Peter Hurck for the GlueX collaboration

Recent results from GlueX

University *of* Glasgow

XVIth Quark Confinement and the Hadron Spectrum Conference
Cairns Convention Centre

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

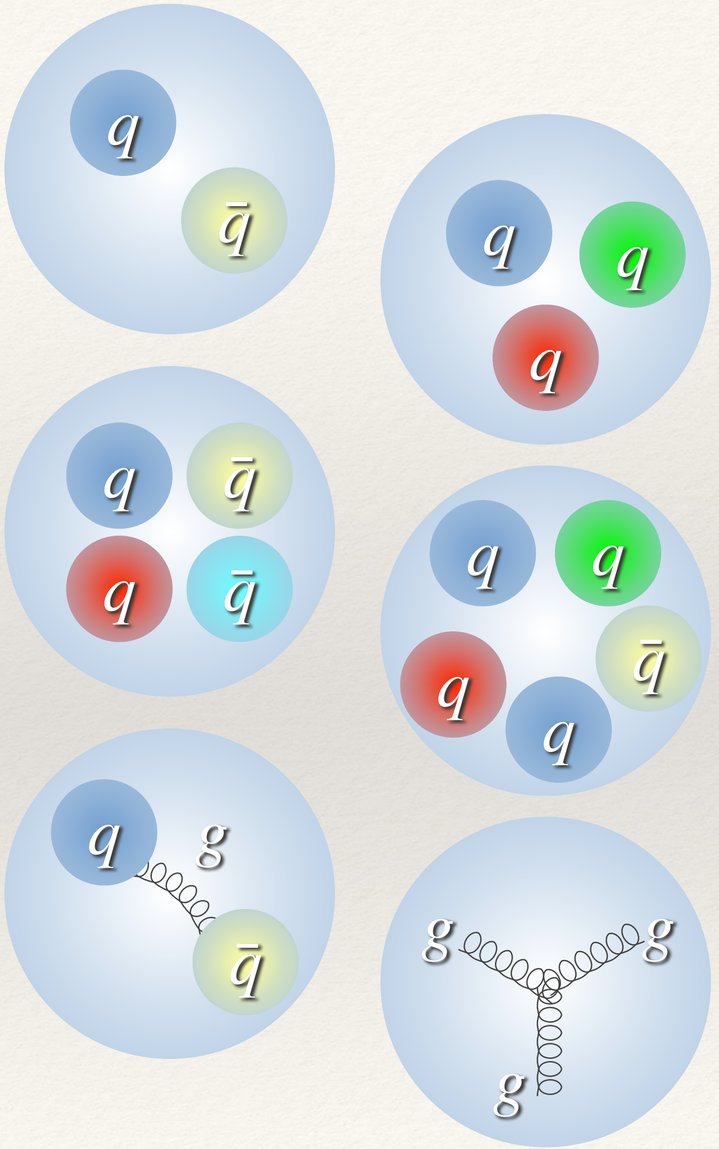
California Institute of Technology, Pasadena, California

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

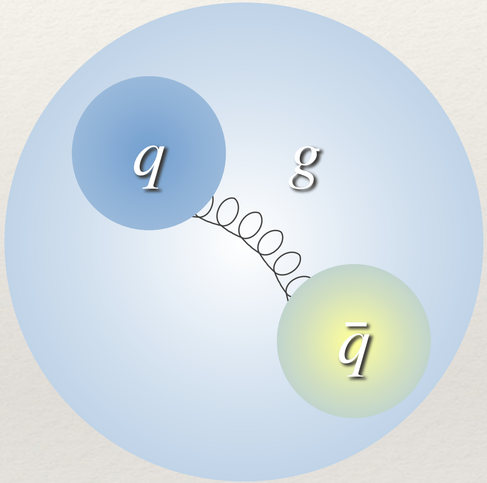


Hybrid mesons

- main objective for GlueX:
  Search and study of hybrid mesons

- In quark model:
  $\vec{J} = \vec{L} + \vec{S}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

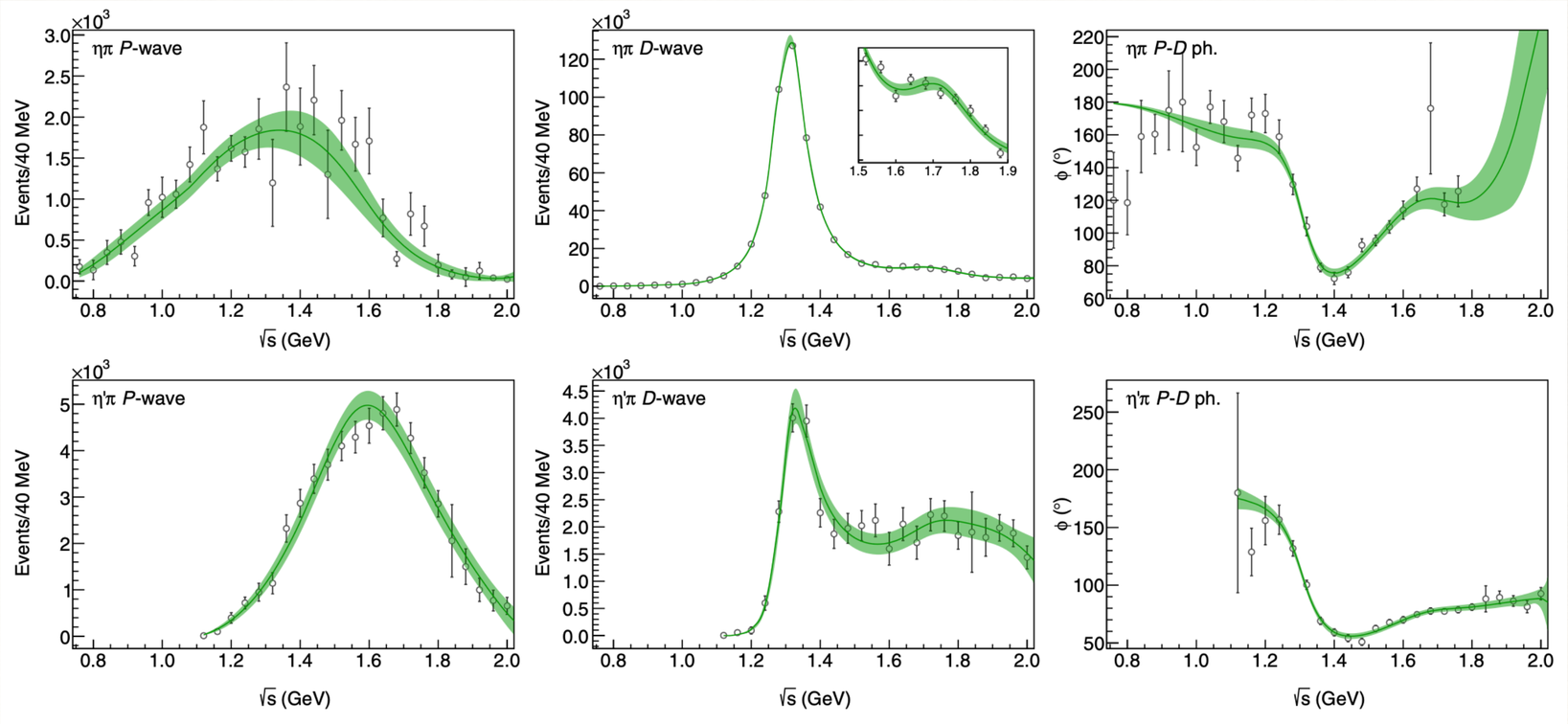
  → <u>not</u> allowed:
  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$



- "Exotic" quantum numbers are "smoking gun" for something not being pure $q\bar{q}$

Hybrid mesons - evidence

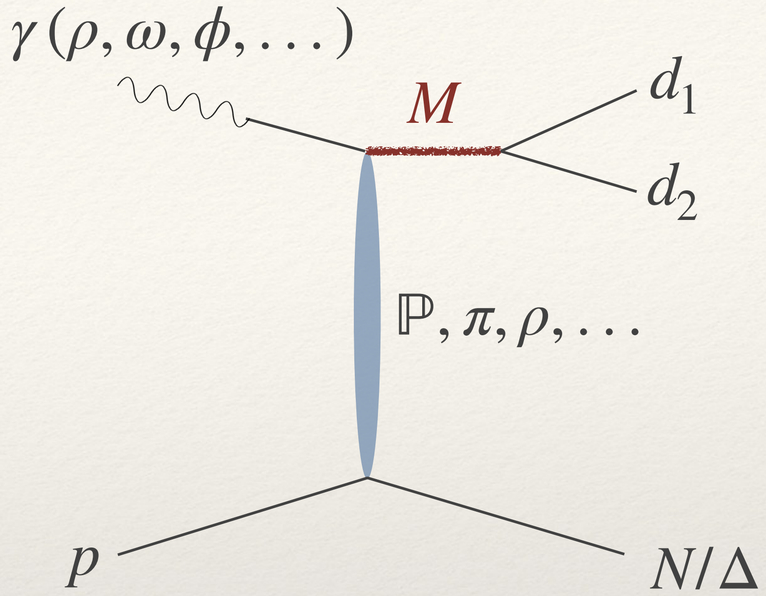
- Experimental evidence for a 1^{-+}:
  - $\pi_1(1400)$: GAMS, VES, E852, CBAR, COMPASS
  - $\pi_1(1600)$: VES, E852, COMPASS
- JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ data from COMPASS



mass $= 1564 \pm 24 \pm 86$ MeV

width $= 492 \pm 54 \pm 102$ MeV

Towards hybrids at GlueX

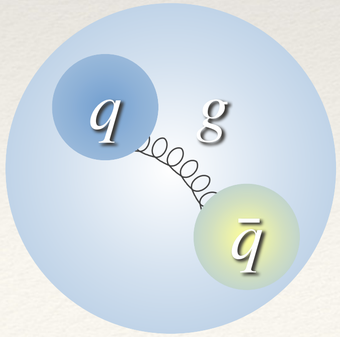


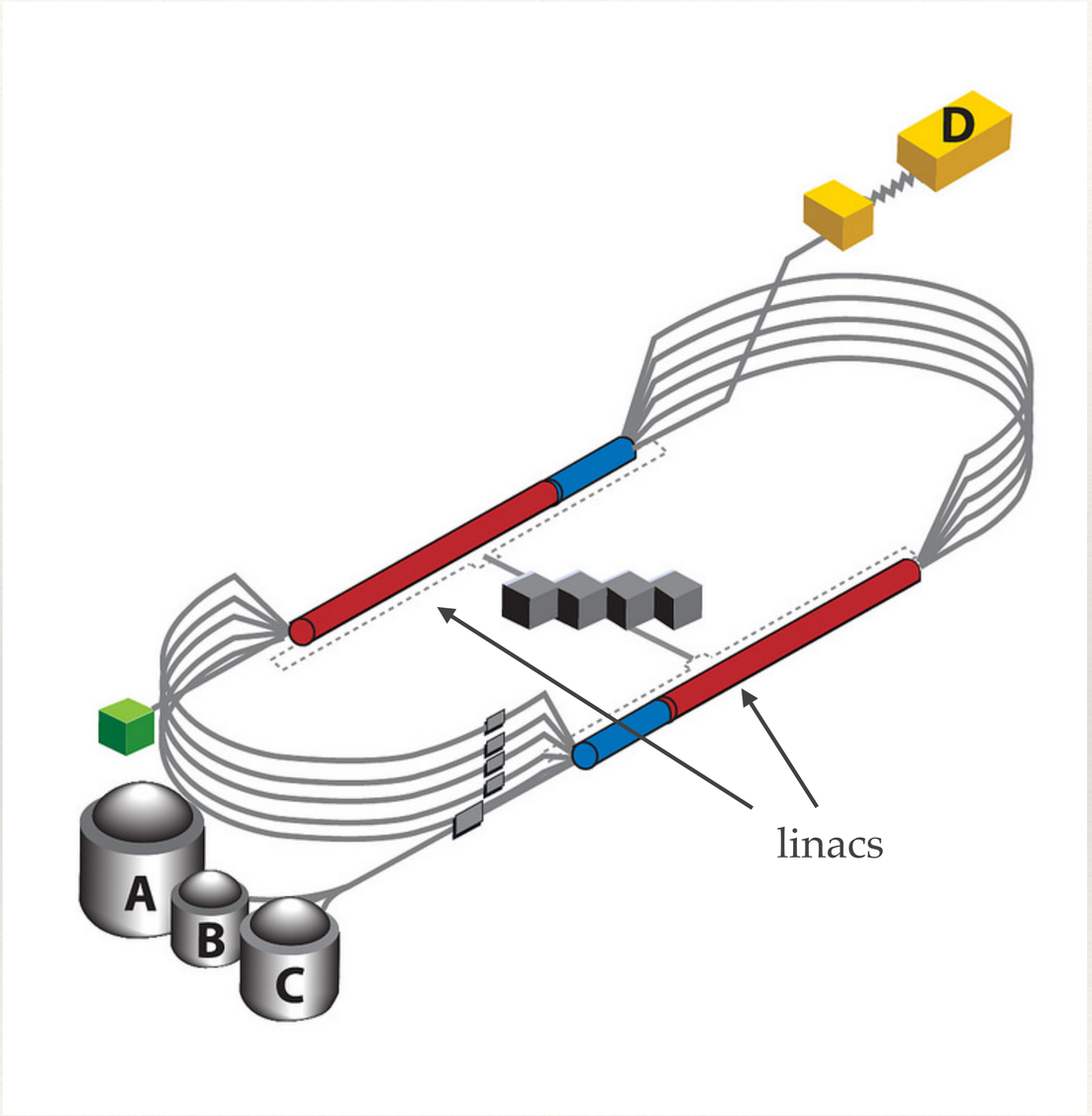
- Photoproduction complementary to pion production
  - Utilize polarization to understand production mechanisms
- Study production mechanisms to inform choice of wave sets for PWA (beam asymmetries, spin density matrix elements)
- Focus on $\eta\pi$ and $\eta'\pi$
  - Look at different production and decay mechanisms
- Work closely with theory colleagues to tackle model complexity

CEBAF at Jefferson Lab

CEBAF at Jefferson Lab

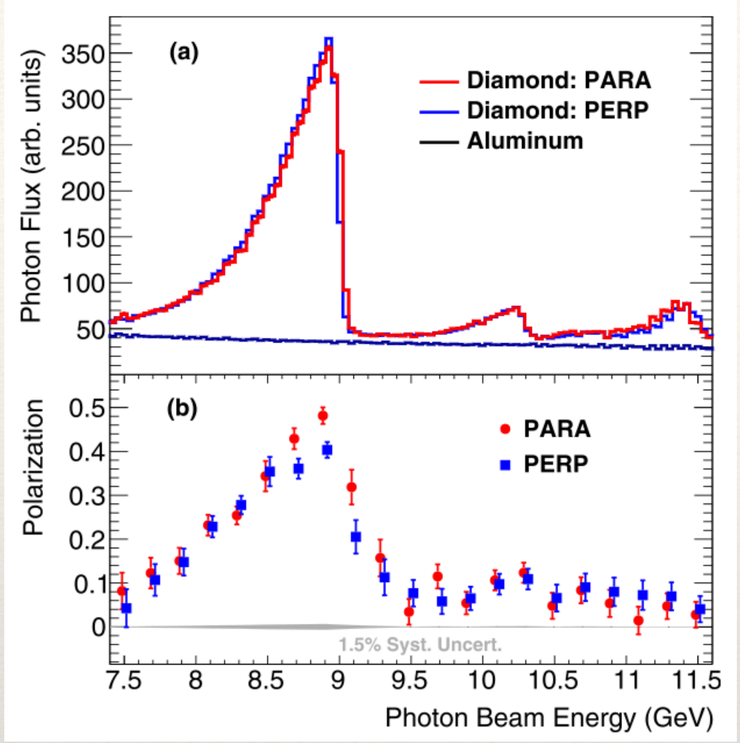
- up to 12 GeV electron beam
- high luminosities for Hall A/C (high resolution spectrometer)
- CLAS12 in Hall B
- GlueX in Hall D
  - Focus on exotic hybrid mesons
    BUT:
    Large data set available to study wide range of reactions



