

# Physics with Strange and Charm Quarks in Photoproduction at

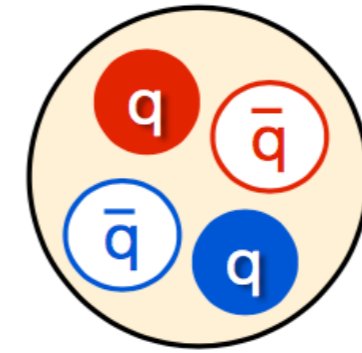
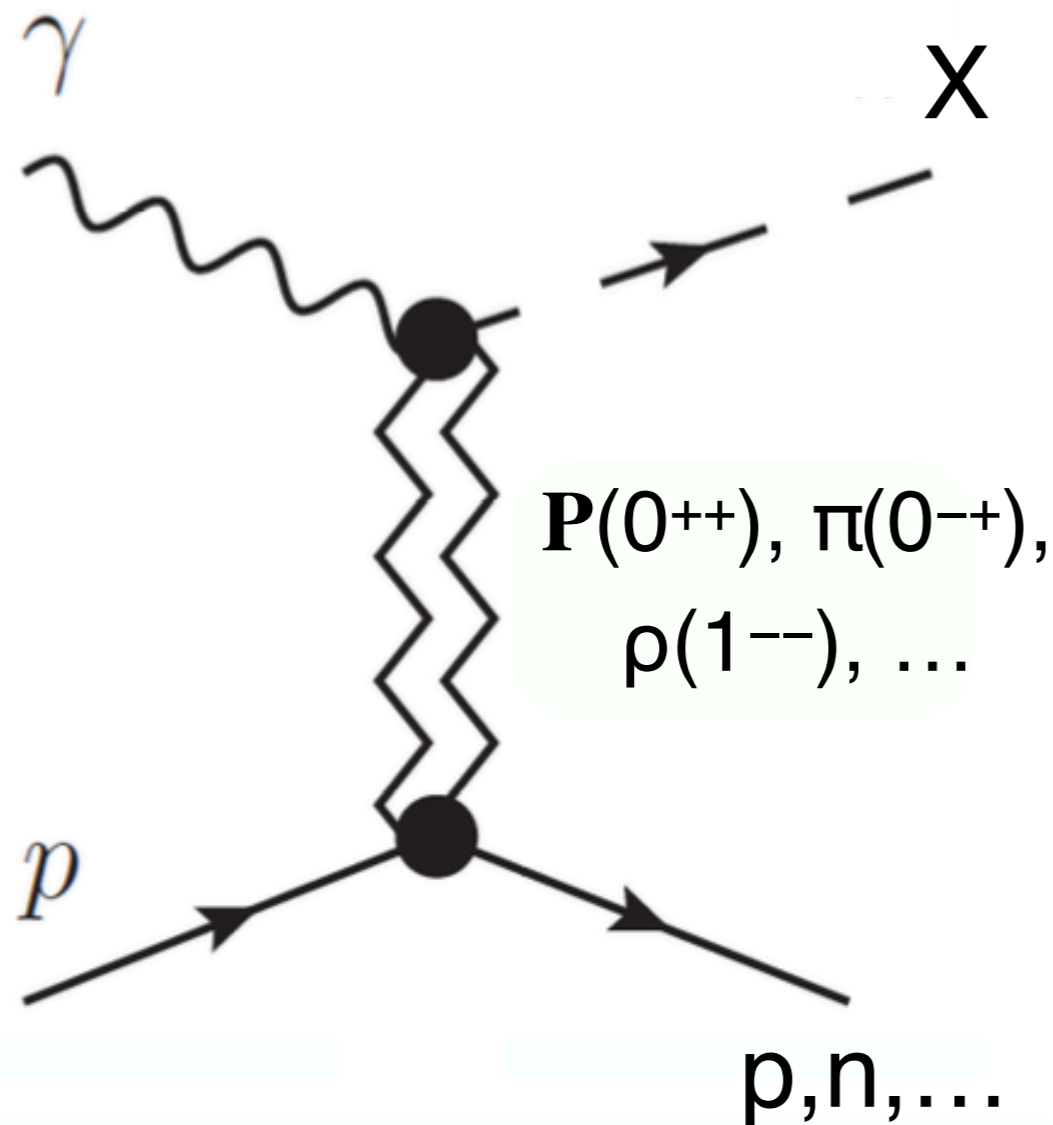
**Sean Dobbs**  
Florida State U.

Physics Opportunities With Proton Beams at SIS100  
February 9, 2024

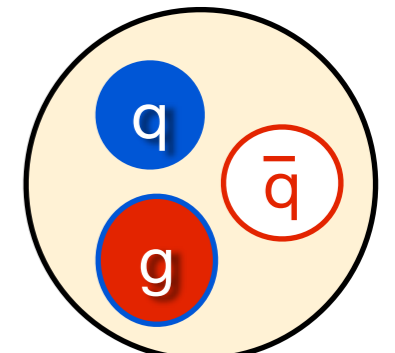


# Hadron Spectroscopy and Photoproduction

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



tetraquark



hybrid meson

- Photons couple to proton through exchanged QNs, can produce mesons of any  $J^{PC}$
- Photon **polarization** provides constraints on production processes, probe of hadron properties

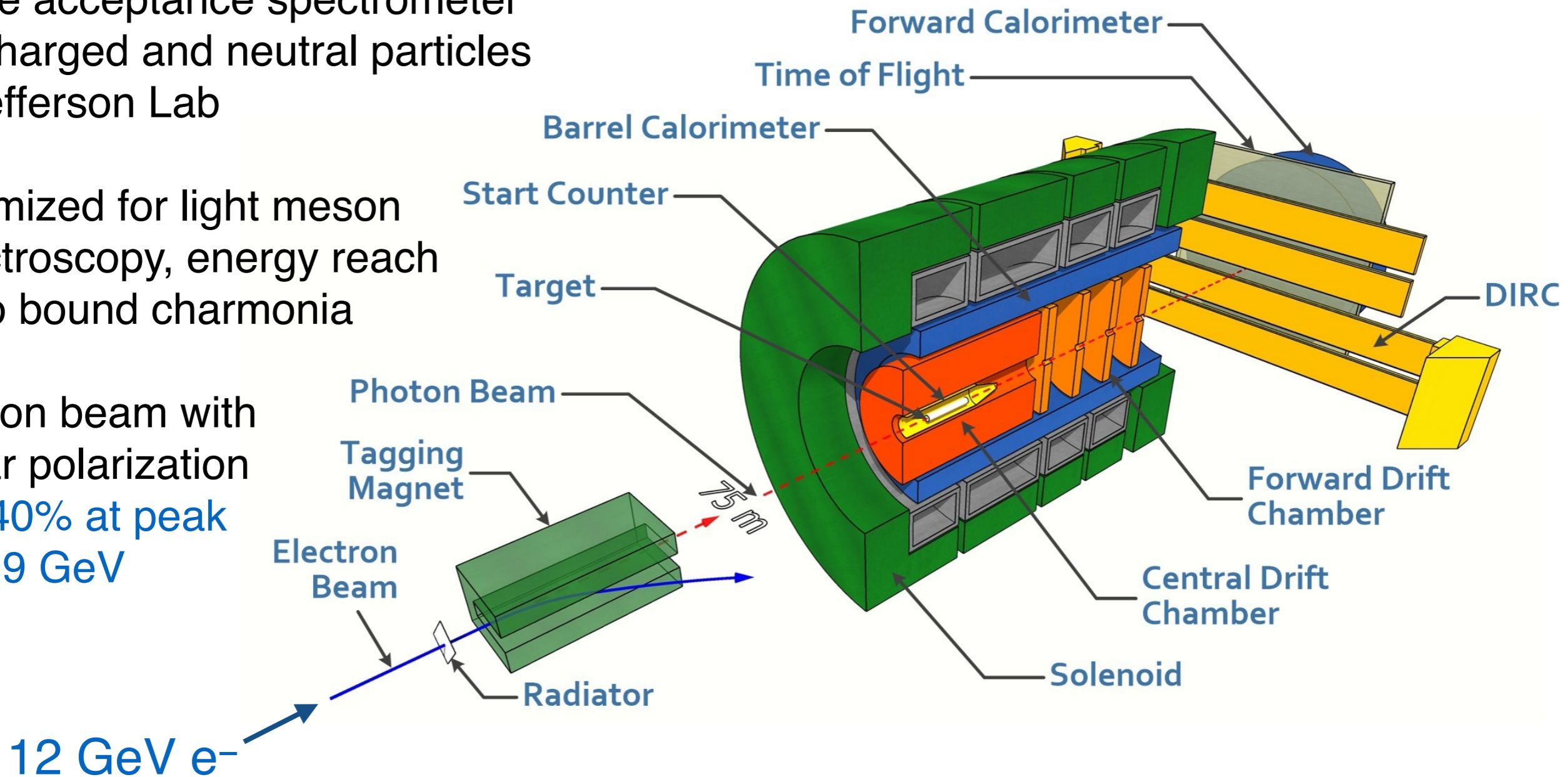


# The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

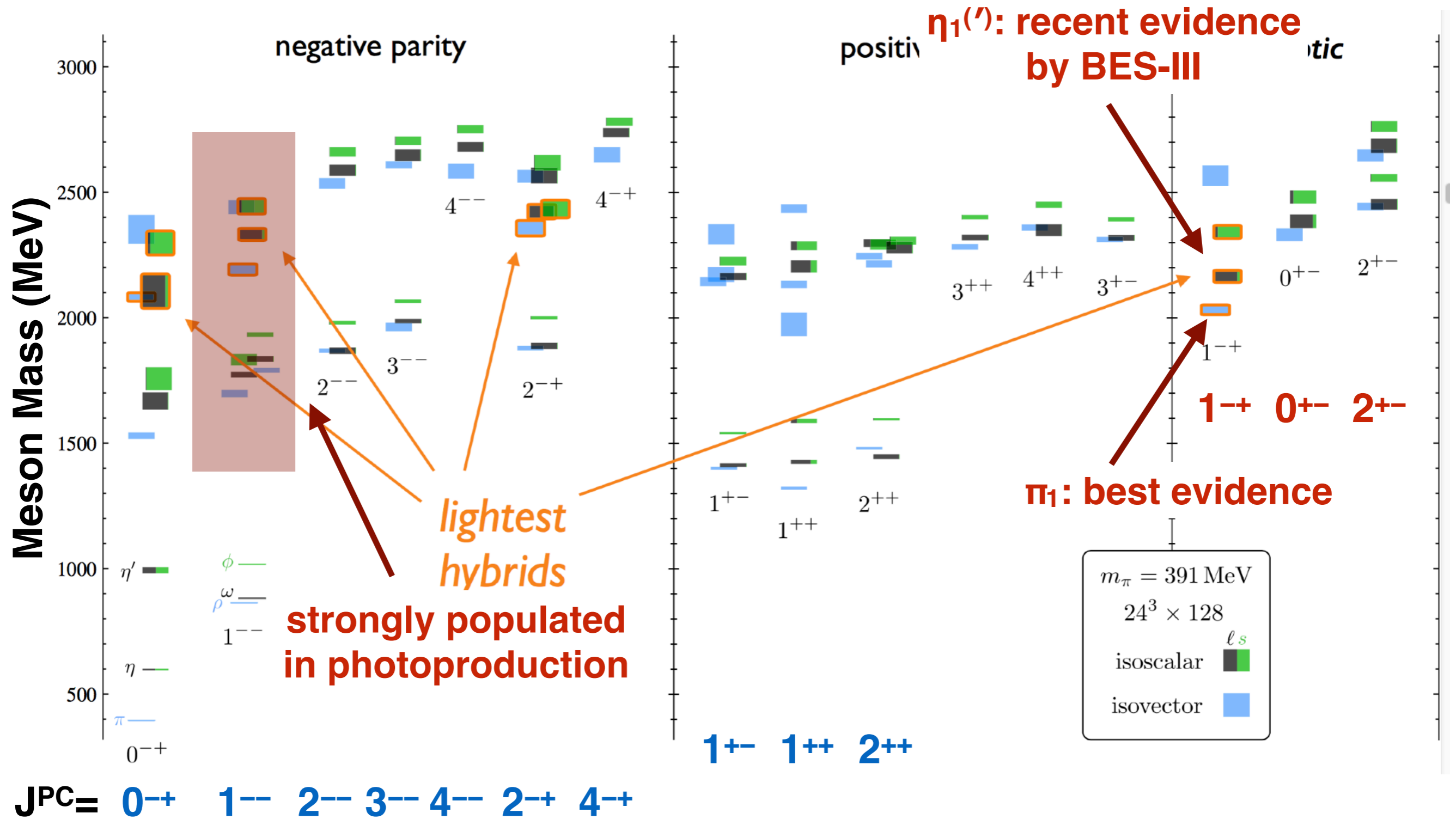
Optimized for light meson spectroscopy, energy reach up to bound charmonia

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



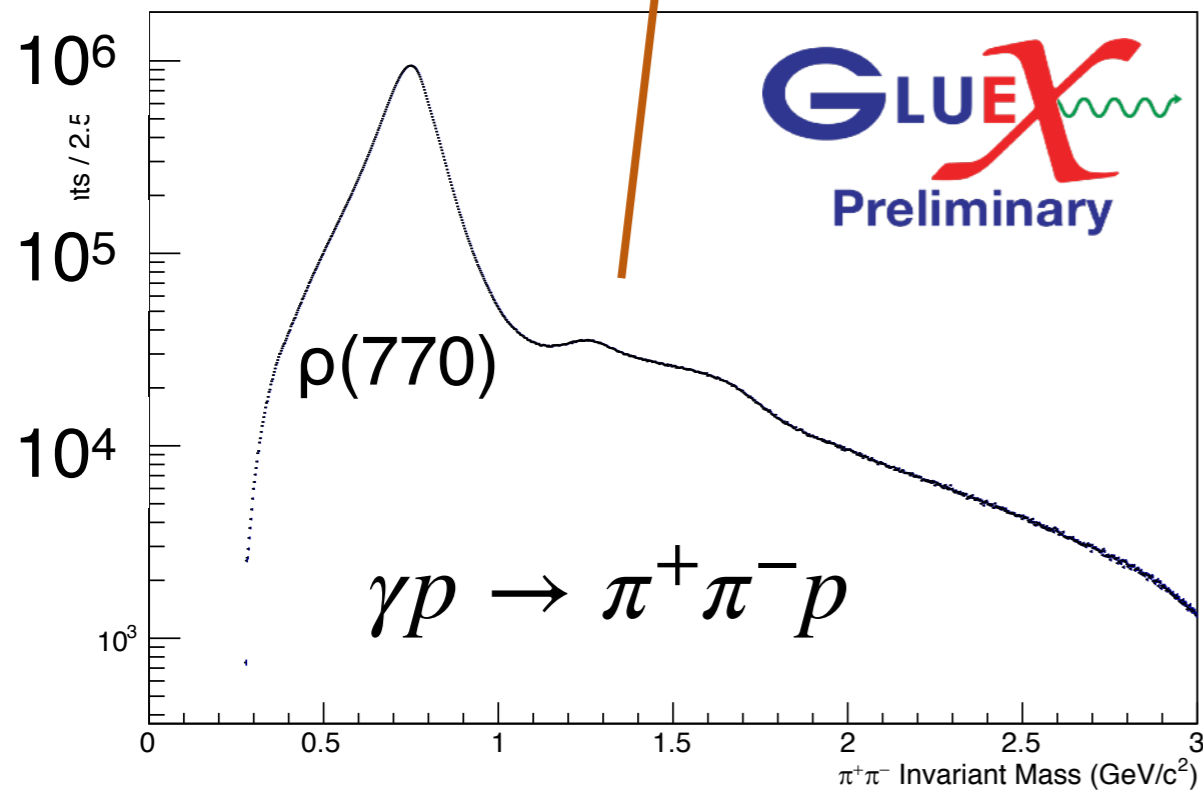
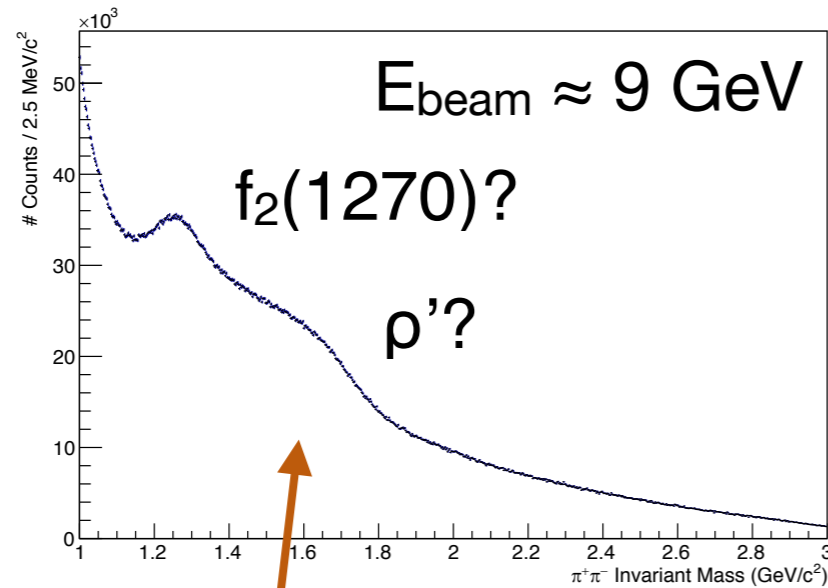
- **GlueX-I (2017–2018):**  $L = 305 \text{ pb}^{-1}$  [ $E_\gamma > 8$  GeV]
- **GlueX-II (2020–2025?):**  $L = 320 \text{ pb}^{-1}$  (so far)  
expect 3-4x GlueX-I

# Light Meson Spectrum from Lattice QCD

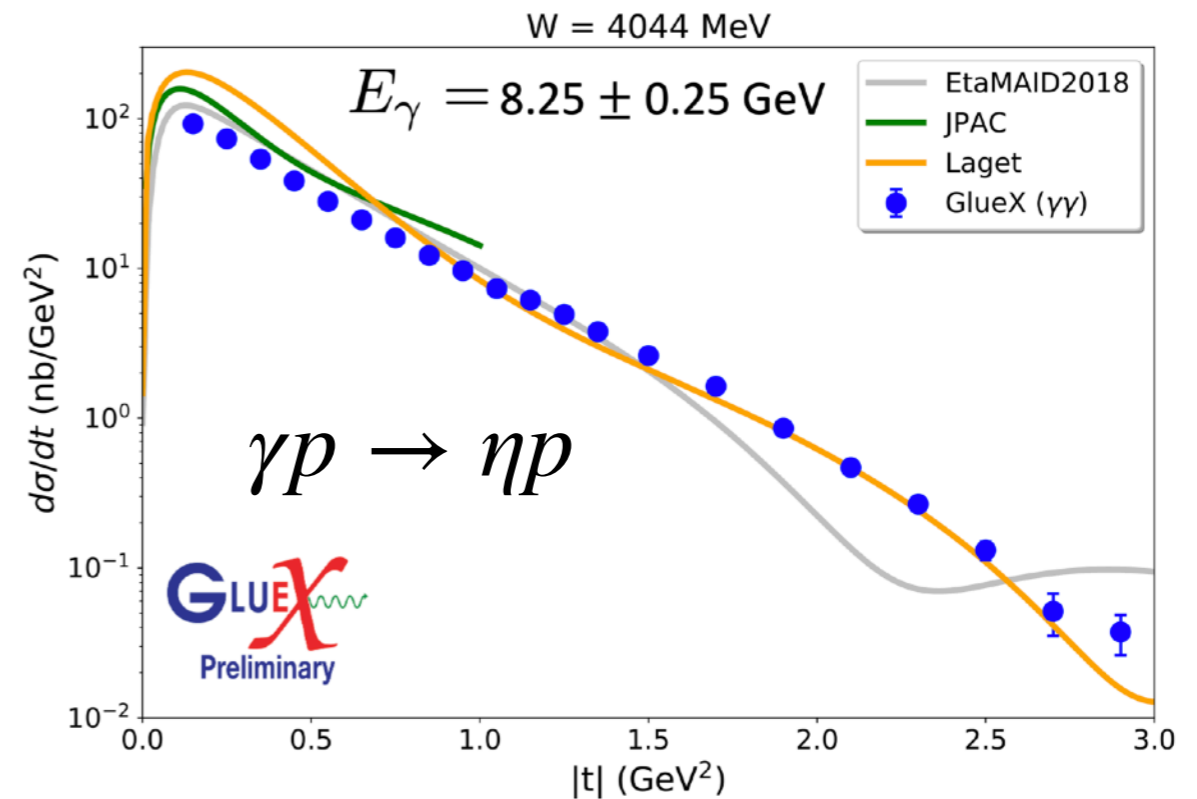


HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

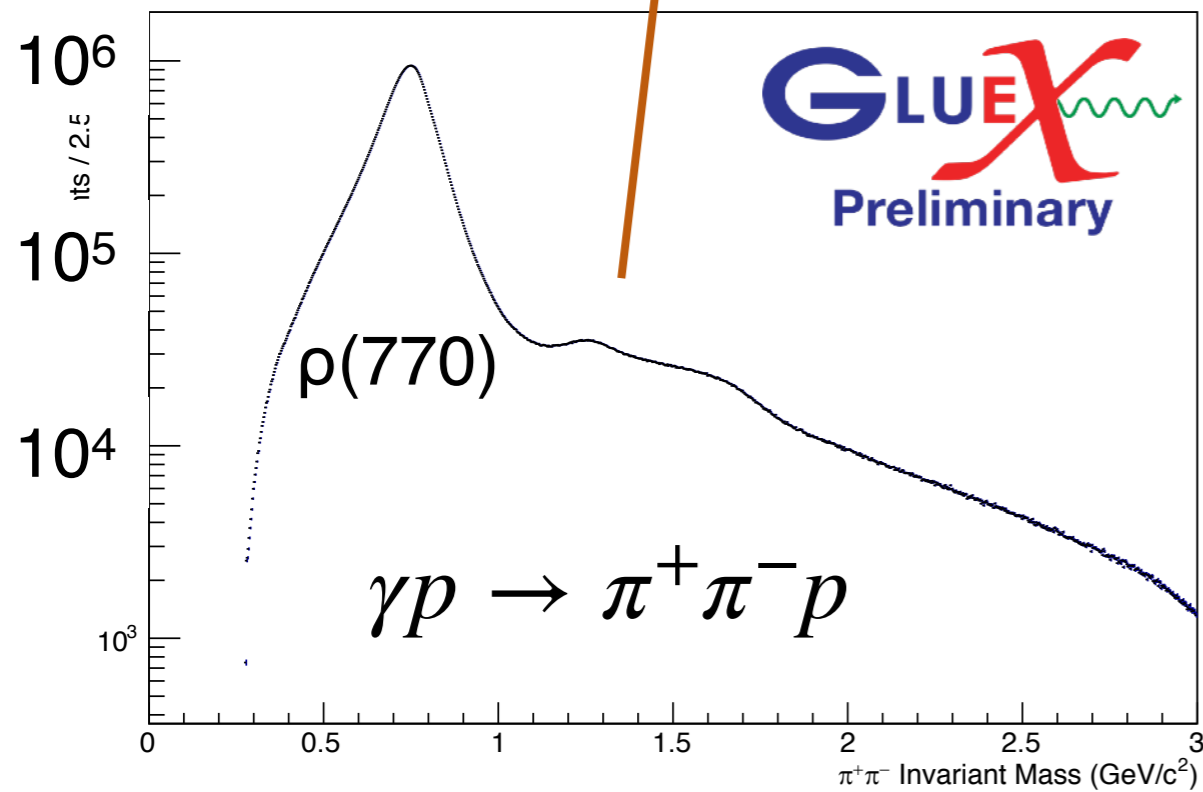
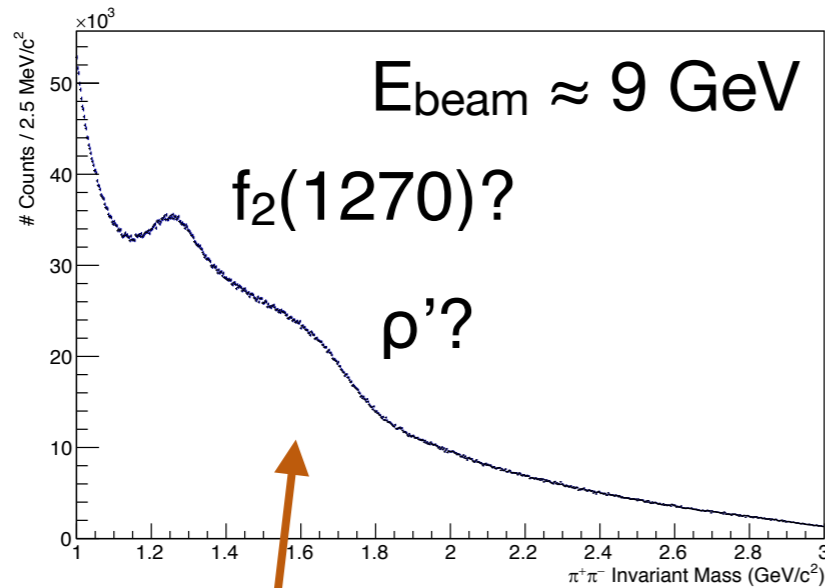
# GlueX: High Statistics Photoproduction Data



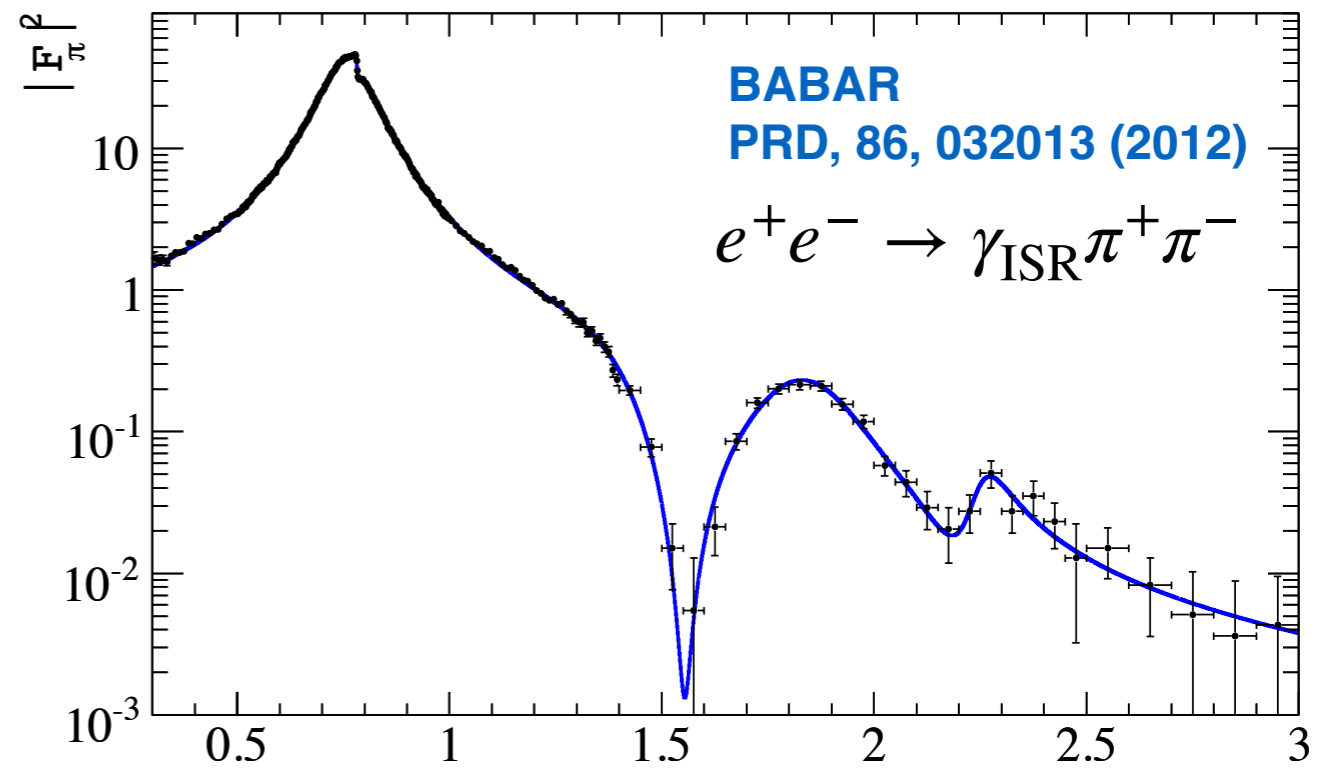
- GlueX has collected **orders of magnitude** more data than previous experiments at  $E_\gamma \approx 9 \text{ GeV}$



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



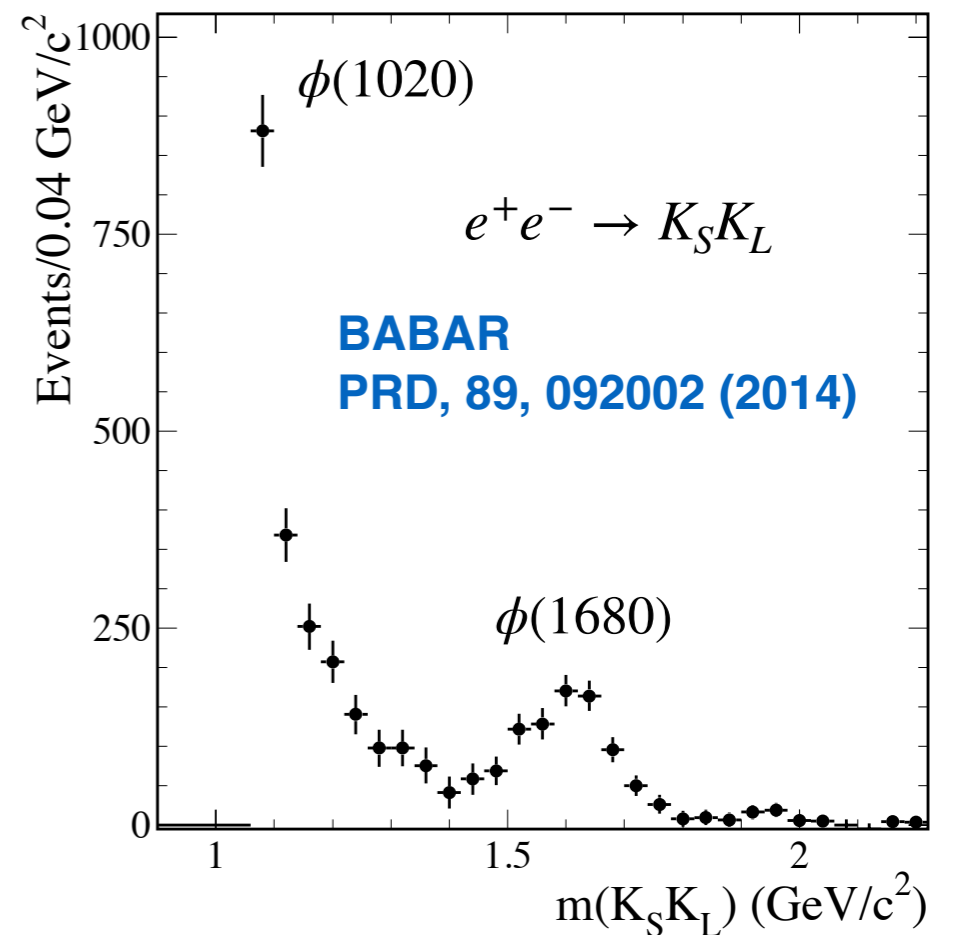
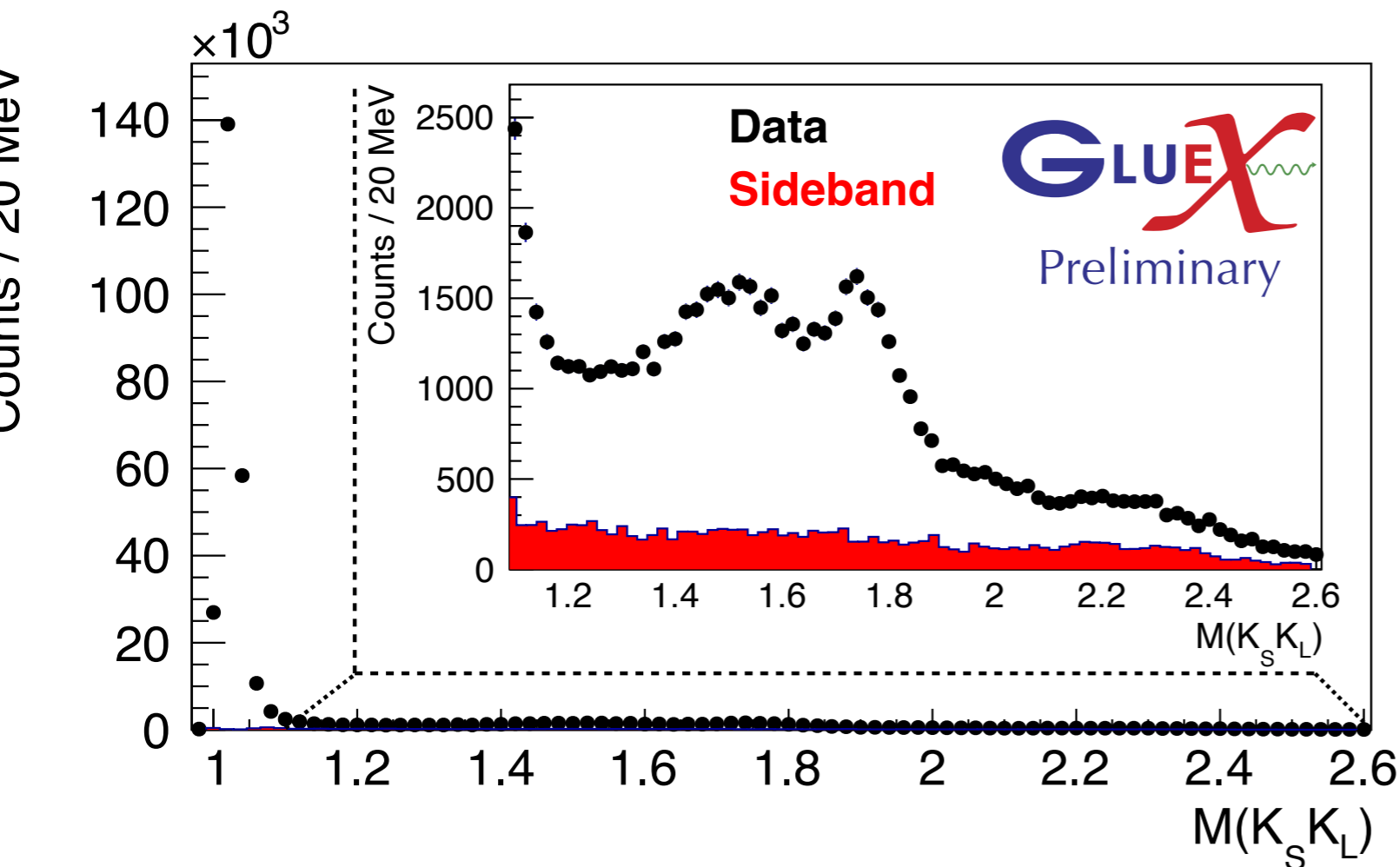
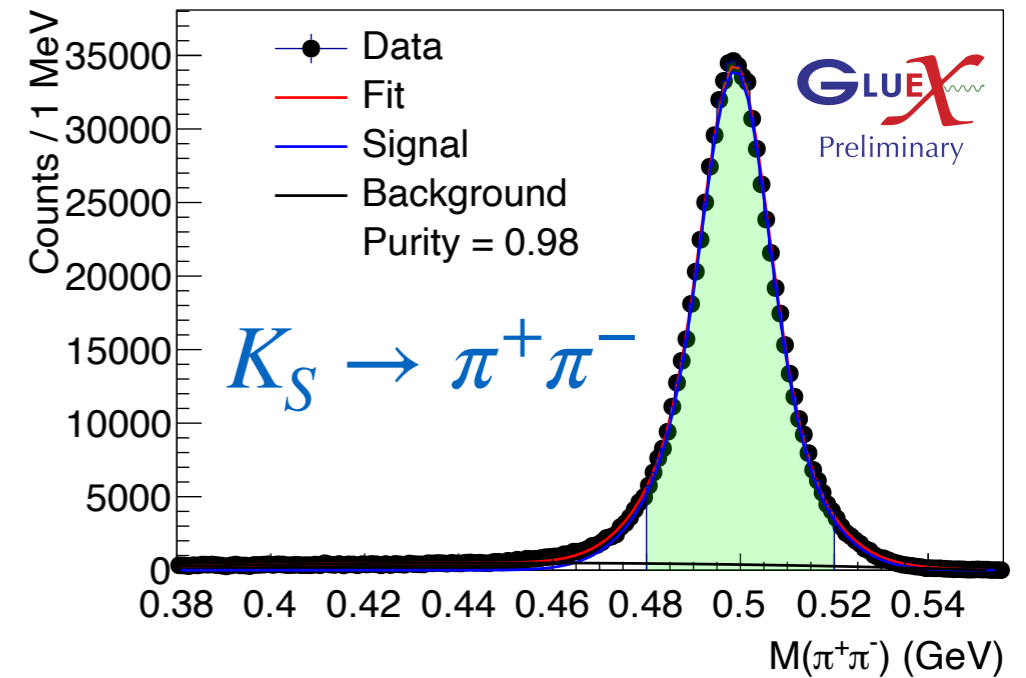
- GlueX can access excited vector mesons decaying to e.g.  $\pi^+\pi^-$  and  $\omega\pi$
- Need consistent understanding of spectra in photoproduction and  $e^+e^-$  annihilation



$$m_{\pi^+ \pi^-} [GeV/c^2]$$

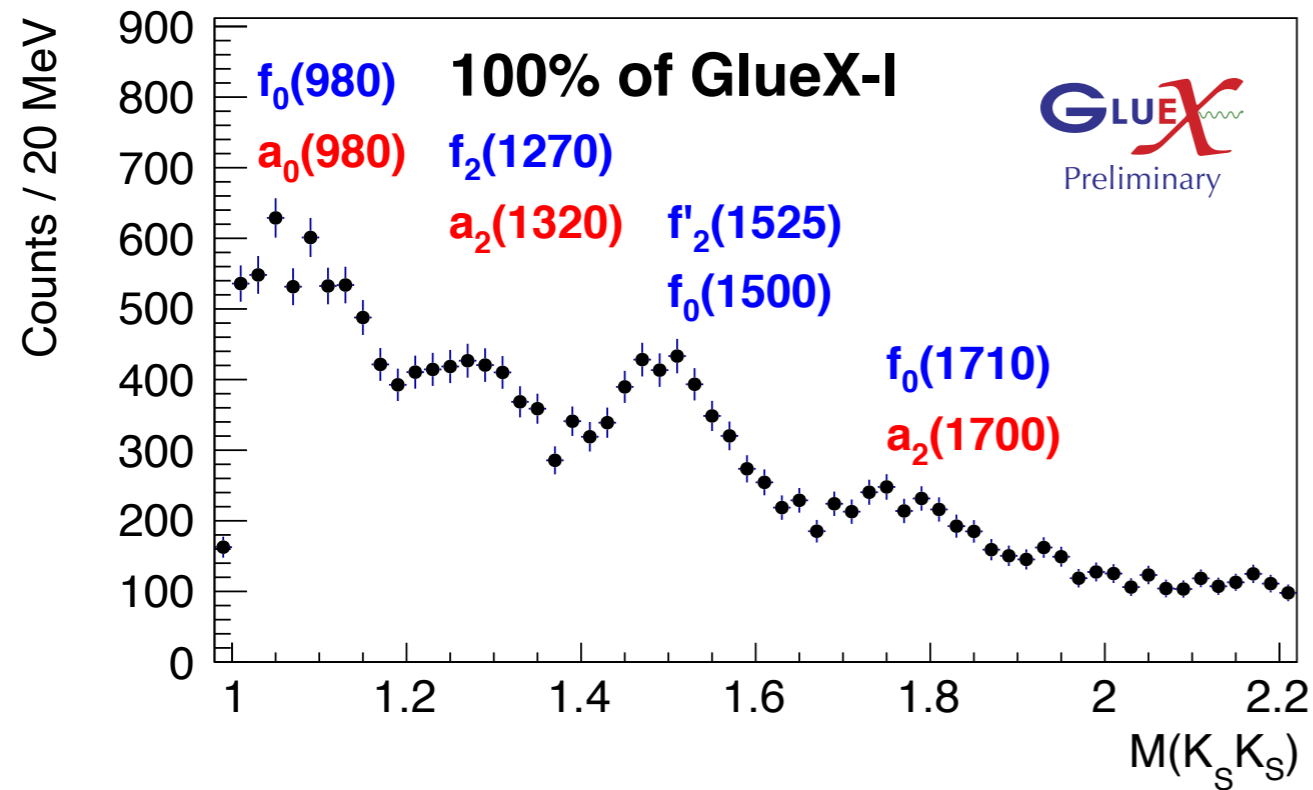
# High Statistics $K\bar{K}$ and Excited Vectors

- Clear signal of  $K_S K_L$ ,  $K_S \rightarrow \pi^+ \pi^-$  seen
- Detailed  $\phi$  measurements underway
- Preliminary PWA shows  $K_S K_L$  spectrum is predominantly P-wave
- Two peaks in photoproduction vs. one in  $e^+ e^-$  annihilation?

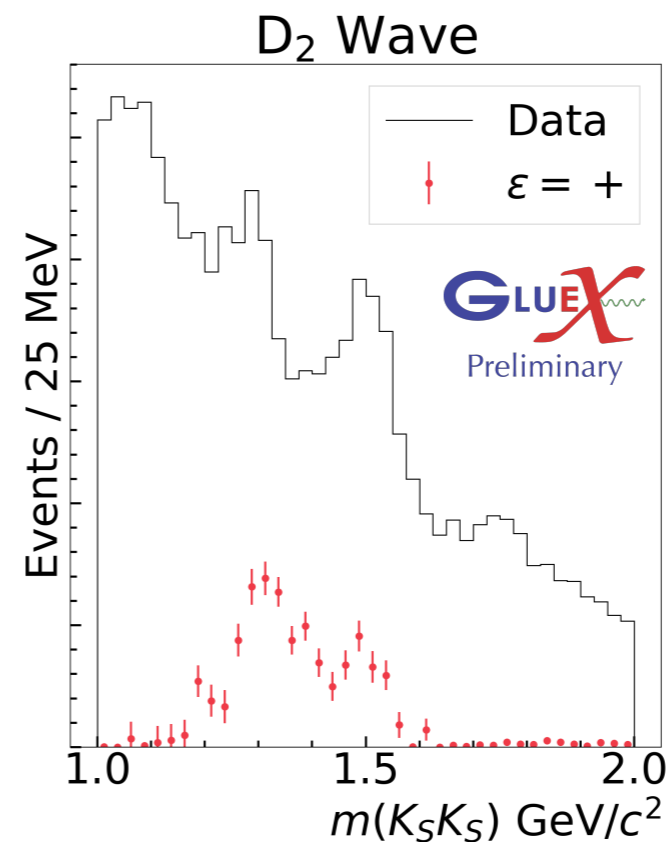
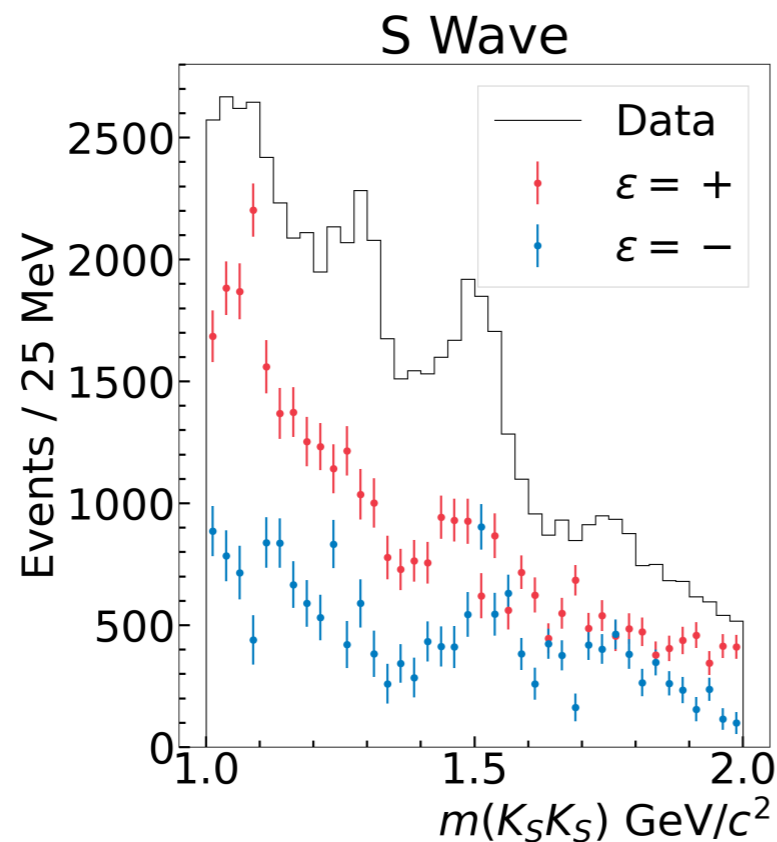




# $K_S K_S$ Spectrum — Scalar and Tensor Mesons



- The  $K_S K_S$  final state allows study of scalar and tensor mesons
  - $K_S K_S: J^{PC} = \text{even}^{++}$
- Partial wave analysis underway
- Laying groundwork for future coupled channel fits

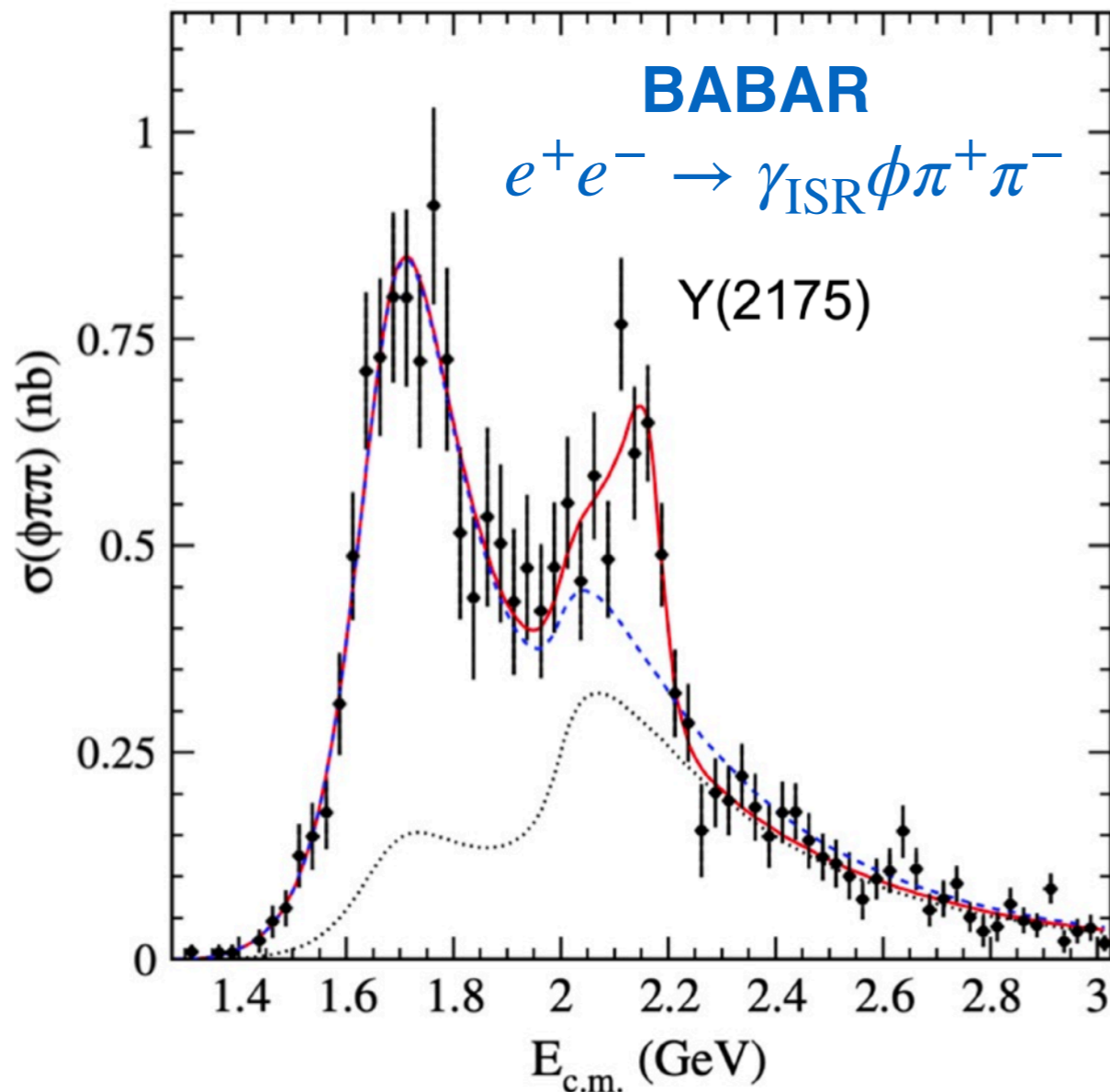




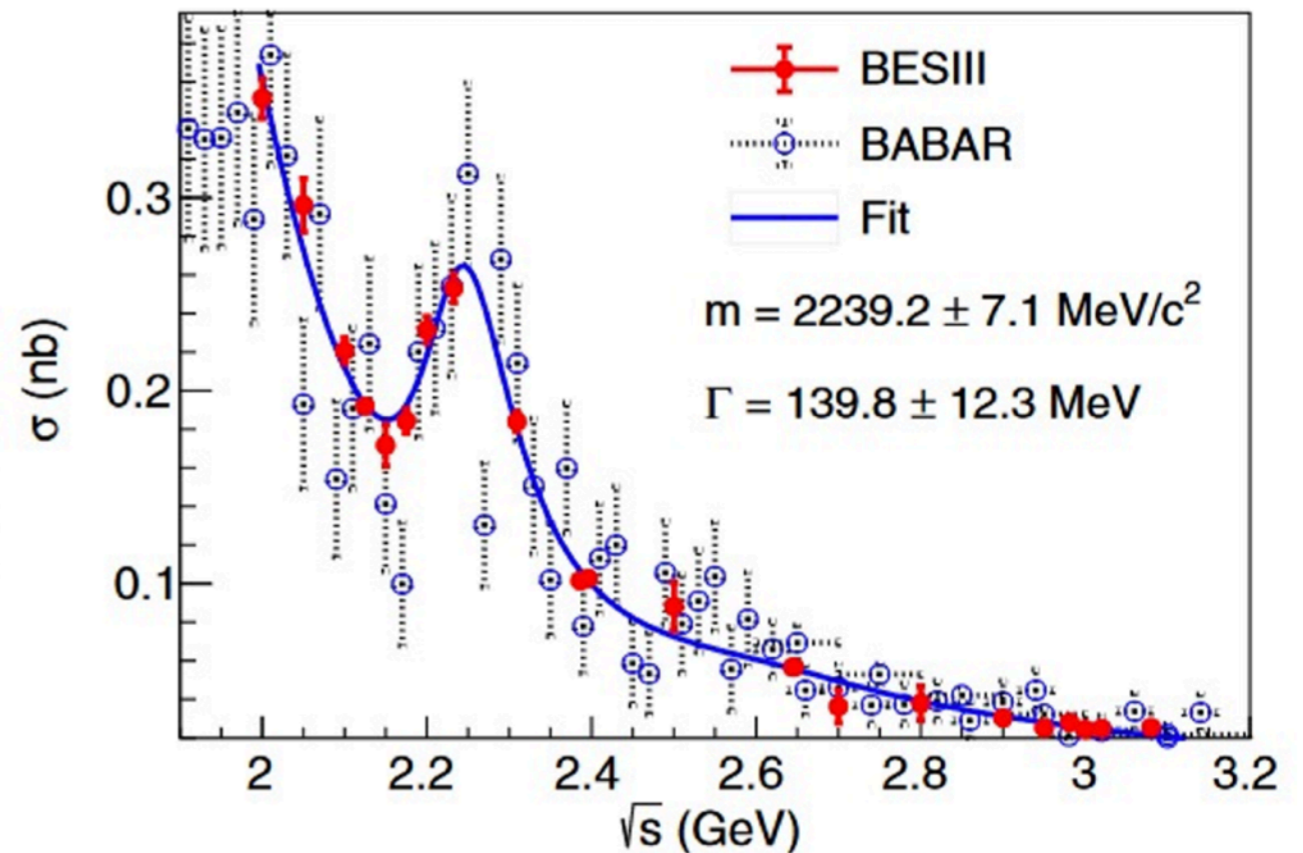
# Search for the $Y(2175)$

- 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]



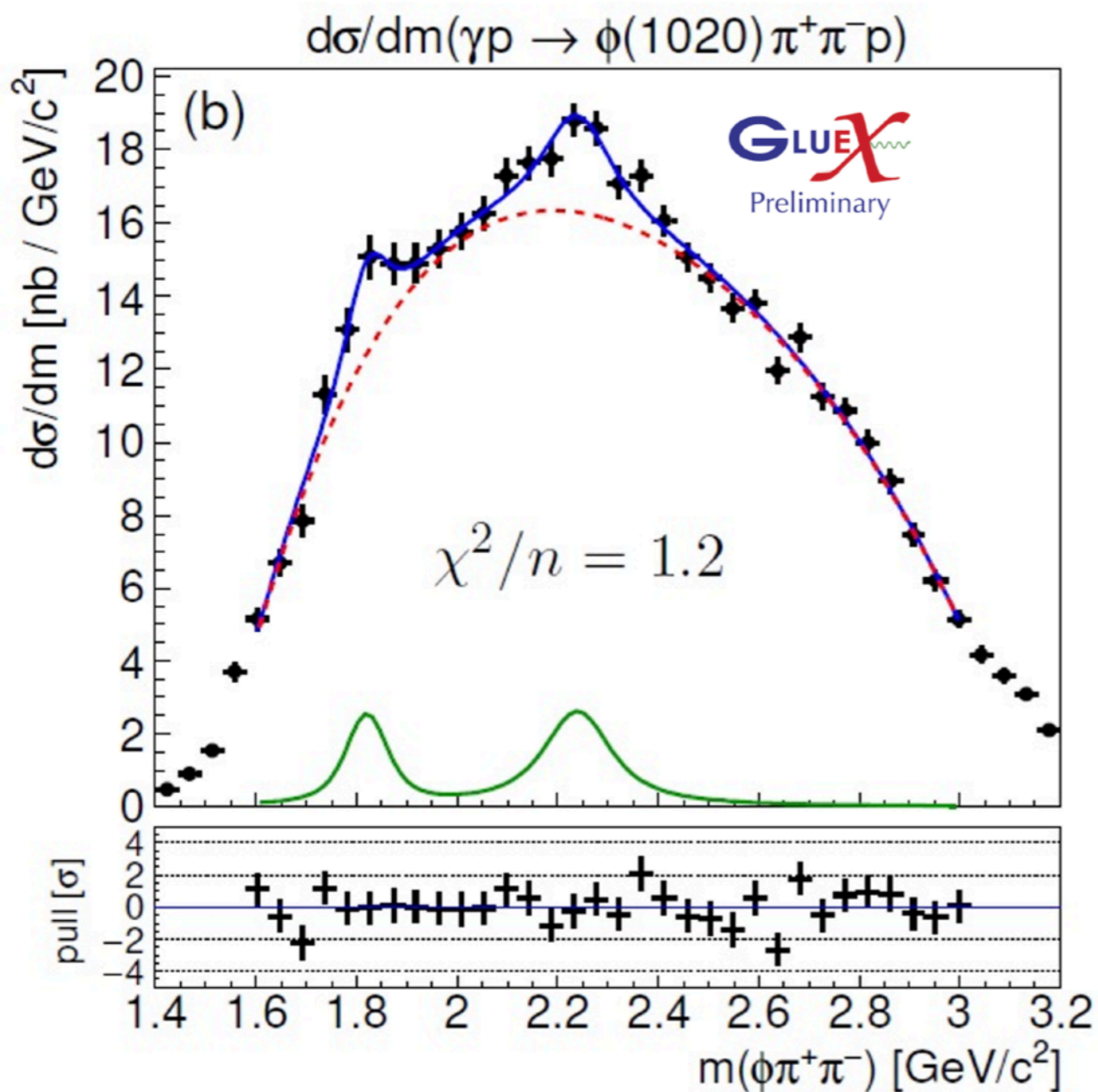
$e^+e^- \rightarrow K^+K^-$  cross section at  $\sqrt{s} = 2.00 - 3.08 \text{ GeV}$

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

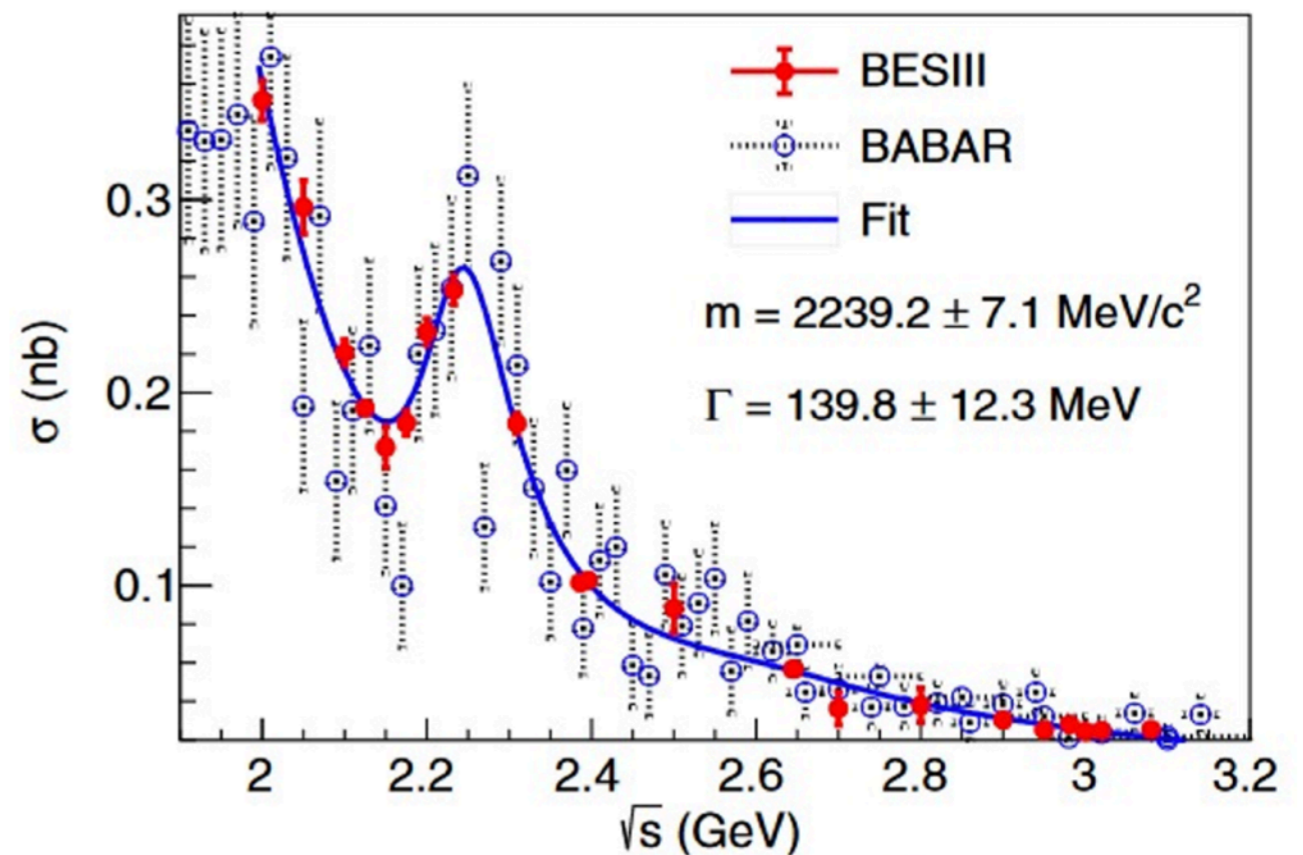
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

# Search for the $Y(2175)$

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



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



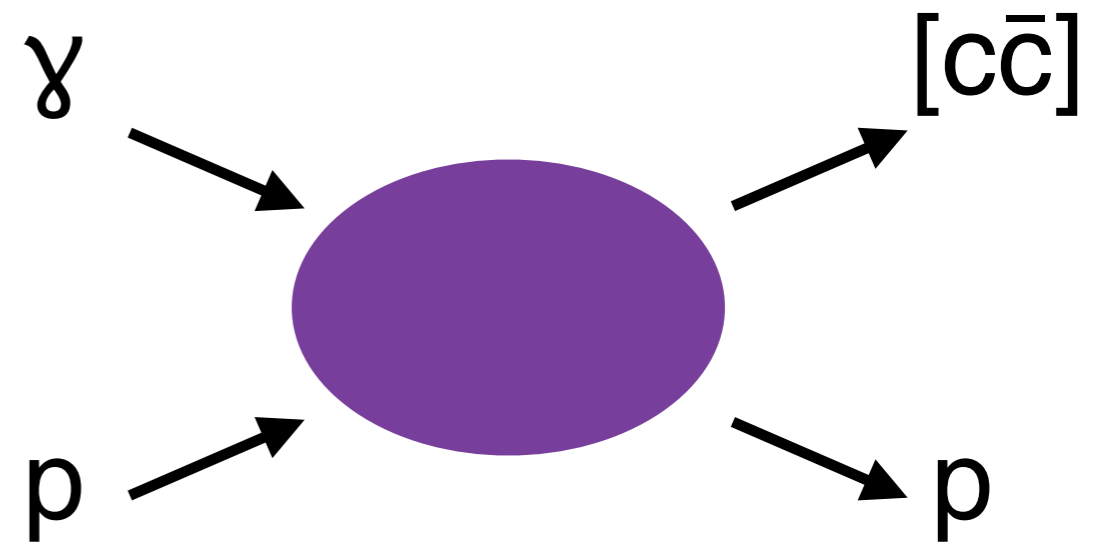
$e^+e^- \rightarrow K^+K^-$  cross section at  $\sqrt{s} = 2.00 - 3.08 \text{ GeV}$

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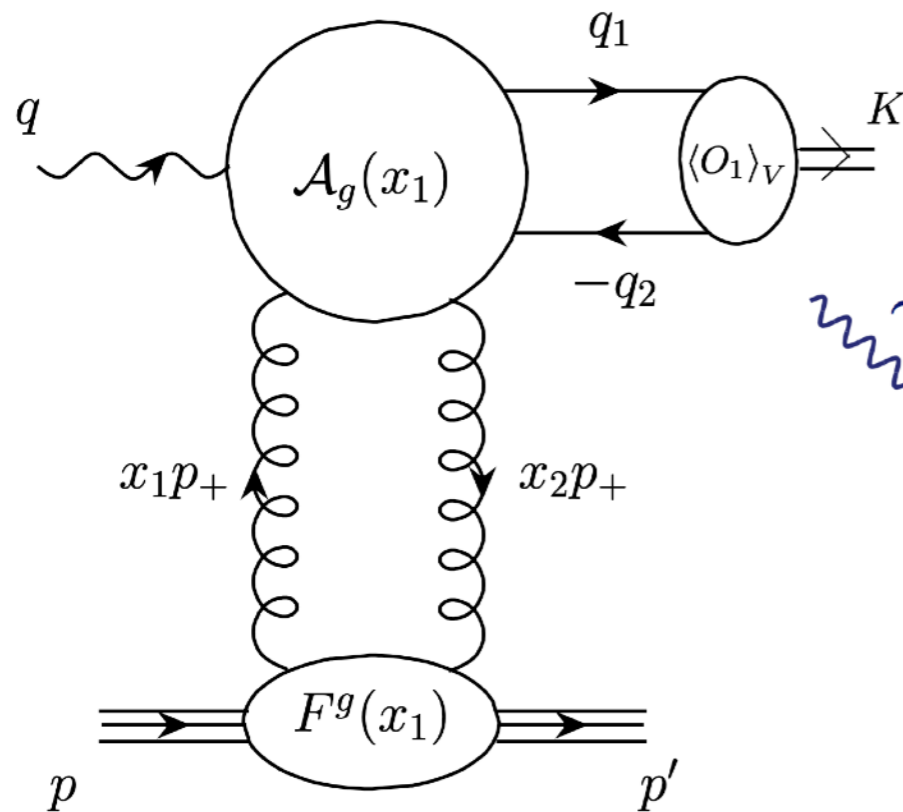
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

# Charmonium Photoproduction Near Threshold

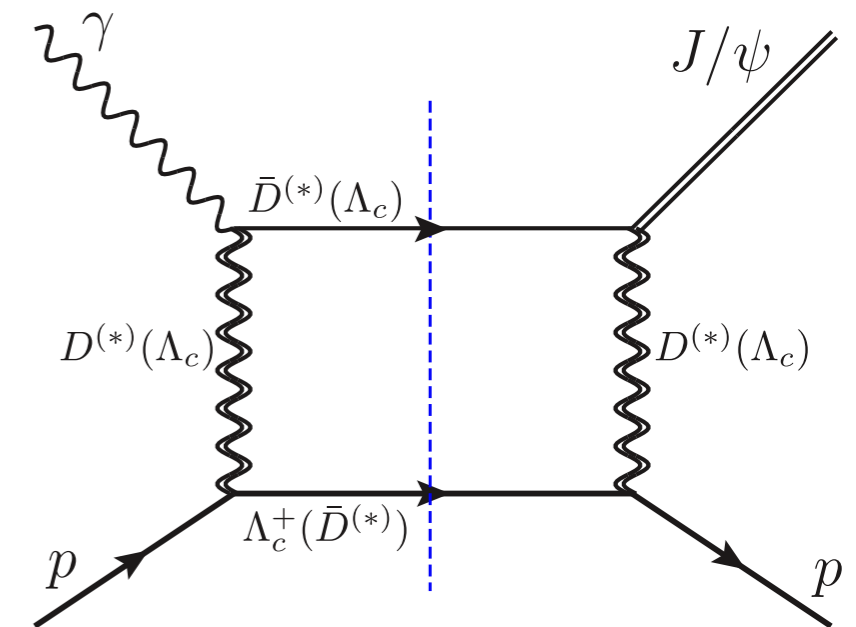
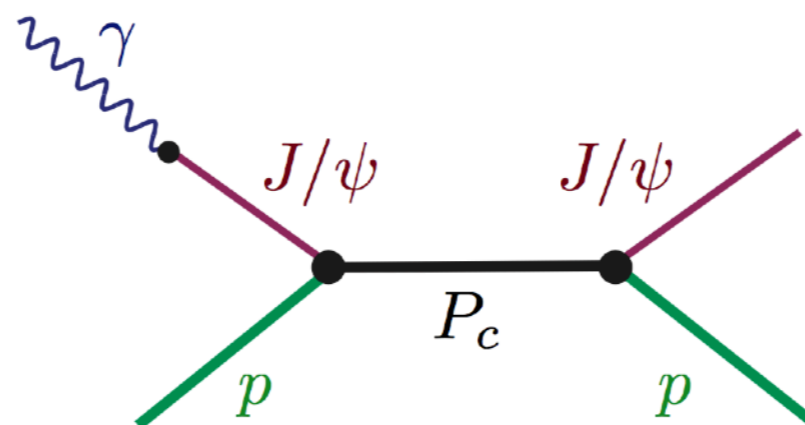
- Near-threshold production allows study of the  $c\bar{c}+N$  interaction
- Interest in using gluon exchange as a probe of proton structure, search for  $P_c$  resonances, etc...
- Understanding of production mechanism critical to interpretation.



See talk by D. Winney on Tuesday



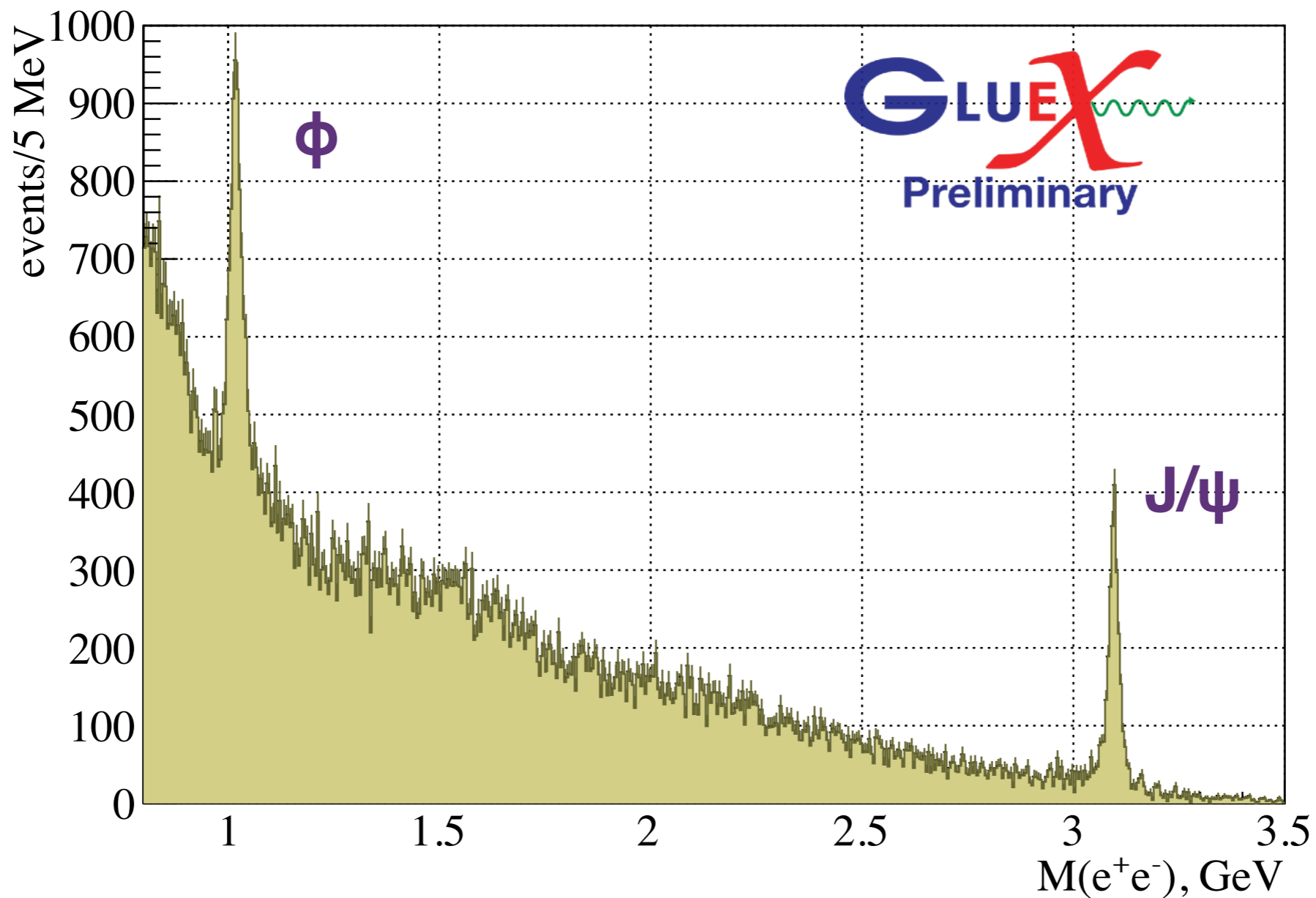
EPJC 34, 297 (2004)



EPJC 80, 1053 (2020)



# J/ $\psi$ Photoproduction at GlueX: Mass Spectrum

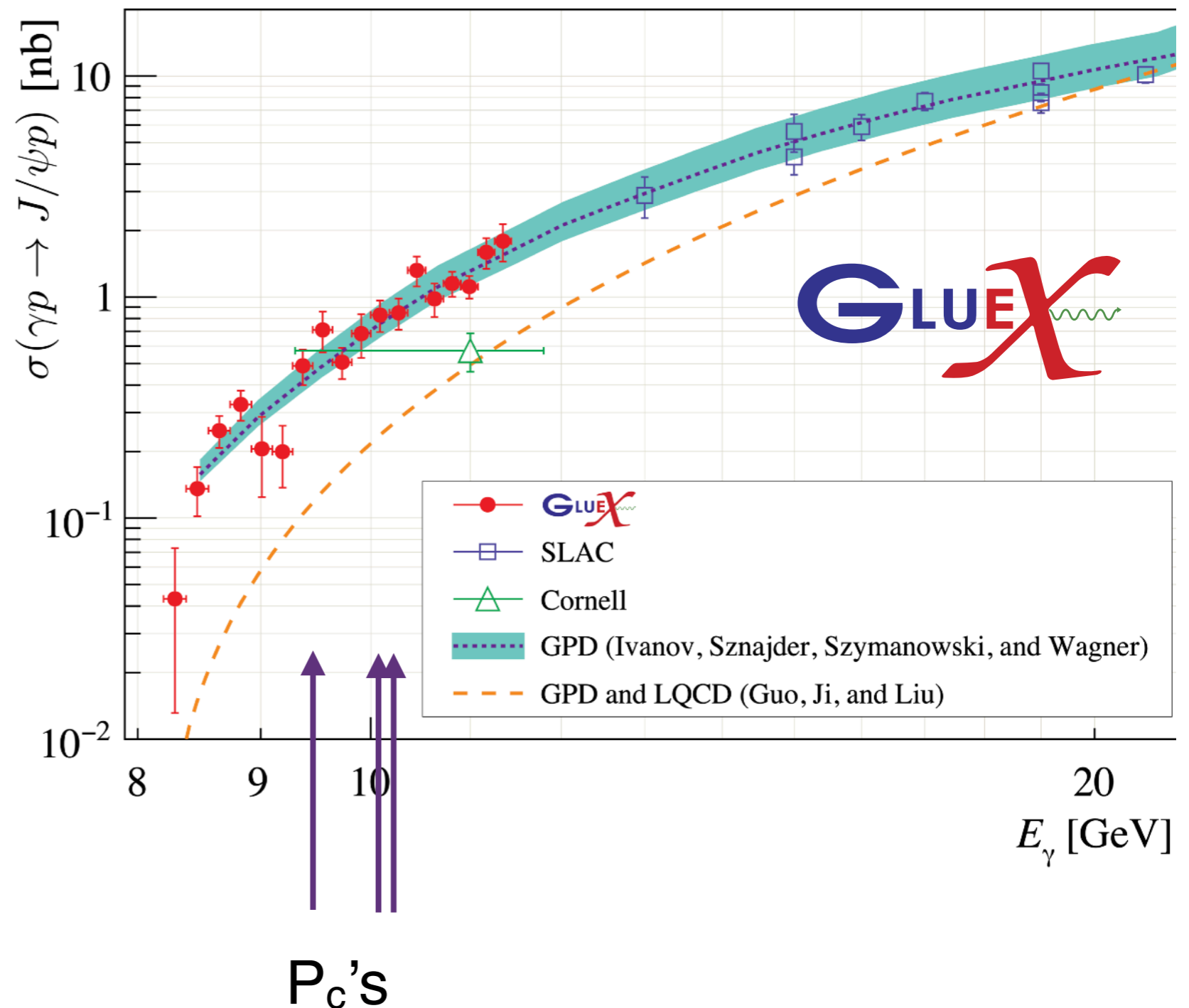


- Reconstruct  $p \gamma \rightarrow p + J/\psi, J/\psi \rightarrow e^+e^-$
- Calculate  $J/\psi$  cross sections normalized by non-resonant  $e^+e^-$

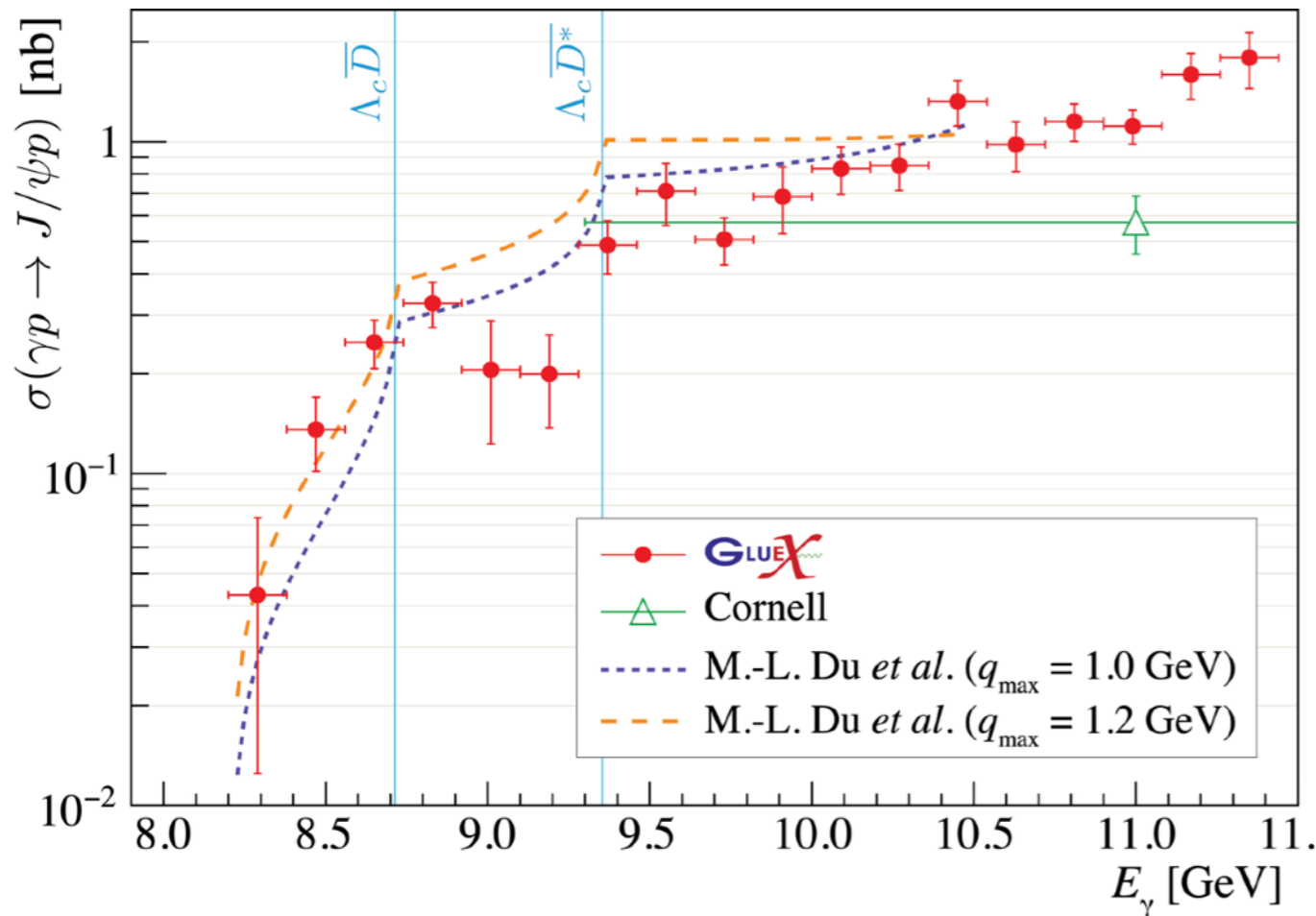
# Latest GlueX-I $J/\psi \rightarrow e^+e^-$ Photoproduction Results

GlueX, PRC 108, 025201 (2023)

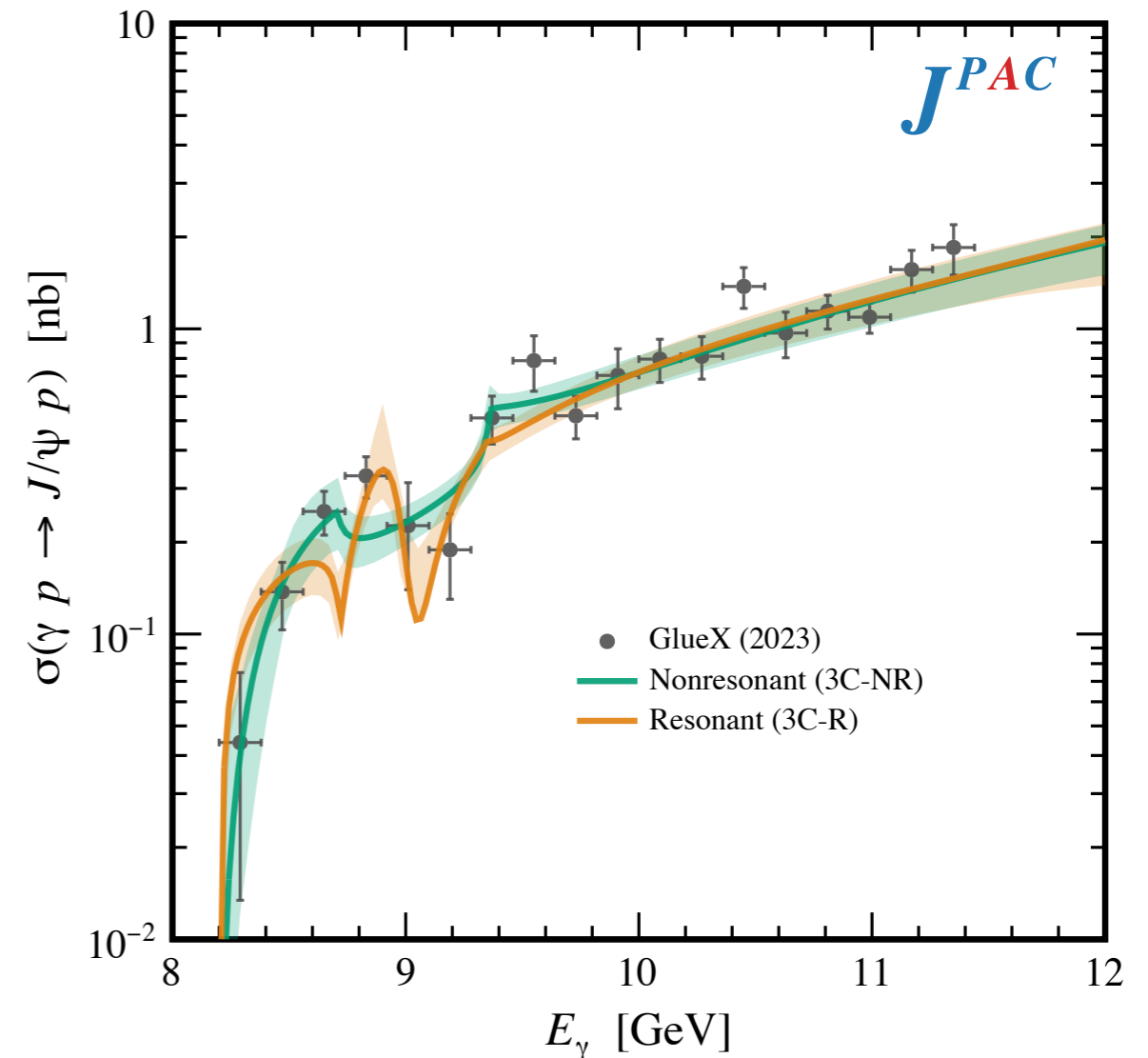
- Full GlueX-I data yields  $2270 \pm 58$   $J/\psi$ 's
- Overall normalization uncertainty  $\sim 20\%$
- “Dip” above 9 GeV has  $2.6\sigma$  ( $1.3\sigma$ ) local (global) significance
- No evidence of narrow  $P_c$  production
- $J/\psi \rightarrow \mu^+\mu^-$  under analysis



# Threshold Effects?



PRC 108, 025201 (2023); EPJC 80, 1053 (2020)

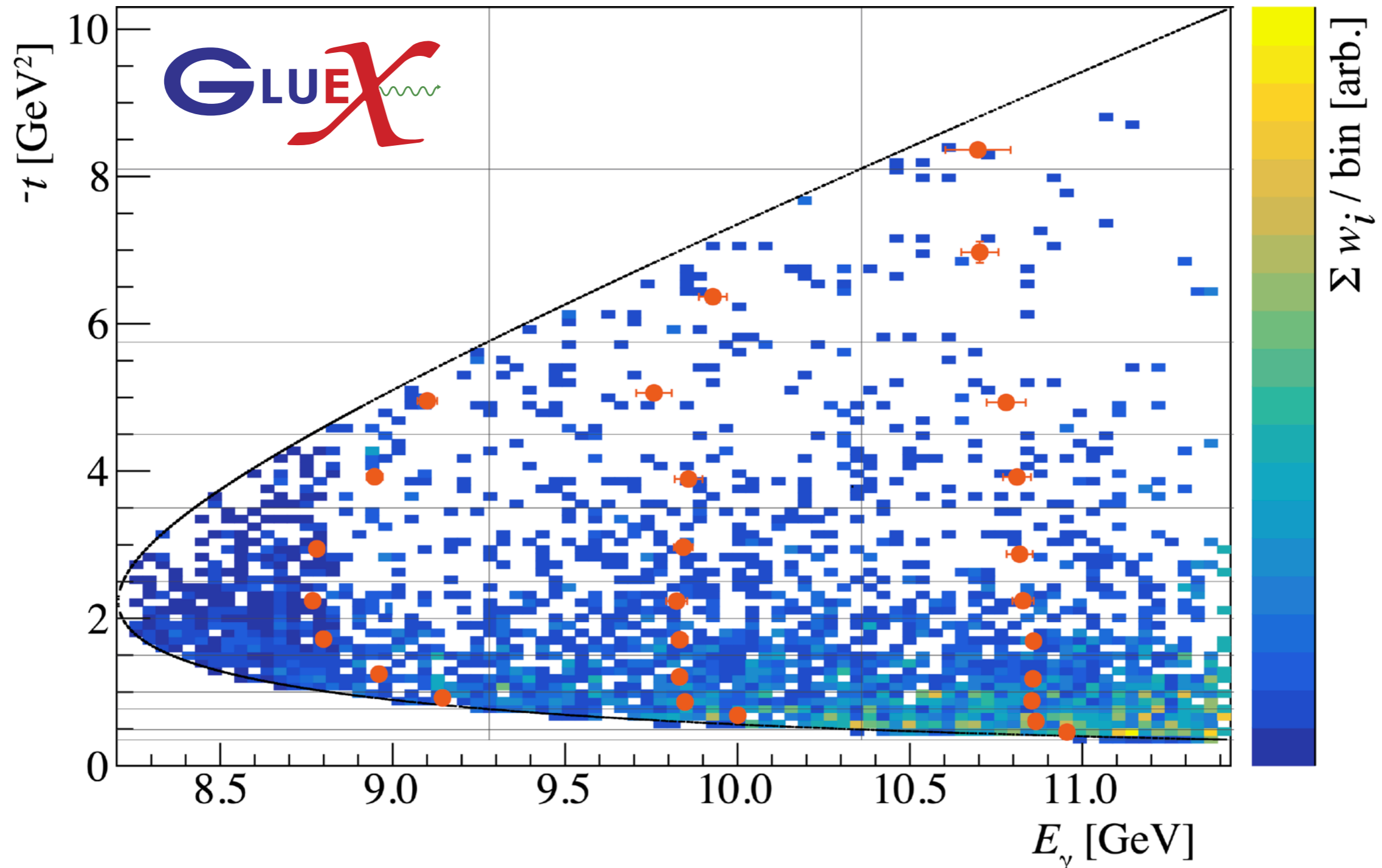


PRD 108, 054018 (2023)

- Structures seen near open-charm thresholds
- More precision required — GlueX-II will provide factor  $\sim 3$  more data
- Polarization observables can provide additional insight

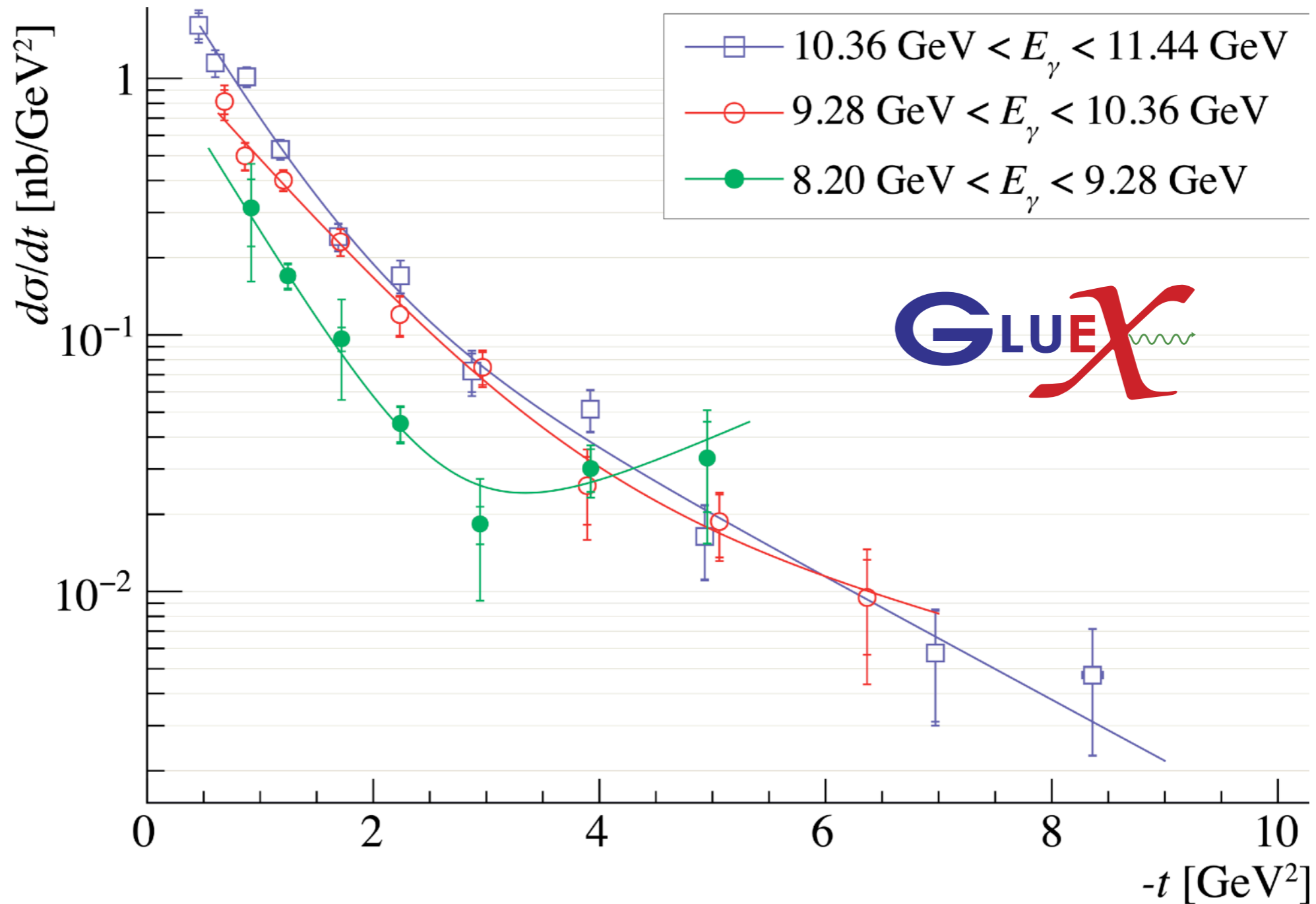


# GlueX-I J/ψ Differential Cross Sections



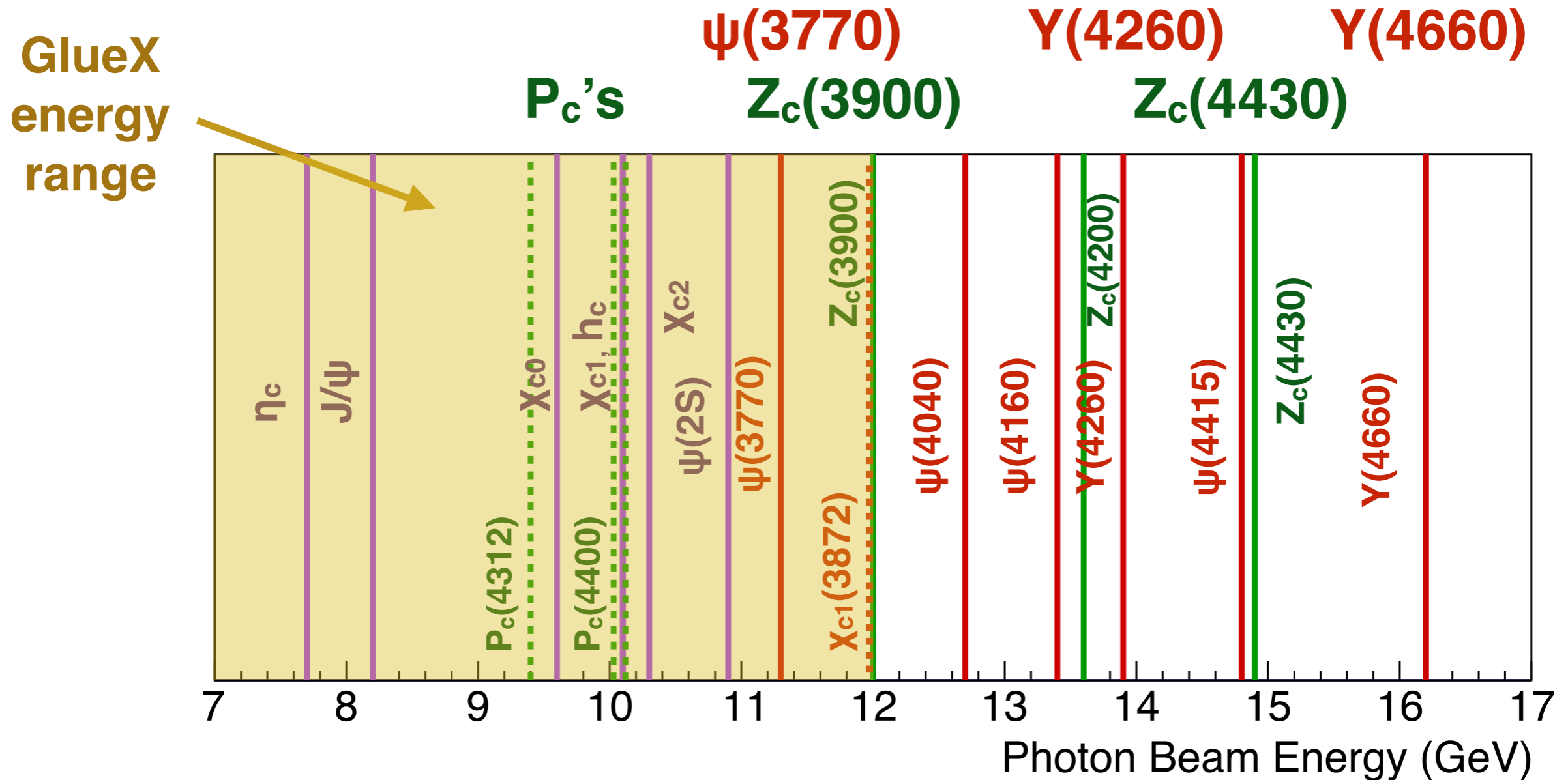
- Calculate  $d\sigma / dt$  including event-by-event luminosity weighting
- Report cross sections at bin means (points)

# GlueX-I J/ψ Differential Cross Sections



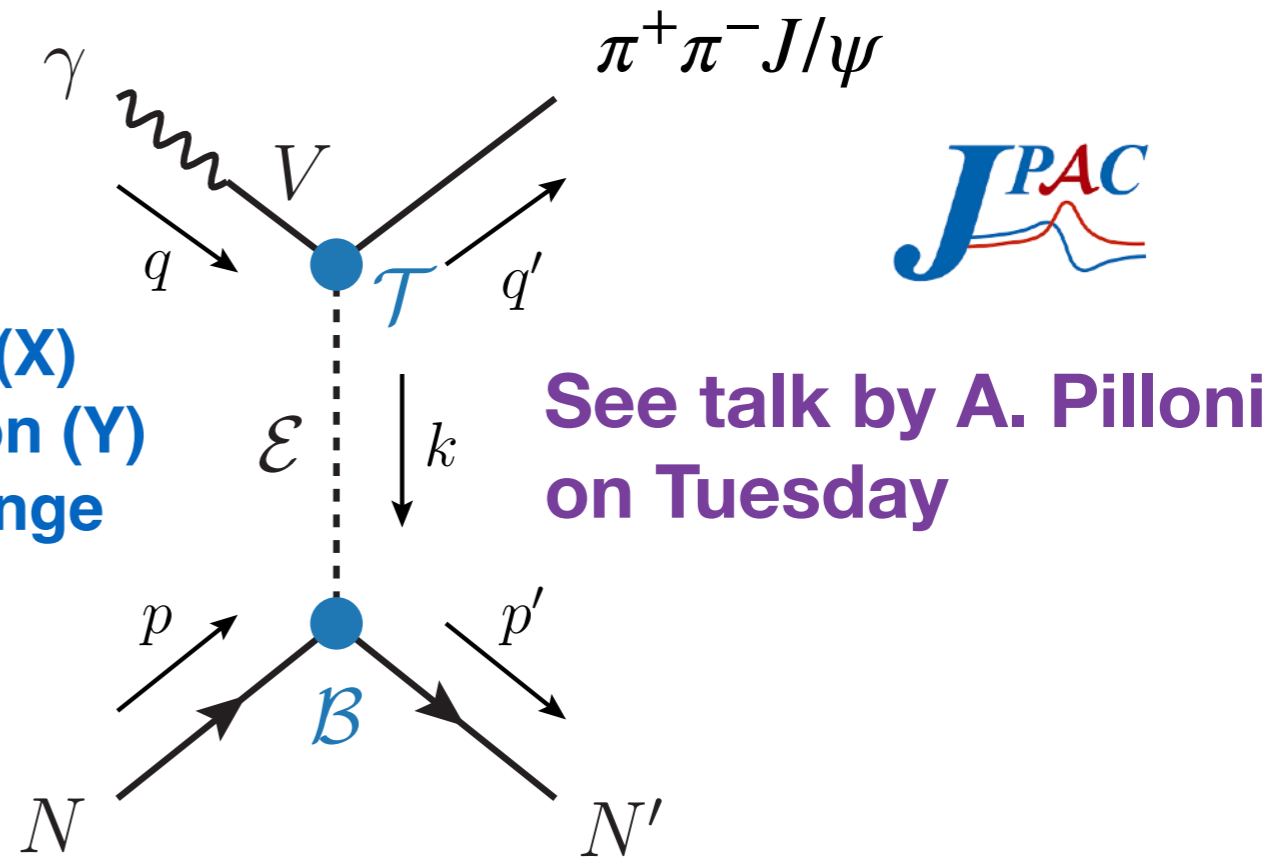
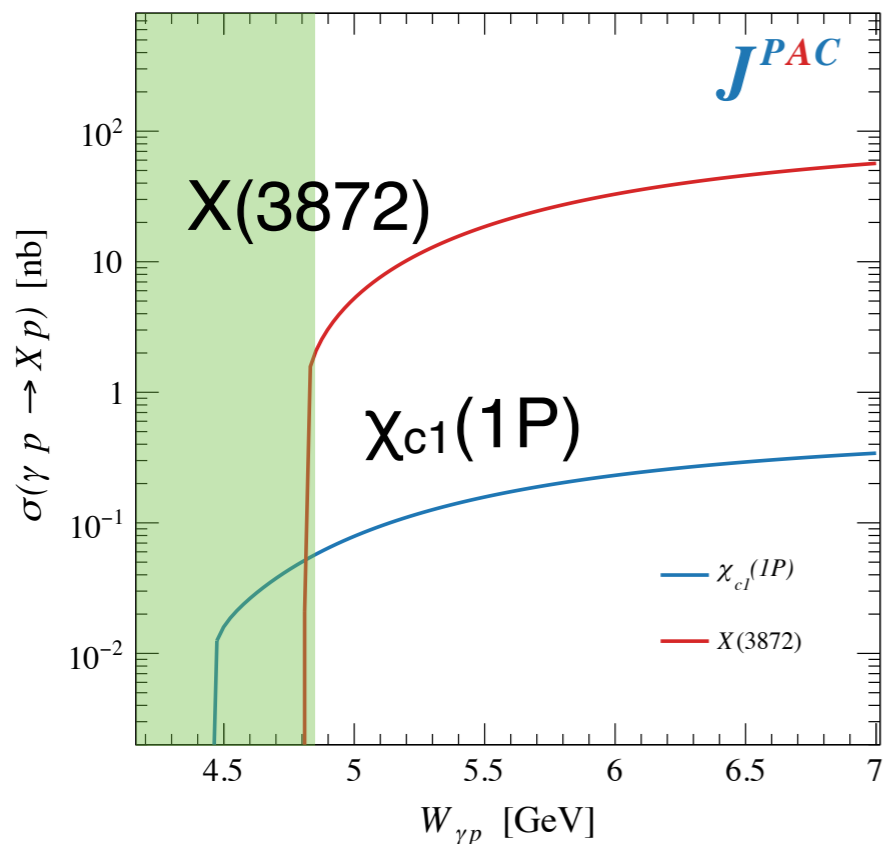
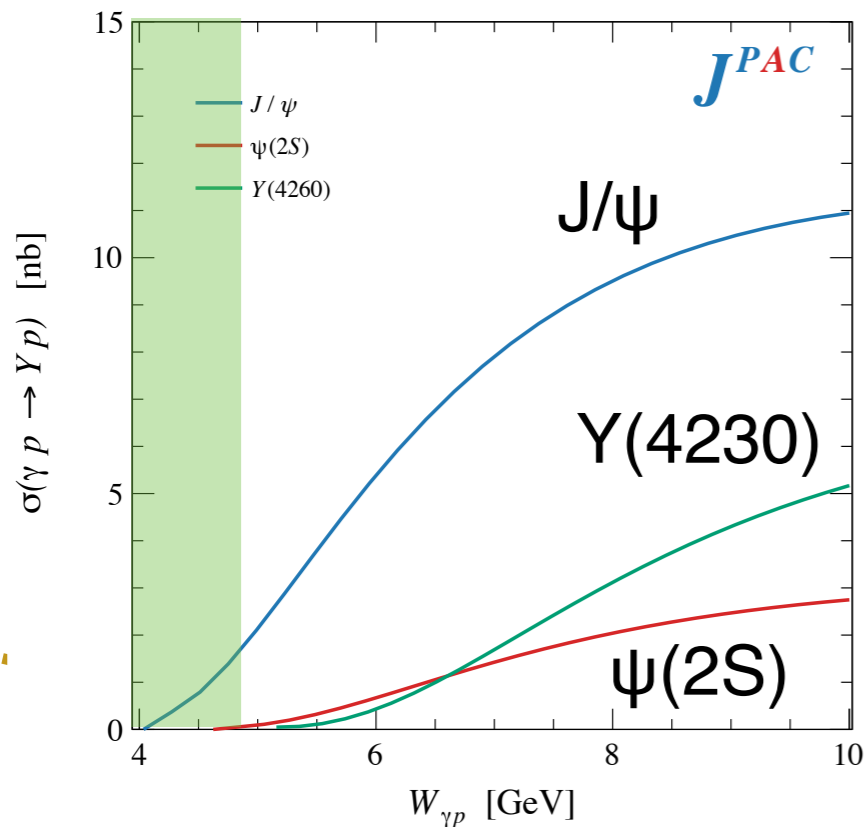
- Differential cross sections generally consistent with expectations of gluonic exchange, except near threshold

# Charmonium Photoproduction Near Threshold



- Thresholds for states above the  $D\bar{D}$  threshold extend to higher energies — future machines (EIC, JLab@22 GeV)

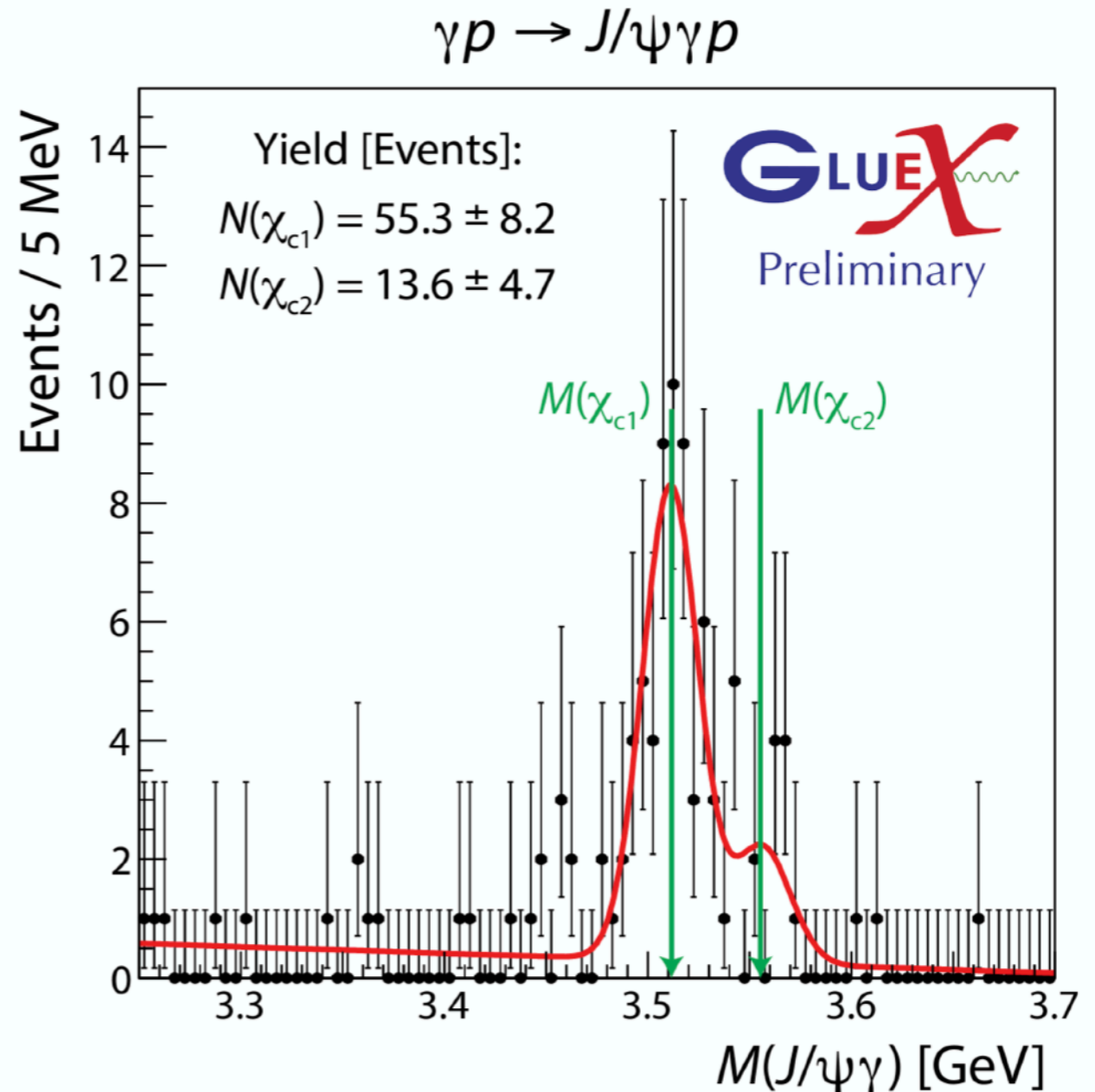
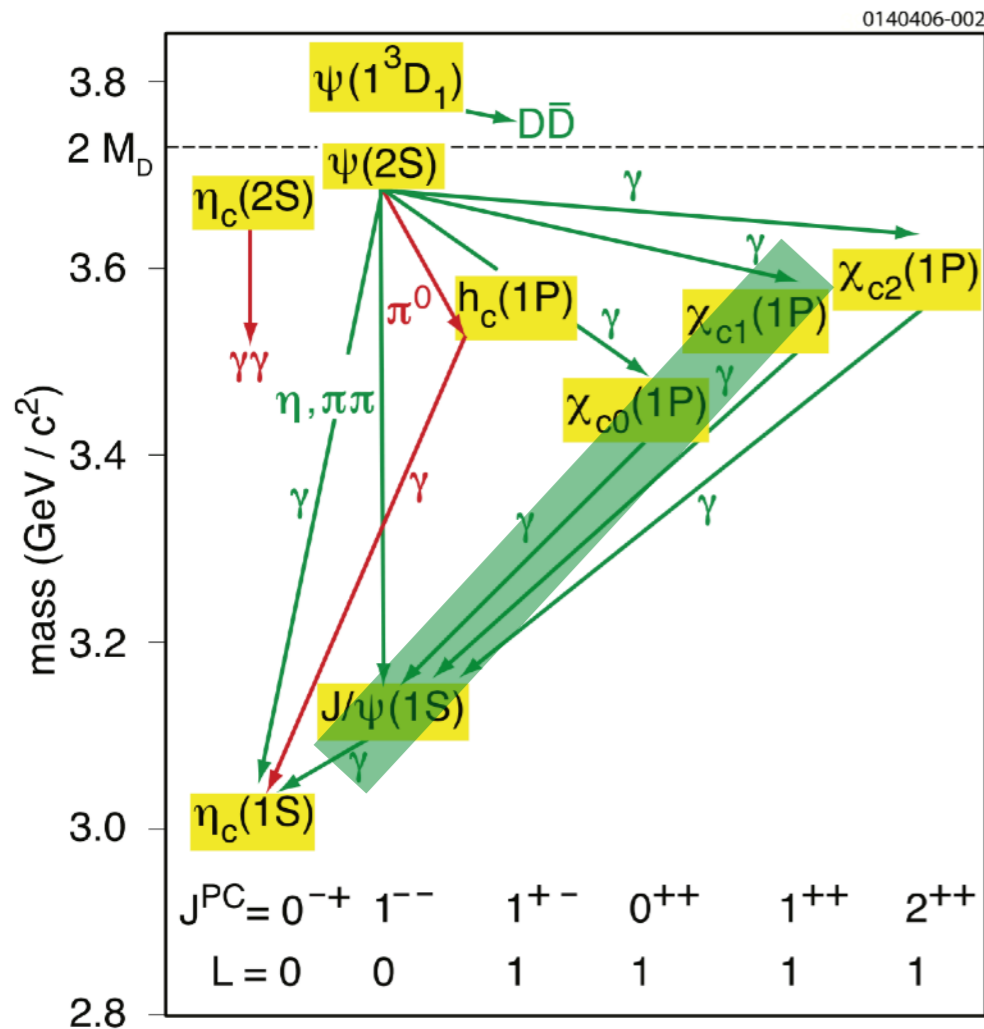
# JPAC predictions for higher energy photoproduction



PRD 102, 114010 (2020)

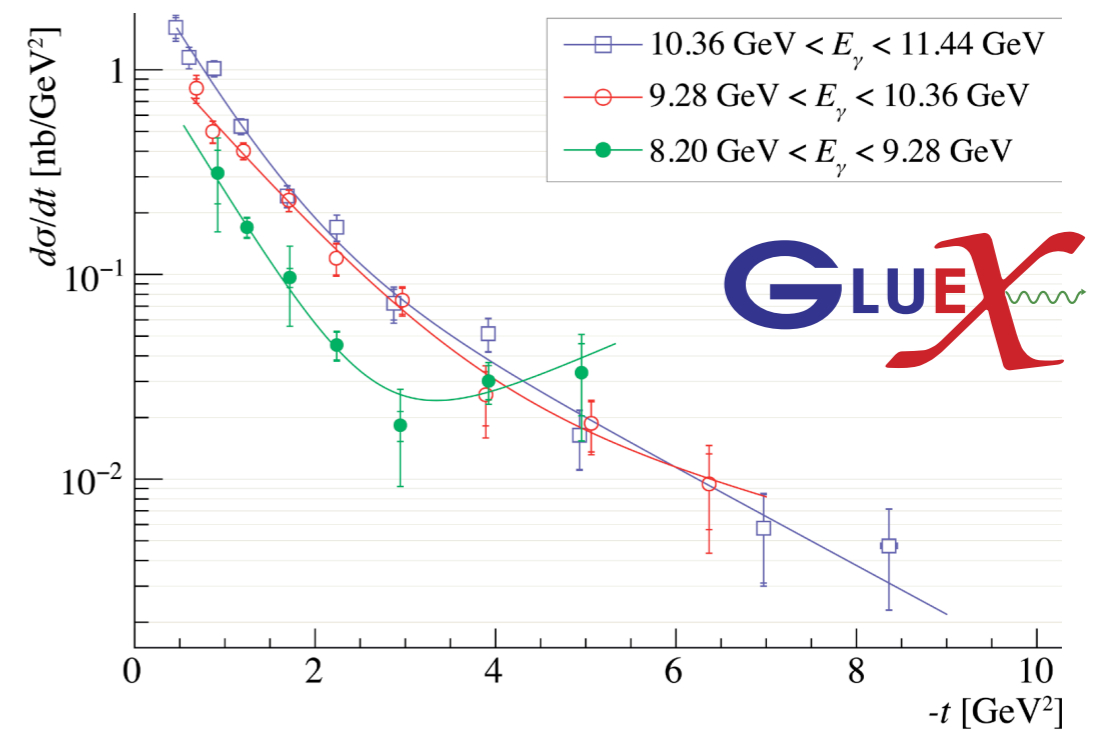
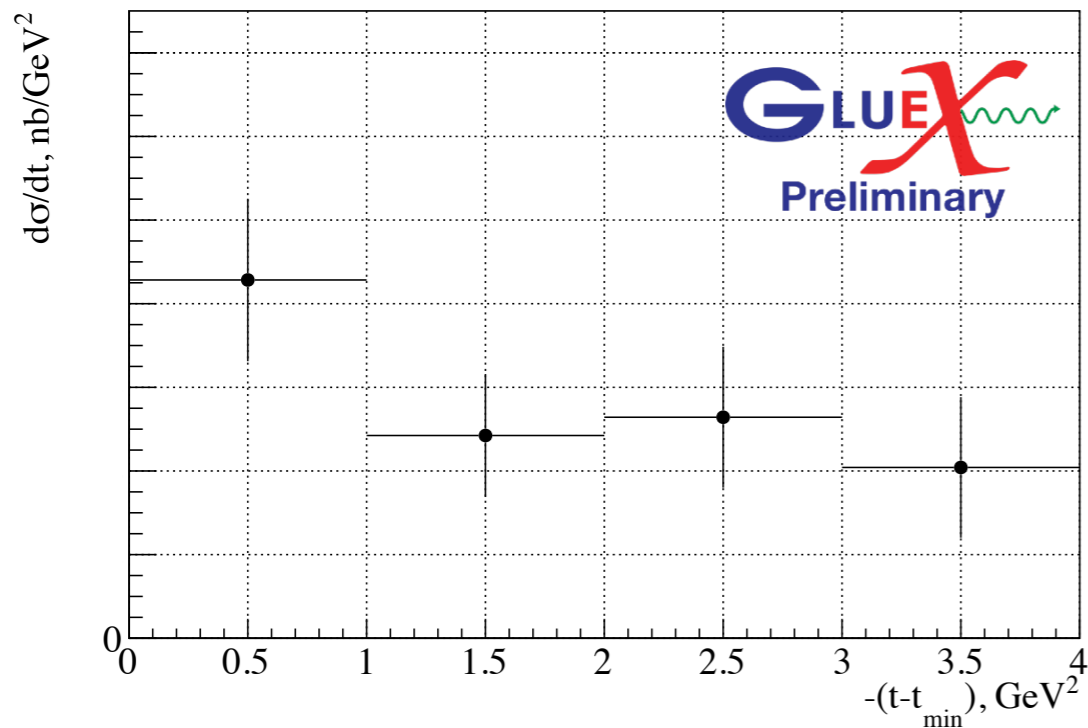
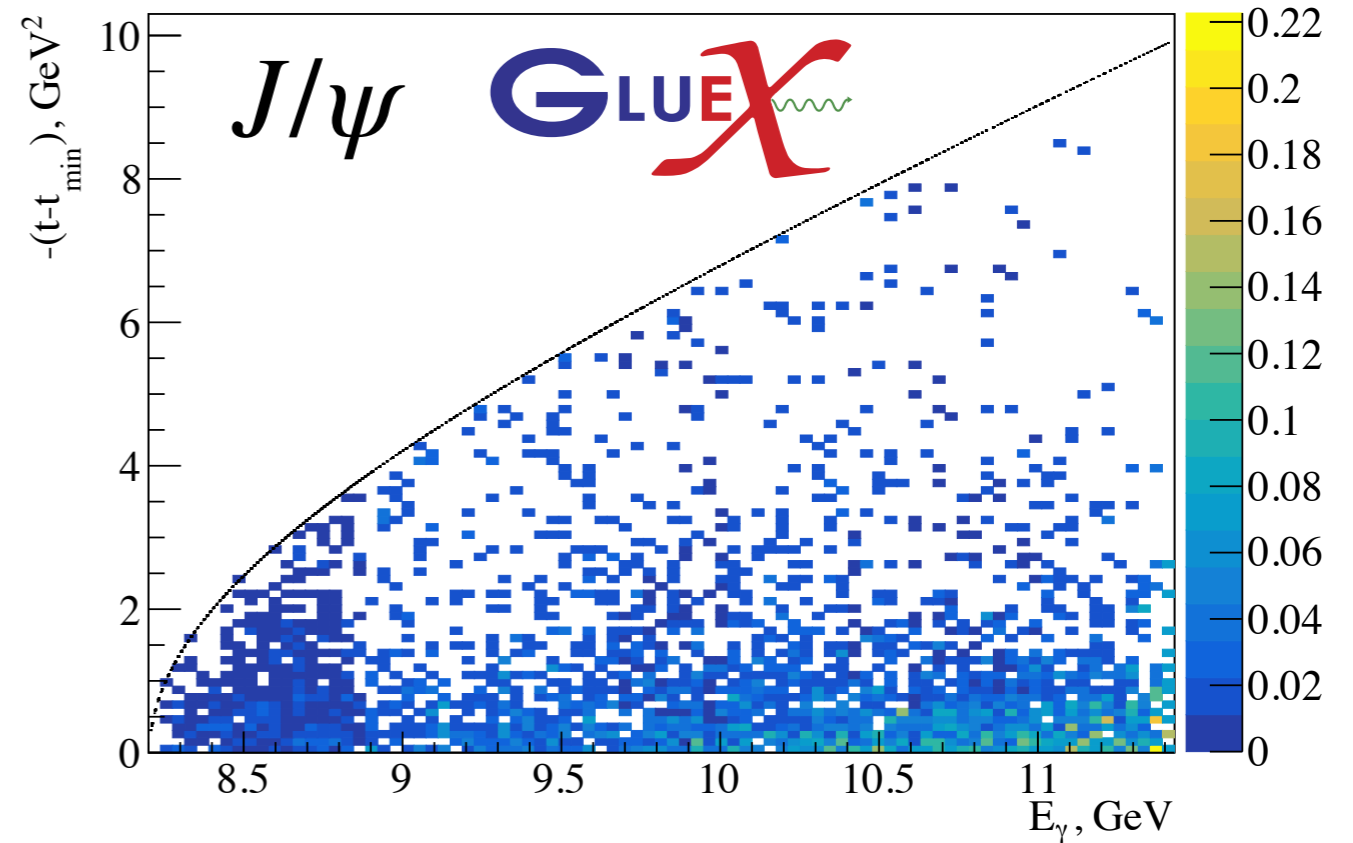
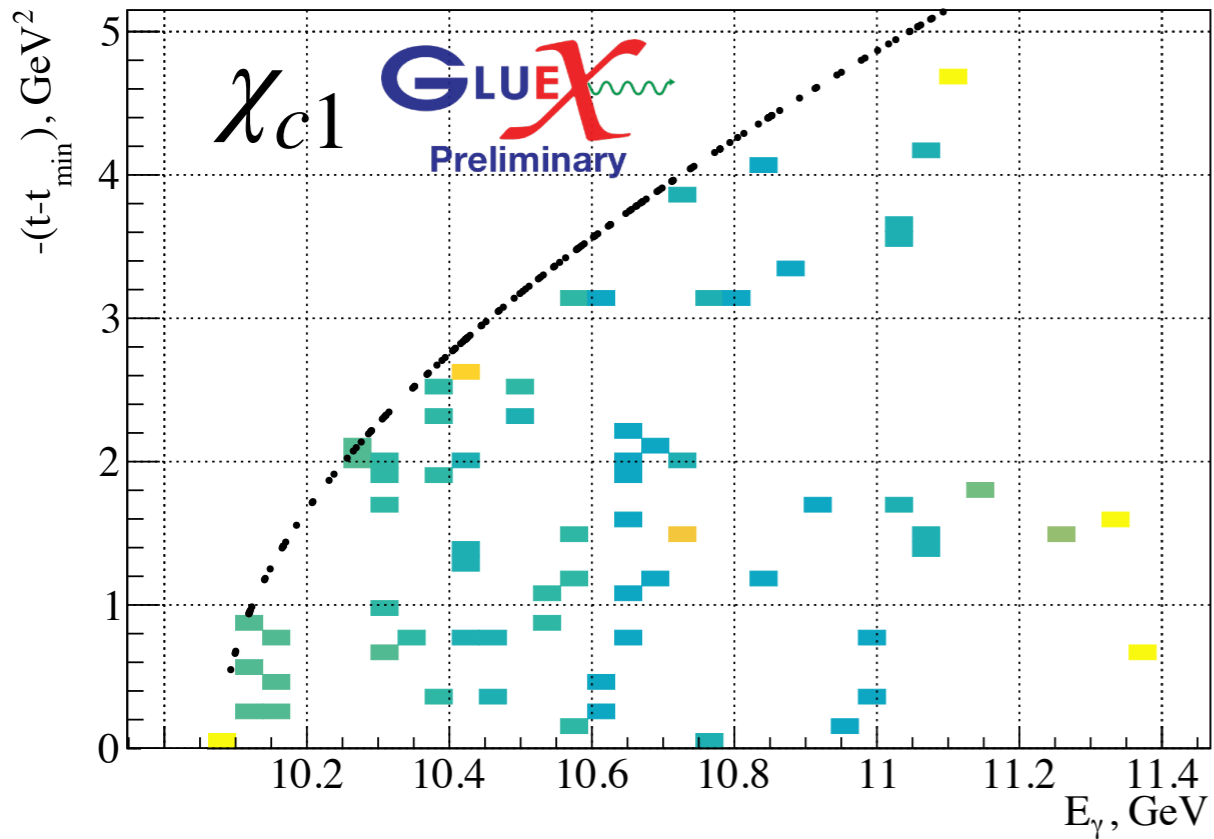
- JPAC predictions for higher energy photoproduction using fixed-spin exchanges near threshold
- GlueX can test model by measuring  $\chi_{c1}(1P)$ ,  $\psi(2S)$  production

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



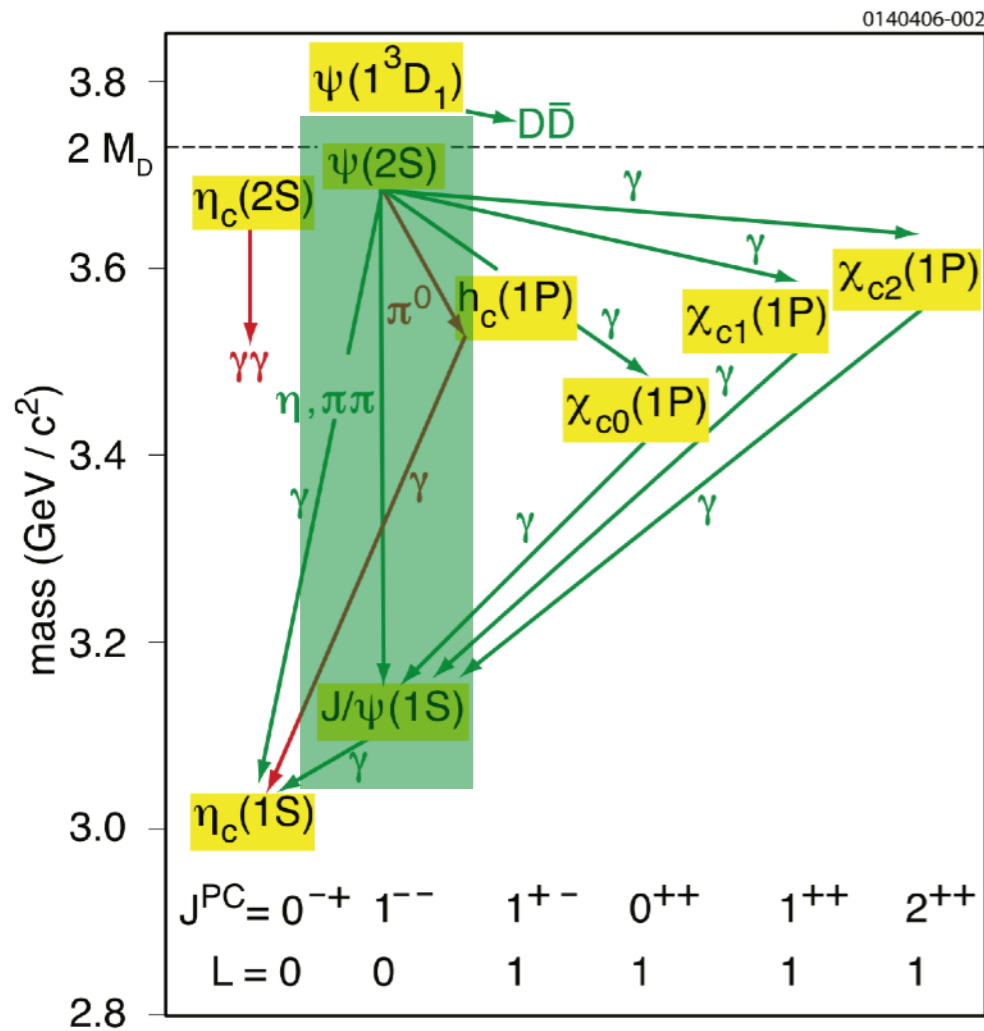
- $\chi_{c1}(1^{++})$  photoproduction: probe of different parity  $C=+$
- JPAC model estimate using known  $\chi_{c1} \rightarrow \gamma(\rho, \omega, \phi, J/\psi)$  couplings
- Look for  $\gamma p \rightarrow \chi_{cJ} p \rightarrow (\gamma J/\psi) p \rightarrow (\gamma e^+ e^-) p$

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



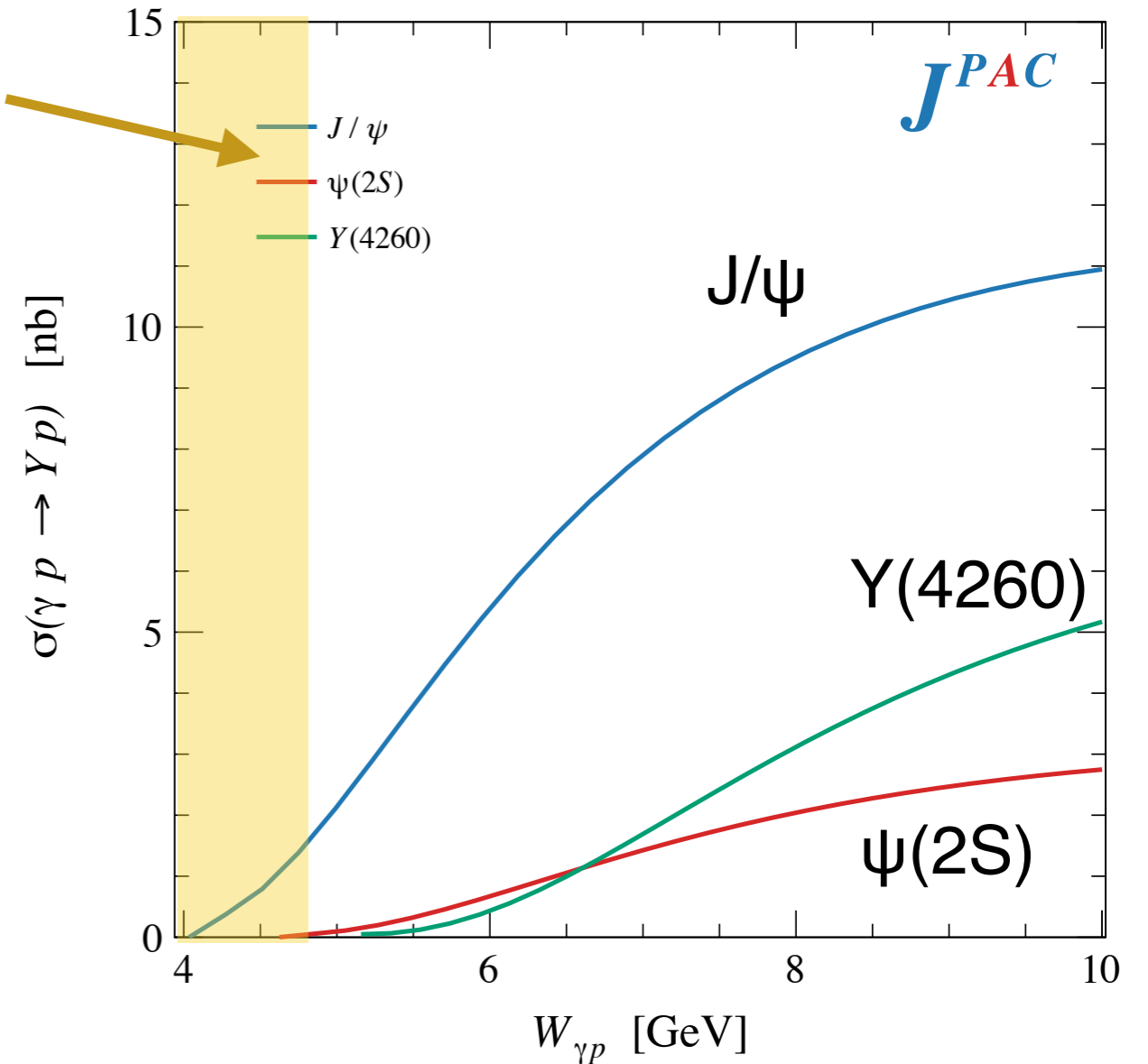


# $\psi(2^3S_1)$ Photoproduction at GlueX



GlueX  
energy  
range

JPAC: PRD 102, 114010 (2020)

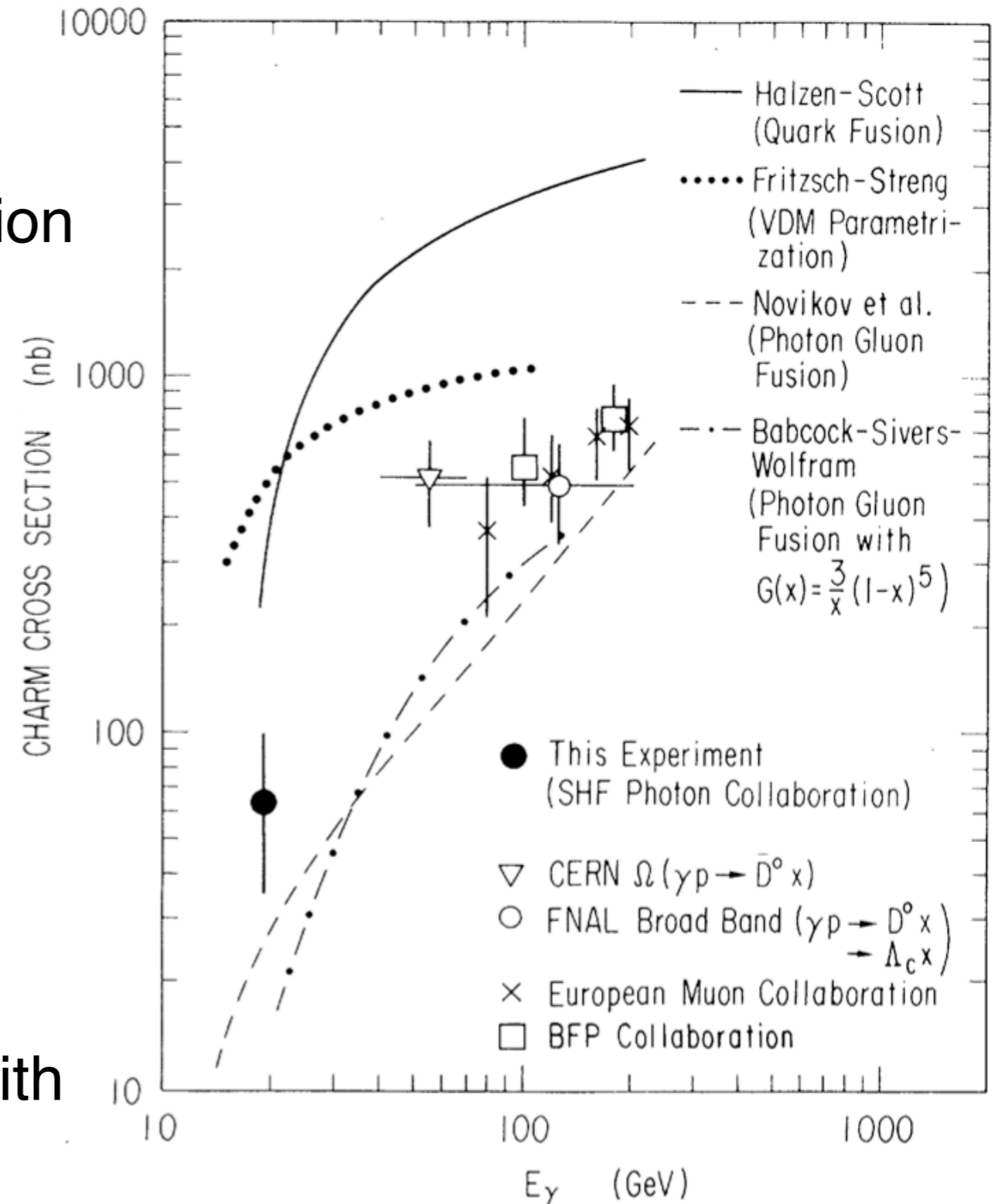


- $\psi(2S)$  photoproduction: probe of wave function dependence
- JPAC model estimates using known  $\Gamma_{\gamma gg}(\psi(2S)) / \Gamma_{\gamma gg}(J/\psi)$
- Can search for  $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi$  and  $\psi(2S) \rightarrow e^+ e^-$

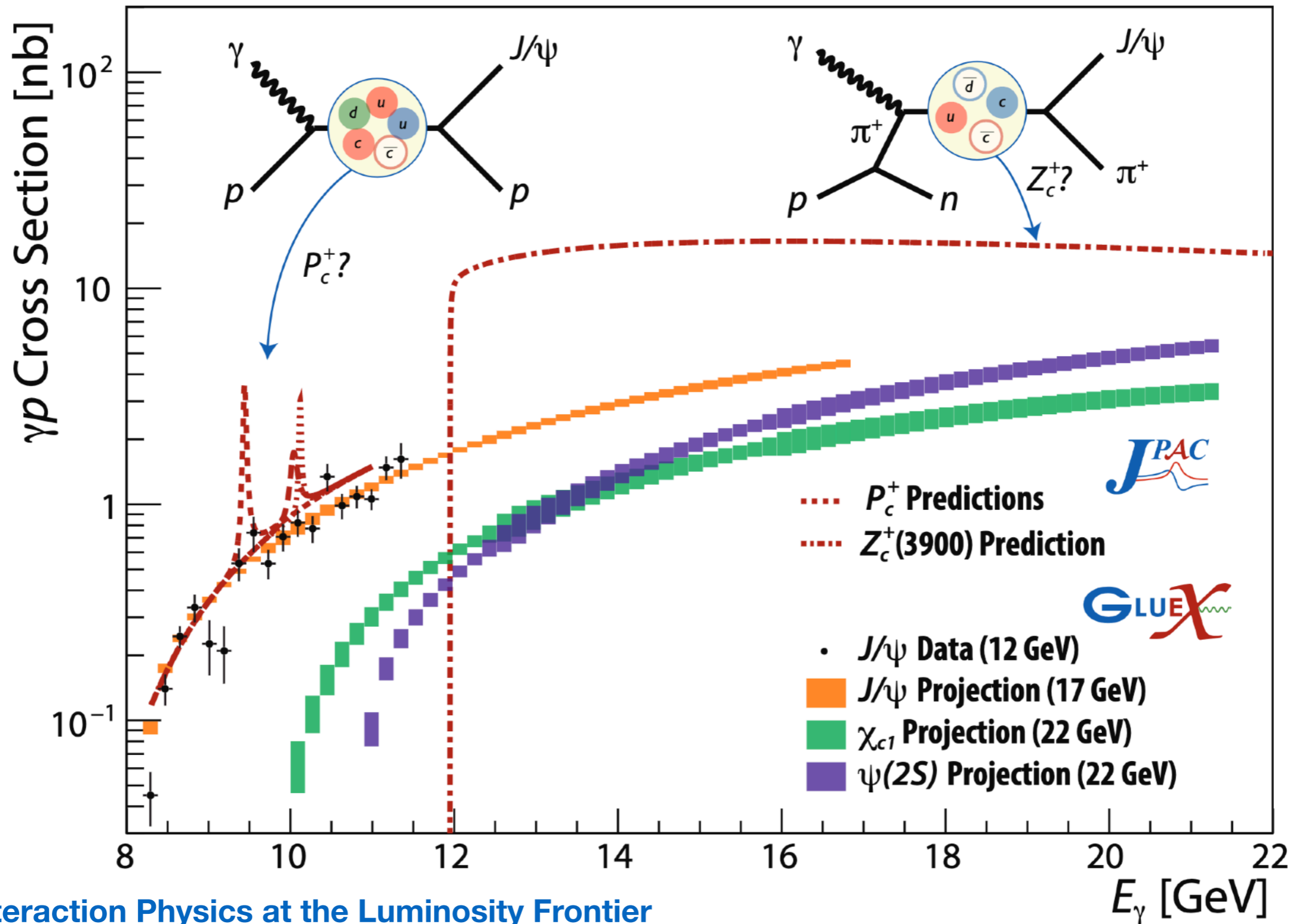
# Open Charm Production Near Threshold

PRL 51, 156 (1983)

- Hadron ( $c\bar{c}$ ) molecules like to decay to open-charm final states, can we see them at GlueX?
- Also will help with  $J/\psi$  interpretation
- Open charm photoproduction cross section measured at SLAC for  $E_\gamma \approx 20$  GeV based on  $\sim 50$  events
- Roughly 5-10 larger than  $J/\psi$  cross section
- Exclusive reconstruction of e.g.  $D^{(*)0} \Lambda_c^+$  is a factor  $\approx 25$  lower due to b.f.s
- Likely need full GlueX-II statistics with improved  $\pi/K$  separation



# Projections for Future JLab Upgrades



Strong Interaction Physics at the Luminosity Frontier  
with 22 GeV Electrons at Jefferson Lab - [arXiv:2306.09360](https://arxiv.org/abs/2306.09360)

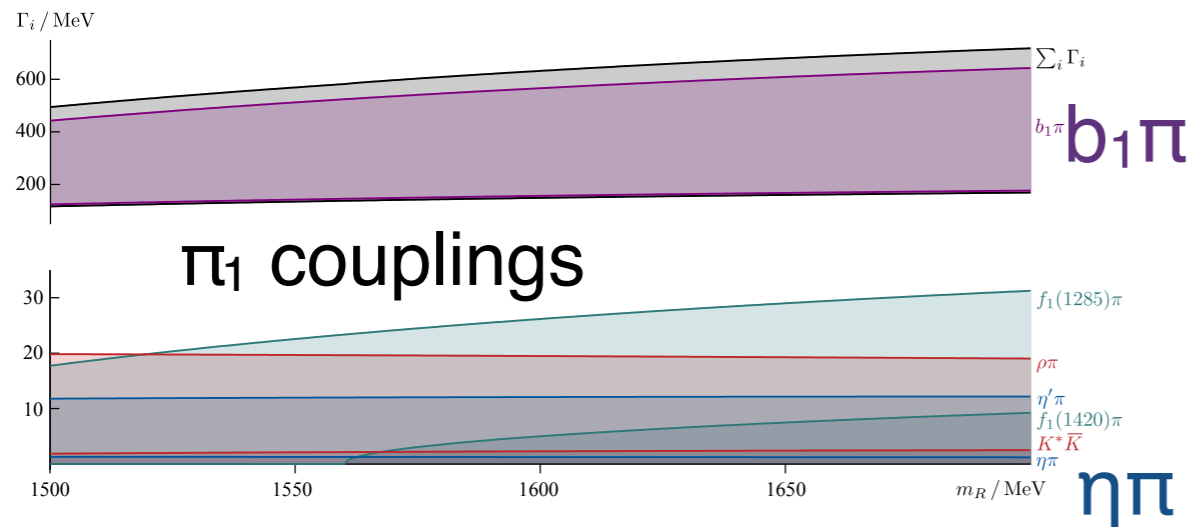
# Summary and Prospects

- GlueX has collected a large photoproduction dataset
- Amplitude analyses of light quark mesons under way
  - Excited vector mesons are near-term priorities
  - Searching for strange-quark XYZ analogues
- Measurements of  $J/\psi$  production near threshold show unexpected features
  - The ongoing GlueX-II run will provide more precision
- Other measurements of bound charmonia are possible with the growing GlueX data set
- GlueX-II run in progress, planned to end around 2025
  - Upgrades considered include GEM-TRD, high-luminosity GlueX-III, CEBAF energy upgrade
  - Other approved experimental programs includes JLab Eta Factory, spectroscopy with intense  $K_L$  beam ( $\approx 10^4/s$ ), polarized target

# Backup Slides

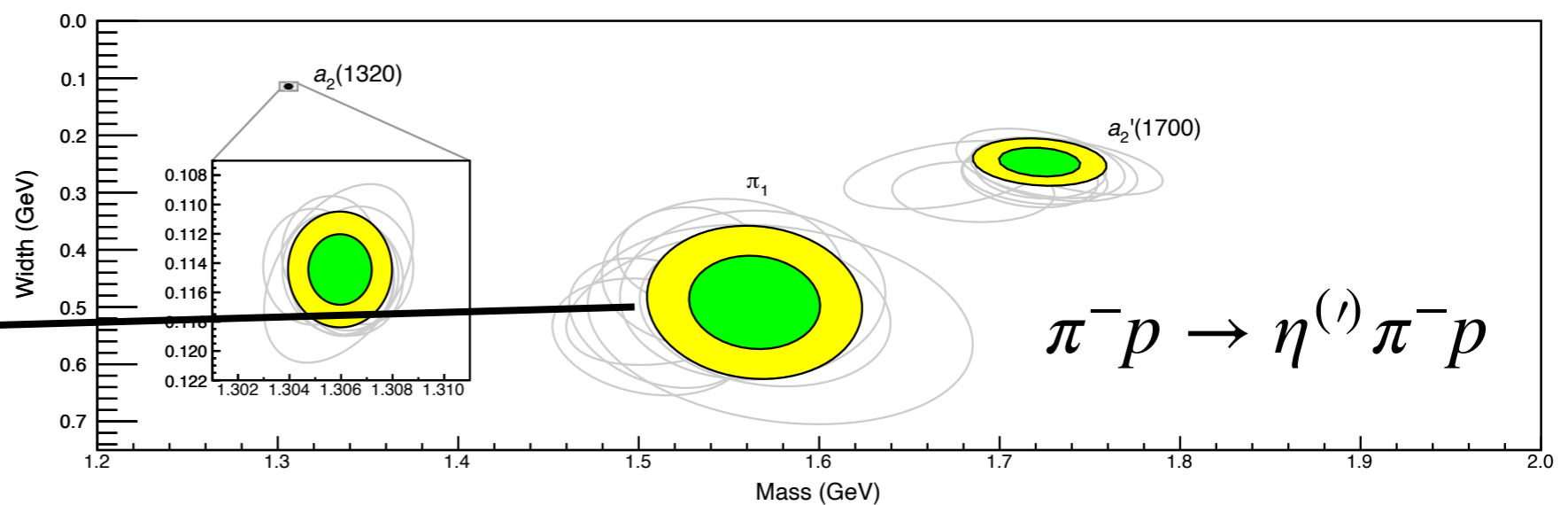
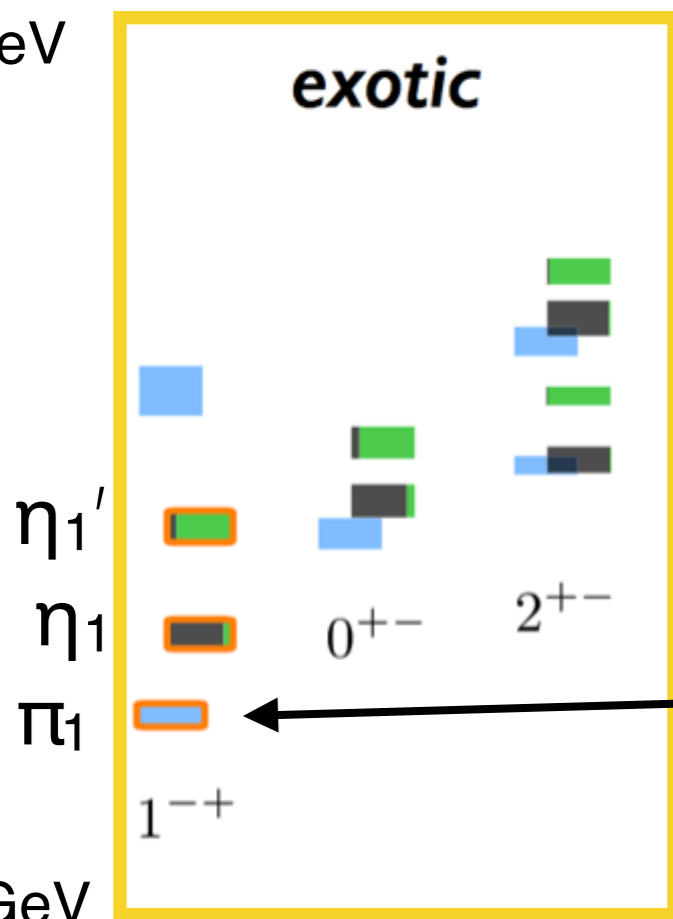
# Hybrid Mesons

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  $\eta_1^{(')}$  from BES-III in  $J/\psi \rightarrow \gamma \eta \eta'$  [[PRL 129, 192002 \(2022\)](#)]
- Need to confirm  $\pi_1$  and  $\eta_1$  and establish the full light quark hybrid spectrum

3 GeV



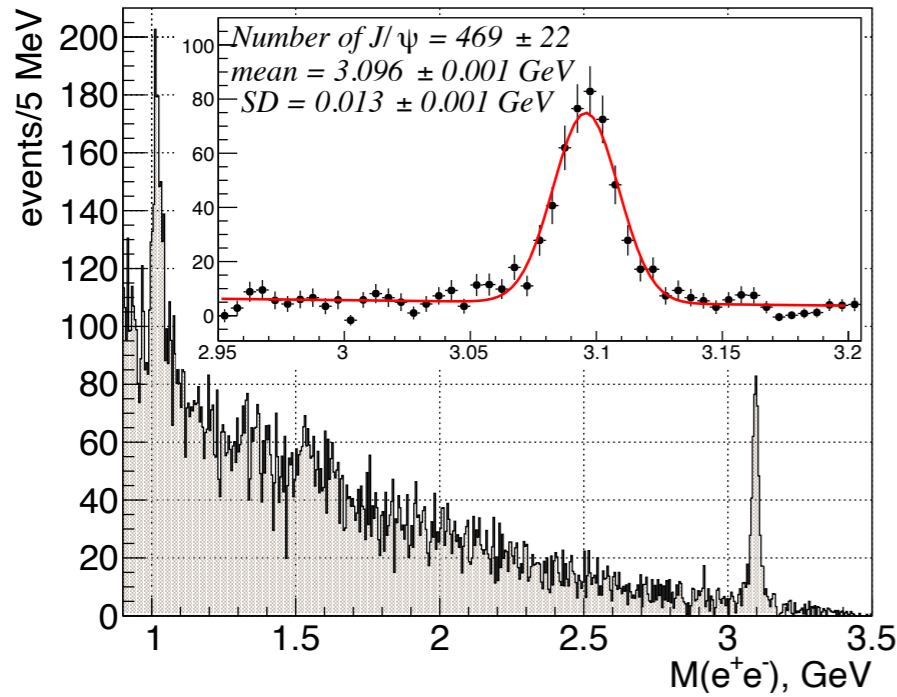
HadSpec: PRD 88, 094505 (2013)

JPAC: PRL 122, 042002 (2019)

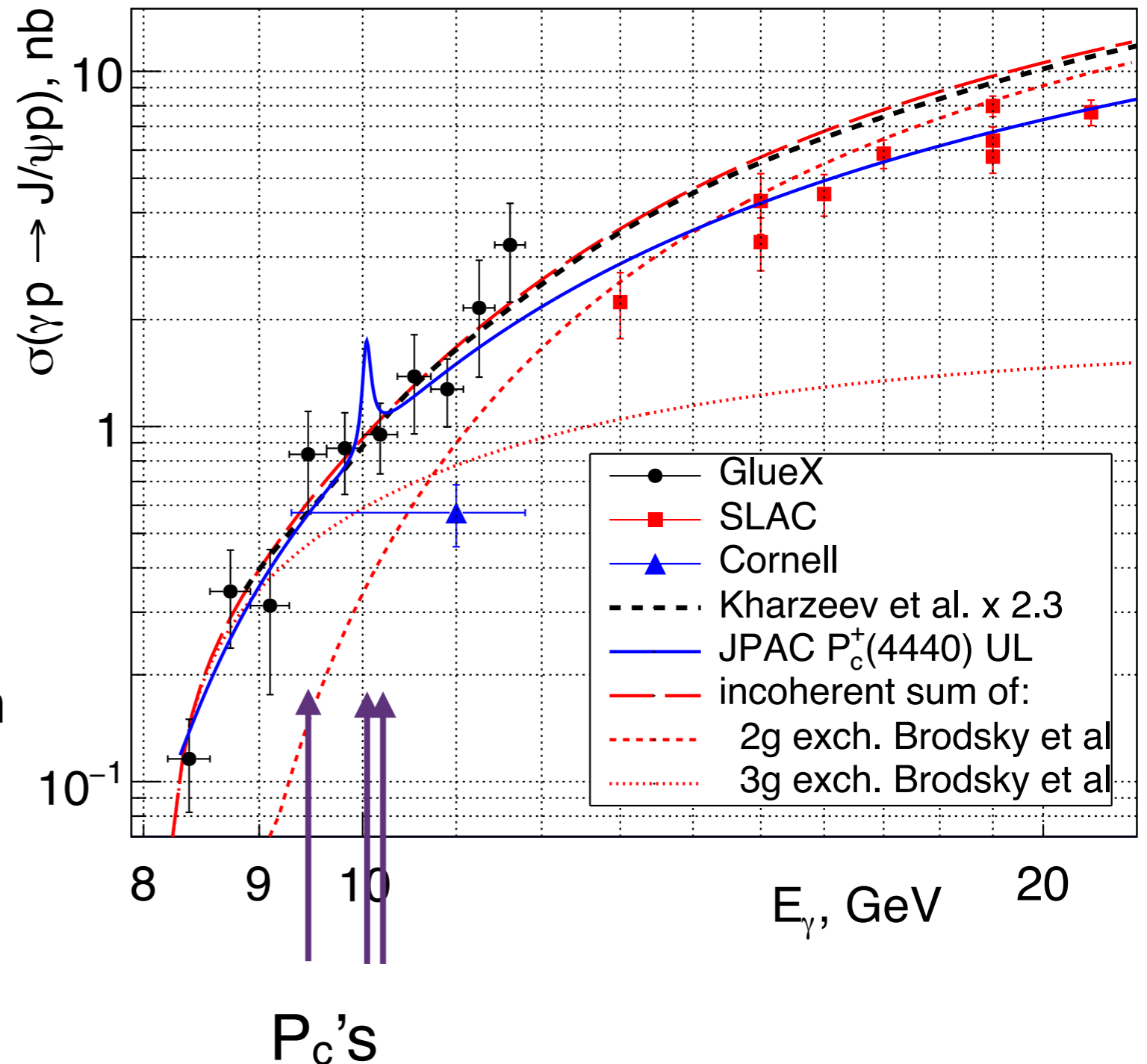


# Published GlueX $J/\psi$ Photoproduction Results

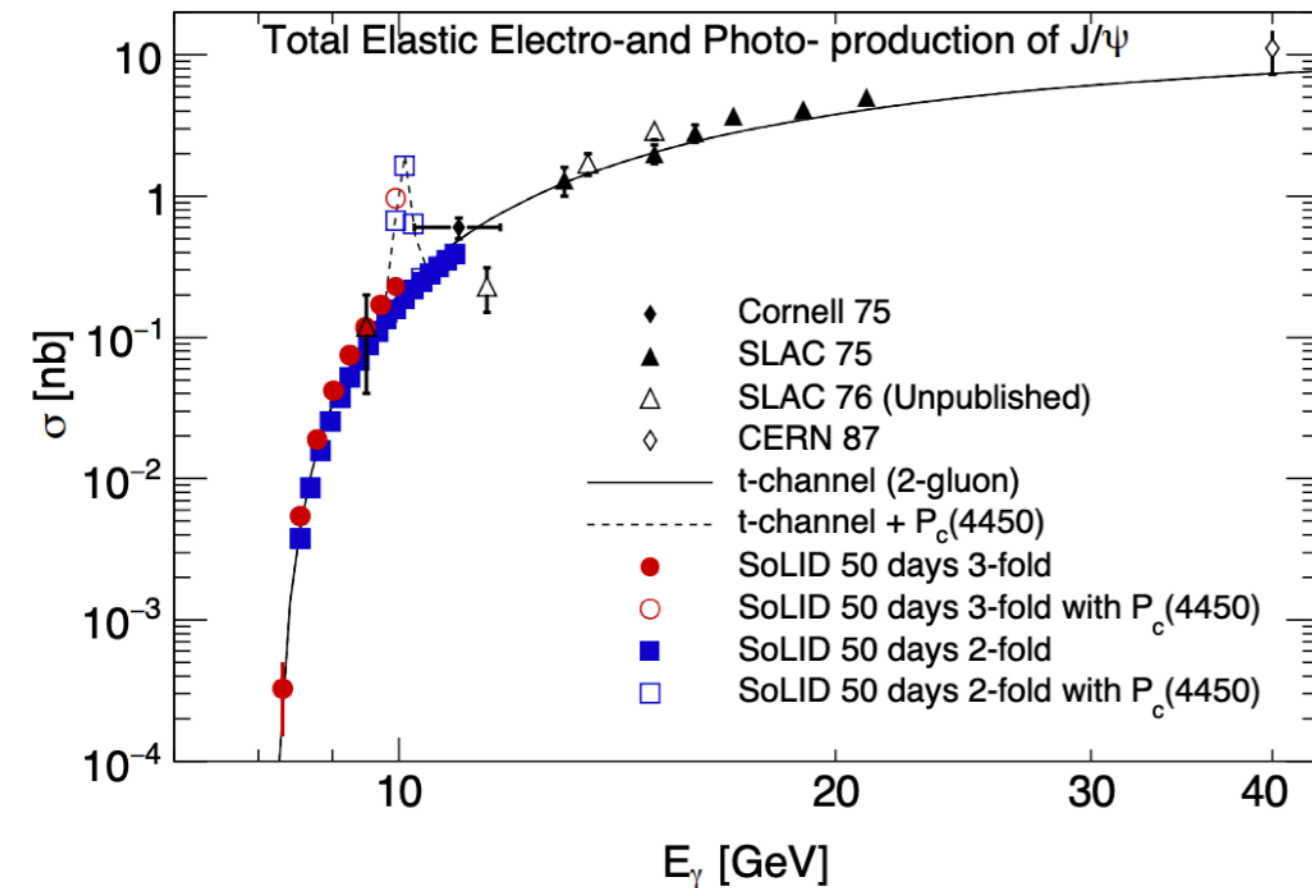
GlueX: PRL 123, 072001 (2019)



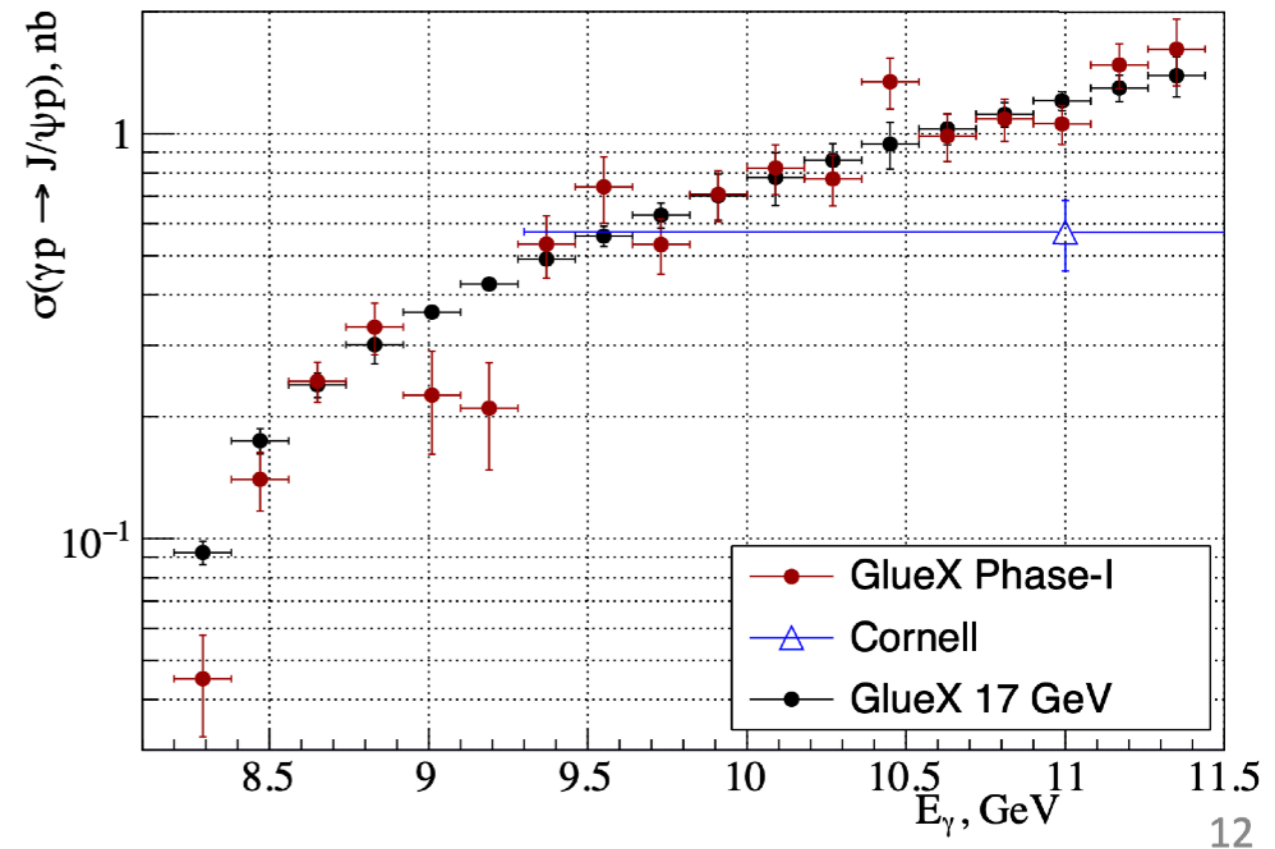
- Used portion of GlueX-I data [469  $J/\psi$ ] to measure cross sections
- Model-dependent limits set on  $P_c$  production, molecular models preferred
- Limits depend on VMD + understanding of production mechanism



# Prospects for future $J/\psi$ production measurements



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

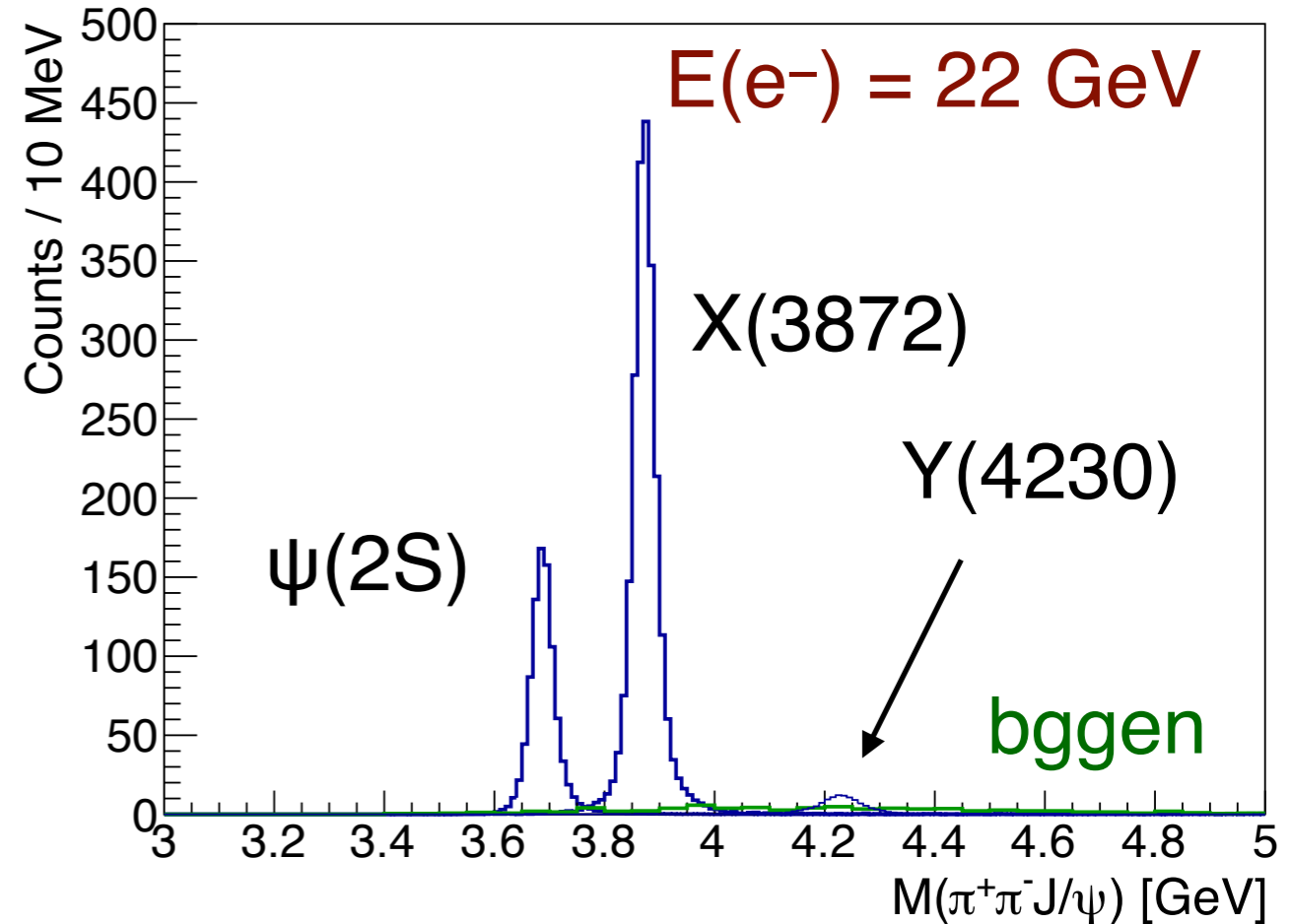
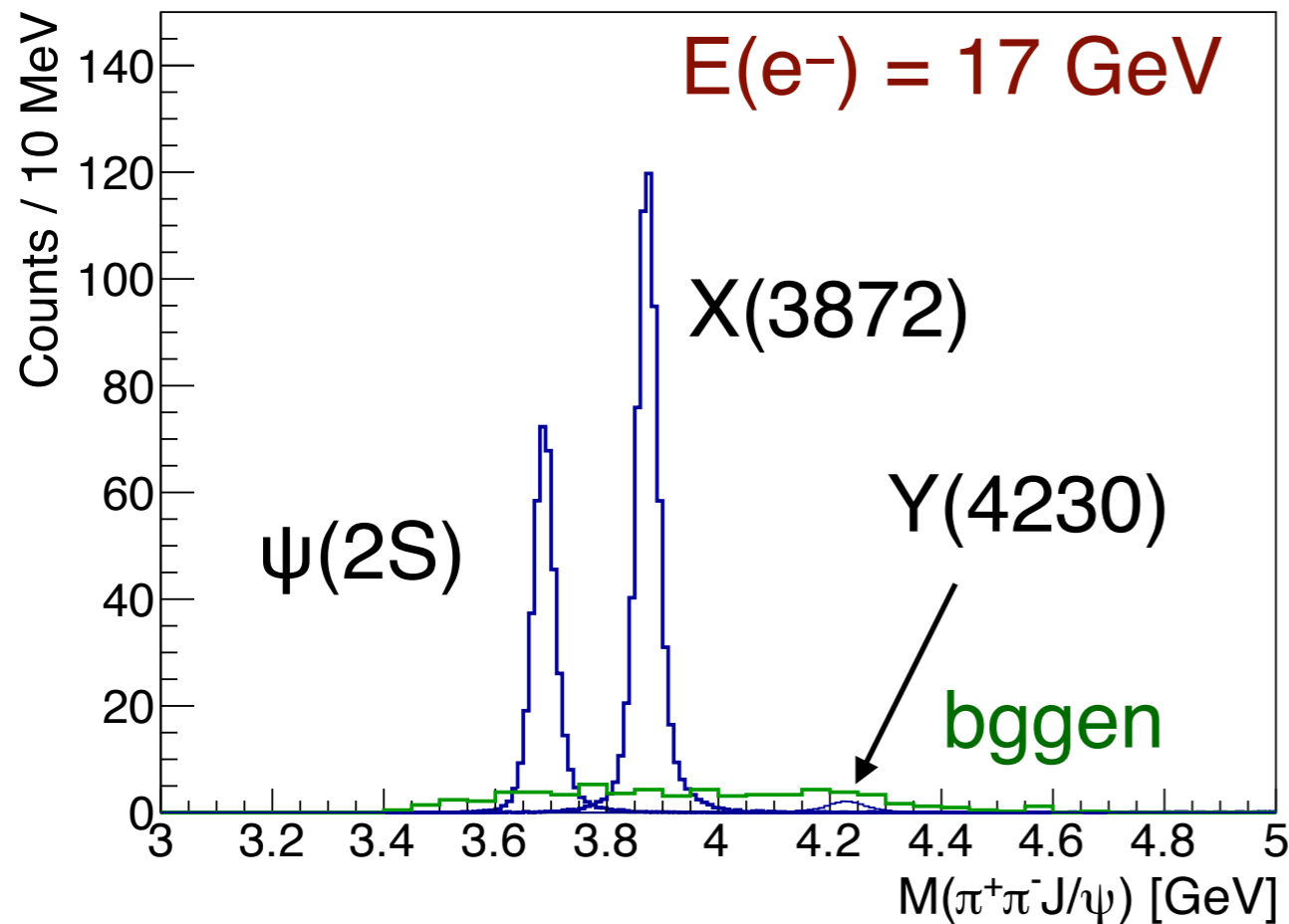


L. Pentchev,  $J/\psi$  + Beyond Workshop

- 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 ( $\mathcal{L} = 10^{37} \text{cm}^{-2} \text{s}^{-1}$ )
- More future: linearly polarized photoproduction at GlueX with energy-upgraded CEBAF

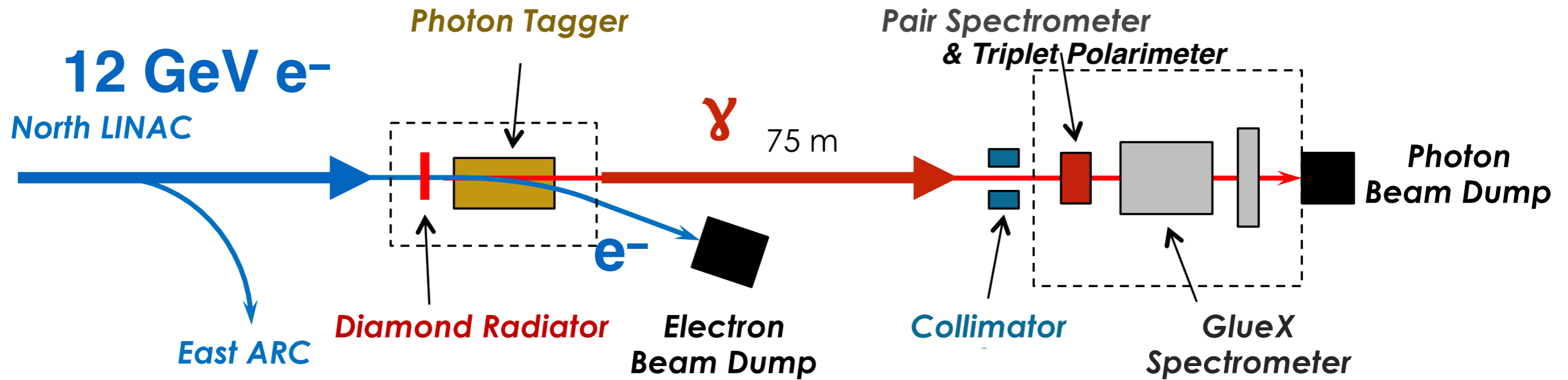
# Projections for $J/\psi\pi^+\pi^-$ Photoproduction at GlueX

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

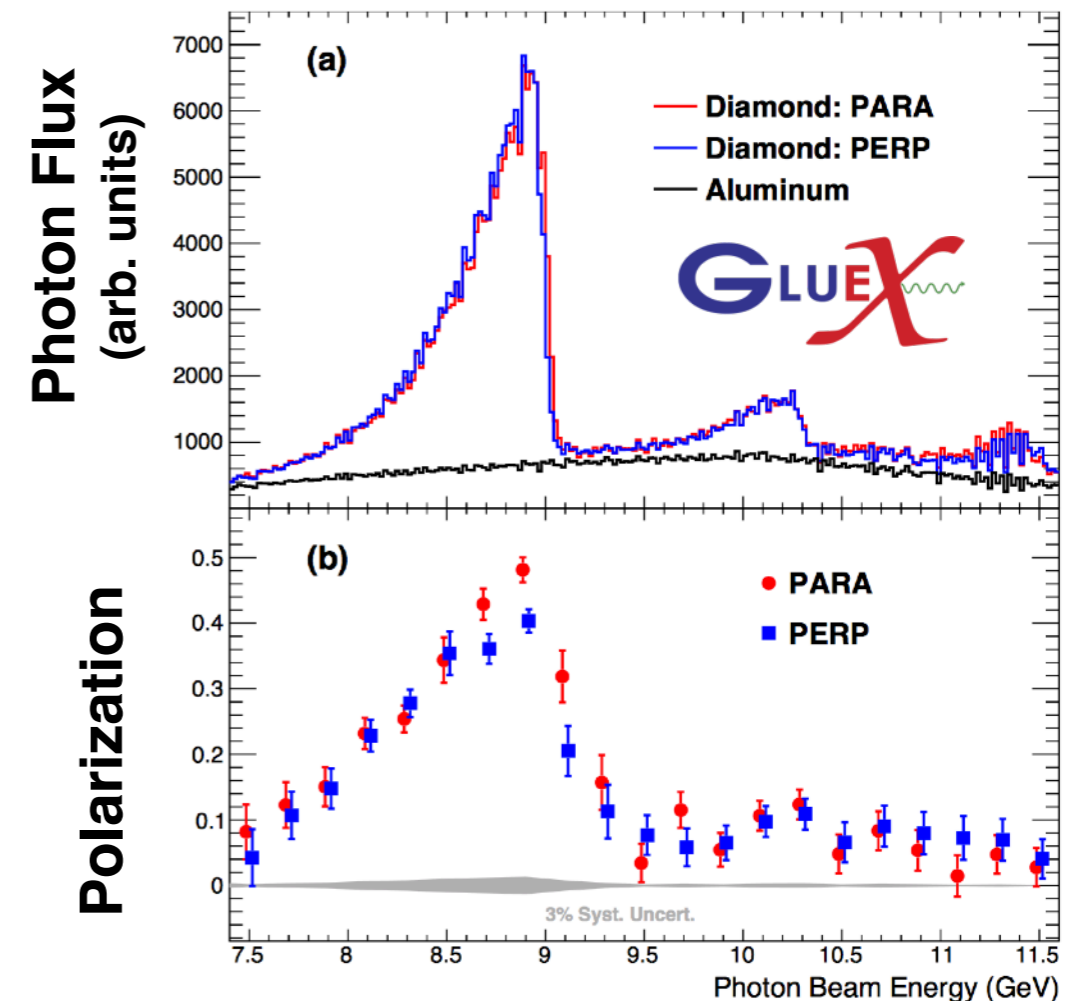


- Assumes 1 year @ 500 pb<sup>-1</sup>, Br(X, Y → π<sup>+</sup>π<sup>-</sup>J/ψ) = 5%
- 17 GeV: N(ψ(2S)) = 400, N(X(3872)) = 650, N(Y(4260)) = 20
- 22 GeV: N(ψ(2S)) = 900, N(X(3872)) = 2300, N(Y(4260)) = 120

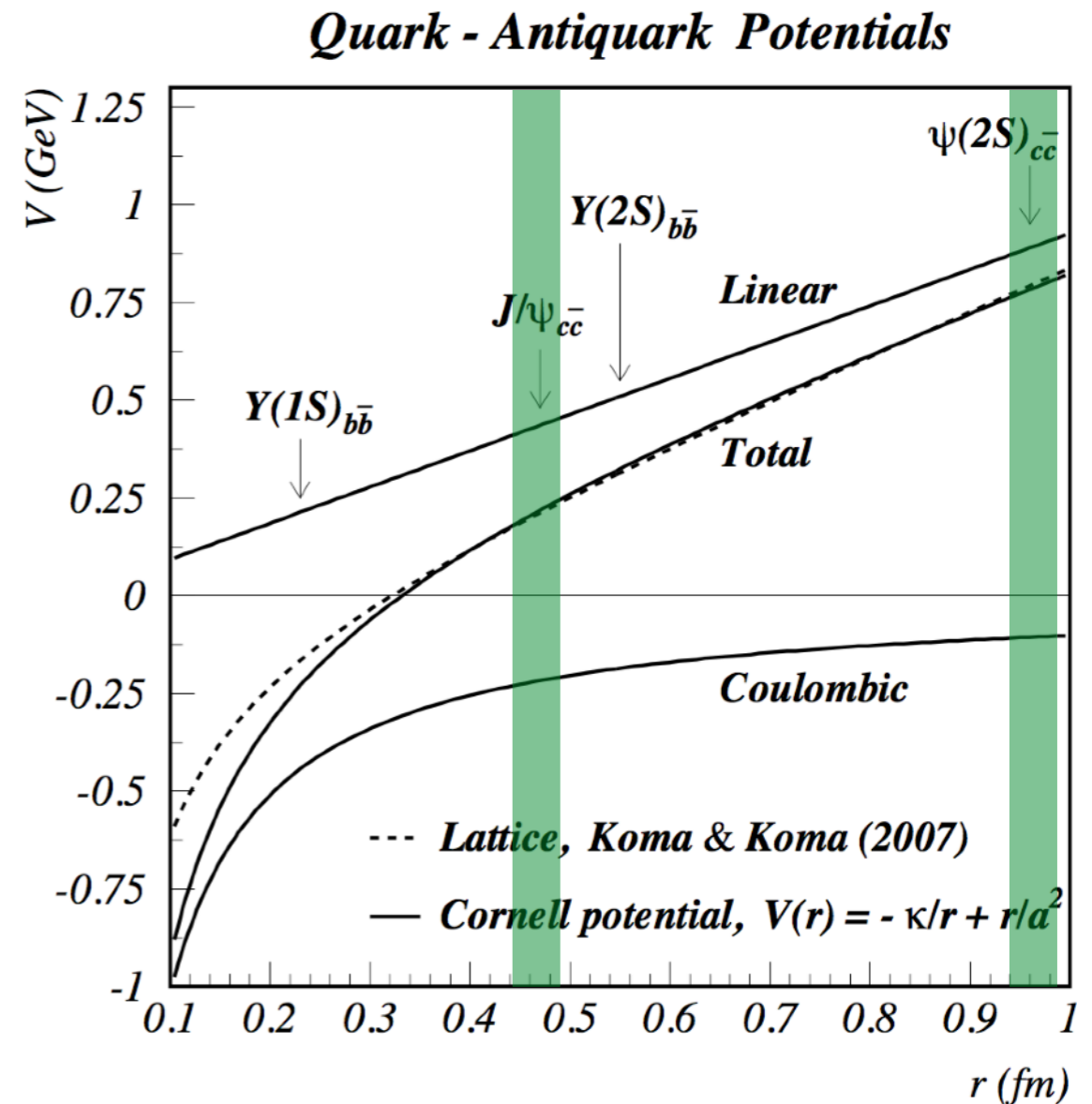
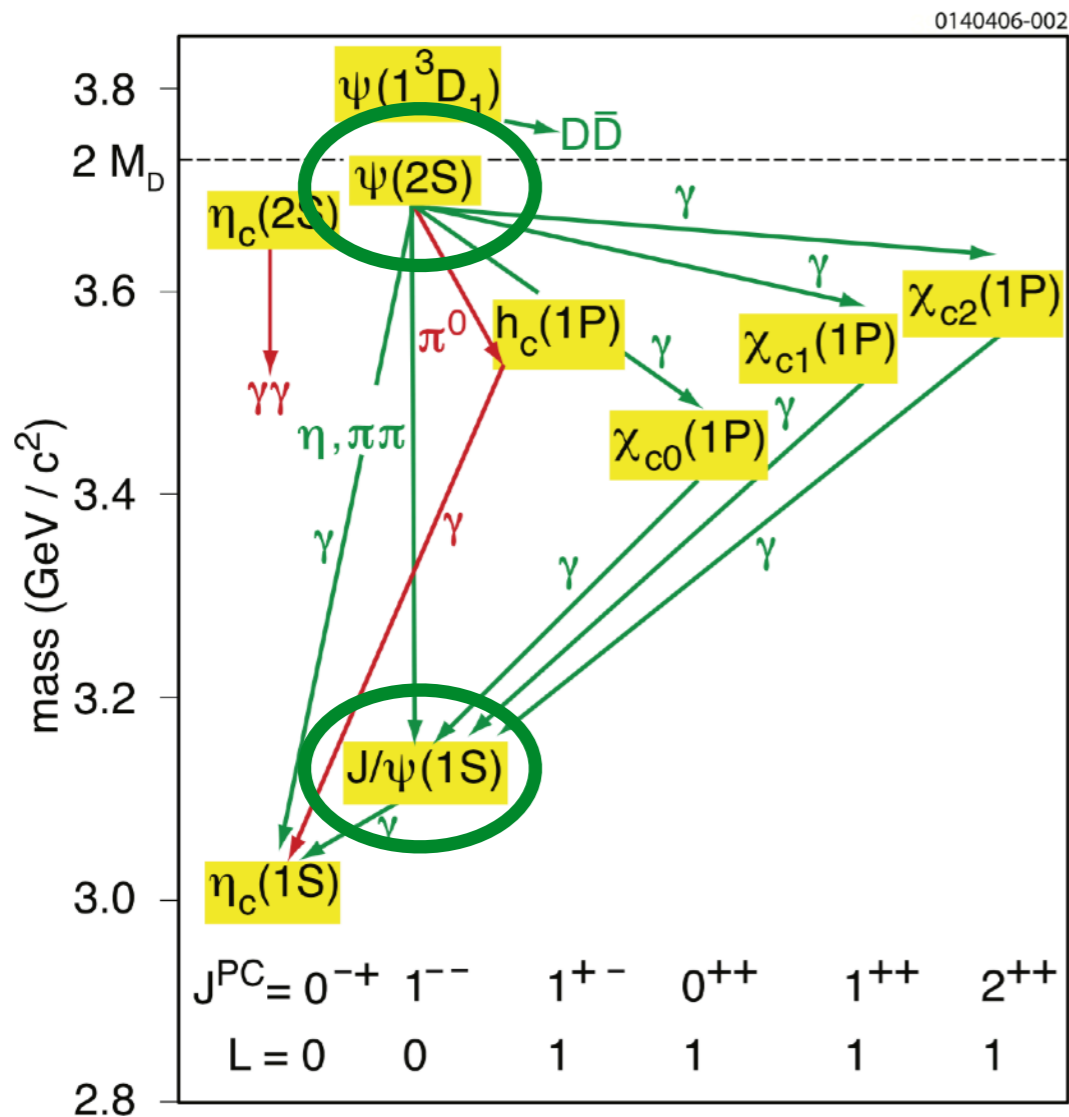
# The GlueX Experiment: Photon Beam



- 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  $\sim 1-5 \times 10^7$   $\gamma/s$  in peak



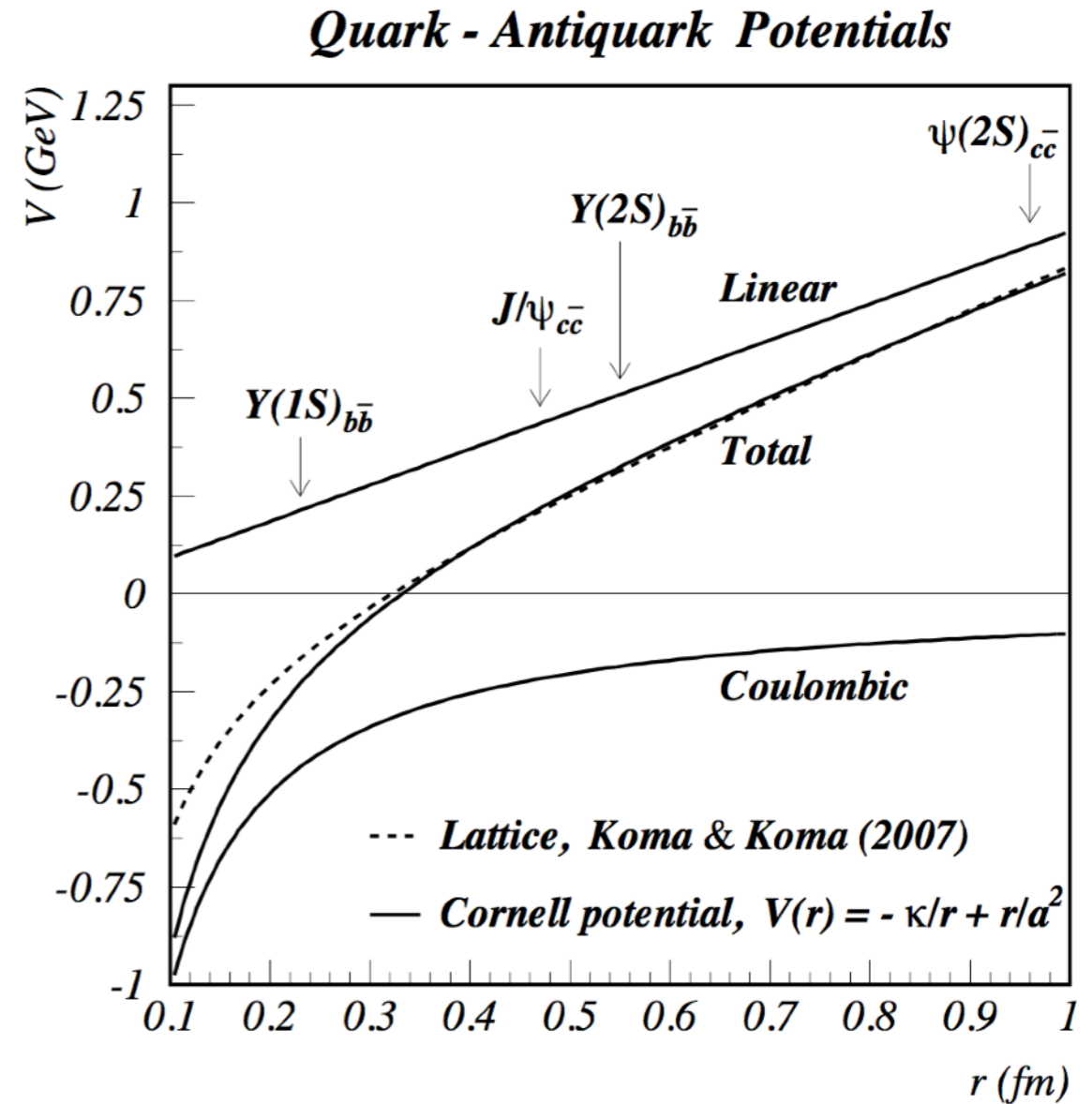
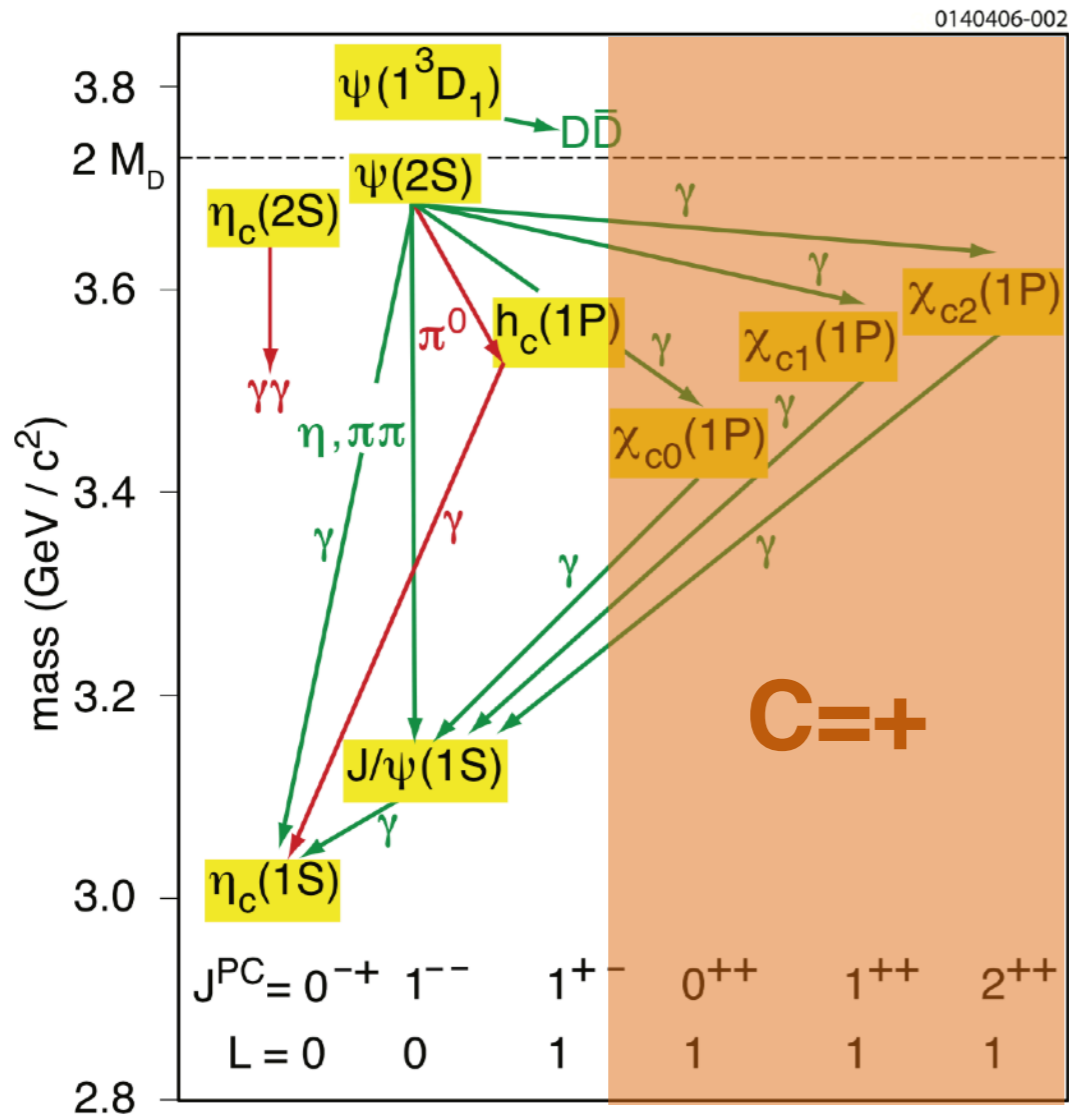
# The Charmonium ( $c\bar{c}$ ) Spectrum



- GlueX can access photoproduction of “bound” charmonia
- Idea: probe dependence of charmonium production based on size of system and different QNs



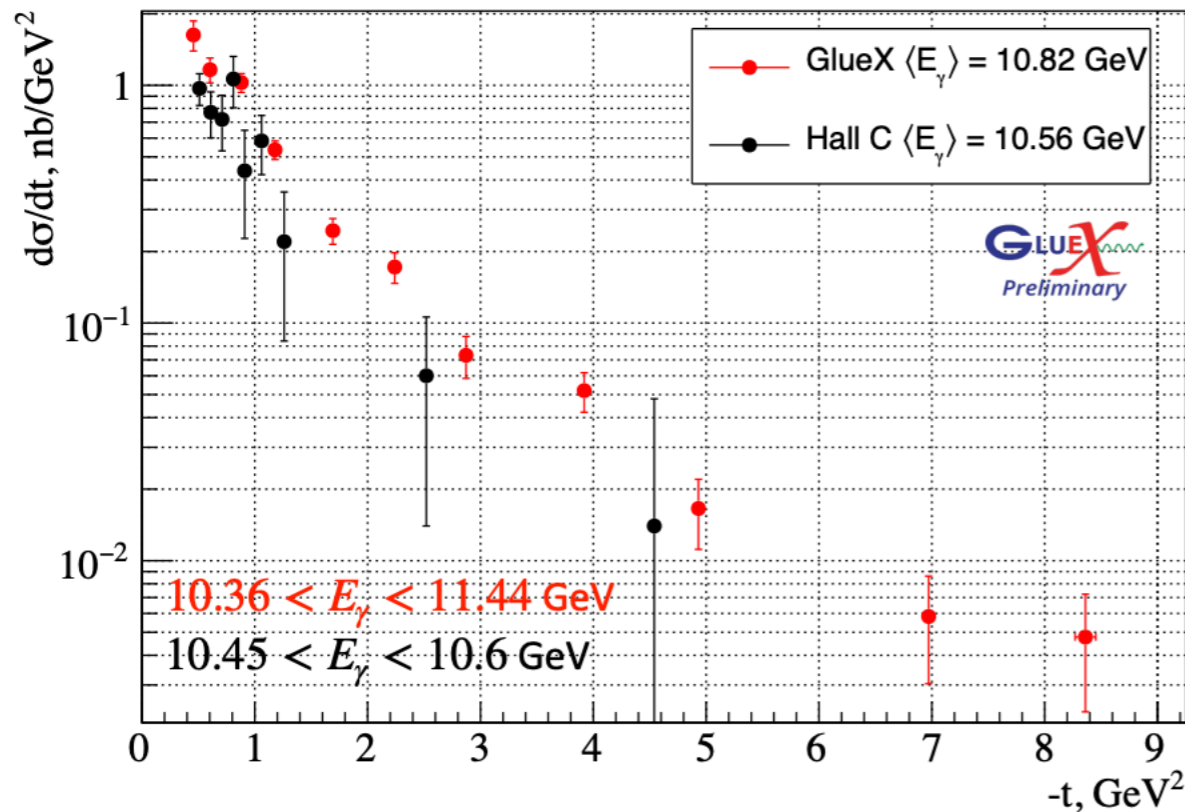
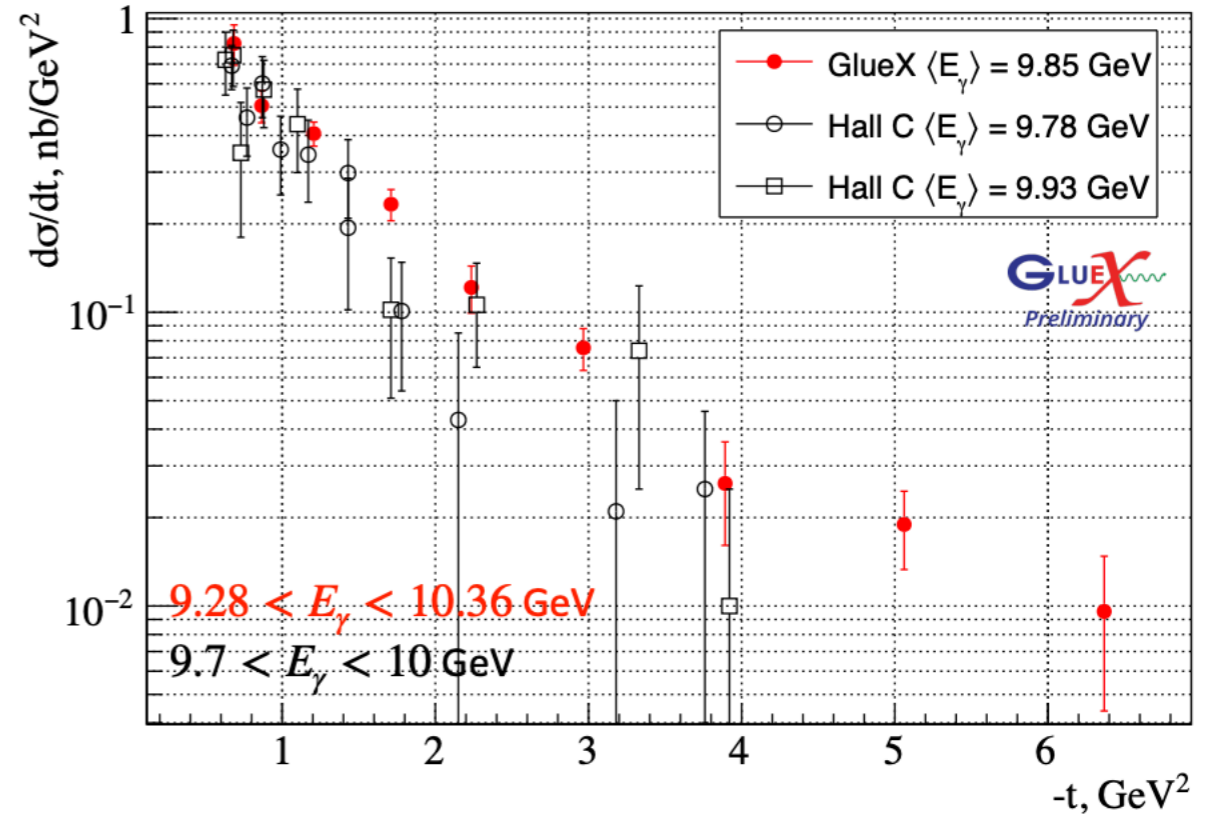
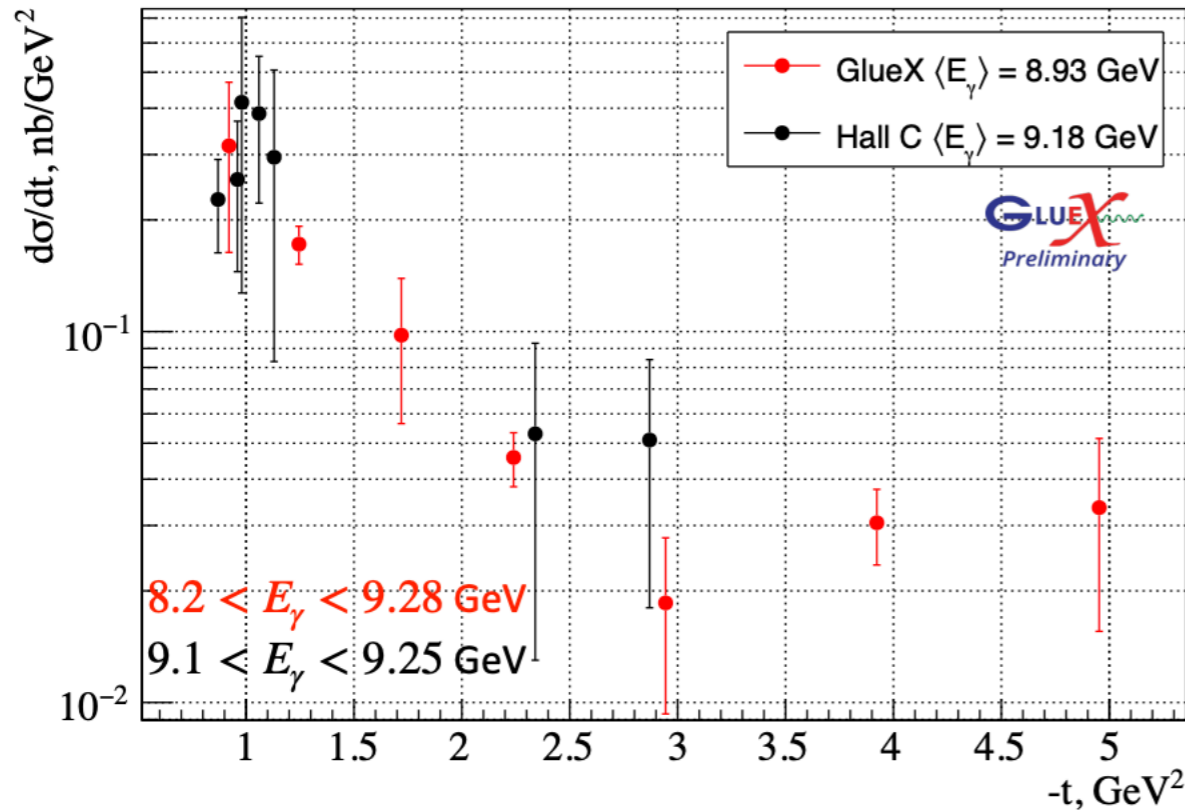
# The Charmonium ( $c\bar{c}$ ) Spectrum



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# Comparison between GlueX and J/ψ-007



- Three GlueX energies compared to closest Hall C (J/ψ-007) energies
- Shown only 4 out of 10 energies for Hall C - common fit of all 10 used to disentangle contributions from  $A_g(t)$  and  $C_g(t)$  (B.Duran <https://arxiv.org/abs/2207.05212>)
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- **Good agreement within the errors;** note also differences in average energies