

The Baryon and Meson Spectroscopy Programs at GlueX

15th International Workshop on the Physics of Excited Nucleons

September 8, 2026 - Seville, Spain

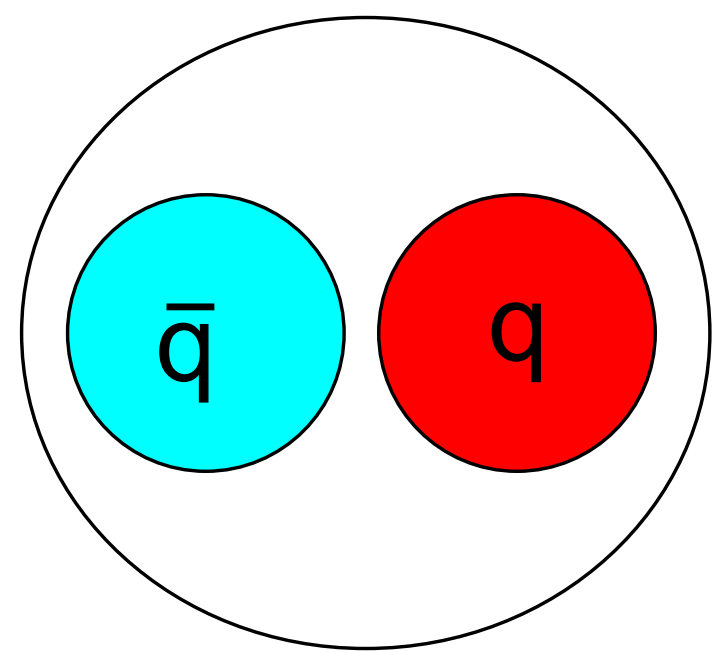
Will Imoehl
Jefferson Lab

On behalf of the GlueX Collaboration

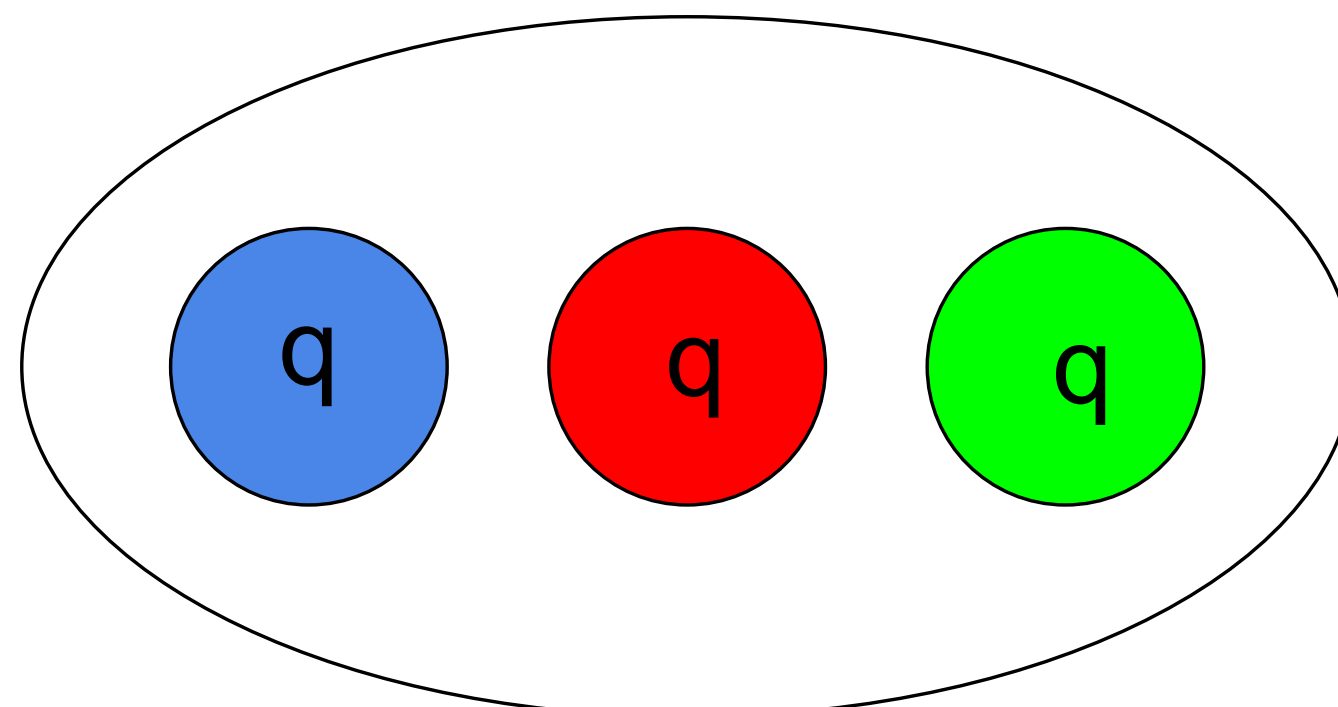


Physics Motivation

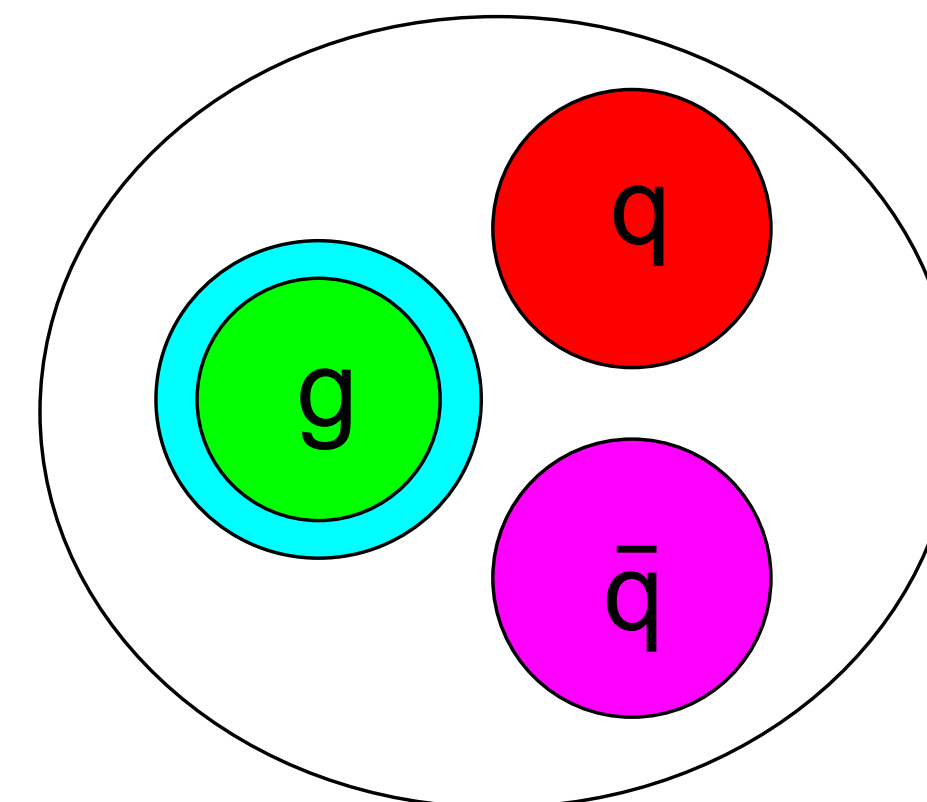
- Complete understanding of QCD should be able to predict entire spectrum of hadrons
- Rich spectrum of conventional mesons and baryons has been observed
- Experimental evidence for light exotic mesons scarcer
- One of GlueX's main goals: map out conventional and exotic hadron spectrum
 - Large emphasis on hybrid mesons - mesons with gluonic excitations



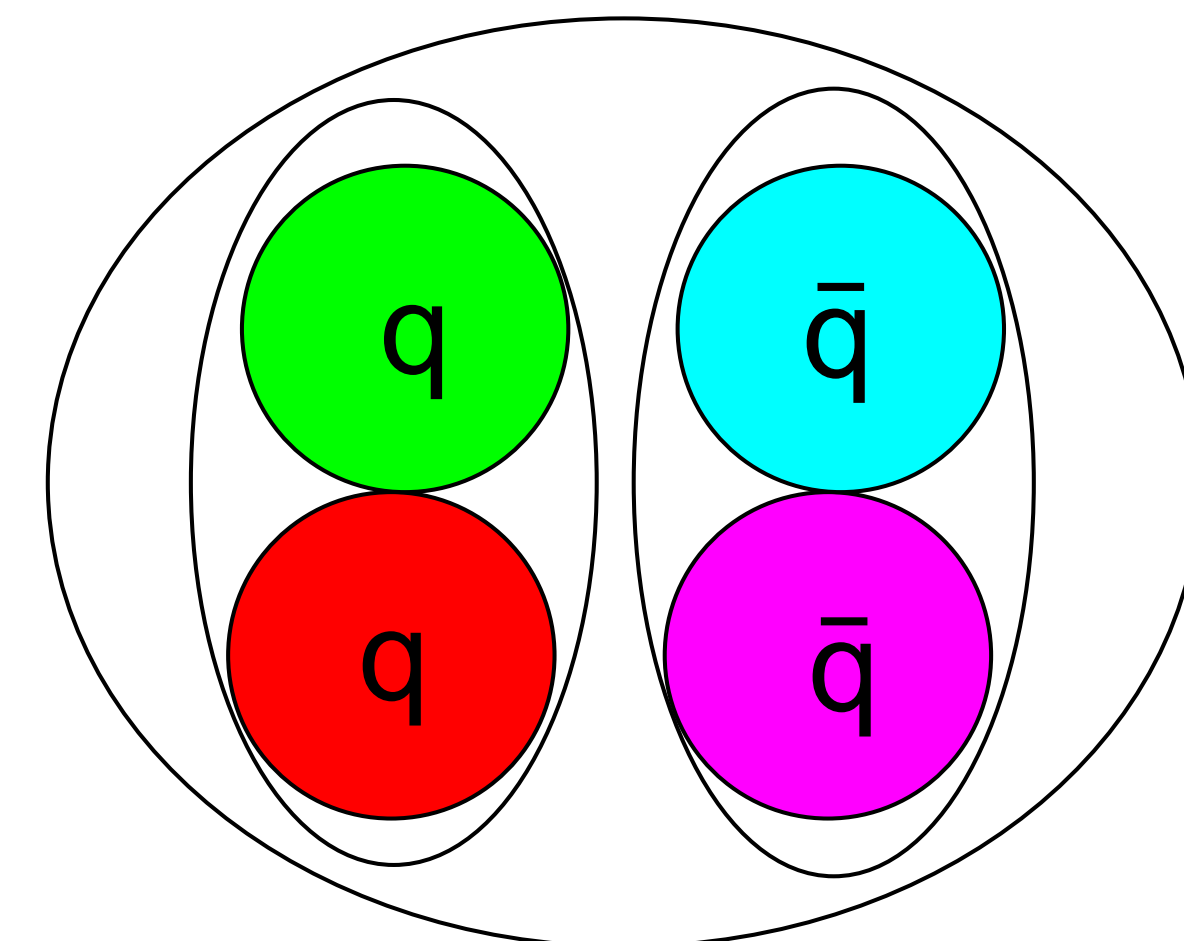
Meson



Baryon



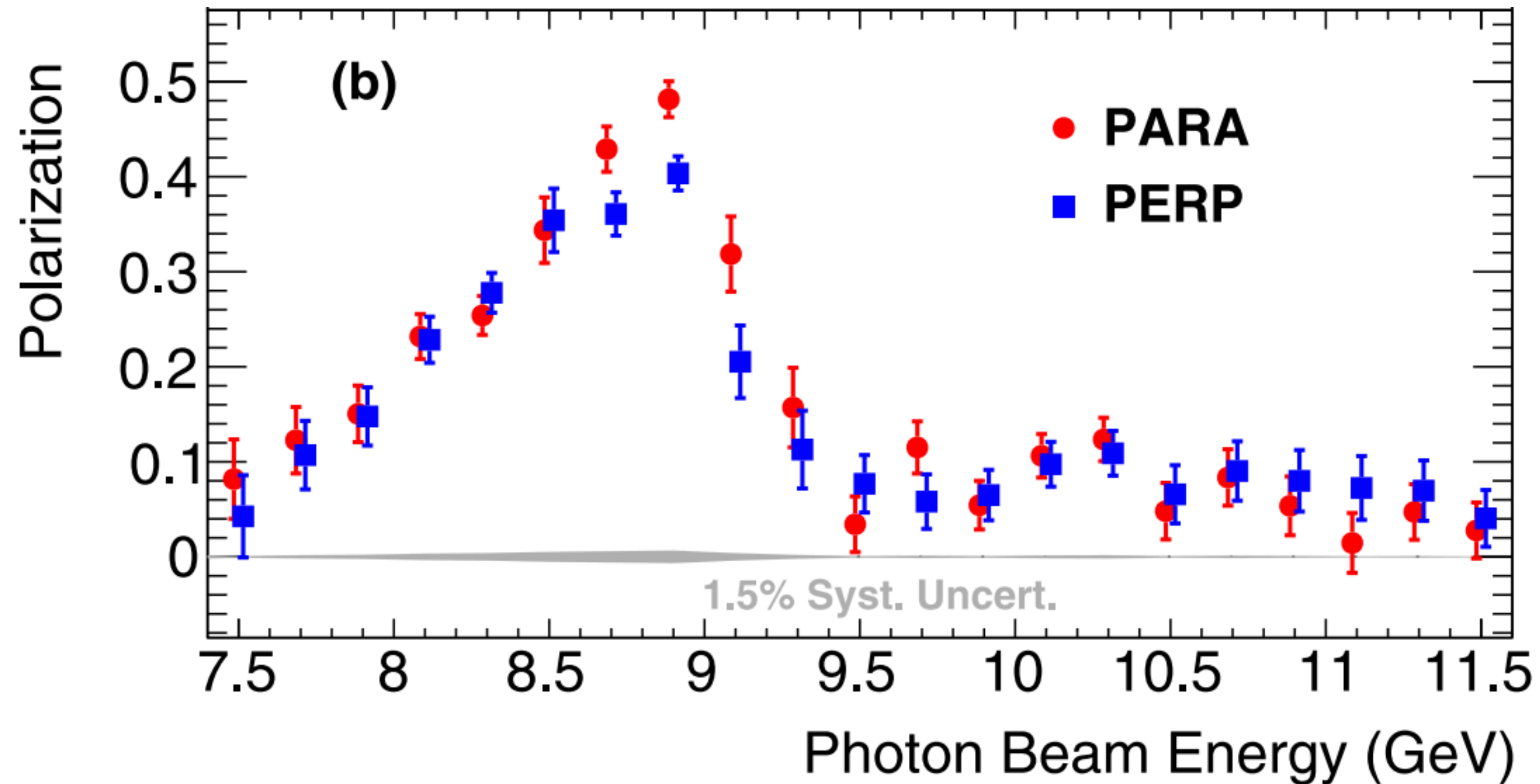
Hybrid Meson



Tetraquark

Jefferson Lab and CEBAF

NIMA 987 (2021) 164807

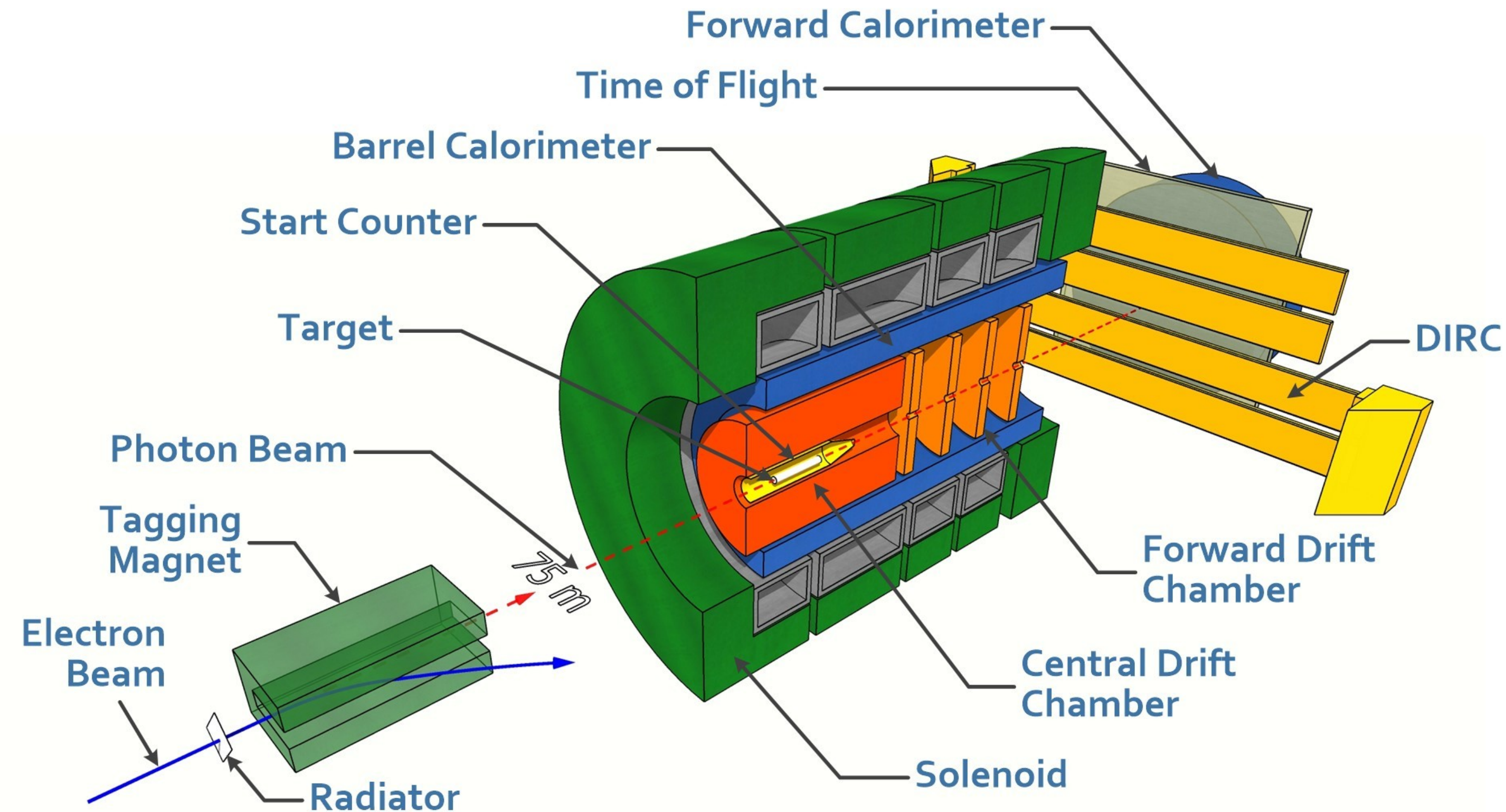


- **CEBAF accelerator** delivers up to 12 GeV electrons to **Hall D**
- Produce linearly polarized photon beam using coherent Bremsstrahlung ($P_\gamma \approx 40\%$)

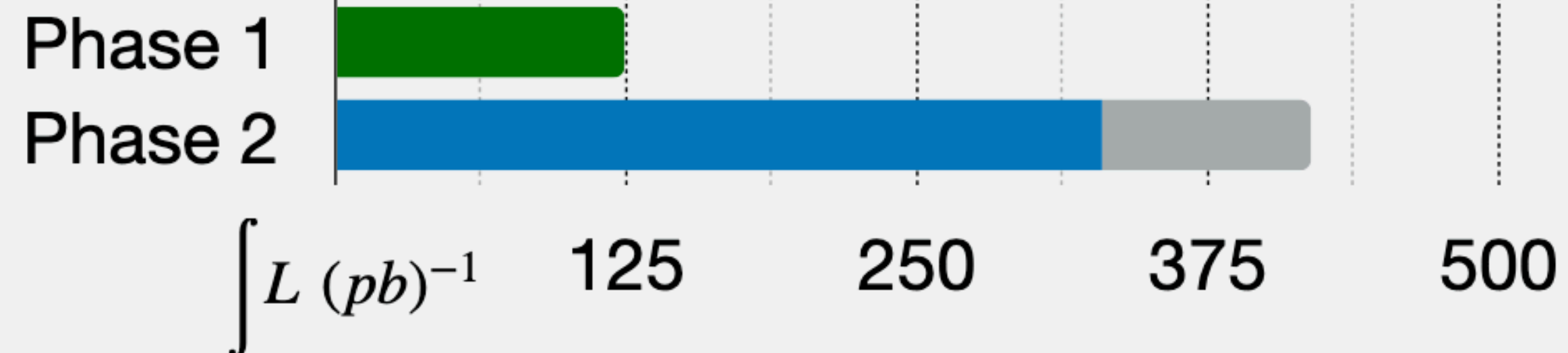


The GlueX Experiment

- Linearly polarized photons hit liquid hydrogen target
- Nearly hermetic detector for both charged and neutral particles
- GlueX-I data completed in 2018
- Phase-II data nearly complete, DIRC for improved π/K PID