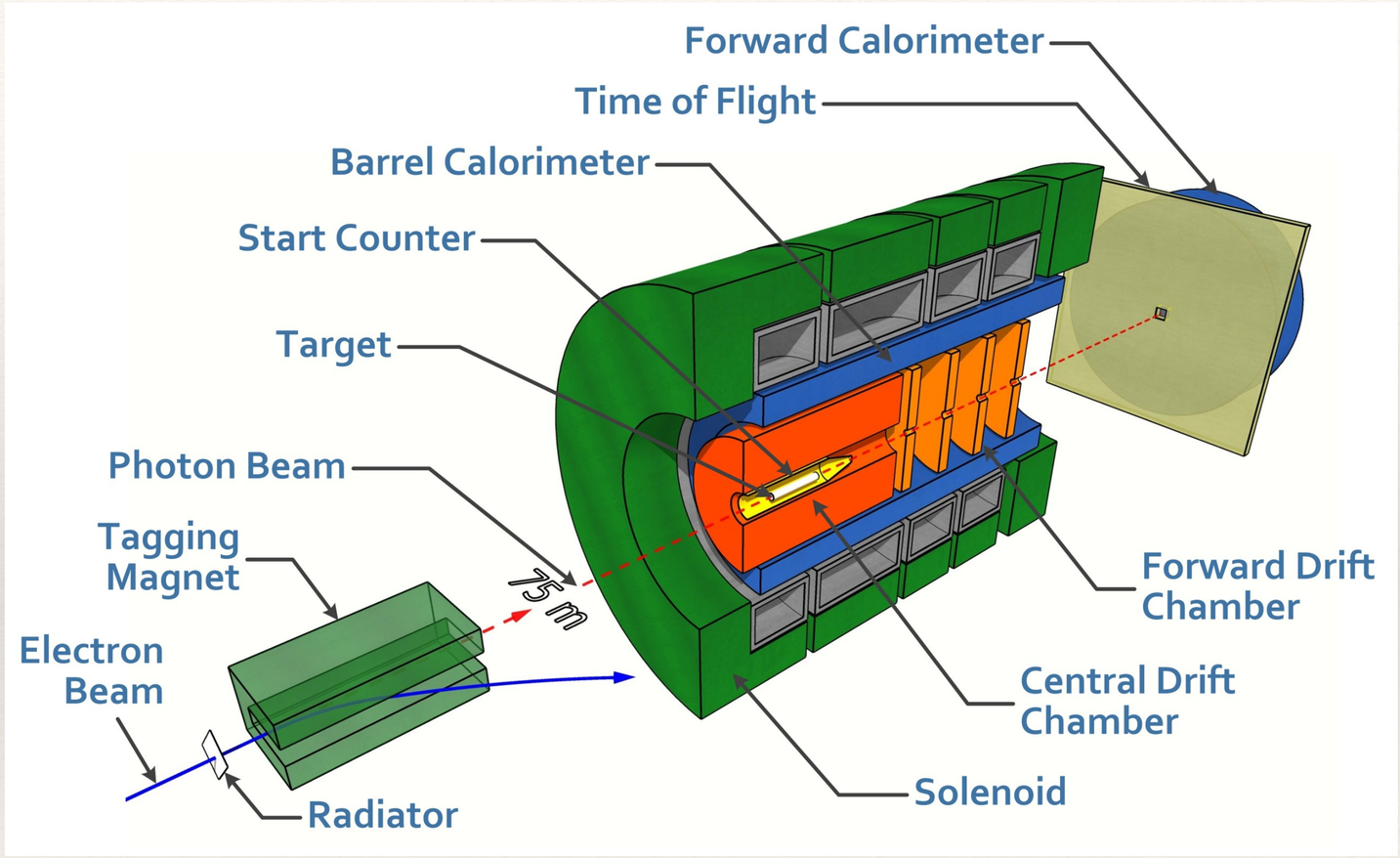


GlueX in Hall D

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



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



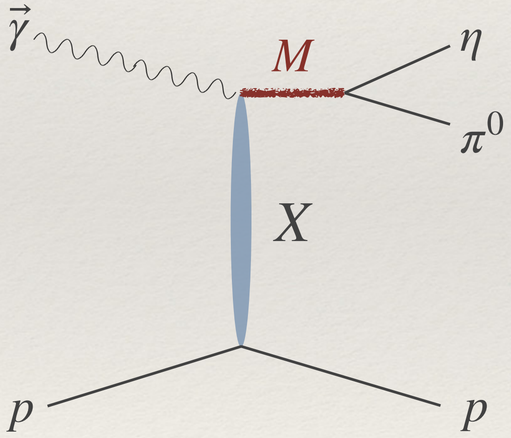
- tag electrons to determine photon energy

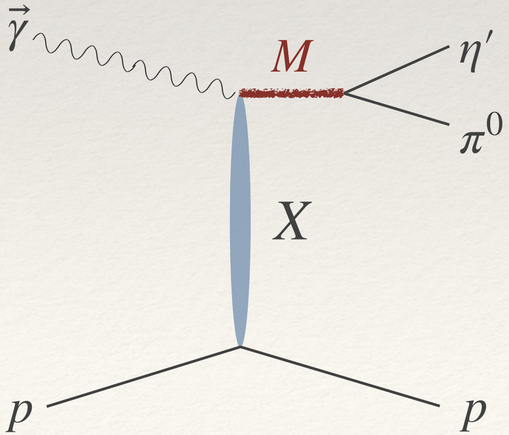
- Acceptance: $\theta_{lab} \approx 1^\circ - 120^\circ$
- Charged particles: $\sigma_p/p \approx 1\% - 3\,\%$
  ($8\% - 9\,\%$ very-forward high-momentum tracks)
- Photons: $\sigma_E/E = 6\,\%/\sqrt{E} \oplus 2\,\%$

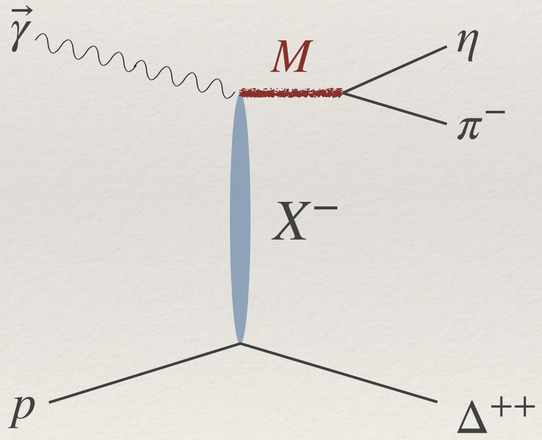
GlueX-I (2017-18): $\mathscr{L} = 305\ \text{pb}^{-1}$ ($E_\gamma > 8$ GeV)
GlueX-II (2020-25): $\mathscr{L} = 320\ \text{pb}^{-1}$, so far
ultimately 3-4x GlueX-I expected

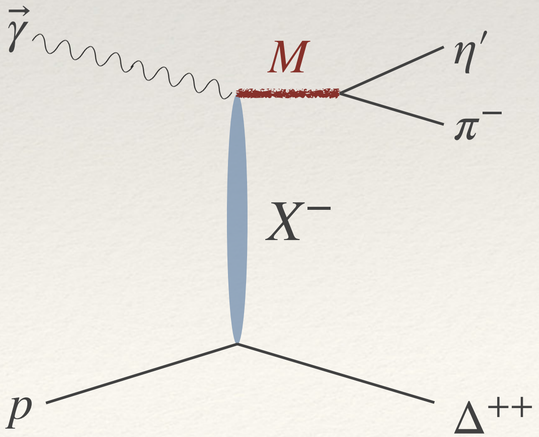
Hybrid search in $\eta\pi$

- JPAC coupled channel fit to $\eta\pi$ and $\eta'\pi$ data from COMPASS
- GlueX has access to different decay modes in multiple final states
  - $\gamma p \to \eta\pi^0 p,\ \eta \to \gamma\gamma$
  - $\gamma p \to \eta\pi^0 p,\ \eta \to \pi^+\pi^-\pi^0$
  - $\gamma p \to \eta'\pi^0 p,\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$
  - $\gamma p \to \eta\pi^-\Delta^{++},\ \eta \to \pi^+\pi^-\pi^0$
  - $\gamma p \to \eta\pi^-\Delta^{++},\ \eta \to \gamma\gamma$
  - $\gamma p \to \eta'\pi^-\Delta^{++},\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$



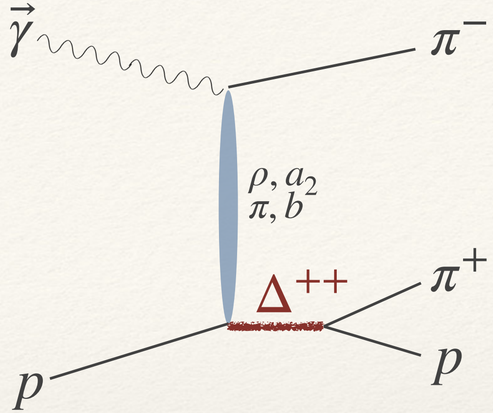


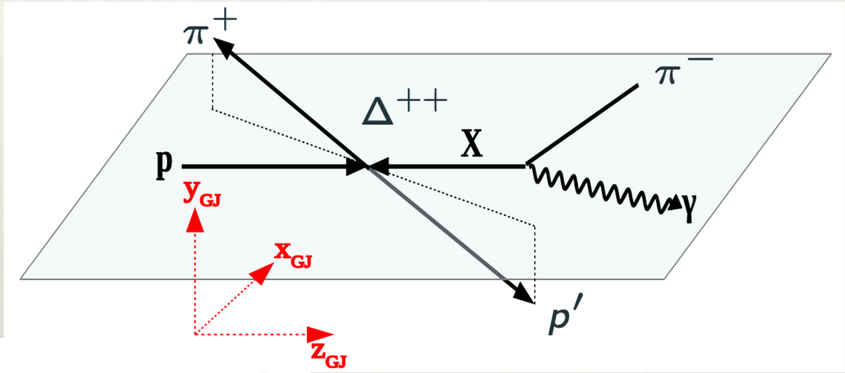




Spin density matrix elements

- SDMEs ρ^i_{jk} contain information on the spin-polarization of the produced state
- Measure angular distribution of decay products
- Learn about production mechanism
  - Study the naturality $\eta = P(-1)^J$ of the exchanged particle X





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

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

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

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

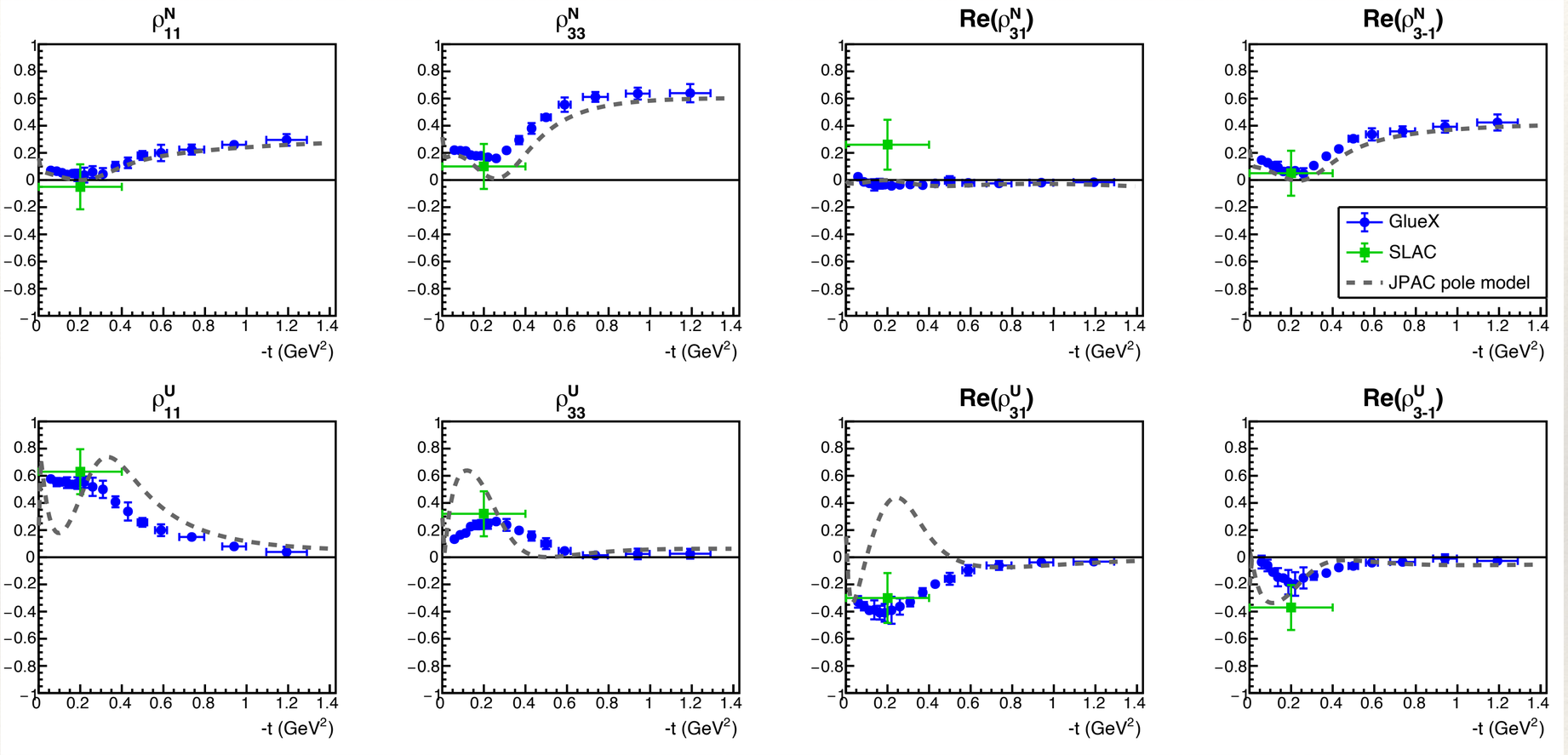
$\Delta^{++}(1232)$ SDMEs

arXiv:2406.12829 [nucl-ex]
submitted to Phys. Lett. B

- Orders of magnitude improvement over previous data
- Data will be used to describe bottom vertex of reaction (couplings)
  - Important for hybrid search
- Good description of natural exchange by JPAC model

JPAC, Physics Letters B 779 (2018) 77–81

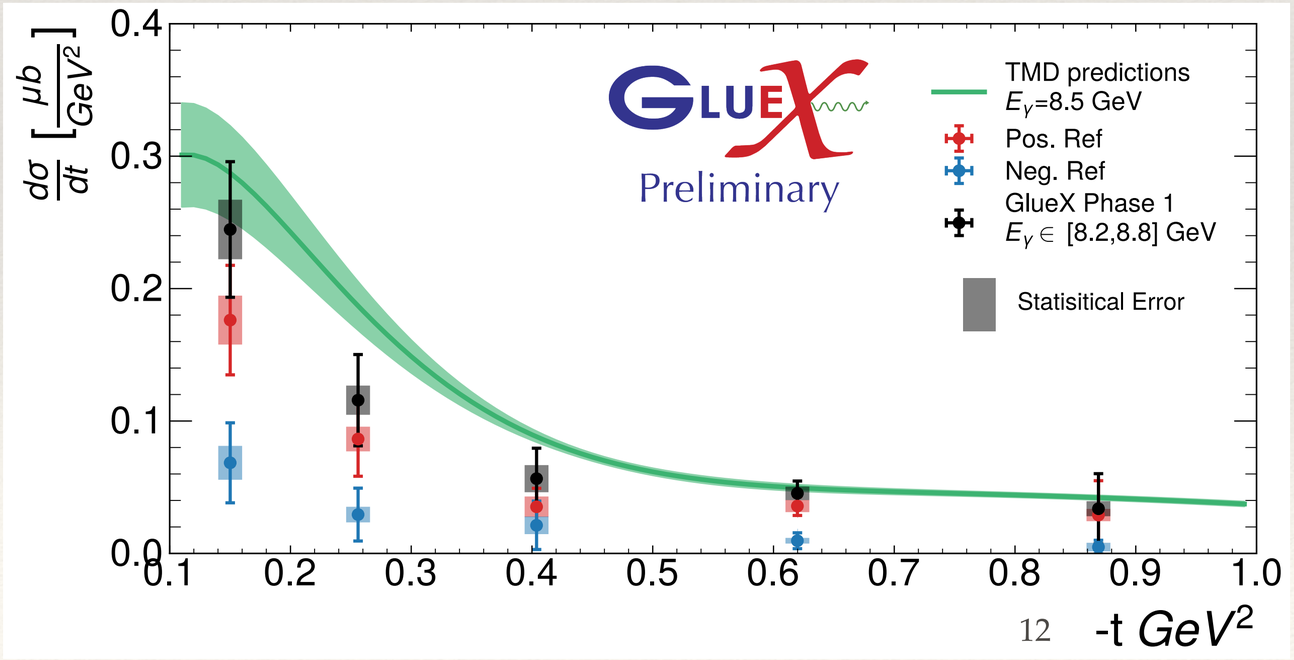
$$\rho_{ij}^{N/U} = \rho_{ij}^{0} \pm \rho_{ij}^{1}$$



