# Hadron Spectroscopy with GlueX


**Sean Dobbs**

Florida State U.


11th Workshop of the APS Topical Group on Hadronic Physics
(GHP2025)
March 14, 2025

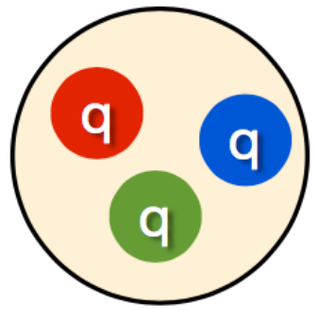
Jefferson Lab

GlueX

# QCD and Hadron Spectroscopy

- Quantum Chromodynamics (**QCD**)
  - Degrees of freedom:
    quarks and gluons
- Recent progress in studying QCD through spectrum of bound states
  - New high-intensity experiments
  - More rigorous theoretical tools
- Open questions:
  - What is the origin of confinement?


**mesons**




**baryons**

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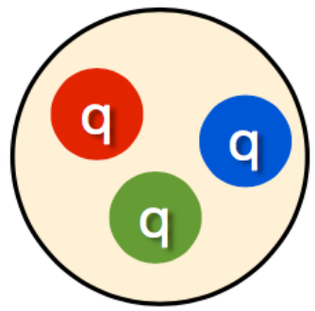


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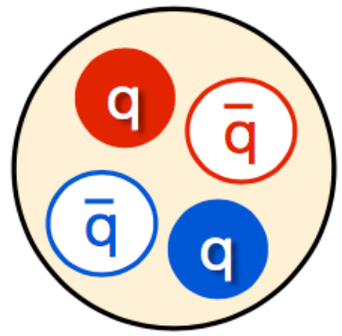
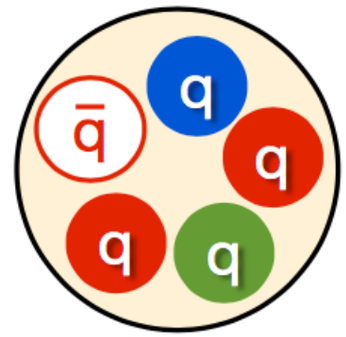
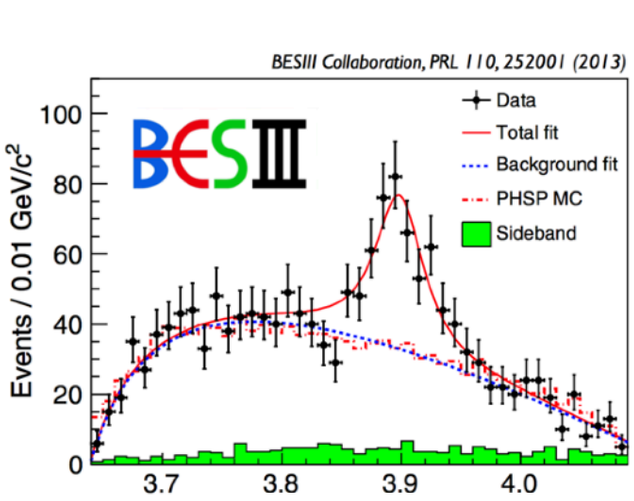


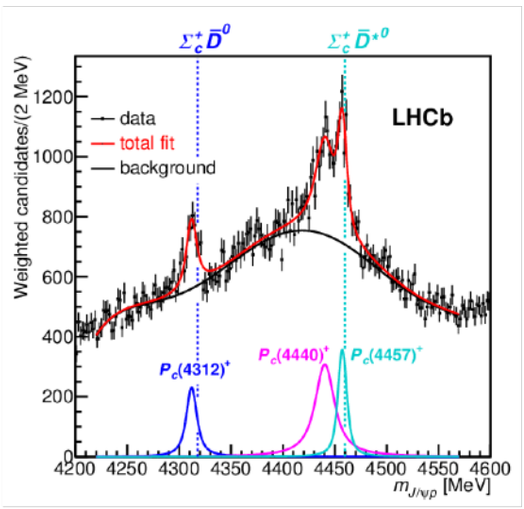

**tetraquark**




**pentaquark**




M(J/ψ π±)

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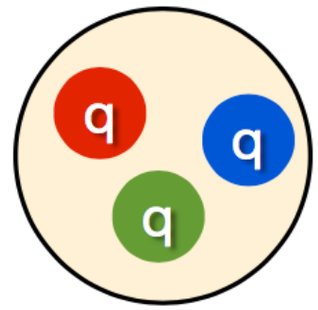


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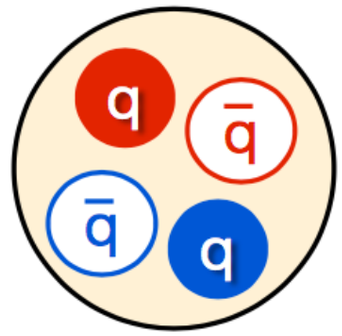


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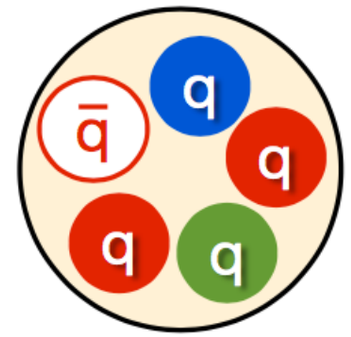


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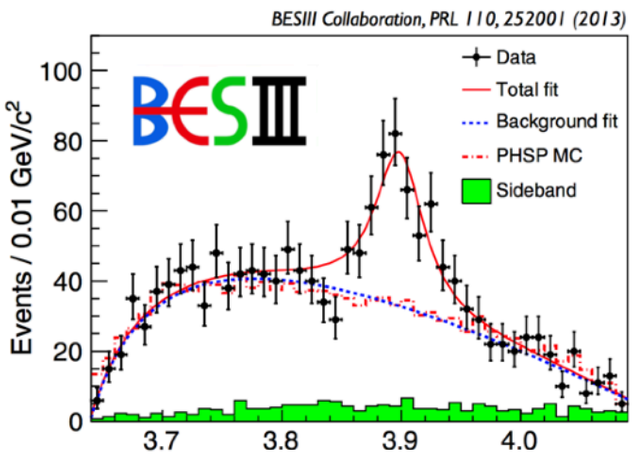


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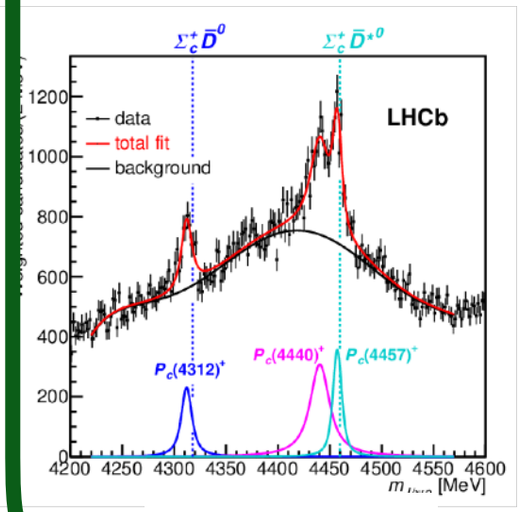


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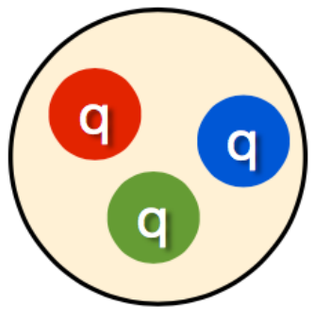


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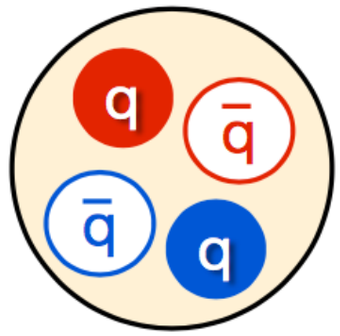


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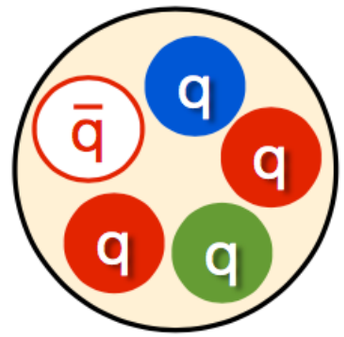


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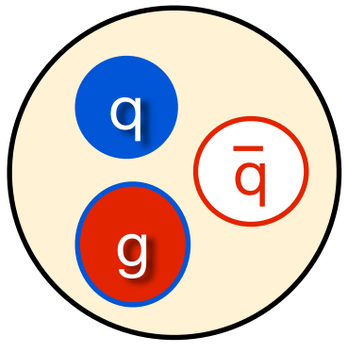
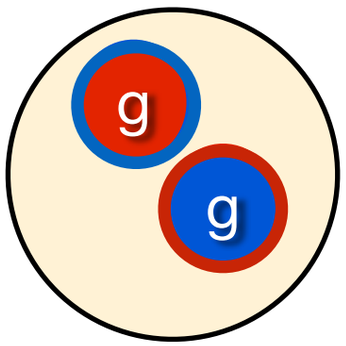



**hybrid meson**




**glueball**

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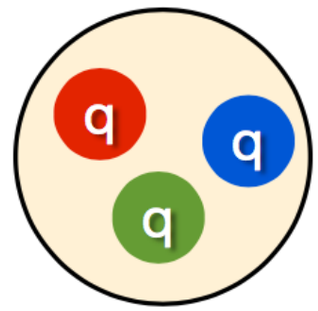


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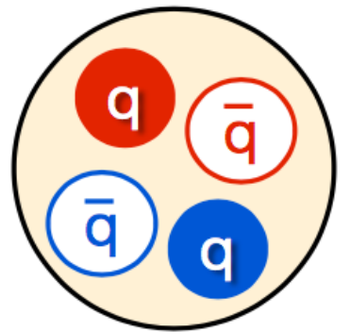


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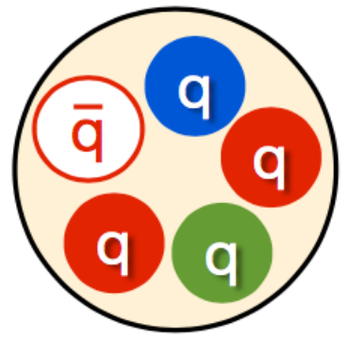


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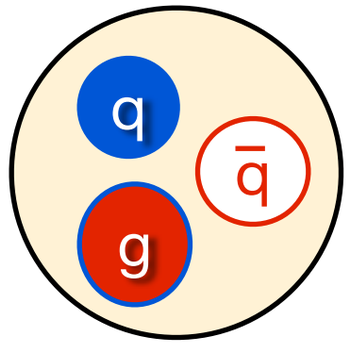


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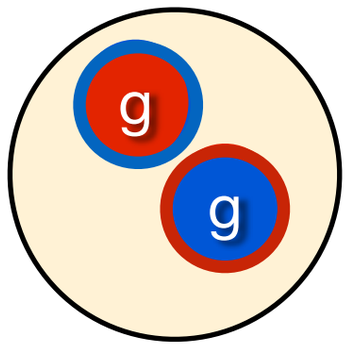


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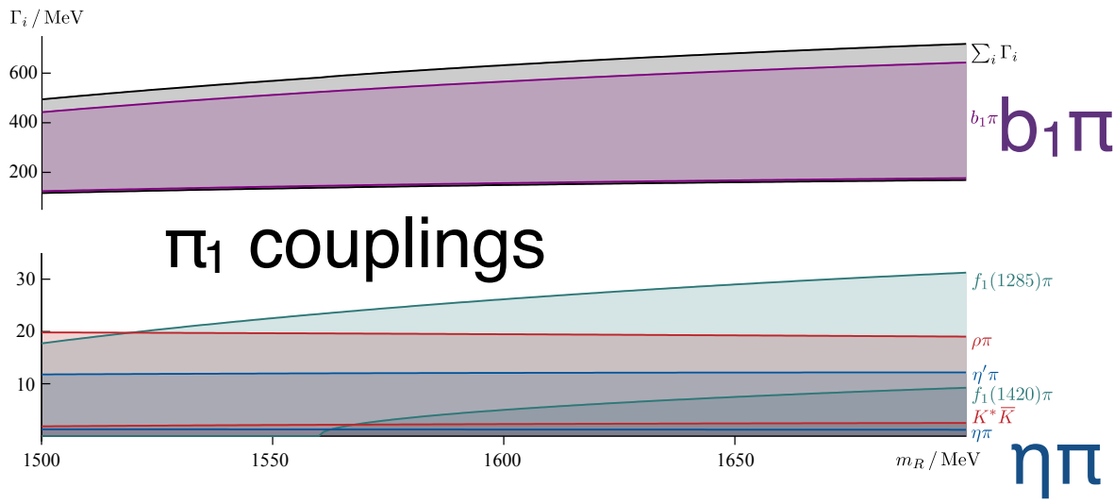
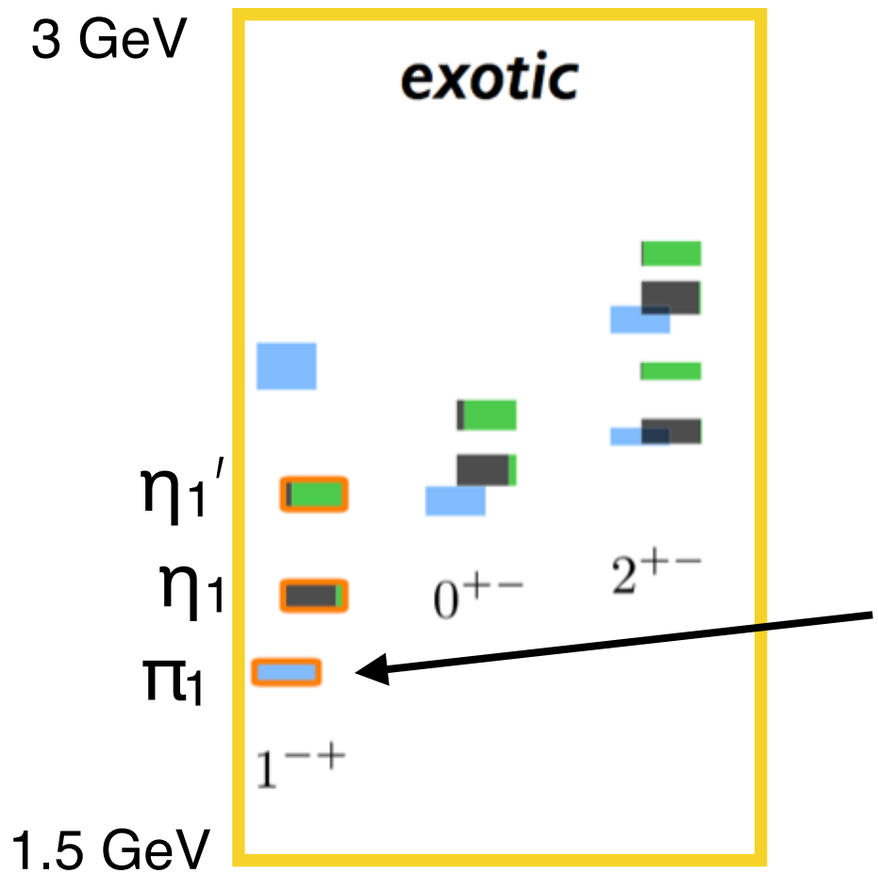
# Hybrid Mesons

**HadSpec: PRD 103, 054502 (2021)**

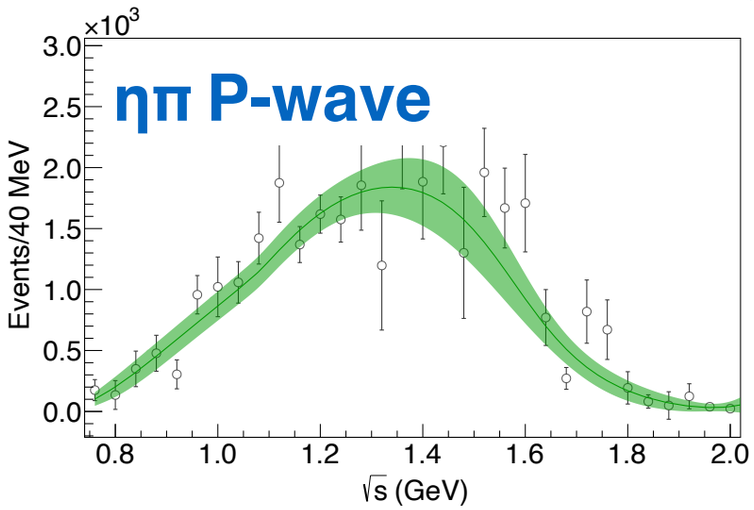


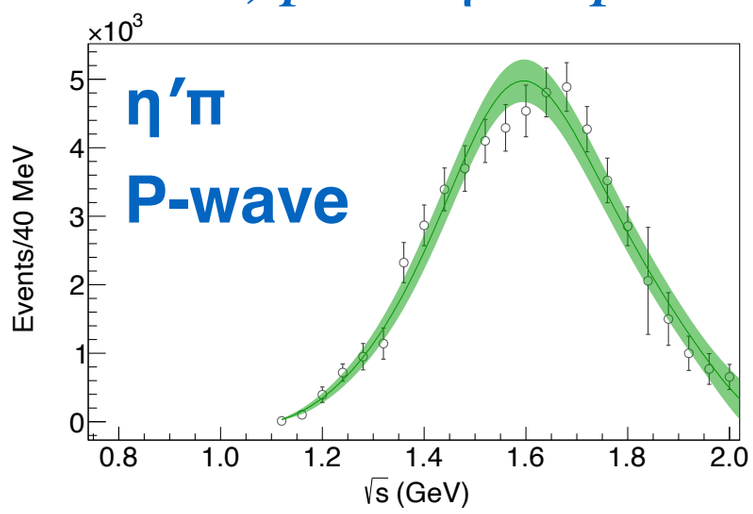




**HadSpec: PRD 88, 094505 (2013)**

- Long history of search for “hybrid” mesons with gluonic excitations
- Best evidence is for $\pi_1(1600)$ in COMPASS pion-production data
- Recent evidence for $\eta_1^{(\prime)}$ from BES-III in $J/\psi \to \gamma\eta\eta'$
- Need to confirm $\pi_1$ and $\eta_1$ and establish the full (normal and exotic) light quark hybrid spectrum

COMPASS : $\pi^-(190\ \mathrm{GeV})\, p \to \eta^{(\prime)}\pi\, p$

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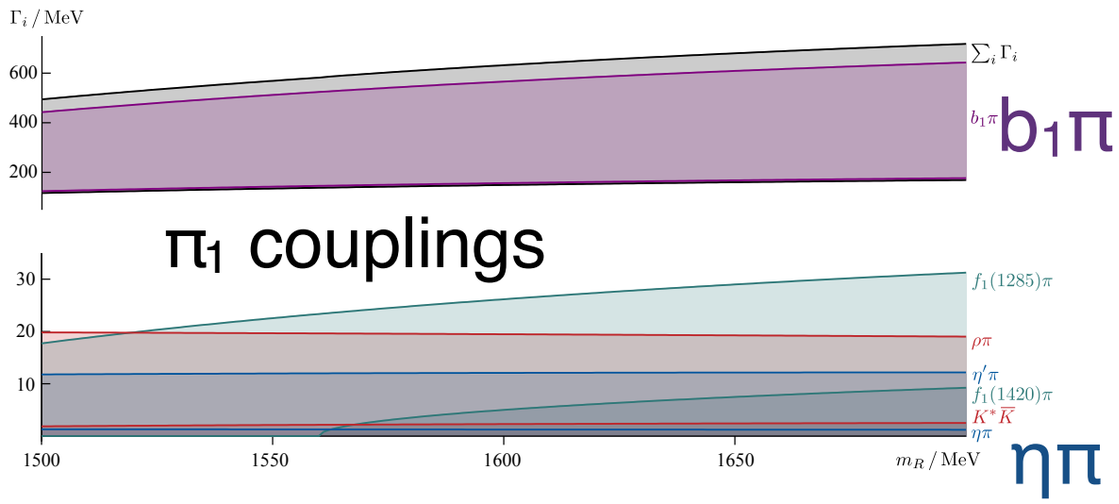


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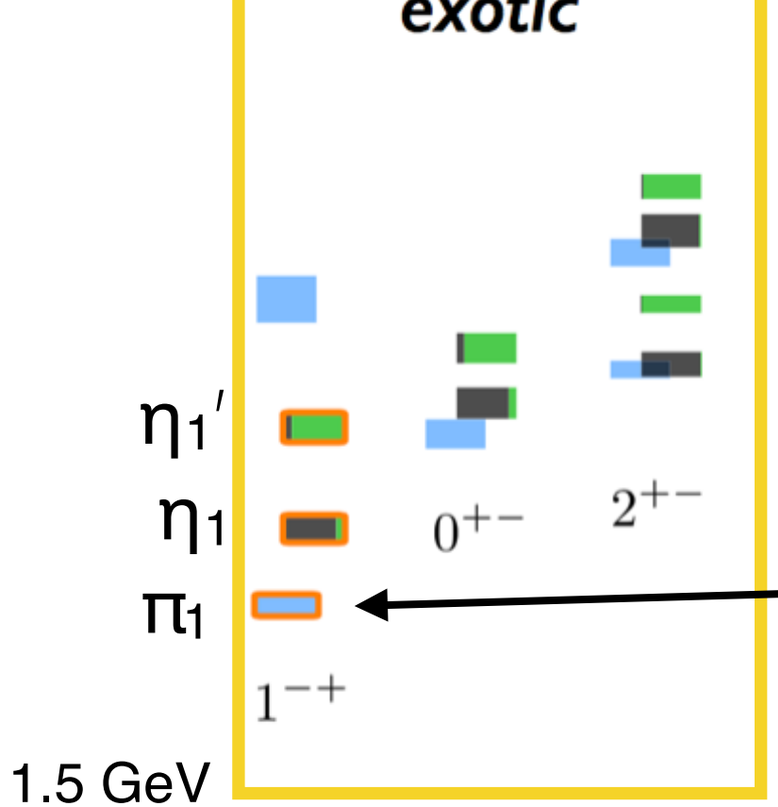


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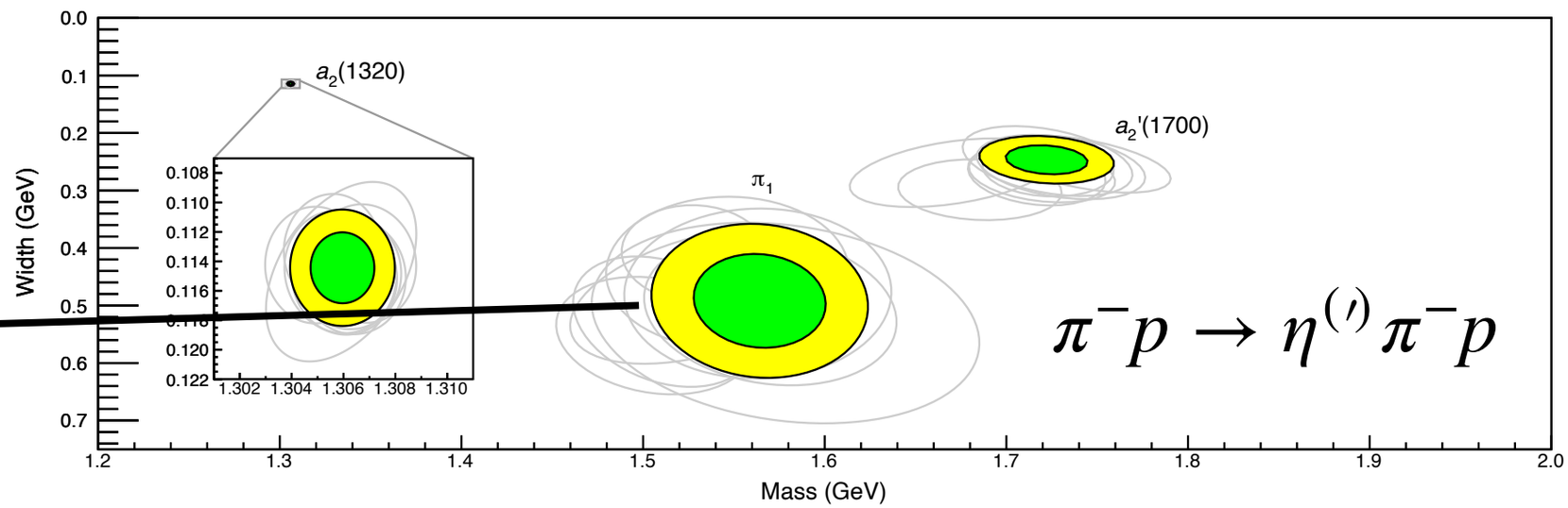


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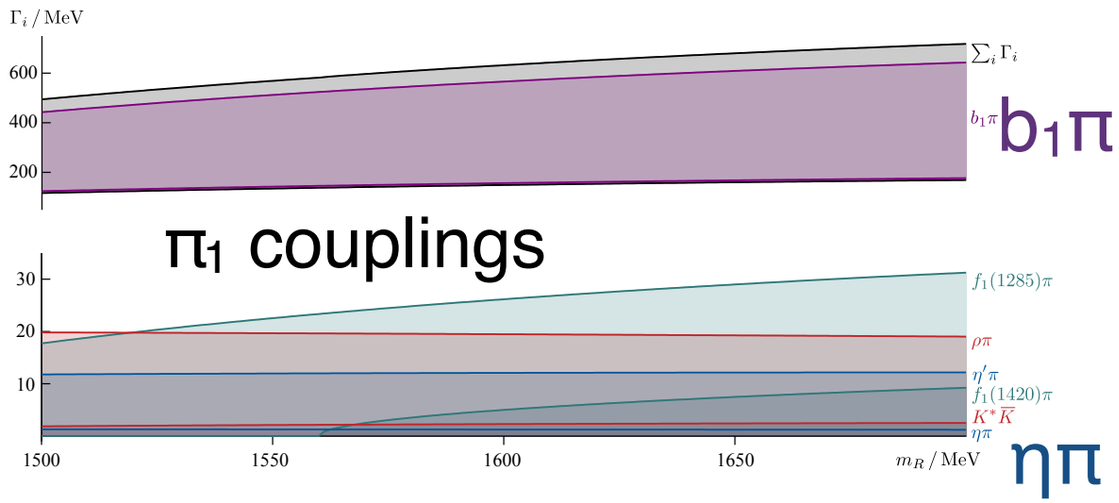


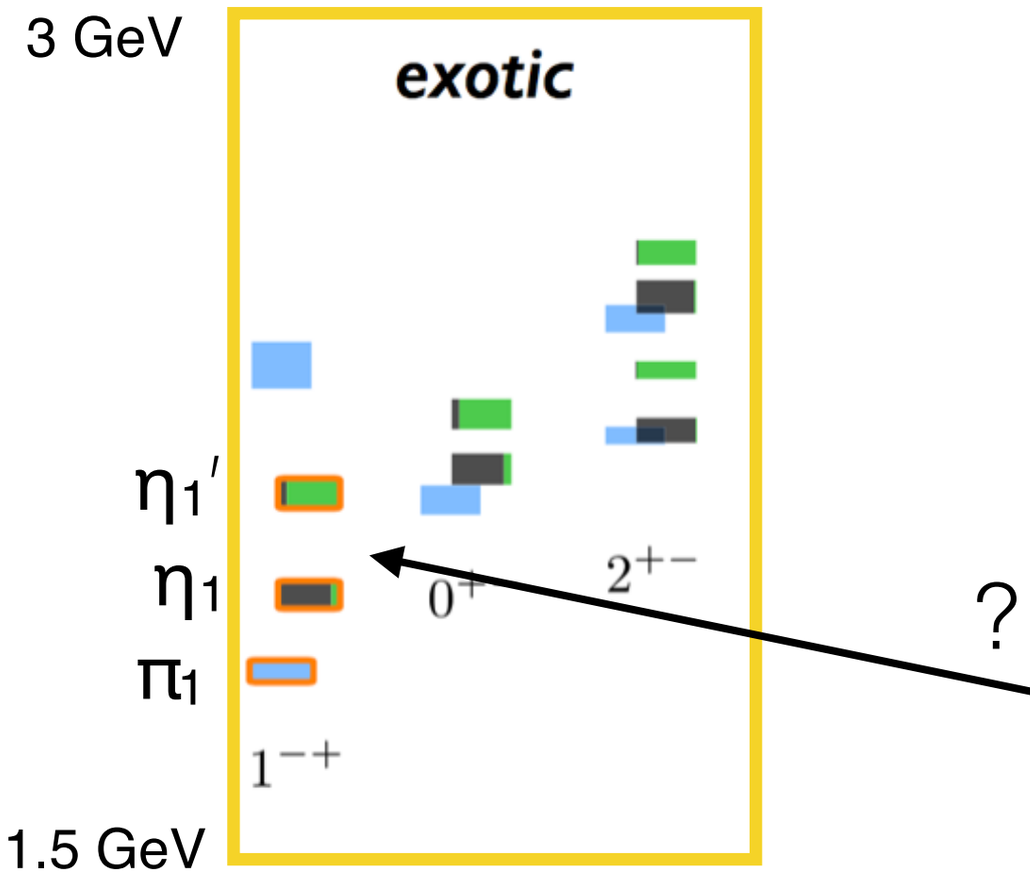


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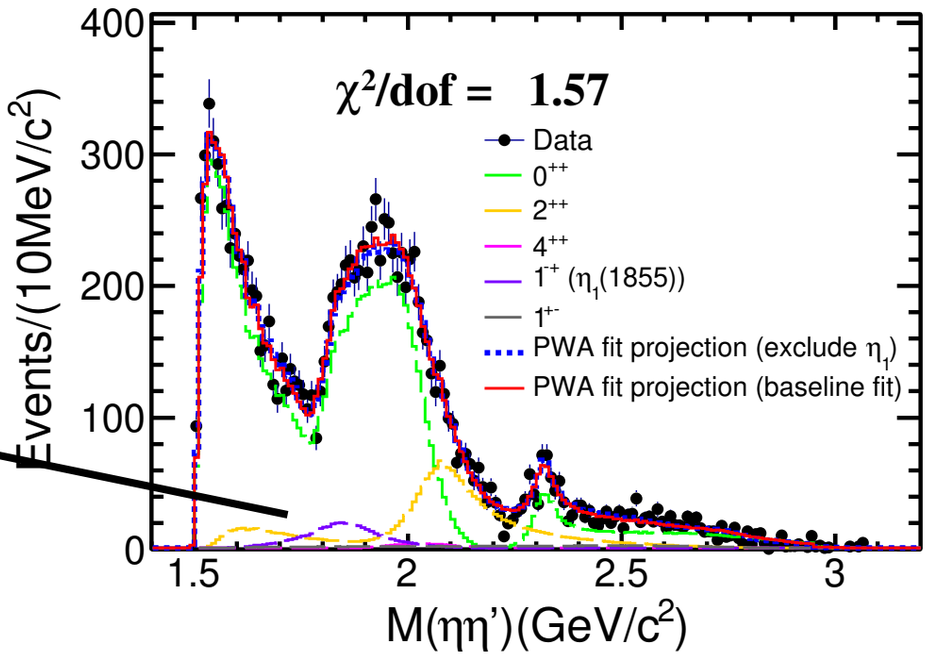


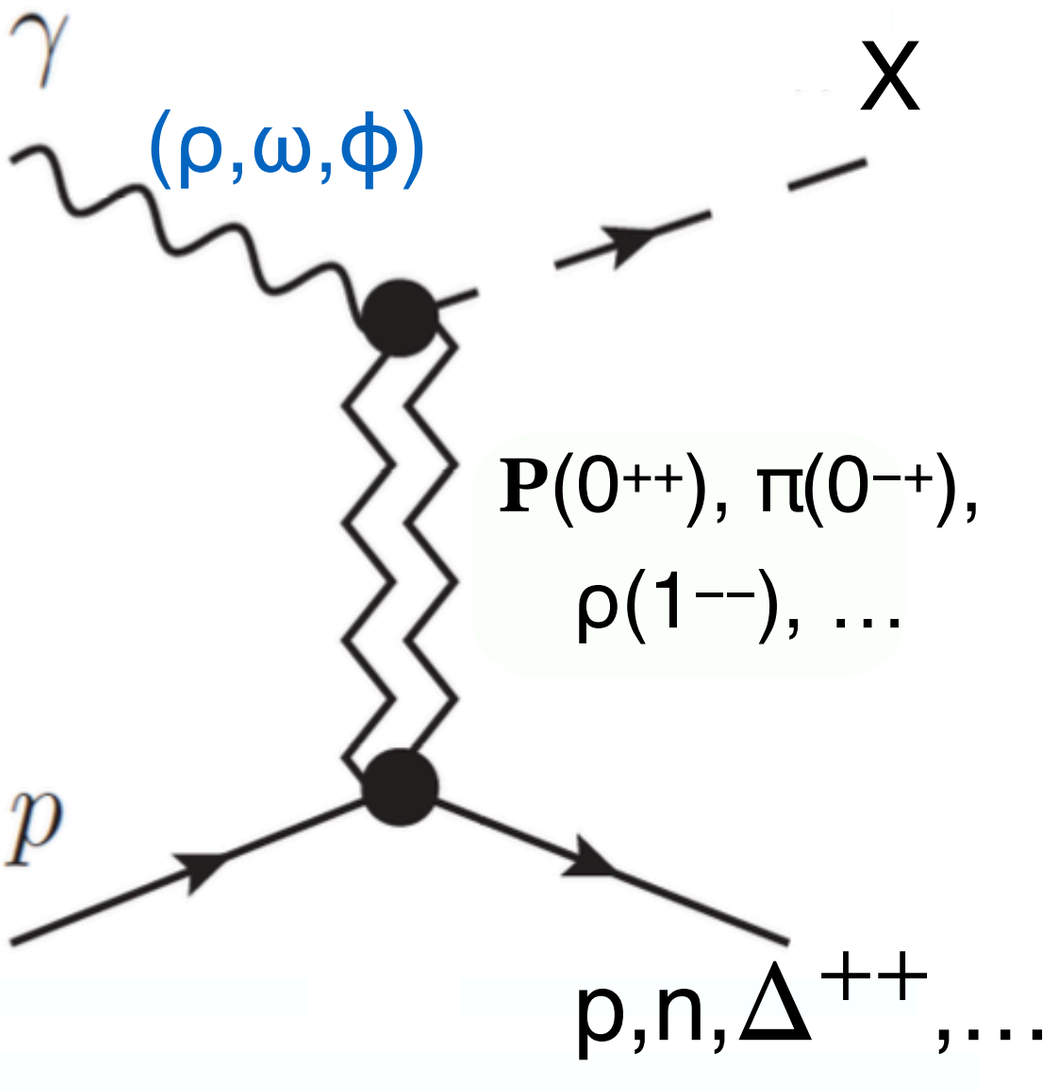

**BESIII**

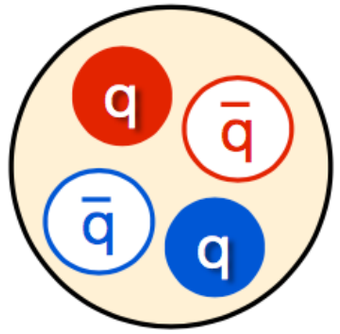
$J/\psi \to \gamma\eta\eta'$

**BESIII: PRL 129, 192002 (2022)**

# Hadron Spectroscopy and Photoproduction

- Photoproduction is an essential process to study normal hadrons and to search for exotic hadrons

