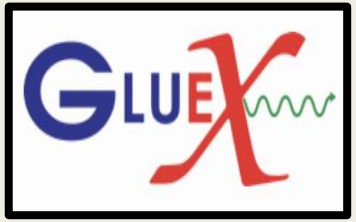
EXCLUSIVE J/ψ WITH GLUEX

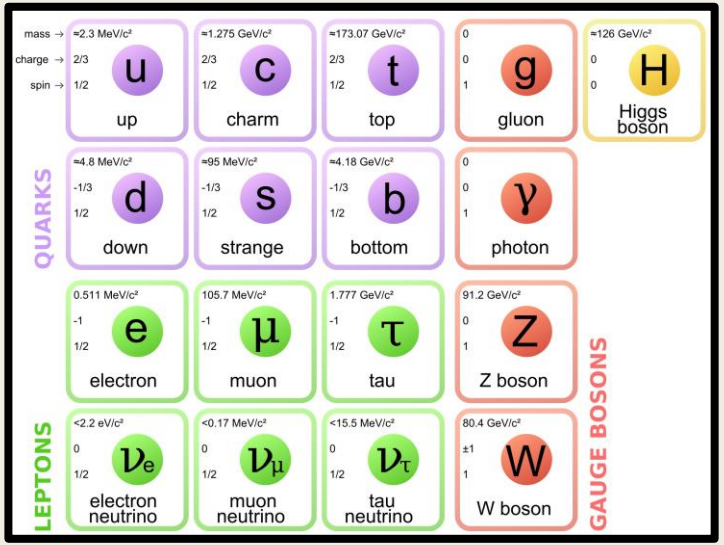


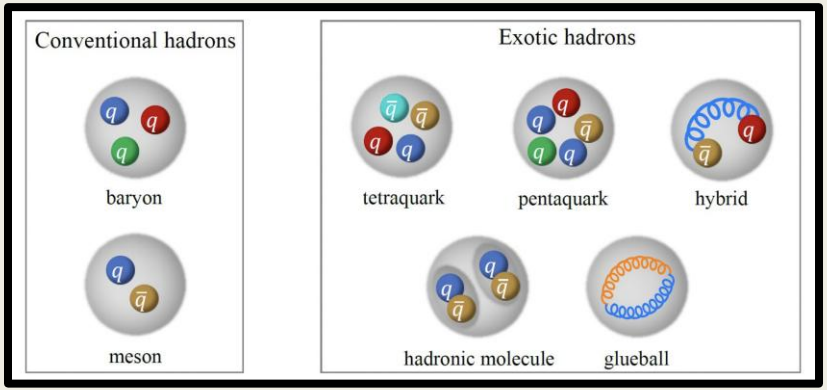
By: Dr. Donavan Ebersole

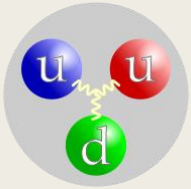
FSU

Quantum Chromodynamics

- Quantum Chromodynamics (QCD)- theory of quarks and gluons.
- Predicts rich spectrum of hadrons, groups of quarks bound by gluons
- The proton
  - *One of the building blocks of matter*
  - *A baryon with up-up-down quark content.*
- Charmonium
  - *charm and anticharm quark pair*
  - J/ψ - first excited state ($n^{2S+1}L_J = 1^3S_1$)





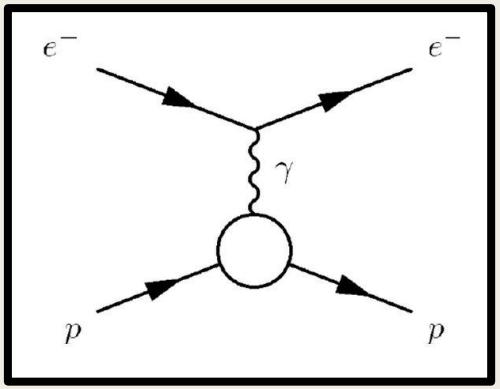


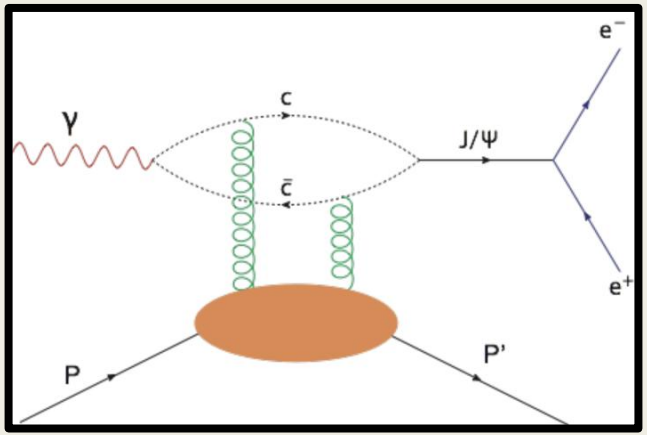
Proton

Charmonium- J/ψ

Proton Charge and Mass Radius

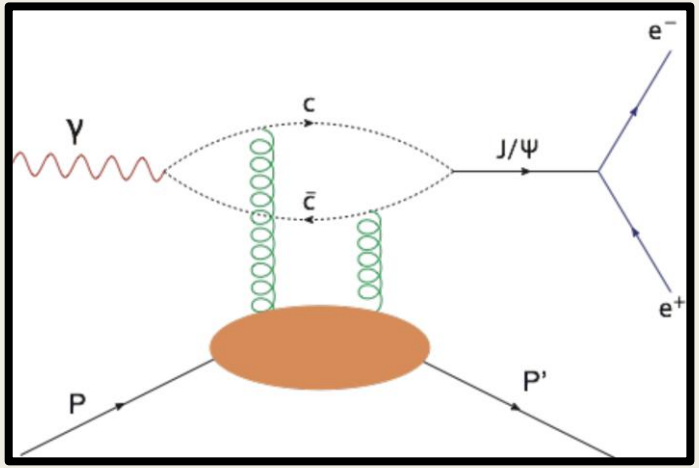
- Proton Charge Radius
  - *Electron/muon scattering experiments*
  - *Electromagnetic form factors*
- Proton Mass- dominated by distribution of gluons
- Proton Mass Radius
  - *Electron/muon scattering can't probe gluonic contributions*
- How can J/ψ help?
  - *Charm quarks predicted to interact via gluonic exchange with proton*
  - *Could probe into the gluonic distribution in the proton*
  - *Gluonic interaction is suggested to dominate at the J/ψ threshold*



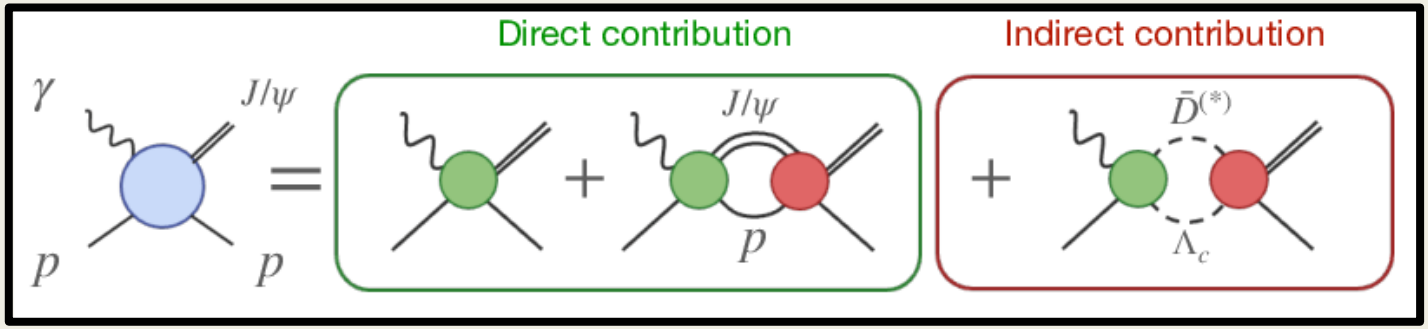


Assumptions of Gluonic Interaction

- Vector Meson Dominance
  - *Model describes photon-hadron interactions*
  - *Suggests photons oscillate into vector meson ($\rho, \omega, \phi, J/\psi$) that interact with proton*
  - *Possibly breaks down for heavier quarks*
- Factorization
  - *Assumes gluonic interaction can factorize into an upper, "hard" part and a lower, "soft" part*
    - "Hard" part- described by QCD
    - "Soft" part- described by generalized parton distribution functions (GPDs)
- Dominant interaction at Threshold
  - *Assumes no s-channel or loop contributions*



