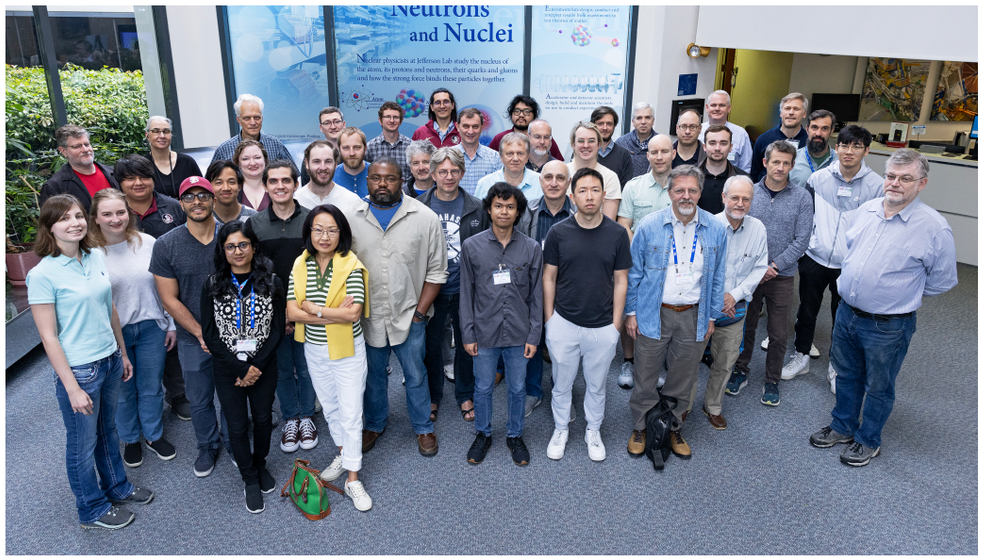
GlueX III: a path to the luminosity frontier in Hall D

PR12-24-006

Justin Stevens, on behalf of the GlueX Collaboration



May Collaboration Meeting "PhysicsFest": 30+ unique analyses presented

Dear Members of the Jefferson Lab PAC:

I am writing to convey the GlueX Collaboration's *endorsement* of the proposal PR12-24-006 titled **GlueX-III: a path to the Luminosity Frontier in Hall D** that has been submitted to PAC 52.

This endorsement implies a commitment of the entire collaboration to operate the detector, staff shifts, calibrate and process the data, as well as provide support for and review of the final data analysis. The procedure for obtaining endorsement is defined in the bylaws of the GlueX Collaboration (available at *www.gluex.org*) and is overseen by the GlueX Collaboration Board. An ad hoc committee was appointed to review the technical feasibility and physics merit of this proposal. After evaluation of the outcome of this review, the Board recommended a vote of endorsement to the entire collaboration. Finally, the Collaboration granted endorsement via a positive vote: 93 of 132 eligible voters cast a ballot, and the votes were overwhelmingly in favor of endorsing the proposal. On behalf of the GlueX Collaboration, I would like to express our enthusiasm for executing the physics program in this proposal.

Sincerely,

Matthew Shepherd
GlueX Collaboration Spokesperson

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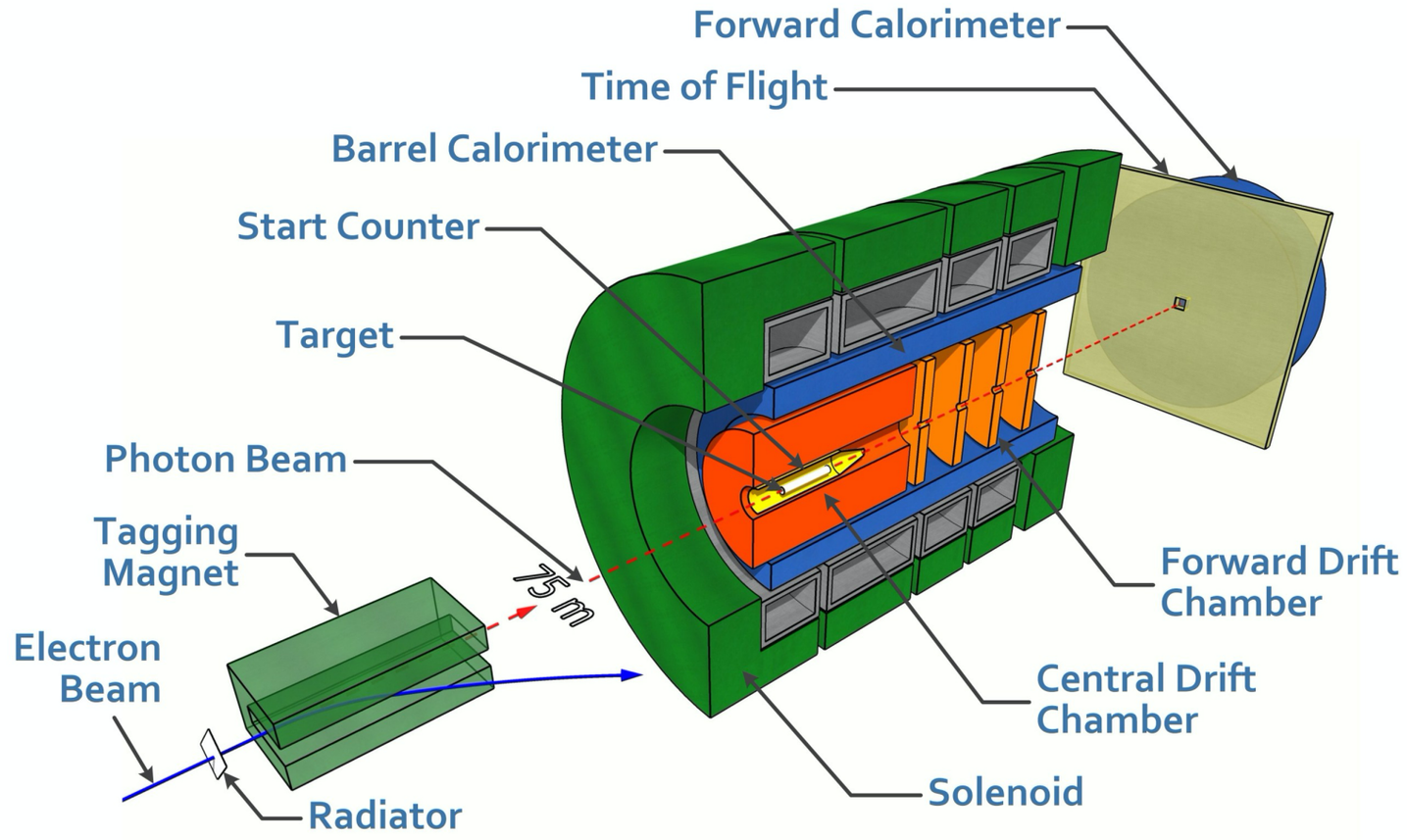
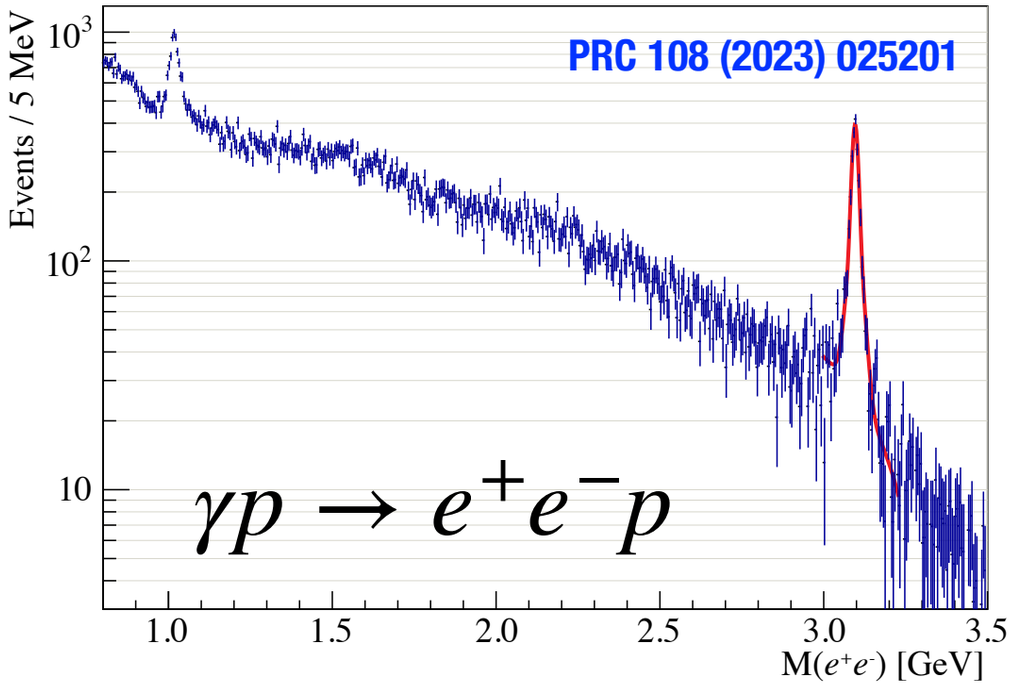
GlueX-III: Executive Summary

- **Beam Request:**
  - 200 PAC days at 12 GeV, 600 nA (twice GlueX-II)
- **Enables a broad Physics Program:**
  - More than doubling J/ψ precision: probe $c\bar{c}$ production mechanism and proton's gluonic structure
  - Unique access to *5x more* χ_{cJ} and *10x more* $\psi(2S)$ than expected from currently approved GlueX running
  - Extend hybrid program: establish π_1 photoproduction mechanism and search for η_1 and kaon hybrids

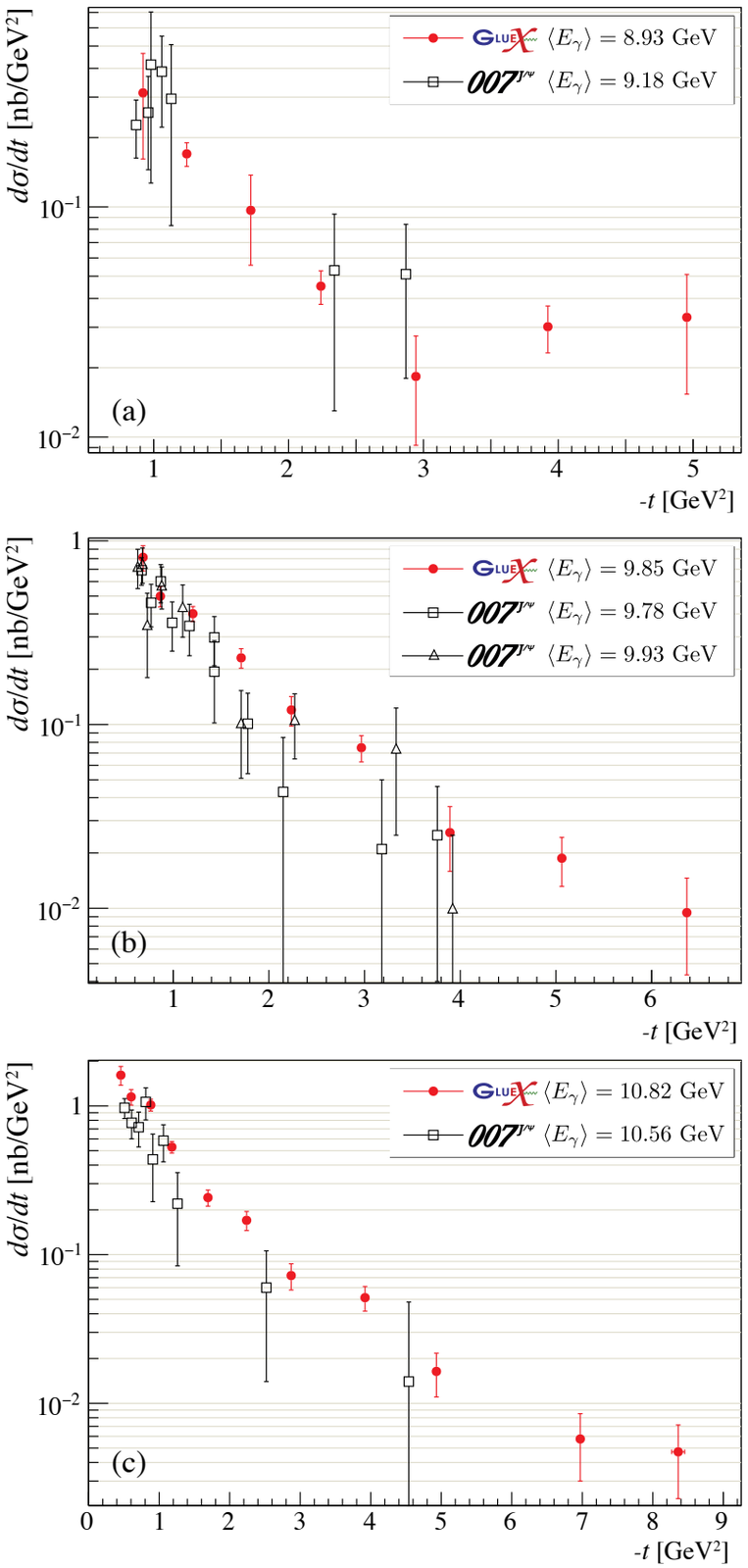
The GlueX Beamline and Detector
NIM A 987, 164807 (2021)



- **GlueX-I (2016-2018):** 120 PAC days with 150-250 nA
- World-unique polarized photoproduction data: 30+ PhDs, 10 papers: ALP search, production dynamics, hyperons, exotics, etc.
- First observation of J/ψ at JLab; published precision total and differential cross sections: 2.2k J/ψ