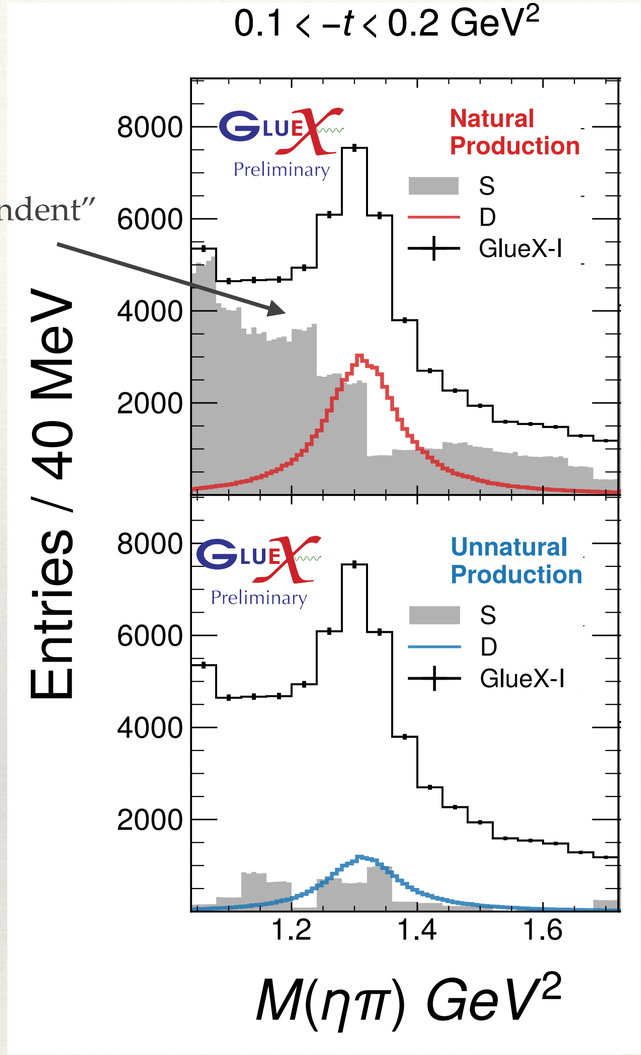
Towards a PWA in $\eta\pi^0$ - $a_2(1320)$ cross-section

L. Ng, M. Albrecht

- First look at PWA in $\gamma p \to \eta\pi^0\, p$
- Study $a_2(1320)$ cross-section
- Positive helicity (natural exchange, e.g. ρ) dominates
- a_2 predominantly D_2 wave, consistent with helicity=2 dominance at Belle ($\gamma\gamma \to \eta\pi^0$) *Belle, Phys. Rev. D* ***80****, 032001*



"Mass independent" S-wave

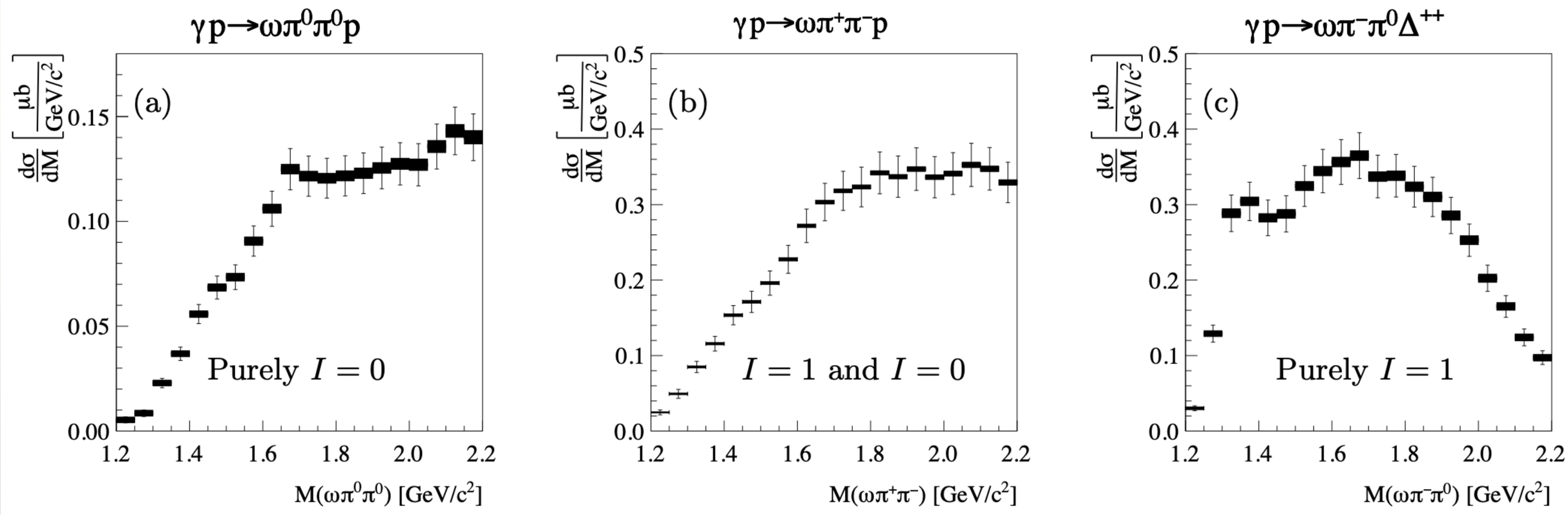


Mixed method: imposing BW shape on a_2 improves fit

Publication in preparation

$\pi_1(1600)$ upper limits

arXiv:2407.03316 [nucl-ex]

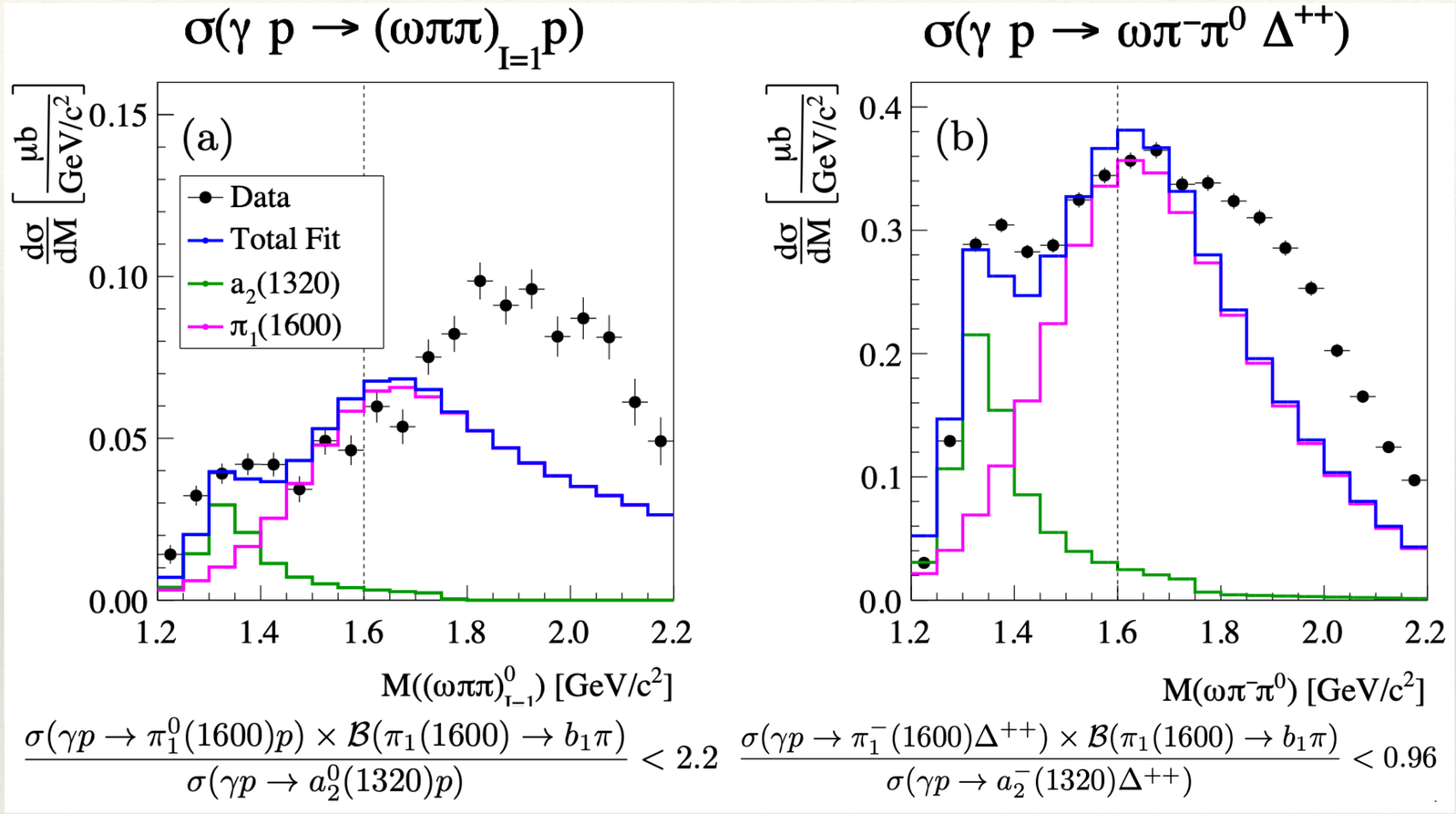


- Set upper limit on $\pi_1(1600)$ using isospin separation, assume no $I = 2$
  - $\sigma((\omega\pi\pi)^0)_{I=1} = \sigma(\omega\pi^+\pi^-) - 2\sigma(\omega\pi^0\pi^0)$
  - $\sigma((\omega\pi\pi)^-)_{I=1} = \sigma(\omega\pi^-\pi^0)$
- Fit $\sigma(\omega\pi\pi)_{I=1}$ using known shapes for a_2 (PDG) and π_1 (JPAC)

$\pi_1(1600)$ upper limits

arXiv:2407.03316 [nucl-ex]

- Fit $M(\omega\pi\pi)_{I=1} < 1.6\,\mathrm{GeV}/c^2$
- Fix a_2 size to measured cross-section adjusted with known BR
- π_1 BR from lattice
- Only free parameter is π_1 normalisation!
- π_1 upper limits similar in size to a_2 cross-sections



$$\frac{\sigma(\gamma p \to \pi_1^0(1600)p) \times \mathcal{B}(\pi_1(1600) \to b_1\pi)}{\sigma(\gamma p \to a_2^0(1320)p)} < 2.2$$

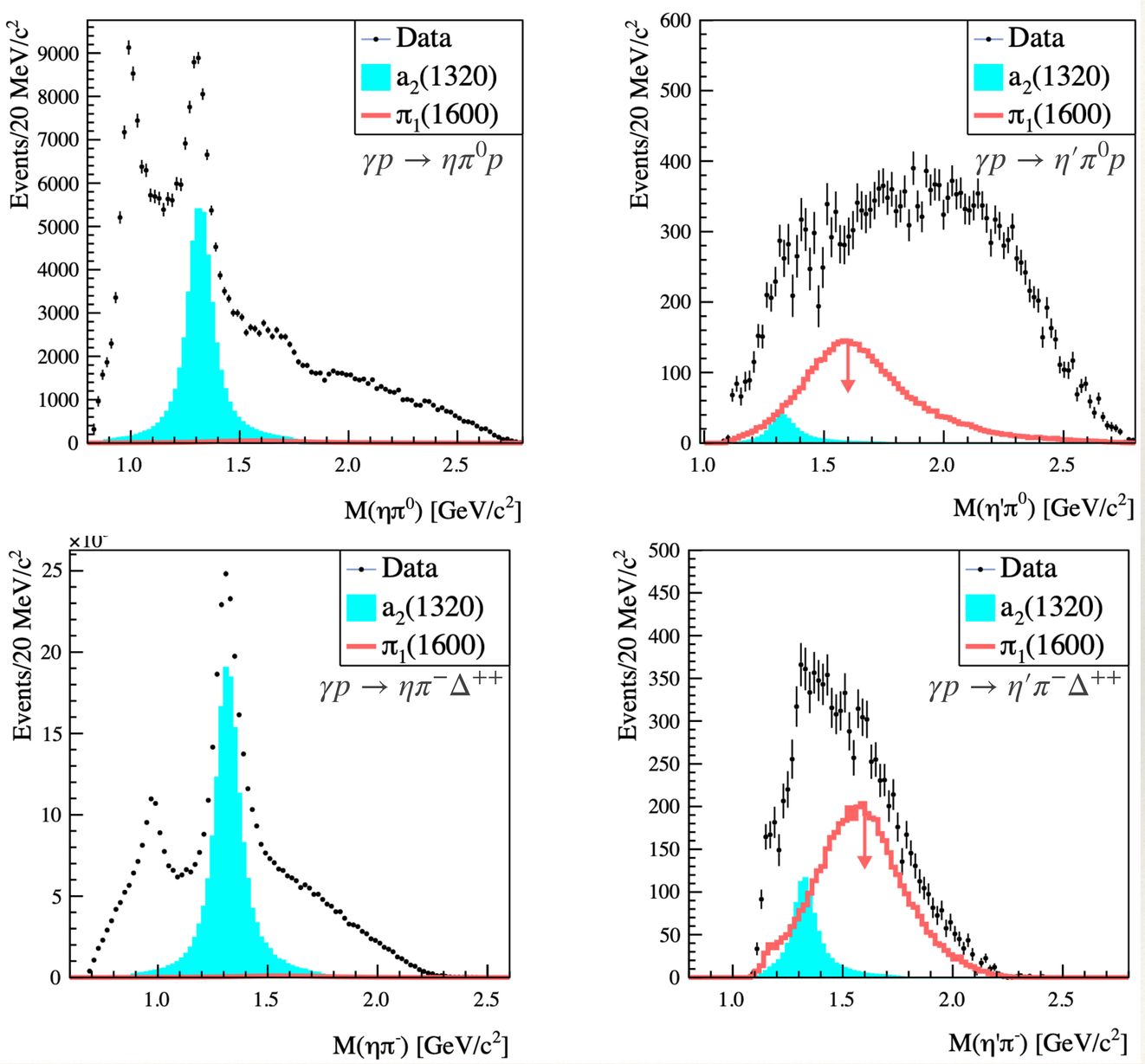
$$\frac{\sigma(\gamma p \to \pi_1^-(1600)\Delta^{++}) \times \mathcal{B}(\pi_1(1600) \to b_1\pi)}{\sigma(\gamma p \to a_2^-(1320)\Delta^{++})} < 0.96$$

π_1 projections to $\eta\pi$ and $\eta'\pi$

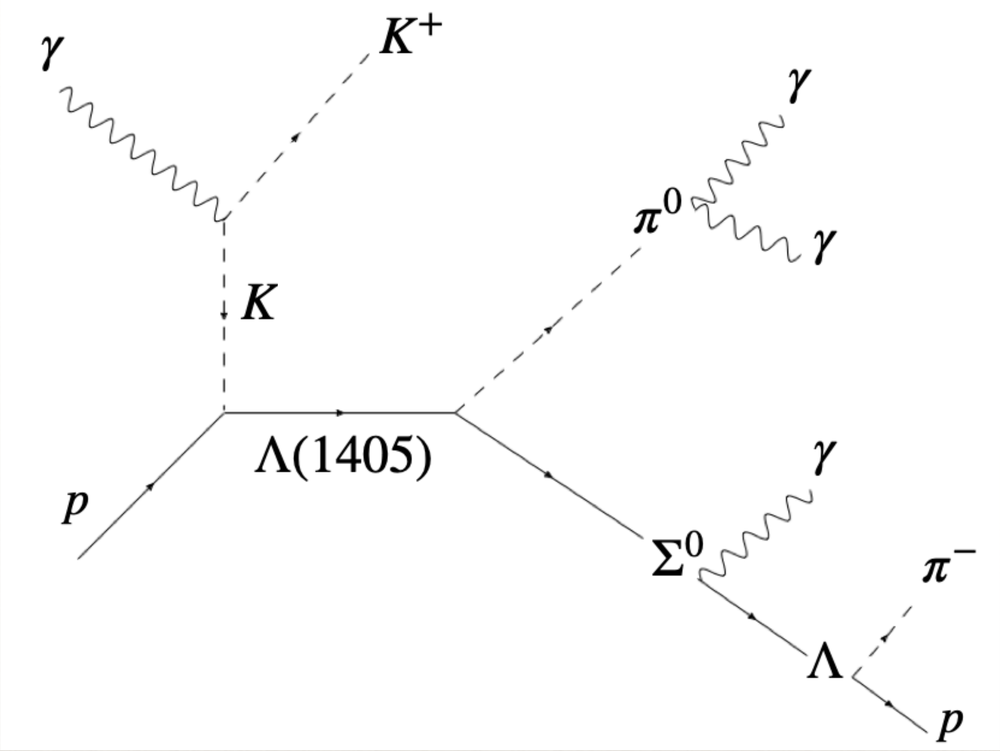
arXiv:2407.03316 [nucl-ex]

- $\pi_1 \to \eta\pi$ expected to be very small
- $\pi_1 \to \eta'\pi$ potentially dominating the spectrum
- First limit on size of photoproduction cross-sections
- Guidance for amplitude analysis

