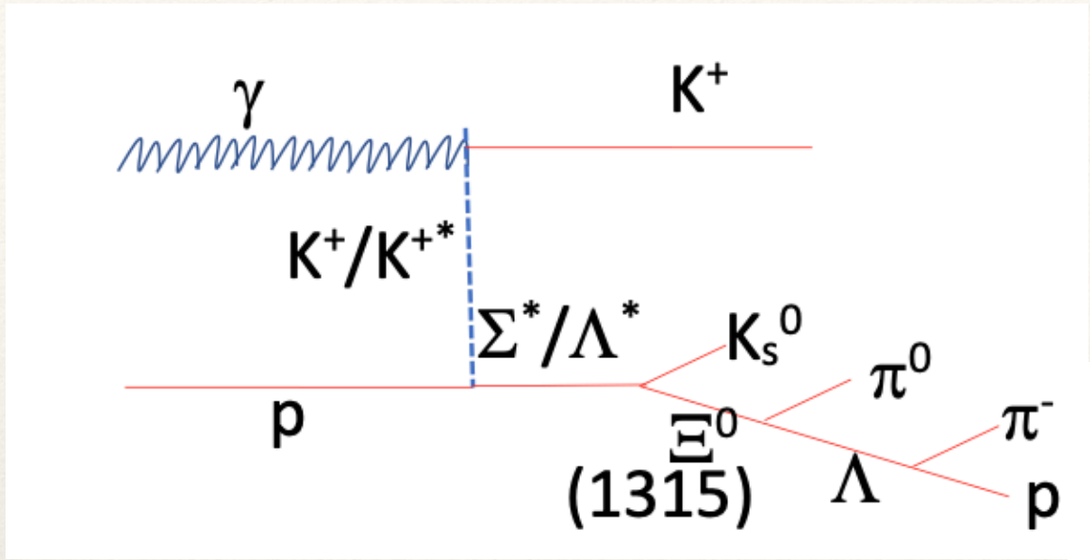




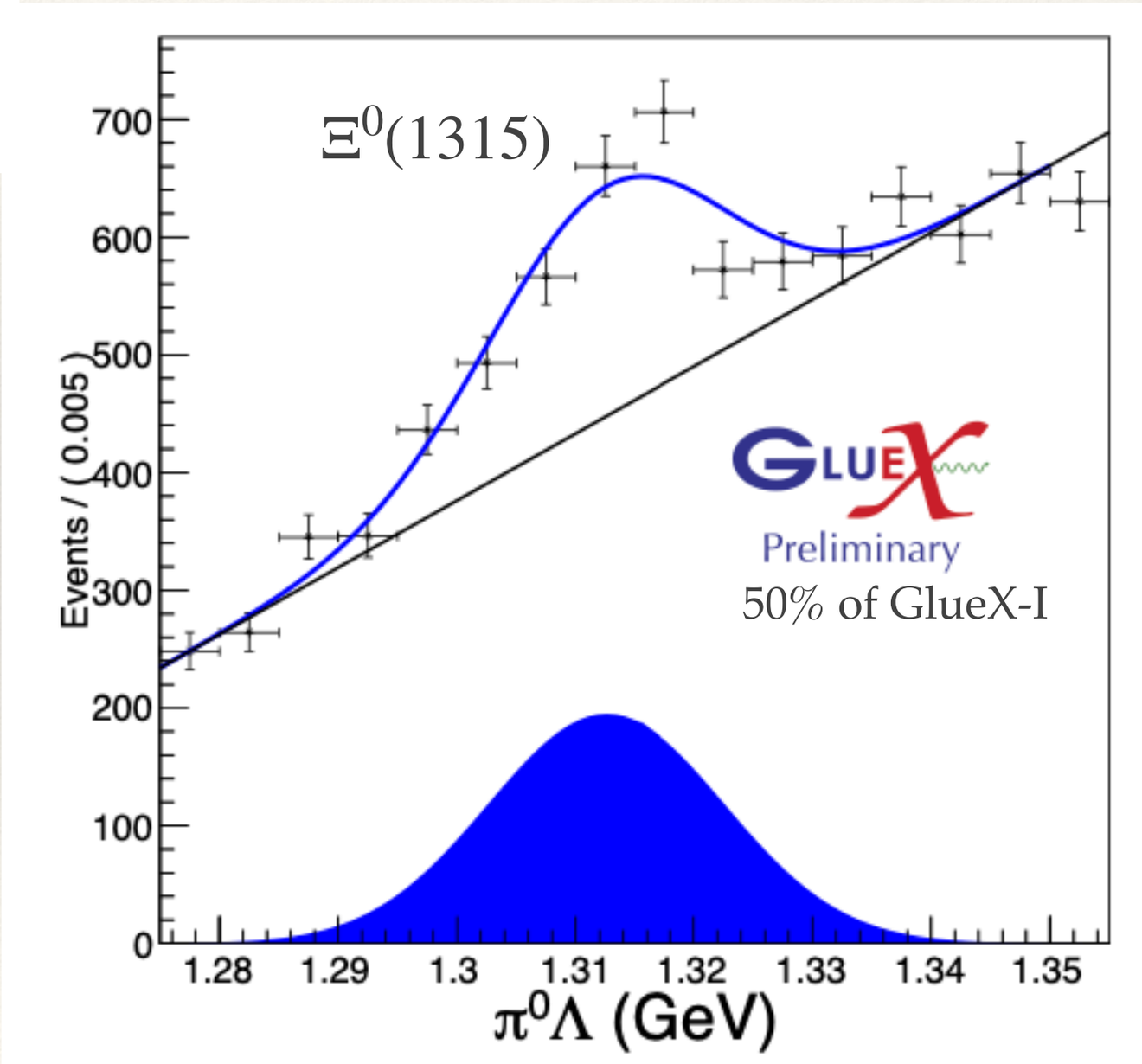


Cascades at GlueX

C. Akondi (SESAPS 2021)

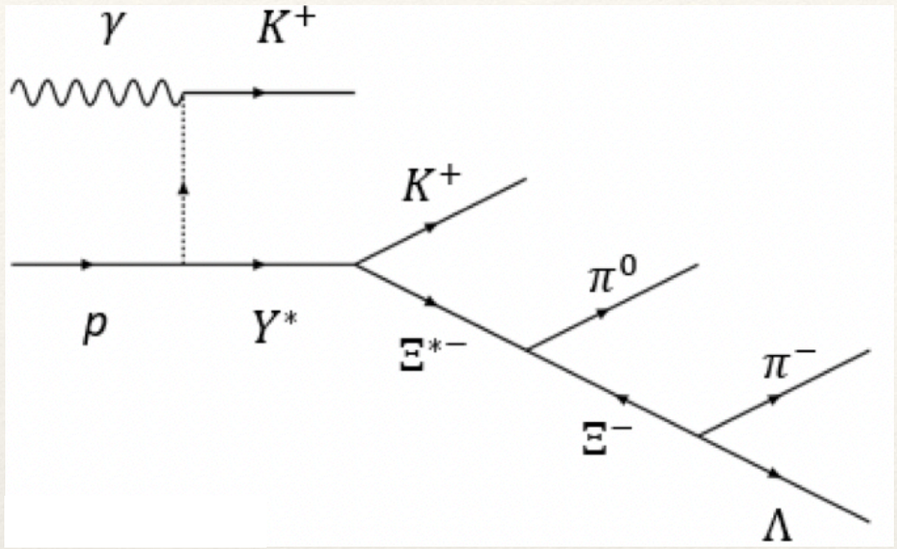


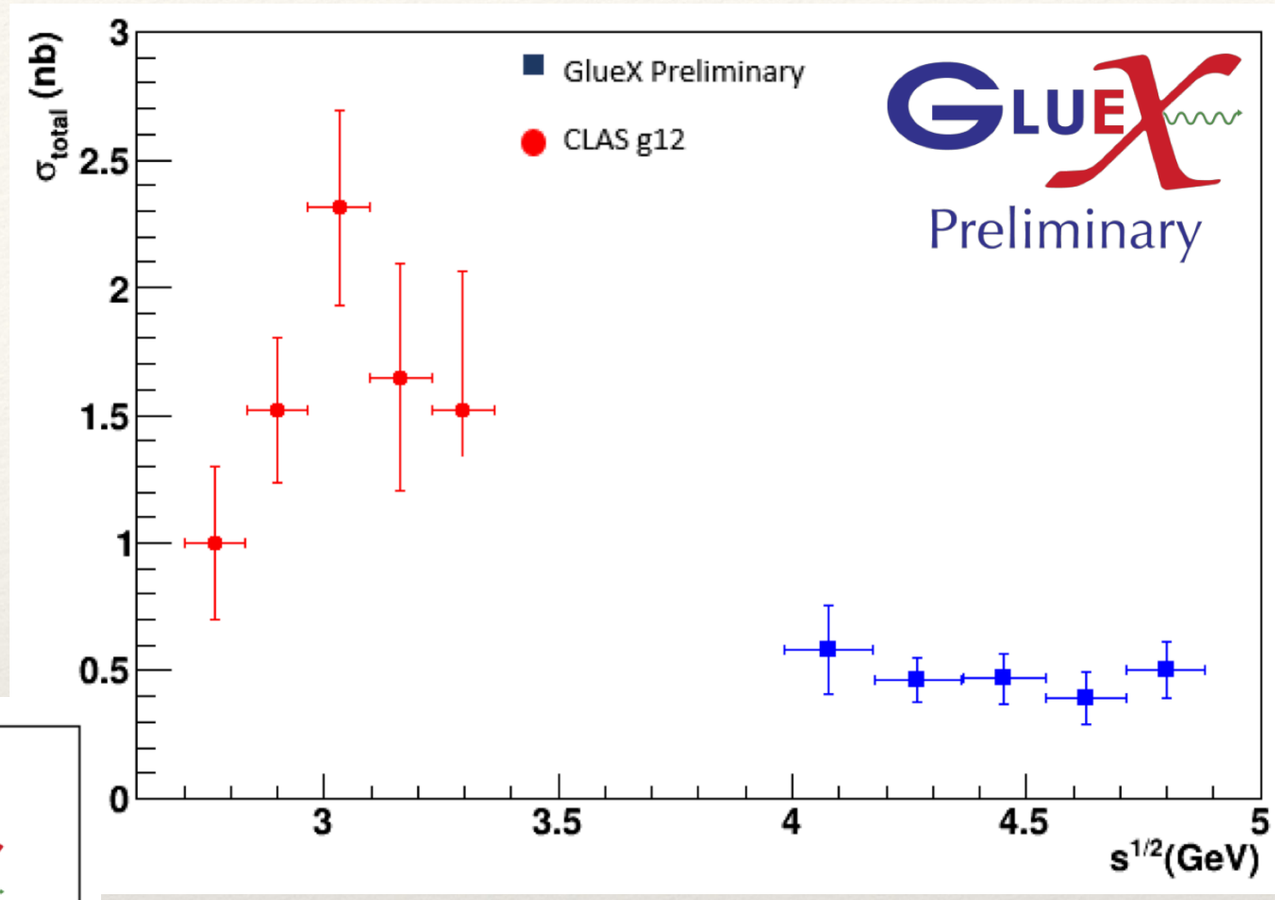
- We see both ground states
- Measure cross-sections for Ξ^-
- Less stats for Ξ^0 but clear signal

