Recent Results and Future Prospects from GlueX and beyond

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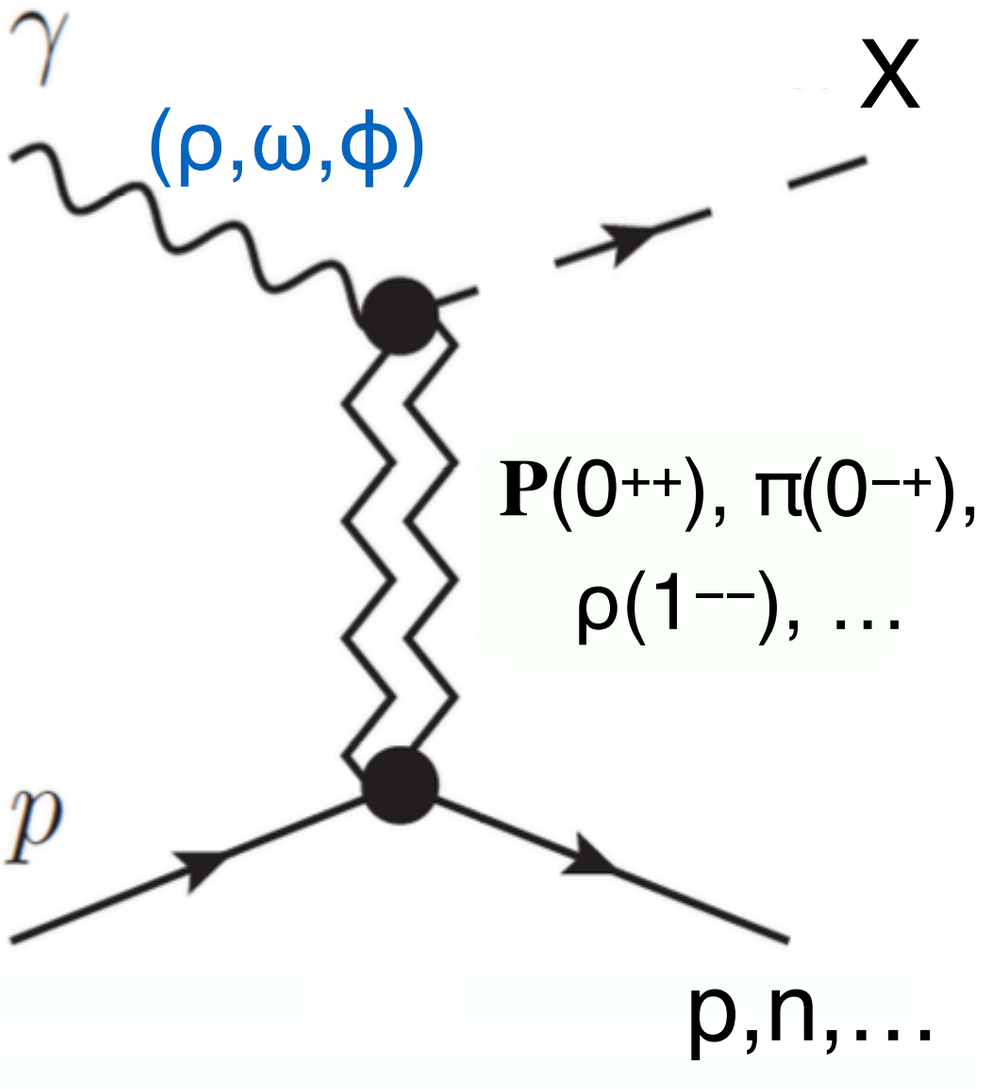
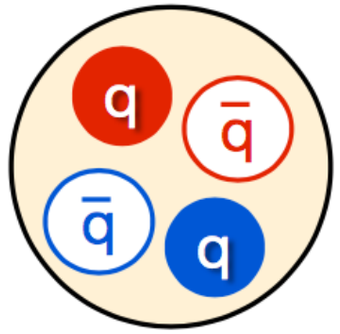
Exotic Heavy Meson Spectroscopy and Structure with EIC
August 15, 2022

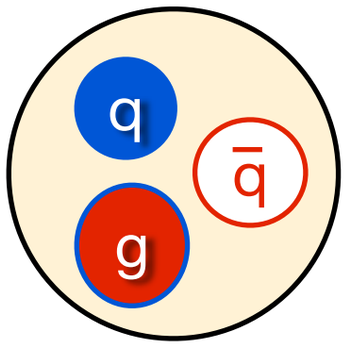
Hadron Spectroscopy and Photoproduction

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





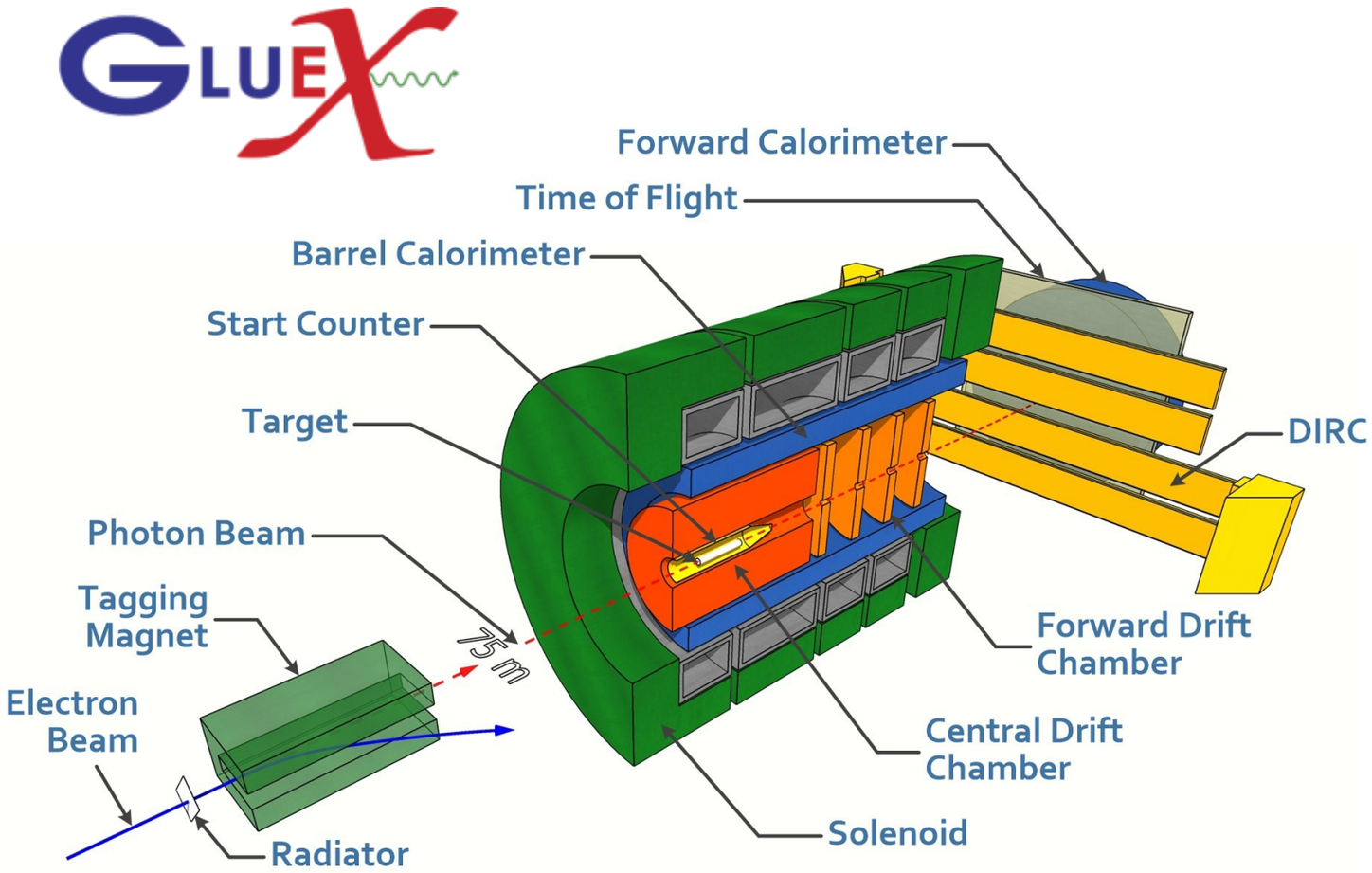
tetraquark

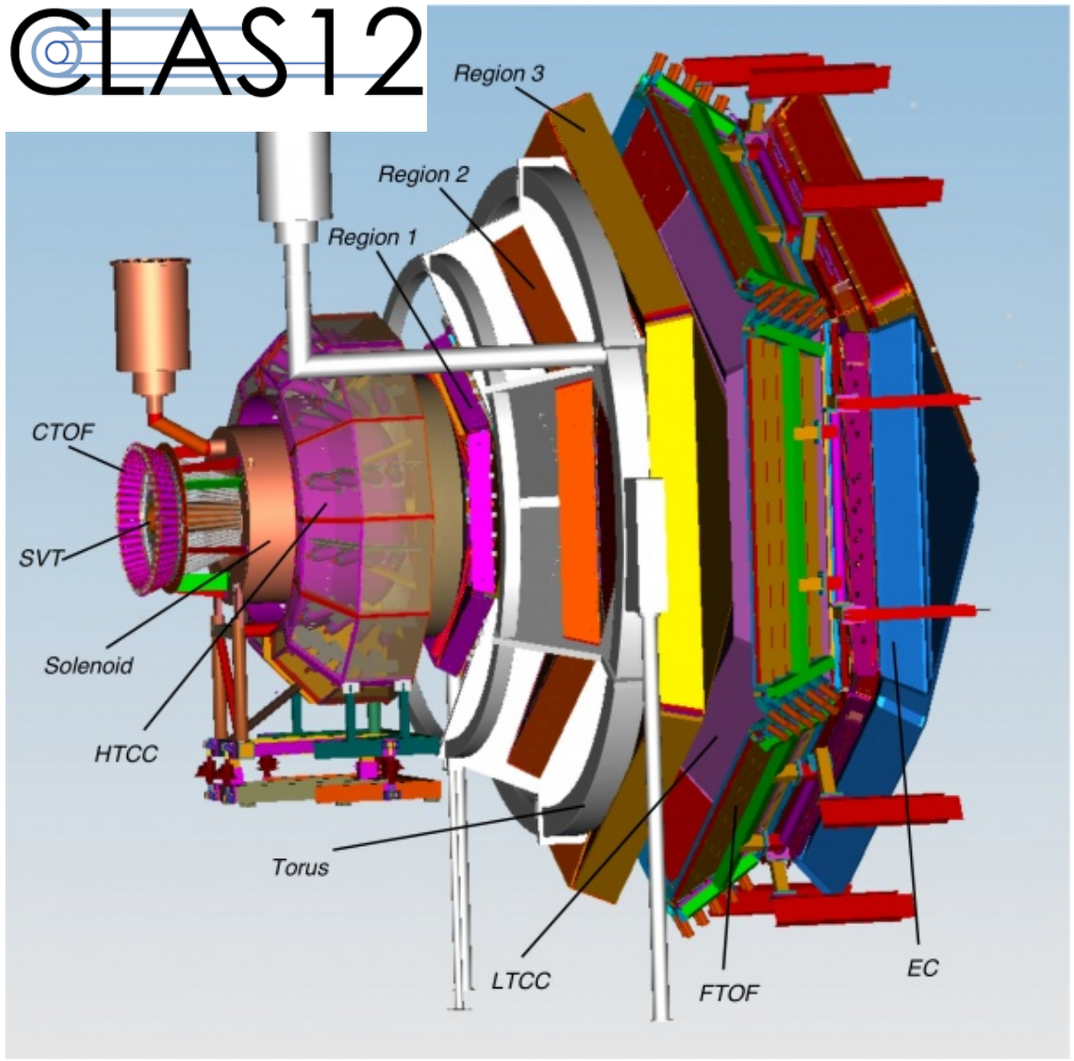


hybrid meson

- Can produce mesons of any J^{PC} through VMD
- Photon polarization provides constraints on production processes
- Studies of polarization transfer and other production observables provides additional insight into hadron properties

The GlueX and CLAS12 Experiments @ JLab





- Tagged photon beam peaked at $E_\gamma \approx 9$ GeV
- Linear polarization ≈35% in peak
- 4π acceptance, loose trigger
- GlueX-I (2017-8), GlueX-II (2020-5?)

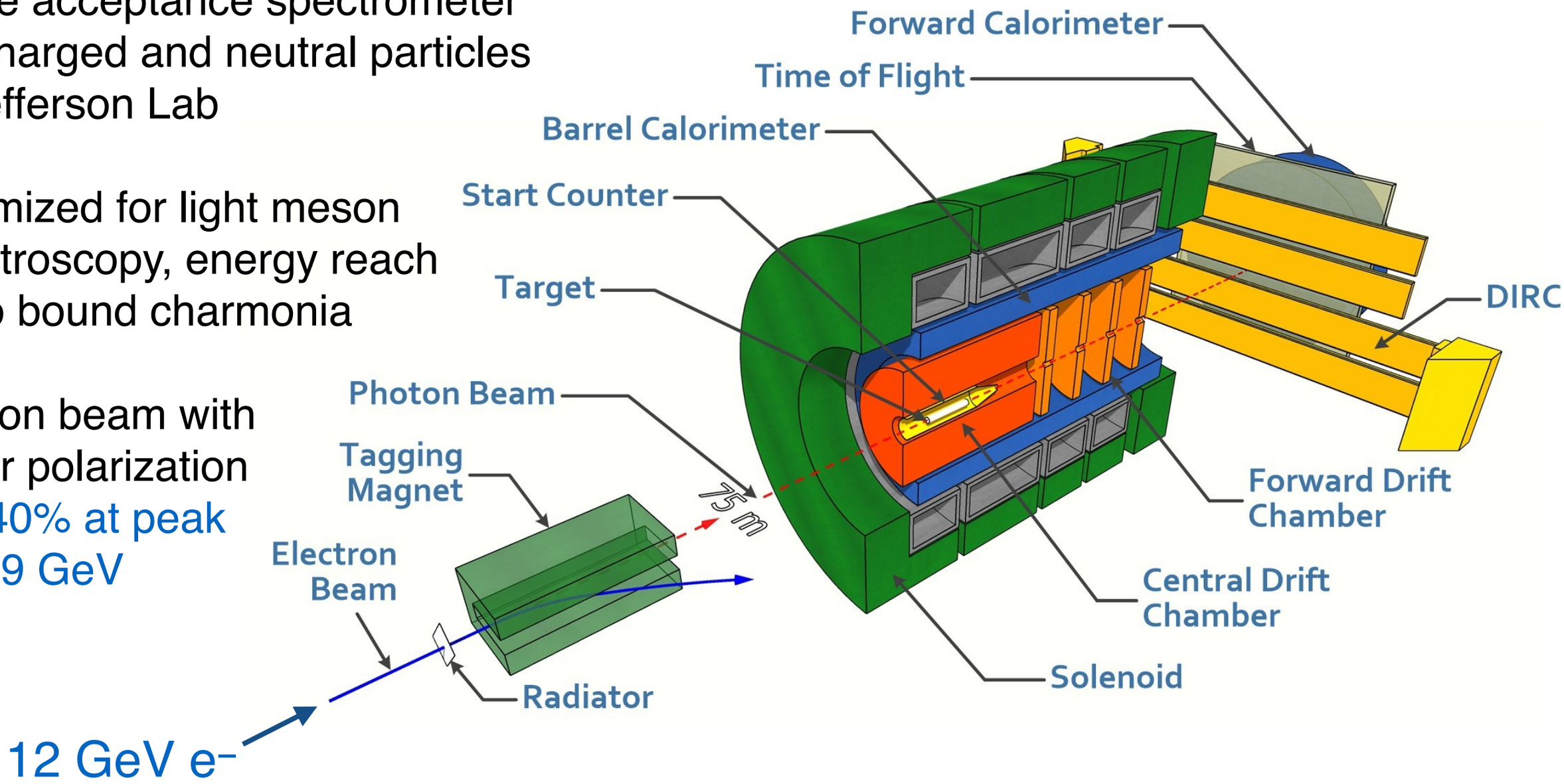
- Electron beam with $E_e < 11$ GeV
- Forward tagger for photoproduction
- Excellent PID
- Program with variety of targets

The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

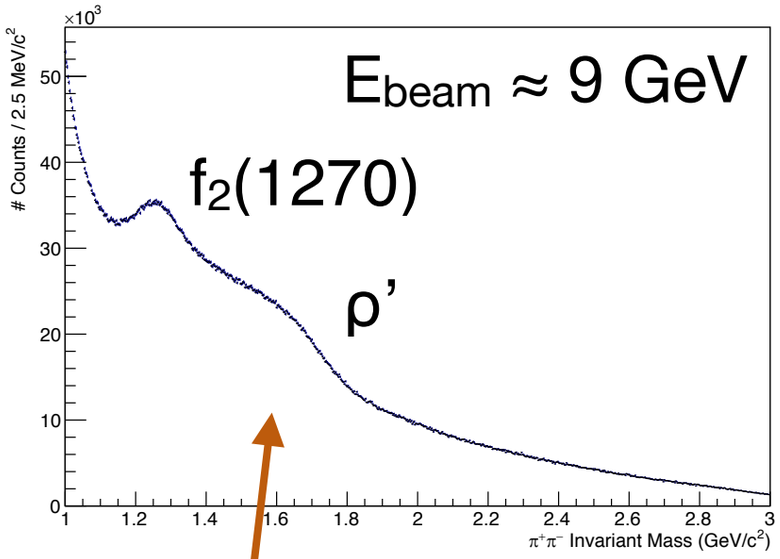
Optimized for light meson spectroscopy, energy reach up to bound charmonia

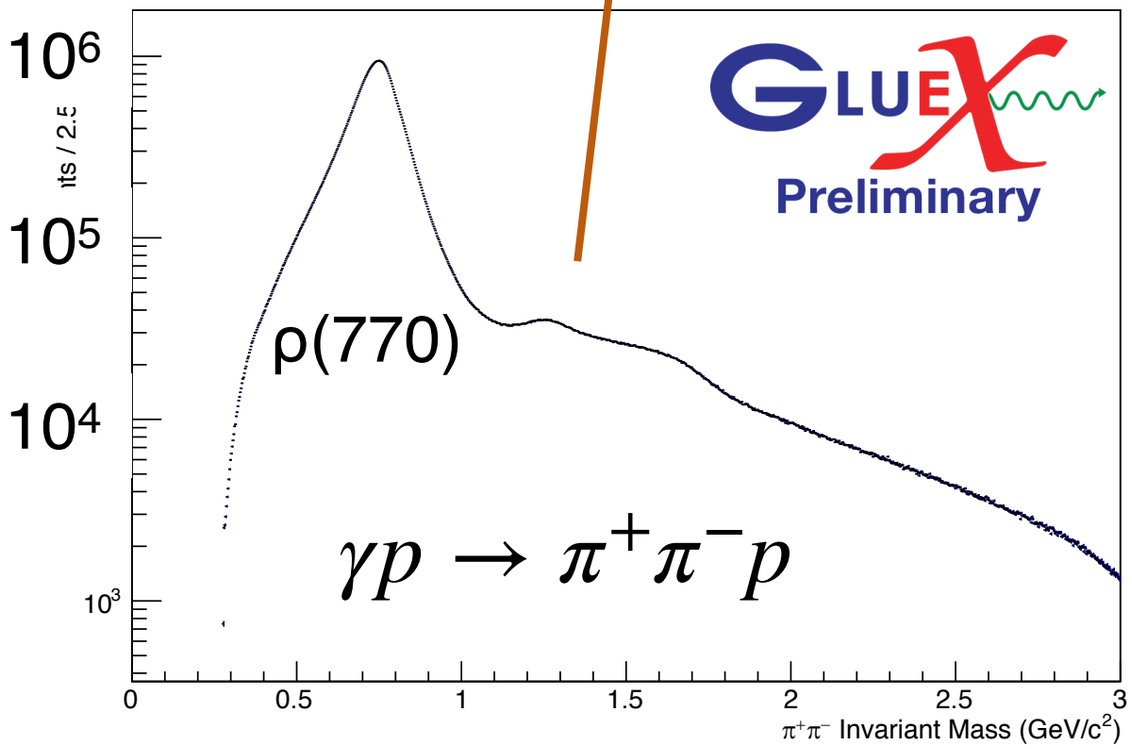
Photon beam with linear polarization
$P \approx 40\%$ at peak
$E_\gamma \approx 9$ GeV



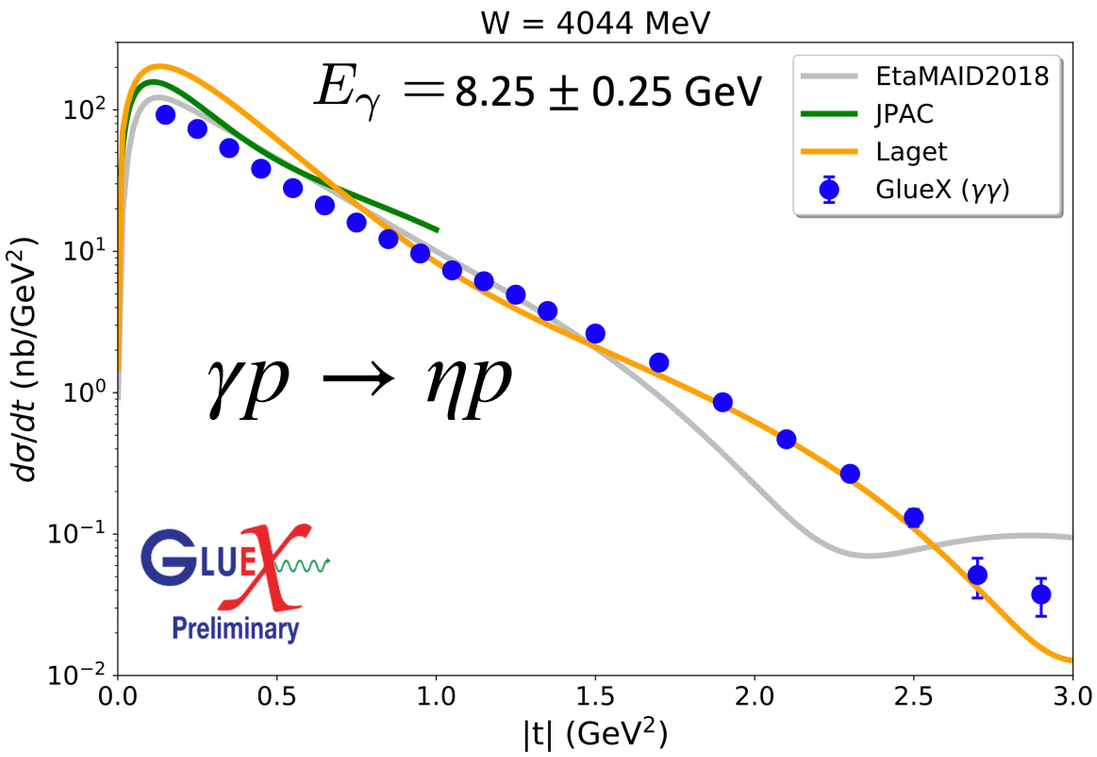
- **GlueX-I (2017–2018): $L = 305$ pb^{-1} [$E_\gamma > 8$ GeV]**
- **GlueX-II (2020–2025?): $L = 320$ pb^{-1} (so far)**
  expect 3-4x GlueX-I

GlueX: High Statistics Photoproduction Data



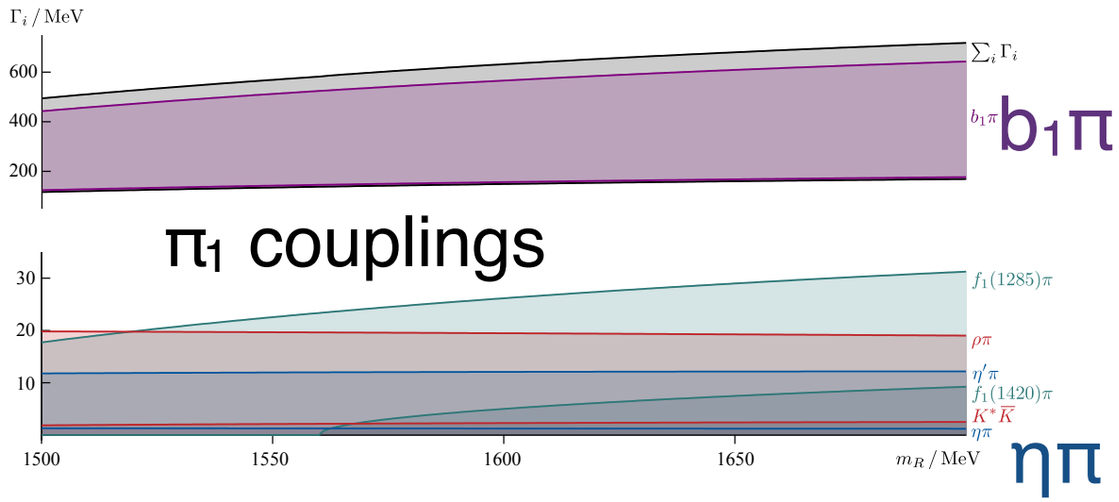


- GlueX has collected orders of magnitude more data than previous experiments at $E_\gamma \approx 9$ GeV
  - > 5 times more η(‘)π than COMPASS
    – amplitude analysis underway
- Hybrid search range allows searching for strange XYZ partners
  - $\phi(2170)$, Z_s, …