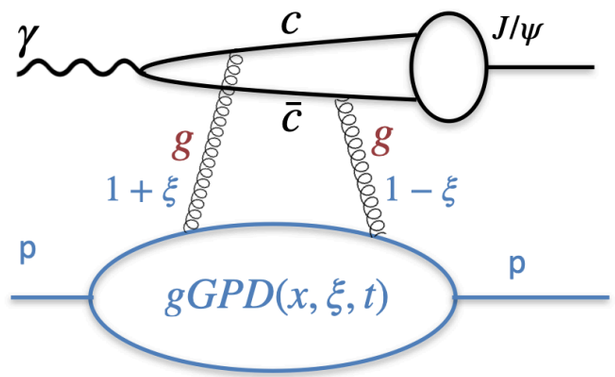


Interpretation of GlueX-I results



PRC 108 (2023) 025201
Nature 615 (2023) 813

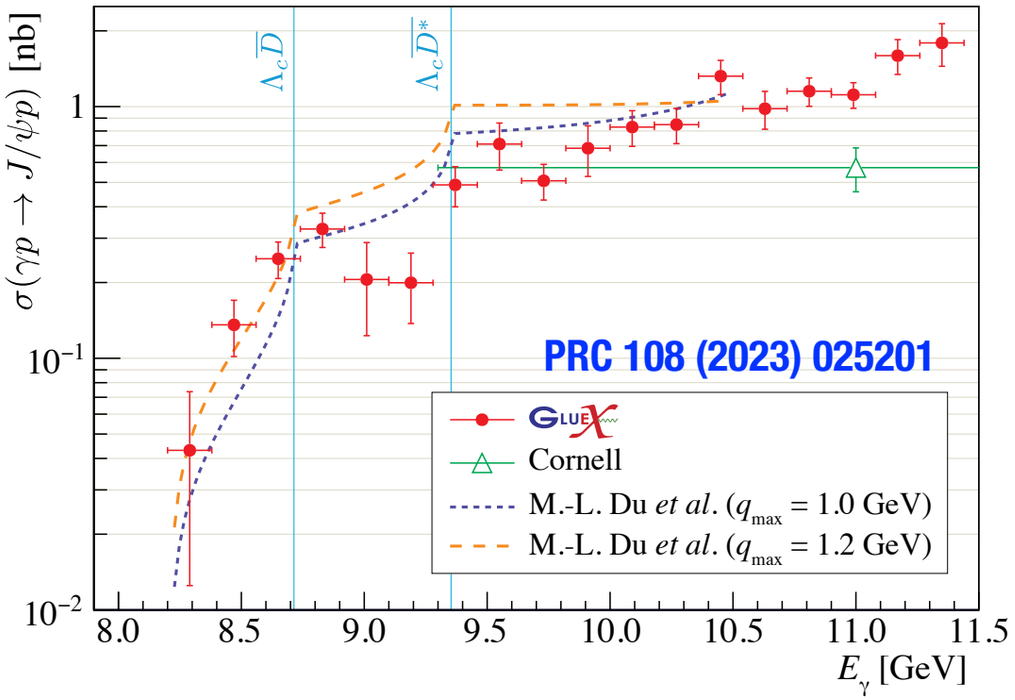
t-channel: gluon GPDs, mass radius

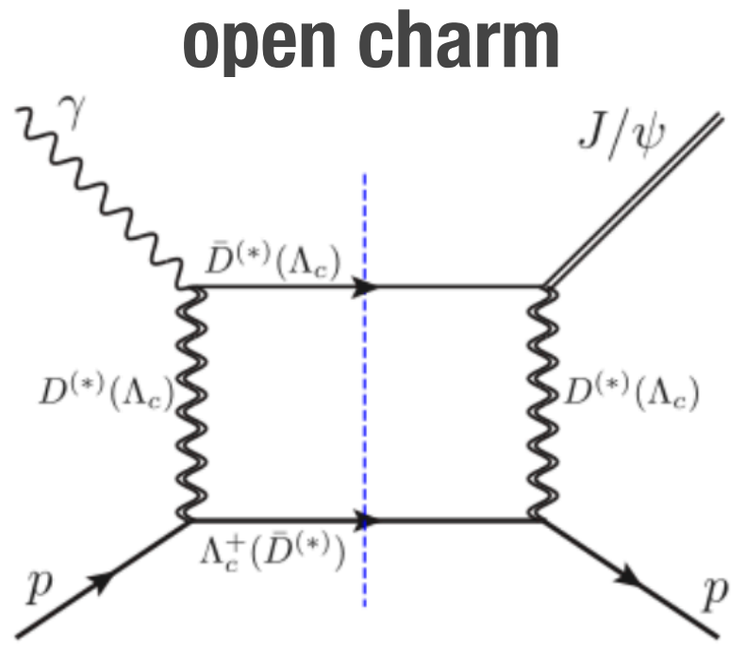


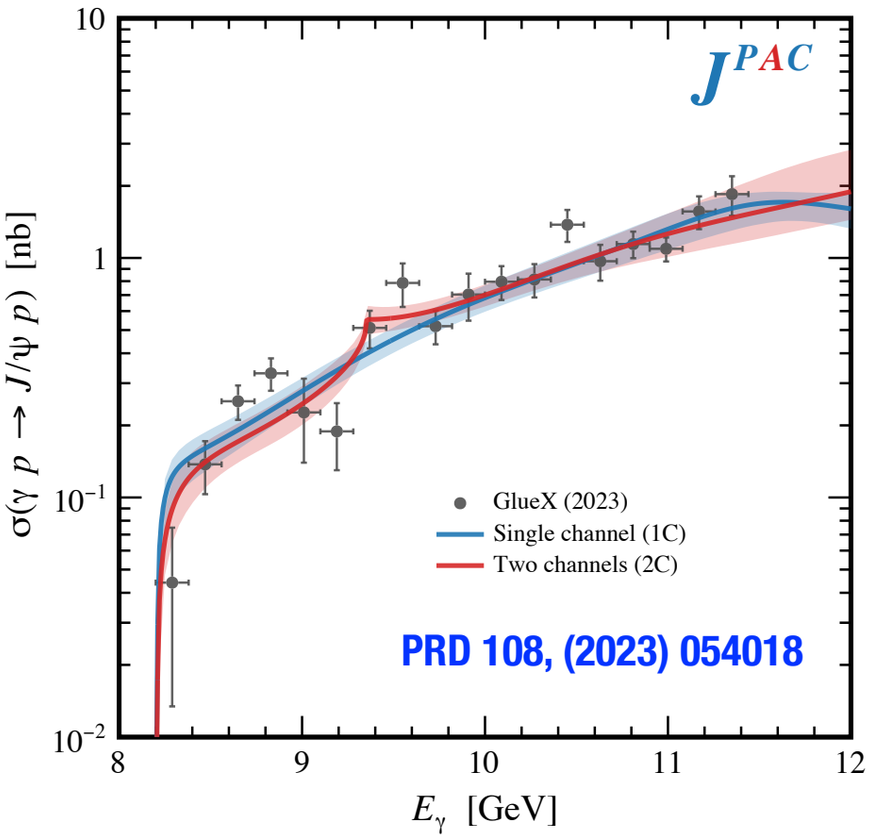
- Partonic approach provides sensitivity to gluonic structure of the nucleon through differential cross section $d\sigma/dt$, with consistent between $J/\psi - 007$ (Hall C) and GlueX-I

- Significant interest in sensitivity to gluon GPDs, mass radius, etc.
  - GPDs: **Guo, Ji, Yuan: PRD 109 (2024)** **Guo, Ji, Liu, Yang: PRD 108 (2023)**
  - Lattice: **Hackett, Pefkou, Shanahan: arXiv:2310.08484** **Pefkou, Hackett, Shanahan: PRD 105 (2022)**
  - Holographic: **Mamo and Zahed: PRD 106 (2022), PRD 108 (2023)** **Hatta and Yang: PRD 98 (2018)**

Interpretation of GlueX-I results







- Mesonic approach sensitive to “cusps” near opening of open charm thresholds in total cross section
- Fits with both single channel (Pomeron) exchange and multichannel (Pomeron + open charm) are compatible with GlueX-I and $J/\psi - 007$ data

Proposed J/ψ results from GlueX-III

- Existing data consistent with multiple production mechanisms, requiring new data

In 2023 two Letters of Intent (LOIs) were submitted to PAC51, describing higher precision measurements of the J/ψ cross section (LOI-12-23-010 [9]) and a high-luminosity program (LOI-12-23-007 [10]). This proposal combines these efforts to run concurrently, as recommended by the PAC.

The PAC51 report noted:

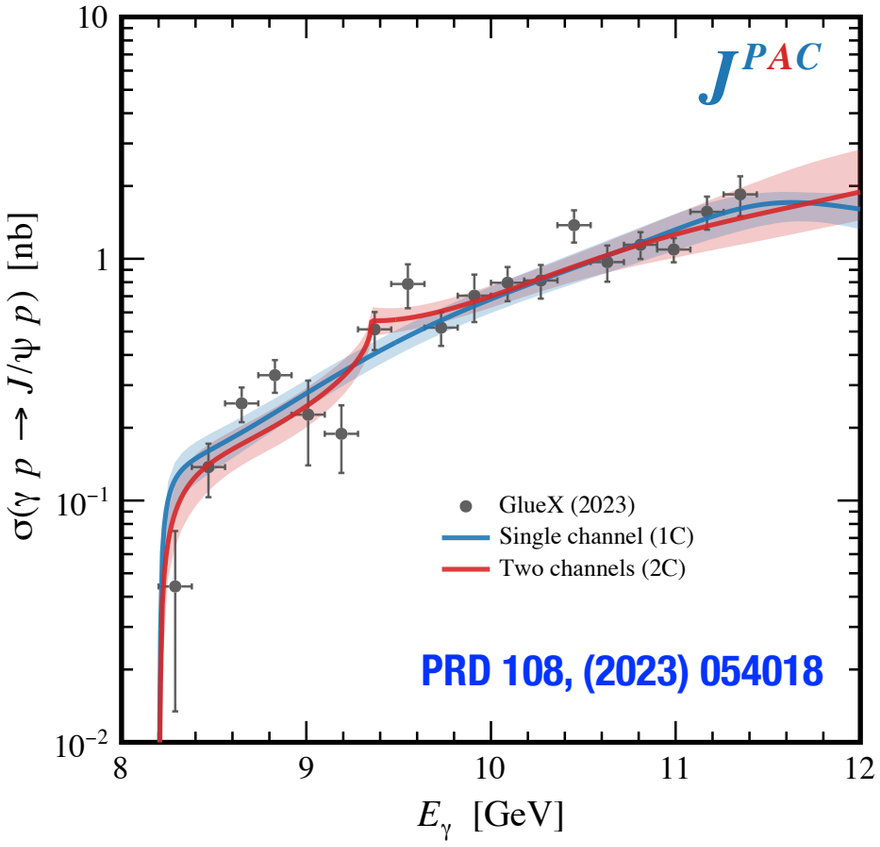
> The ability to use the proposed data to discriminate between models of charmonium photoproduction drives the needed precision of the measurement. The proposers should work with theory colleagues to achieve more realistic estimates of the uncertainty of theory predictions from both partonic and mesonic approaches, and to identify the discrimination power of the improved data quantitatively.

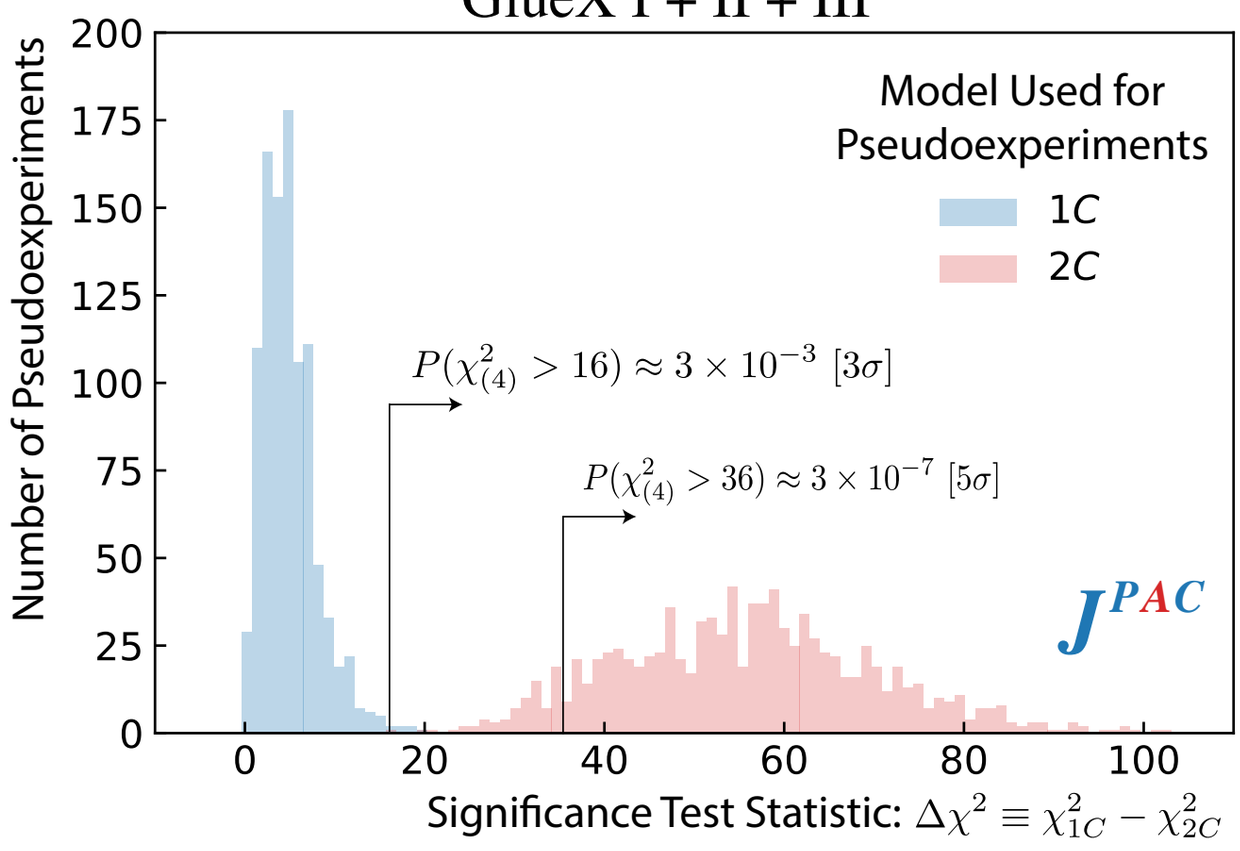
- Two high-level results expected from GlueX-III:
  - Pin down mesonic (open charm) contributions
  - Test partonic (gluon) approach with scaling of differential cross sections

Sensitivity to open charm contribution

- Sensitivity of GlueX I+II+III determined in collaboration with JPAC from pseudodata generated with the 1C and 2C models

- If the new data follows the 2C model, then it will be significantly distinguishable from the 1C hypothesis