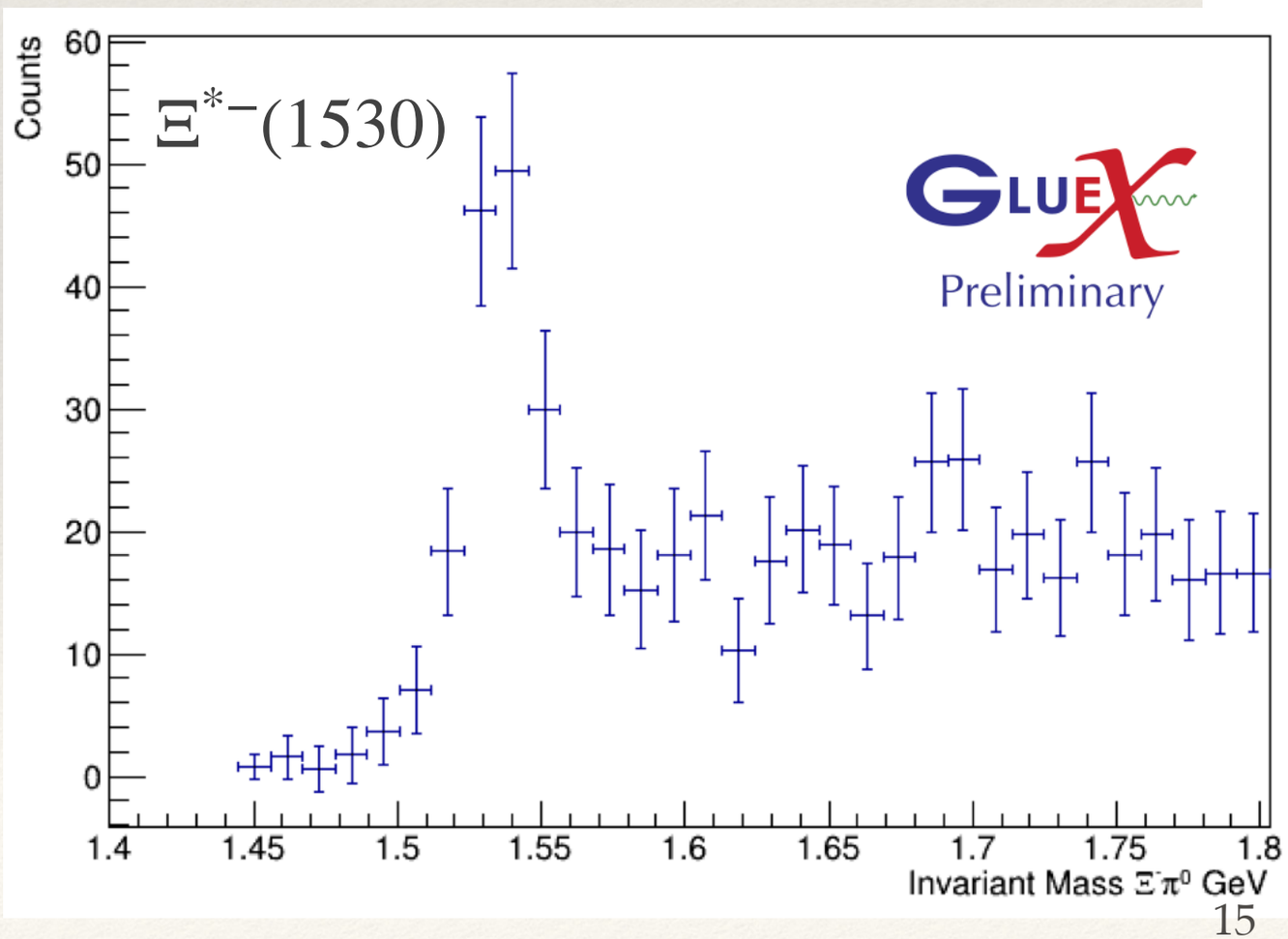


Further Cascades at GlueX

B. Sumner (GHP 2023)



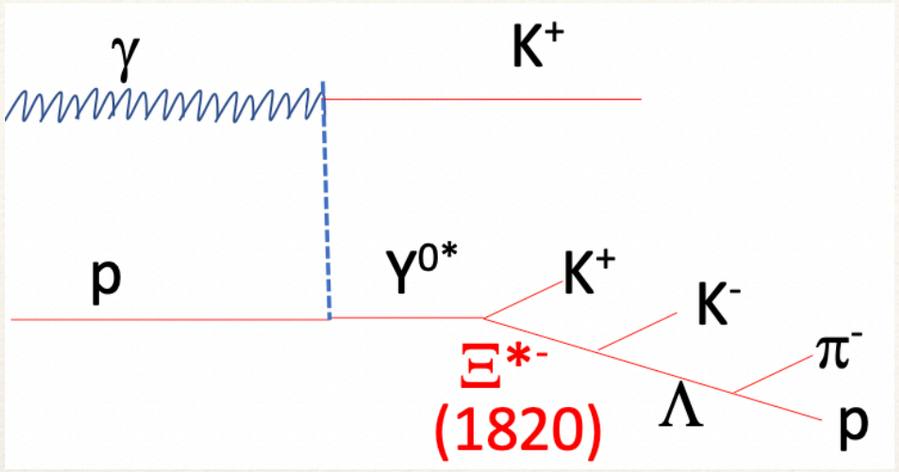




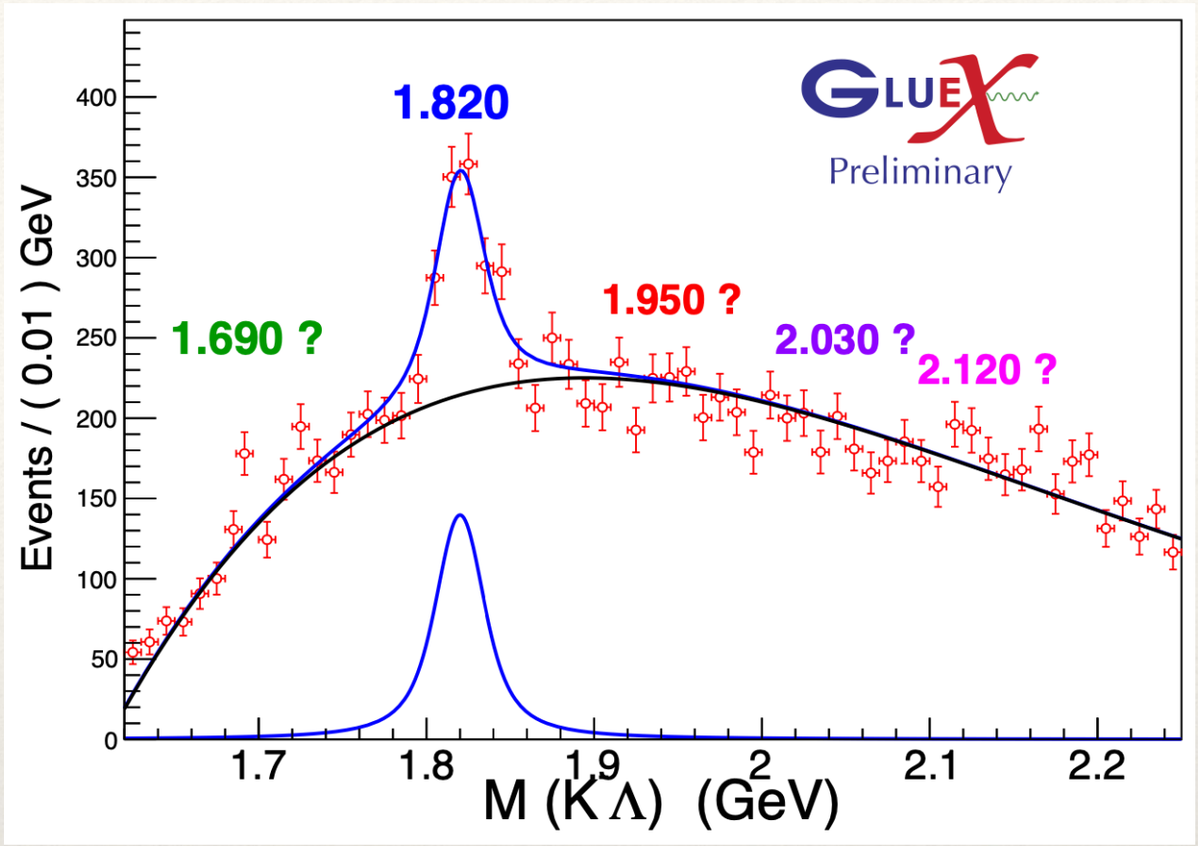
- Measure $\Xi^{*-} \to \Xi^{-}\pi^{0}$ and determine total Ξ^{*-} cross-section via isospin symmetry

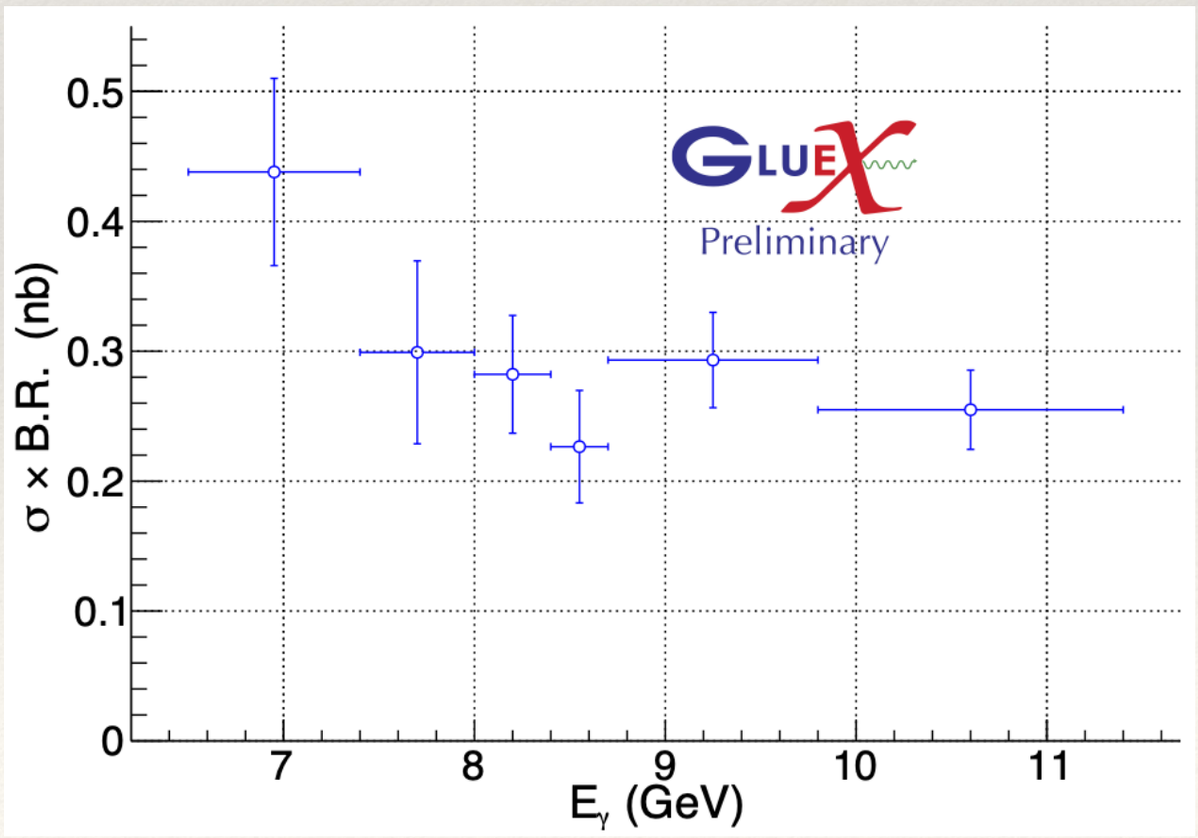
$\Xi^-(1820)$

C. Akondi (GHP 2023)



- Excited $\Xi(1820)$ with $J^P = \frac{3^-}{2}$
- *** resonance seen in $K^-\Lambda$ decays
- First measurement of $\Xi(1820)$ in photoproduction
- Only dominating feature in the $K^-\Lambda$ invariant mass