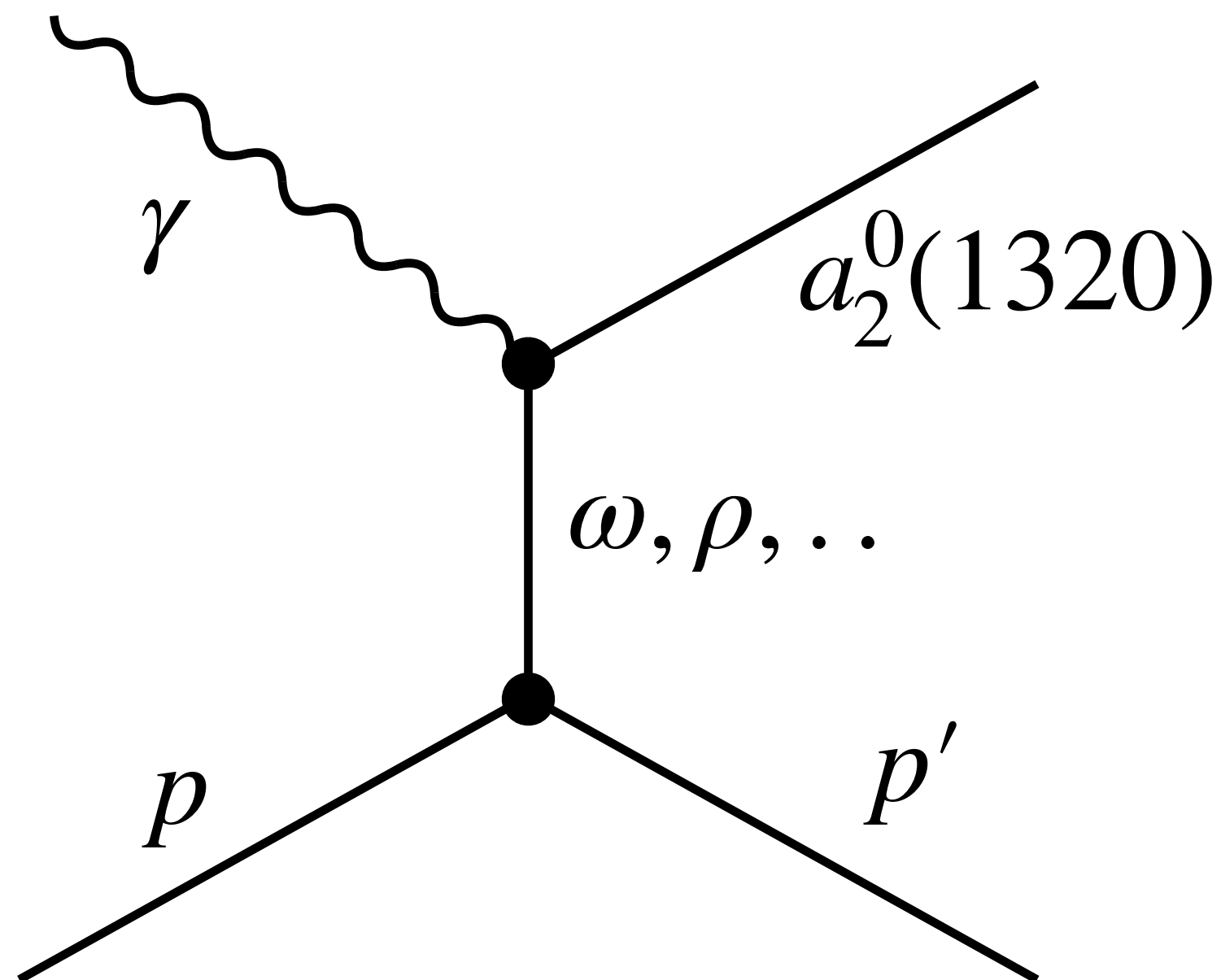


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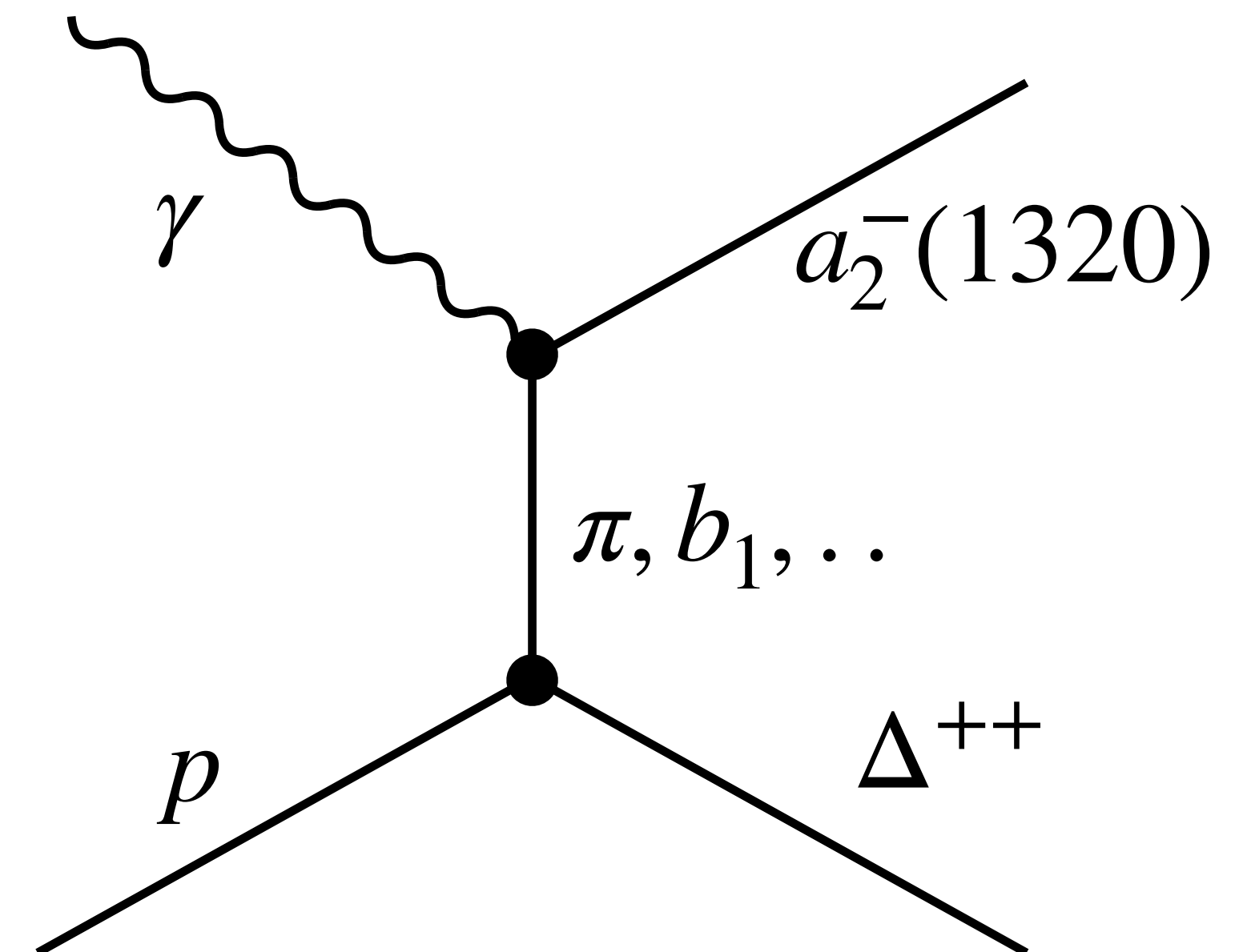


Production of Mesons and Baryons at GlueX

- t -channel exchange dominates at our beam energies
- Photon $\leftrightarrow$ vector meson, which then exchanges a particle with the target proton
- Can produce mesons and baryons through these processes
- t is the four-momentum transferred from beam photon to meson system



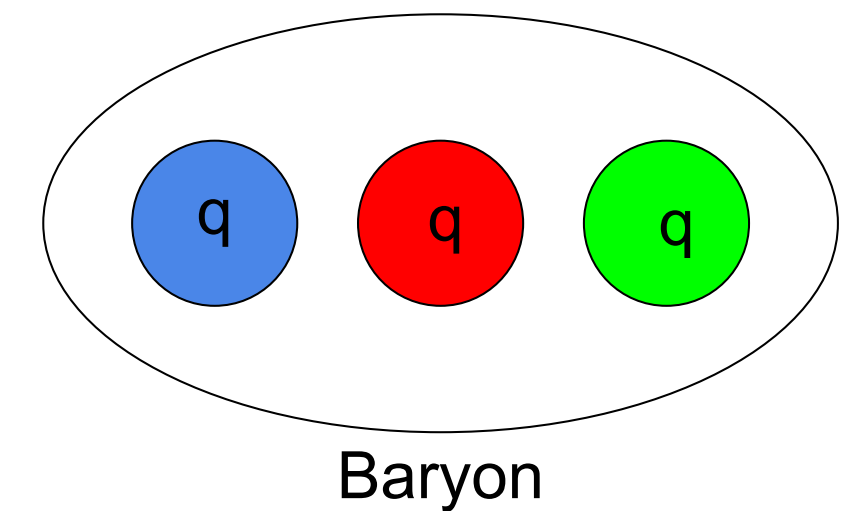
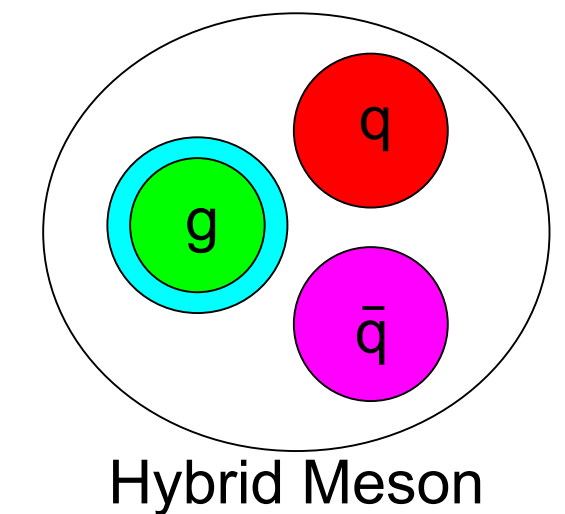
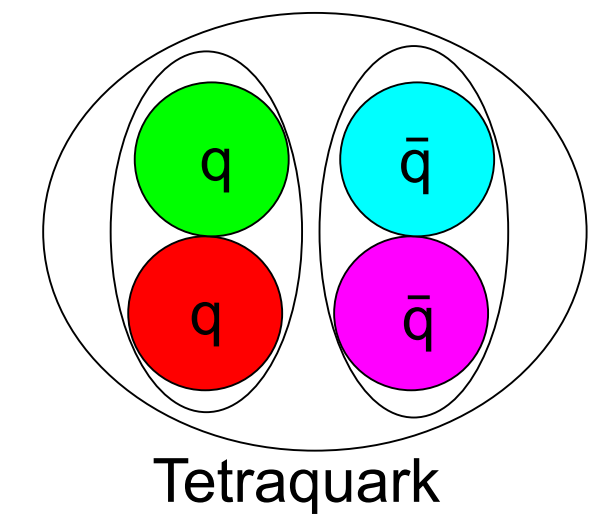
$$t = (p(\gamma) - p(a_2))^2$$



Overview of GlueX Spectroscopy Programs

Selection of results from meson and baryon programs, including

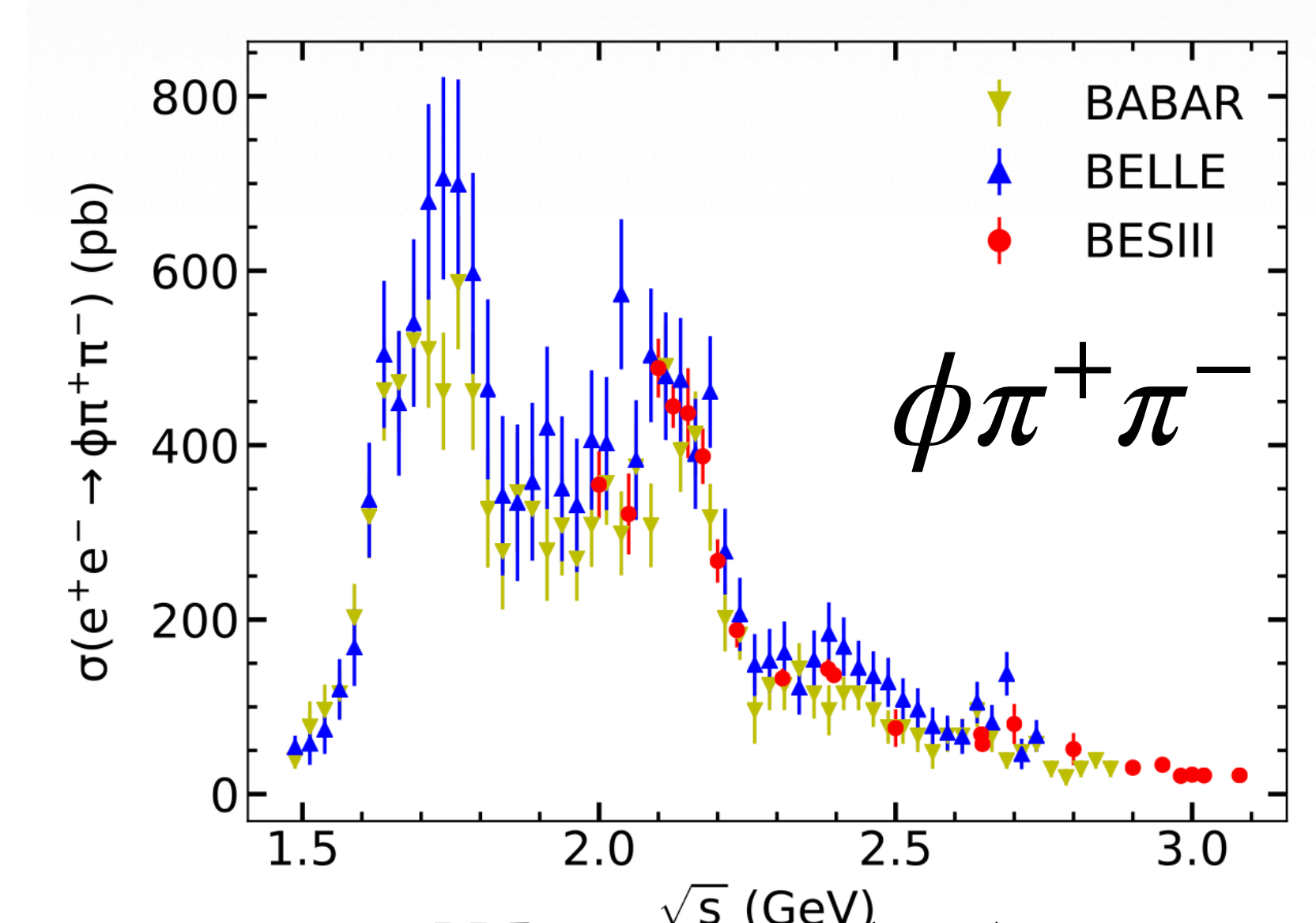
- Search for exotic mesons in $\phi\pi^+\pi^-$
- Status of the hybrid meson search
 - Sensitivity studies, conventional mesons
- Studies on Δ^{++} production and decays
 - Beam asymmetry, SDMEs, double SDMEs, factorization studies
- Baryon spectroscopy (Ξ states)
- Underlying baryon dynamics (baryon-antibaryon, $\Lambda(1405)$)



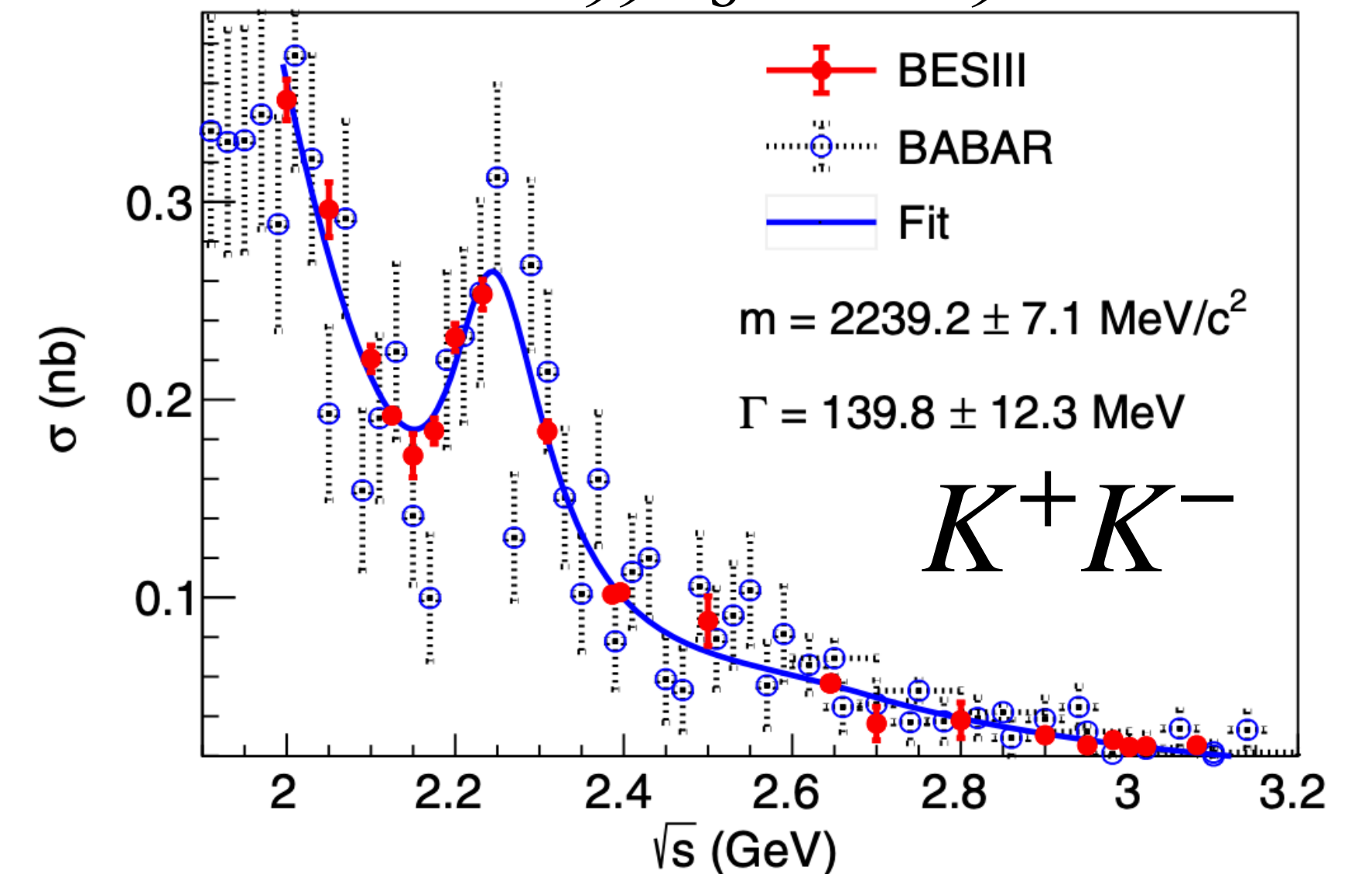
Hidden Strange Exotic Mesons

- Charmonium spectrum has too many vector mesons
 - $Y(4230)$ is well established four-quark candidate
- Similar situation may be happening in $s\bar{s}$ system
- $\phi(2170)$ is best four-quark candidate in $s\bar{s}$
 - Observed at e^+e^- colliders by multiple experiments
 - Reconstructed in $\phi(2170) \rightarrow \phi\pi^+\pi^-$
- Structure found at higher mass in $e^+e^- \rightarrow K^+K^-$
 - Unclear if related to $\phi(2170)$

PRD 108, 032011 (2023)



PRD 99, 032001 (2019)



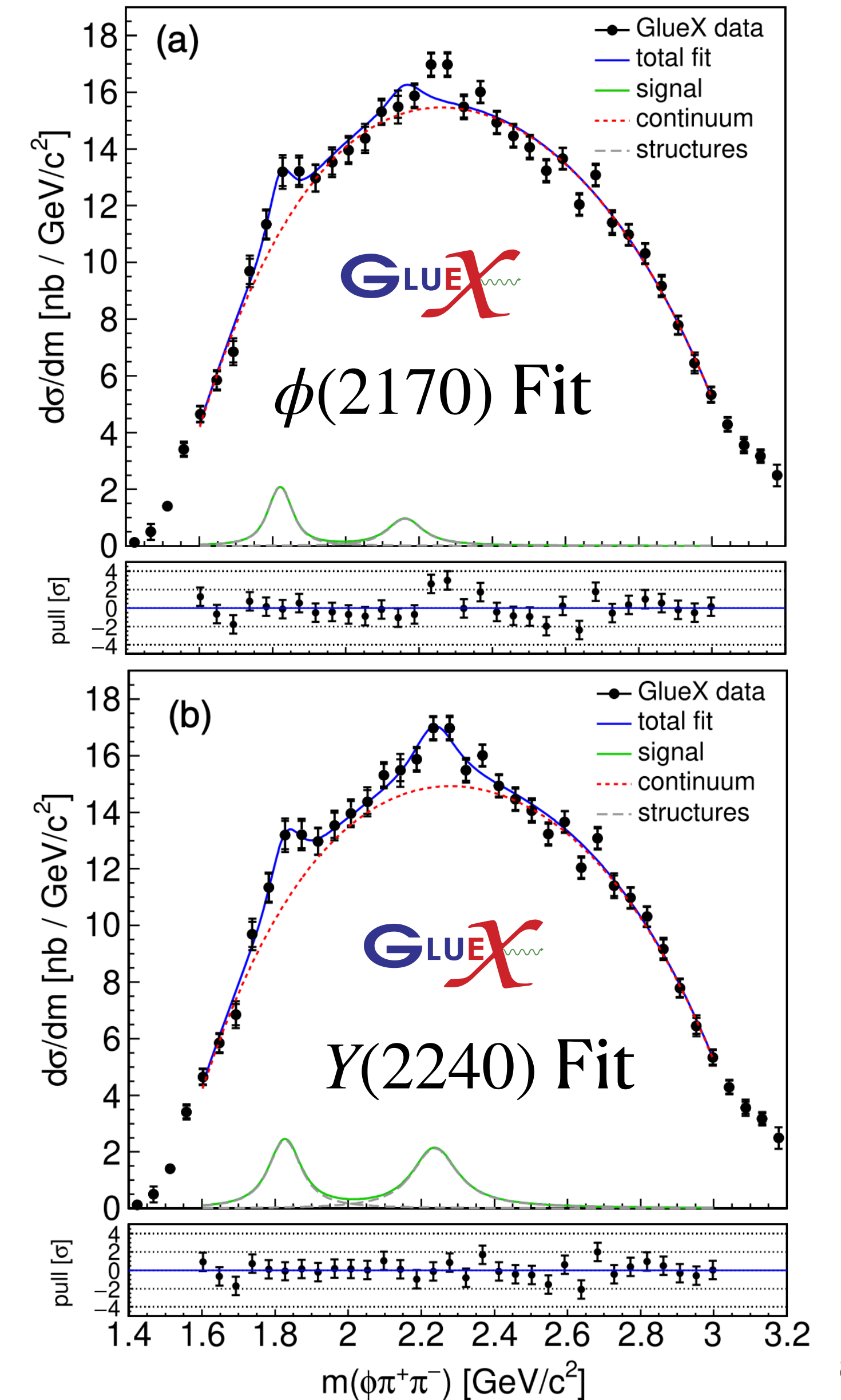
Search for the $\phi(2170)$ in $\phi\pi^+\pi^-$ PRL 136, 251902 (2026)