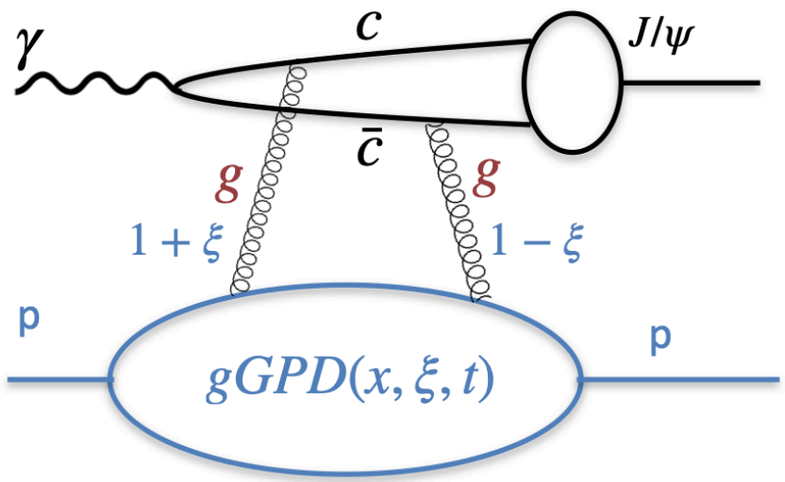


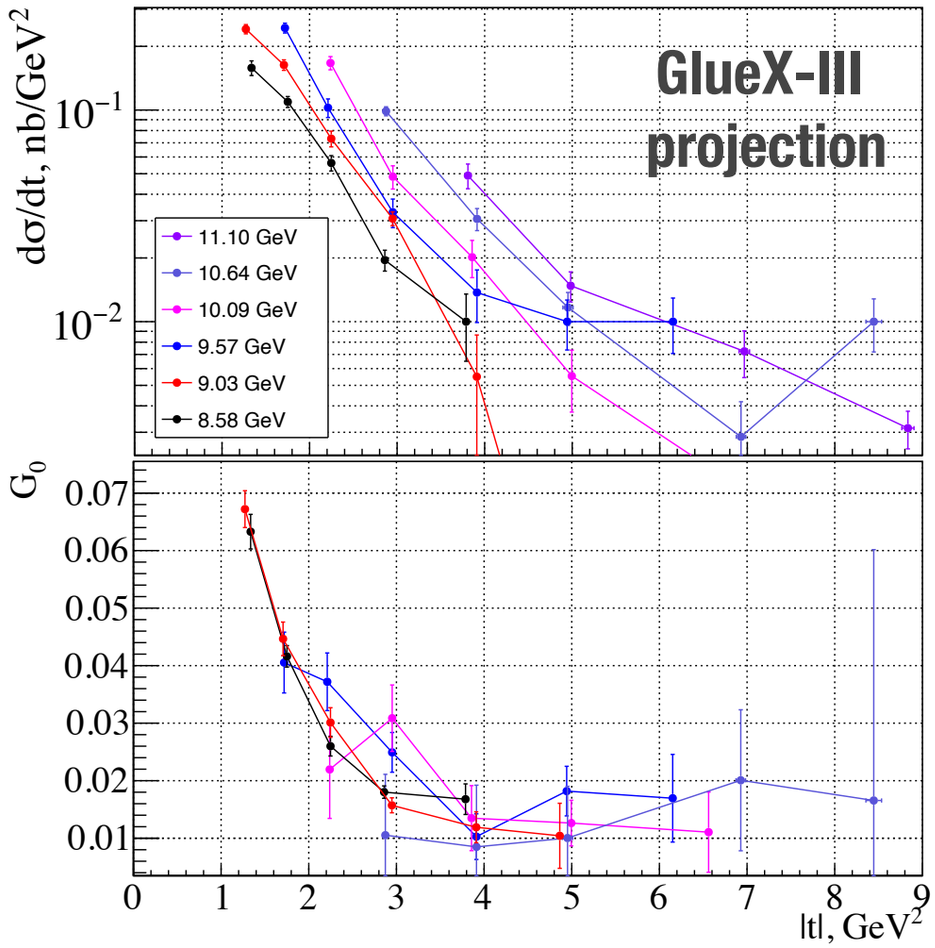
Test scaling of $d\sigma/dt$

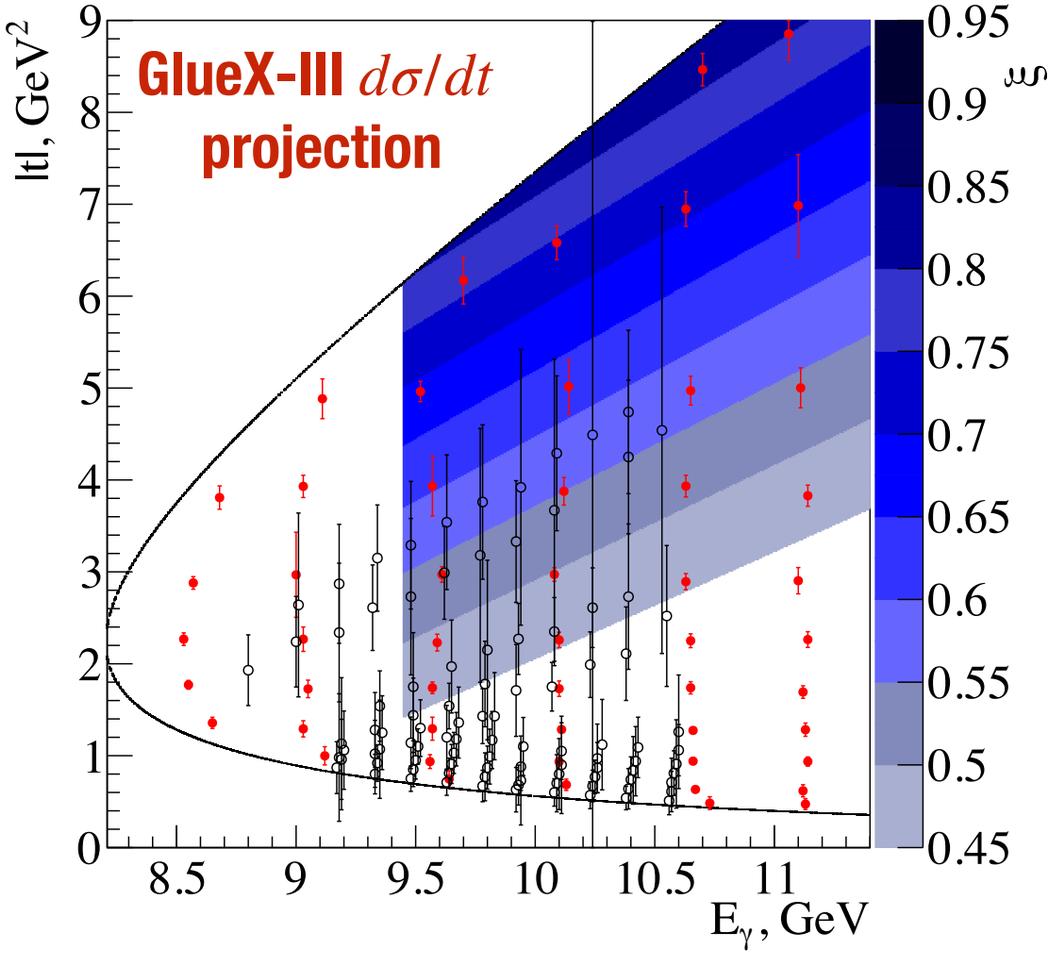
- Precision cross sections with improved binning in E_γ and t: access to **large** ξ

- Test ξ scaling prediction of GPD and Holographic approaches

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p \to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t)] + \dots$$

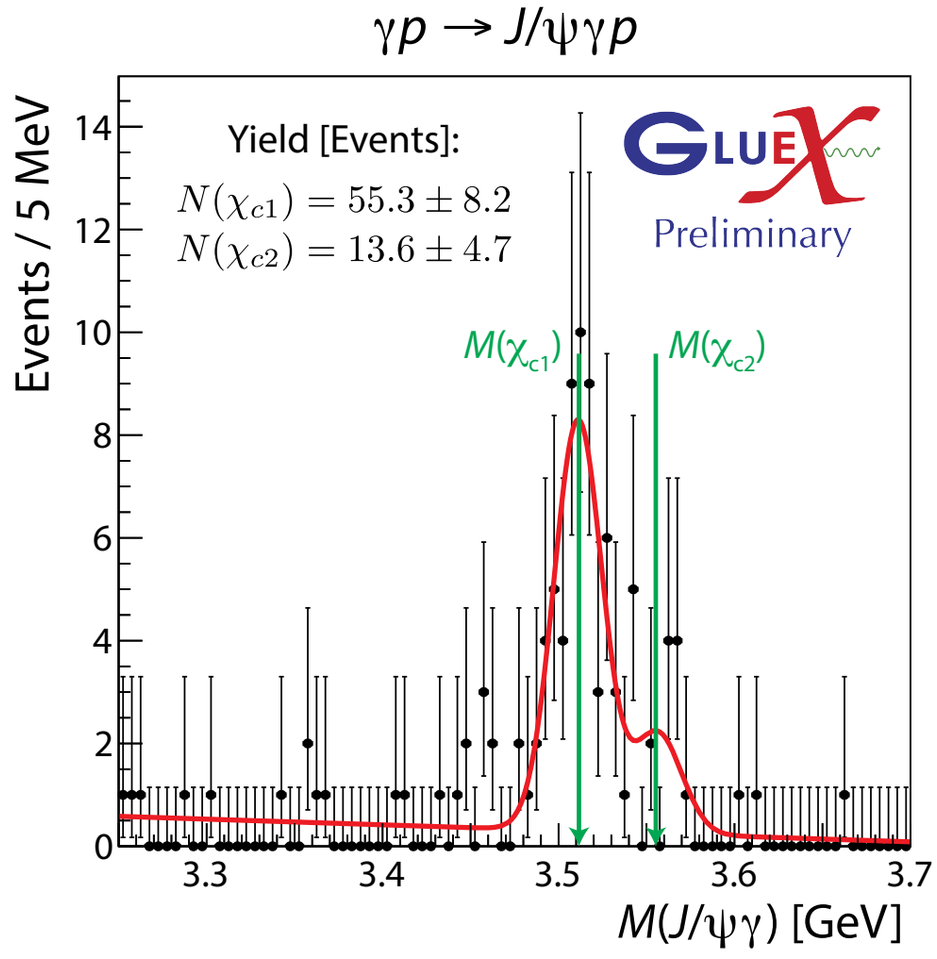






Beyond the J/ψ: limitations of GlueX-II

- **GlueX-II (2020-2026?):** 200 PAC days with 300 nA
- Analyzed 1/3 of approved data, expect 5.4k J/ψ when completed
- First observation of χ_{cJ} photoproduction with current GlueX data



$BR(\chi_{c1} \to \gamma J/\psi) = 34.3\,\%$

$BR(\chi_{c2} \to \gamma J/\psi) = 19.5\,\%$

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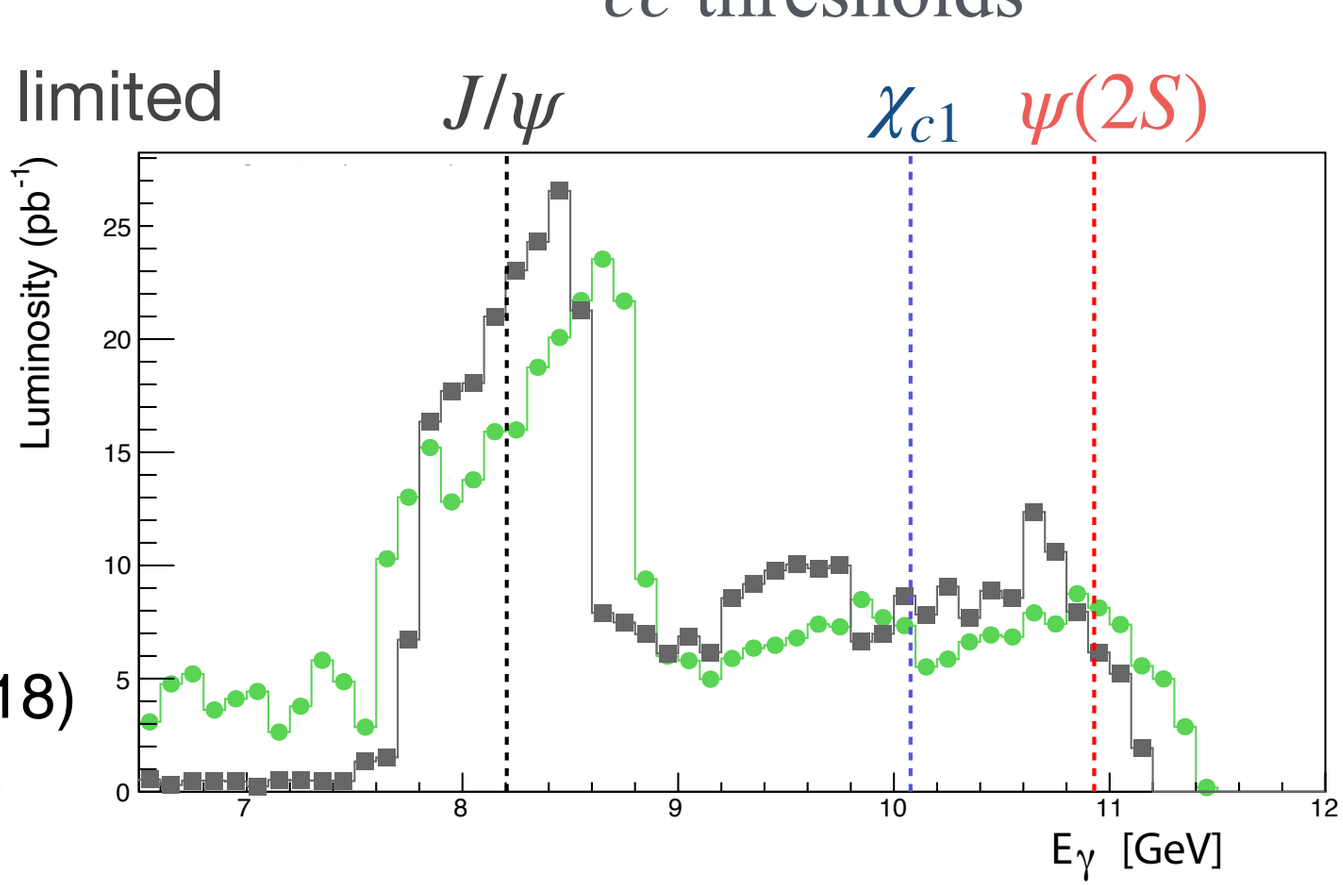
- Phasespace for χ_{cJ} and $\psi(2S)$ limited by electron beam energy

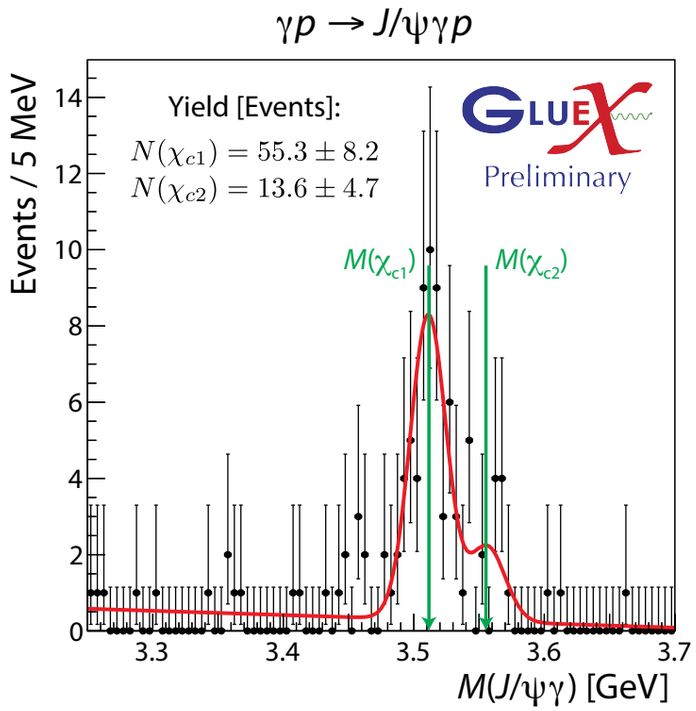
$E_e \approx 11.6GeV$ ● GlueX-I (2017-18)

$E_e \approx 11.4GeV$ ■ GlueX-II (2020)



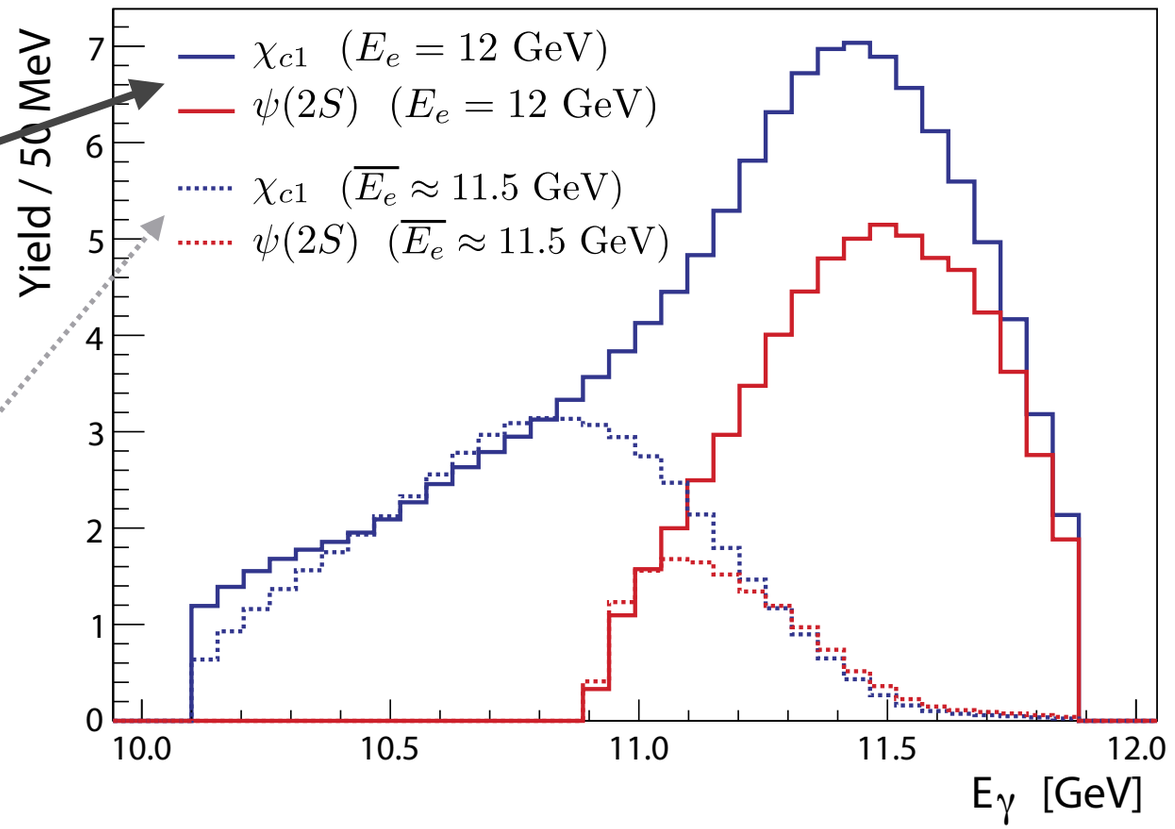
Uniqueness of GlueX-III $c\bar{c}$ program

- First observation of C-even χ_{cJ} photoproduction with current GlueX data
  - Requires broad calorimeter coverage for radiative decay
  - Significant impact of CEBAF energy reaching full 12 GeV



Potential with full 12 GeV

Current Data



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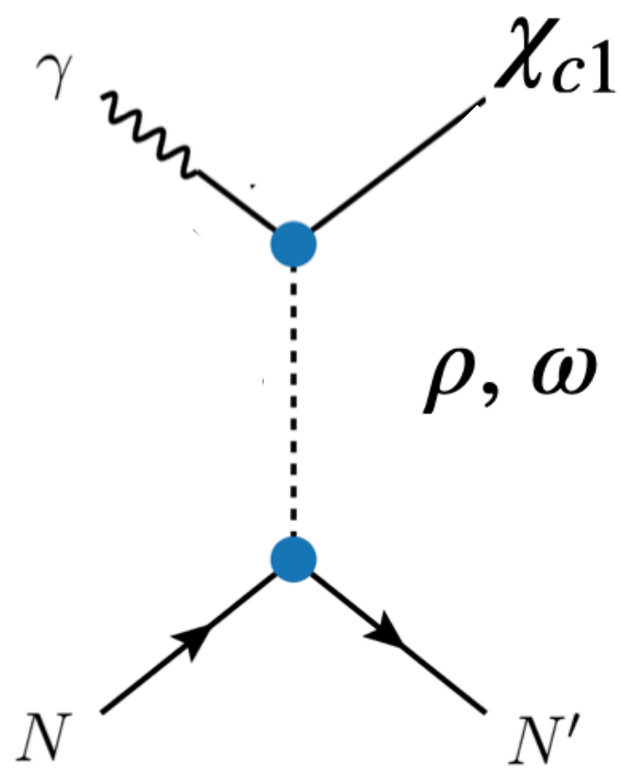
JPAC