Submitted to PRL



$\Lambda(1405)$ line shape measurement

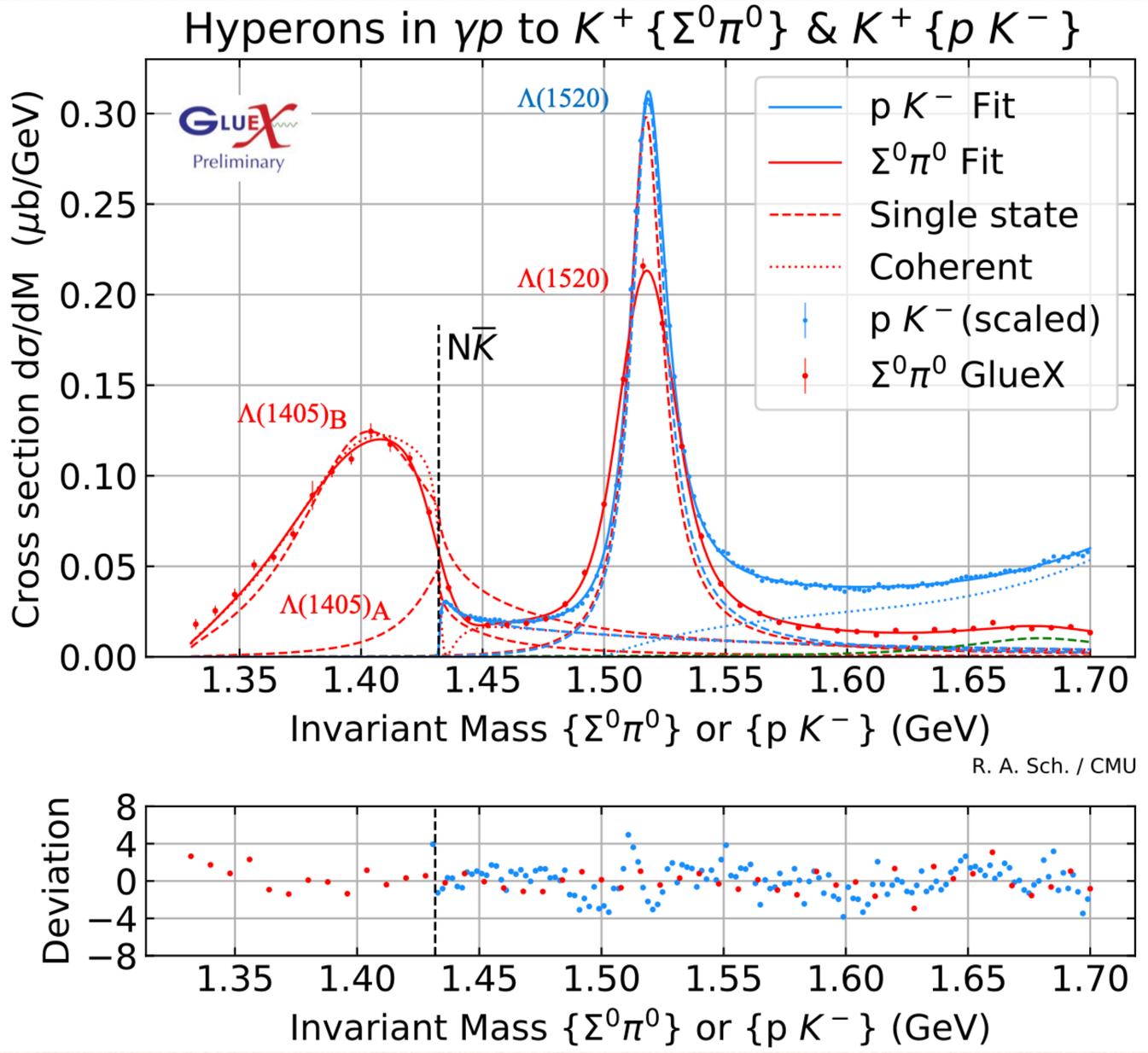


$\Lambda(1405) \to \Sigma^0\pi^0$ ($I = 0$) is free from $\Sigma(1385)$ background

- 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

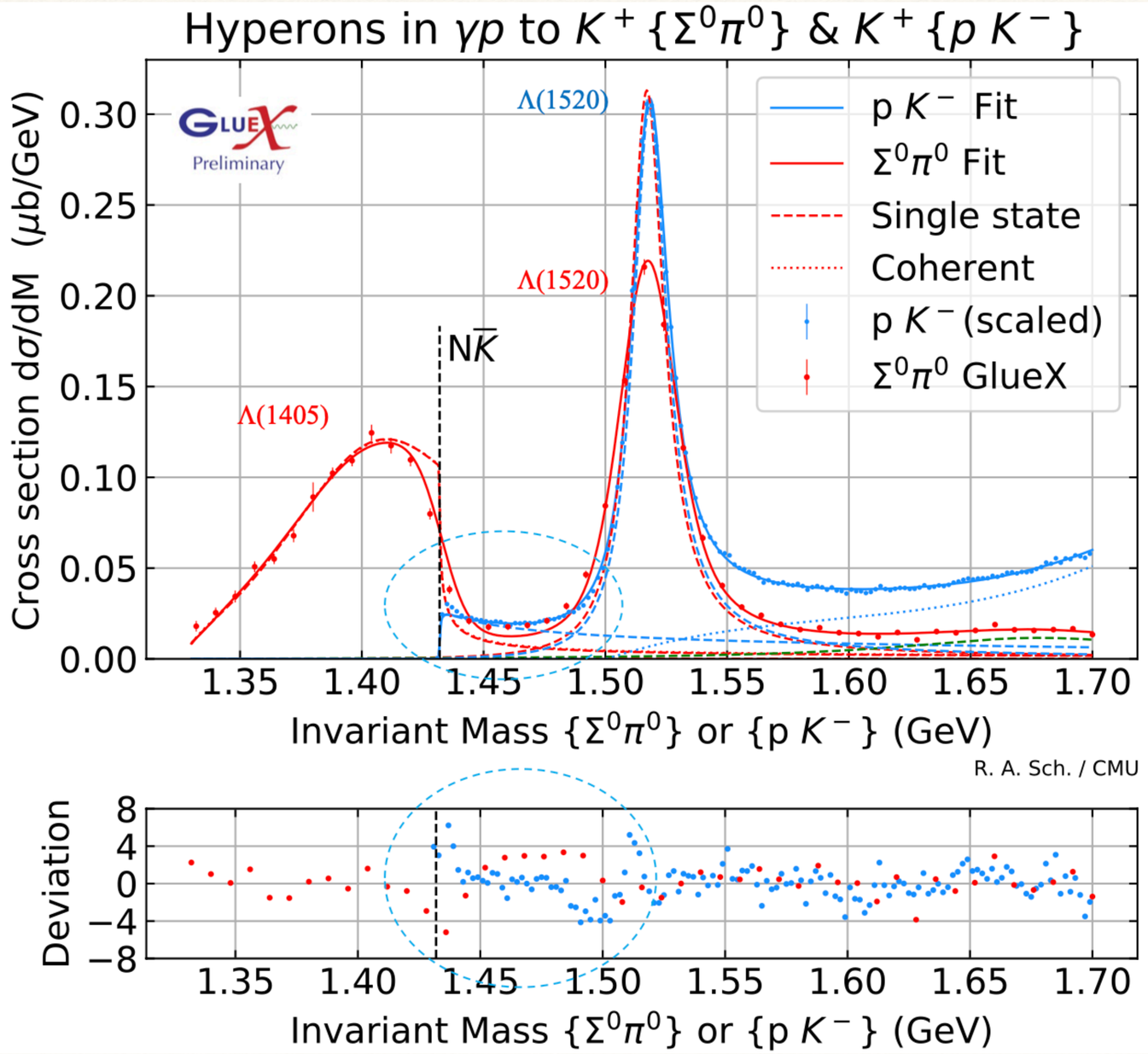
R. Schumacher
(NSTAR2024)



- combined fit of $\Sigma^0\pi^0$ and pK^- data
- K-matrix fit with 2-pole ansatz for Λ(1405)
- convolution with experimental resolutions
- very good agreement for Λ(1520)

Λ(1405) line shape measurement

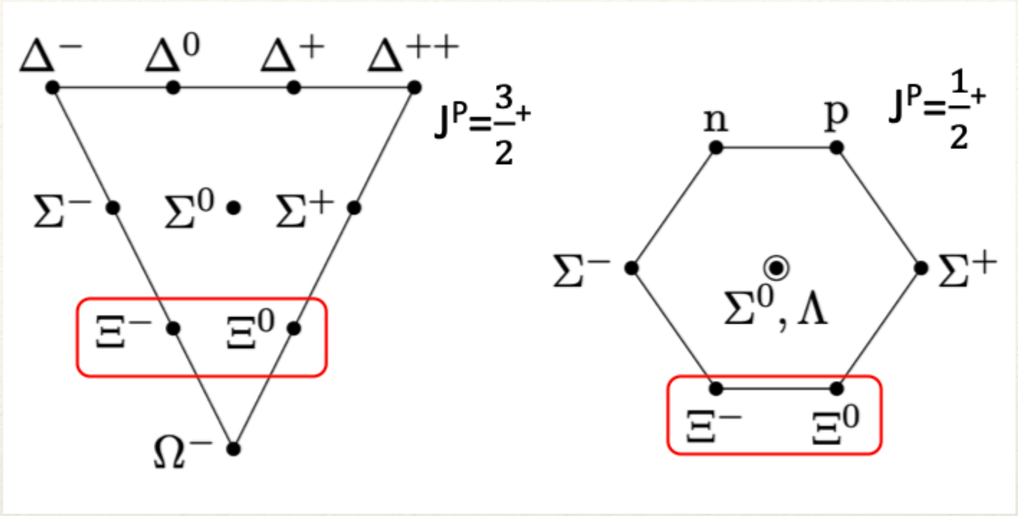
R. Schumacher
(NSTAR2024)



- combined fit of $\Sigma^0\pi^0$ and pK^- data
- K-matrix fit with 1-pole ansatz for Λ(1405)
- convolution with experimental resolutions
- poorer fit than 2-pole ansatz, especially in the threshold region

Cascades at GlueX

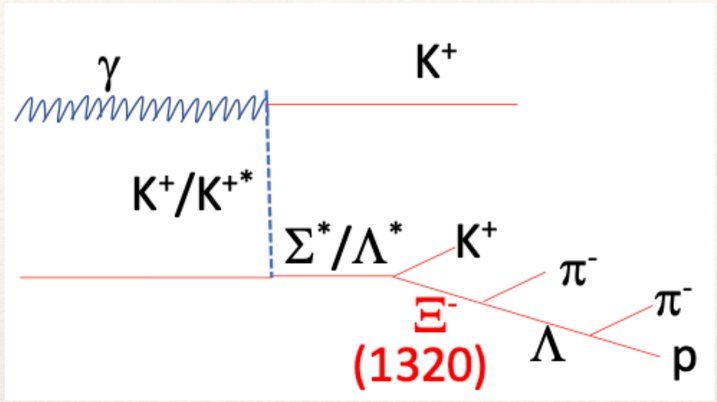
- Only six well known states (>3***)
- Would expect as many Ξs as *N**s and Δs
- Not many photoproduction experiments have been performed so far ($S = -2$)
- GlueX with its good charged and neutral final state particle coverage could help here
- Difficult analyses due to many final state particles

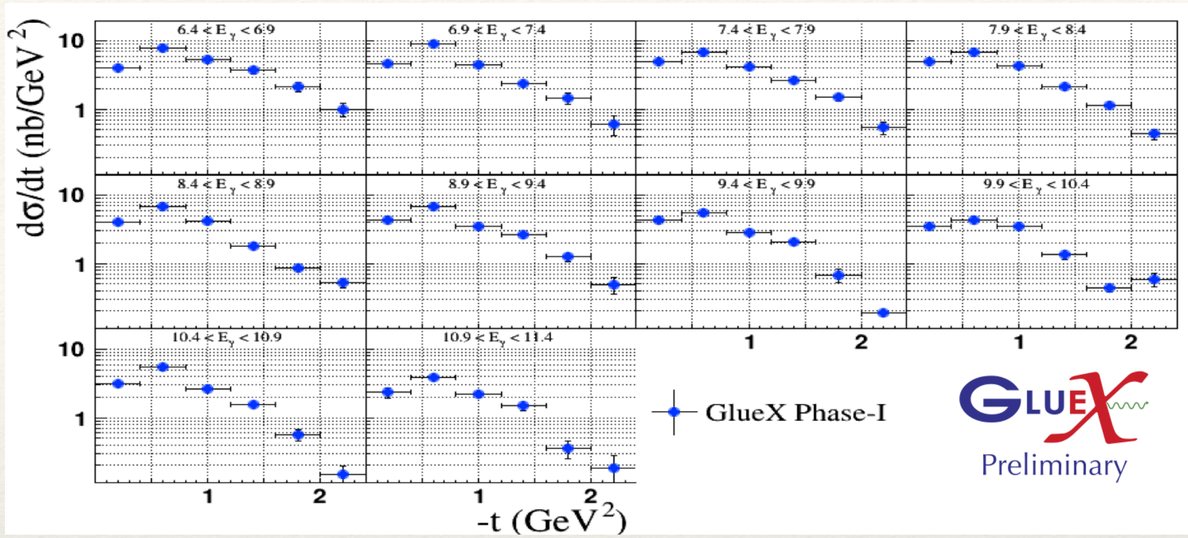


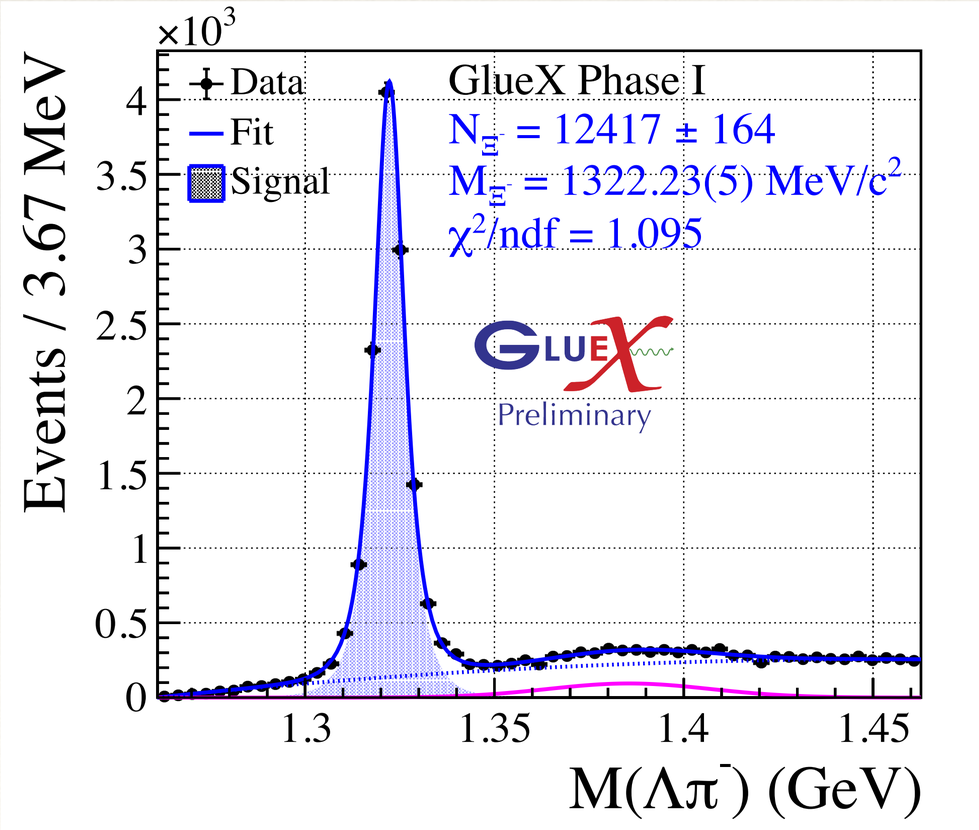
Particle	J^P	Overall Status	Ξπ	ΛK	ΣK	Ξ(1530)π
Ξ(1318)	$1/2^+$	****				
Ξ(1530)	$3/2^+$	****	****			
Ξ(1620)		*	*			
Ξ(1690)		***		***	**	
Ξ(1820)	$3/2^-$	***	**	***	**	**
Ξ(1950)		***	**	**		*
Ξ(2030)		***		**	***	
Ξ(2120)		*		*		
Ξ(2250)		**				
Ξ(2370)		**				
Ξ(2500)		*		*	*	