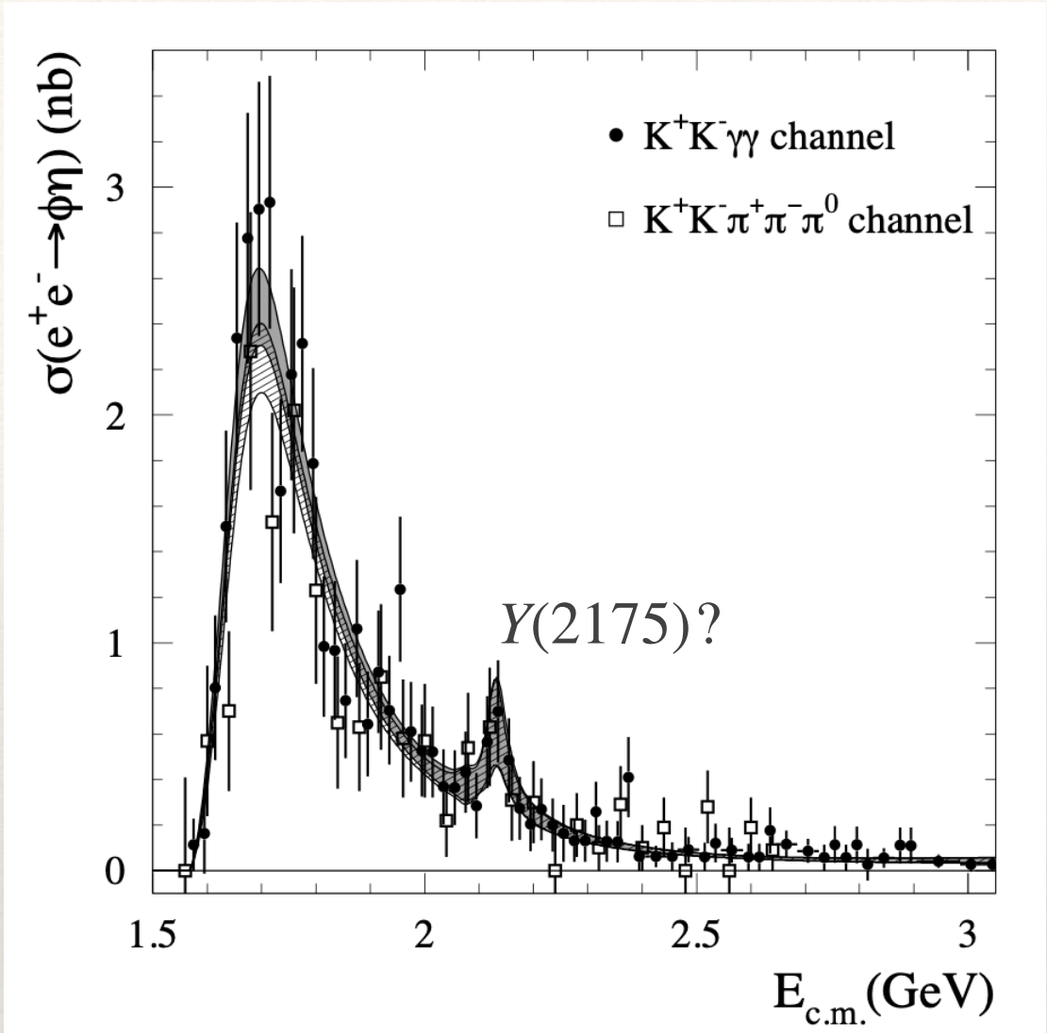


Y(2175) aka $\phi(2170)$

BaBar: Phys. Rev. D 77, 092002 (2008)

- BaBar (ISR):
  - Peaking structure at around 2175 MeV in $e^+e^- \to \phi f_0(980) \to \phi\pi\pi$
  - Peaking structure at around 2125 MeV in $e^+e^- \to \phi\eta$
- BES then also saw peak in $\phi f_0(980)$ in $J/\psi \to \eta\phi f_0(980) \to \eta\phi\pi\pi$:
  - Observed at 2186 MeV
- Strangeness rich environment
- Interpretation not clear, masses vary a lot
- Strange partner of $Y(4230)$?