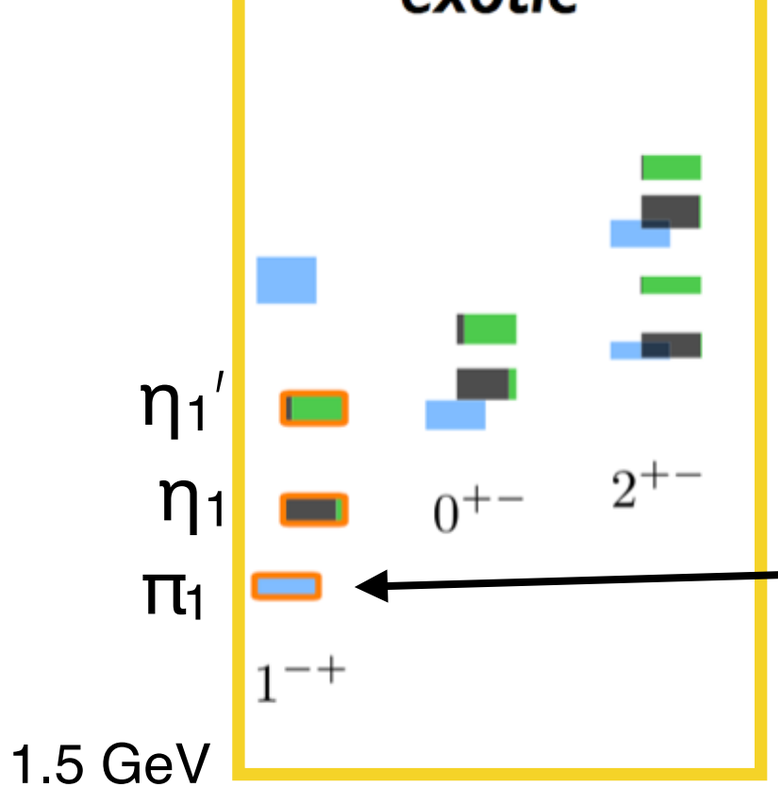


Hybrid Mesons

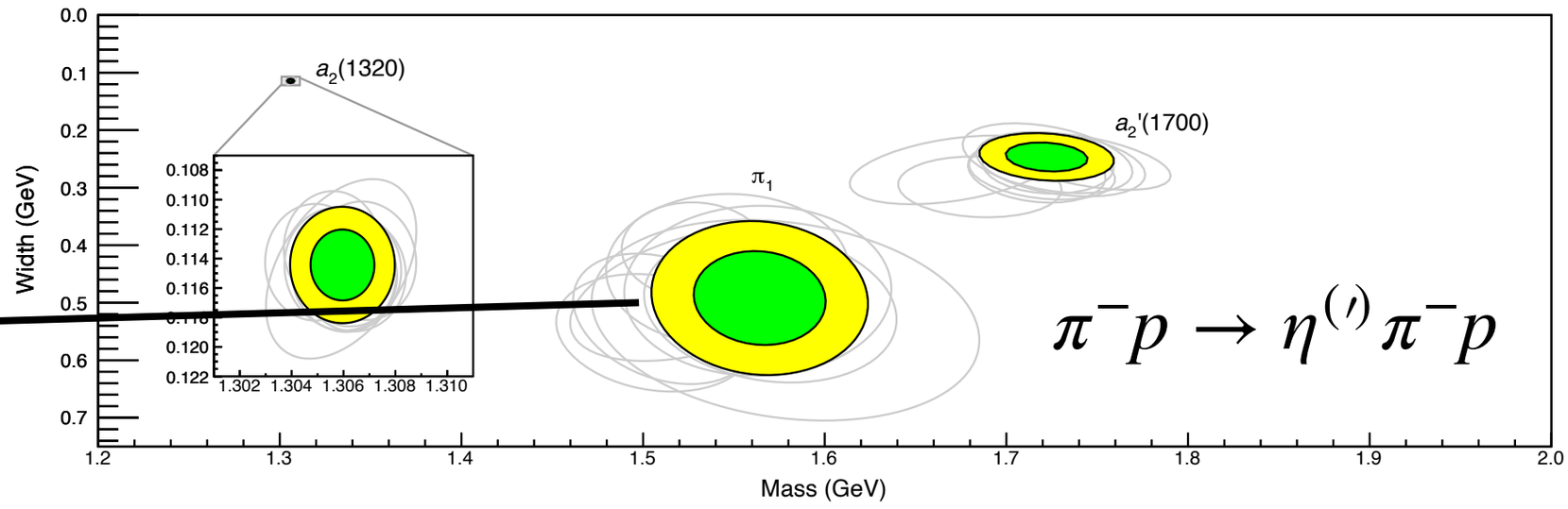
HadSpec: PRD 103, 054502 (2021)



- 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 $J/\psi \to \gamma\eta\eta'$ [arXiv:2202.00621]
- Need to confirm π_1 and η_1 and establish the full light quark hybrid spectrum → insight to the heavy quark hybrid spectrum



HadSpec: PRD 88, 094505 (2013)



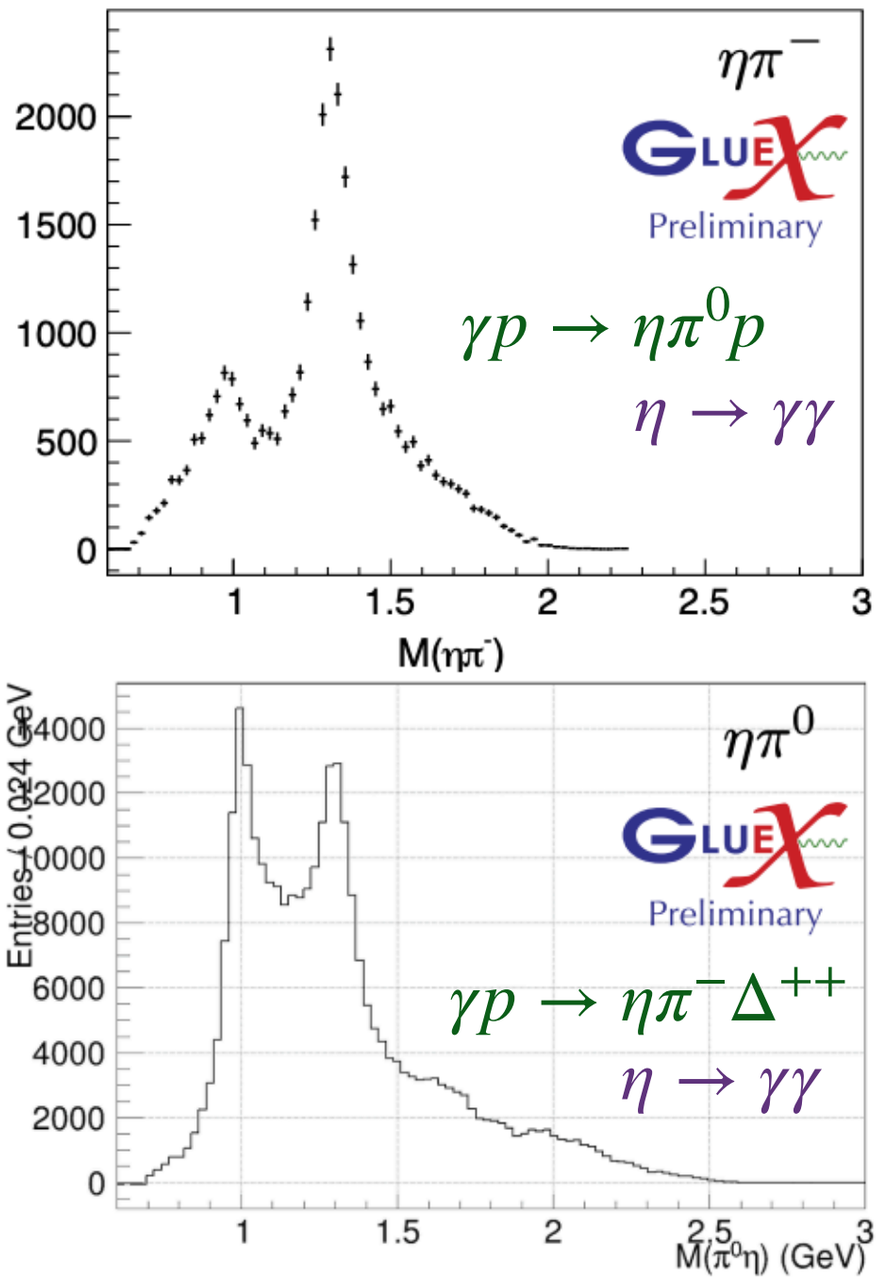
JPAC: PRL 122, 042002 (2019)

ηπ Amplitude Analysis at GlueX

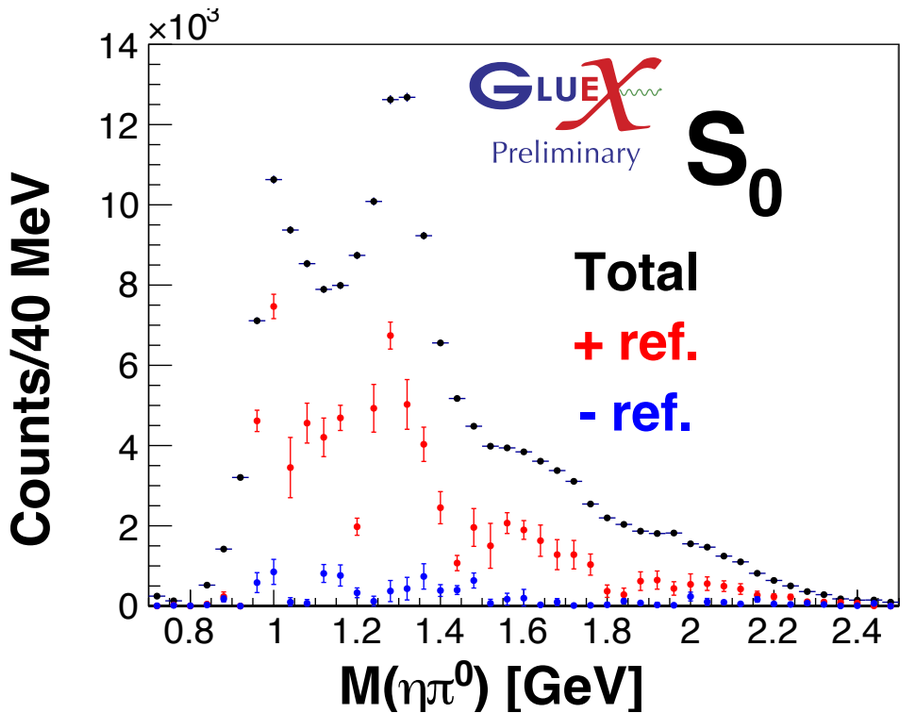
- πη / πη′ "golden channels" for π_1 search: small b.f. but experimentally clean
  - Odd L πη(′) → exotic J^{PC}
  - Study known a_0/a_2 in πη
  - Apply analysis to πη′ with stronger π_1
- Can study several channels
  - $\gamma p \to \eta\pi^0 p$ $\quad$ $\gamma p \to \eta\pi^- \Delta^{++}$
  - Control understanding of production
- with multiple η decays
  - $\eta \to \gamma\gamma$ $\quad$ $\eta \to \pi^+\pi^-\pi^0$
  - Control understanding of acceptance and backgrounds
- Use polarization to control acceptance, help separate amplitudes
- Currently also studying various vector-pseudoscalar channels

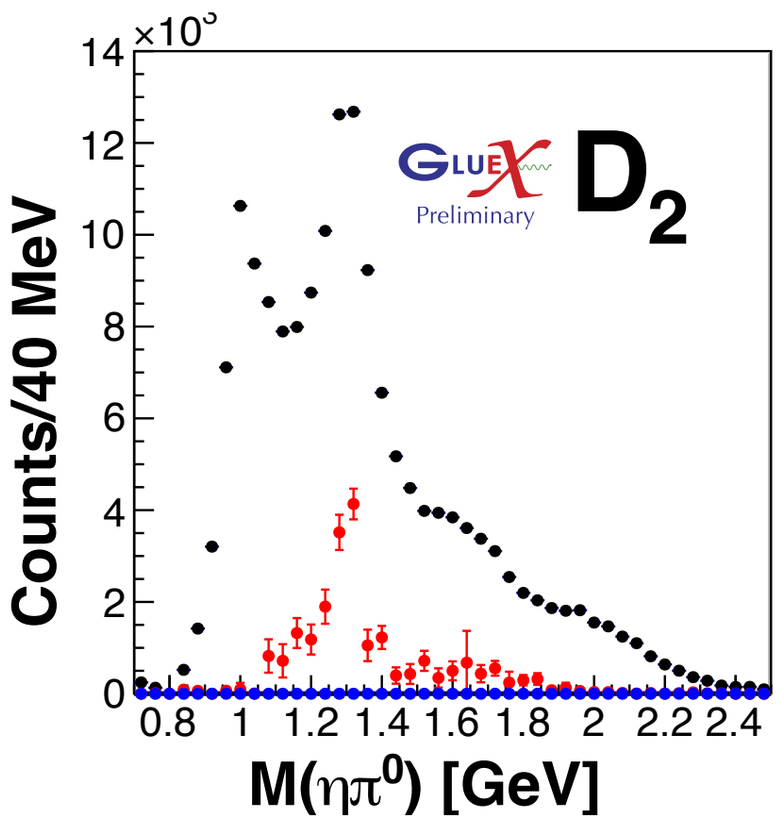
GlueX-I Data

$0.1 < -t < 0.3$ GeV^2

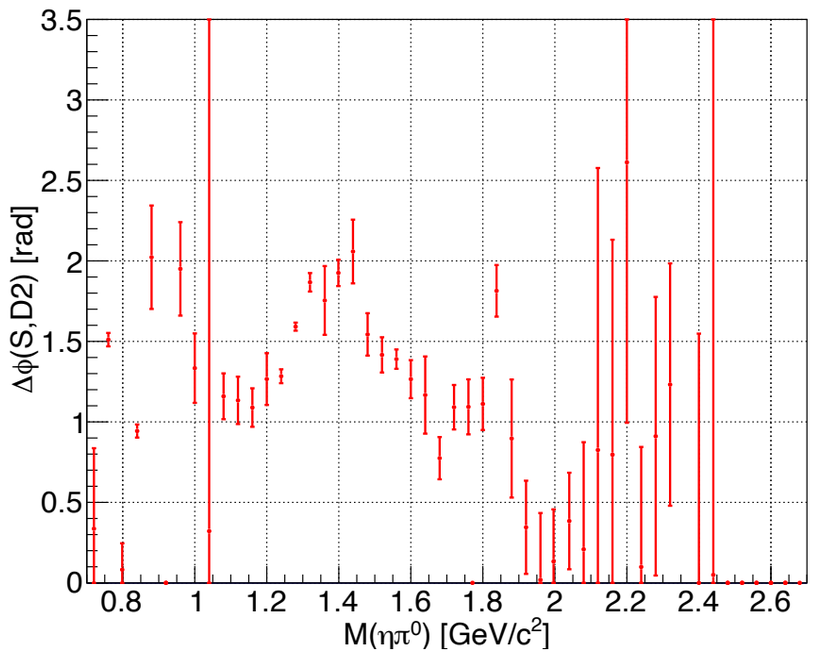


Fit to $\gamma p \to \eta\pi^0 p$ Data ($-t = 0.1 - 0.3$ GeV^2)





- Combined fit, all polarization orientations

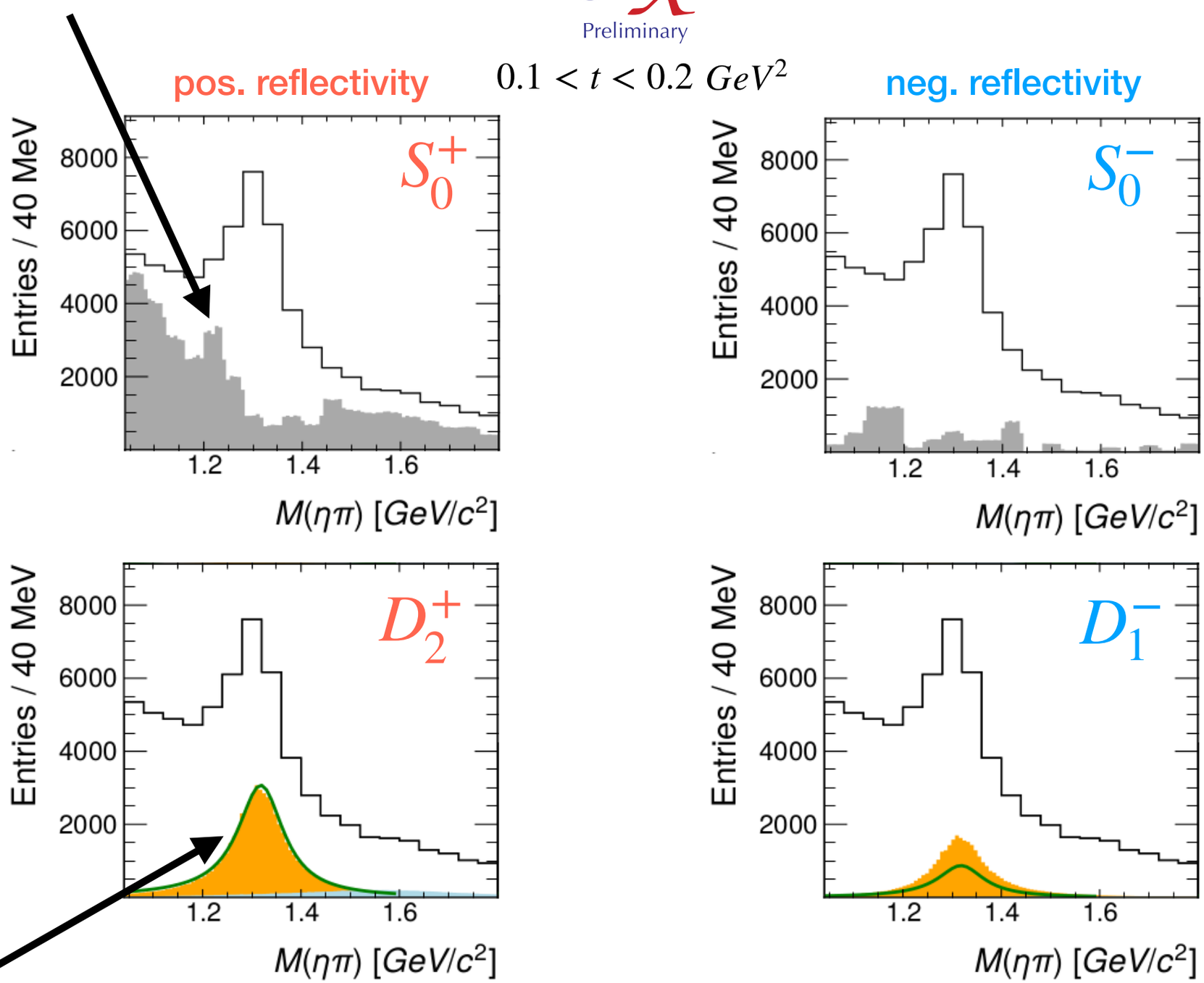


- Statistical uncertainties (MINUIT) only
- Phase between S^+ and D_2^+ waves shows motion at $a_2(1320)$ position
- Strongly depends on waveset
- **Perform semi - mass independent fit to extract a_2 contribution**

M.Albrecht (JLUO 2022)

Semi-model independent fit ($\gamma p \to \eta\pi^0 p$)

"mass-independent" S-wave

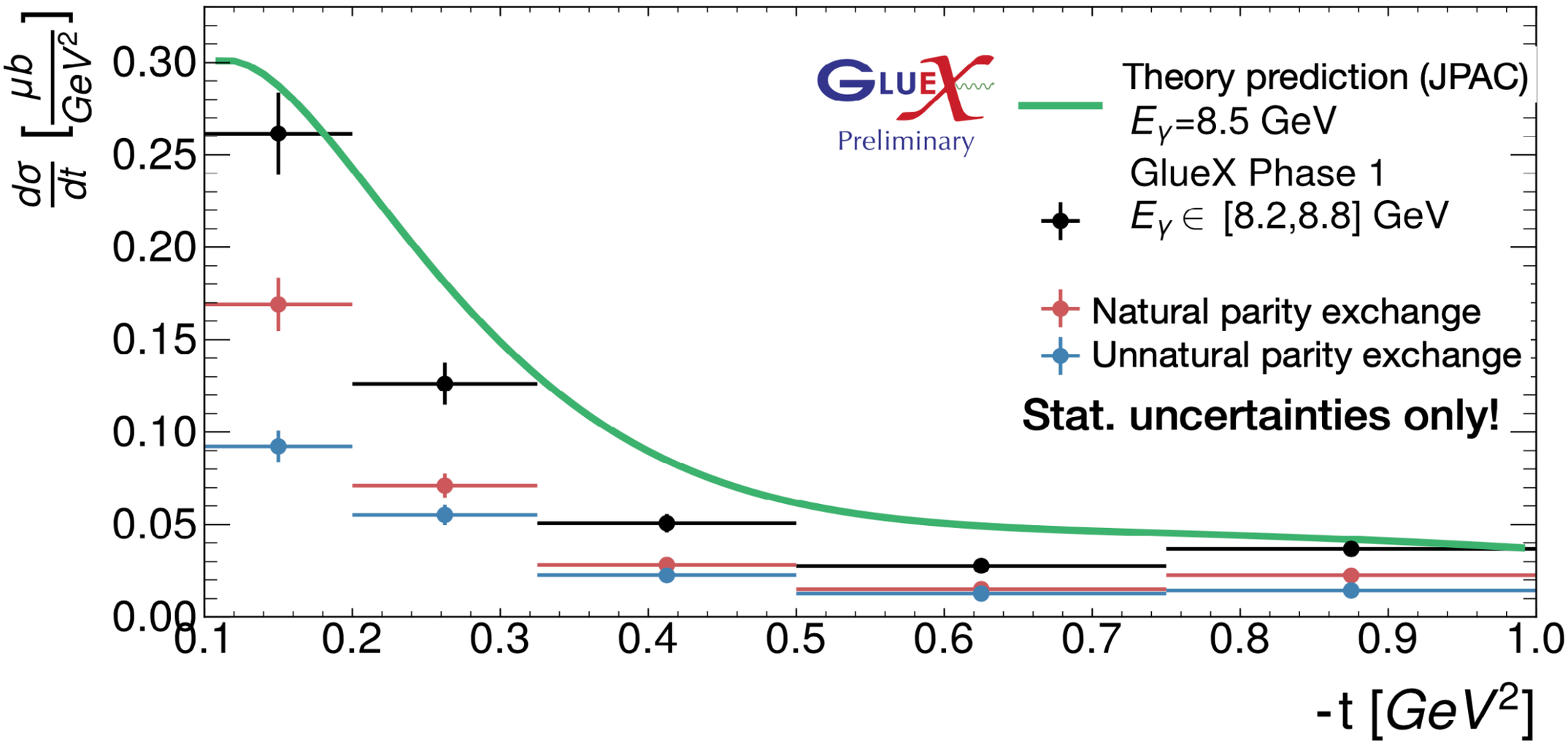


$a_2(1320)$: Breit-Wigner

M.Albrecht (JLUO 2022)

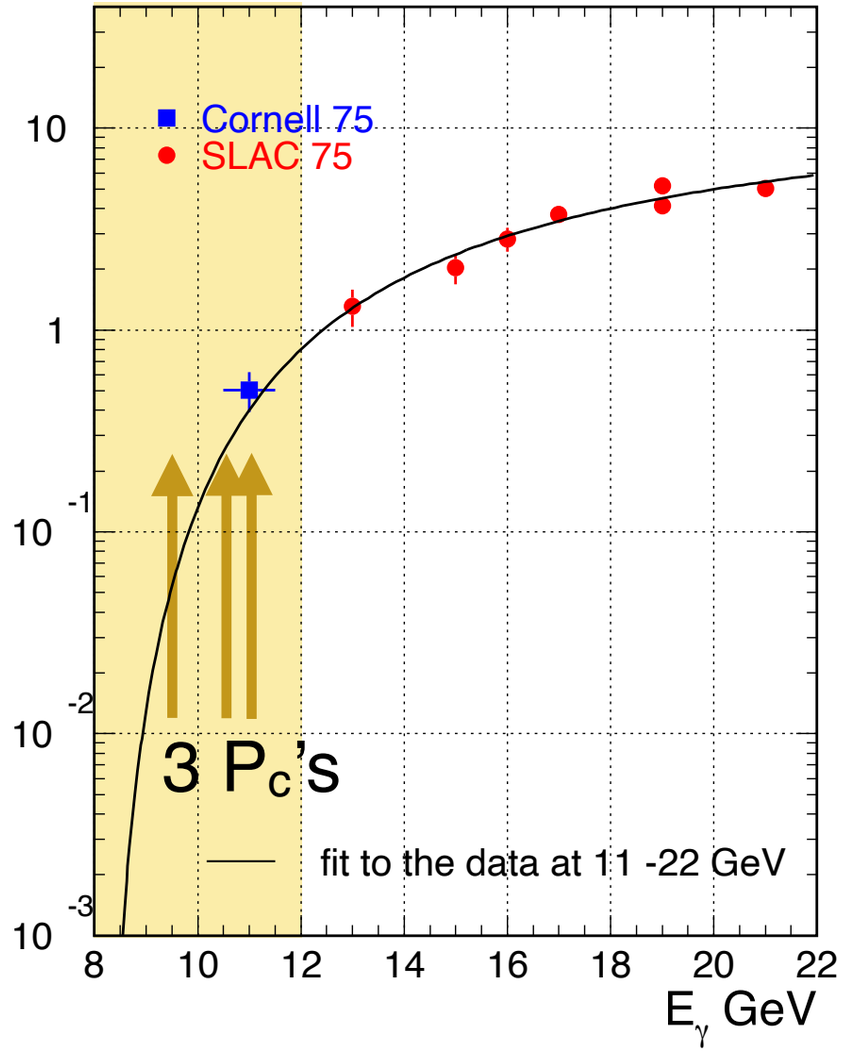
Preliminary $\gamma p \to a_2(1320)p$ Cross Section

- Preliminary cross sections agree with with JPAC prediction
- Analysis techniques applicable at higher energies
- Photon polarization crucial to control contributions from different production amplitudes

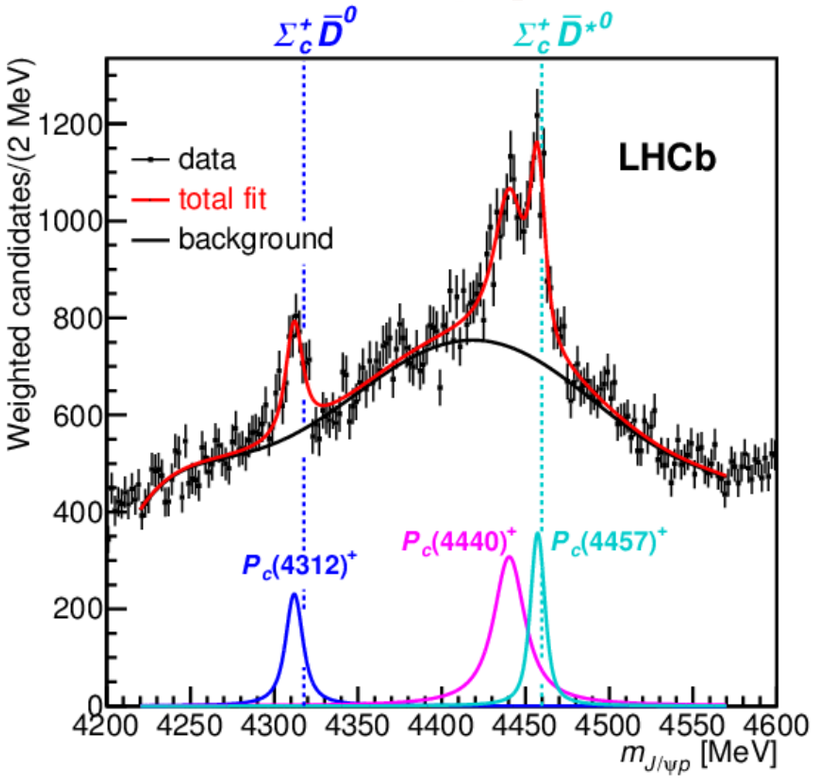


Charmonium Photoproduction Near Threshold

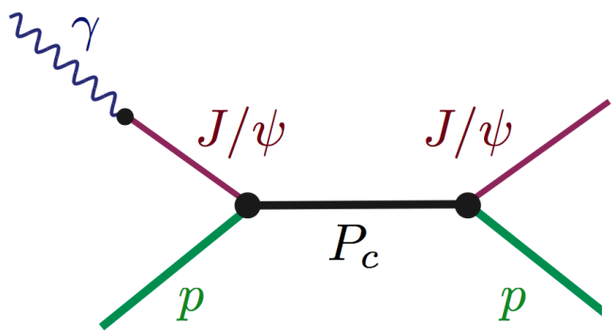
- Production of $c\bar{c}$ near threshold probes the distribution of gluons in the proton and the nature of the proton mass
- Can also look for s-channel production of resonant states



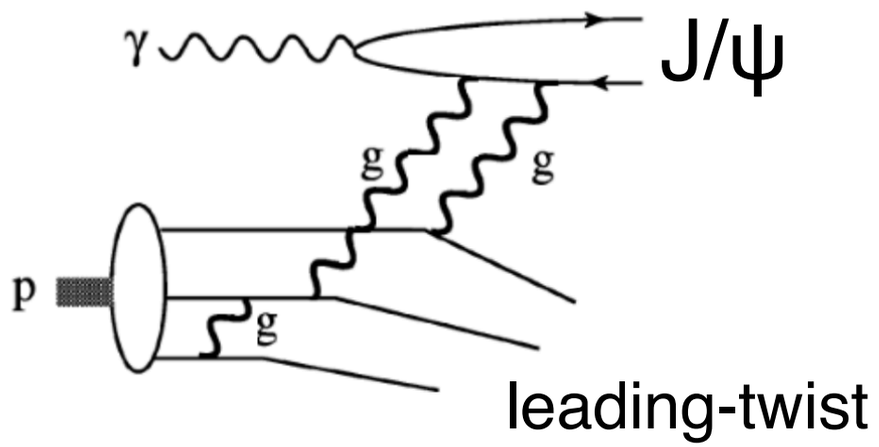
$\Lambda_b \to J/\psi\, p\, K^-$



LHCb, PRL 122, 222001 (2019)

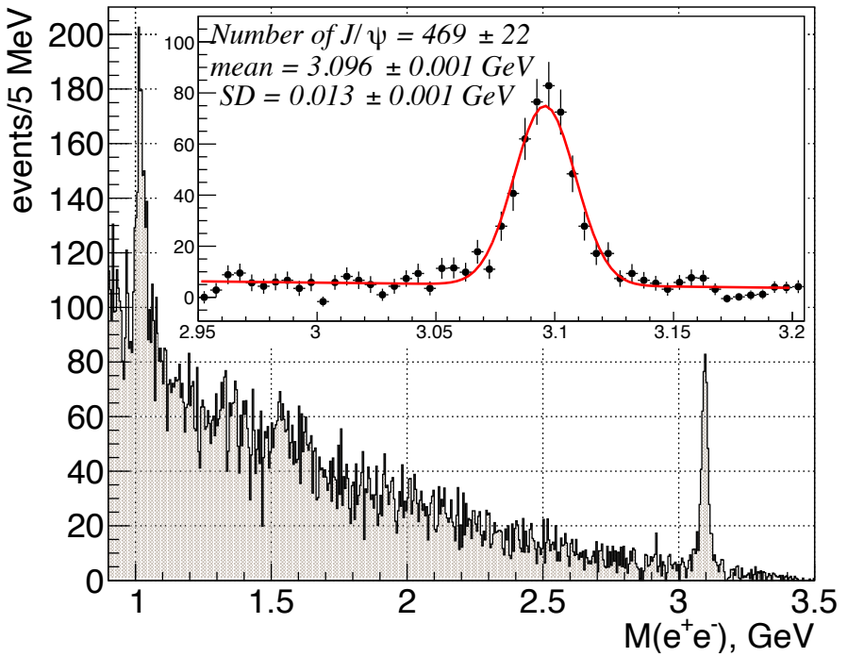


$\gamma\, p \to P_c \to J/\psi\, p$



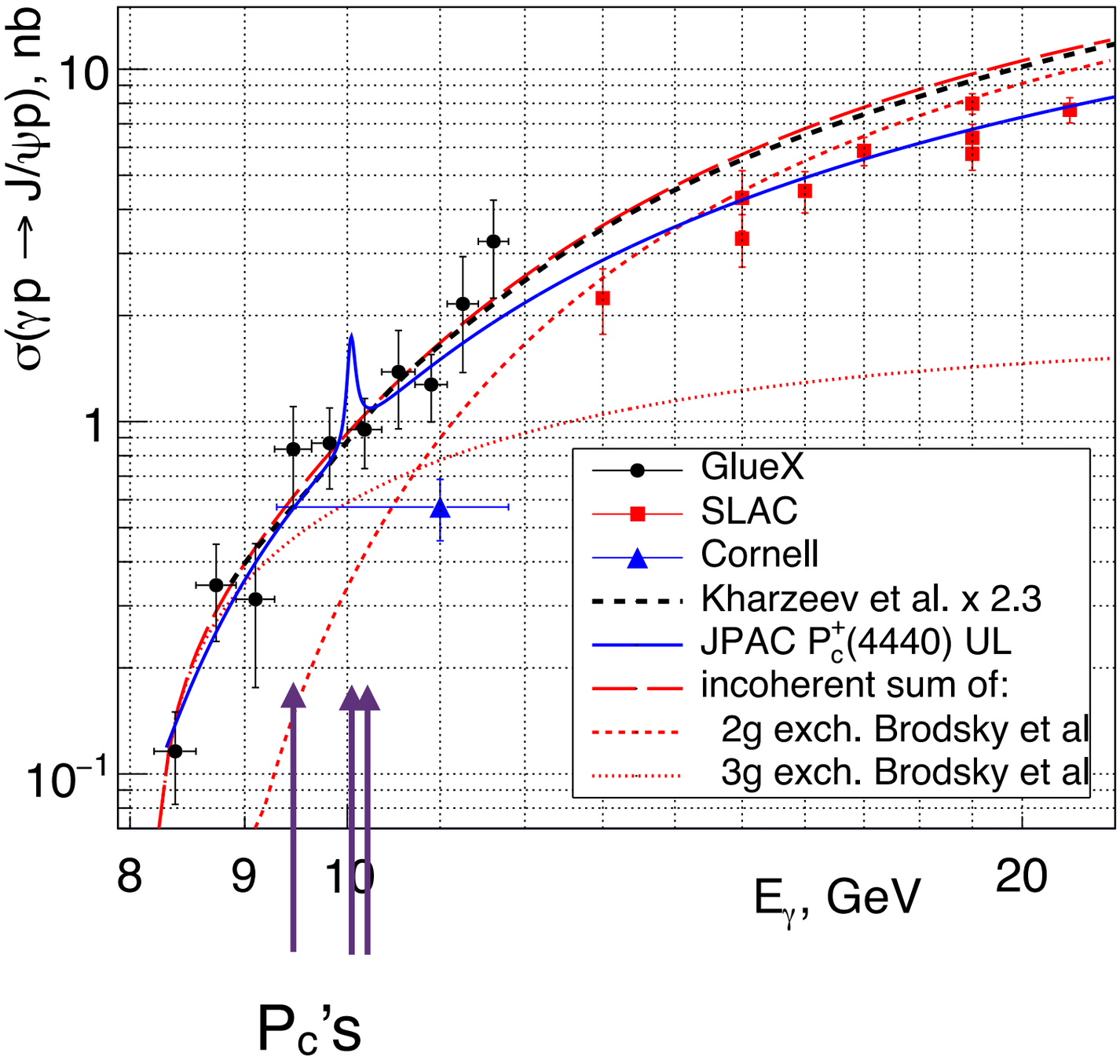
leading-twist

Published GlueX J/ψ Photoproduction Results

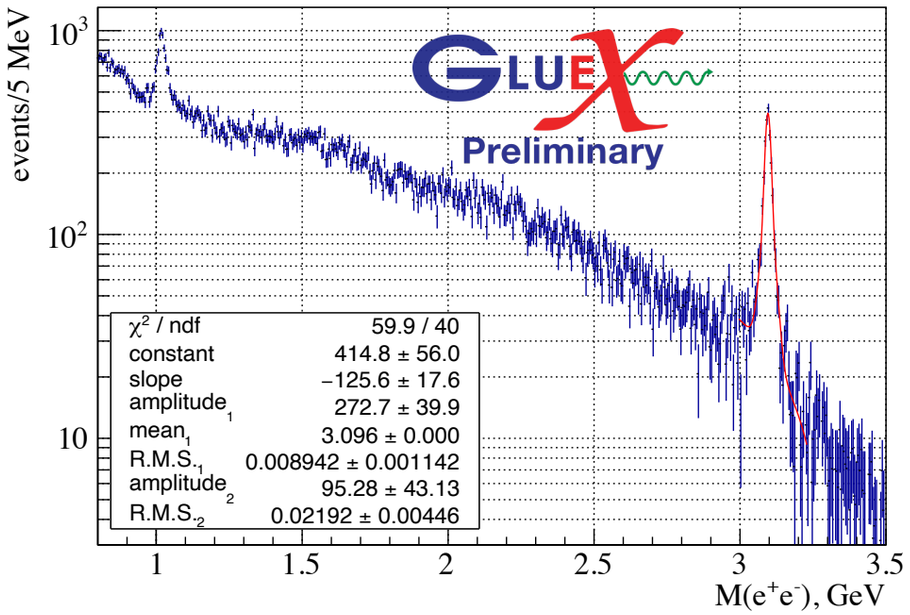


- Used portion of GlueX-I data [469 J/ψ] to measure cross sections
- Model-dependent limits set on P_c production, molecular models preferred
- Limits depend on VMD + understanding of production mechanism

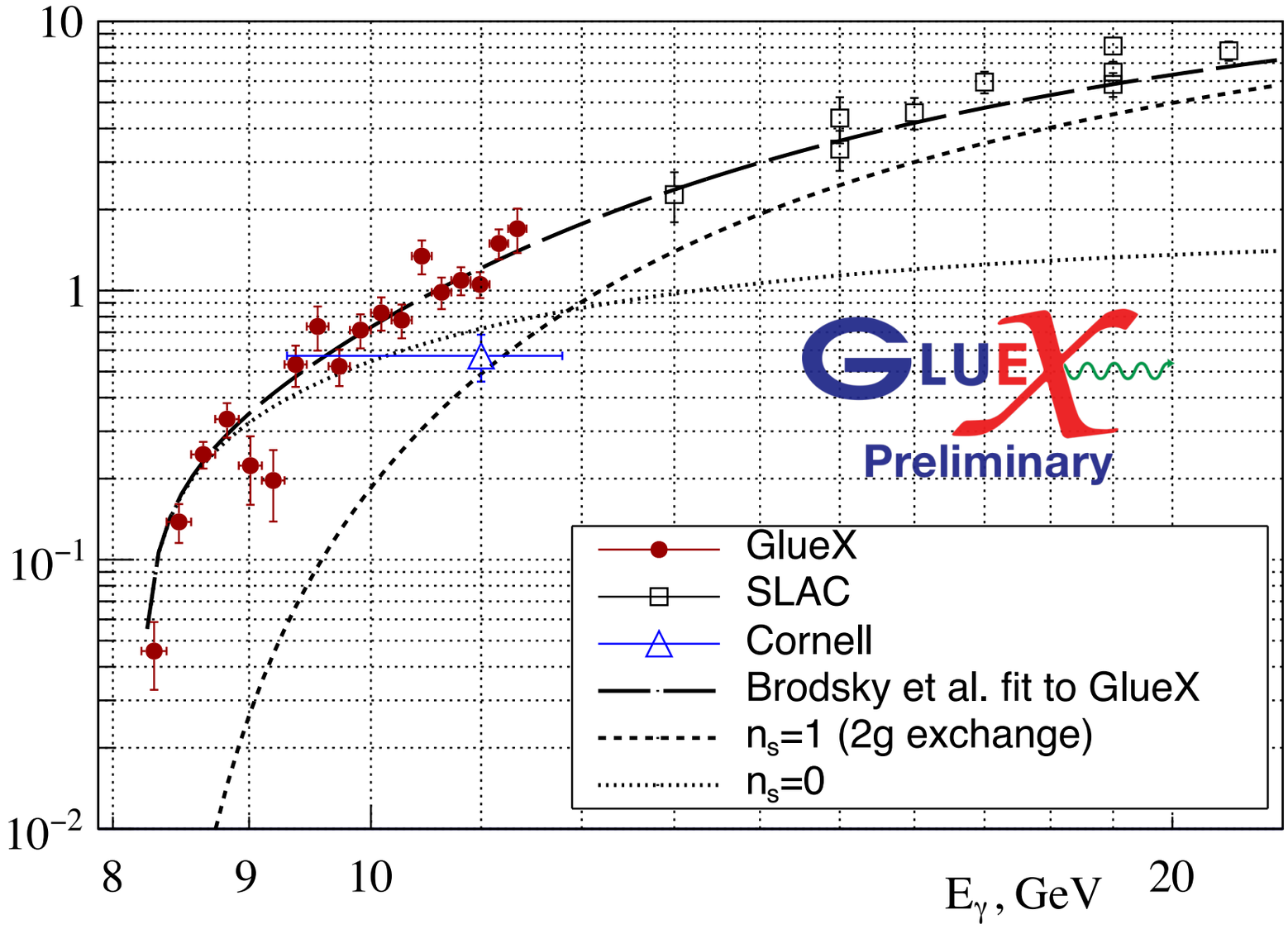
GlueX: PRL 123, 072001 (2019)



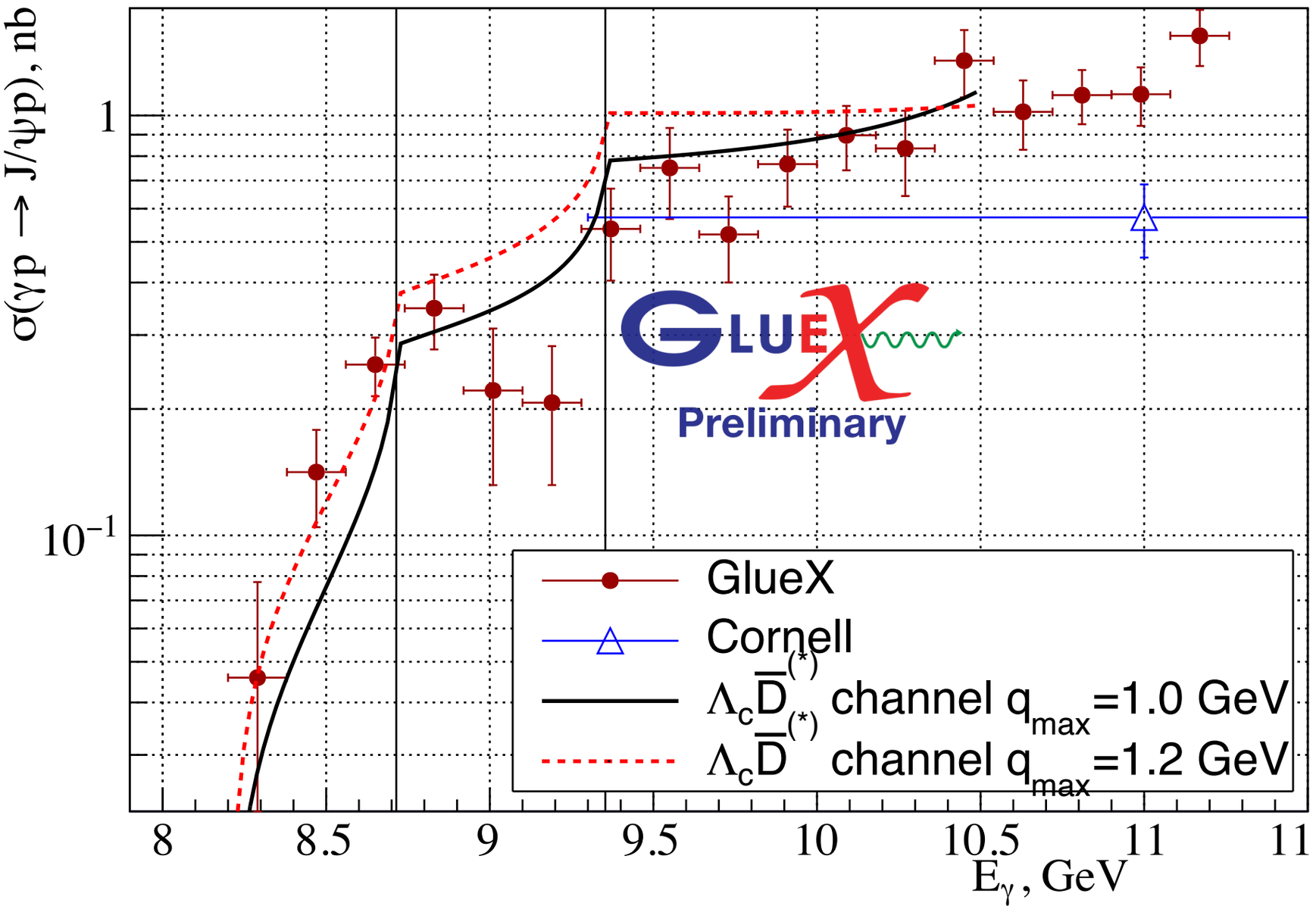
Preliminary GlueX-I J/ψ Photoproduction Results



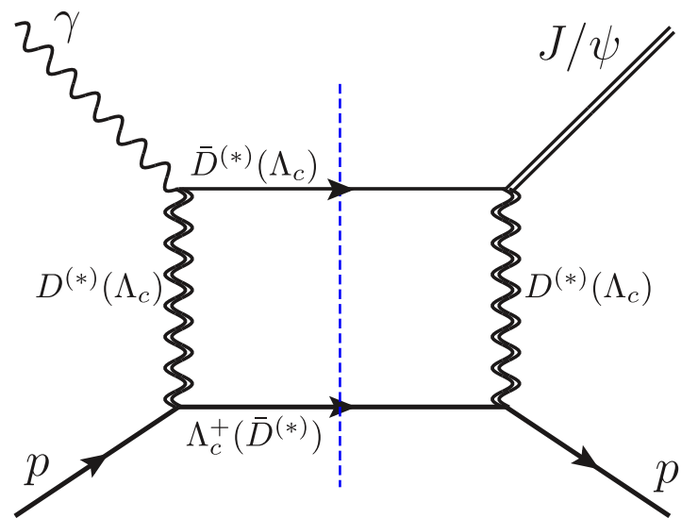
- Full GlueX-I data yields 2270 ± 58 J/ψ's
- Overall normalization uncertainty ~20%
- "Dip" above 9 GeV has 2.6σ (1.3σ) local (global) significance



Comparing GlueX-I results to models

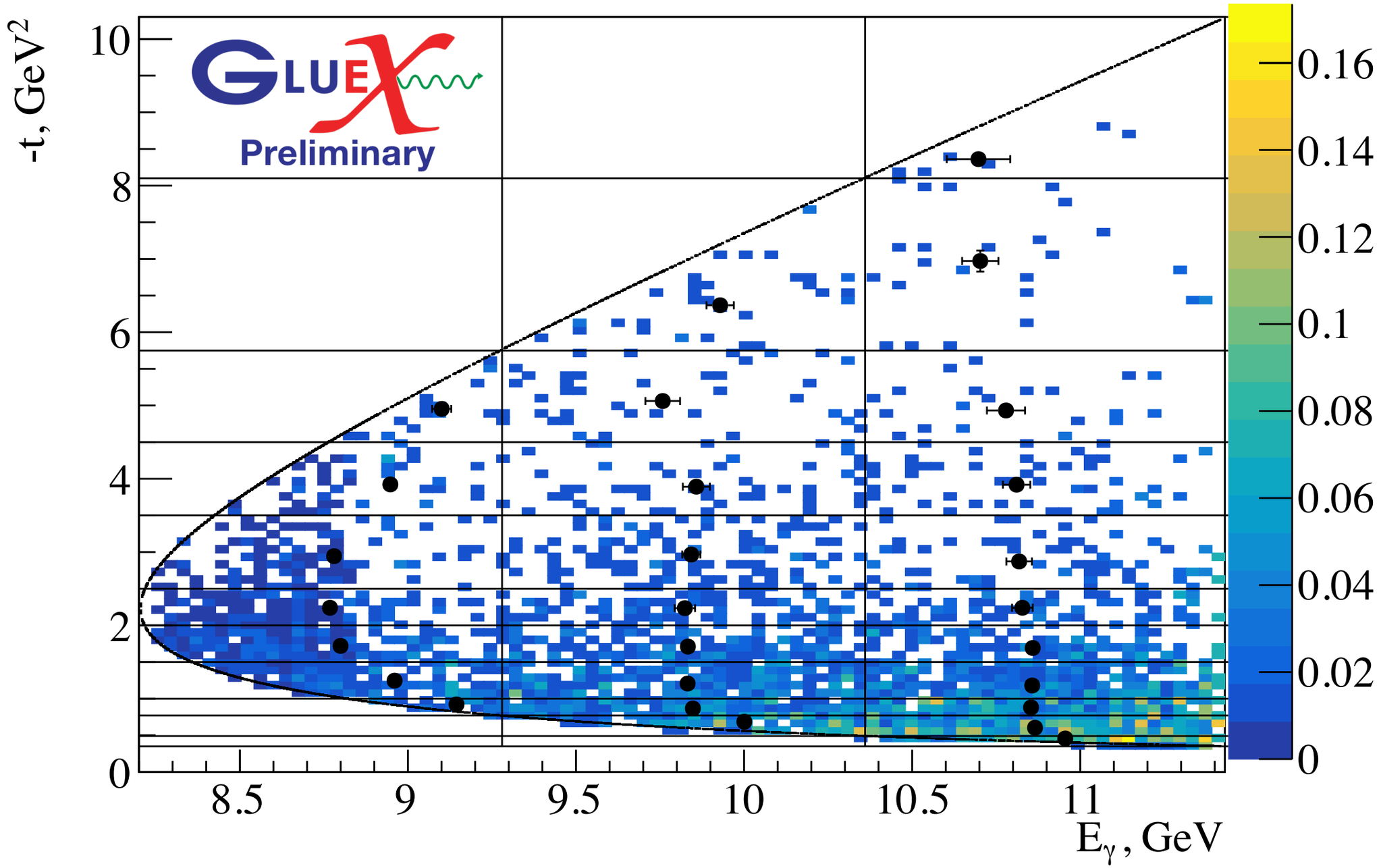


Du et al., EPJC 80, 1053 (2020)



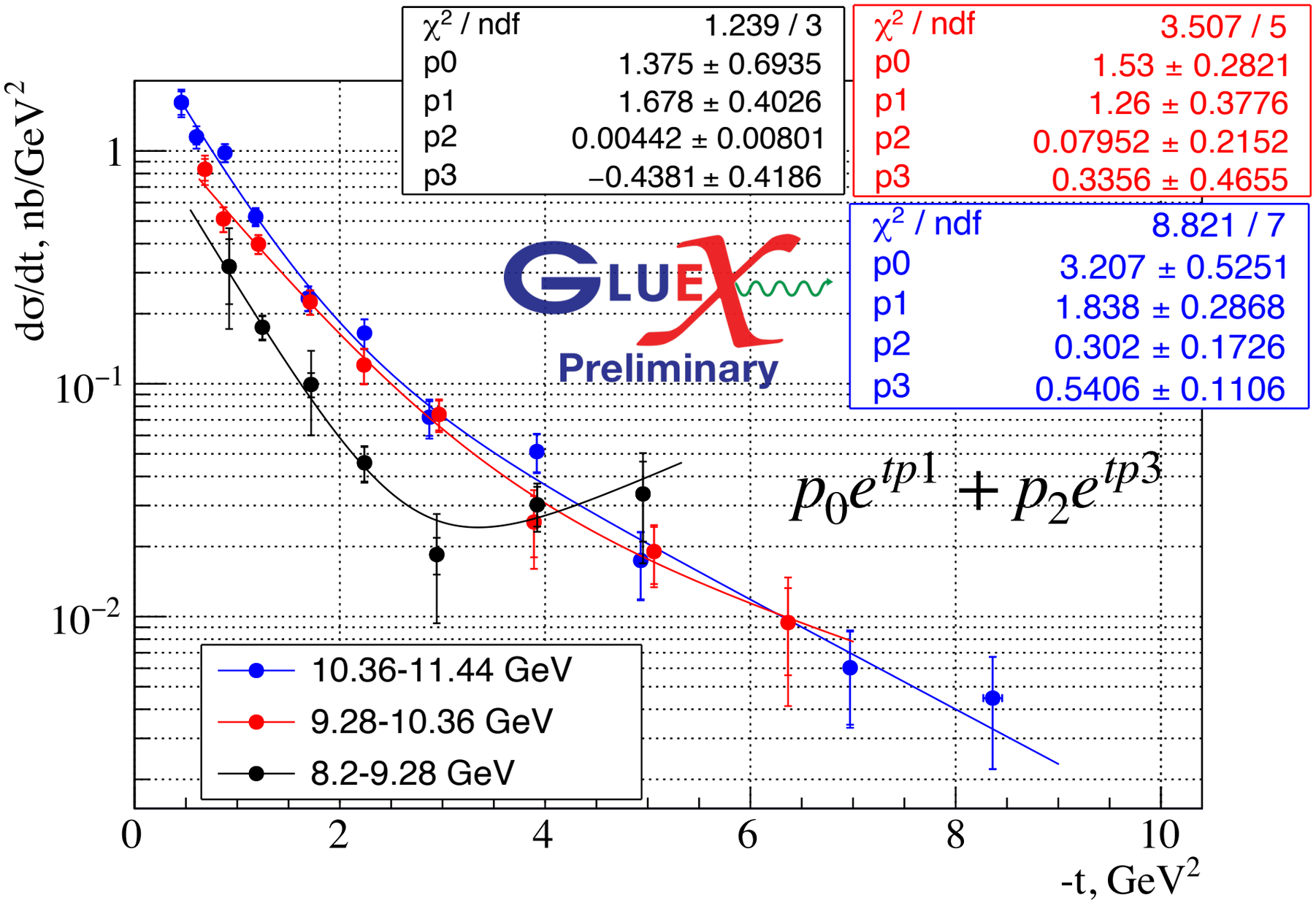
- Model with open-charm loops provides better description of cross-section than models that use QCD factorization
  - Also predicts shallower t-dependence
- Should expect contributions from both processes

Preliminary GlueX-I J/ψ Differential Cross Sections



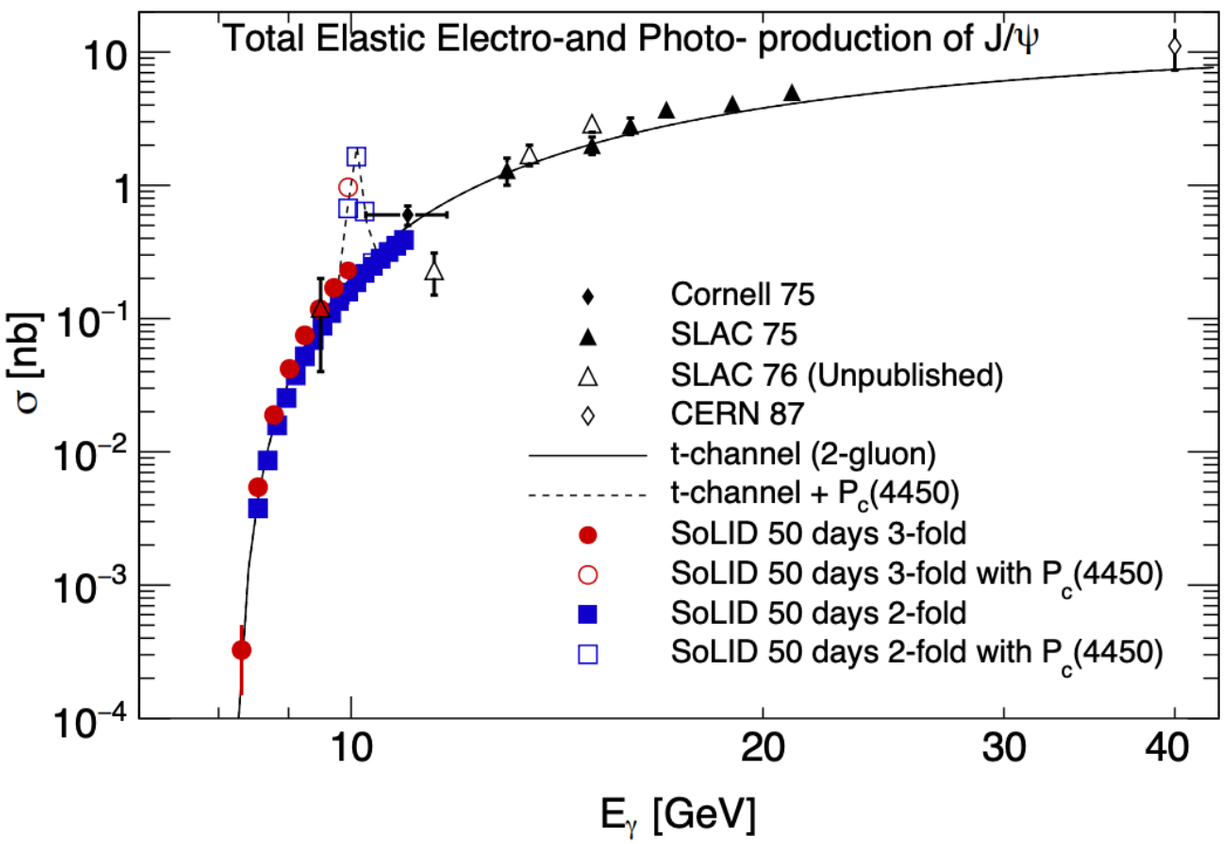
- Calculate dσ / dt including event-by-event luminosity weighting
- Report cross sections at bin means (points)

Preliminary GlueX-I J/ψ Differential Cross Sections

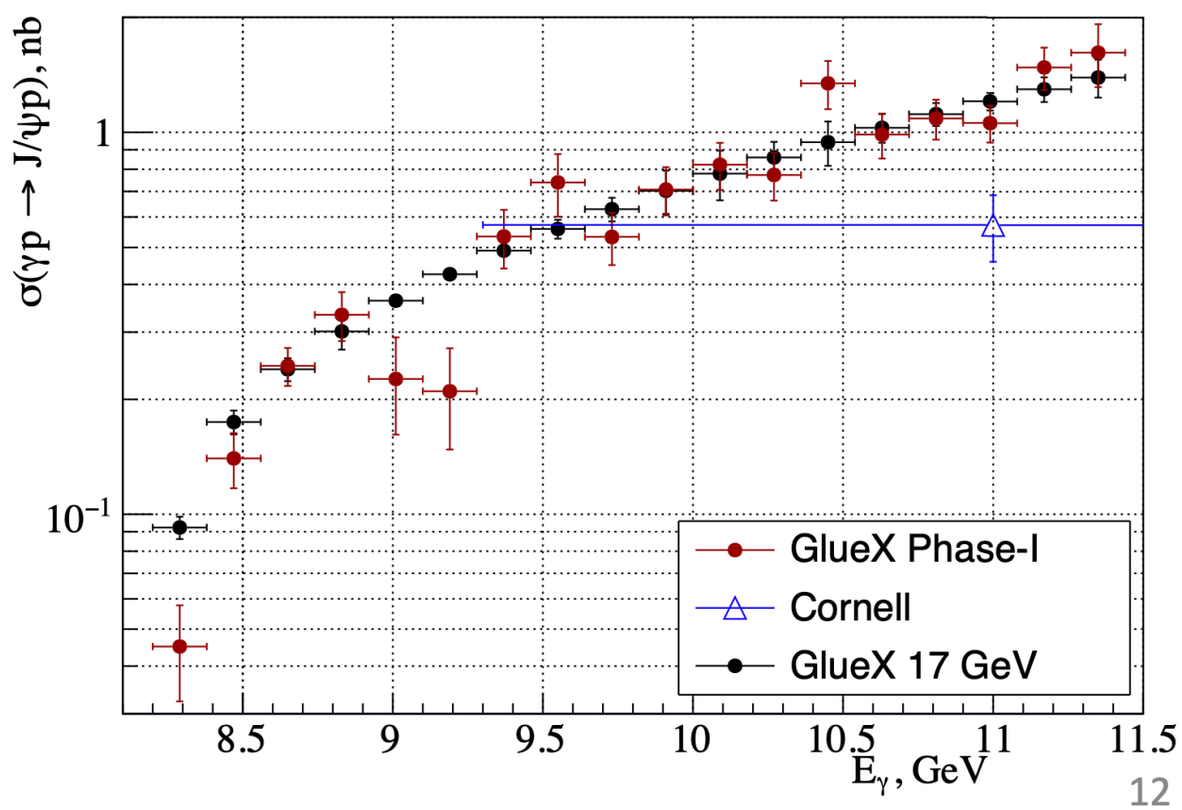


- Differential cross sections generally consistent with expectations of gluonic exchange (except near threshold?)

Prospects for future J/ψ production measurements



S. Joosten and Z.E. Meziani, *PoS* QCDEV2017 (2018) 017



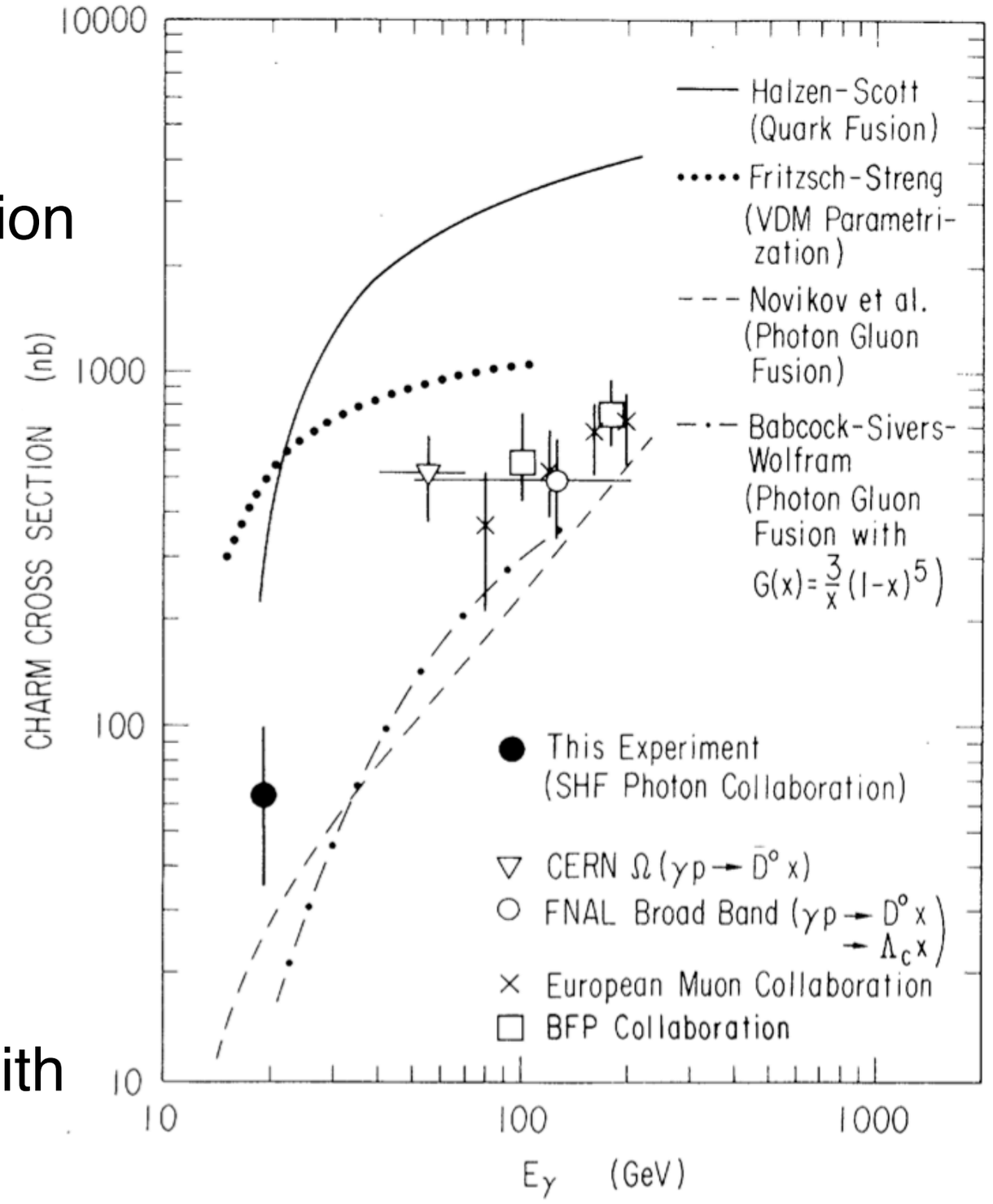
L. Pentchev, J/ψ + Beyond Workshop

- JLab Hall C measurements also see no clear P_c, limits are similarly model-dependent, CLAS12 measurements under way
  - Proposal for double polarization measurements in Hall A
- Future: electro- and photoproduction at SOLID ($\mathscr{L} = 10^{37}\mathrm{cm}^{-2}s^{-1}$)
- More future: linearly polarized photoproduction at GlueX with energy-upgraded CEBAF

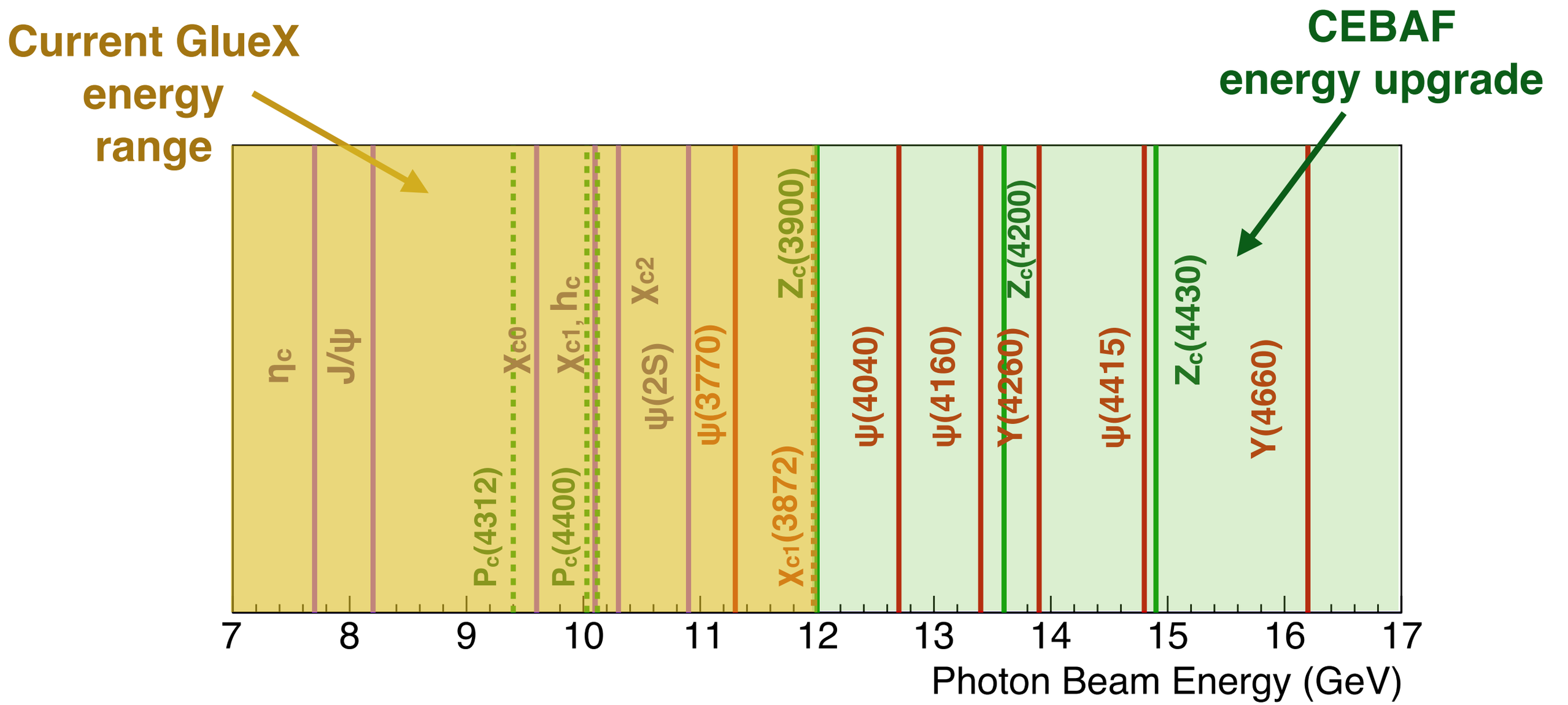
Open Charm Production Near Threshold

- 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
- Likely need full GlueX-II statistics with improved π/K separation

PRL 51, 156 (1983)

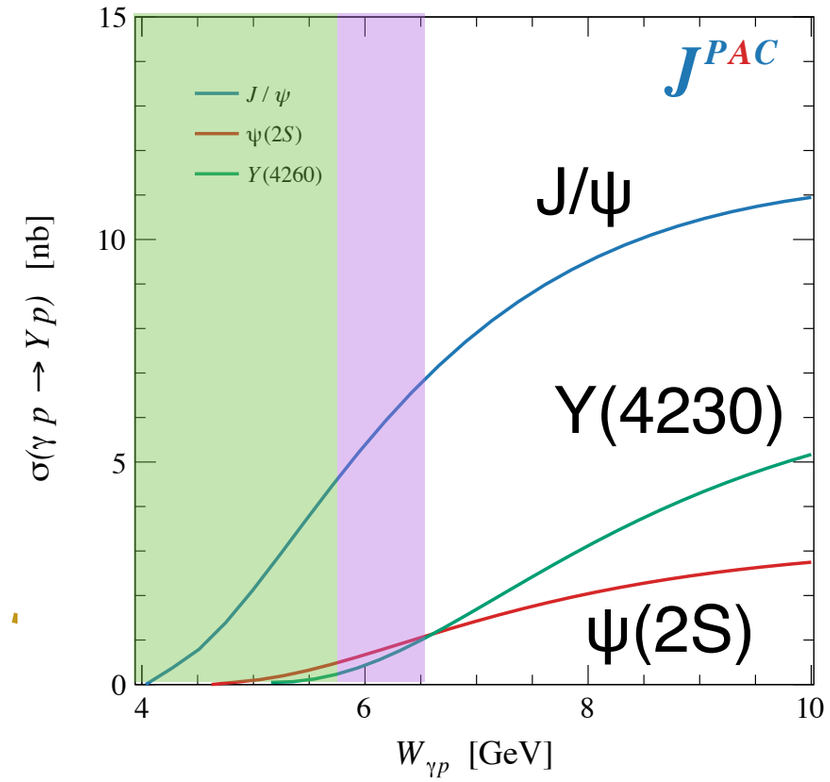


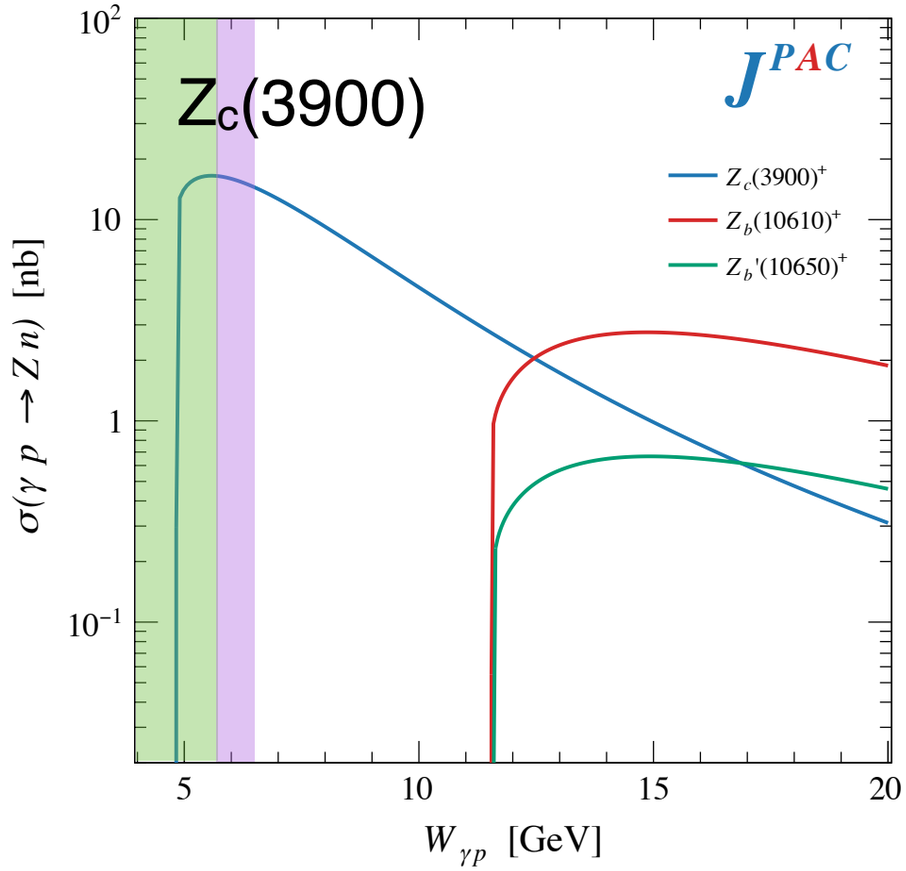
Charmonium Photoproduction Near Threshold

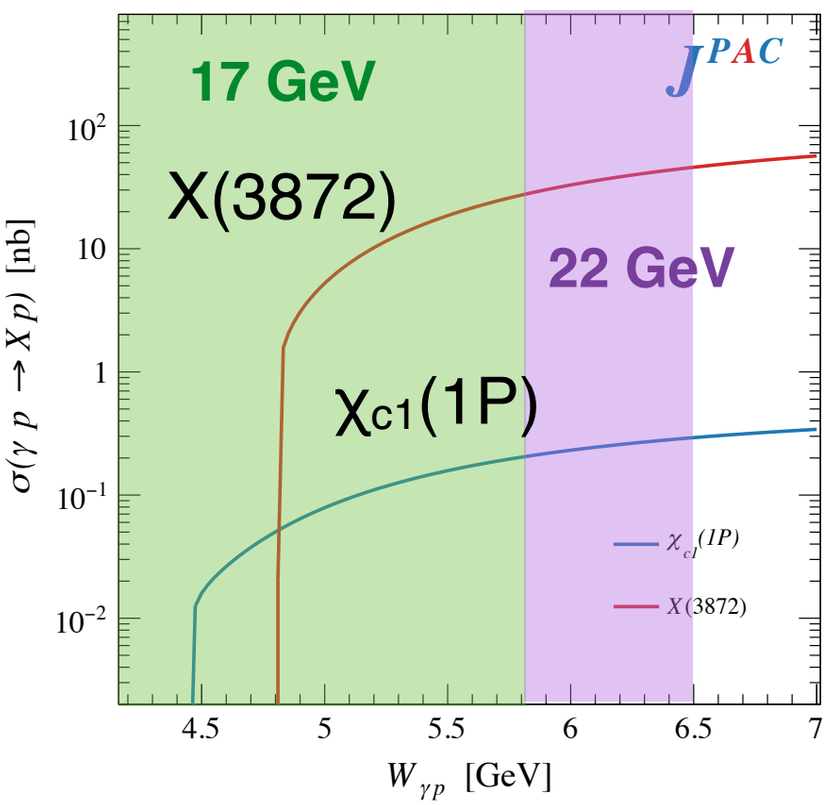


- Current max CEBAF energy allows study of bound $c\bar{c}$, P_c states
- 17 GeV e^- gives access to most exotic candidates
- 22 GeV e- gives good phasespace, linear polarization

JPAC Cross Section Predictions



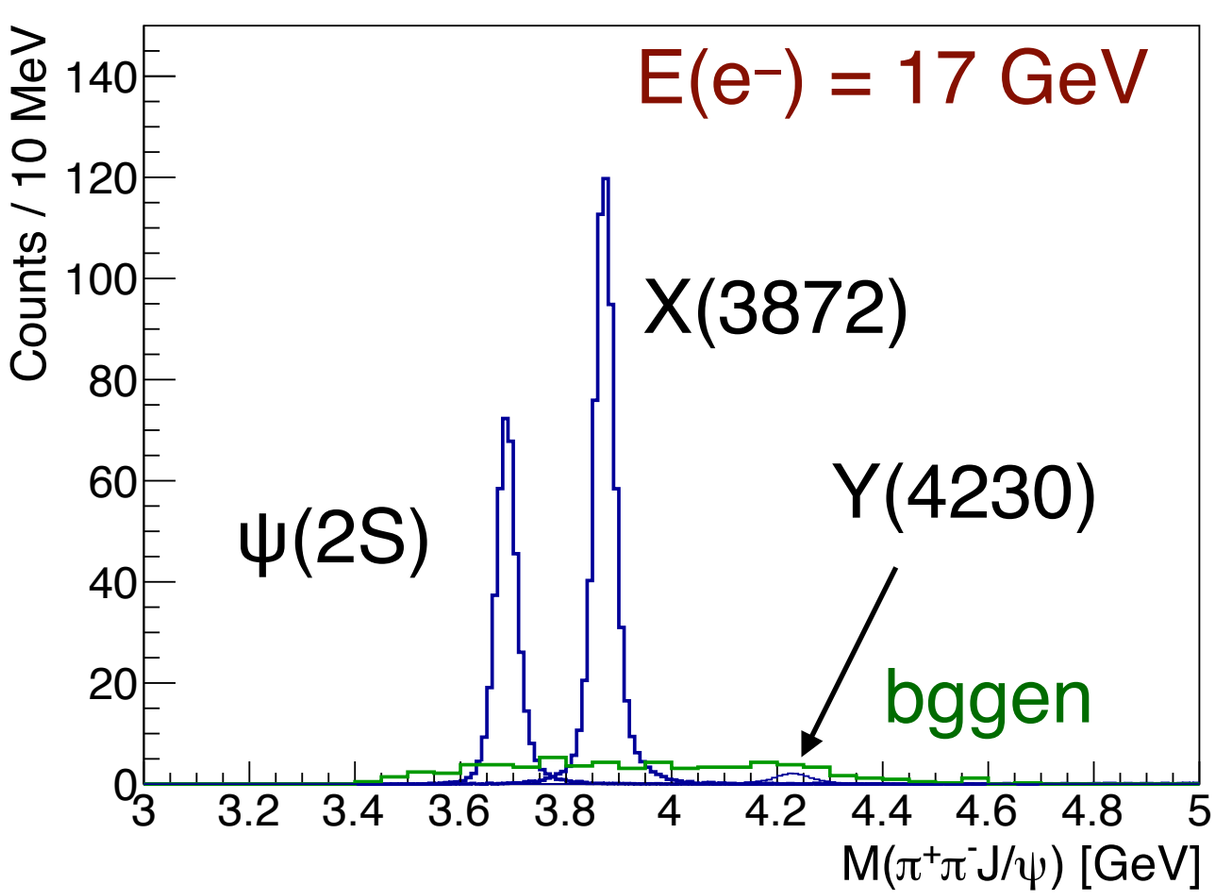


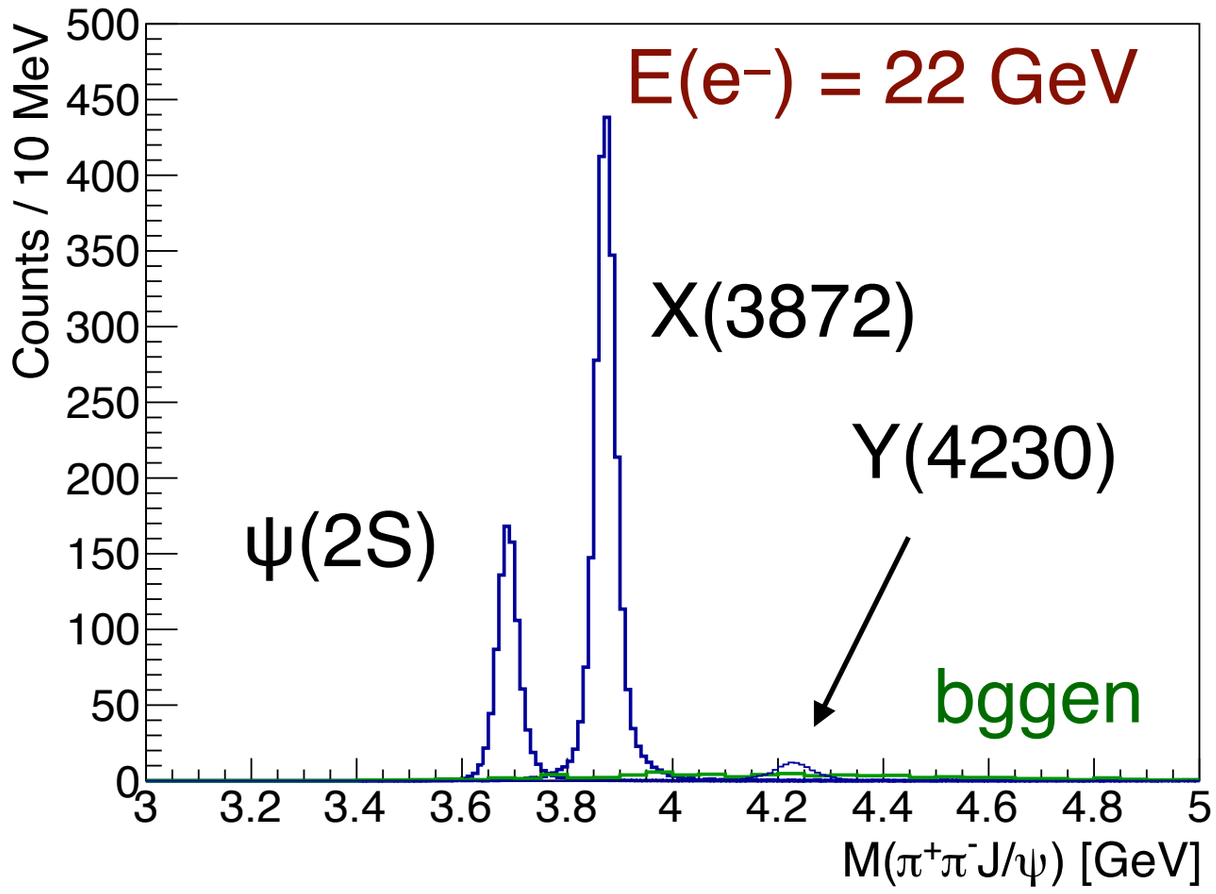


- JPAC predictions using fixed-spin exchanges near threshold
  - **PRD 102, 114010 (2020)**
- GlueX can test model by measuring $\chi_{c1}(1P)$, $\psi(2S)$ production

Projections for J/ψ$\pi^+\pi^-$ Photoproduction at GlueX

$\gamma p \rightarrow J/\psi\pi^+\pi^- p$, $J/\psi \rightarrow e^+e^-$

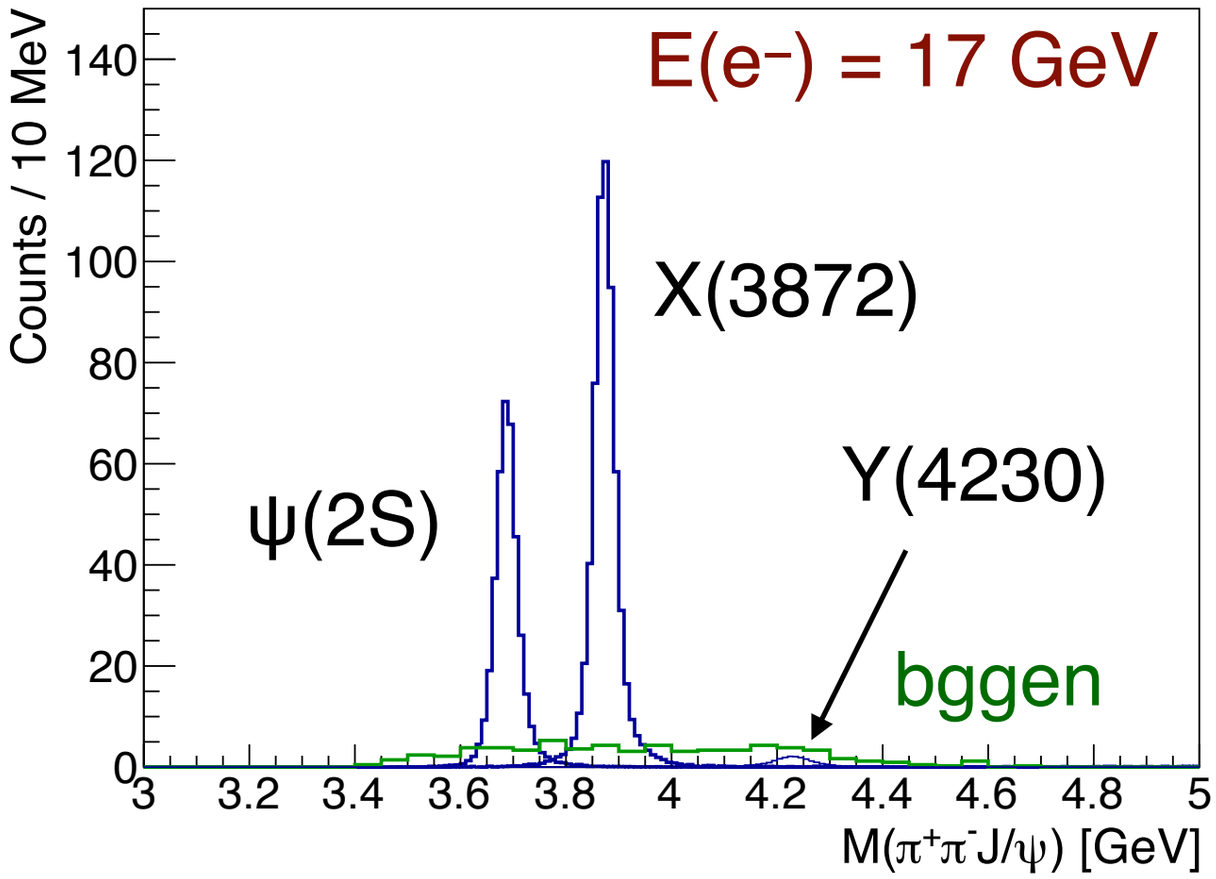




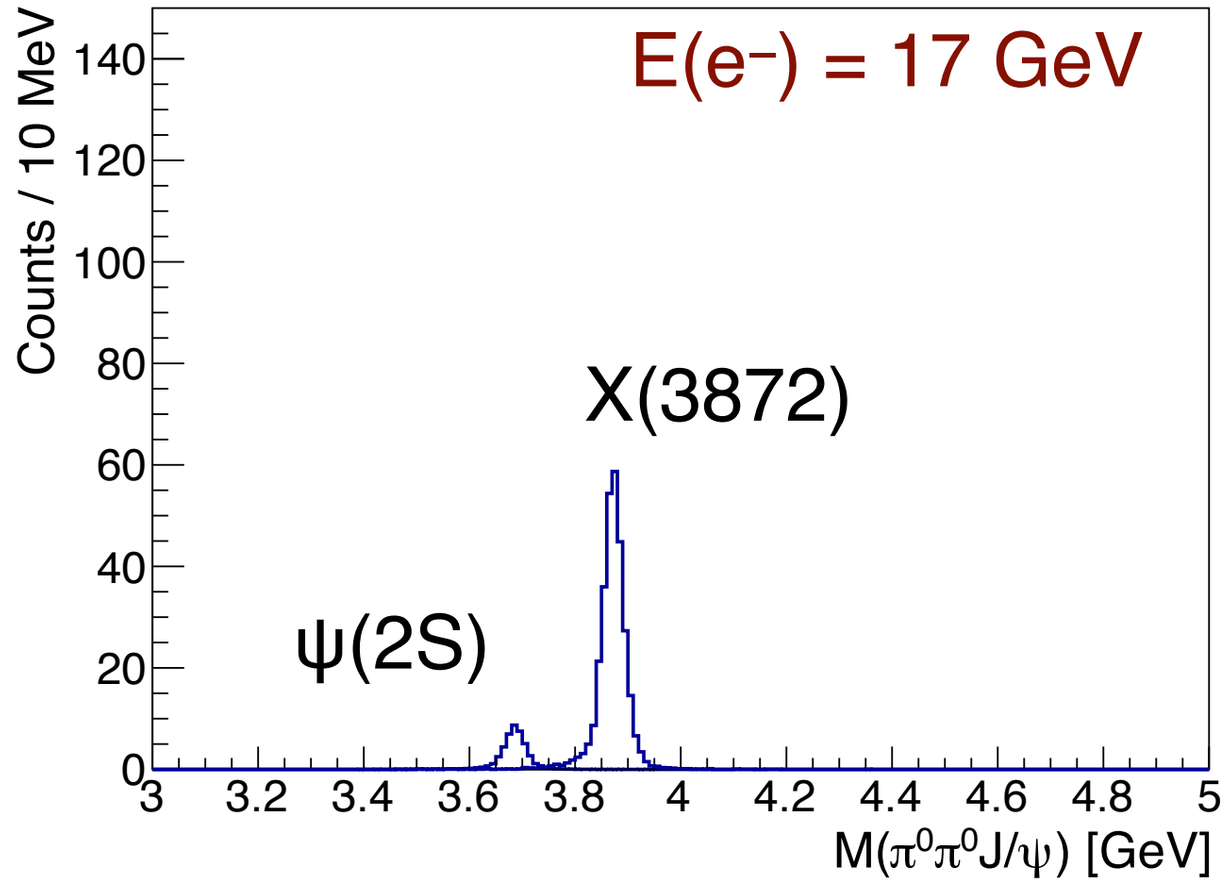
- Assumes 1 year @ 500 pb^{-1}, Br(X,Y$\rightarrow \pi^+\pi^- J/\psi$) = 5%
- 17 GeV: N(ψ(2S)) = 400, N(X(3872)) = 650, N(Y(4260)) = 20
- 22 GeV: N(ψ(2S)) = 900, N(X(3872)) = 2300, N(Y(4260)) = 120

Projections for J/ψ$\pi\pi$ Photoproduction at GlueX

$\gamma p \rightarrow J/\psi\pi^+\pi^- p$, $J/\psi \rightarrow e^+e^-$



$\gamma p \rightarrow J/\psi\pi^0\pi^0 p$, $J/\psi \rightarrow e^+e^-$



- Assumes 1 year @ 500 pb^{-1}, Br(X,Y$\rightarrow \pi^+\pi^- J/\psi$) = 5%
- 17 GeV [$J/\psi\pi^+\pi^-$]: N(ψ(2S)) = 400, N(X(3872)) = 650
- 17 GeV [$J/\psi\pi^0\pi^0$]: N(ψ(2S)) = 40, N(X(3872)) = 300

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
- First amplitude analyses of $\eta\pi$ and $\eta'\pi$ aim to identify the π_1 in photoproduction—could lead to predictions for production of $c\bar{c}$ hybrids
- First detailed studies of J/ψ photoproduction near threshold
- GlueX-II run in progress, planned to end around 2025

- Some discussion items for the EIC:
  - Exclusive production is powerful for understanding production mechanisms, semi-exclusive might have larger cross sections
    - How does this affect polarization observables?
  - Pentaquarks likely difficult to observe in $J/\psi+p$ or $J/\psi+\Lambda$
  - Open-charm final states are crucial to understanding molecular states, expands range of accessible states
  - EIC has unique energy reach: access to X(6900) and b-quark exotics

Backup Slides

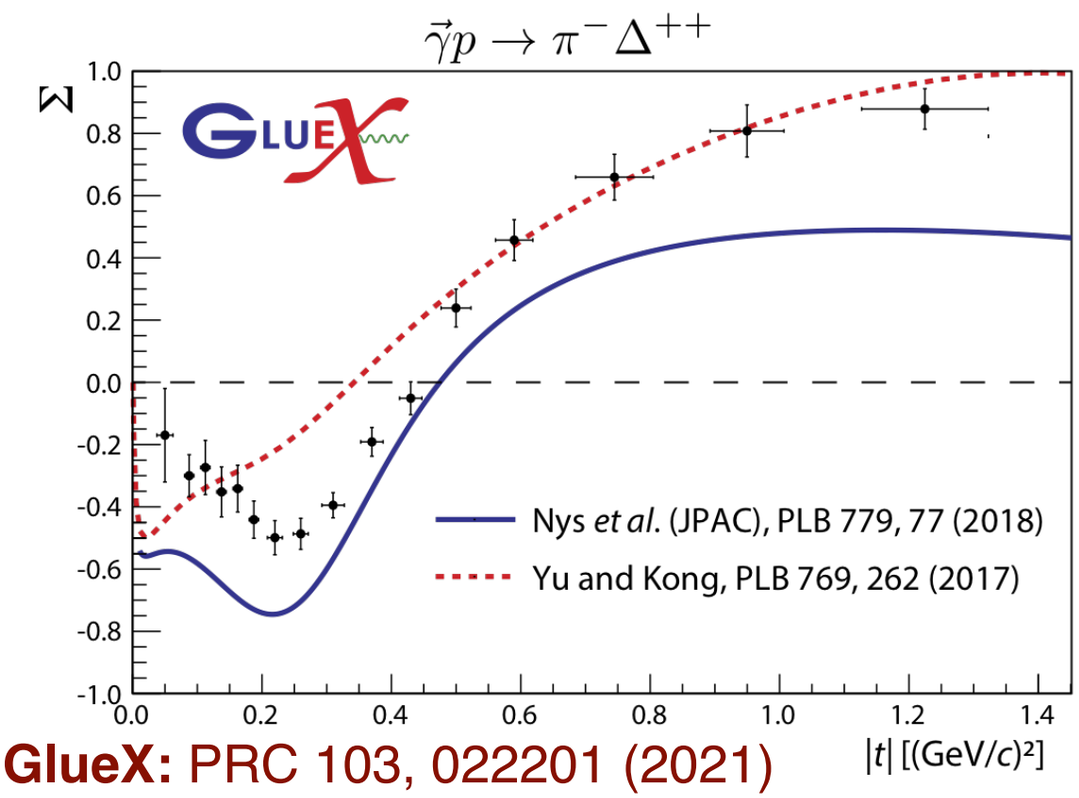
Searching for Exotics in Photoproduction @ GlueX

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

Collect Data

↓

Understand production mechanisms using polarization: Σ, SDMEs, …

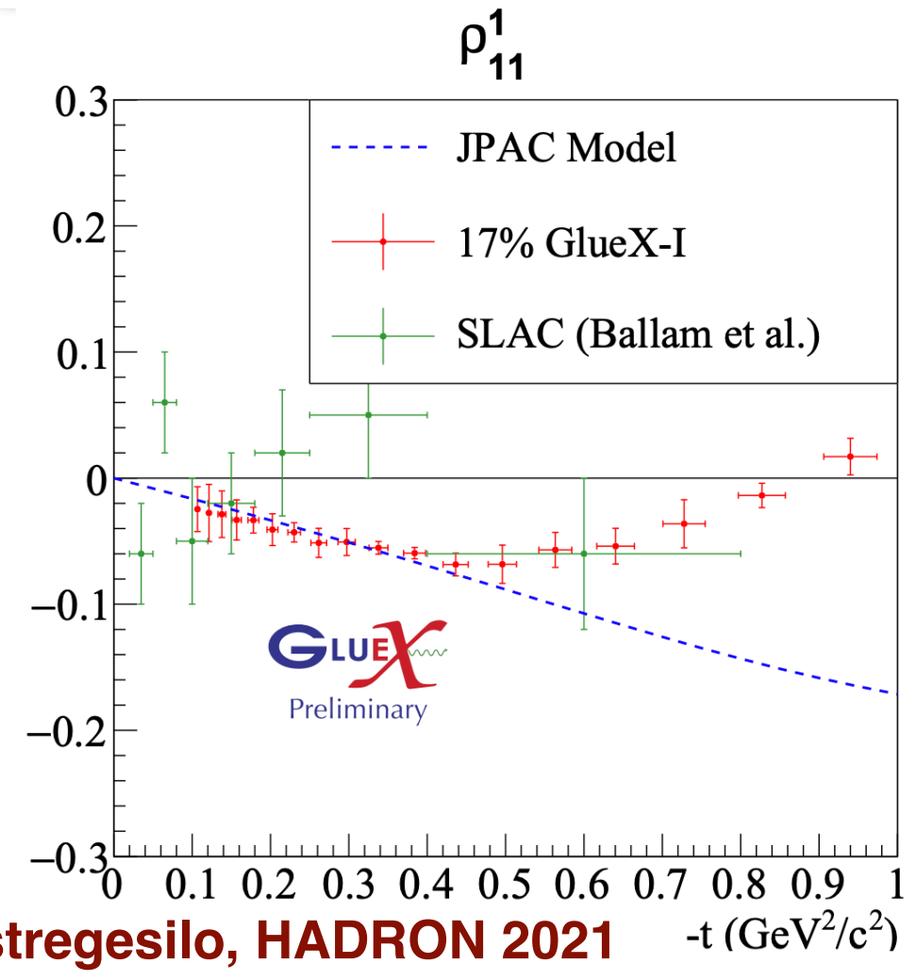


GlueX: PRC 103, 022201 (2021)

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, 022201 (2021)
$K^+\Lambda(1520)$: sub. to PRC
More coming…

SDMEs: ρ, ω, ϕ in progress



A. Austregesilo, HADRON 2021

Searching for Exotics in Photoproduction @ GlueX

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

Collect Data

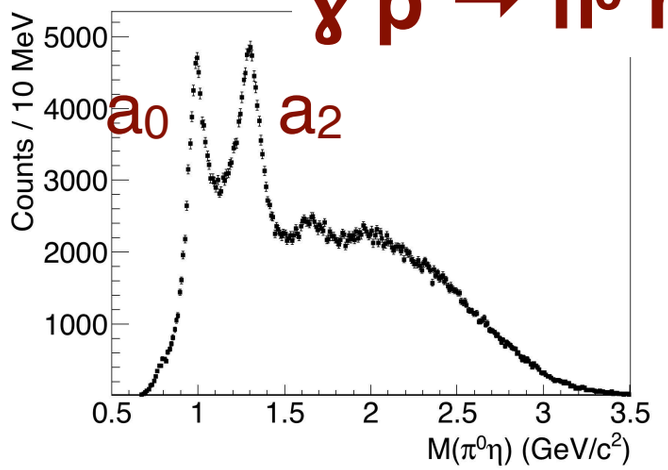
↓

Understand production mechanisms using polarization: Σ, SDMEs, …

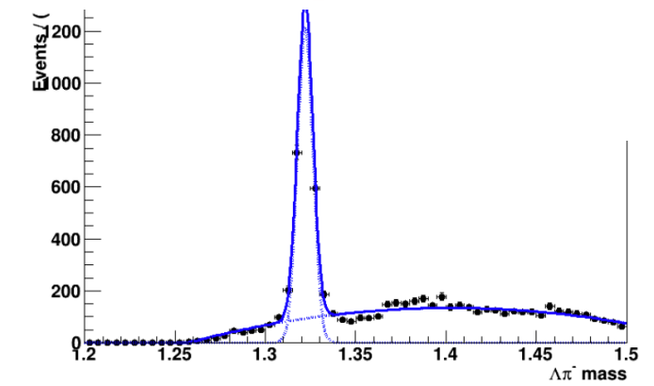
↓

Measure cross sections and identify known mesons with amplitude analysis

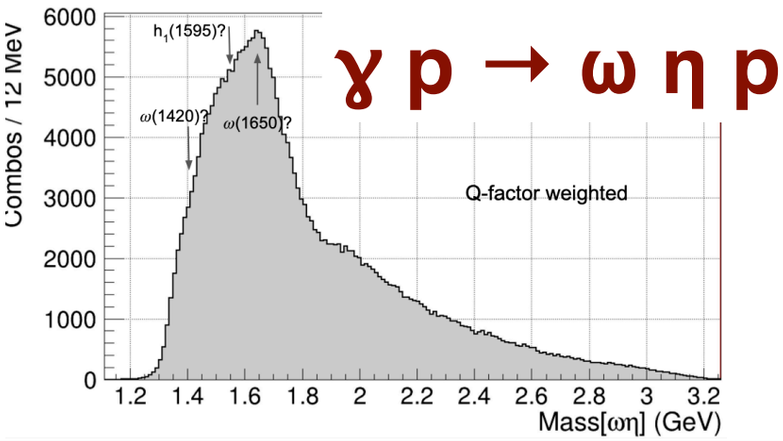
$\gamma p \to \pi^0 \eta p$



$\gamma p \to K^+K^+\Xi^-$

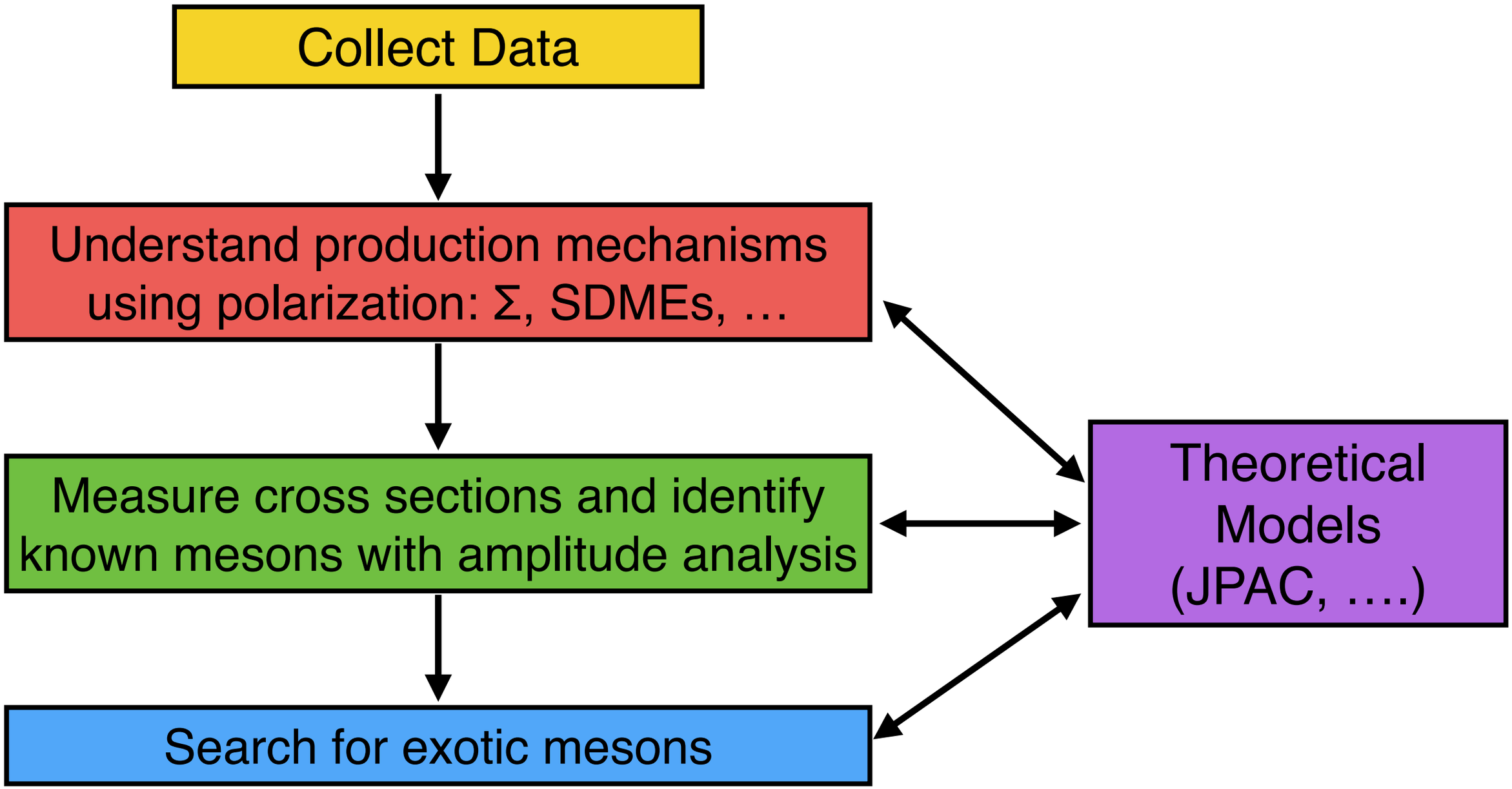


$\gamma p \to \omega \eta p$



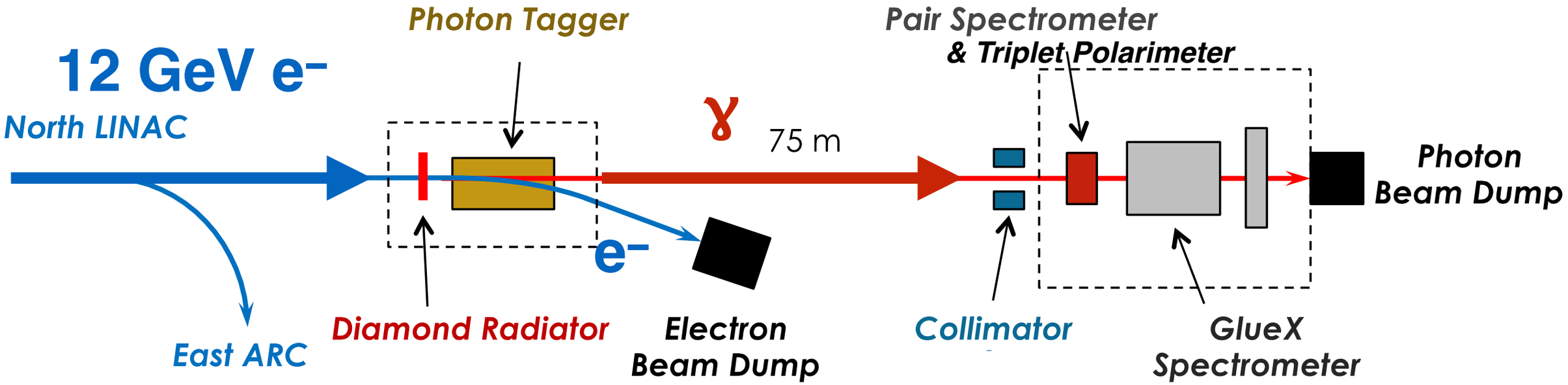
Searching for Exotics in Photoproduction @ GlueX

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

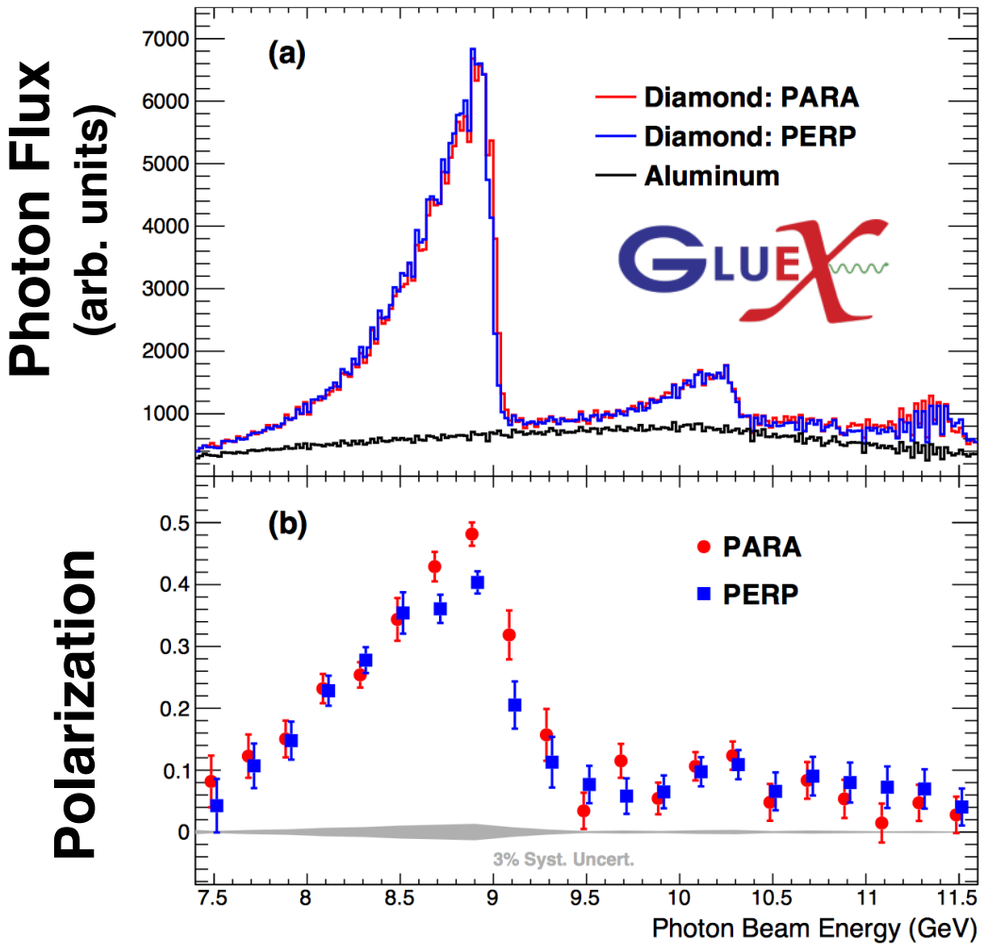


Start with $\eta\pi^0/\eta'\pi^0$ before moving to more complicated final states

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



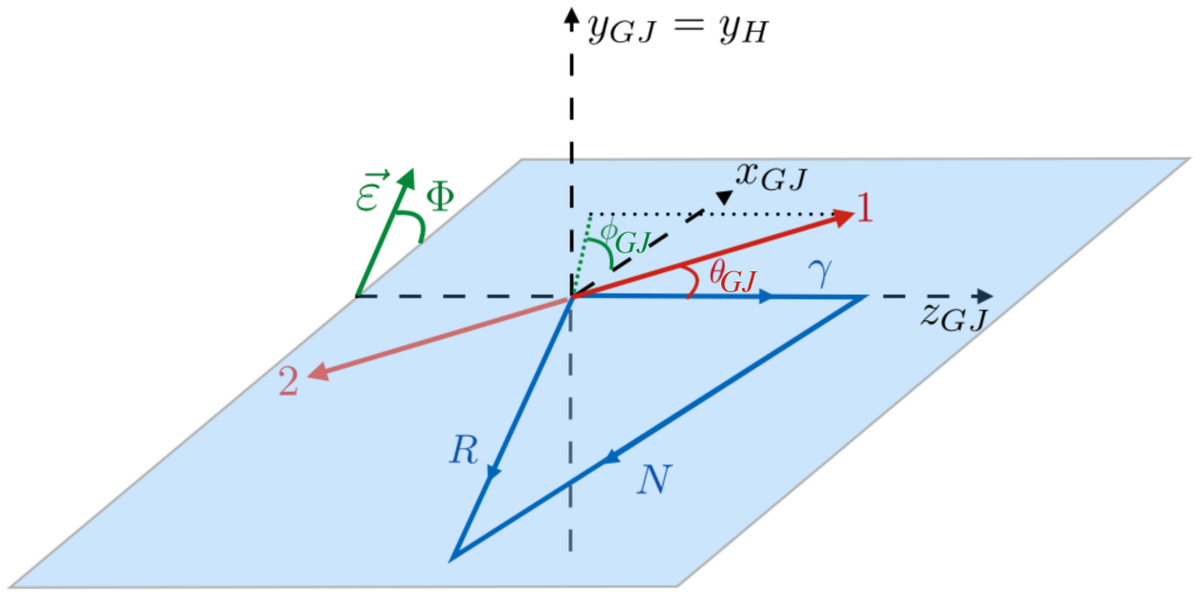
The GlueX Experiment in Hall D @ JLab

- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
  - Large acceptance solenoidal spectrometer
  - Linearly polarized photon beam peaking at 9 GeV
  - Detects all decay products from full hadronic photoproduction rate
- 100+ Collaborators from 26 institutions

Definition of Amplitudes

- Described by three angles: $\cos(\theta)_\eta$ and ϕ_η in the $\eta\pi$ rest frame, angle Φ between polarization vector and production plane

- Amplitudes incorporate beam polarization, are eigenstates of reflectivity $\epsilon = \pm 1$



[V.Mathieu et.al. (JPAC), PRD100(2019) 5, 054017]

- Basis: Z_l^m amplitudes defined as $Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi}$

$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \right|^2 + (1-P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \right|^2 +$$
$$(1+P_\gamma) \left| \sum_{\ell,m} [\ell]^{(+)}_{m;k} \mathrm{Re}[Z^m_\ell(\Omega,\Phi)] \right|^2 + (1+P_\gamma) \left| \sum_{\ell,m} [\ell]^{(-)}_{m;k} \mathrm{Im}[Z^m_\ell(\Omega,\Phi)] \right|^2 \Bigg\}$$

- Complexity: Positive and negative reflectivity, $m = -l ... l$ allowed

- Frequent exchange with JPAC

Study of $b_1(1235)$ Decay: Example Fit

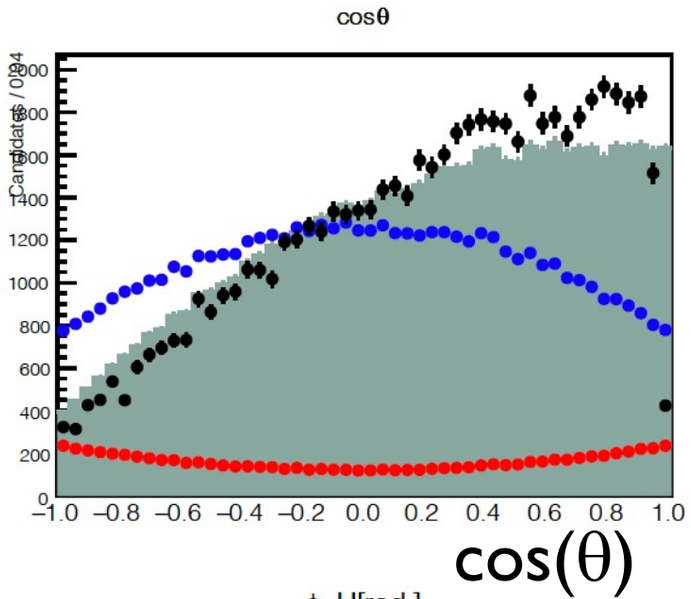
GlueX Data

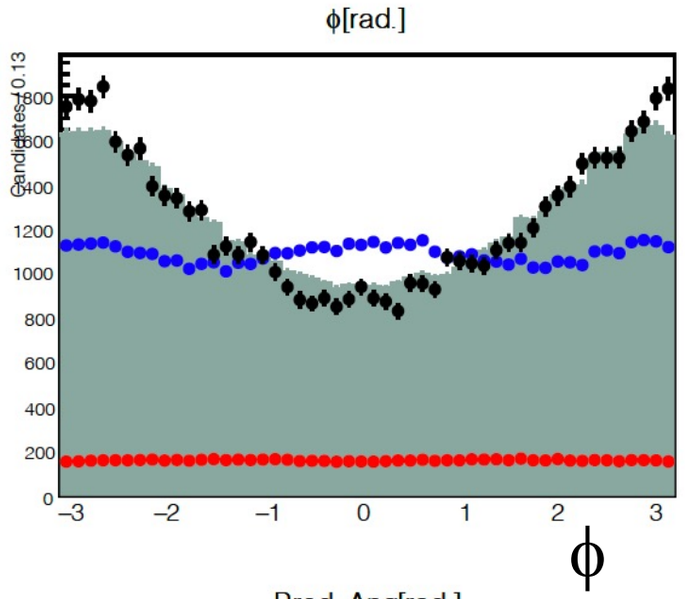
Fit Results

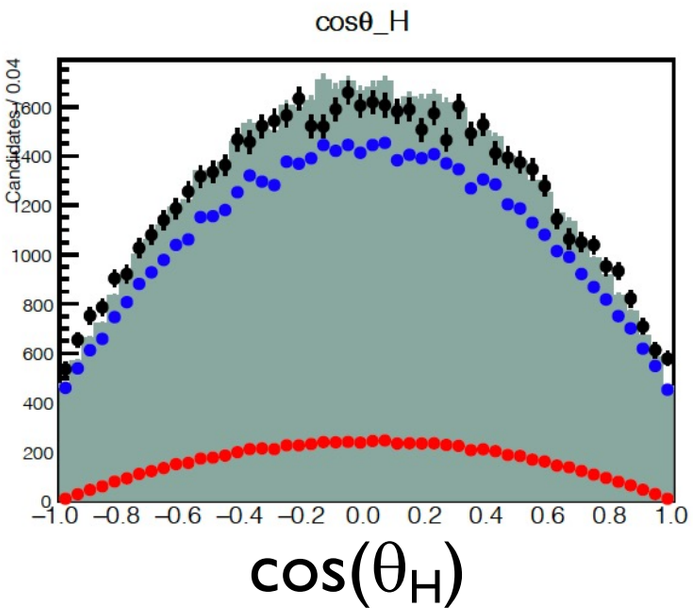
b_1 $[1^+]^{(\pm)}$ (S+D)

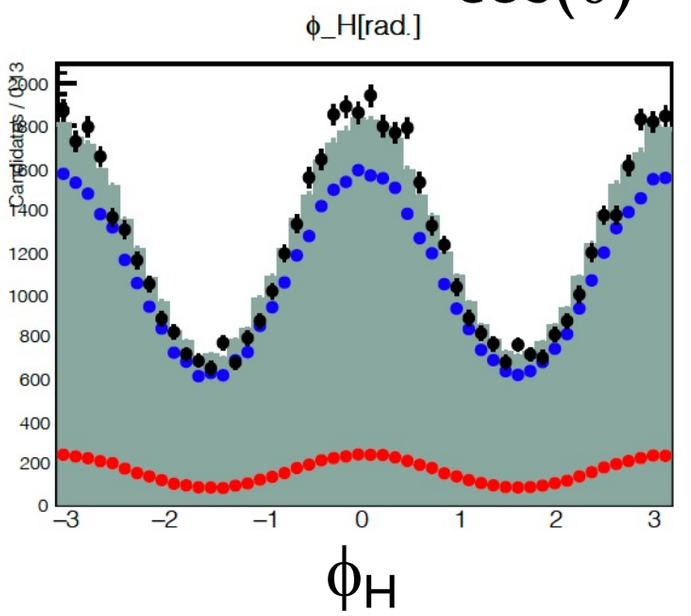
ρ $[1^-]^{(\pm)}$ P

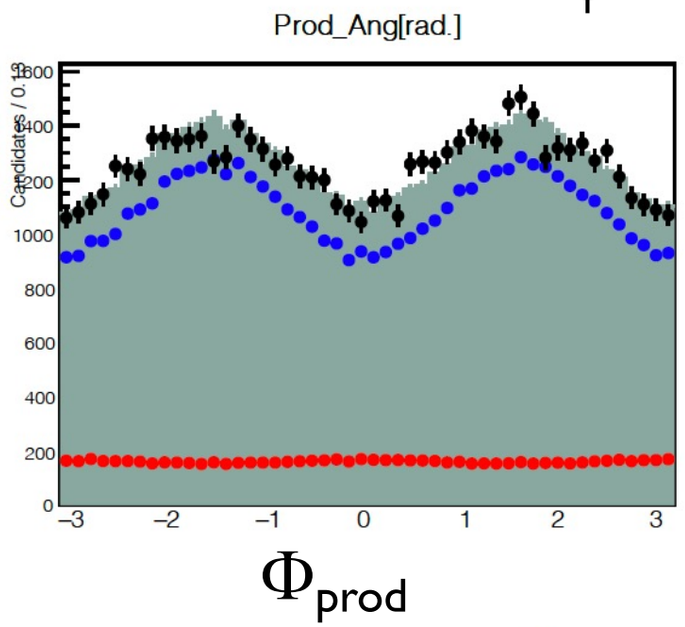
GlueX Preliminary







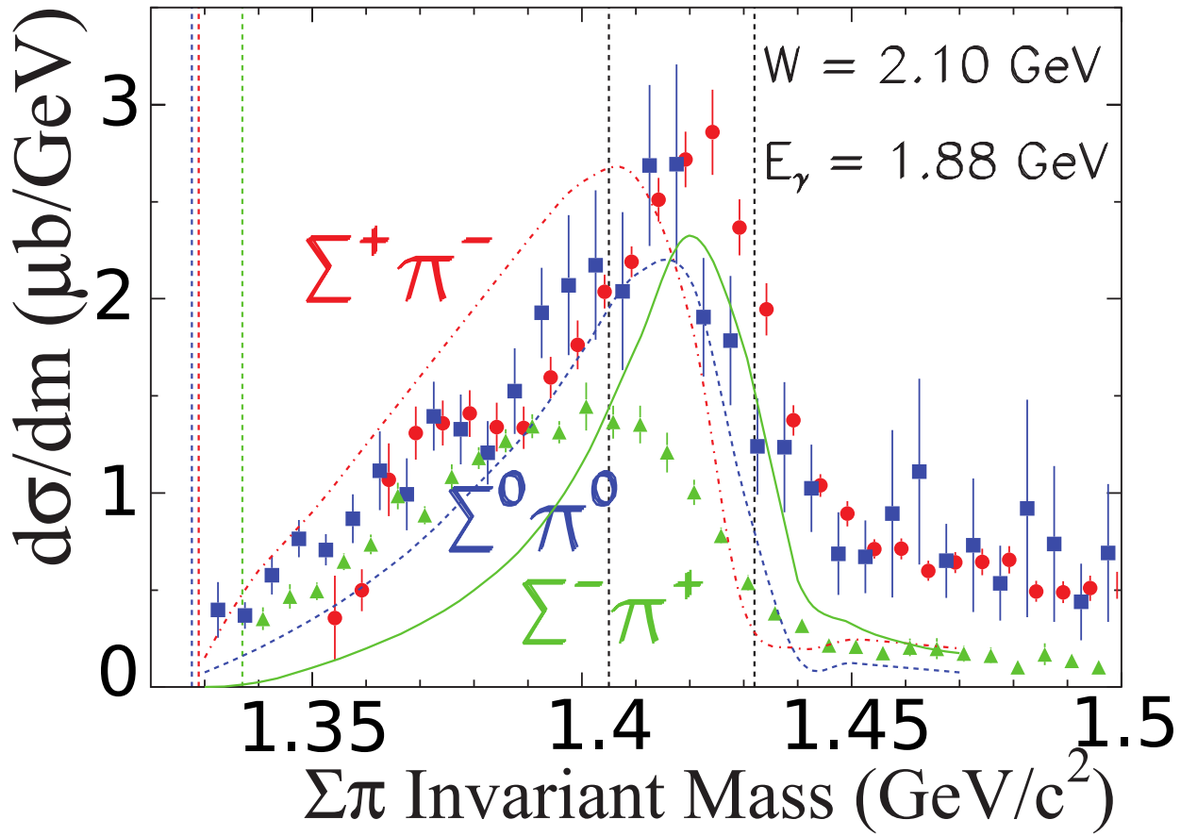


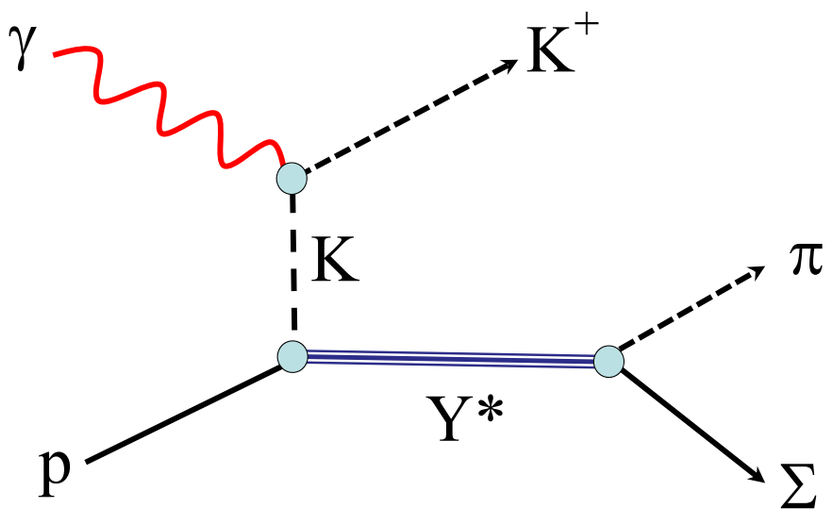


- Independent fits for each beam polarization orientation
- Inclusion of 1^- and 1^+ waves leads to good description of angular distributions

Λ(1405) in Photoproduction

- Λ(1405) lies just below $\bar{K}N$ threshold
  - I=0 $J^P = 1/2^-$
  - Decays to Σπ
- Lineshape not simple B-W
- Nature of state has been long discussed
  - 2 poles?
  - Something else?
- Current lineshape studies limited by knowledge of $\Sigma^0\pi^0$ channel
  - Pure I=0, no Σ(1385) bkgd.





CLAS, PRC 87, 035206 (2013)

PPNP 120,103868 (2021)
EPJST 230, 1593 (2021)

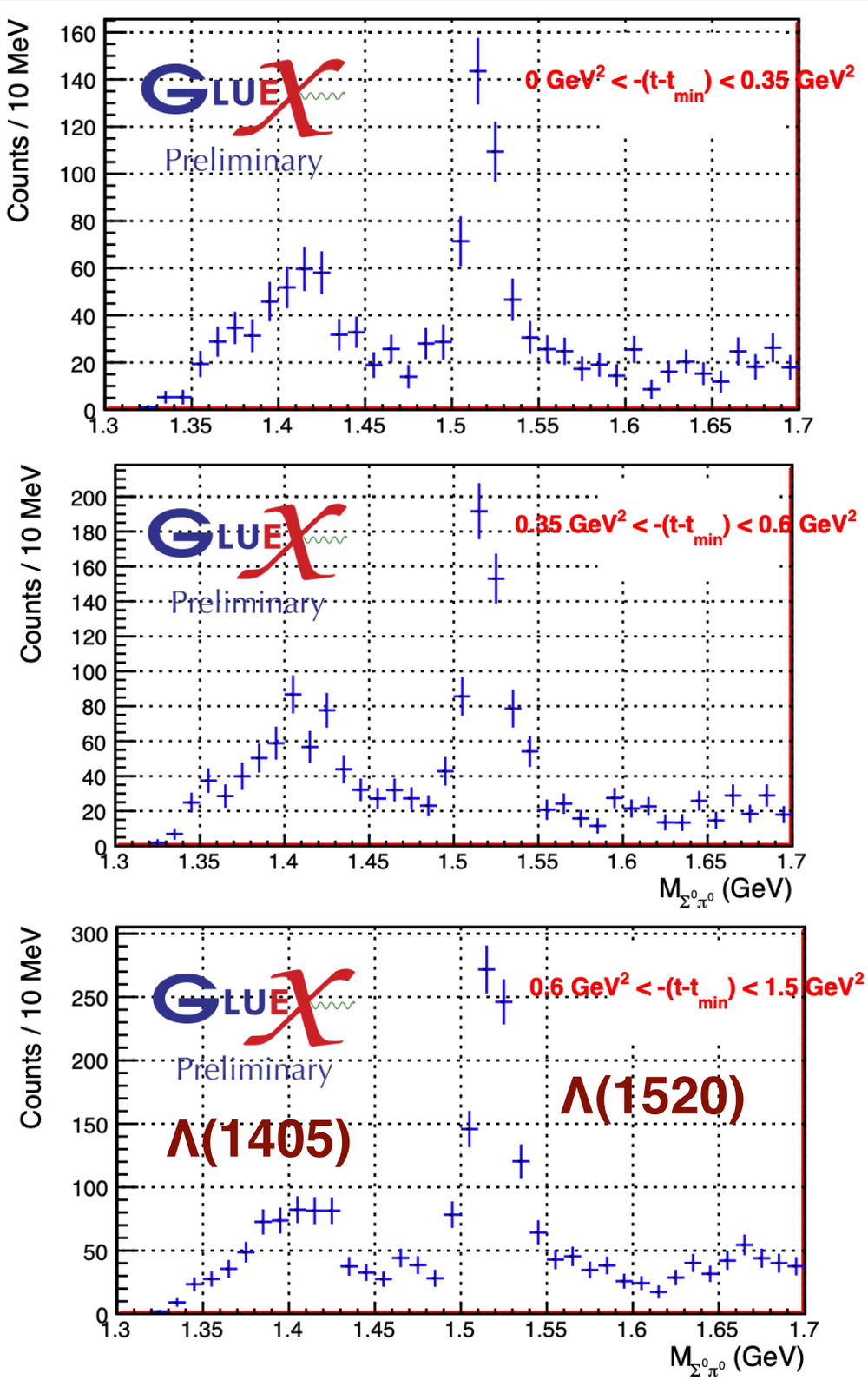
Λ(1405) in Photoproduction @ GlueX

- Mass spectra shown for 20% of GlueX-I data in

  $\gamma p \rightarrow K^+ \Sigma^0 \pi^0$

- Yields shown in 3 t-bins without acceptance correction
  - Clear Λ(1405) and Λ(1520) signals

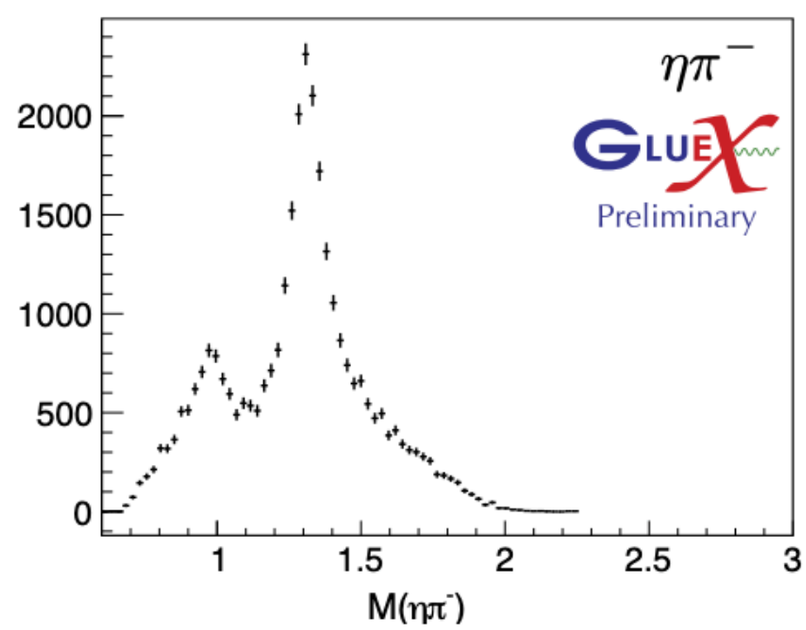
- With full GlueX-I data, we can study E_γ and t-dependence of lineshape using largest sample of $\Sigma^0 \pi^0$ available (>10k events in Λ(1405) region)

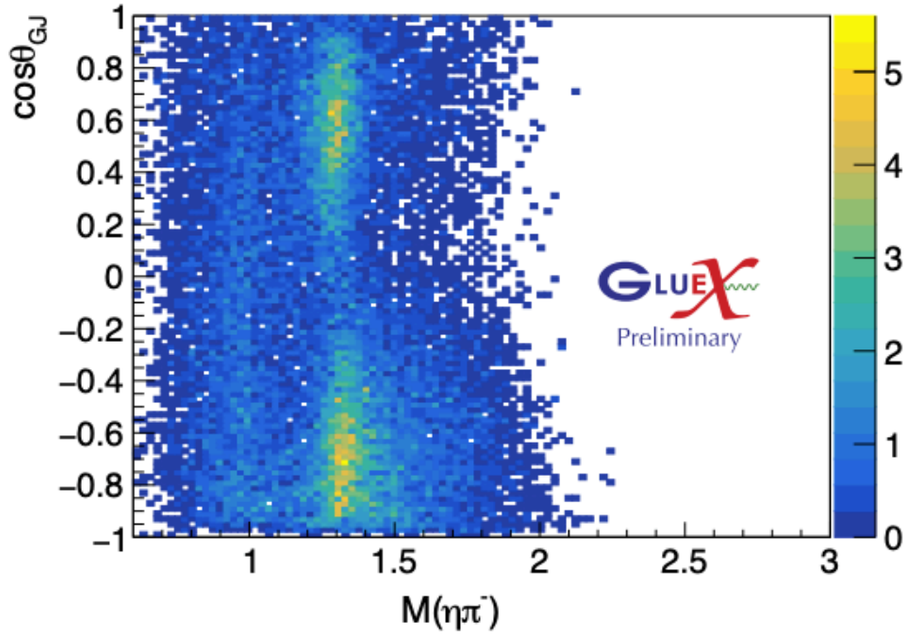


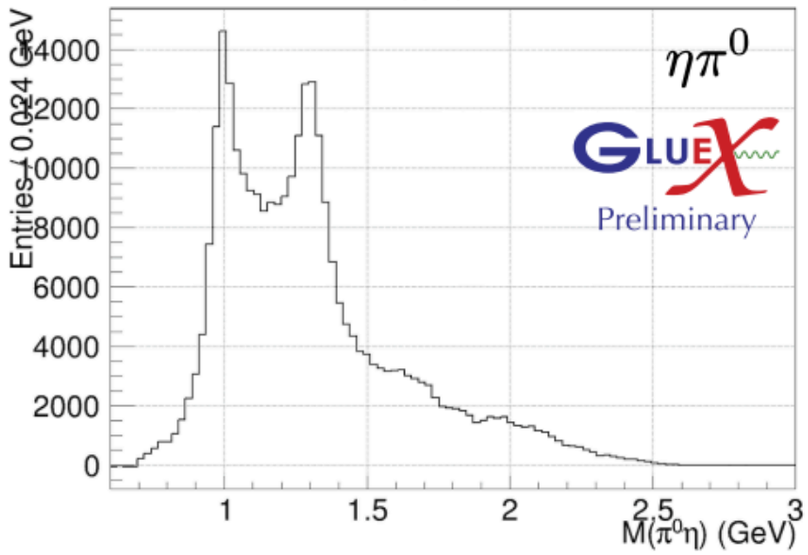
ηπ Amplitude Analysis at GlueX

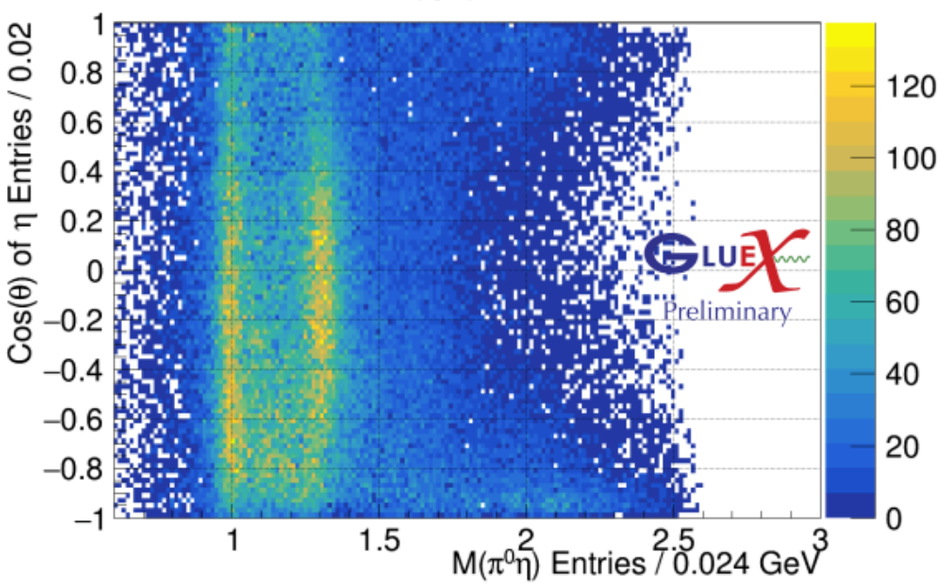
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- Different angular dependence → different dominant production wave
  - D_1 for $\eta\pi^-$, D_2 for $\eta\pi^0$