Search for $\phi(2170)$ at GlueX by measuring $\sigma(\gamma p \rightarrow \phi\pi^+\pi^-p)$

Fit model:

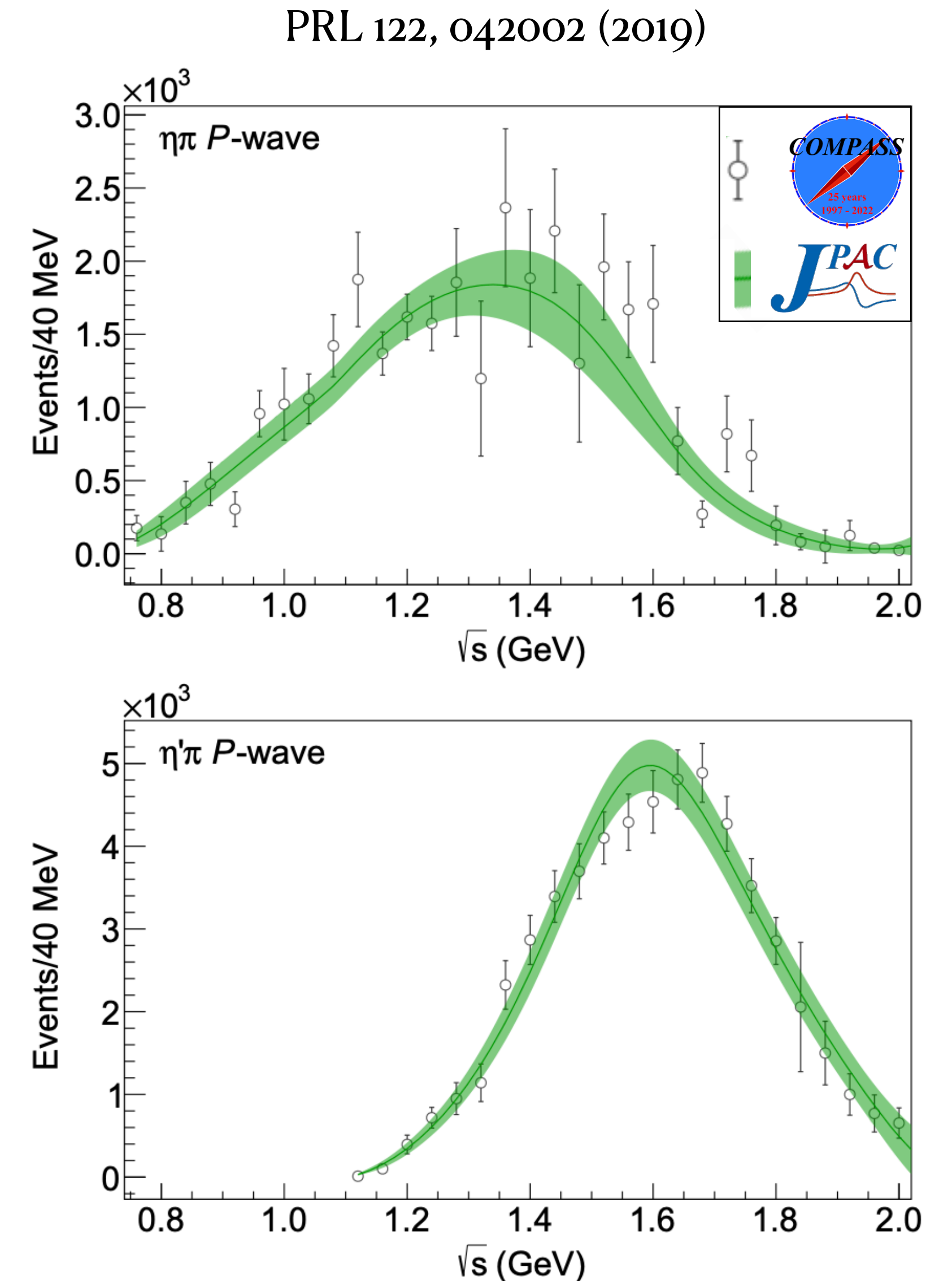
- **Continuum background** (4th-order polynomial)
- Breit-Wigner at 1.82 GeV/c²
 - $\phi_3(1850)?$, $X(1830)$ via K^*K^* rescattering?
- Signal modeled as either
 - $\phi(2170)$ with PDG parameters (top)
 - “ $Y(2240)$ ” parameters from BESIII (bottom)

Data not consistent with PDG $\phi(2170)$ parameters, but observe peak consistent with BESIII peak parameters



Hybrid Meson Search

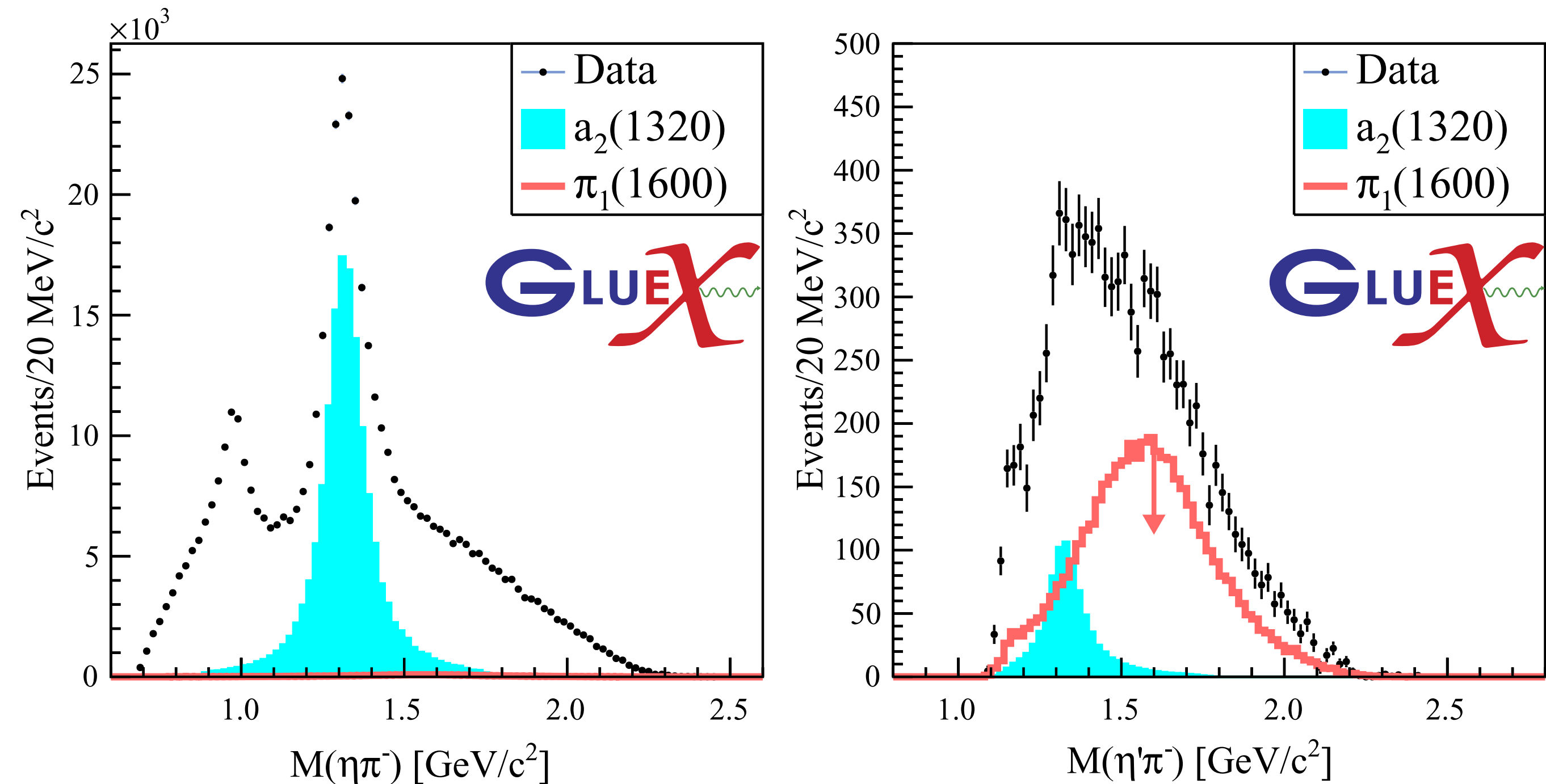
- Hybrid meson spectrum can tell us how valence gluons contribute to QCD bound states
- $\pi_1(1600)$ is best established hybrid meson candidate
 - Spin-exotic - $J^{PC} = 1^{-+}$ not allowed for $q\bar{q}$
 - Decays to $\eta^{(\prime)}\pi$ in a P -wave - “smoking gun” exotic signal
 - Seen by multiple experiments, in multiple decays
 - Mass and width appear different for $\eta\pi$ and $\eta'\pi$
 - JPAC able to fit both distributions with single resonance pole



$\pi_1(1600)$ Upper Limits Projected to $\eta^{(\prime)}\pi$

- Measure upper limit on $\pi_1(1600)$ production cross section
- Project upper limit to other channels
- In $\eta\pi$, $a_2(1320)$ is large and maximum $\pi_1(1600)$ contribution is small
- In $\eta'\pi$, $a_2(1320)$ smaller, and can't rule out large $\pi_1(1600)$ contribution

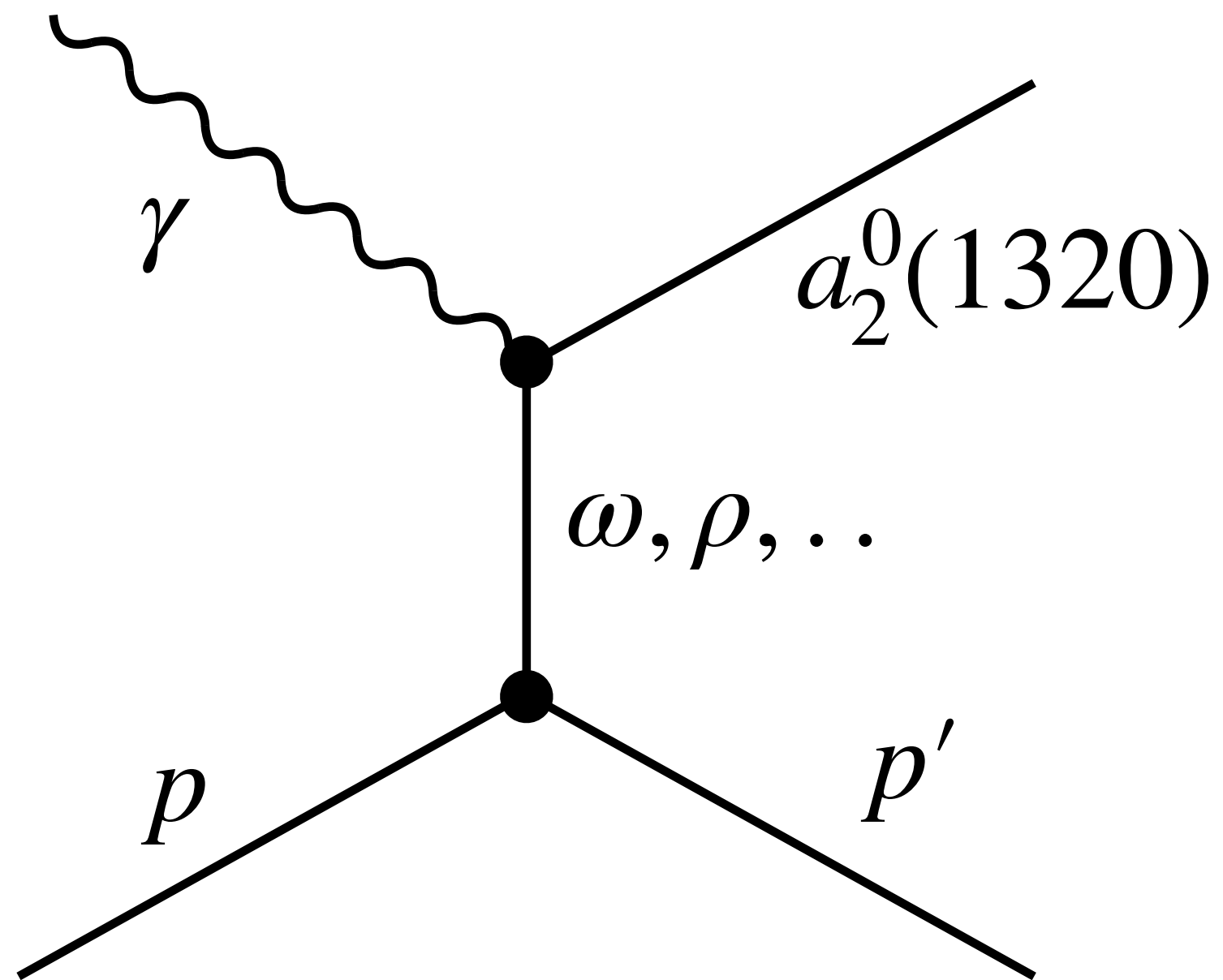
PRL 133, 261903 (2024)



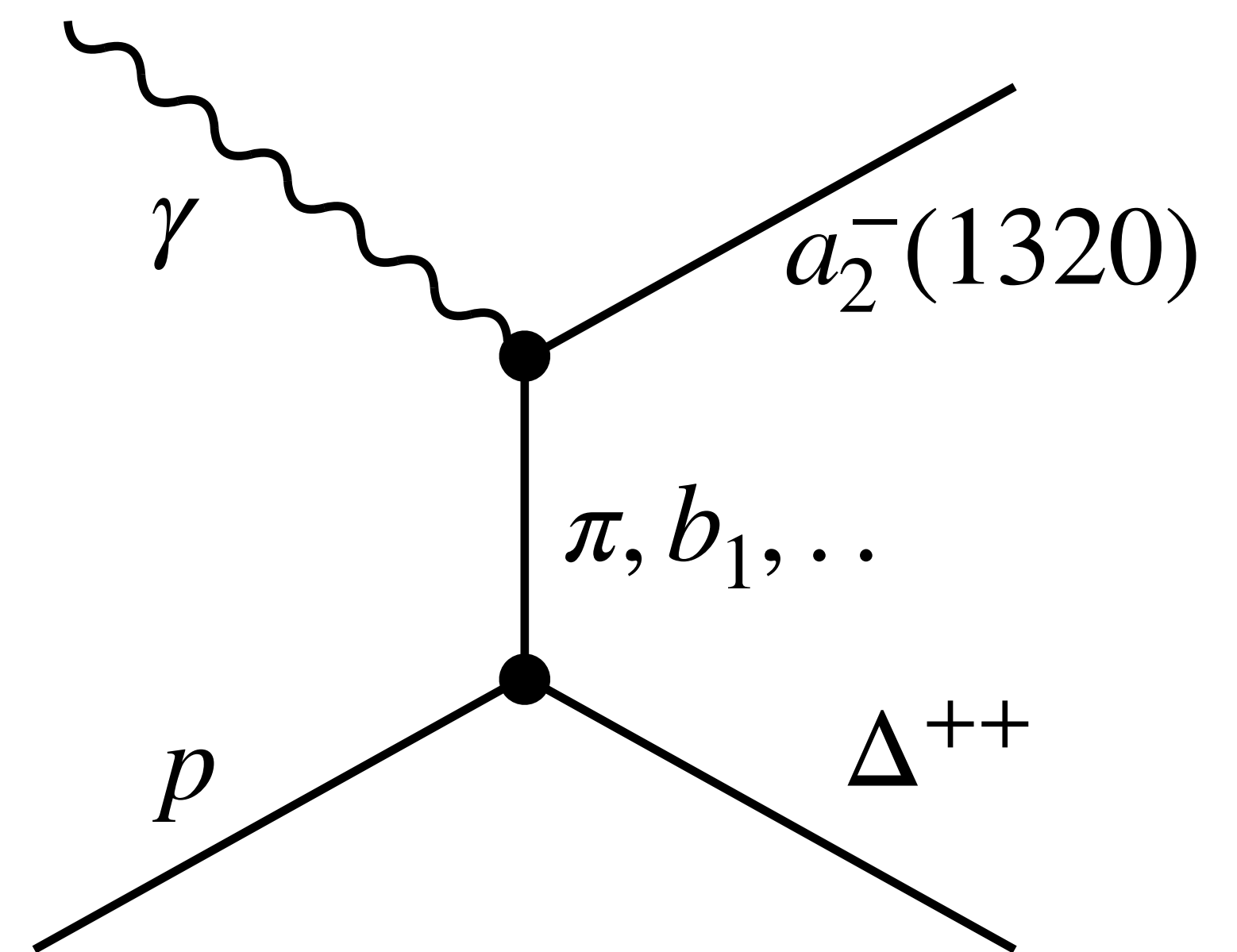
We can use $\eta\pi$ to understand $a_2(1320)$, but $\eta'\pi$ has better sensitivity to $\pi_1(1600)$

Separating Production Mechanisms

- Broad overlapping resonances require partial wave analysis techniques
- Beam polarization separates **Natural** and **Unnatural** exchanges
- **Natural:** $J^P = 0^+, 1^-, 2^+, \dots$; **Unnatural:** $J^P = 0^-, 1^+, 2^-, \dots$



Natural Exchange

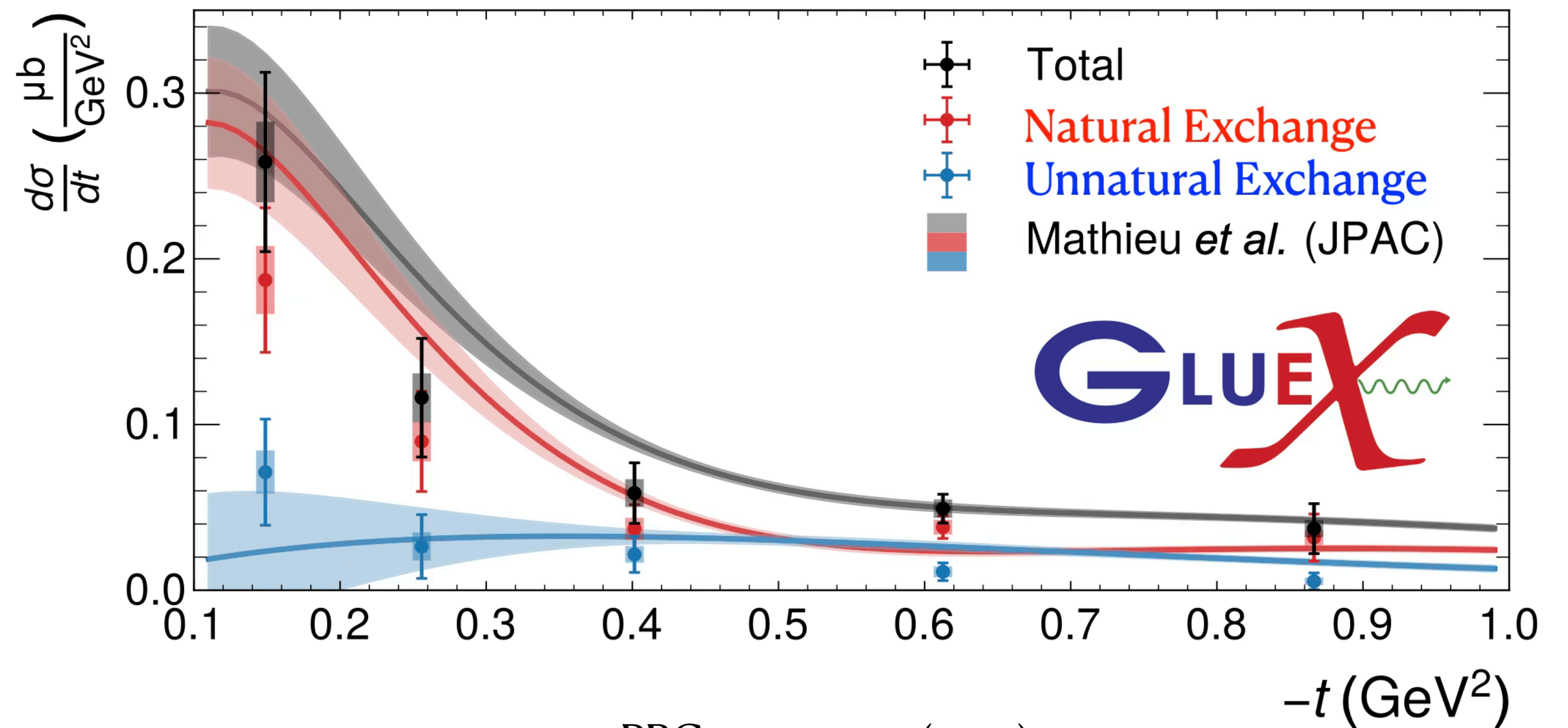


Unnatural Exchange

$a_2^0(1320)$ Cross Section

$$\gamma p \rightarrow \eta \pi^0 p$$

- First separation of **natural** and **unnatural** exchanges
 - Comes from GlueX's unique photon beam polarization
- Cross section measured here can be used as reference in the more complex $\eta' \pi^0$ analysis