Models in J/ψ Photoproduction Dynamics

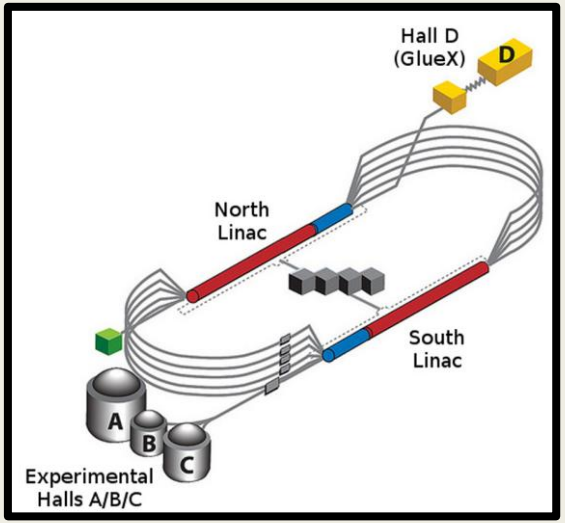


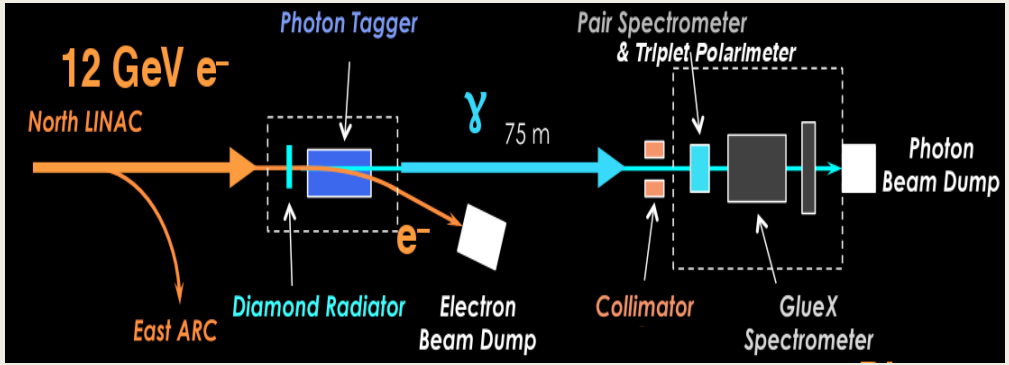
JPAC arxiv:2305.01449 (2023)

- Kharzeev et al. (PRD 104 (5 Sept. 2021), p. 054015) calculated proton mass radius from slope of $\frac{d\sigma(\gamma p \to J/\psi p)}{d(-t)}$
  - assumed an elastic interaction between the J/ψ *and the proton*
- However, open-charm intermediate states could contribute
  - *Violate assumptions of gluonic exchange*

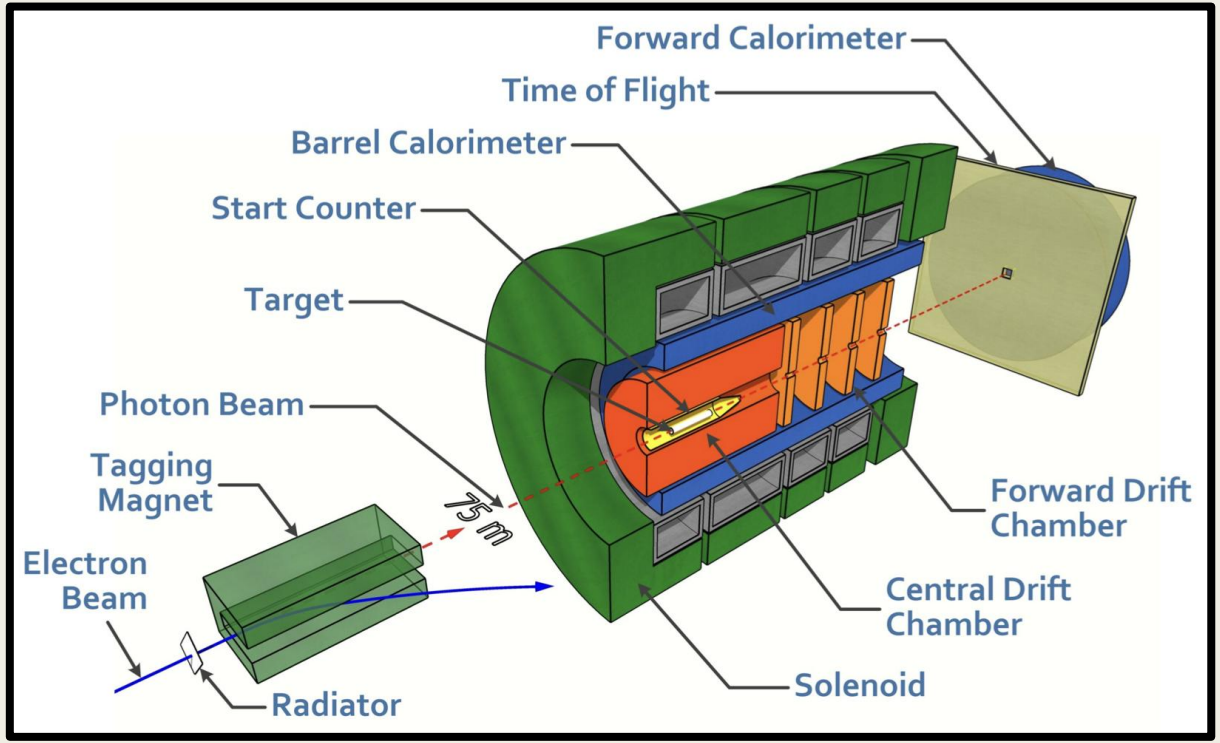
Thomas Jefferson National Accelerator Facility

- A National Laboratory located in Newport News, Virginia
- Hosts the Continuous Electron Beam Accelerator Facility (CEBAF)
- GlueX located in Hall D
  - *Receives 12 GeV electrons after 5.5 turns through CEBAF*
  - *Electron beam hits a diamond radiator*
  - *Producing a linearly polarized beam of photons via Bremsstrahlung radiation*





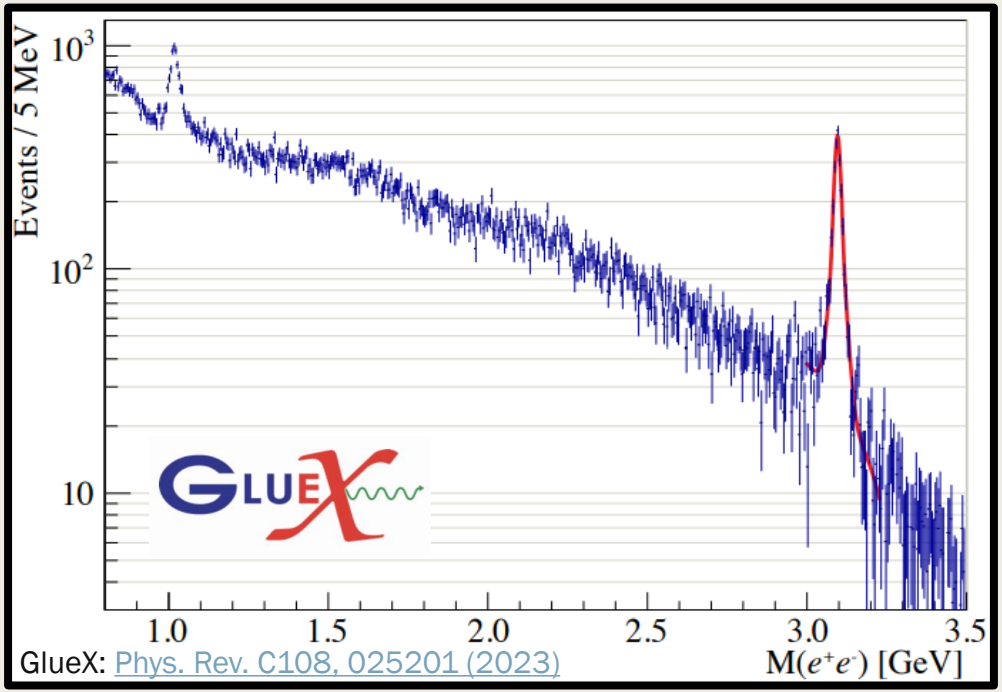
The GlueX Spectrometer



- Photon beam incident onto a fixed liquid hydrogen target
- The spectrometer,
  - Near 4π coverage
  - Composed of several sub-detectors and a solenoid magnet
  - Can detect a wide range of neutral and charged particles
- Tracking:
  - $\frac{\sigma_p}{p} \sim 1 - 5\ \%$
- Calorimetry:
  - $\frac{\sigma_E}{E} \sim \frac{6\ \%}{\sqrt{E}} \oplus 4.5\ \%$