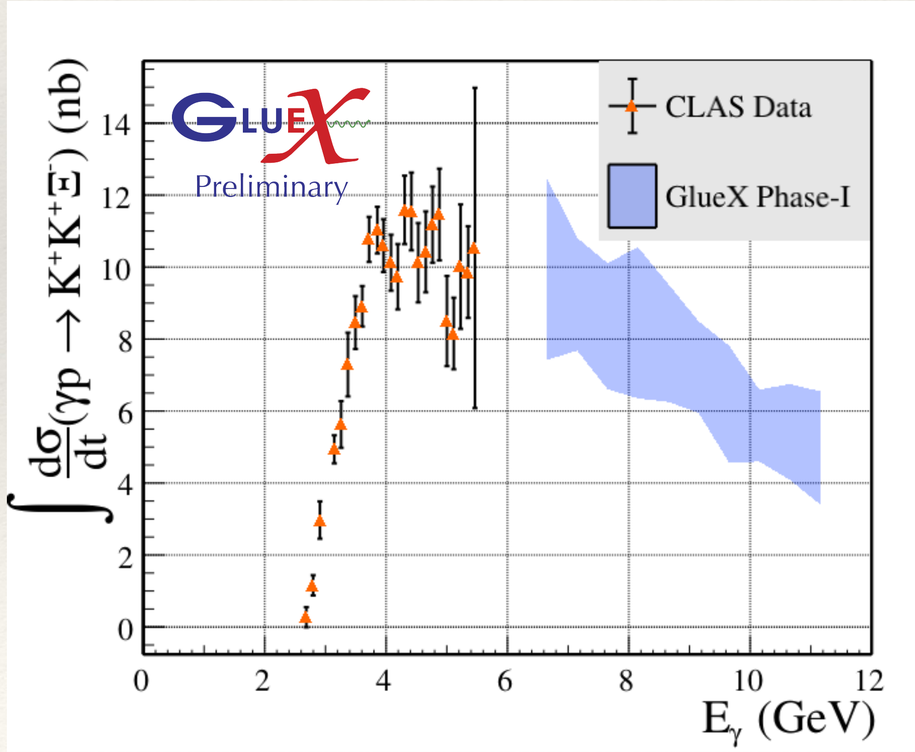
Cascades at GlueX

J. Hernandez

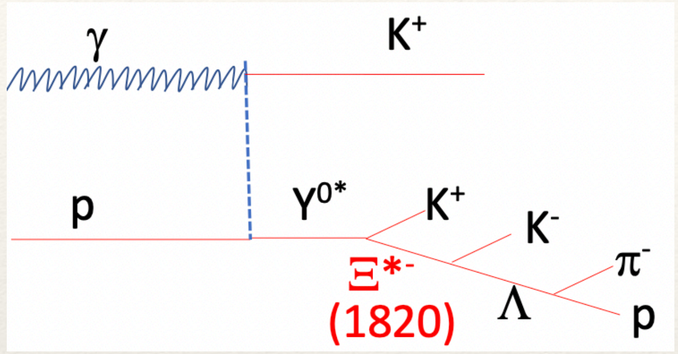


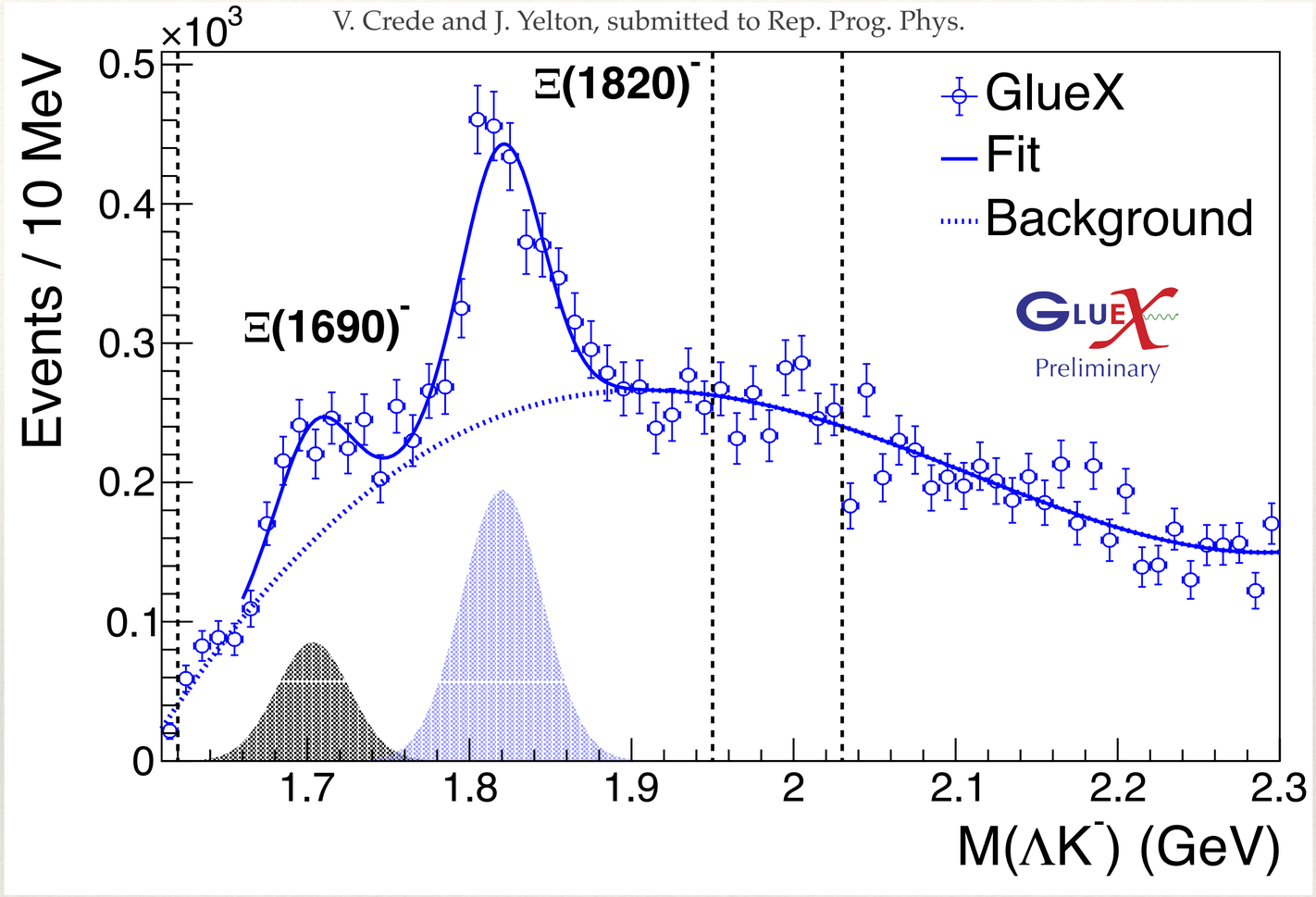






$\Xi^-(1820)$



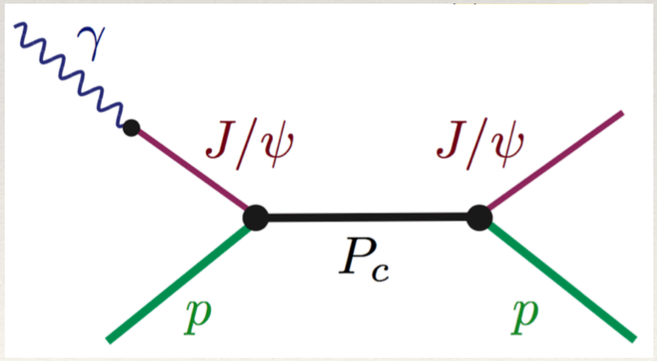


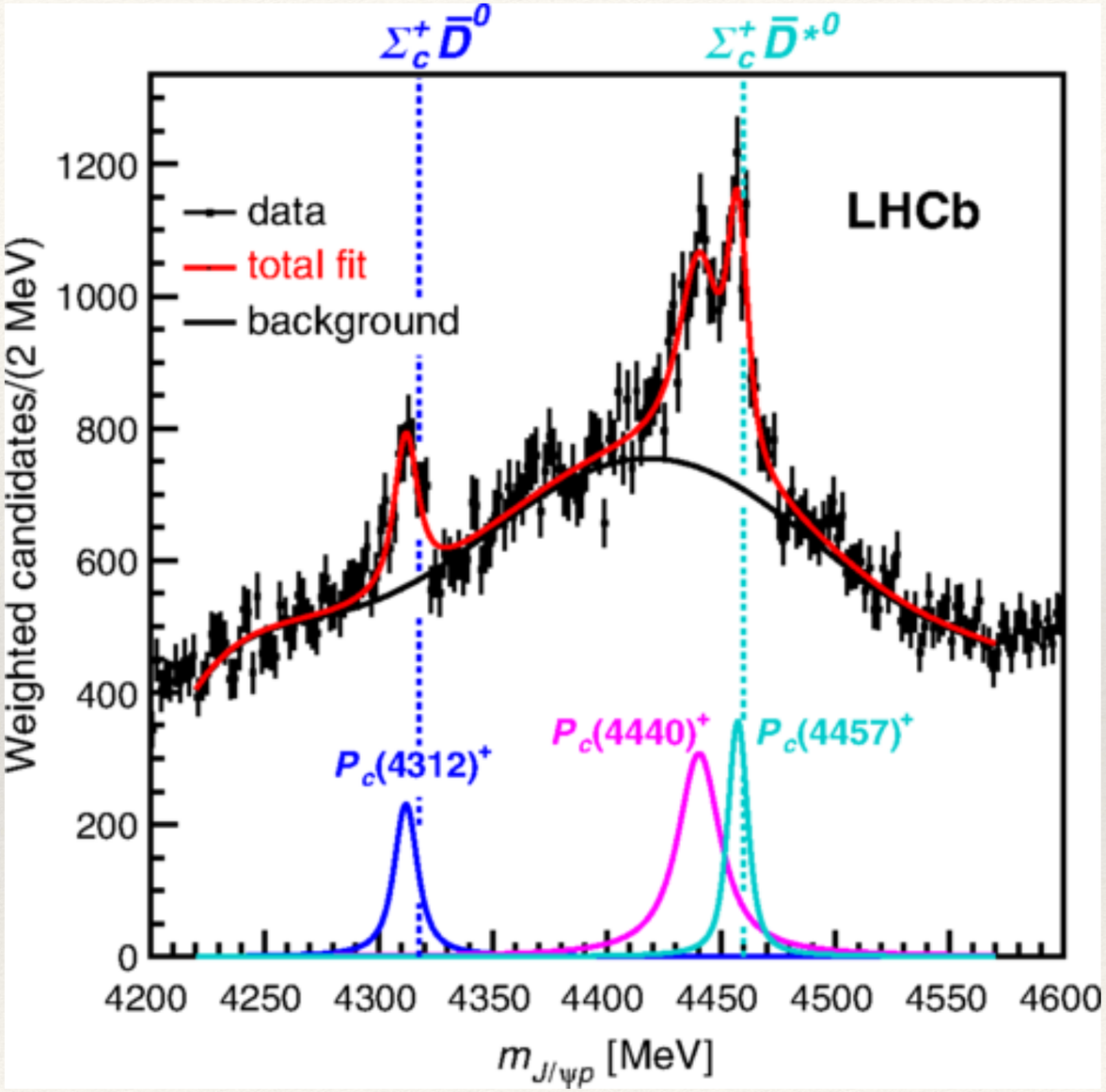
- Excited $\Xi(1820)$ with $J^P = \frac{3}{2}^-$
- *** resonance seen in $K^-\Lambda$ decays
- First measurement of $\Xi(1820)$ in photoproduction
- Only dominating feature in the $K^-\Lambda$ invariant mass

$J/\psi p$

- LHCb sees pentaquark signal in $\Lambda_b^0 \to J/\psi p K^-$
- GlueX can search for s-channel production
- Study production mechanism of J/ψ

VMD

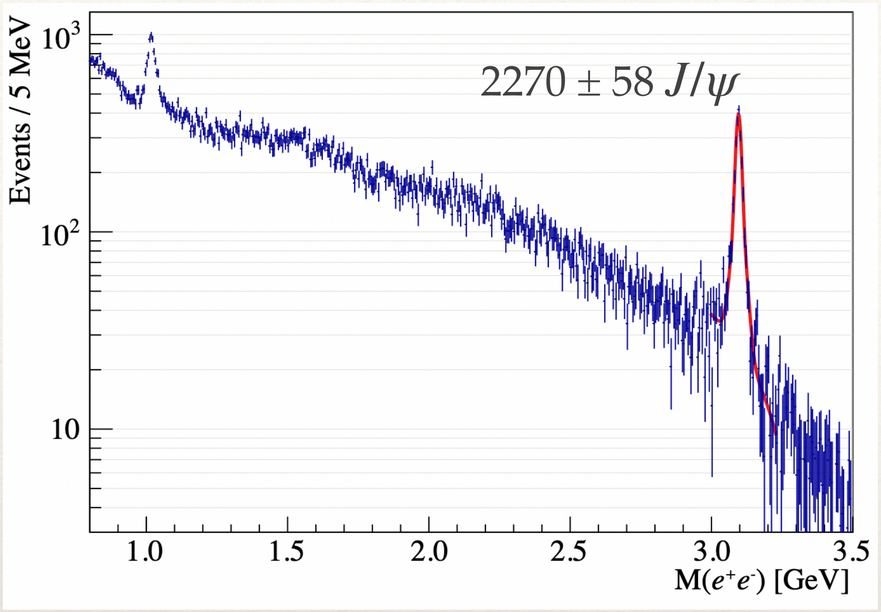




LHCb, Phys. Rev. Lett. **122**, 222001

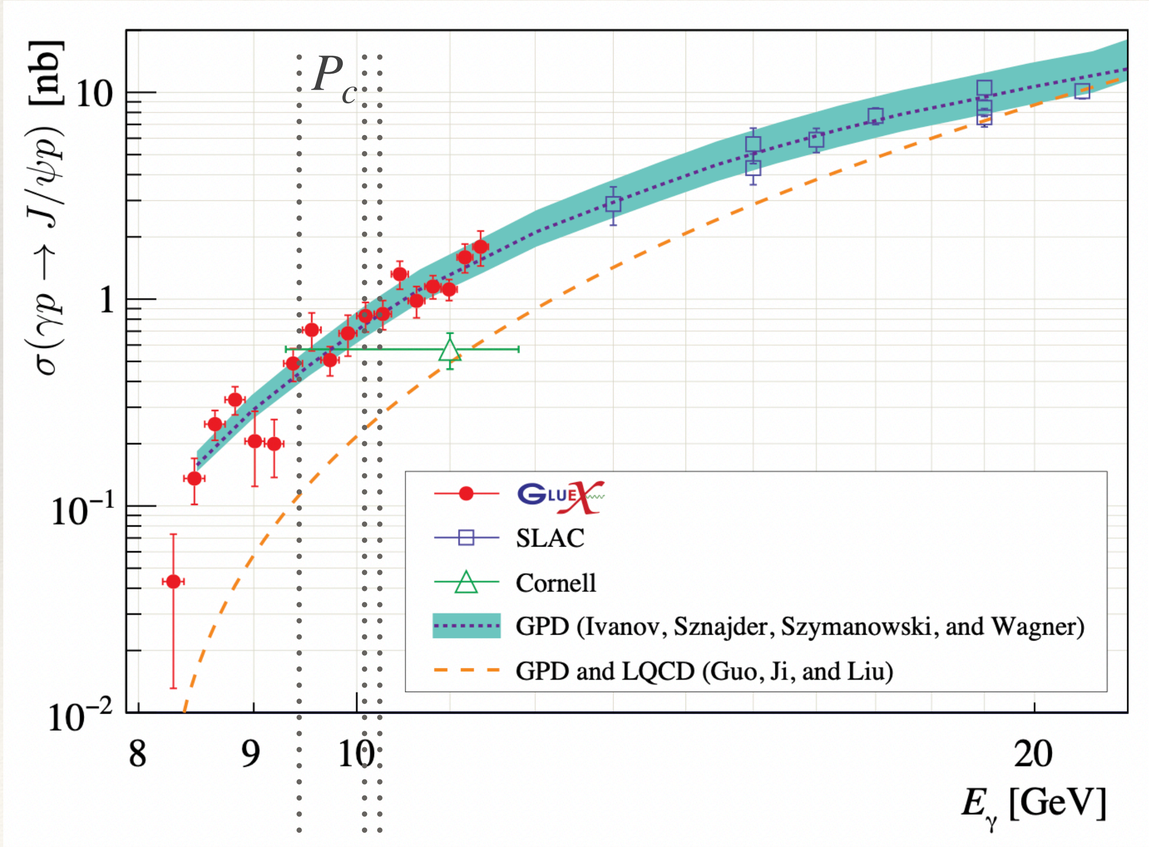
$J/\psi p$

GlueX, Phys. Rev. C 108, 025201 (2023)