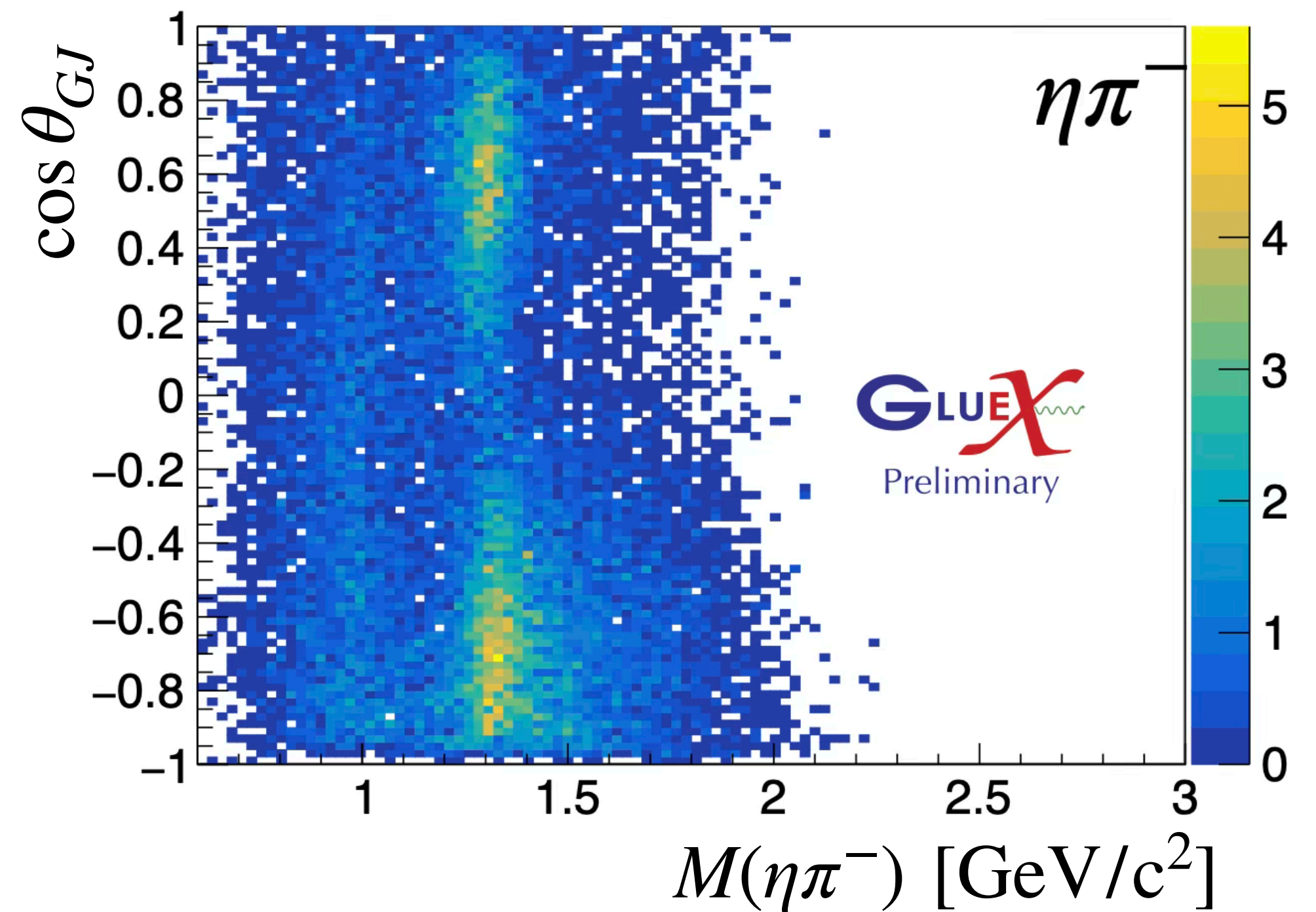
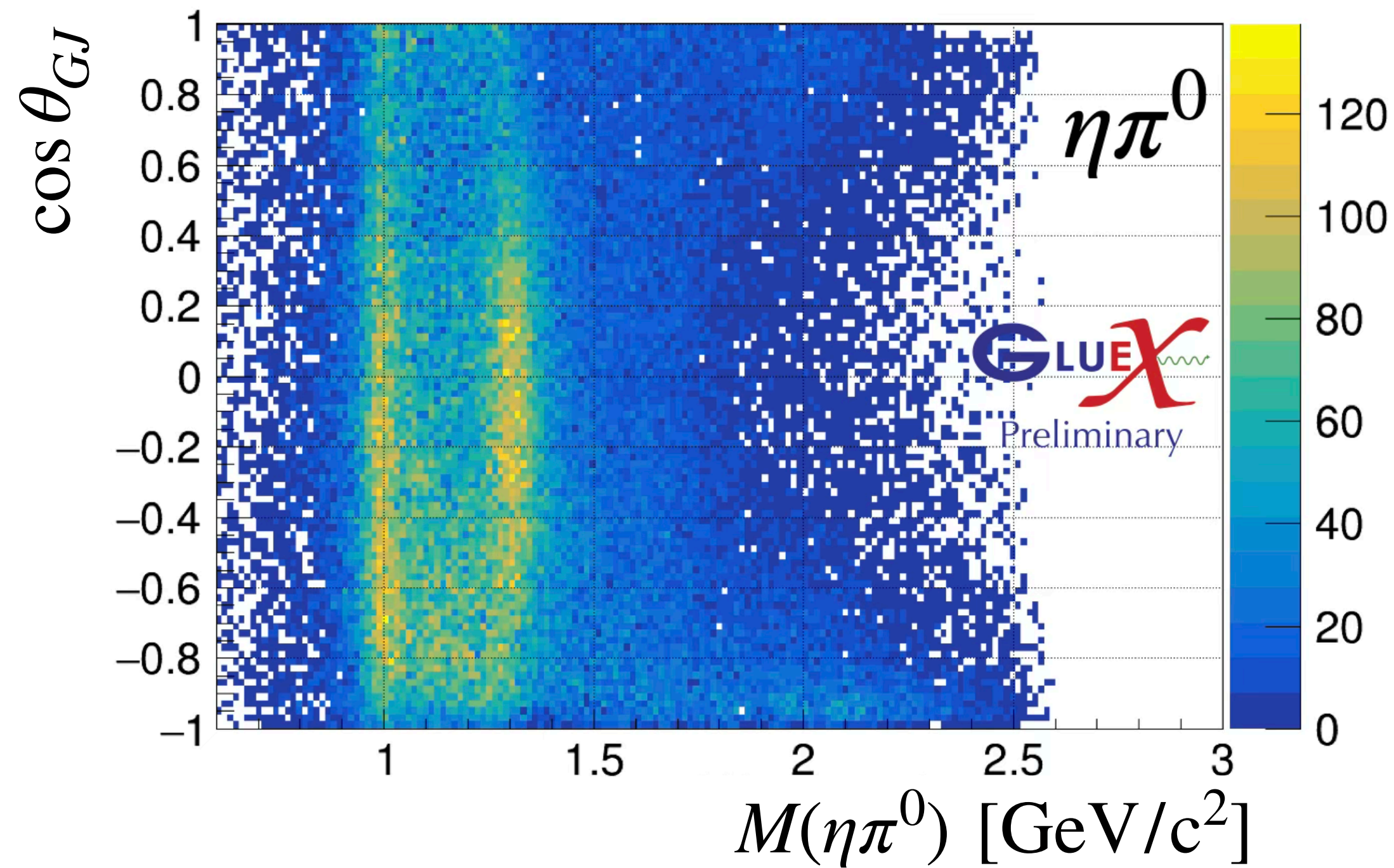


PRC 112, 015204 (2025)

Gives conventional meson anchor for hybrid meson searches in $\eta^{(\prime)}\pi$ channels

Production of $a_2^-(1320)$

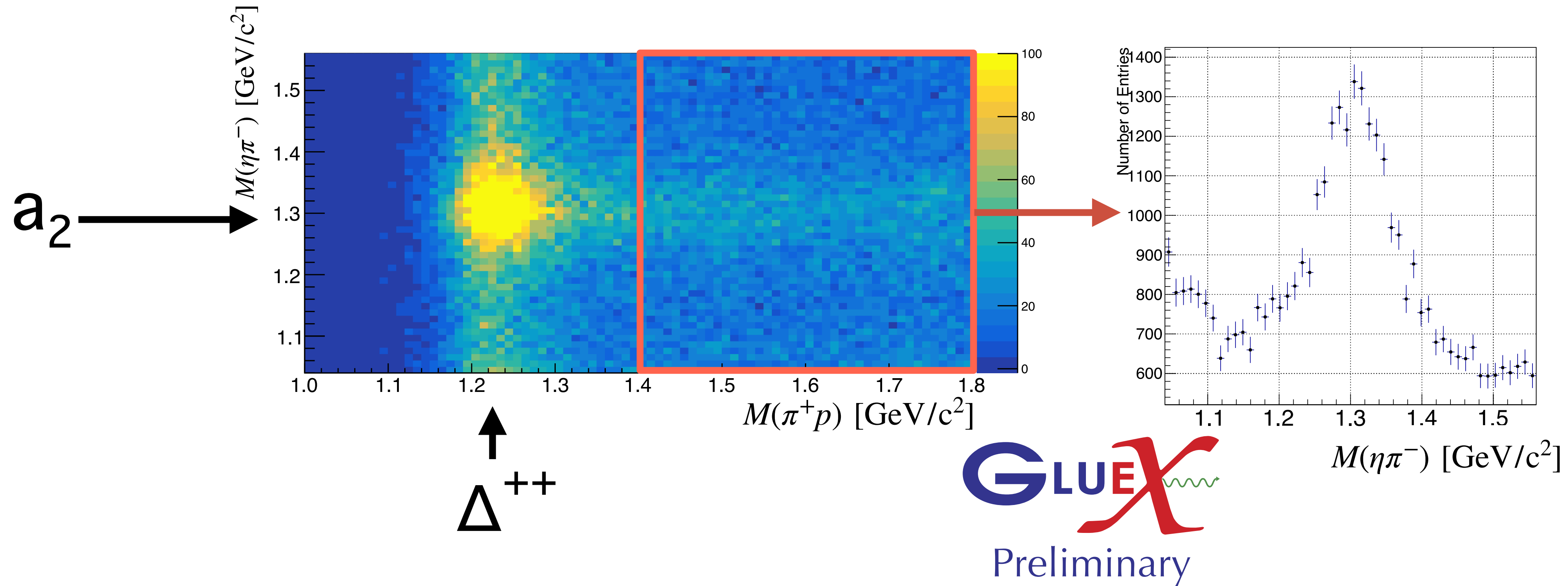
- Want to extend hybrid search to charge-exchange processes like $\gamma p \rightarrow \eta \pi^- \Delta^{++}$
- Both charged and neutral $\eta\pi$ have $a_0(980)$ and $a_2(1320)$



$a_2^0(1320)$ and $a_2^-(1320)$ populate different spin states due to different production

Complications with Unstable Recoil Baryons

- non- Δ^{++} background that increases with increasing $-t$



- Need to model both production and decay of Δ^{++}

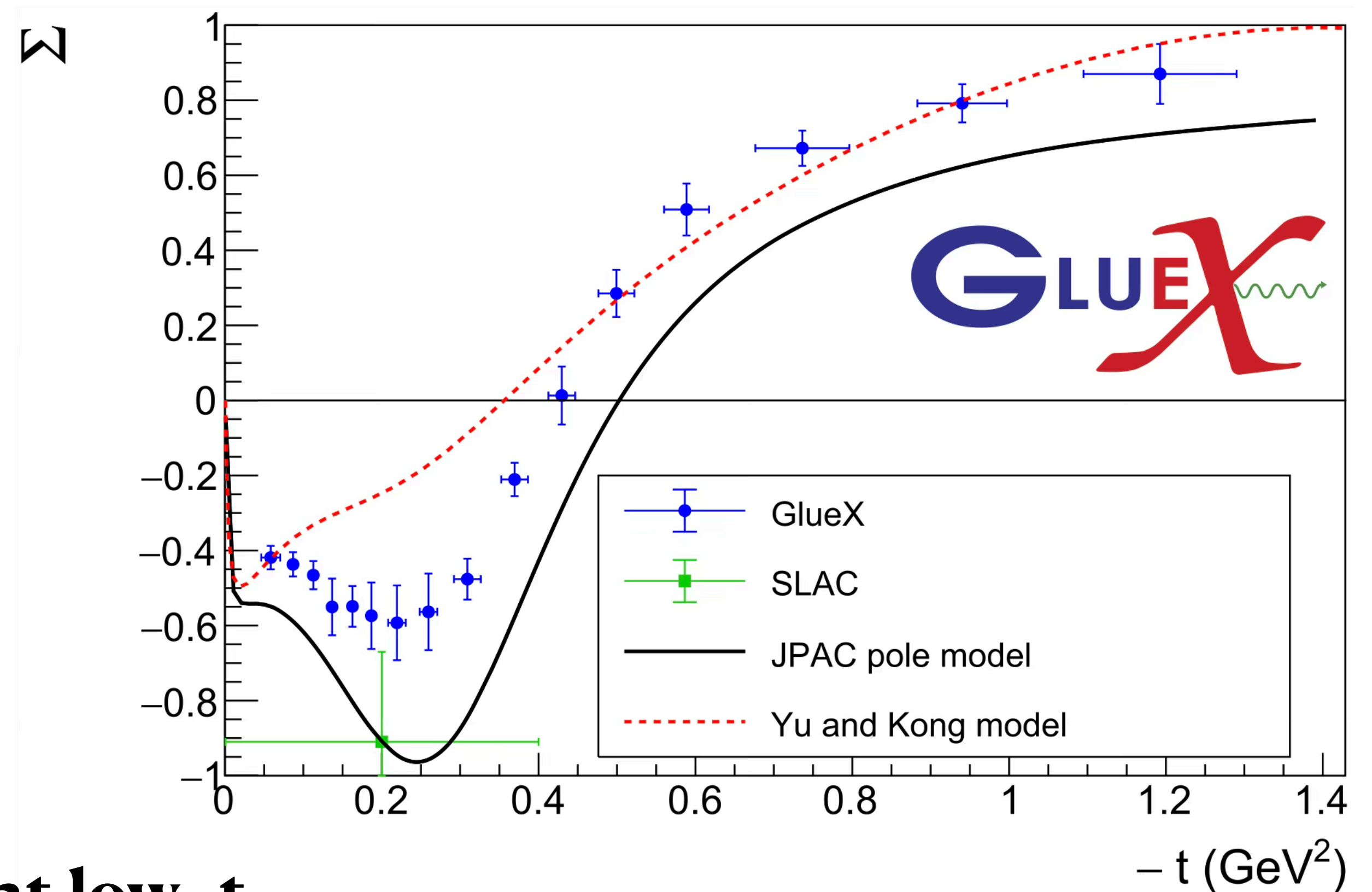
Understanding Δ^{++} production and decays essential for hybrid search in charge-exchange processes

Δ^{++} Production Mechanisms

- Reconstruct process $\gamma p \rightarrow \pi^- \Delta^{++}(1232)$ with $\Delta^{++} \rightarrow p \pi^+$

PLB 863, 139368 (2025)

- Measure beam asymmetry
 - $+1 \implies$ all **natural** exchange
 - $-1 \implies$ all **unnatural** exchange
- **Unnatural** dominates for $-t < 0.4 \text{ GeV}^2$
- **Natural** dominates when $-t > 0.4 \text{ GeV}^2$



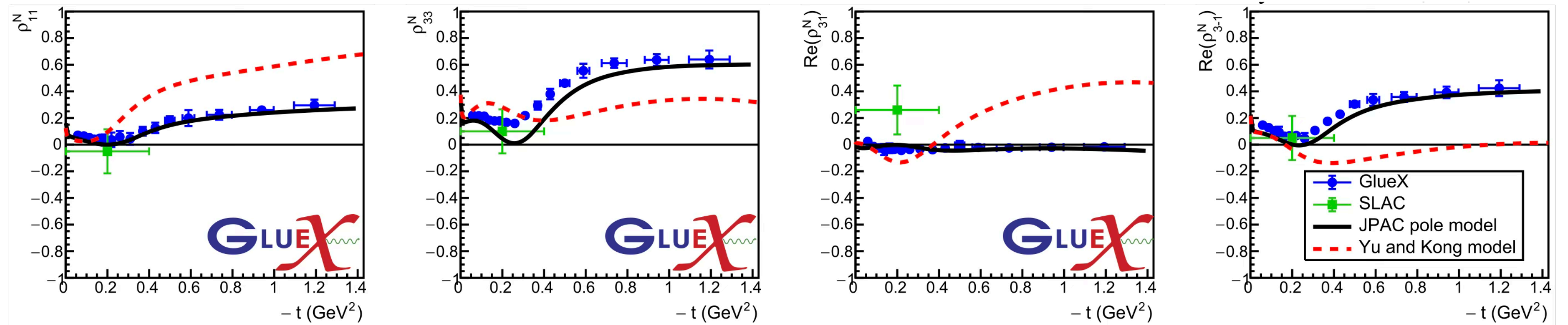
Shows us unnatural exchange dominates at low $-t$

Understanding Δ^{++} Through SDMEs

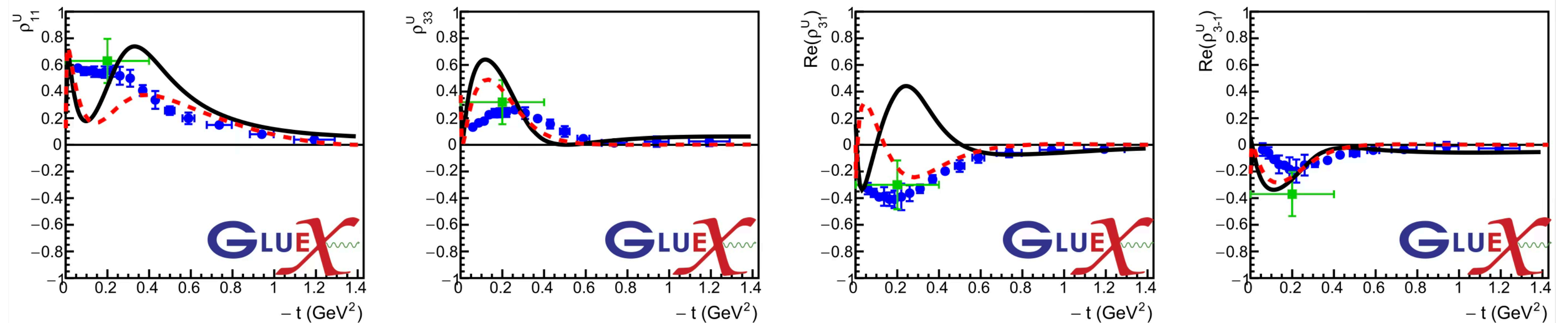
- Linear combinations give natural and unnatural SDMEs separately
- Natural exchanges well described by model, discrepancy for unnatural exchanges

Natural Exchange

PLB 863, 139368 (2025)



Unnatural Exchange



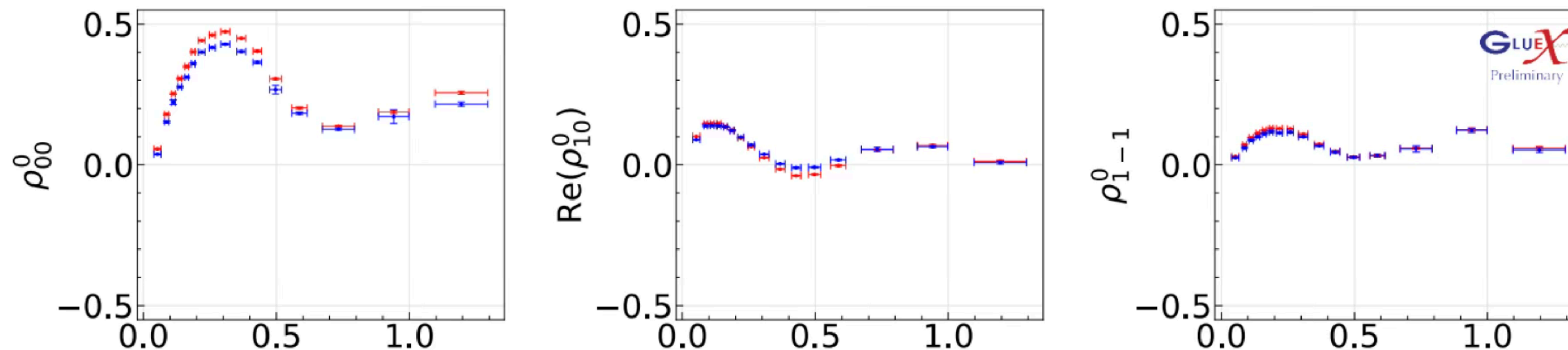
Important input for improving theory description of unnatural exchange

$\rho^- \Delta^{++}$ Double SDMEs - Factorization Studies

- Question: Can upper and lower vertices be treated independently?