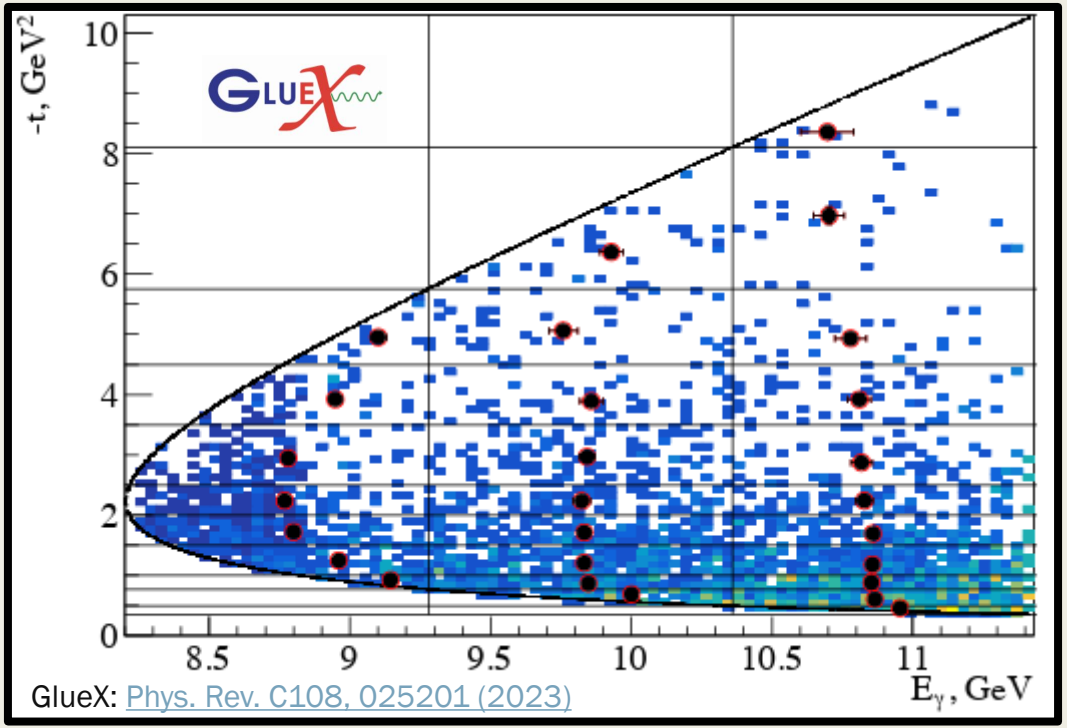
GlueX NIM- NIM A 987 (2021) 164807

Exclusive $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$ at GlueX



- Exclusivity of the reaction: kinematic fit
- 13 MeV mass resolution
- J/ψ yields extracted from fits of distributions - 2270 ± 58 J/ψ's
- BH(1.2 – 2.5 GeV) used for normalization

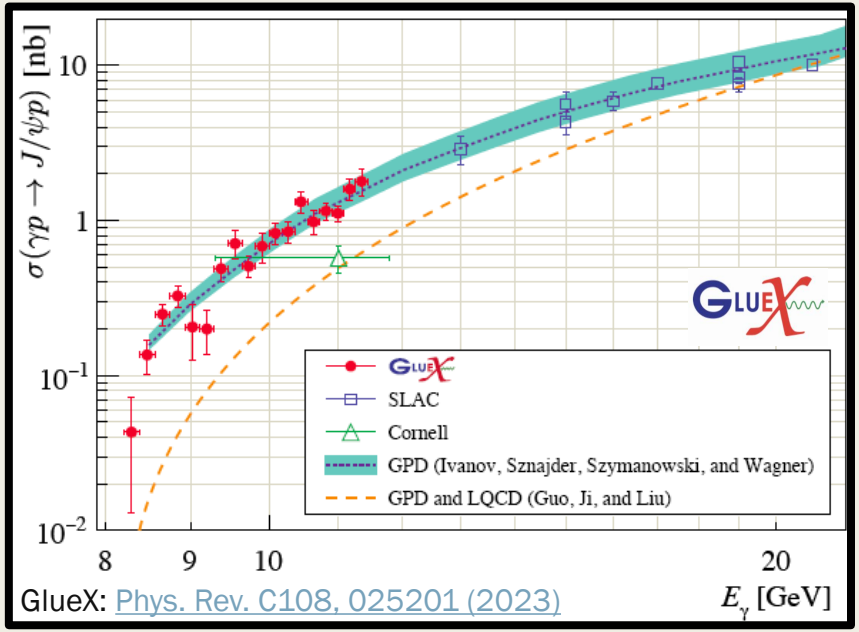
Threshold region coverage

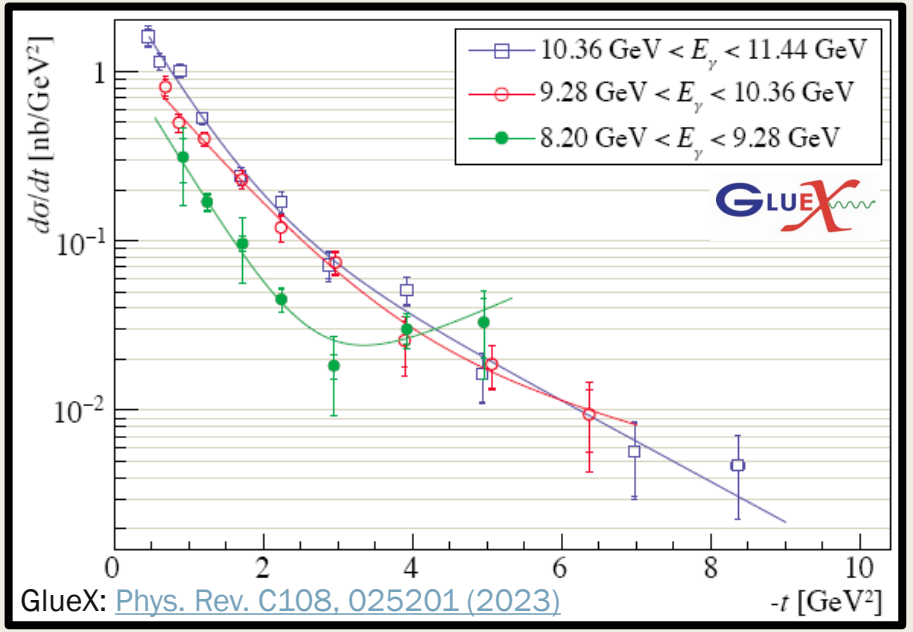


GlueX: Phys. Rev. C108, 025201 (2023)

- Event-by-event weighting by luminosity
- Dots - mean energy and t-value for the corresponding bin
- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors

GlueX results: $J/\psi \rightarrow e^+e^-$ total and differential cross-sections

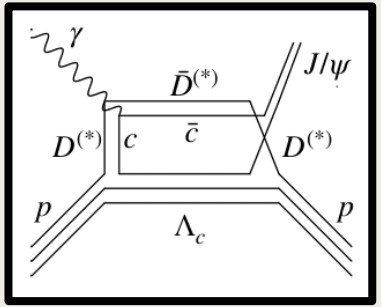


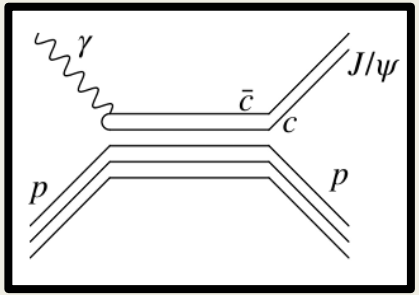


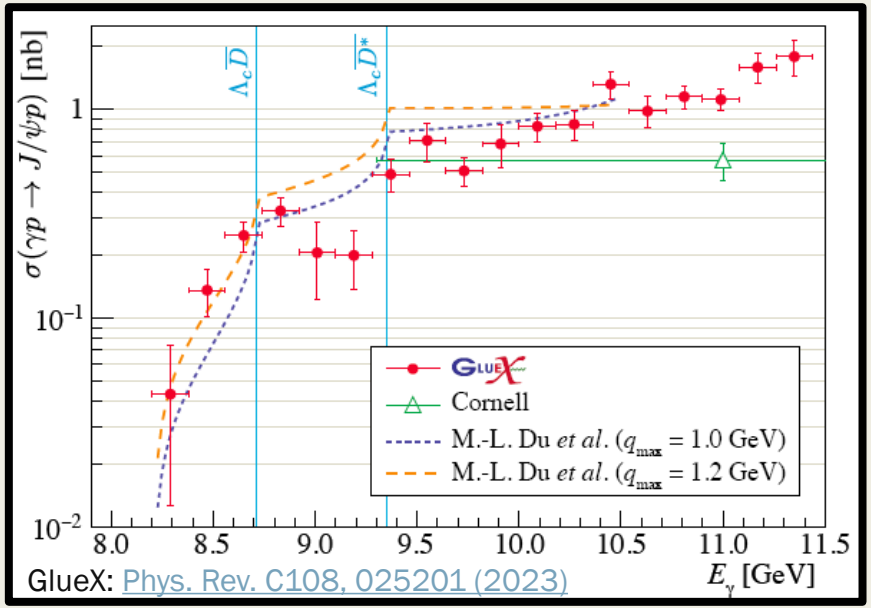
- σ_{tot} increasing with energy approximately following the phase space
- Possible structure at $\sigma(8.6 - 9.6GeV)$
  - 2.6σ - statistical significance of the two "dip" points
  - 1.3σ – using look-elsewhere method

