Prospects for Charmonium + XYZ Spectroscopy at GlueX

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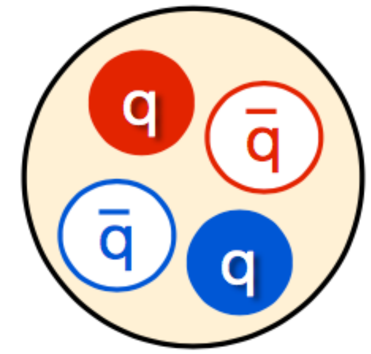
Peter Pauli

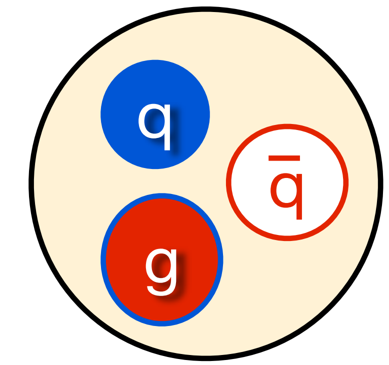
Hadron Spectroscopy with a CEBAF Energy Upgrade Workshop
June 17, 2022

Hadron Spectroscopy and Photoproduction

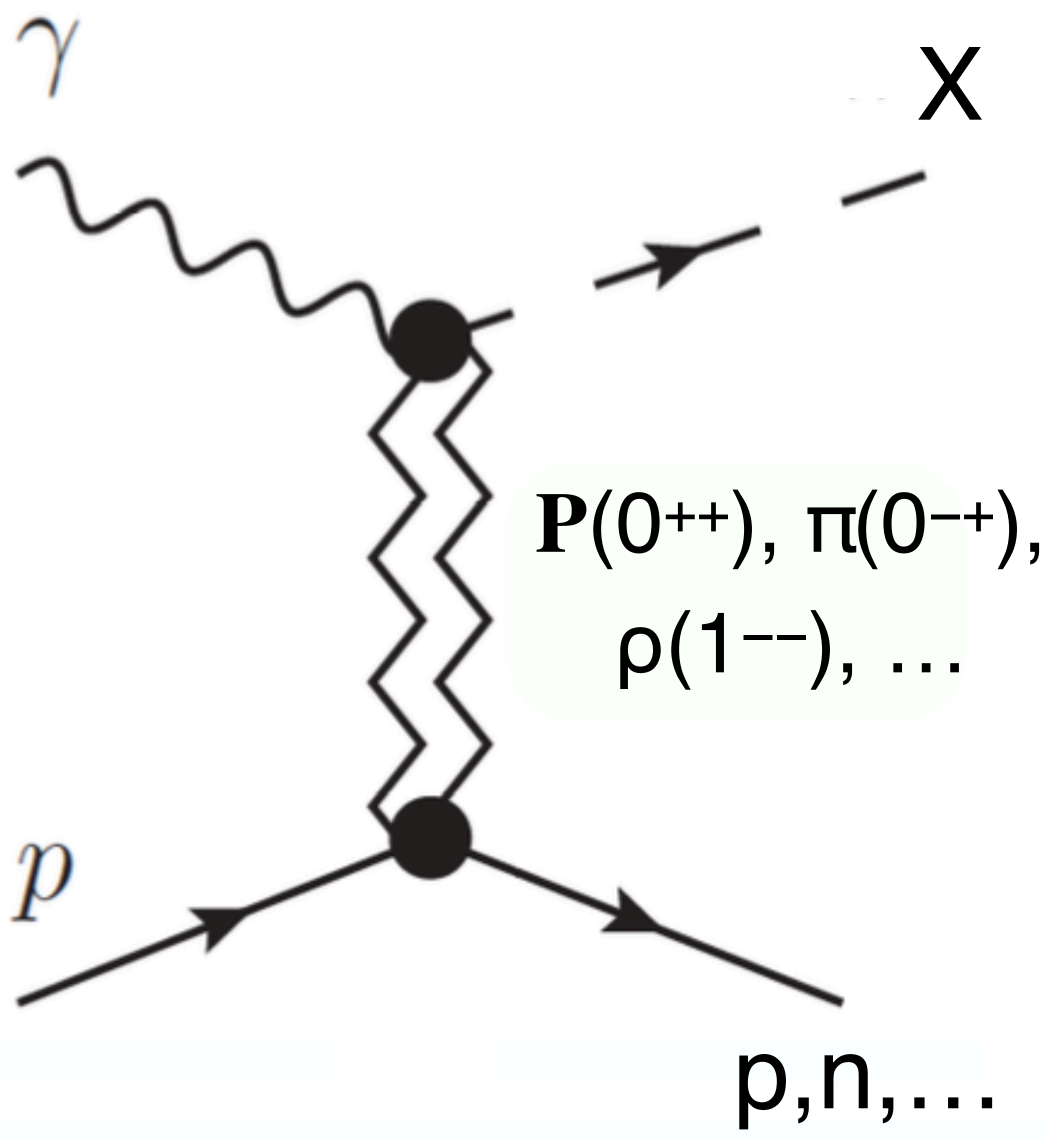
- Photoproduction is an essential process to study normal hadrons and to search for exotic hadrons



tetraquark

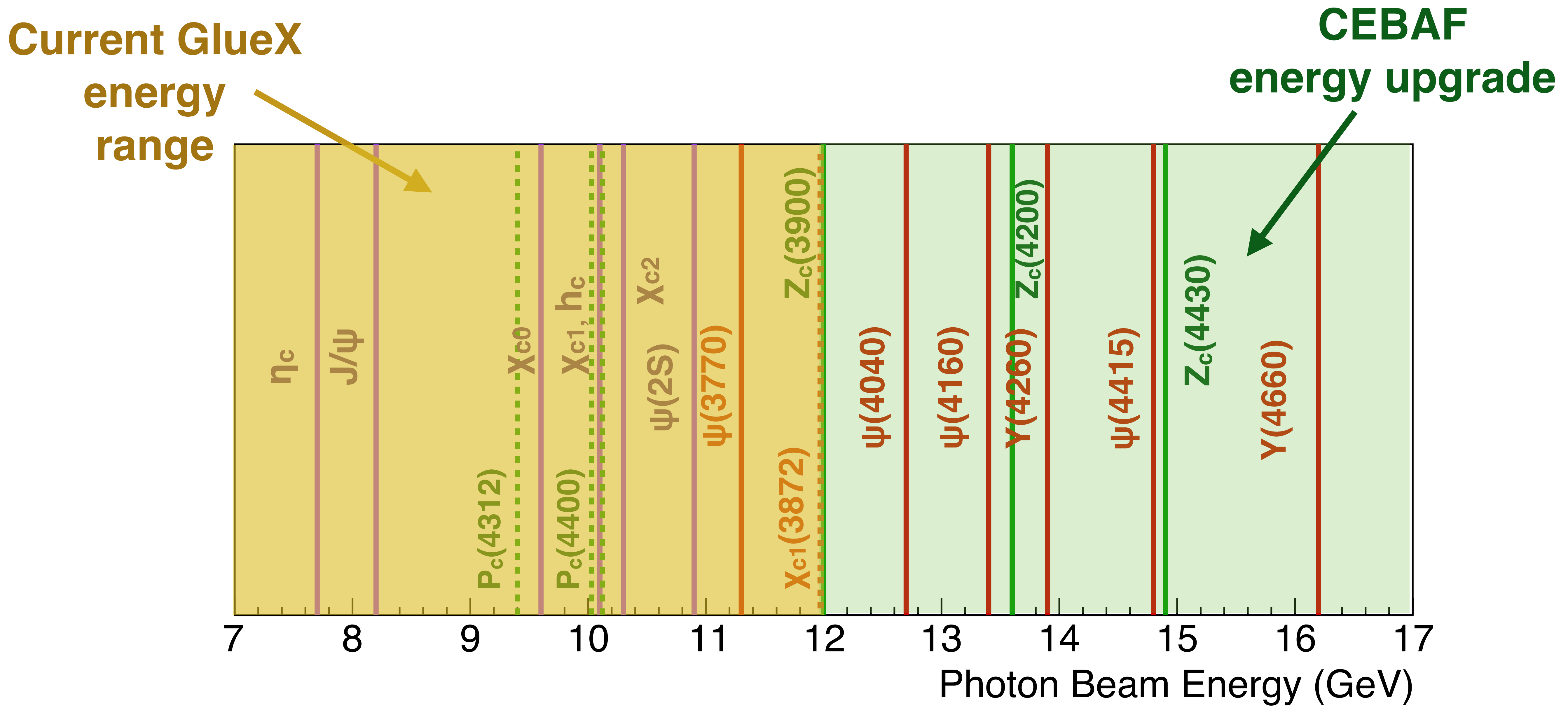


hybrid meson



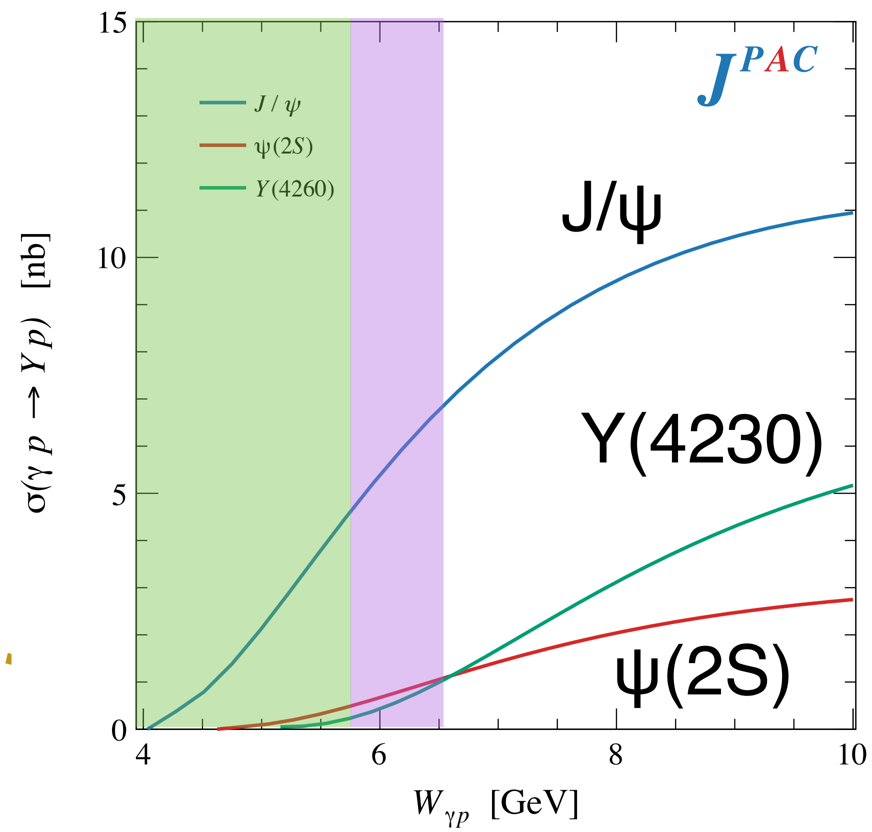
- Can produce mesons of any J^{PC} through VMD
- Photon polarization provides constraints on production processes
- GlueX has excellent opportunity to search for XYZ states (and others!) in a wide range of final states
  - Large acceptance for charged + neutral particles

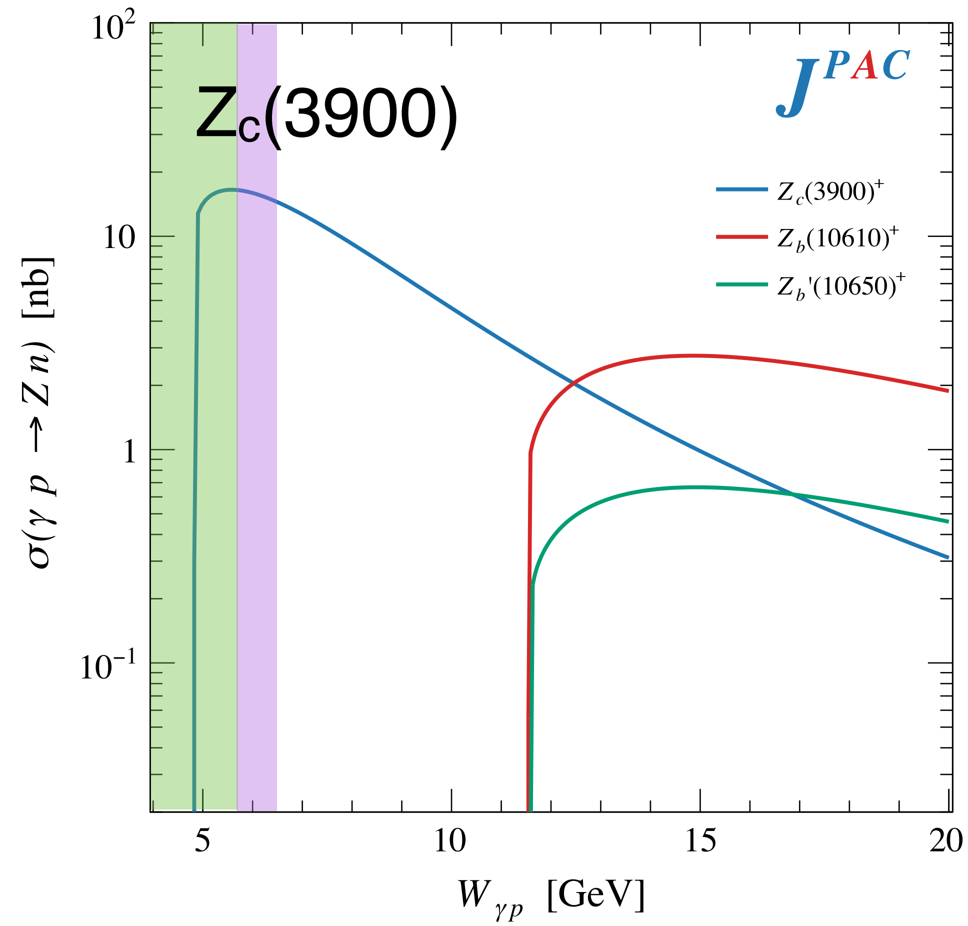
Charmonium Photoproduction Near Threshold

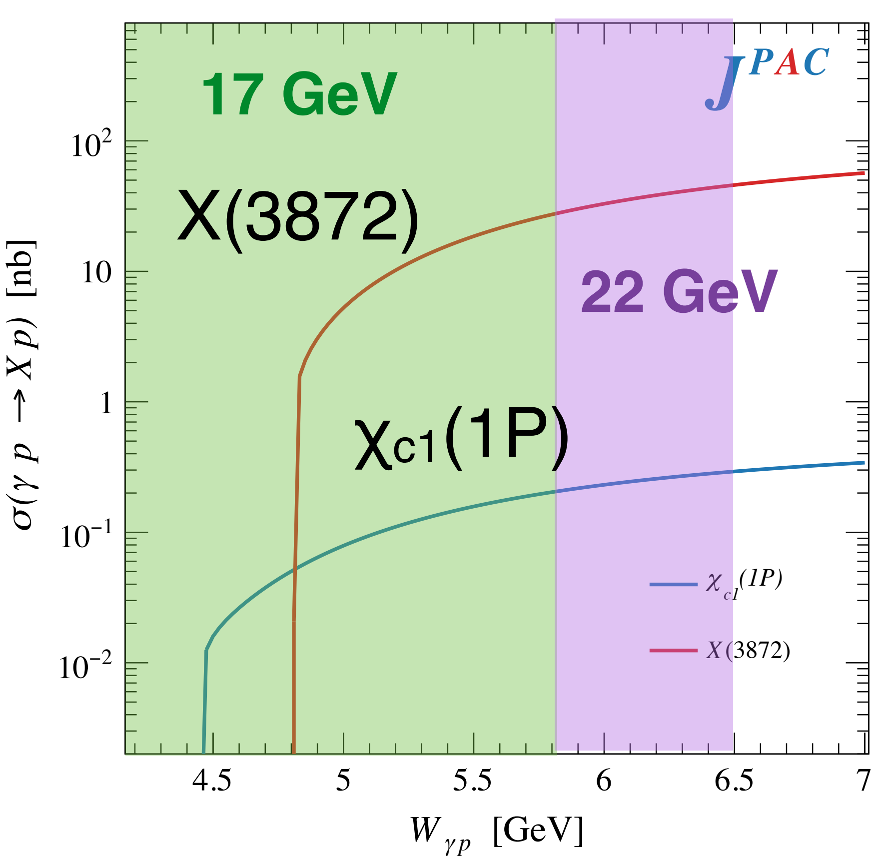


- Current max CEBAF energy allows study of bound $c\bar{c}$, P_c states
- 17 GeV e^- gives access to most exotic candidates
- 22 GeV e- gives good phasespace, linear polarization

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

Selected Charmonium + XYZ thresholds and decays

State	Threshold [GeV]	Suggested Decays (B.F.)
$\eta_c(1S)$	7.7	$K_S K\pi$ (2.3%), $K^+K^-\pi^0$ (2.3%), $\eta\pi\pi$ (1.7%)
$J/\psi(1S)$	8.2	e^+e^- (6%), $\mu^+\mu^-$ (6%)
$\chi_{c1}(1P)$	10.1	$\gamma J/\psi$ (34%)
$h_c(1P)$	10.1	$\gamma\eta_c(1S)$ (51%)
$\psi(2S)$	10.9	$\pi^+\pi^- J/\psi$ (35%), $\pi^0\pi^0 J/\psi$ (18%)
X(3872)	11.9	$\pi^+\pi^- J/\psi$ ($\approx$ 4%), $\omega J/\psi$ ($\approx$ 4%), $\bar{D}^{*0}D^0$ ($\approx$ 50%)
$Z_c(3900)$	12.0	$\pi J/\psi$, $\bar{D}^*D$
Y(4230)	13.7	$\pi\pi J/\psi$, $\eta J/\psi$, $\pi\pi h_c$
$Z_c(4020)$	13.6	πh_c
$Z_{cs}(3985)\Lambda$	14.3	(KJ/ψ), $\bar{D}^*D_s$

- Open charm production important for understanding molecular states
- Q: what can we project from light quark meson production?

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XYZ's at GlueX

- Many different XYZ states, many possible decay channels
  - First study best understood states as benchmarks
- First goal: XYZ production in their discovery modes
  - $X(3872)$, $Y(4230) \to J/\psi\pi^+\pi^-$, $Z_c^{\pm}(4230) \to J/\psi\pi^{\pm}$
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- Next: Can we identify non-J/ψ charmonium decays?
  - Most likely (?): $h_c(1P)$, $J^{PC} = 1^{+-}$, $Br(h_c \to \gamma\, \eta_c) \approx 50\%$
  - Opens up: $Y(4230) \to h_c\pi^+\pi^-$, $Z_c^\pm(4230) \to h_c\pi^\pm$

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  - Crucial for understanding "molecular" XYZP states
- Measurements with linear polarization under consideration

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will cover this today

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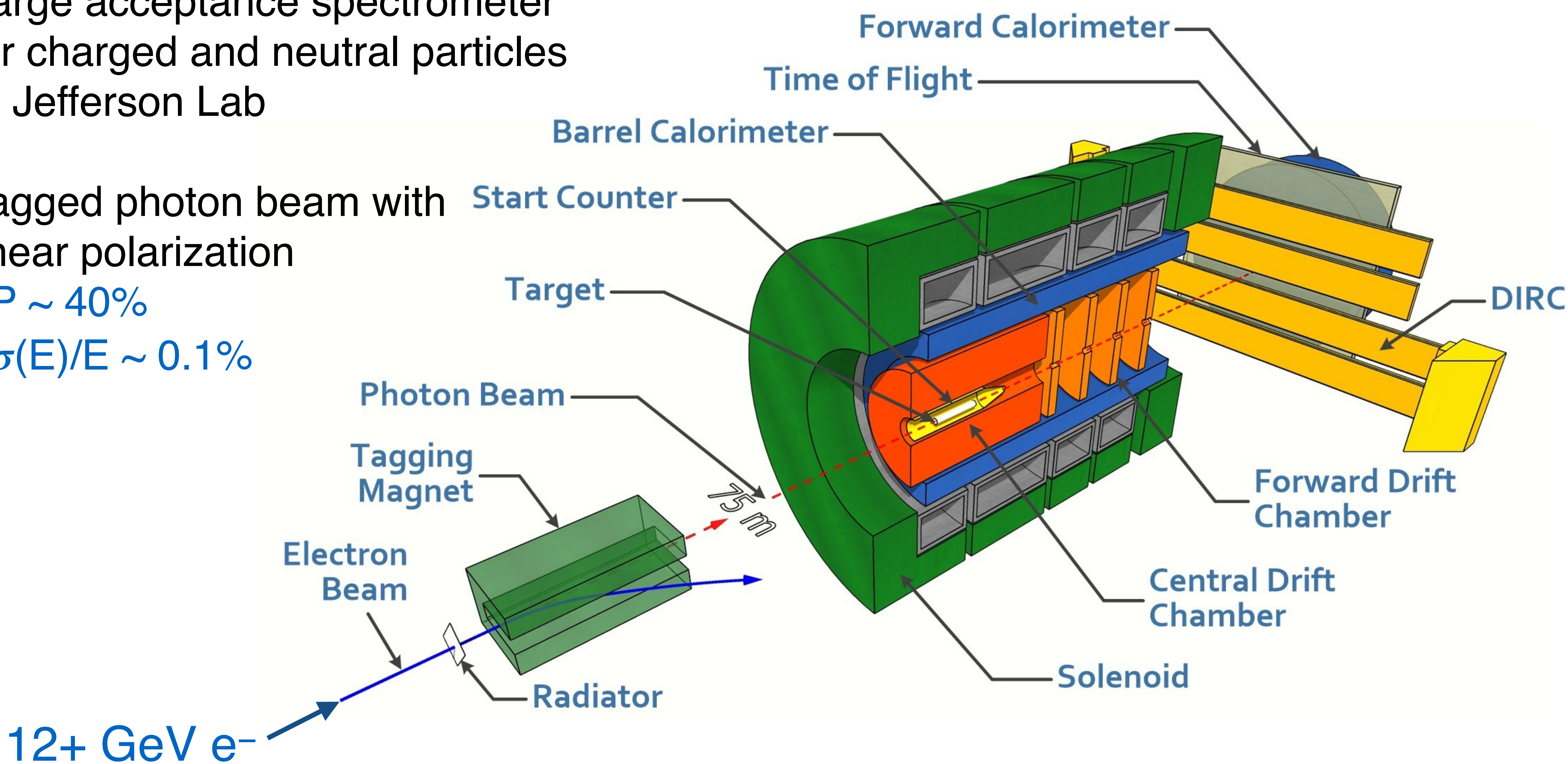
The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles at Jefferson Lab

Tagged photon beam with linear polarization

$P \sim 40\%$

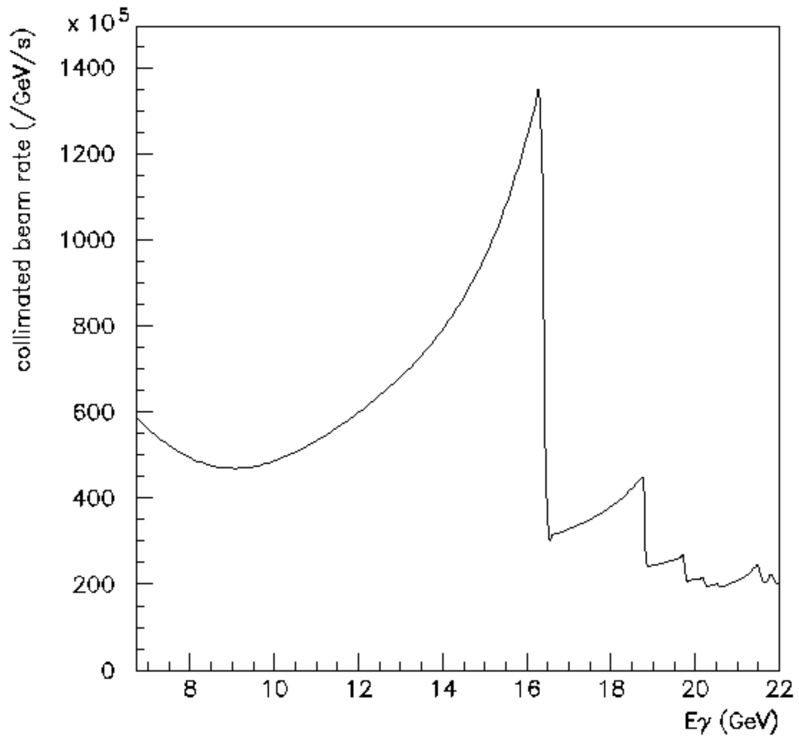
$\sigma(E)/E \sim 0.1\%$



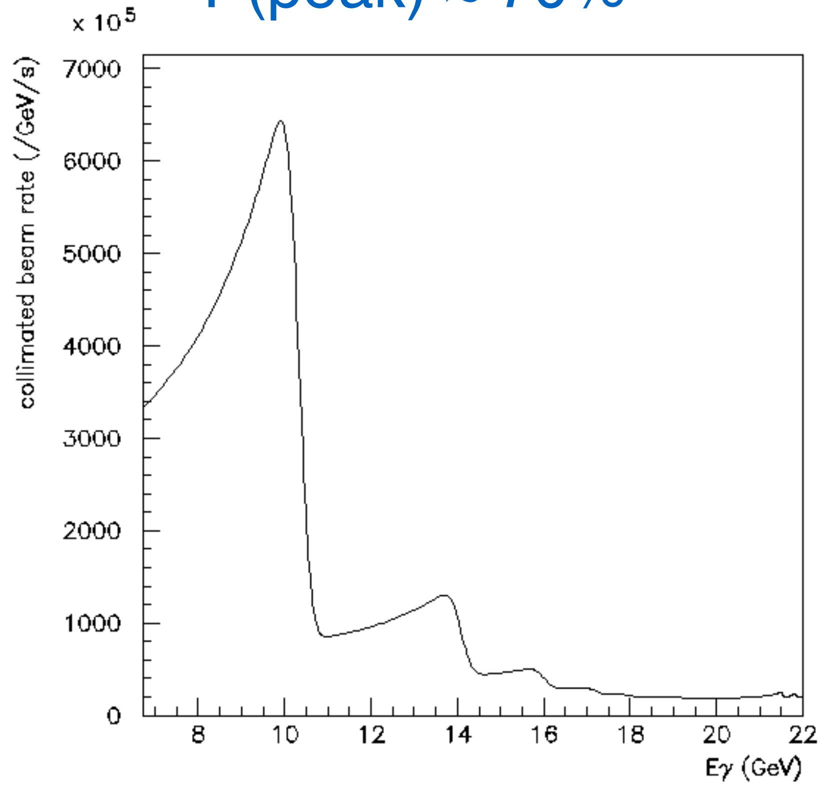
- Simulations performed with baseline GlueX-II spectrometer
- Assumes modest beam-line upgrades to handle higher energy electrons

Luminosity Expectations @ GlueX

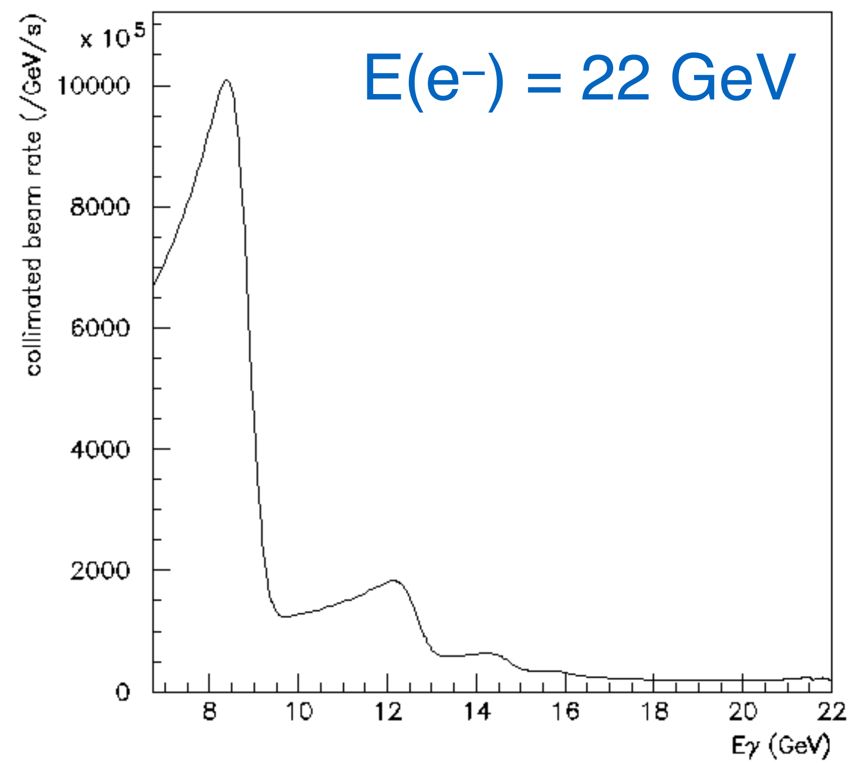
E(peak) = 16.5 GeV
P(peak) ≈ 35%



E(peak) = 10.5 GeV
P(peak) ≈ 70%

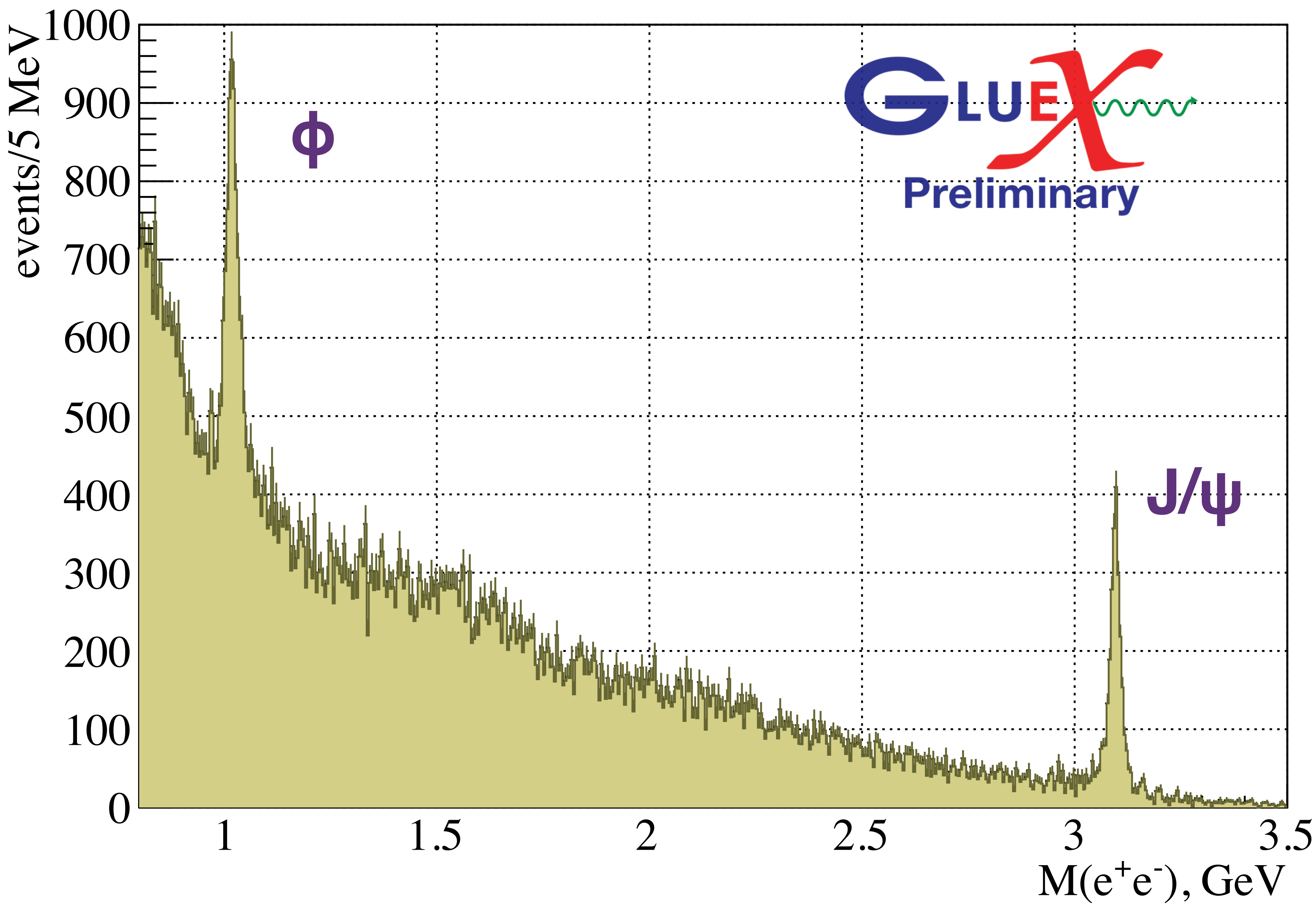


E(peak) = 9 GeV
P(peak) ≈ 80%



- Baseline: GlueX-II in 2020 @ 500 pb^{-1} / “year” ($E_\gamma > E_{e-} / 2$)
- This is the lower limit, ideas exist on how to go higher
  - Simple tagger upgrades → factor 4 increase
  - More restrictive trigger (think J/ψ → e+e–)
  - Rate limitations due to forward tracker / TOF ?
    → can imagine new detectors

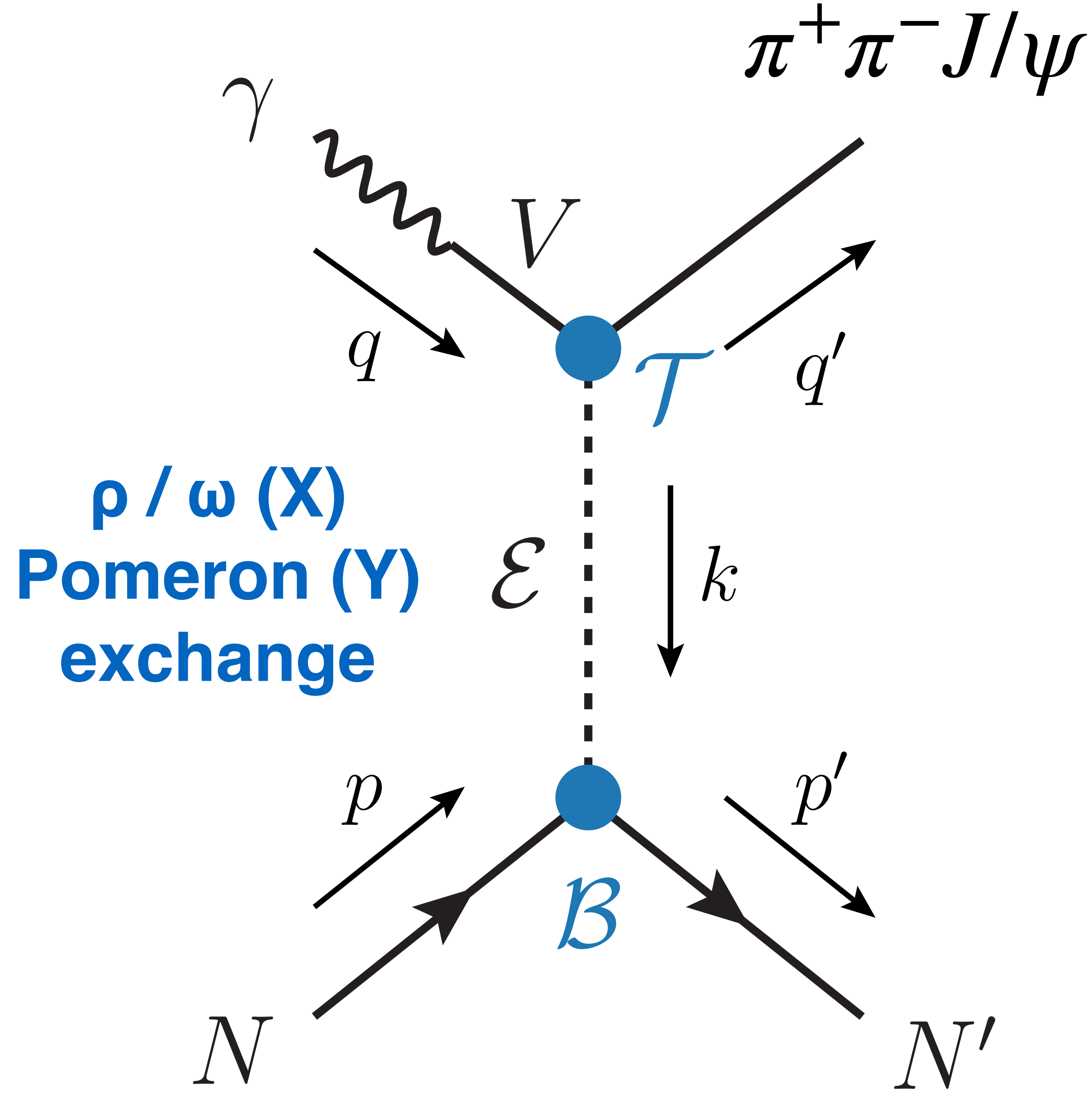
Reminder: J/ψ Photoproduction at GlueX



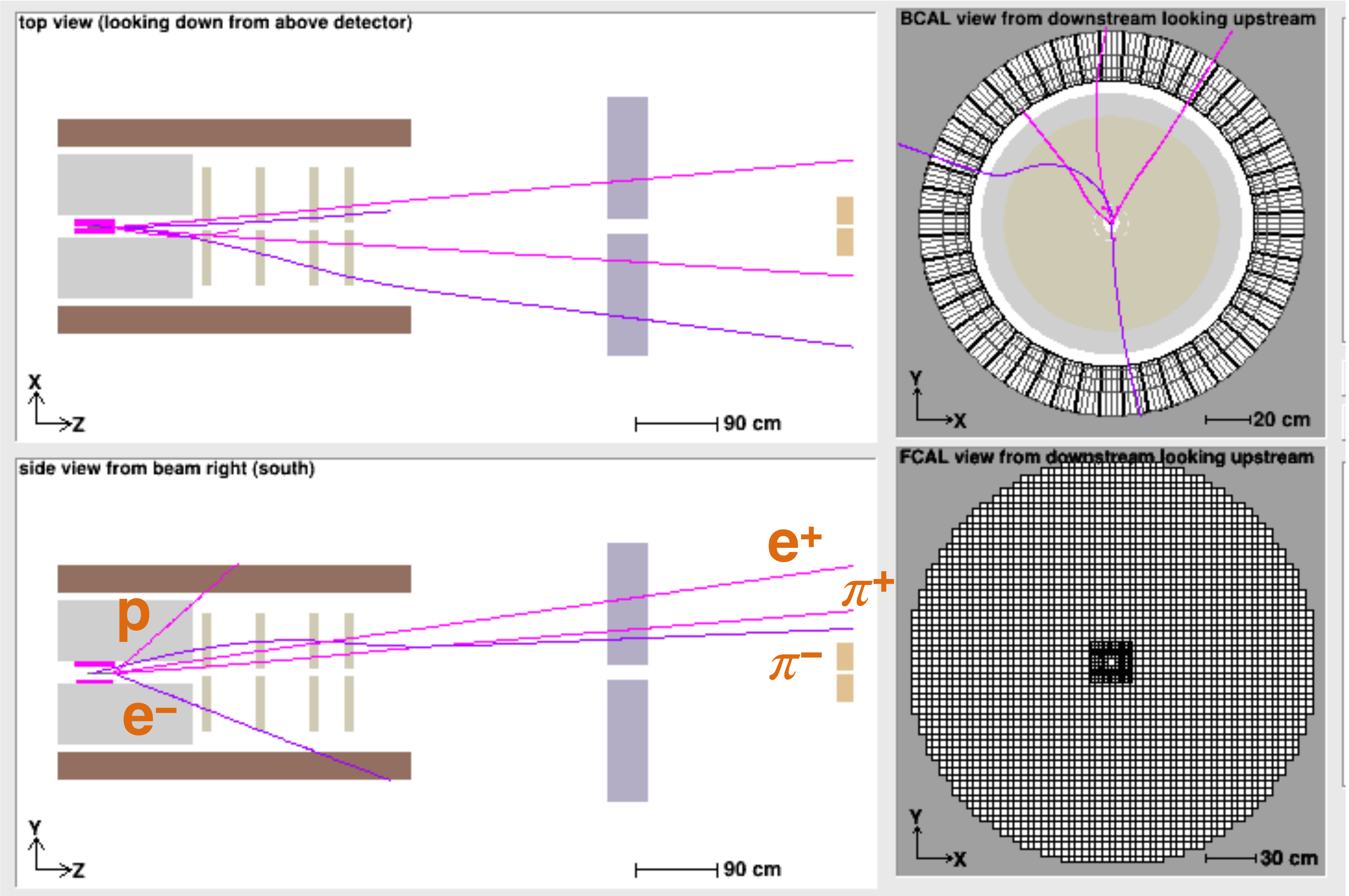
- Reconstruct full reaction: **p γ → p + J/ψ, J/ψ → e^+e^-**
- Tagged photon + kinematic fit provides excellent mass resolution

X, Y Production at GlueX

- Benchmark: X(3872), Y(4320) production with $\pi\pi J/\psi$ decay
  - $\gamma p \to \pi^+\pi^- J/\psi p$
- Performed simulations in hdgeant4 using base GlueX detector
- 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

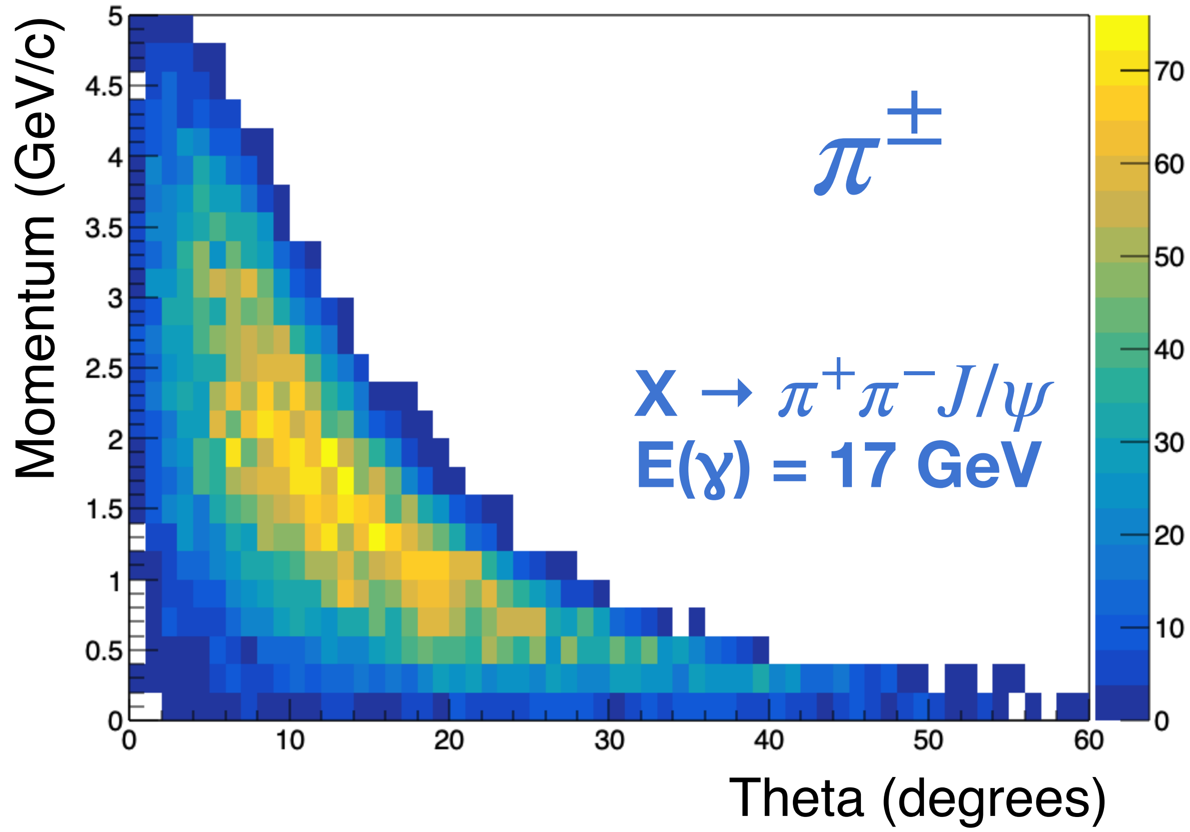


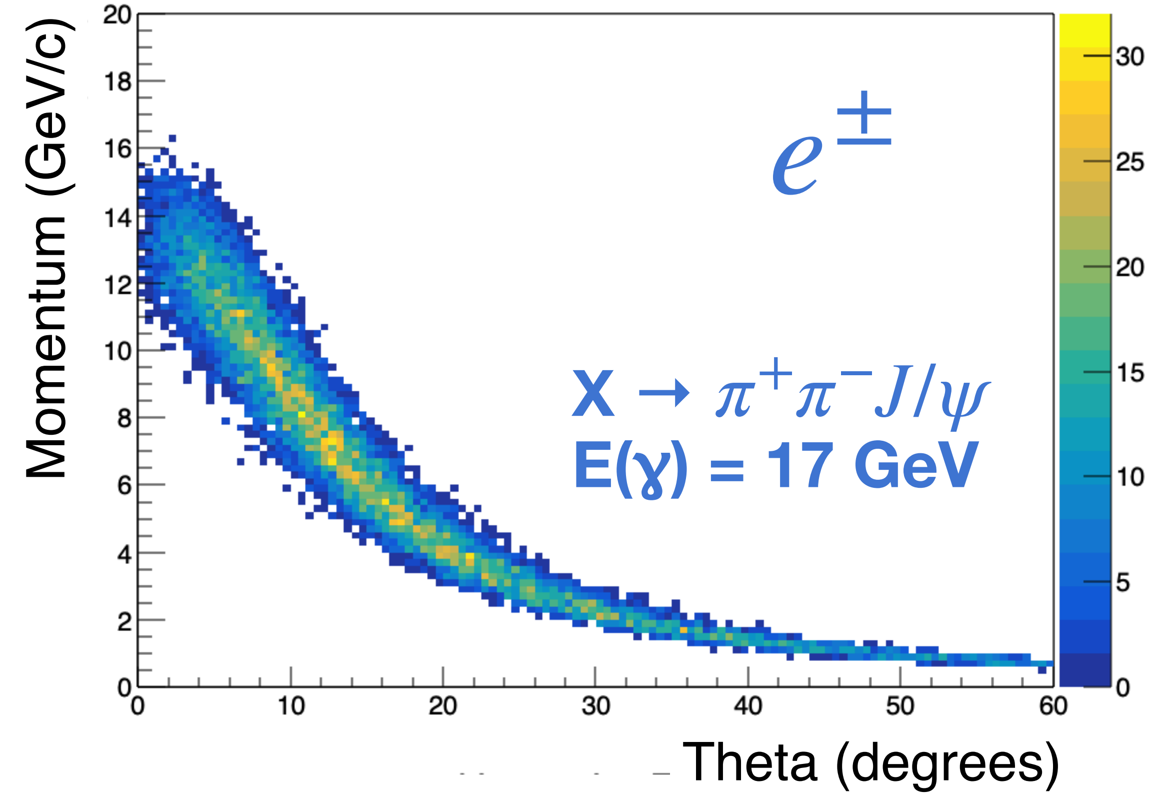
Example γp → X(3872)p, X → $\pi^+\pi^- J/\psi$ event



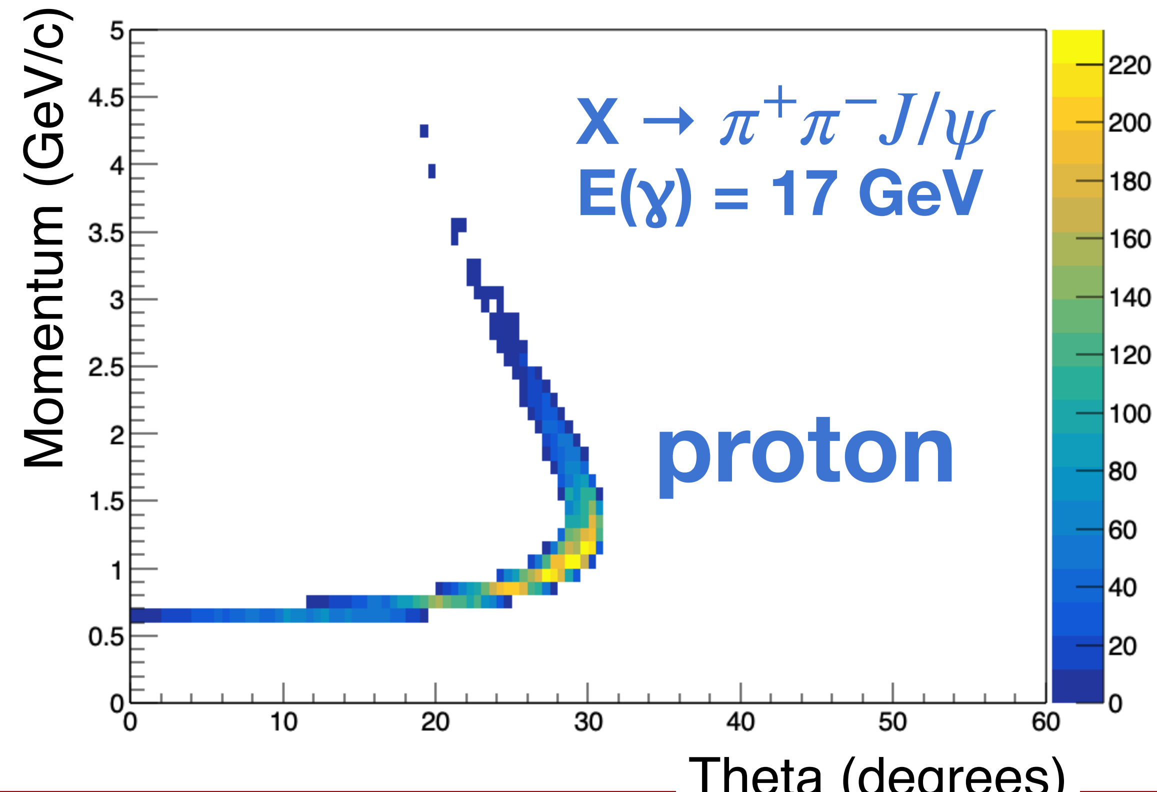
- All reaction products well within GlueX acceptance

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

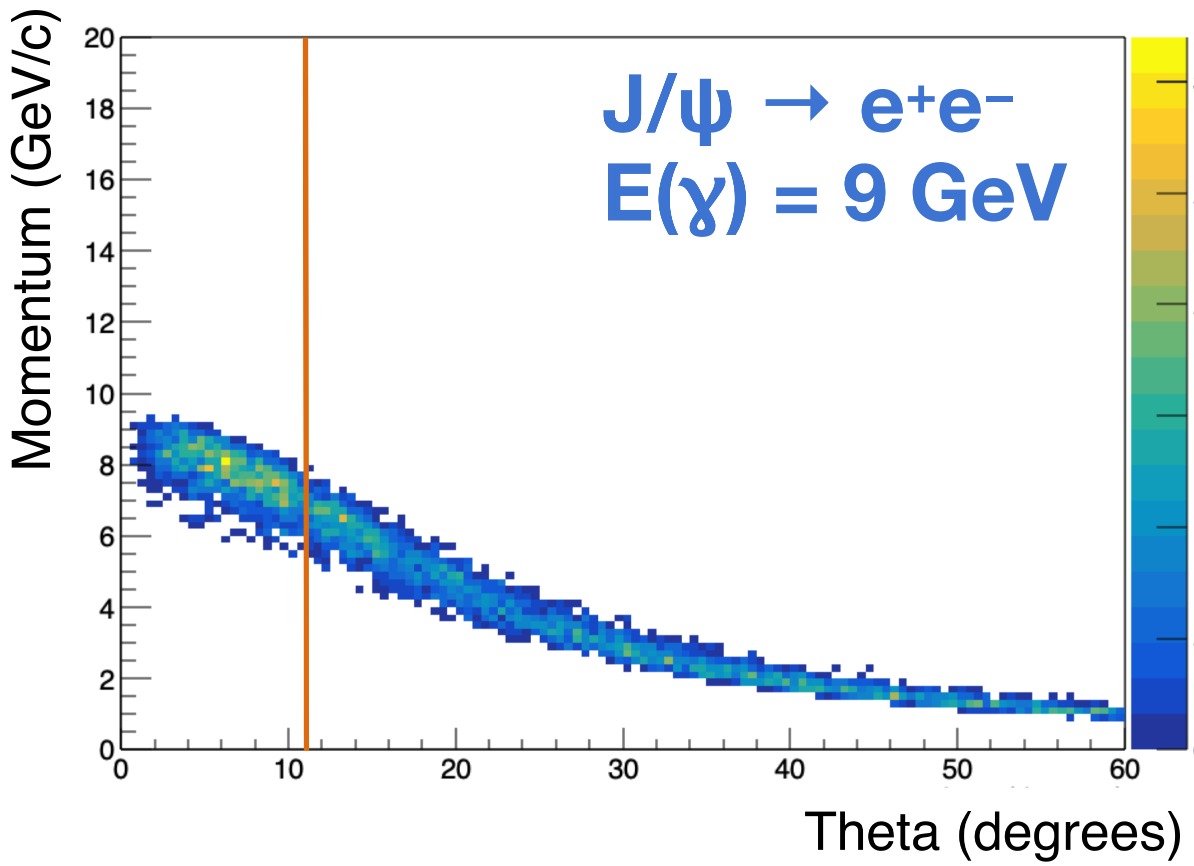


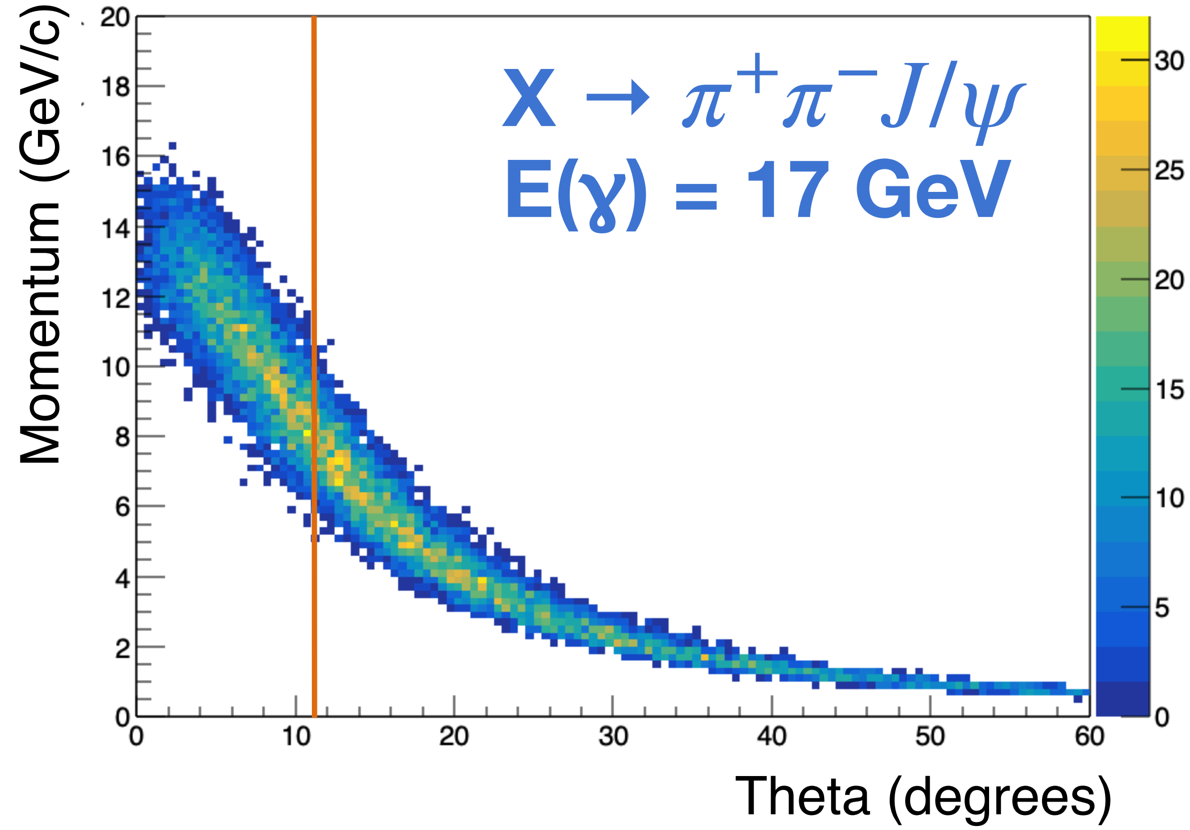


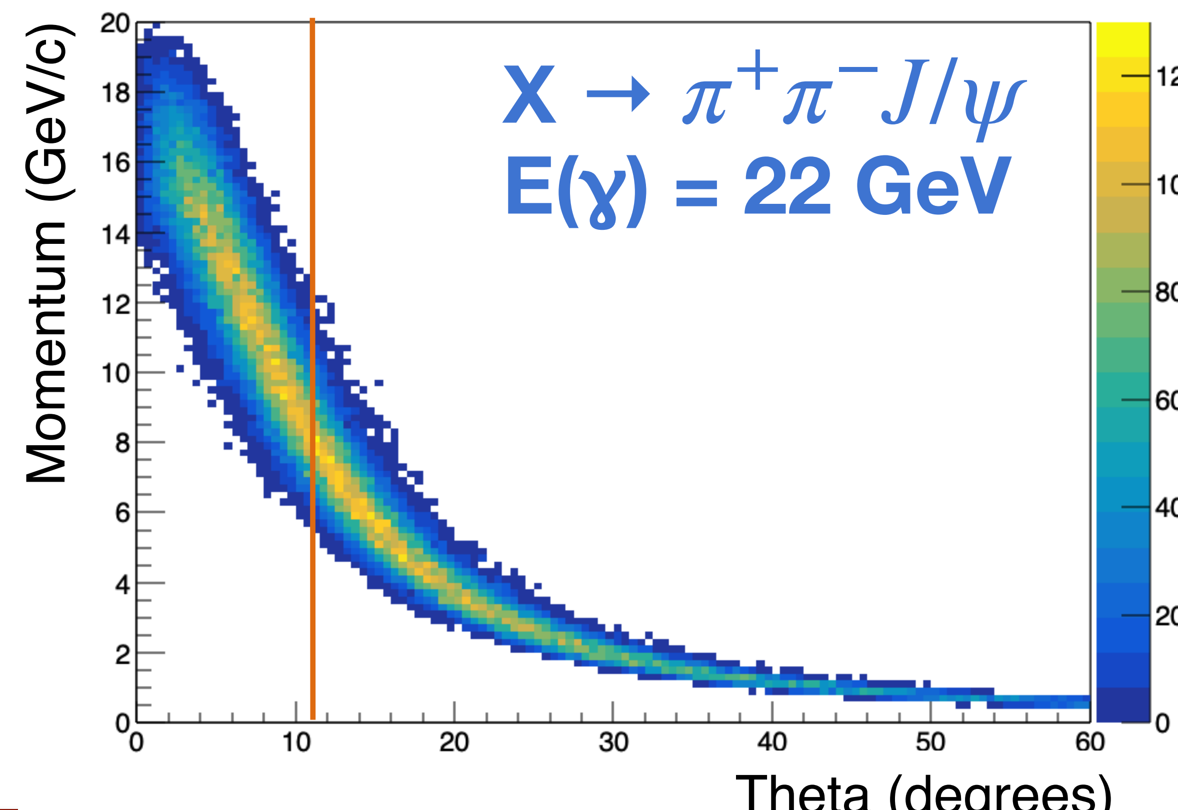
- Example: X → $\pi^+\pi^- J/\psi$ decay products are well within GlueX acceptance



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



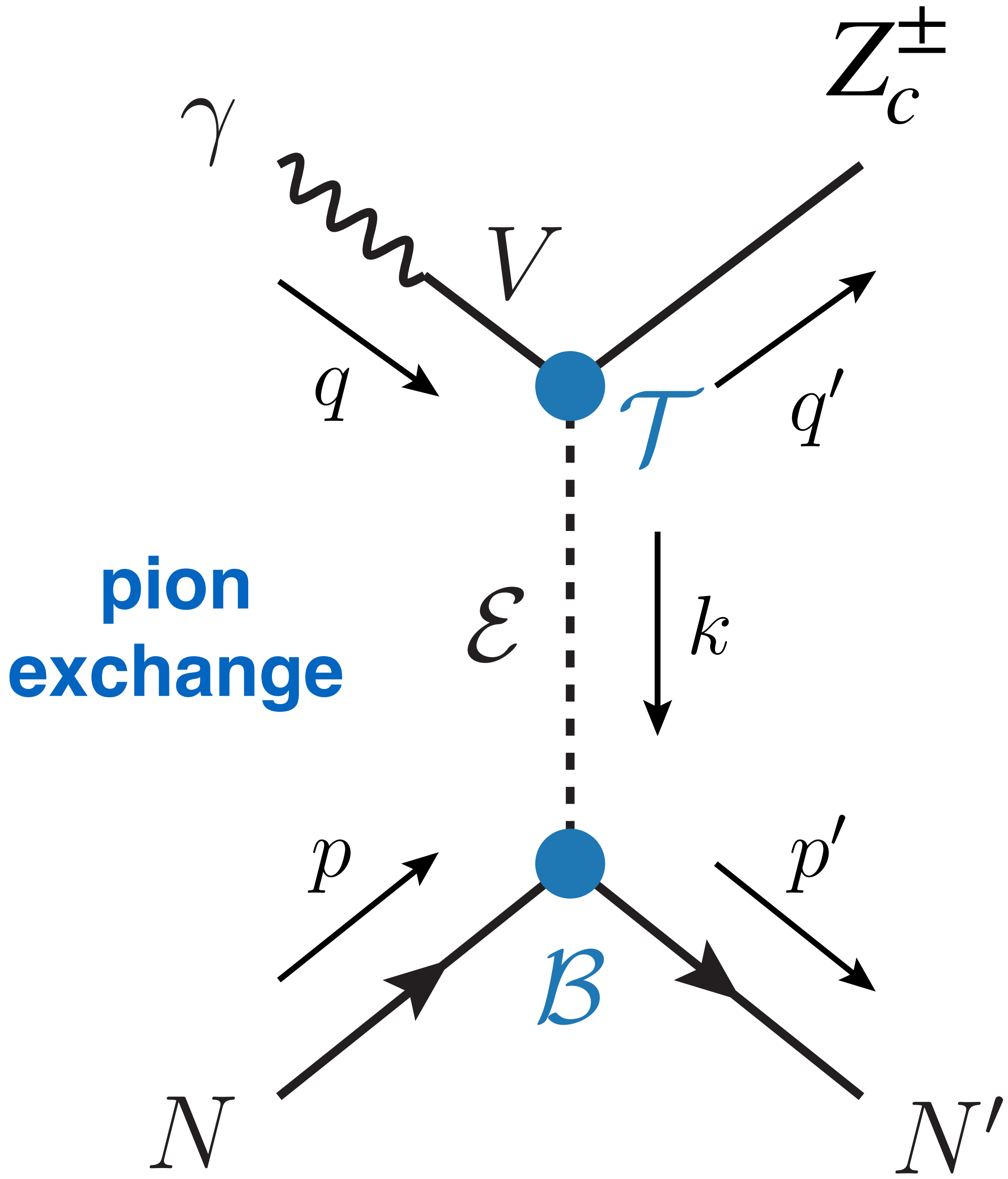




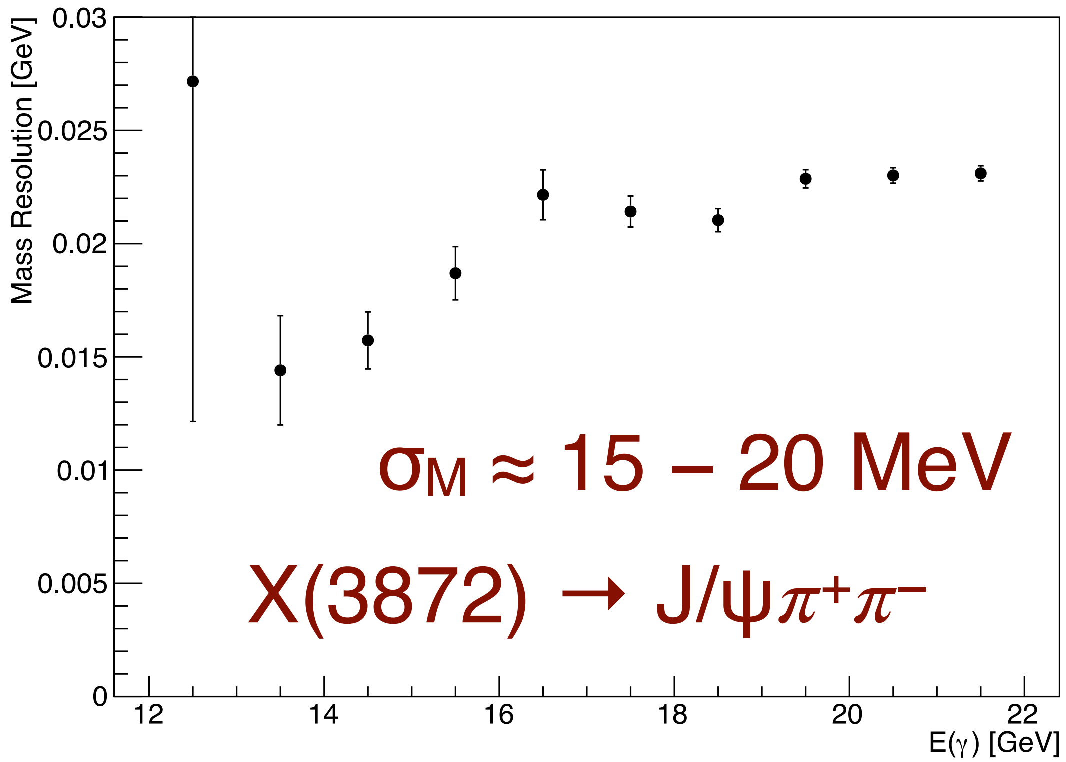
- Electrons/positrons from J/ψ decay spread across large angular range
- Line illustrates separation between forward and central calorimeters

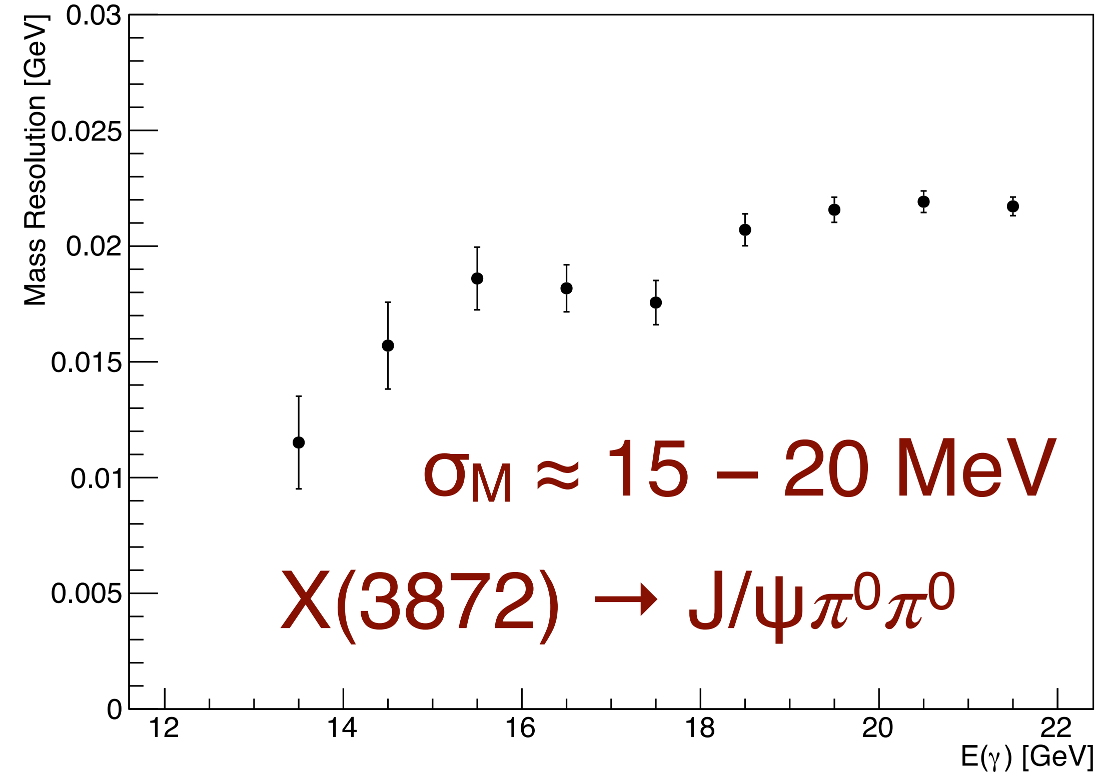
Z_c Production at GlueX

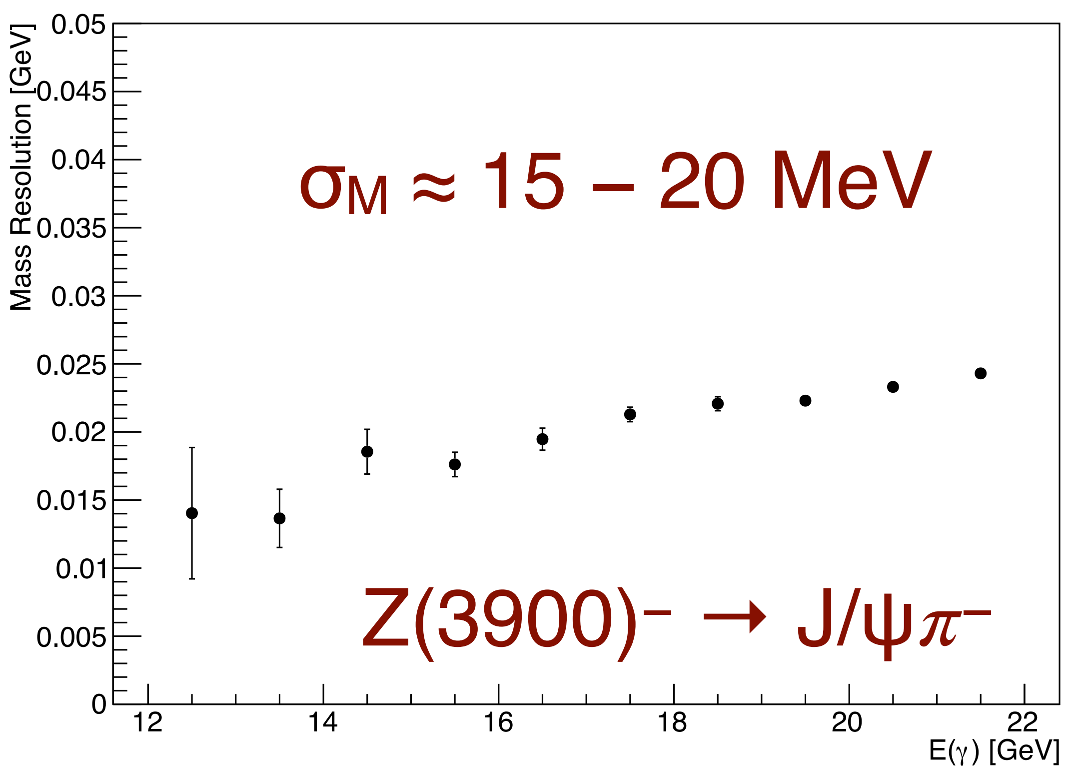
- Benchmark: $Z_c(3900)$ production with $\pi J/\psi$ decay
- Z_c has isopin=1, many ways to produce it:
  - $\gamma p \to Z_c^0 p$
  - $\gamma p \to Z_c^0 n$
  - $\gamma n \to Z_c^- p$
  - $\gamma p \to Z_c^- \Delta^{++}$

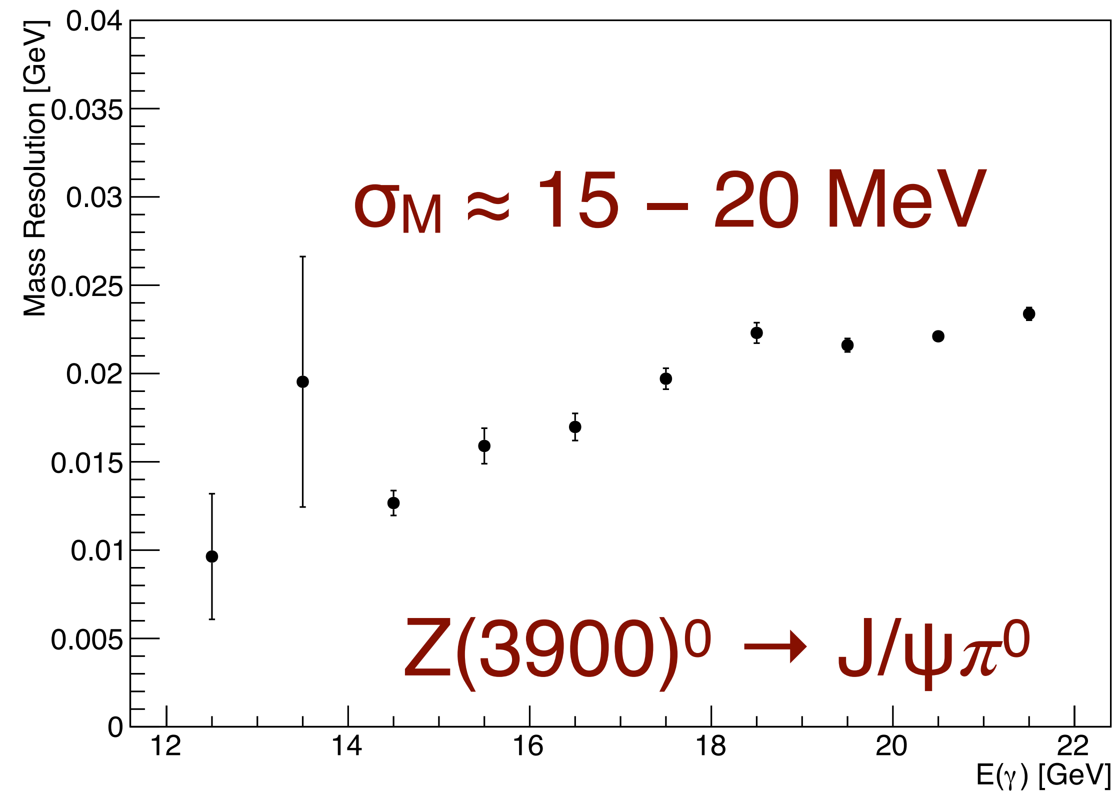


Resolutions vs. Beam energy

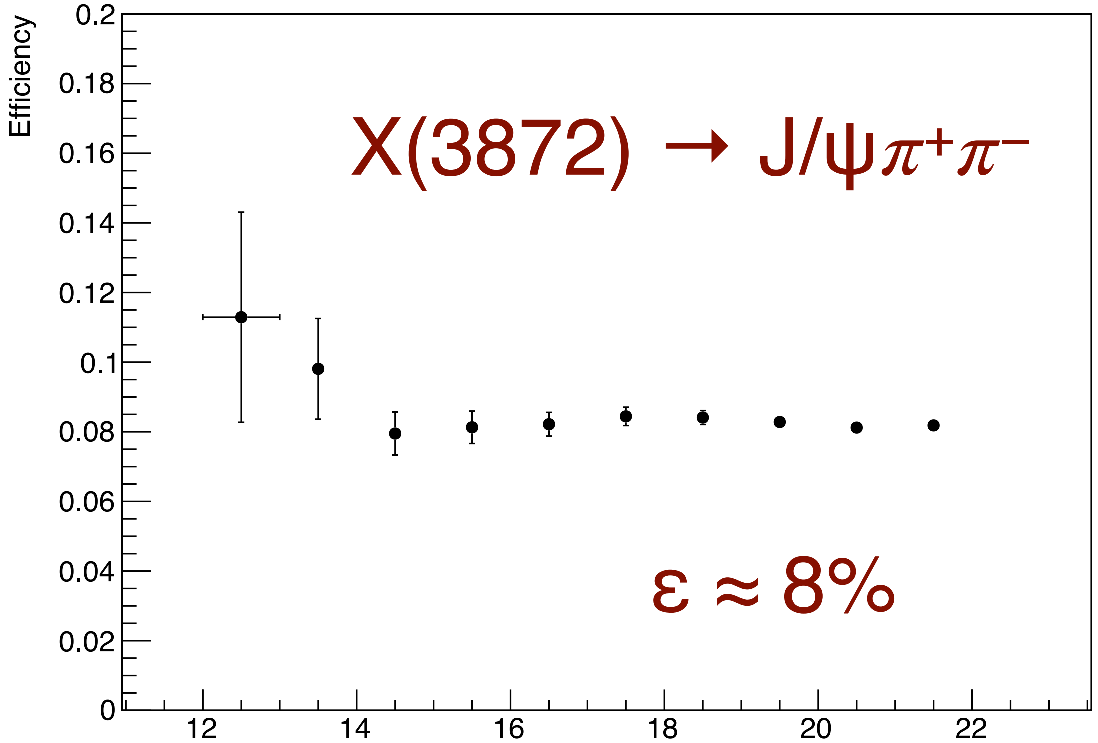


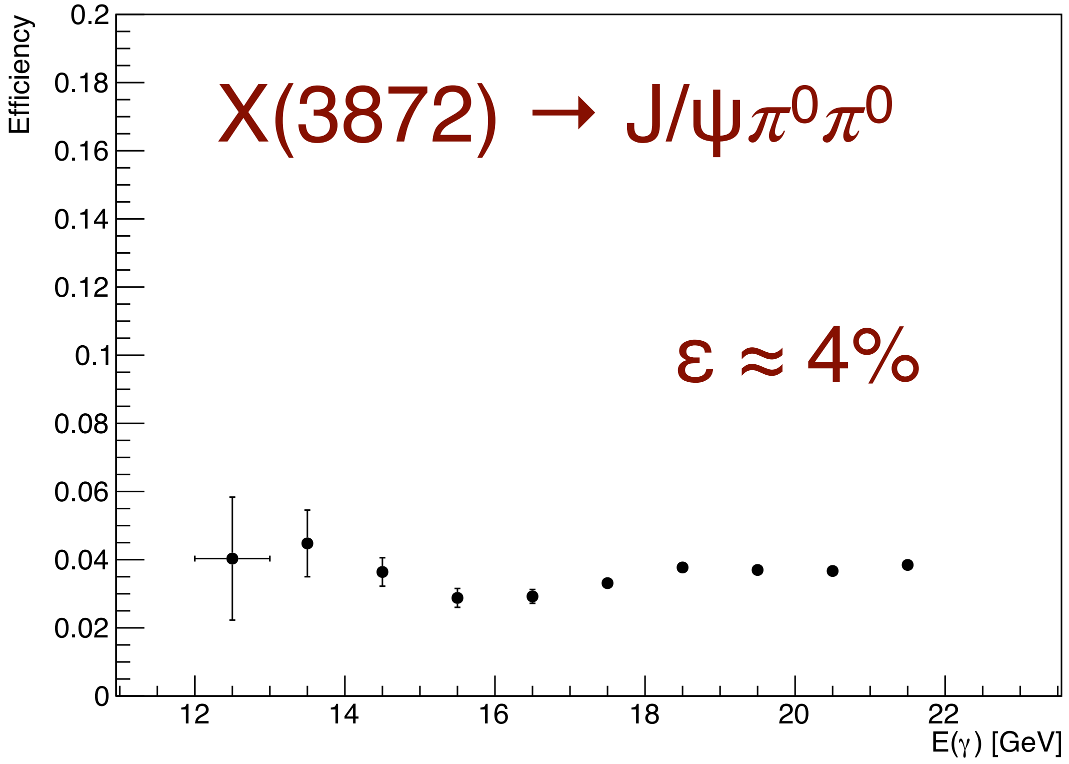


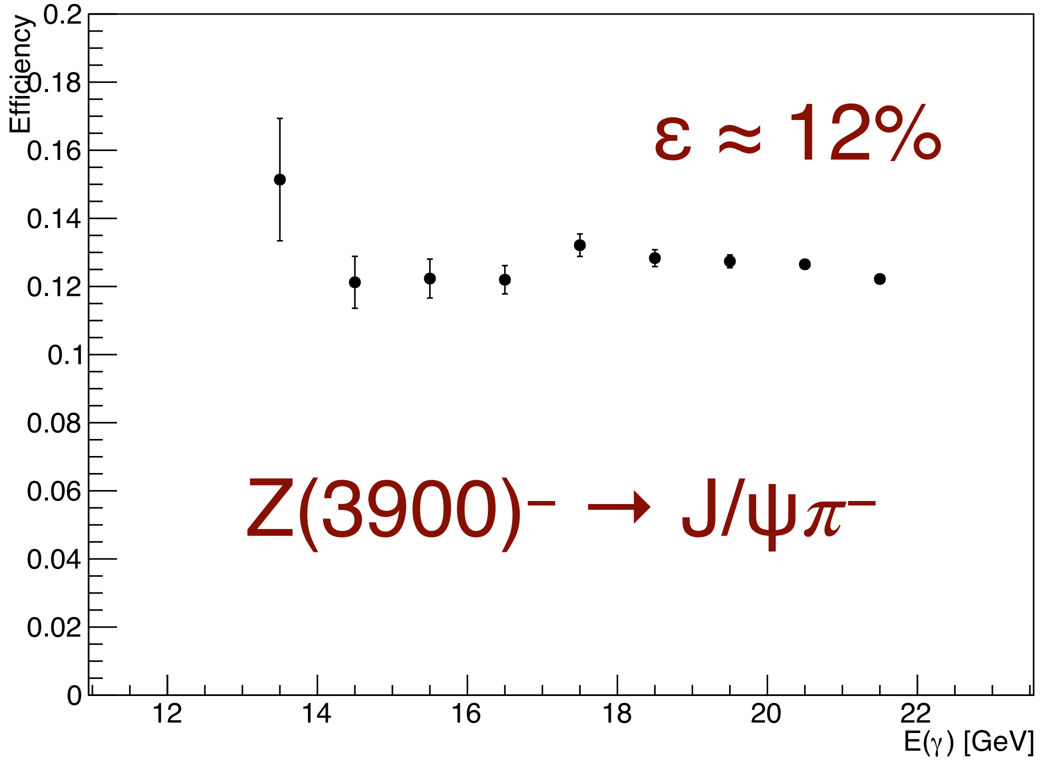


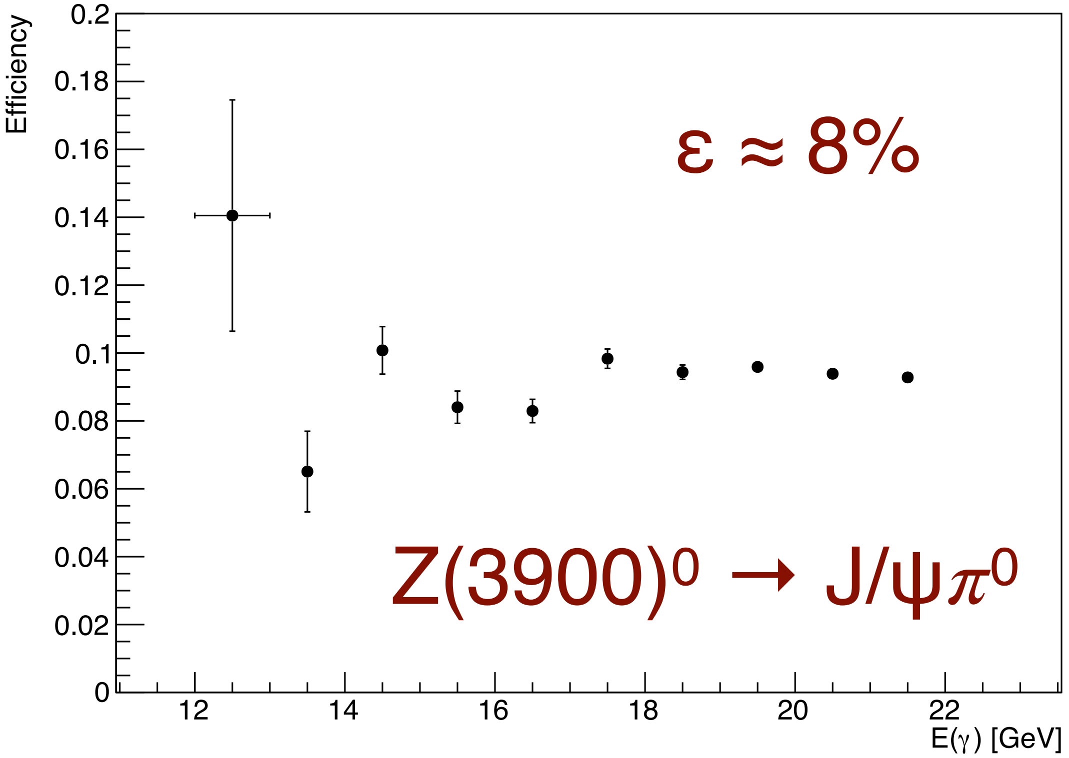


Efficiencies vs. Beam energy





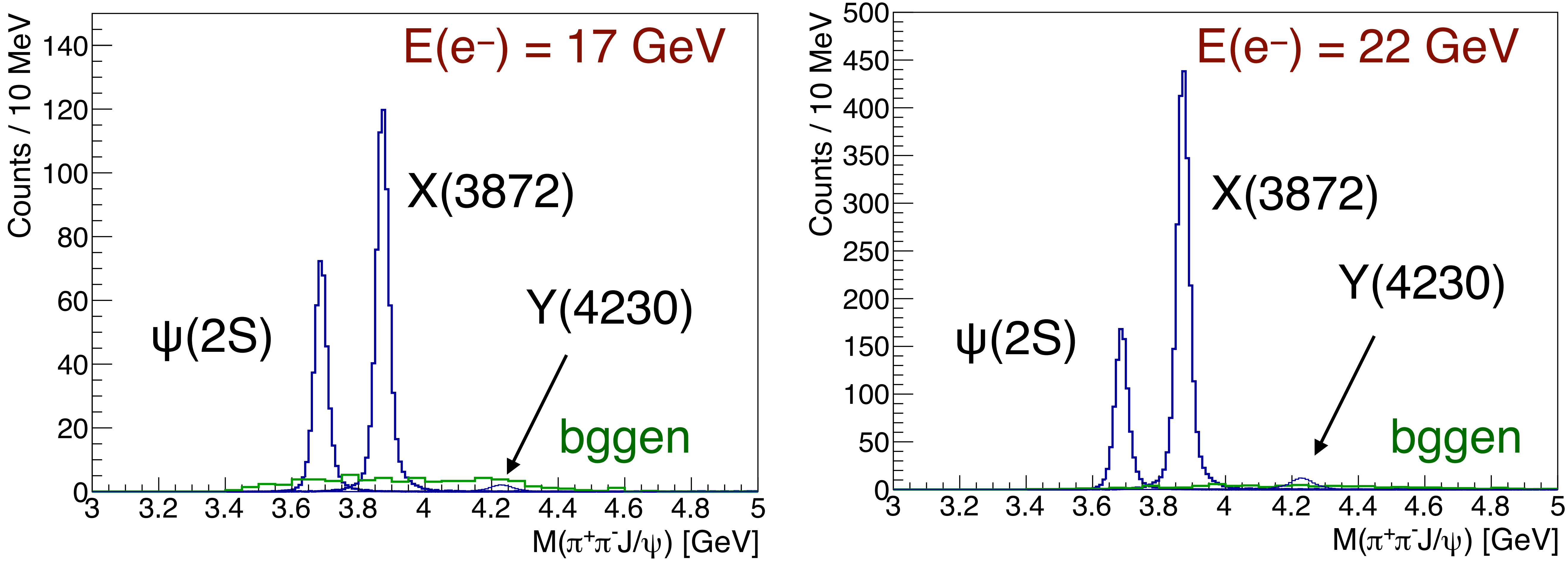




- n.b.: $\varepsilon(J/\psi \to e^+e^-) \approx 15 - 20$ %

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

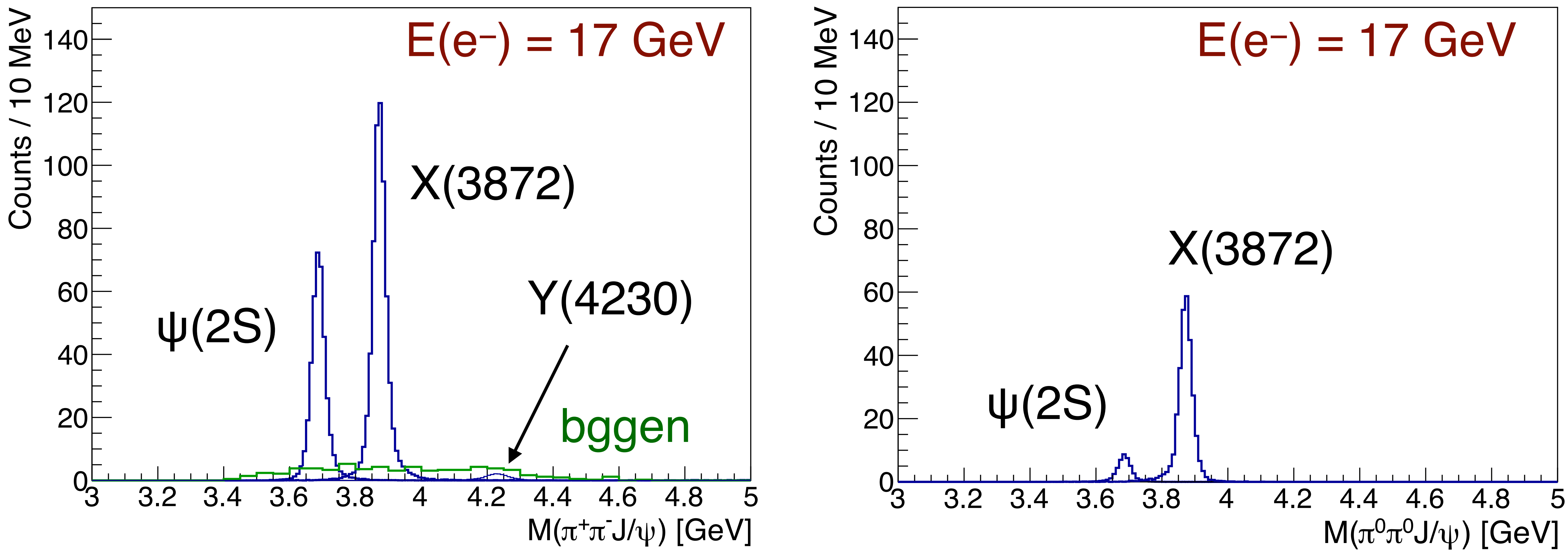
$\gamma p \to J/\psi \pi^+\pi^- p$, $J/\psi \to e^+e^-$



- Assumes 1 year @ 500 pb^{-1}, $Br(X,Y \to \pi^+\pi^- J/\psi) = 5\%$
- 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

γp → J/ψ$\pi^+\pi^-$p, J/ψ → e^+e^- γp → J/ψ$\pi^0\pi^0$p, J/ψ → e^+e^-



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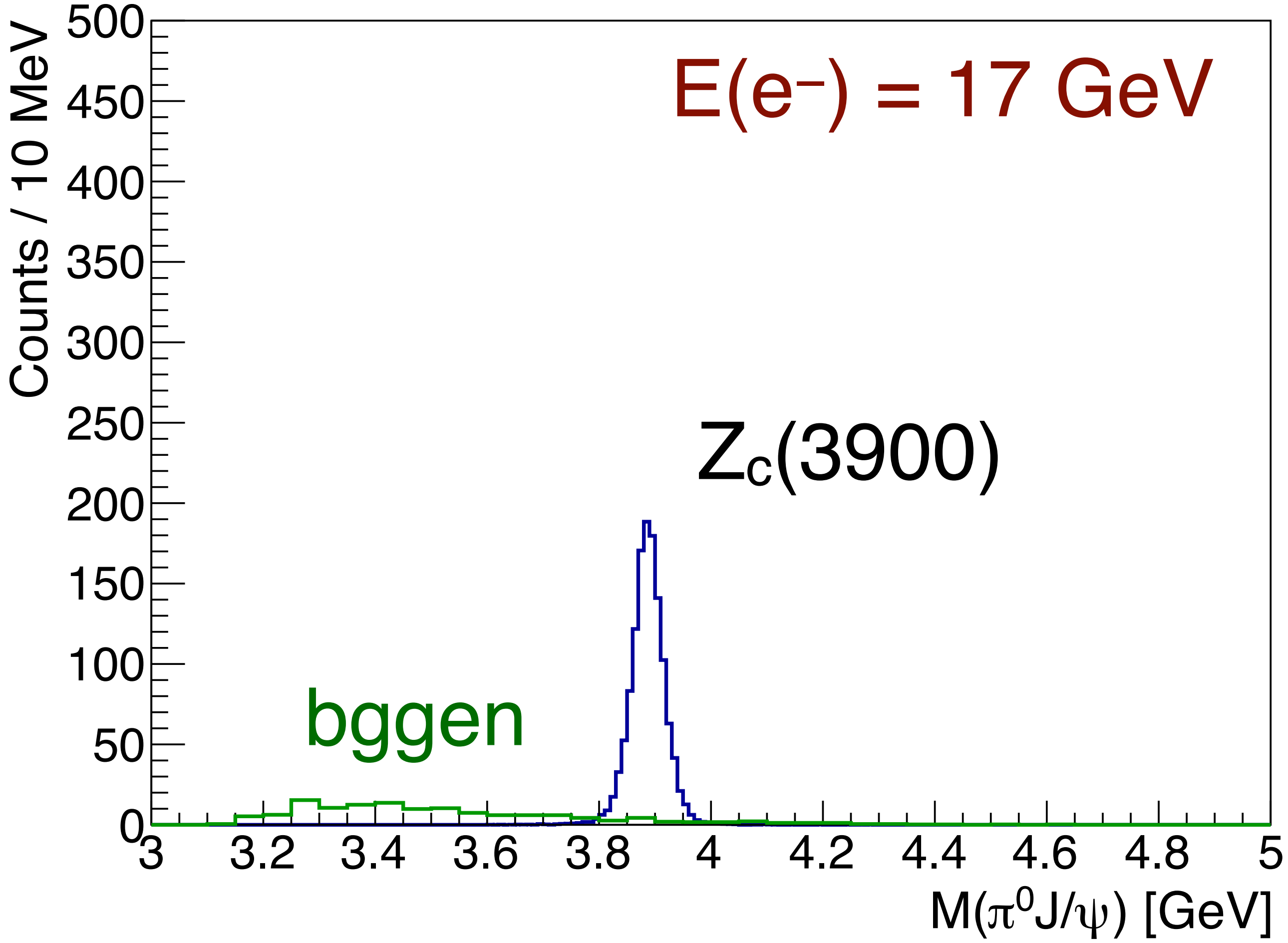
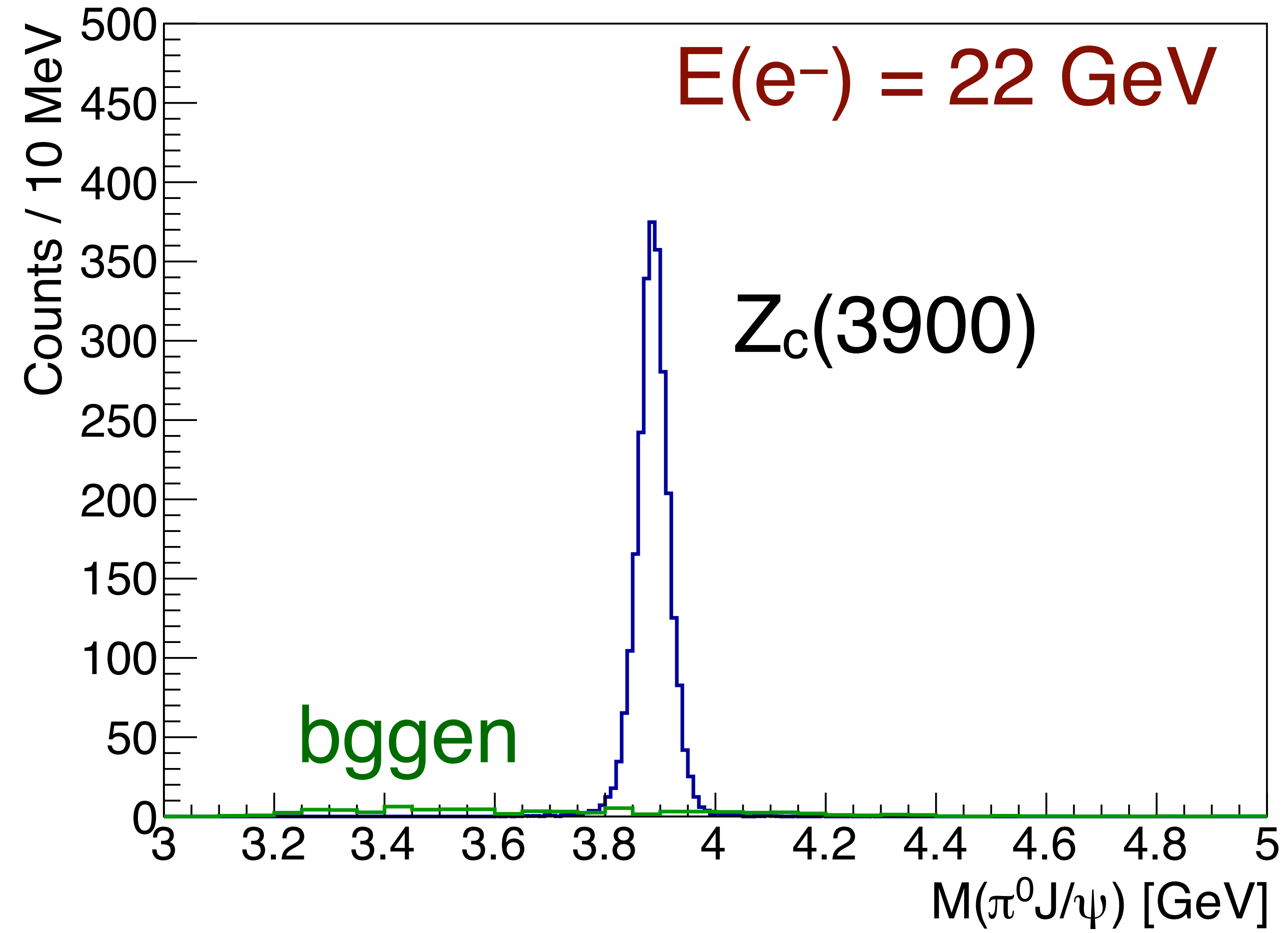
- 17 GeV [J/ψ$\pi^+\pi^-$]: N(ψ(2S)) = 400, N(X(3872)) = 650
- 17 GeV [J/ψ$\pi^0\pi^0$]: N(ψ(2S)) = 40, N(X(3872)) = 300

Projections for J/ψπ^0 Photoproduction at GlueX

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

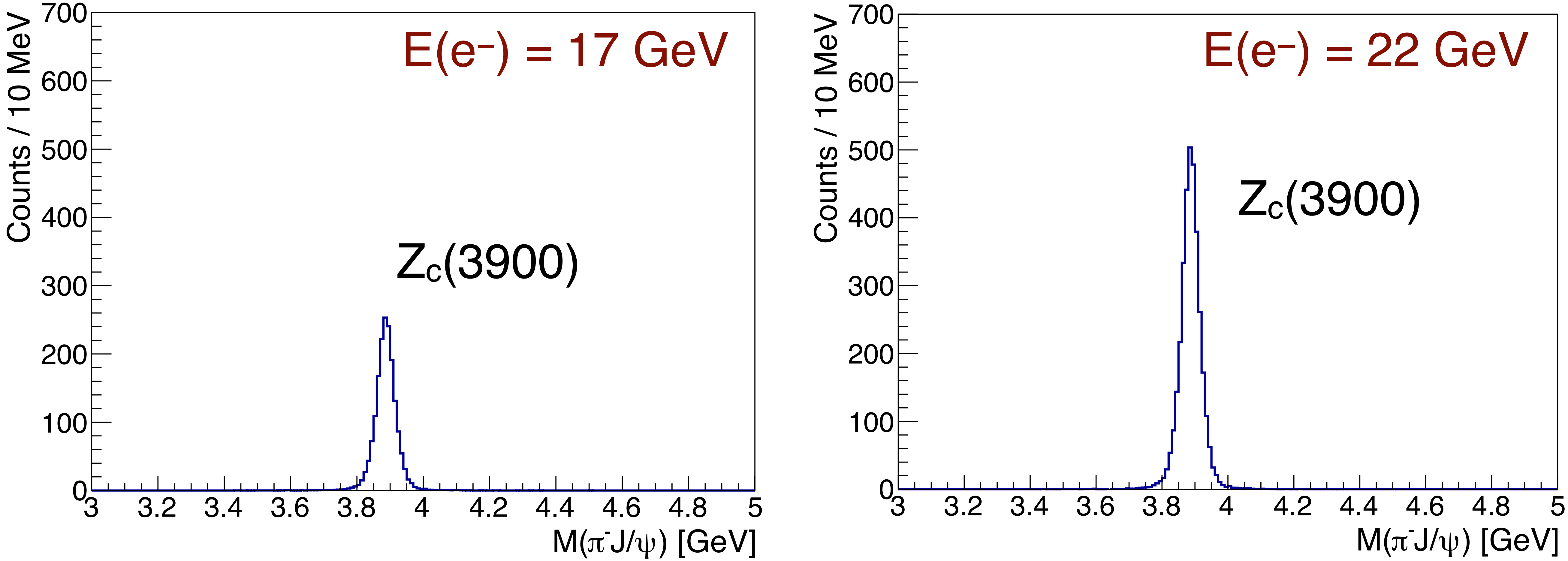




- Assumes 1 year @ 500 pb^{-1}, Br($Z^0 \to \pi^0 J/\psi$) = 5%
- N(X3872, J/ψπ^0): 17 GeV = 1300, 22 GeV = 2500
- For illustration, assumes same cross section as $\gamma p \to Z_c^+ n$
  For $\gamma p \to Z_c^0 p$, expect vector exchange to dominate?
  Can guess at suppression factor, but calculation would be better

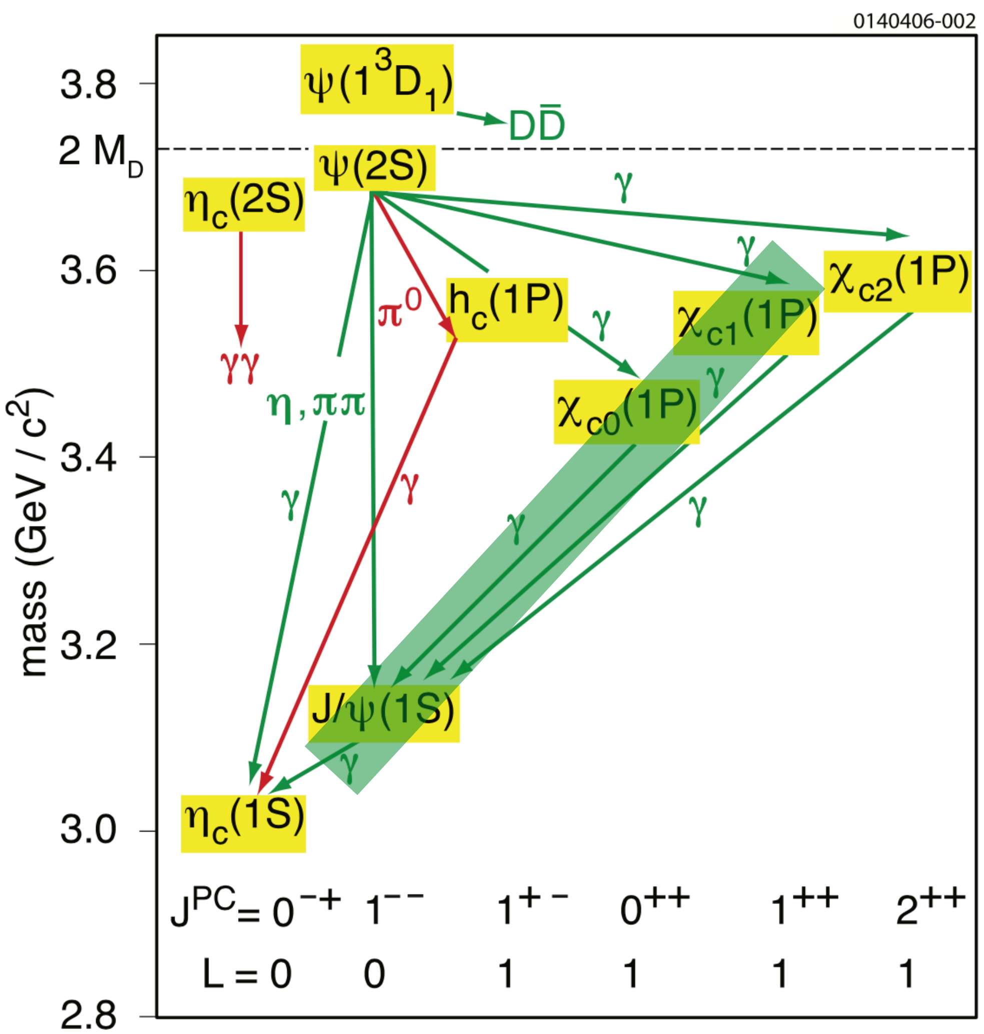
Projections for J/ψπ^- Photoproduction at GlueX

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



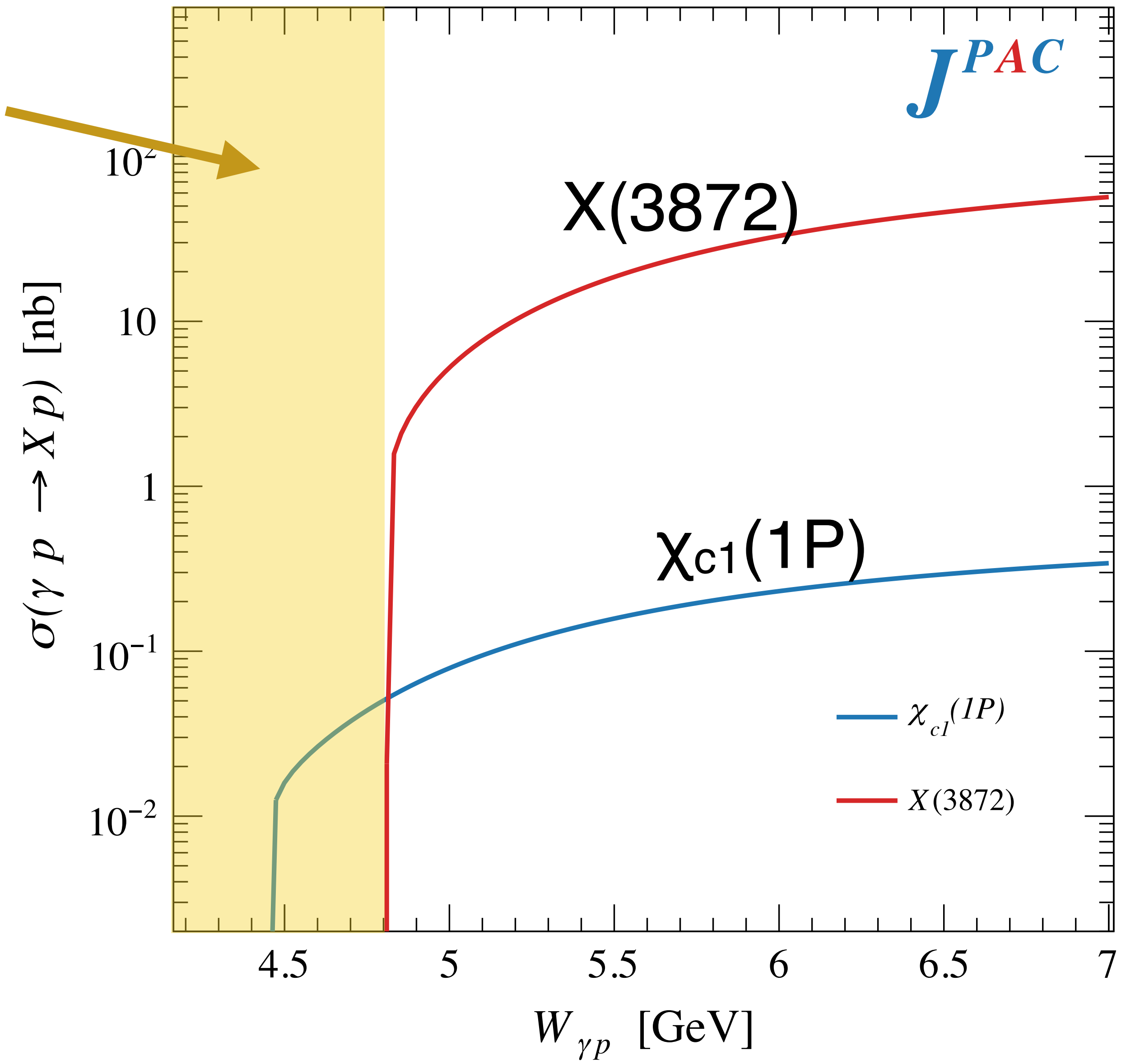
- Assumes 1 year @ 500 pb^{-1}, $Br(Z^- \rightarrow \pi^- J/\psi) = 5\%$
- N(X3872, J/ψπ^-): 17 GeV = 1700, 22 GeV = 3400
- Uses JPAC prediction, assumes pure neutron target

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



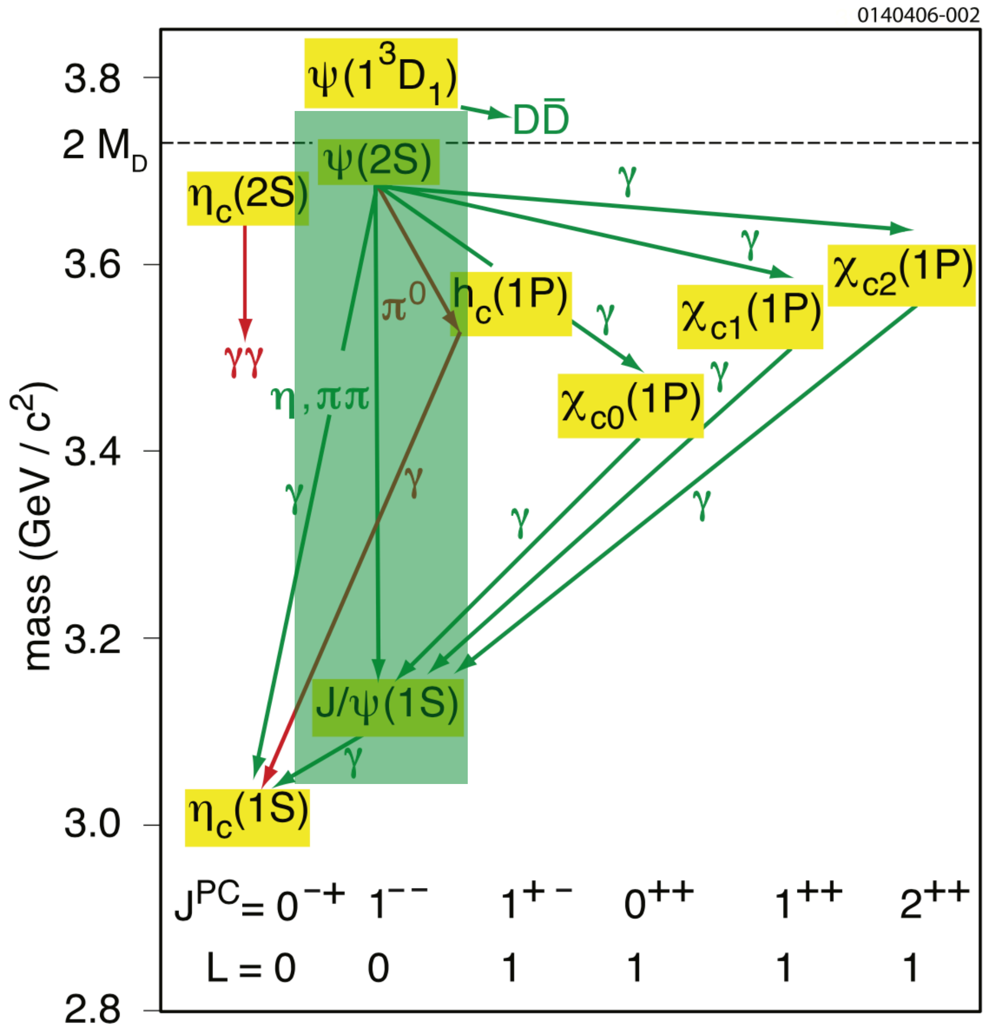
GlueX energy range

JPAC: PRD 102, 114010 (2020)

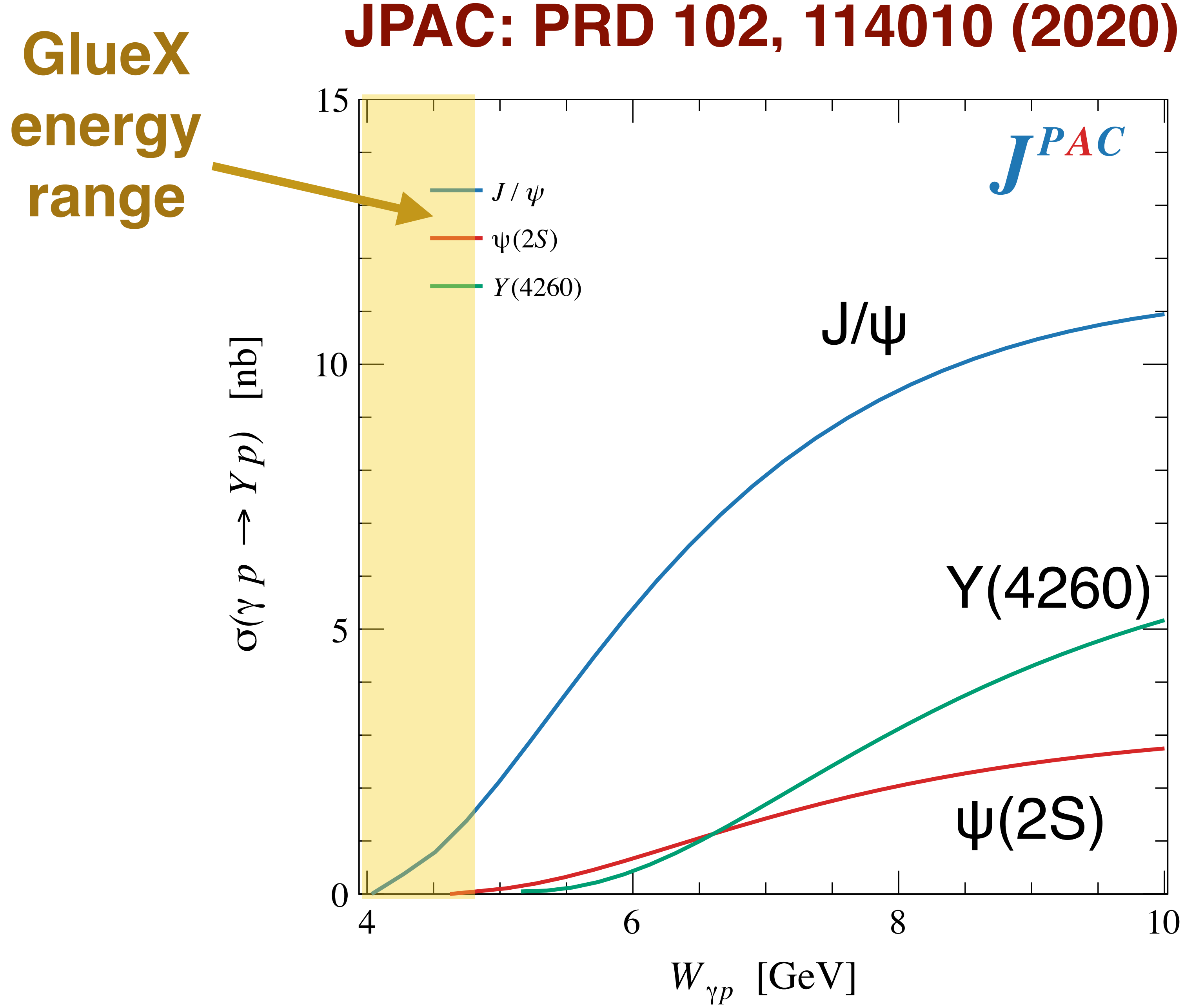


- $\chi_{c1}(1^{++})$ photoproduction: probe of different parity, P_c search
- JPAC model estimate using known $\chi_{c1} \to \gamma(\rho,\omega,\phi,J/\psi)$ couplings
- GlueX-I expectation: $N(\chi_{c1} \to \gamma J/\psi,\ J/\psi \to e^+e^-) = O(50)$

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



JPAC: PRD 102, 114010 (2020)



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

Light hadron spectroscopy at GlueX at higher energies

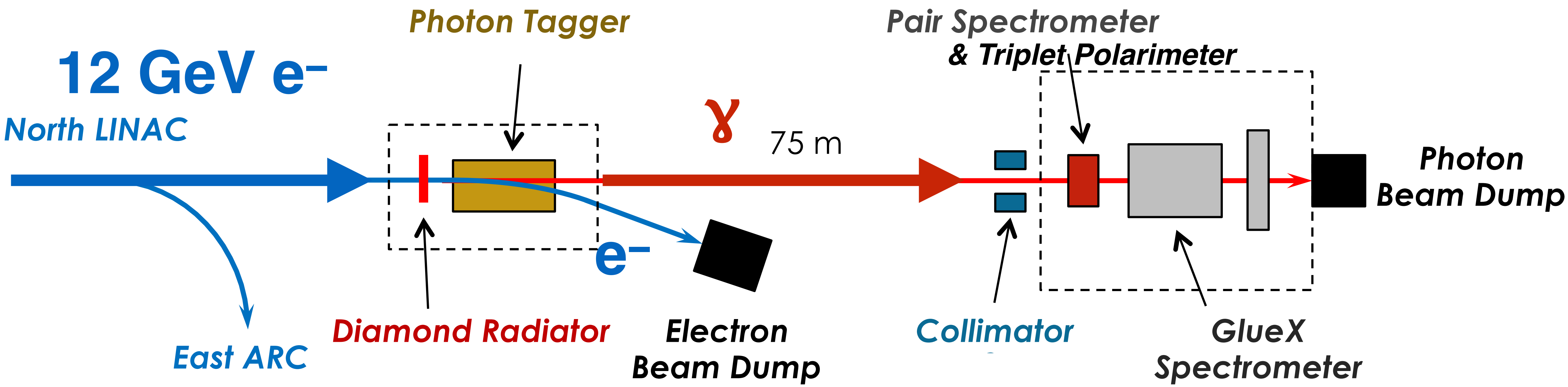
- At higher beam energies, GlueX can continue to support a rich program of light hadron spectroscopy
- Potential benefits:
  - Higher linear polarization (up to ~80%) leads to large increase in polarized FOM for PWA (P^2L)
  - Better kinematic separation between mesons / baryons, etc.
  - Kinematic fit 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

Summary and Prospects

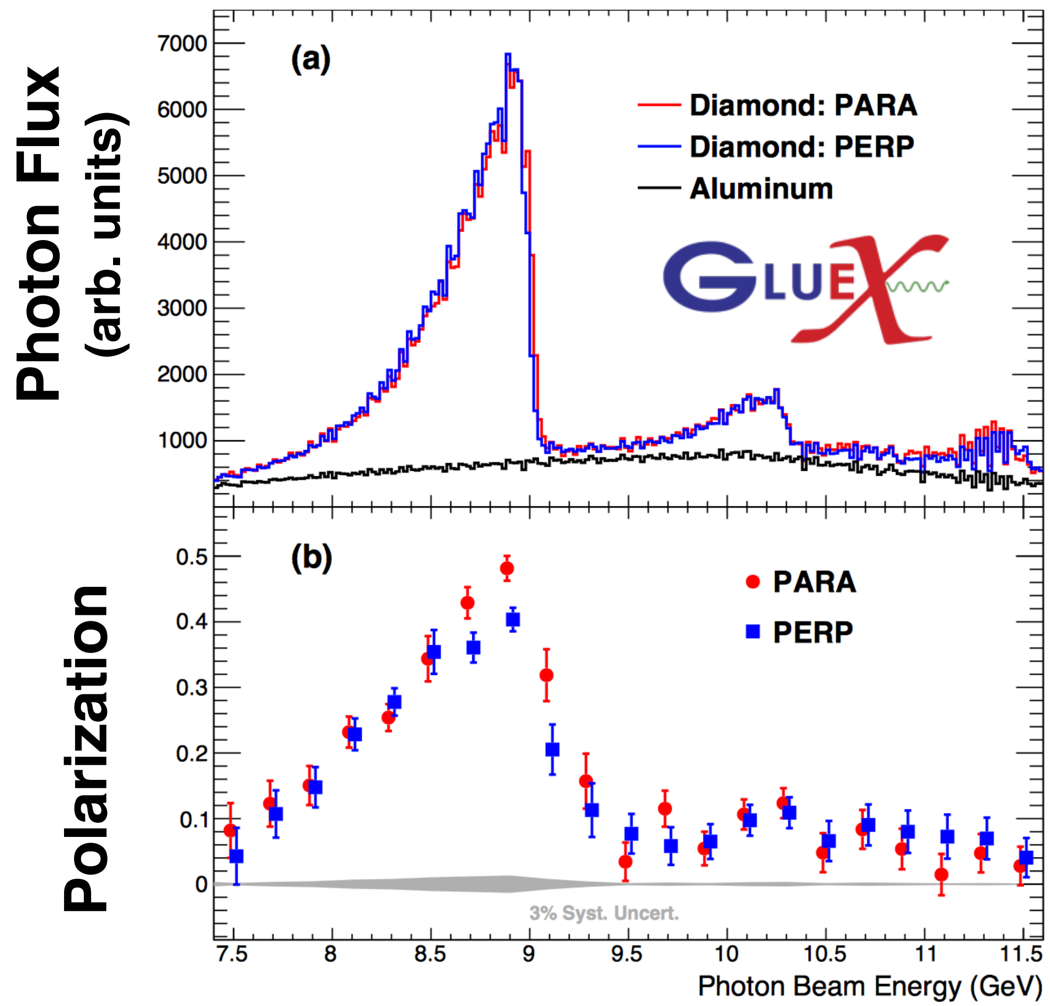
- Measuring XYZ states in photoproduction is crucial to determine their nature
- Simulations show that the baseline GlueX detector can cleanly identify interesting samples of well-known XYZ states in decays containing J/ψ's
  - Benchmark for lesser understood XYZ states, potential improvements for higher luminosity running
  - Expected detector upgrades: FCAL-II, forward GEM-TRD
- Many other interesting topics under study:
  - Additional Z_c production modes
  - Non-J/ψ decays of XYZ
  - Improved background studies
  - Measurements with linear polarization
  - Open charm production

Backup Slides

The GlueX Experiment: Photon Beam



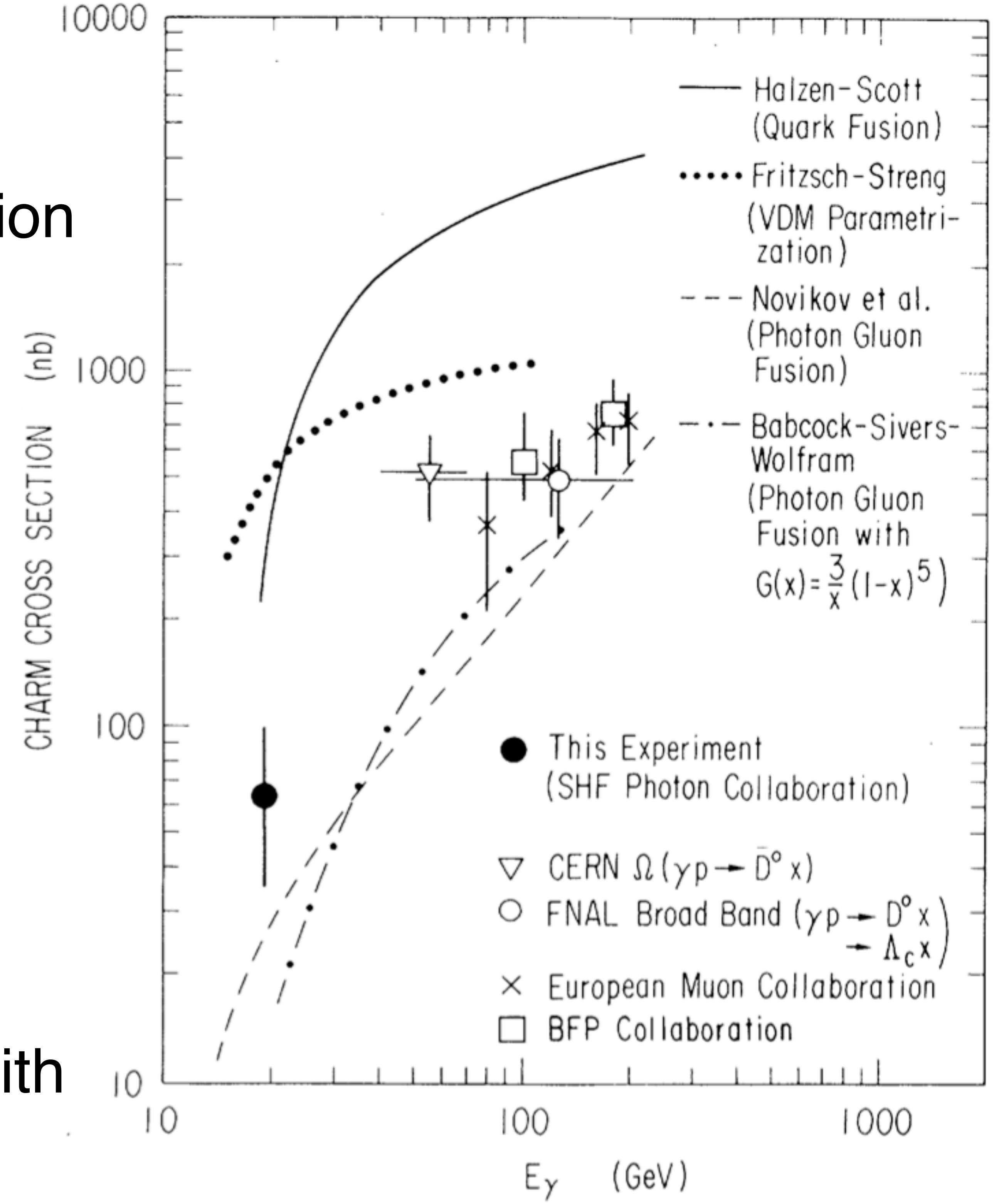
- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of ~1–5 × 10^7 γ/s in peak



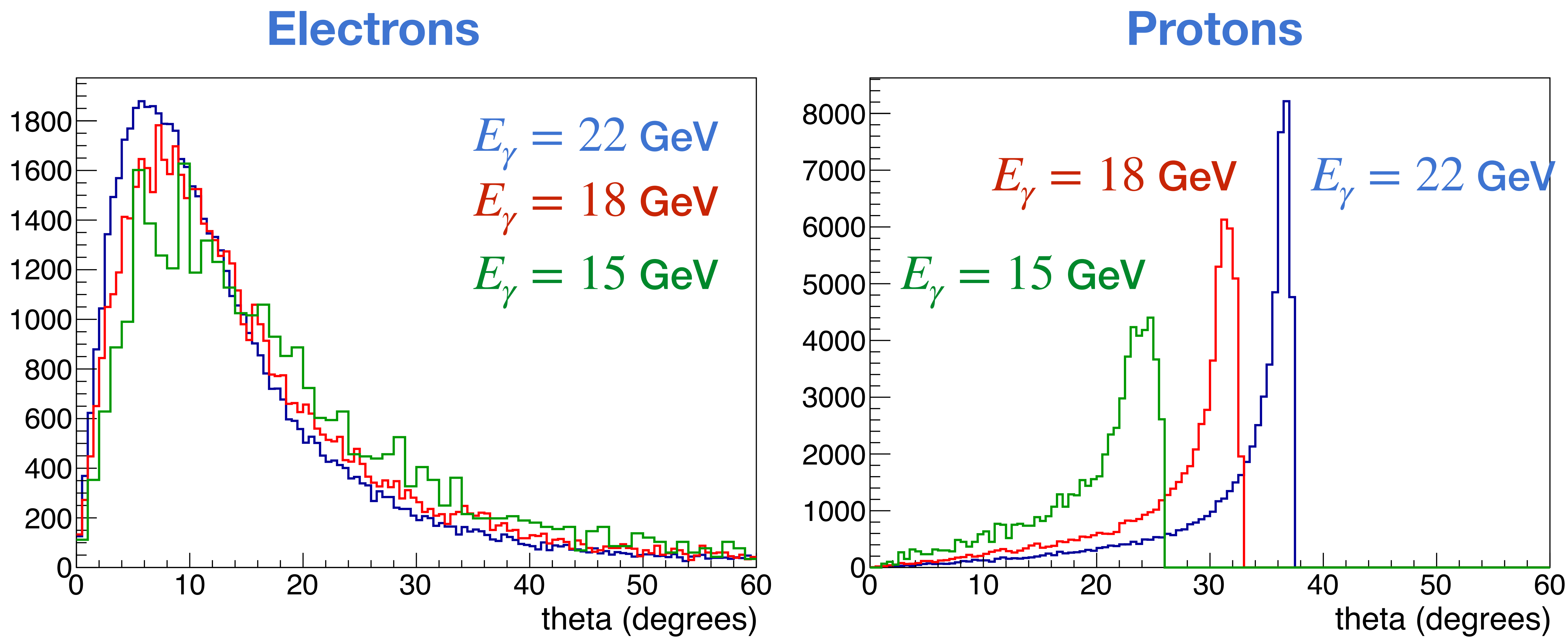
Open Charm Production Near Threshold

- 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)

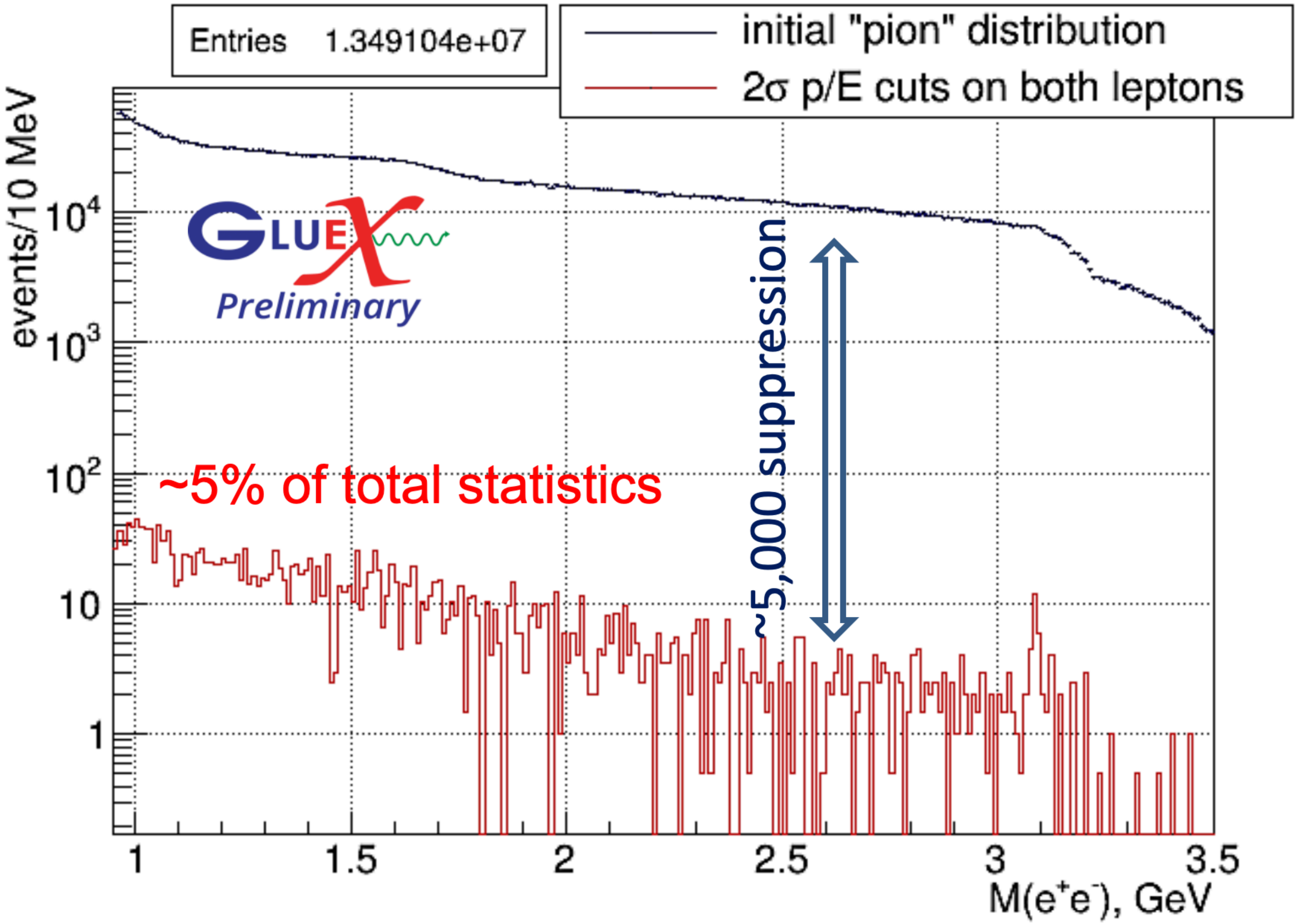


Kinematics of ɣp → X(3872)p, X → $\pi^+\pi^- J/\psi$

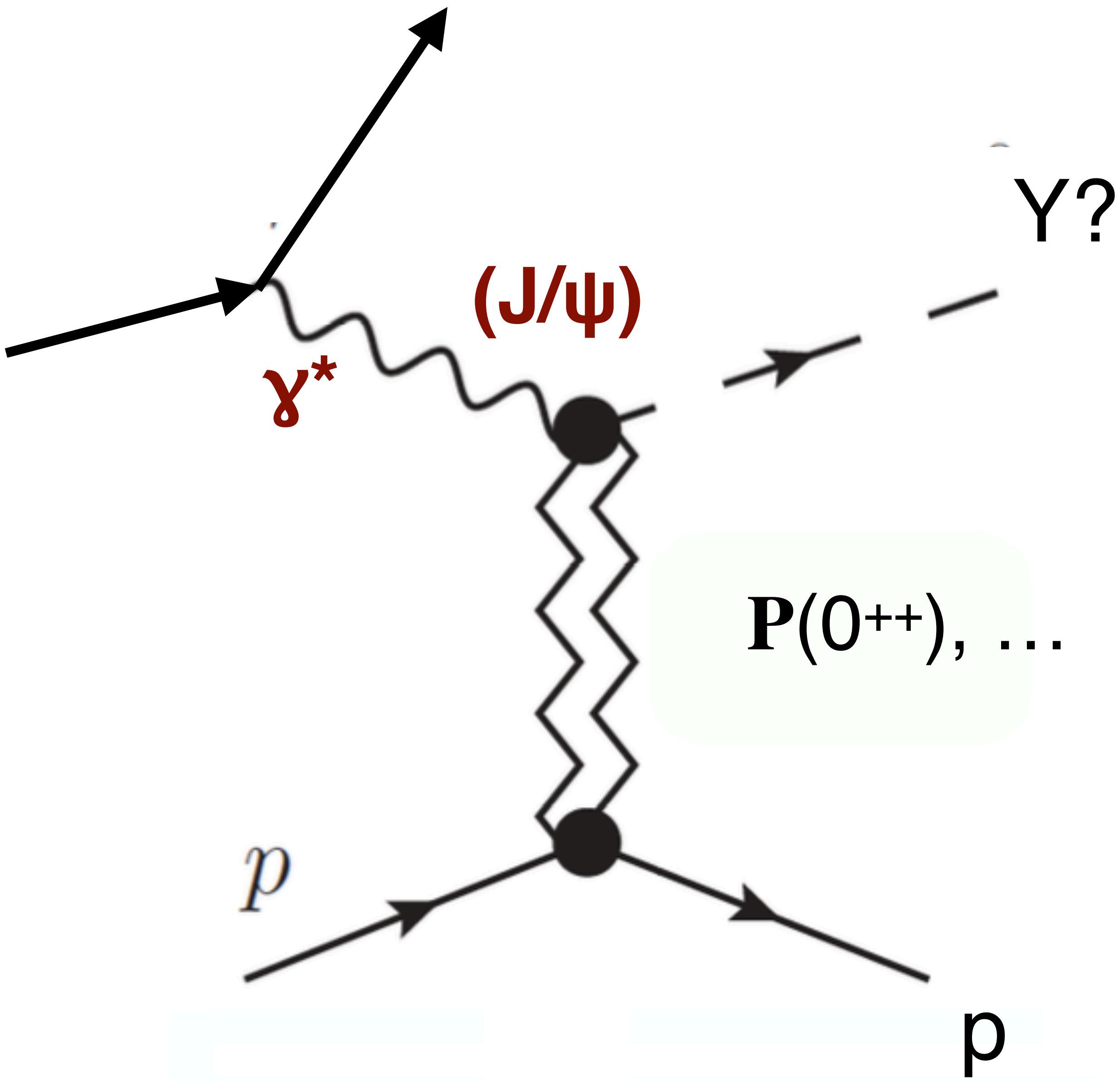


- Histograms normalized to same area
- Electrons/positrons from J/ψ decay spread across large angular range
- At higher energies, recoil protons more central

J/ψ @ GlueX: Background Rejection



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