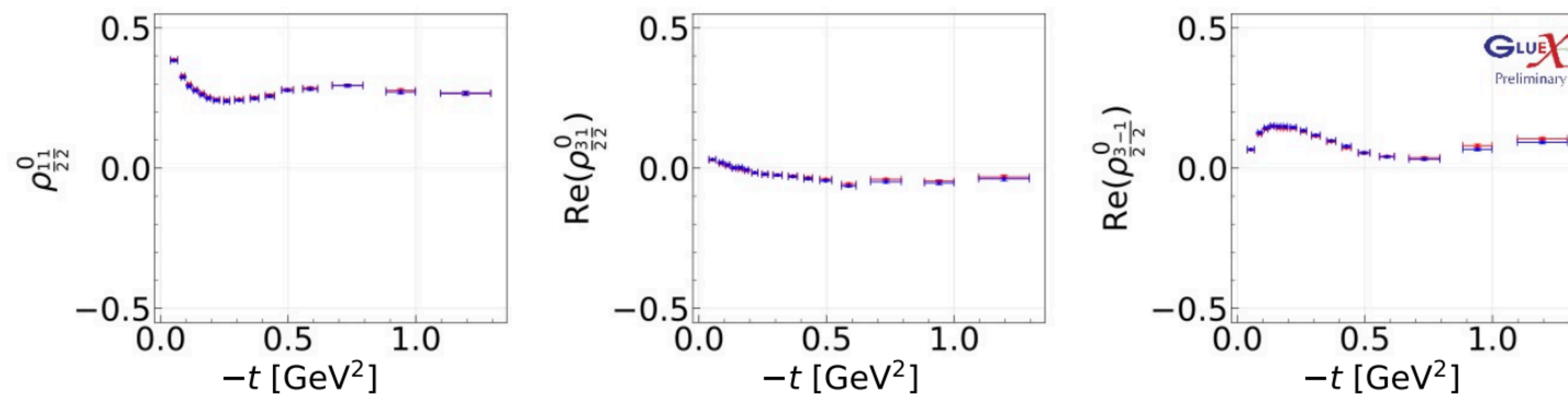
ρ^- – SDMEs

Factorized model Full model

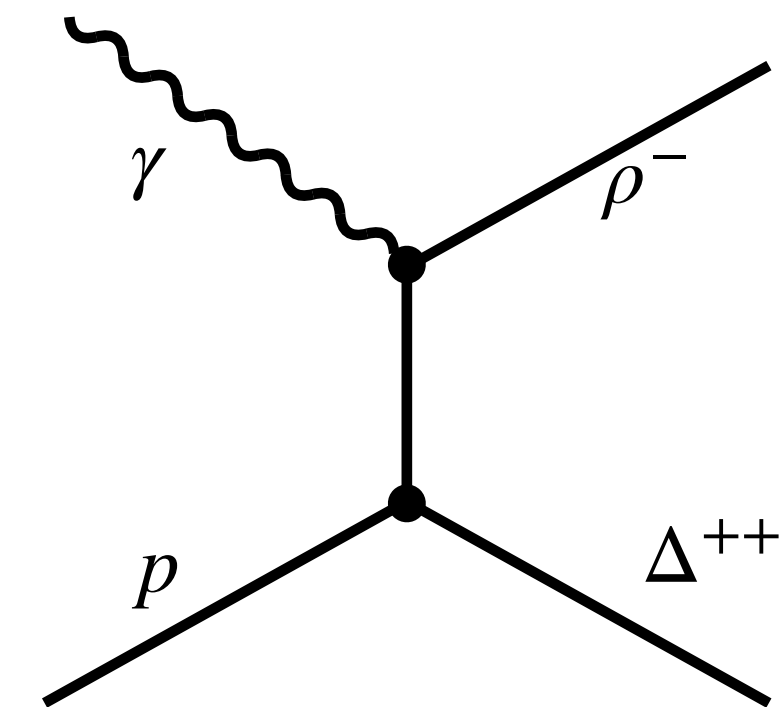


Δ^{++} – SDMEs

Factorized model Full model



- Full model vs factorized model
- Factorization appears to hold



Factorization will reduce complexity of models in important, low statistics hybrid search channels

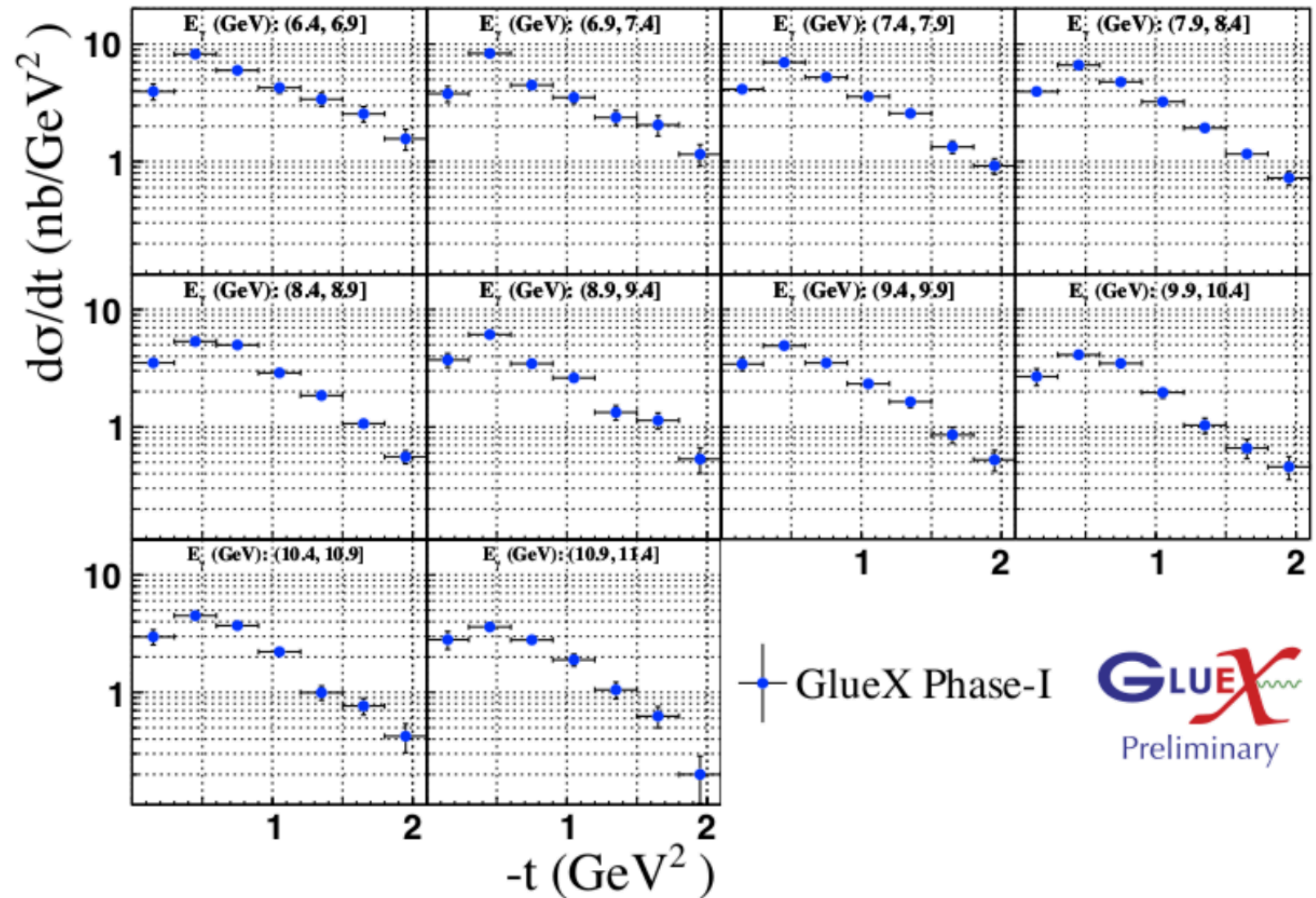
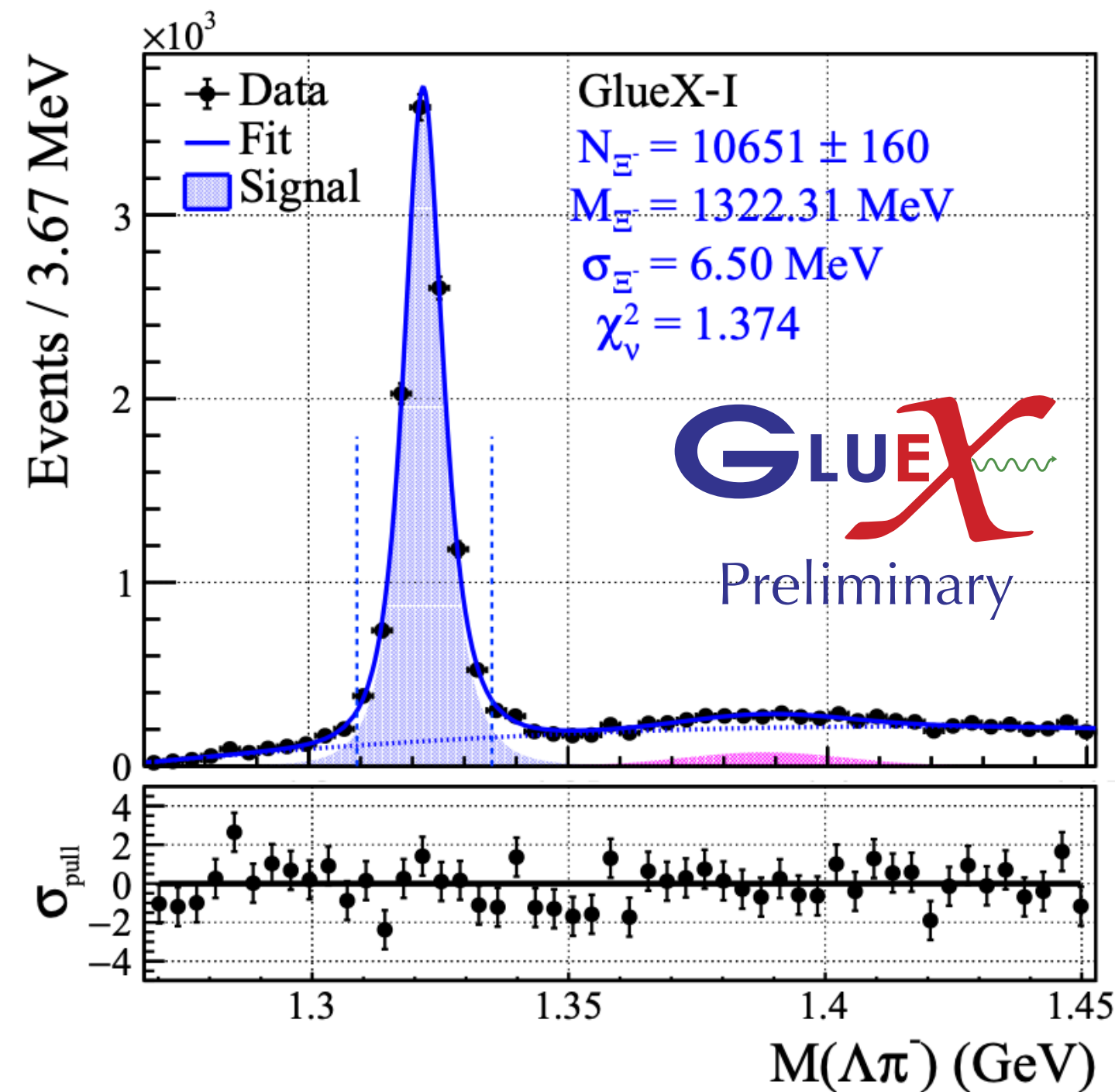
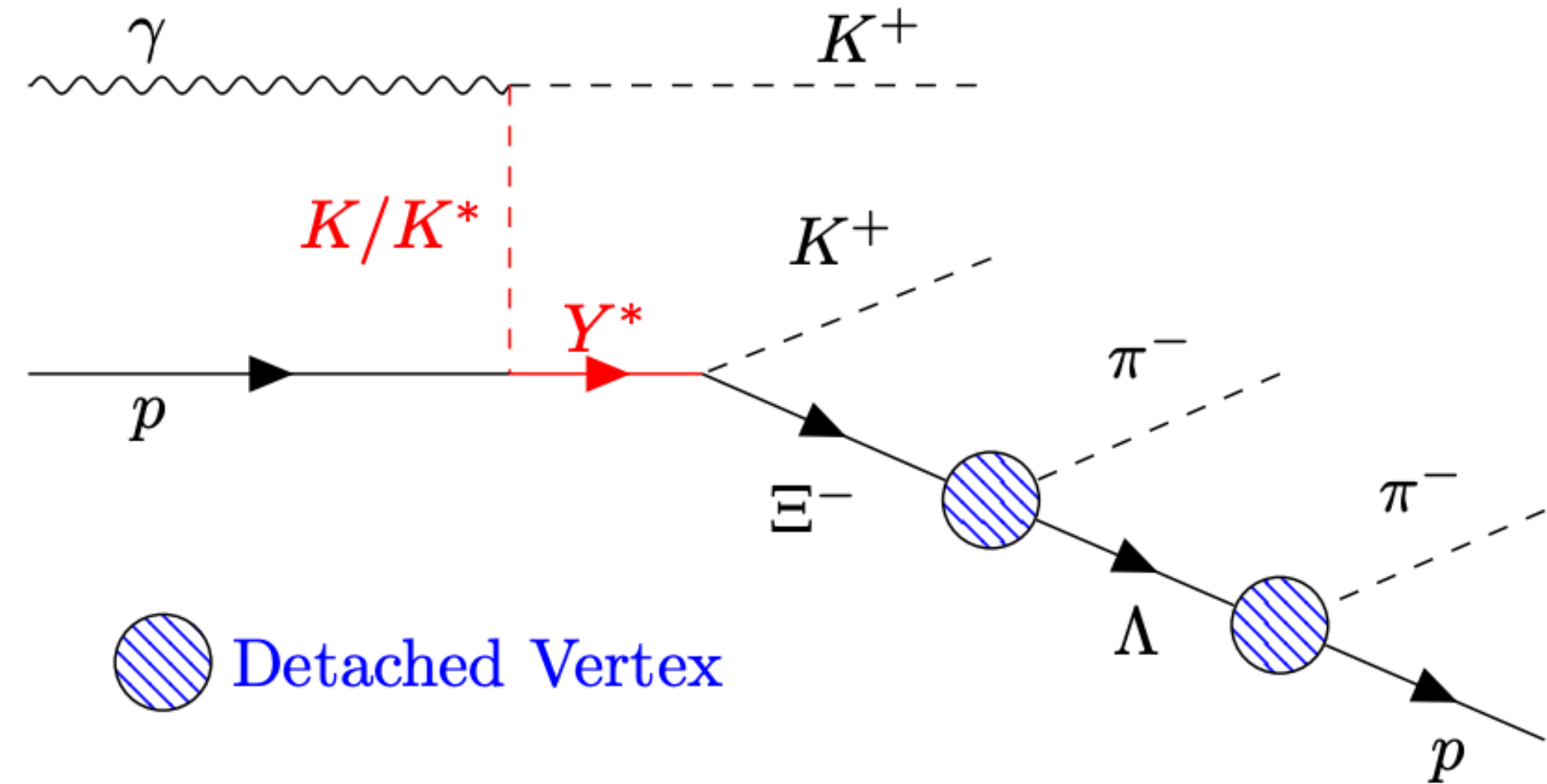
Cascade Spectroscopy Program

In addition to baryon production and decay, can also study spectrum of baryons

Particle	J^P	Overall status
$\Xi(1320)$	$1/2+$	****
$\Xi(1530)$	$3/2+$	****
$\Xi(1620)$		**
$\Xi(1690)$	$1/2-$	***
$\Xi(1820)$	$3/2-$	****
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

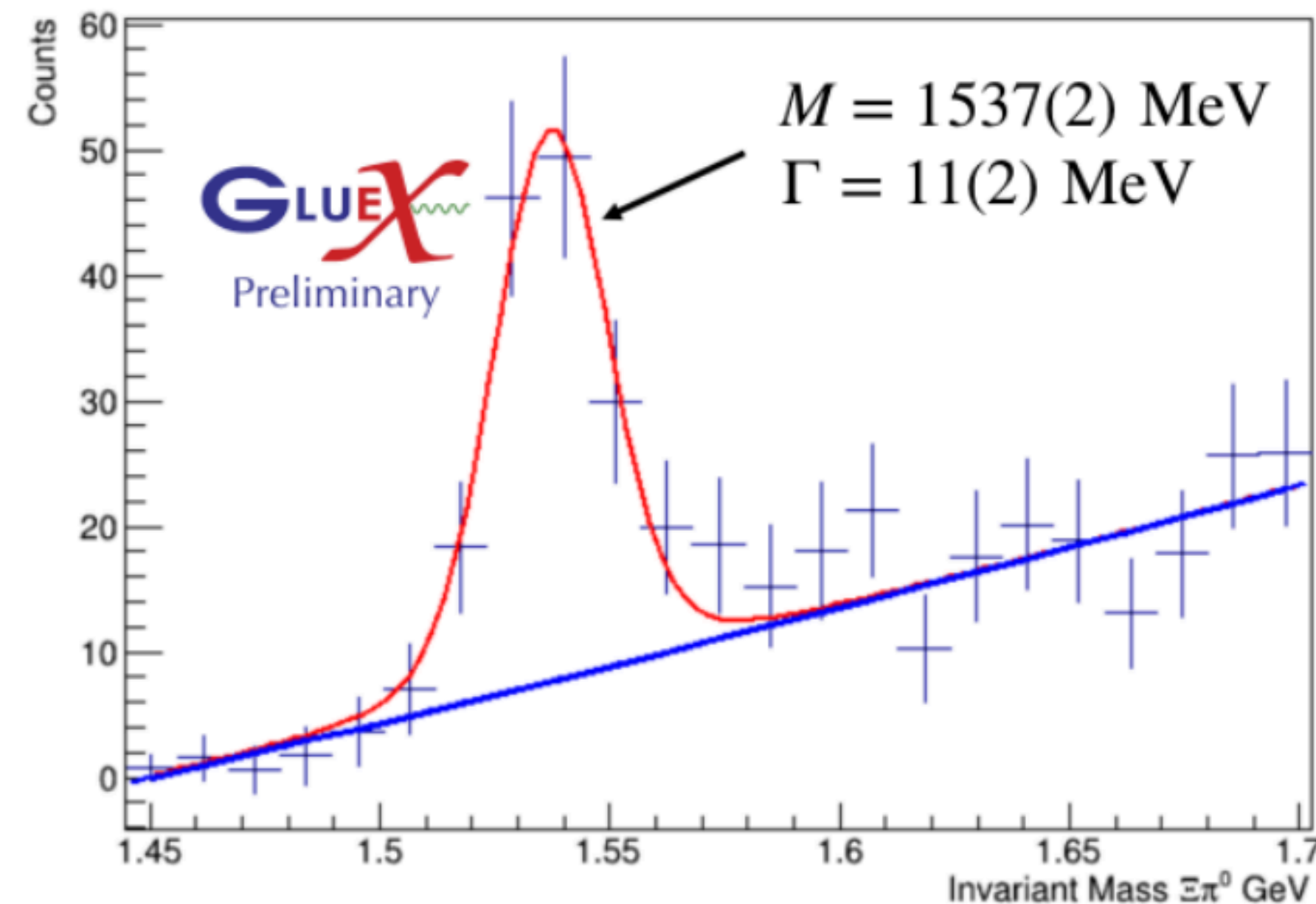
- Only 3 cascade states have “four star” status
- GlueX can produce these doubly strange baryons against recoiling kaons
- GlueX detector capable of reconstructing complicated final state topologies
- Goal: find cascades that are predicted but not well established experimentally

$\Xi(1320)^-$ Photoproduction

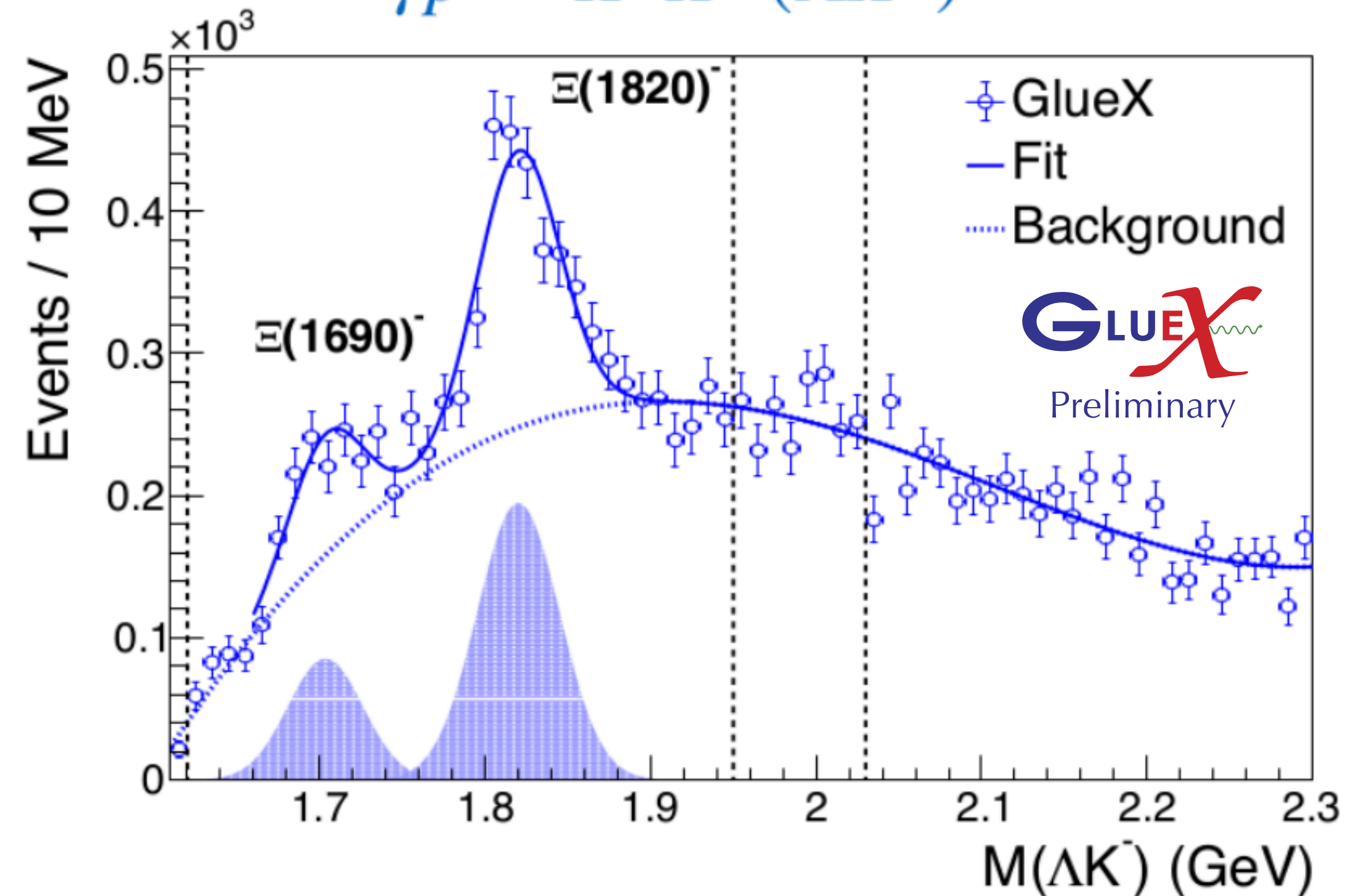


Excited Cascade Cross Sections

$$\gamma p \rightarrow K^+ K^+ \Xi(1530)^-, \quad \Xi(1530)^- \rightarrow \Xi(1320)^- \pi^0$$