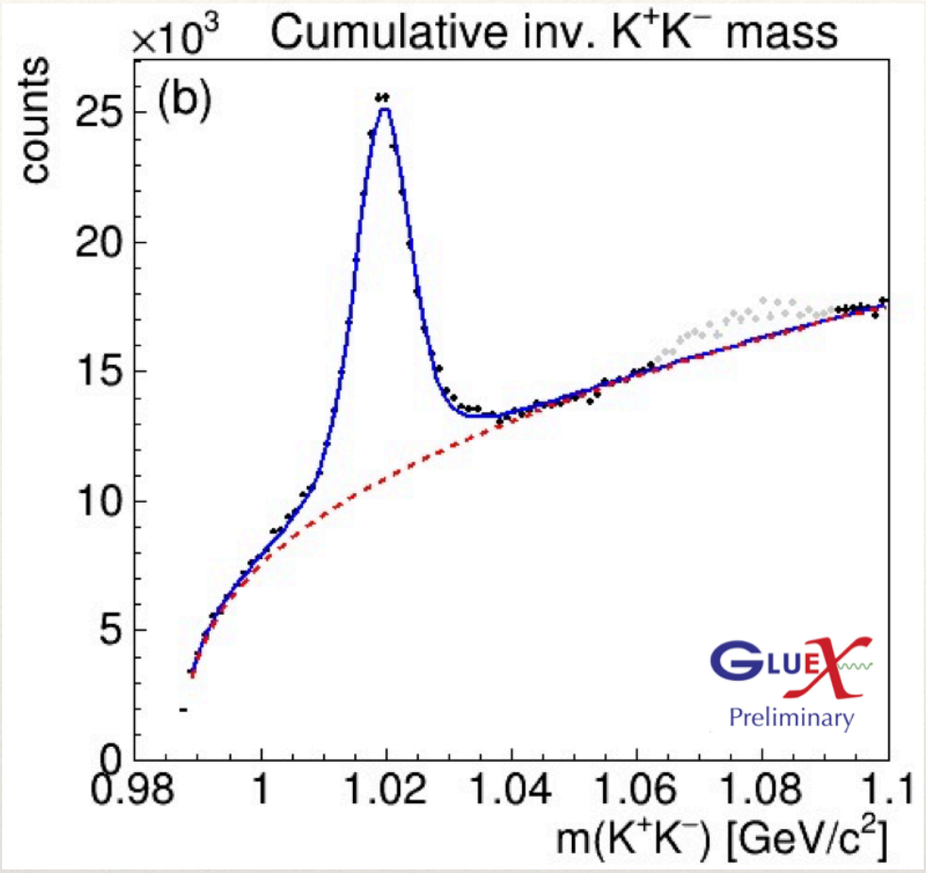
  $Y(4230) \to J/\psi\pi^+\pi^-$



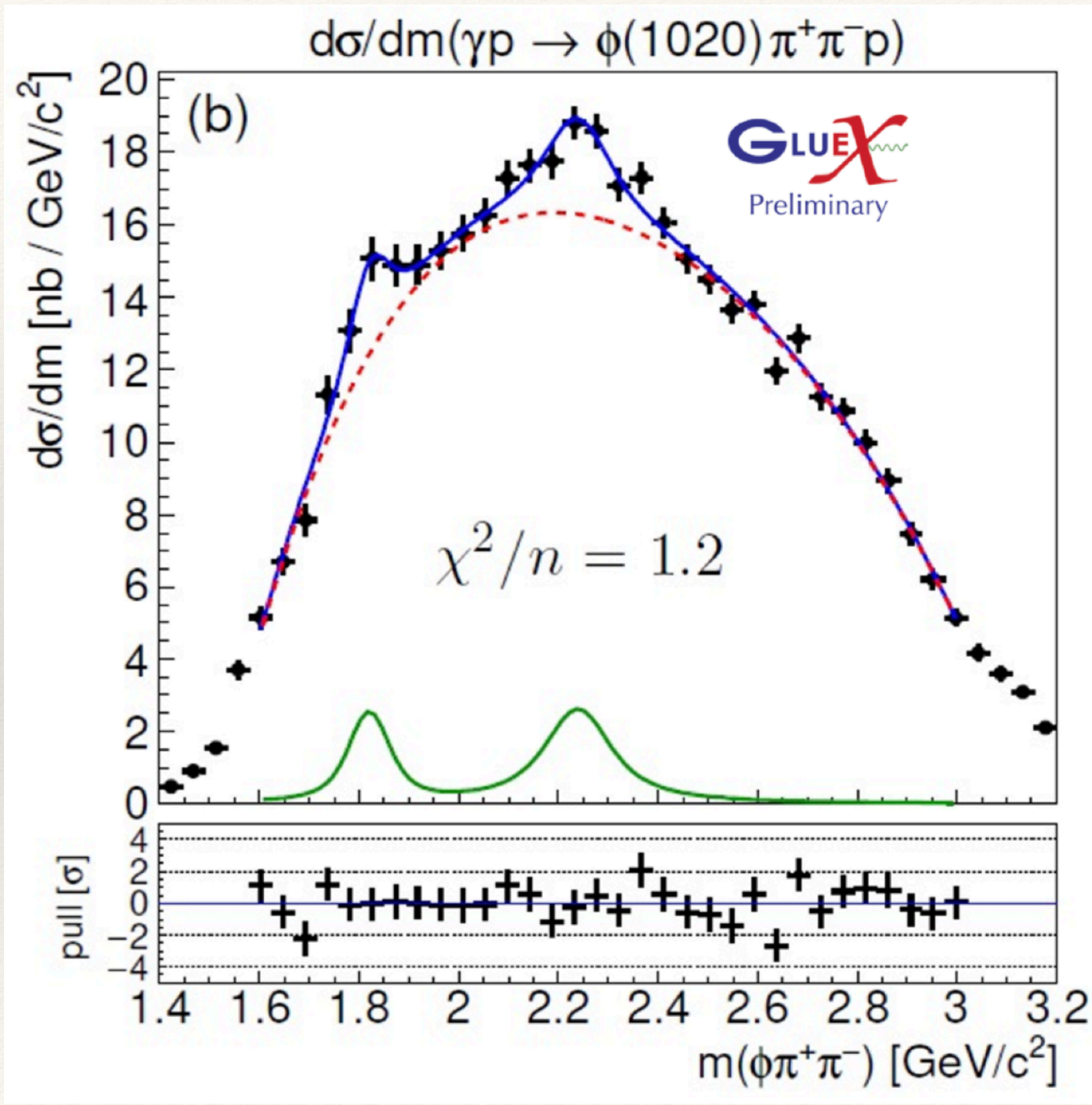
	$\frac{\chi^2}{\text{n.d.f.}} = \frac{184.9}{160-16} = 1.28$	
R with $I=0$	ϕ'	ϕ''
$\Gamma^R_{ee}\mathcal{B}^R_{KK^*(892)}$(eV)	367±47	-
$\Gamma^R_{ee}\mathcal{B}^R_{\phi\eta}$(eV)	154±32	1.7±0.8
$1-\mathcal{B}^R_{KK^*(892)}-\mathcal{B}^R_{\phi\eta}$	0.33±0.14	-
M_R(MeV)	1709±19	2127±24
Γ_R(MeV)	325±68	60±50

Y(2175) aka $\phi(2170)$

F. Nerling
(MESON2023)

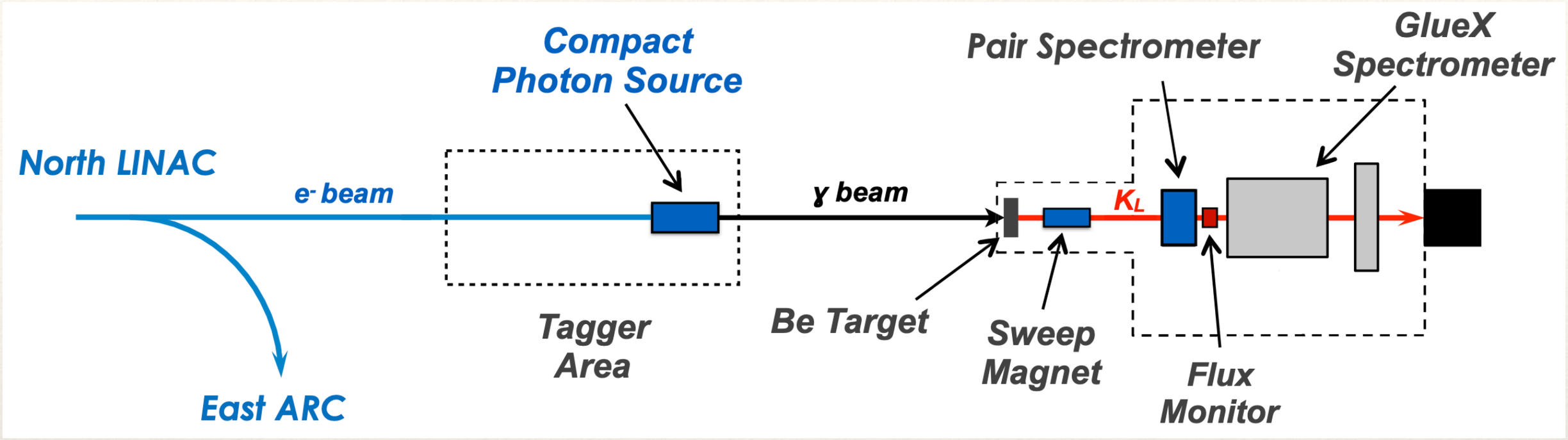


search in $\gamma p \to \phi\pi\pi\ p$, with $\phi \to K^+K^-$

