Recent Results and Perspectives from the GlueX Experiment

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4th Workshop on Future Directions in Spectroscopy Analysis
(FDSA2022)
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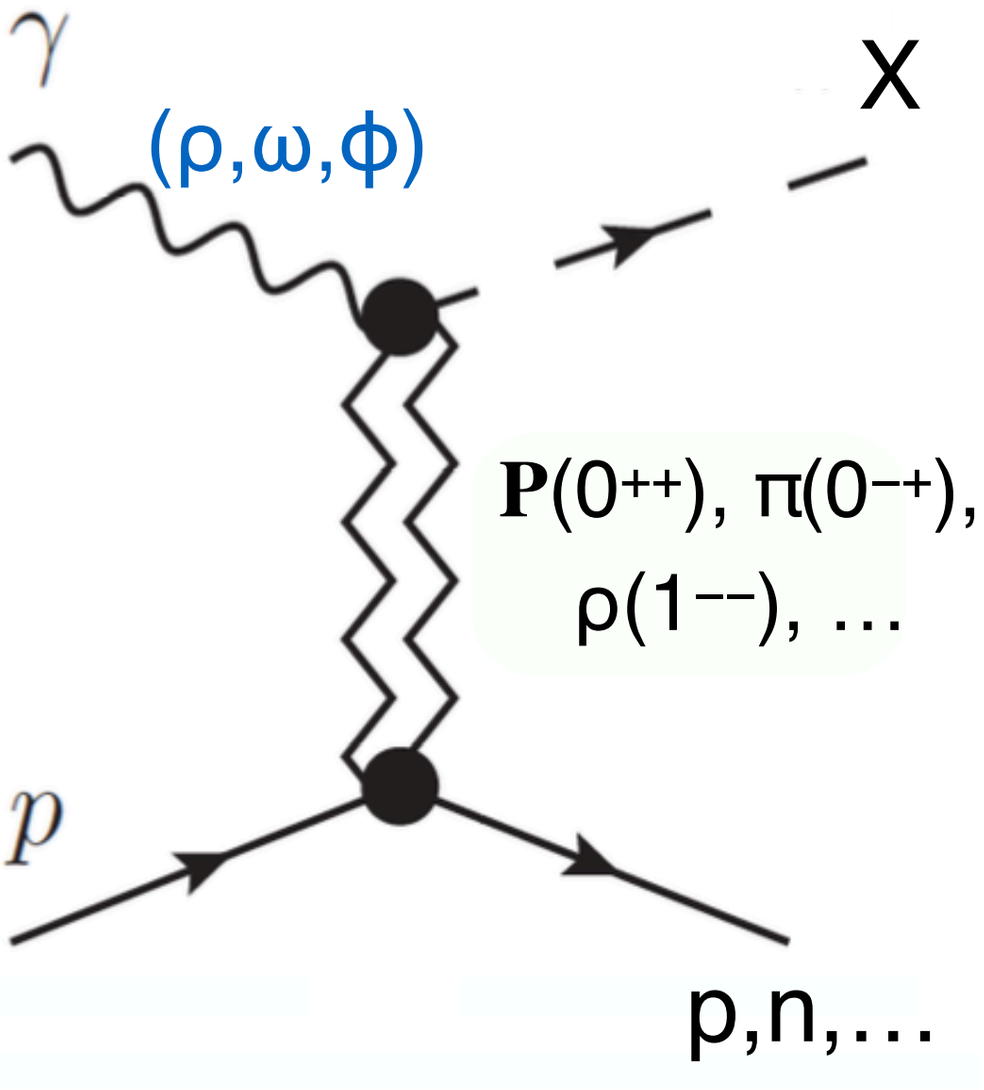
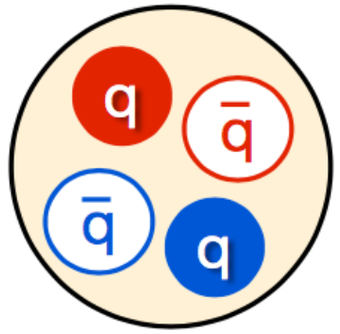
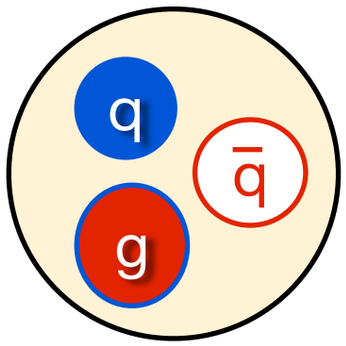
Hadron Spectroscopy and Photoproduction

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





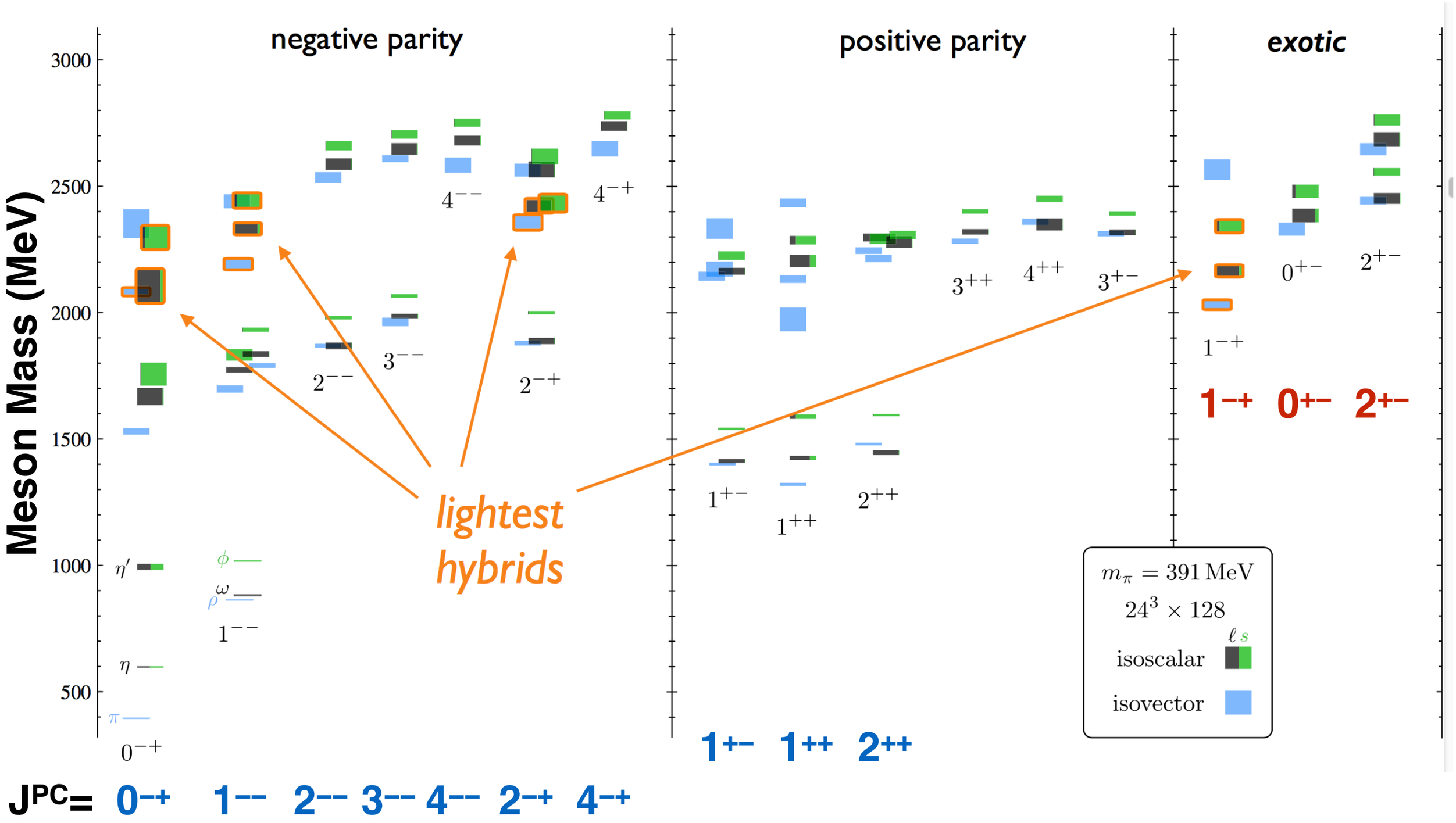
tetraquark



hybrid meson

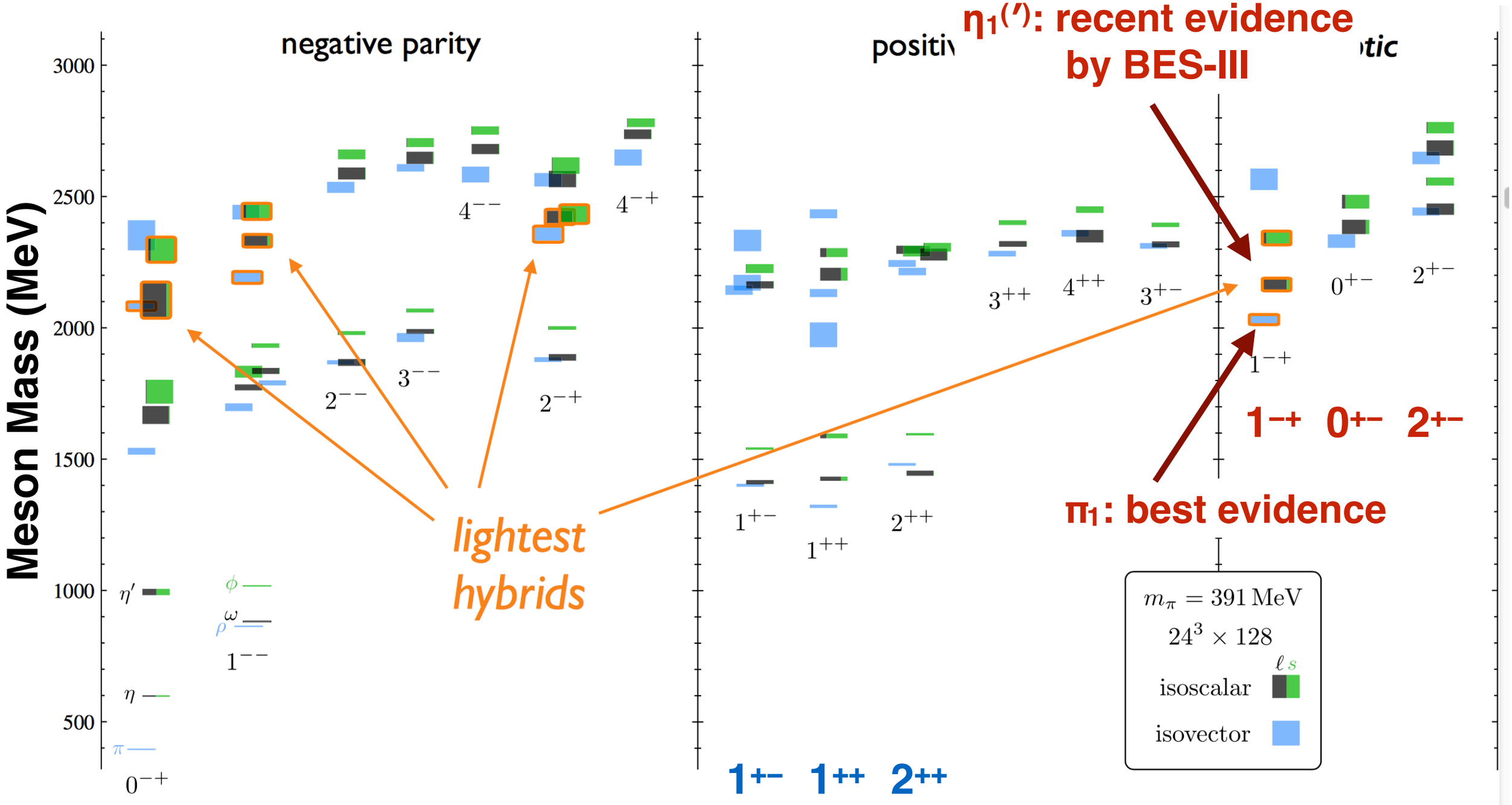
- Can produce mesons of any J^{PC} through VMD
- Photon polarization provides constraints on production processes
- Studies of polarization transfer and other production observables provides additional insight into hadron properties

Light Meson Spectrum from Lattice QCD



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

Light Meson Spectrum from Lattice QCD



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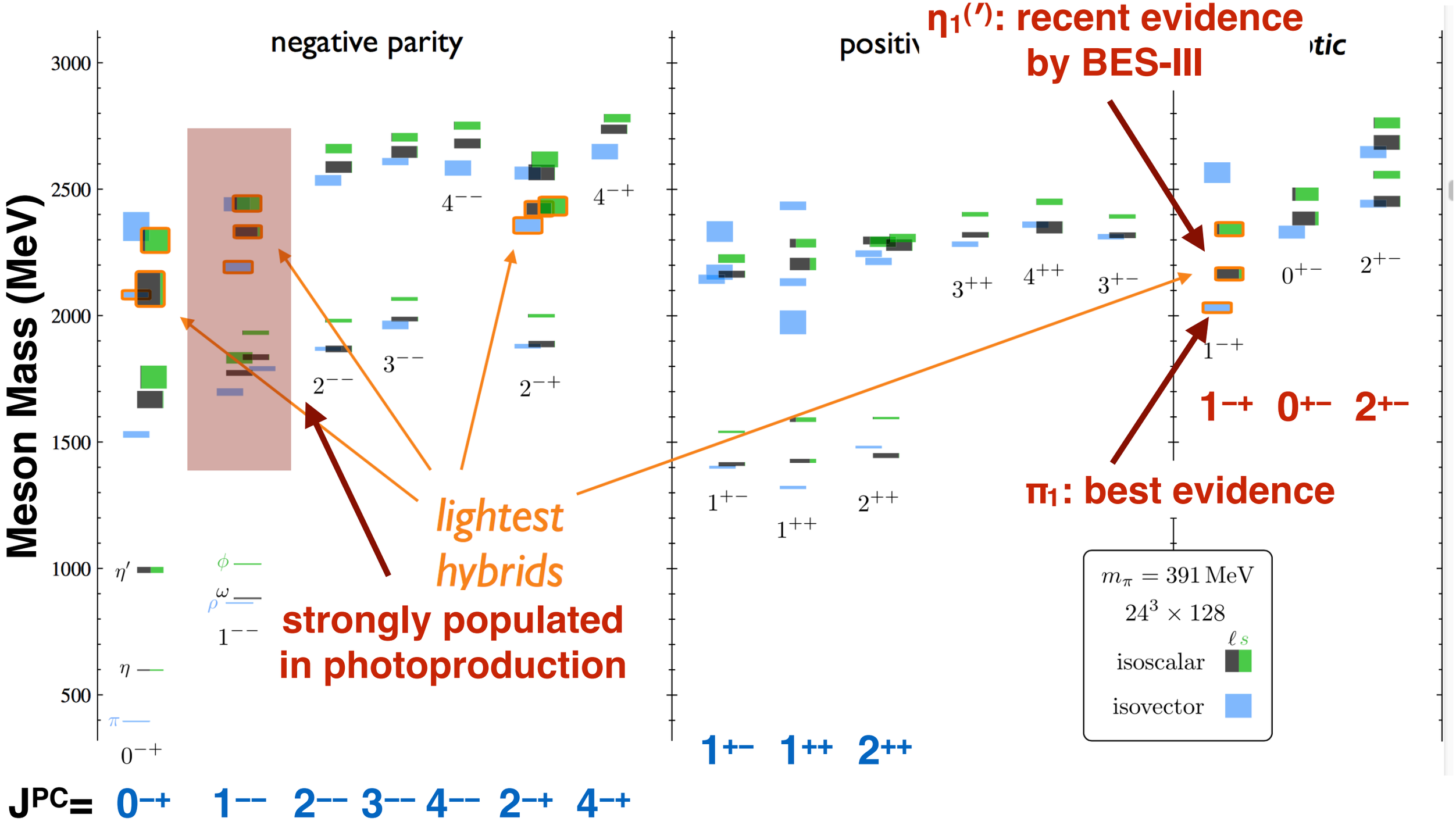
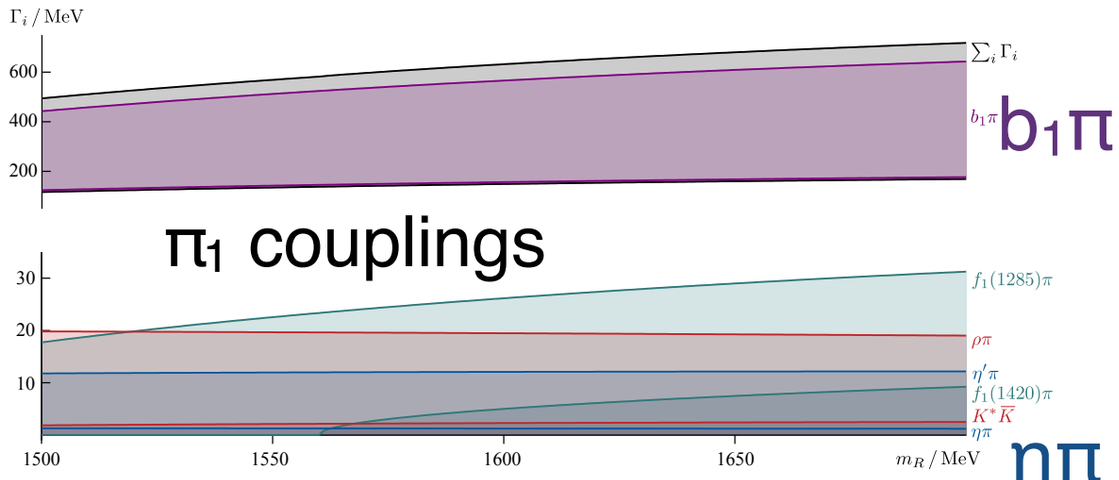
Light Meson Spectrum from Lattice QCD



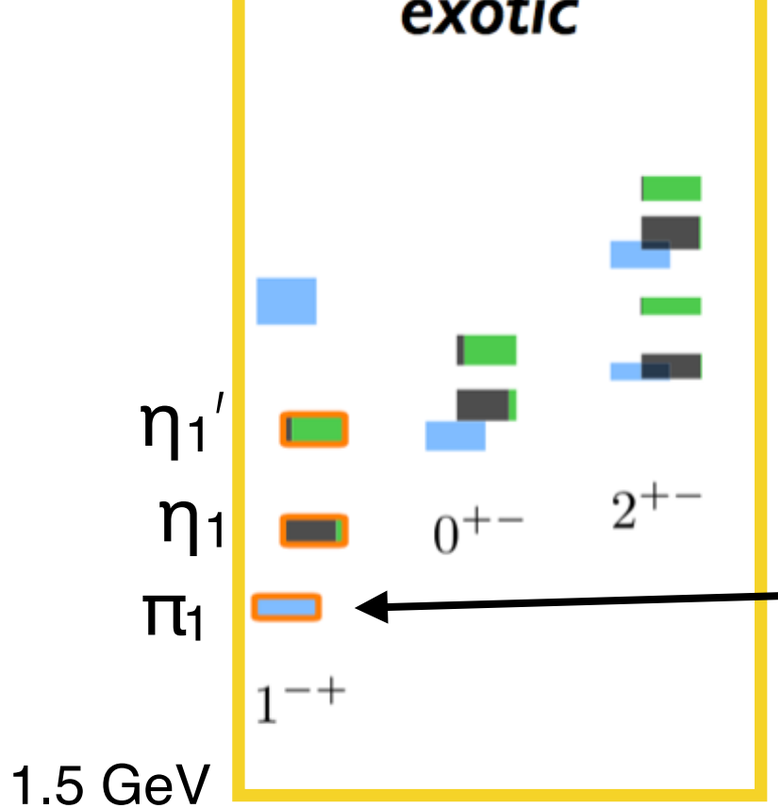
HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Hybrid Mesons

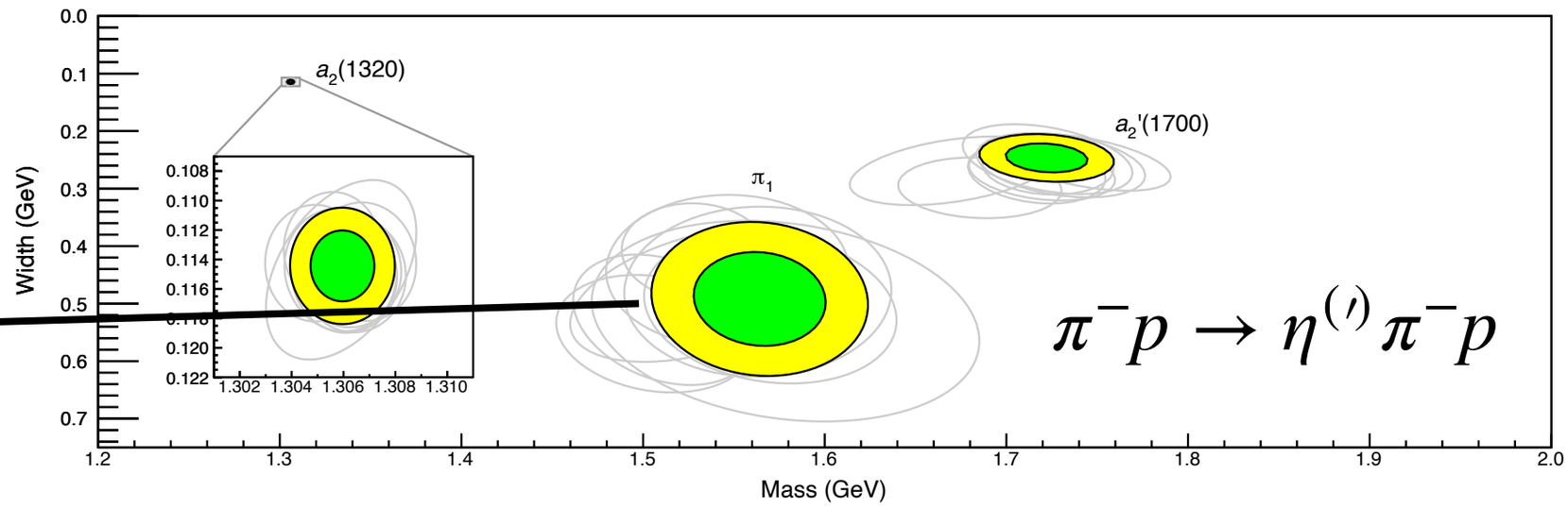
HadSpec: PRD 103, 054502 (2021)



- 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/ψ→ɣηη′ [PRL 129, 192002 (2022)]
- Need to confirm π_1 and η_1 and establish the full light quark hybrid spectrum



HadSpec: PRD 88, 094505 (2013)



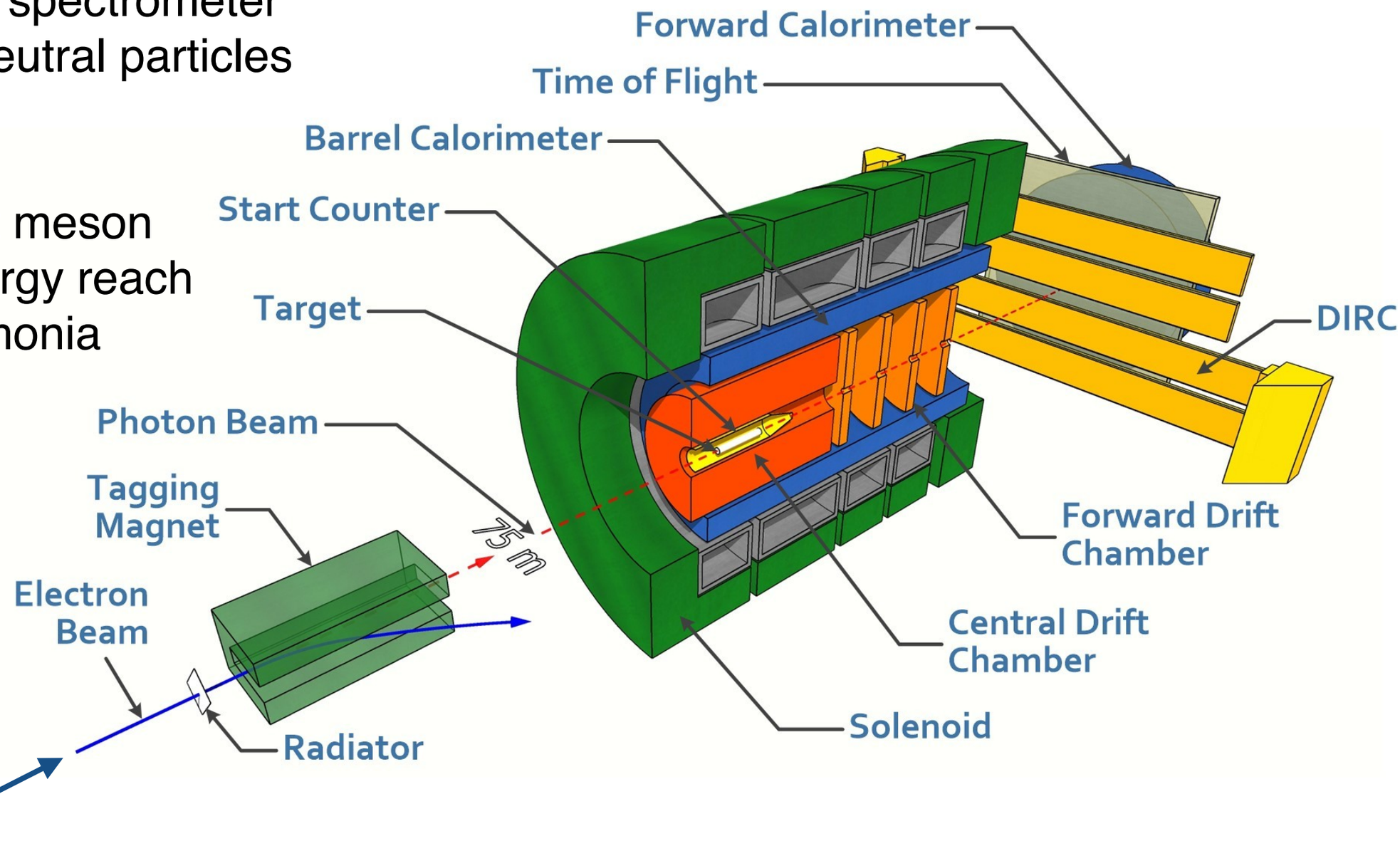
JPAC: PRL 122, 042002 (2019)

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 (2020–2025?): $L = 320$ pb^{-1} (so far)**
  expect 3-4x GlueX-I

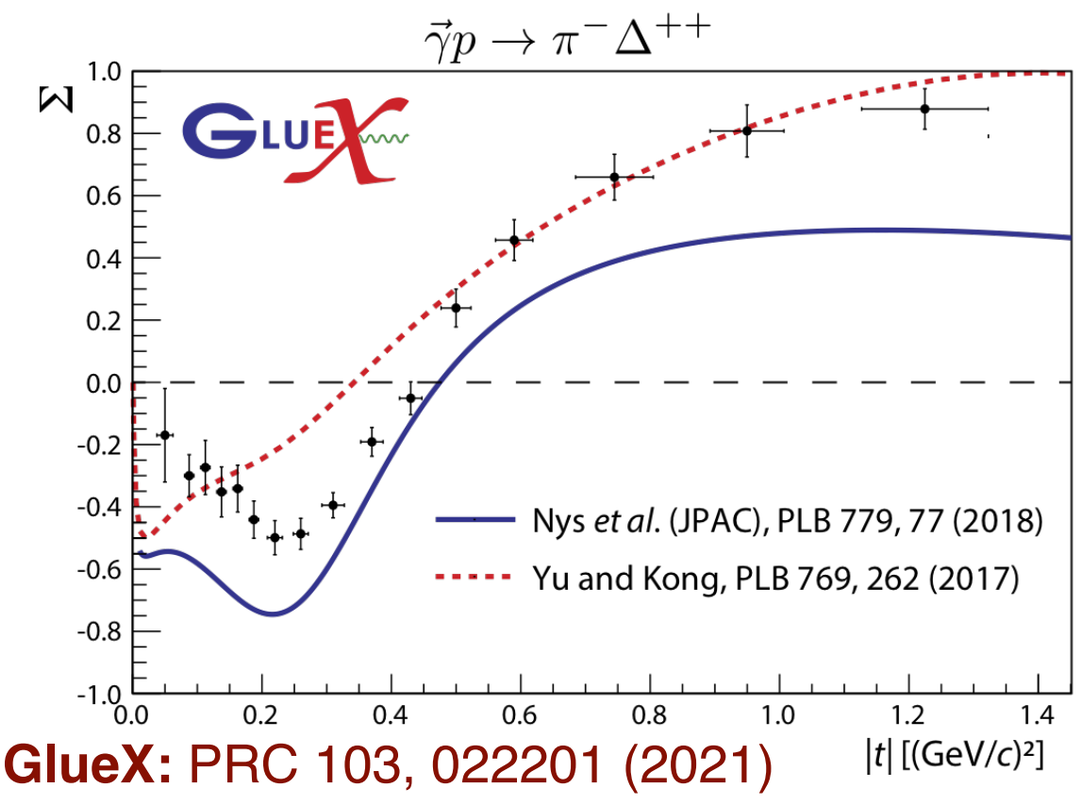
Searching for Exotics in Photoproduction @ GlueX

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

Collect Data

↓

Understand production mechanisms using polarization: Σ, SDMEs, …

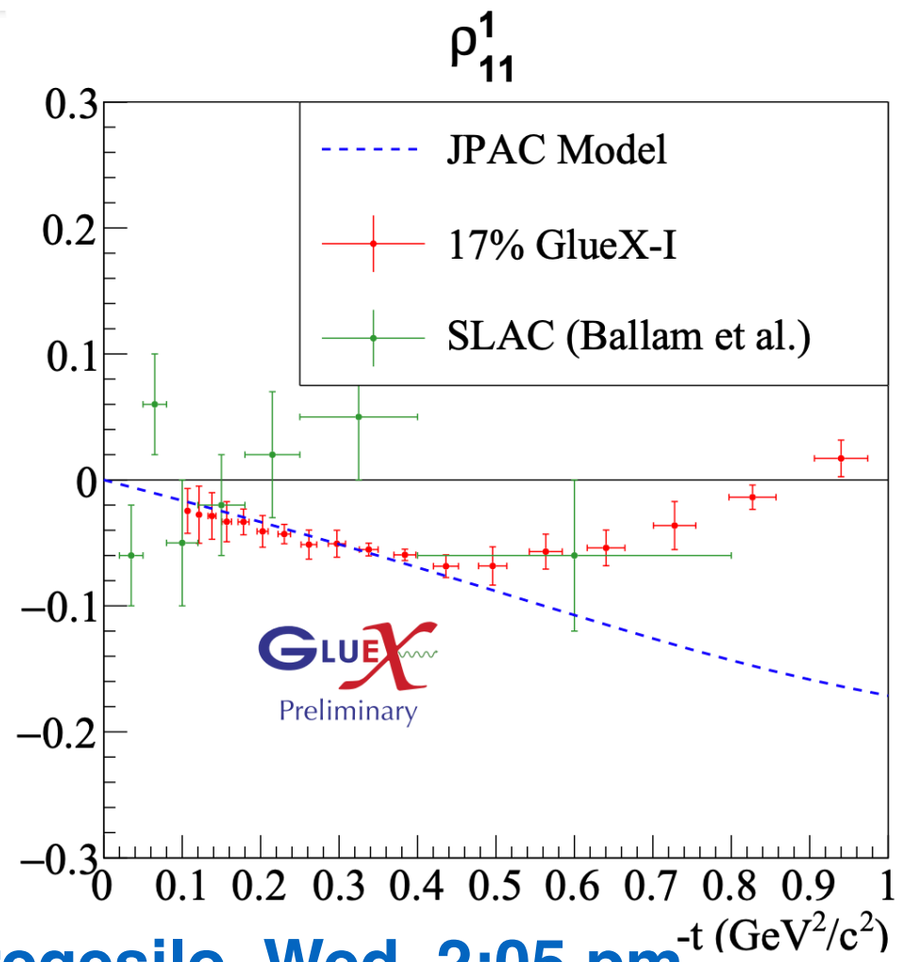


GlueX: PRC 103, 022201 (2021)

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)
$K^+\Lambda(1520)$: Phys. Rev. C105, 035201 (2022)
More coming…

SDMEs: ρ, ω, ϕ in progress



A. Austregesilo, Wed. 2:05 pm

Searching for Exotics in Photoproduction @ GlueX

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

Collect Data

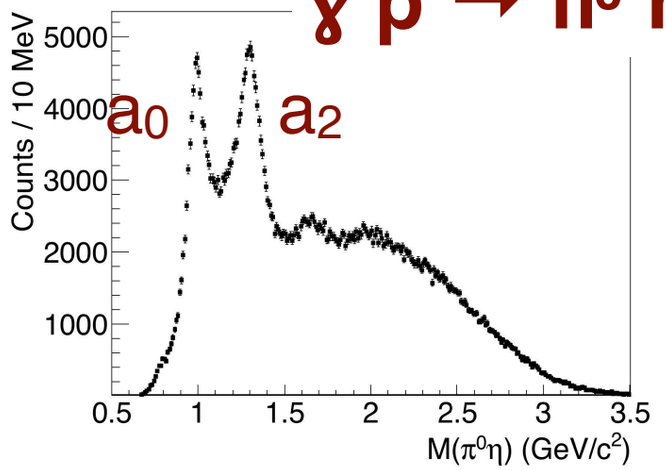
↓

Understand production mechanisms using polarization: Σ, SDMEs, …

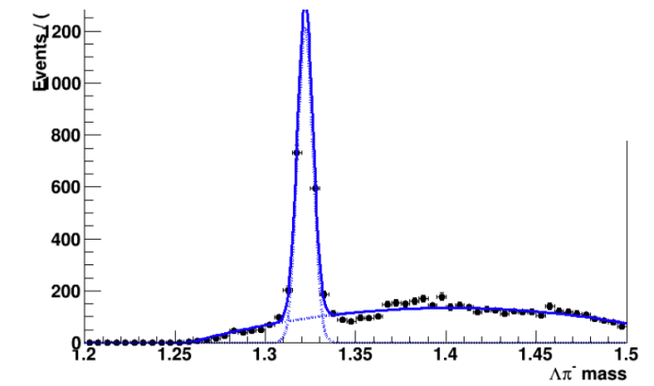
↓

Measure cross sections and identify known mesons with amplitude analysis

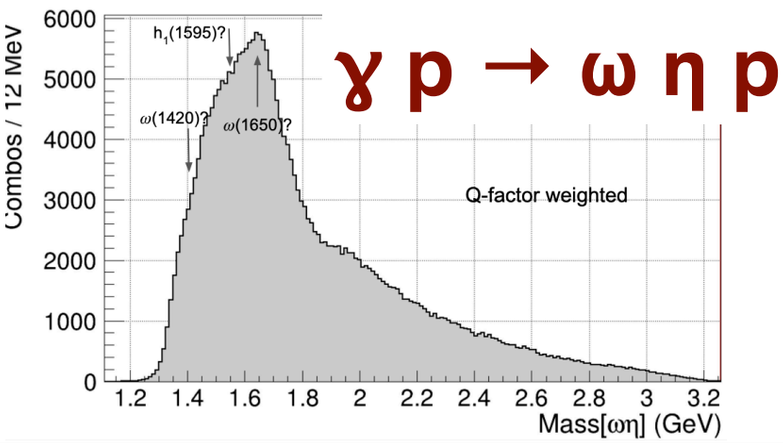
$\gamma p \to \pi^0 \eta p$



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

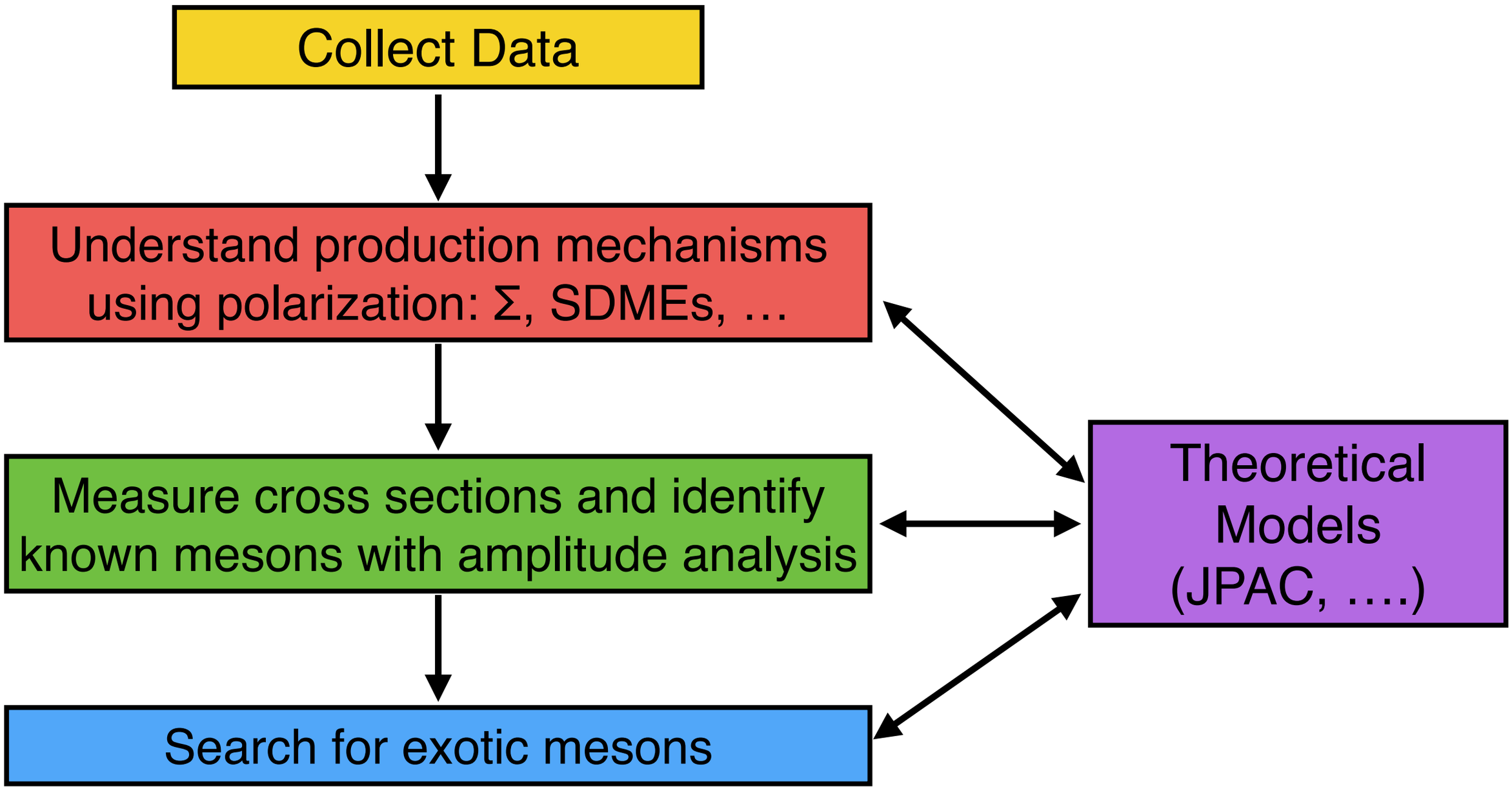


$\gamma p \to \omega \eta p$



Searching for Exotics in Photoproduction @ GlueX

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



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

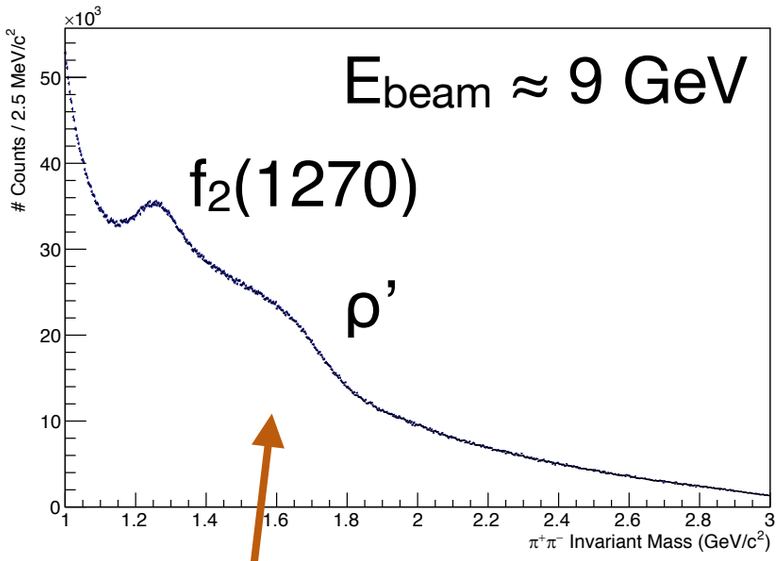
Possible Exotic Hybrid Meson Decays

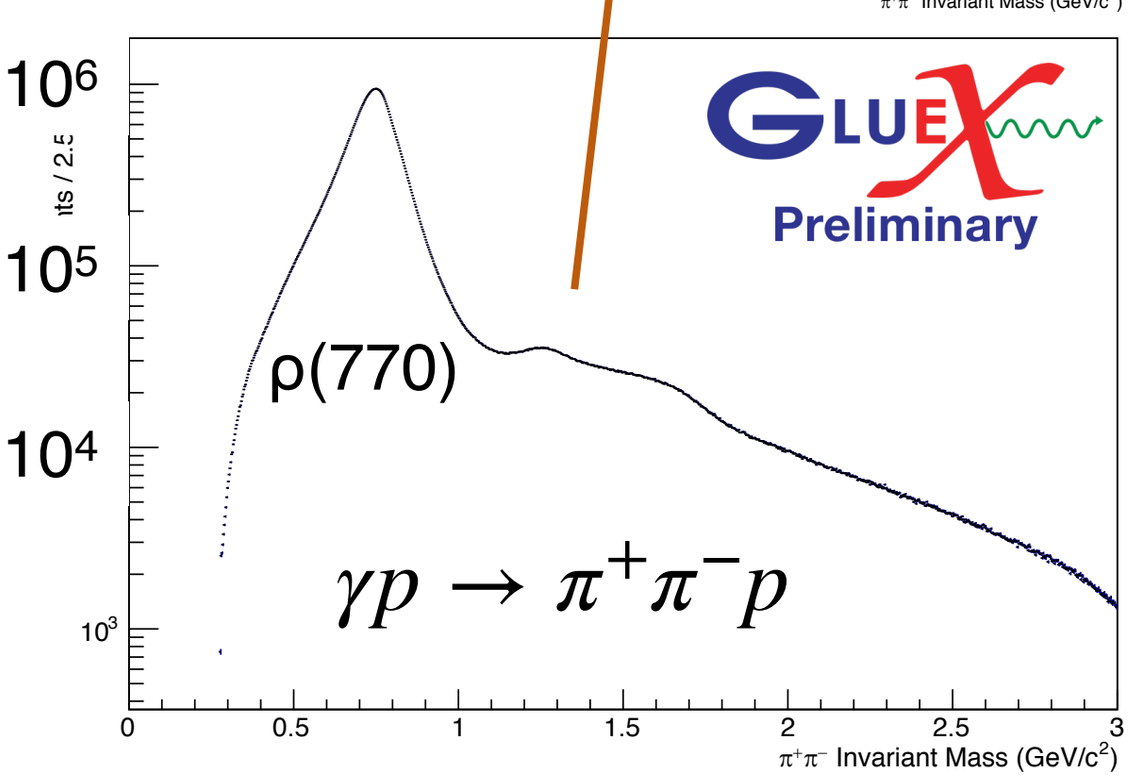
π_1: $\eta\pi$ / $\eta'\pi$, η_1: $\eta\eta'$

h_2,ω_0: $\omega\eta$, h_2',ϕ_0: $\phi\eta$
ρ_0: $\omega\pi$, $\phi\pi$

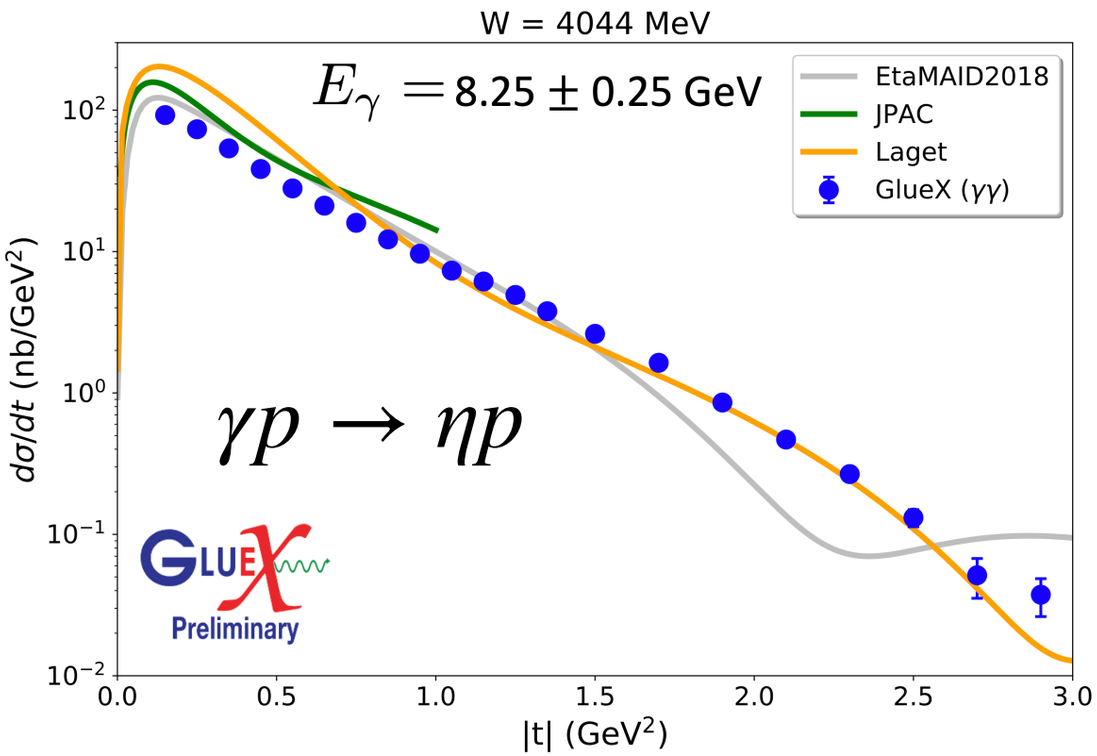
η_1,b_2: $\eta\pi\pi$, η_1',h_2': $KK\pi$

GlueX: High Statistics Photoproduction Data

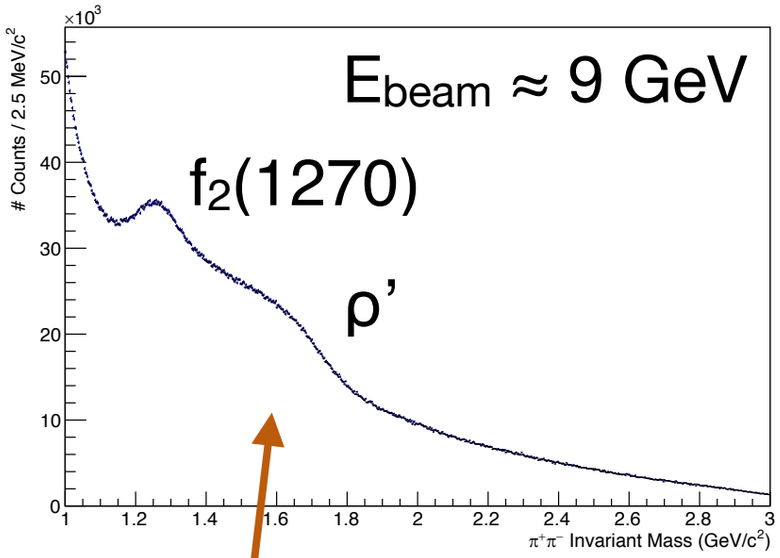


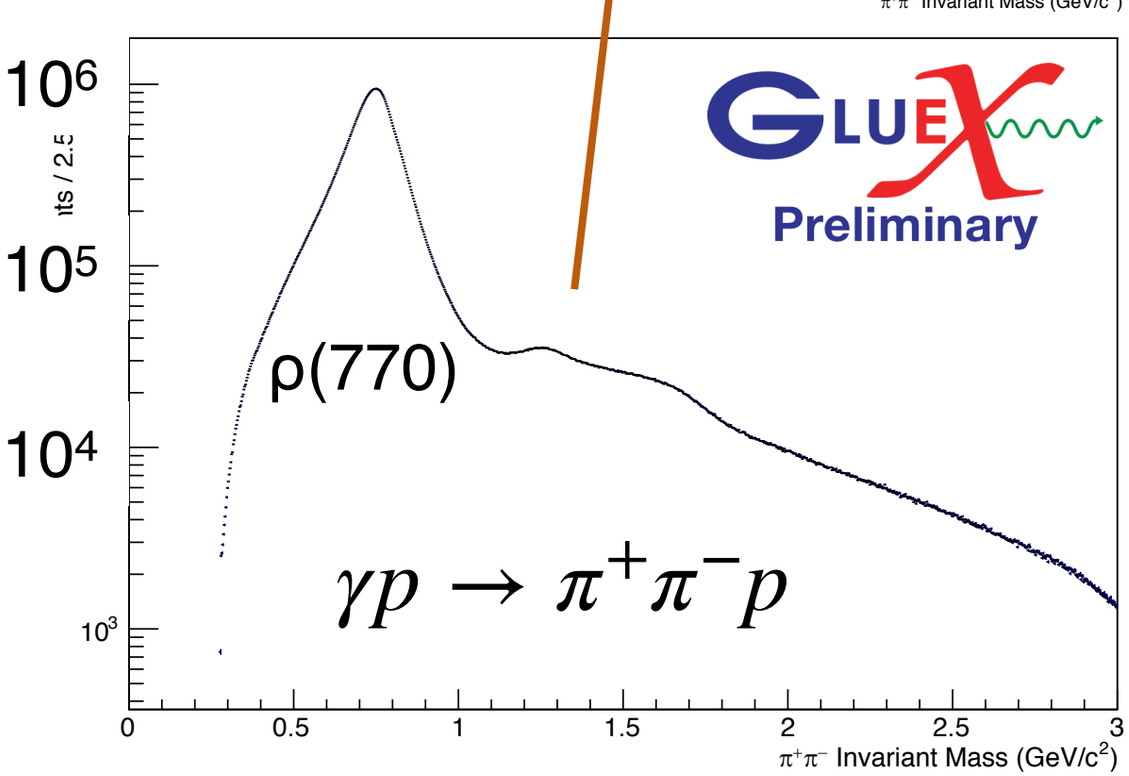


- GlueX has collected orders of magnitude more data than previous experiments at $E_\gamma \approx 9$ GeV

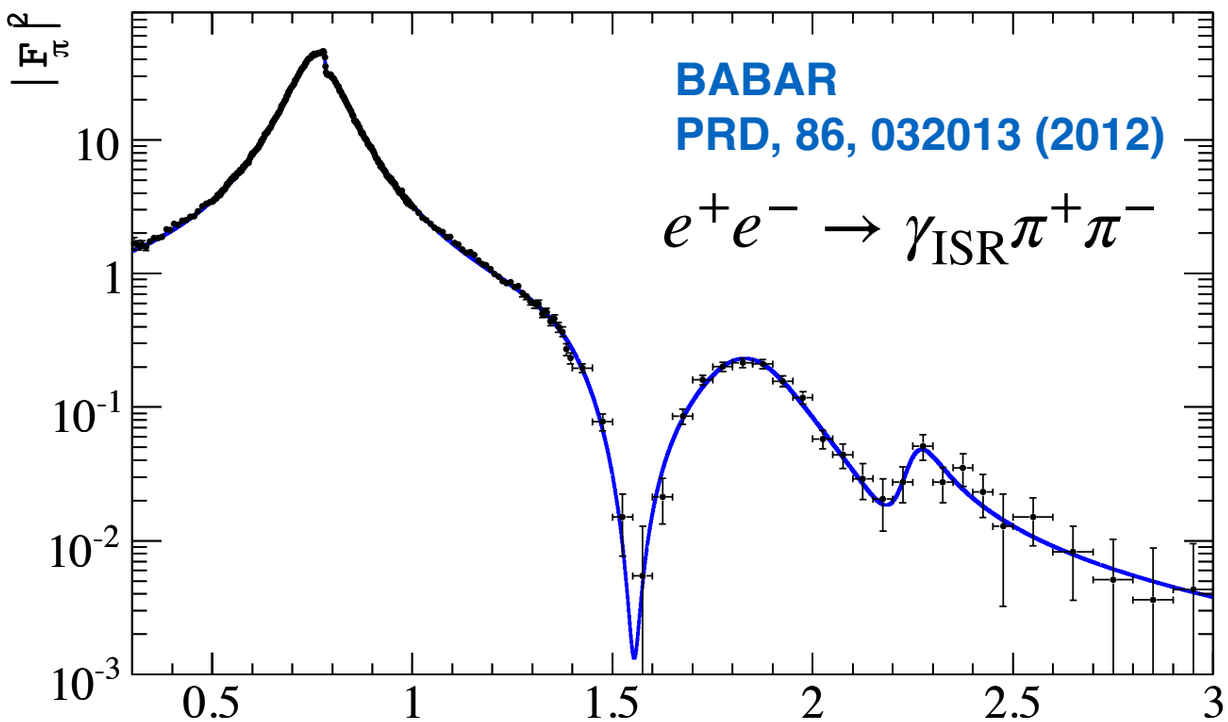


High Statistics $\pi^+\pi^-$ and Excited Vectors



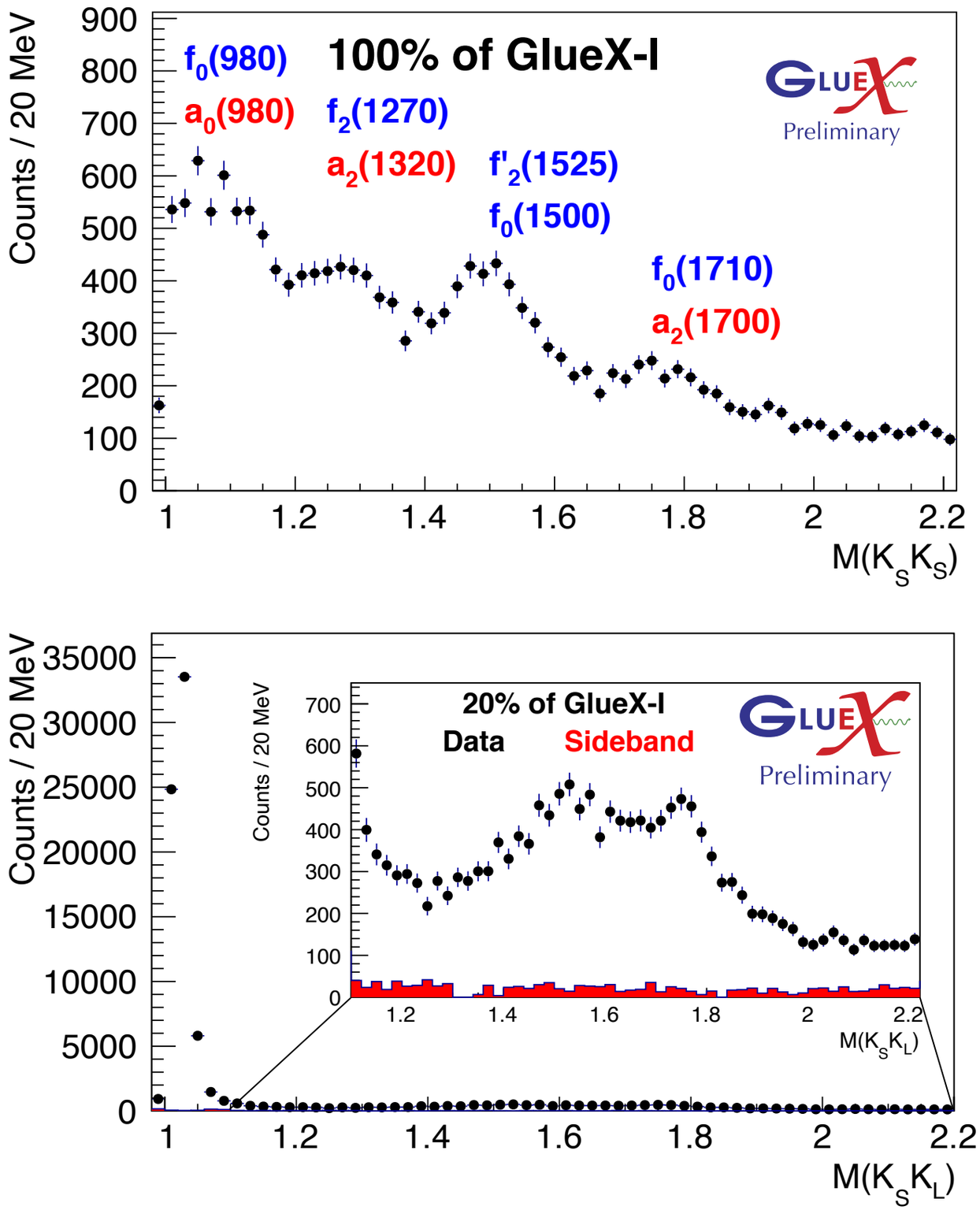


- GlueX can access excited vector mesons decaying to e.g. $\pi^+\pi^-$ and $\omega\pi$
- Need consistent understanding of spectra in photoproduction and e^+e^- annihilation

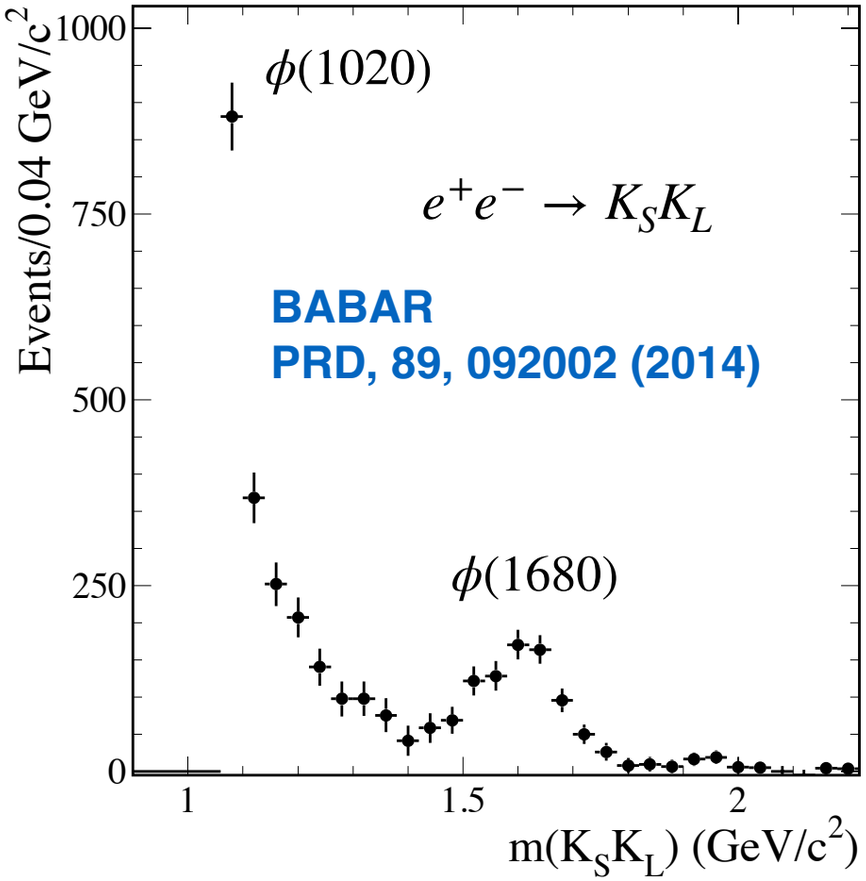


A. Austregesilo, Wed. 2:05 pm

High Statistics $K\bar{K}$ and Excited Vectors



- Can extend studies to $K\bar{K}$
  - K_SK_S: $J^{PC} = even^{++}$
  - K_SK_L: $J^{PC} = odd^{--}$
- Comparison with e^+e^- annihilation
- Future coupled channel fits for K_SK_S



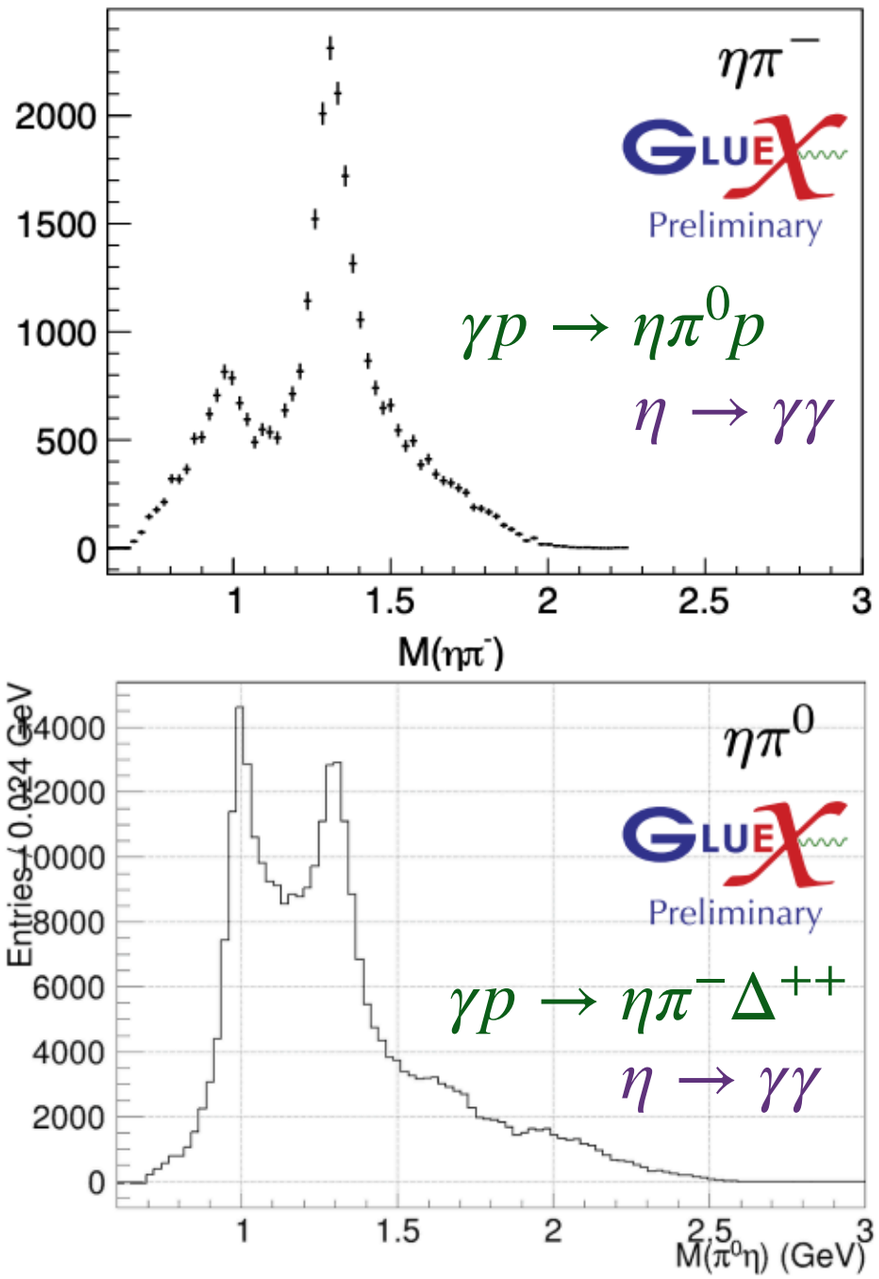
ηπ Amplitude Analysis at GlueX

- $\pi\eta$ / $\pi\eta'$ "golden channels" for π_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 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
- Fits with different levels of model-dependence

M. Albrecht, Tue. 2:05 pm

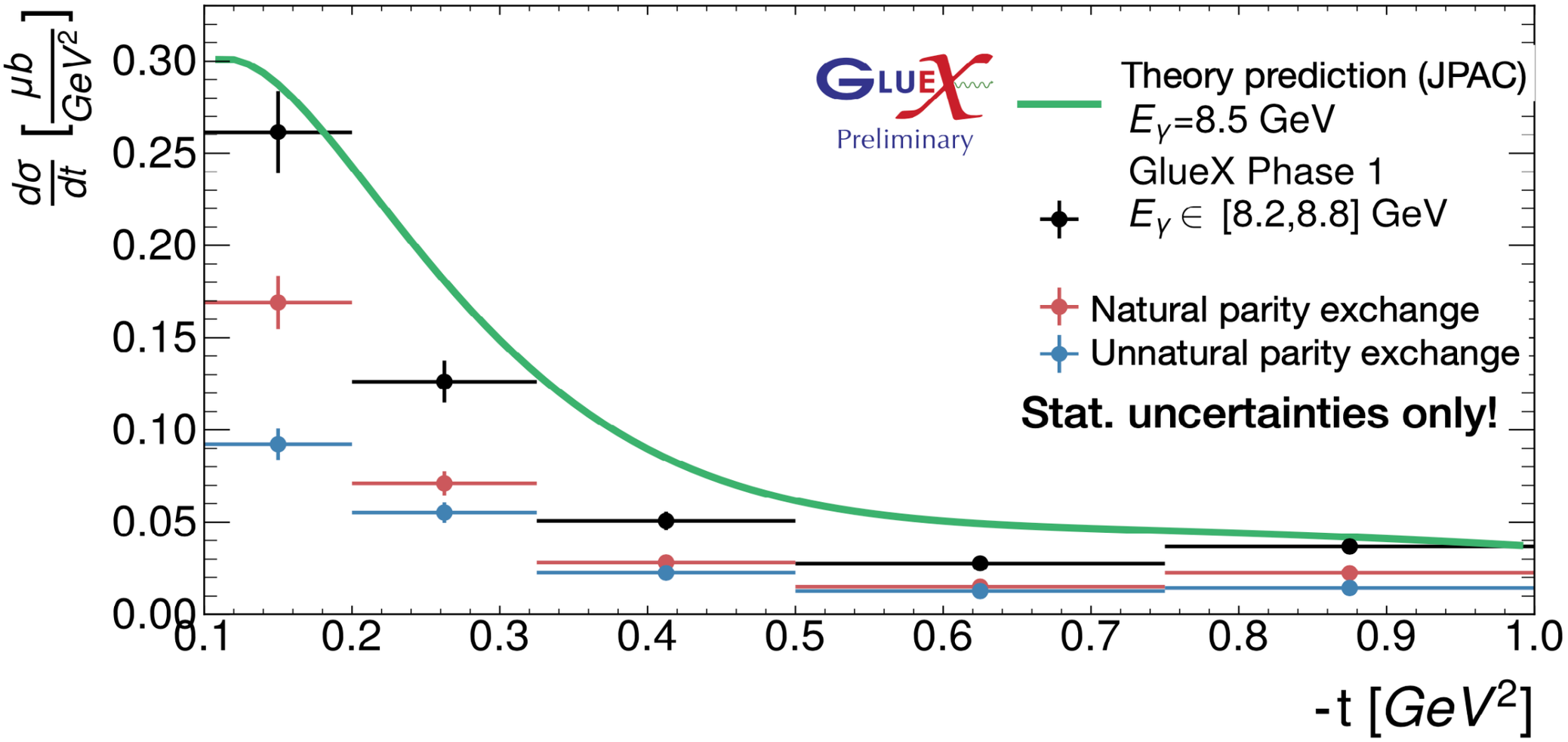
GlueX-I Data

$0.1 < -t < 0.3$ GeV^2



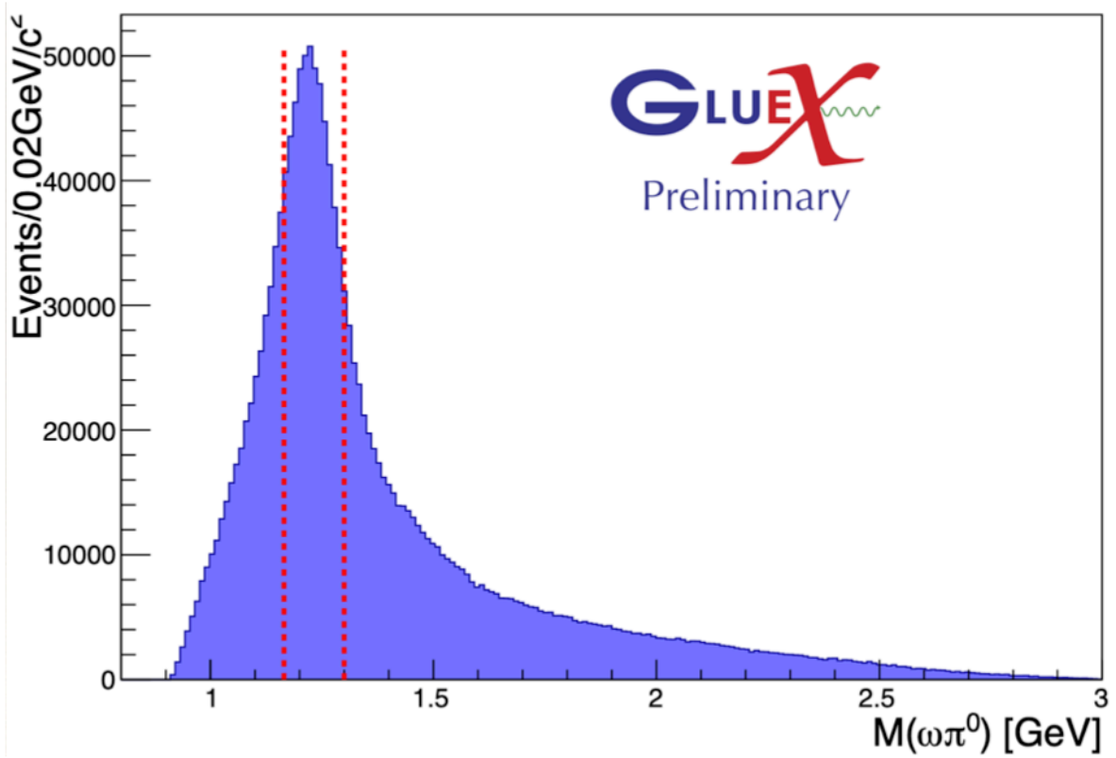
Preliminary $\gamma p \to a_2(1320)p$ Cross Section

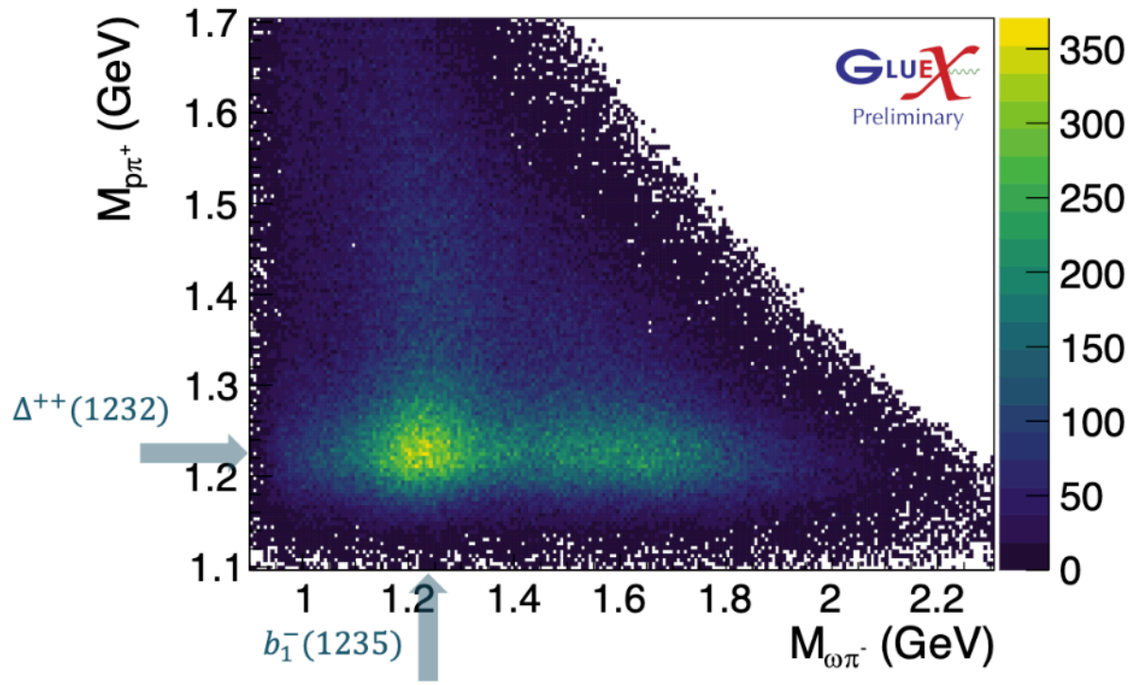
- Preliminary cross sections agree with with JPAC prediction
  - Can also extract amplitudes for individual waves
- Photon polarization crucial to control contributions from different production amplitudes
- Informs amplitude fits for exotic waves



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 $\omega\pi$
  - Large samples of millions of events
  - 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
  - $\gamma p \rightarrow b_1^0 p \rightarrow \omega\pi^0 p$
  - $\gamma p \rightarrow b_1^- \Delta^{++} \rightarrow \omega\pi^- \Delta^{++}$





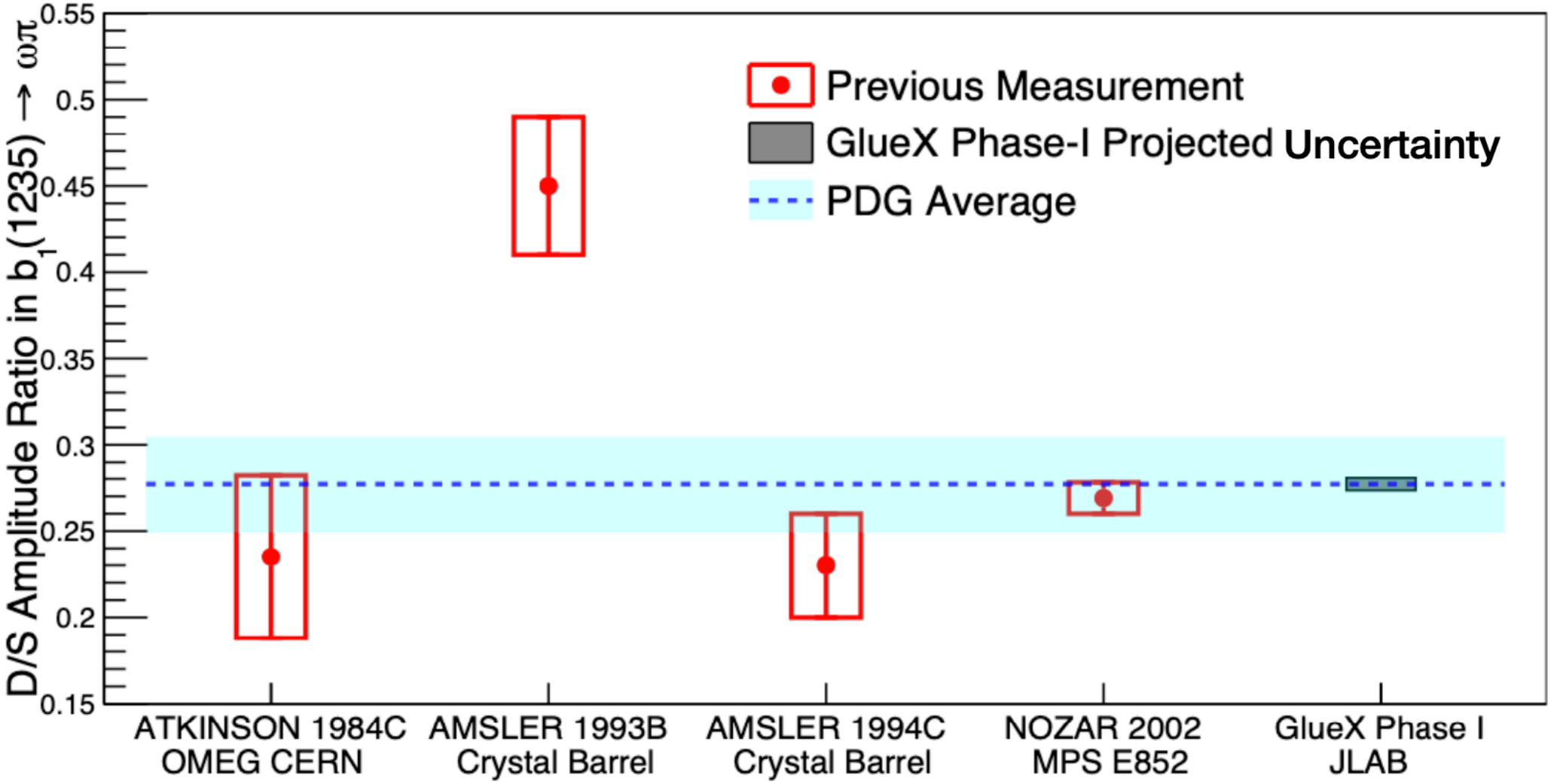
Study of $b_1(1235)$ at GlueX: S/D ratio

- 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)

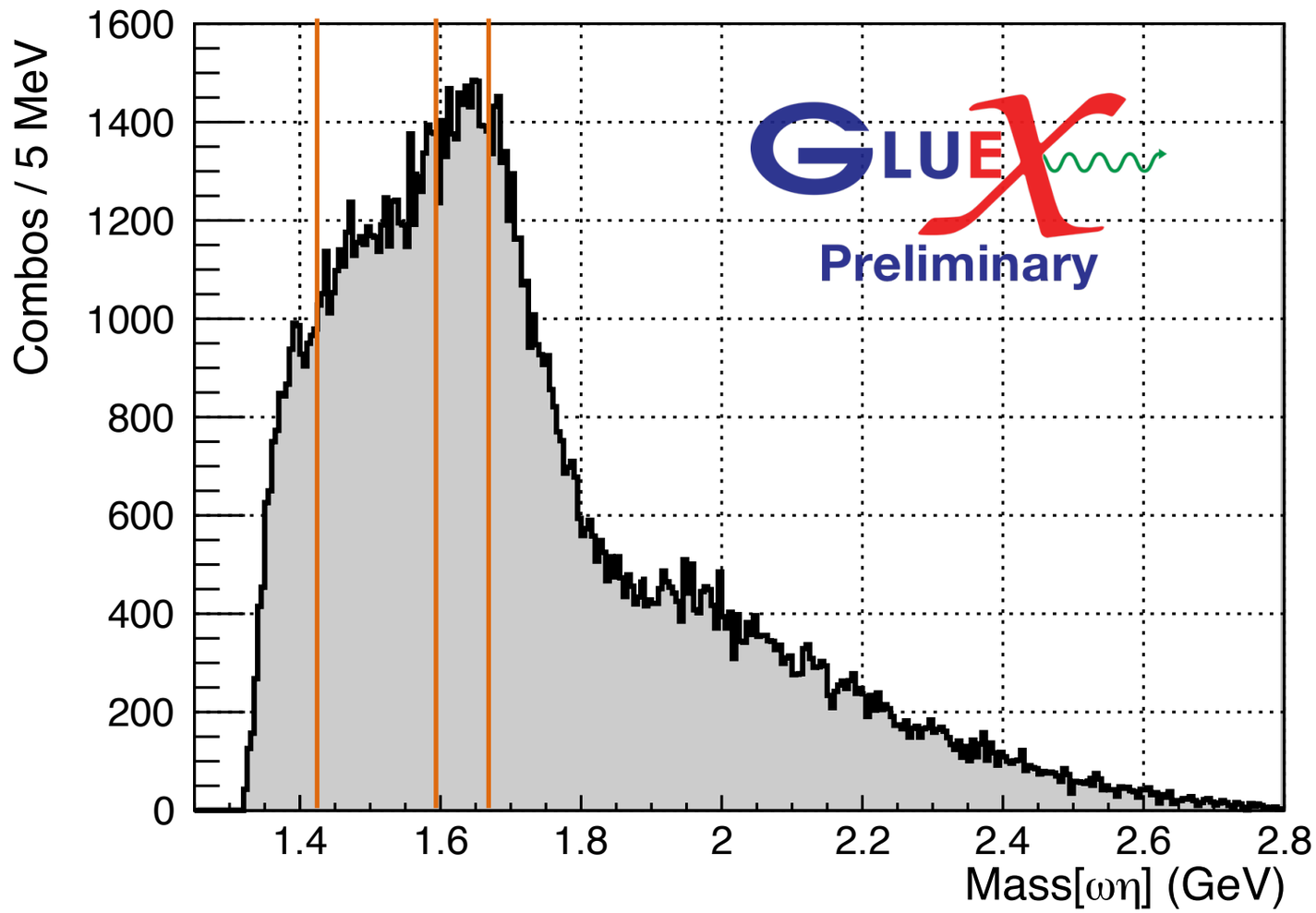
LCQD: $|D/S| = 0.27(20)$

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



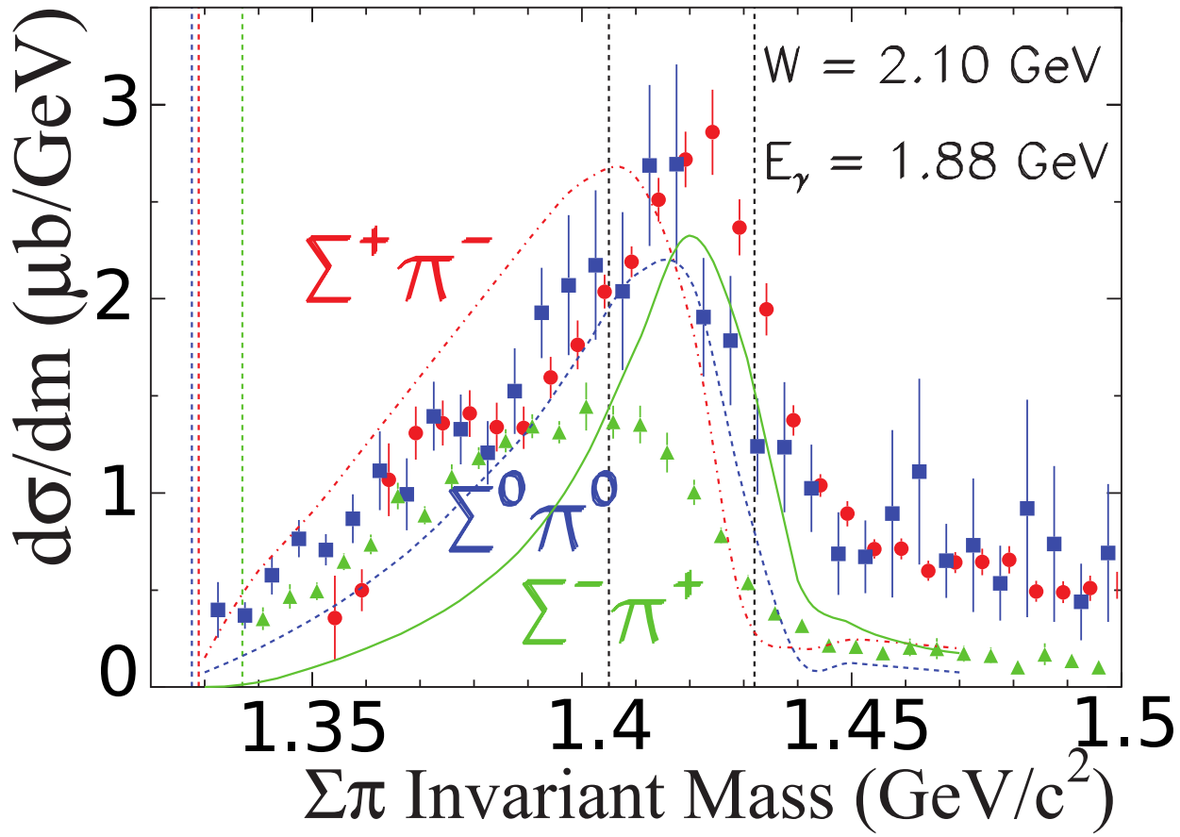
ωη Photoproduction at GlueX

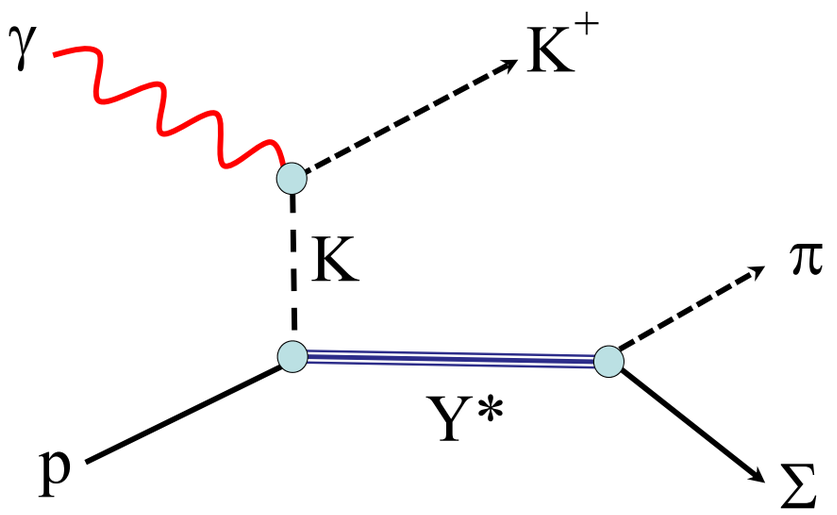
- ωη photoproduction probes the production of I=0 states:
  - Normal: ω (1^{--}), h_1 (1^{+-})
  - Exotic: 0^{--}, 2^{+-}
  - Unobserved: 2^{--}
- 145k events seen in GlueX-I data
- Amplitude analysis in progress



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.





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

CLAS, PRC 87, 035206 (2013)

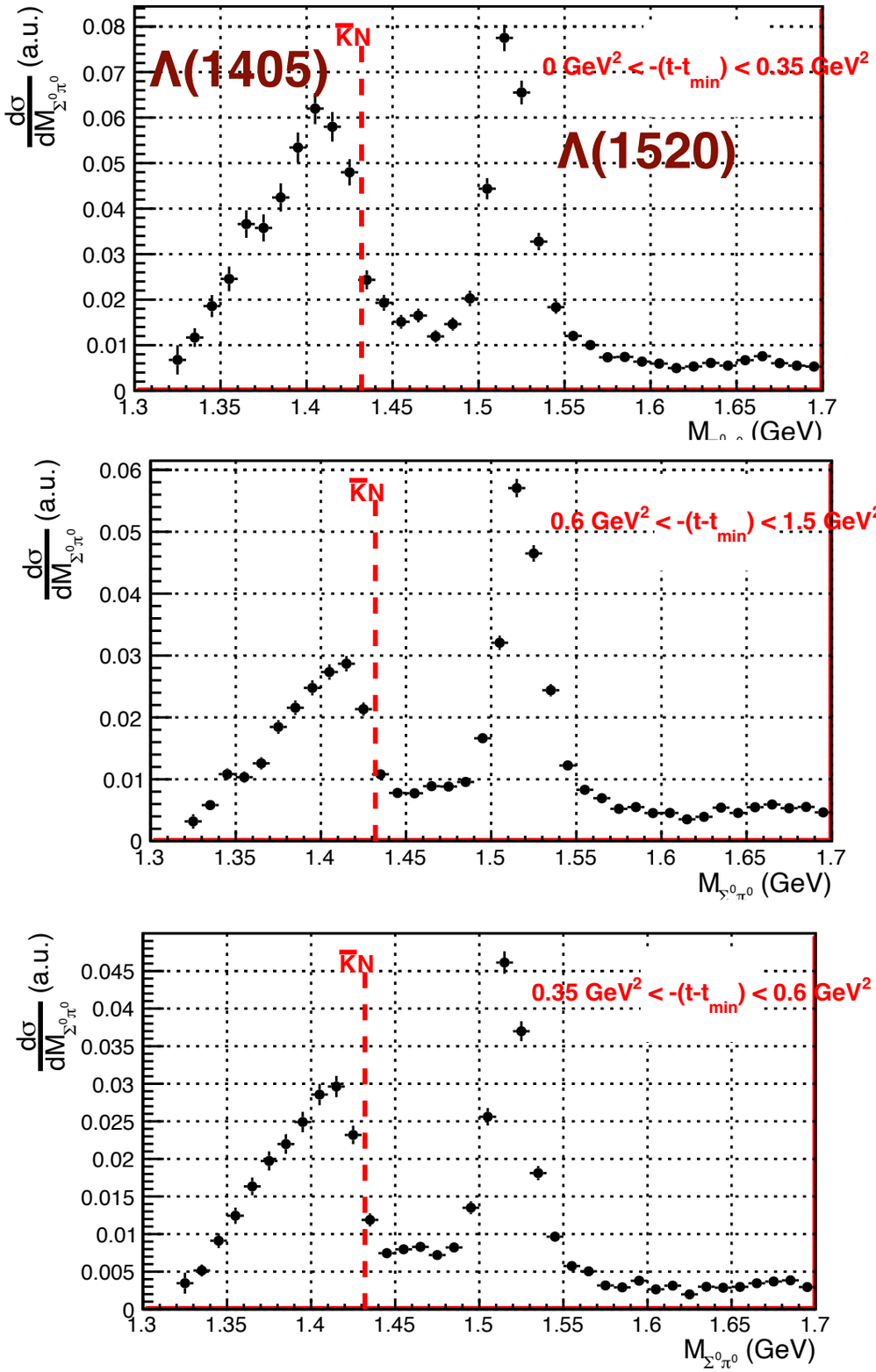
Λ(1405) in Photoproduction @ GlueX

- Preliminary efficiency-corrected mass spectra shown for GlueX-I data in

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

- Yields shown in 3 t-bins
  - Clear Λ(1405) and Λ(1520) signals

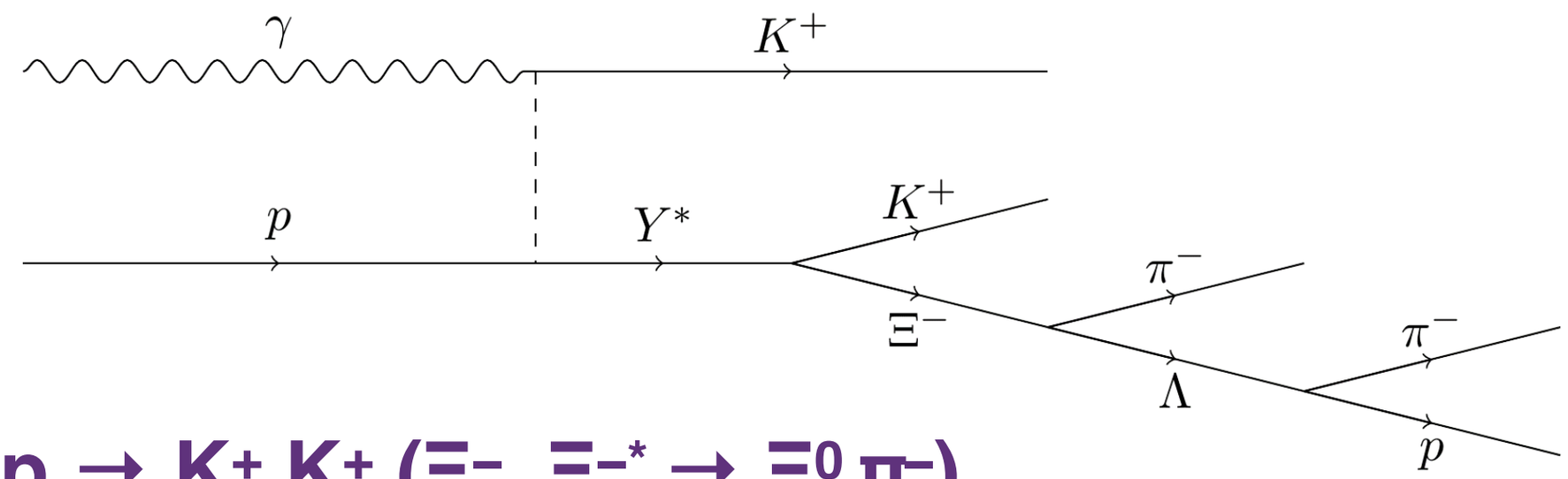
- With full GlueX-I data, we can study E_γ and t-dependence of lineshape using largest sample of $\Sigma^0 \pi^0$ available (>10k events in Λ(1405) region)



Prospects for Cascade Spectroscopy

- The Cascade (ssd, ssu) spectrum is poorly known — nothing new since 1988!
  - LQCD predicts rich spectrum, many narrow states
- CLAS observed photoproduction of ground states
  - Production of excited cascades via a forward-going kaon?

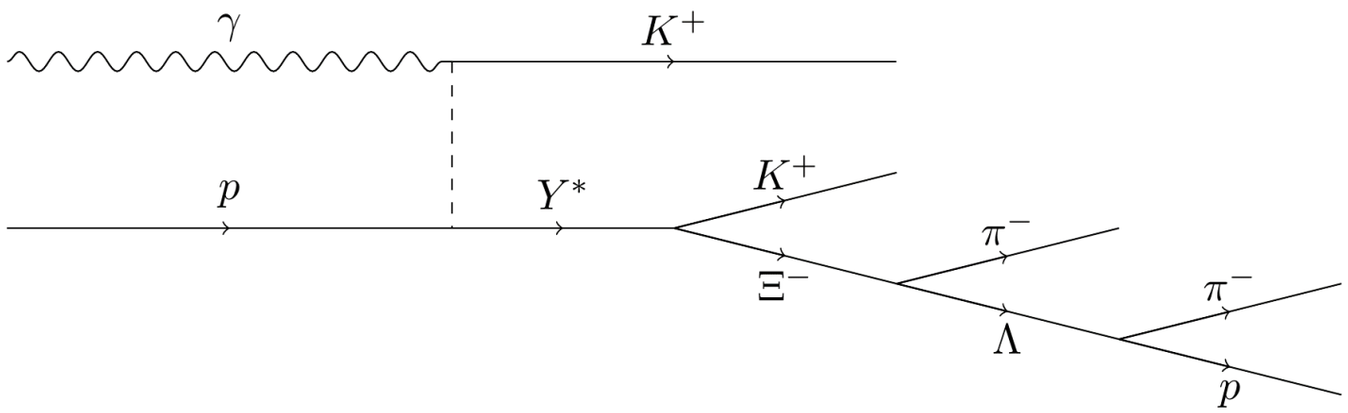
State		Quality
$\Xi(1320)$	$(1/2)^+$	****
$\Xi(1530)$	$(3/2)^+$	****
$\Xi(1690)$		***
$\Xi(1820)$	$(3/2)^-$	***
$\Xi(1950)$		***
$\Xi(2030)$		***

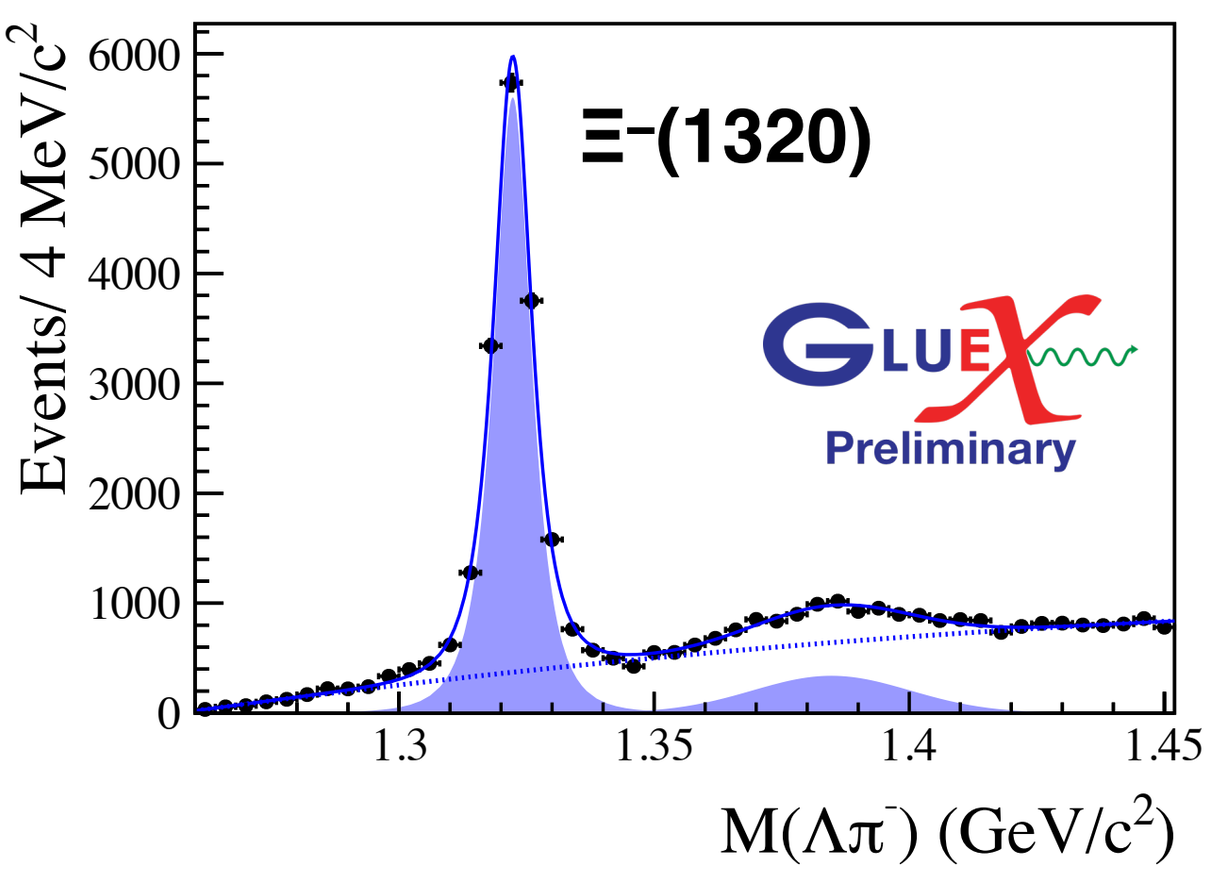


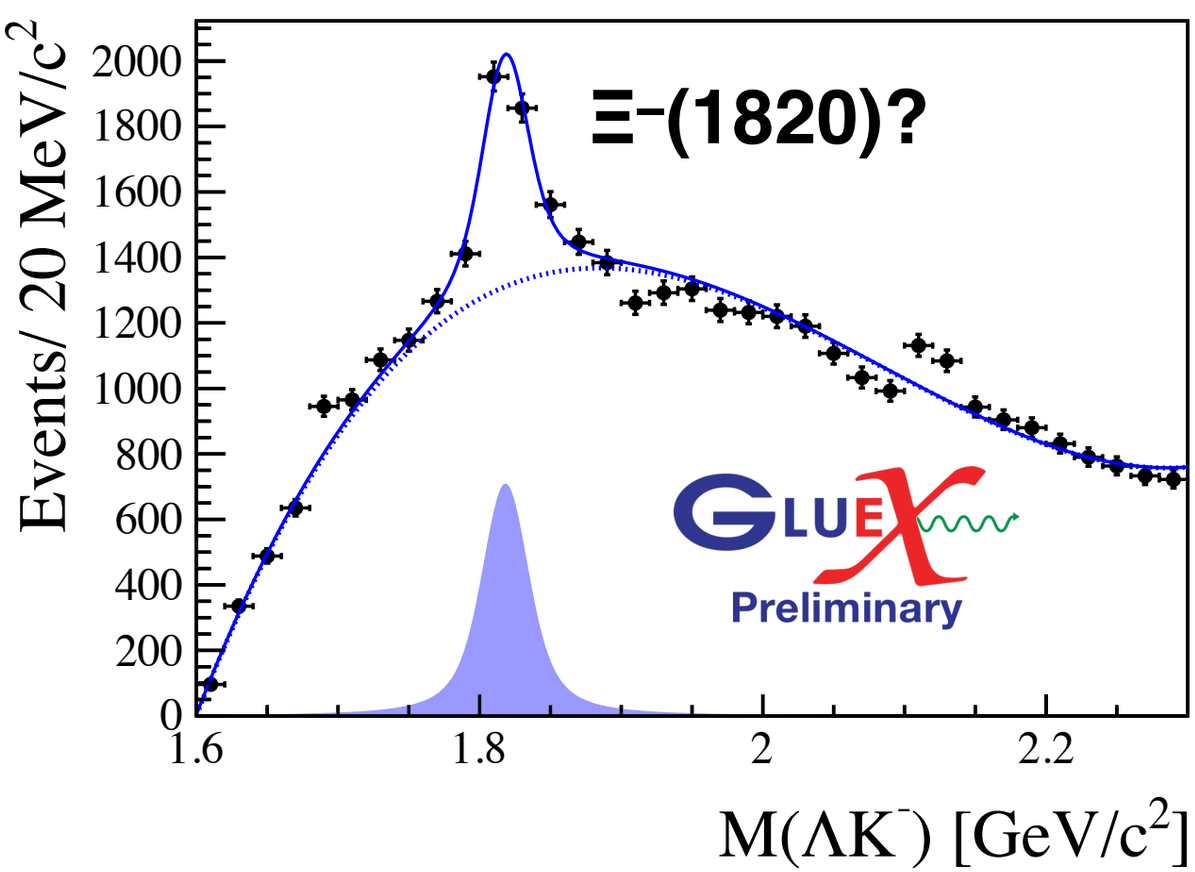
γ + p → K+ K+ (Ξ−, Ξ−* → Ξ0 π−)

Hunting for Excited Cascades

- GlueX has identified peaks corresponding to several of these states
- Cross sections and polarization observables are being measured

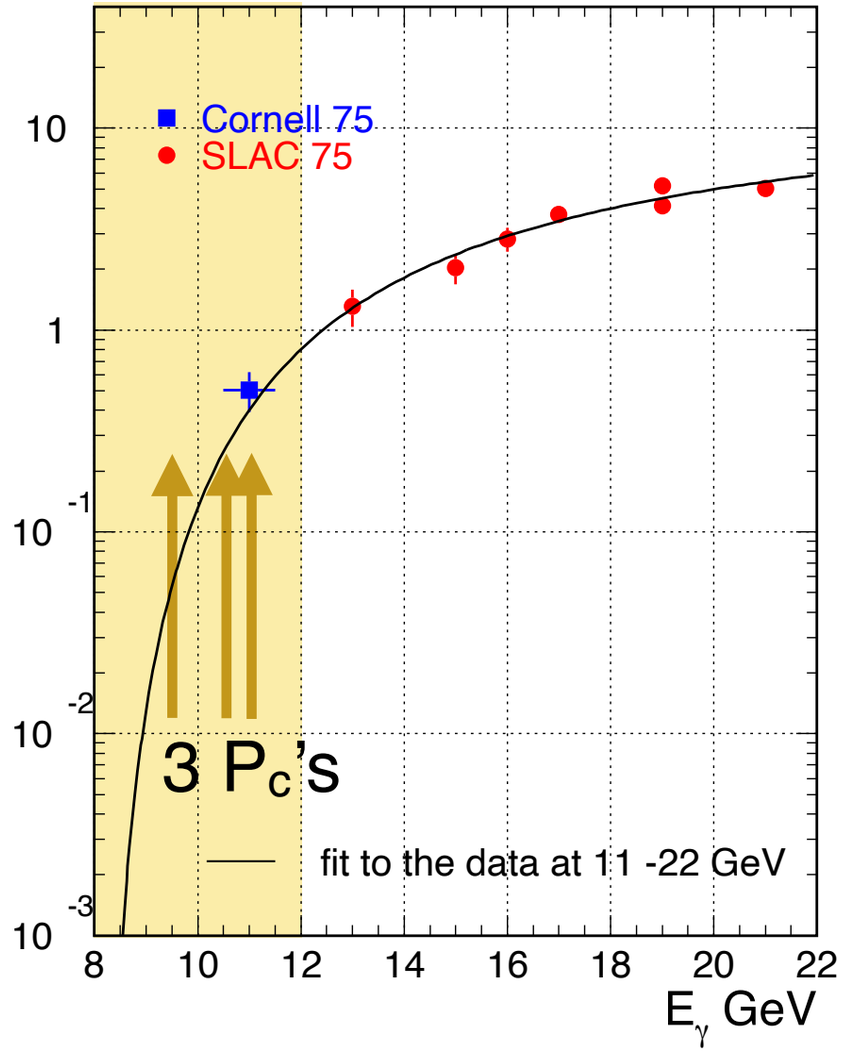




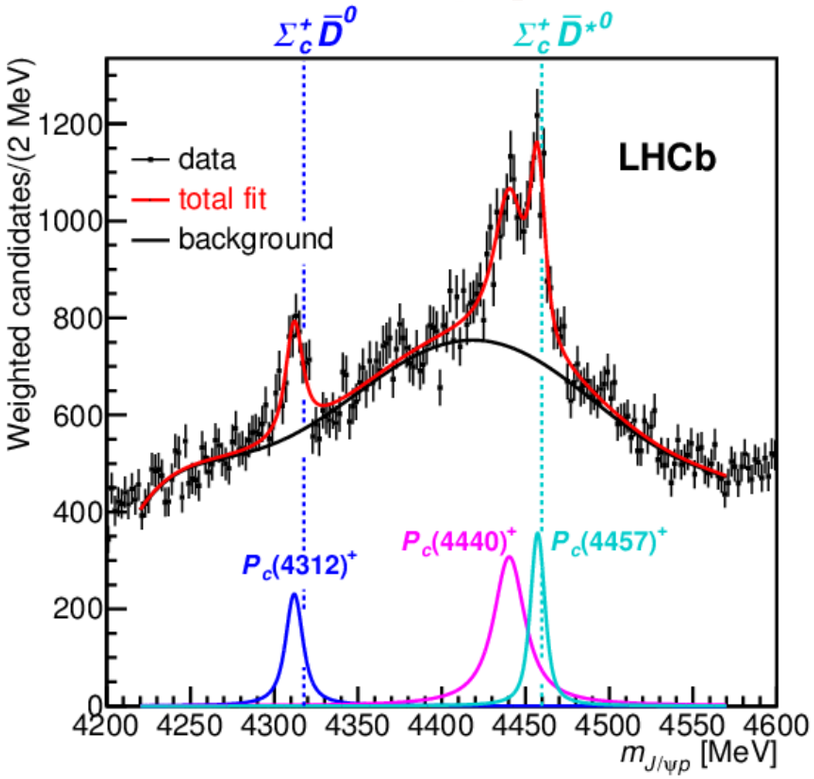


Charmonium Photoproduction Near Threshold

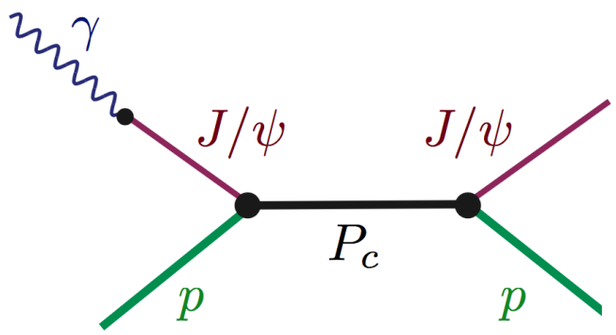
- Production of $c\bar{c}$ near threshold probes the distribution of gluons in the proton and the nature of the proton mass
- Can also look for s-channel production of resonant states



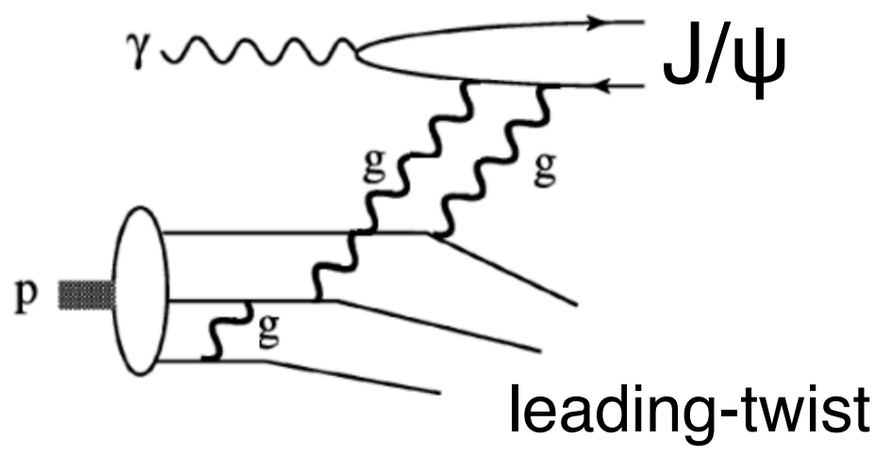
$\Lambda_b \to J/\psi\, p\, K^-$



LHCb, PRL 122, 222001 (2019)

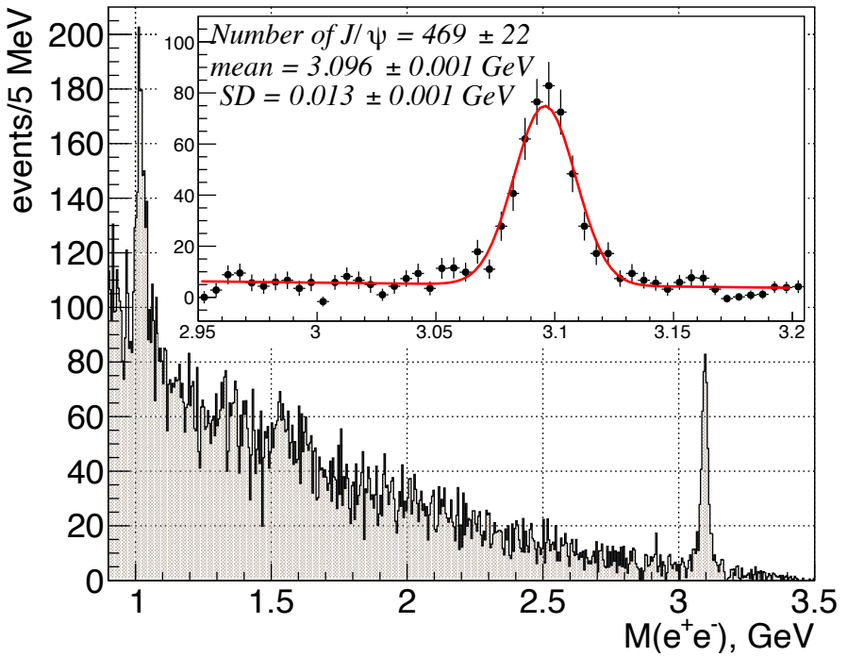


γ p → Pc → J/ψ p



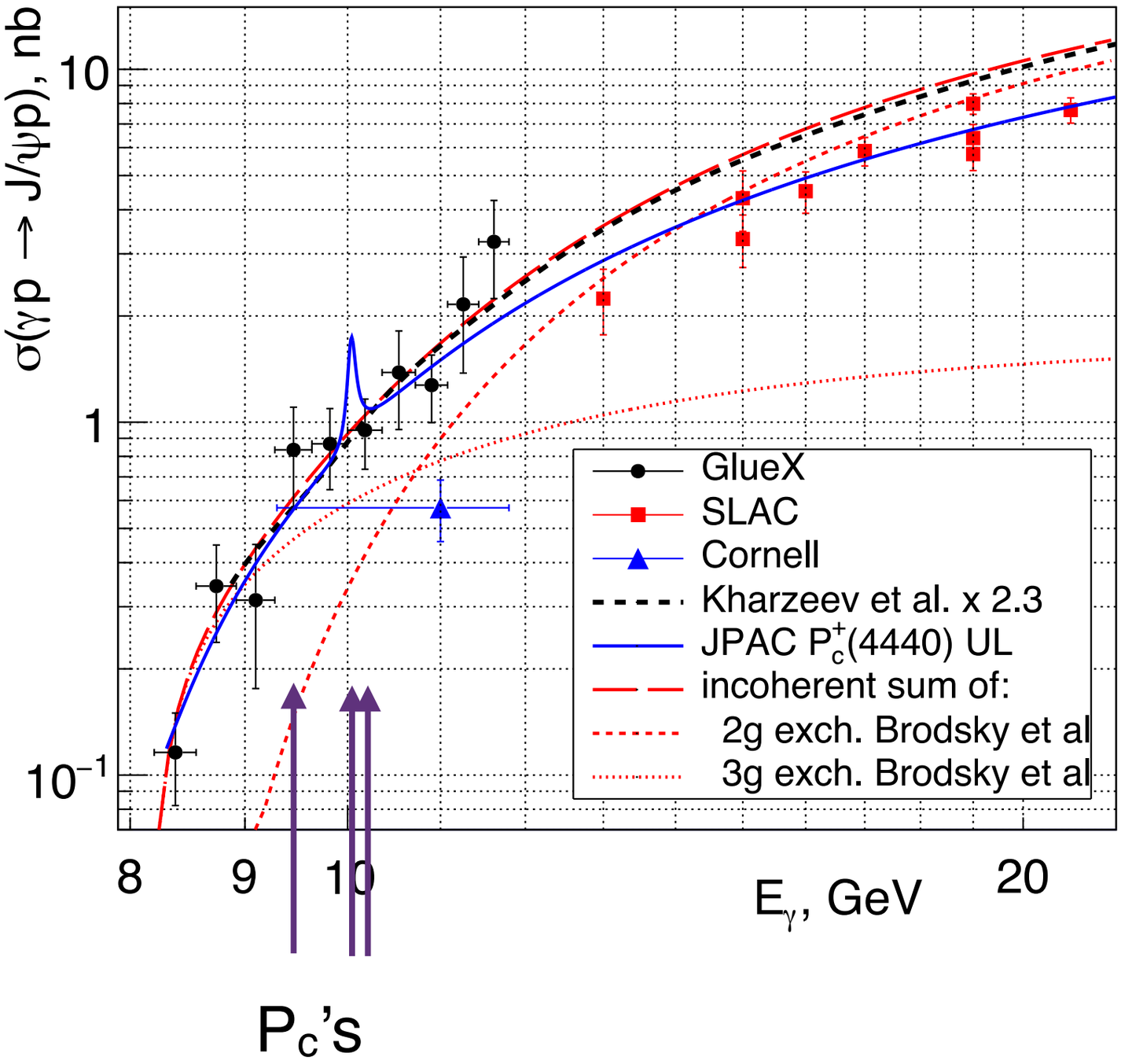
leading-twist

Published GlueX J/ψ Photoproduction Results

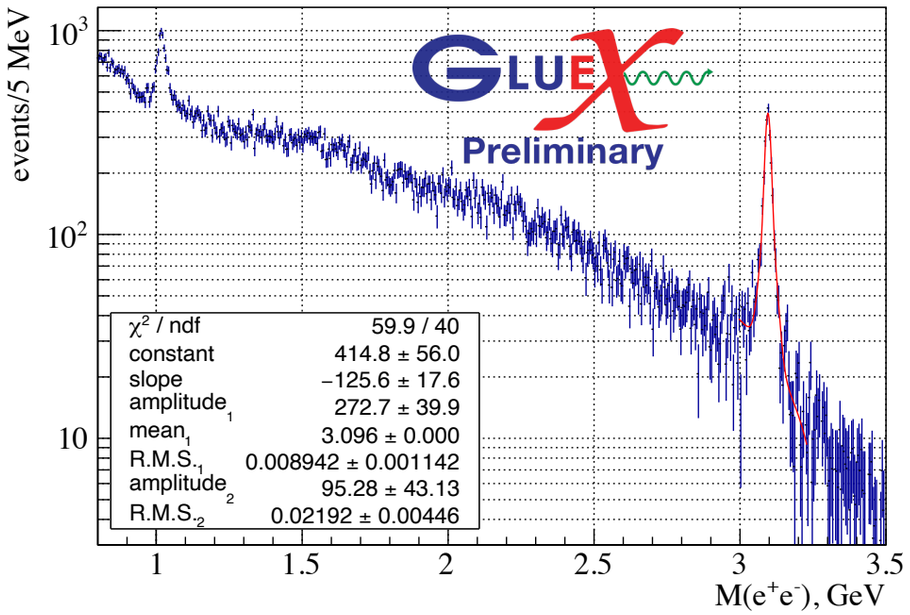


- Used portion of GlueX-I data [469 J/ψ] to measure cross sections
- Model-dependent limits set on P_c production, molecular models preferred
- Limits depend on VMD + understanding of production mechanism

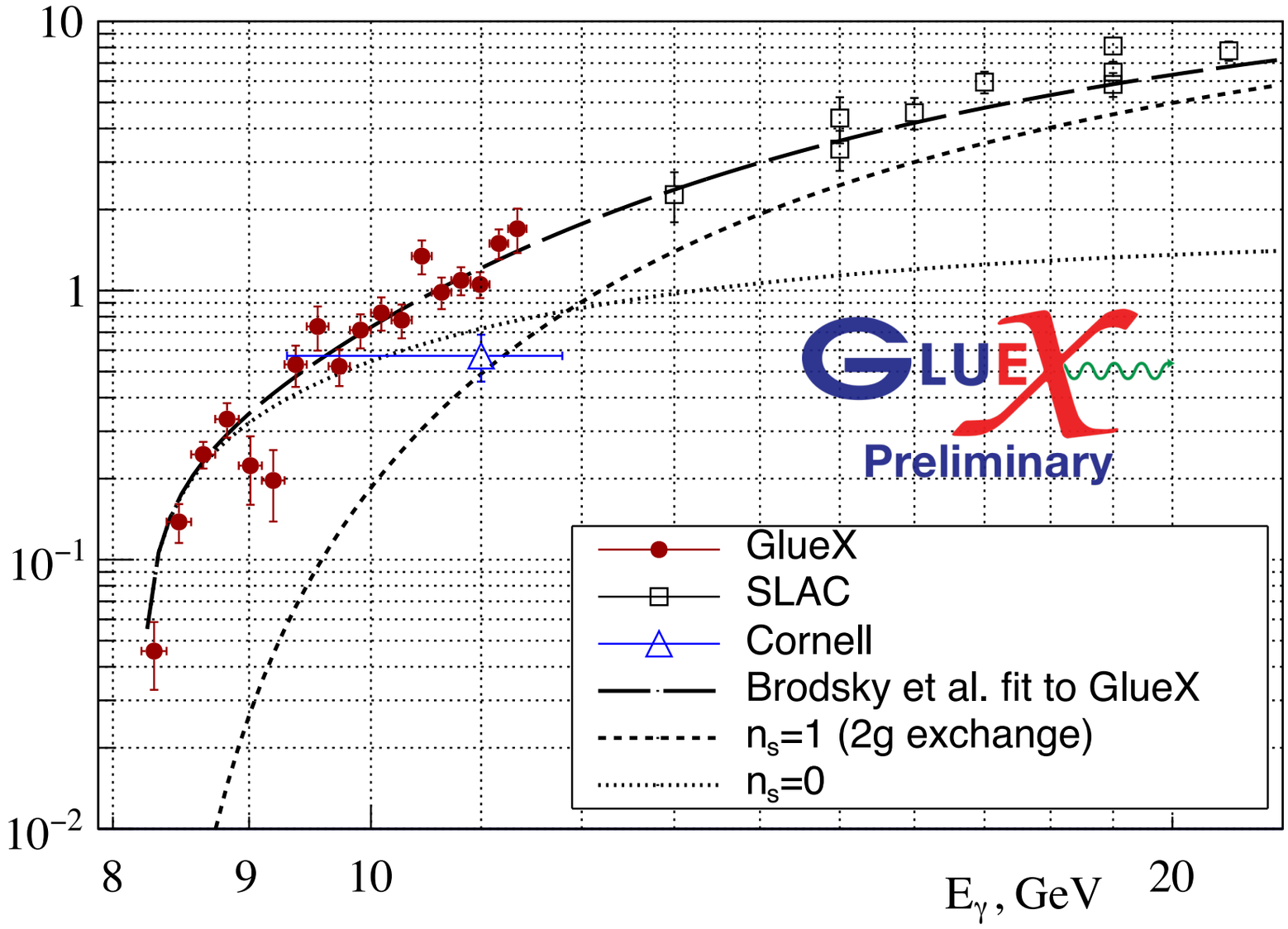
GlueX: PRL 123, 072001 (2019)



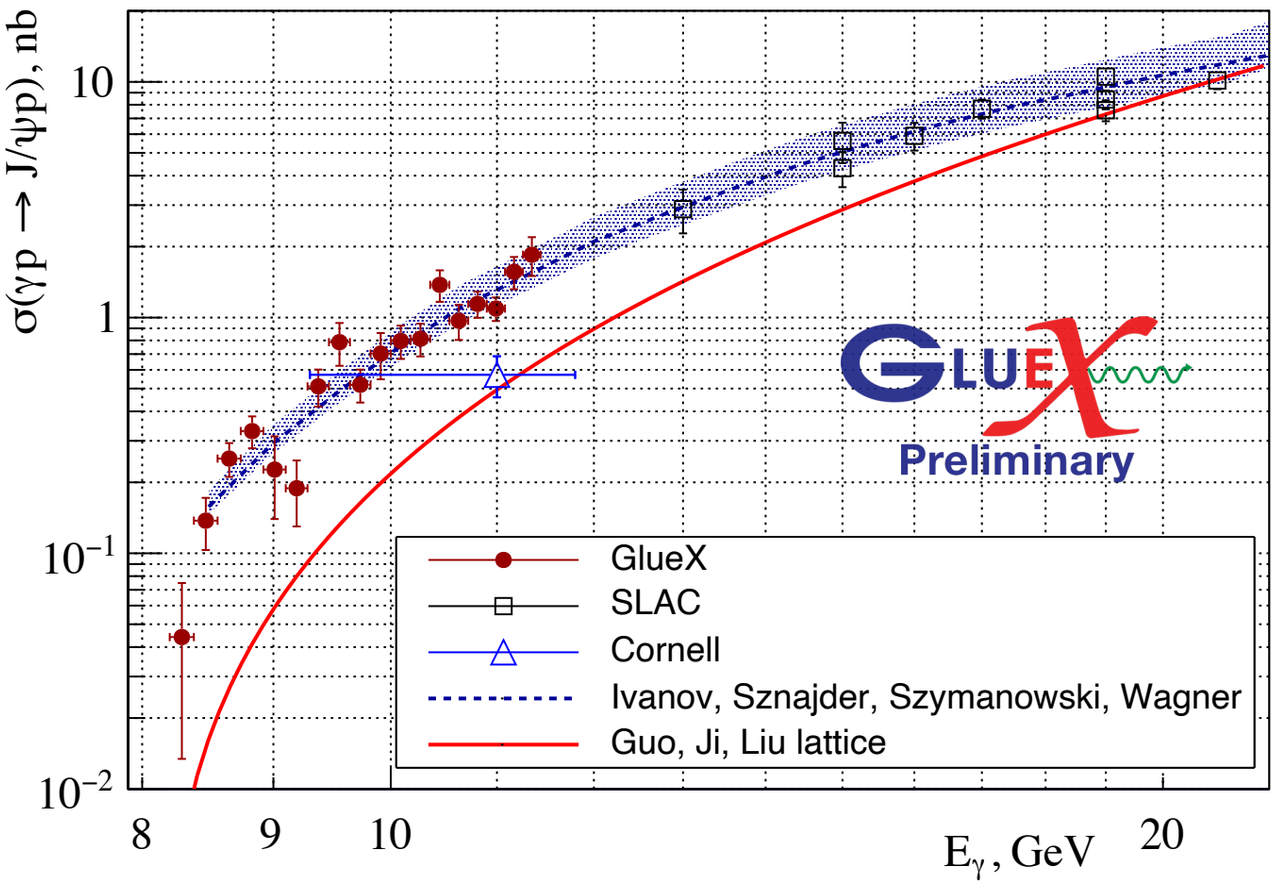
Preliminary GlueX-I J/ψ Photoproduction Results



- 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

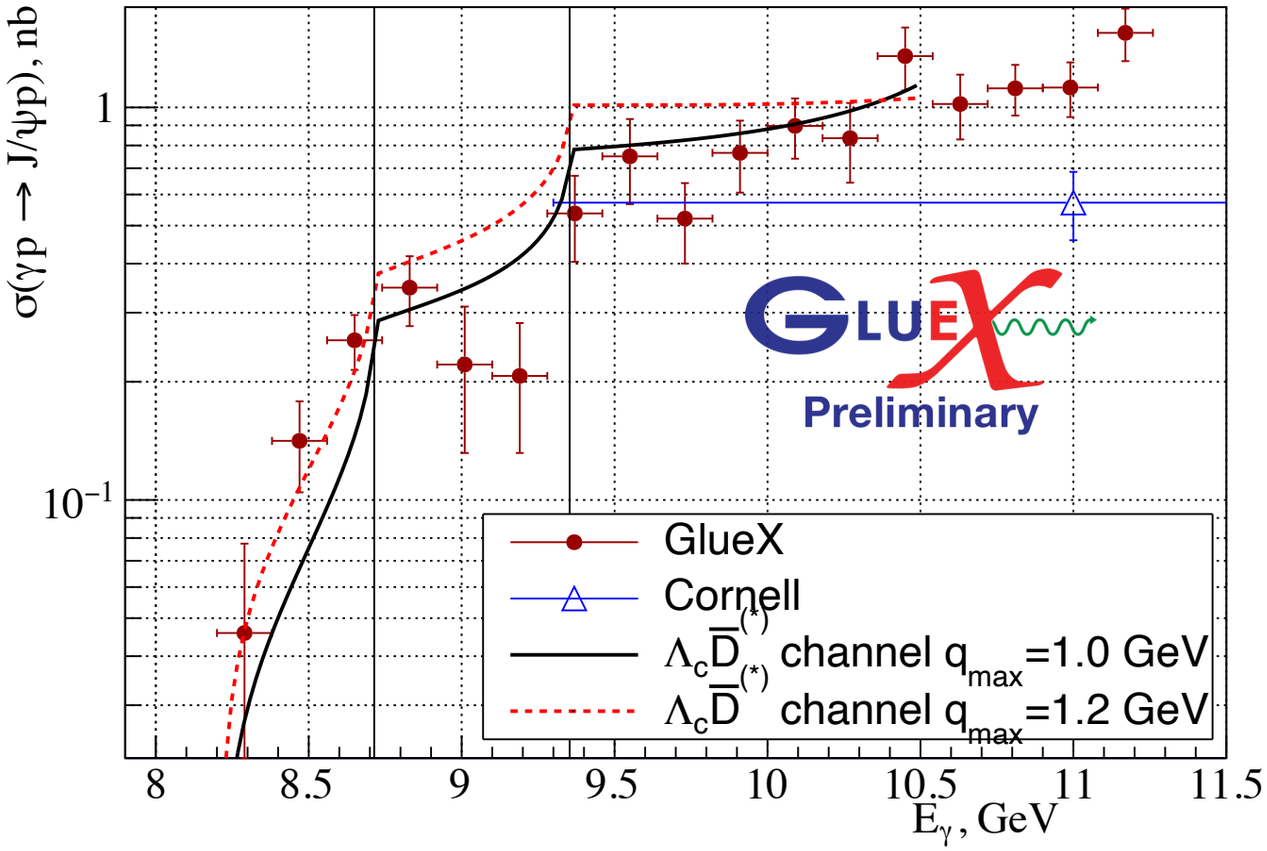


Comparing GlueX-I results to models

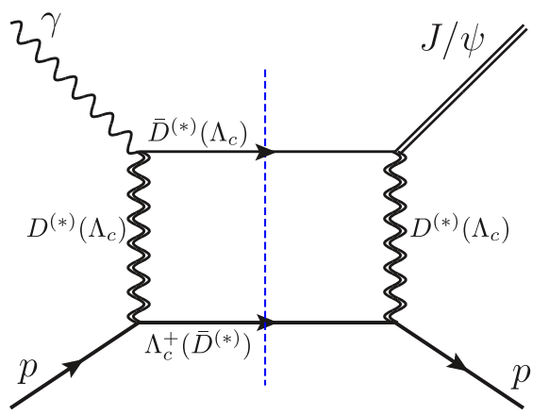


- Models based on gluon exchange and QCD factorization predict smooth energy dependence, connect to gluonic structure of the proton

GLJ: PRD 103, 096010 (2021)
ISSW: EPJC 34, 297 (2004)

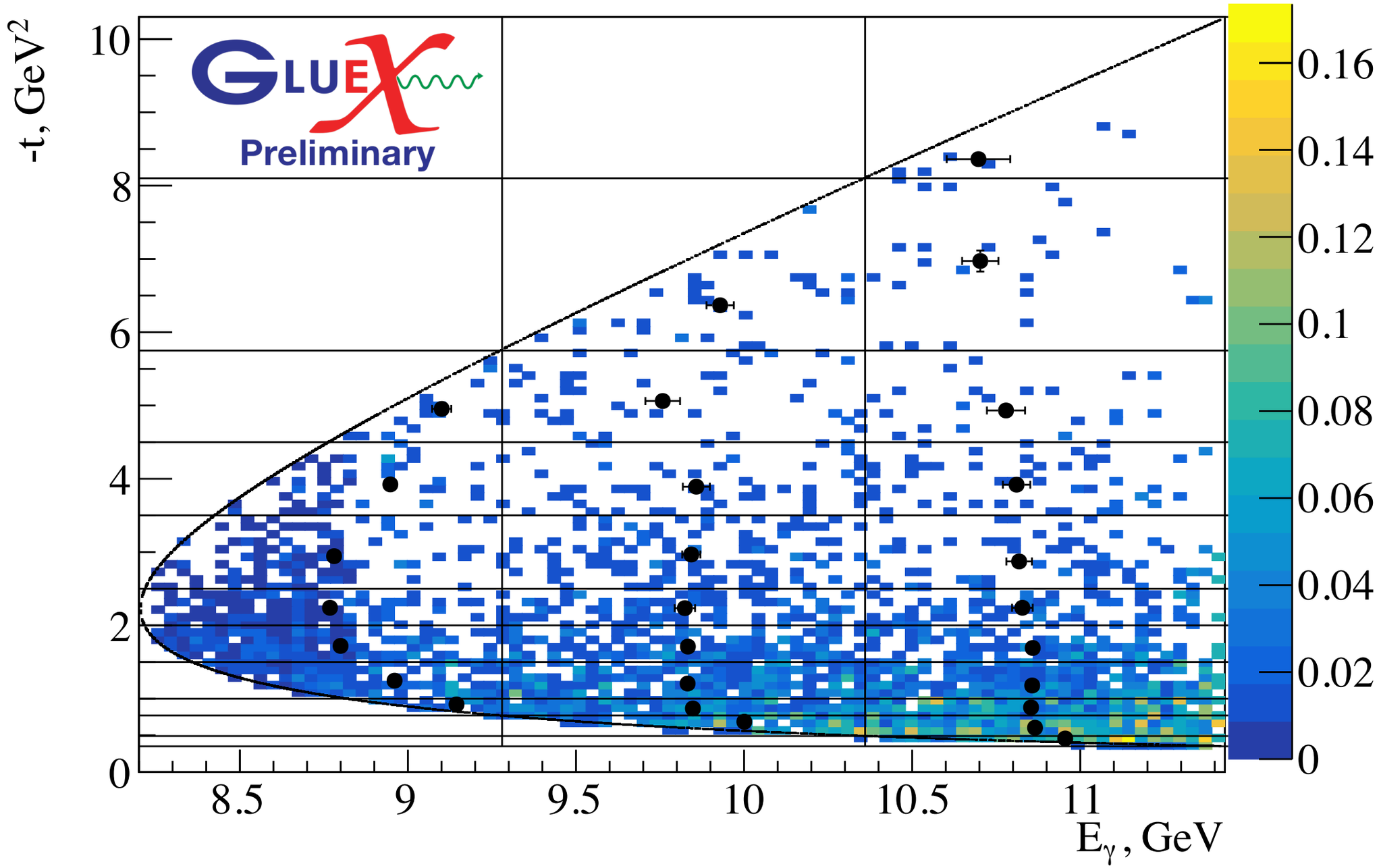


- Models with open-charm exchange predict structures at thresholds, shallow t-dependence



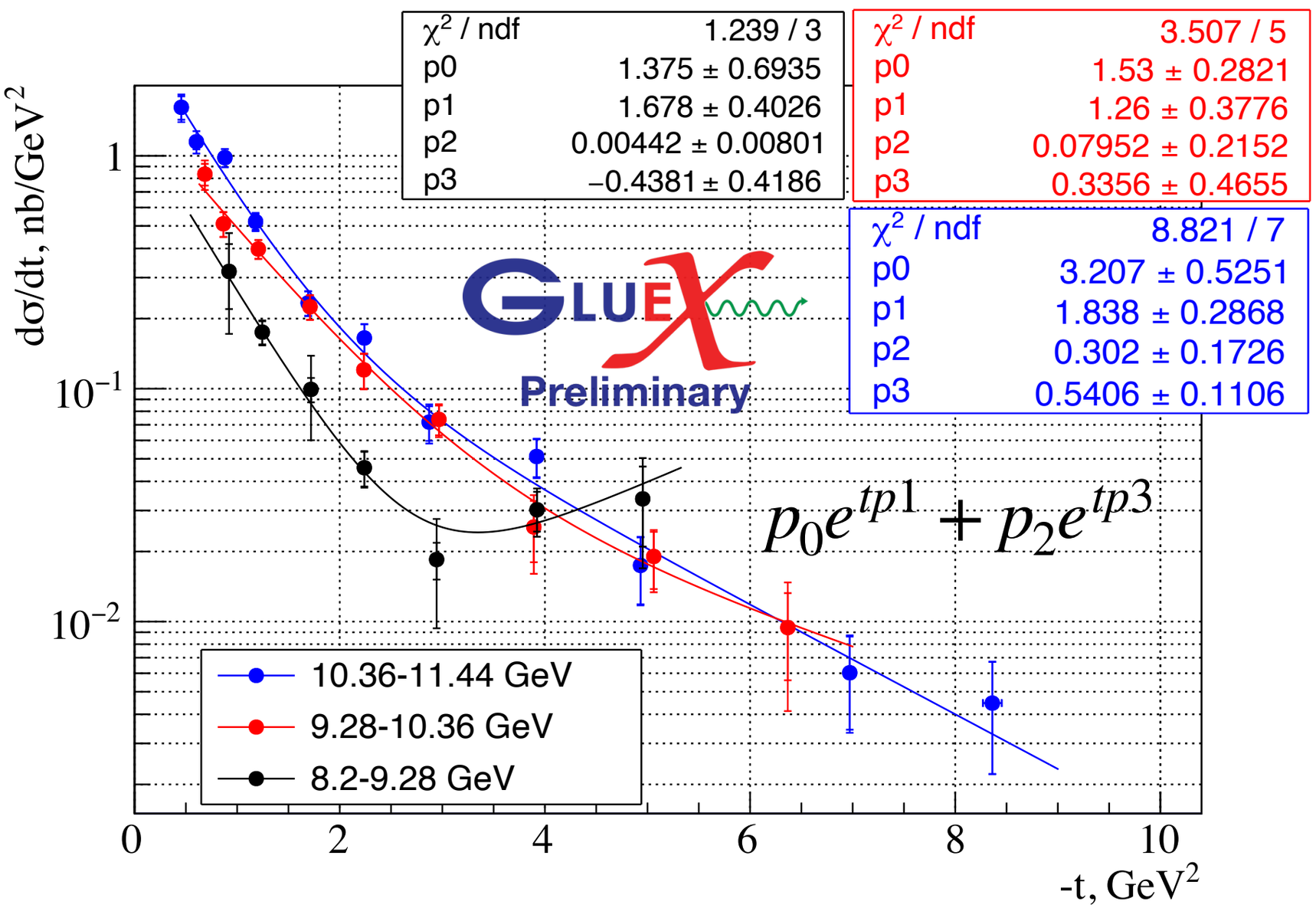
Du et al., EPJC 80, 1053 (2020)

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
- Room for contributions of box diagrams, etc.—affects P_c interpretation

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 π_1 in photoproduction
  - Analysis of $\omega\pi$ focusing on study of b_1 and ρ's
    - Next step: apply techniques to other PS-PS, V-PS final states
- Measurements of hyperons like $\Lambda(1405)$ and Ξ baryons promise to provide insight into their structure
- First detailed studies of J/ψ photoproduction near threshold
- GlueX-II run in progress, planned to end around 2025
  - Other approved experimental programs includes JLab Eta Factory, spectroscopy with intense K_L beam ($\approx 10^4$/s), polarized target

Backup Slides

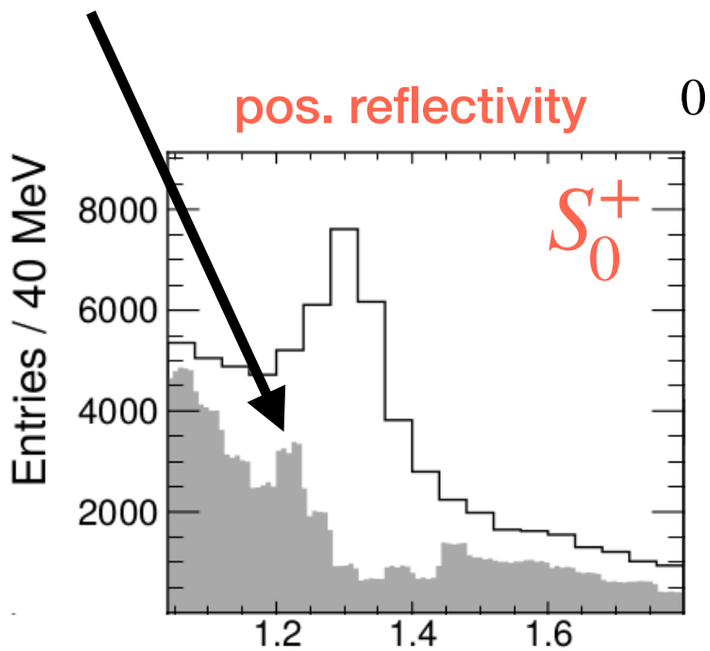
Semi-model independent fit ($\gamma p \to \eta\pi^0 p$)

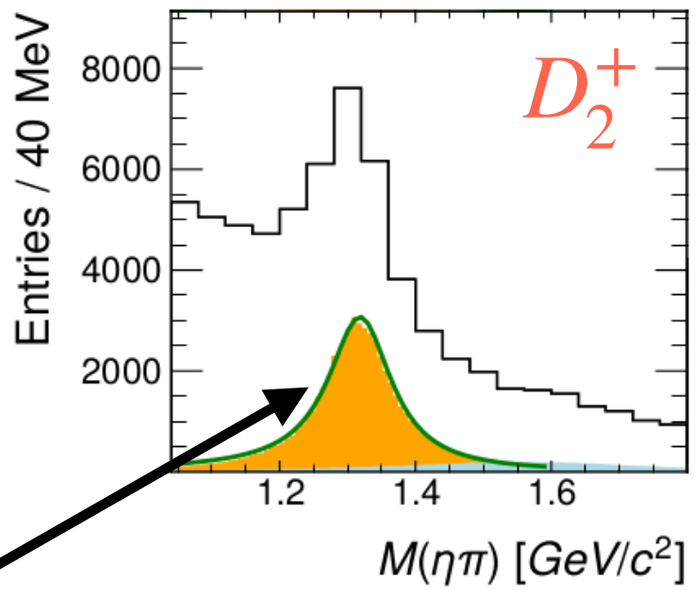
"mass-independent" S-wave

GlueX Preliminary

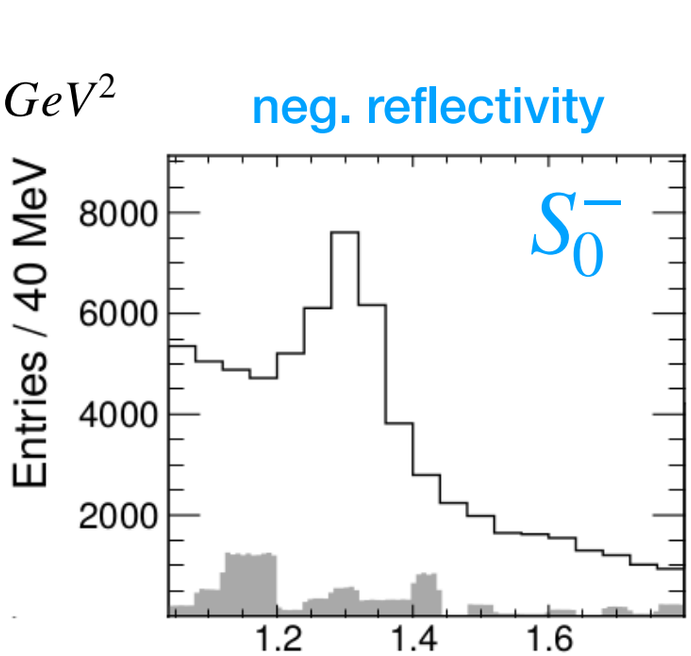
$0.1 < t < 0.2\ GeV^2$

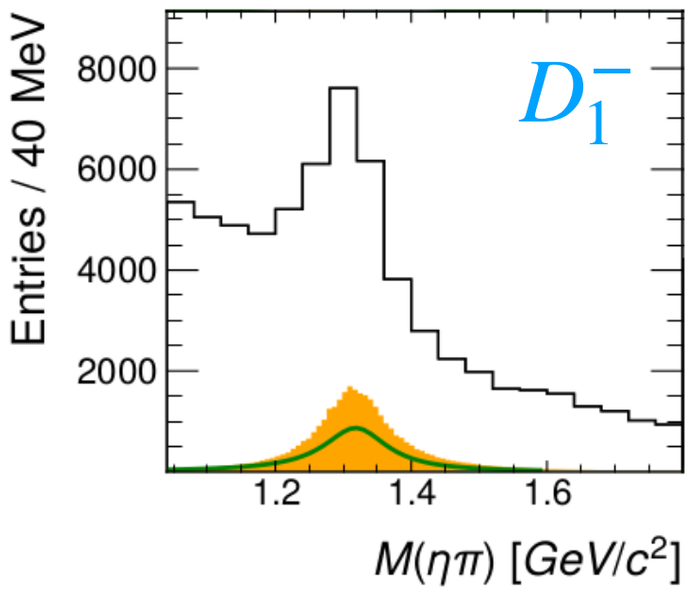
pos. reflectivity





neg. reflectivity

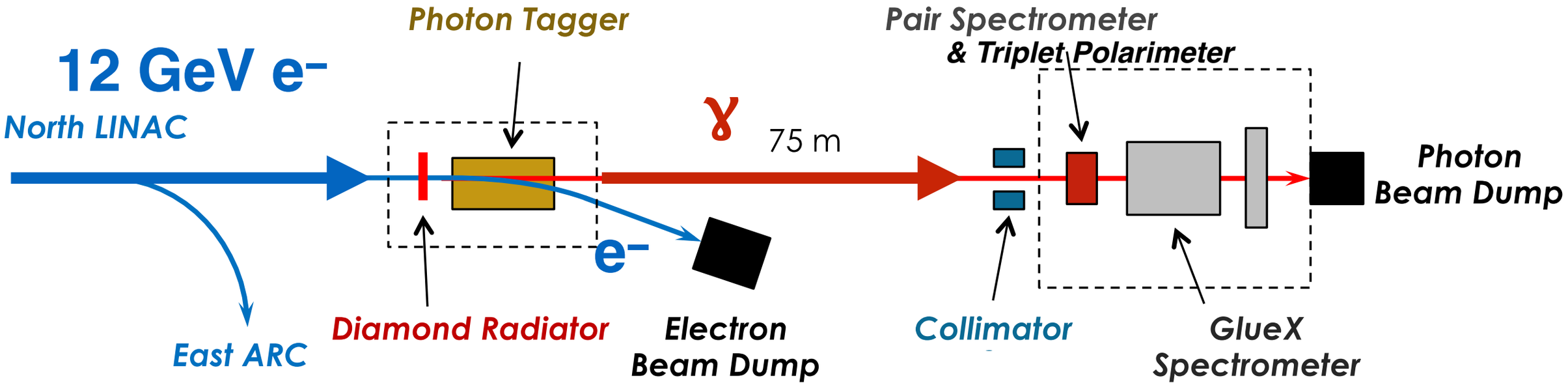




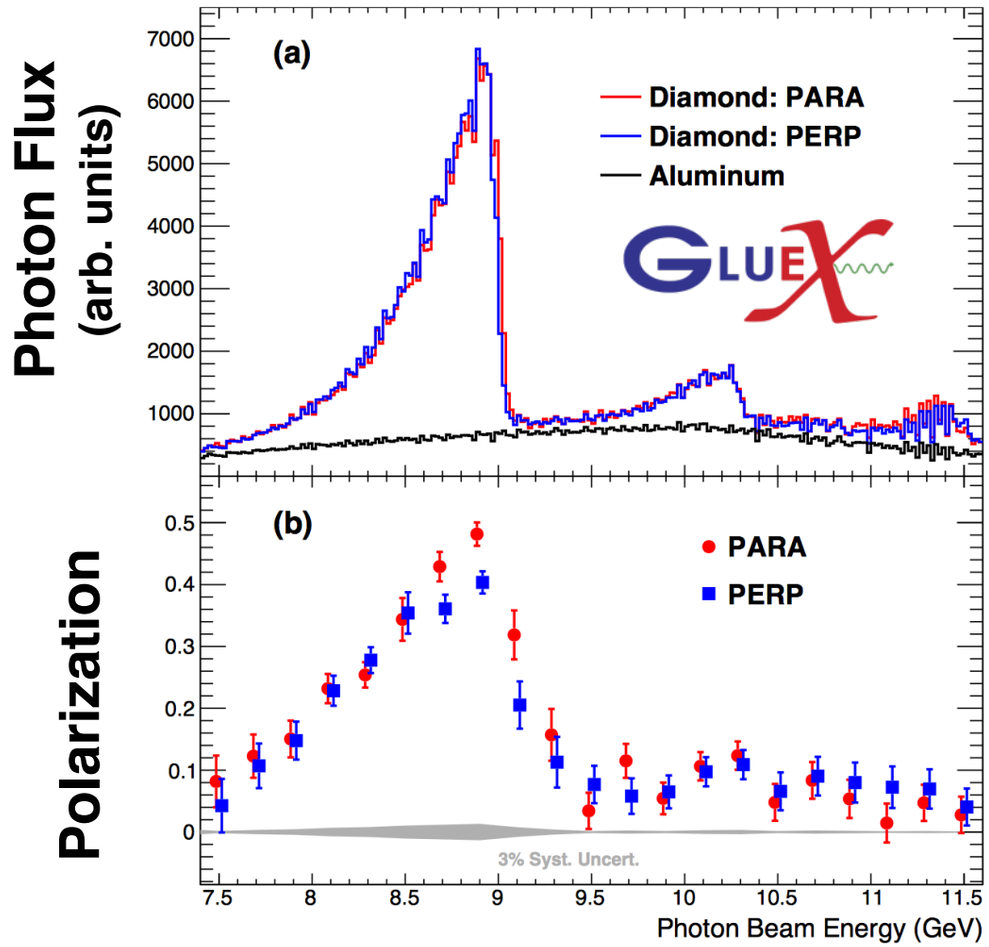
$a_2(1320)$: Breit-Wigner

M.Albrecht (JLUO 2022)

The GlueX Experiment: Photon Beam



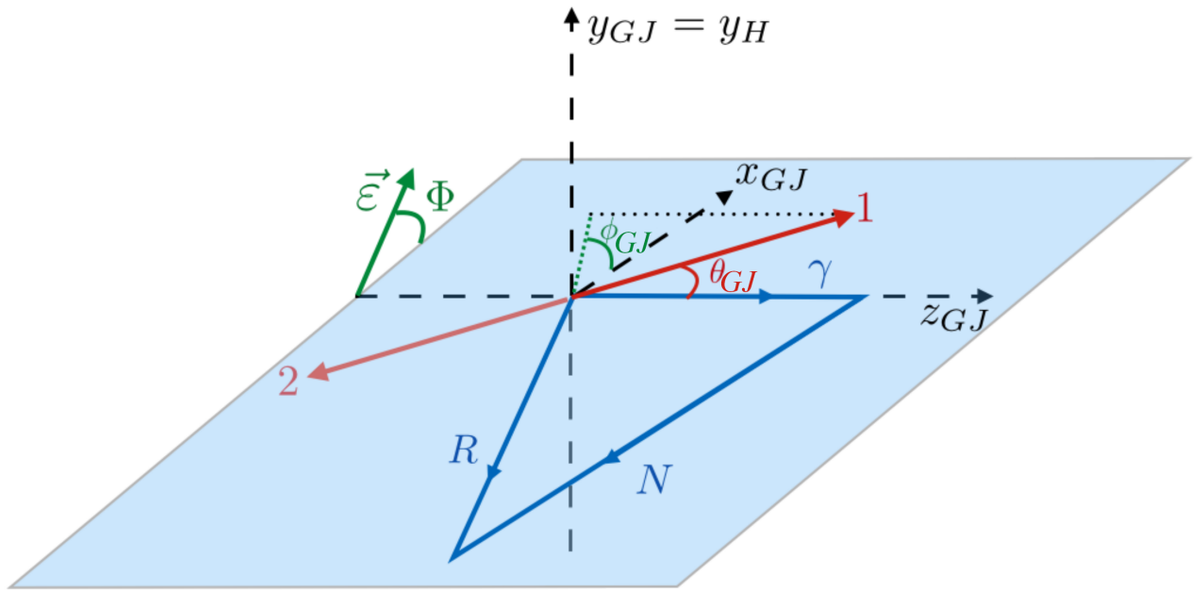
- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of ~1–5 $\times$ 10^7 γ/s in peak



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

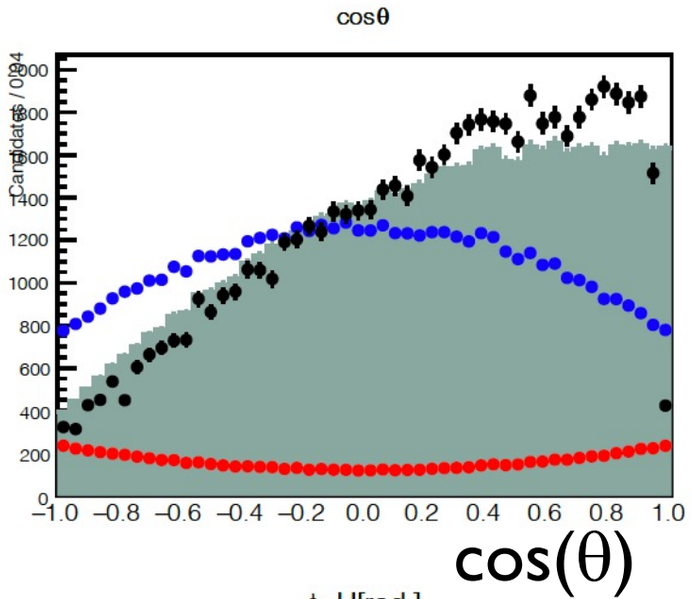
GlueX Data

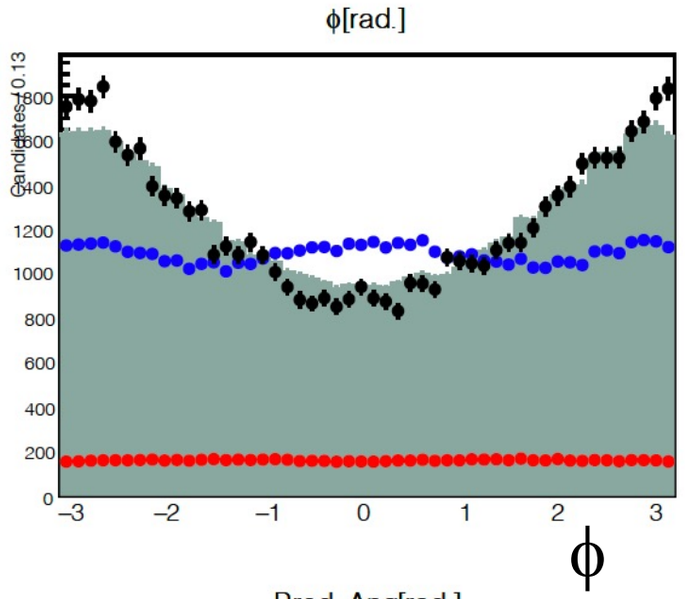
Fit Results

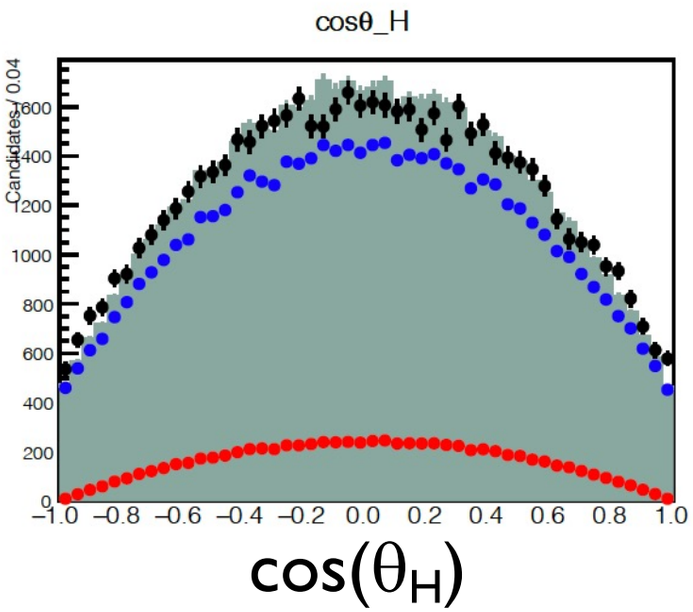
b_1 $[1^+]^{(\pm)}$ (S+D)

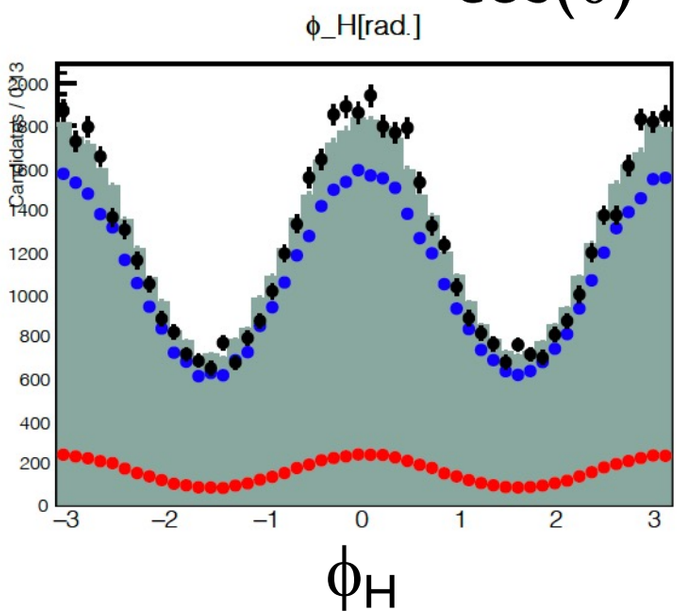
ρ $[1^-]^{(\pm)}$ P

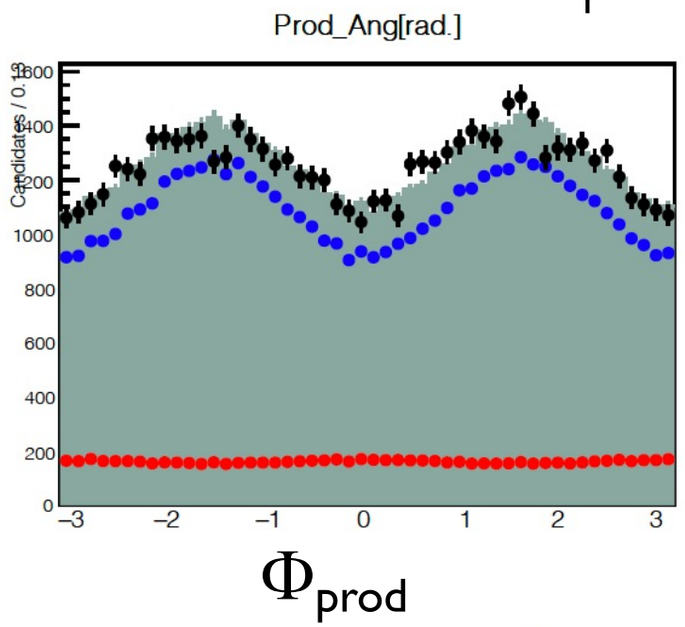
GlueX Preliminary









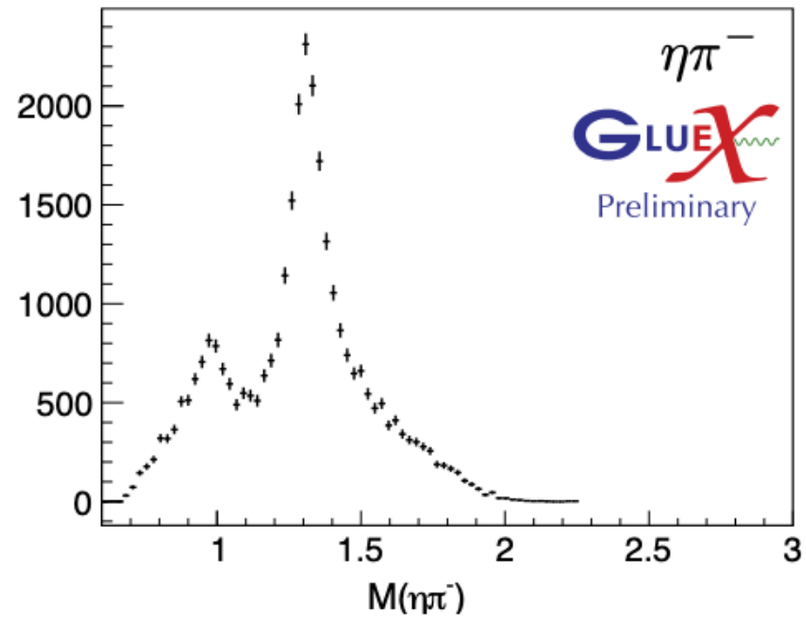


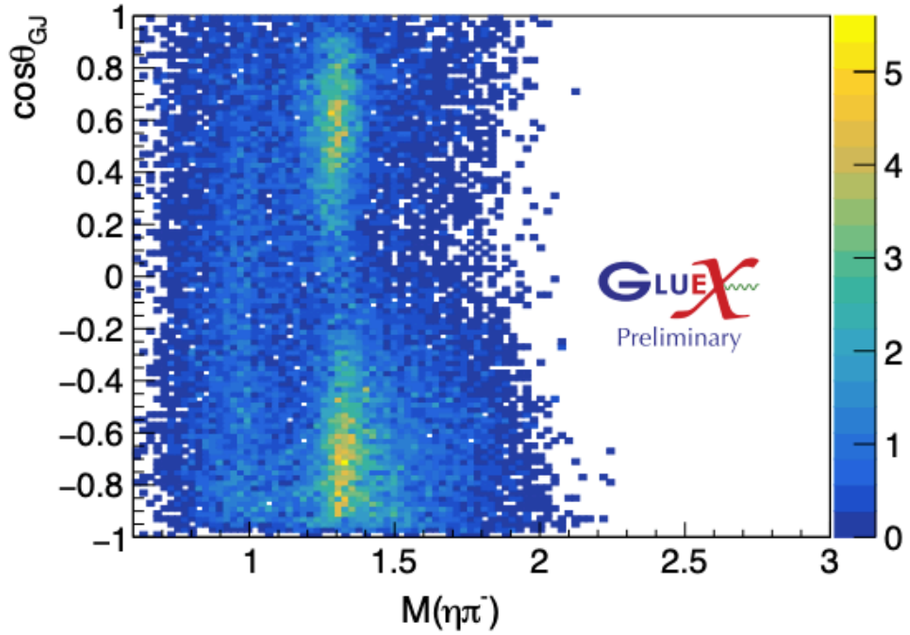
- Independent fits for each beam polarization orientation
- Inclusion of 1^- and 1^+ waves leads to good description of angular distributions

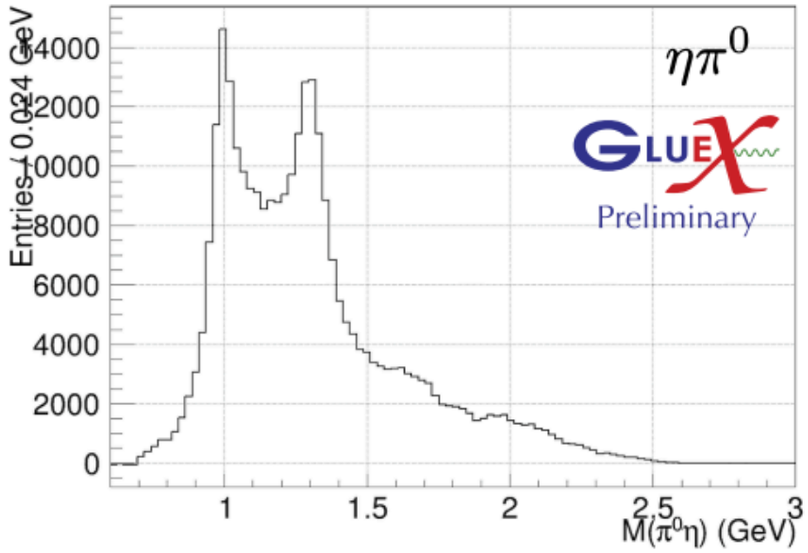
ηπ Amplitude Analysis at GlueX

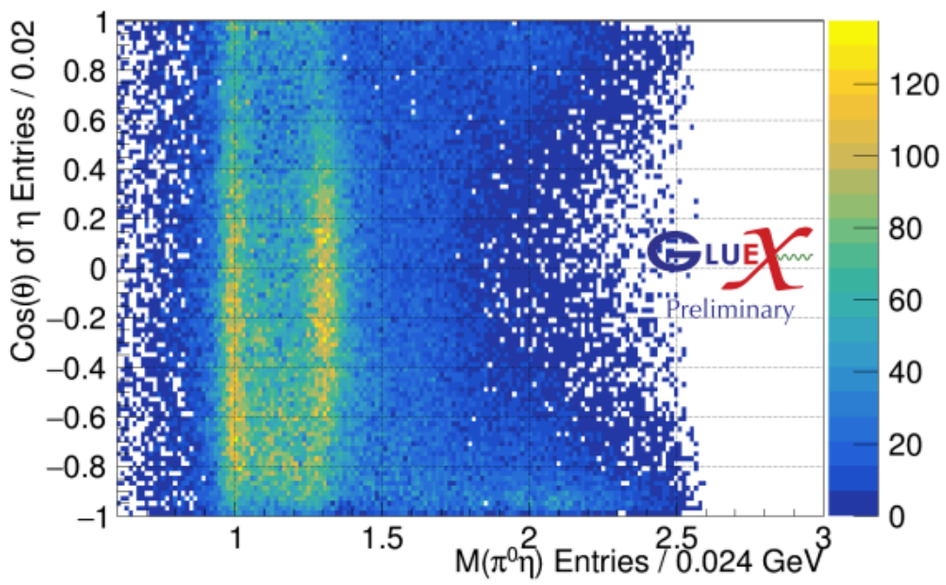
- Clear signals at $a_0(980)$ and $a_2(1320)$ masses
- Different angular dependence → different dominant production wave
  - D_1 for $\eta\pi^-$, D_2 for $\eta\pi^0$

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





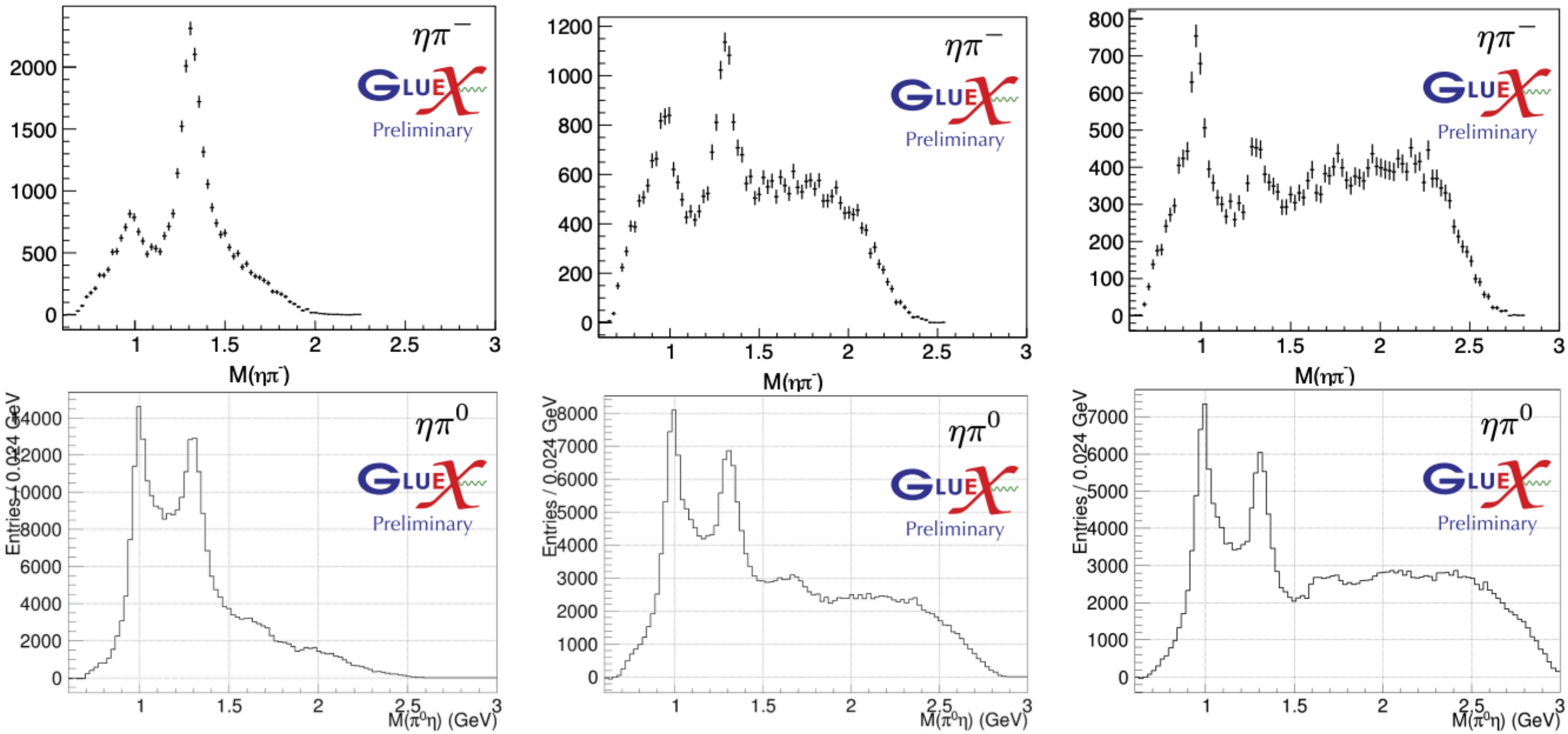




ηπ Amplitude Analysis at GlueX

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

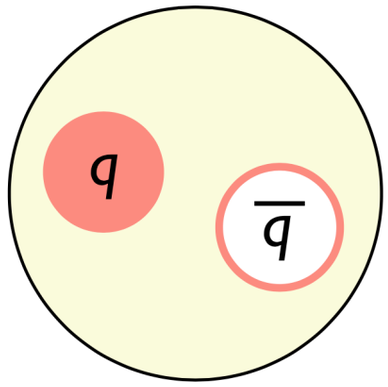
$0.1 < -t < 0.3$ GeV^2 | $0.3 < -t < 0.6$ GeV^2 | $0.6 < -t < 1.0$ GeV^2



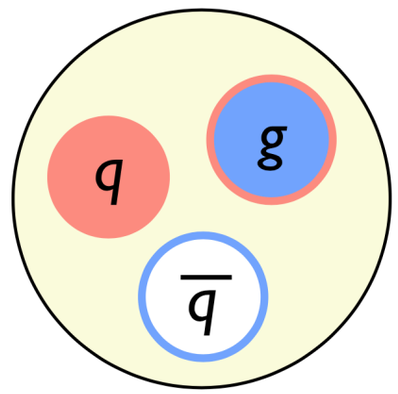
Searching For Hybrid Mesons

- 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



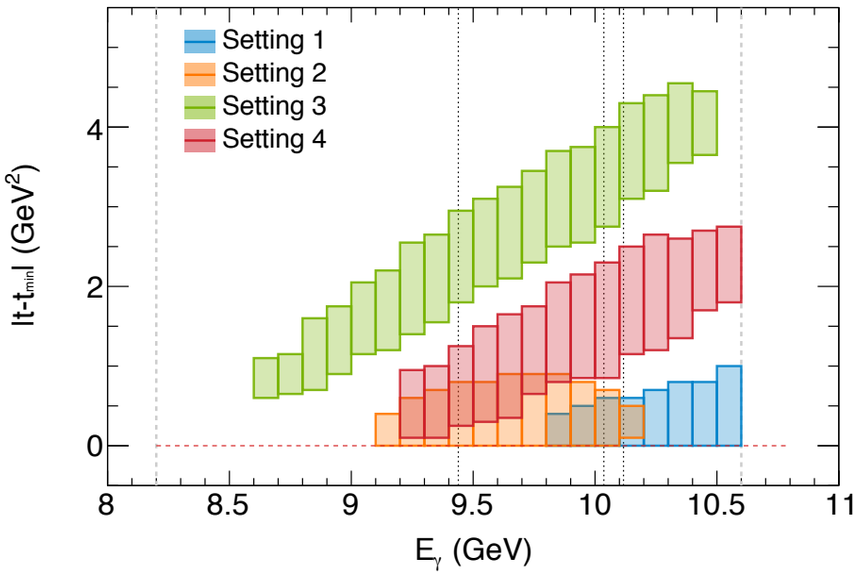
$(J^{PC})_g = 1^{+-}$

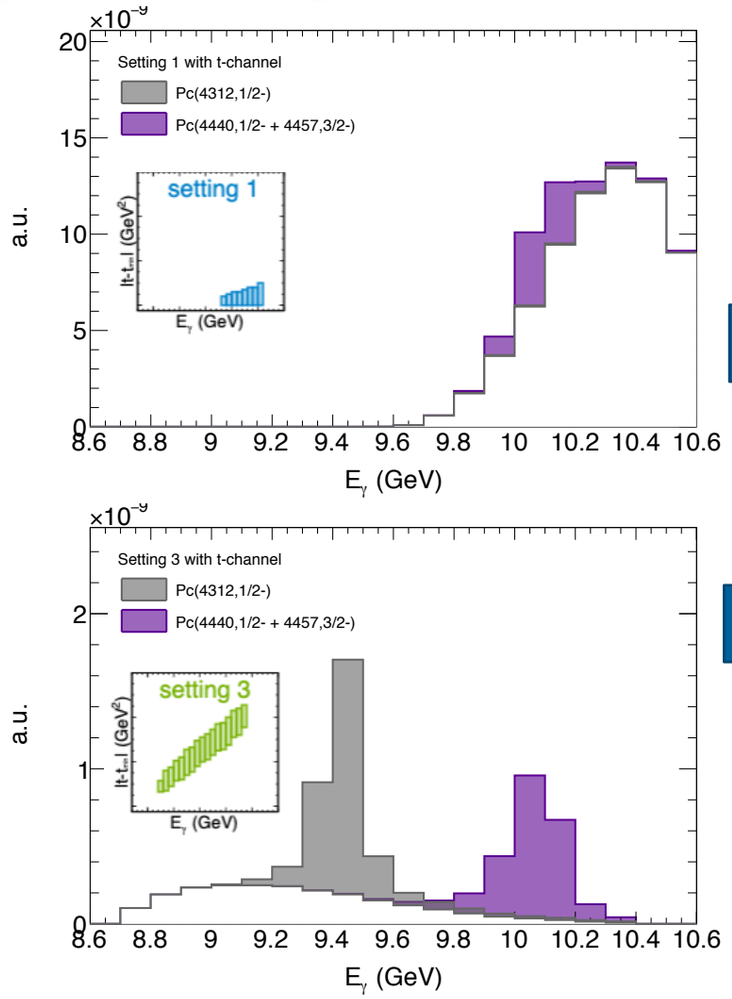
"Hybrid" Meson

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

HIGH-T SETTINGS CRUCIAL FOR SENSITIVITY

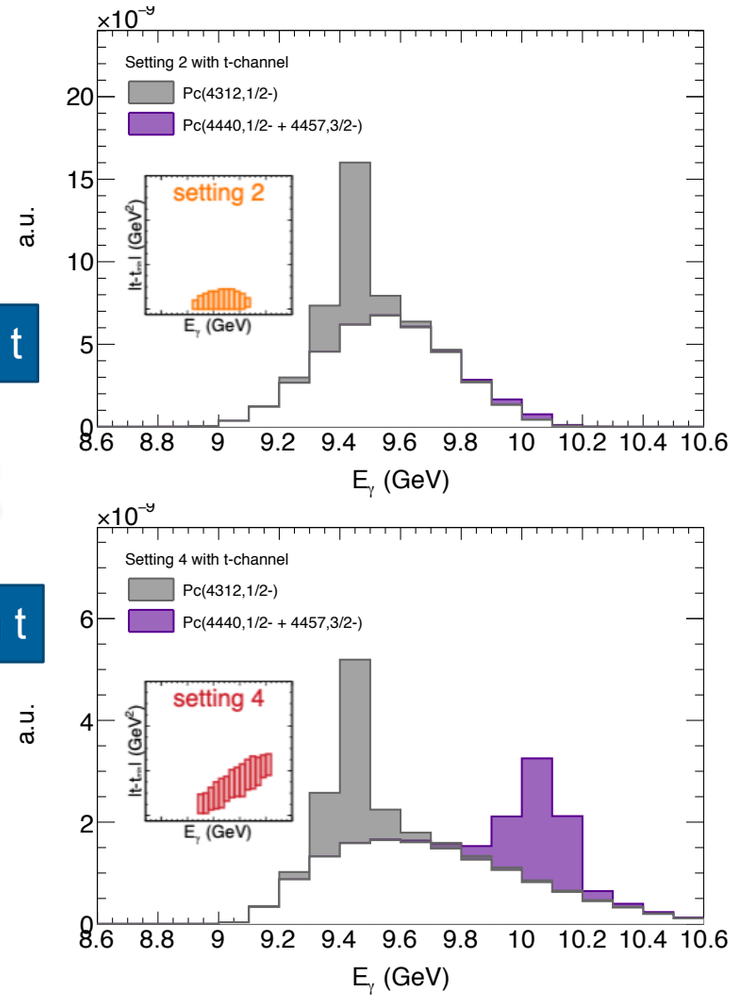
Improved sensitivity at high t for a given coupling





Low t

High t



4% scale uncertainty on cross section

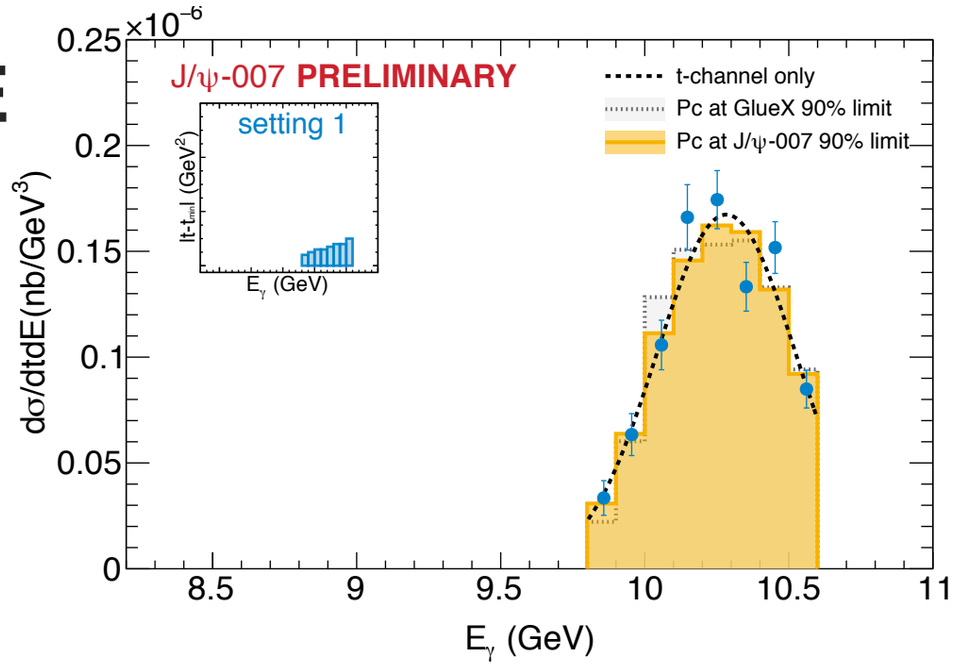
SIGNIFICANCE FIT

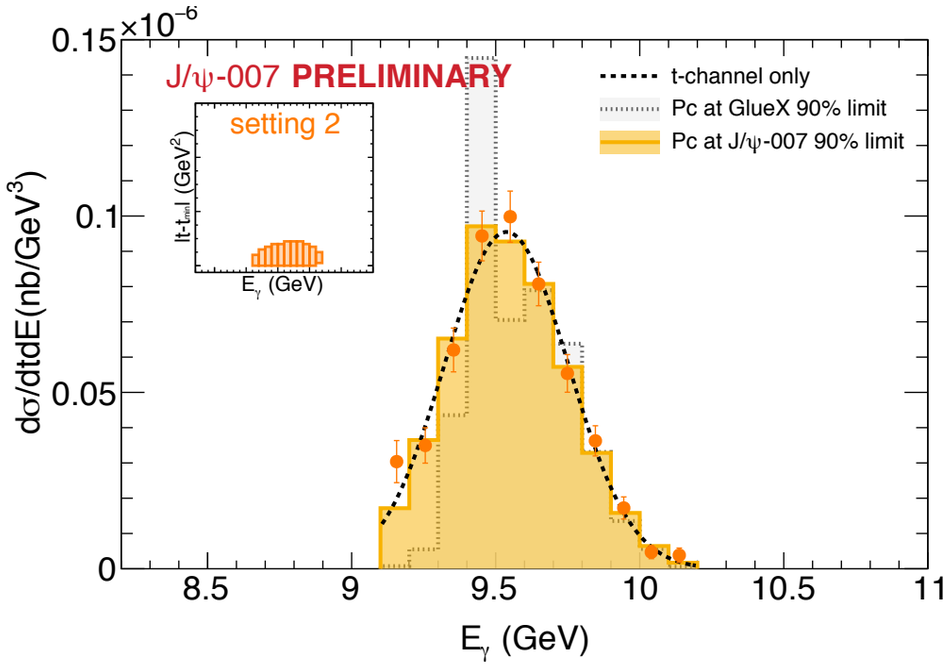
Fit 1: bare Gaussian shape describes the cross section well

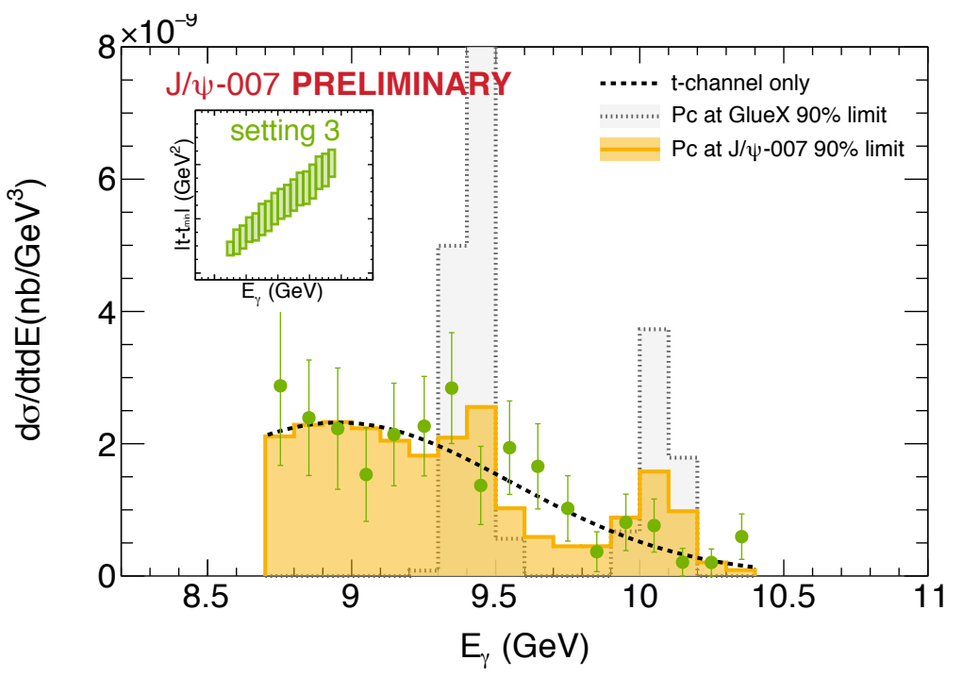
Fit 2: Signal + background at GlueX upper limit (90% confidence interval). The resonances lead to major tension with the data at high-t.

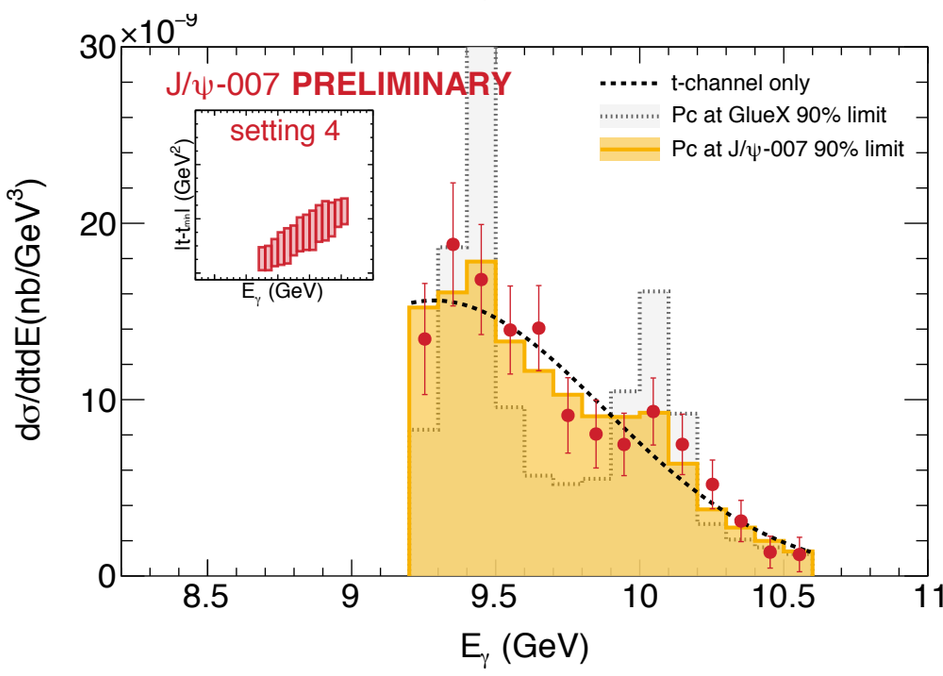
Fit 3: Same as 2, but with Pc at upper limit (90% confidence interval) from the preliminary J/ψ-007 results themselves

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

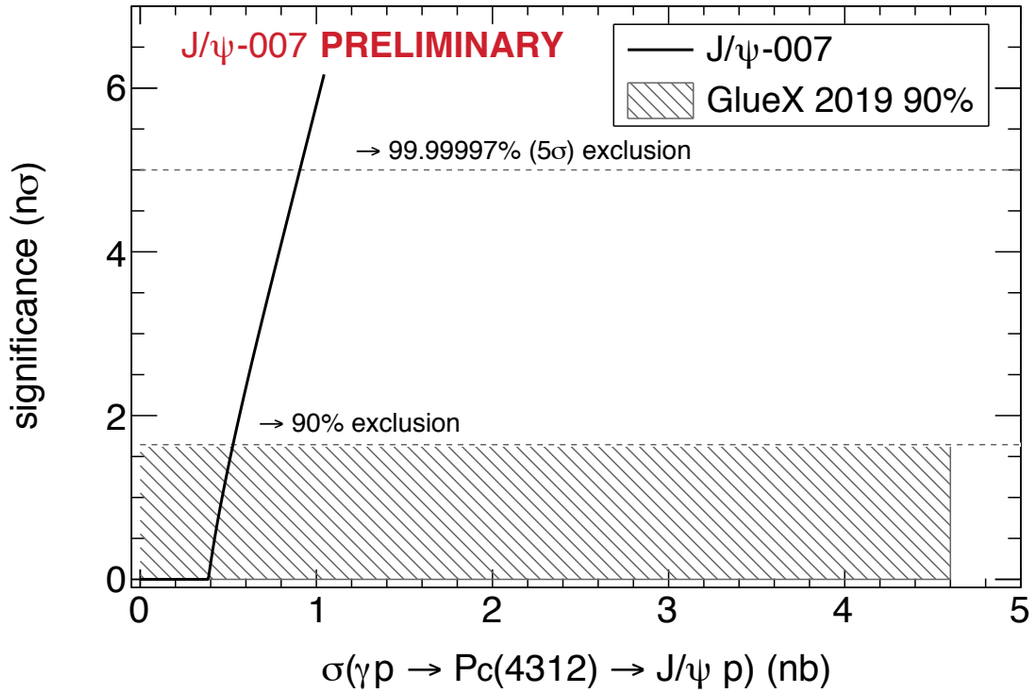
Cross-section at the resonance peak for model-independent upper limits

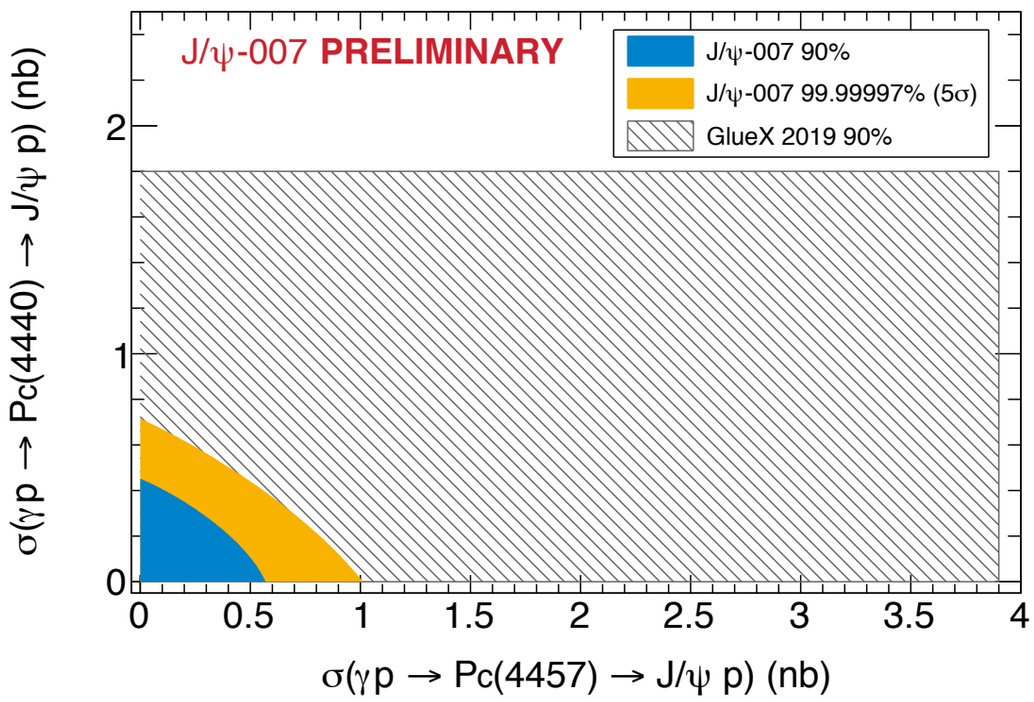
Upper limit for P_c cross section almost order of magnitude below GlueX limit.

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

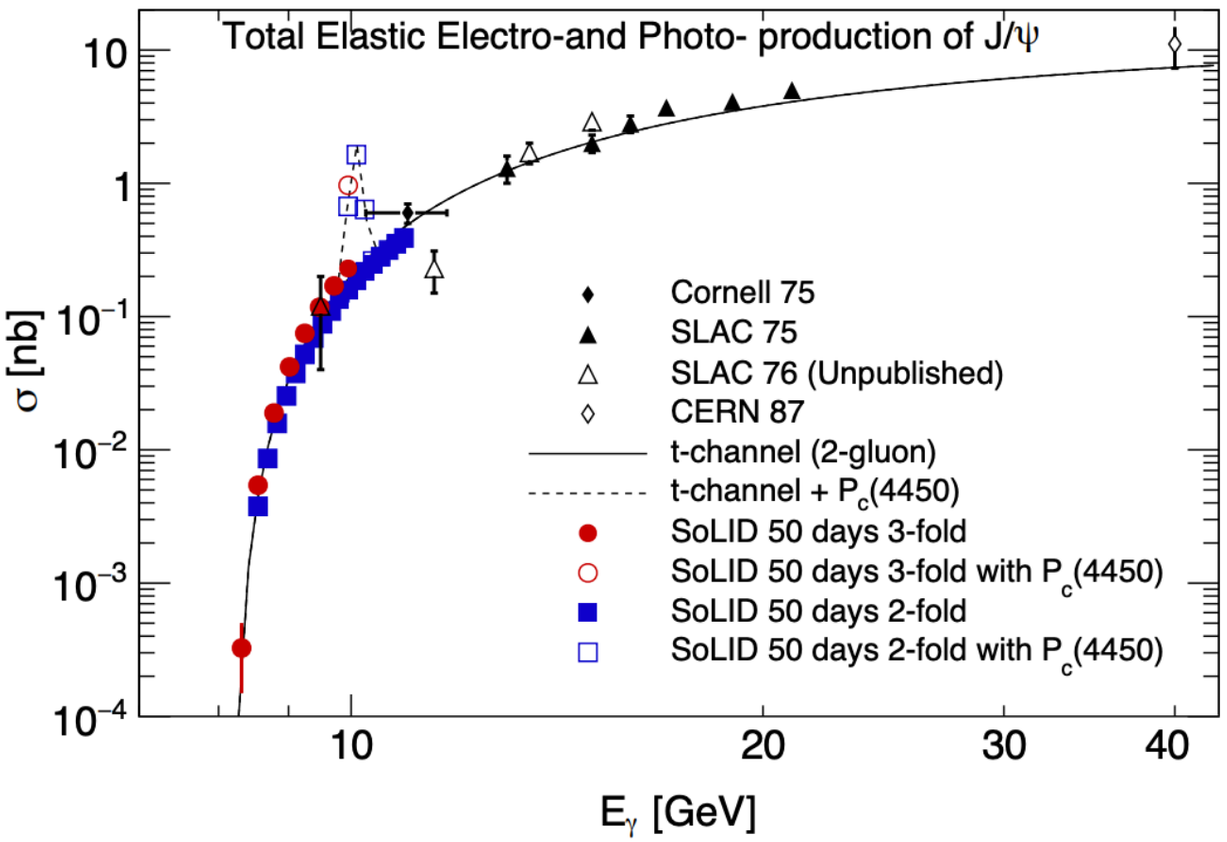
Door is still open for molecular states, but will be very hard to measure in photoproduction due to small overlap with both γp initial state and J/ψp final state.

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**

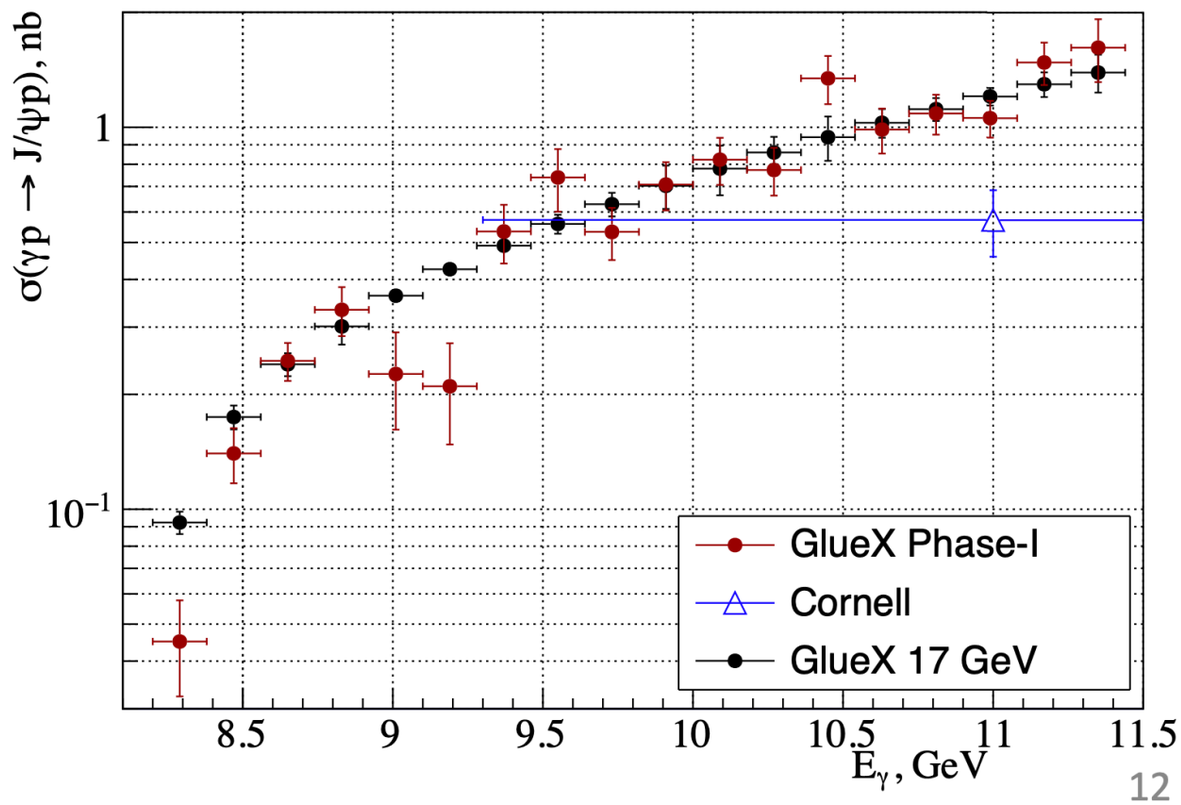




Prospects for future J/ψ production measurements



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



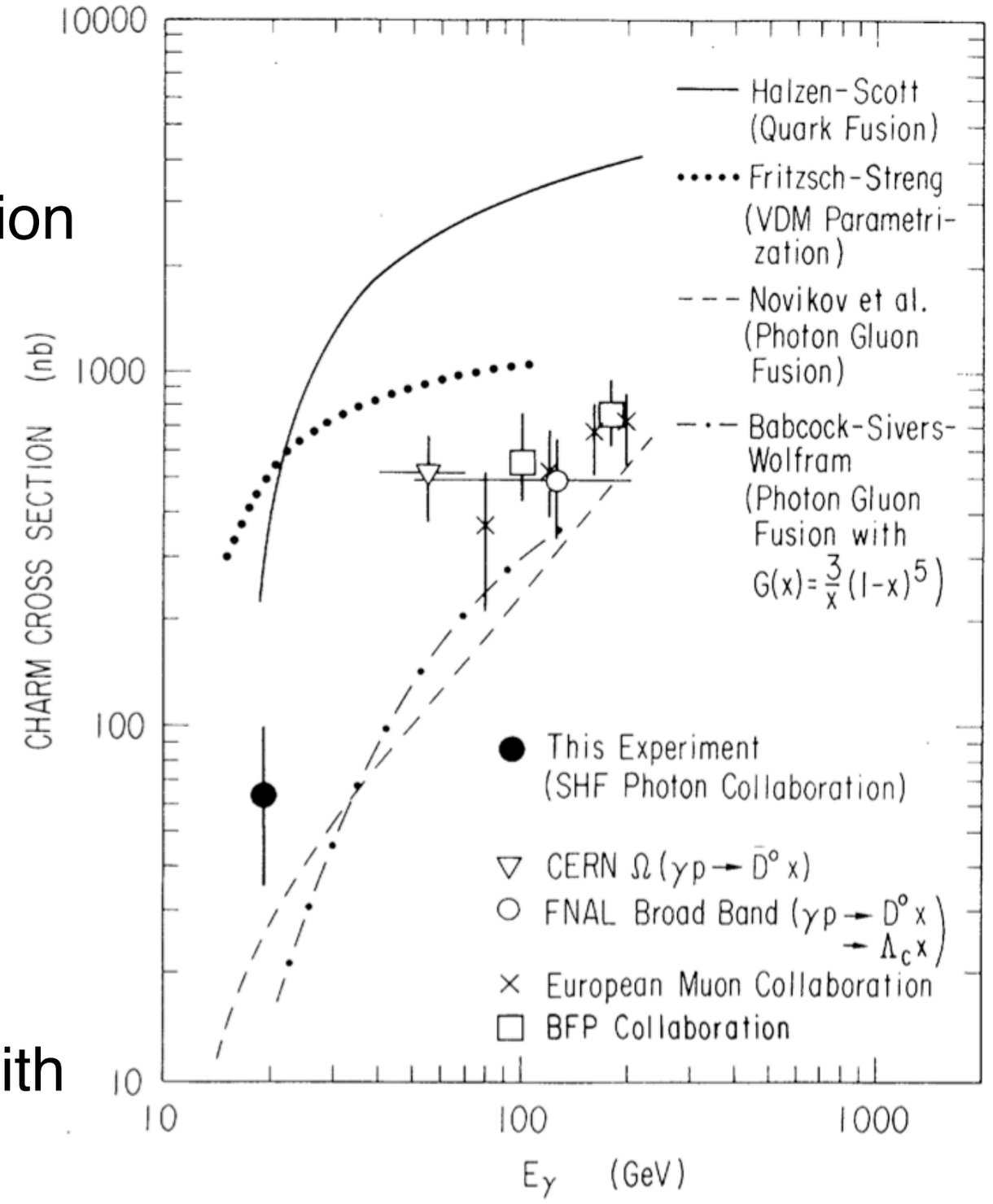
L. Pentchev, J/ψ + Beyond Workshop

- 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

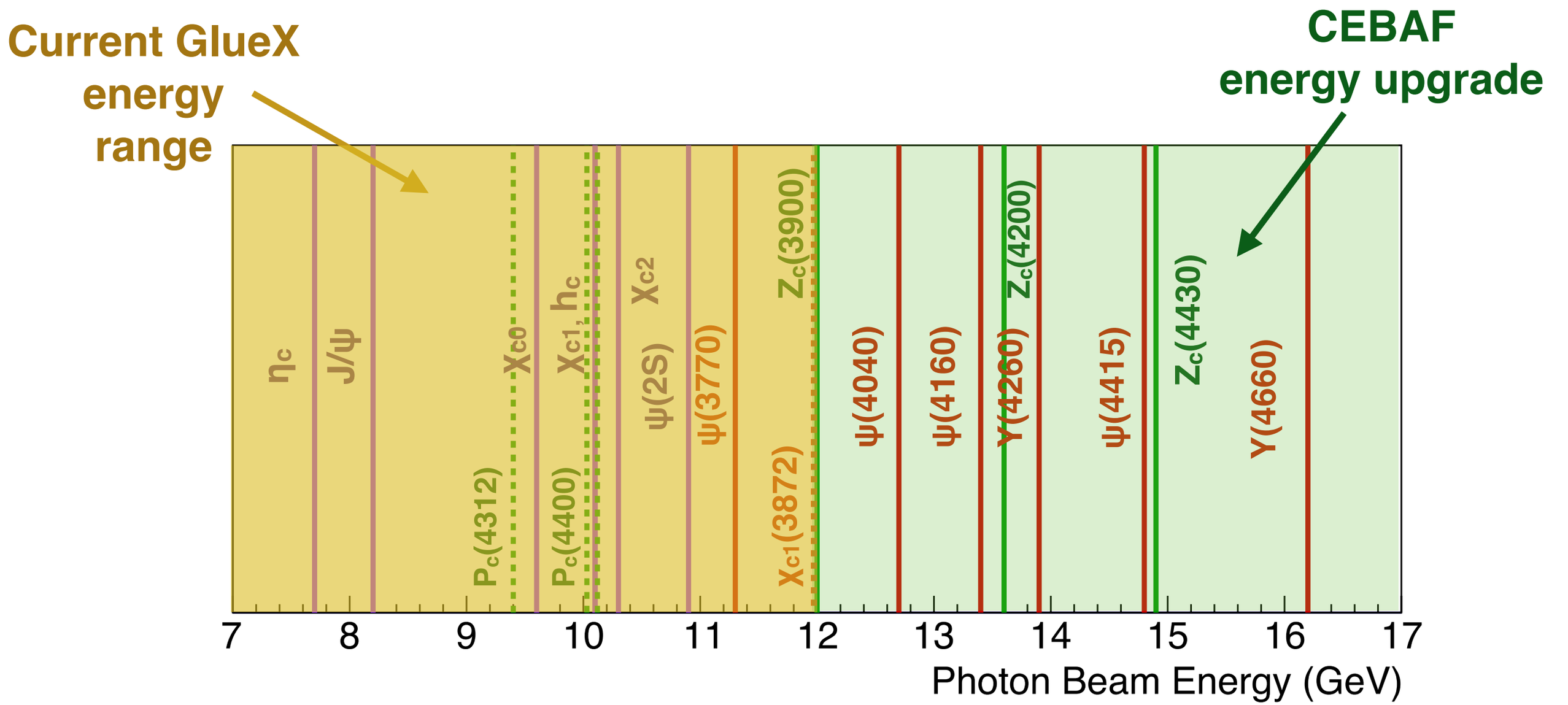
Open Charm Production Near Threshold

- 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)

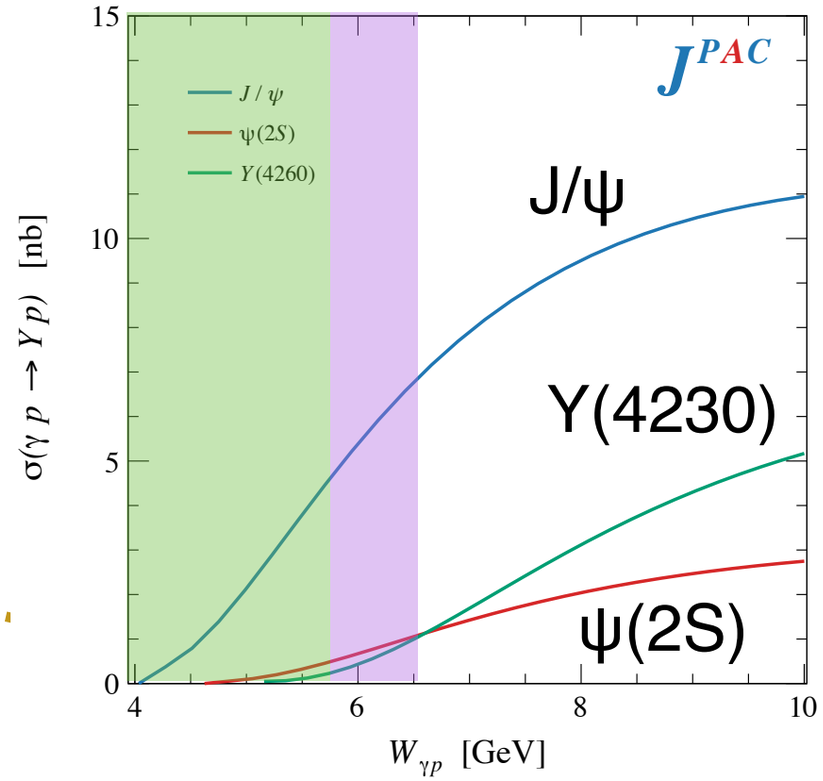


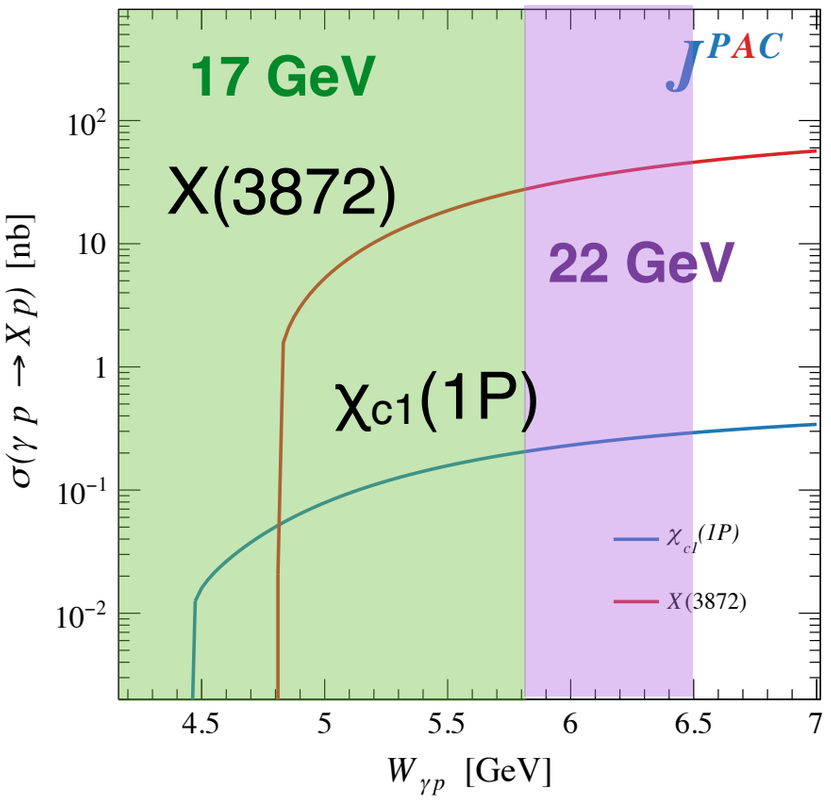
Charmonium Photoproduction Near Threshold

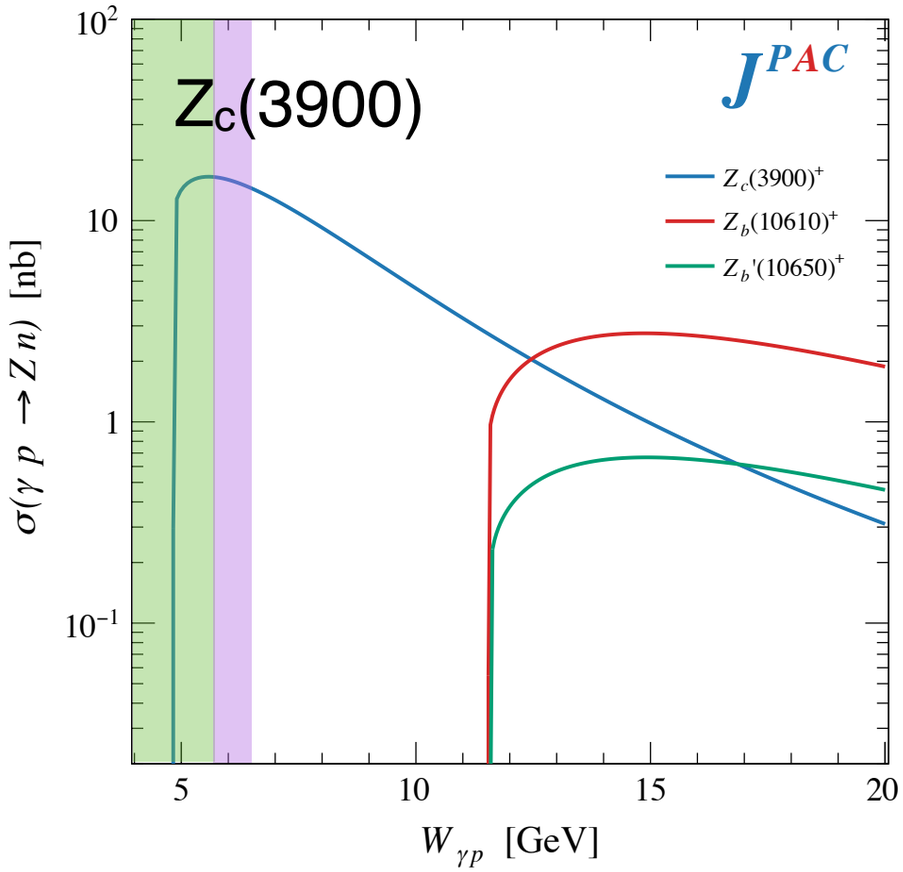


- Current max CEBAF energy allows study of bound $c\bar{c}$, P_c states
- 17 GeV e^- gives access to most exotic candidates
- 22 GeV e- gives good phasespace, linear polarization

JPAC Cross Section Predictions



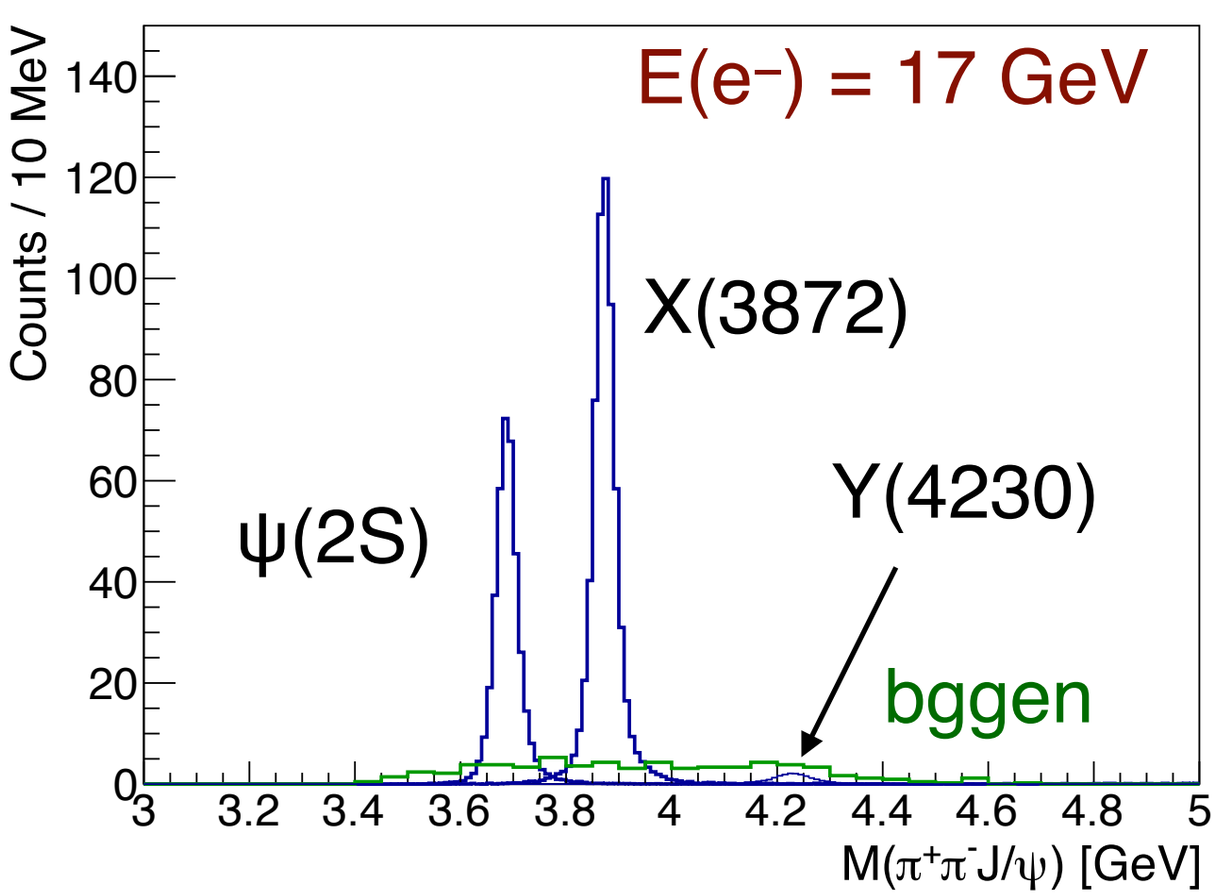


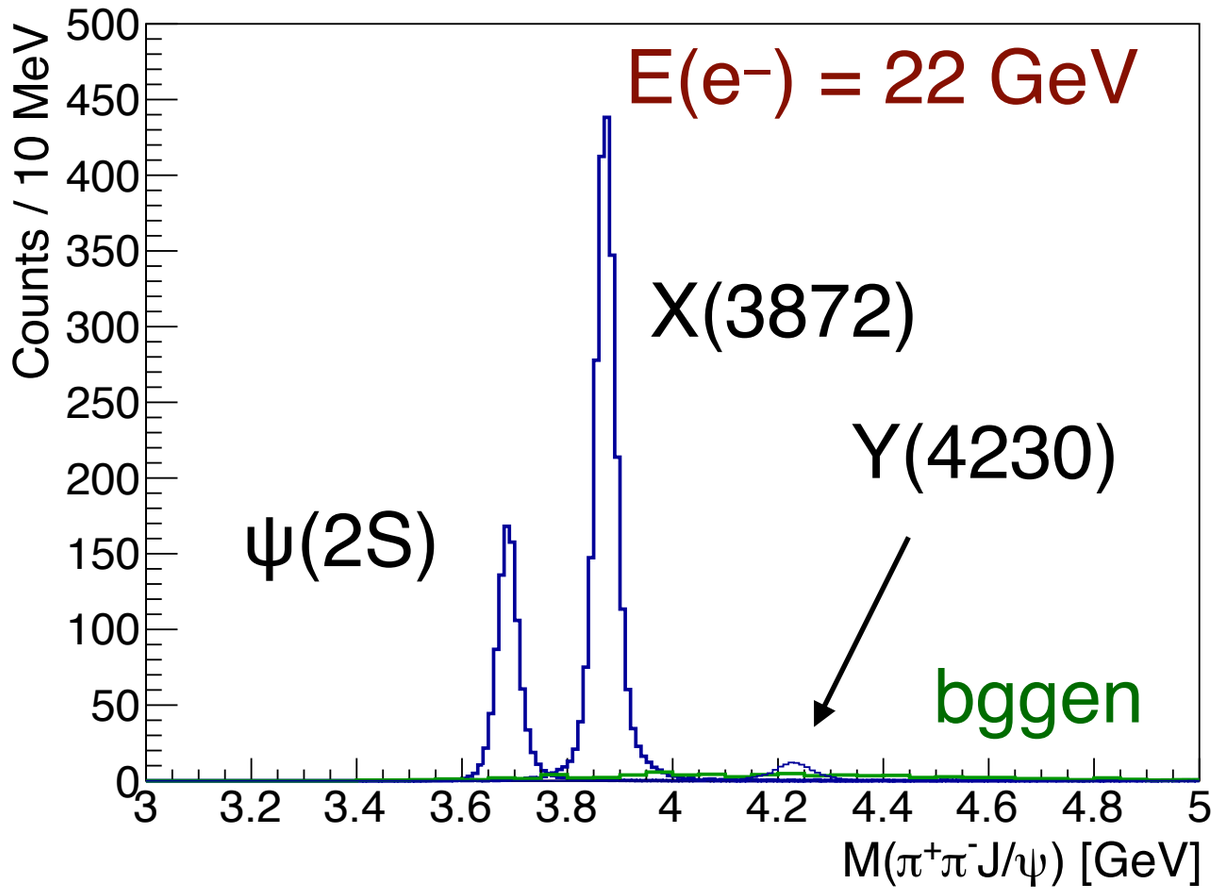


- JPAC predictions using fixed-spin exchanges near threshold
  - **PRD 102, 114010 (2020)**
- GlueX can test model by measuring χc1(1P), ψ(2S) production

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

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

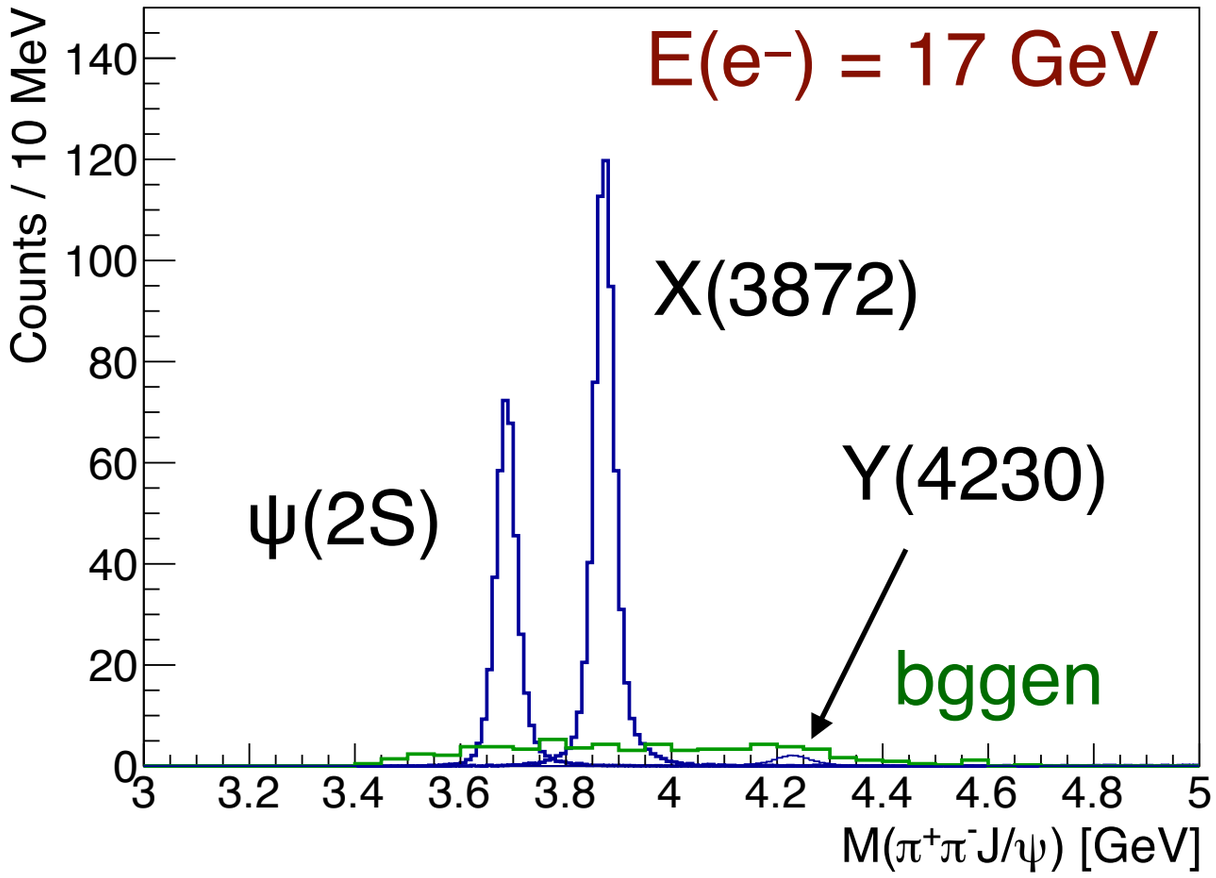




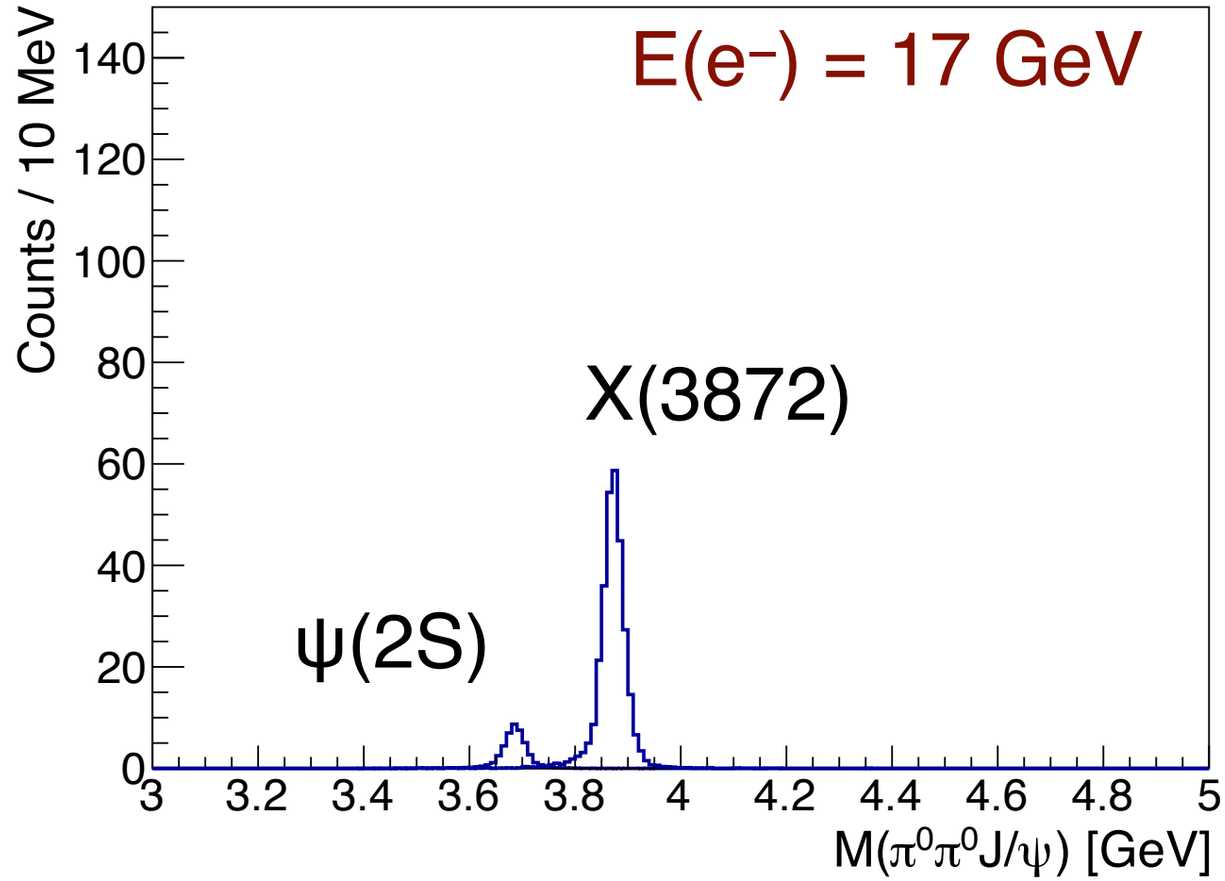
- Assumes 1 year @ 500 pb^{-1}, Br(X,Y$\rightarrow \pi^+\pi^- J/\psi$) = 5%
- 17 GeV: N(ψ(2S)) = 400, N(X(3872)) = 650, N(Y(4260)) = 20
- 22 GeV: N(ψ(2S)) = 900, N(X(3872)) = 2300, N(Y(4260)) = 120

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