$$\gamma p \rightarrow K^+ K^+ (\Lambda K^-)$$



V. Crede and J. Yelton, sub. to Rep. Prog. Phys.

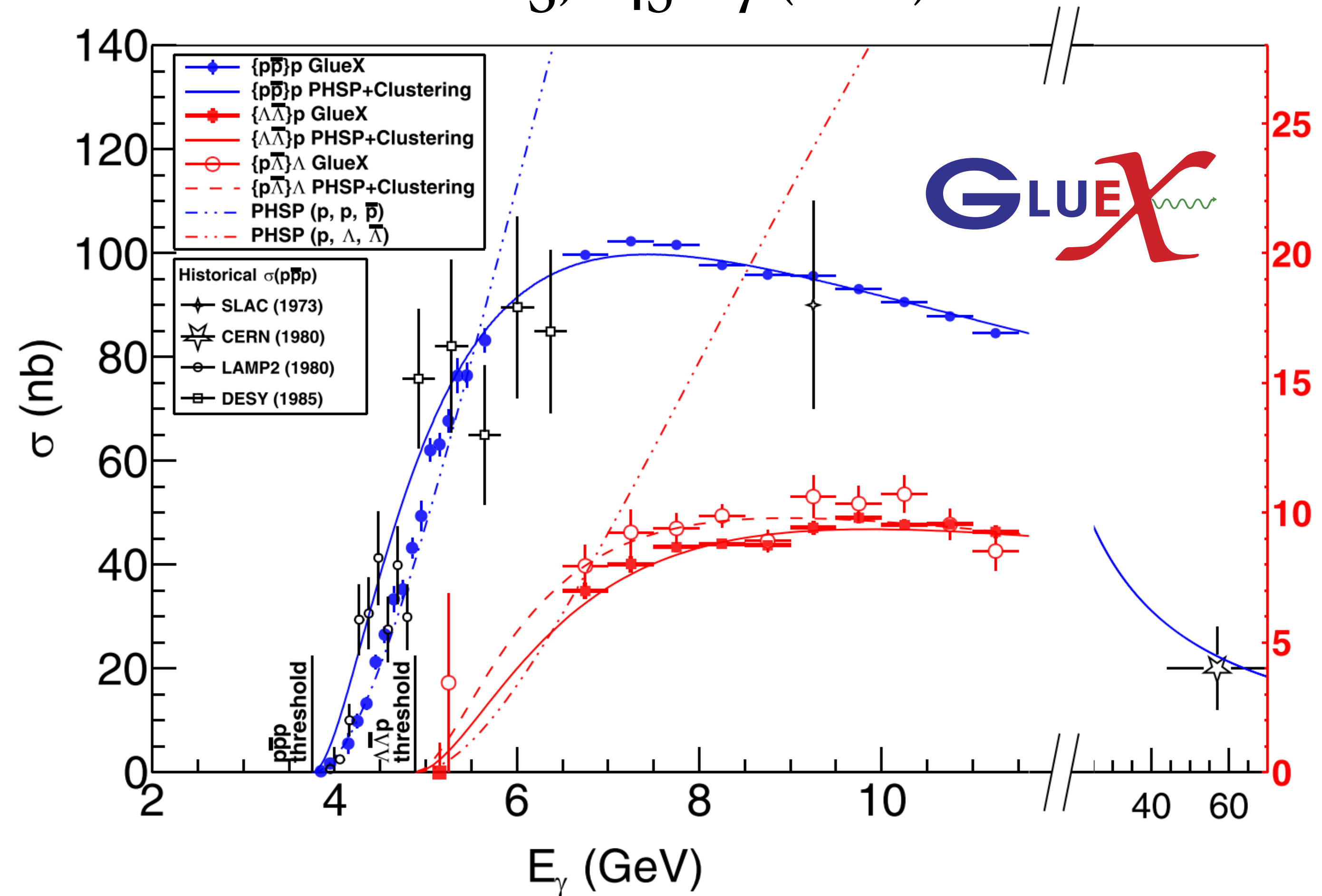
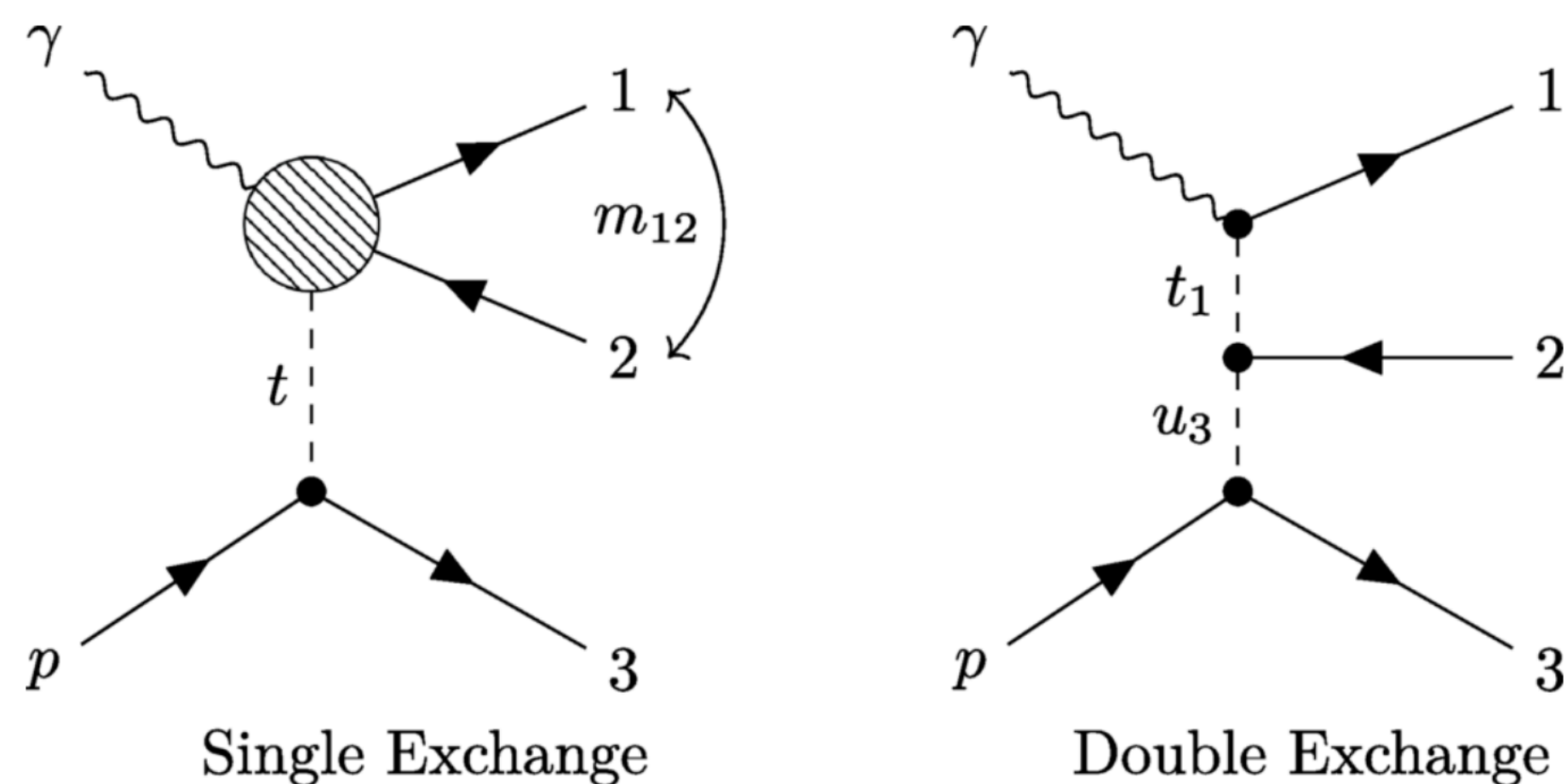
Find evidence for $\Xi(1530)^-$, $\Xi(1690)^-$, and $\Xi(1820)^-$ at GlueX

GlueX can produce, reconstruct cascades in complicated decay modes

Baryon-Antibaryon Studies

PRC 113, 045207 (2026)

- Measure cross sections for $\gamma p \rightarrow p\bar{p}p$ and $\gamma p \rightarrow \Lambda\bar{\Lambda}p$
- No evidence of narrow “baryonium”-like structures
- Double-t-channel phenomenological model matches data well

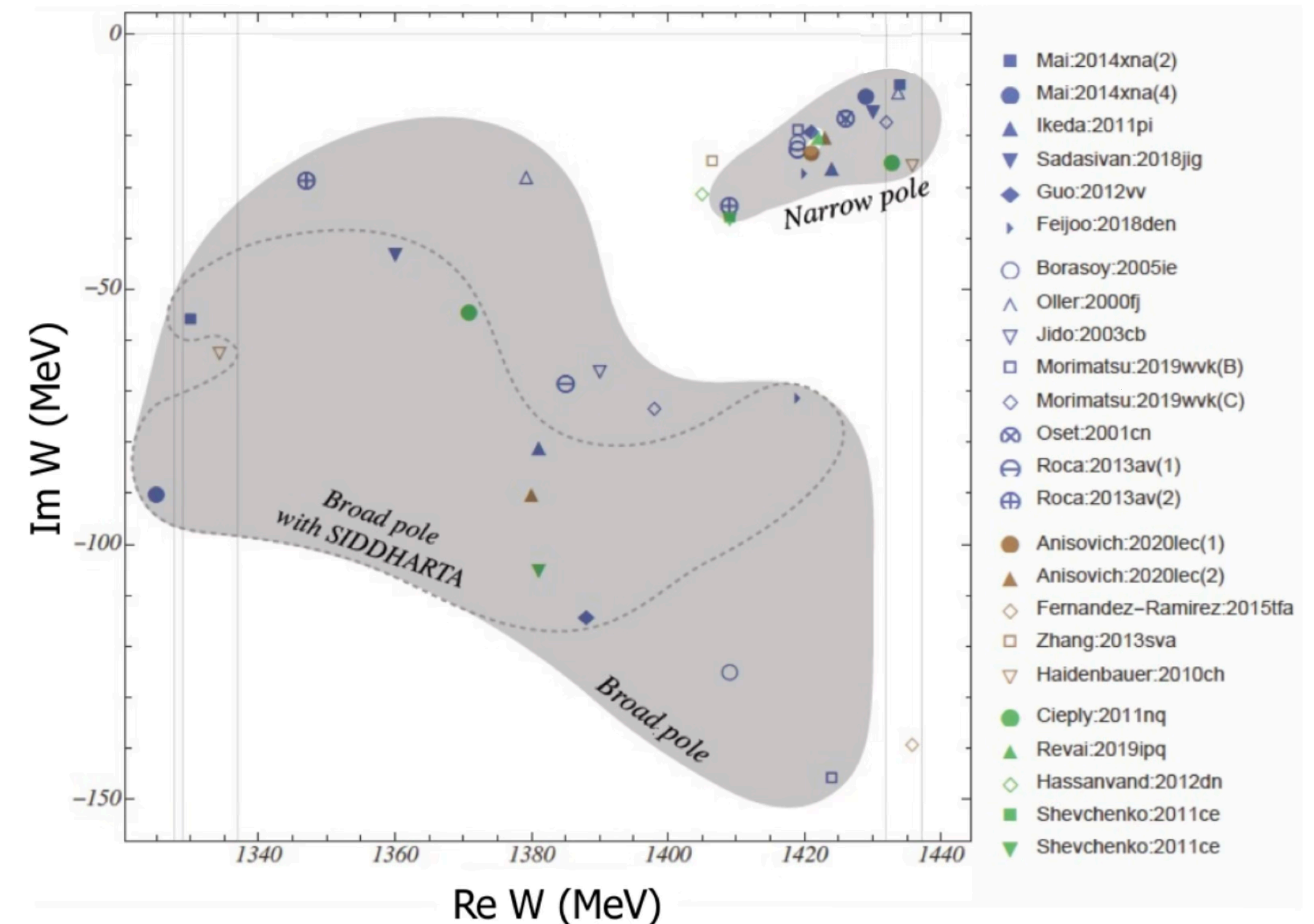
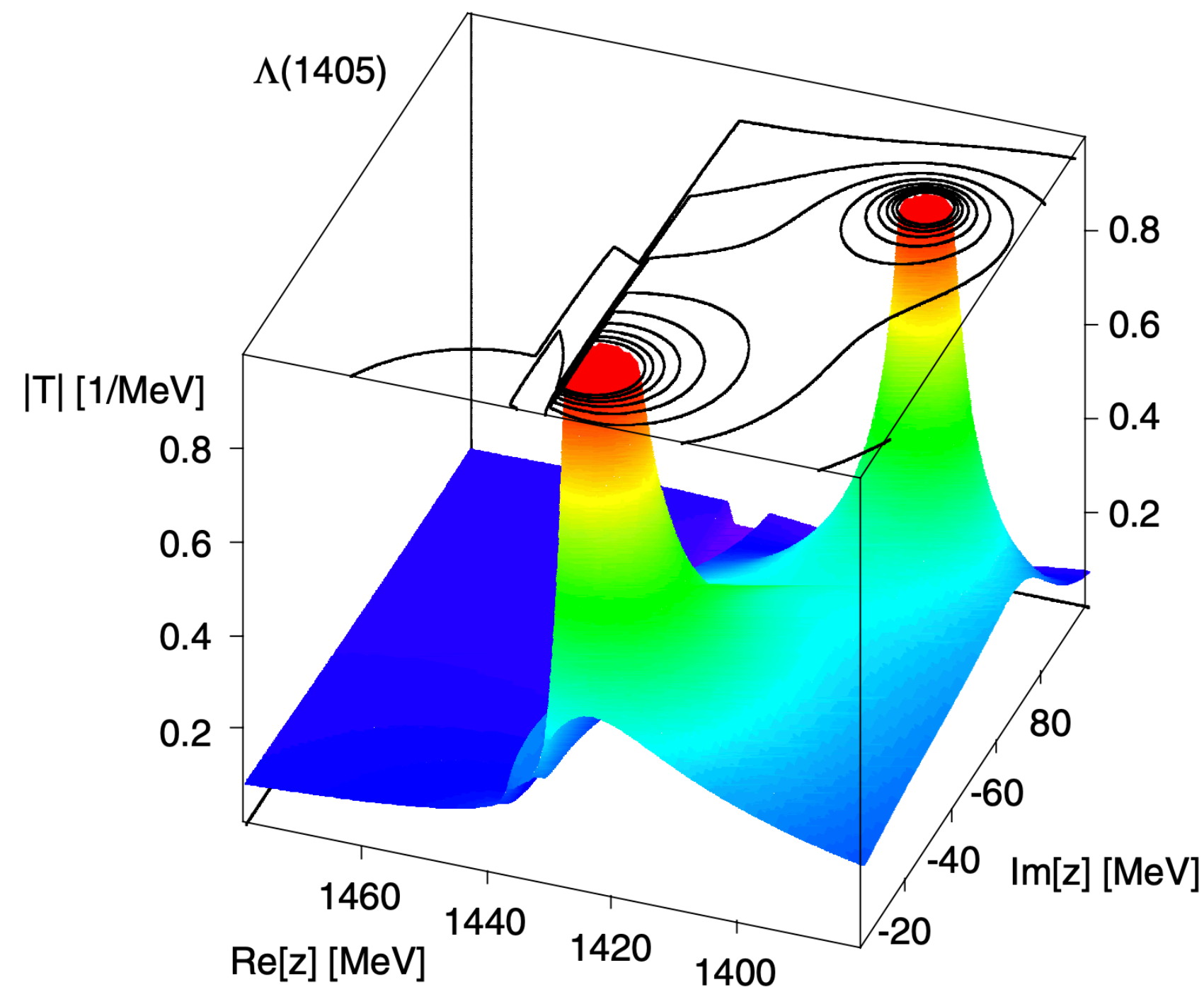


Large cross sections - opens door to additional baryon-antibaryon studies

$\Lambda(1405)$ Physics Motivation

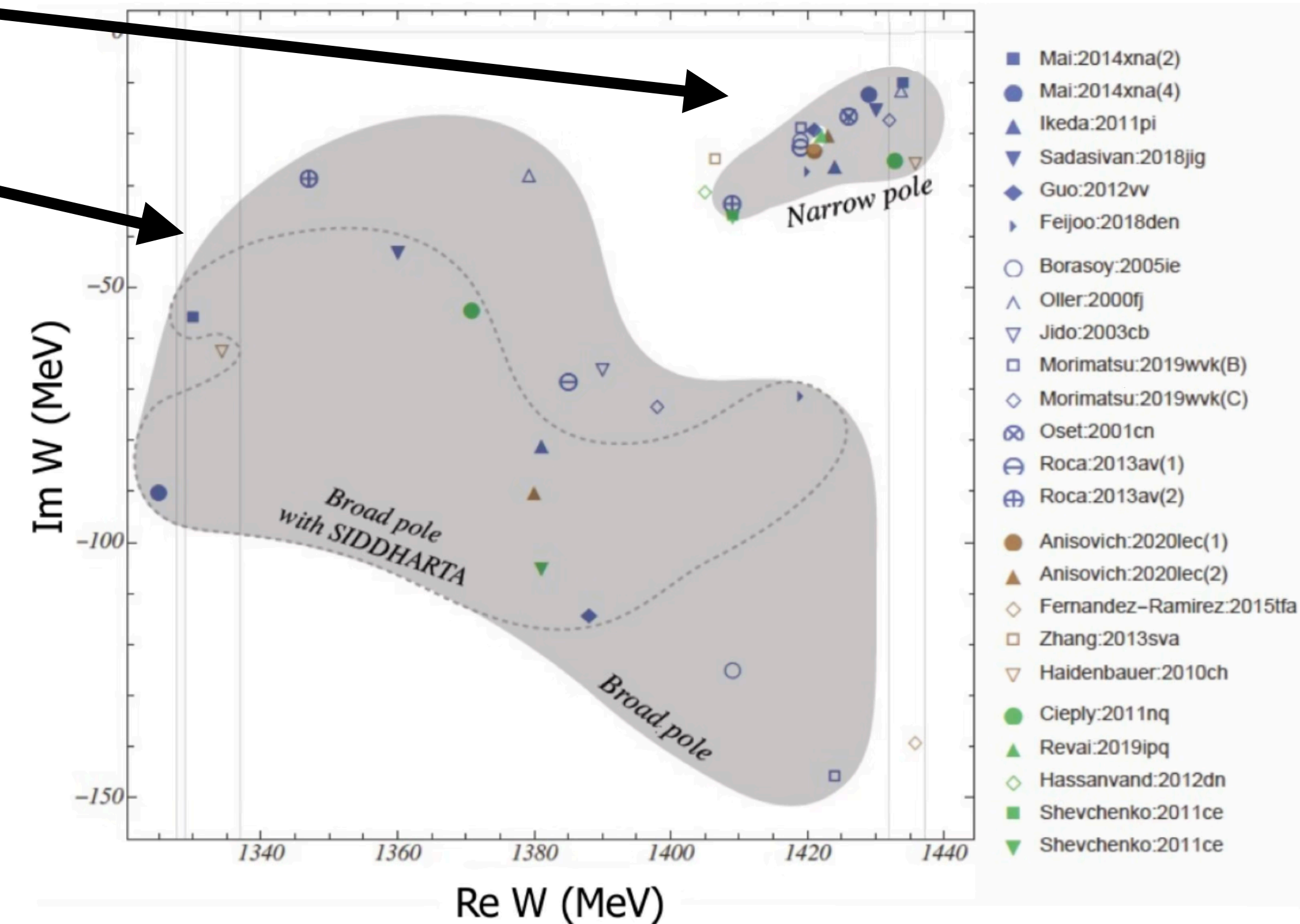
- $\Lambda(1405)$ too light compared to $\Lambda(1520)$
- Chiral unitary models, CPT, LQCD predict two $I = 0$ states in this region
- Near $N\bar{K}$ and $\Sigma^0\pi^0$ thresholds - possible molecular component?