- $\frac{d\sigma}{dt}$ exponentially falling with t-dependence
- Enhancement of $\frac{d\sigma}{dt}$ at high t (for the lowest energy slice), indicates contribution beyond gluon exchange

Other reaction mechanisms: open-charm, 5q exchange

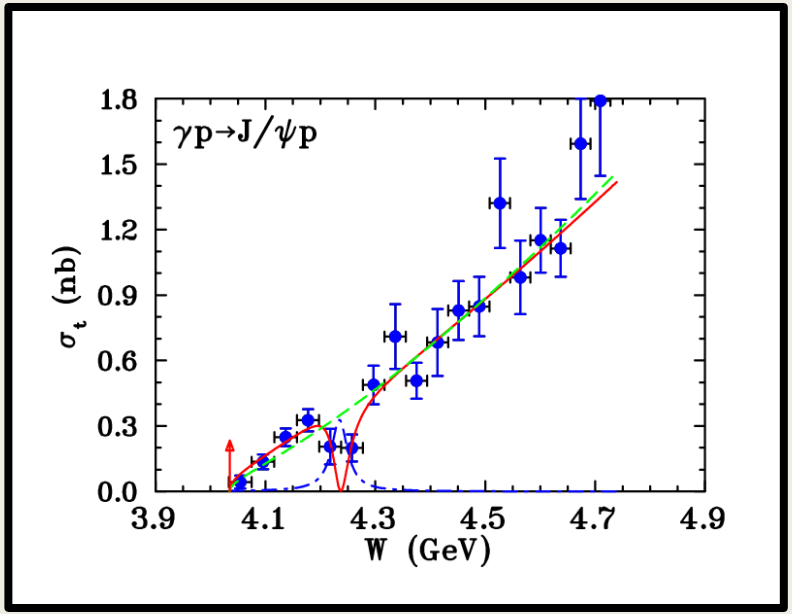






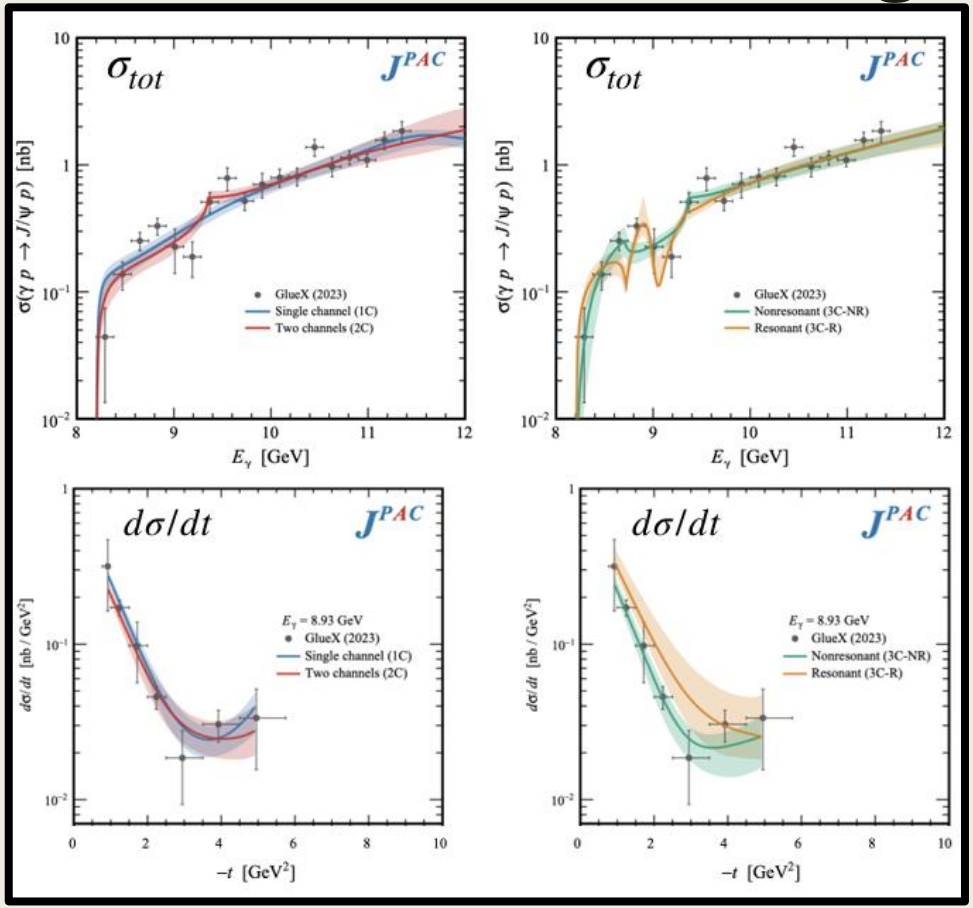
GlueX: Phys. Rev. C108, 025201 (2023)

Du et al. EPJ C80 (2020)



Strakovsky et al. arxiv:2304.04924 (2023)

Gluon or charm exchange: JPAC interpretation



Phenomenological model based on s-channel PW expansion ($l \leq 3$):

- (1C) $J/\psi p$ interaction
- (2C) $J/\psi p$ and $\bar{D}^* \Lambda_c$
- (3C-NR) $J/\psi p$, $\bar{D}^* \Lambda_c$, $\bar{D} \Lambda_c$ (non-resonant solution)
- (3C-R) $J/\psi p$, $\bar{D}^* \Lambda_c$, $\bar{D} \Lambda_c$ (resonant solution)

No stat. significant preference:

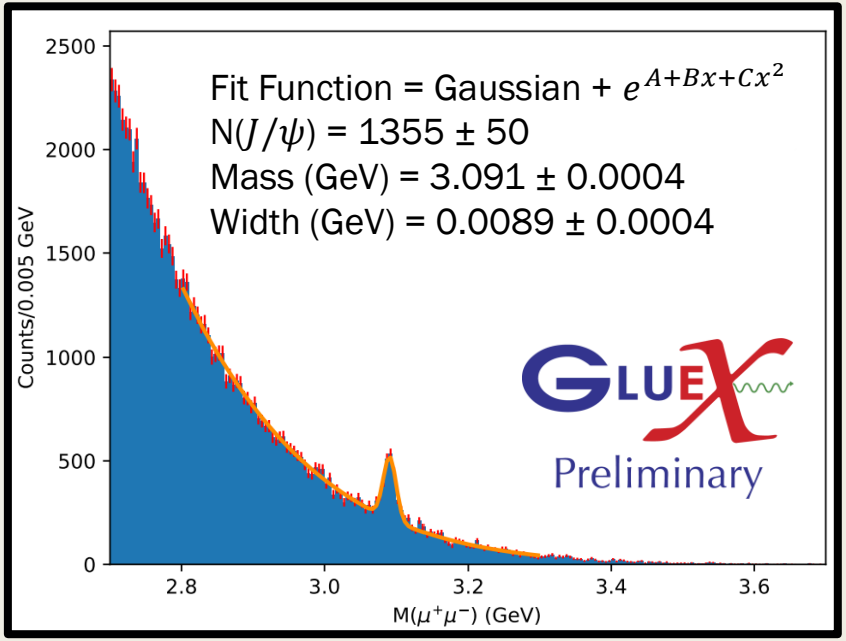
- 9 GeV structure requires sizable contribution from open charm
- Severe violation of VMD and factorization not excluded
- s-channel resonance not excluded
- t-enhancement indicates s-channel contribution: due to proximity to threshold or open-charm exchange

JPAC arxiv:2305.01449 (2023)

Why $J/\psi \rightarrow \mu^+\mu^-$ at GlueX?