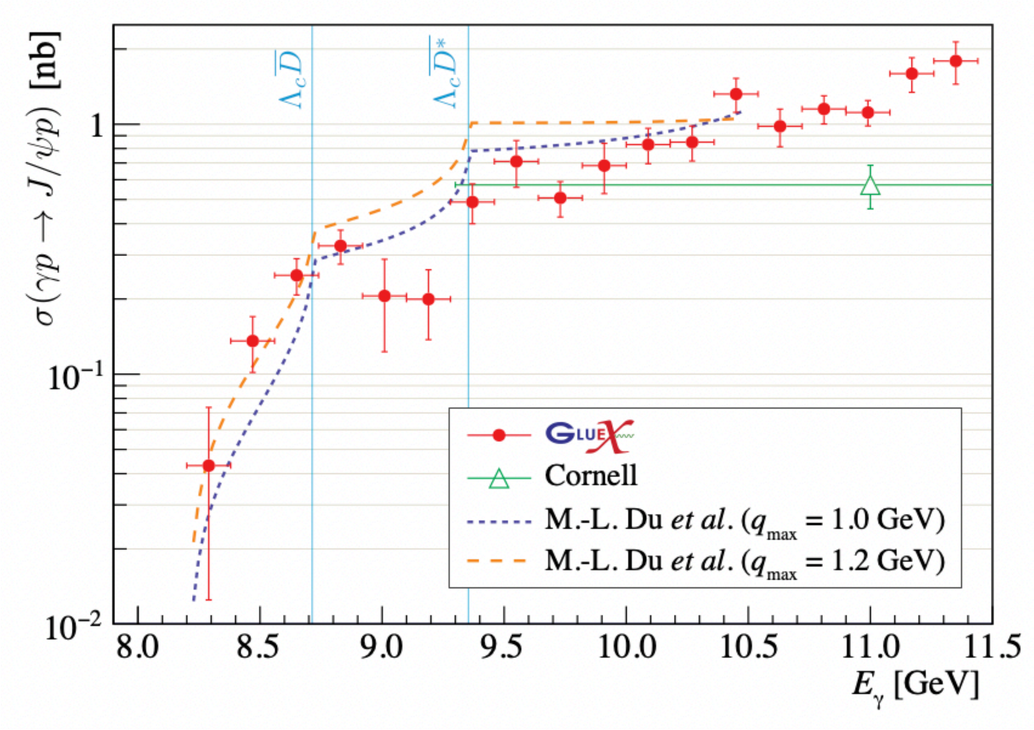
- measure leptonic decay $\gamma p \to J\psi p \to e^+e^- p$
- exclusive reaction
- normalise cross-section to non-resonant e^+e^- production (Bethe-Heitler)

- 20% overall normalisation uncertainty
- No peaks at P_c masses
  (set model dependent upper limits)
- Dip at ~9 GeV has 2.6σ significance
  (with look-elsewhere-effect 1.3σ)



$J/\psi p$

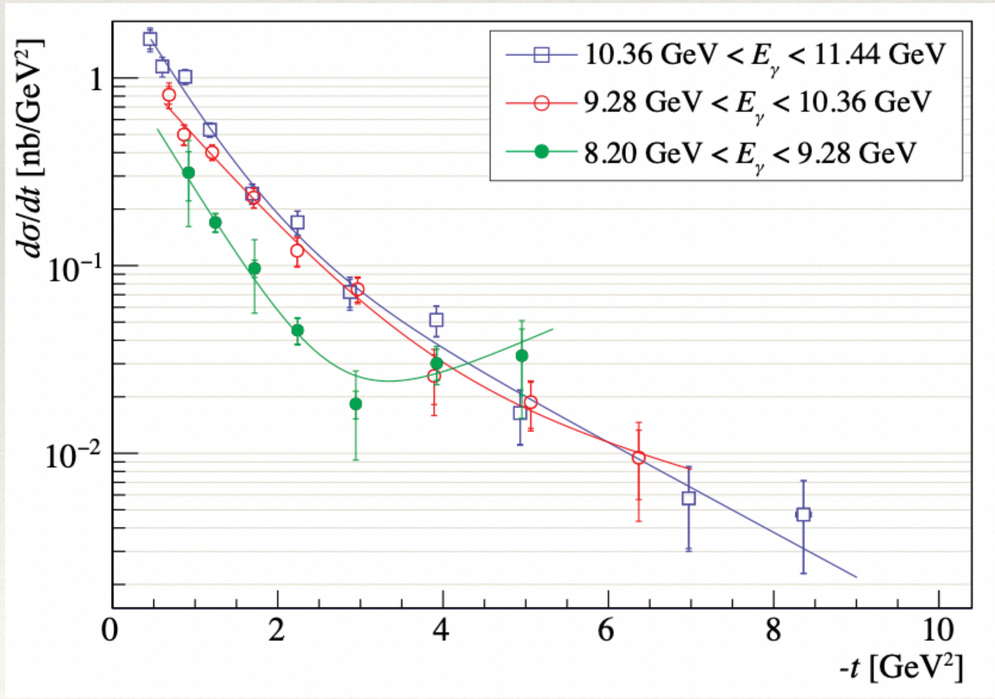
GlueX, Phys. Rev. C 108, 025201 (2023)



M.-L. Du et al. Deciphering the mechanism of near-threshold J/ψ photoproduction. Eur. Phys. J. C 80, 1053 (2020)

- Du et al. propose production through $\Lambda_c \bar{D}$ and $\Lambda_c \bar{D}^*$
  - Generate cusp structures
- JPAC describes data well with small number of partial waves enforcing low energy unitarity → factorization violation

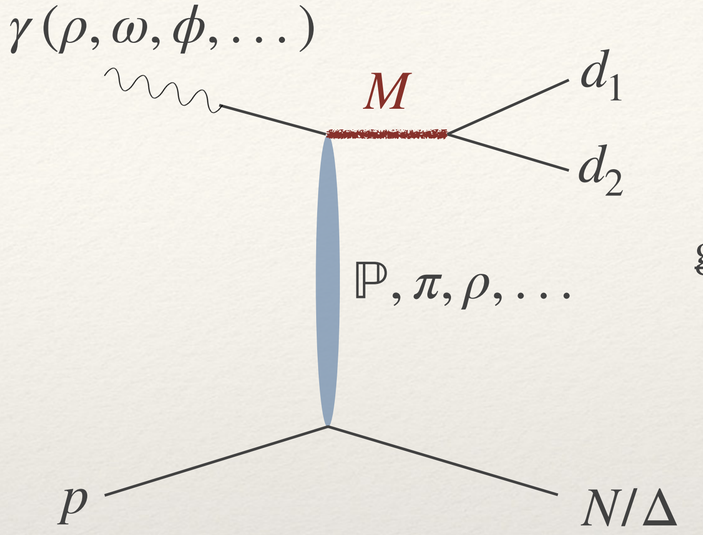
JPAC, PRD 108, 054018 (2023)



- Flattening of $d\sigma/dt$ in lowest energy range
- Indication of s- or u-channel contribution?
- Need better understanding of production mechanism

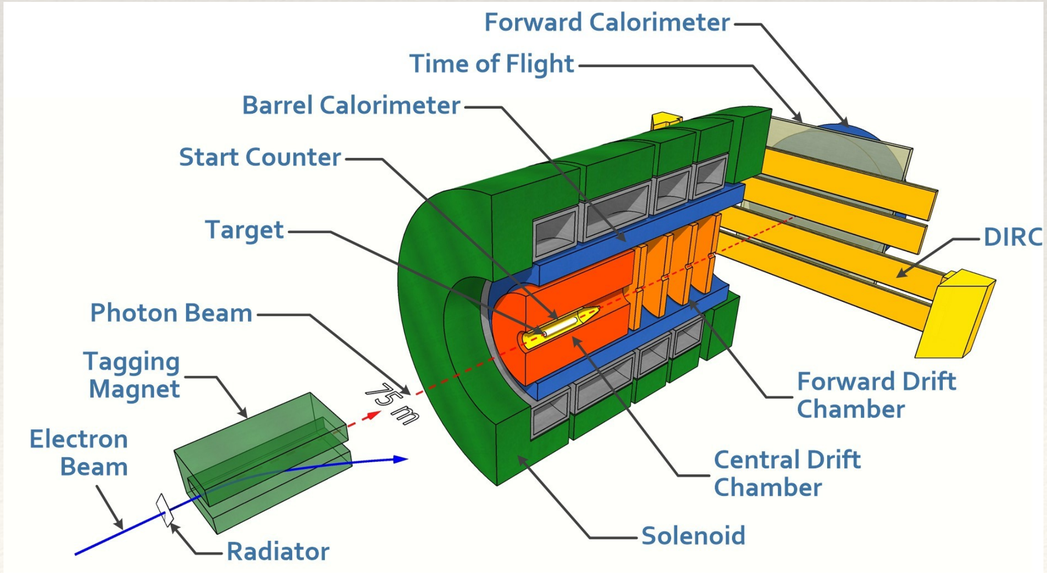
Summary

- GlueX has a unique data set with unprecedented statistical precision in its energy range
- Start with studying production mechanisms (SDMEs) and develop PWA in parallel
- $\pi_1(1600)$ upper limits, guide for future searches
- Many more interesting analyses in the pipeline and room for other physics
  - $\Lambda(1405)$
  - cascades
  - charmonium



Acknowledgments:

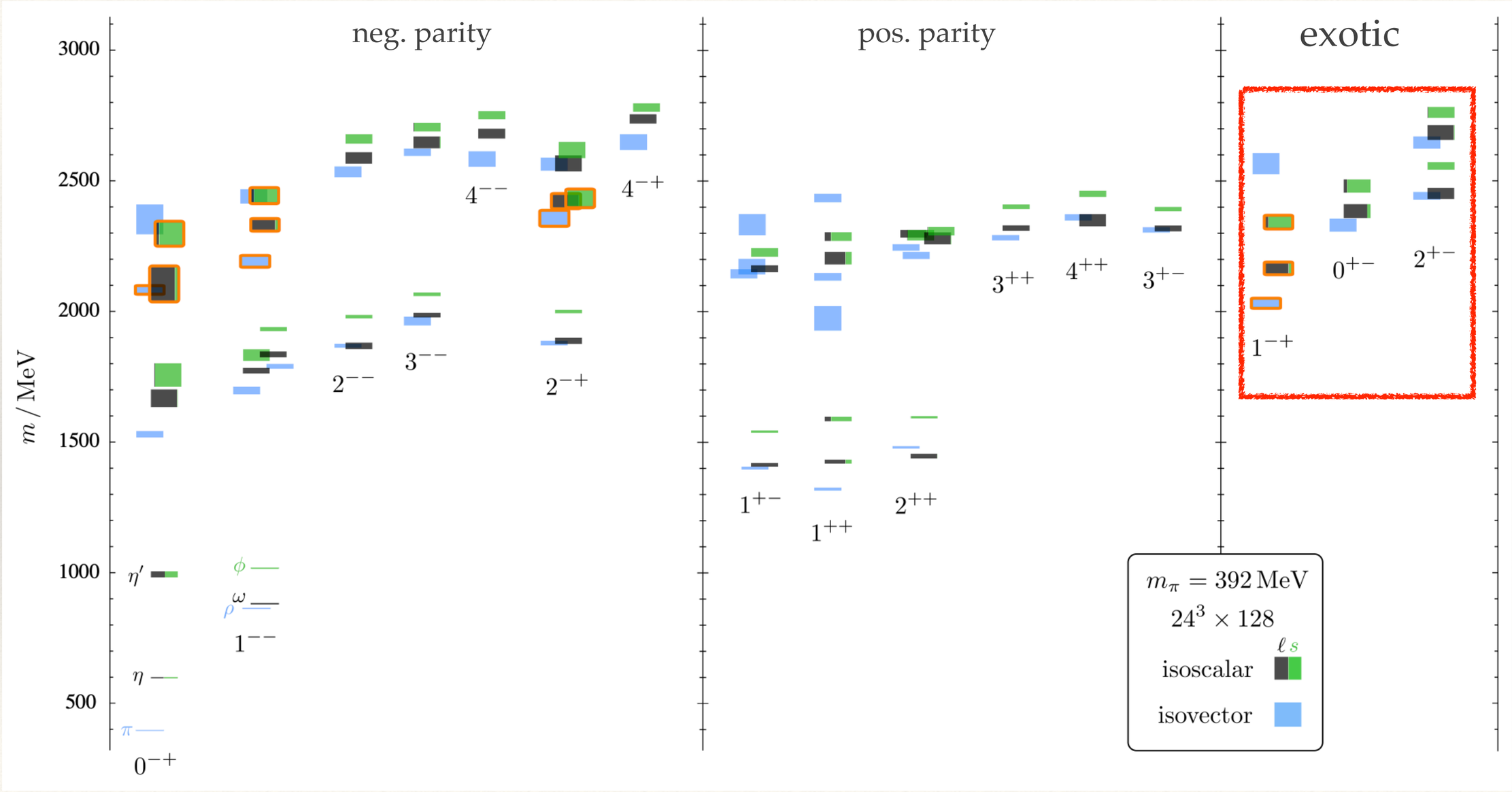
gluex.org/thanks



Backup

Light quark mesons from lattice QCD

hadspec collaboration

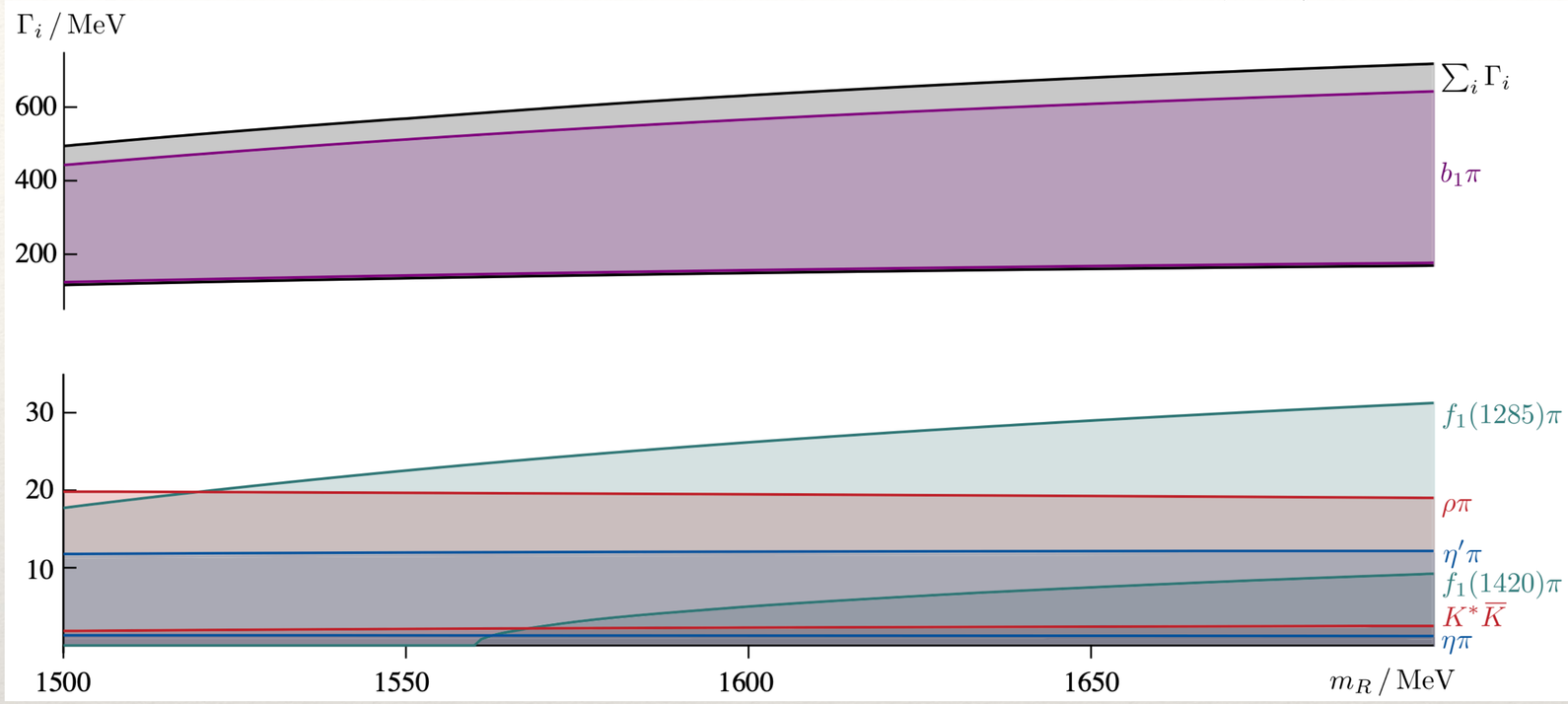


hadspec, Phys. Rev. D 88, 094505

1^{-+} hybrid from lattice QCD

hadspec collaboration

*hadspec, Phys. Rev. D **103**, 054502*

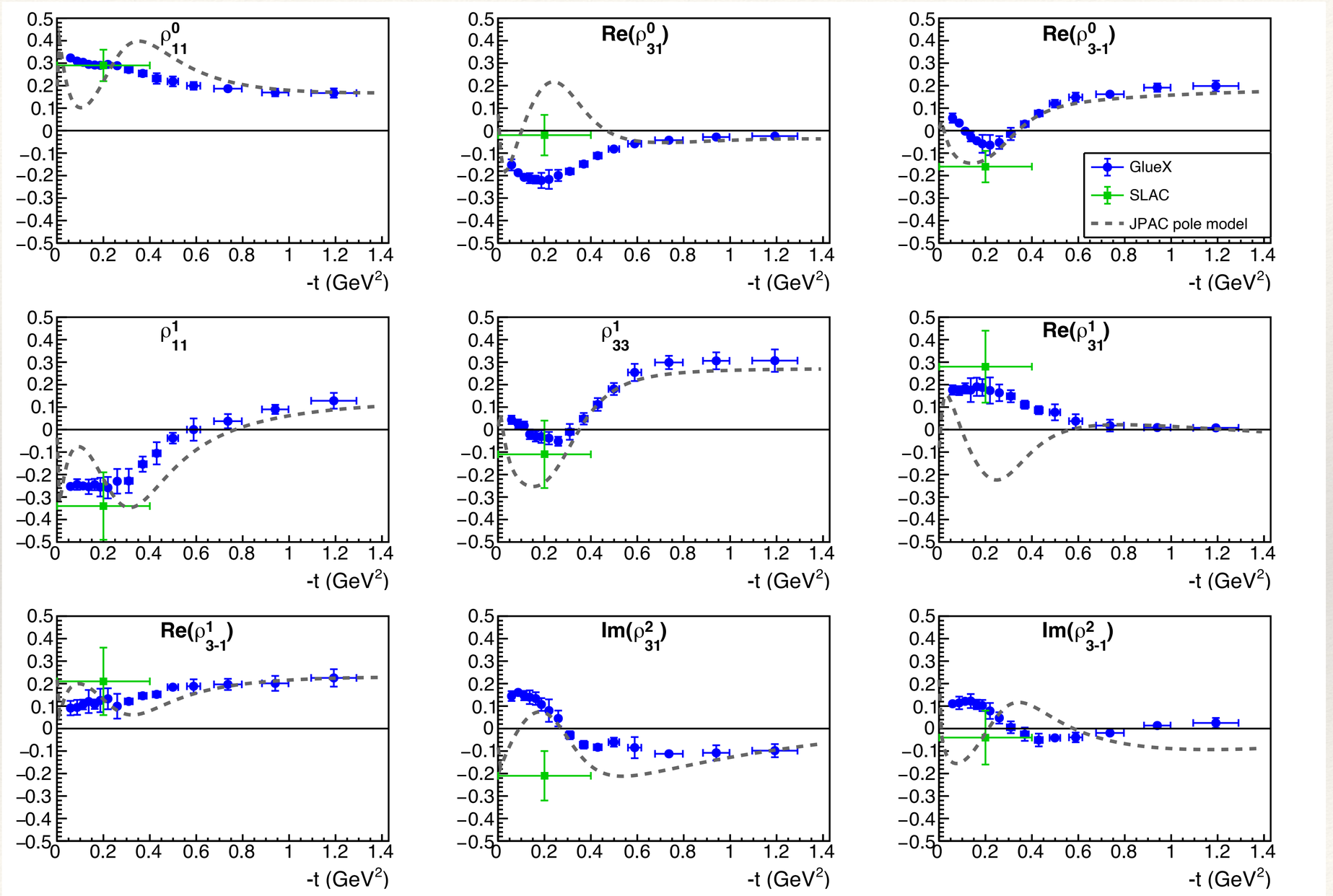


- LQCD indicates that $b_1\pi$ is the dominant decay mode
  - Experimentally challenging
- Start with $\eta\pi$, $\eta'\pi$
  - Smaller expected branching ratio but large statistics
  - Narrow peaks and pseudo scalars

$\Delta^{++}(1232)$ SDMEs

arXiv:2406.12829 [nucl-ex]
submitted to Phys. Lett. B

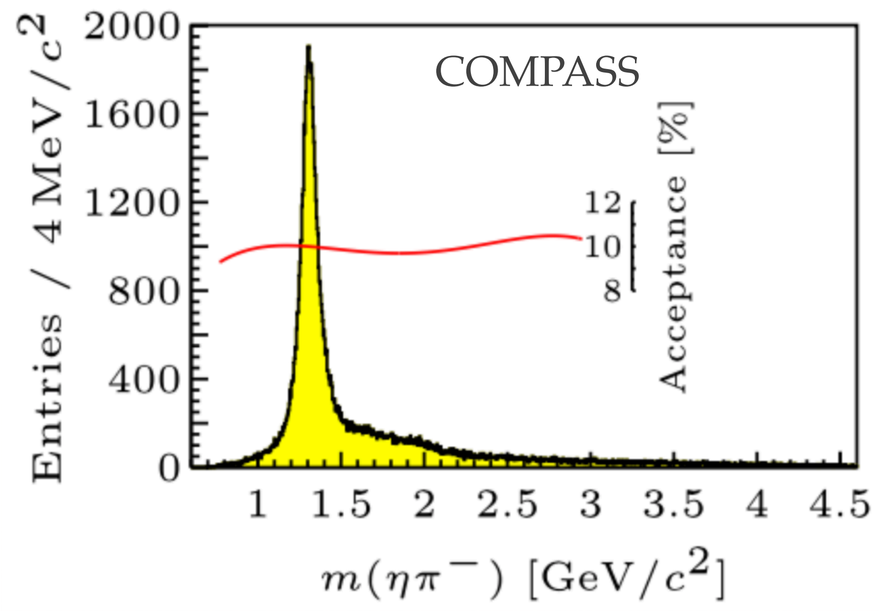
$\gamma p \to \pi^- \Delta^{++}(1232)$
$\to \pi^- \pi^+ p$

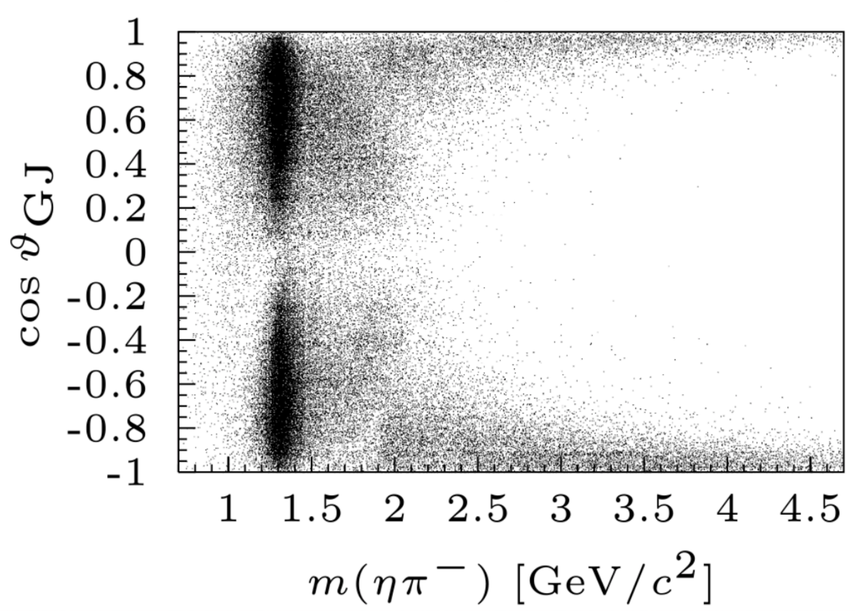


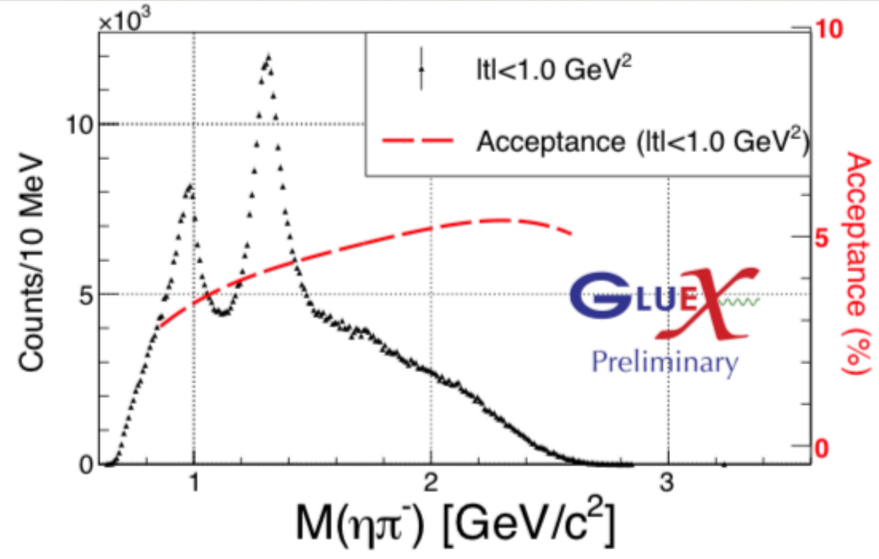
JPAC, Physics Letters B 779 (2018) 77–81

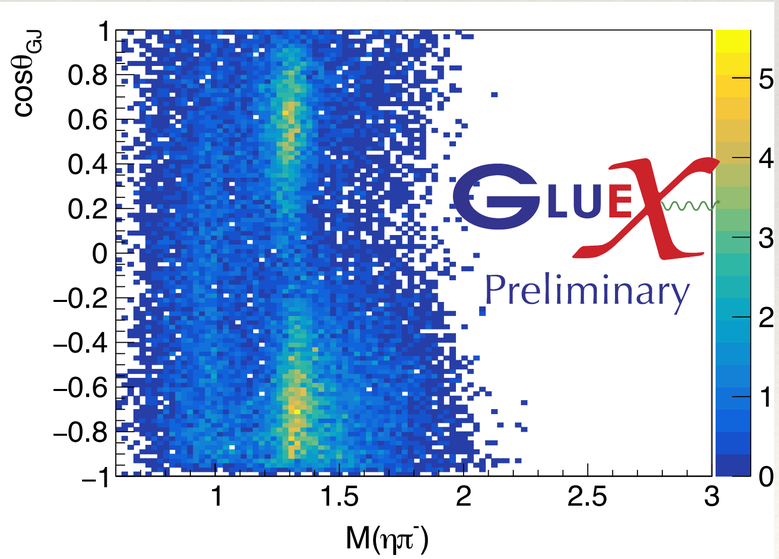
Hybrid search in $\eta\pi^-$

COMPASS, Phys. Lett. B 740 (2015) 303–311

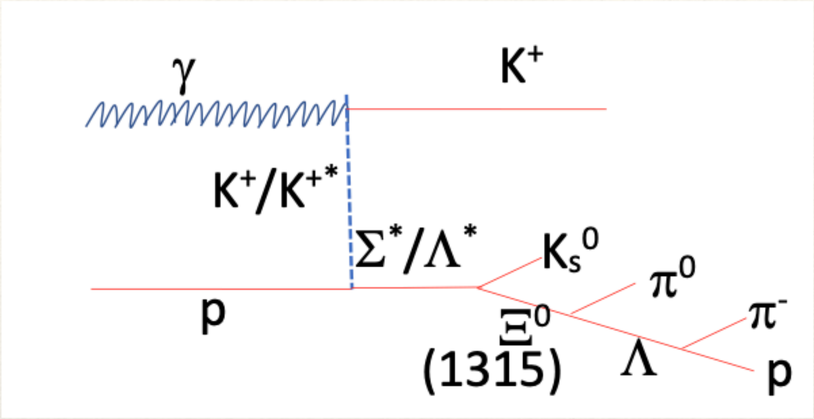




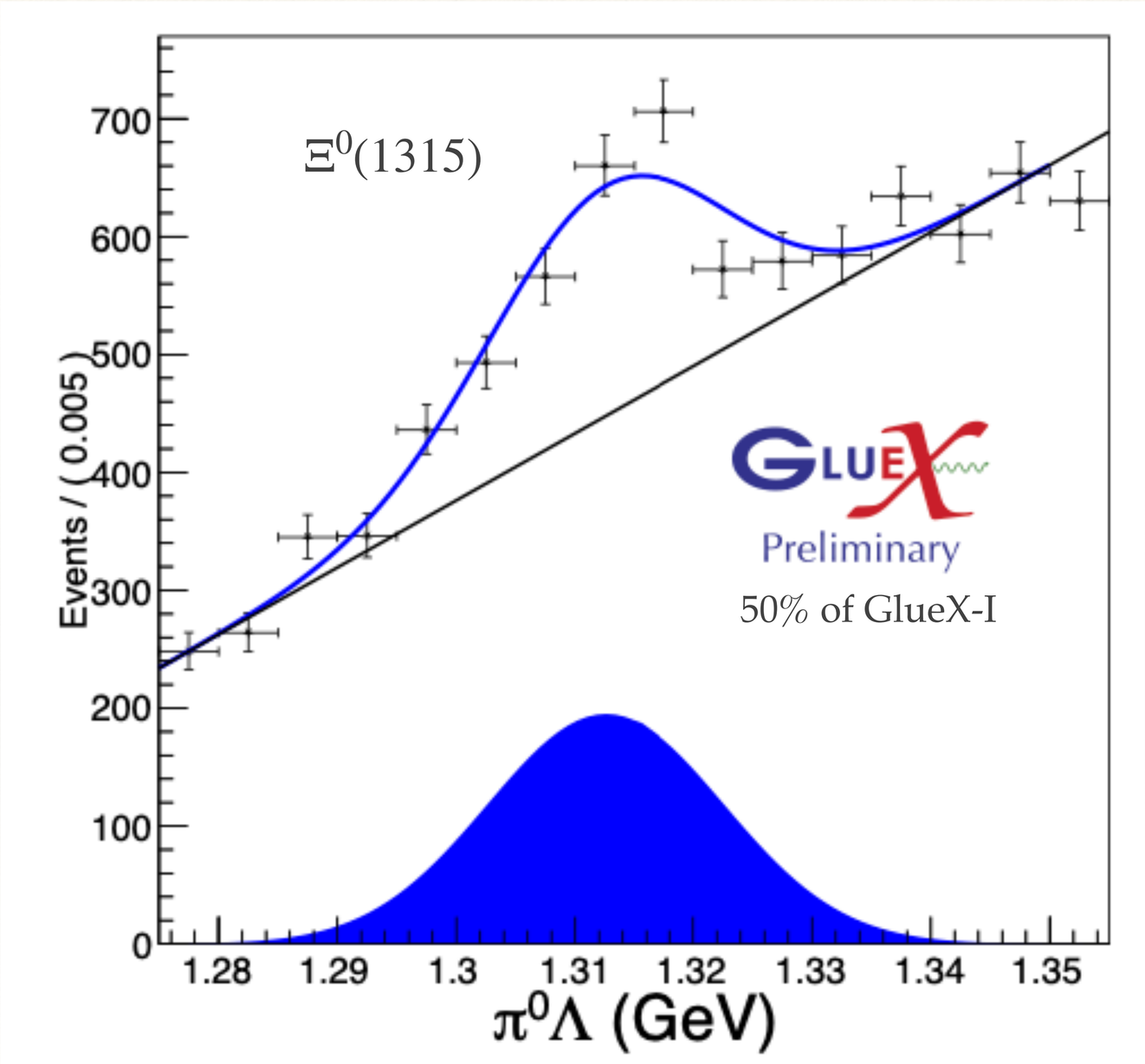




Cascades at GlueX

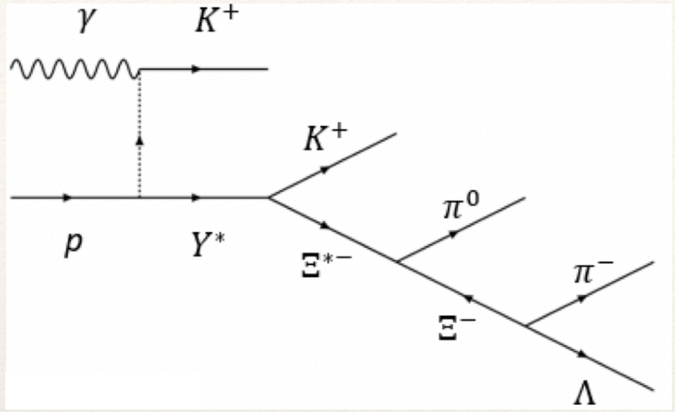


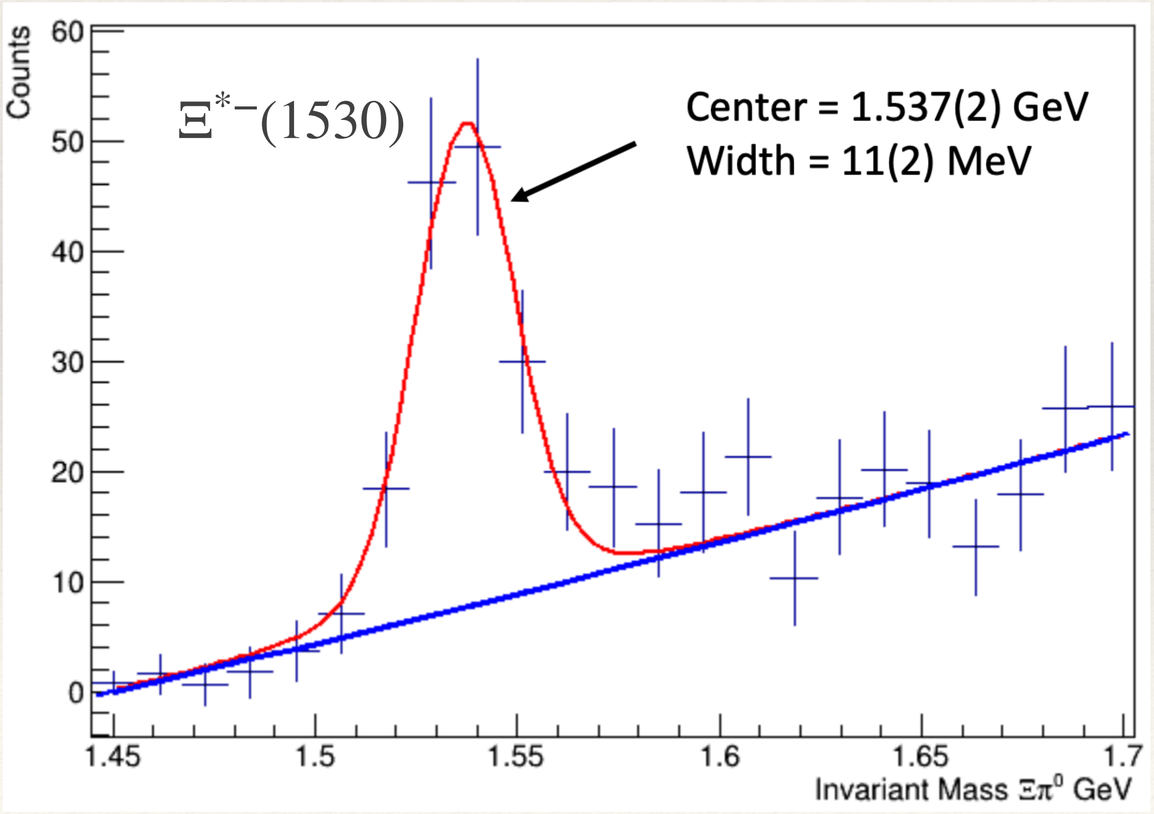
- We see both ground states
- Measure cross-sections for Ξ^-
- Less stats for Ξ^0 but clear signal