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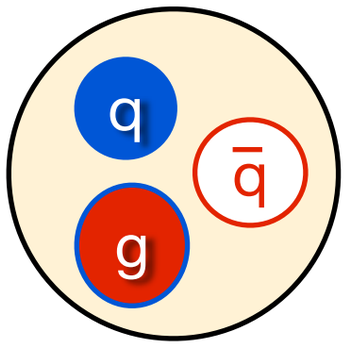



**hybrid meson**

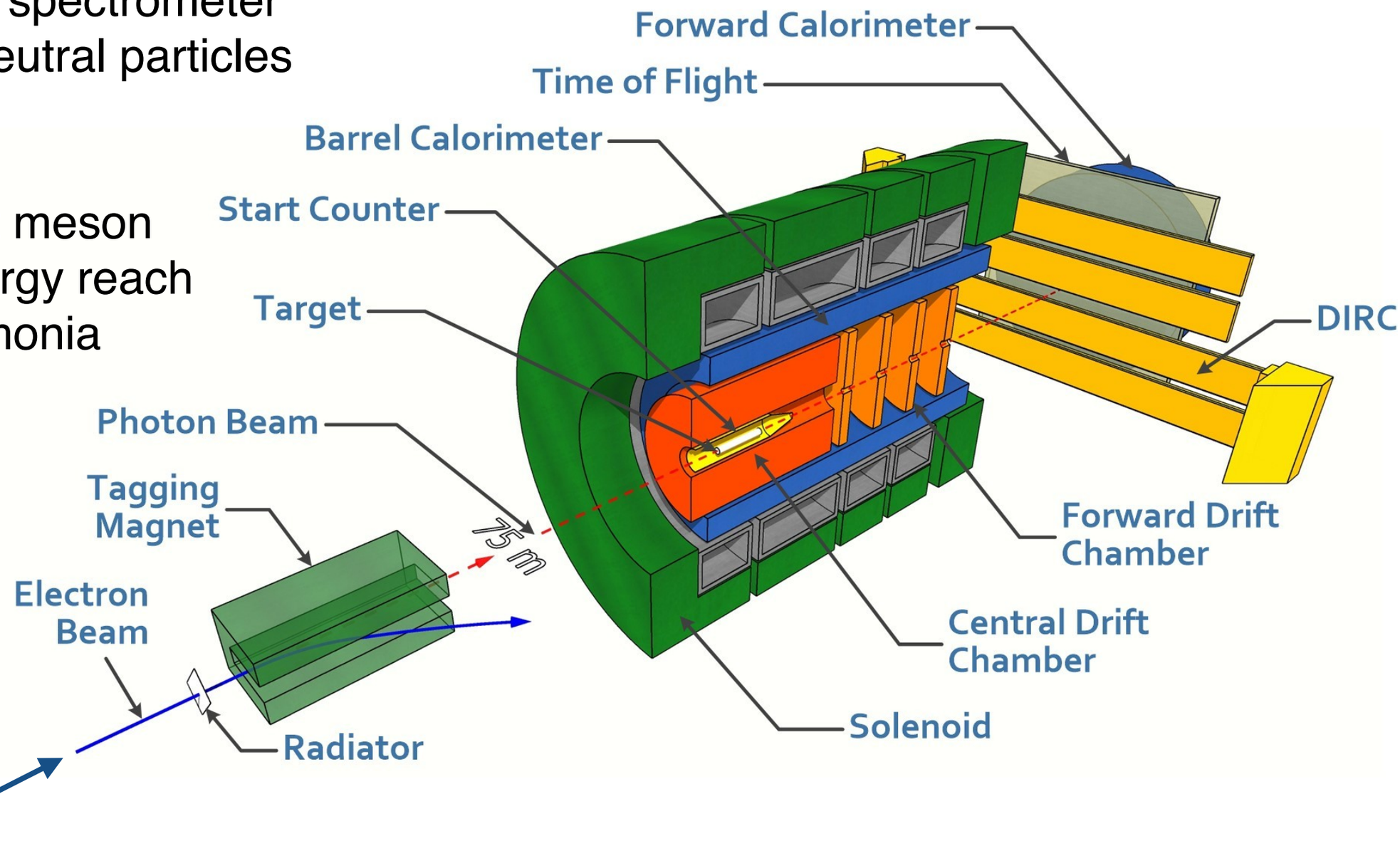
- Can produce mesons of any $J^{PC}$ through VMD
- Photon polarization provides constraints on production processes
- Little data existed for final states with neutral particles
- Idea: confirm and extend our knowledge of exotic hadrons in a new process

# The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

Optimized for light meson spectroscopy, energy reach up to bound charmonia

Photon beam with linear polarization
P ≈ 40% at peak
$E_\gamma \approx 9$ GeV




- **GlueX-I (2017–2018): $L = 305$ pb$^{-1}$ [$E_\gamma > 8$ GeV]**
- **GlueX-II (2020–2026?): $L = 320$ pb$^{-1}$ (so far)**
  **expect 3-4x GlueX-I**

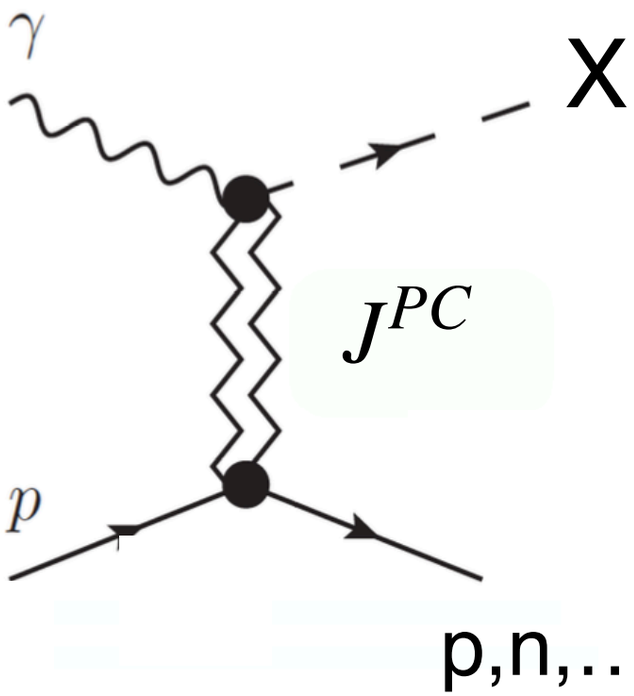
# Searching for Exotics in Photoproduction @ GlueX

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

↓

Understand production mechanisms using polarization: Σ, SDMEs, …




$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

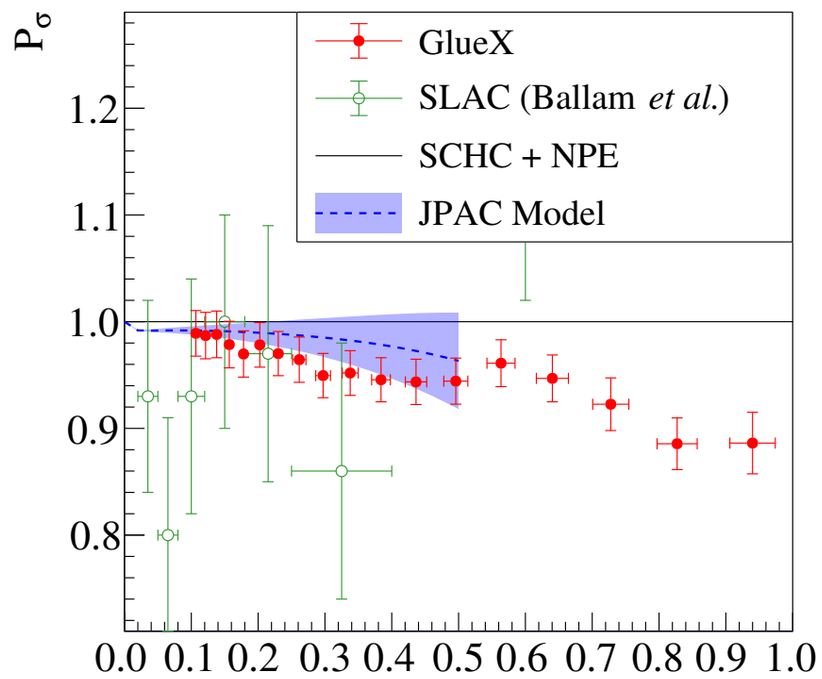
Natural $P = (-1)^J$ and
Unnatural $P = -(-1)^J$
exchanges

**Beam Asymmetry Σ**

**$(\pi^0/\eta)p$:** Phys. Rev. C95, 042201 (2017)
**$(\eta/\eta')p$:** Phys. Rev. C100, 052201(R) (2019)
**$K^+\Sigma^0$:** Phys. Rev. C101, 065206 (2020)
**$\pi^-\Delta^{++}$:** Phys. Rev. C103, 0[illegible] 21)
**$K^+\Lambda(1520)$:** Phys. Rev. C10[illegible] (2022)
Updates on the way…

**SDMEs:**

$\rho(770)$**:** Phys. Rev. C108, 055204 (2023)
$\omega(782)$**:** in progress
$\phi(1020)$: paper under Collaboration review
$\pi^-\Delta^{++}$: Phys. Lett. B863, 139368 (2025)
$K^+\Lambda(1520)$: Phys. Rev. C105, 035201 (2022)
More coming…




**GlueX:** Phys. Rev. C 108, 055204 (2023)

# Searching for Exotics in Photoproduction @ GlueX

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

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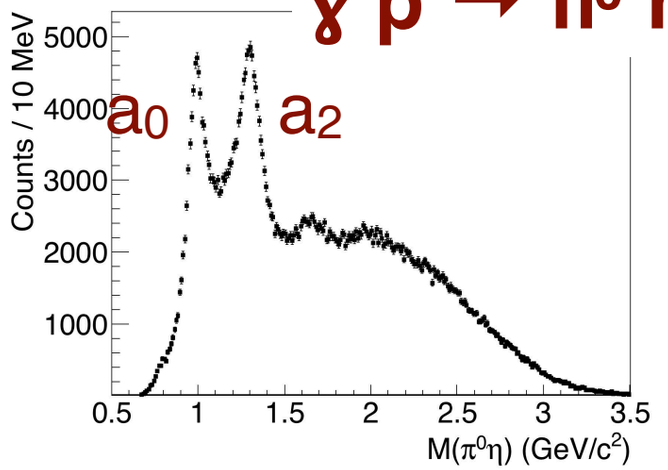
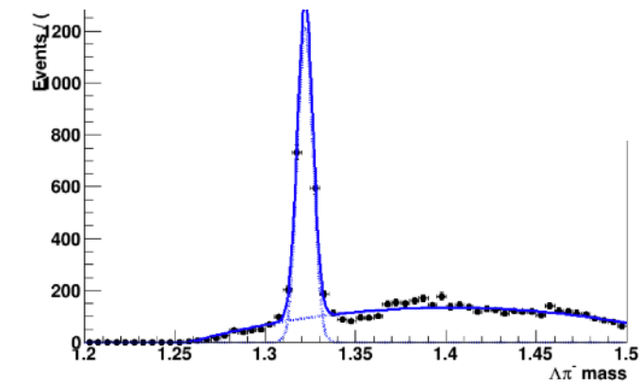
Measure cross sections and identify known hadrons

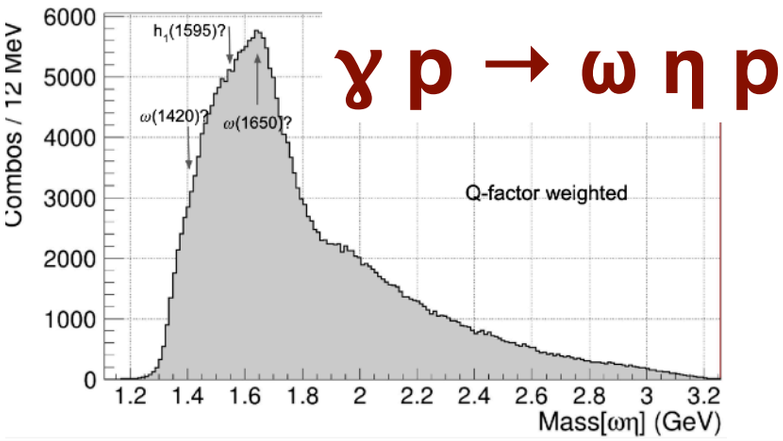
**γ p → π⁰ η p**




**γp → K⁺K⁺Ξ⁻**




**γ p → ω η p**




**See talk at Fri. 2:25 pm on $\Lambda(1405)$ and $\Lambda(1520)$ at GlueX**

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Collect Data

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Search for exotic mesons

Theoretical Models (JPAC, ….)

See talk by A. Jackura, Fri. 2:50 pm

ExoHad
Exotic Hadrons Topical Collaboration

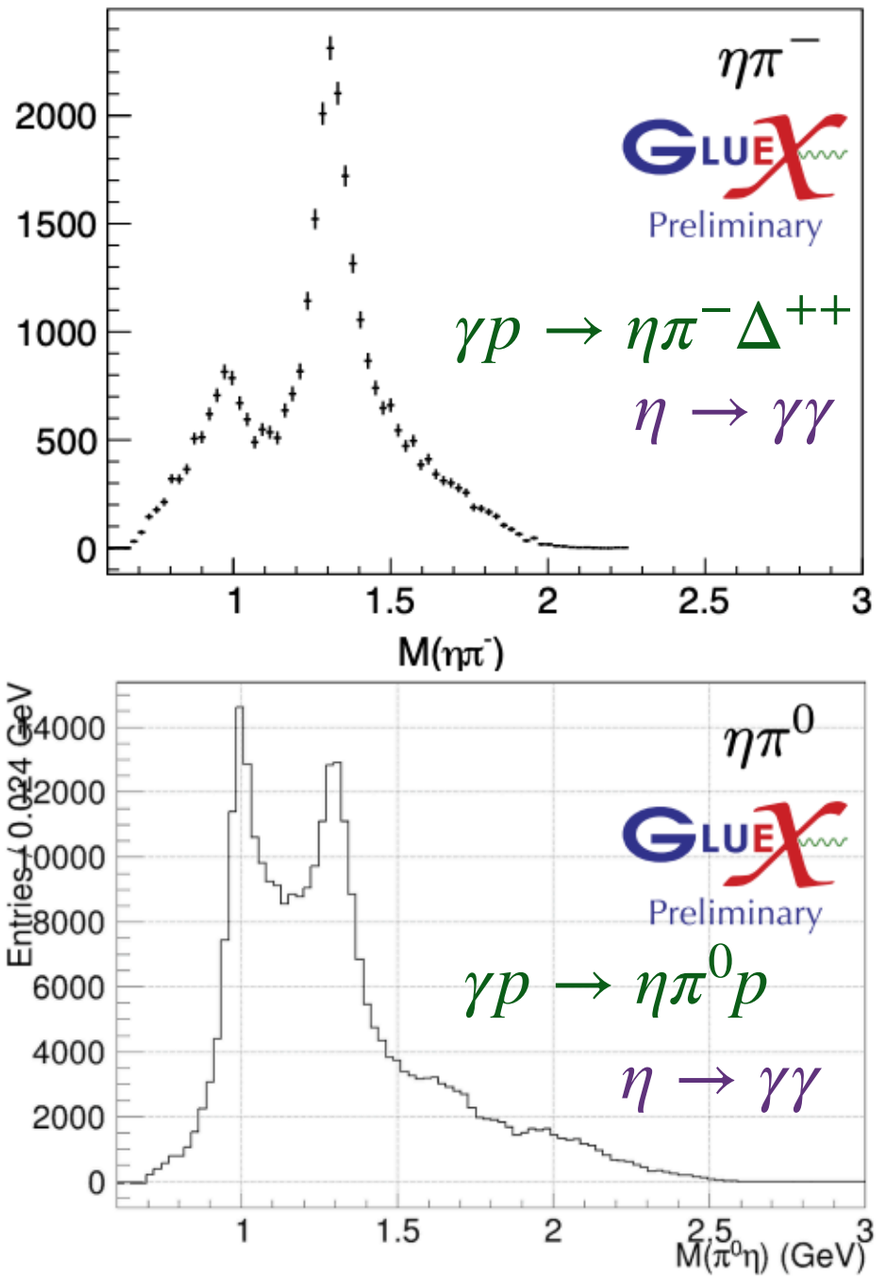
JPAC

# ηπ Amplitude Analysis at GlueX

- $\pi\eta$ / $\pi\eta'$ "golden channels" for $\pi_1$ search: small b.f. but experimentally clean
  - Odd L $\pi\eta^{(\prime)}$ → exotic $J^{PC}$
  - Study known $a_0/a_2$ in $\pi\eta$
  - Apply analysis to $\pi\eta'$ with stronger $\pi_1$
- Can study several channels
  - $\gamma p \to \eta\pi^0 p$ $\gamma p \to \eta\pi^- \Delta^{++}$
  - Control understanding of production with multiple $\eta$ decays
    - $\eta \to \gamma\gamma$ $\eta \to \pi^+\pi^-\pi^0$
    - Control understanding of acceptance and backgrounds
- Use polarization to control acceptance, help separate amplitudes
- Fits with different levels of model-dependence

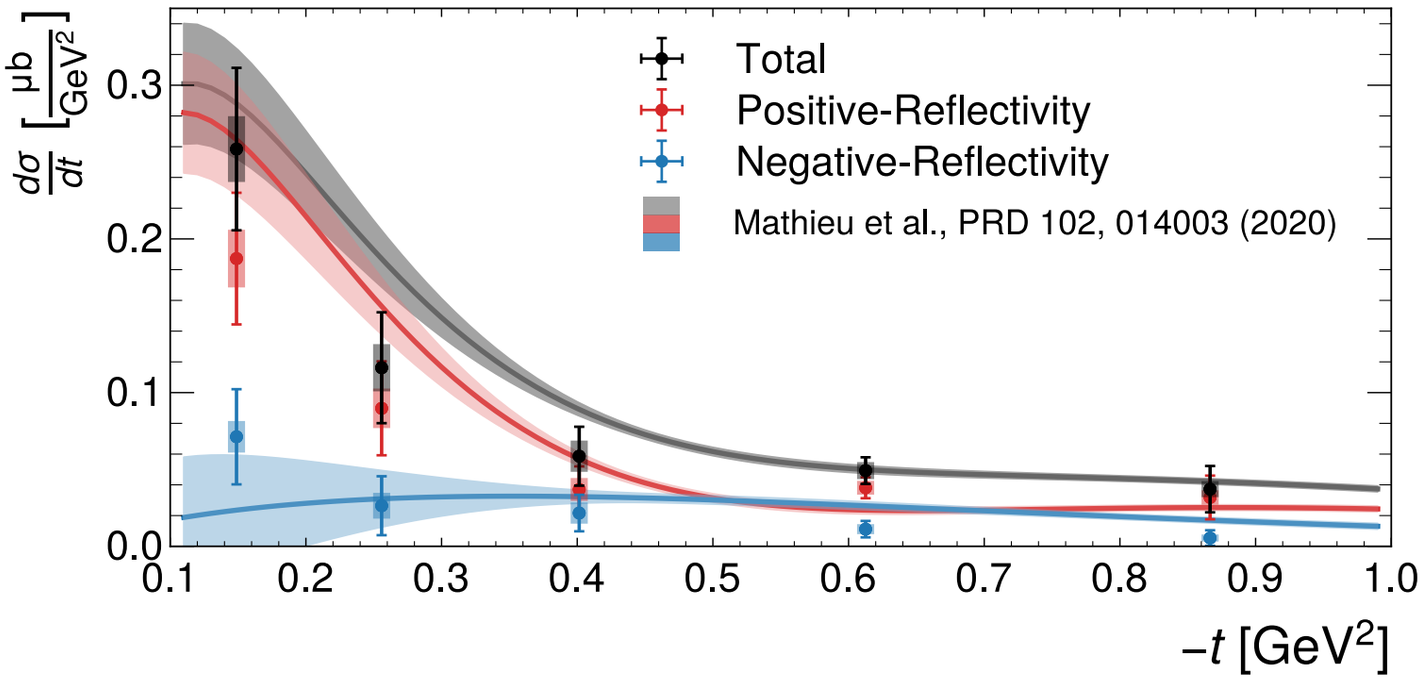
GlueX-I Data

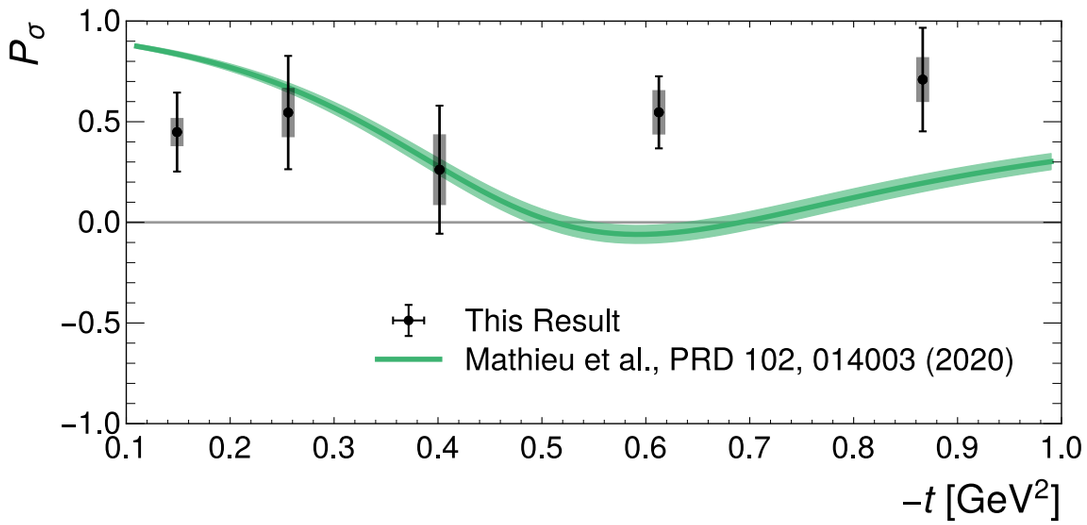
$0.1 < -t < 0.3$ GeV$^2$



# $\gamma p \to a_2(1320)p$ Cross Section

- First separation of $\gamma p \to a_2(1320)p$ cross section into reflectivity components
- Cross sections agree with with JPAC prediction
  - Natural exchange dominant, unnatural exchange constant over $-t$
  - Can also extract amplitudes for individual waves
- Informs amplitude fits for exotic waves



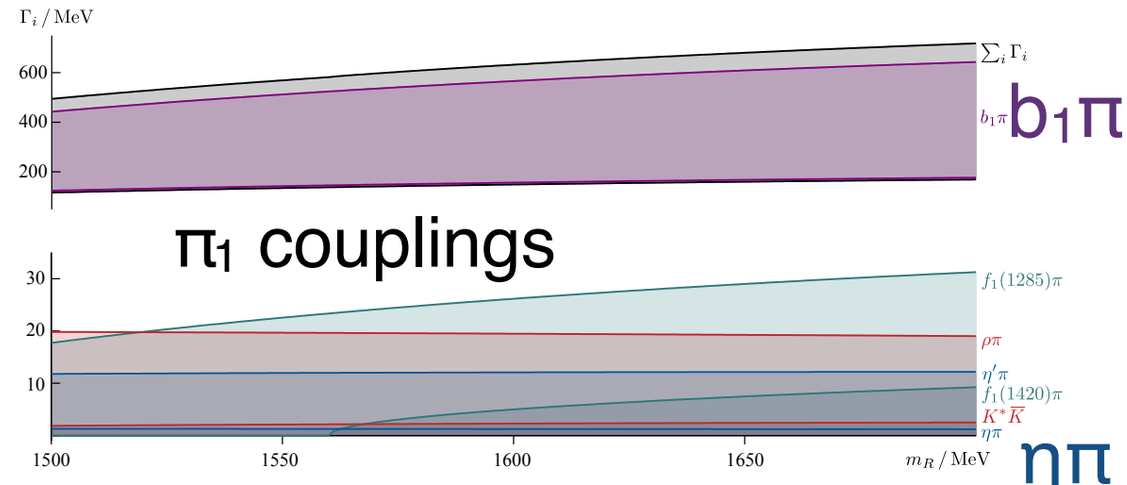




**GlueX:** submitted to Phys. Rev.

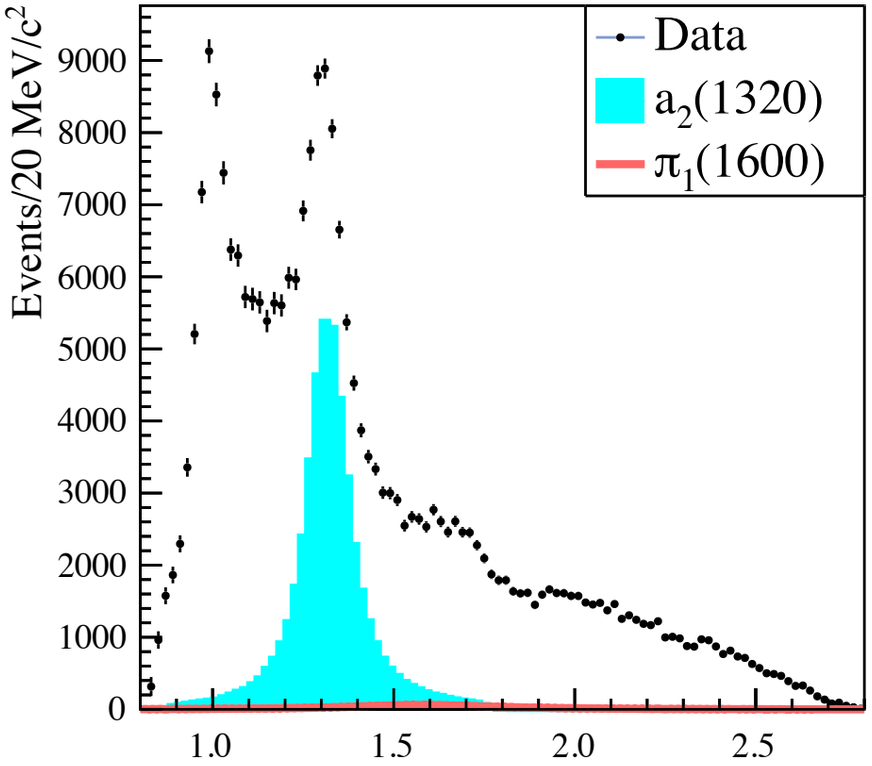
# Upper limits on $\pi_1(1600)$ contributions to $\eta^{(\prime)}\pi$

- Both $a_2(1320)$ and $\pi_1(1600)$ decay to $\eta^{(\prime)}\pi$ and $\omega\pi\pi$
- Used measurements of $dM/d\sigma$ for $\omega\pi\pi$ to set upper limit for $\pi_1(1600)$ contribution and project to $\eta^{(\prime)}\pi$
- $\pi_1(1600)$ could be dominant contribution to $\eta'\pi^0$

**HadSpec: PRD 103, 054502 (2021)**

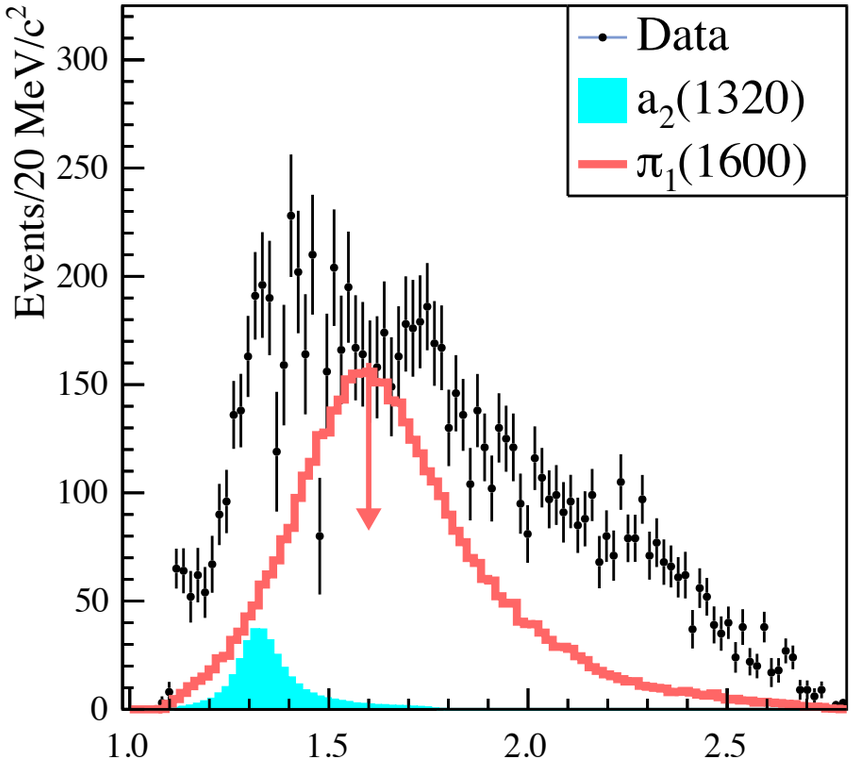



$$\gamma p \to \eta\pi^0 p$$




**GlueX:** Phys. Rev. Lett. 133, 261903 (2024)

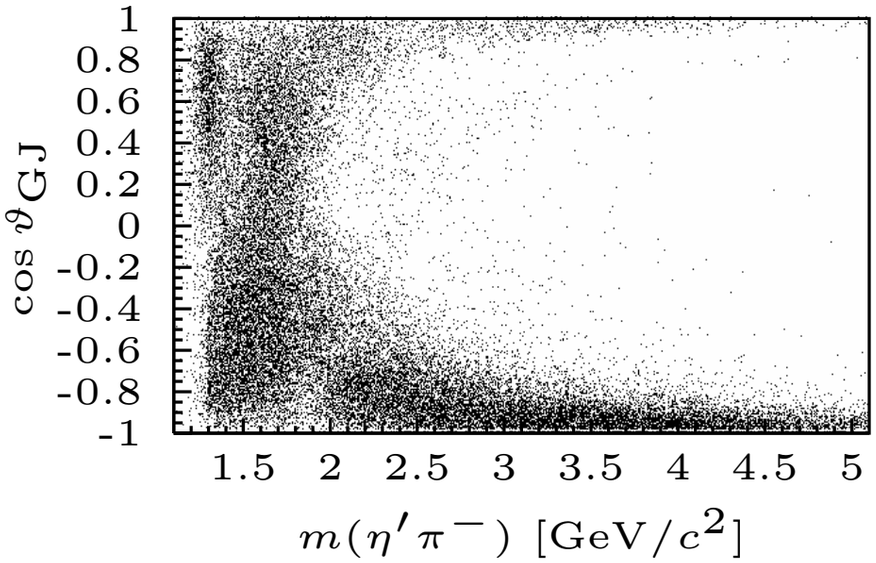
$$\gamma p \to \eta'\pi^0 p$$



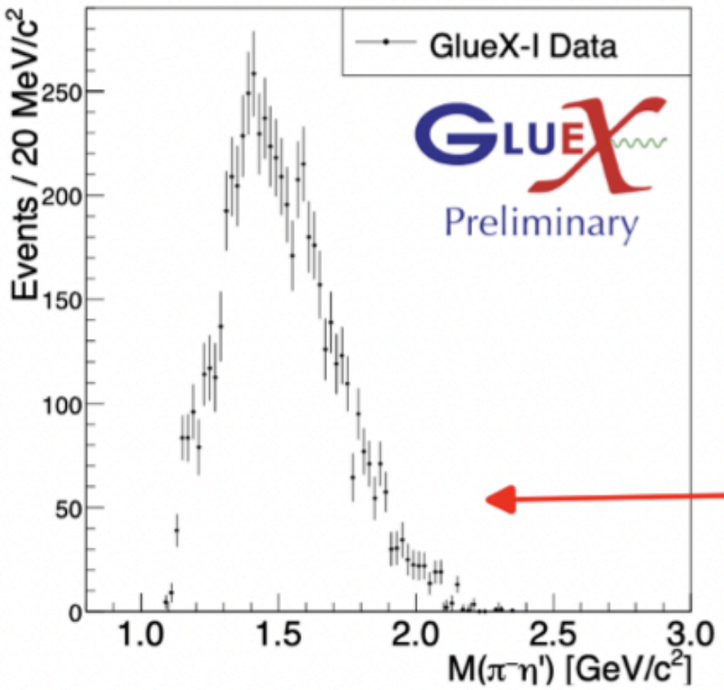
# First look at $\gamma p \to \eta' \pi^- \Delta^{++}$

- Study of $\eta'\pi$ mass vs. $\cos\theta_{\mathrm{GJ}}$ illustrates population of different partial waves
- Clear forward/backward asymmetry, similar to COMPASS measurement
- Steady progress in amplitude and moment analysis

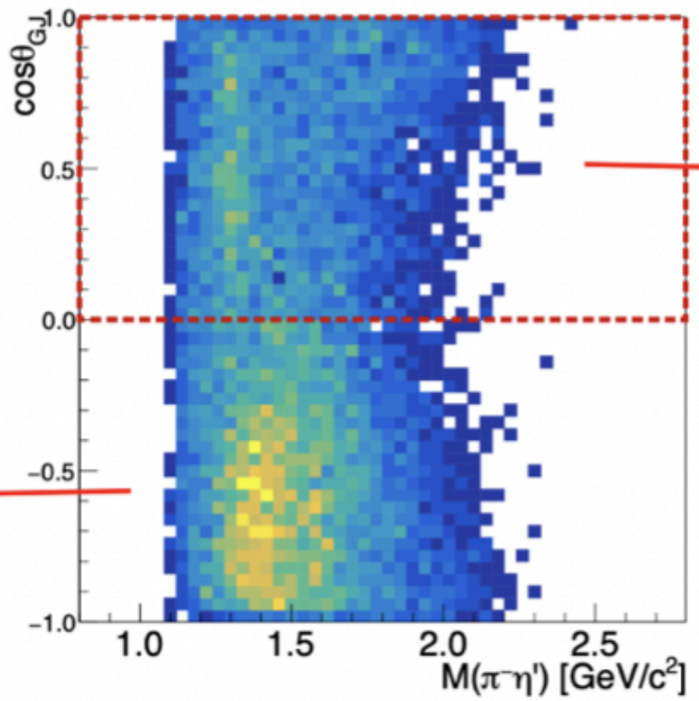
**COMPASS: PLB 740, 303 (2015)**



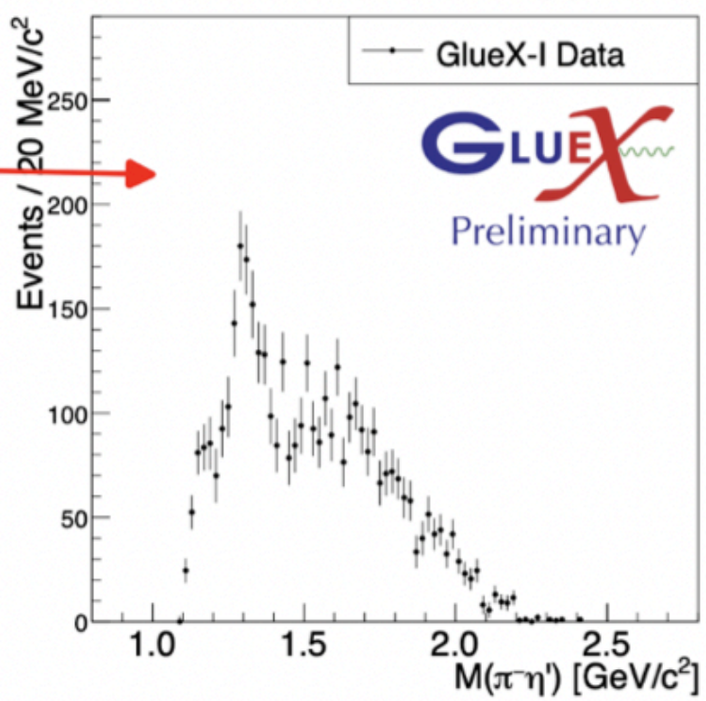

$m(\eta'\pi^-)$ for $\cos\theta^{\eta'}_{\mathrm{GJ}} < 0$



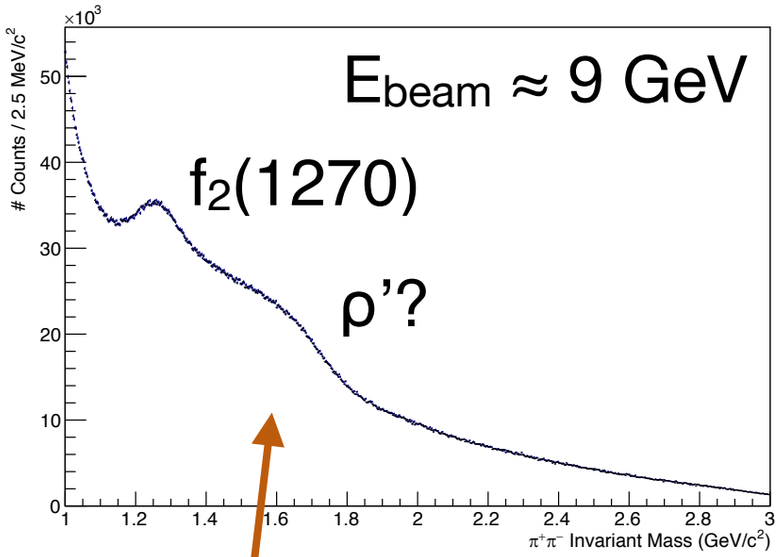

$\cos\theta^{\eta'}_{\mathrm{GJ}}$ vs. $m(\eta'\pi^-)$

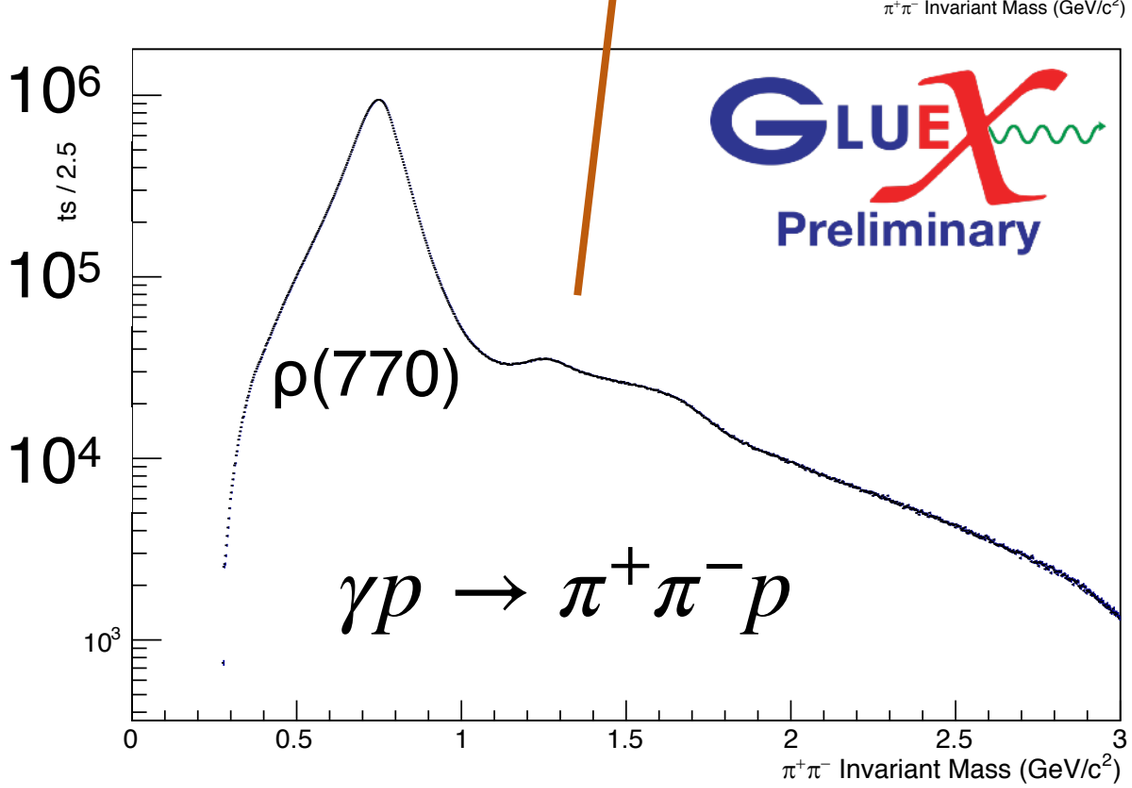



$m(\eta'\pi^-)$ for $\cos\theta^{\eta'}_{\mathrm{GJ}} > 0$

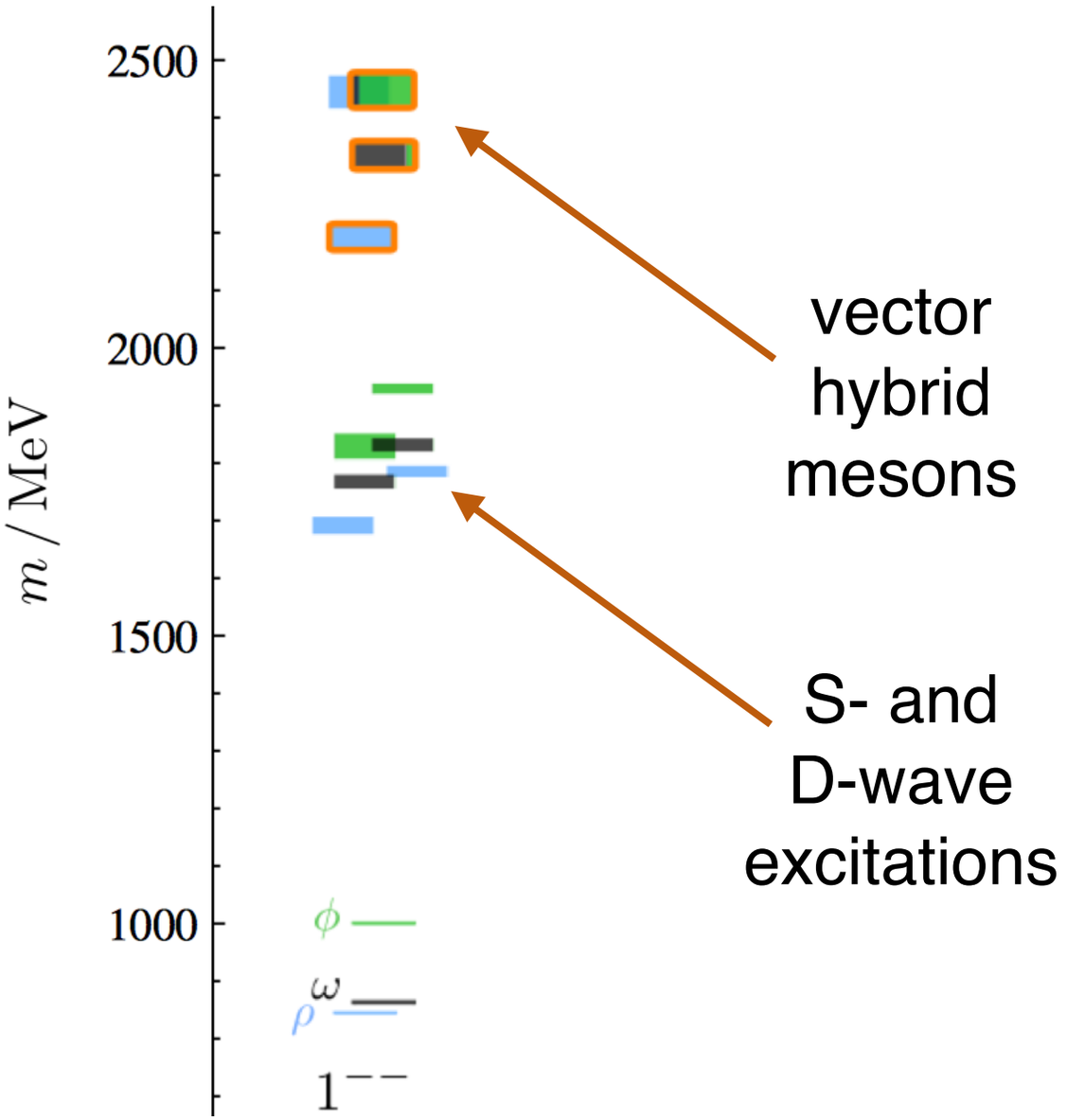


# Excited Vectors and Photoproduction



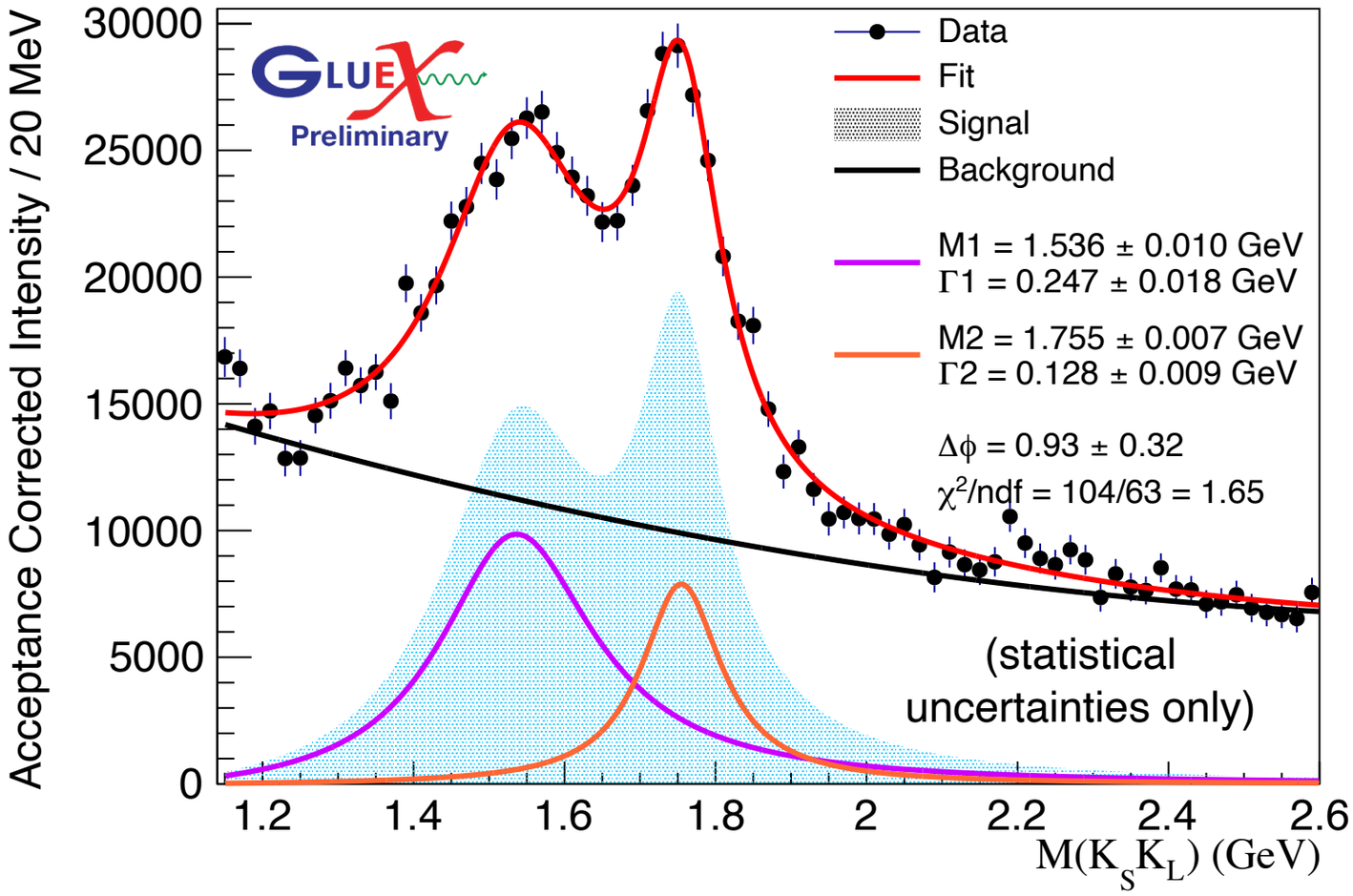

- Vector mesons have same QNs as photons, should be strongly excited in photoproduction
- Hybrid mesons with vector QNs are predicted



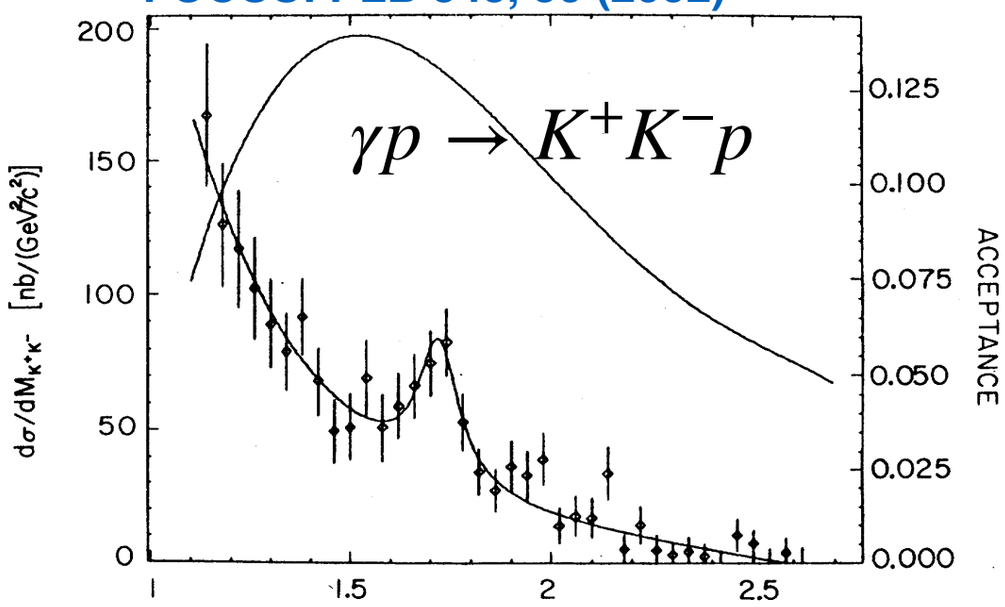

**HadSpec: PRD 88, 094505 (2013)**

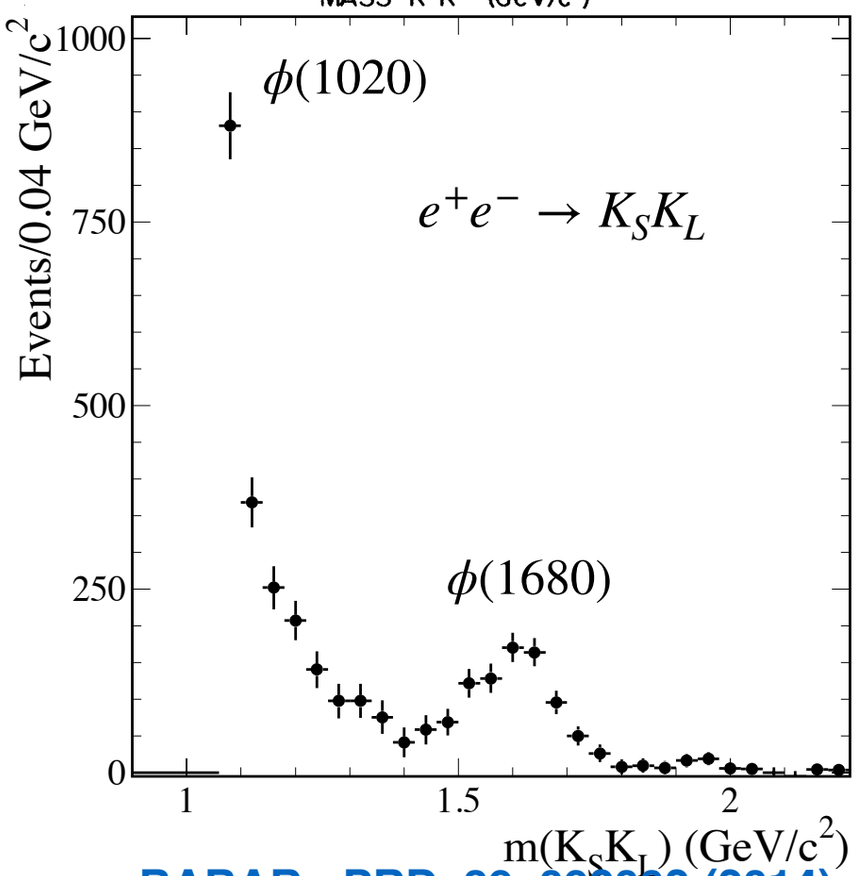
# Excited Vectors in $K_S K_L$

- Study of $\gamma p \to K_S K_L p$ populates $J^{PC} = \text{odd}^{--}$ mesons: $1^{--}$, $3^{--}$, …
- Two peaks fit well by sum of two Breit-Wigners
- Many candidate vectors in this mass region
- Plan to study $t$-dependence, PWA, …




FOCUS: PLB 545, 50 (2002)



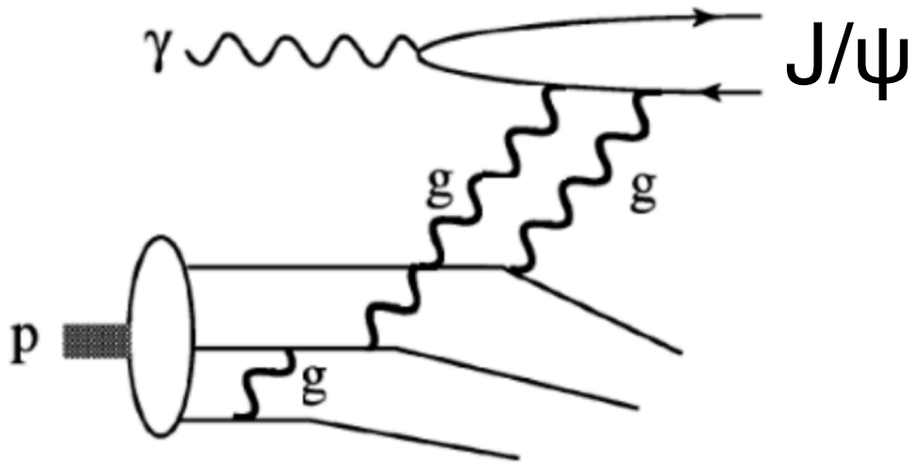




BABAR: PRD, 89, 092002 (2014)

# Charmonium Photoproduction Near Threshold

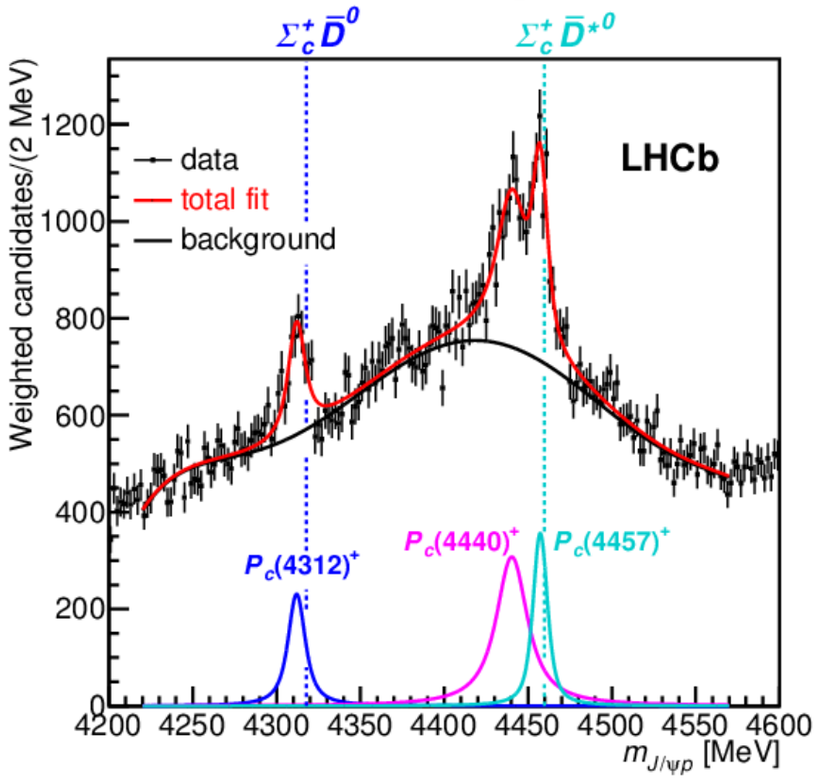
- Production of $c\bar{c}$ near threshold probes the distribution of gluons in the proton and the nature of the proton mass
- Can also look for s-channel production of resonant states

See talk by S. Joosten, Sat. 8:30 am

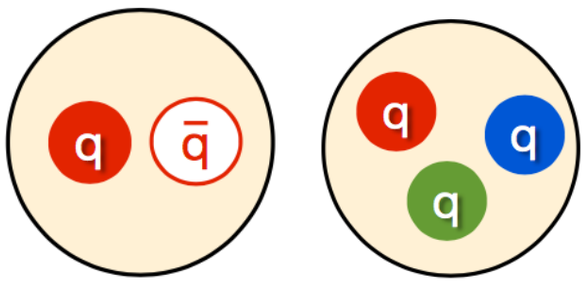



leading-twist

## $\Lambda_b \to J/\psi\, p\, K^-$

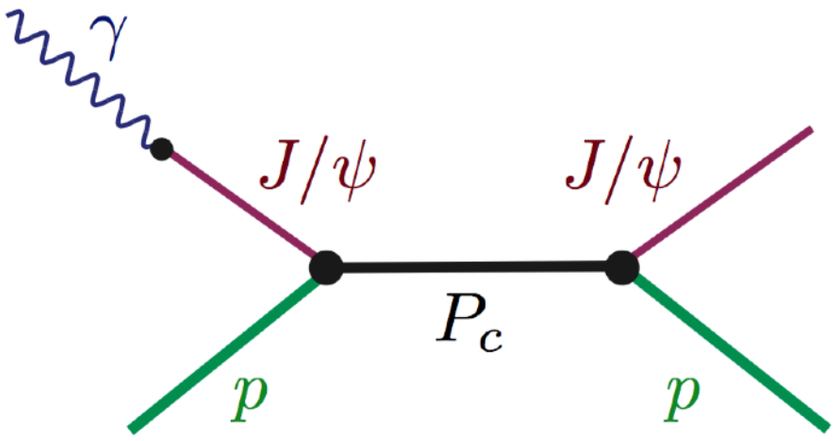



**LHCb, PRL 122, 222001 (2019)**



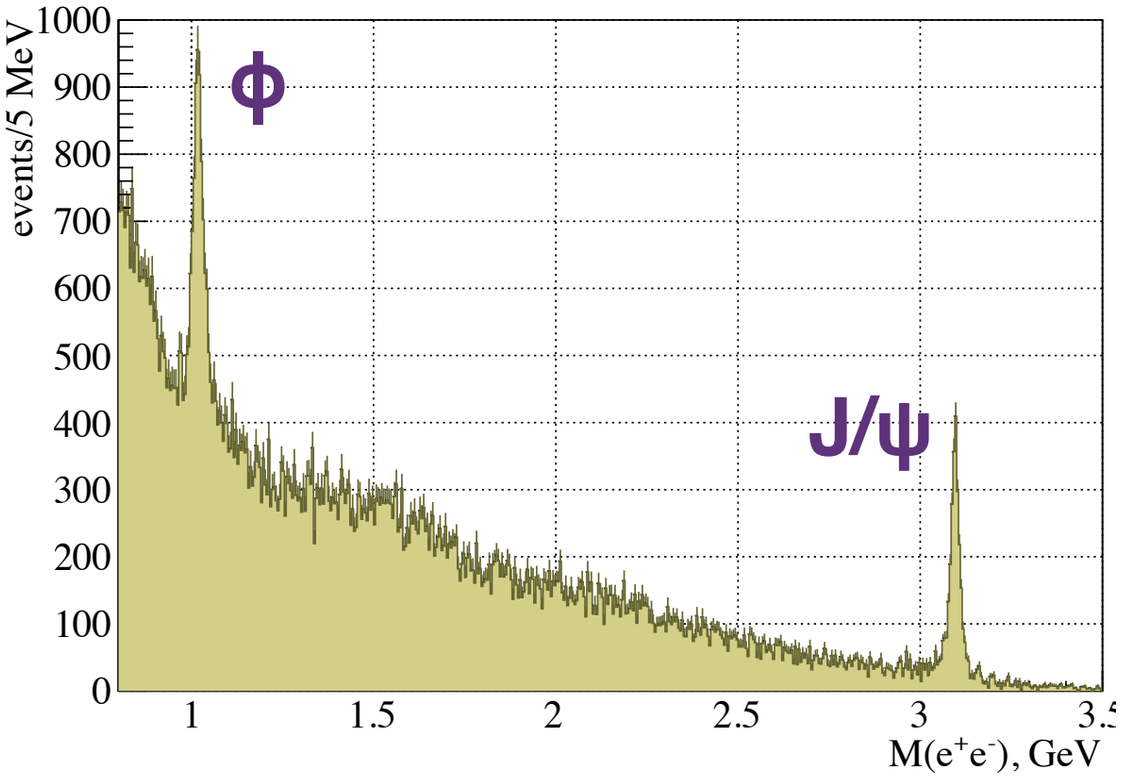

**hadronic molecule?**

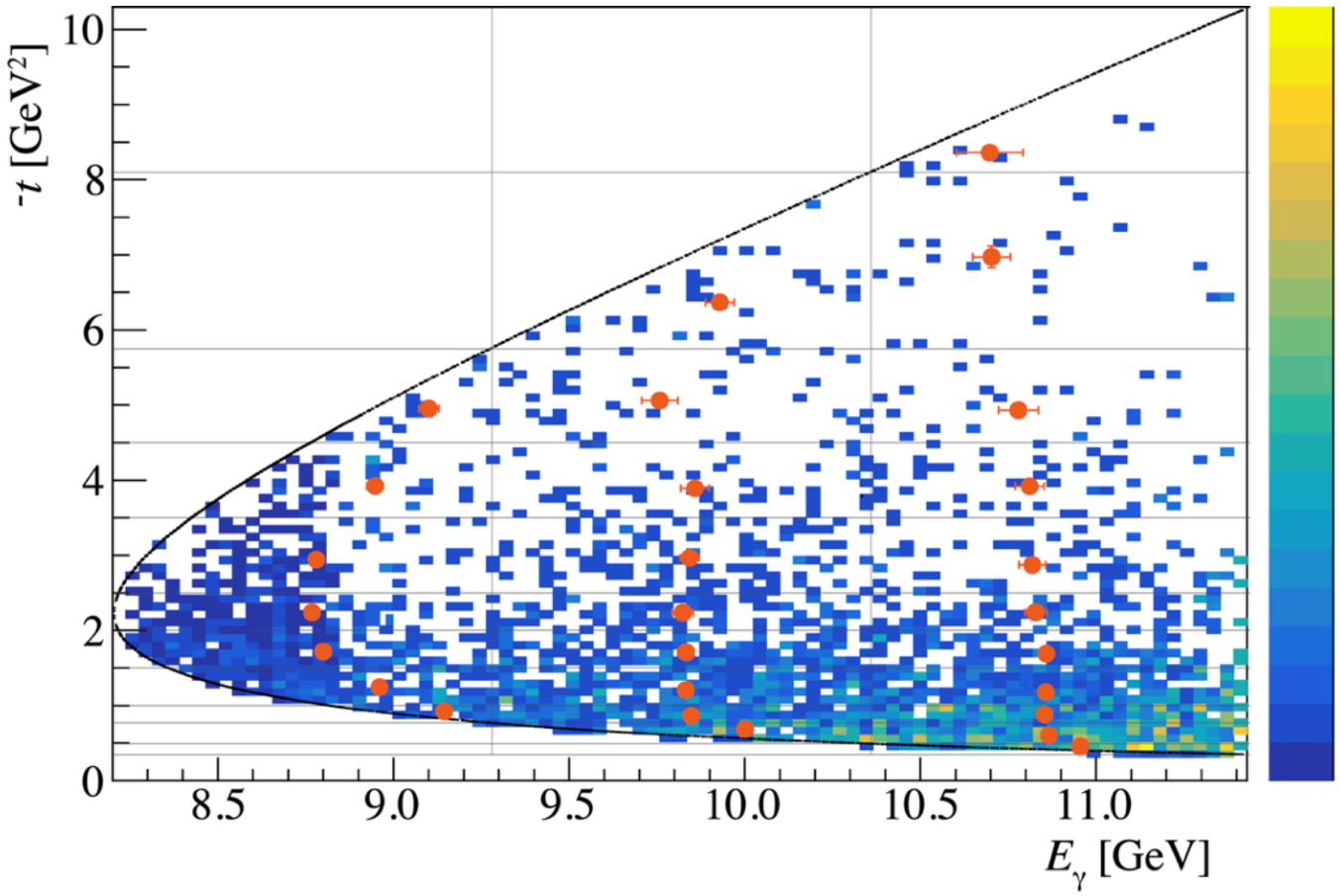

**pentaquark?**




**γ p → $P_c$ → J/ψ p**

# J/ψ Photoproduction at GlueX: Mass Spectrum



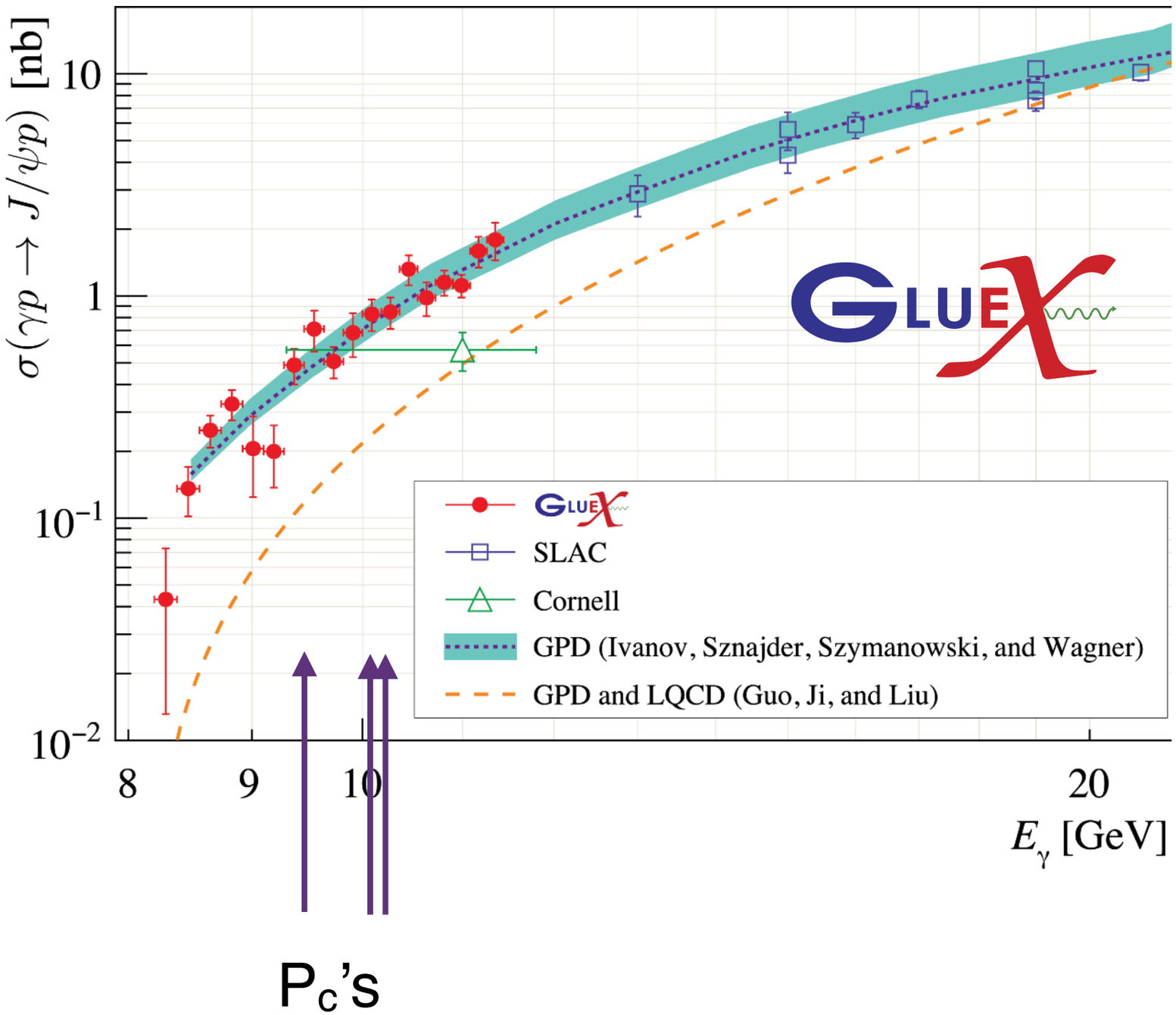




- Reconstruct **p γ → p + J/ψ, J/ψ → e⁺e⁻**
- Calculate J/ψ cross sections normalized by non-resonant e⁺e⁻
- Full kinematic coverage

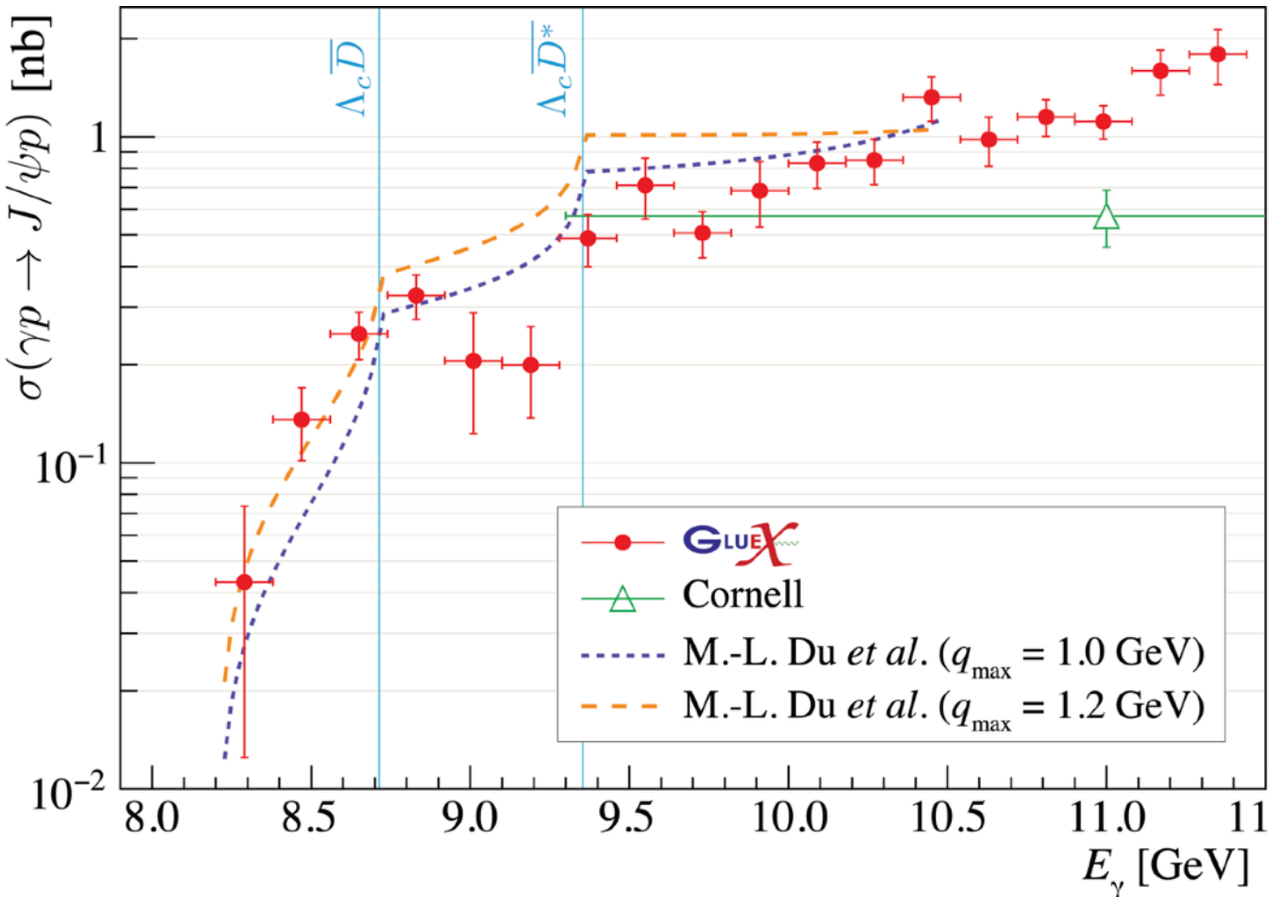
# Latest GlueX-I $J/\psi \to e^+e^-$ Photoproduction Results

- Full GlueX-I data yields $2270 \pm 58$ J/ψ's
- Overall normalization uncertainty ~20%
- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance
- No evidence of narrow $P_c$ production, tension with molecular interpretation?
- Differential cross sections generally consistent with expectations of gluonic exchange, except near threshold

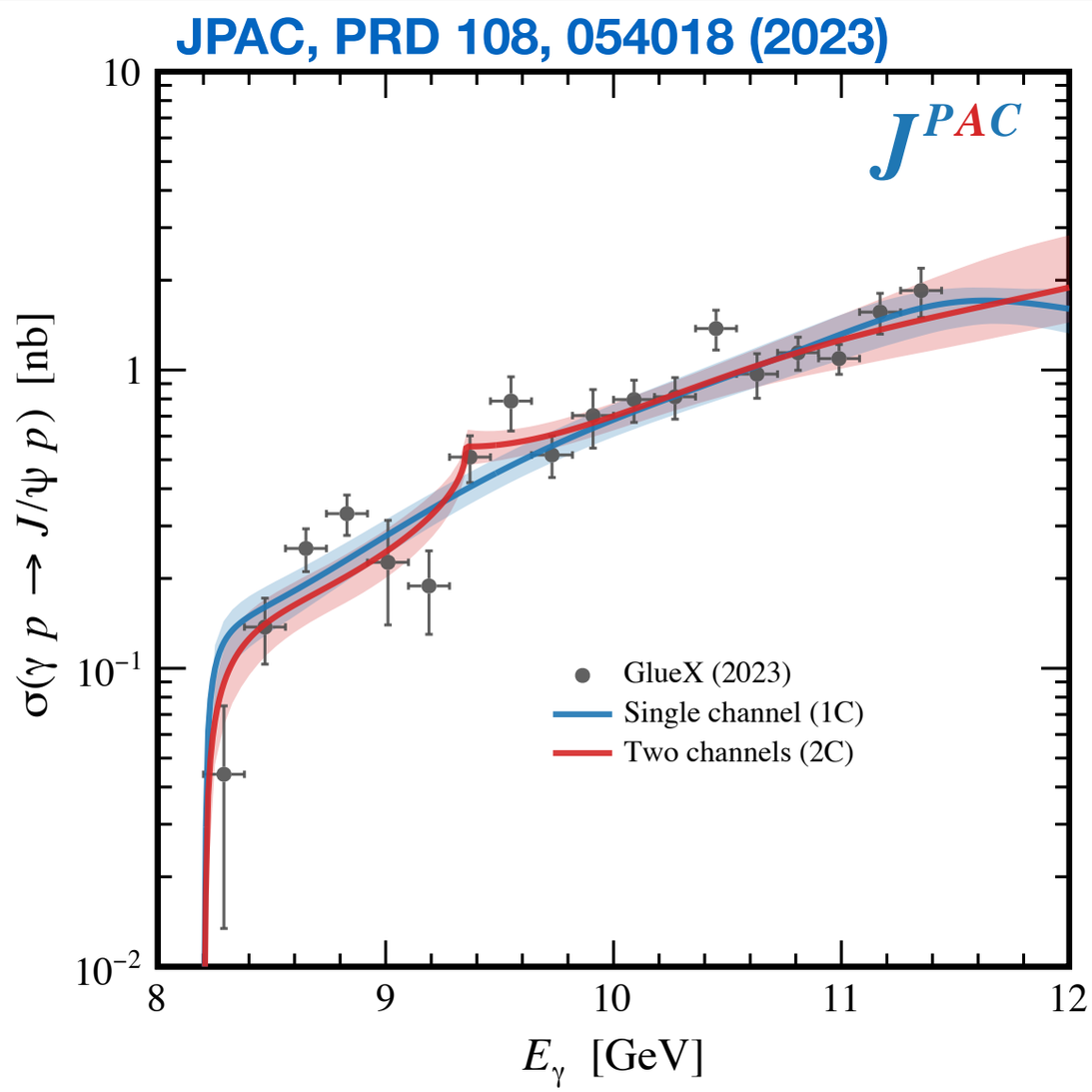
GlueX, PRC 108, 025201 (2023)



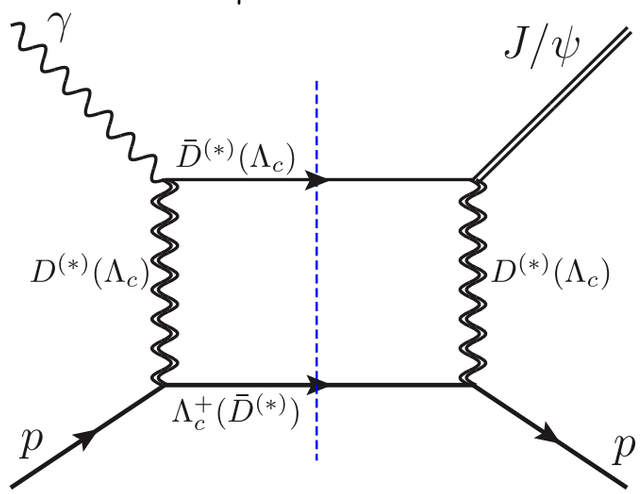
# Threshold Effects?



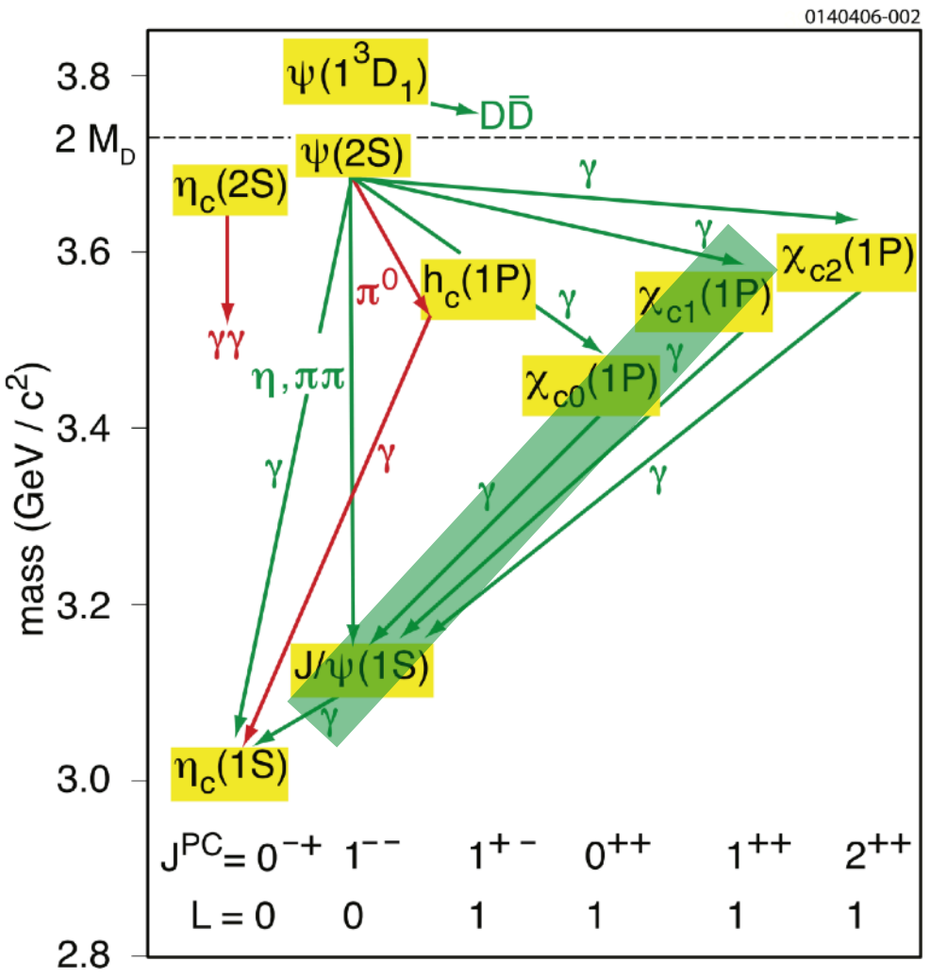

GlueX PRC 108, 025201 (2023)
Du et al., EPJC 80, 1053 (2020)

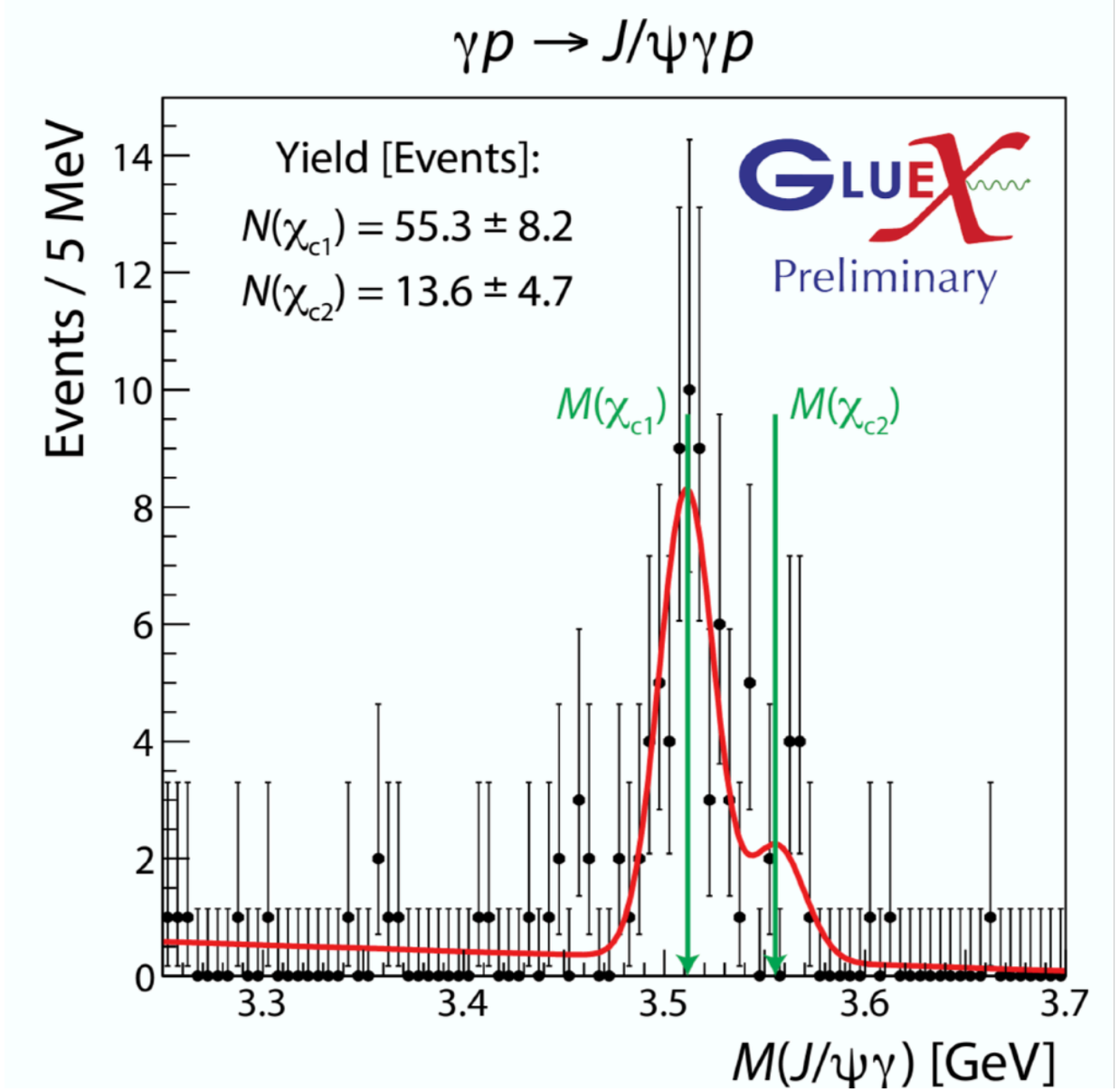



- Structures seen near open-charm thresholds
- More precision required — GlueX-II will provide factor ~3 more data
- Efforts underway to search for $\gamma p \to \overline{D}^{(*)}\Lambda_c^+$



# $\chi_{c1}(1^3P_1)$ Photoproduction at GlueX

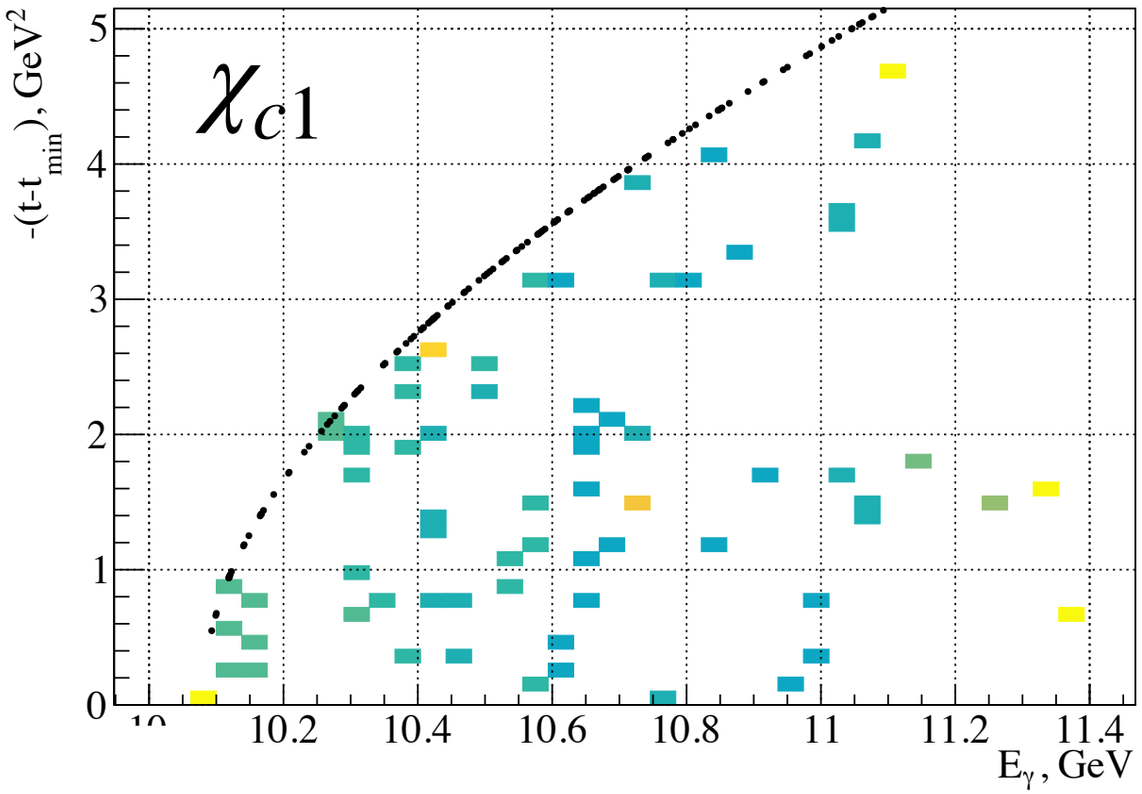


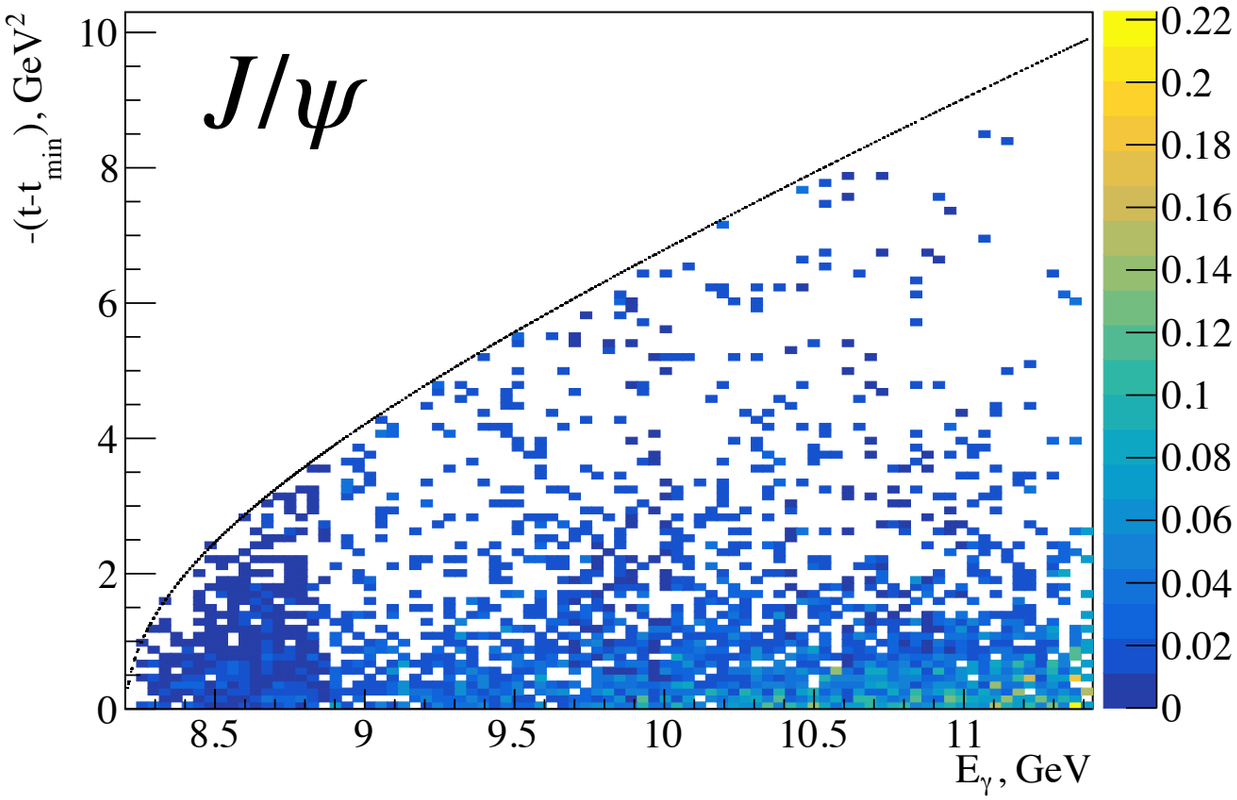



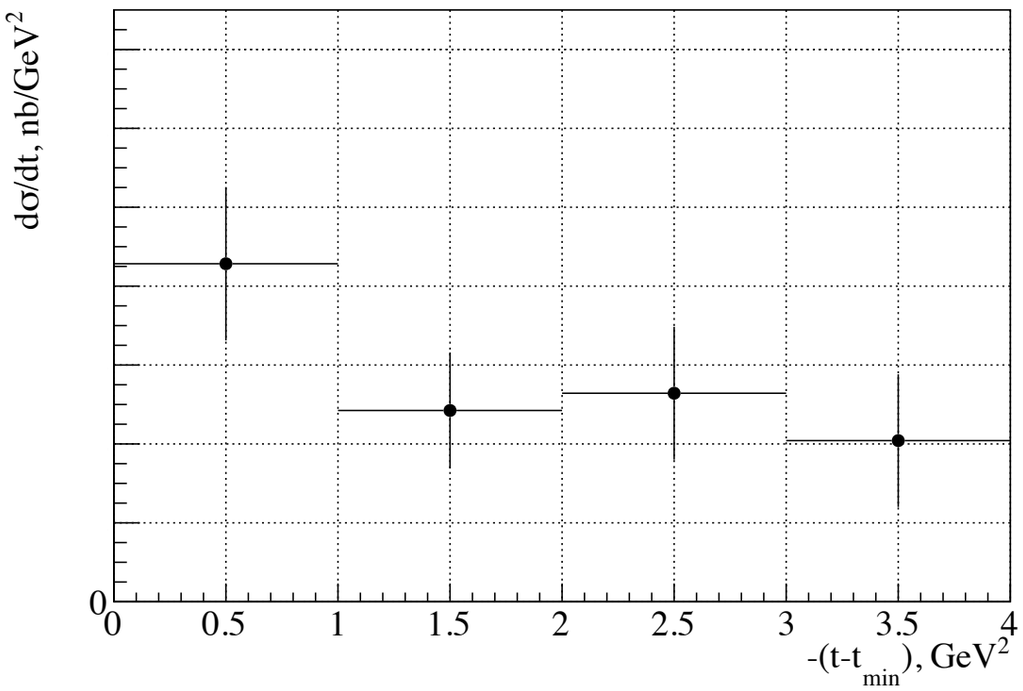

- $\chi_{c1}(1^{++})$ photoproduction: probe of different parity C=+
- Test of "Odderon-like" couplings and fixed-spin exchange models
- Look for $\gamma p \to \chi_{cJ} p \to (\gamma J/\psi) p \to (\gamma e^+ e^-) p$

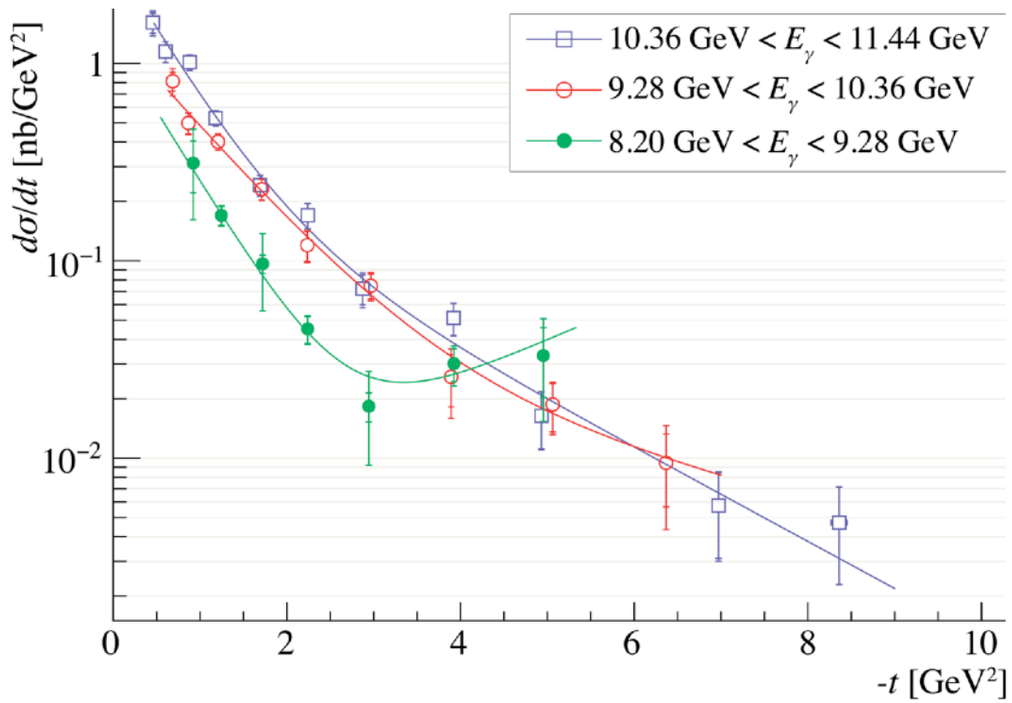
**JPAC, PRD 108, 054018 (2023)**

# $\chi_{c1}(1^3P_1)$ Photoproduction at GlueX



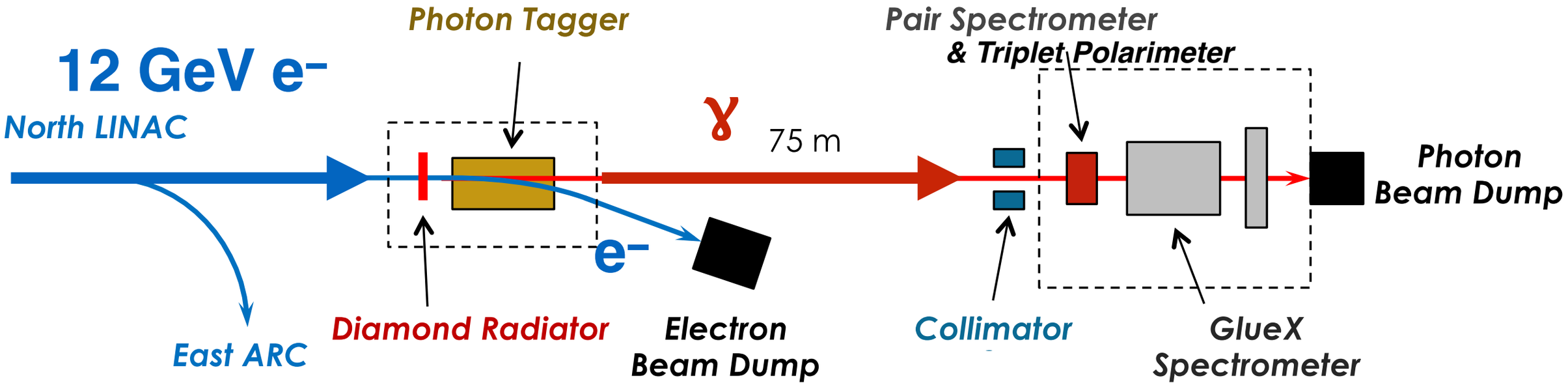
# Summary and Prospects

- Photoproduction is an interesting process to look for exotic hadrons — crucial to confirm their production in new processes
- GlueX has collected the world's largest photoproduction dataset
  - Collaboration with theory is crucial for understanding
- First amplitude analyses of $\eta\pi$ and $\eta'\pi$ aim to identify the $\pi_1$ in photoproduction
- Analysis of excited vectors promises to give new insight to their spectrum, first step towards looking for non-exotic QN hybrid mesons at GlueX
- First detailed studies of $J/\psi$ photoproduction near threshold
- GlueX-II run in progress, planned to end during 2026
  - Other approved experimental programs includes JLab Eta Factory, spectroscopy with intense $K_L$ beam ($\approx 10^4$/s), elliptically polarized photons, polarized target, higher-intensity GlueX-III…

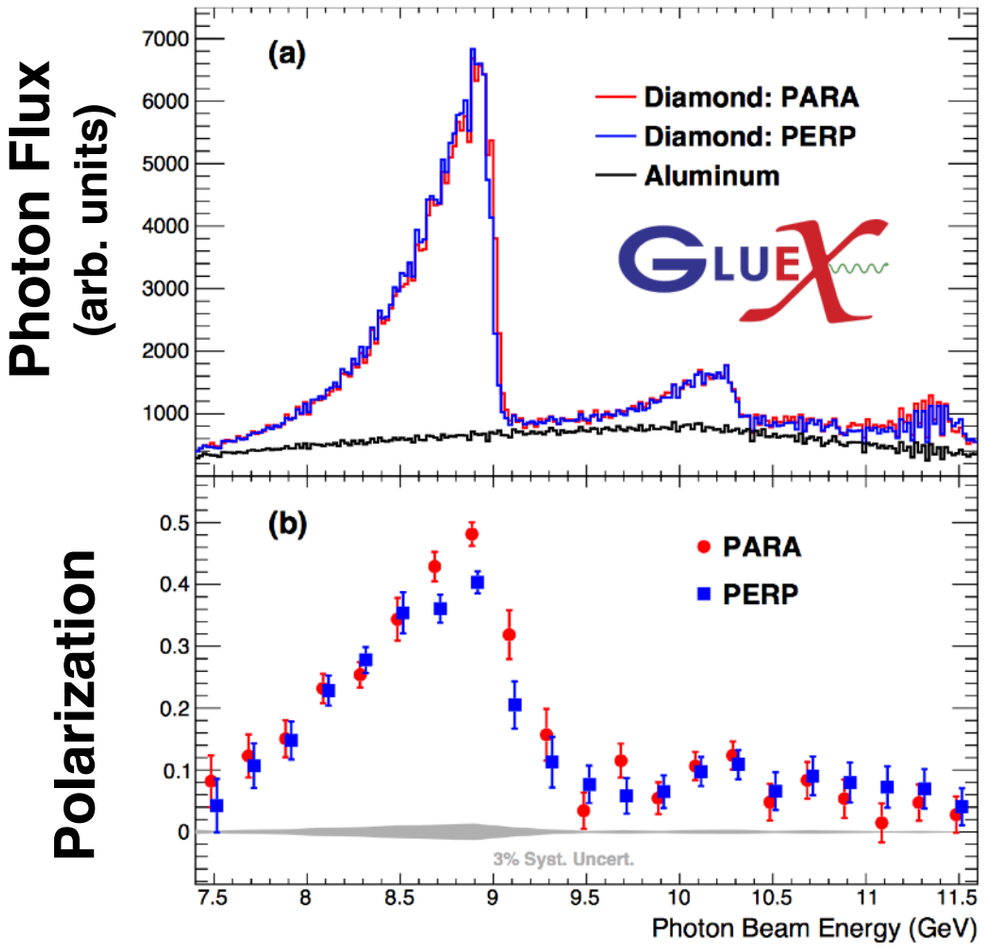
**GlueX acknowledges the support of several funding agencies and computing facilities: http://gluex.org/thanks**

# Backup Slides

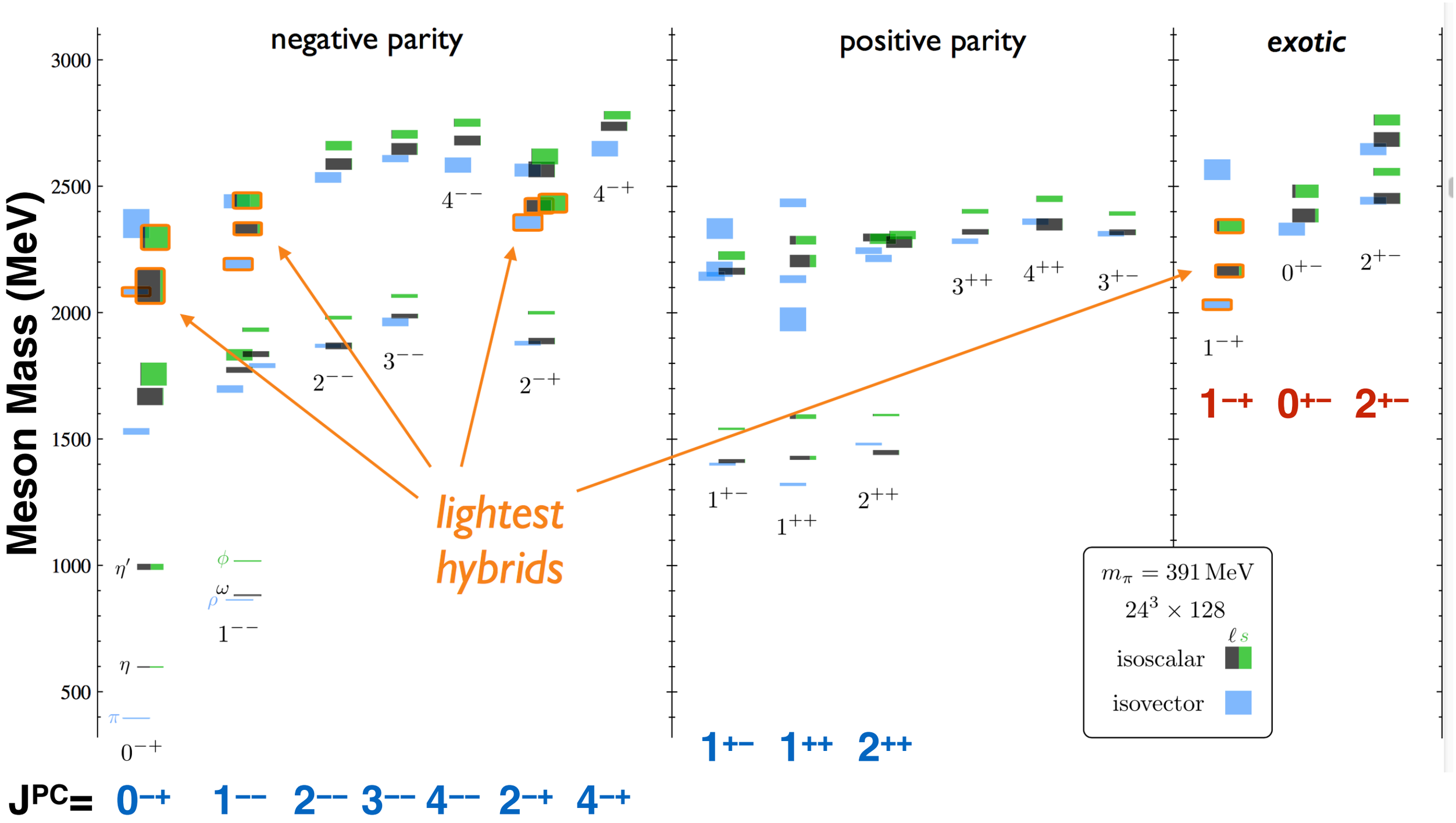
# The GlueX Experiment: Photon Beam




- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of ~1–5 $\times$ $10^7$ γ/s in peak

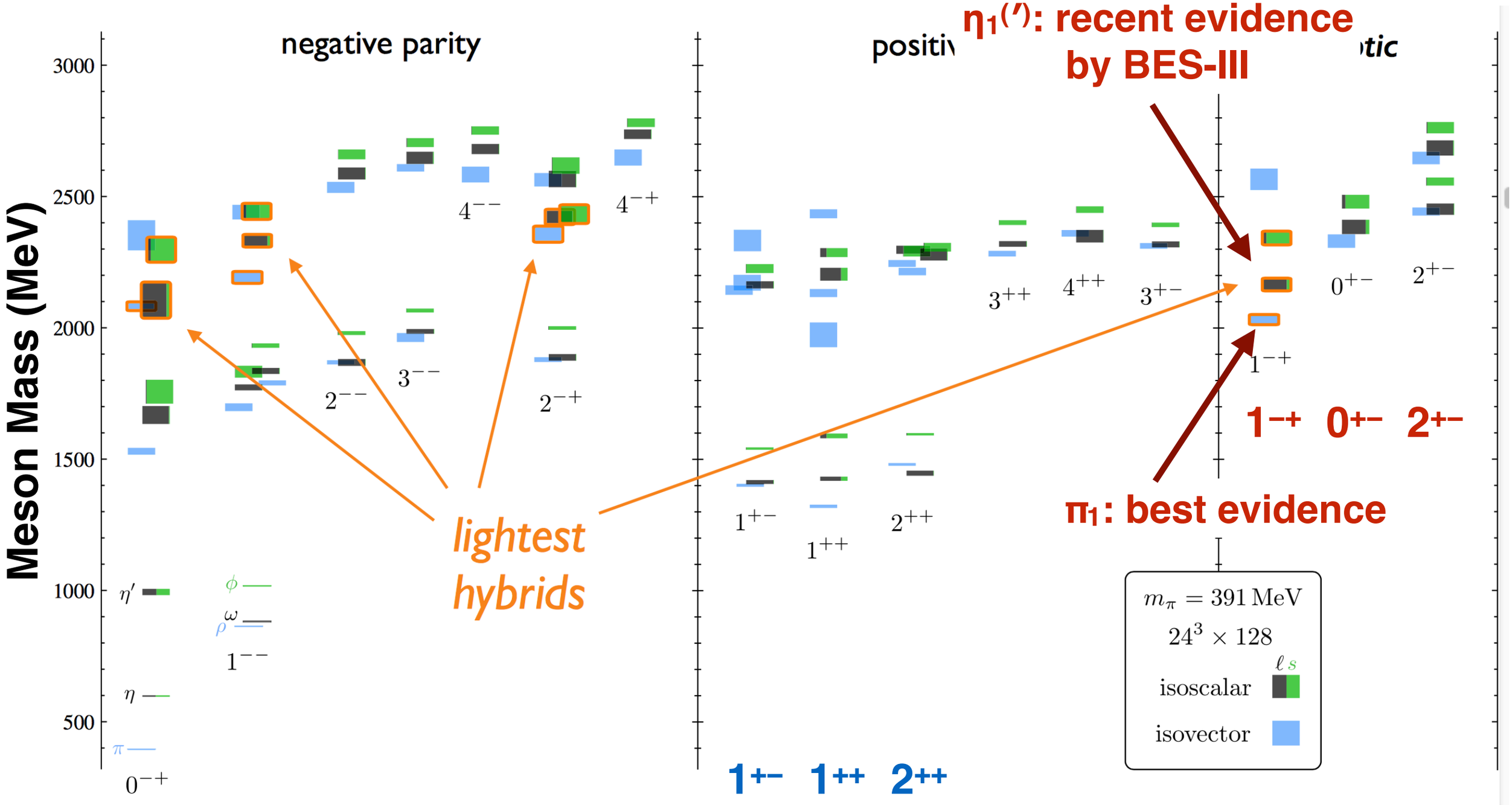


# Light Meson Spectrum from Lattice QCD



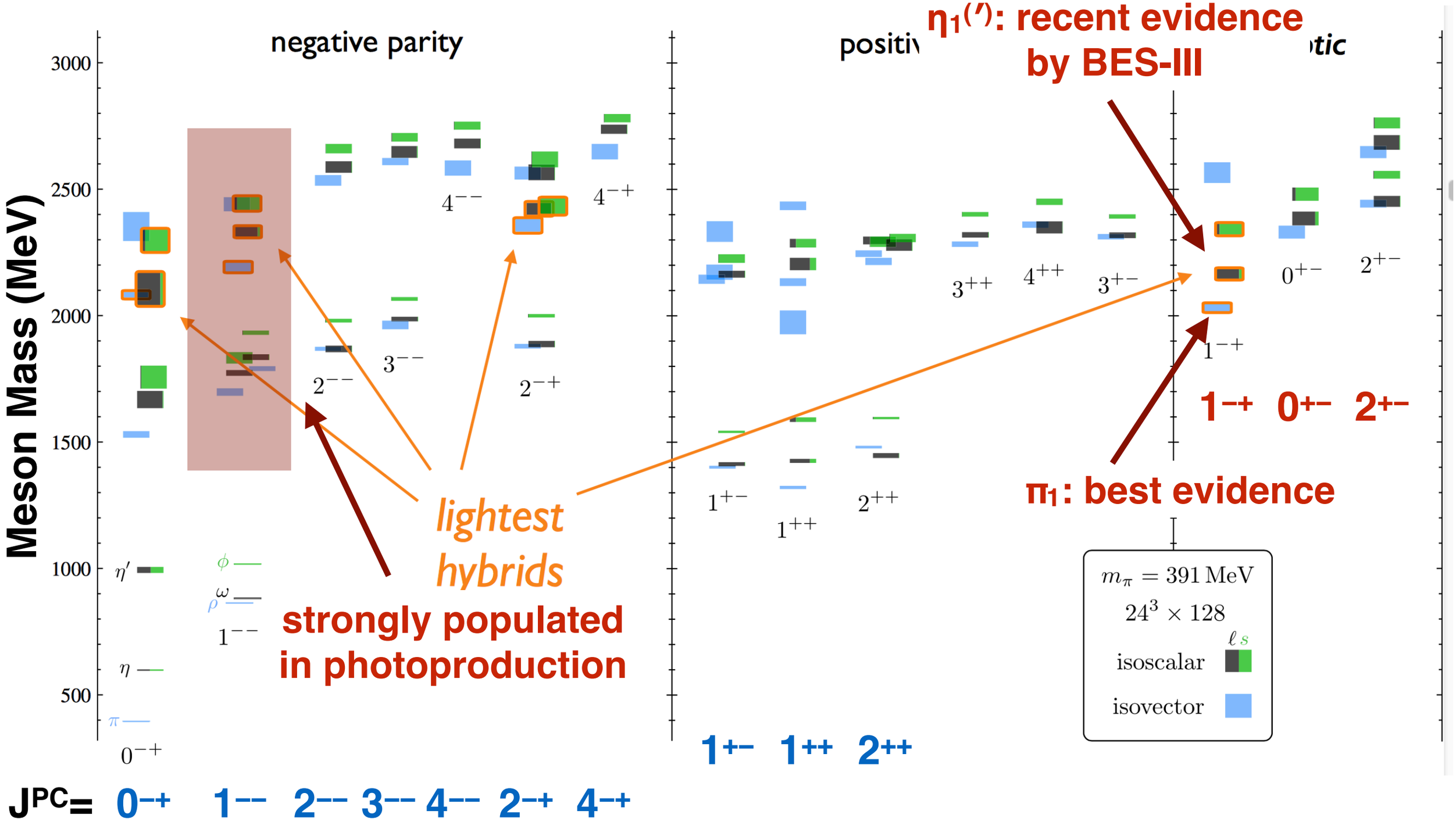

**HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)**

# Light Meson Spectrum from Lattice QCD




**HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)**

# Light Meson Spectrum from Lattice QCD




**HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)**

# Searching for Exotics in Photoproduction @ GlueX

GlueX Data

Pseudoscalar + Pseudoscalar
$\pi\pi$ / $K\bar{K}$ / $\pi\eta$ / $\pi\eta'$ / $\eta\eta'$

Vector + Pseudoscalar
$\omega\pi$ / $\omega\eta$ / $\phi\pi$ / $\phi\eta$ / $\phi\omega$

3-body final states
$\eta\pi\pi$ / $K\bar{K}\pi$ / …

Complexity

## Possible Exotic Hybrid Meson Decays

$\pi_1$: $\eta\pi$ / $\eta'\pi$, $\eta_1$: $\eta\eta'$

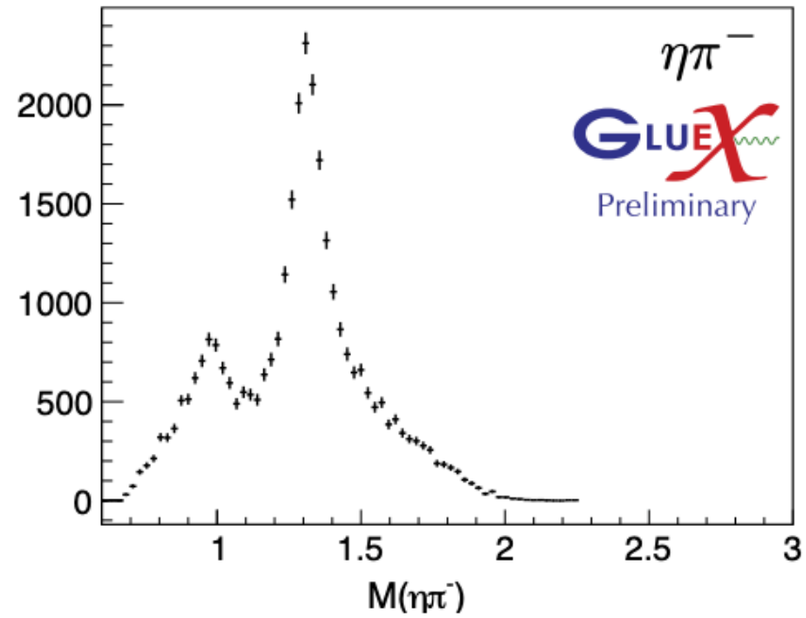
$h_2$,$\omega_0$: $\omega\eta$, $h_2'$,$\phi_0$: $\phi\eta$
$\rho_0$: $\omega\pi$, $\phi\pi$

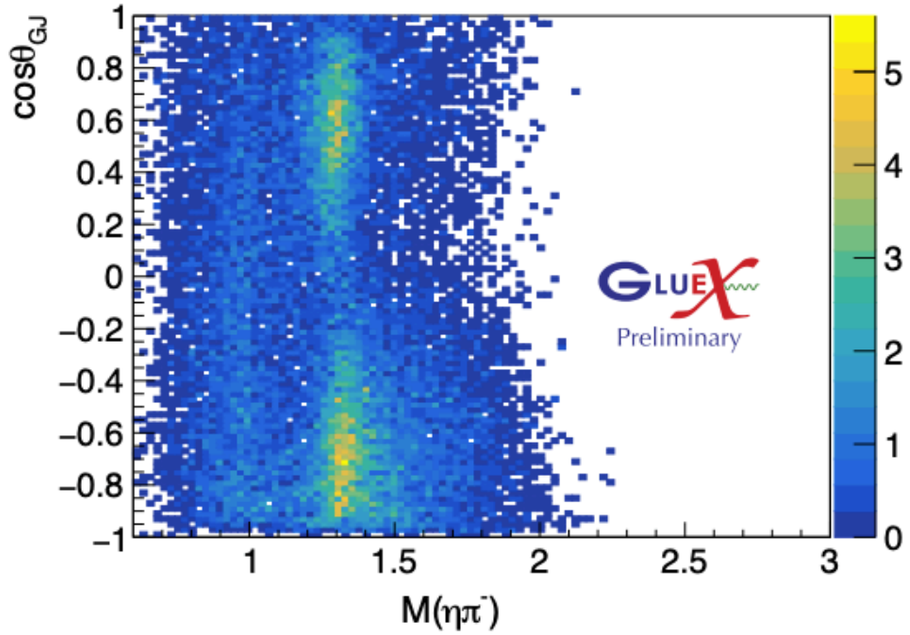
$\eta_1$,$b_2$: $\eta\pi\pi$, $\eta_1'$,$h_2'$: $KK\pi$

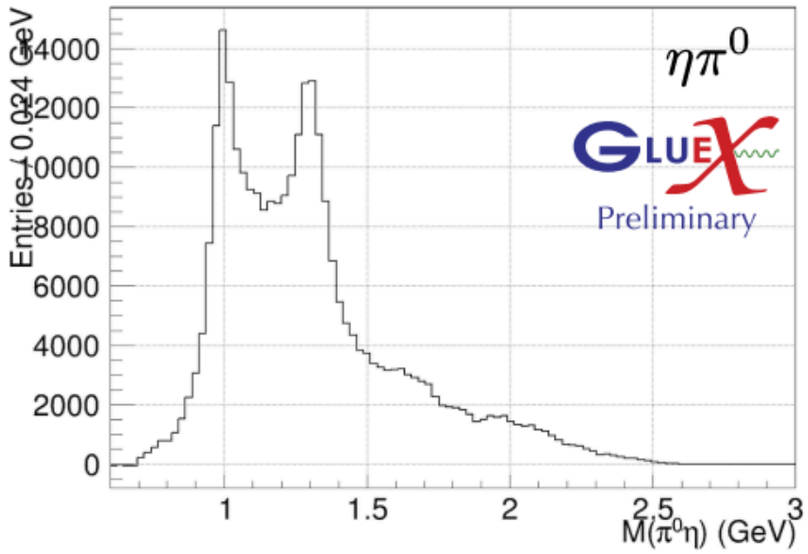
# ηπ Amplitude Analysis at GlueX

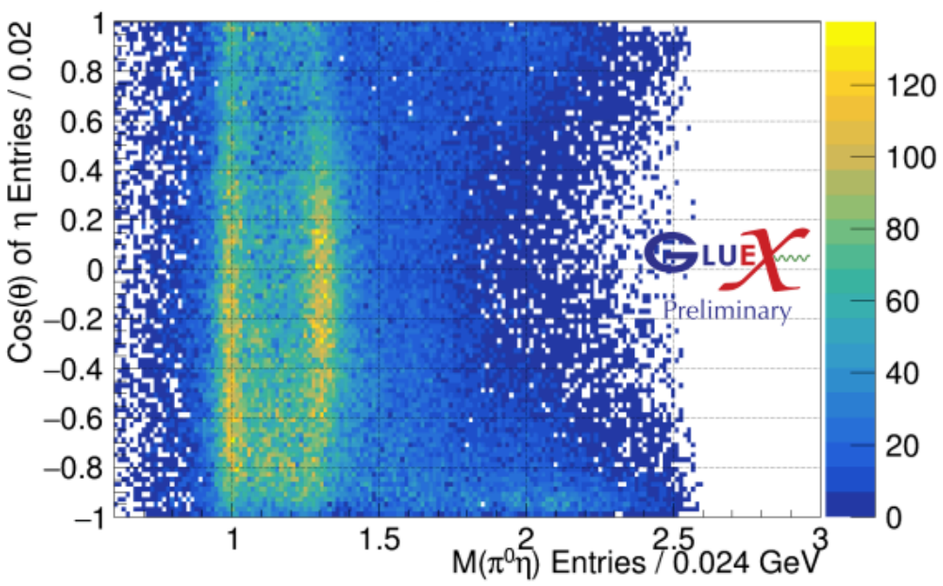
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- Different angular dependence → different dominant production wave
  - $D_1$ for $\eta\pi^-$, $D_2$ for $\eta\pi^0$

$$0.1 < -t < 0.3 \text{ GeV}^2$$



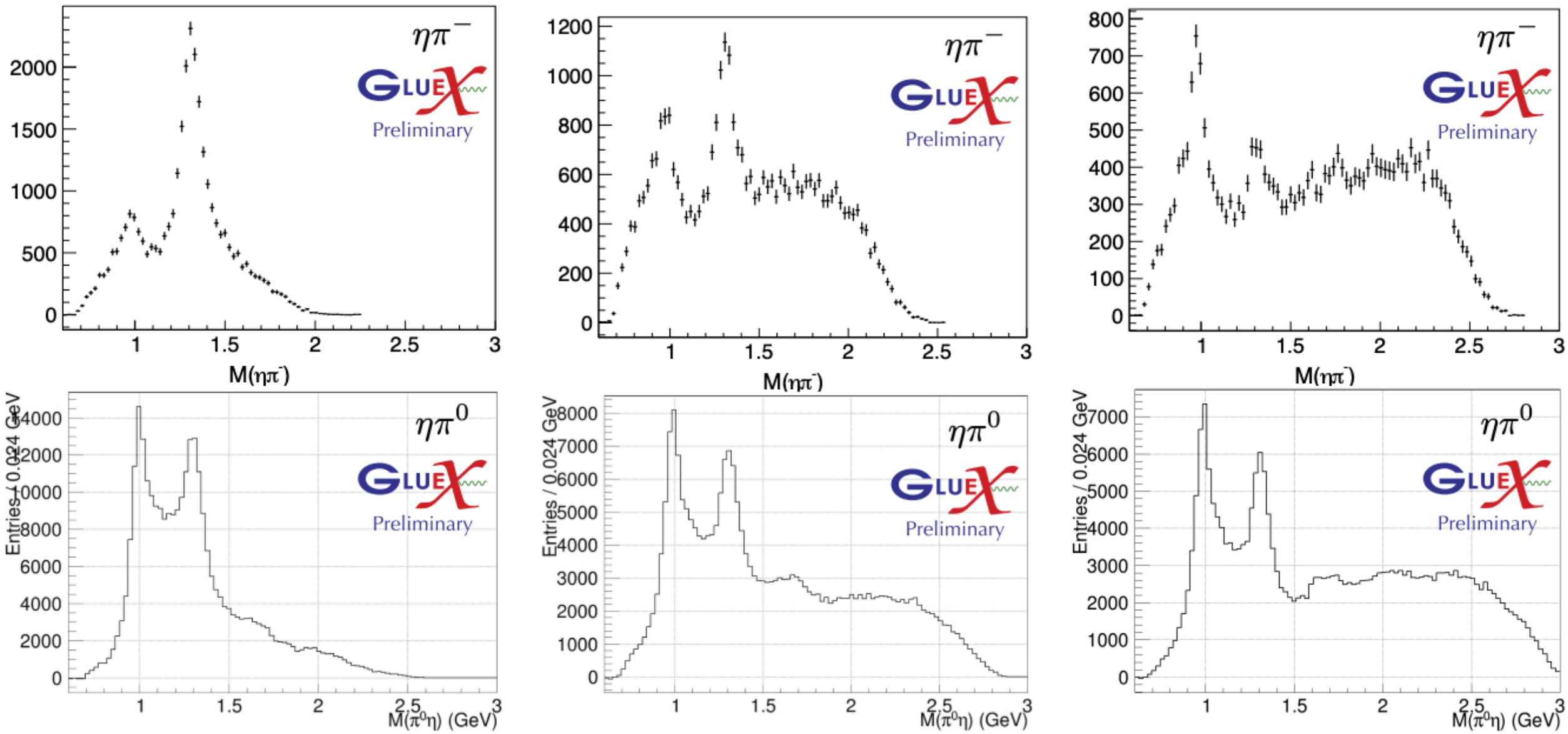



# ηπ Amplitude Analysis at GlueX

- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
  - Peaks have different t-dependence

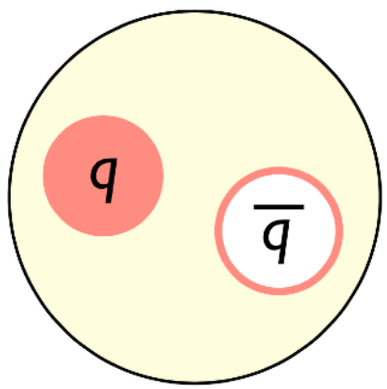
$0.1 < -t < 0.3$ GeV$^2$ | $0.3 < -t < 0.6$ GeV$^2$ | $0.6 < -t < 1.0$ GeV$^2$



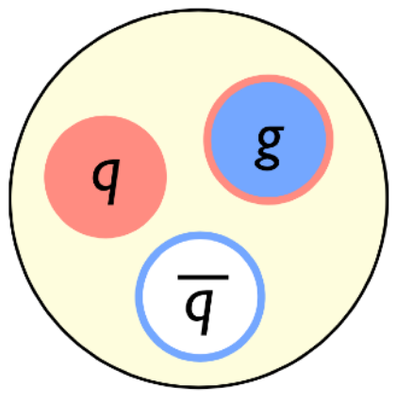
# Searching For Hybrid Mesons

- Mesons grouped into nonets of similar $J^{PC}$
  - Must establish quantum numbers and pole parameters through amplitude analysis
- Meson QNs
  - Allowed: $0^{-+}$, $0^{++}$, $1^{--}$, $1^{+-}$, $2^{++}$, $2^{-+}$,…
  - Forbidden: $0^{--}$, $0^{+-}$, $1^{-+}$, $2^{+-}$, …
- Hybrid Meson QNs
  - $0^{-+}$, $0^{+-}$, $1^{--}$, $1^{-+}$, $2^{-+}$, $2^{+-}$, …
- Hybrid mesons can be found with **normal** and **exotic** quantum numbers

$J=L+S \quad P=(-1)^{L+1} \quad C=(-1)^{L+S}$




"Normal" Meson




$(J^{PC})_g = 1^{+-}$

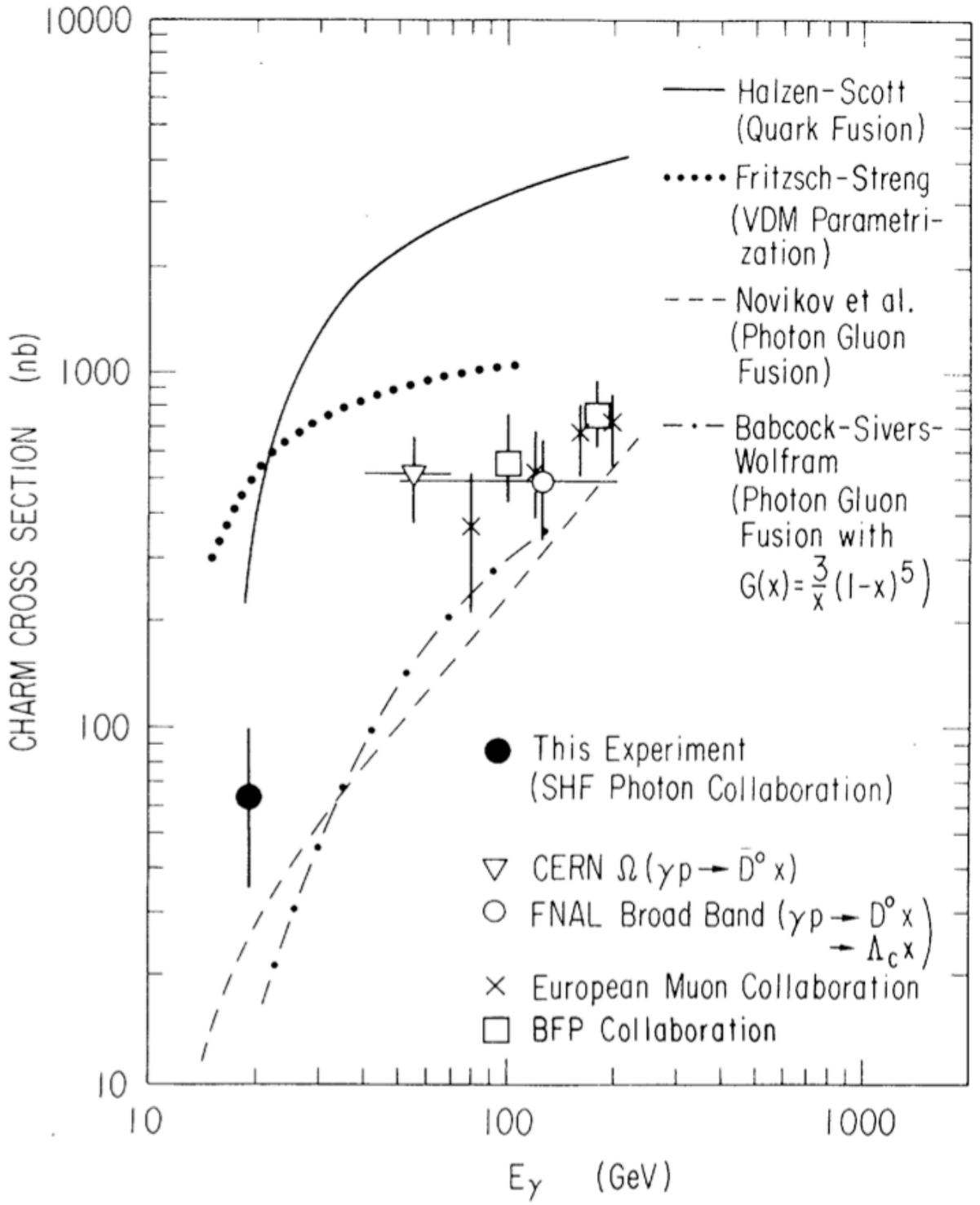
"Hybrid" Meson

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

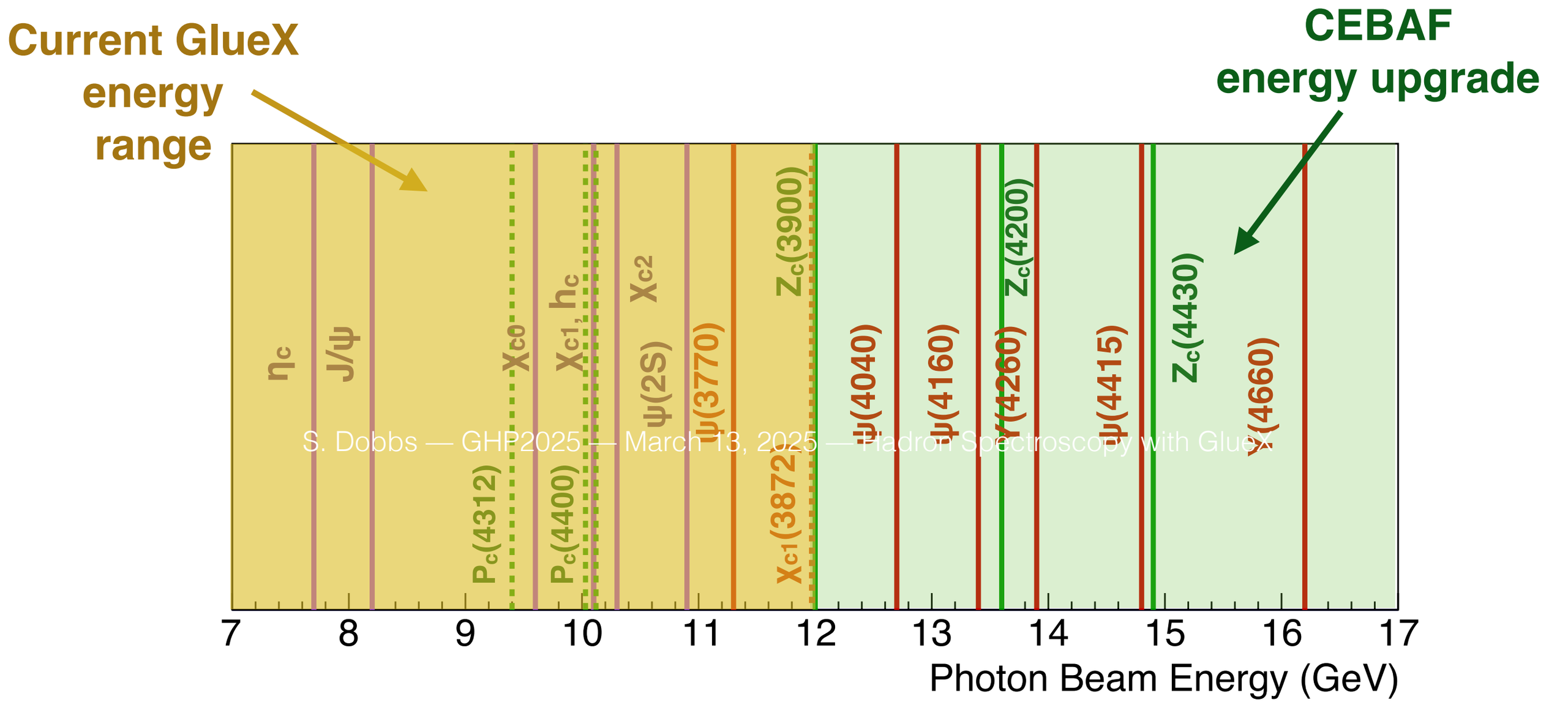
# Open Charm Production Near Threshold

- Hadron ($c\bar{c}$) molecules like to decay to open-charm final states, can we see them at GlueX? (c.f. LHCb)
  - Also will help with J/ψ interpretation
- Open charm photoproduction cross section measured at SLAC for $E_\gamma \approx 20$ GeV based on ~50 events
  - Roughly 5-10 larger than J/ψ cross section
  - Exclusive reconstruction of e.g. $D^{(*)0}$ $\Lambda_c^+$ is a factor ≈ 25 lower due to b.f.s
- Expect with GlueX-I can set ULs of $\mathcal{O}(10\ \mathrm{nb})$
- Full GlueX-II statistics with improved π/K separation will give enhanced sensitivity

**PRL 51, 156 (1983)**



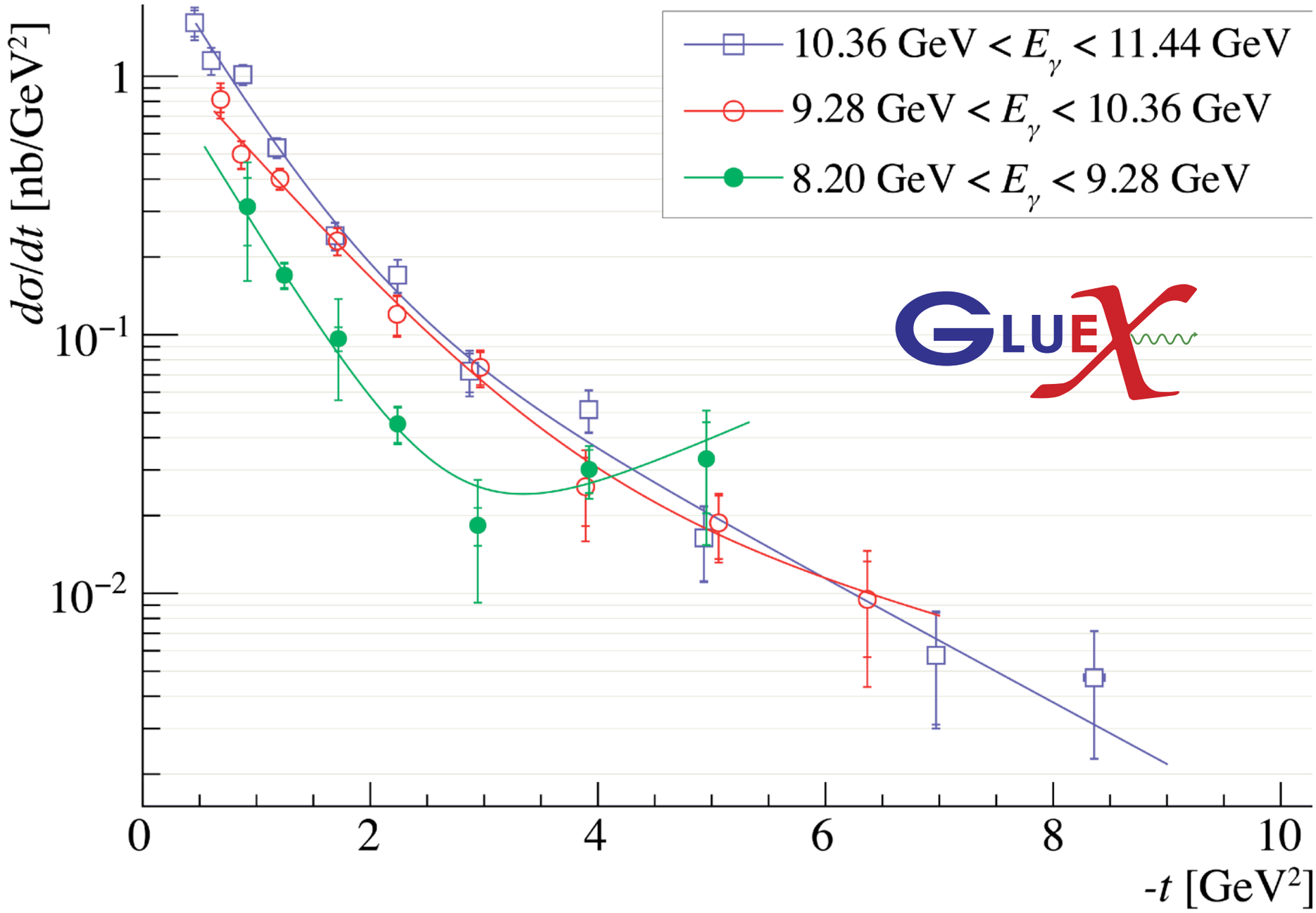
# Charmonium Photoproduction Near Threshold




S. Dobbs — GHP2025 — March 13, 2025 — Hadron Spectroscopy with GlueX

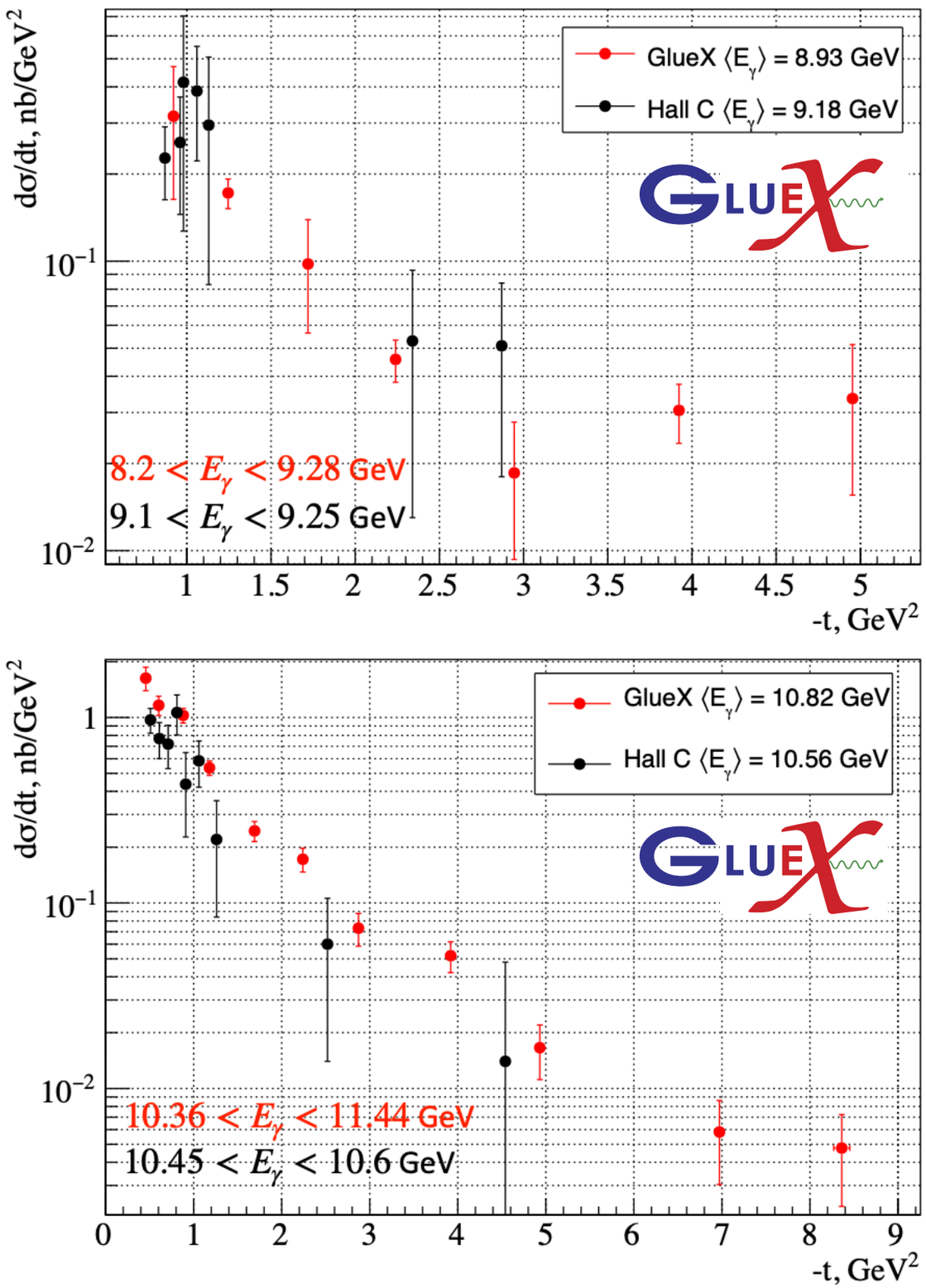
- Current max CEBAF energy allows study of bound $c\bar{c}$, $P_c$ states
- 17 GeV $e^-$ gives access to most exotic candidates
- 22 GeV e- gives good phasespace, linear polarization

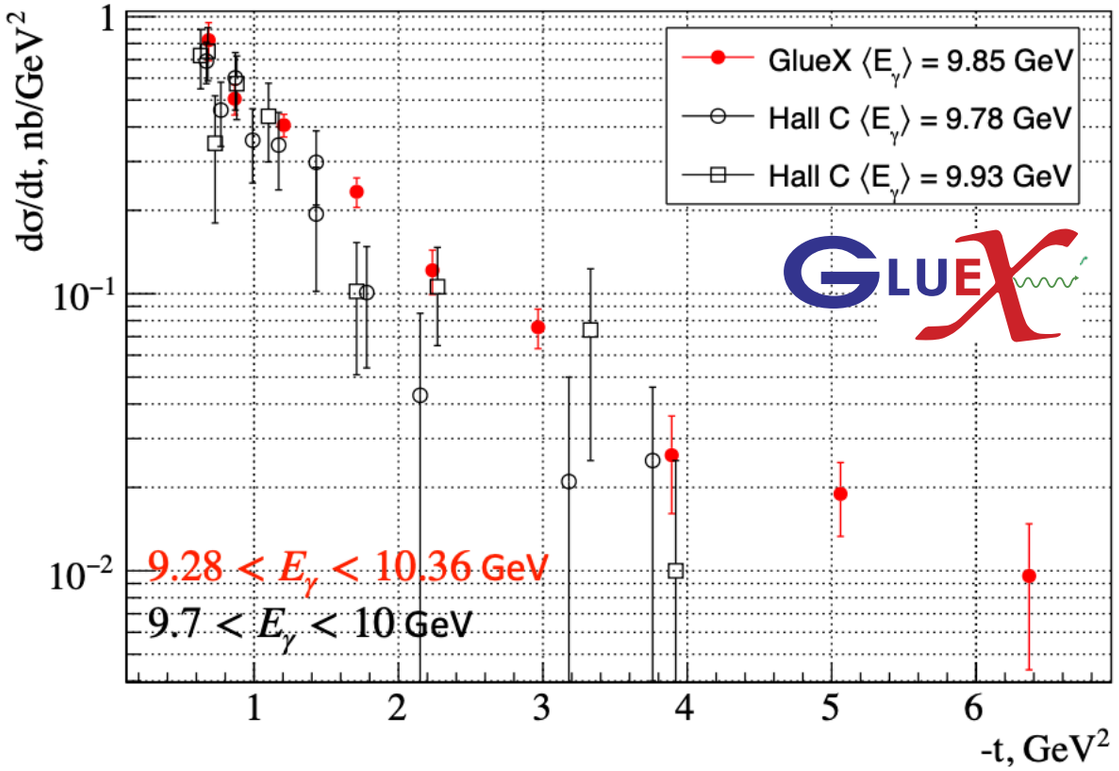
# GlueX-I J/ψ Differential Cross Sections




- Differential cross sections generally consistent with expectations of gluonic exchange, except near threshold

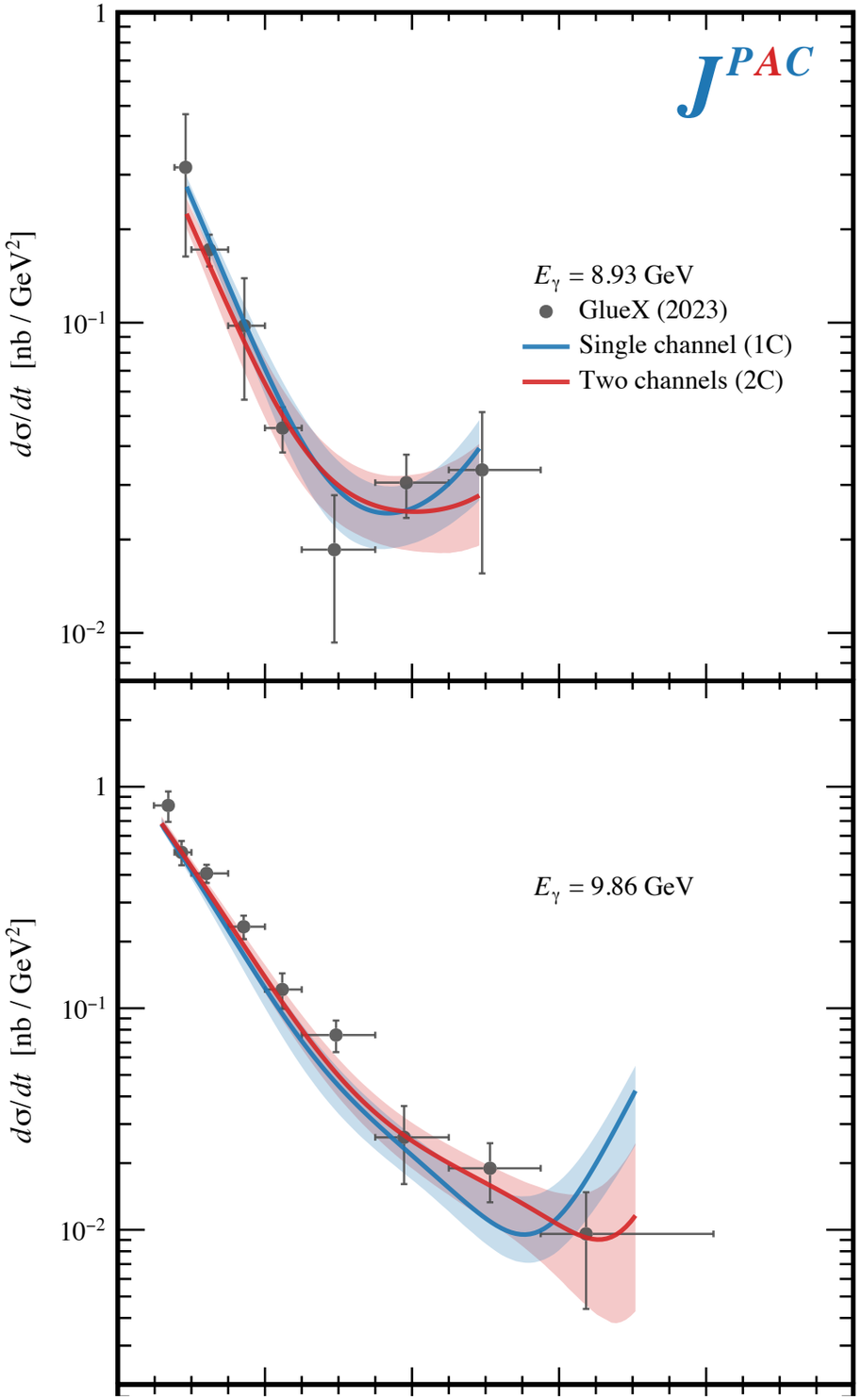
# GlueX-I J/ψ Differential Cross Sections



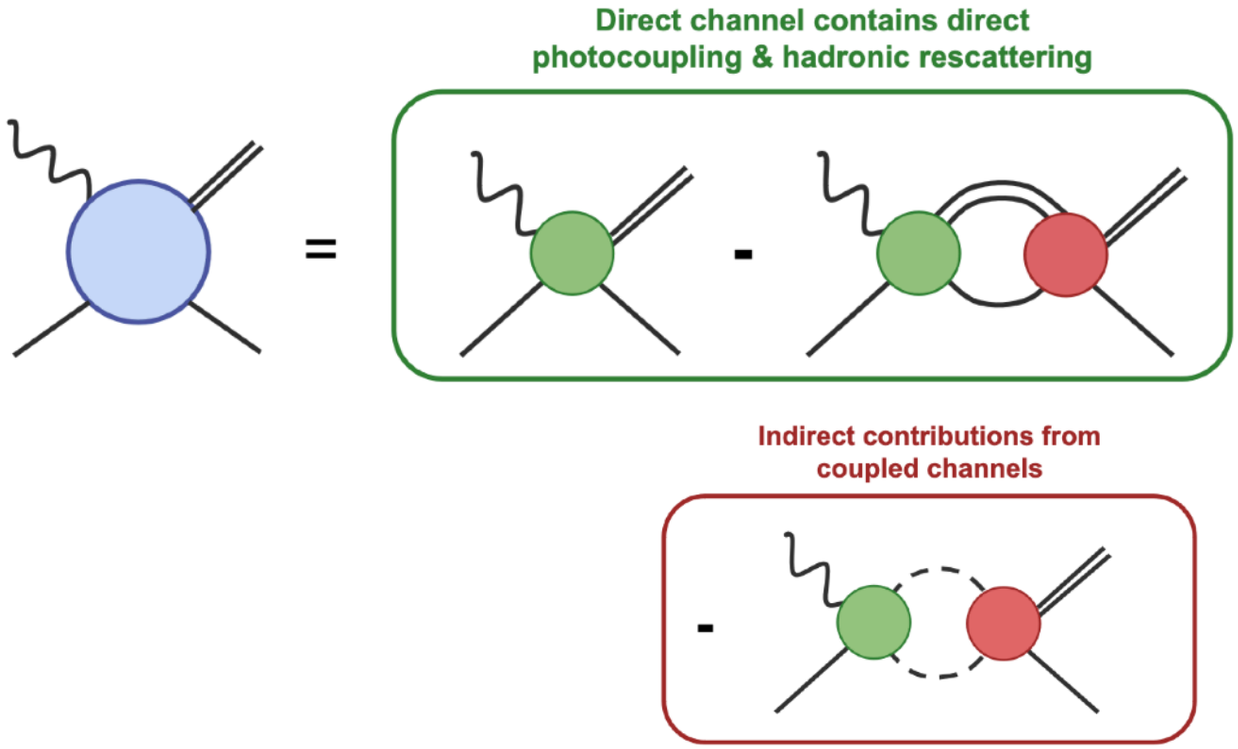

- GlueX and $J/\psi - 007$ results agree well within uncertainties
- Scale uncertainties:
  - 20% for GlueX
  - 4% for $J/\psi - 007$
- Enhancement seen at large $t$ near threshold

# GlueX-I J/ψ Differential Cross Sections




JPAC, PRD 108, 054018 (2023)

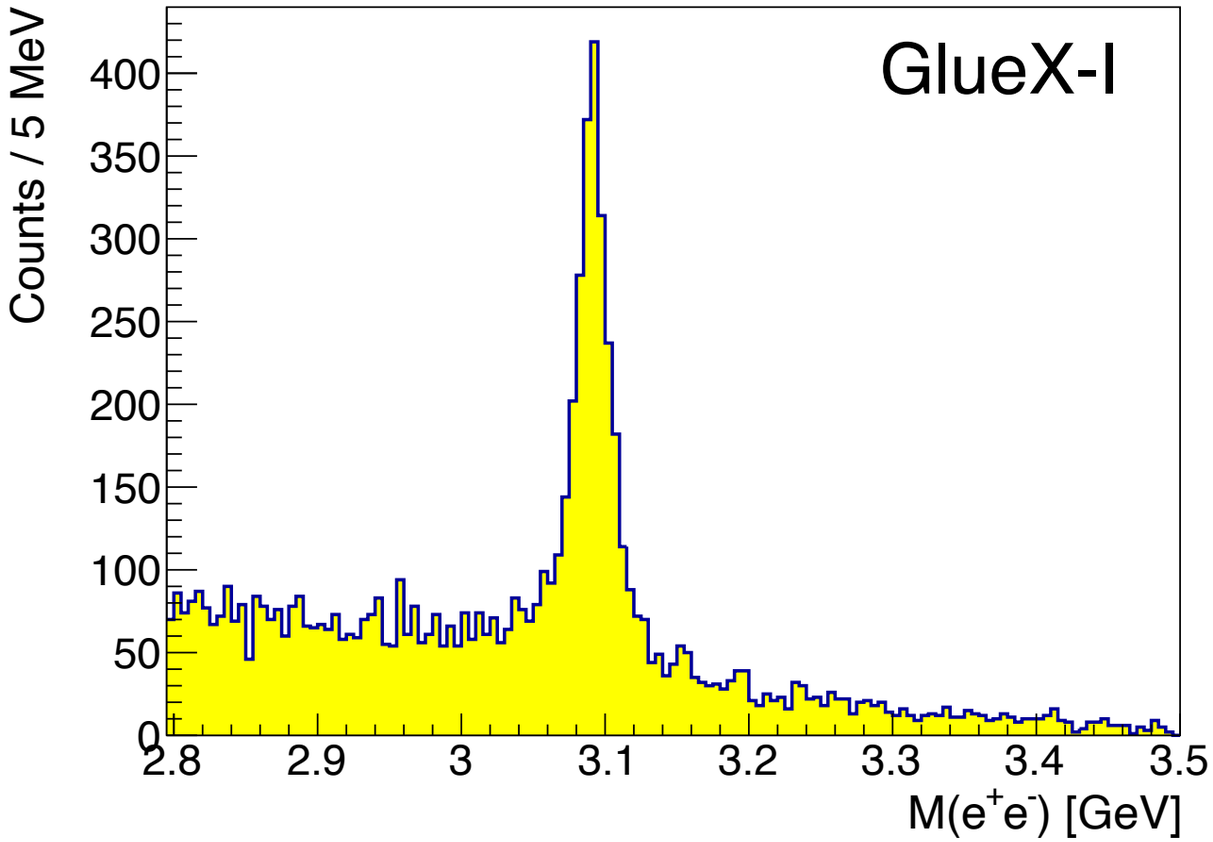
- JPAC fit to GlueX and $J/\psi - 007$ data
  - Up to 3 s-channel partial waves
  - Effective range expansion
  - K-matrix & unitarity
- Describes all observed features well
- Factorization violations > 25% at 90% CL
- More data needed!



# Comparing $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$

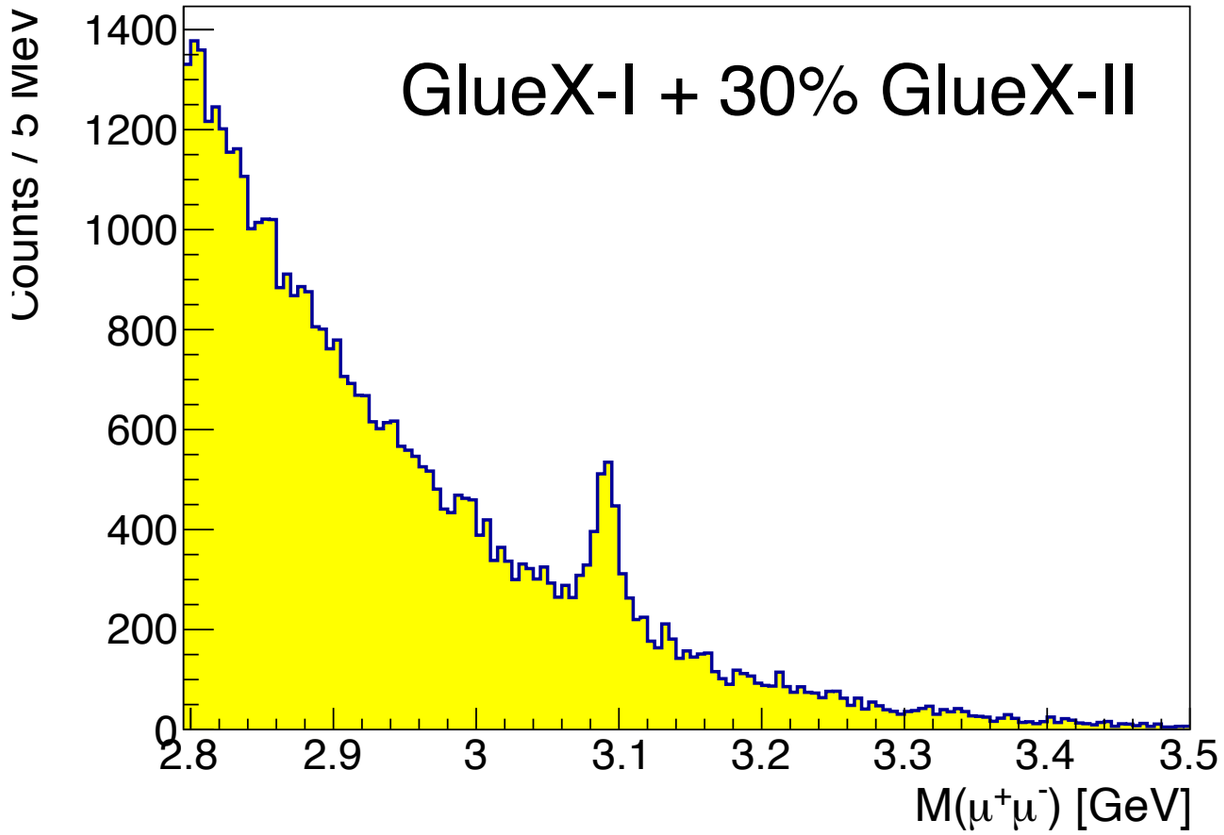
$$J/\psi \to e^+e^-$$

$$N(J/\psi) = 2270 \pm 58$$



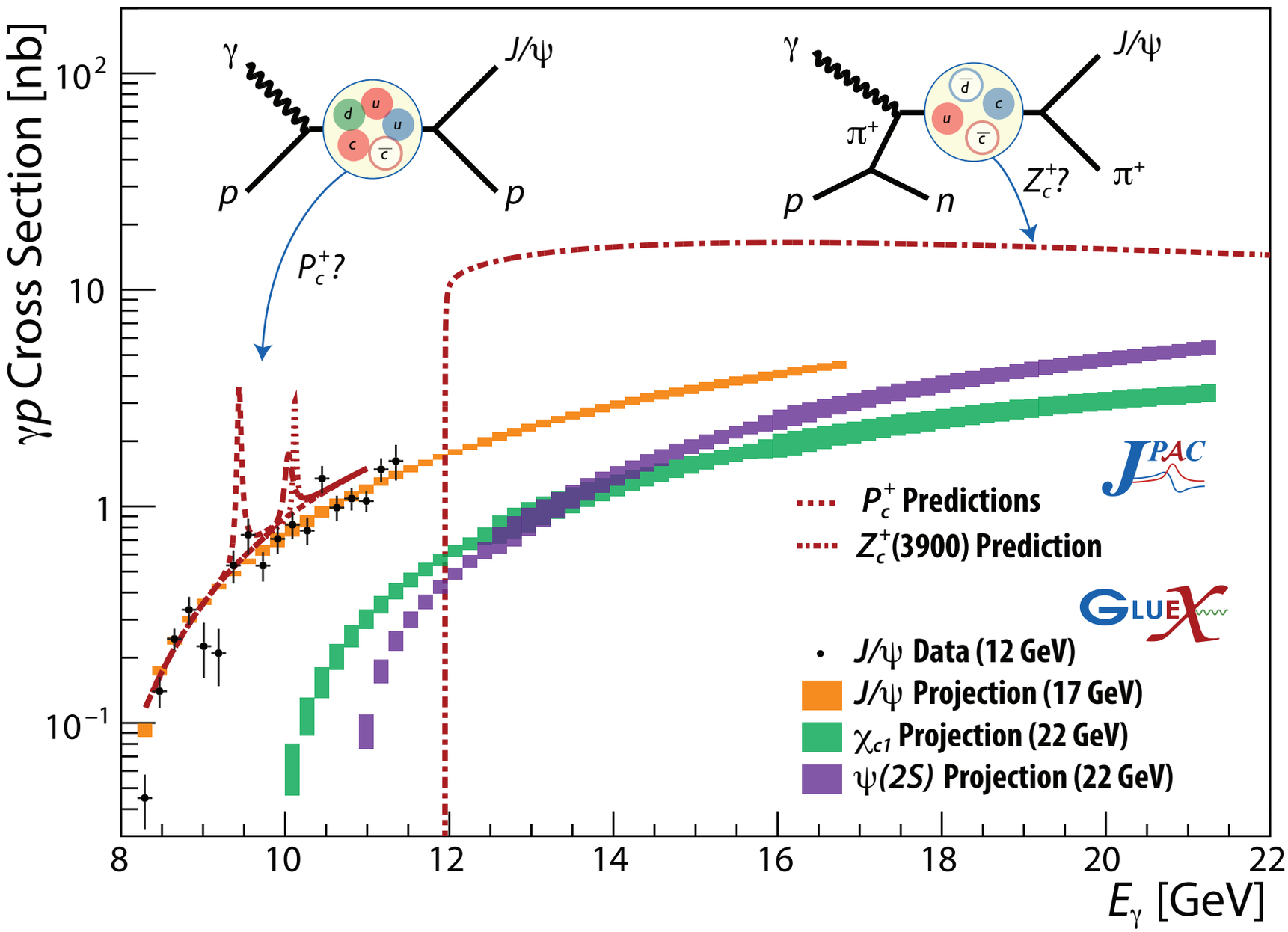

$$J/\psi \to \mu^+\mu^-$$

$$N(J/\psi) = 1778 \pm 65$$




- To confirm the structures observed in the cross section using $J/\psi \to e^+e^-$ events, we can also use $J/\psi \to \mu^+\mu^-$ events
- Detailed study of calorimeter and trigger response in progress
- Expect new results from CLAS12, Hall-C. Eventually: GlueX-III, SOLID

# Projections for Future JLab Upgrades



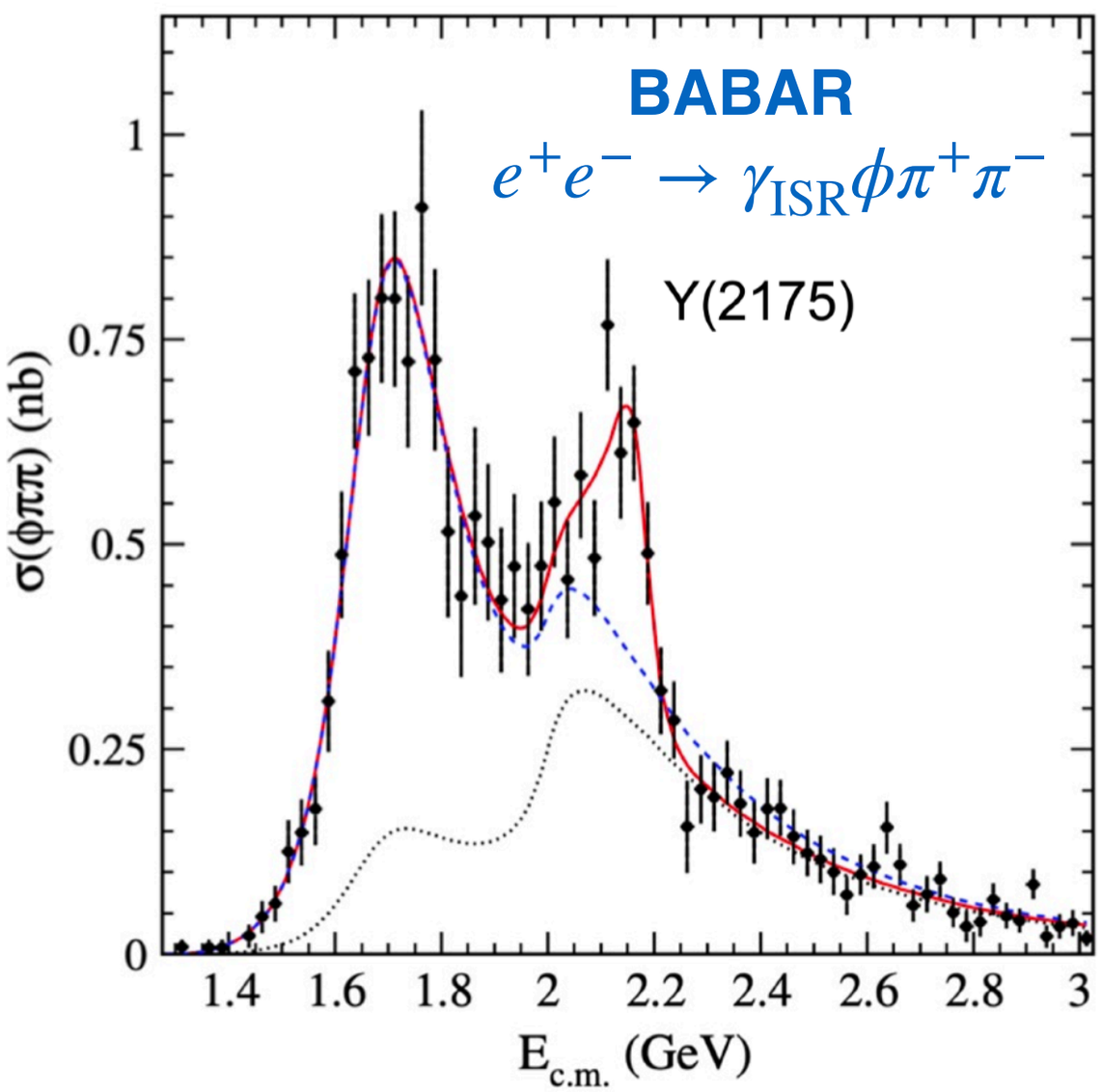

**Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab, EPJA 60, 9 (2024)**

- Projections for GlueX measurements with upgraded CEBAF allow for precision study of charmonium and charmonium-like states with linearly polarized photons

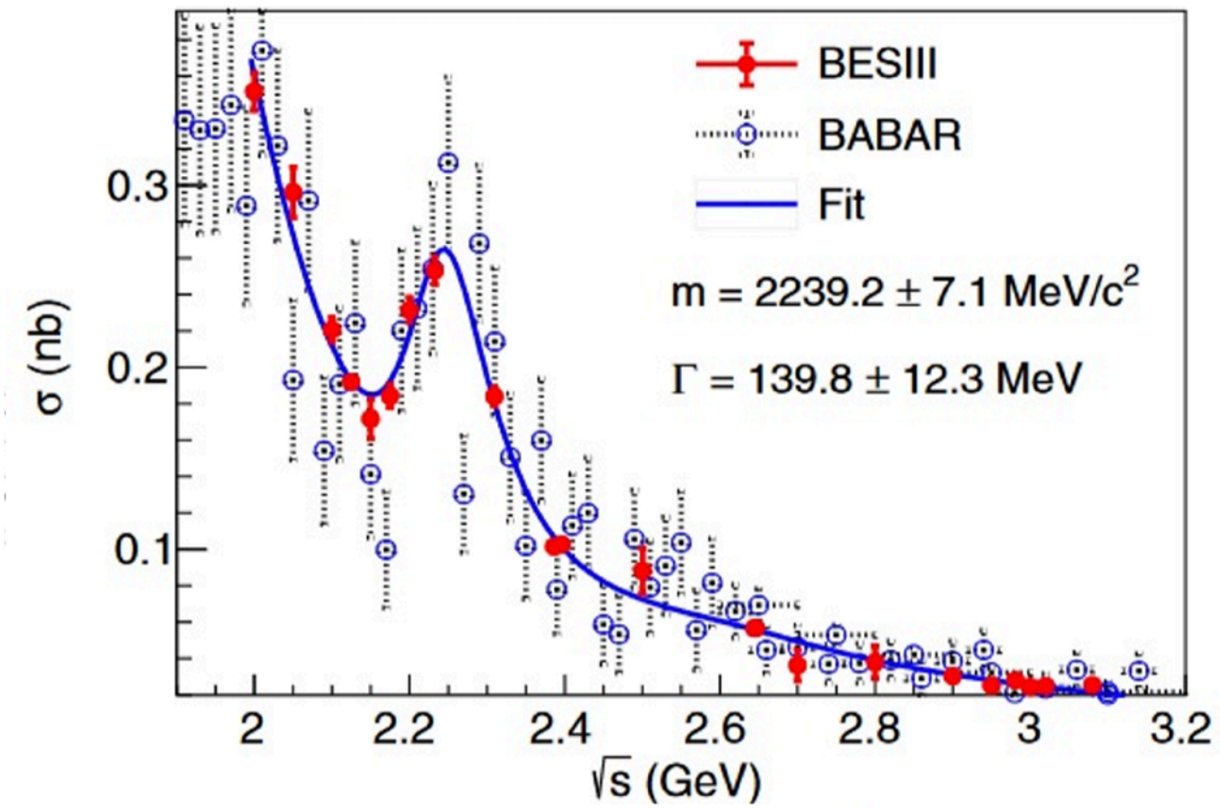
# Search for the Y(2175)

- Can search for the Y(2175) / $\phi(2170)$
  - $s\bar{s}$ partner of the Y(4230)?

[Phys. Rev. D. 74 (2006) 091103]




[Phys. Rev D 99, (2019) 032001]

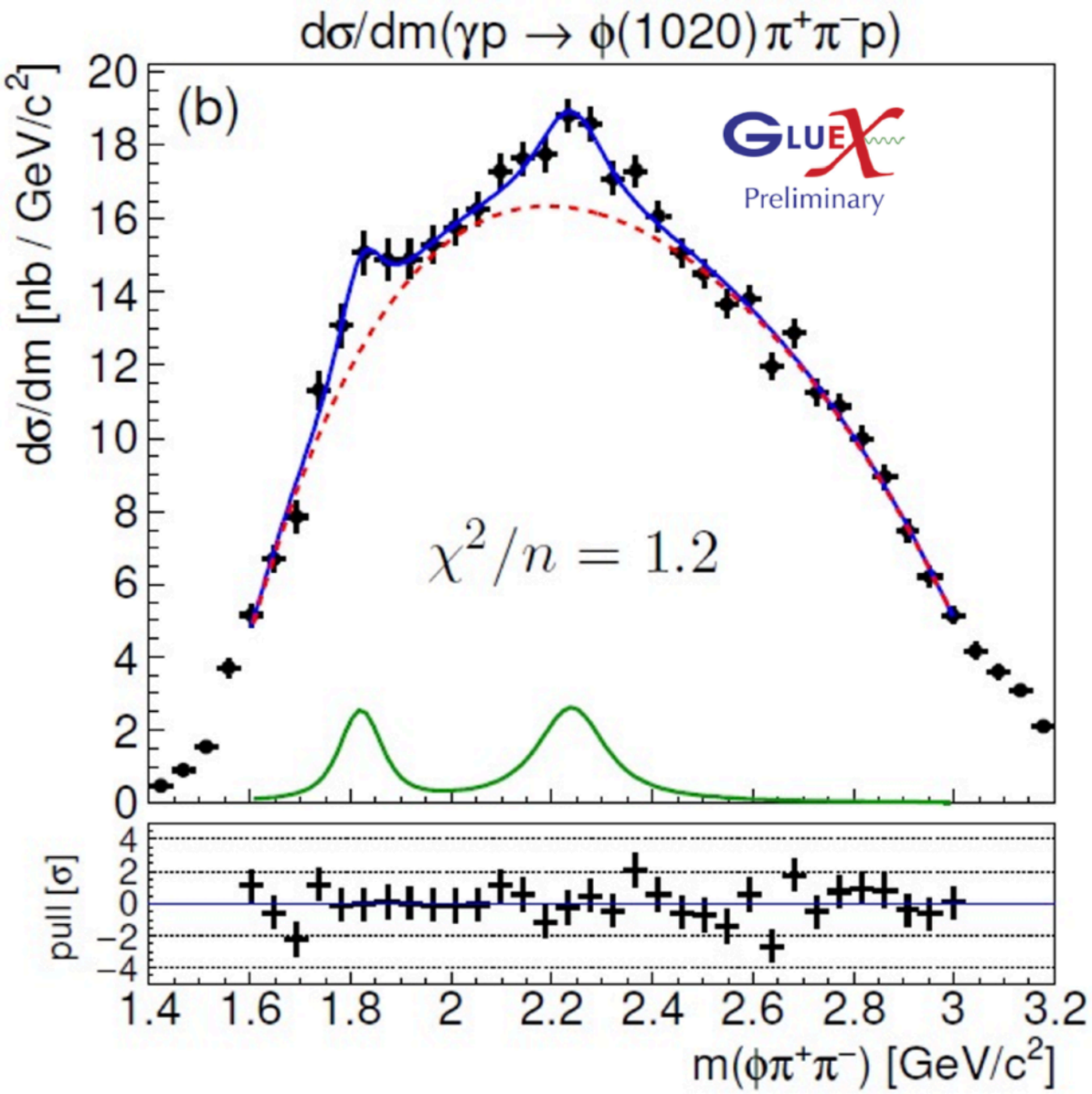



$e^+e^- \to K^+K^-$ cross section at $\sqrt{s} = 2.00 - 3.08$ GeV

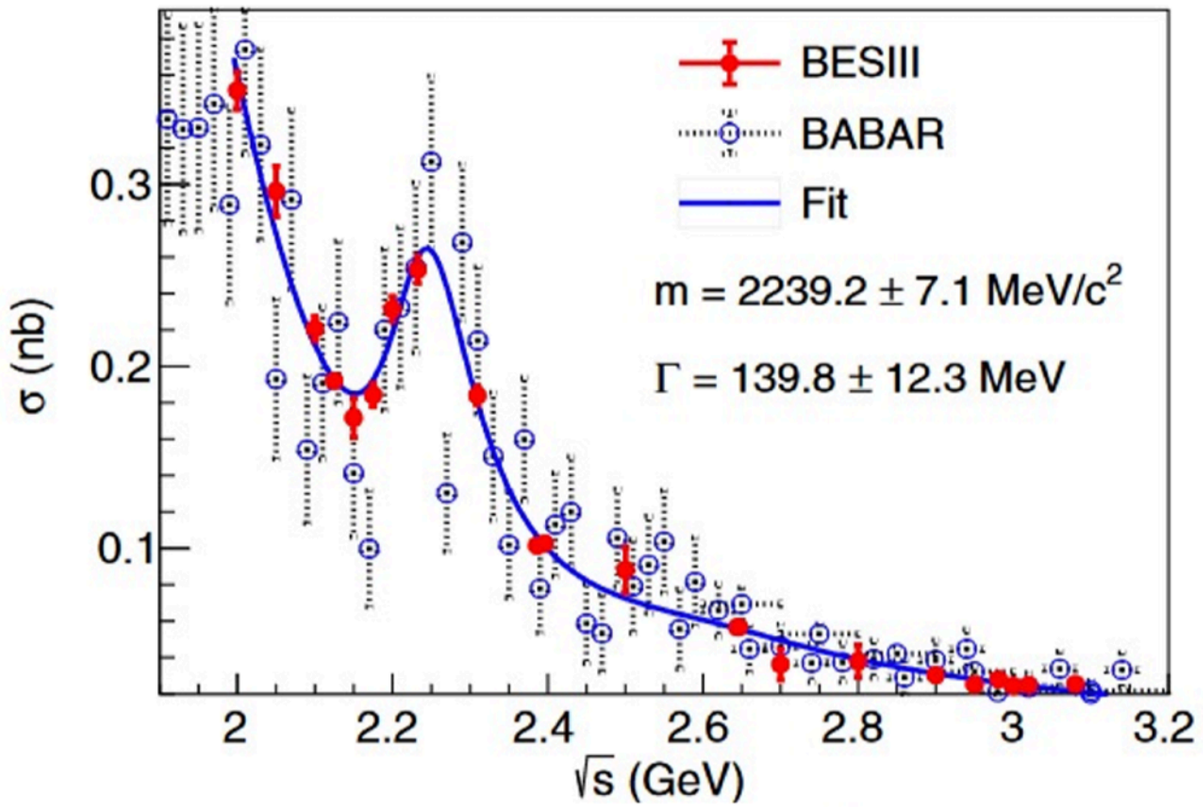
$$M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2$$
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

# Search for the Y(2175)

- No evidence with PDG Y(2175) parameters ($\sigma < 500$ pb)
- Evidence of structures at M ~ 1.8 and ~2.24 GeV




[Phys. Rev. D 99, (2019) 032001]




$e^+e^- \to K^+K^-$ cross section at $\sqrt{s} = 2.00 - 3.08$ GeV

$$M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2$$
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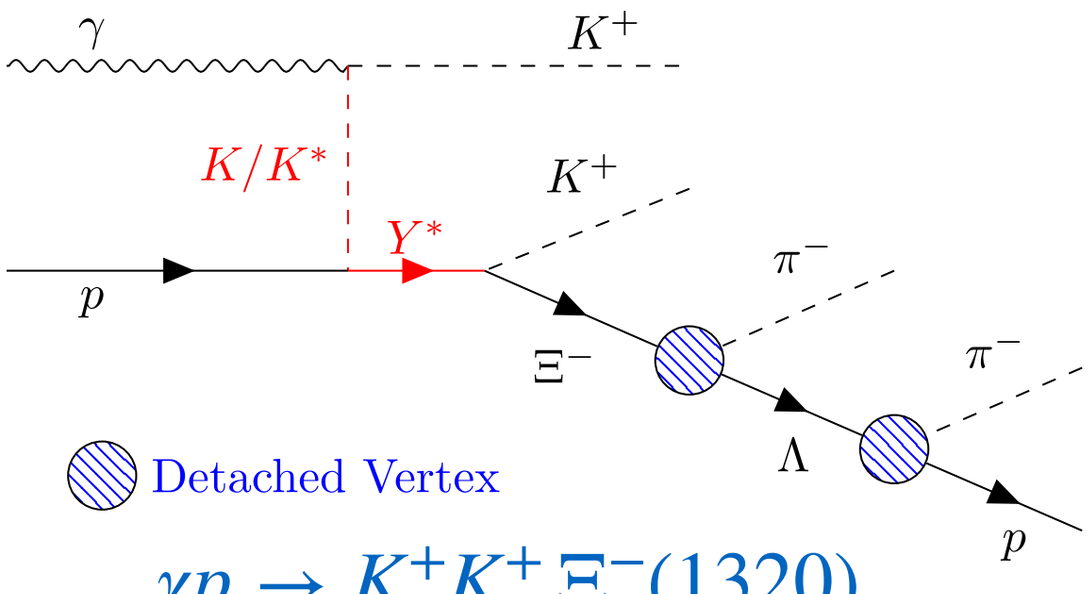
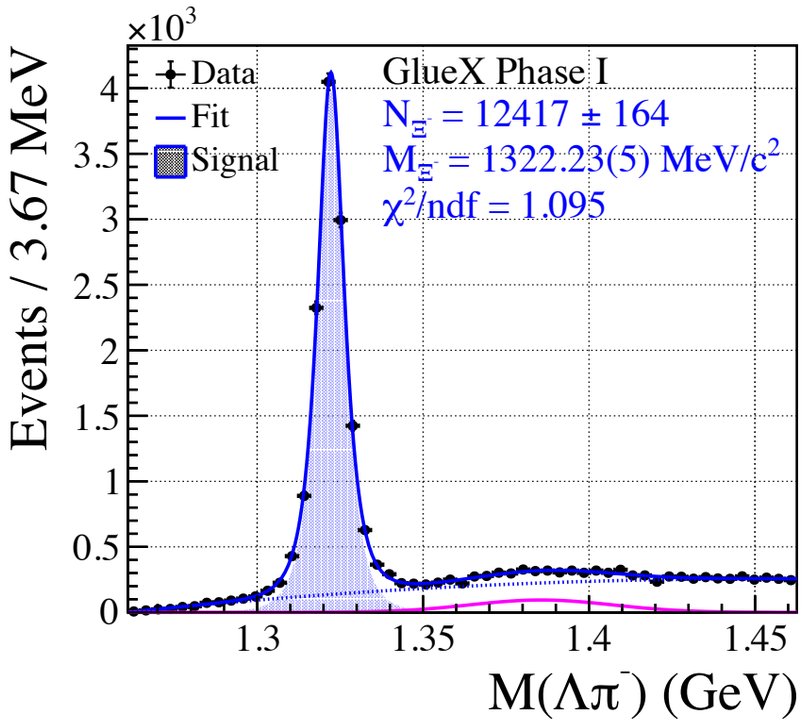
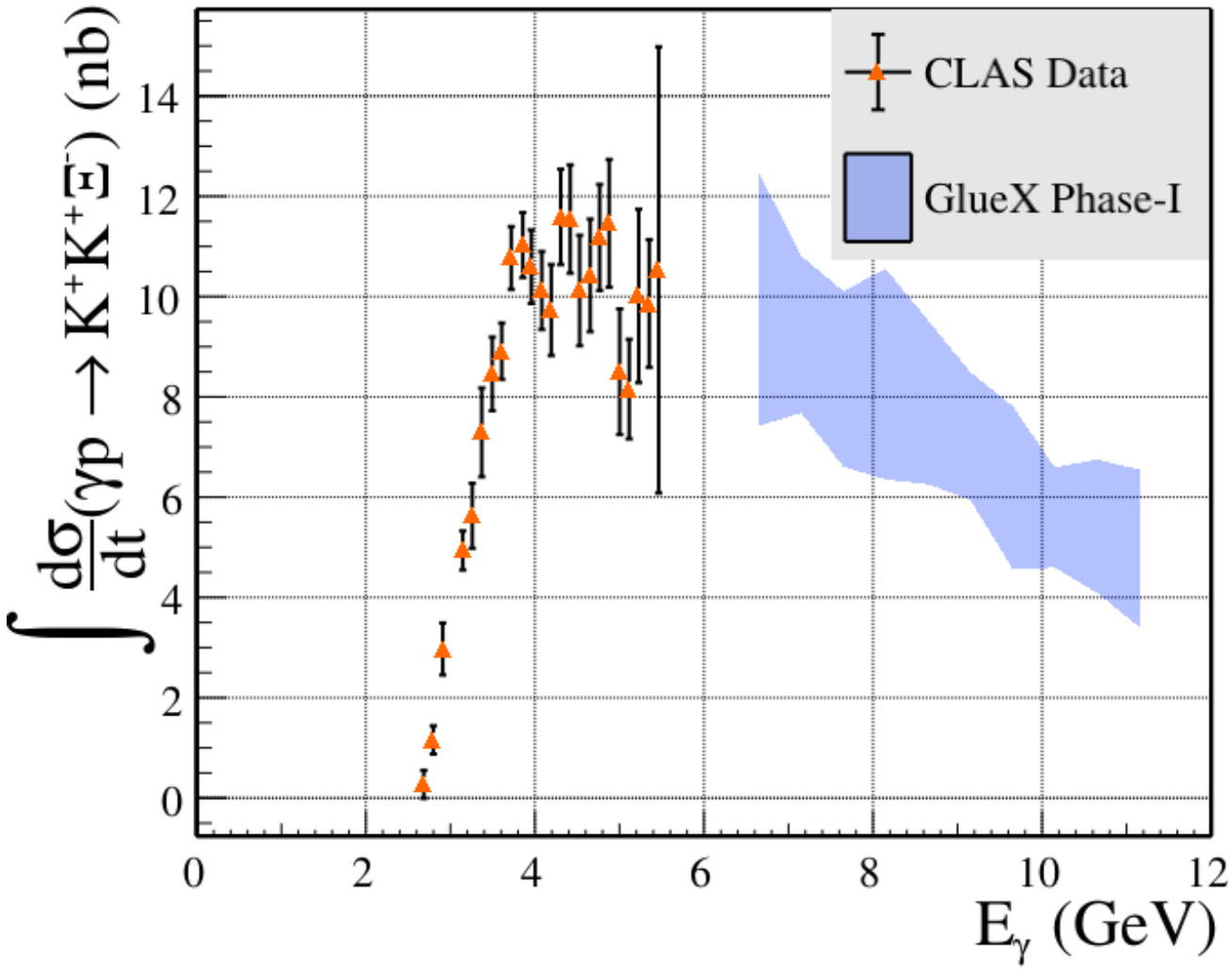
# $\Xi^-(1320)$ Photoproduction

- Detailed $\Xi^-(1320)$ cross section measurements provide baseline for $\Xi$ program, insight into Y* contributions




$\gamma p \to K^+K^+\Xi^-(1320)$



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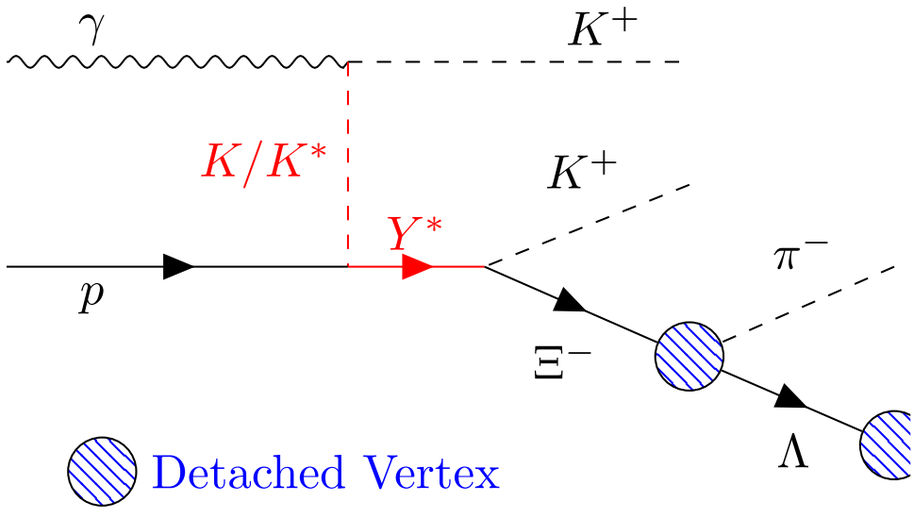
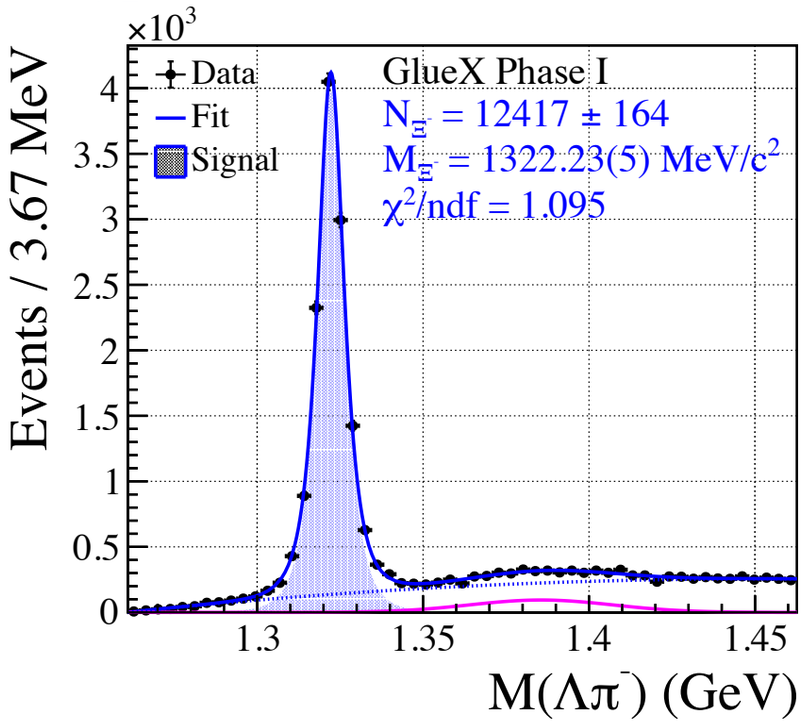
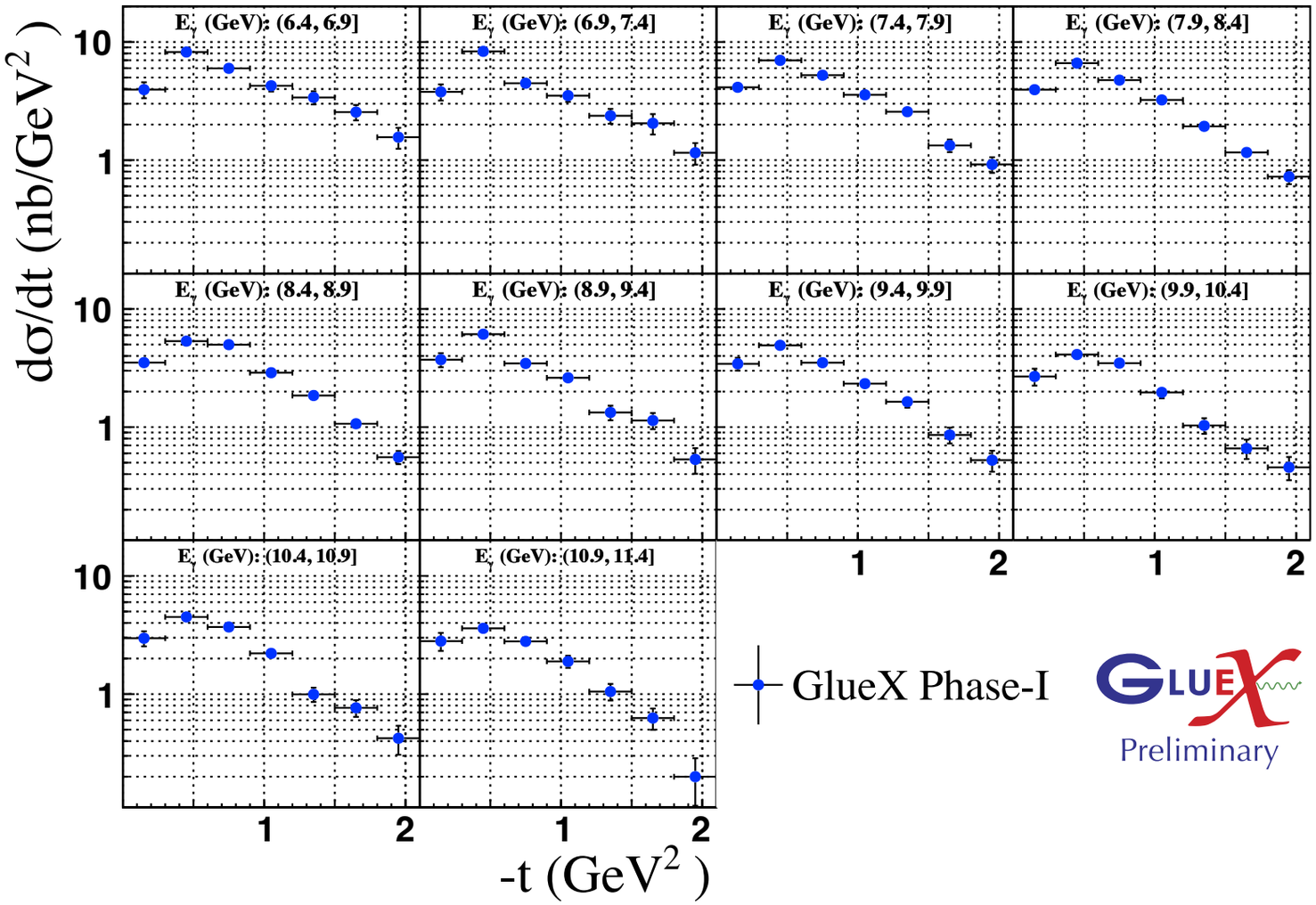



$\gamma p \to K^+K^+\Xi^-(1320)$



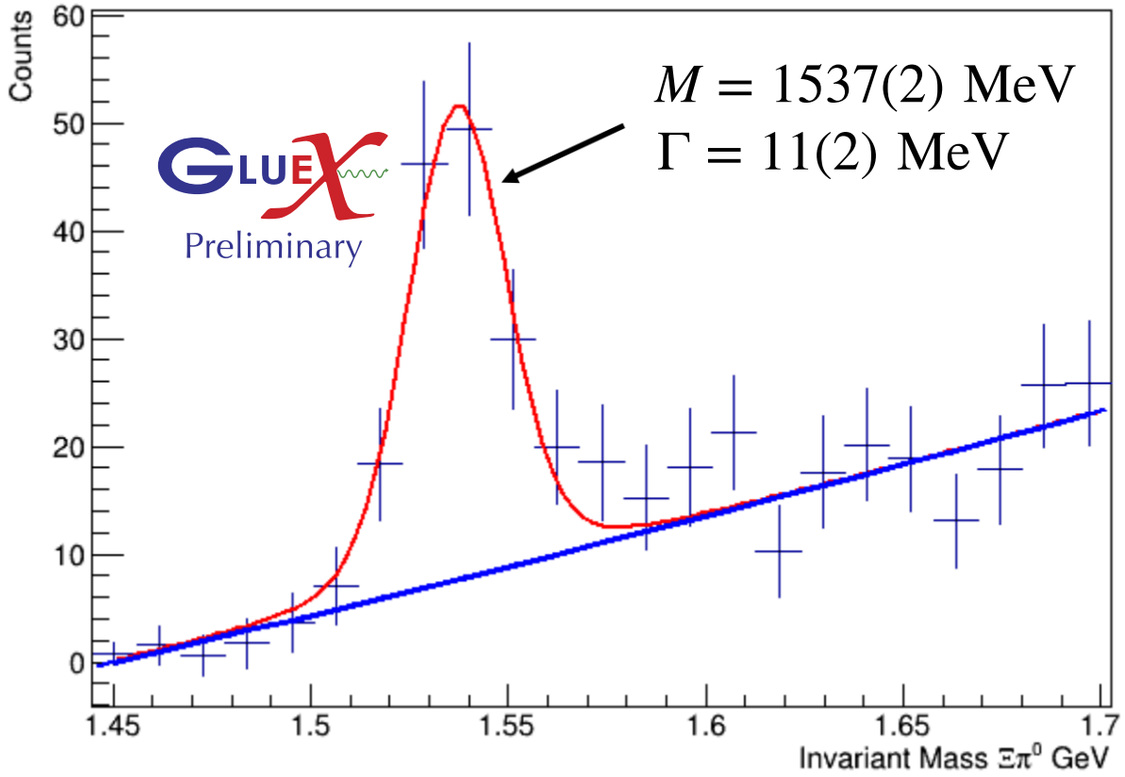



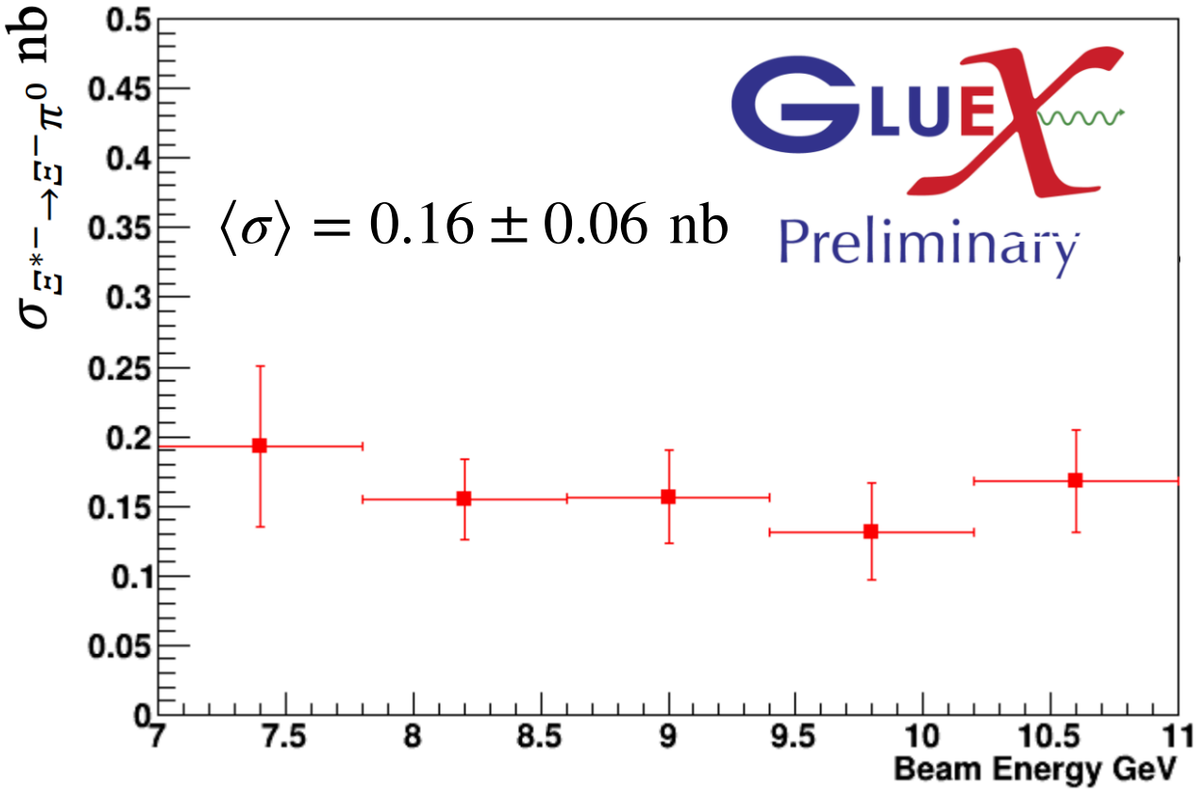

**Inputs to photoproduction models!**

# $\Xi^-(1530)$ Photoproduction

- Ground state decuplet $\Xi(1530)$ measured with 50% GlueX-I data
- Cross section shows no significant energy dependence

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

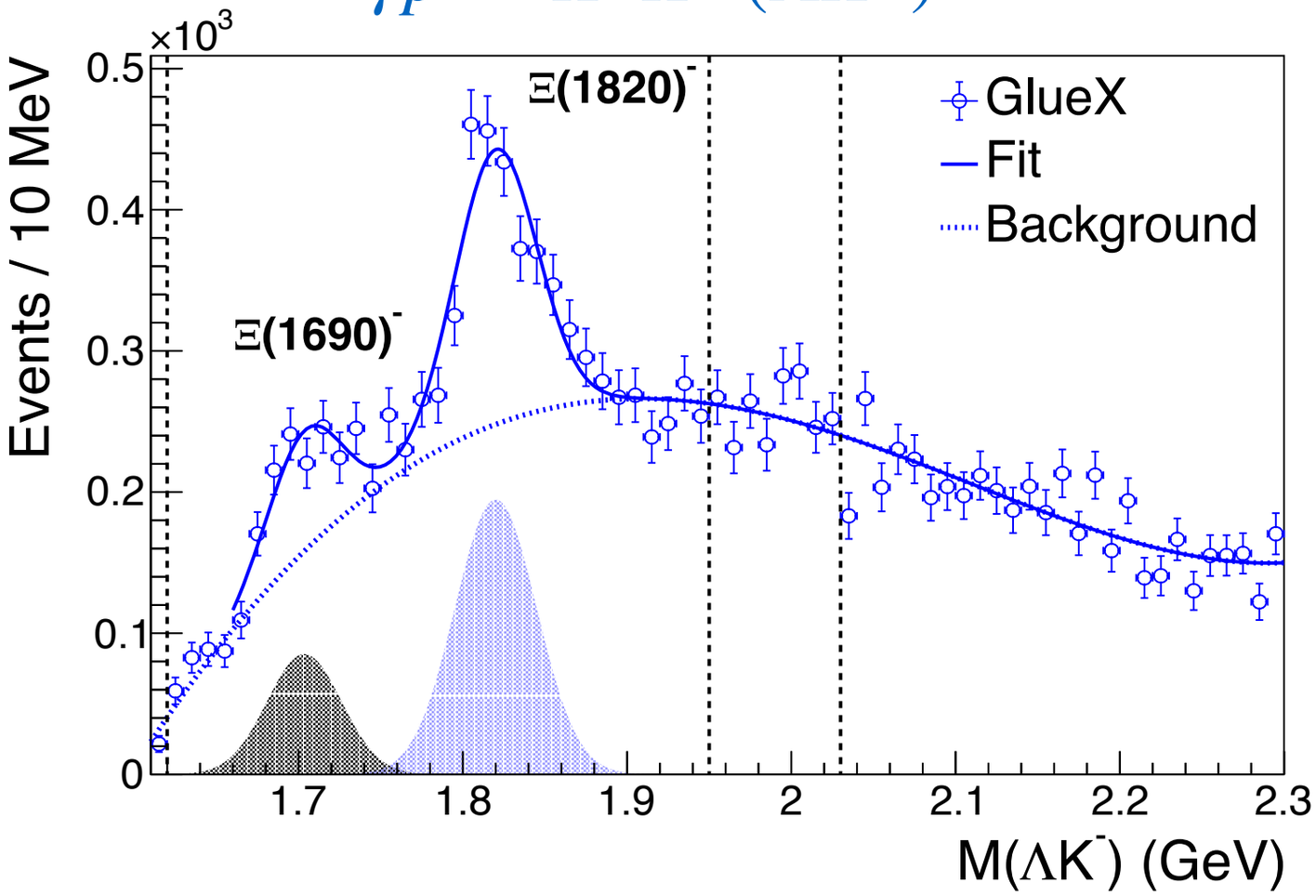


# Hunting for Excited Cascades

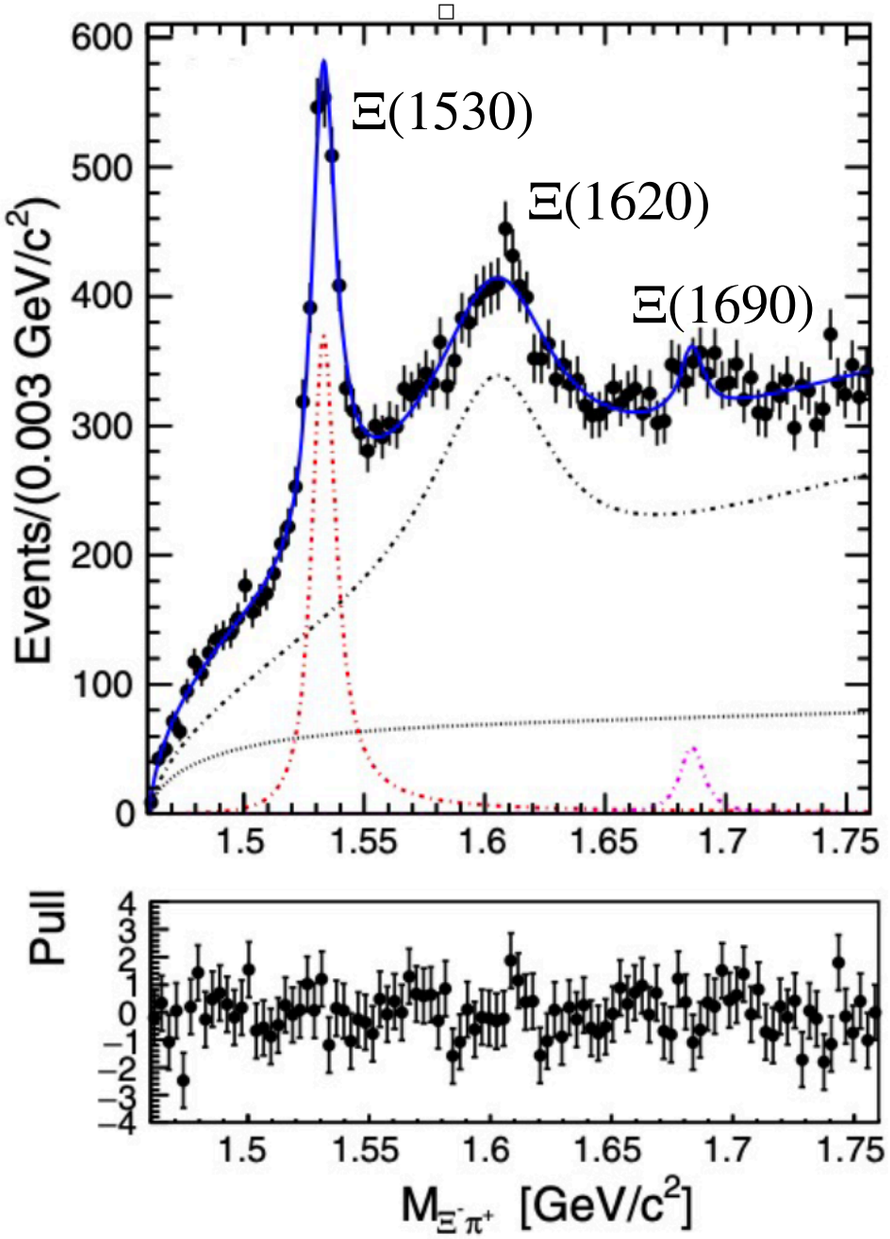
- GlueX finds strong evidence for $\Xi(1690)$ and $\Xi(1820)$ in the $\Lambda K$ channel

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




**V. Crede and J. Yelton, submitted to Rep. Prog. Phys.**

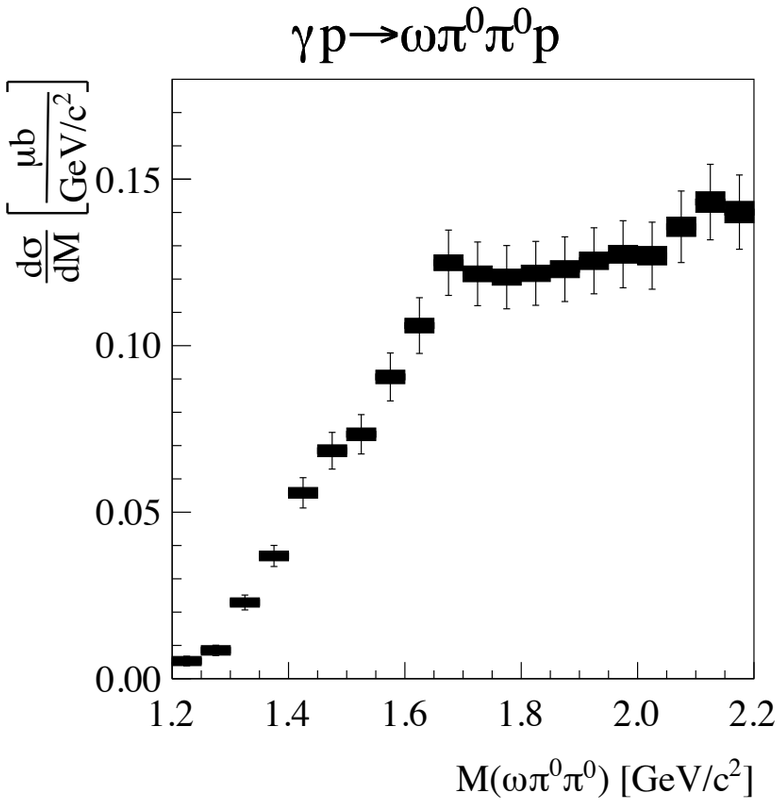
$\Xi_c^+ \to (\Xi^-\pi^+)\pi^+$

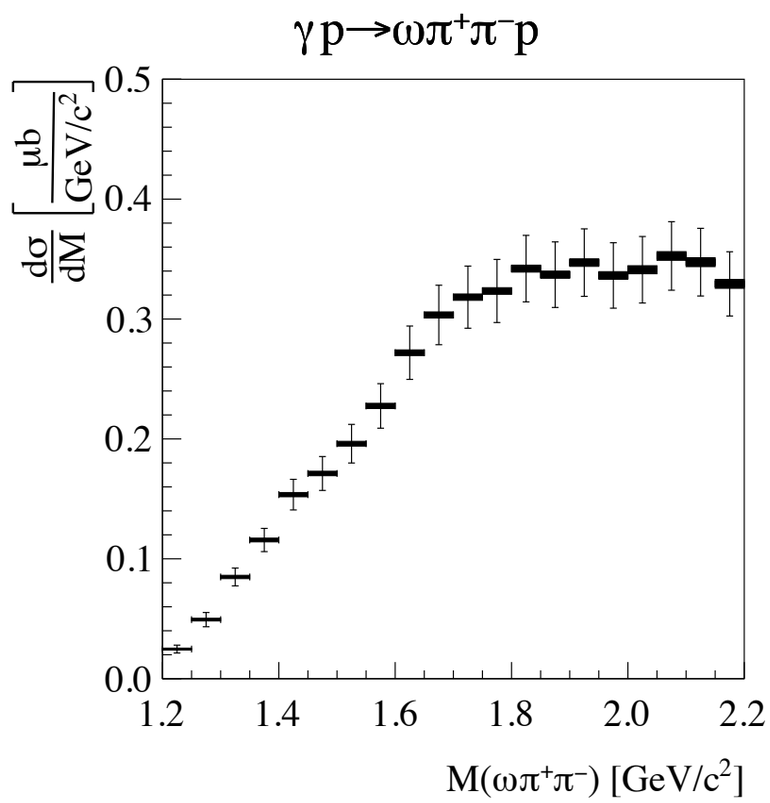


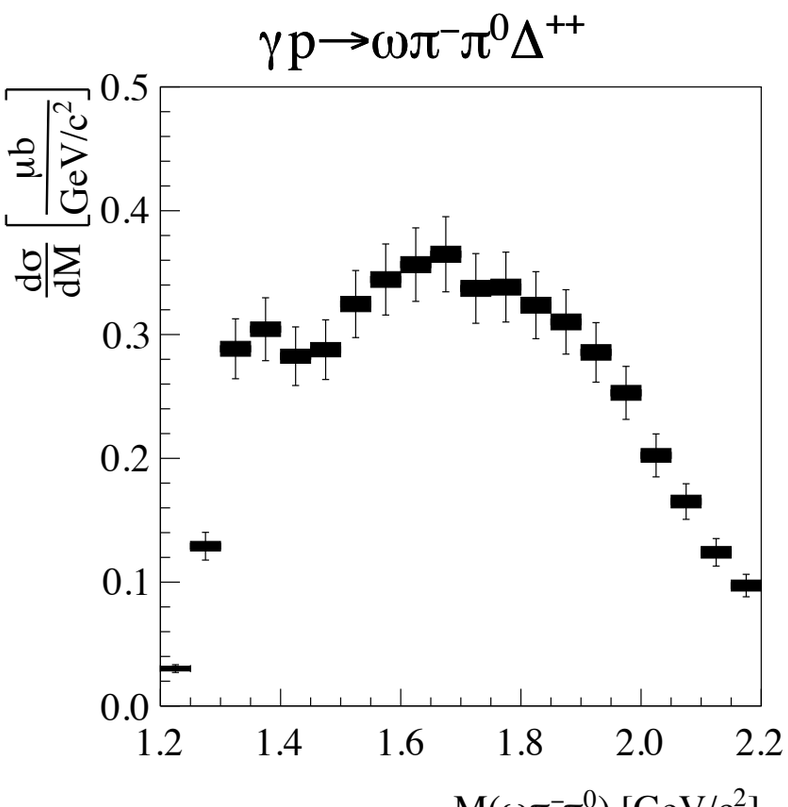

**Belle, PRL 122, 072501 (2019)**

# Cross sections for $\omega\pi\pi$ in GlueX

- Measured $\omega\pi\pi$ photoproduction with $0.1 < -t < 0.5\ \mathrm{GeV}^2$



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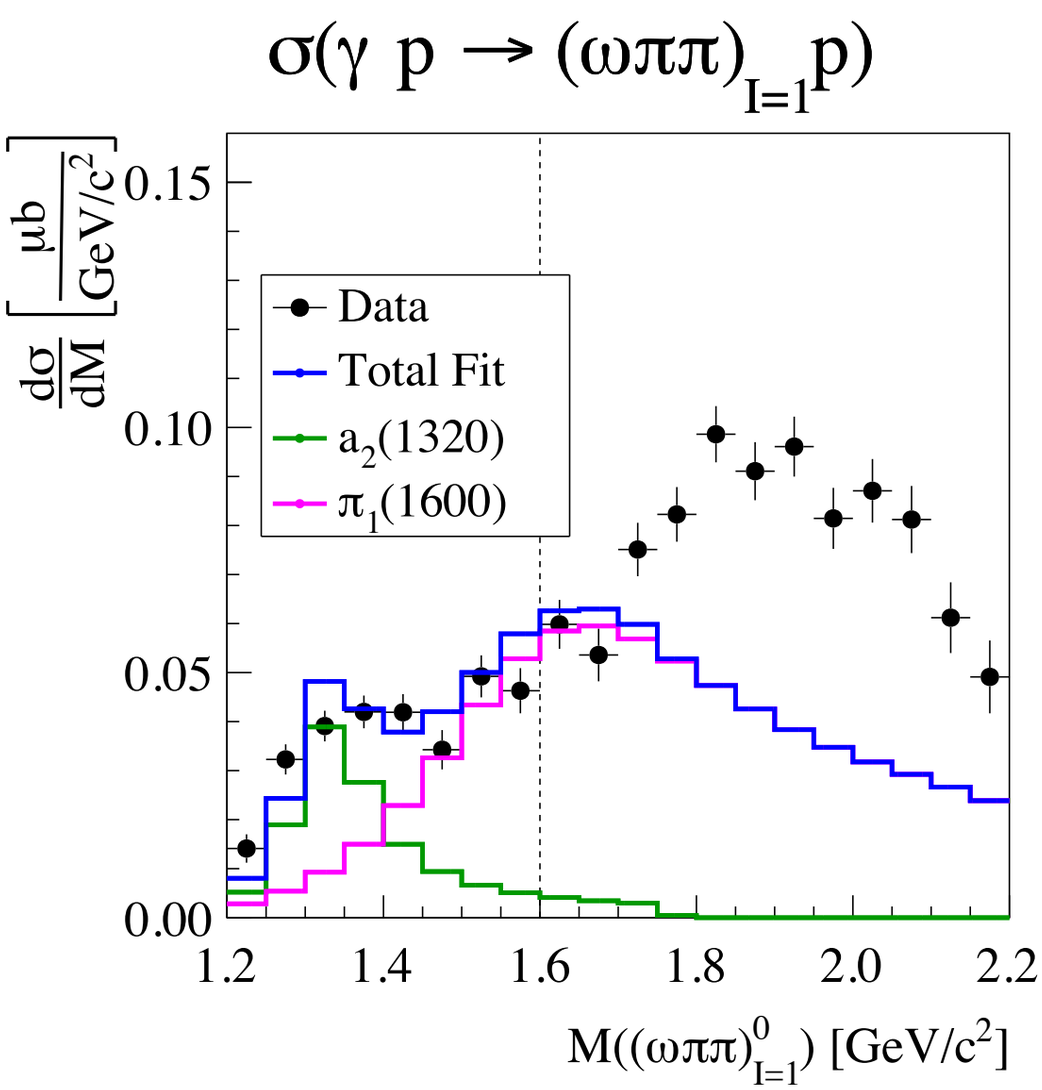
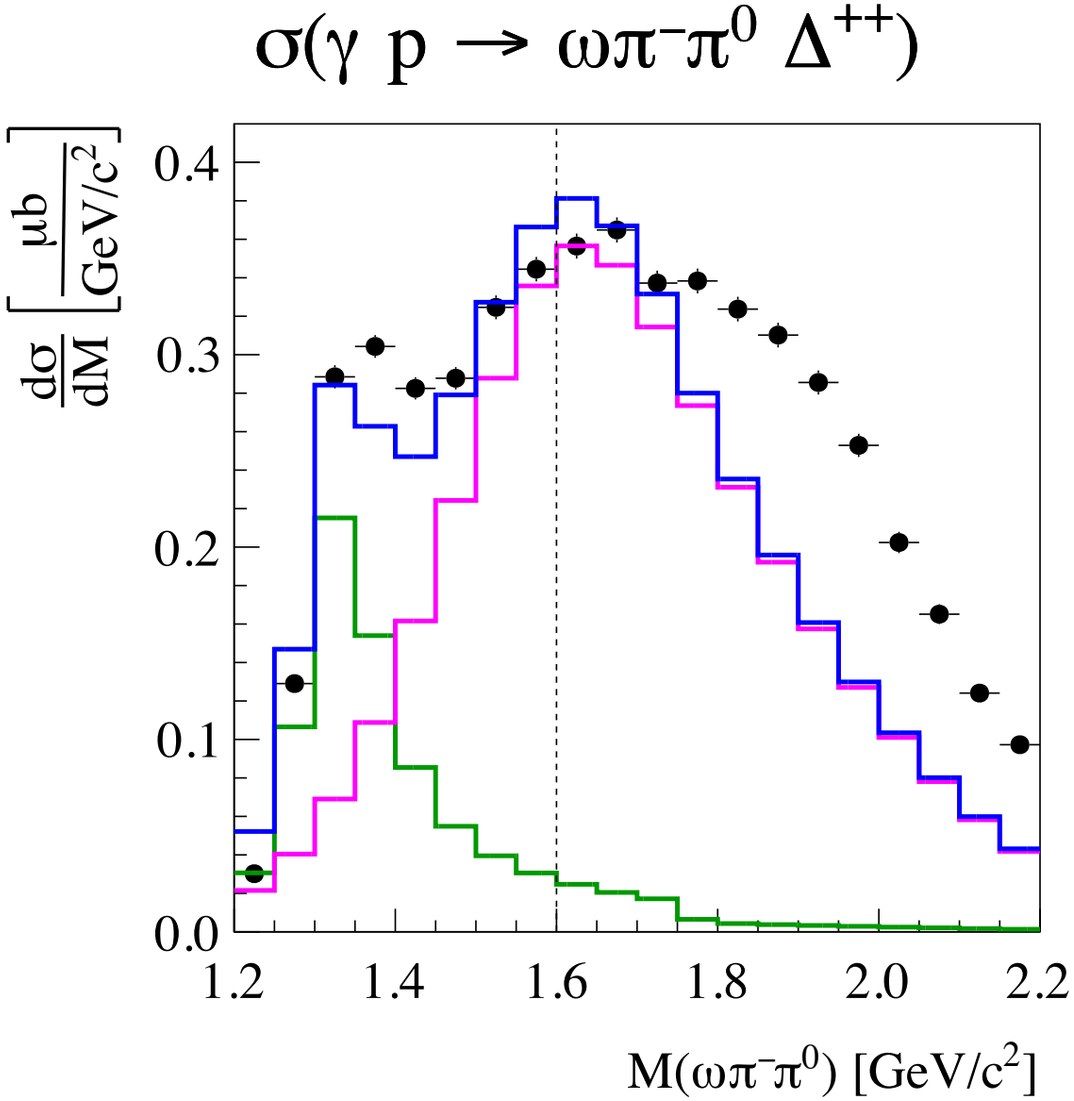
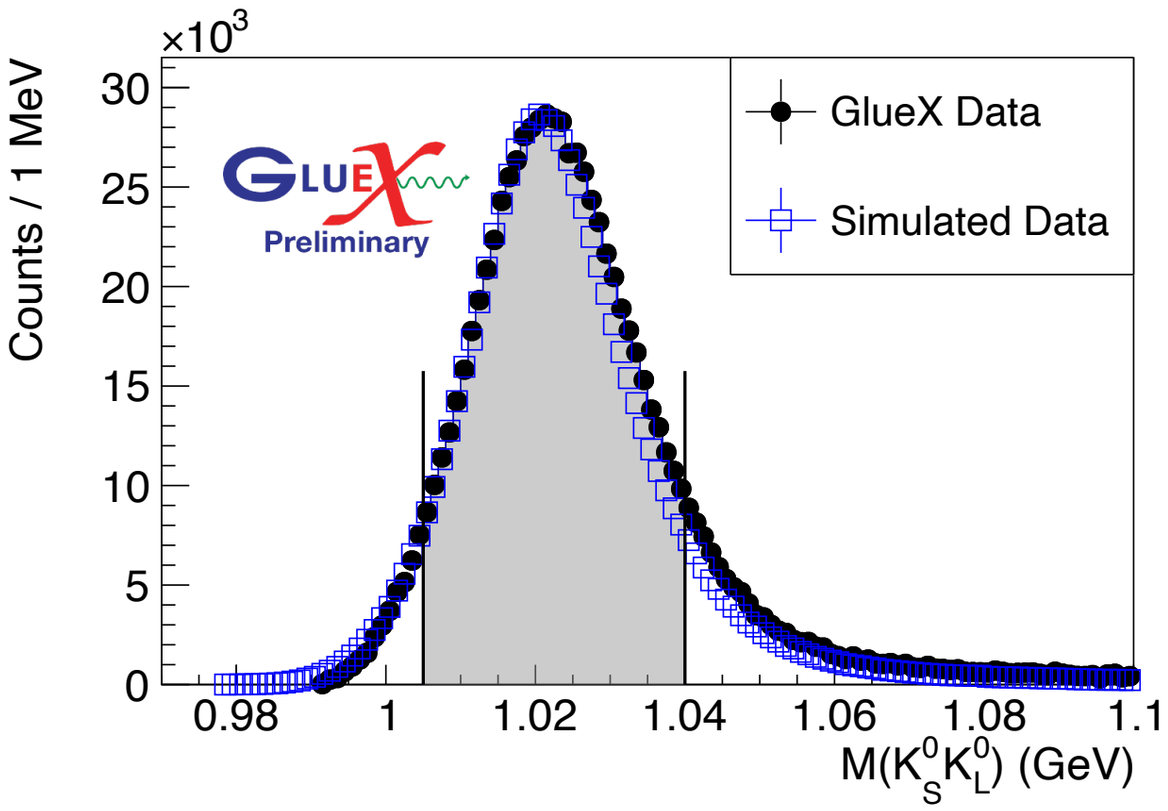
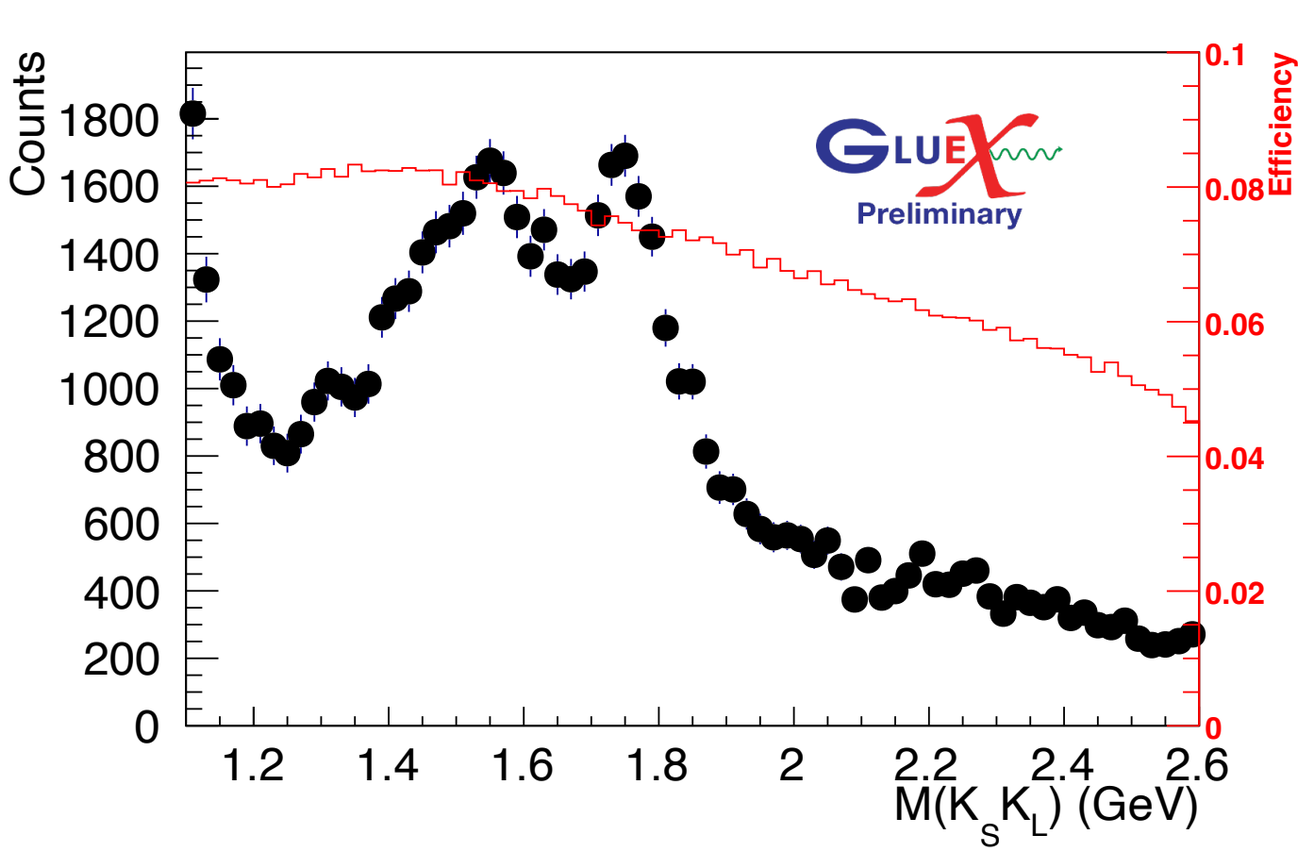


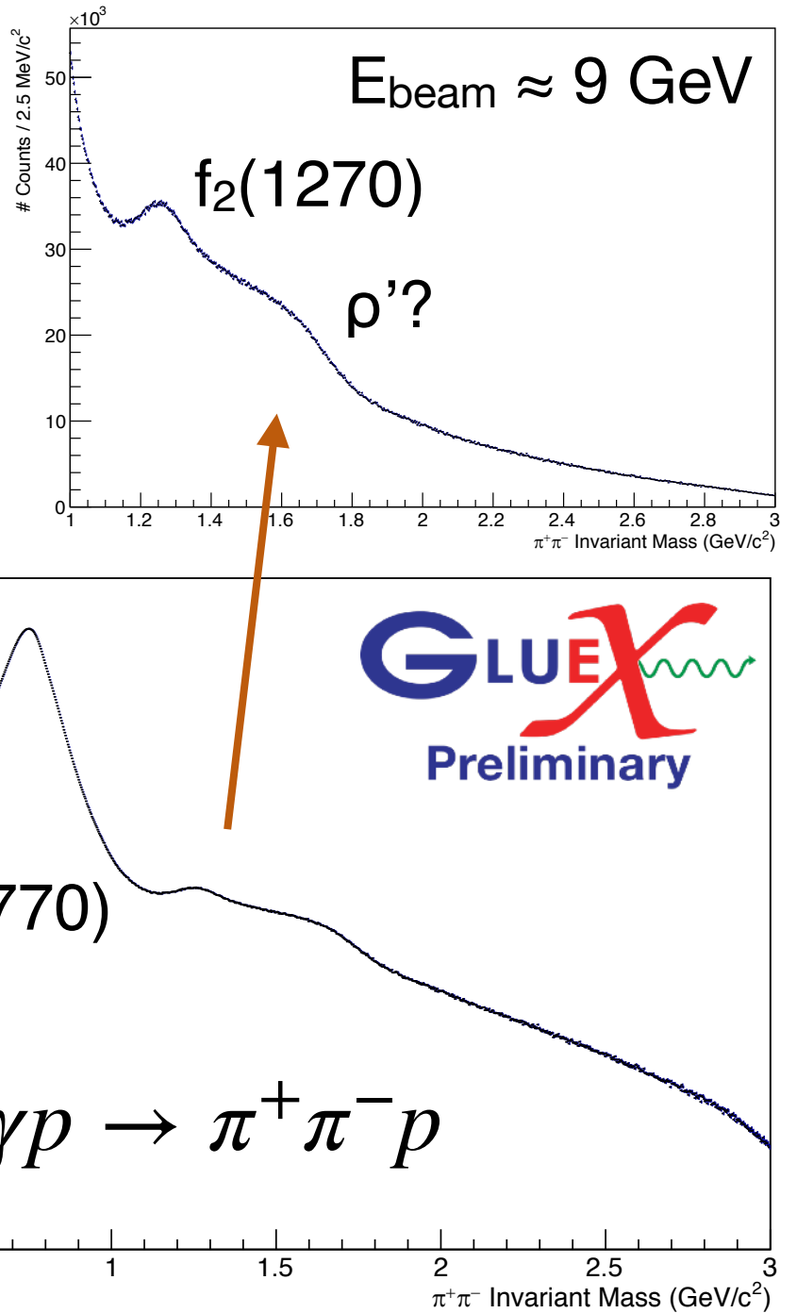
# Excited Vectors in $K_S K_L$

- Study of $\gamma p \to K_S K_L p$ gives insight to $\text{odd}^{--}$ mesons: $1^{--}$, $3^{--}$, …
- Clean $\phi(1020)$ signal seen with GlueX-I data, study SDMEs, cross sections,
- Two clear enhancements at larger mass

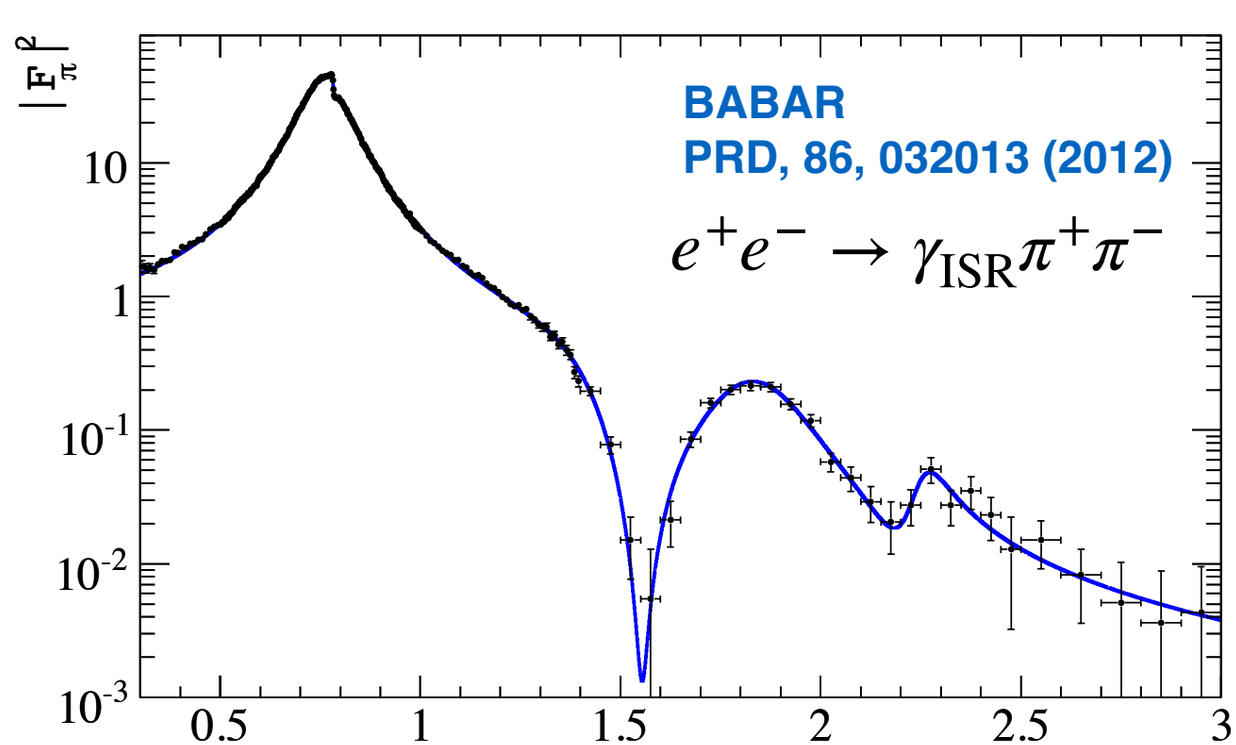


# Excited Vectors and Photoproduction

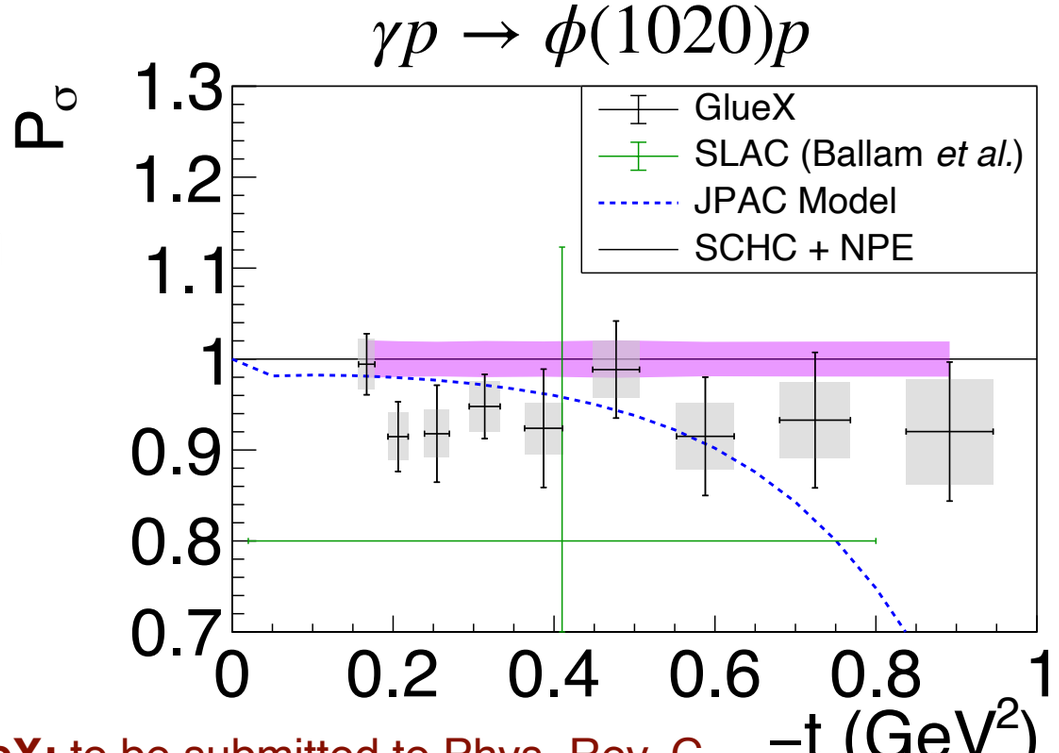



- Vector mesons have same QNs as photons, should be strongly excited in photoproduction
- Need consistent understanding of spectra in photoproduction and $e^+e^-$ annihilation

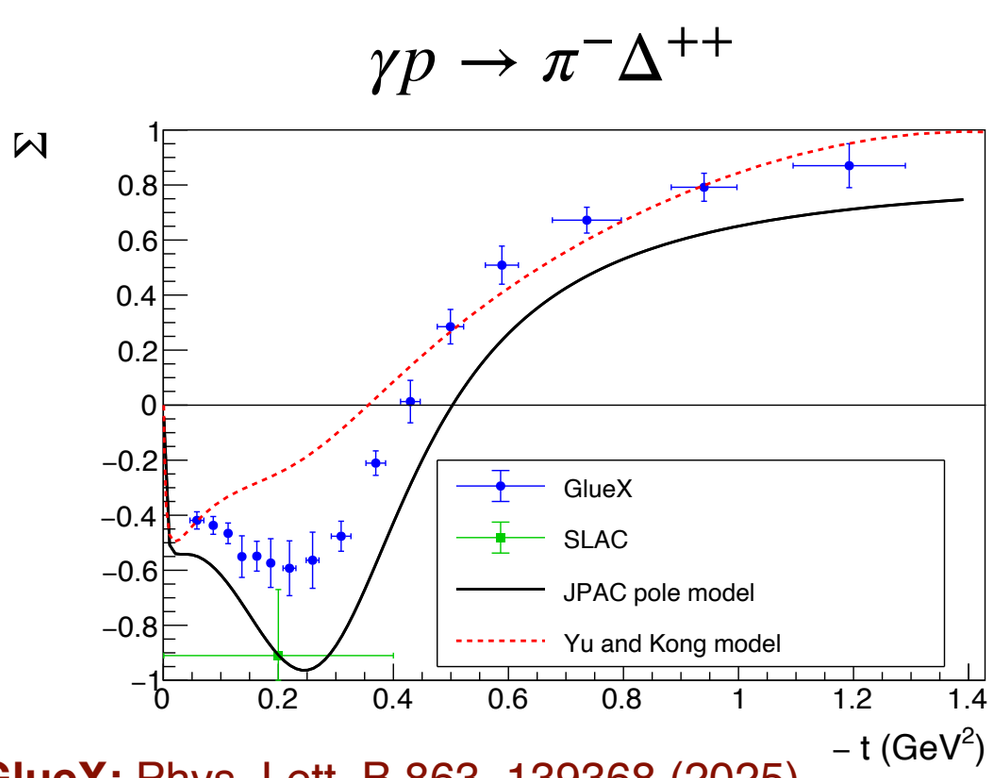


# Polarized Photoproduction @ GlueX

- SDME fits use same fitting framework as amplitude analyses
- GlueX data provides high statistical precision
- General conclusions:
  - Neutral meson production proceeds dominantly through natural exchange
  - Charged mesons see contribution from pion exchange at low $-t$

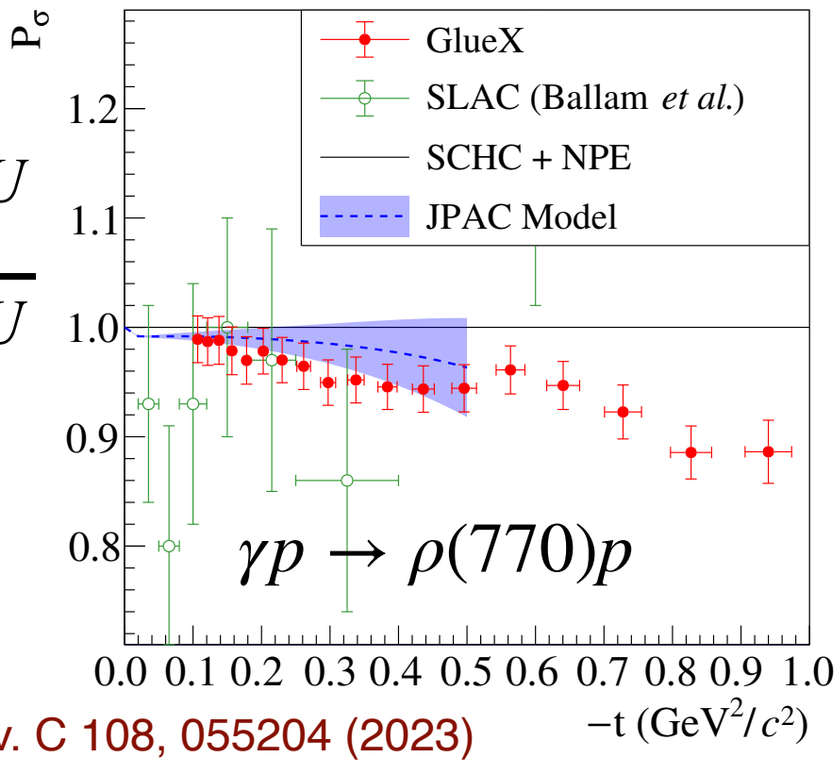



**GlueX:** to be submitted to Phys. Rev. C




**GlueX:** Phys. Lett. B 863, 139368 (2025)

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$




**GlueX:** Phys. Rev. C 108, 055204 (2023)