Scattering amplitude from Chiral Unitary Model



$\Lambda(1405)$ Physics Motivation

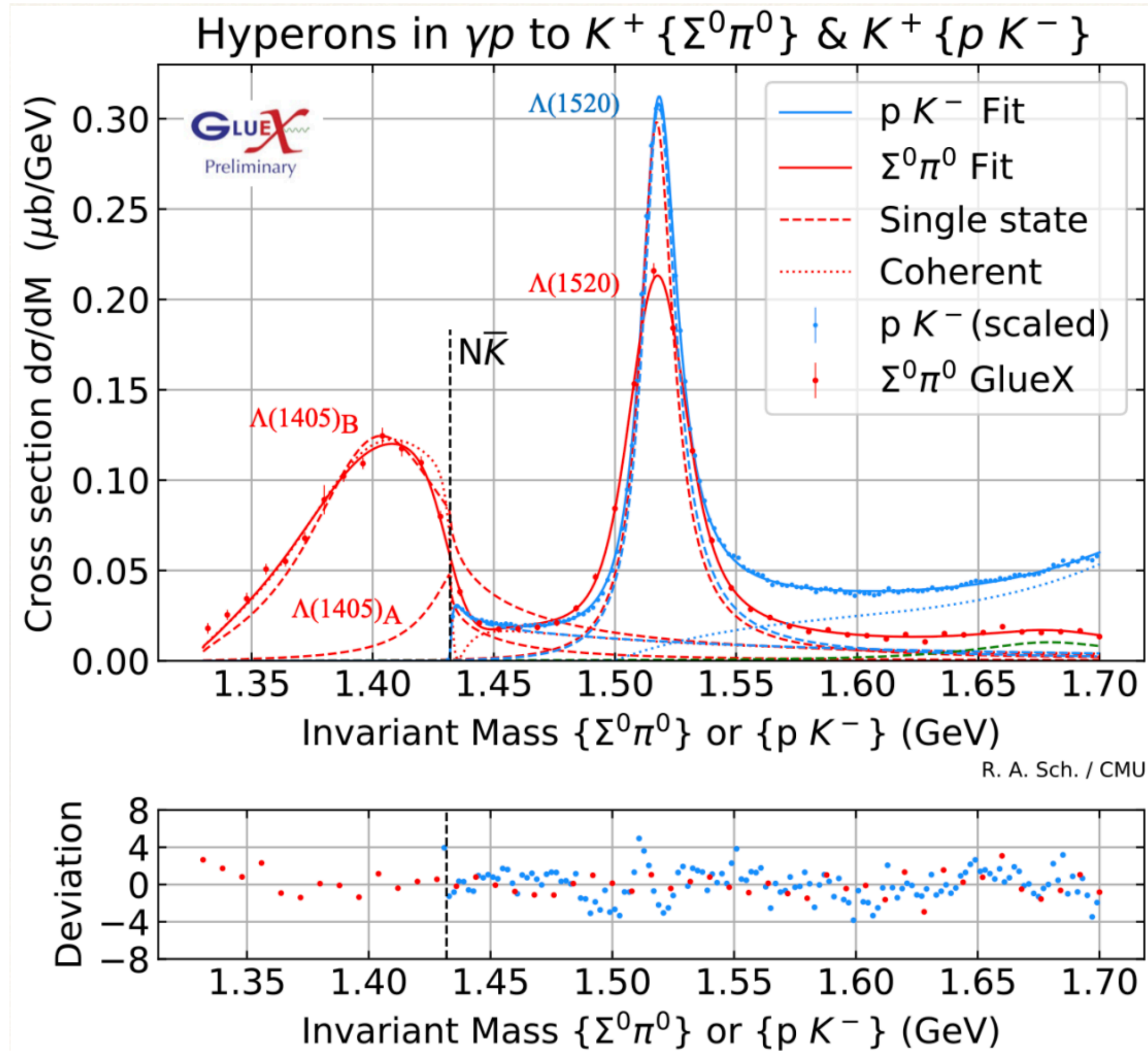
- Higher mass pole couples more strongly to $N\bar{K}$
- Lower mass pole couples more strongly to $\Sigma^0\pi^0$
- We can reconstruct both of these modes at GlueX
 - $\Sigma^0\pi^0$ with $\Sigma^0 \rightarrow \gamma\Lambda, \Lambda \rightarrow \pi^-p$
 - pK^-
- Goal: extract $\Lambda(1405)$ pole position(s) using coupled-channel K-matrix fit



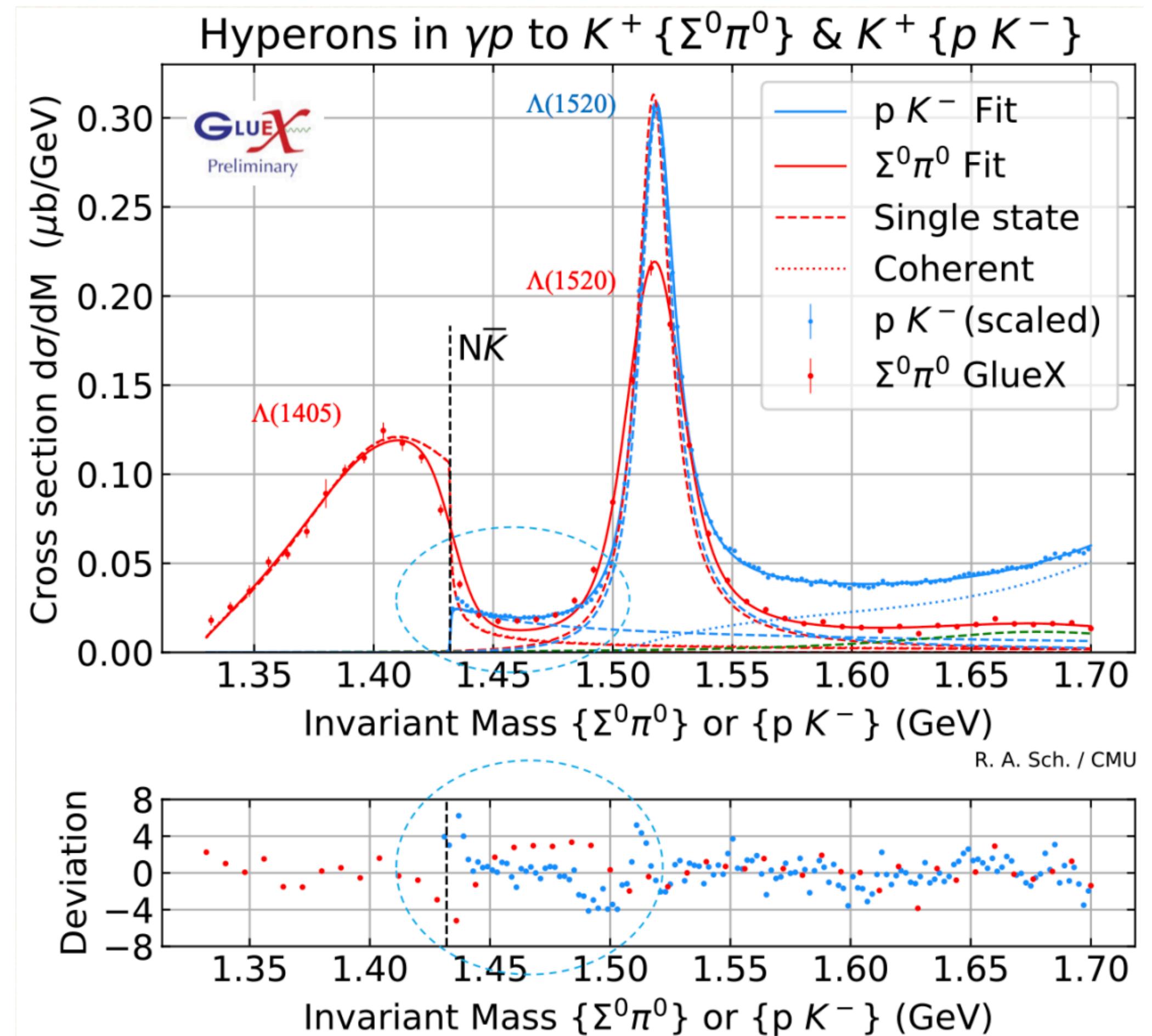
M. Mai - Eur. Phys. J. Spec. Top. 230 (2021) 6, 1593

$\Lambda(1405)/\Lambda(1520)$ Lineshapes

Two pole fit

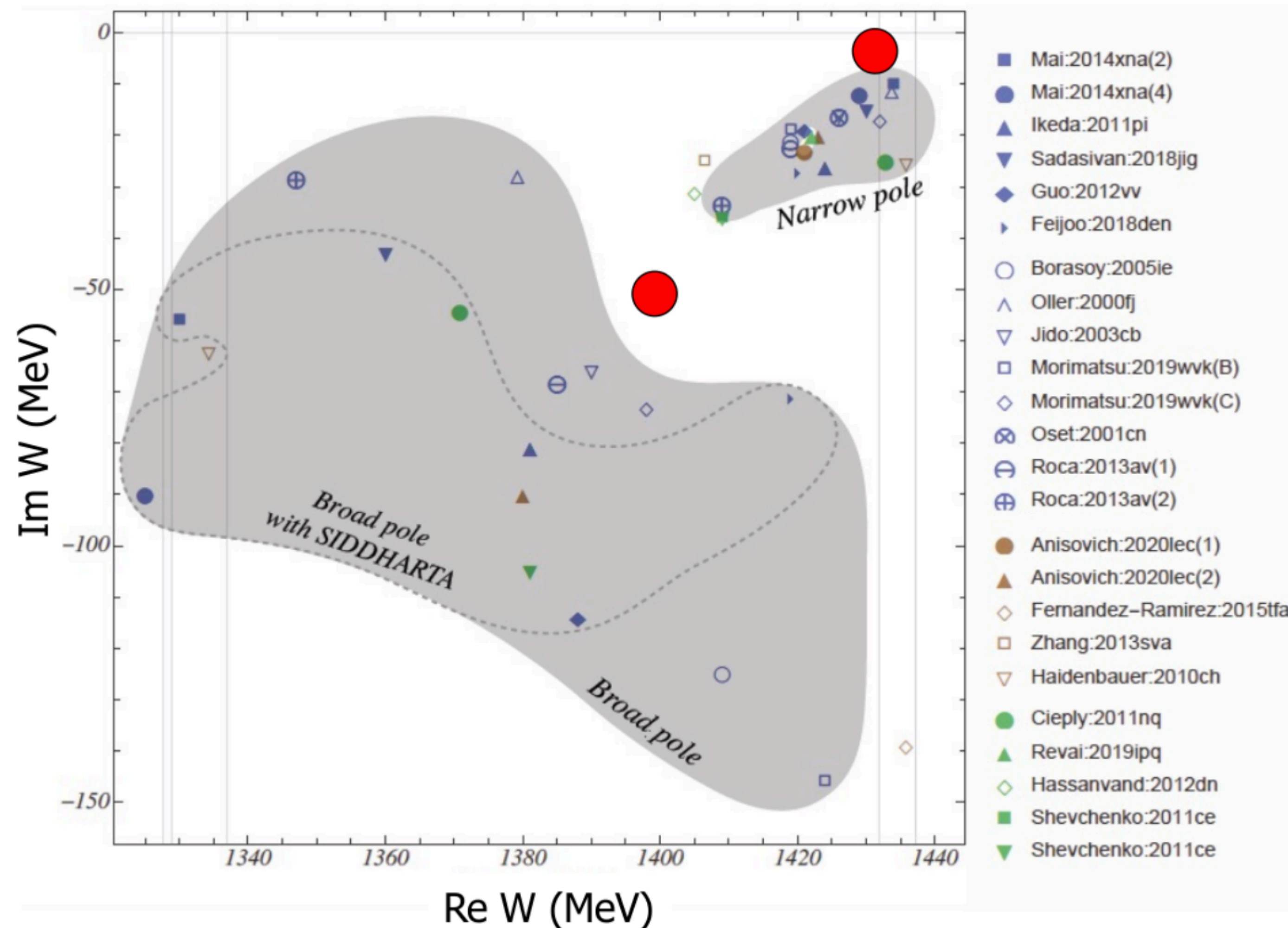


Single pole fit



K-matrix fit with 2-pole ansatz for $\Lambda(1405)$ gives better description of GlueX data

$\Lambda(1405)$ Pole Positions



- Points show GlueX preliminary result
- Systematics nearly finalized
- Publication in preparation

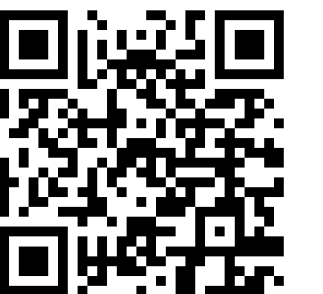
M. Mai - Eur. Phys. J. Spec. Top. 230 (2021) 6, 1593

Summary

- GlueX is mapping out meson and baryon spectra using polarized photoproduction
- Observe peak in $\phi\pi^+\pi^-$ spectrum consistent with $\phi(2240)$ parameters from BESIII
- $a_2^0(1320)$ cross section gives us “standard candle” for $\eta'\pi^0$ analysis
- Δ^{++} SDME analysis has helped improve theory description of unnatural exchanges
- Factorizing meson and baryon amplitudes will enable PWA in statistics limited channels
- Rich cascade spectroscopy program is in progress
- Two-pole K-matrix fit of $\Lambda(1405)$ gives best description of GlueX data

GlueX acknowledges the support of several funding agencies and computing facilities:

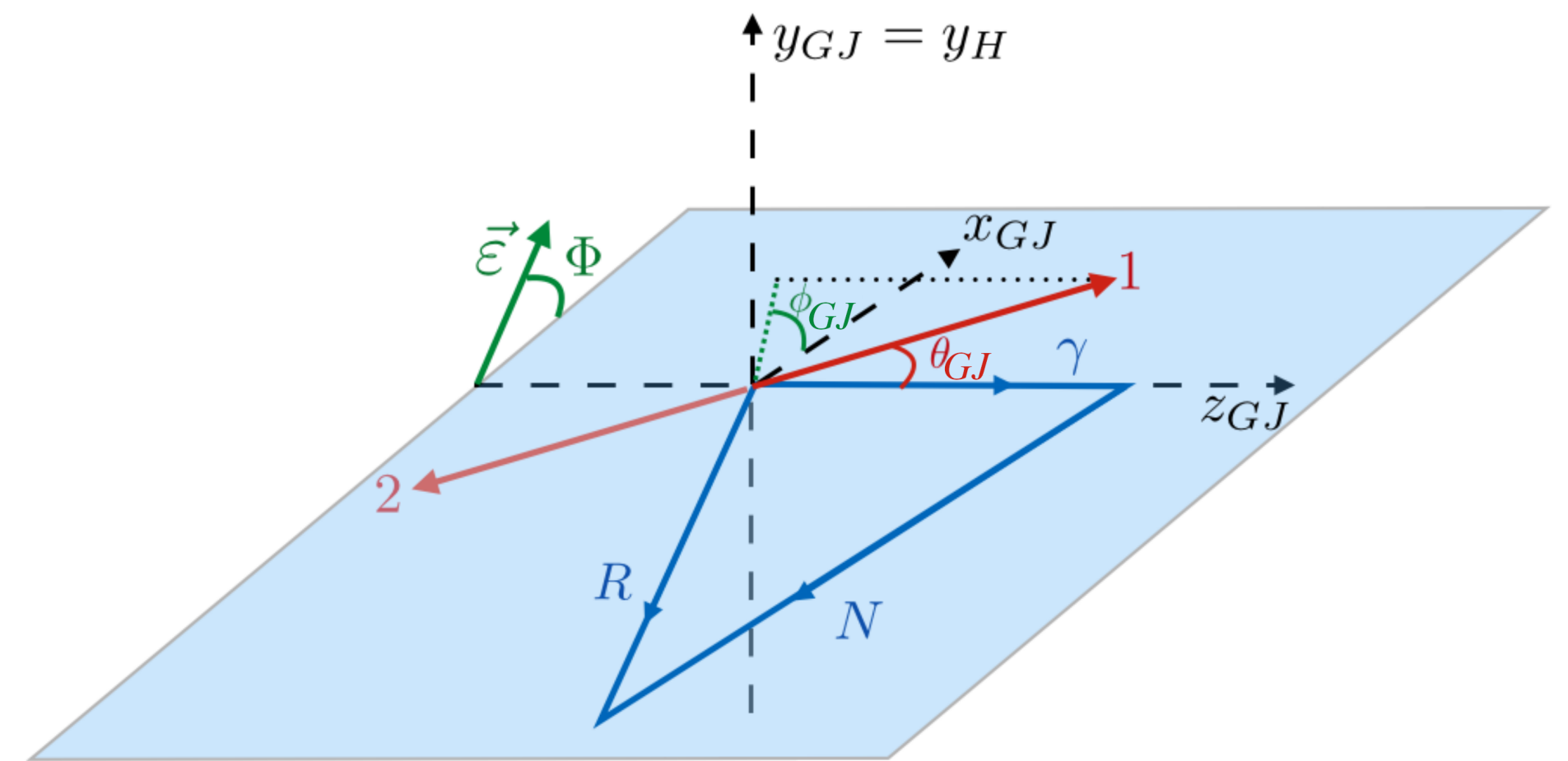
GlueX-3 next year - improved sensitivity to charmonium with new GEM-TRD



Backups

Amplitude Definitions

- Three angles describe the production and decay:
 - Φ is angle between beam polarization vector and the production plane
 - Angles θ and ϕ in parent meson rest-frame
 - Use Z_ℓ^m amplitudes: $Z_\ell^m(\Omega, \Phi) = Y_\ell^m(\Omega)e^{-i\Phi}$



PRD 100, 054017 (2019)

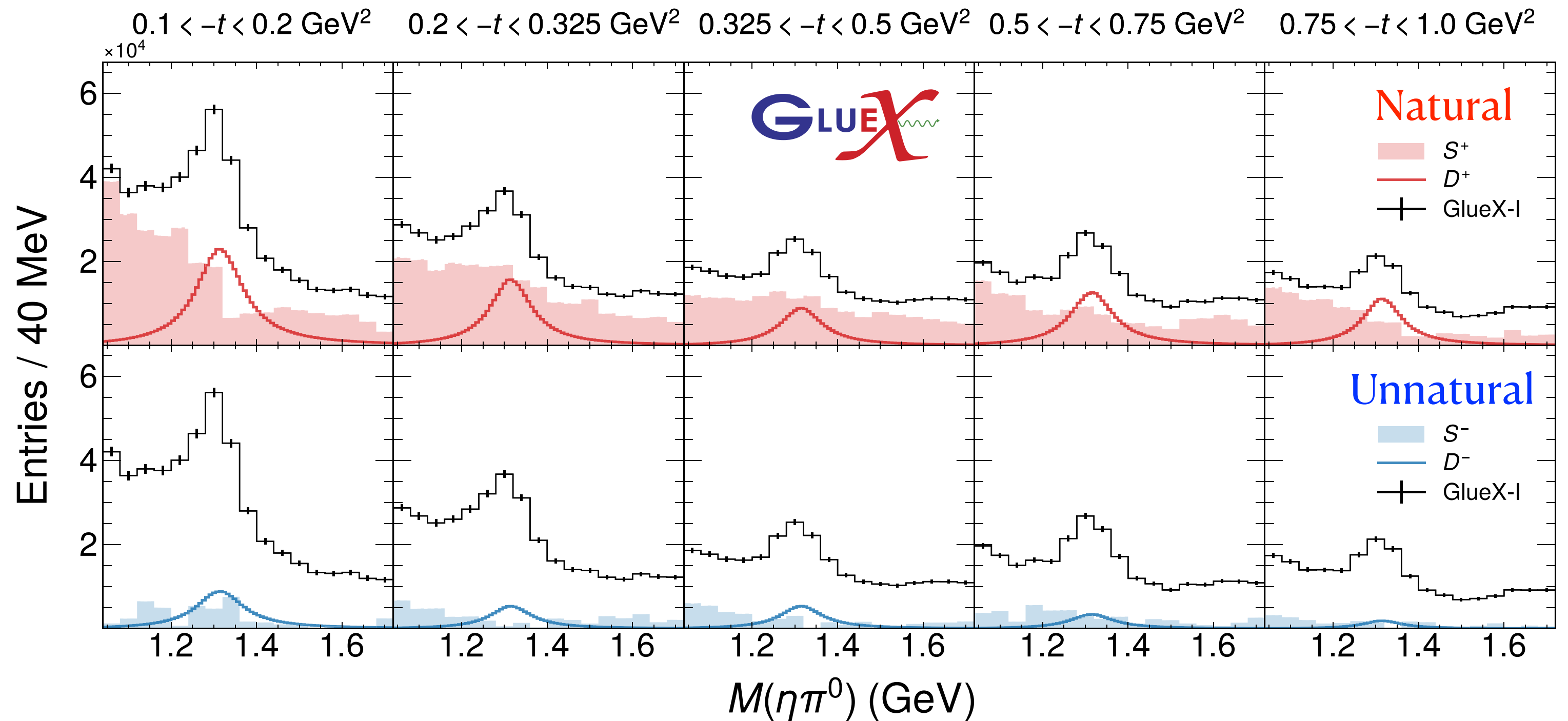
$$I(\Omega, \Phi) = 2\kappa \sum_k \left\{ \begin{array}{l} (1 - P_\gamma) \left| \sum_{\ell, m} [\ell]_{m; k}^{(-)} \text{Re}[Z_\ell^m(\Omega, \Phi)] \right|^2 \\ (1 + P_\gamma) \left| \sum_{\ell, m} [\ell]_{m; k}^{(+)} \text{Re}[Z_\ell^m(\Omega, \Phi)] \right|^2 \end{array} + \begin{array}{l} (1 - P_\gamma) \left| \sum_{\ell, m} [\ell]_{m; k}^{(+)} \text{Im}[Z_\ell^m(\Omega, \Phi)] \right|^2 \\ (1 + P_\gamma) \left| \sum_{\ell, m} [\ell]_{m; k}^{(-)} \text{Im}[Z_\ell^m(\Omega, \Phi)] \right|^2 \end{array} \right\}$$

Natural Exchange (ω , etc)
Unnatural Exchange (π , etc)

Can have $m = -\ell \dots \ell$ - many allowed amplitudes

Semi-Mass Independent PWA of $\eta\pi^0$

- Fully mass independent fits have too many parameters to converge to stable minima
- Introduce physics constraint: model D-wave as $a_2(1320)$ Breit-Wigner
- Use these fits to measure $a_2(1320)$ cross section as function of $-t$

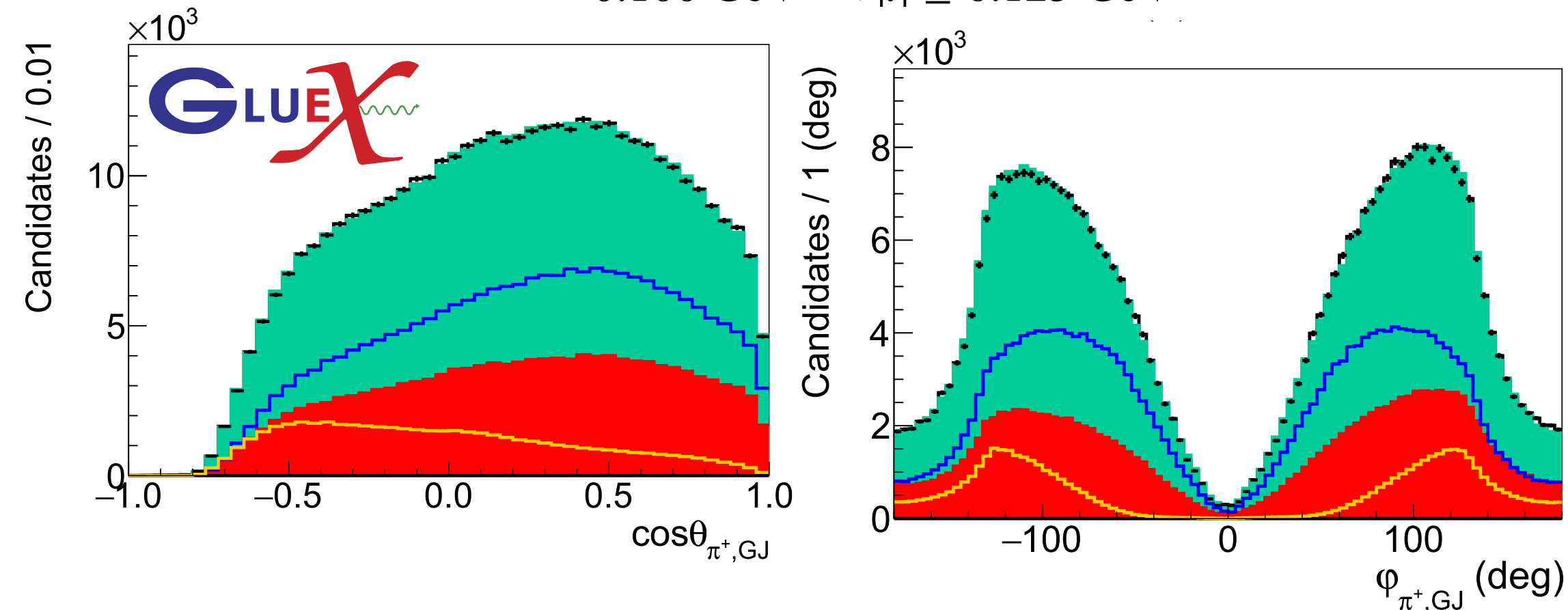


PRC 112, 015204 (2025)

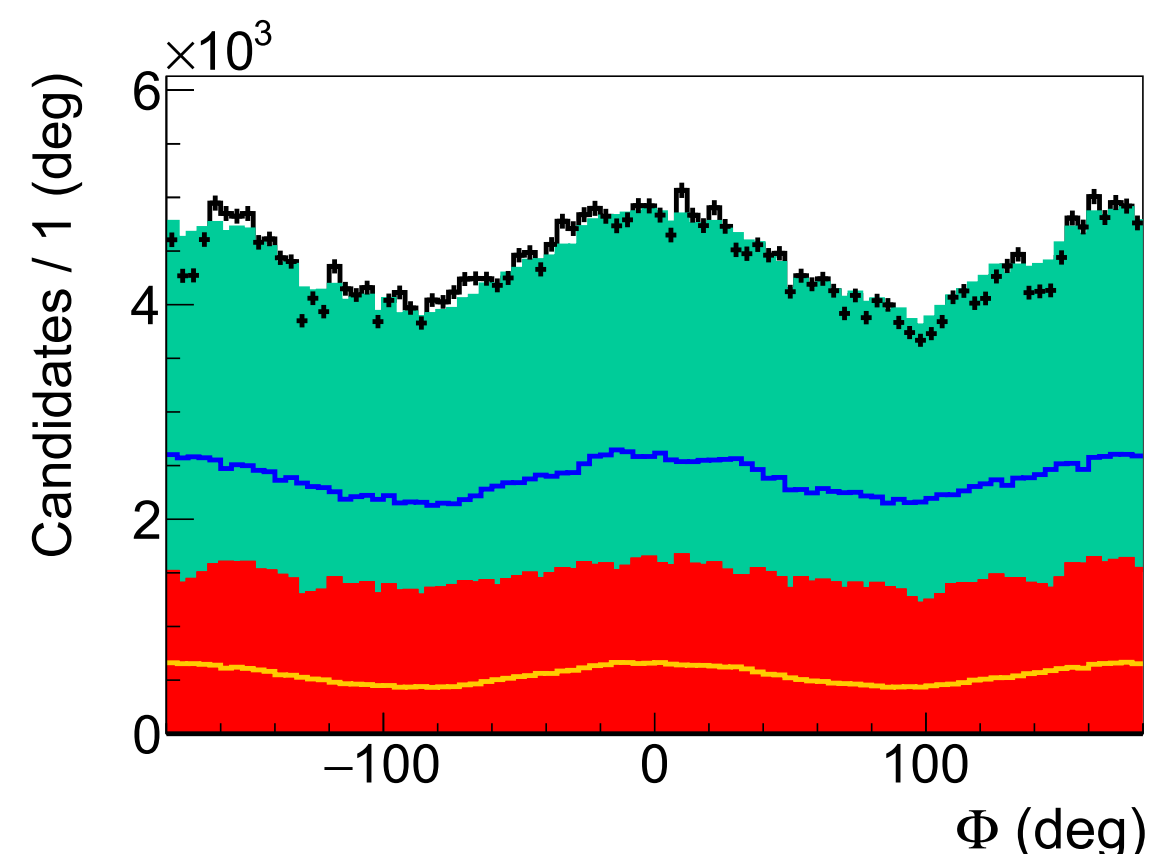
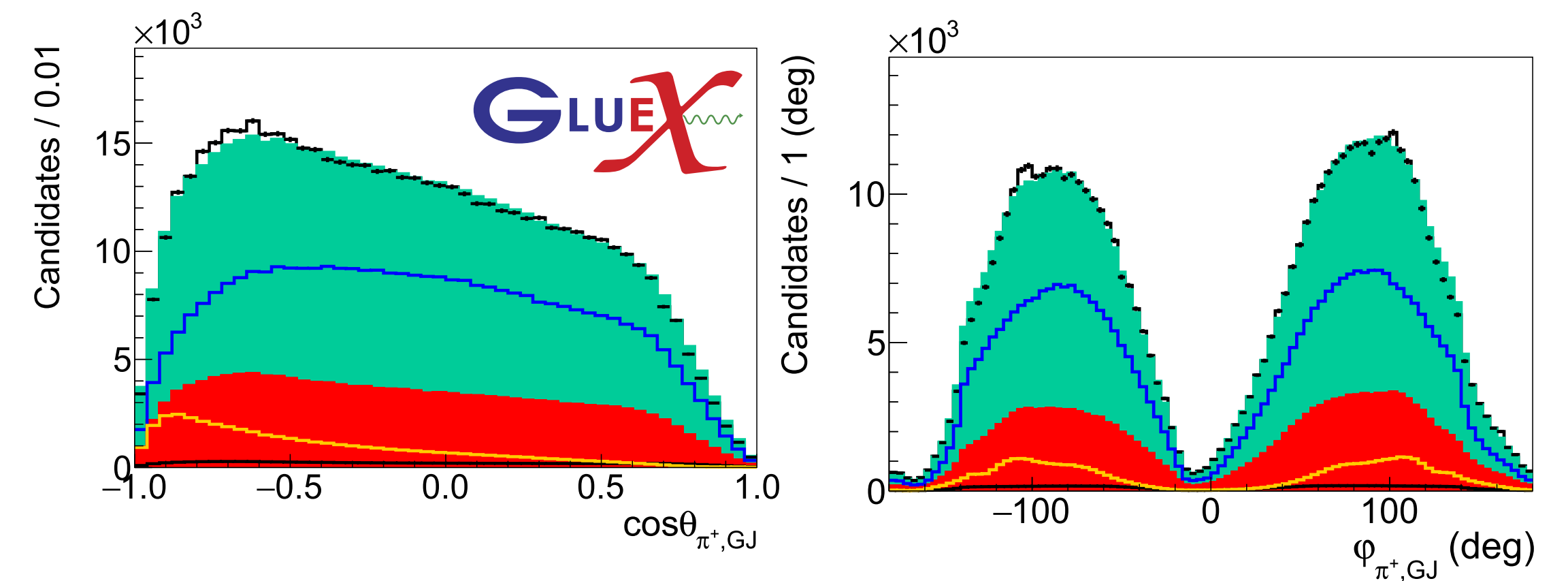
Understanding Δ^{++} Production and Decay

- Reconstruct process $\gamma p \rightarrow \pi^- \Delta^{++}(1232)$ with $\Delta^{++} \rightarrow p\pi^+$
- Measure SDME's - fit Δ^{++} decay angles in bins of $-t$

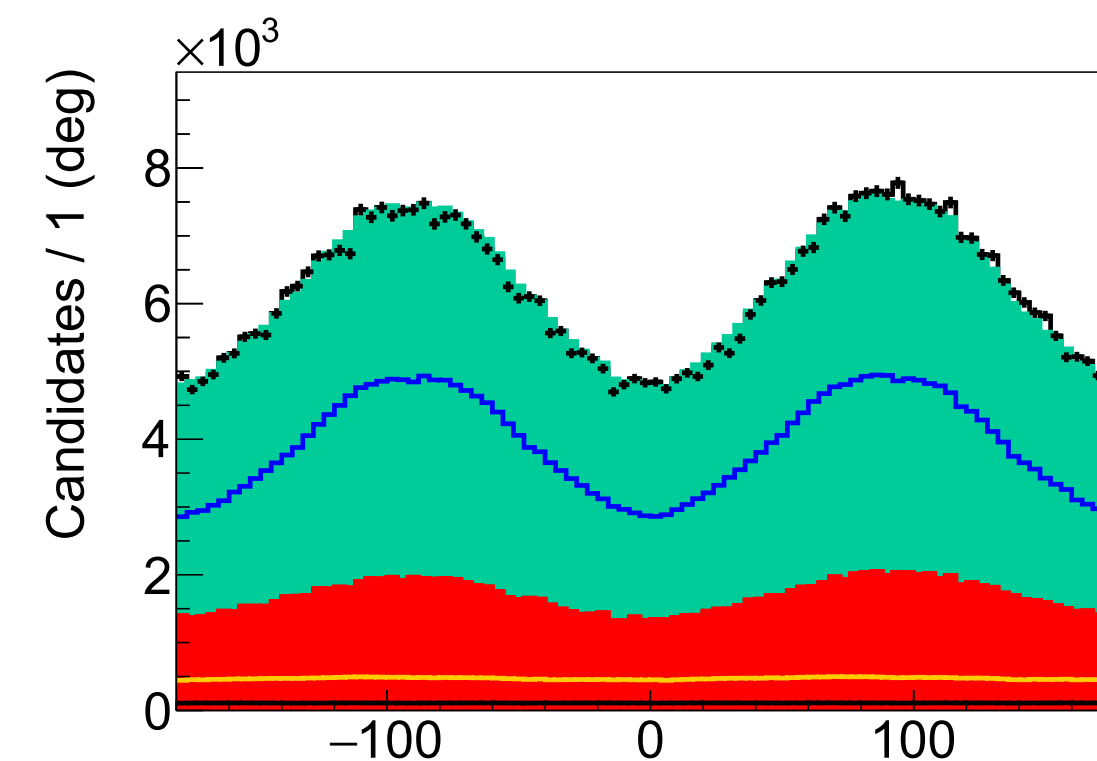
$0.100 \text{ GeV}^2 < |t| \leq 0.125 \text{ GeV}^2$



$0.640 \text{ GeV}^2 < |t| \leq 0.850 \text{ GeV}^2$



PLB 863, 139368 (2025)

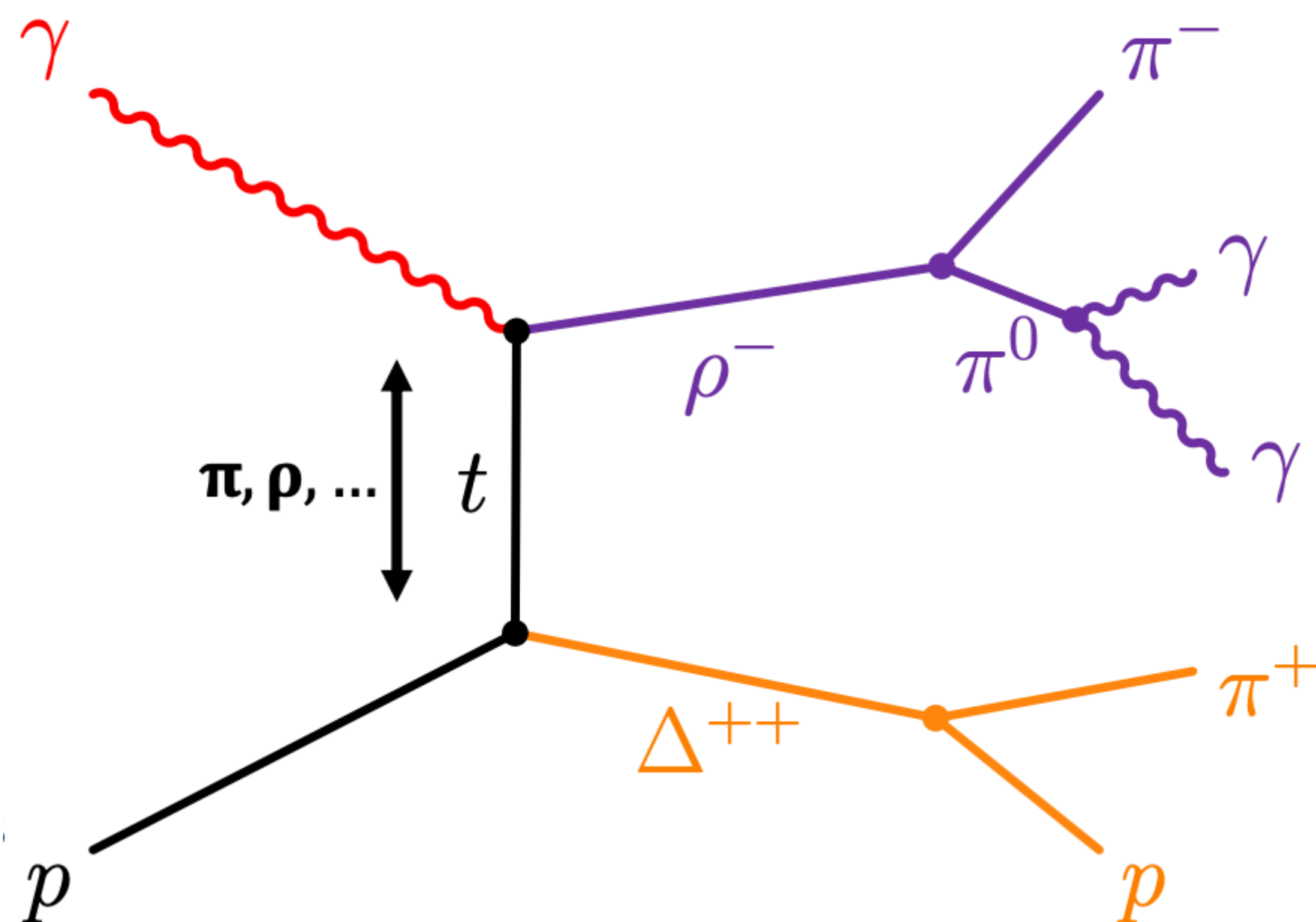


$\rho^-\Delta^{++}$ Double SDMEs

- Question: Can upper and lower vertices be treated independently?
 - Does the amplitude factorize?

Full model

$$I^\alpha = \frac{2\kappa}{\pi} \sum_{l,l'} \sum_{\lambda_\Delta, \lambda_\Delta'} \sum_{m,m'} |\tilde{F}(m_{\pi p}^2)|^2 c_{\lambda_\Delta \lambda_\Delta'}(\Omega_{\pi^+}) \rho_{mm', \lambda_\Delta \lambda_\Delta'}^{\alpha, l, l'}(s, t) c_{mm'}^{l, l'}(\Omega_{\pi^-}) |F(m_{\pi\pi}^2)|^2$$



Factorized model

$$I_{tot} = (I_{0,\rho} + \sum_{\alpha=1,2} P_{\alpha} I_{\alpha,\rho}) I_{0,\Delta}$$

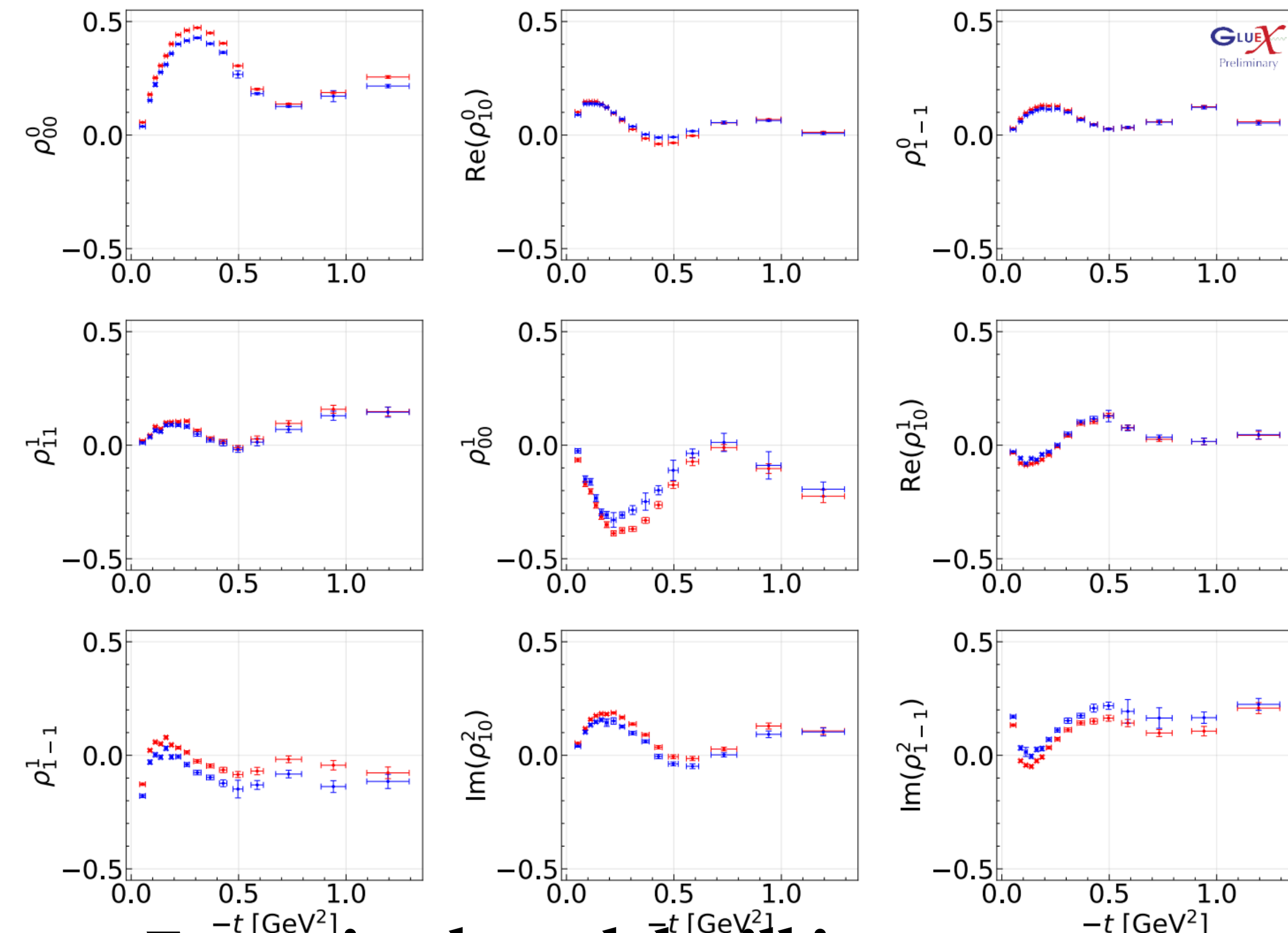
More details on math in V. Mathieu's talk (9/7 18:35)

$\rho^- \Delta^{++}$ Double SDMEs - Factorization Studies

- Question: Can upper and lower vertices be treated independently?

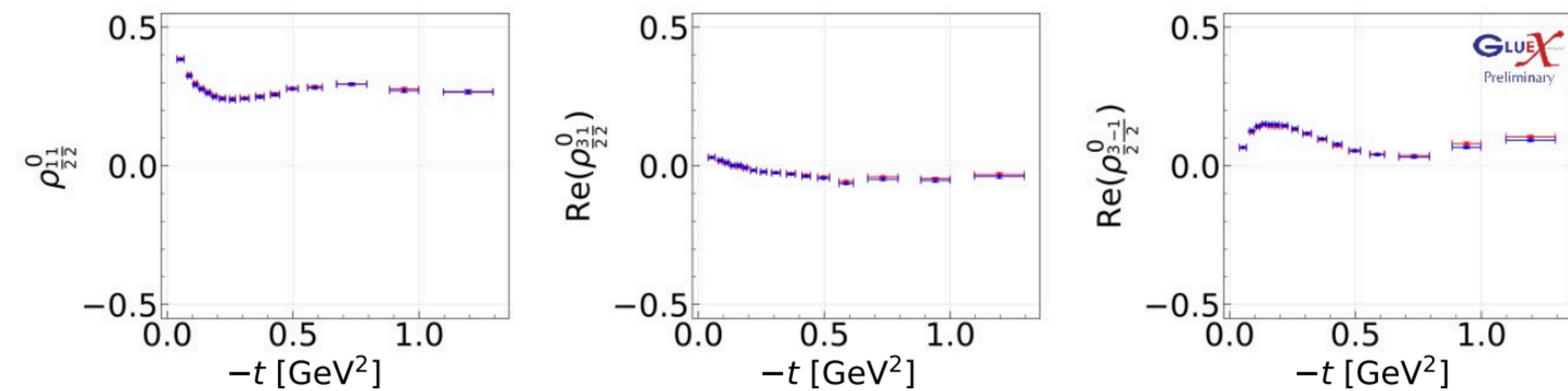
ρ^- – SDMEs

Factorized model Full model



Δ^{++} – SDMEs

Factorized model Full model



- Full model vs factorized model
- Factorization appears to hold

Factorized model will improve convergence for low statistics channels