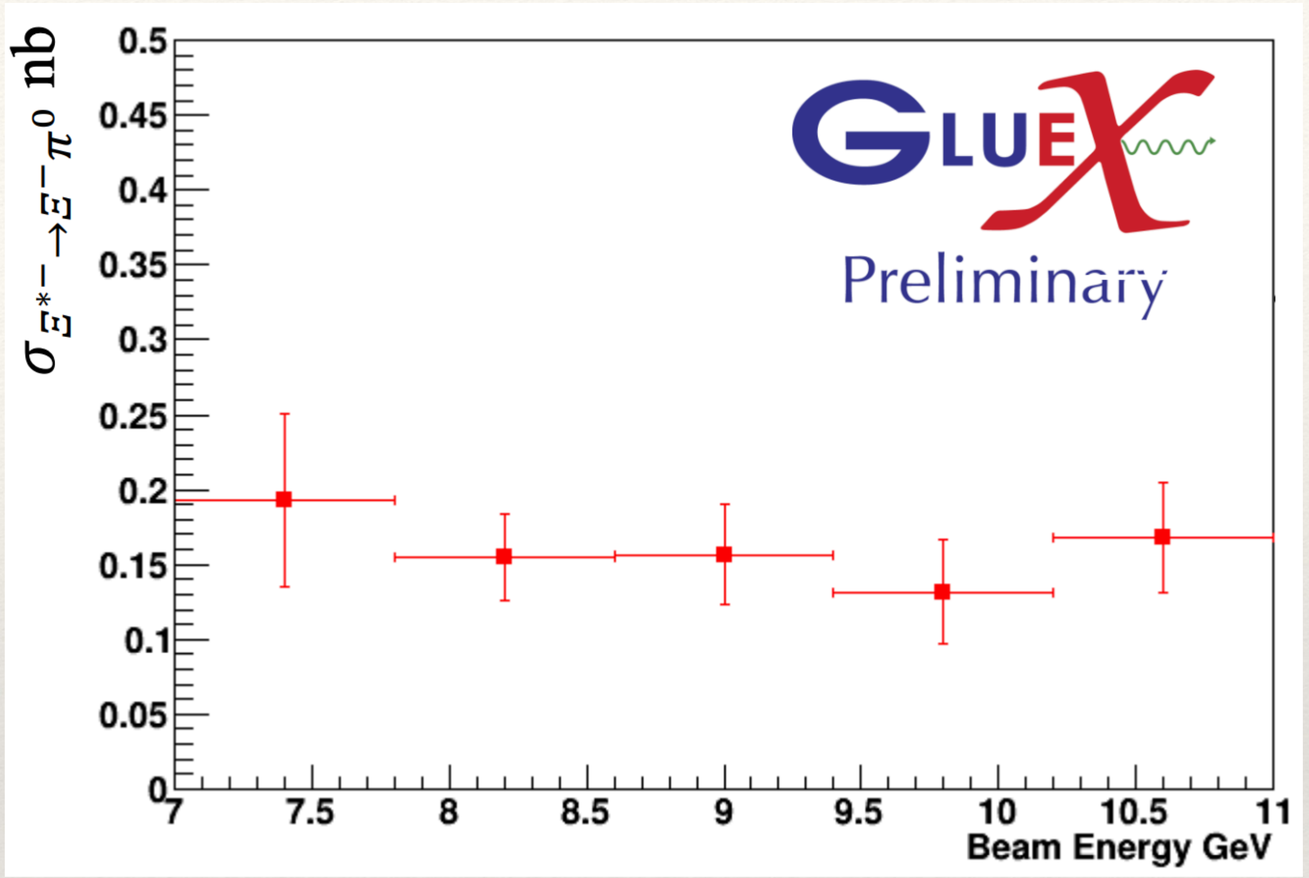


Further Cascades at GlueX

B. Sumner (GHP2023)

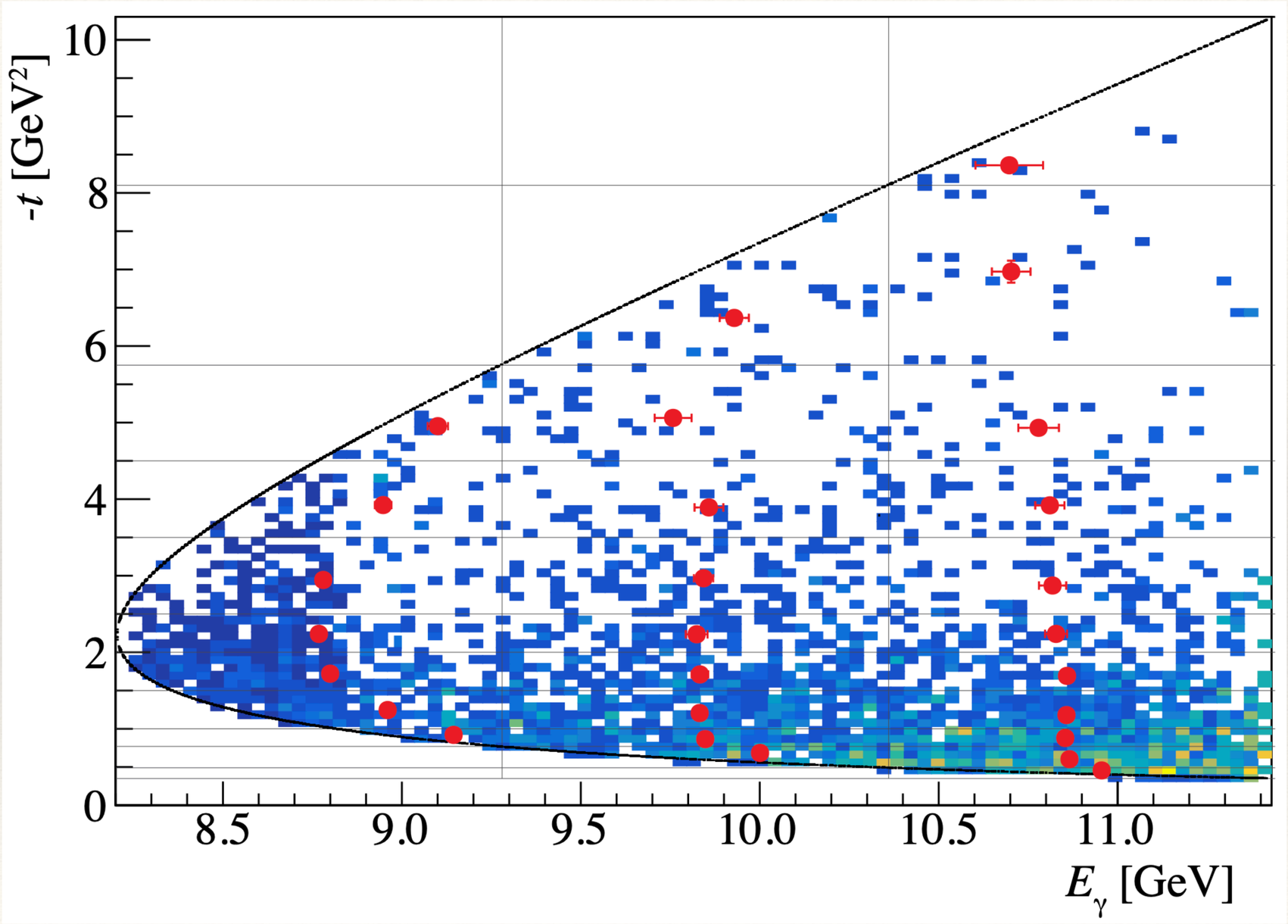




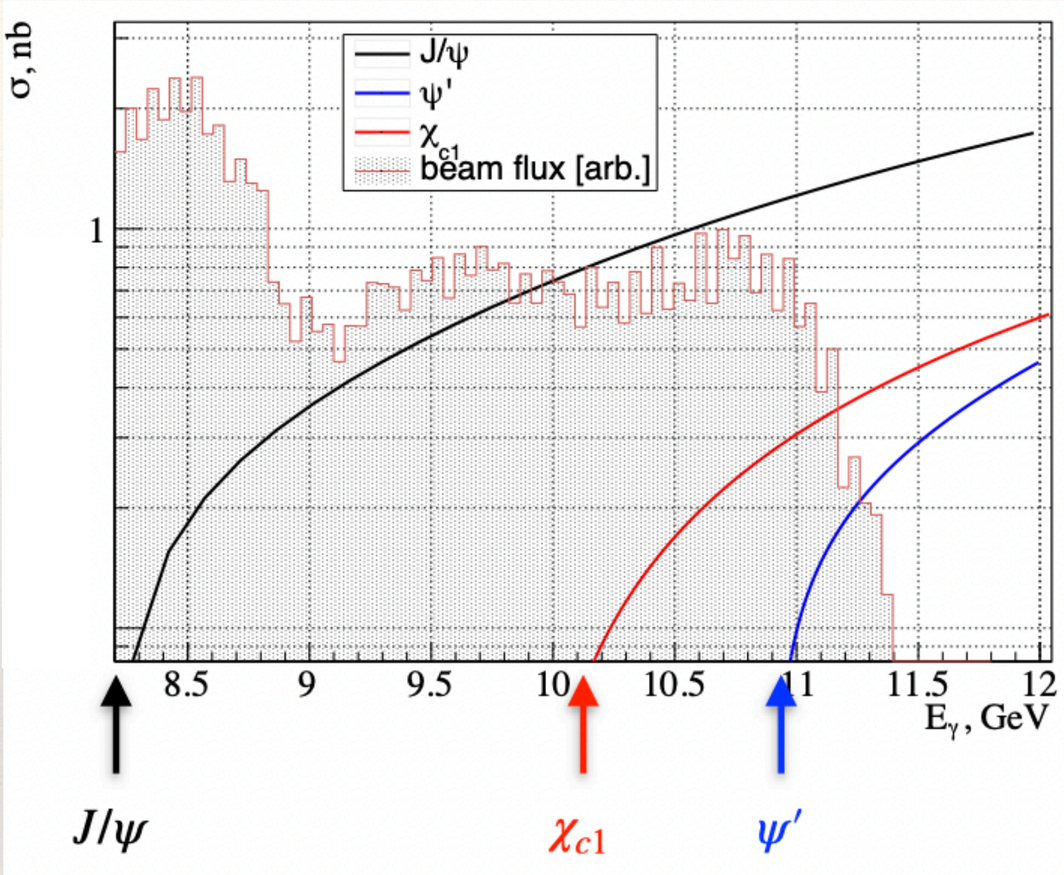


- Measure $\Xi^{*-} \to \Xi^-\pi^0$ and determine total Ξ^{*-} cross-section via isospin symmetry

$J/\psi p$

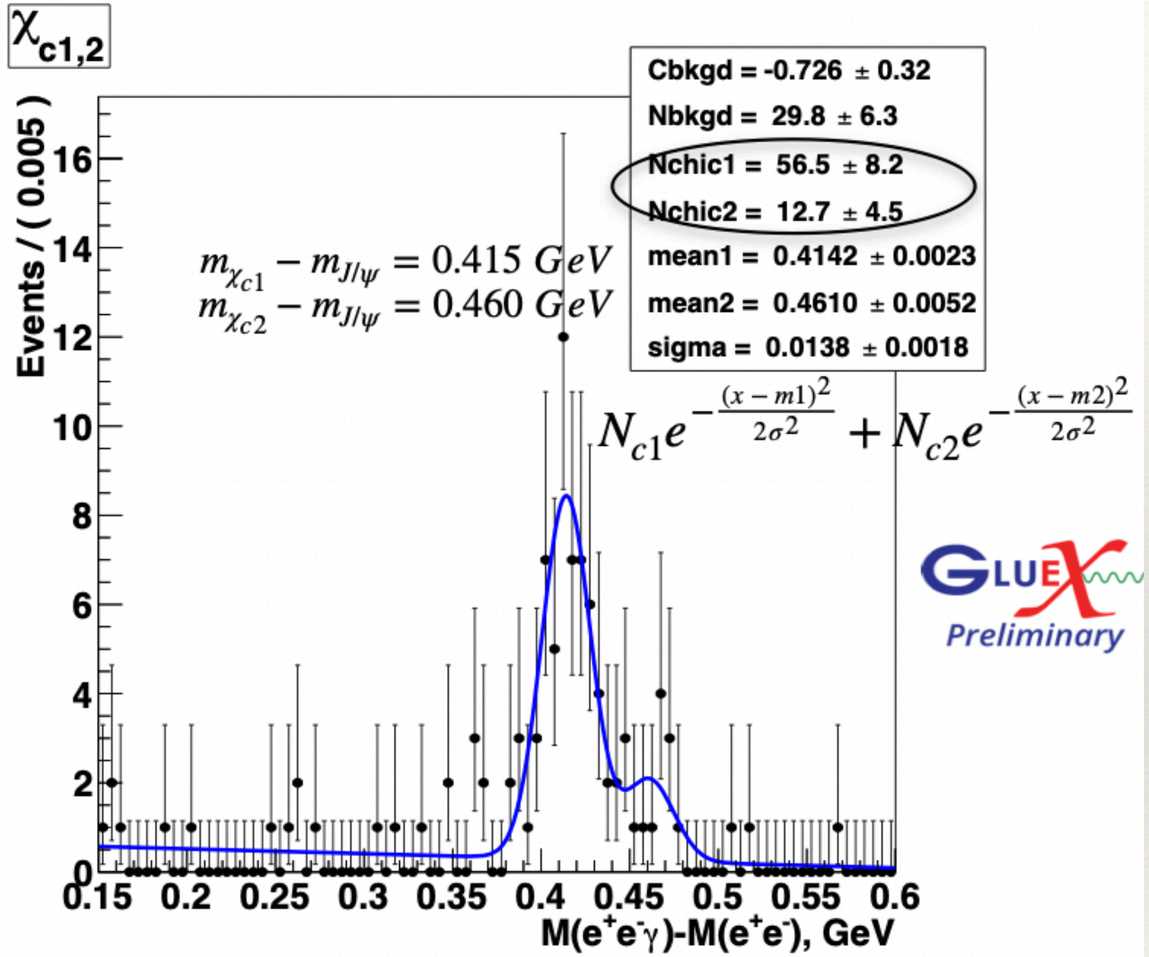


Further Charmonium states



- Small number of χ_{c1} and χ_{c2}
- Even a few ψ'

$$\gamma p \to \chi_c p \to (J/\psi\gamma)\, p \to (e^+e^-\gamma)\, p$$



- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV