Prospects for XYZ Spectroscopy at GlueX

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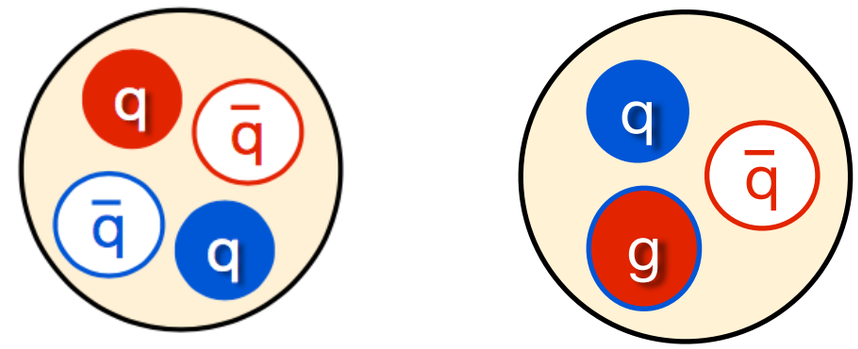
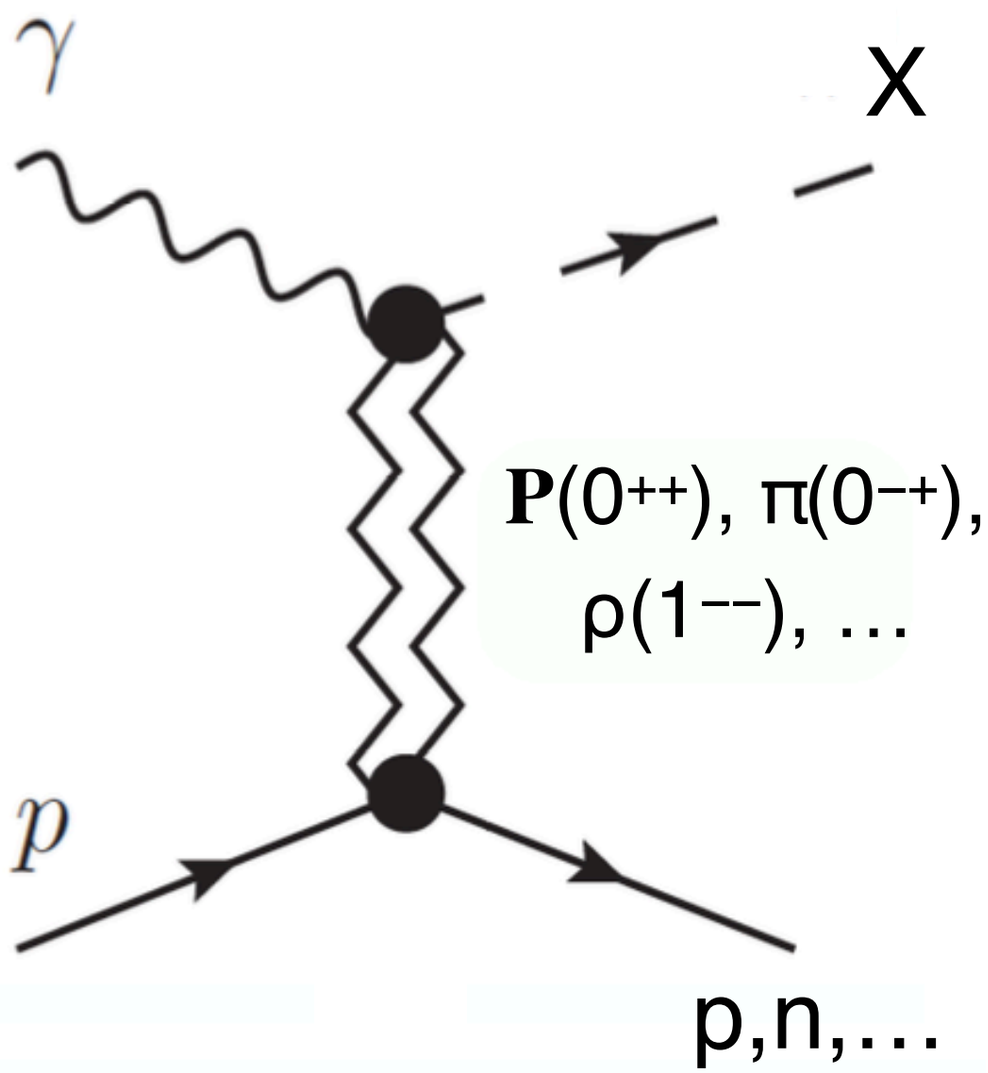
Opportunities with JLab Energy and Luminosity Upgrade
ECT*, Trento, September 27, 2022

Hadron Spectroscopy and Photoproduction

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

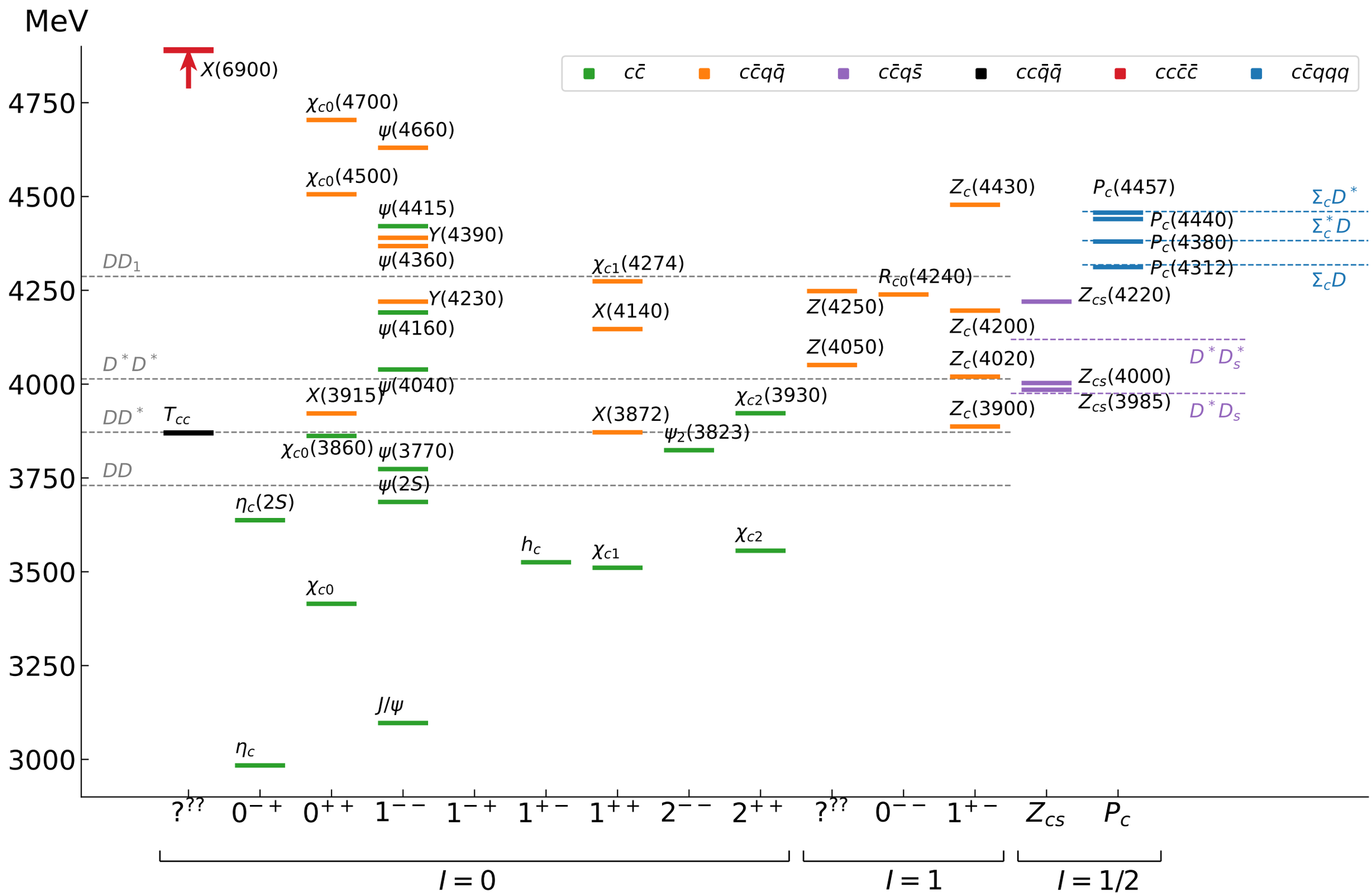


tetraquark **hybrid meson**



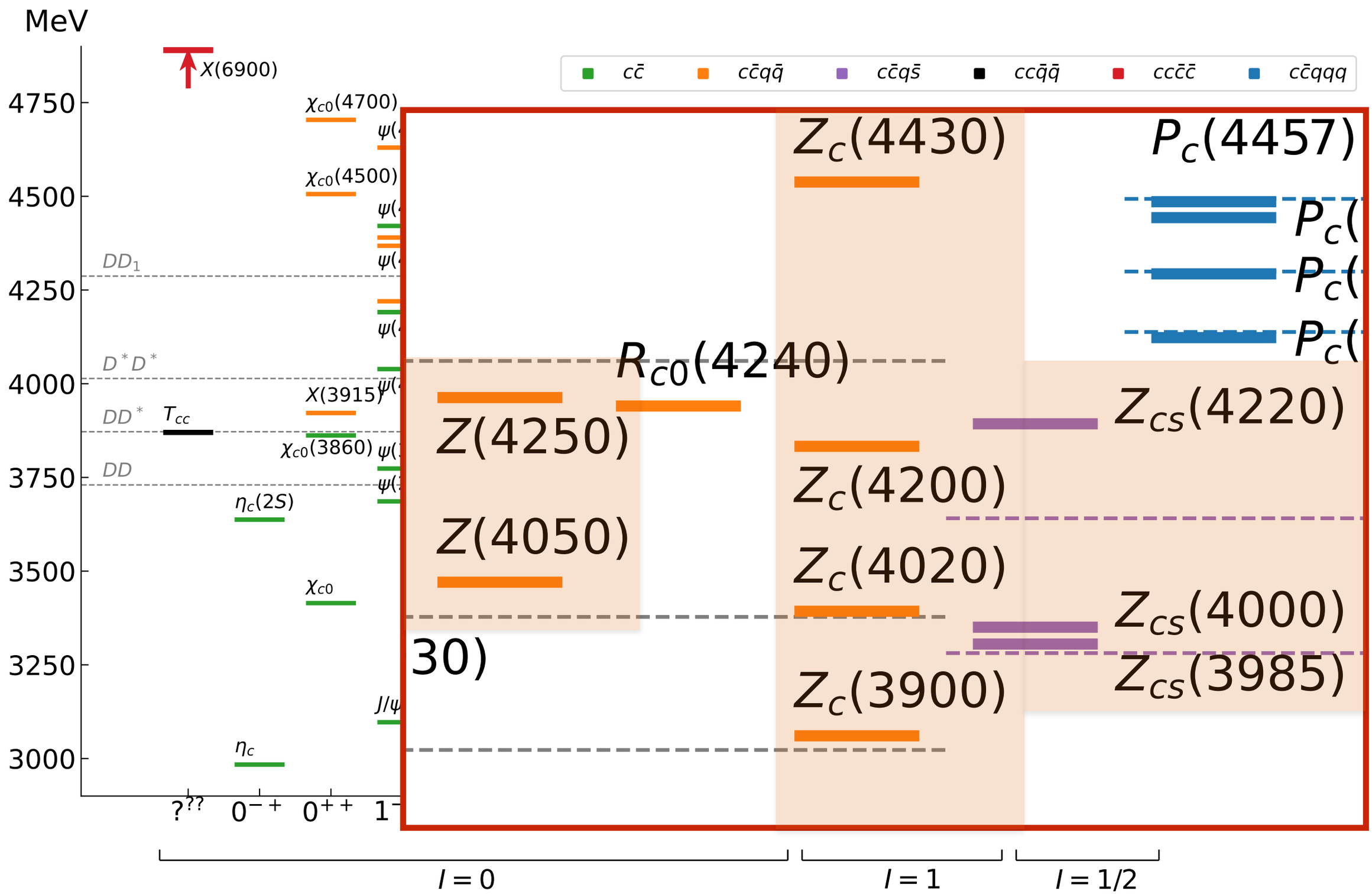
- Can produce mesons of any J^{PC} through VMD
- Photon polarization provides constraints on production processes, insight into structure
- GlueX has excellent opportunity to search for XYZ states (and others!) in a wide range of final states
  - Large acceptance for charged + neutral particles

Current(-ish) State of Exotic Charmonium(-like) States



JPAC Collaboration, arXiv:2112.13436

Current(-ish) State of Exotic Charmonium(-like) States



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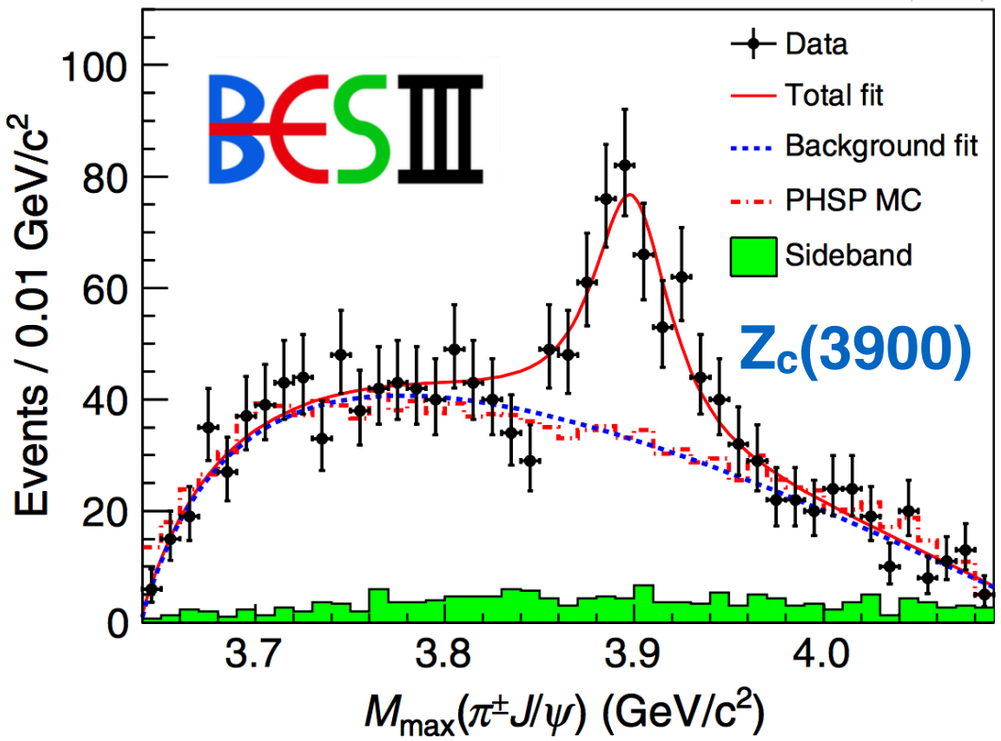
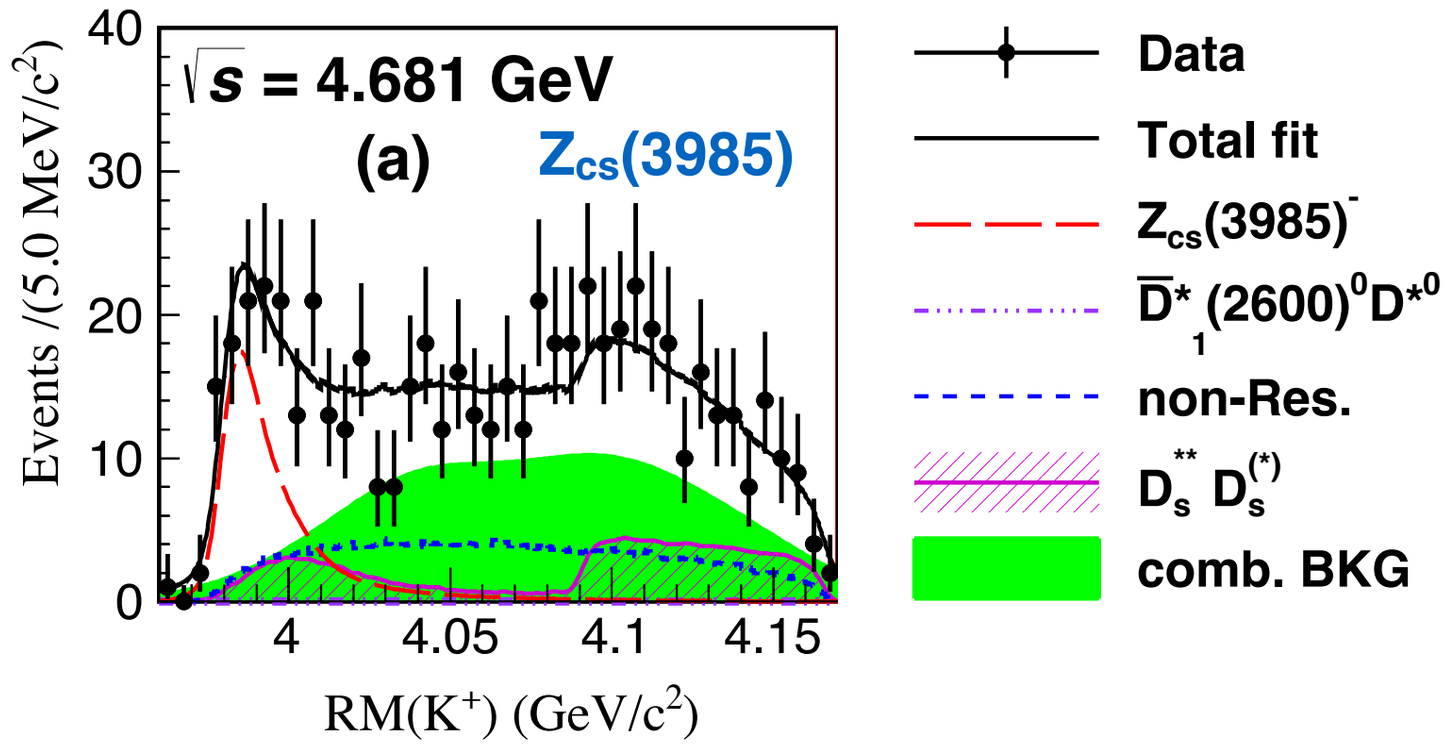
"Z" States

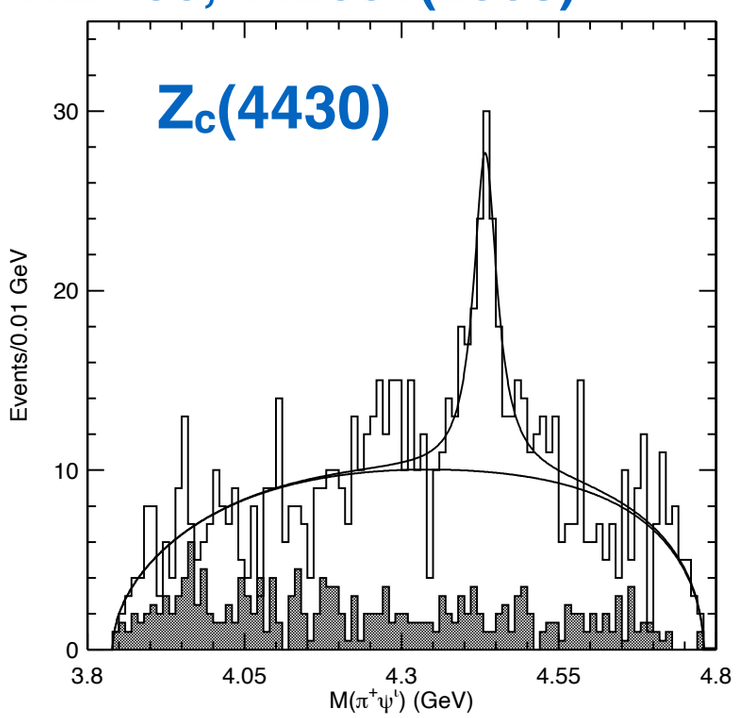
BESIII: PRL 110, 252001 (2013)



BESIII: PRL 126, 102001 (2021)

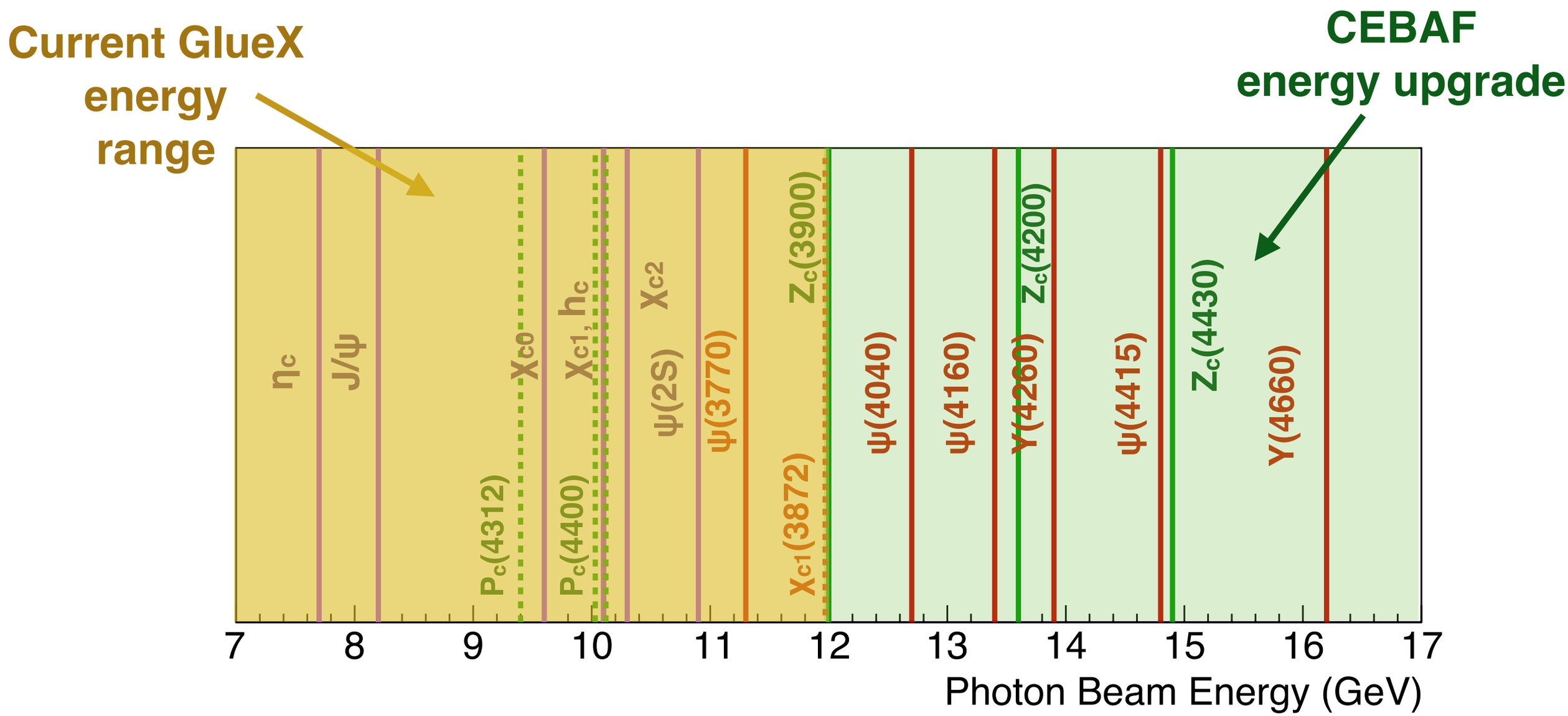


Belle: PRL 100, 142001(2008)



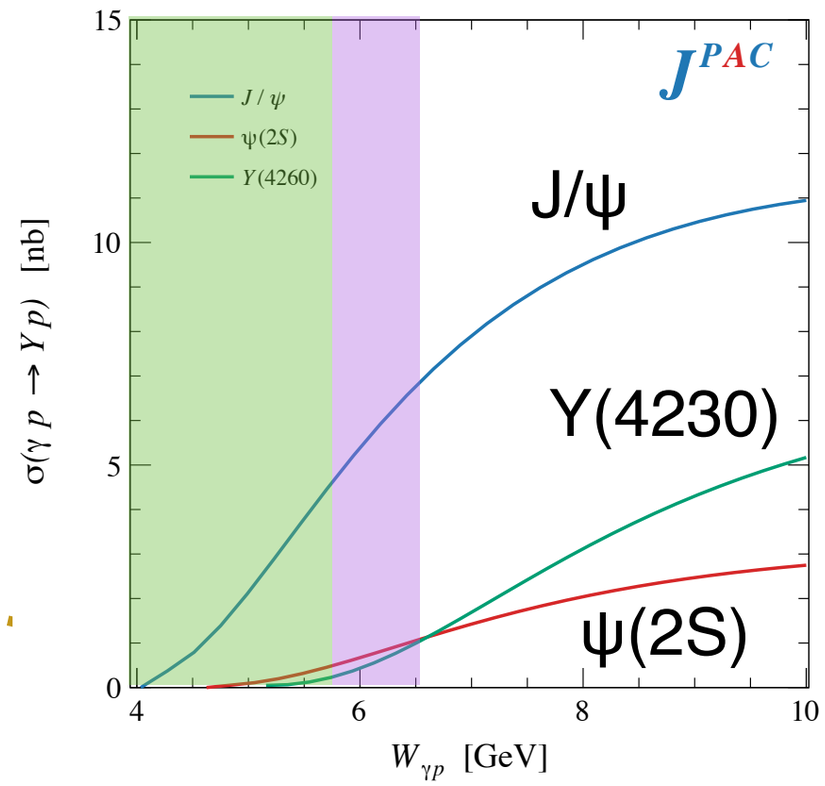
- Decays imply $c\bar{c}q\bar{q}$ quark content
- Spectrum of possible explanations: tetraquark, molecule, virtual state, triangle singularity, …
- Crucial to confirm these states in other production processes, establish multiplets

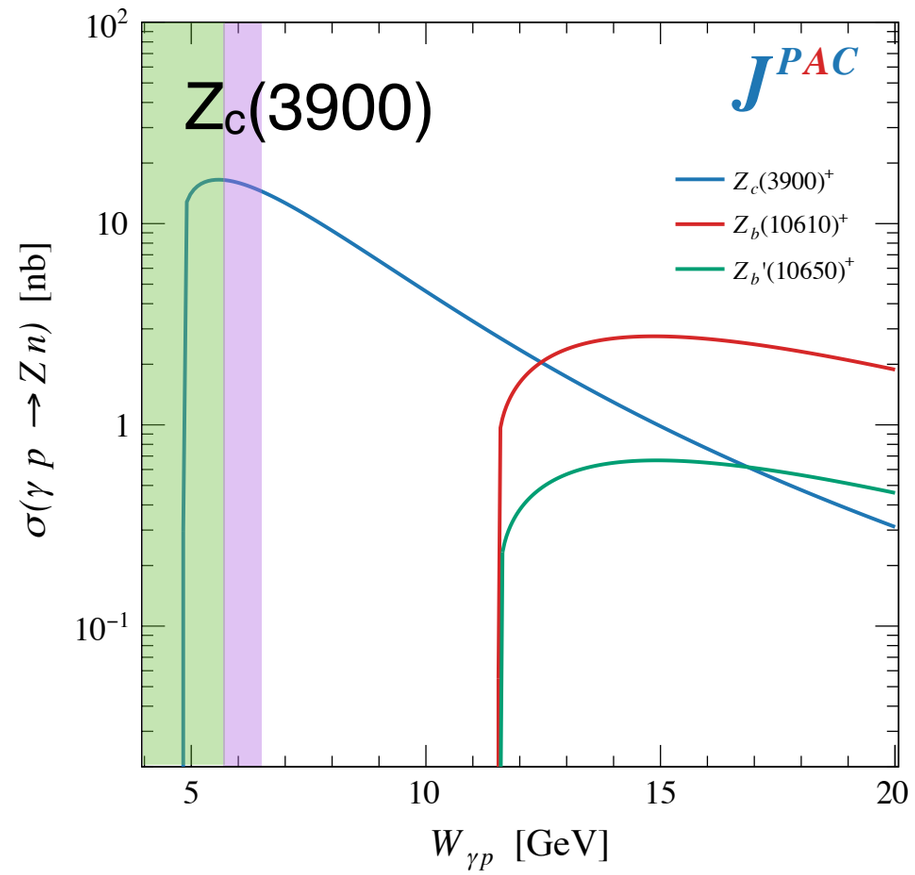
Charmonium Photoproduction Near Threshold

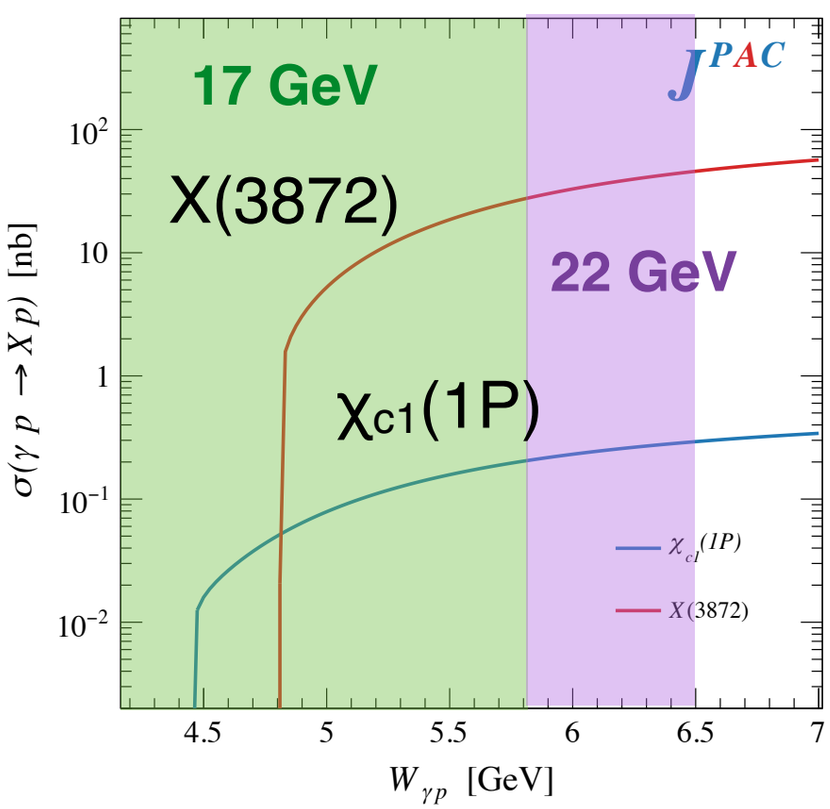


- Current max CEBAF energy allows study of bound $c\bar{c}$, P_c states
- 17 GeV e^- gives access to most exotic candidates
- 22 GeV e- gives good phasespace, linear polarization

JPAC Cross Section Predictions







- JPAC predictions using fixed-spin exchanges near threshold
  - **PRD 102, 114010 (2020) arXiv:2209.05882**
- GlueX can test models by measuring $\chi_{c1}(1P)$, $\psi(2S)$ production

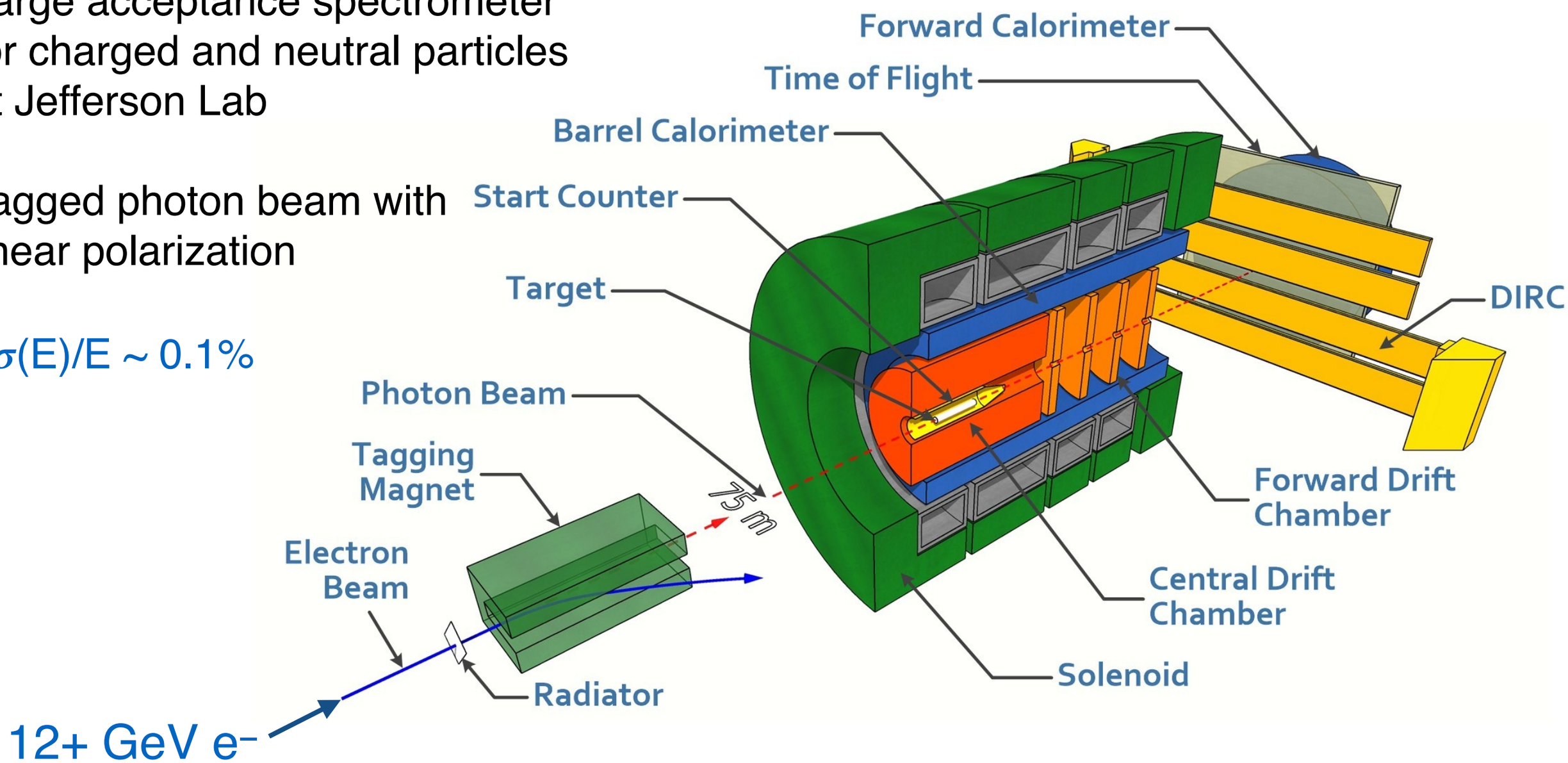
see talk by L. Pentchev

The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

Tagged photon beam with linear polarization

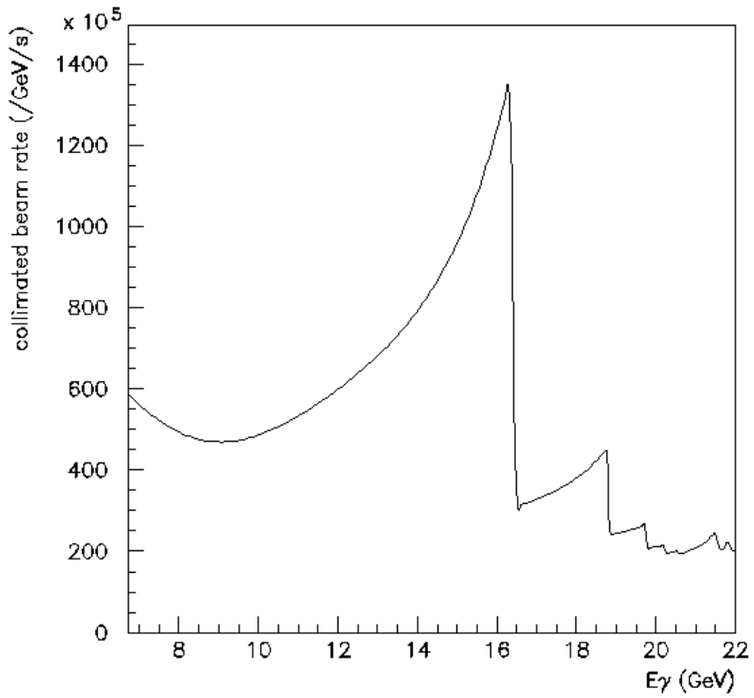
$\sigma(E)/E \sim 0.1\%$



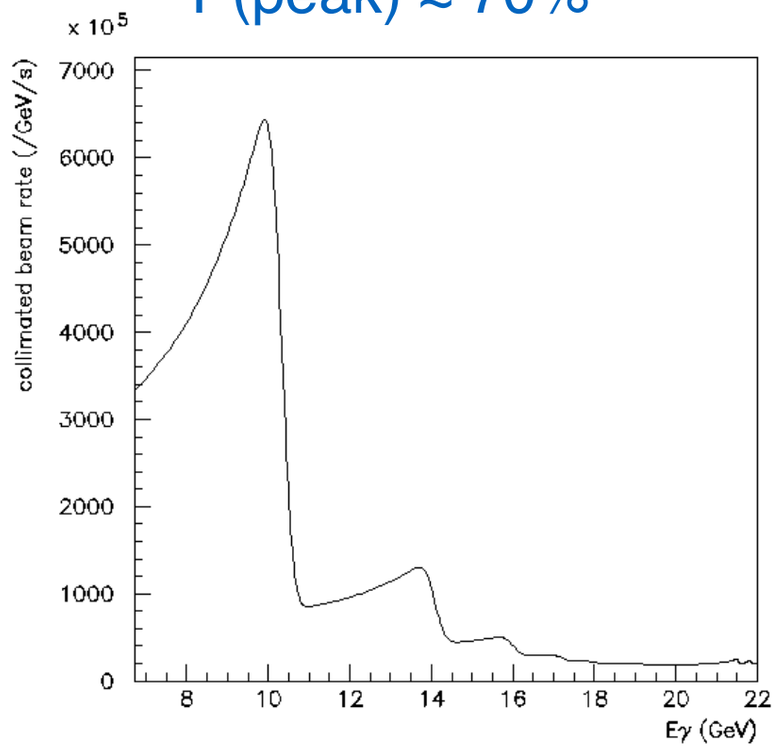
- Simulations performed with baseline GlueX-II spectrometer
- Assumes modest beam-line upgrades to handle higher energy electrons

Luminosity Expectations @ GlueX

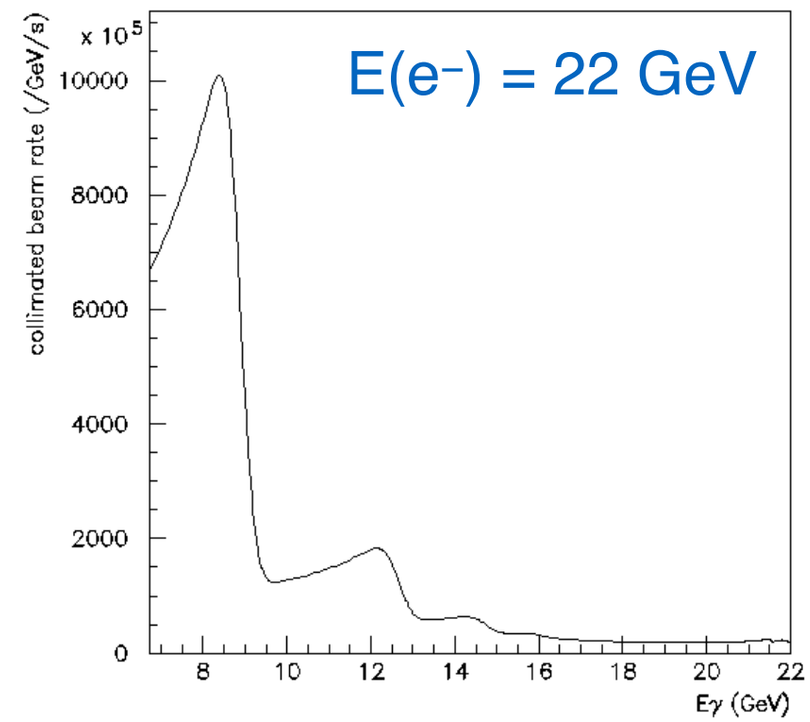
E(peak) = 16.5 GeV
P(peak) ≈ 35%



E(peak) = 10.5 GeV
P(peak) ≈ 70%

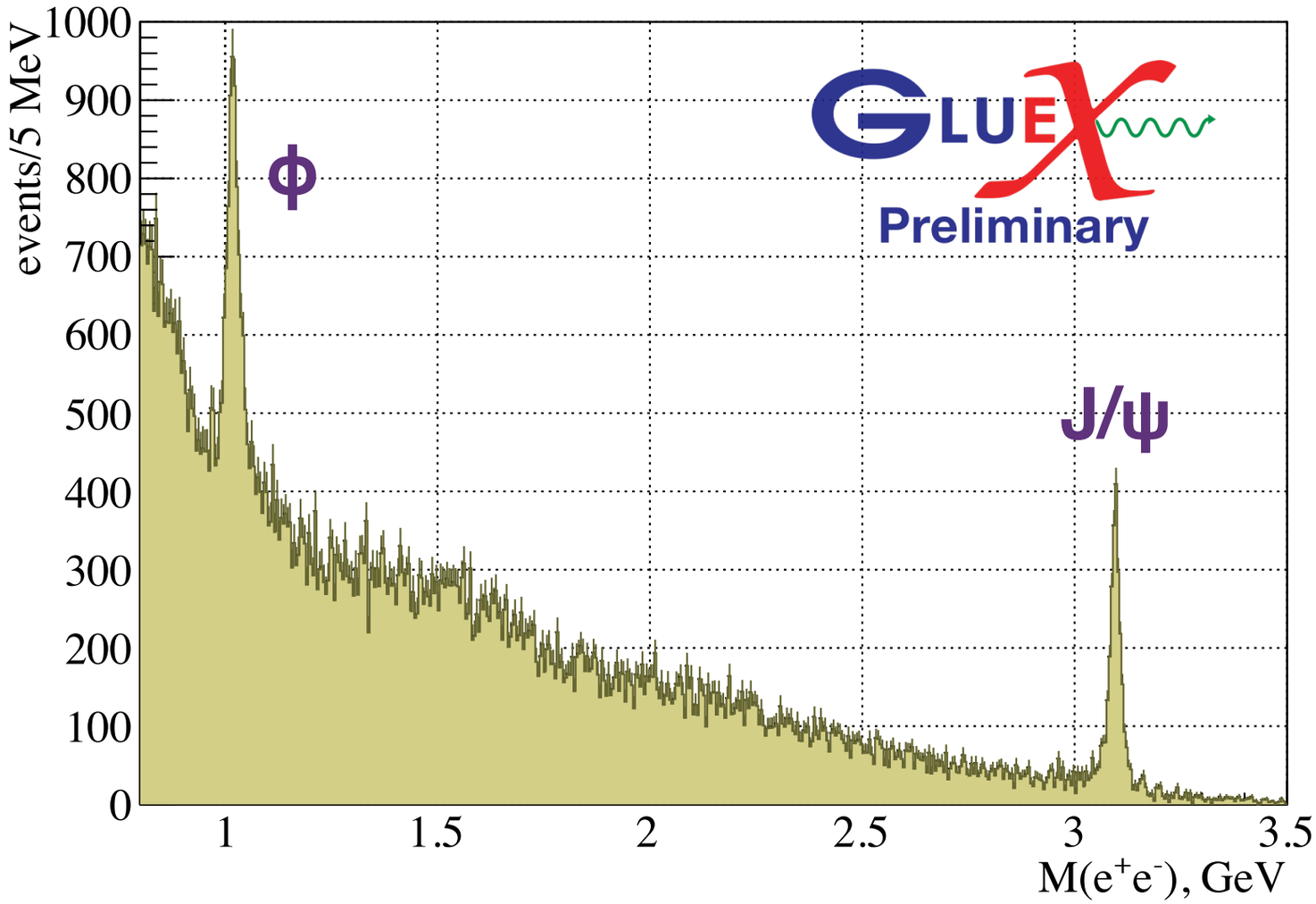


E(peak) = 9 GeV
P(peak) ≈ 80%



- Baseline: "high-intensity" GlueX-II in 2020 @ 500 pb^{-1} / year ($E_\gamma > E_{e-} / 2$)
  - Based on measured tagged photon flux
- This is the **lower limit**, path to higher rates:
  - Simple tagger upgrades → factor 4 increase
  - Upgrades to forward tracking / TOF to reach highest rates

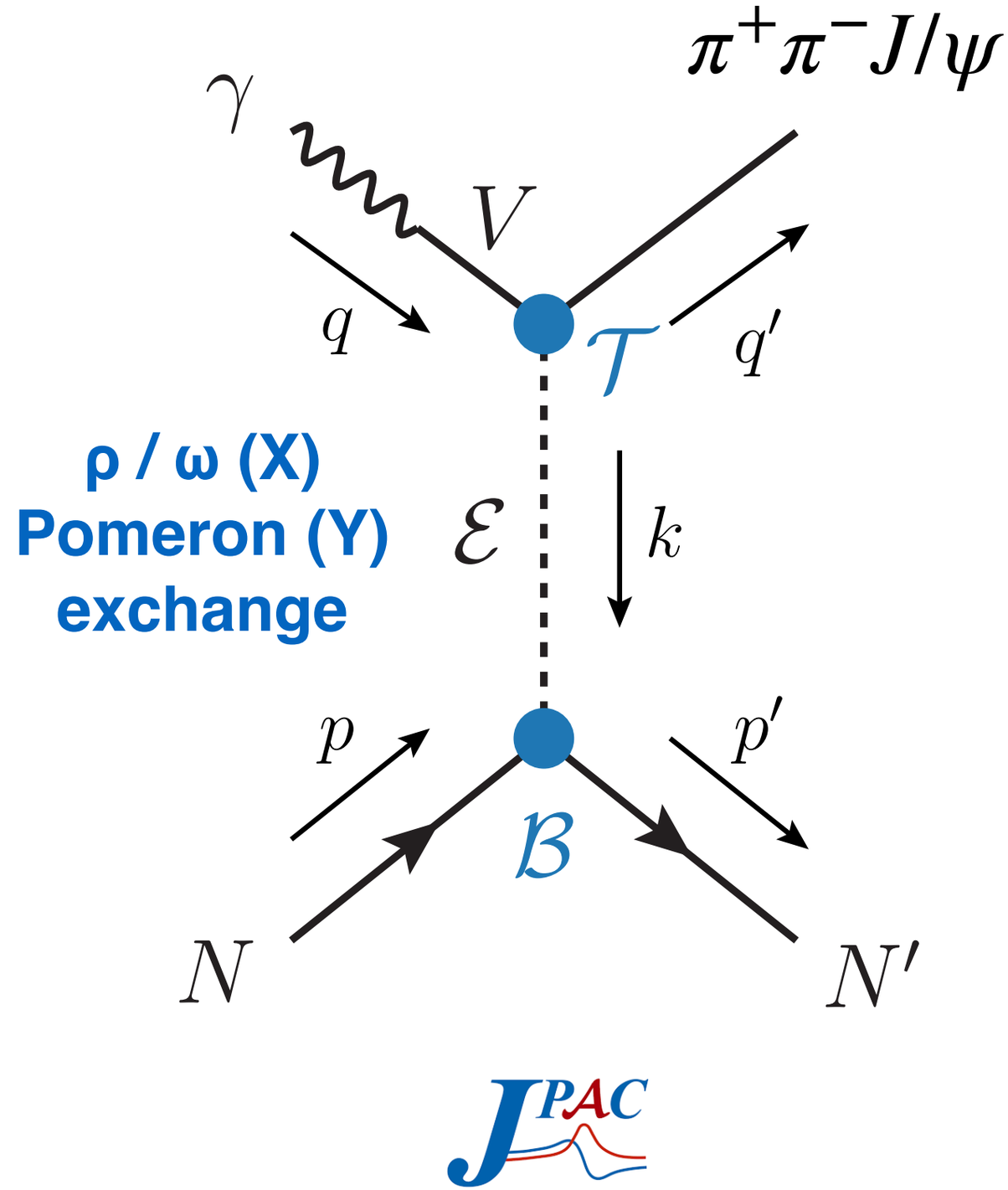
Reminder: J/ψ Photoproduction at GlueX



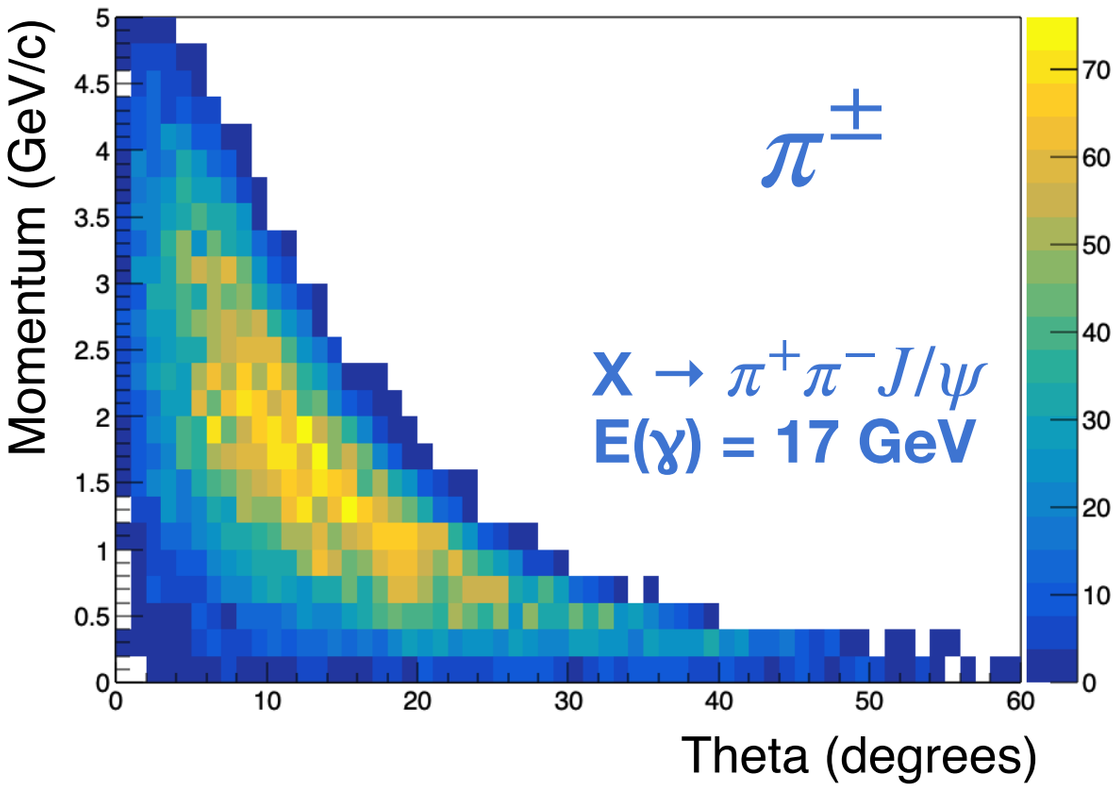
- Reconstruct full reaction: **$p\,\gamma \rightarrow p + J/\psi,\ J/\psi \rightarrow e^+e^-$**
- Tagged photon + kinematic fit provides excellent mass resolution
- This is true for XYZ states as well!
  - Yield estimates assume fully reconstructed events, detector reconstruction efficiency, focus on **$J/\psi \rightarrow e^+e^-$** final states

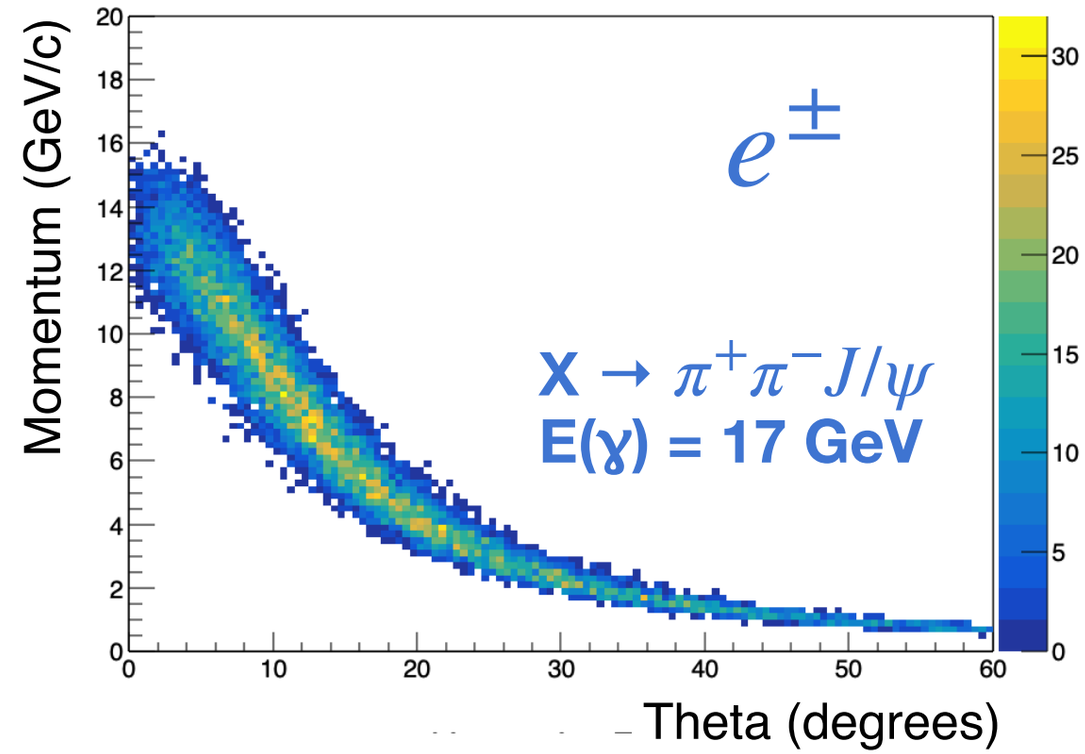
X, Y Production at GlueX

- Benchmark: X(3872), Y(4320) production with $\pi\pi J/\psi$ decay
  - $\gamma p \to \pi^+\pi^- J/\psi p$
- Folded JPAC cross section model with expected coherent bremsstrahlung flux
- Run through full analysis chain
- Background estimation from PYTHIA
  - Note: uncertainty in background due to target excitations

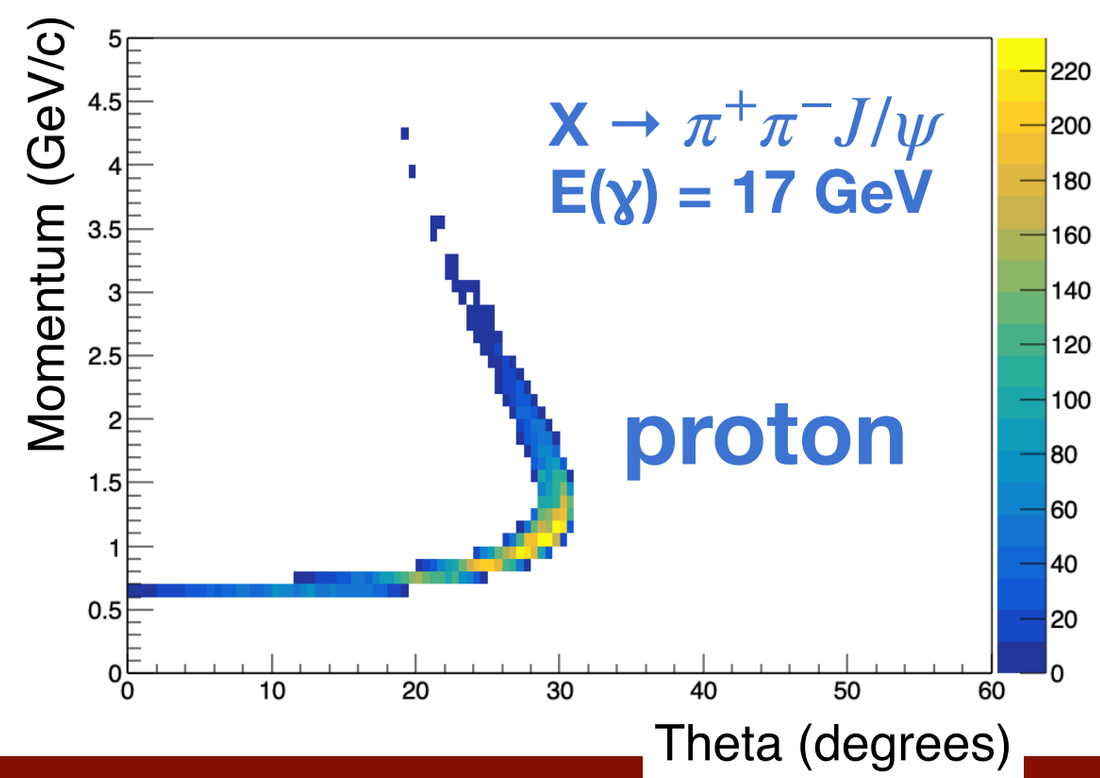


Kinematics of γp → X(3872)p, X → $\pi^+\pi^- J/\psi$



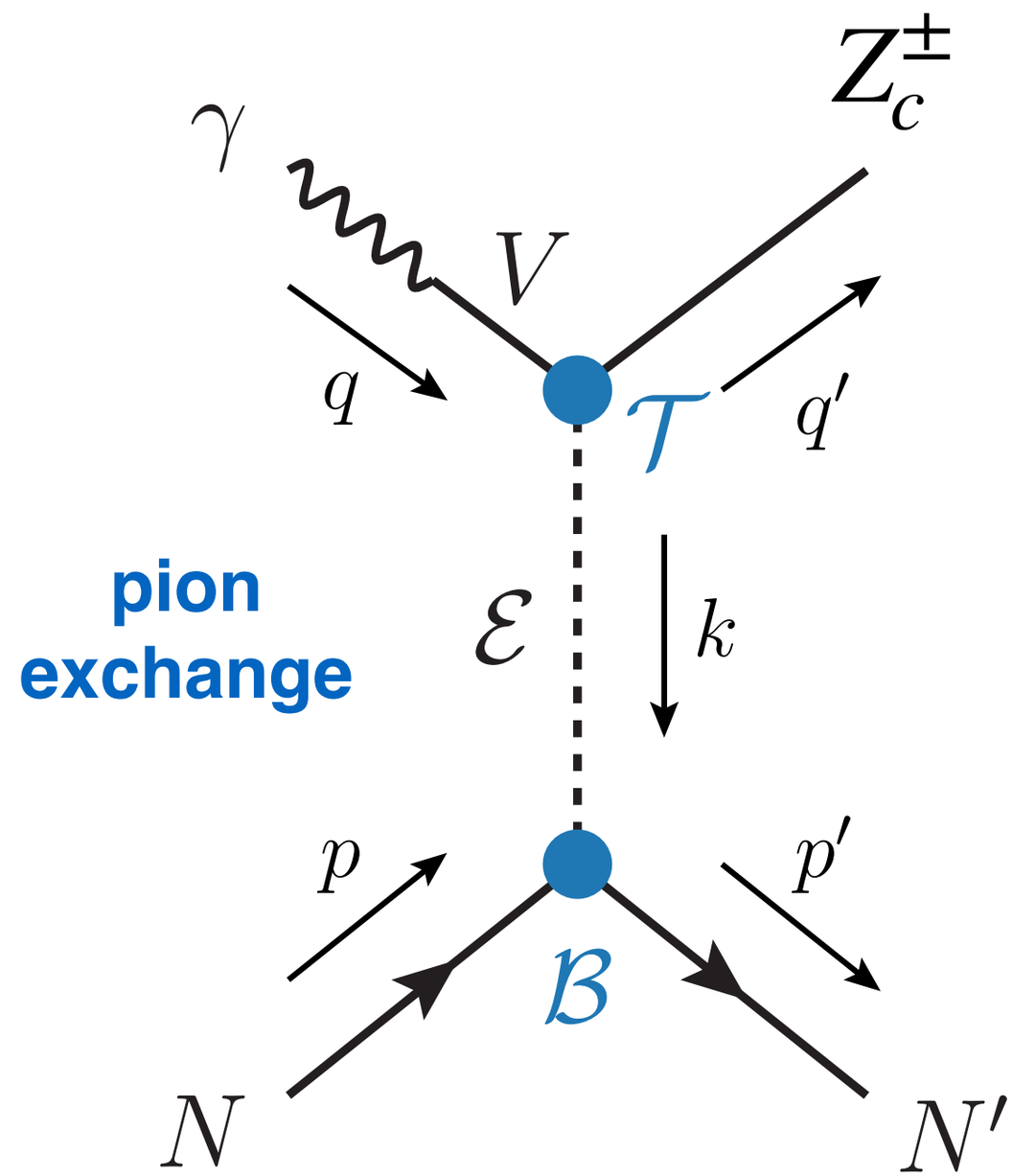


- Example: X → $\pi^+\pi^- J/\psi$ decay products are well within GlueX acceptance

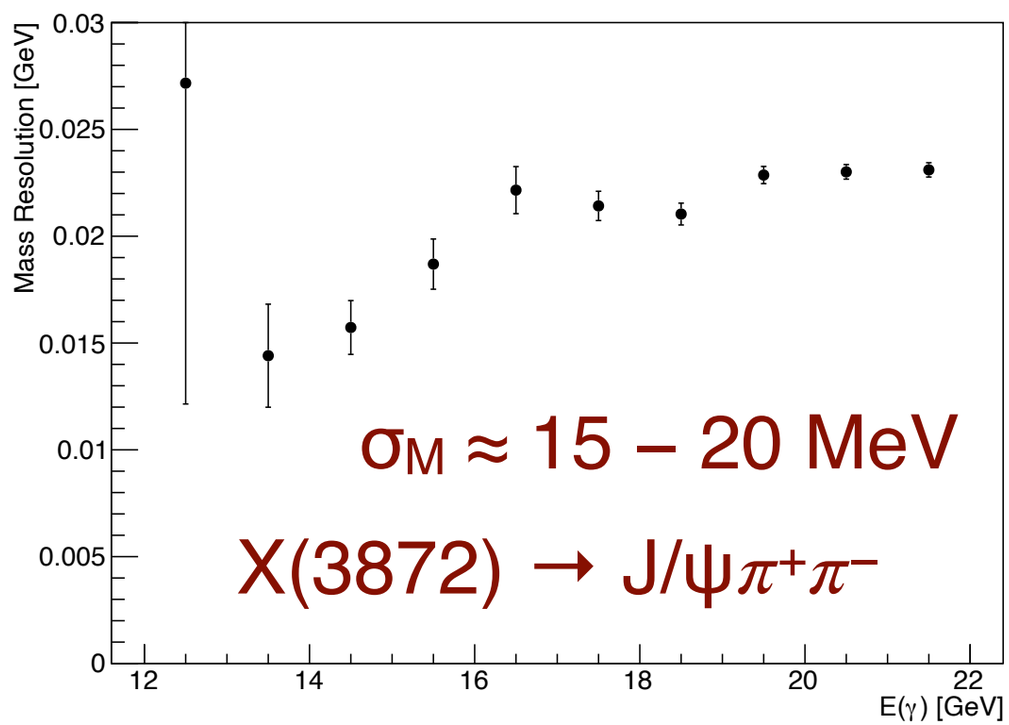


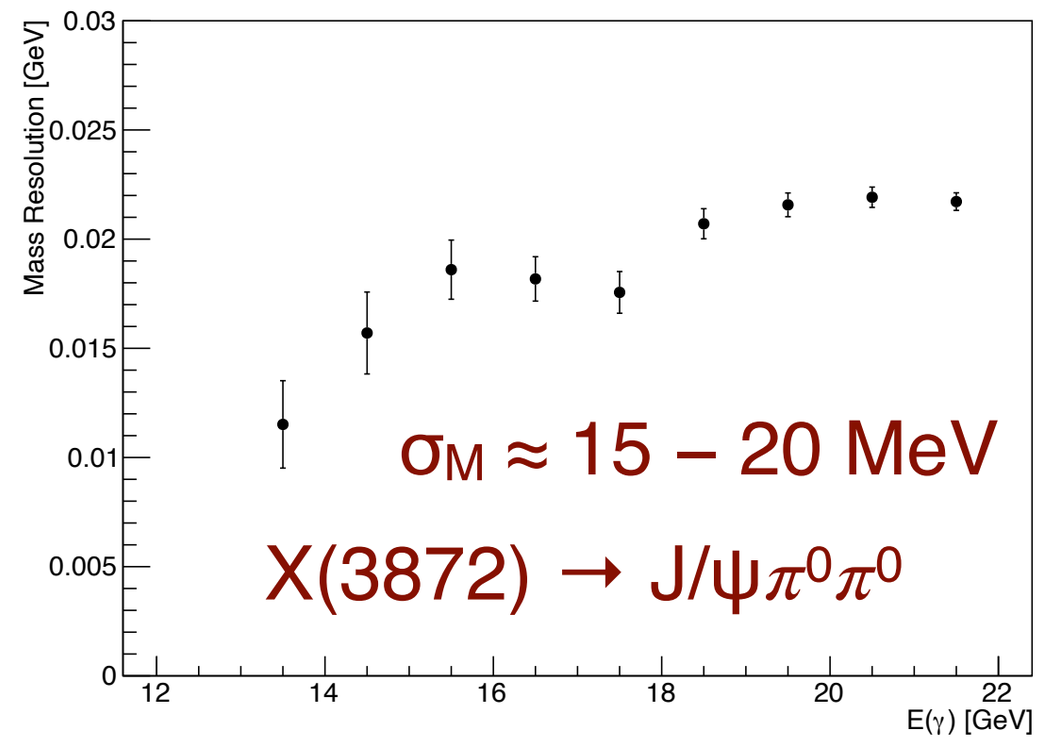
Z_c Production at GlueX

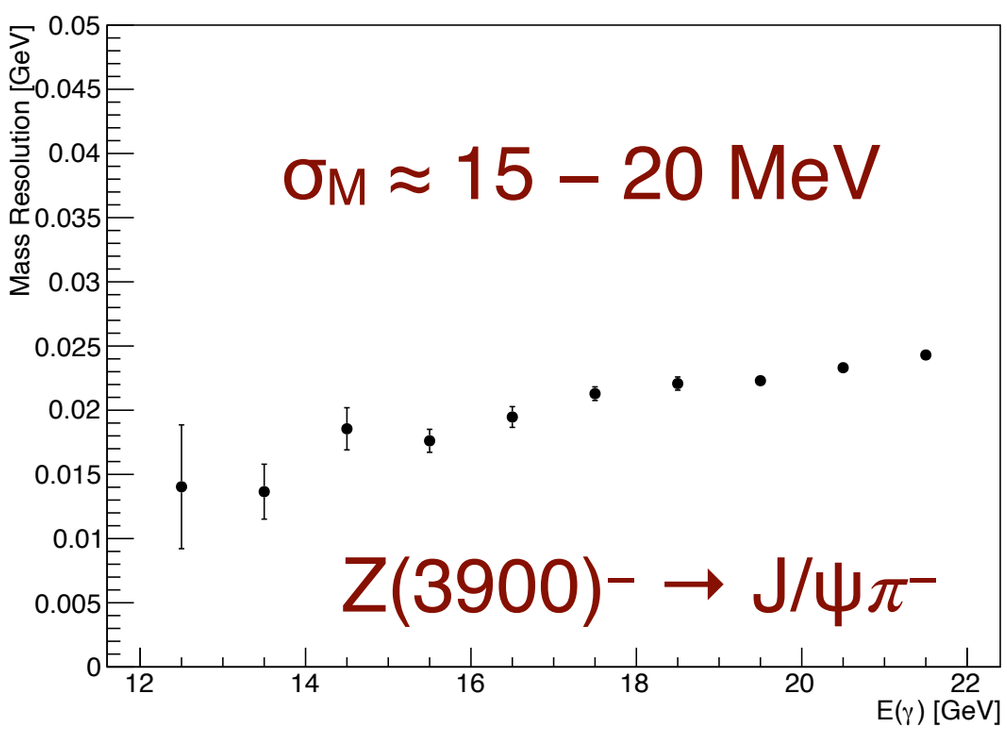
- Benchmark: $Z_c(3900)$ production with $\pi J/\psi$ decay
- Z_c has isopin=1, many ways to produce it:
  - $\gamma p \to Z_c^0 p$
  - $\gamma p \to Z_c^0 n$
  - $\gamma n \to Z_c^- p$
  - $\gamma p \to Z_c^- \Delta^{++}$
- Expected to have similar cross sections, all accessible at GlueX

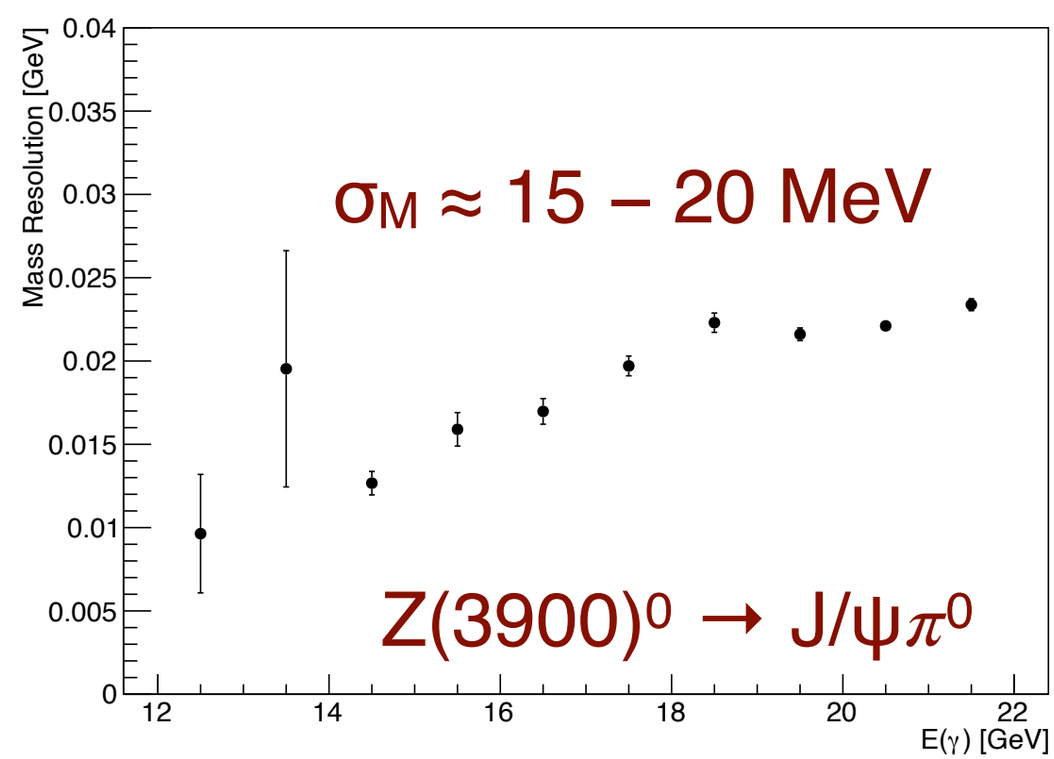


Resolutions vs. Beam energy

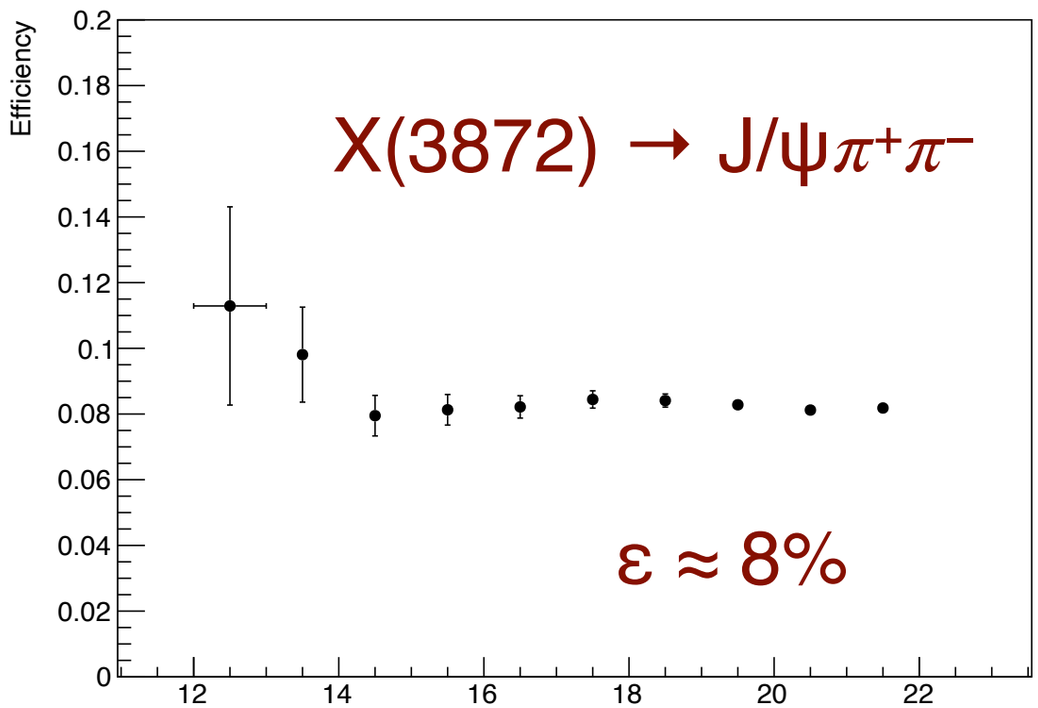


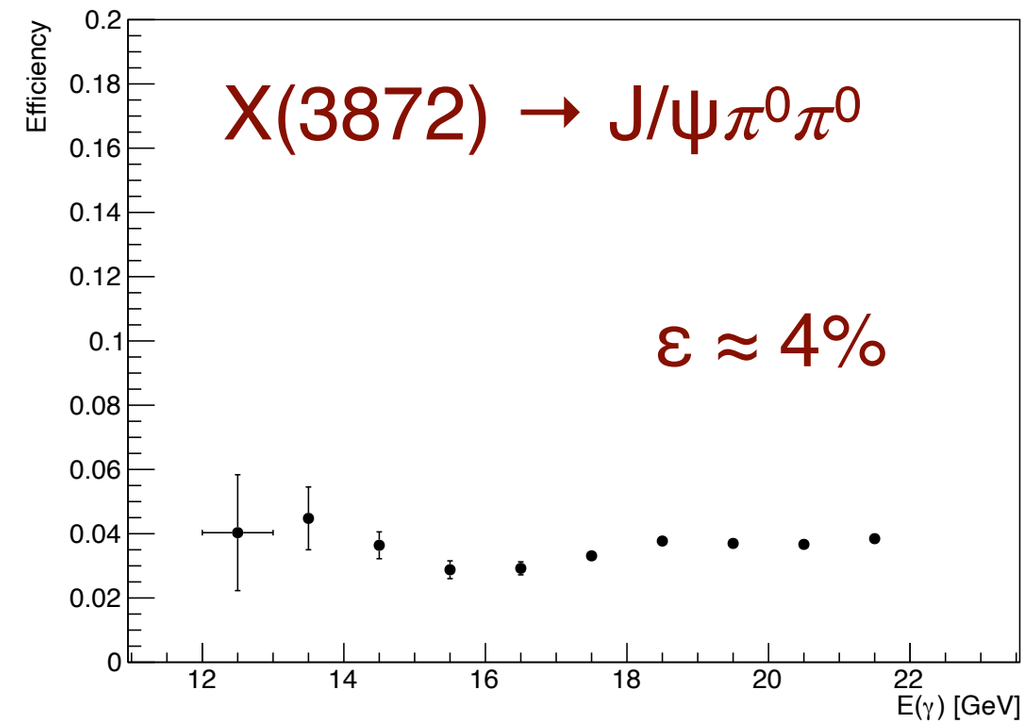


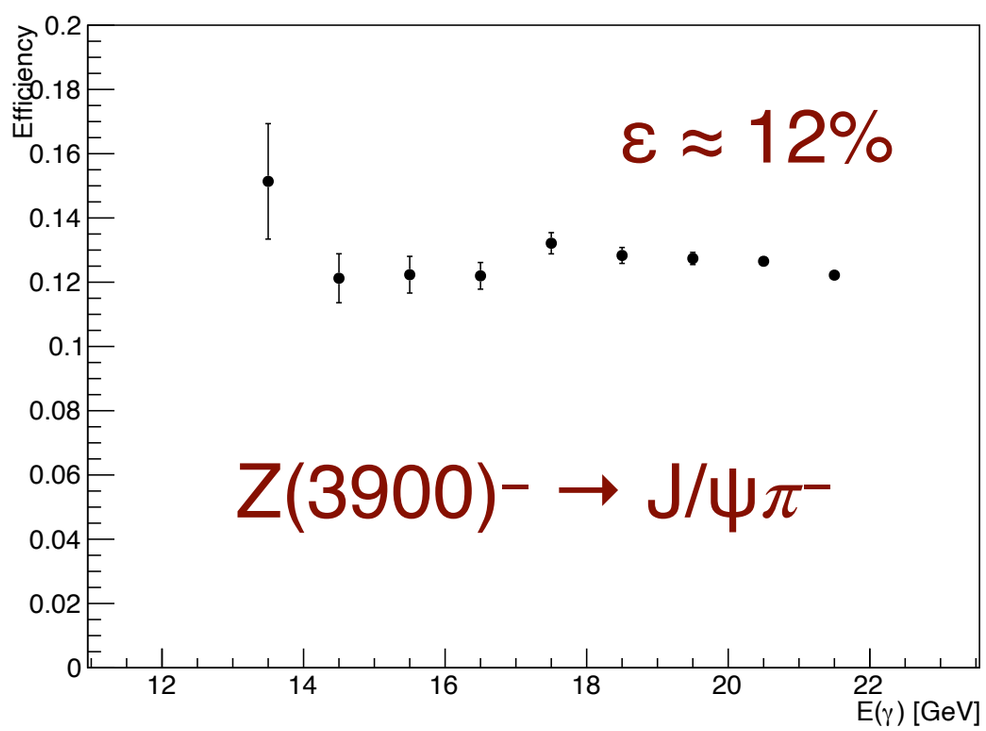


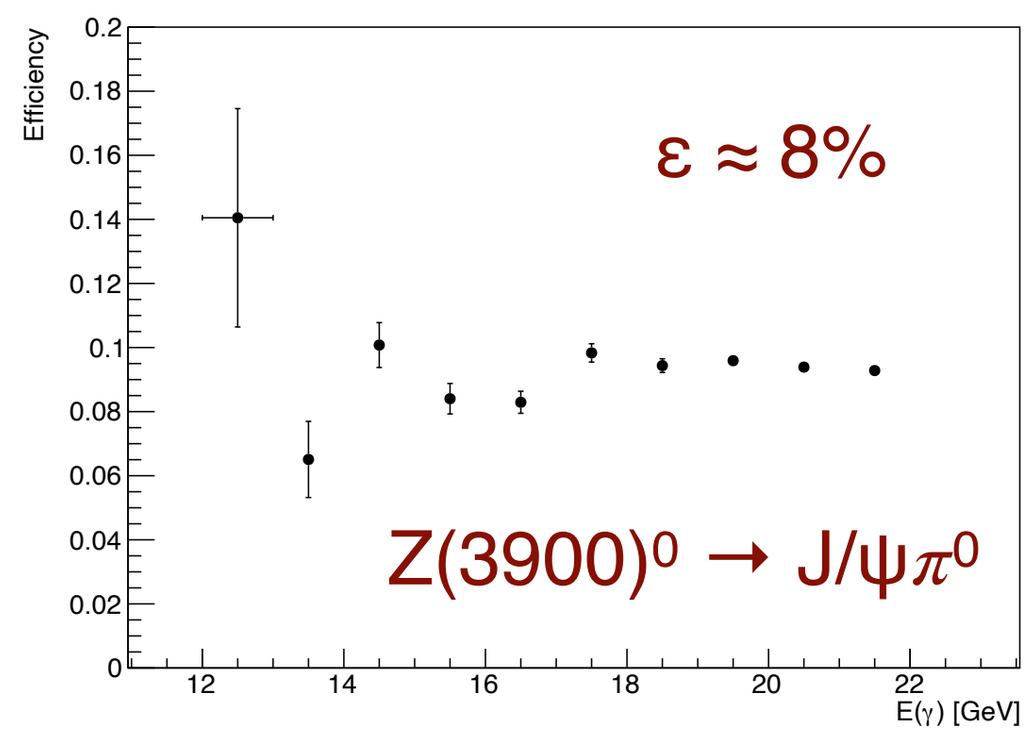


Efficiencies vs. Beam energy





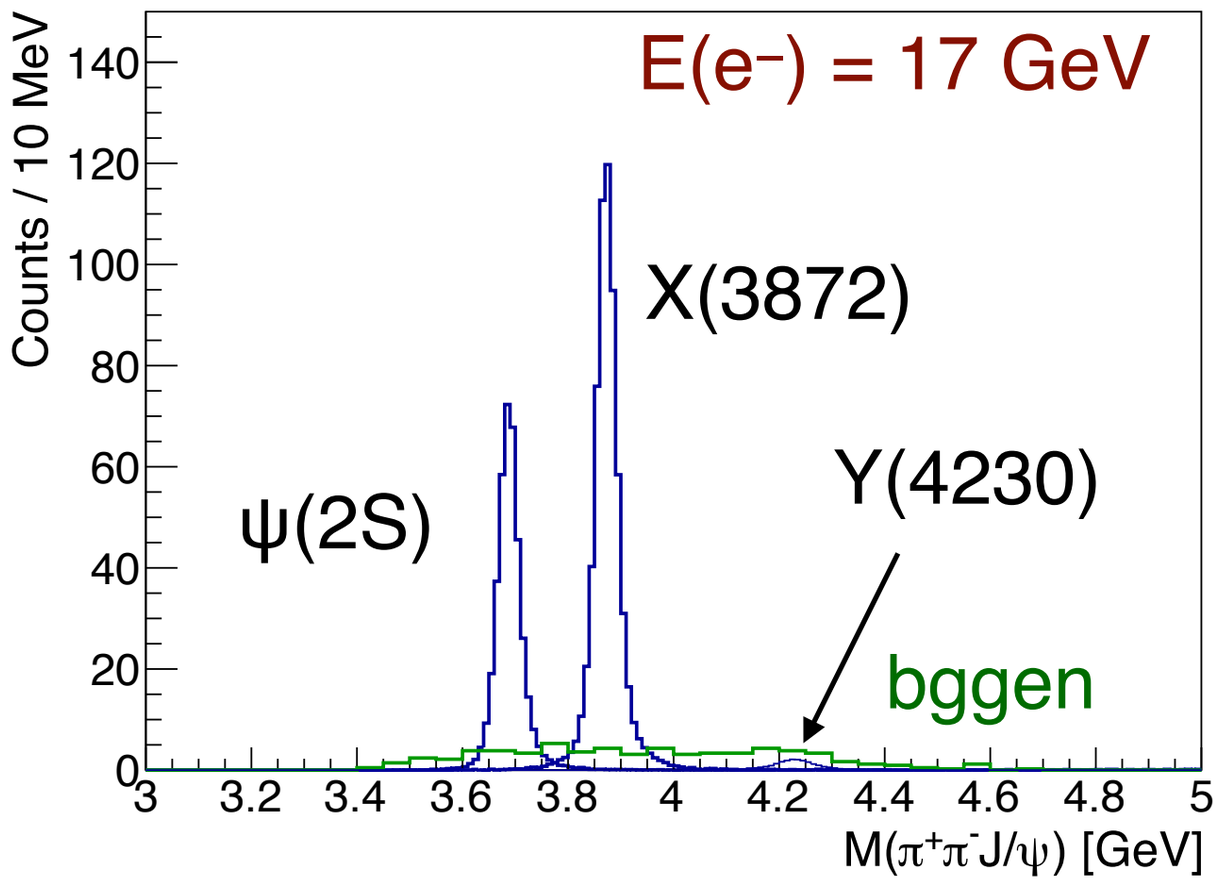


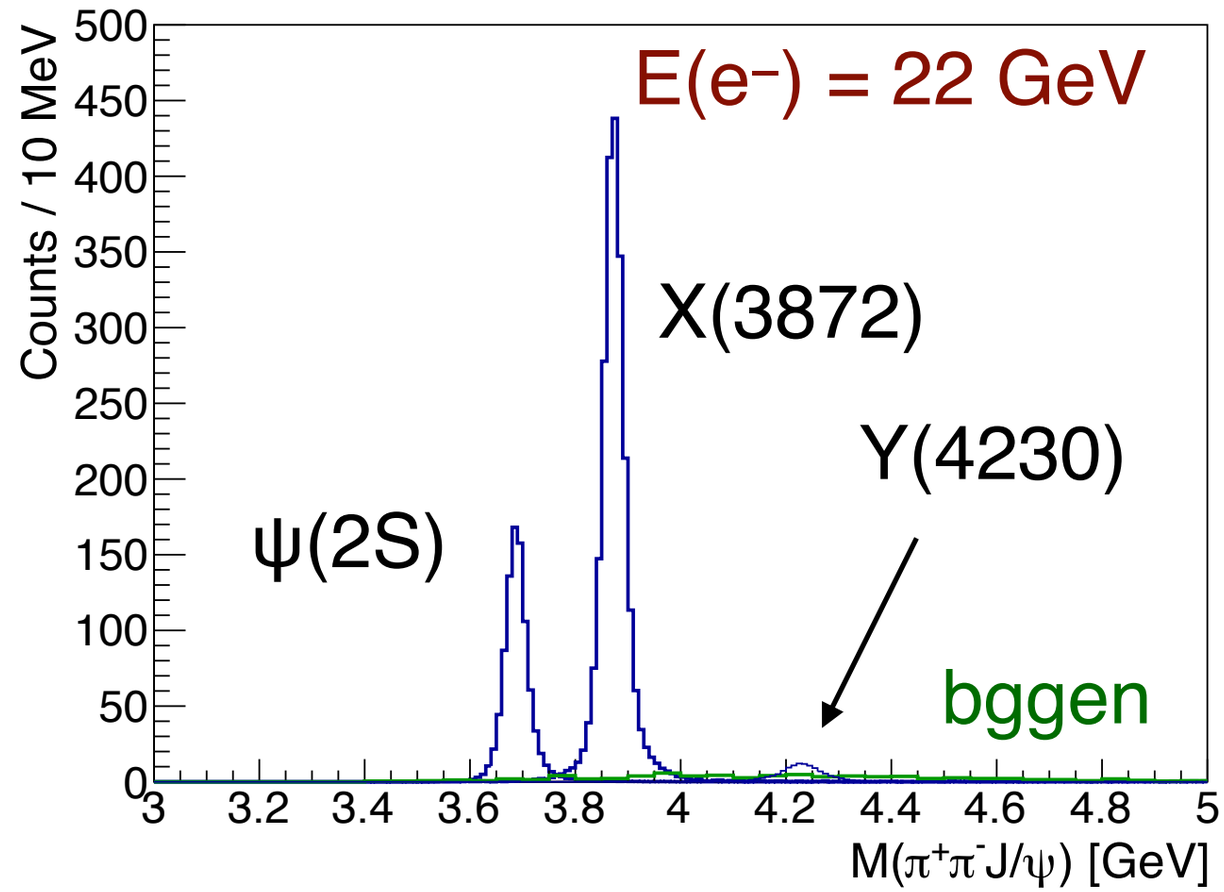


- n.b.: $\varepsilon(J/\psi \to e^+e^-) \approx 15 - 20\ \%$

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

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

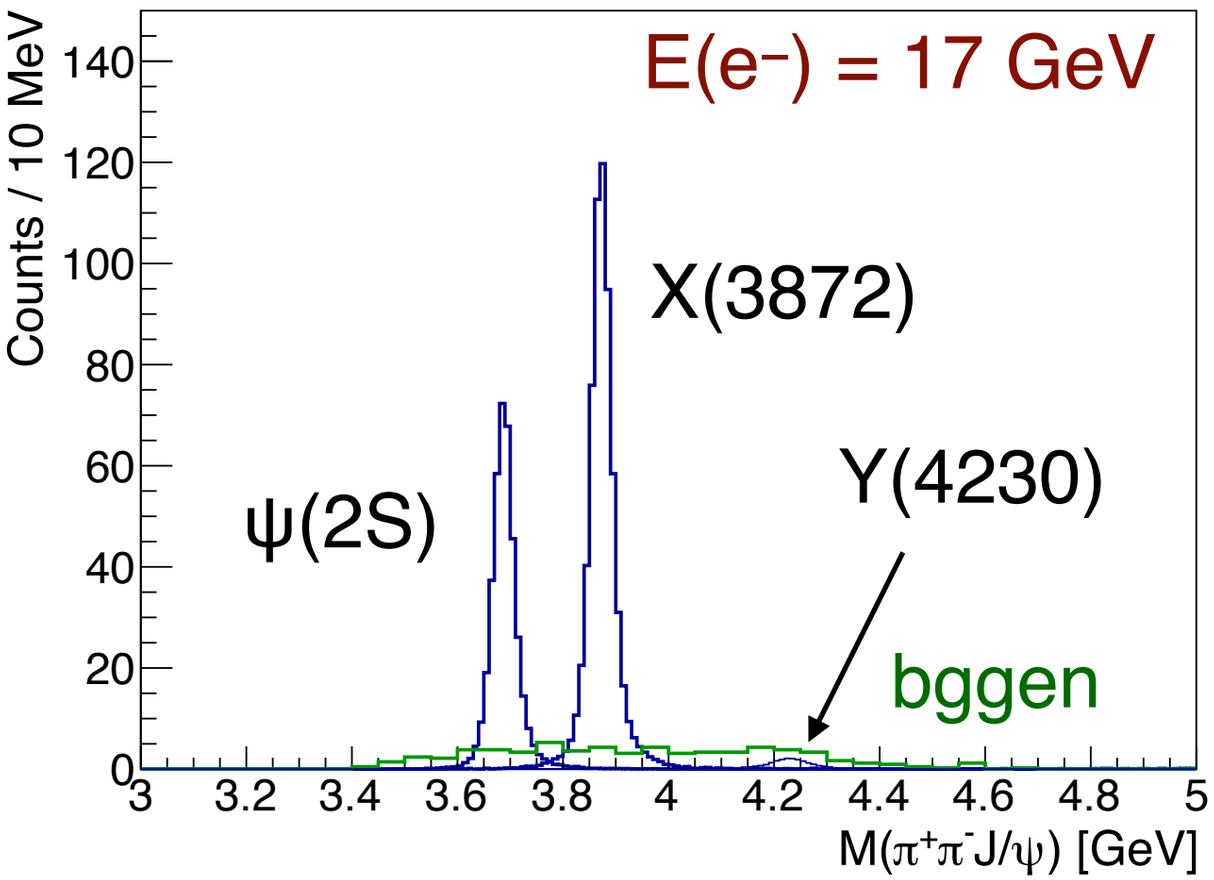




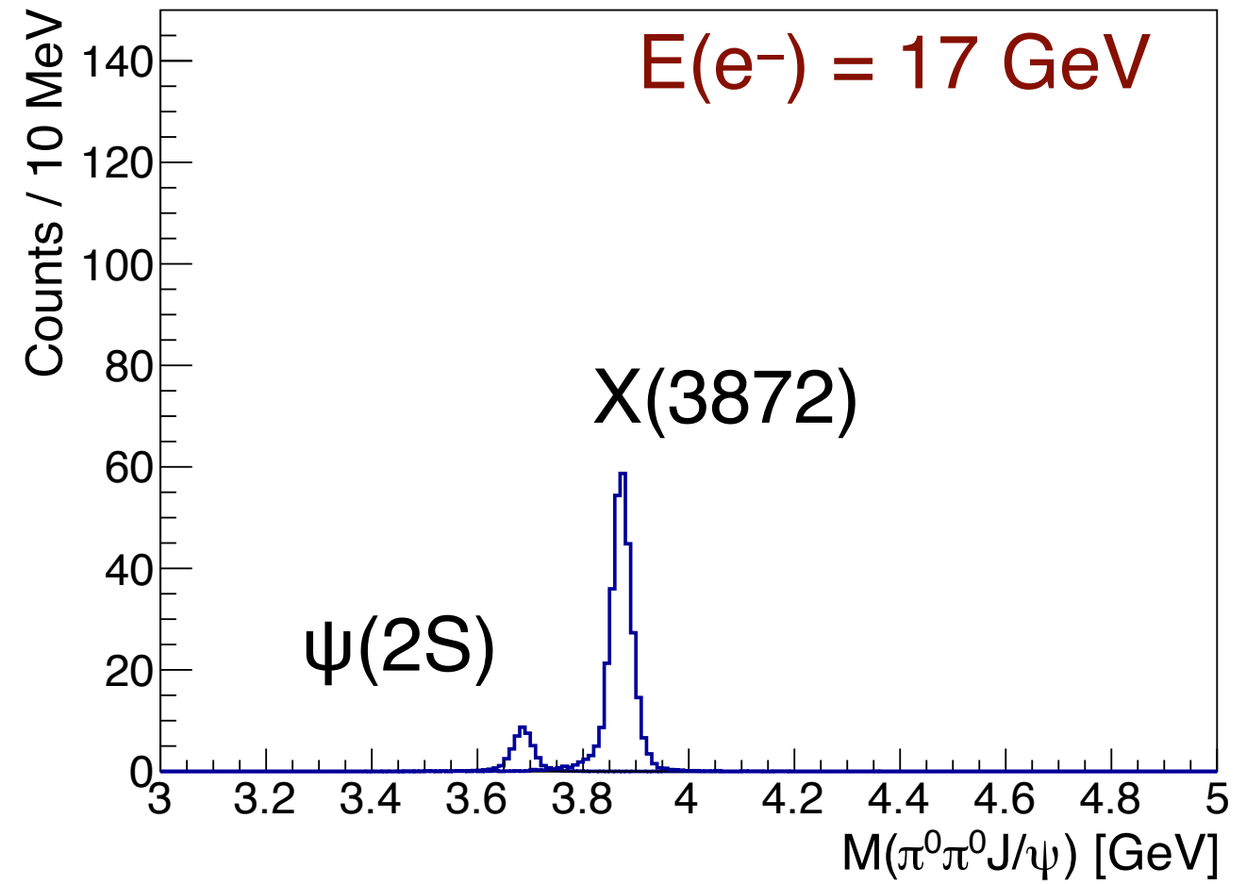
- Assumes 1 year @ 500 pb^{-1}, $Br(X,Y \rightarrow \pi^+\pi^- J/\psi) = 5\%$
- 17 GeV: $N(\psi(2S)) = 400$, $N(X(3872)) = 650$, $N(Y(4260)) = 20$
- 22 GeV: $N(\psi(2S)) = 900$, $N(X(3872)) = 2300$, $N(Y(4260)) = 120$

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

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



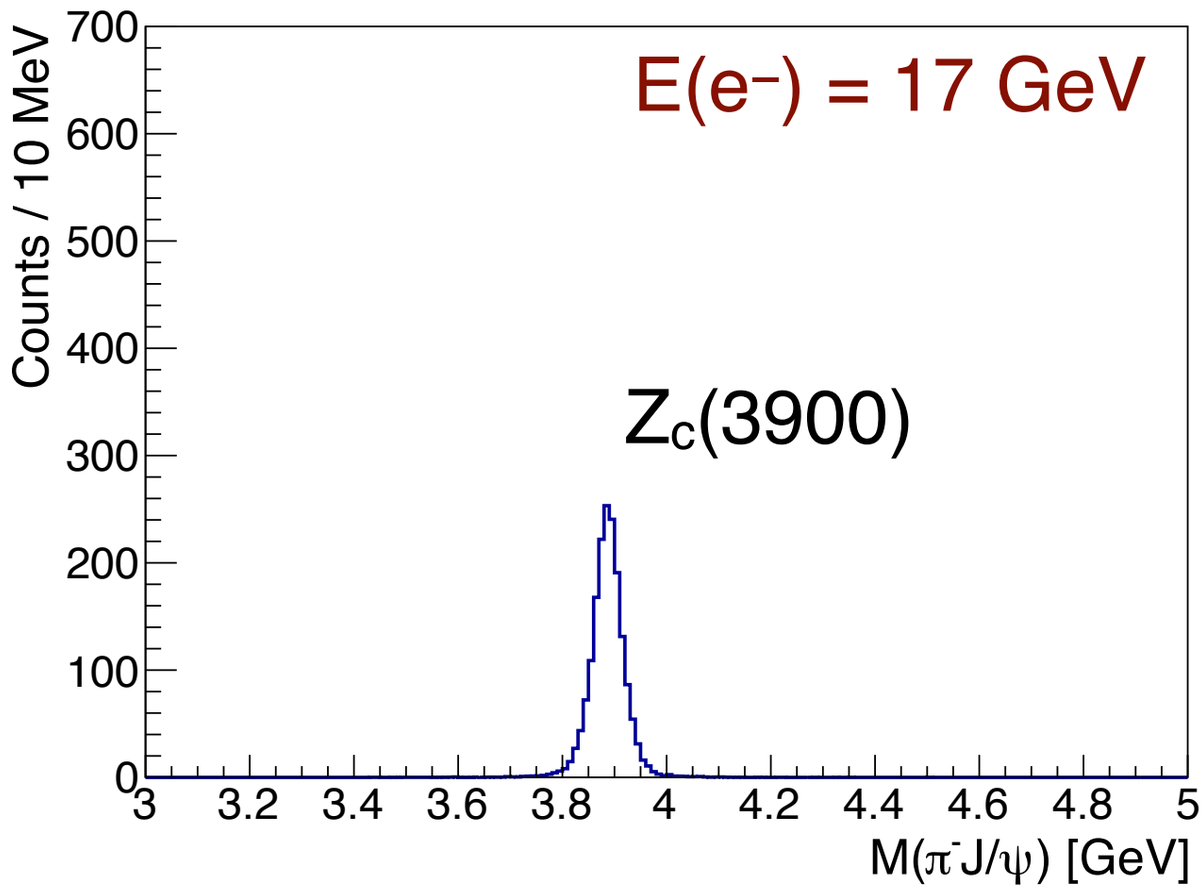
$\gamma p \rightarrow J/\psi\pi^0\pi^0 p$, $J/\psi \rightarrow e^+e^-$

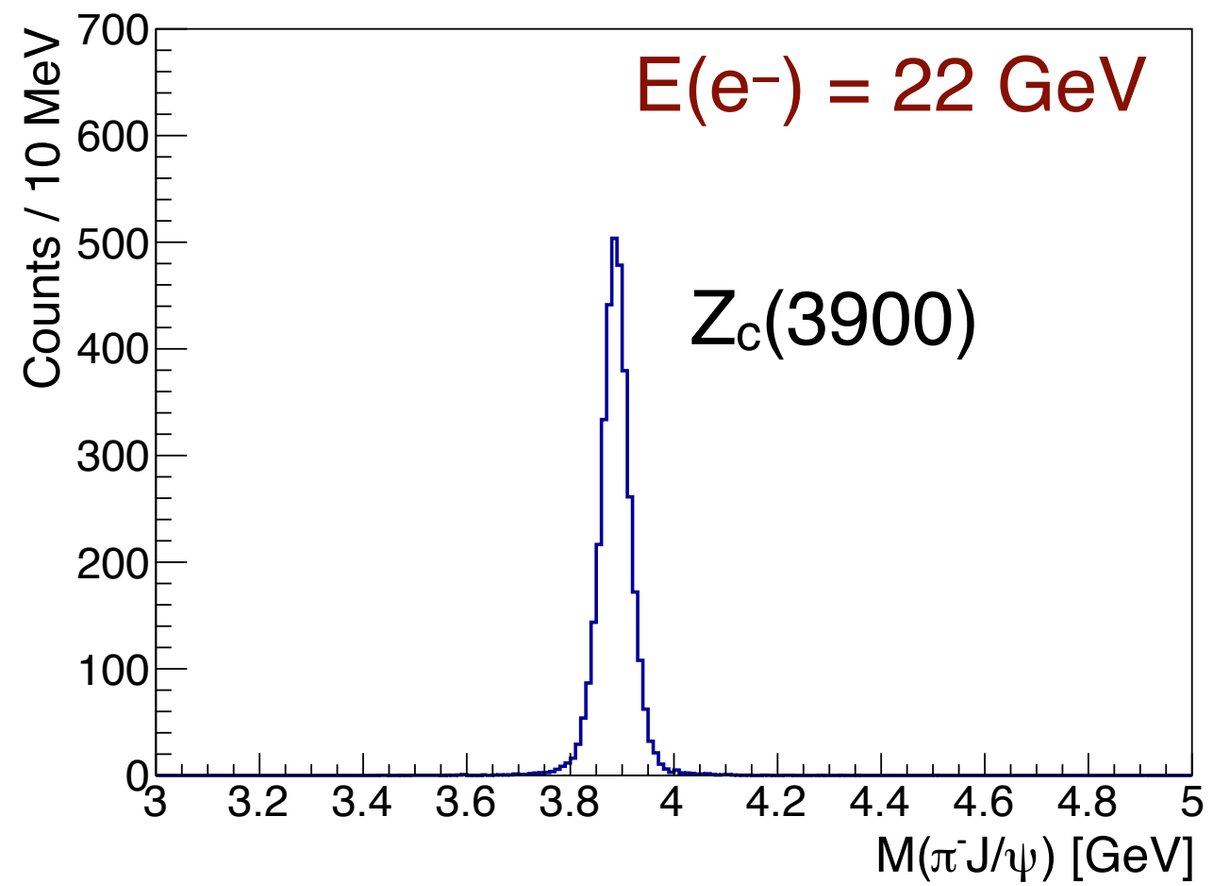


- Assumes 1 year @ 500 pb^{-1}, Br(X,Y→ $\pi^+\pi^-J/\psi$) = 5%
- 17 GeV [$J/\psi\pi^+\pi^-$]: N(ψ(2S)) = 400, N(X(3872)) = 650
- 17 GeV [$J/\psi\pi^0\pi^0$]: N(ψ(2S)) = 40, N(X(3872)) = 300

Projections for J/ψπ^- Photoproduction at GlueX

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

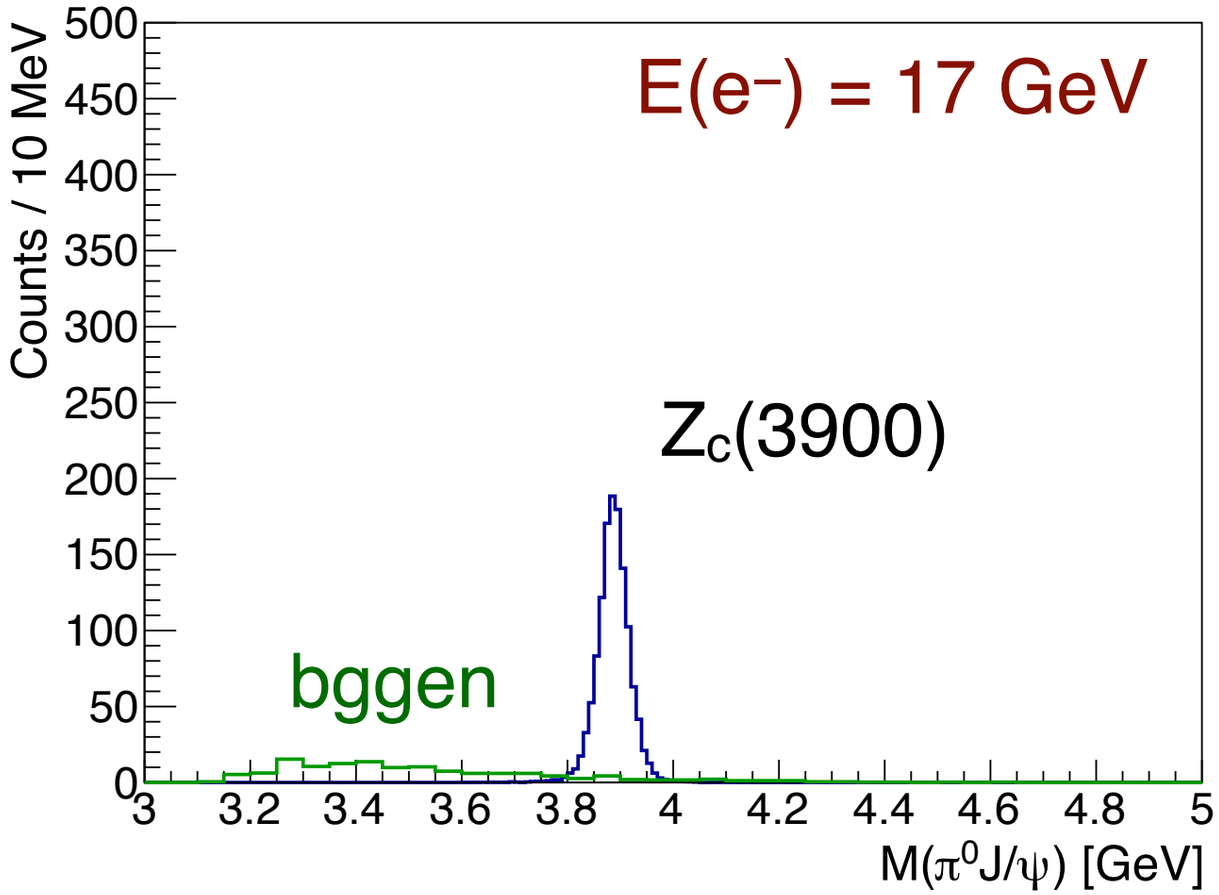


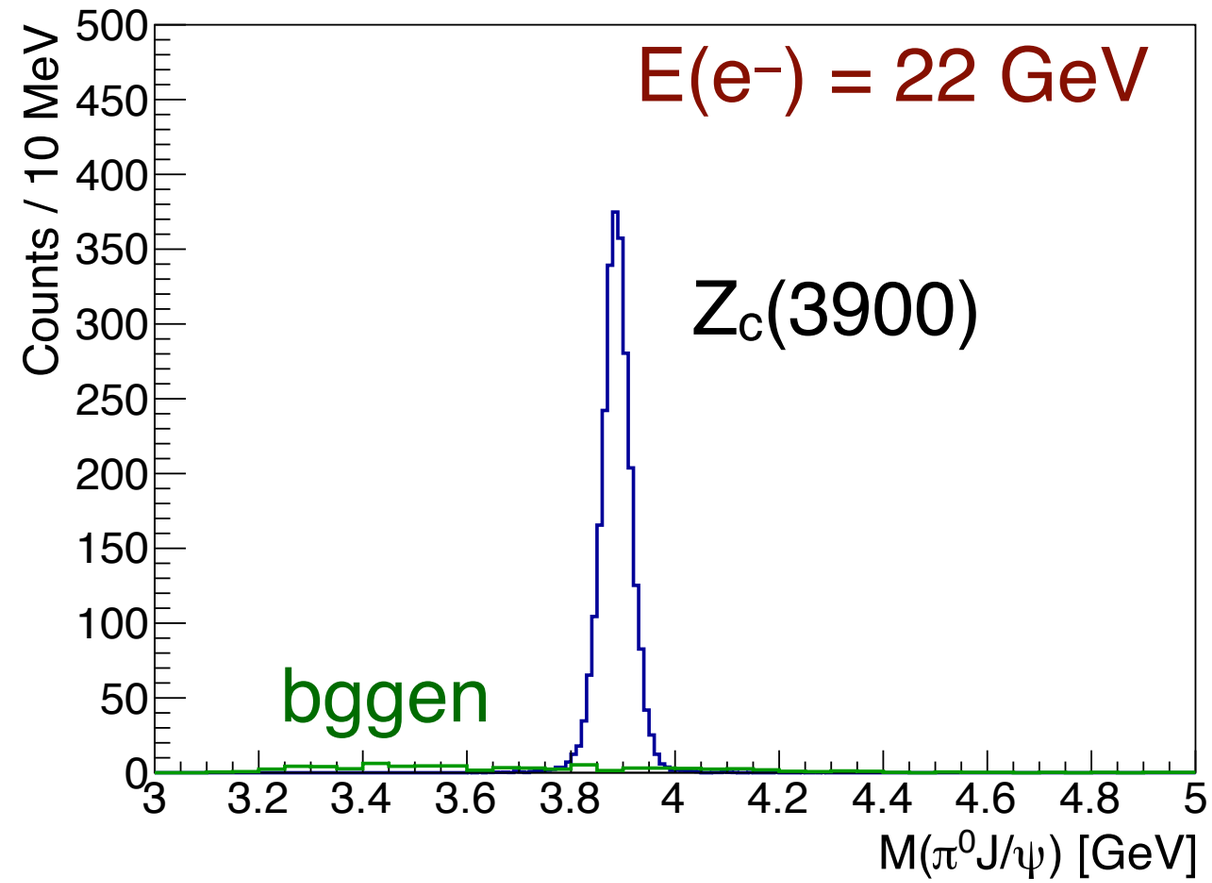


- Assumes 1 year @ 500 pb^{-1}, Br($Z^- \rightarrow \pi^- J/\psi$) = 5%
- N[Z_c(3900), J/ψπ^-]: 17 GeV = 1700, 22 GeV = 3400
- Uses JPAC prediction, neglects nuclear effects

Projections for J/ψπ^0 Photoproduction at GlueX

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





- Assumes 1 year @ 500 pb^{-1}, Br($Z^0 \rightarrow \pi^0 J/\psi$) = 5%
- N[Z_c(3900), J/ψπ^0]: 17 GeV = 1300, 22 GeV = 2500
- Assume same cross section as $\gamma p \rightarrow Z_c^+ n$ as upper limit
  Can clearly extract signals an order of magnitude smaller

Summary and Prospects

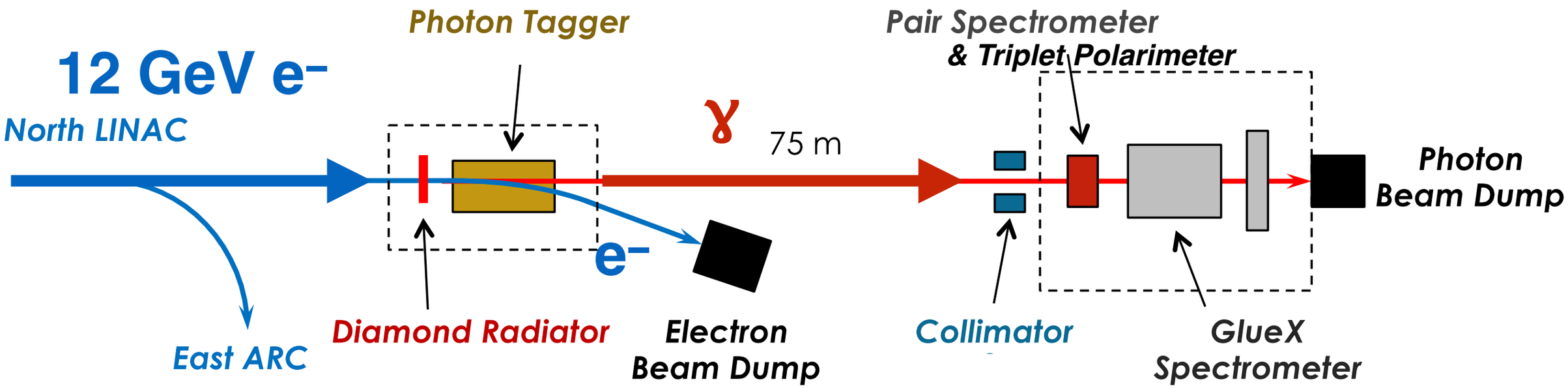
- Measuring XYZ states in photoproduction is crucial to determine their nature
- Simulations show that the baseline GlueX detector can cleanly identify interesting samples of well-known XYZ states in decays containing J/ψ's
  - Benchmark for lesser understood XYZ states, potential improvements for higher luminosity running
  - Expected detector upgrades: FCAL-II, forward GEM-TRD
- Opens path to precision XYZ spectroscopy at GlueX
  - Next steps include study of polarization observables to determine the microscopic structure of these states, alongside guidance from theory

Backup Slides

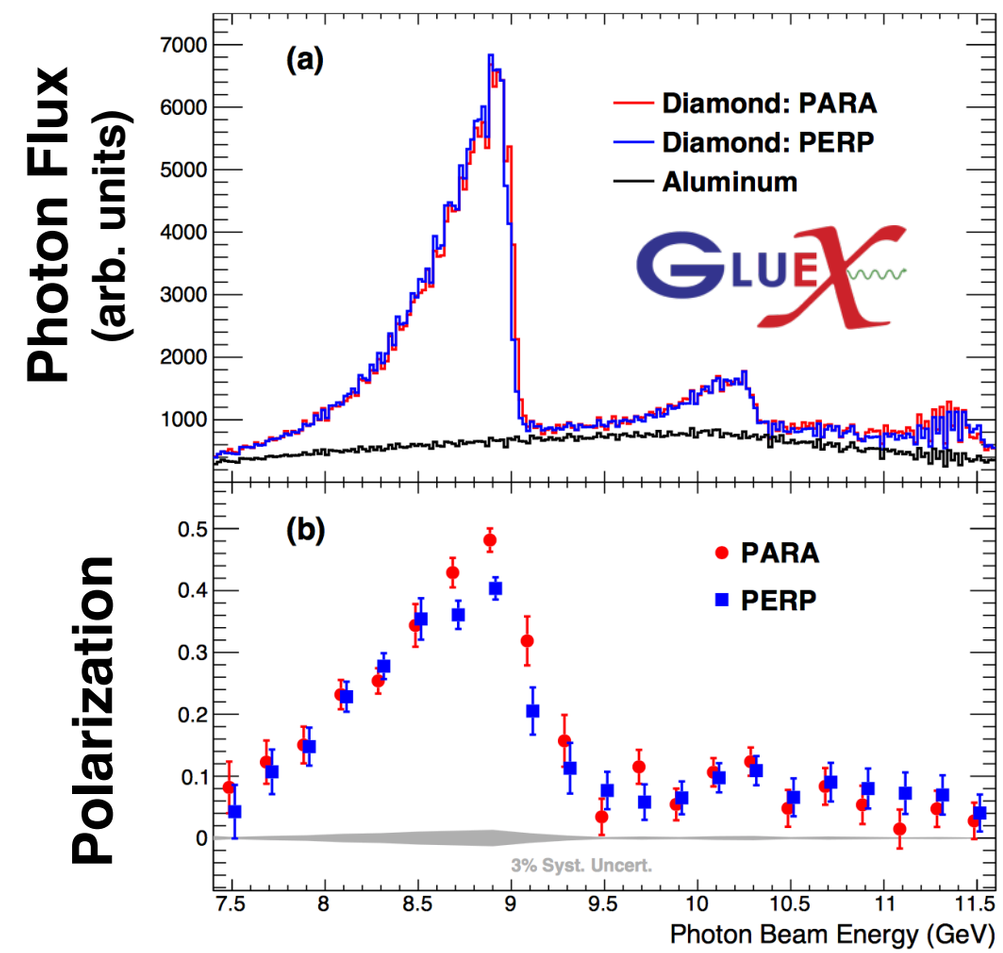
Light hadron spectroscopy at GlueX at higher energies

- At higher beam energies, GlueX can continue to support a rich program of light hadron spectroscopy
- Potential benefits:
  - Higher linear polarization (up to ~80%) leads to large increase in polarized FOM for PWA (P^2L)
  - Better kinematic separation between mesons / baryons, etc.
  - Kinematic fit works well to improve mass resolution
  - Can study beam energy dependence of hybrid xsecs, etc.
- Potential challenges:
  - Impact of larger momentum tracks needs to be evaluated
    - Effect on resolution and pion/kaon separation
  - Impact on efficiency

The GlueX Experiment: Photon Beam



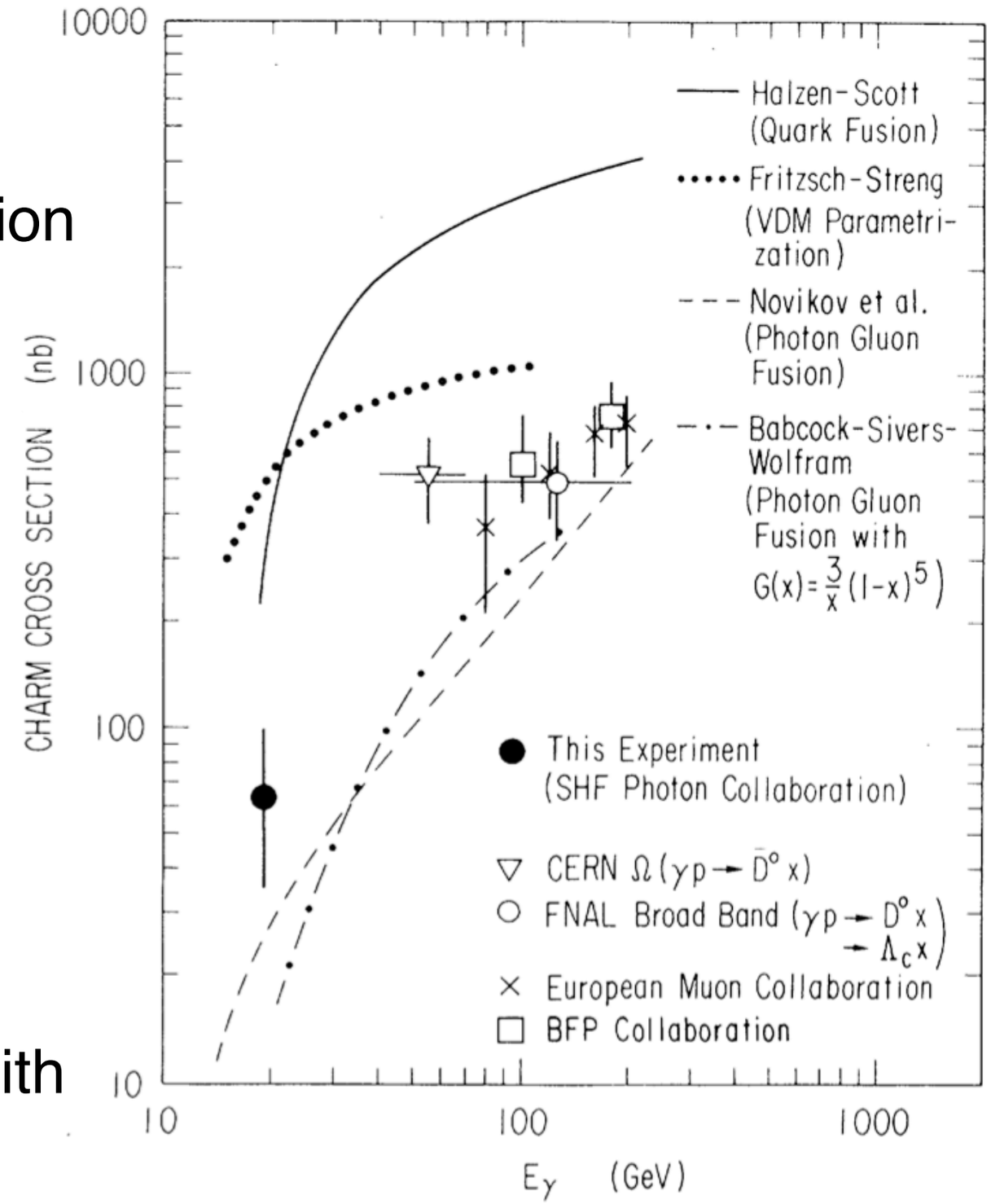
- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of ~1–5 × 10^7 γ/s in peak



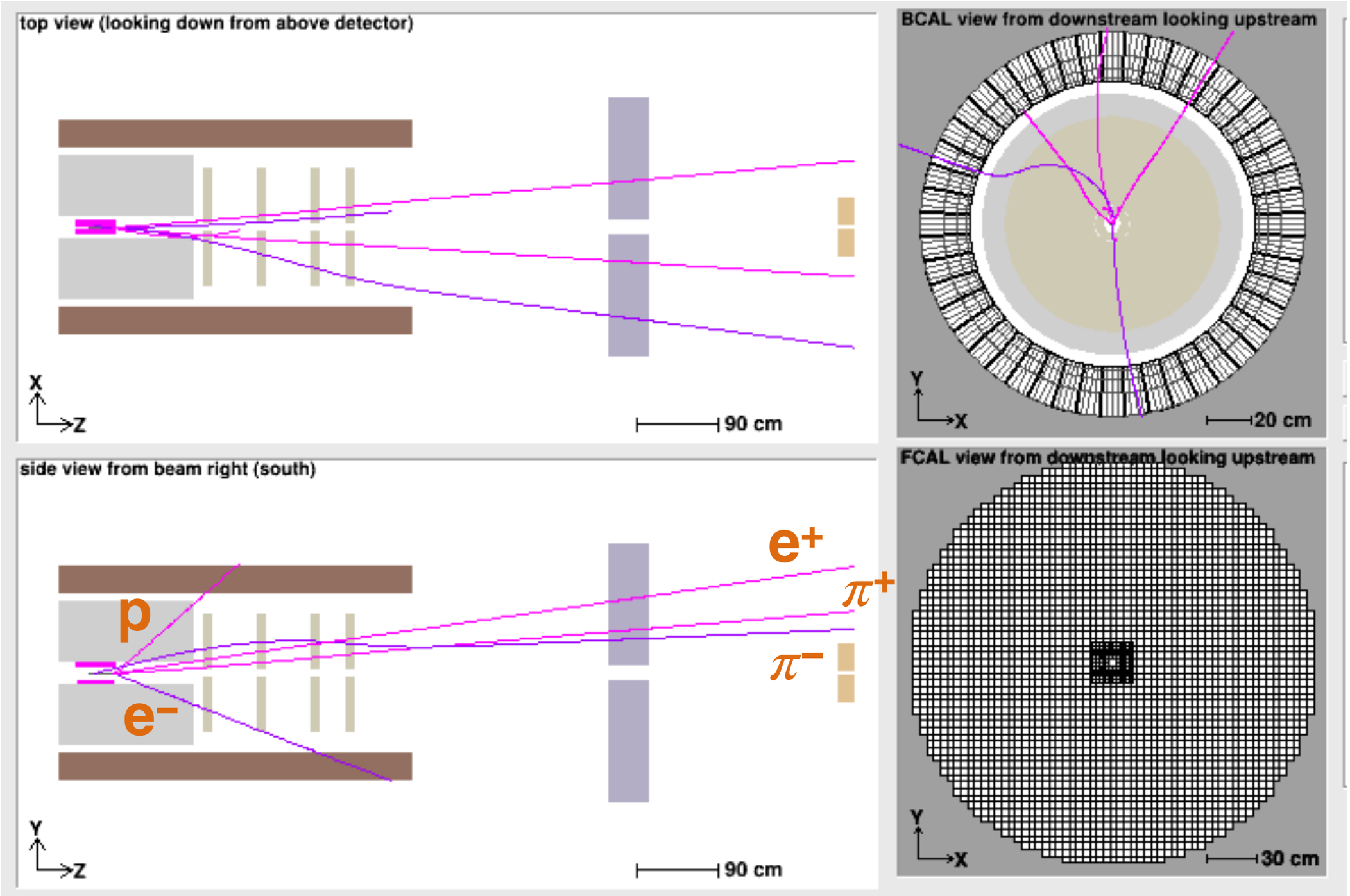
Open Charm Production Near Threshold

- Hadron ($c\bar{c}$) molecules like to decay to open-charm final states, can we see them at GlueX?
  - 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)



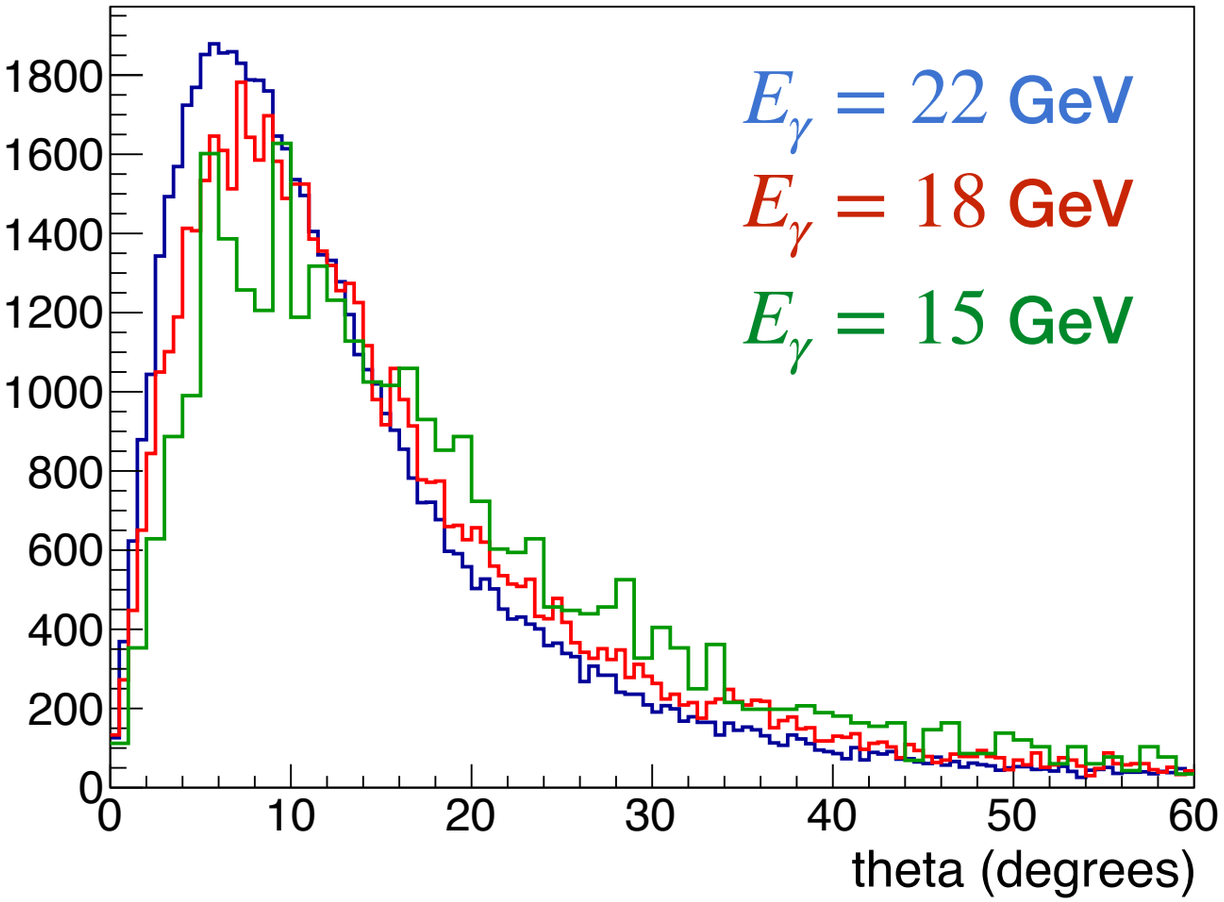
Example $\gamma p \rightarrow X(3872)p$, $X \rightarrow \pi^+\pi^- J/\psi$ event



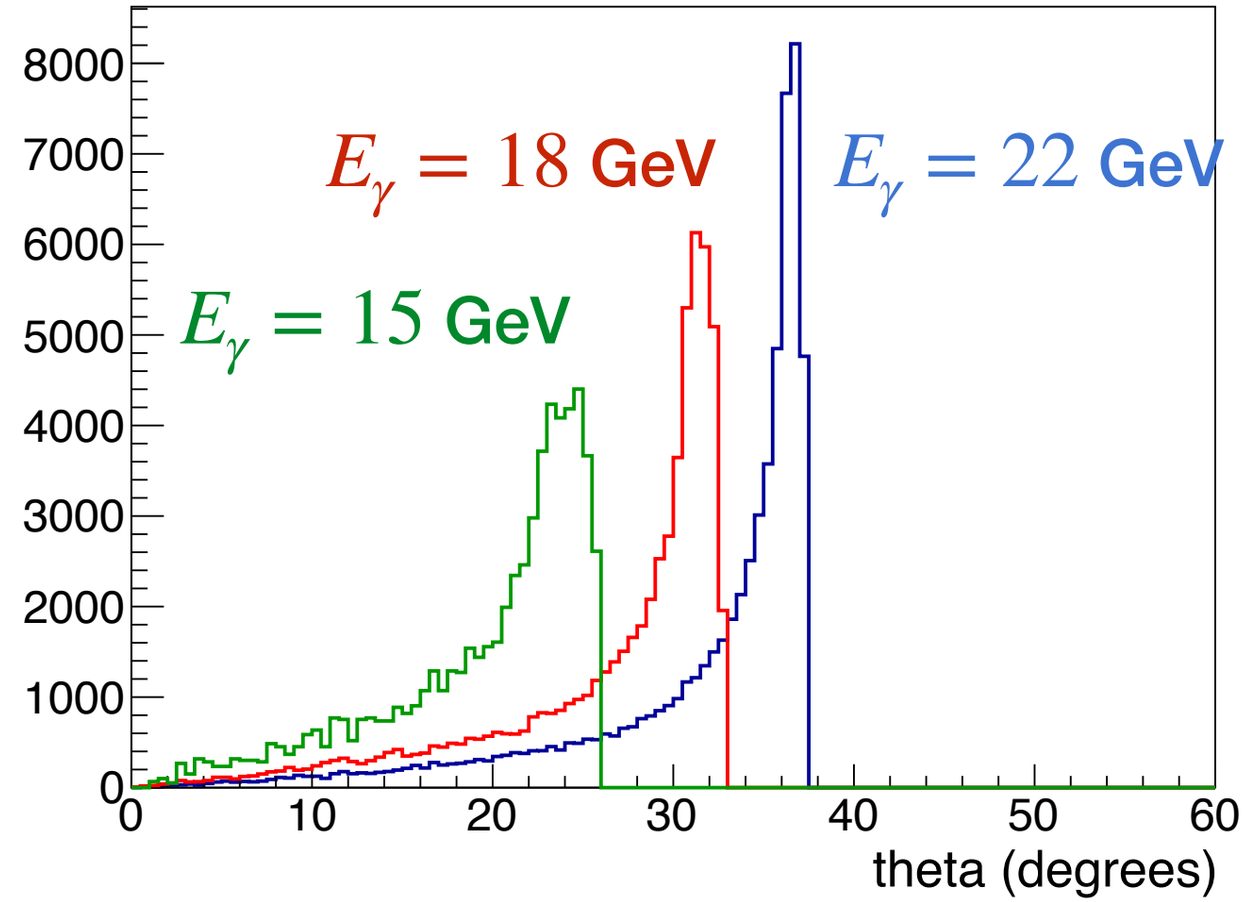
- All reaction products well within GlueX acceptance

Kinematics of γp → X(3872)p, X → $\pi^+\pi^- J/\psi$

Electrons

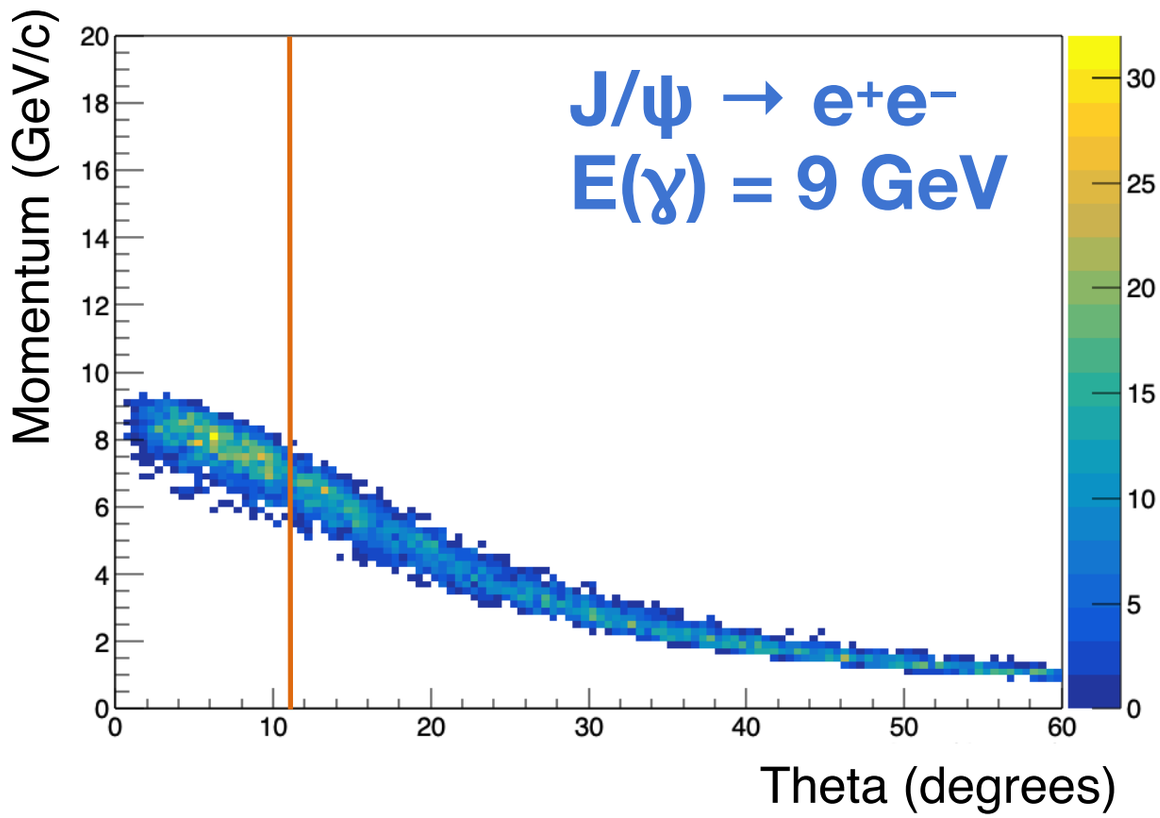


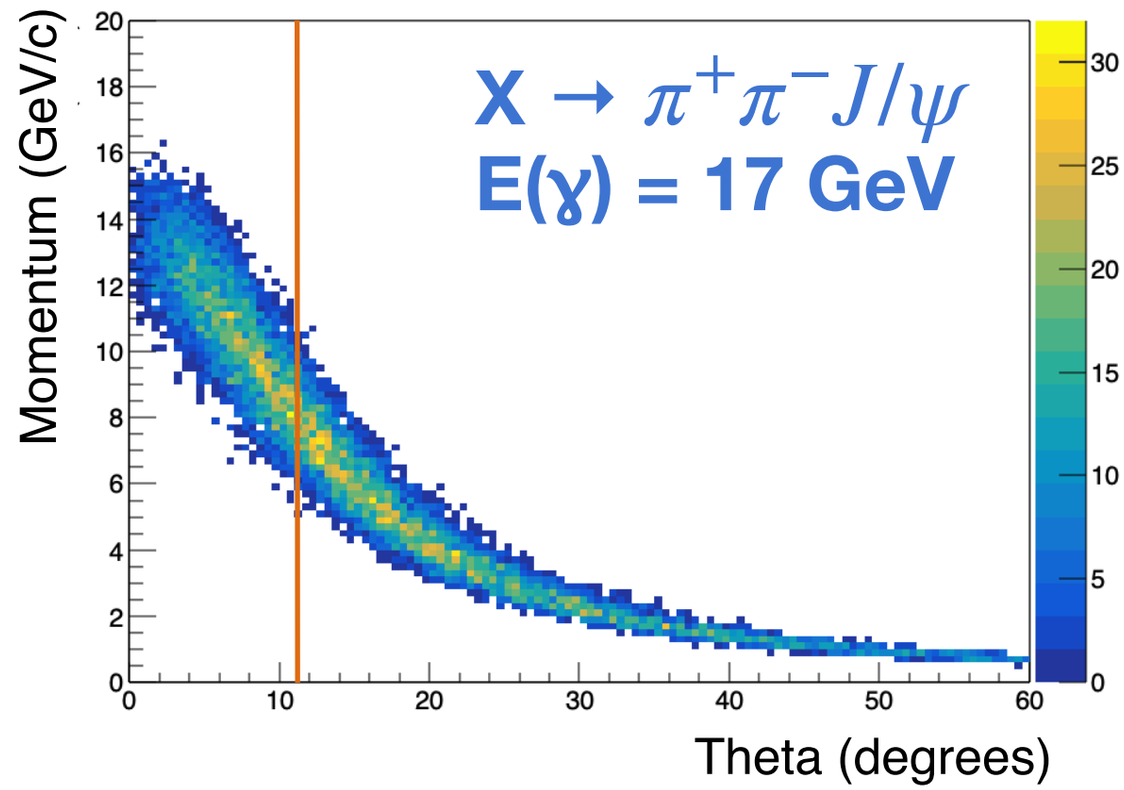
Protons

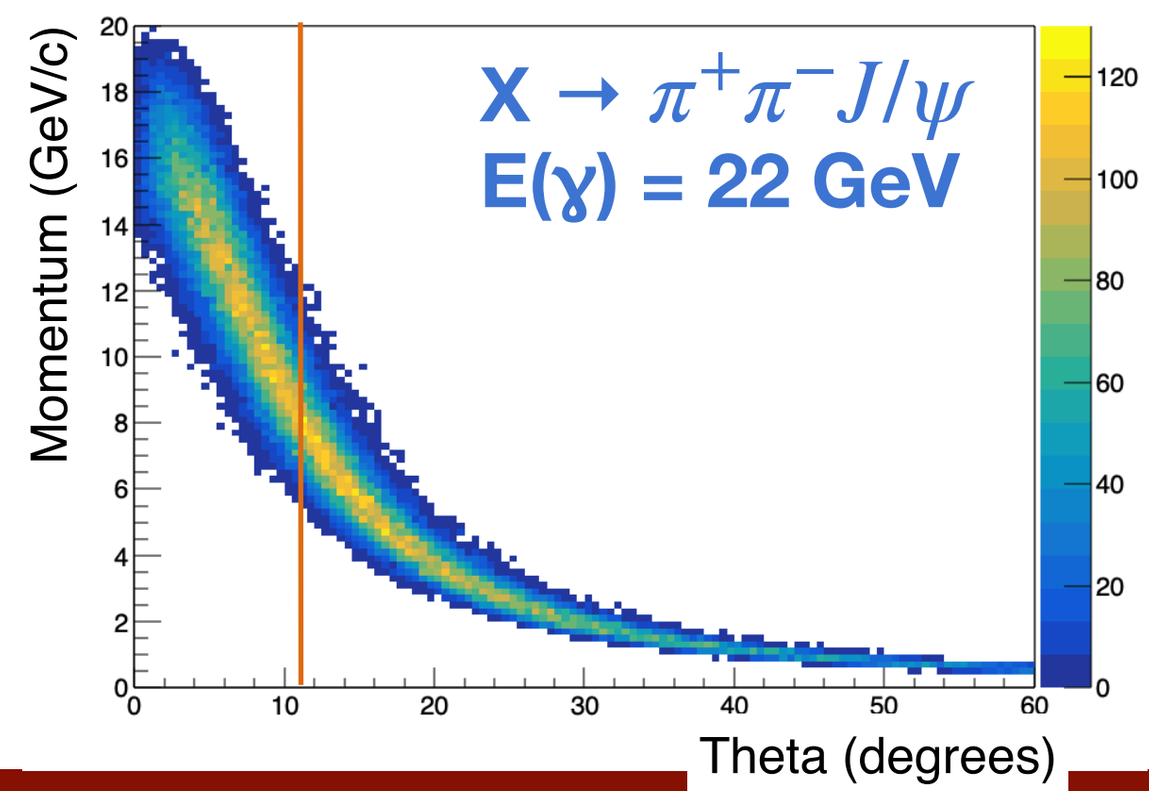


- Histograms normalized to same area
- Electrons/positrons from J/ψ decay spread across large angular range
- At higher energies, recoil protons more central

Electron Kinematics of γp → X(3872)p, X → $\pi^+\pi^- J/\psi$

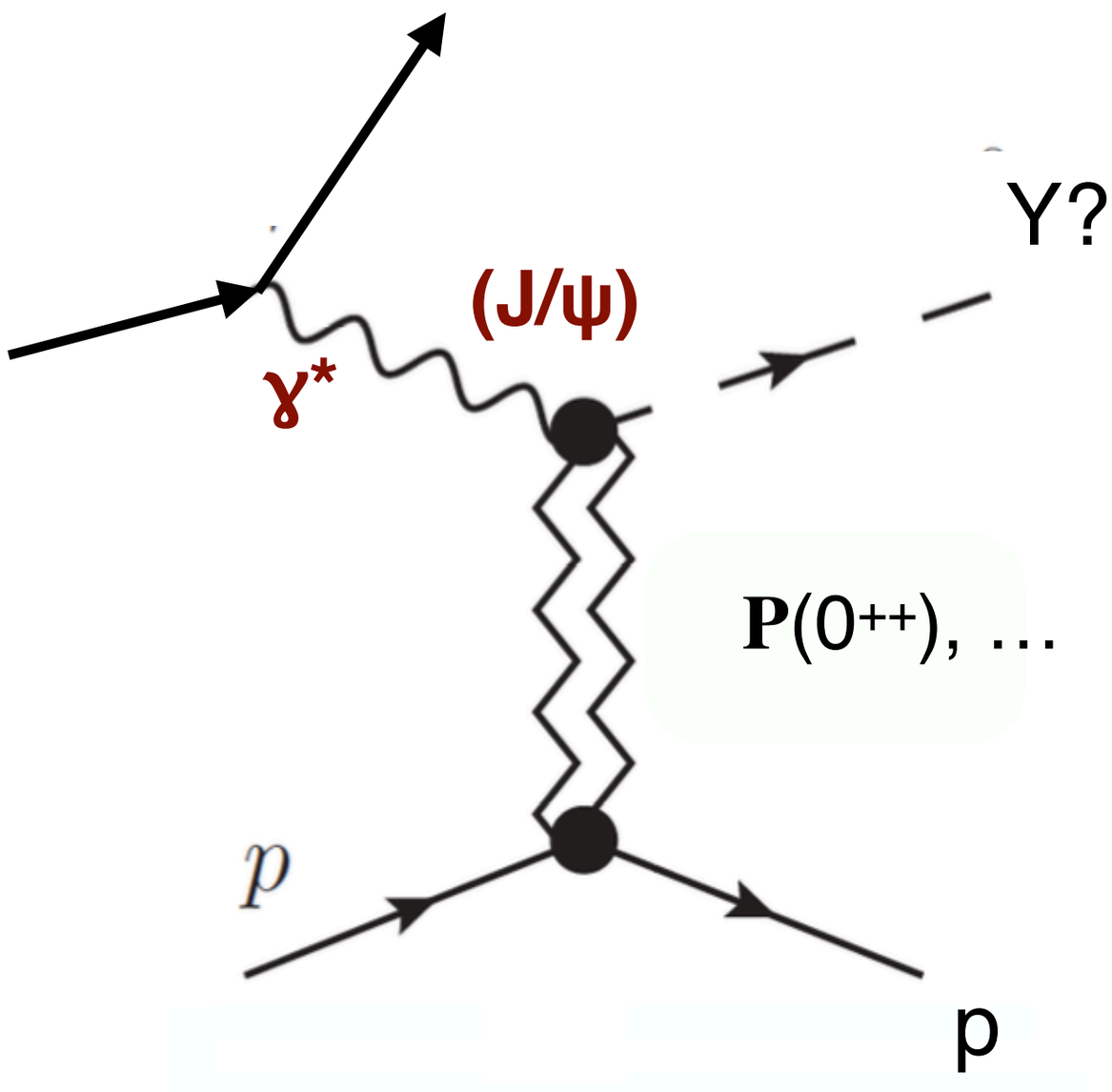






- Electrons/positrons from J/ψ decay spread across large angular range
- Line illustrates separation between forward and central calorimeters

Searching for "Charming" Hybrids



- Hybrid mesons should have charm-quark counterparts
  - Candidates exist
  - (Polarized) photons give clean probe
  - Vector mesons should be well produced via VMD
  - Other QN mesons can be produced as well
- EIC gives required CM energy (and luminosity?) to search for these