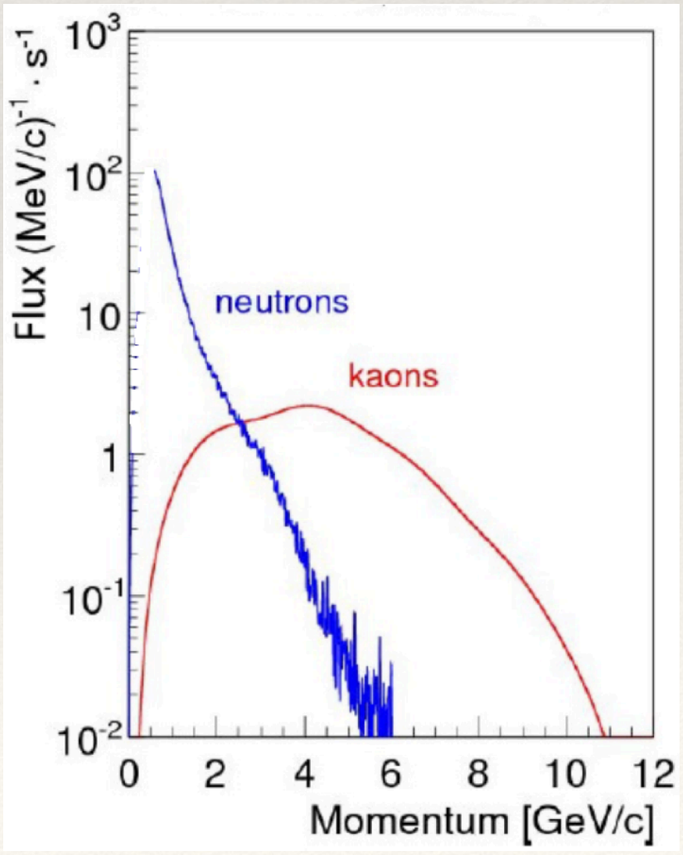


- No evidence for state with PDG parameters
  $m = 2162 \pm 7$ MeV
  $\Gamma = 100^{+31}_{-21}$ MeV
  - UL $\sigma < 500$ pb
- Evidence of structures at
  $m \sim 1.8$ GeV and $m \sim 2.24$ GeV

KLong facility in Hall D



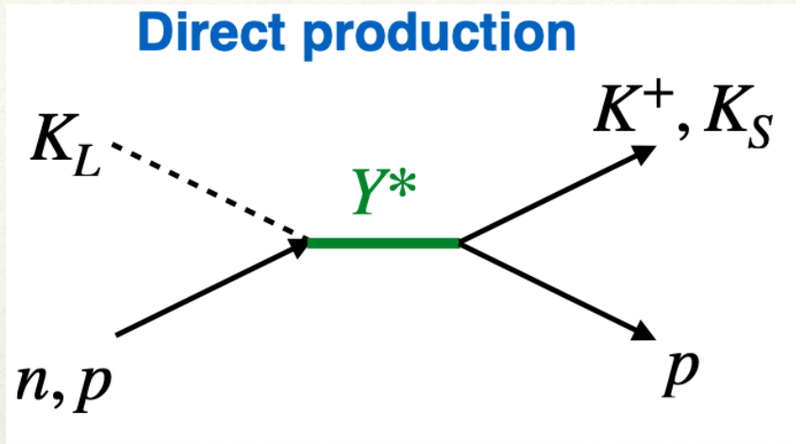
- New kaon beam facility approved to run 200 days in Hall D
  - Study of hyperons and kaon spectroscopy
- Produce $\approx 10^4 K_L\ /s$ (1000 times higher than previous experiments)
- Proton and neutron targets
- Use GlueX spectrometer to identify final state
- Might run 2026-2028

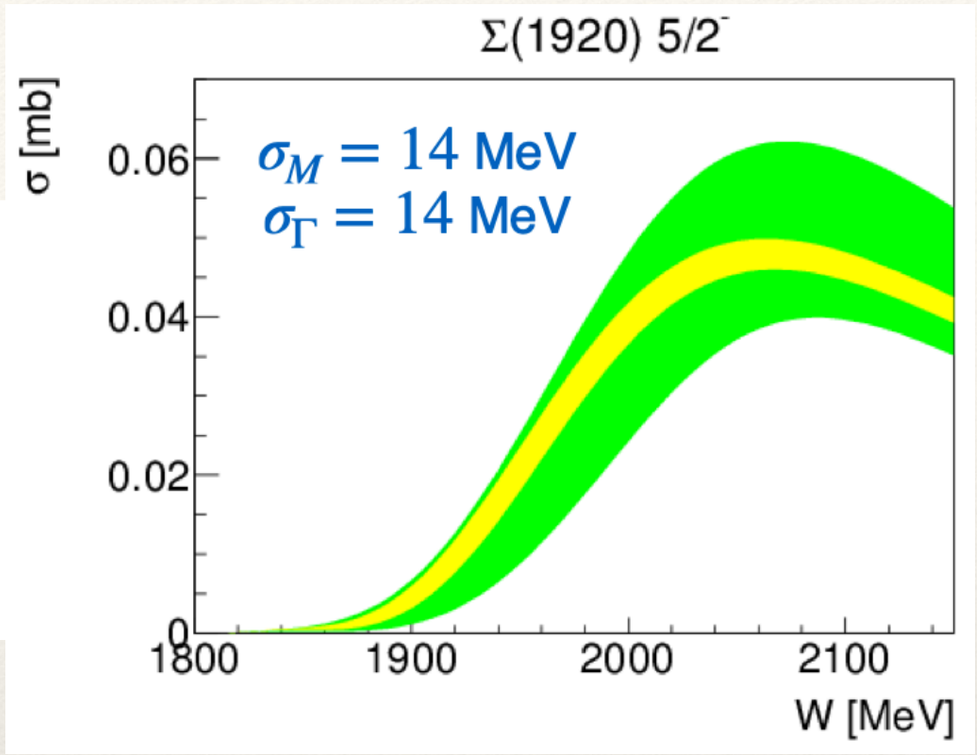


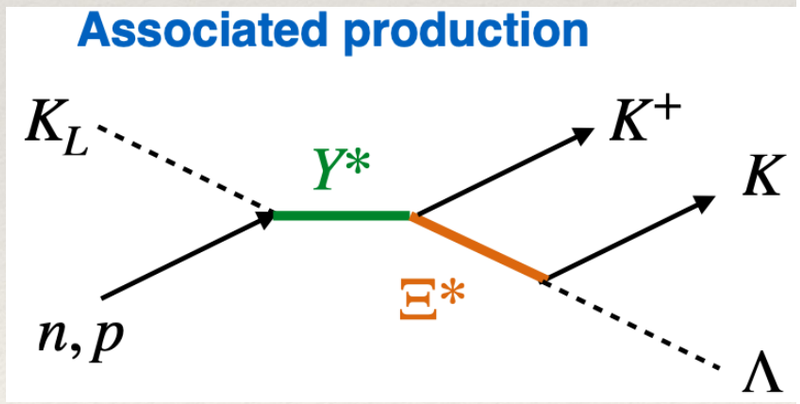
KLong facility in Hall D

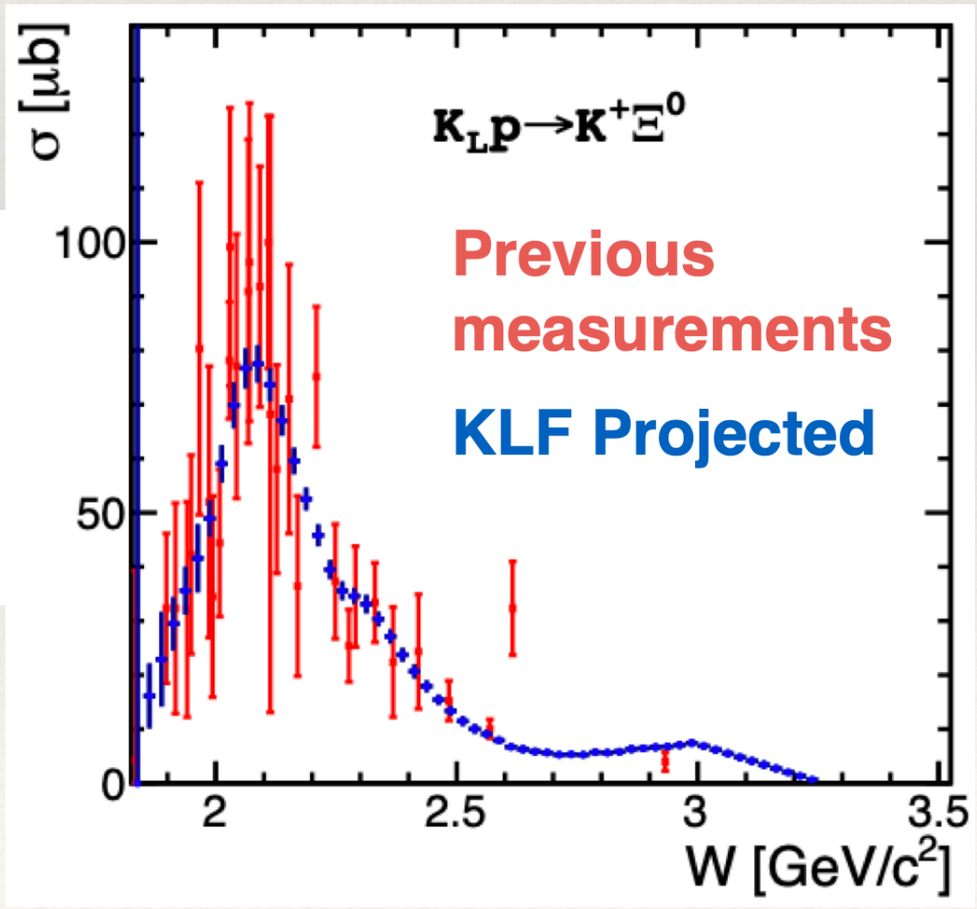
S. Dobbs (HADRON2021)

- Proton target:
  - Only Σ*
- Neutron target:
  - Λ* and Σ*
- Exclusive reconstruction in GlueX spectrometer
- Will provide precision cross-section measurements









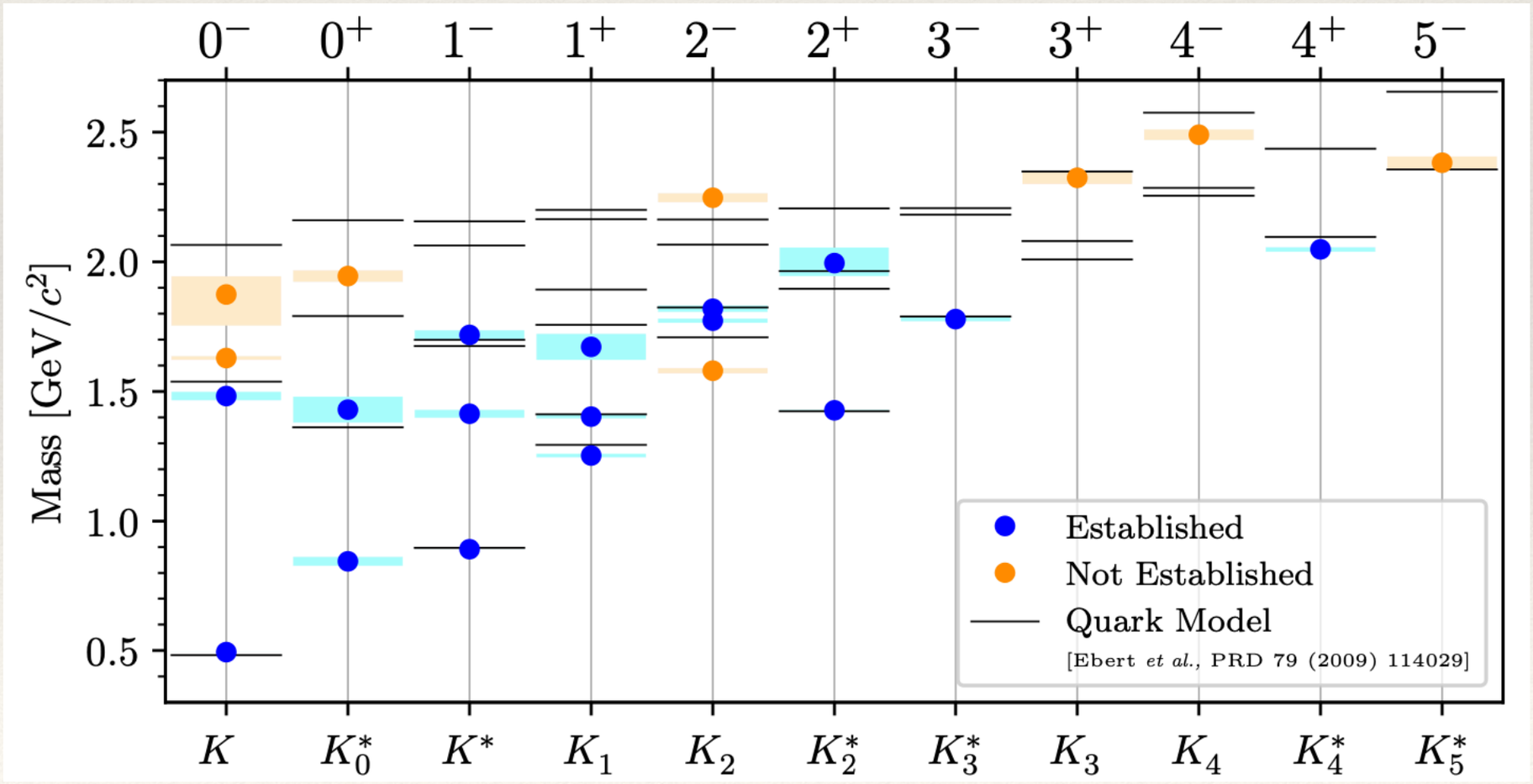
Kaon spectroscopy at AMBER

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update.

STRANGE ($S = \pm 1$, $C = B = 0$)	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
→ • $K^*_0(700)$	$1/2(0^+)$
aka κ; was $K^*_0(800)$	
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
• $K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
→ $K(1630)$	$1/2(?^?)$
• $K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
→ • $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
• $K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
→ $K(3100)$	$?^?(?^{??})$
aka $K^?_J(3100)$	

→ New since 1990

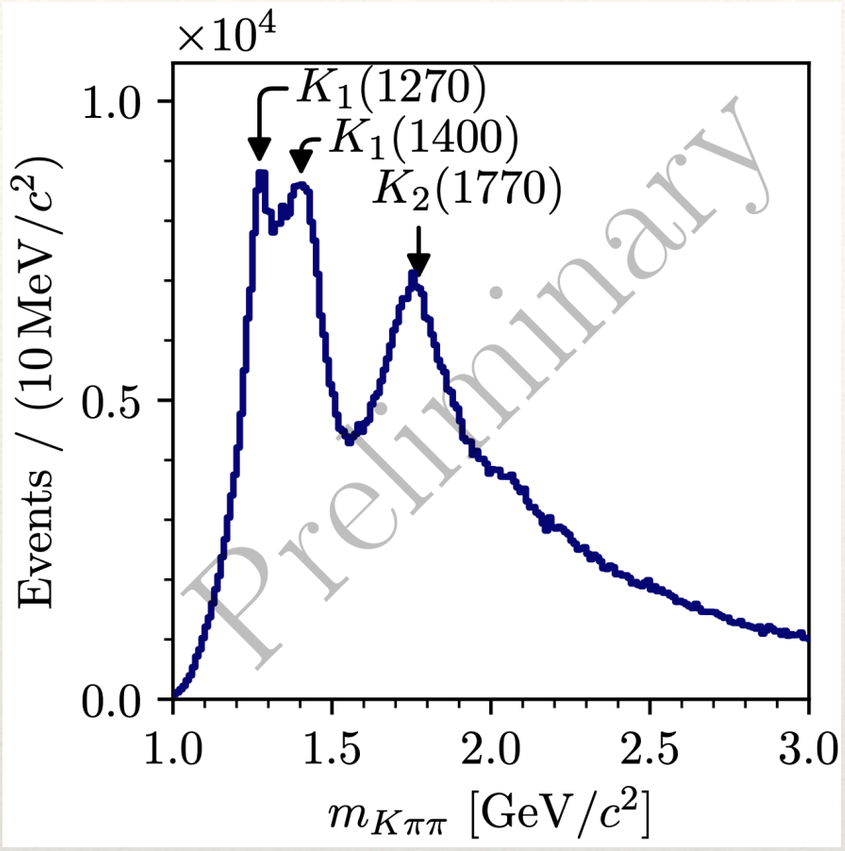
- A rich spectrum of kaon resonances is expected from quark model calculations
- So far 25 states known, of which 16 considered *established*
- Only 4 (!) new states since 1990 added to PDG
- Strange hybrid mesons or other exotics?

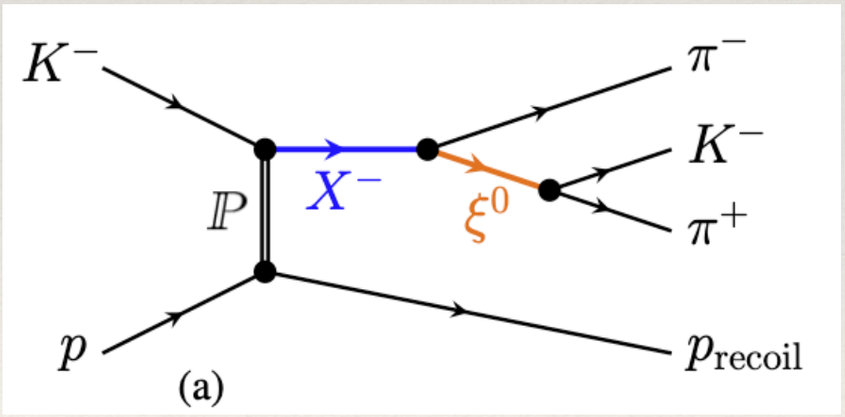


S. Wallner, EPJ Web Conf. 274 (2022) 03010

Previous work at COMPASS

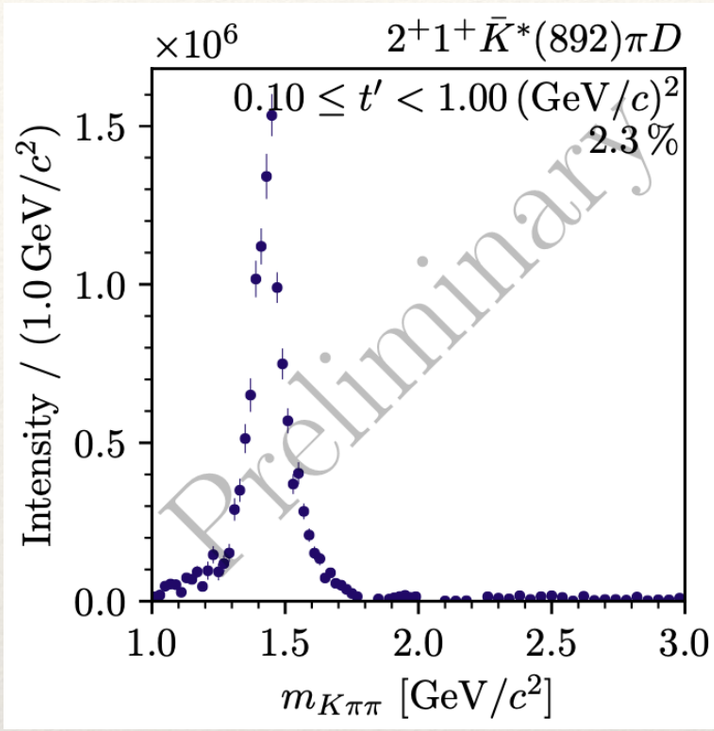
B. Grube, Perceiving the Emergence of Hadron Mass through AMBER@CERN, 2021



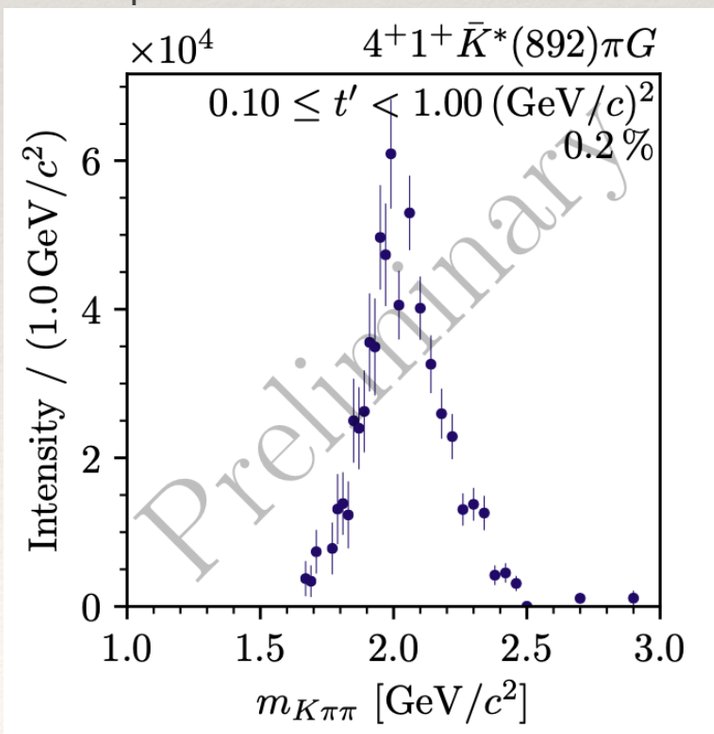


- COMPASS identified 720k exclusive $K\pi\pi$ events
- Partial wave analysis performed and promising preliminary results
- Problems:
  - PID, π/K separation reliable up to ~45 GeV
  - kinematic regions with vanishing acceptance ultimately results in leakages between partial waves

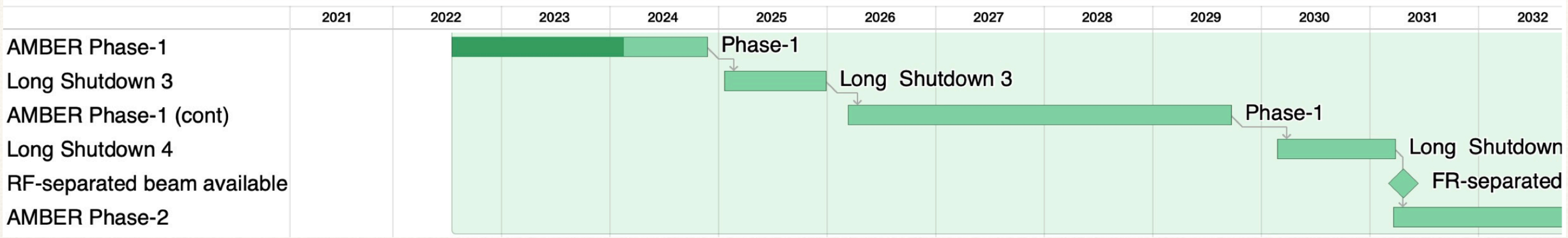
$K_2^*(1430) \rightarrow K^*(892)\pi$



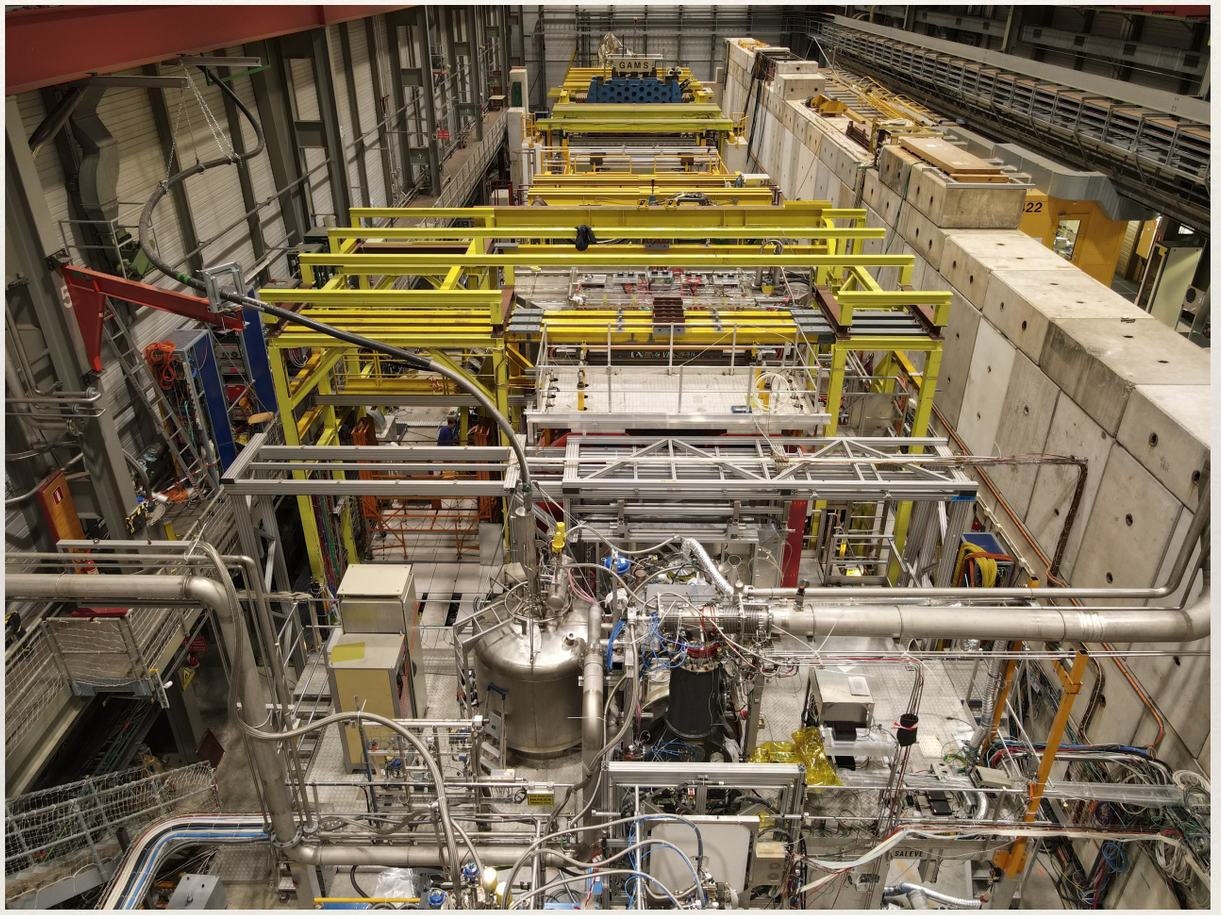
$K_4^*(2045) \rightarrow K^*(892)\pi$



AMBER



https://amber.web.cern.ch/



- AMBER phase-1 underway
  - Focus on $\bar{p}$ production (HK 12.3)
  - r_p measurement (HK 70.1)
  - DY physics
- Studies for phase-2 proposal ongoing
  - Kaon spectroscopy
  - Work ongoing to optimise experiment configuration
  - Aim: record ~20 times more $K\pi\pi$ data compared to COMPASS

Summary

- GlueX provides valuable photoproduction data for many different reactions
  - DIRC upgrade will boost analysis power for strange final states
- KLong will be the next big neutral kaon beam facility
  - New data for hyperon spectroscopy
- AMBER will rewrite the kaon section of the PDG
- In addition
  - CLAS12 (Very strange group, MesonEx)
  - J-PARC (E31: Λ(1405), E72: Λ*(1665) search, E97: Cascade spectroscopy, …)
- The next decade will boost our understanding of strange hadrons

Apparatus for Meson and Baryon Experimental Research