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





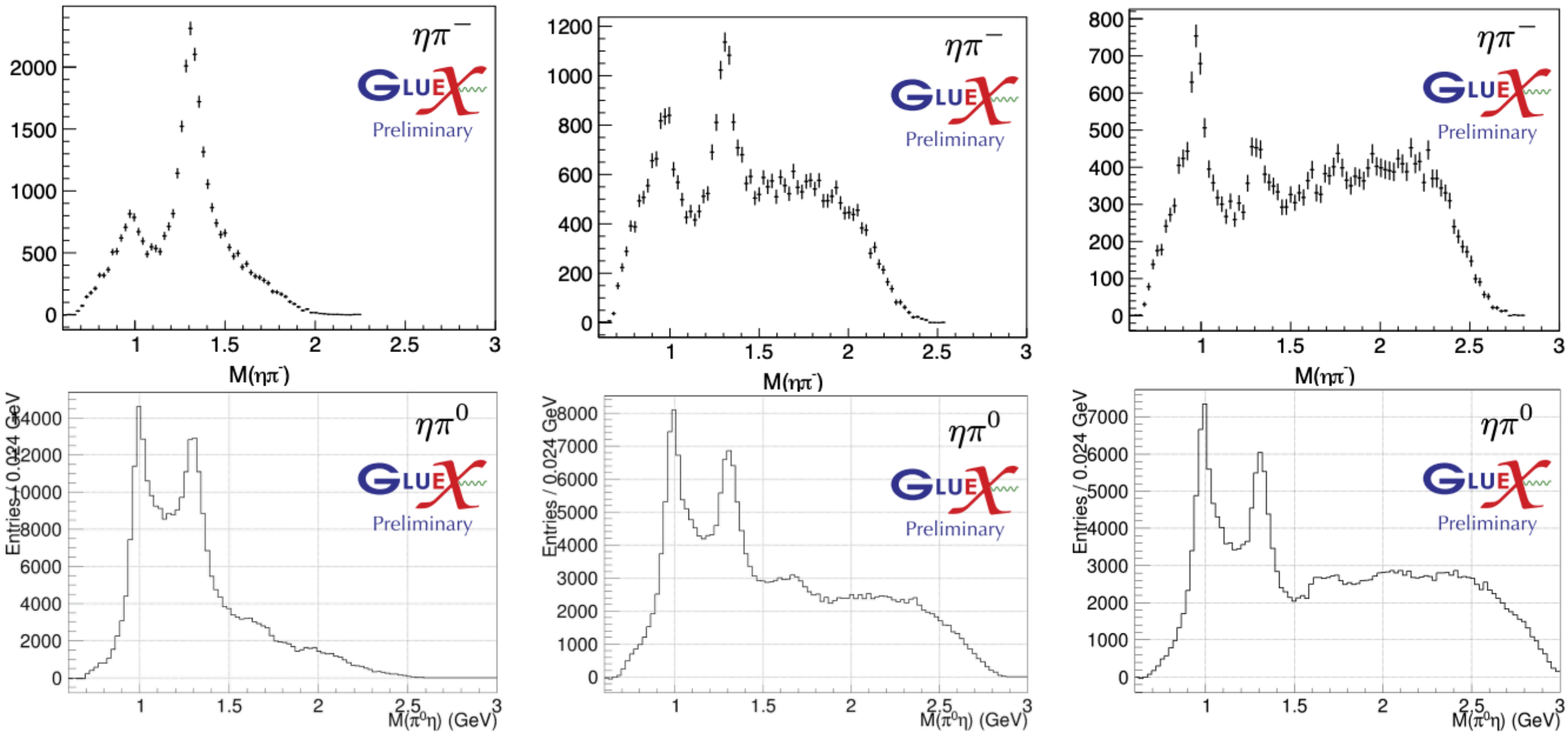




ηπ Amplitude Analysis at GlueX

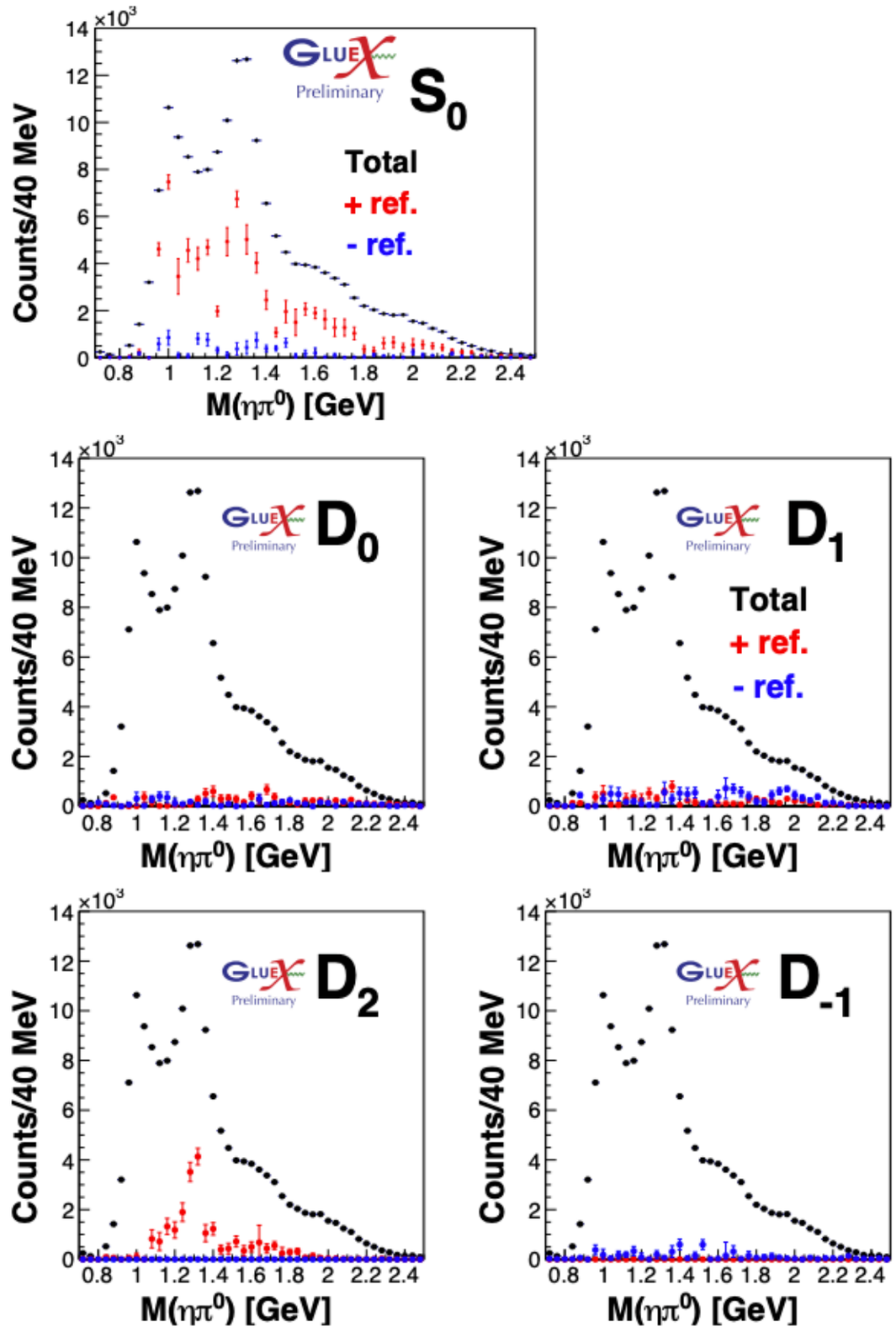
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
  - Peaks have different t-dependence

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



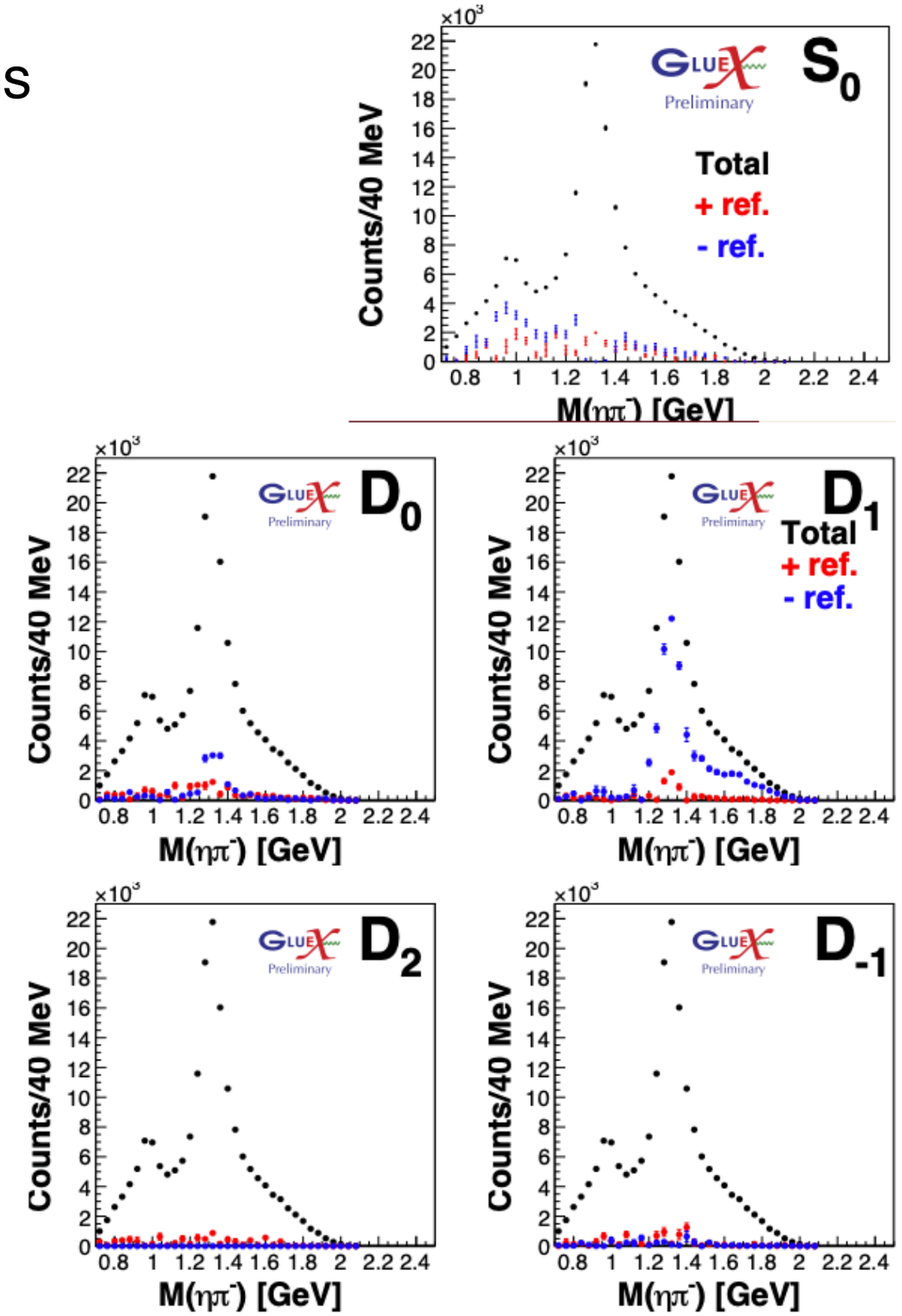
Fit to GlueX data for $\gamma p \to \eta\pi^0 p$ [$0.1 < -t < 0.3$ GeV^2]

- Preliminary fit to data allows us to start understanding features
- Combined fit to all polarization orientations with new photoproduction model
  JPAC: PRD 100, 054017 (2019)
- Waveset based on TMD model
  JPAC: PRD 102, 014003 (2020)
  - $S_0^{\pm}, D_0^{\pm}, D_1^{\pm}, D_2^{+} D_{-1}^{-}$
- Large S-wave contribution
  - Non-resonant? a_0's?
- Clear signal in m=+2 D-wave [$a_2(1320)$]
  - Dominant ρ/ω exchange
  - Similar to helicity-2 dominance in $\gamma\gamma \to \eta\pi^0$ at Belle
- Systematic studies of wavelets, leakage, ambguities, etc. ongoing



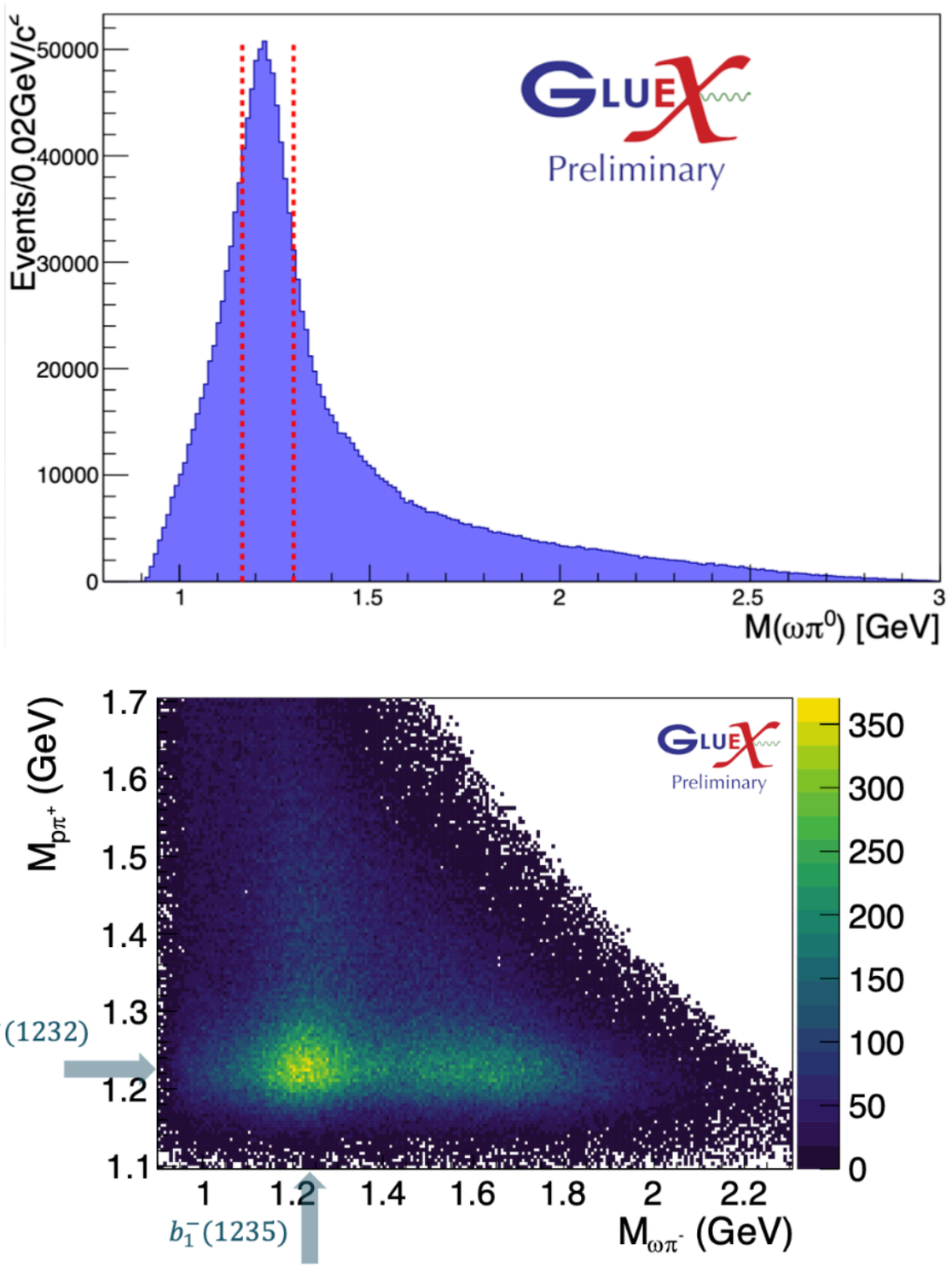
Fit to GlueX data for $\gamma p \to \eta\pi^-\Delta^{++}$ [$0.1 < -t < 0.3$ GeV^2]

- Combined fit to all polarization orientations with new photoproduction model
  JPAC: PRD 100, 054017 (2019)
- Large S-wave contribution
  - Strongest in $a_0(980)$ region
- Clear signal in m=–1 D-wave [$a_2(1320)$], negative reflectivity
  - Dominant π exchange
  - Tail related to $a_2(1700)$?
- Systematic studies ongoing
- Next steps:
  - Near-term goal: a_2 production studies
  - Understand other processes which could generate asymmetry, e.g., baryon prod., Double Regge exch.



Study of $b_1(1235)$ at GlueX

- LQCD predicts dominant π_1 decay to be $b_1\pi$ ($\rightarrow 5\pi$)
- First step: understand b_1 production and decay to $\omega\pi$
  - Also search for excited vectors and others
    - Extend analysis to other VP channels ($\omega\eta$, $\phi\pi$, $\phi\eta$, …)
- Access to charged and neutral b_1
  - $\gamma p \rightarrow b_1^0 p \rightarrow \omega\pi^0 p$
  - $\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega\pi^- \Delta^{++}$



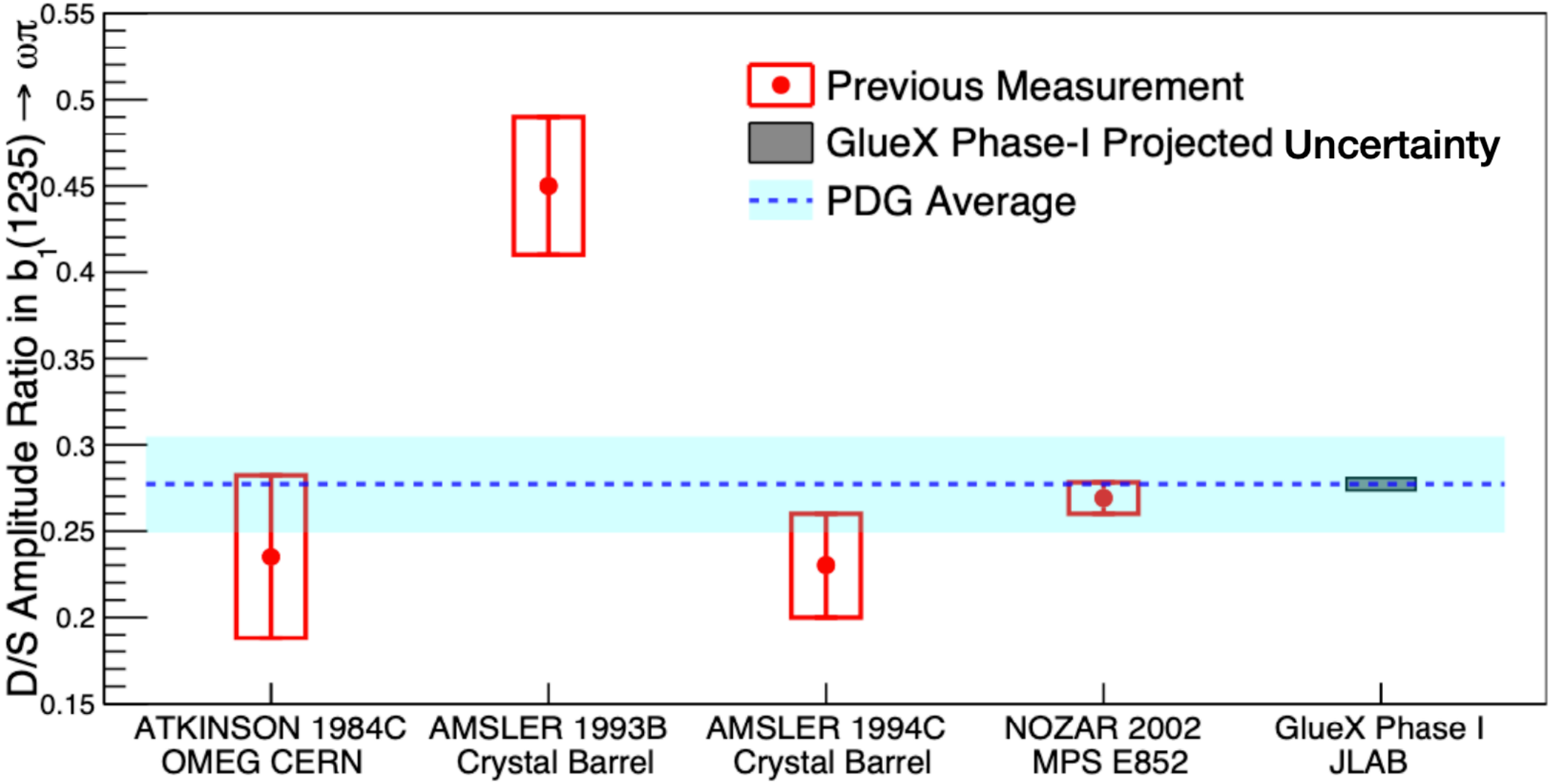
Study of $b_1(1235)$ at GlueX: S/D ratio

- Can use amplitude model for VP photoproduction to measure ratio of D/S amplitudes in $b_1 \rightarrow \omega\pi$

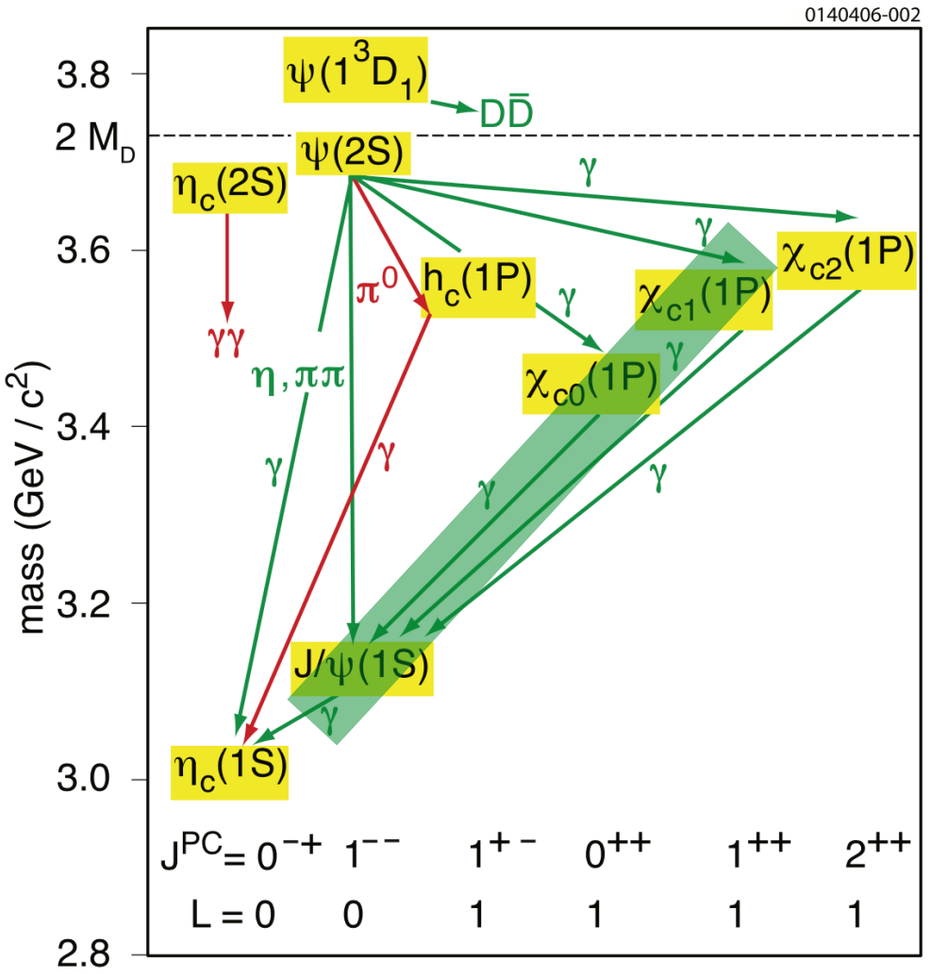
HadSpec: PRD 100, 054506 (2019)

LCQD: $|D/S| = 0.27(20)$

- First test of model finds good fits with 1^+ and 1^- waves near b_1 peak

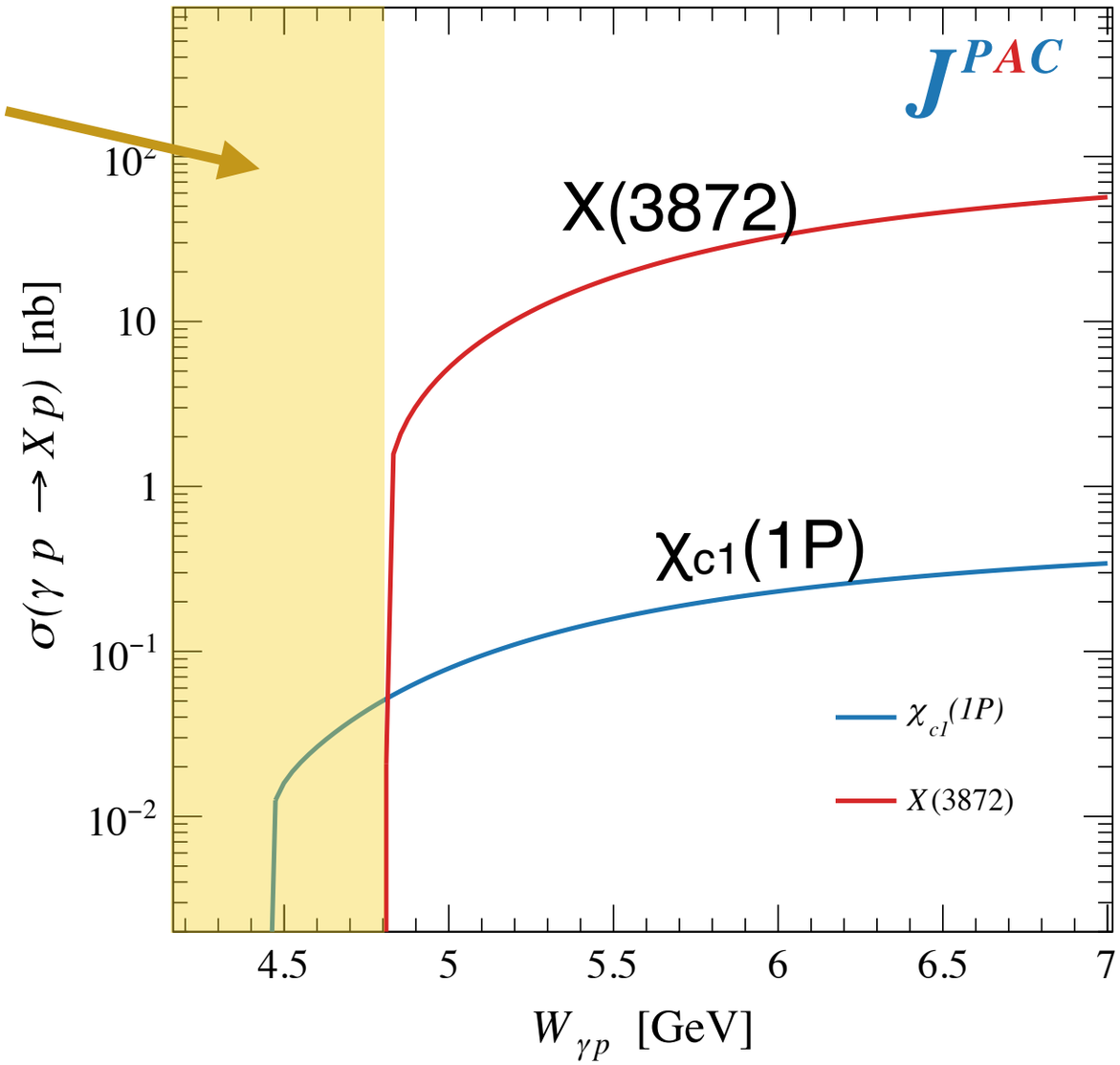


$\chi_{c1}(1^3P_1)$ Photoproduction at GlueX



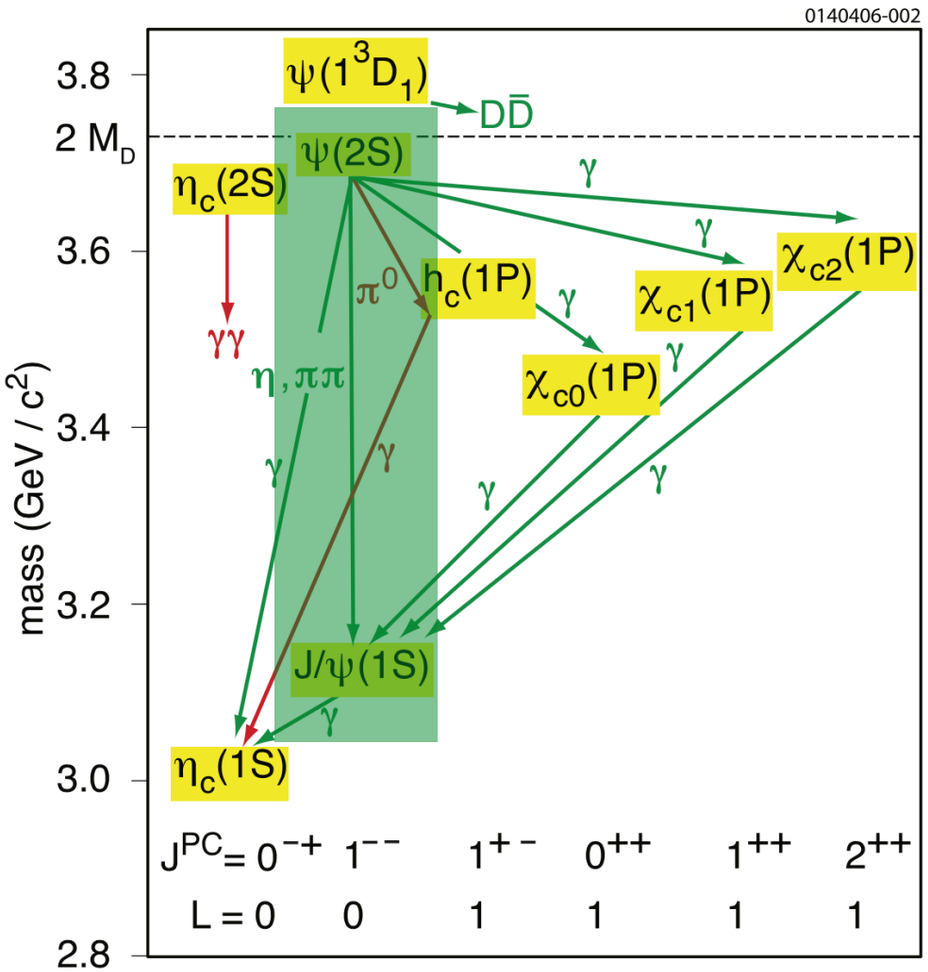
GlueX energy range

JPAC: PRD 102, 114010 (2020)



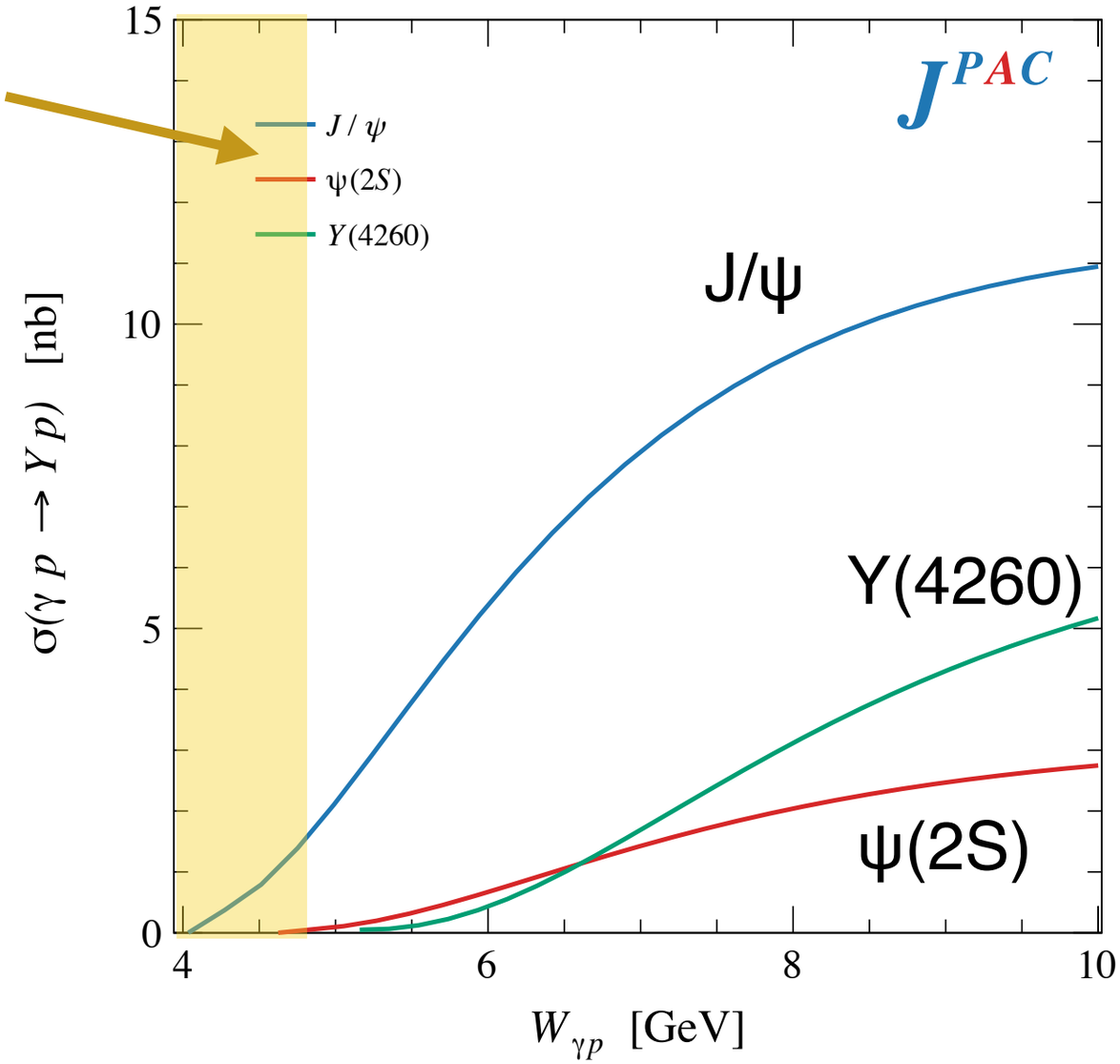
- $\chi_{c1}(1^{++})$ photoproduction: probe of different parity, P_c search
- JPAC model estimate using known $\chi_{c1} \to \gamma(\rho,\omega,\phi,J/\psi)$ couplings
- GlueX-I expectation: $N(\chi_{c1} \to \gamma J/\psi, J/\psi \to e^+e^-) = O(50)$

$\psi(2^3S_1)$ Photoproduction at GlueX



GlueX energy range

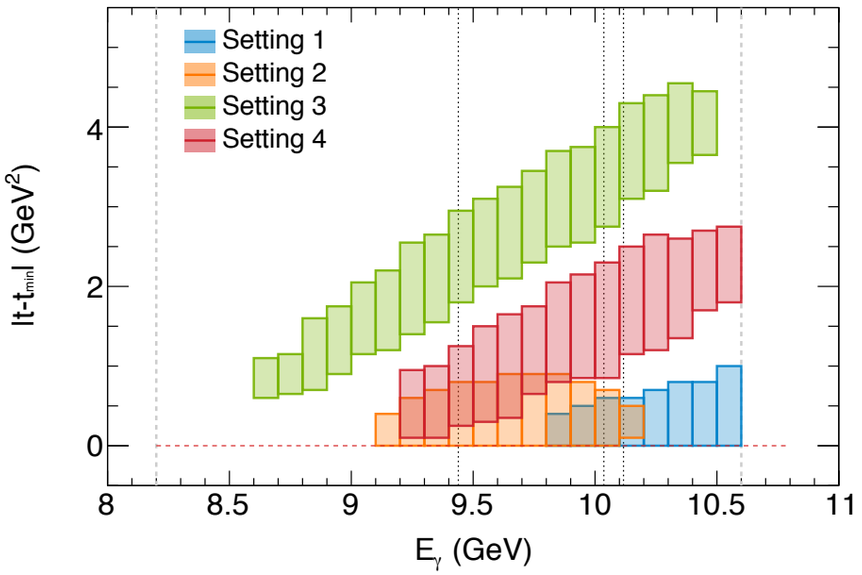
JPAC: PRD 102, 114010 (2020)

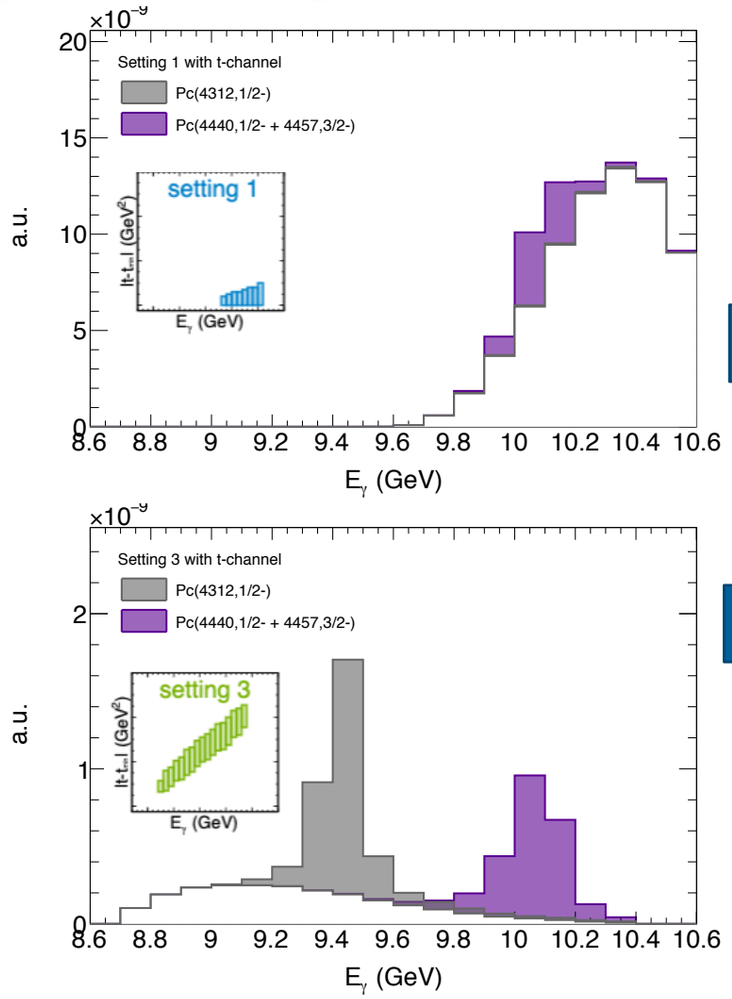


- ψ(2S) photoproduction: probe of wave function dependence
- JPAC model estimates using known $\Gamma_{\gamma gg}(\psi(2S)) / \Gamma_{\gamma gg}(J/\psi)$
- GlueX-I expectation: $N(\psi(2S) \rightarrow \pi^+\pi^- J/\psi, J/\psi \rightarrow e^+e^-) < 10$

HIGH-T SETTINGS CRUCIAL FOR SENSITIVITY

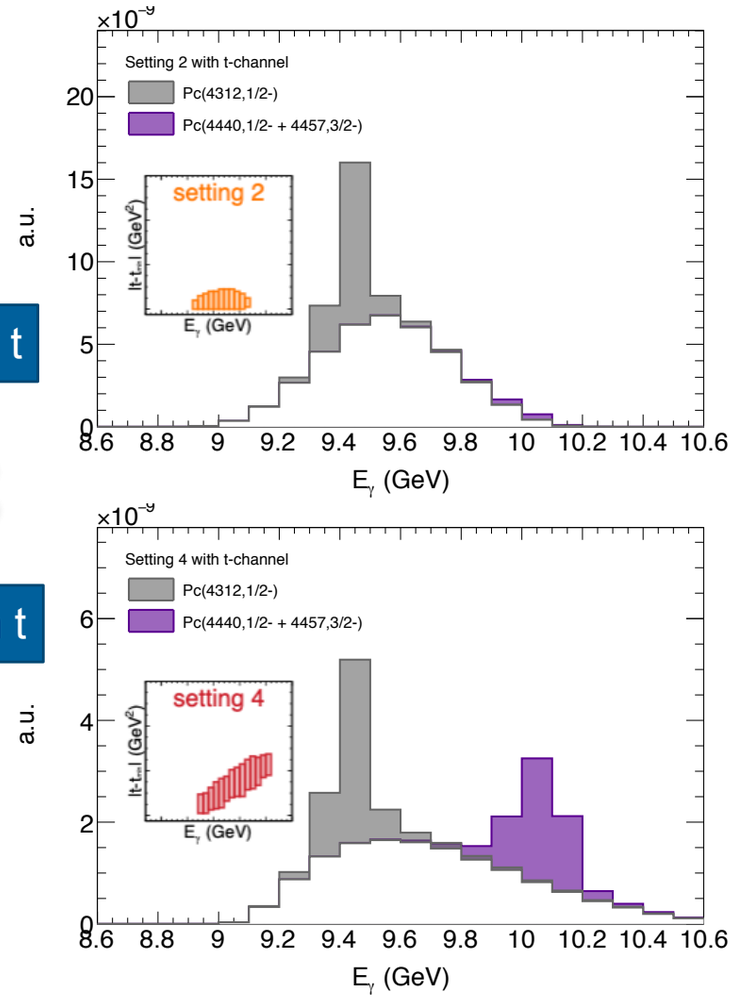
Improved sensitivity at high t for a given coupling





Low t

High t



4% scale uncertainty on cross section

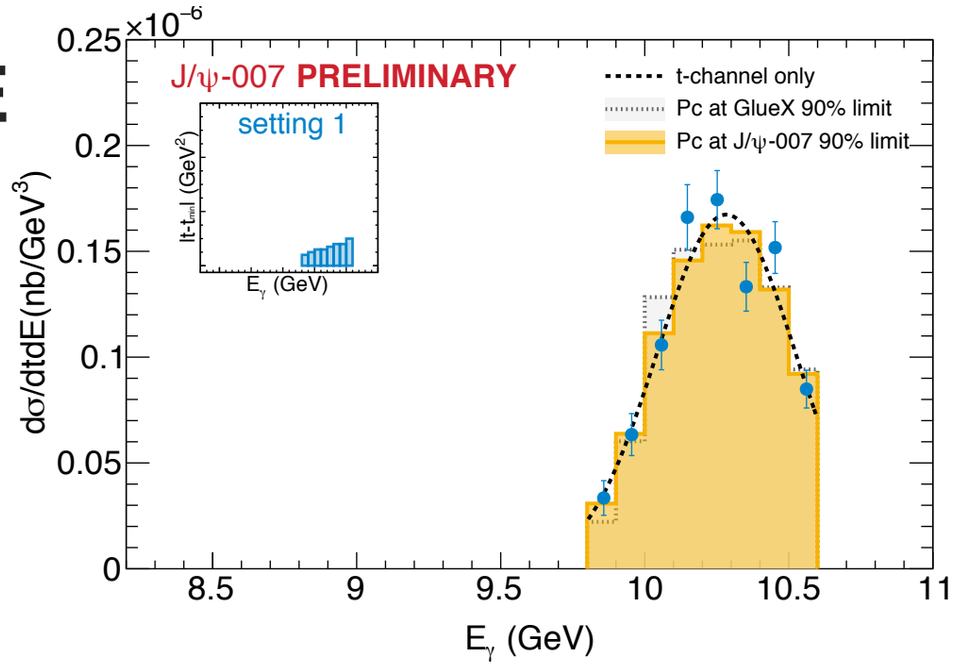
SIGNIFICANCE FIT

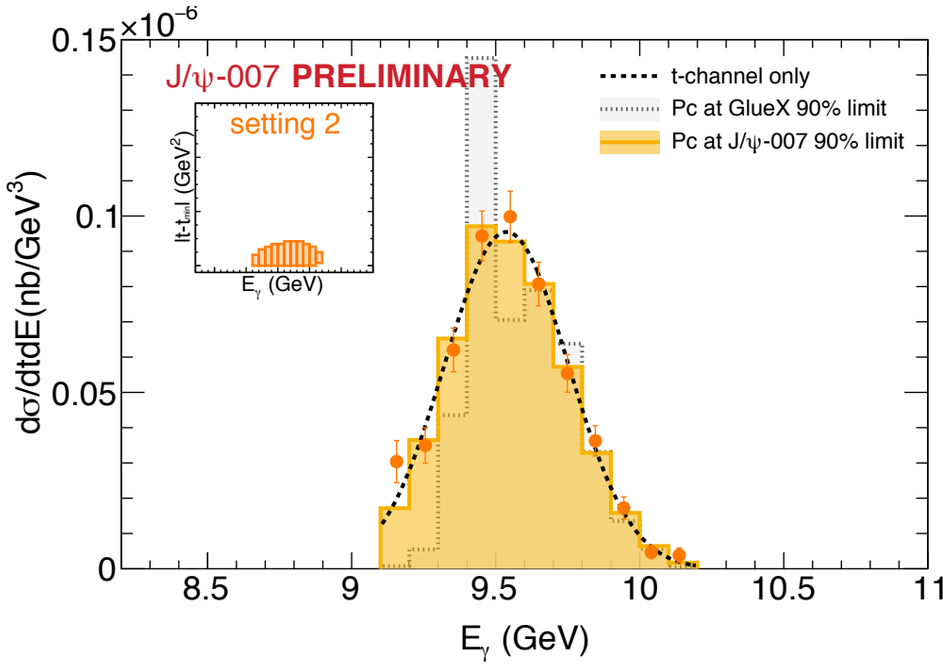
Fit 1: bare Gaussian shape describes the cross section well

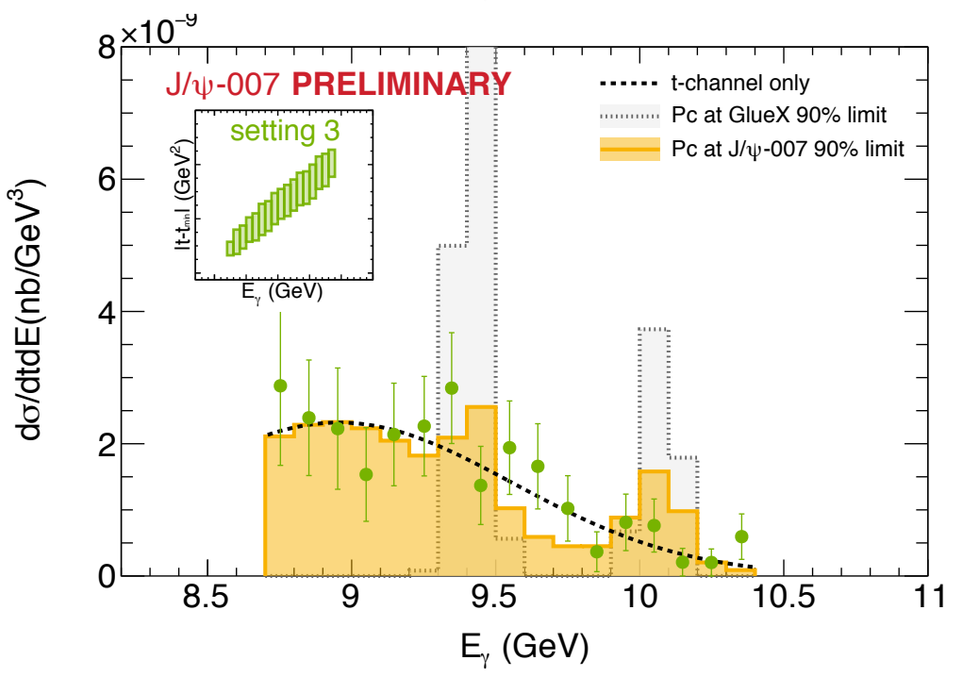
Fit 2: Signal + background at GlueX upper limit (90% confidence interval). The resonances lead to major tension with the data at high-t.

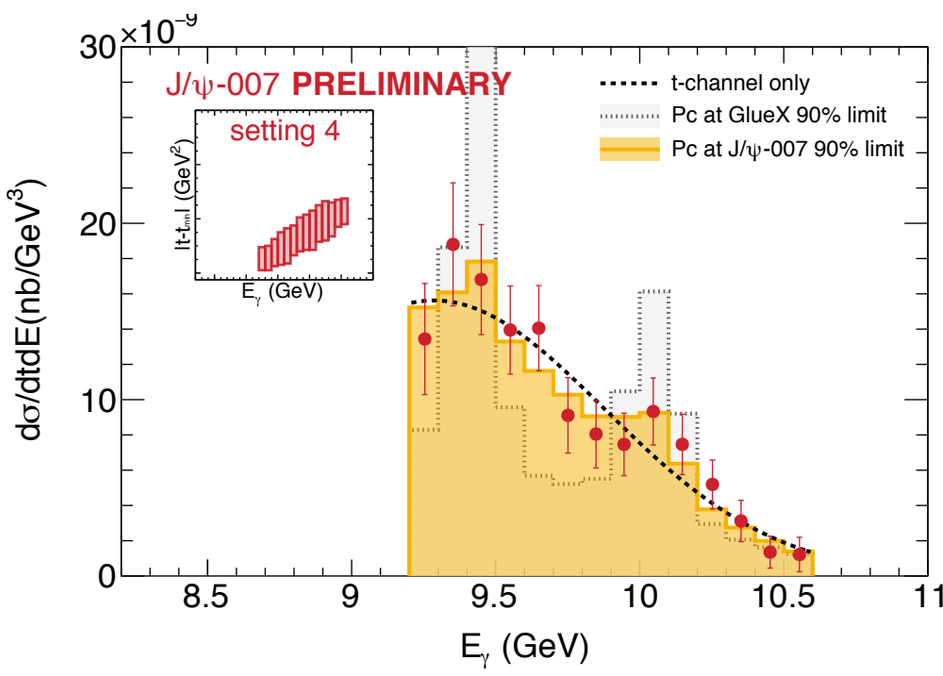
Fit 3: Same as 2, but with Pc at upper limit (90% confidence interval) from the preliminary J/ψ-007 results themselves

The data suggest a stringent upper limit on the resonant cross section (see next slide).









4% scale uncertainty on cross section limit

RESULTS AND IMPLICATIONS

Cross-section at the resonance peak for model-independent upper limits

Upper limit for P_c cross section almost order of magnitude below GlueX limit.

Results are inconsistent with reasonable assumptions for true 5-quark states.

Door is still open for molecular states, but will be very hard to measure in photoproduction due to small overlap with both γp initial state and J/ψp final state.

To learn more we need a large-acceptance high-intensity photoproduction experiment, and potentially access to polarization observables. **This can be achieved with the SoLID-J/ψ experiment**