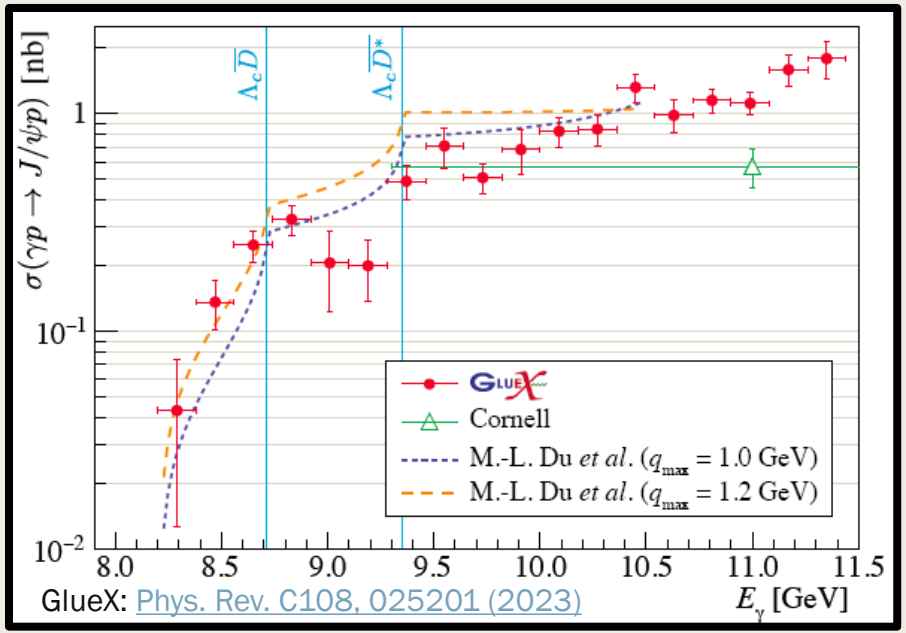
- Branching ratios are the same for both channels
  - *Increase our J/ψ statistics*
- Large (~20%) normalization uncertainty in $J/\psi \rightarrow e^+e^-$ cross section
  - Primarily from the relative measurement to *Bethe-Heitler* process
- $J/\psi \rightarrow \mu^+\mu^-$
  - Absolute cross section measurement
    - Could help reduce this normalization uncertainty
  - *Detector response to the electrons and muons is different*
  - *Can be used as a cross check for the behavior seen in the total and differential cross sections*

Exclusive $\gamma p \rightarrow J/\psi p \rightarrow \mu^+\mu^- p$ at GlueX

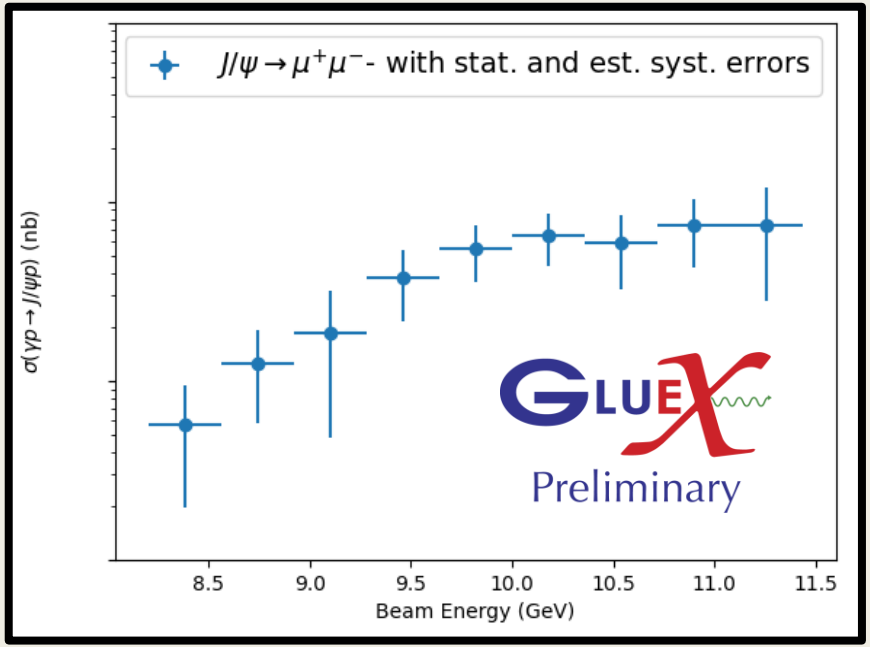


- Exclusivity of the reaction: kinematic fit- forces exclusivity and p^μ conservation
- Use energy deposition in calorimeters for particle identification
- Use opening angle between muons to remove large baryon background
  - Pions misidentified as muons → one pion at greater angle in baryon decays
- Mass distribution- Observed yield after selections
  - No efficiency correction

Comparing e^+e^- and $\mu^+\mu^-$ cross sections

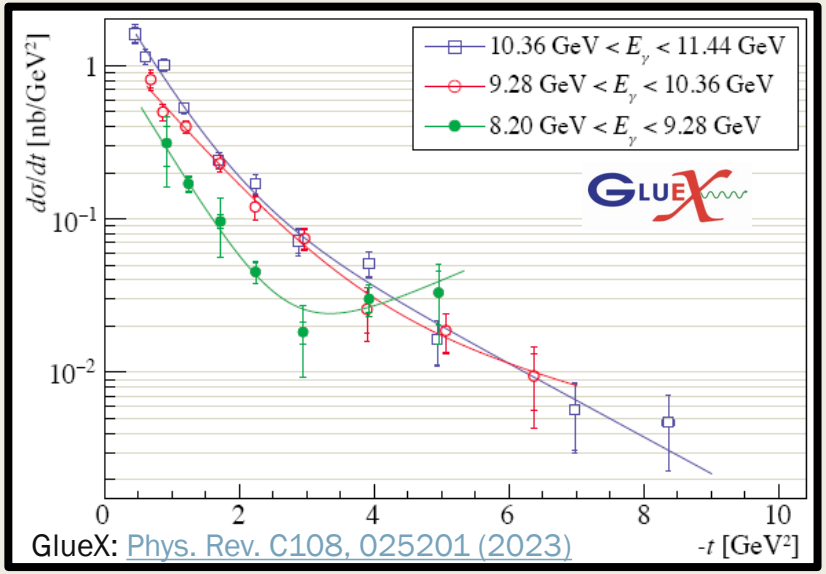


GlueX: Phys. Rev. C108, 025201 (2023)

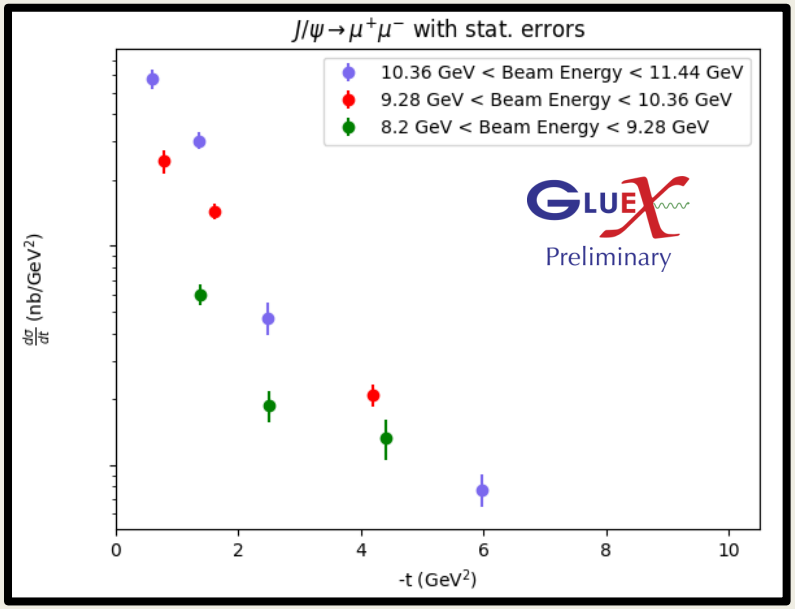


- Cross section with statistical and preliminary systematic uncertainties
  - Large systematic uncertainties in $\mu^+\mu^-$ cross section
- Measurements are consistent in general shape
  - Normalization uncertainty in $\mu^+\mu^-$ cross section

Comparing e^+e^- and $\mu^+\mu^-$ differntial cross sections



GlueX: Phys. Rev. C108, 025201 (2023)



- Just statistical uncertainty for $\mu^+\mu^-$
  - Systematic uncertainties not included but contributes greatly to uncertainties
- See a flattening at low beam energy and high-t in both channels
- Normalization uncertainty in $\mu^+\mu^-$ cross section

Future at GlueX- Approved Phase-III Proposal

Run Period	PAC Days	J/ψ Yield
All Phase I	120	2,180
2020 Phase II	67.5	1,780
2023 Phase II	28.1	*741*
2024-2025 Phase II (planned)	109	*2,874*
This Proposal	200	*11,271*
Projected Total		18,846

Proposal # PR12-24-006 for PAC52

- Currently in Phase-II
  - *Should triple the e^+e^- published statistics (Just Phase-I)*
  - *Doubles the $\mu^+\mu^-$ statistics (Phase-I + 2020 Phase-II)*
- Approved for Phase-III
  - *Twice the Phase-I and Phase-II photon beam intensity*
  - *Should J/ψ double the combined Phase-I and Phase-II statistics*
  - *Predicts a high likelihood that added GlueX-III data could rule out the 1C model at the 5σ level*

Summary

- Summary:
  - *Successfully calculated a total and differential cross section of the reaction* $\gamma p \rightarrow J/\psi p$ *both leptonic decays*
  - *Possible dip structure at* $\sigma(8.6 - 9.6GeV)$ *in* e^+e^- *channel*
  - *Flattening of diff. cross section at high-t in both channels*
    - Helps distinguish between J/ψ photoproduction models
- Future Work:
  - *Large increase in data over next few years*
  - *Phase-III predicted to rule out the 1C (*$J/\psi p$ *interaction) model at the* 5σ *level*

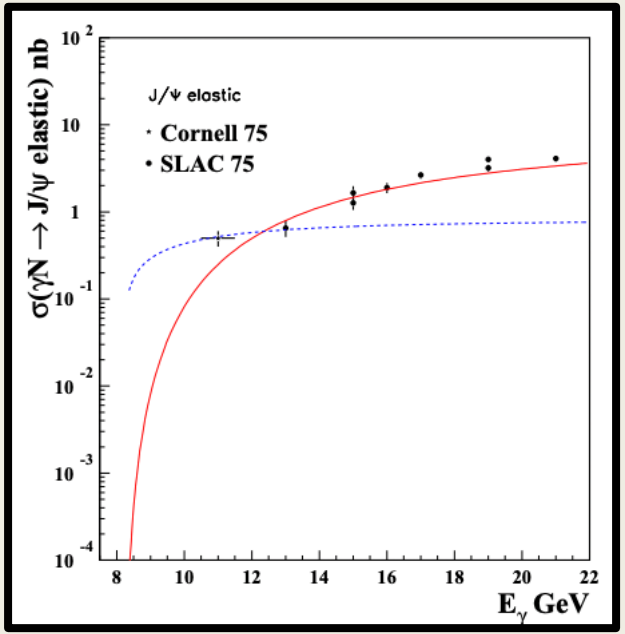
GlueX Acknowledgements:

http://gluex.org/thanks

Back up slides

Previous Measurements: SLAC and Cornell

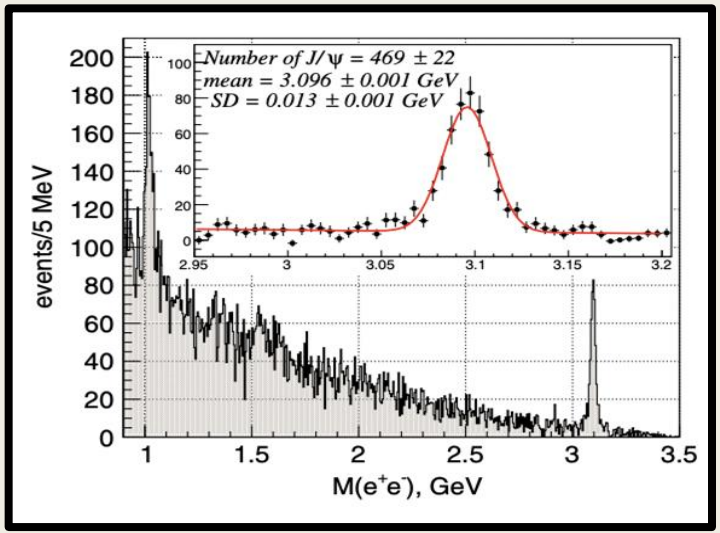
- SLAC and Cornell- First J/ψ photoproduction measurements at energies near threshold
- Both experiments predominantly used nuclear targets
- Both experiments had only inclusive measurements since they did not detect the recoiling proton
  - *Because of this, they both have access to a limited range of Mandlestam-t values, which leads to greater systematic uncertainties in their measurement.*
- These measurements were also done at least 1.5 GeV above the J/ψ threshold.



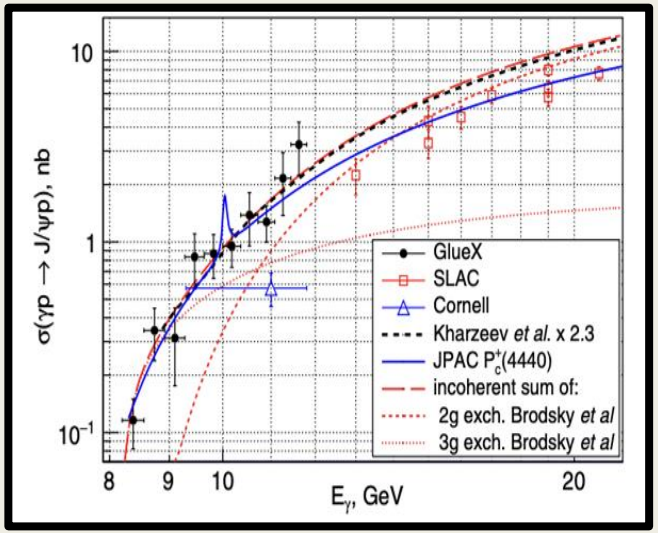
Brodsky et al.: PLB 498 (2001), pp. 23–28

Previous Measurements: GlueX Collaboration (1st Publication)

- GlueX- published measurements of the $\gamma p \rightarrow J/\psi p$ cross-section through the decay of $J/\psi \rightarrow e^+ e^-$
  - *Total integrated luminosity 68pb^{-1} at or above the J/ψ threshold*
- Relative cross-section measurement to the Bethe-Heitler process
  - *This contributes significantly to a large (~27%) systematic normalization uncertainty*
- No evidence for P_c^+ states that were found by LHCb



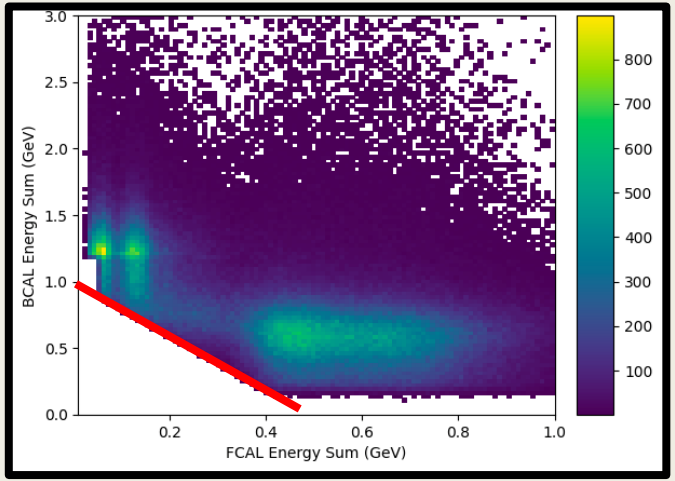
GlueX: PRL 123 (7 Aug. 2019), p. 072001



GlueX: PRL 123 (7 Aug. 2019), p. 072001

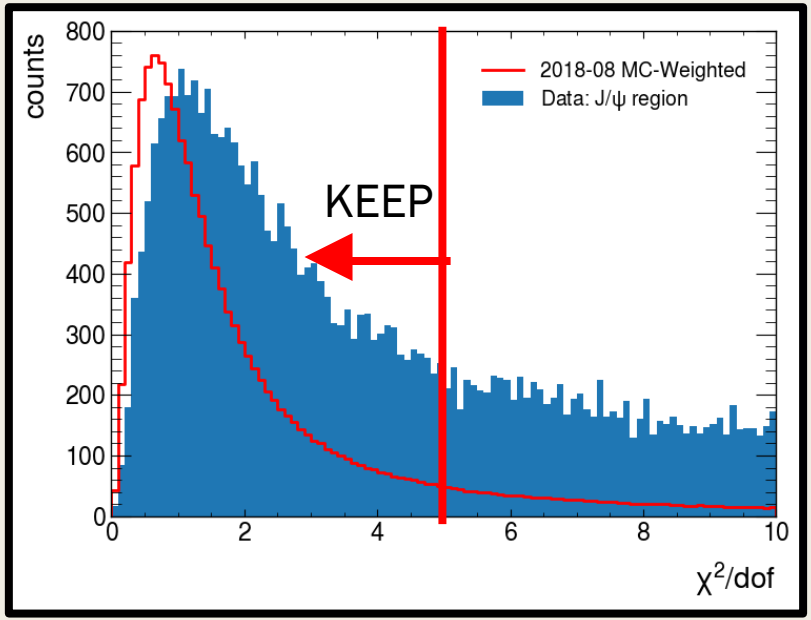
Data Used and Goal of Event Selections

- Proposed exclusive reaction:
  - $\gamma p \rightarrow J/\psi p \rightarrow \mu^+\mu^- p$
  - *Phase-I data: taken from 2017-2018*
    - a luminosity of 304 pb^{-1} above the J/ψ threshold
  - *Subset of Phase-II data: taken in 2020*
    - a luminosity of 321 pb^{-1} above the J/ψ threshold



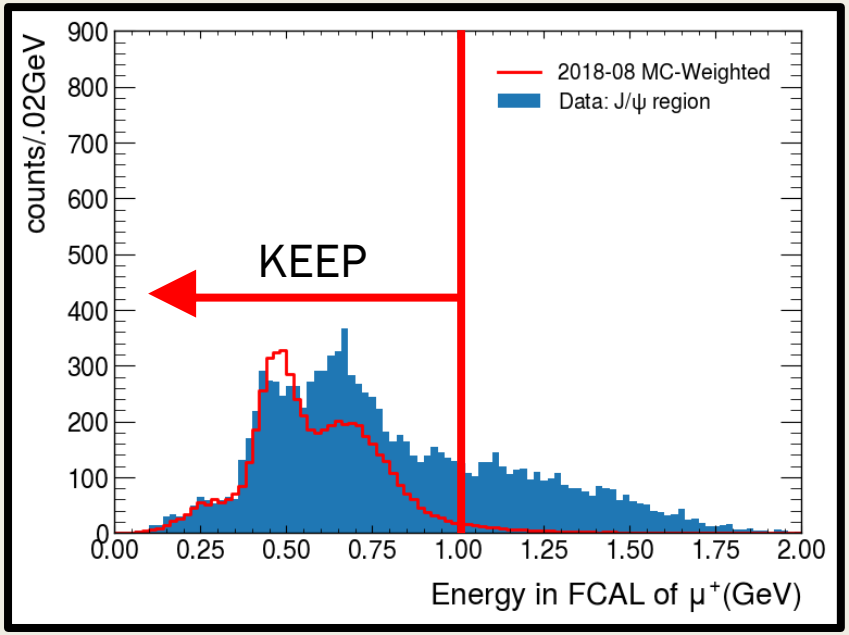
Event Selection	Importance of Selection
$E_{BCAL,total}$ > 1.2 GeV or $E_{BCAL,total}$ + 0.5*$E_{FCAL,total}$ > 1 GeV	Physics Trigger
Beam Energy > 8.2 GeV	Removes events below J/ψ threshold
$\chi^2/dof < 5$	Requires exclusivity and conservation of p^μ
Energy/Path Length in BCAL of $\mu^\pm$ < .012 GeV/cm	Distinguishes between muons and pions
Energy in FCAL of $\mu^\pm$ < 1 GeV	
$\theta(\mu^\pm) < 12.5°$ and $\theta(\mu^\pm) < 40°$	Removes pion events formed by baryon decay

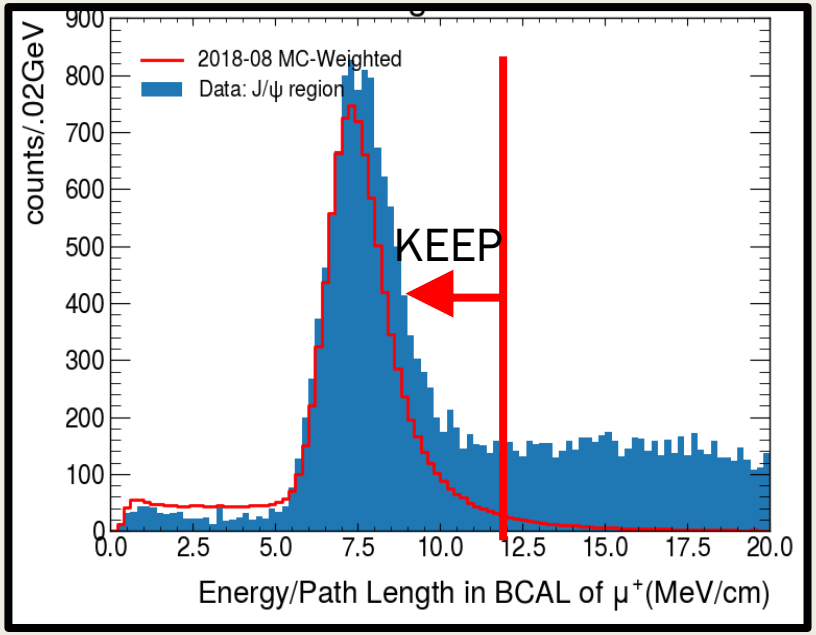
Event Selections- χ^2/dof



- Used to determine the exclusivety of an event
- In the J/ψ region
  - *A long tail in data, probably from events with extra, undetected particles*
- The red line signifies my selection
  - *Did some studies to optimize the chosen selection*

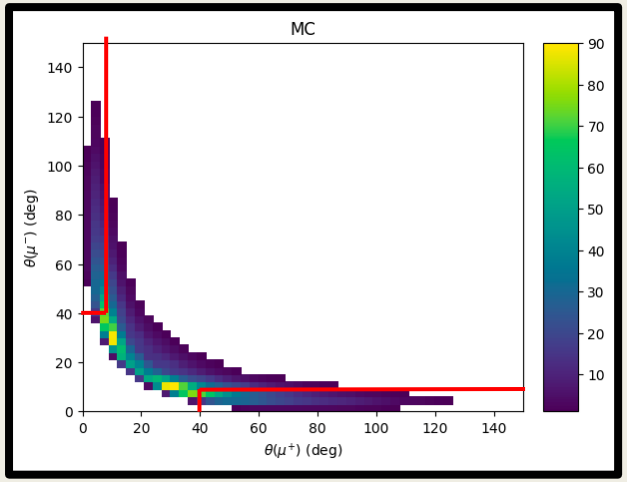
Event Selections- BCAL and FCAL selections New MC

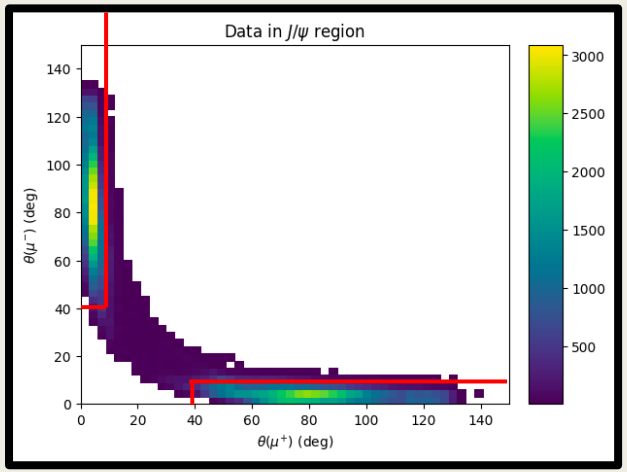




- With corrections to the MC simulations, much better matching in J/ψ region
  - Differences mostly from large pion background
  - Make loose selections to mitigate differences
- Keep events to the left of the red line

New θ cut- Theta Distributions

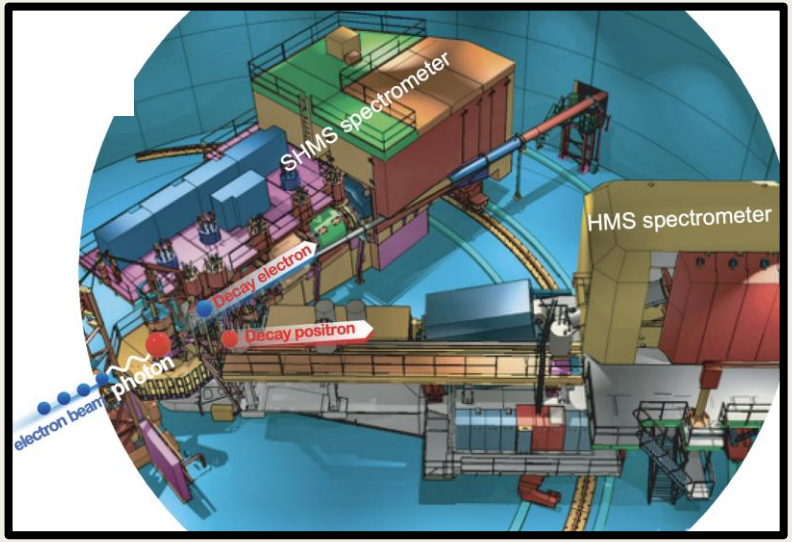




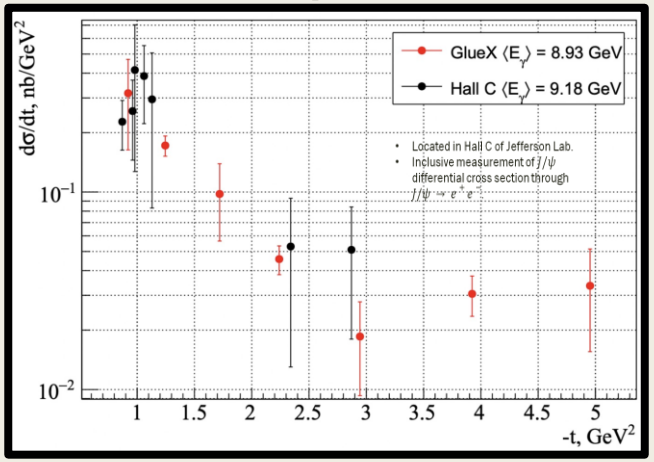
- Comparing data to MC
  - Muons tend to have smaller angles
- Pions from baryon decay
  - One pion has large θ in the lab frame
  - Expect the large angles to be from misidentified pions
  - For instance:
    - $\gamma p \rightarrow \Delta^{++}\pi^- \rightarrow (\pi^+ p)\pi^-$
    - $\gamma p \rightarrow \Delta^0\pi^+ \rightarrow (\pi^- p)\pi^+$
    - $\gamma p \rightarrow N^*\pi^+ \rightarrow (\pi^- p)\pi^+$
- Theta Cut: $\theta(\mu^{\pm}) < 12.5°$ and $\theta(\mu^{\mp}) < 40°$

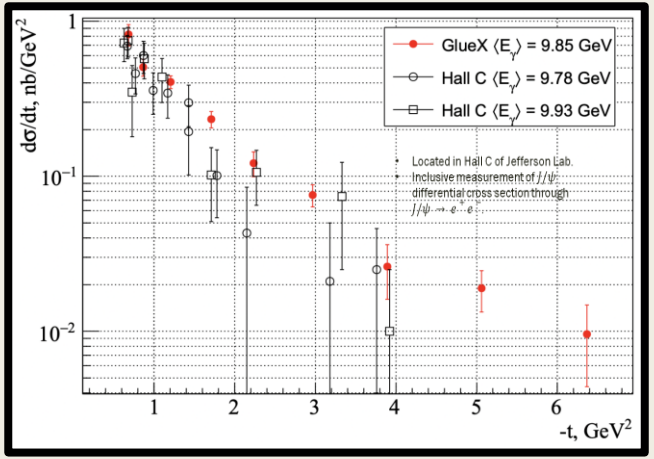
Previous Measurements: J/ψ – 007 Experiment

- Located in Hall C of Jefferson Lab.
- Inclusive measurement of J/ψ differential cross section through $J/\psi \rightarrow e^+ e^-$

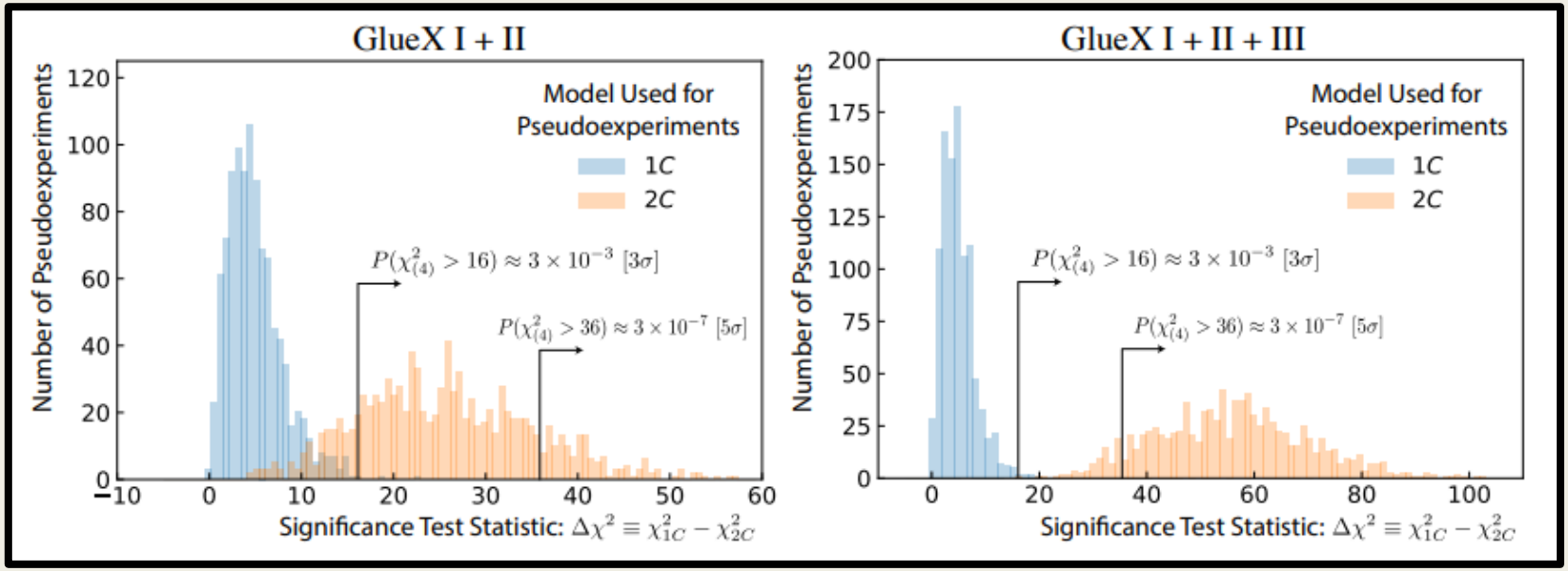


Duran, B., Meziani, ZE., Joosten, S. et al. Determining the gluonic gravitational form factors of the proton. Nature 615, 813–816 (2023)

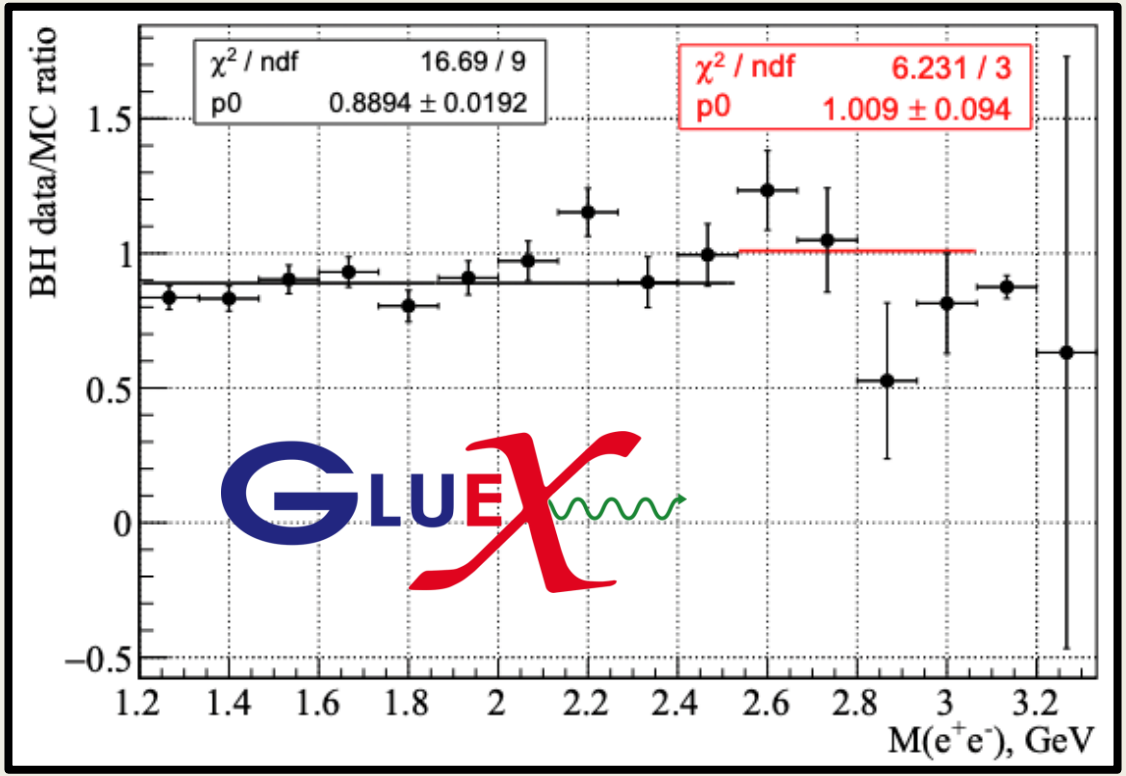




GlueX Phase-III



- Plots of the χ^2 difference for 1C ($J/\psi p$ interaction) and 2C ($J/\psi p$ and $\bar{D}^* \Lambda_c$) JPAC model
- Shows a high likelihood that added GlueX-III data could rule out the 1C model at the 5σ level


χ^2 / ndf 16.69 / 9
p0 0.8894 ± 0.0192
χ^2 / ndf 6.231 / 3
p0 1.009 ± 0.094
BH data/MC ratio
1.5
1
0.5
0
−0.5
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
M(e⁺e⁻), GeV
GLUEX