PRD 102, 114010 (2020)

- Provide data for more holistic theoretical description of threshold $c\bar{c}$ production: $J/\psi, \chi_{cJ}, \psi(2S)$



Uniqueness of GlueX-III $c\bar{c}$ program

- First observation of C-even χ_{cJ} photoproduction with current GlueX data
  - Requires broad calorimeter coverage for radiative decay
  - Significant impact of CEBAF energy reaching full 12 GeV
- Provide data for more holistic theoretical description of threshold $c\bar{c}$ production: $J/\psi, \chi_{cJ}, \psi(2S)$
- Important to validate production models for $c\bar{c}$ and potentially more exotic states at EIC and JLab 22 GeV

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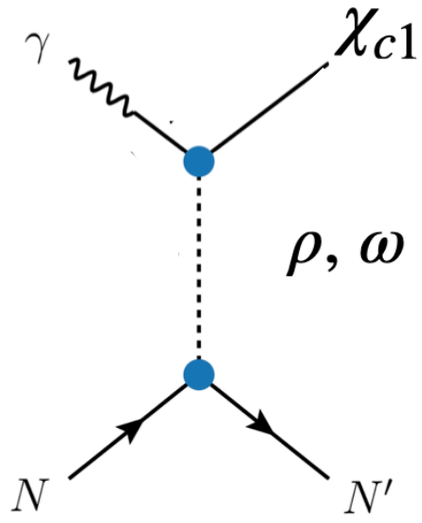
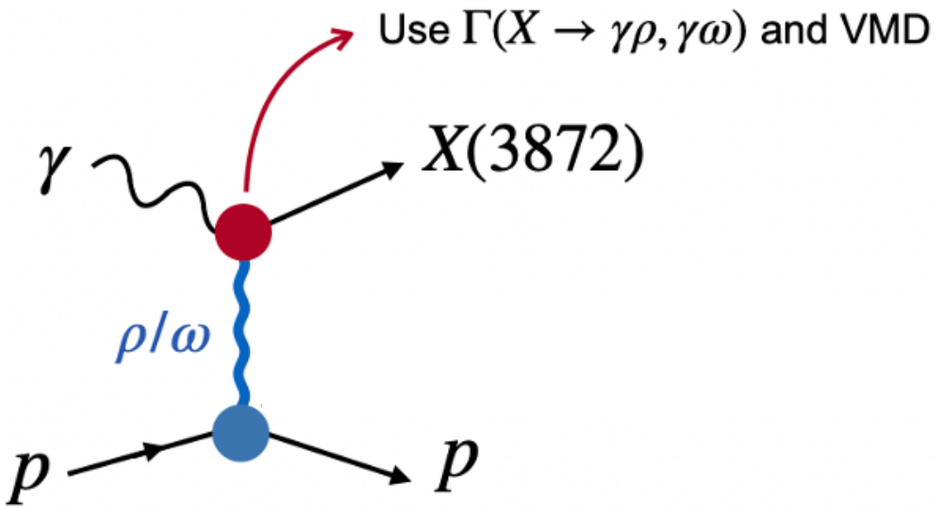
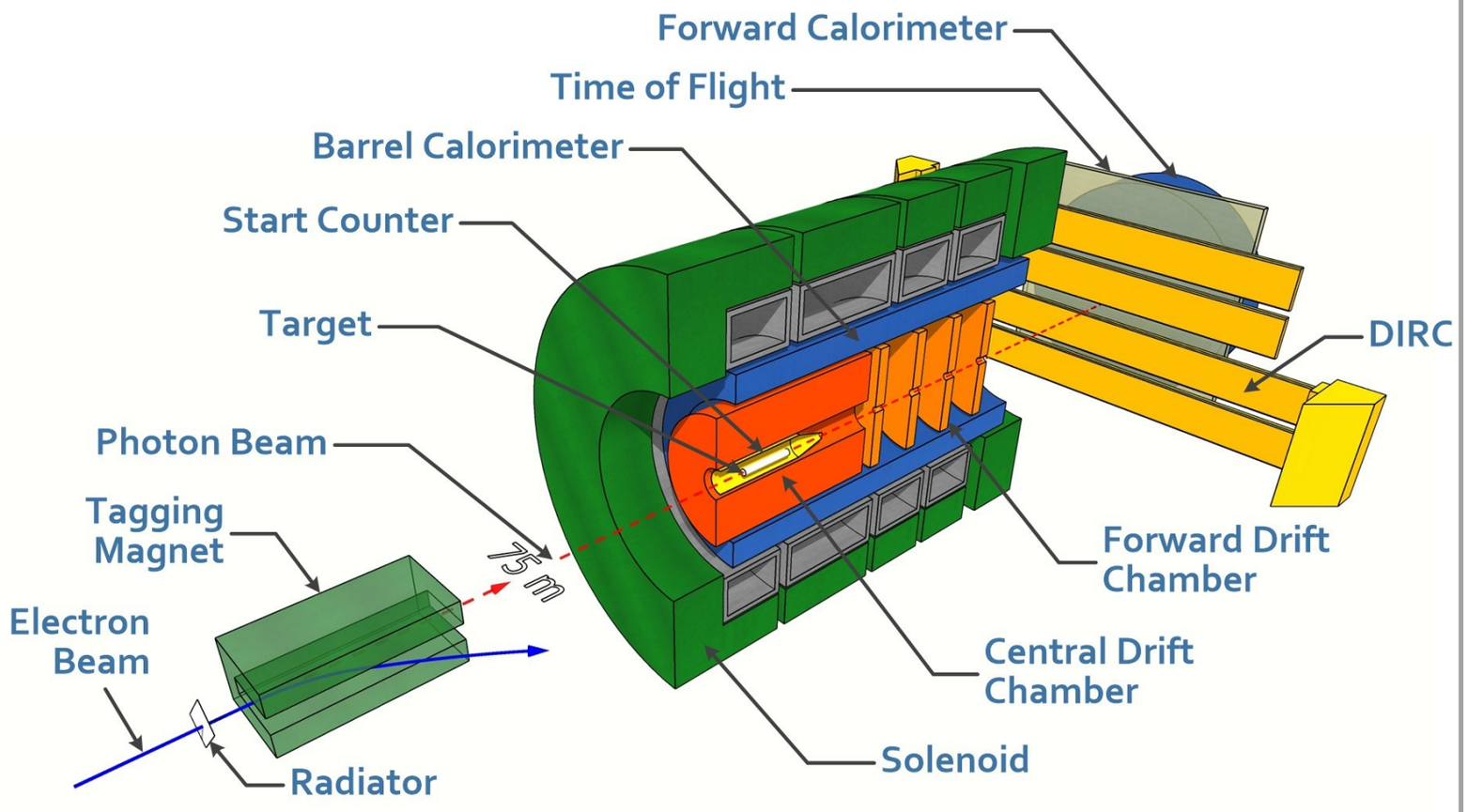
PRD 102, 114010 (2020)

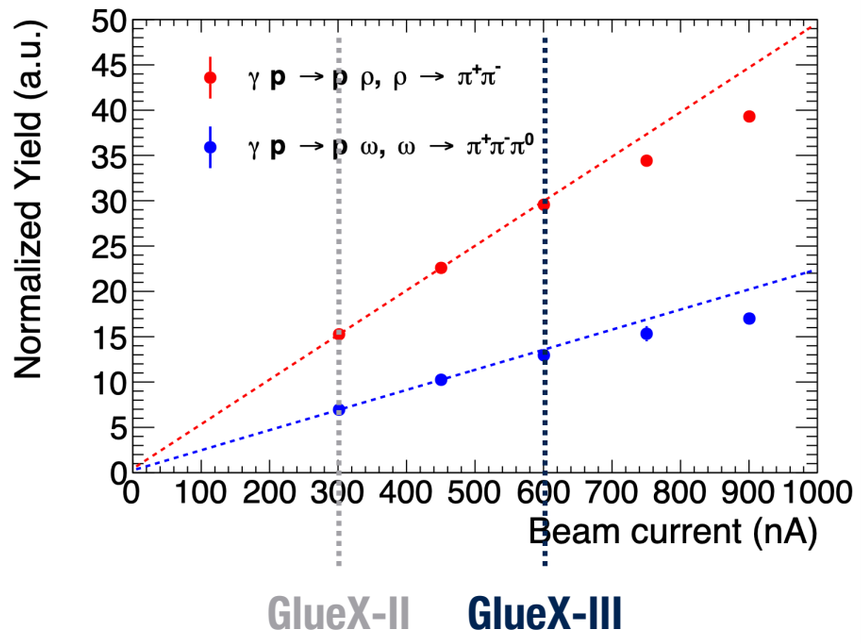






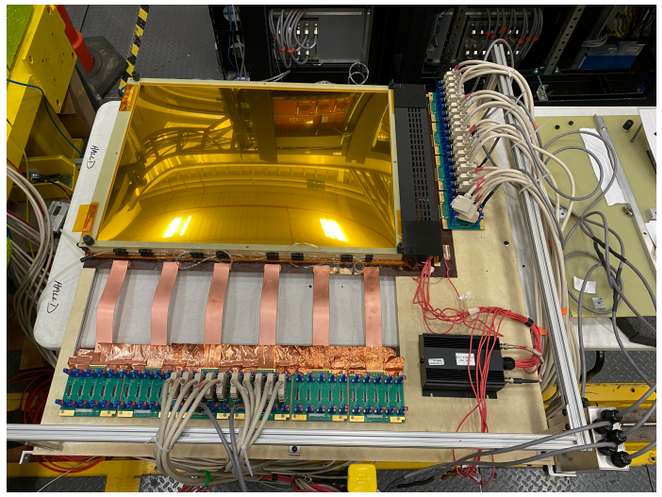
- **GlueX-III (this proposal):** 200 PAC days at *12 GeV* with 600 nA

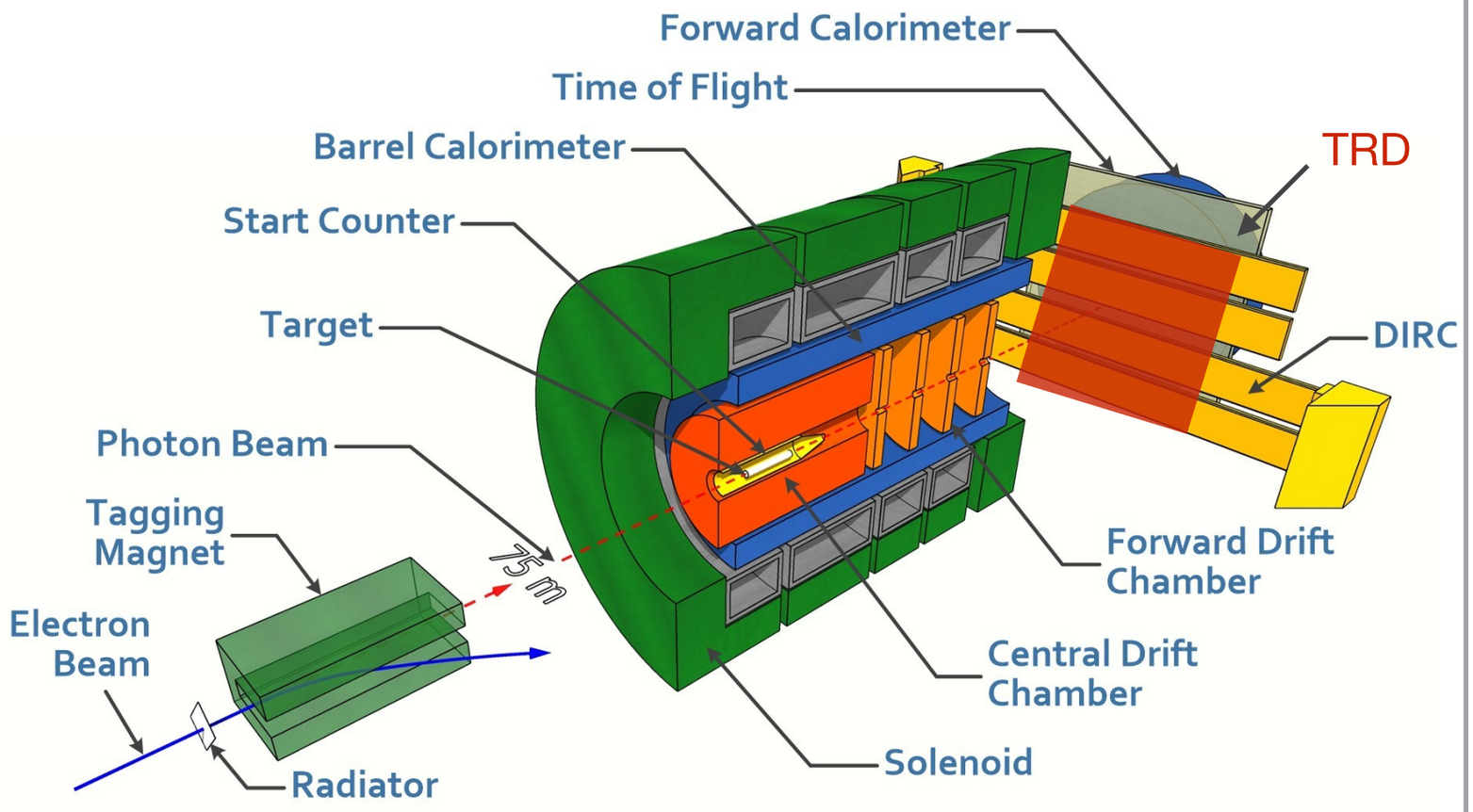
- Proof of principle data in 2023 to demonstrate performance of existing detectors



GlueX III

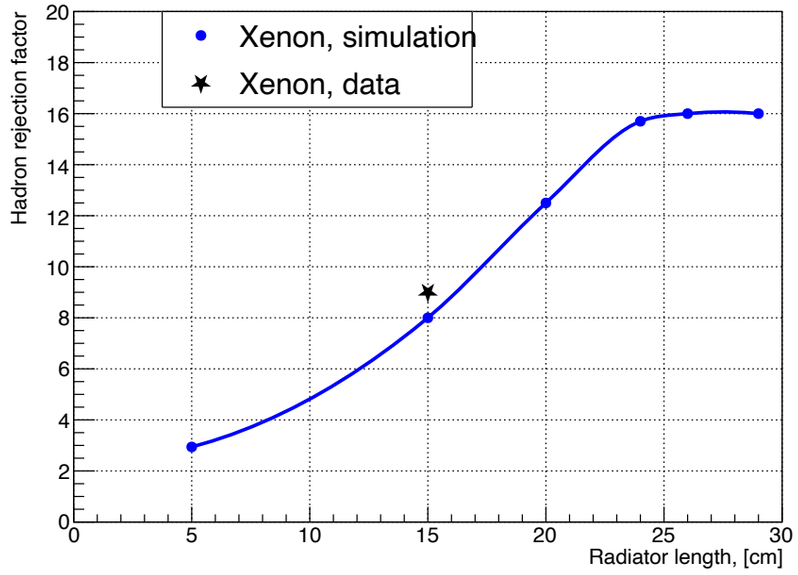
TRD 1/4 scale prototype



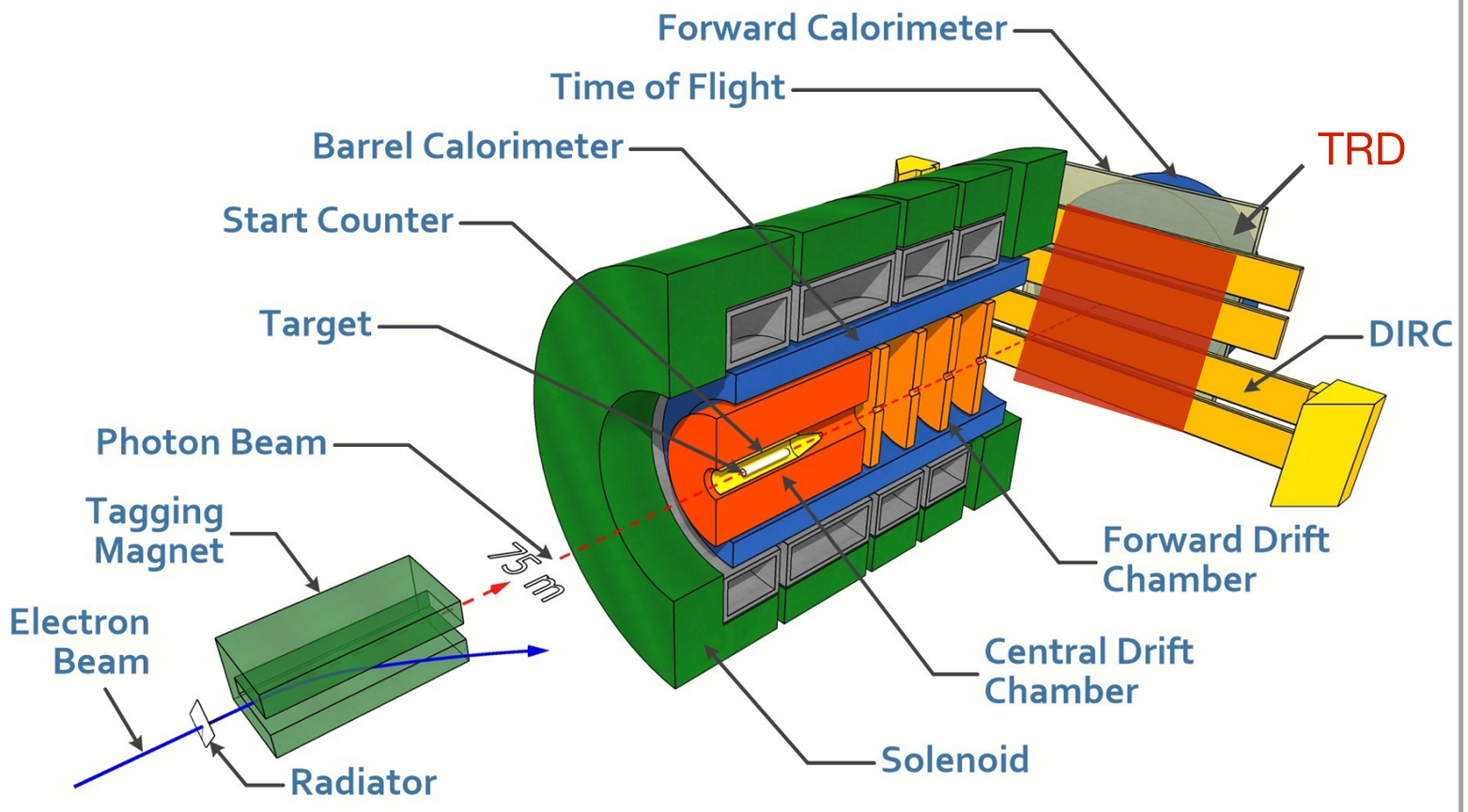


- **GlueX-III (this proposal):** 200 PAC days at *12 GeV* with 600 nA
- Proof of principle data in 2023 to demonstrate performance of existing detectors
- Transition Radiation Detector (TRD): provides factor ~10 $\pi^{\pm}$ suppression at 90% $e^{\pm}$ efficiency

TRD prototype performance



GlueX III



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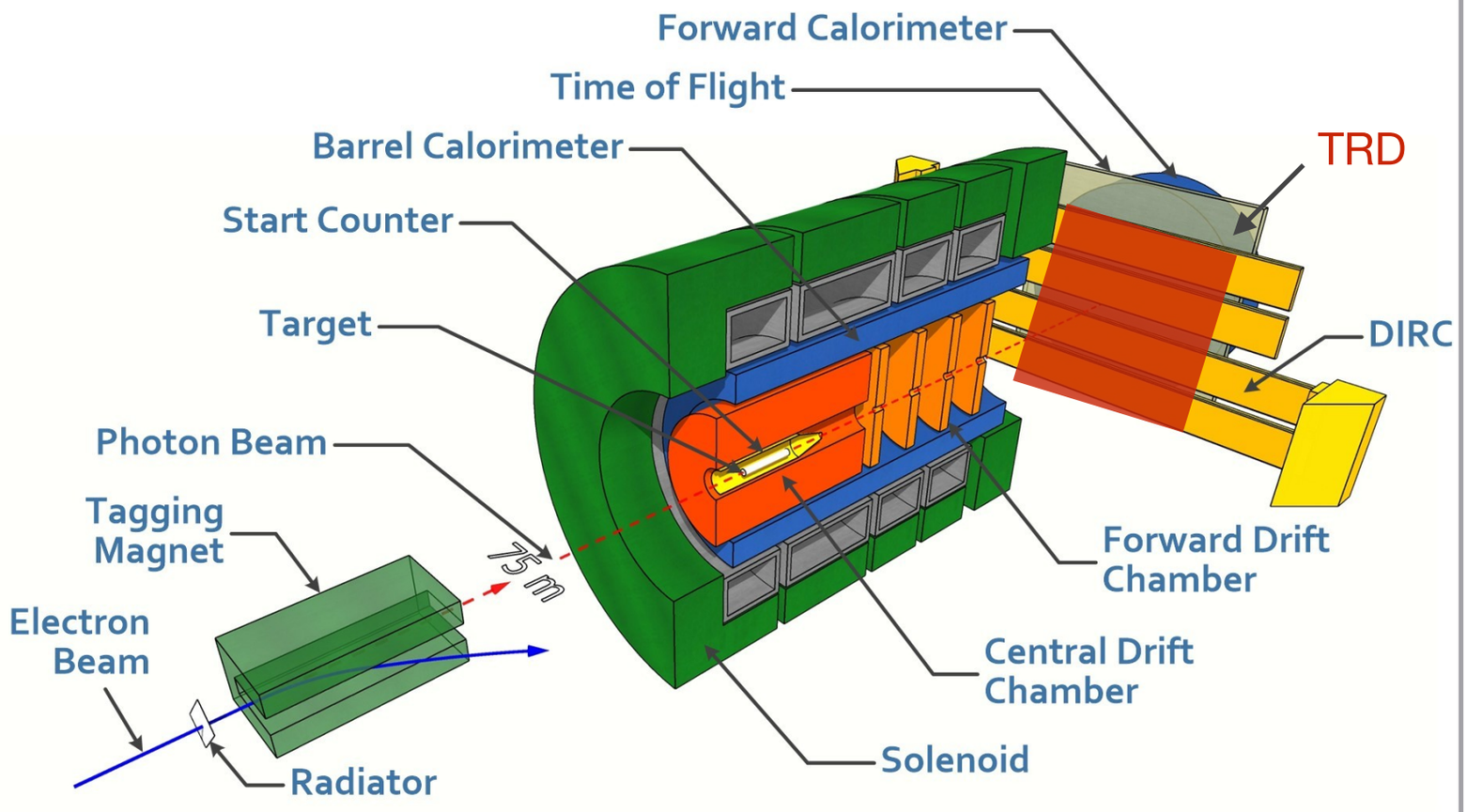
GlueX III



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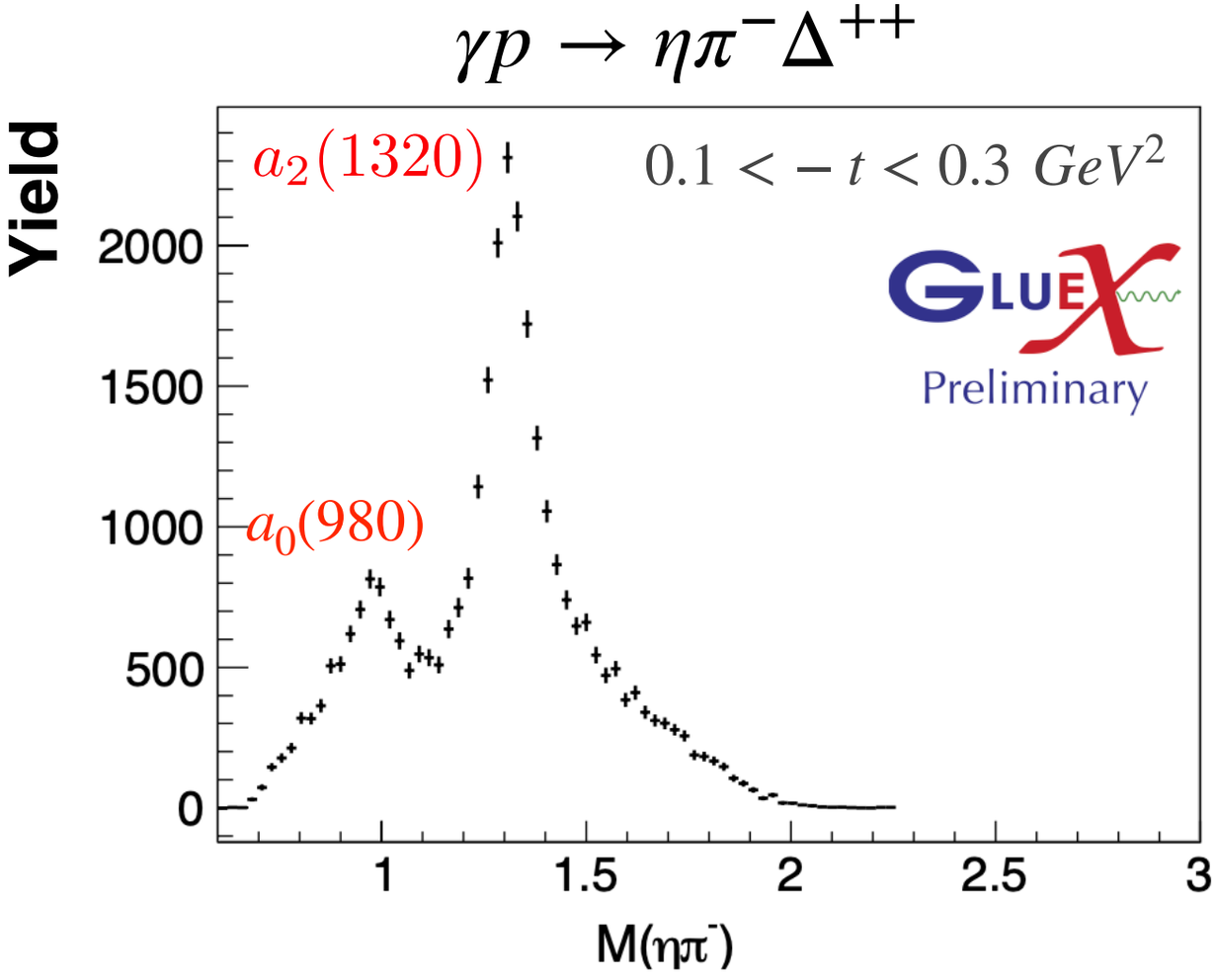
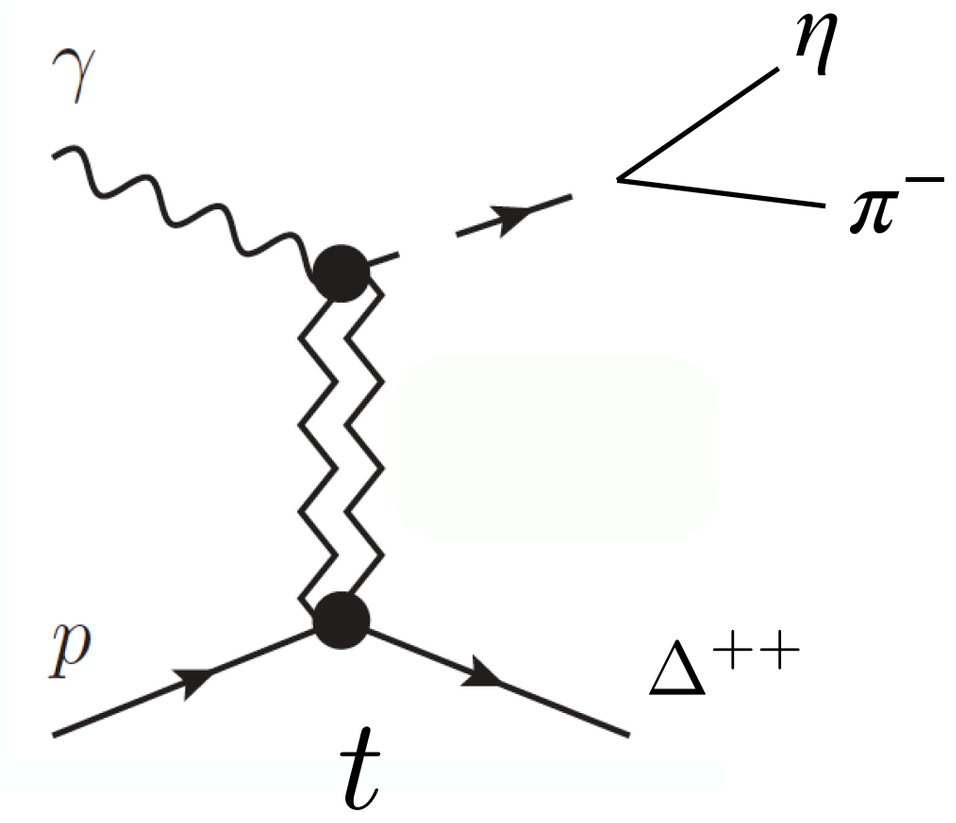
+ Extending hybrid meson spectroscopy

Status of meson spectroscopy: $\eta^{(\prime)}\pi$ example

- Broad overlapping resonances requires amplitude analysis, described by production and decay angles
- Polarized photon beam provides new information on production mechanism





$\eta\pi$ spectroscopy at GlueX

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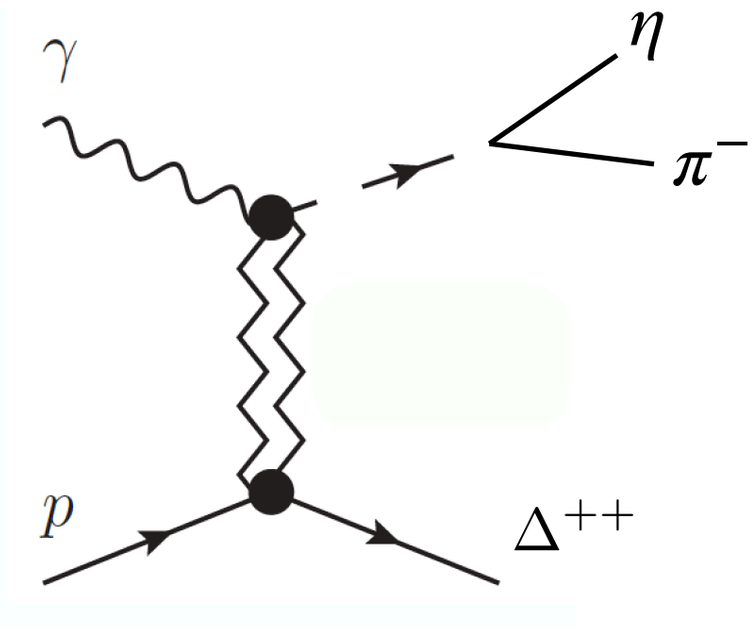

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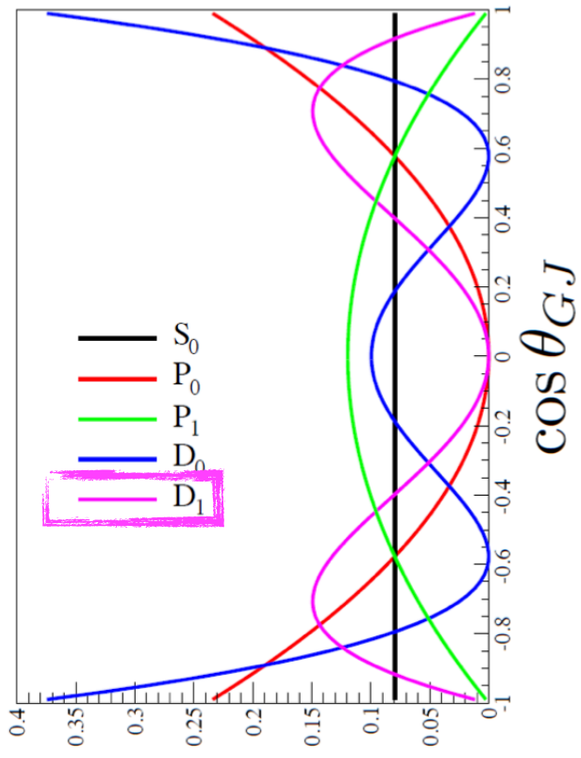

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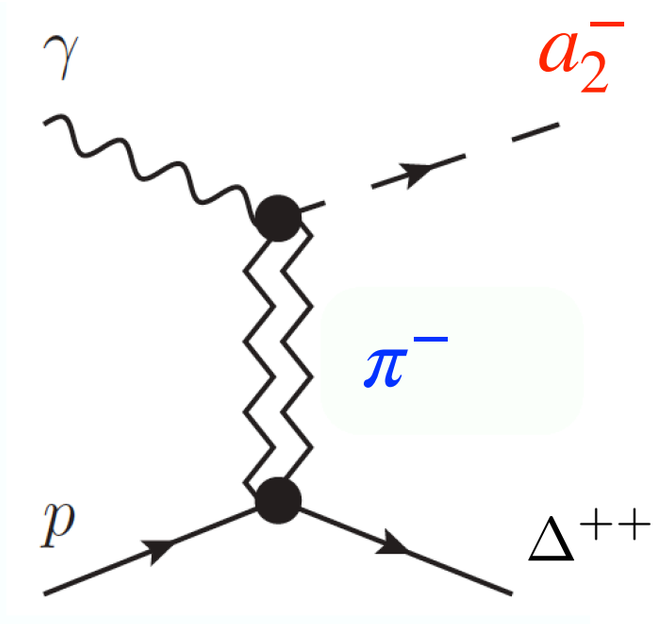
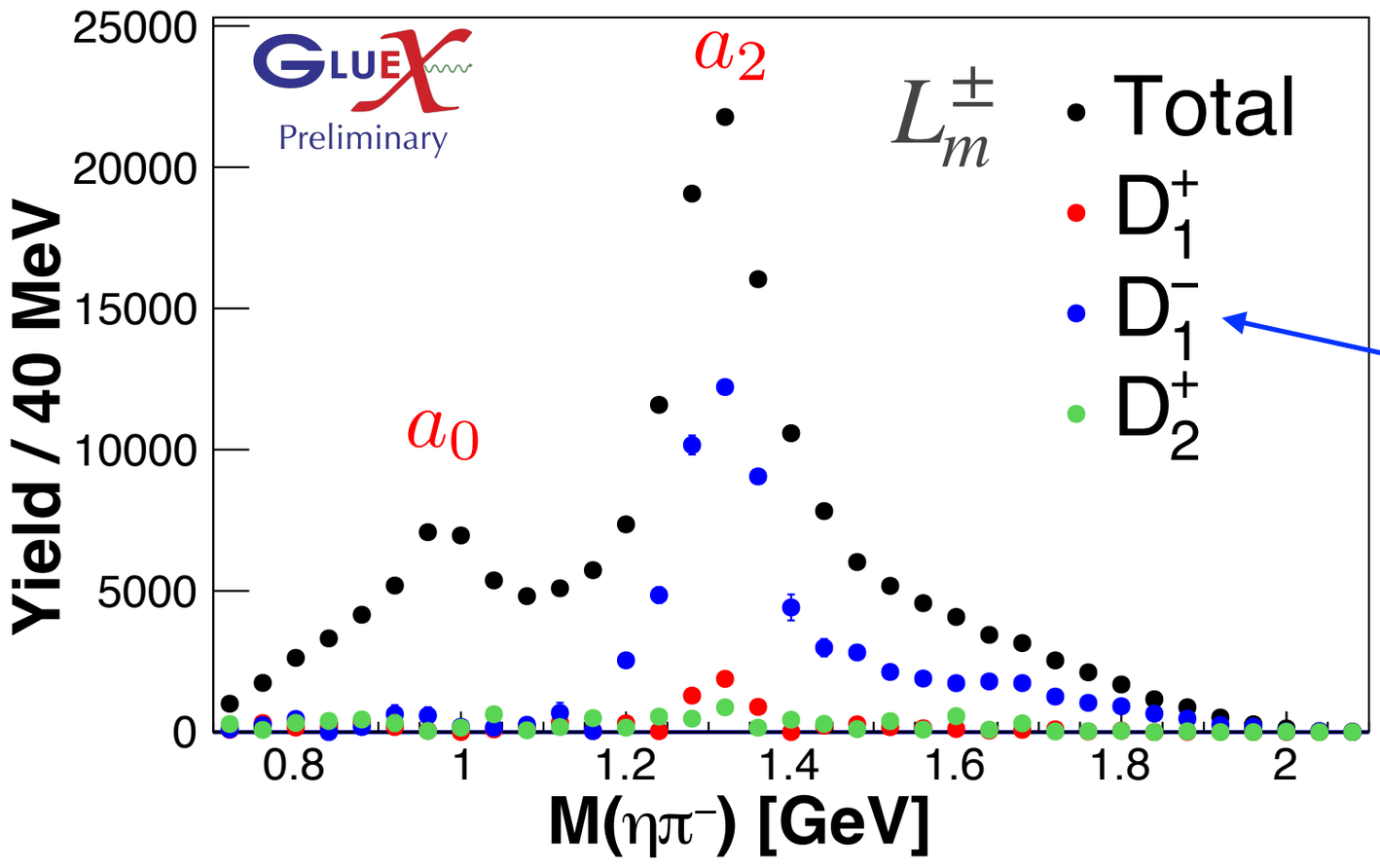




- Understanding production mechanism for conventional mesons, *e.g.* a_2^- through unnatural (π) exchange

Status of exotic π_1 search with GlueX-I

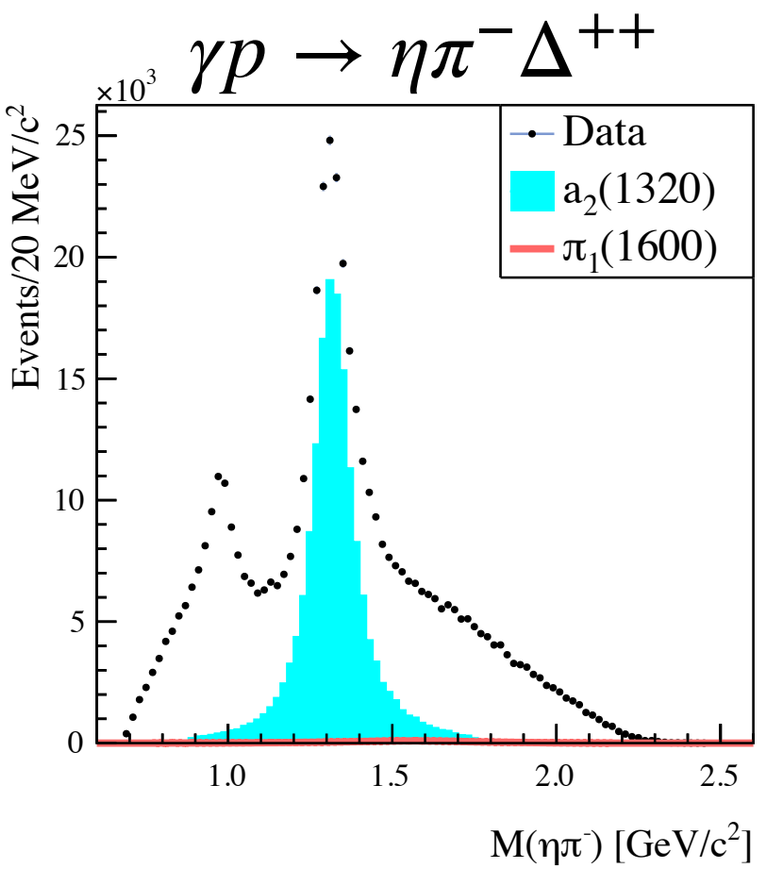
- Recent Lattice QCD prediction for $\pi_1(1600)$ decay widths allowed us to set the first upper limit on exotic photoproduction

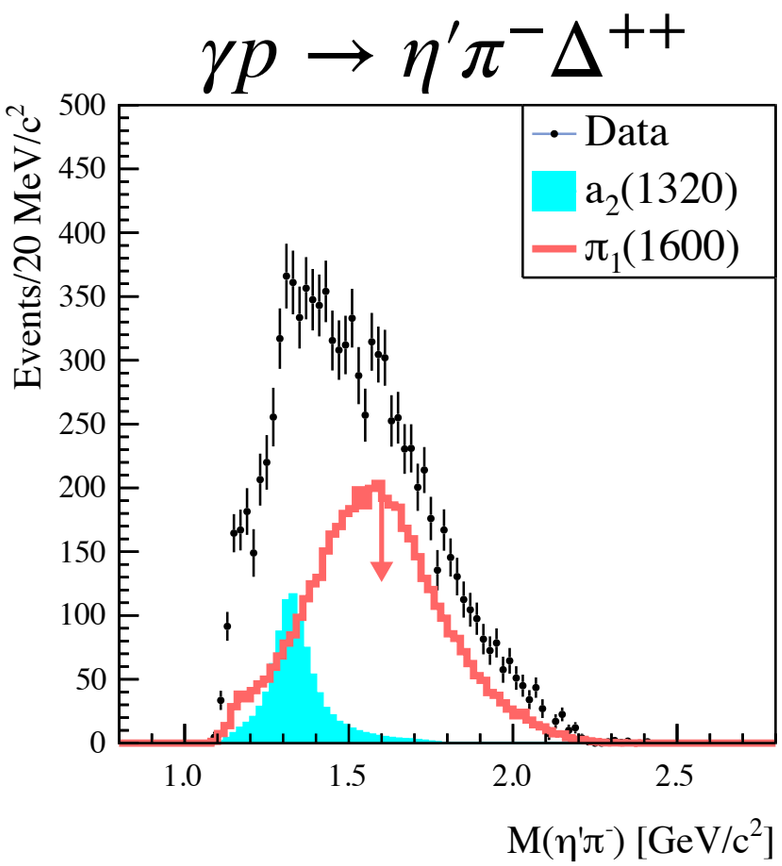
An Upper Limit on the Photoproduction Cross Section of the Spin-Exotic $\pi_1(1600)$

arXiv:2407.03316
Submitted to PRL

- Project upper limits onto $\pi_1(1600)$ decay modes for observation in pion production: $\eta\pi$ and $\eta'\pi$

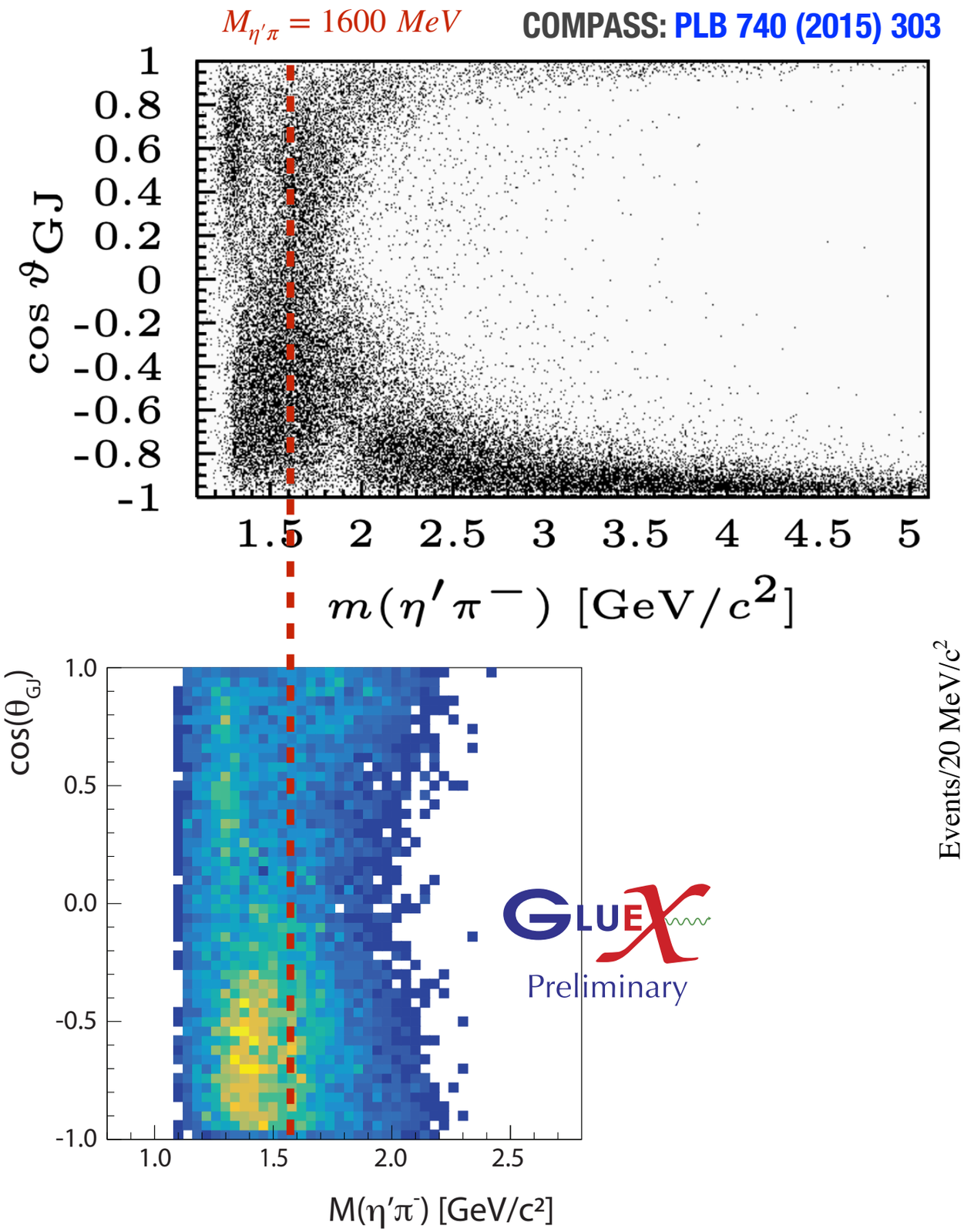
Large π_1 excluded from $\eta\pi$



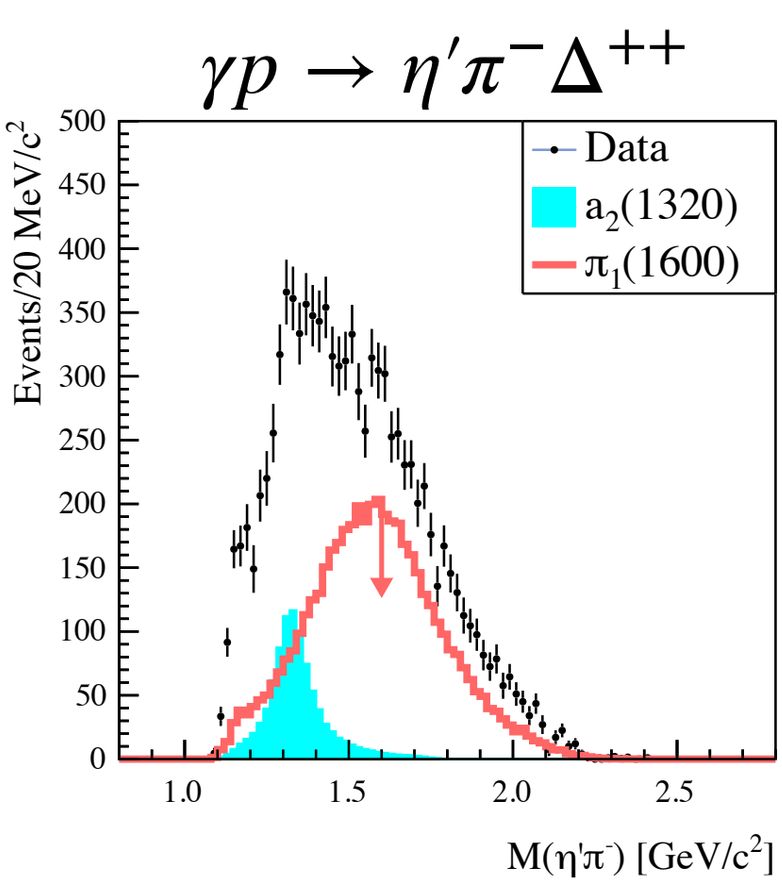


π_1 could be significant relative to a_2

Prospects for $\pi_1 \rightarrow \eta^{(\prime)}\pi$ with GlueX-I



- Promising $\eta'\pi^-$ channel with similar forward/backward asymmetry to COMPASS
- Potential for interference between odd (π_1 P-wave) and even (a_2 D-wave) partial waves

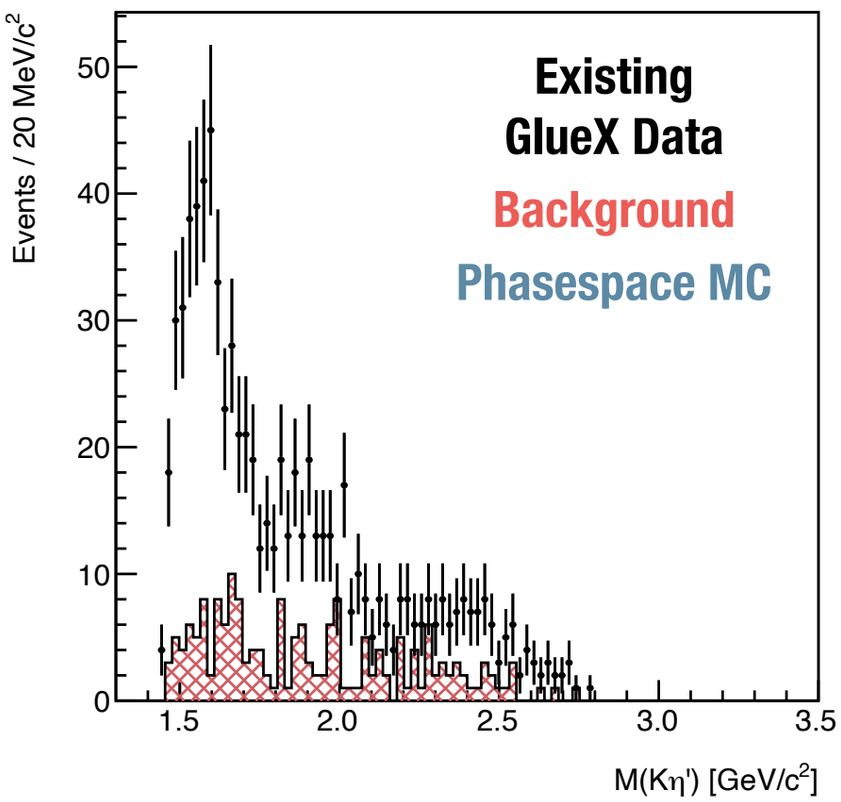


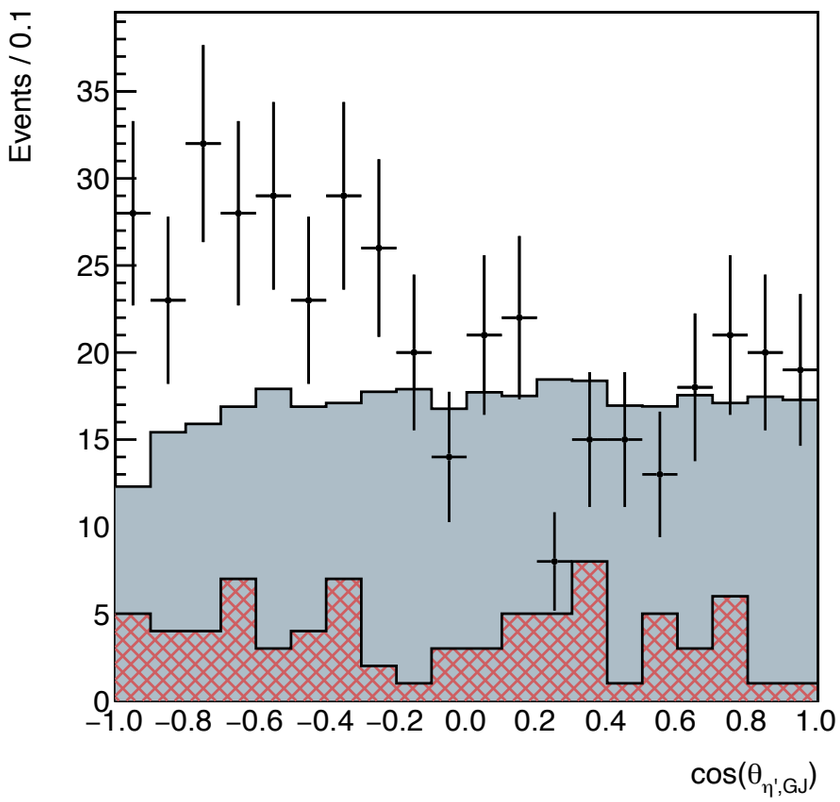
π_1 could be significant relative to a_2

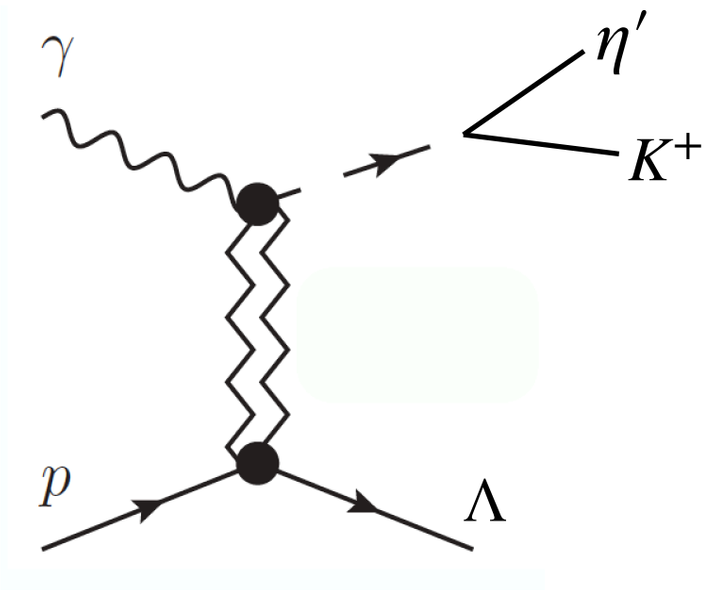
arXiv:2407.03316
Submitted to PRL

Extending hybrid program with GlueX-III

- Many studies will still be statistics-limited after GlueX I+II are completed, focus on rare production or decay
  - Establish the π_1 and its production mechanism, with unique sensitivity to photocouplings
  - Search for exotic hybrid nonet, including $\eta_1^{(\prime)} \to \eta'\eta$ candidate observed at BESIII and hybrid kaon partners







Summary

- The GlueX experiment has acquired an unprecedented polarized photoproduction dataset and the meson spectroscopy program is well underway

- Broad interest in threshold $c\bar{c}$ production for both spectroscopy and structure, but more data needed on production mechanism for interpretation

- GlueX-III provides unique sensitivity to understanding the J/ψ production mechanism and the only opportunity to study χ_{cJ} and $\psi(2S)$ at JLab with 12 GeV

- Extension of light hadron spectroscopy in parallel with $c\bar{c}$ program utilizes same well-developed infrastructure

GlueX acknowledgements: gluex.org/thanks

Backup

Summary of $c\bar{c}$ data and projections

Table 1: A summary of the completed and scheduled GlueX-II experiment.

Topic	Proposal Number	Approved	Completed (2020-2023)	Scheduled ~~(2024-2025)~~
GlueX-II with DIRC	E12-12-002	220	102	109
JEF	E12-12-002A	100	0	109
Total Unique	-	220	102	109

2025-2026?

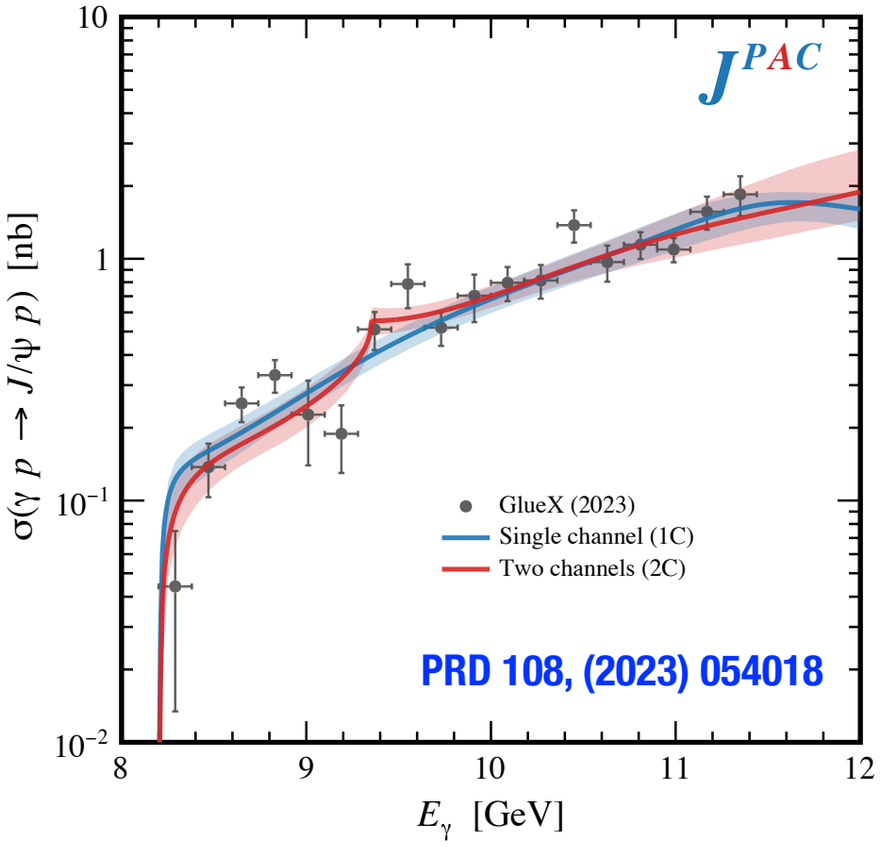
Table 2: J/ψ, χ_{c1}, and $\psi(2S)$ yield estimation based on actual measurements in 2020 and allocated PAC days, scaled by the proposed luminosity increase, also taking into account the electron beam energy increase to the nominal 12 GeV and reduction in the reconstruction efficiency. The 2020 results are preliminary. The 2023 data have not been processed yet and the numbers are estimated based on previous yields. All numbers in italics are projections based on previously collected and analyzed data.

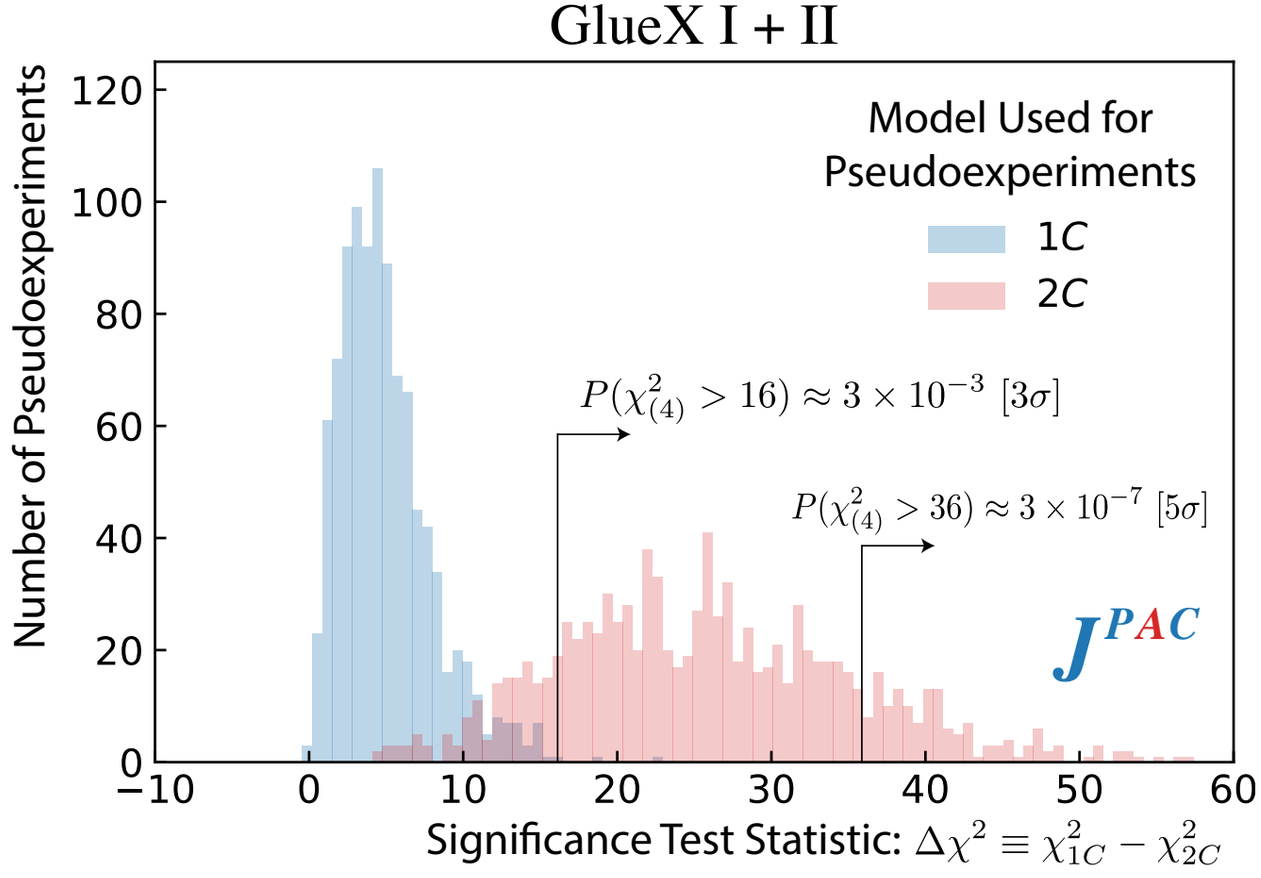
Run Period	PAC Days	J/ψ Yield	In coh. peak	χ_{c1} Yield	$\psi(2S)$ Yield
All Phase I	120	2,180	326	↓	↓
2020 Phase II	67.5	1,780	162	55	12
2023 Phase II	28.1	*741*	*67*	↓	↓
2025-2026? Phase II (planned)	109	*2,874*	*262*	*48*	*11*
This Proposal	200	*11,271*	*1,795*	*364*	*178*
Projected Total		18,846	2,612	467	201

Sensitivity to open charm contribution

- Sensitivity of GlueX I+II+III determined in collaboration with JPAC from pseudodata generated with the 1C and 2C models

- If the new data follows the 2C model, then it will be significantly distinguishable from the 1C model

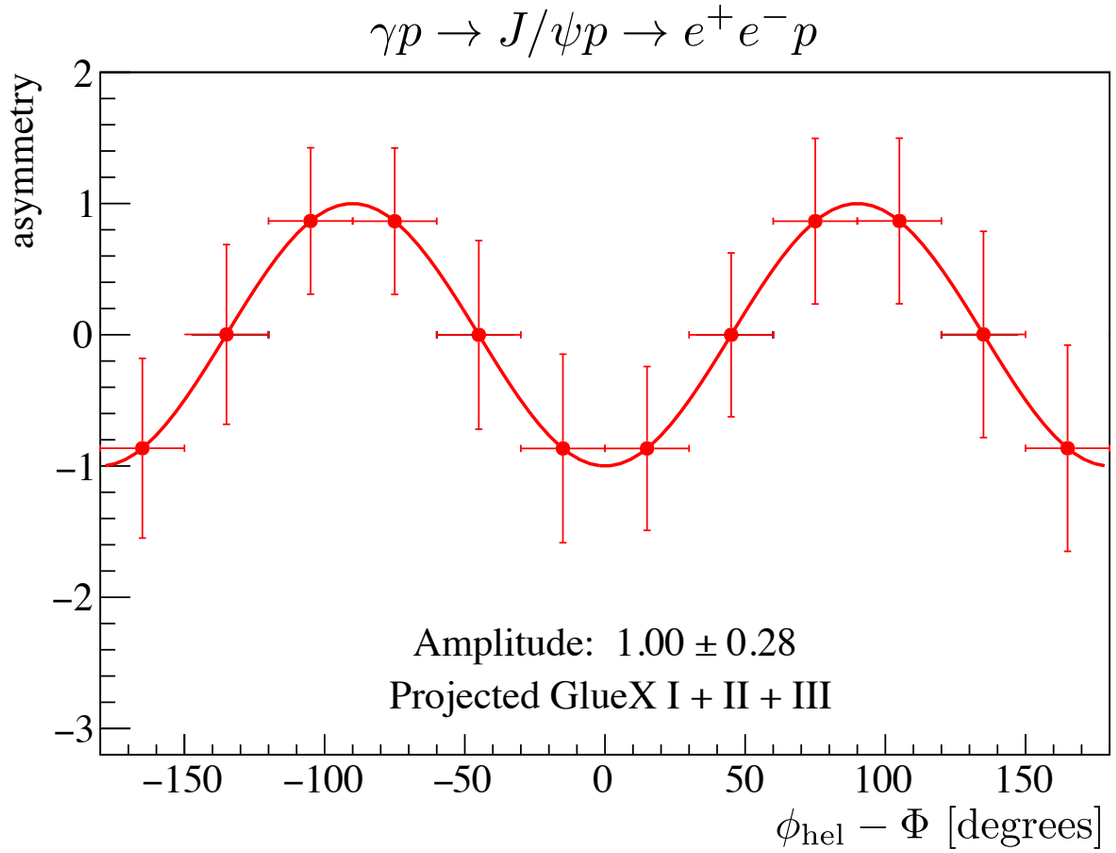




Linearly polarized beam asymmetry

$$A = \frac{2}{P_\gamma} \frac{Y_{J/\psi}(0°) - Y_{J/\psi}(90°)}{Y_{J/\psi}(0°) + Y_{J/\psi}(90°)}$$

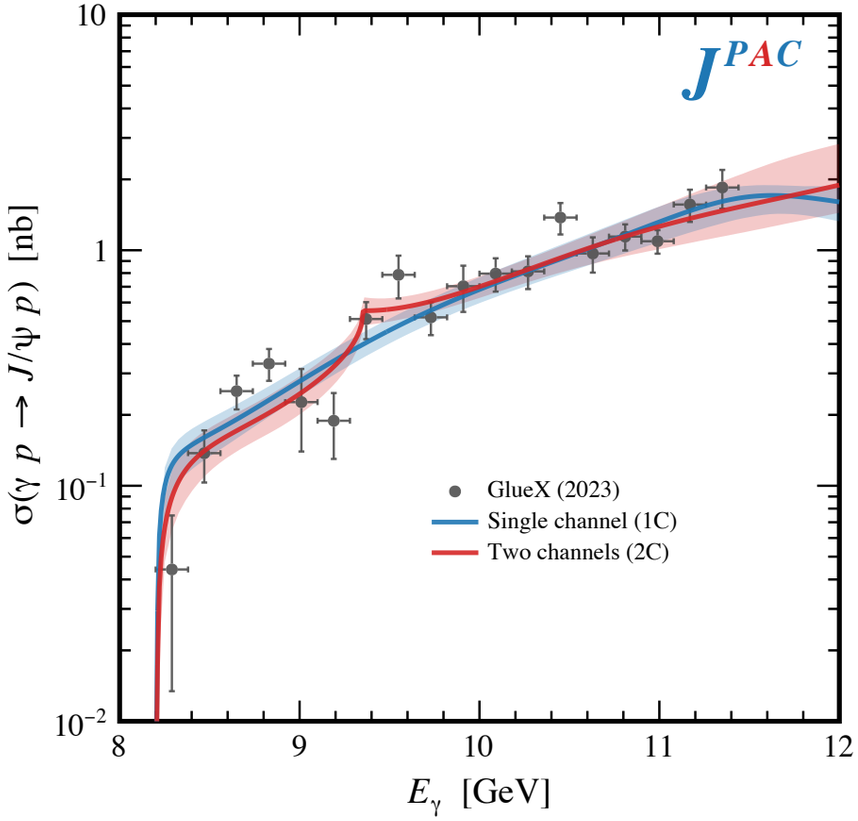
$$A = \Sigma \cos(2(\phi_{hel} - \Phi))$$

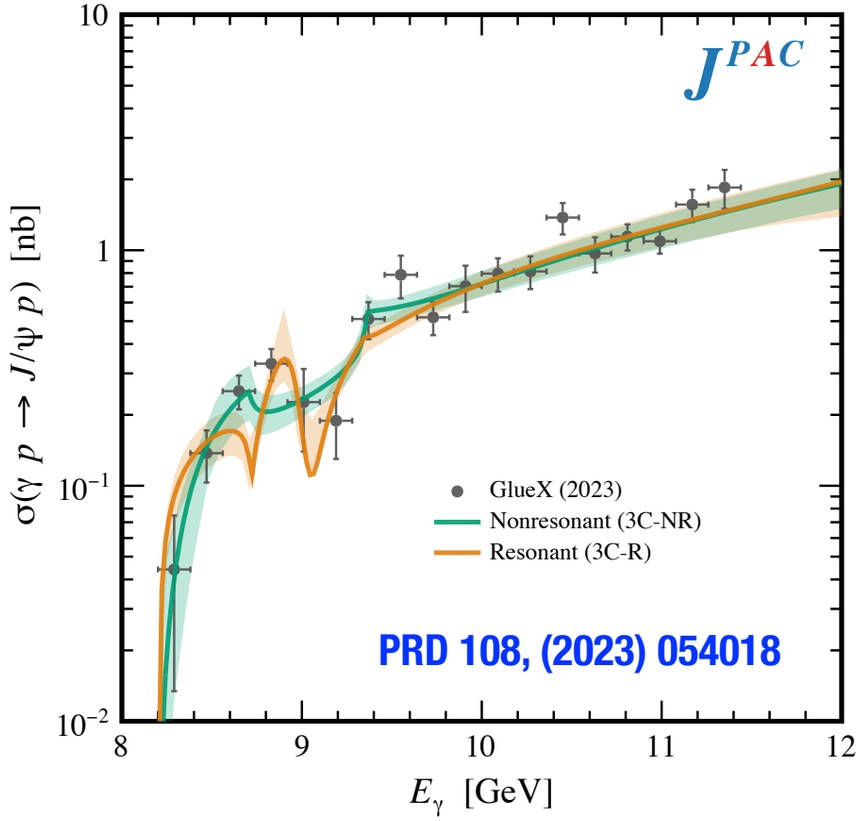


- Σ asymmetry sensitive to exchange naturality:
  +1 = natural (2-gluon) vs -1 = unnatural (3-gluon) exchange

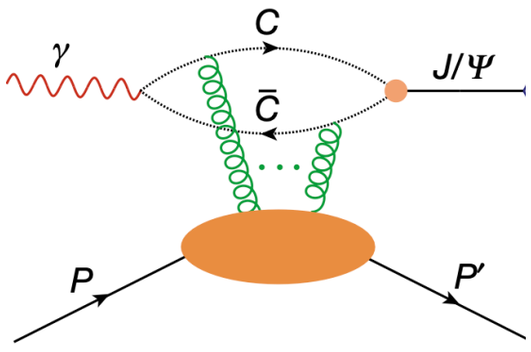
- GlueX-III roughly triples the J/ψ yield in the linearly polarized coherent peak to determine exchange naturality

Interpretation of GlueX-I results

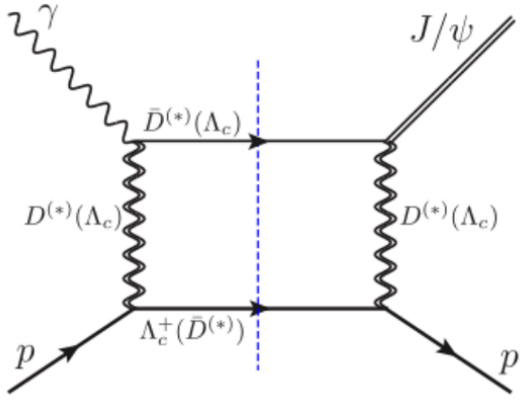




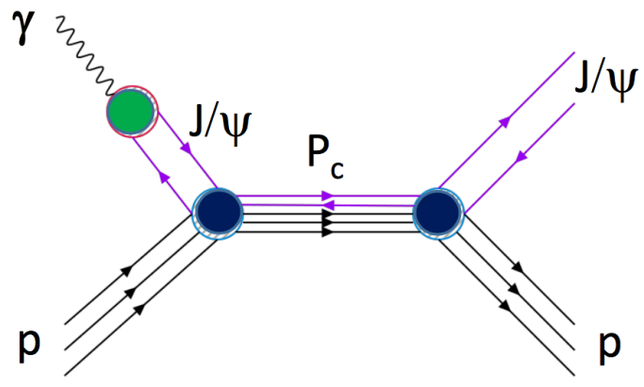
t-channel:
gluon GPDs, mass radius



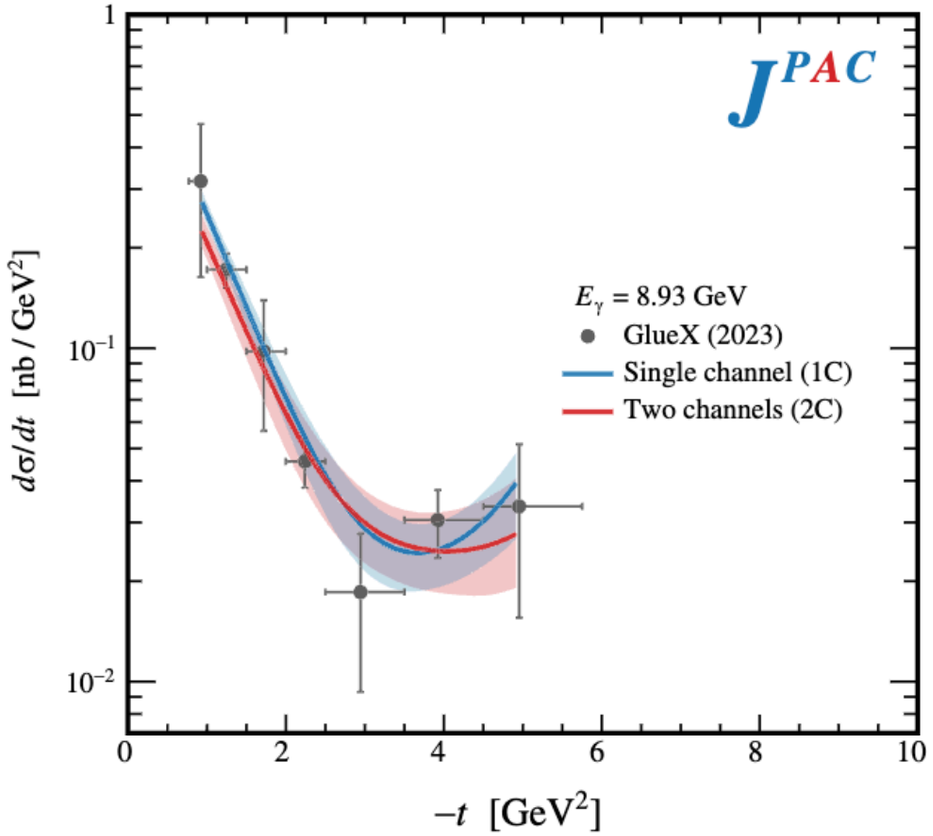
open charm:
$\bar{D}^*\Lambda_C$, $\bar{D}\Lambda_c$

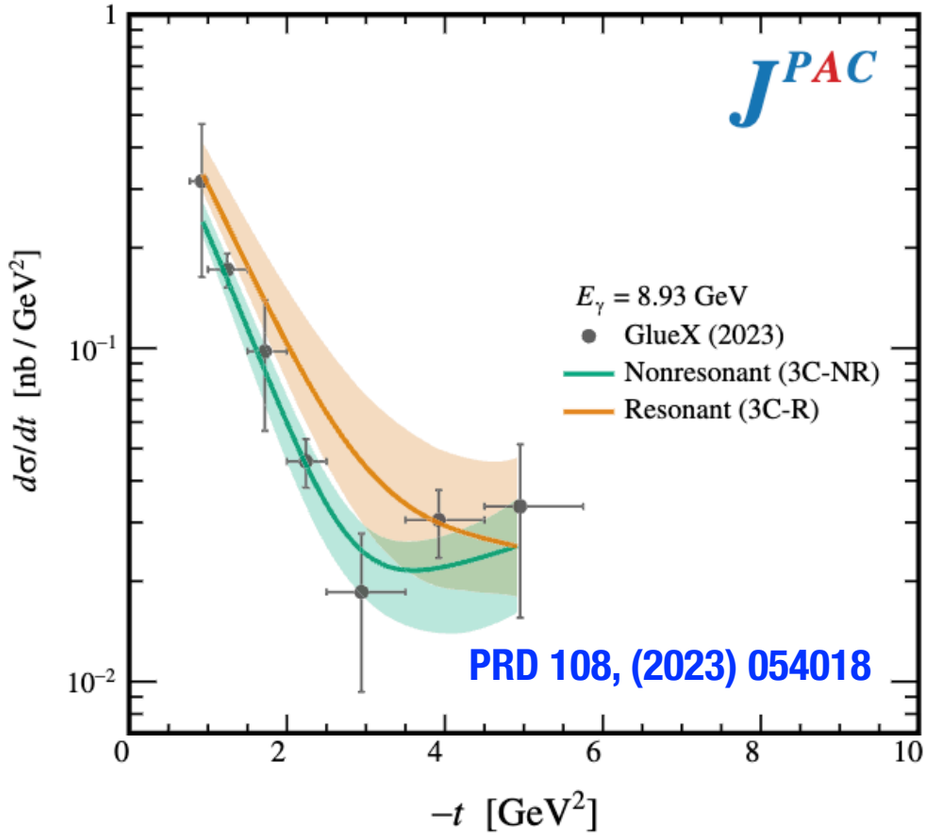


s-channel:
pentaquarks



Interpretation of GlueX-I results





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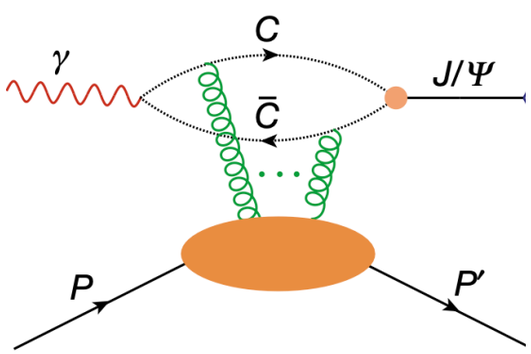
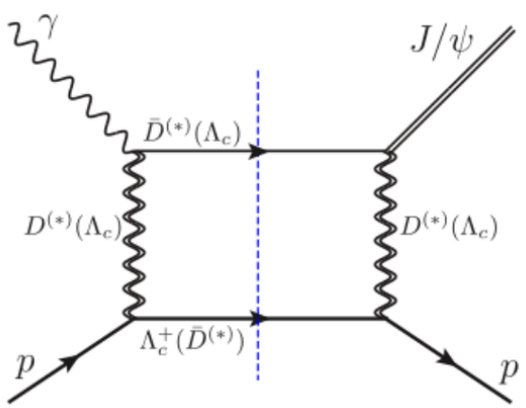
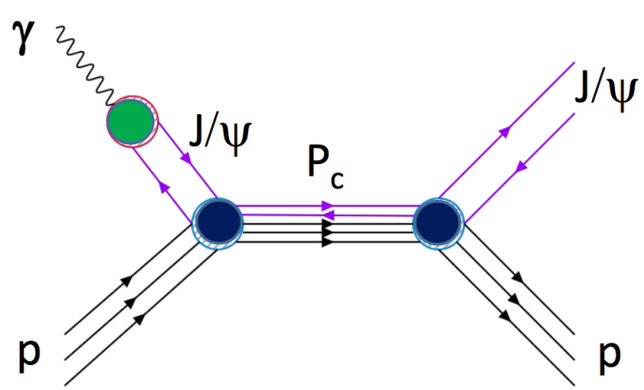


open charm:
$\bar{D}^*\Lambda_C$, $\bar{D}\Lambda_c$

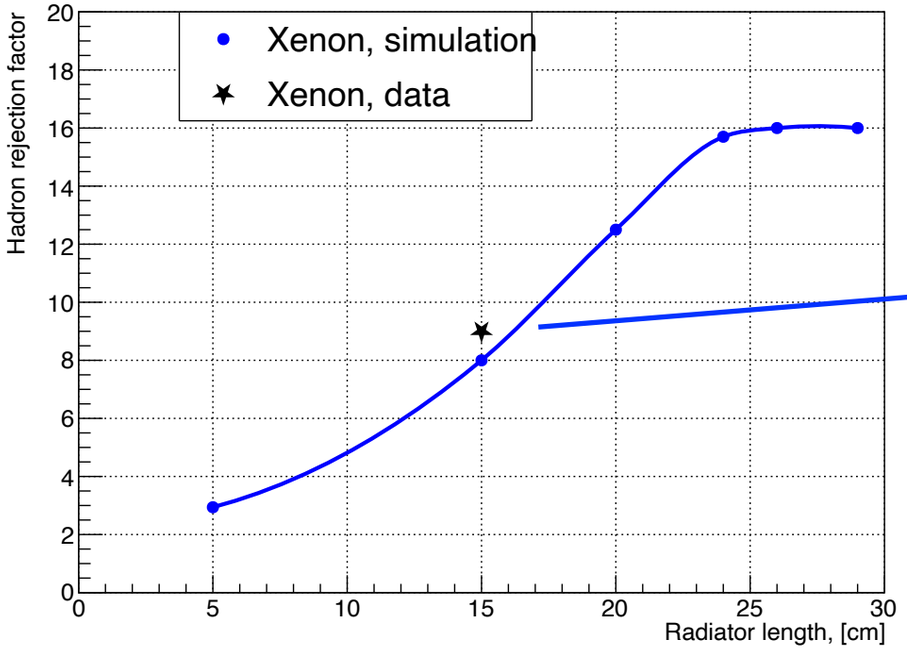


s-channel:
pentaquarks



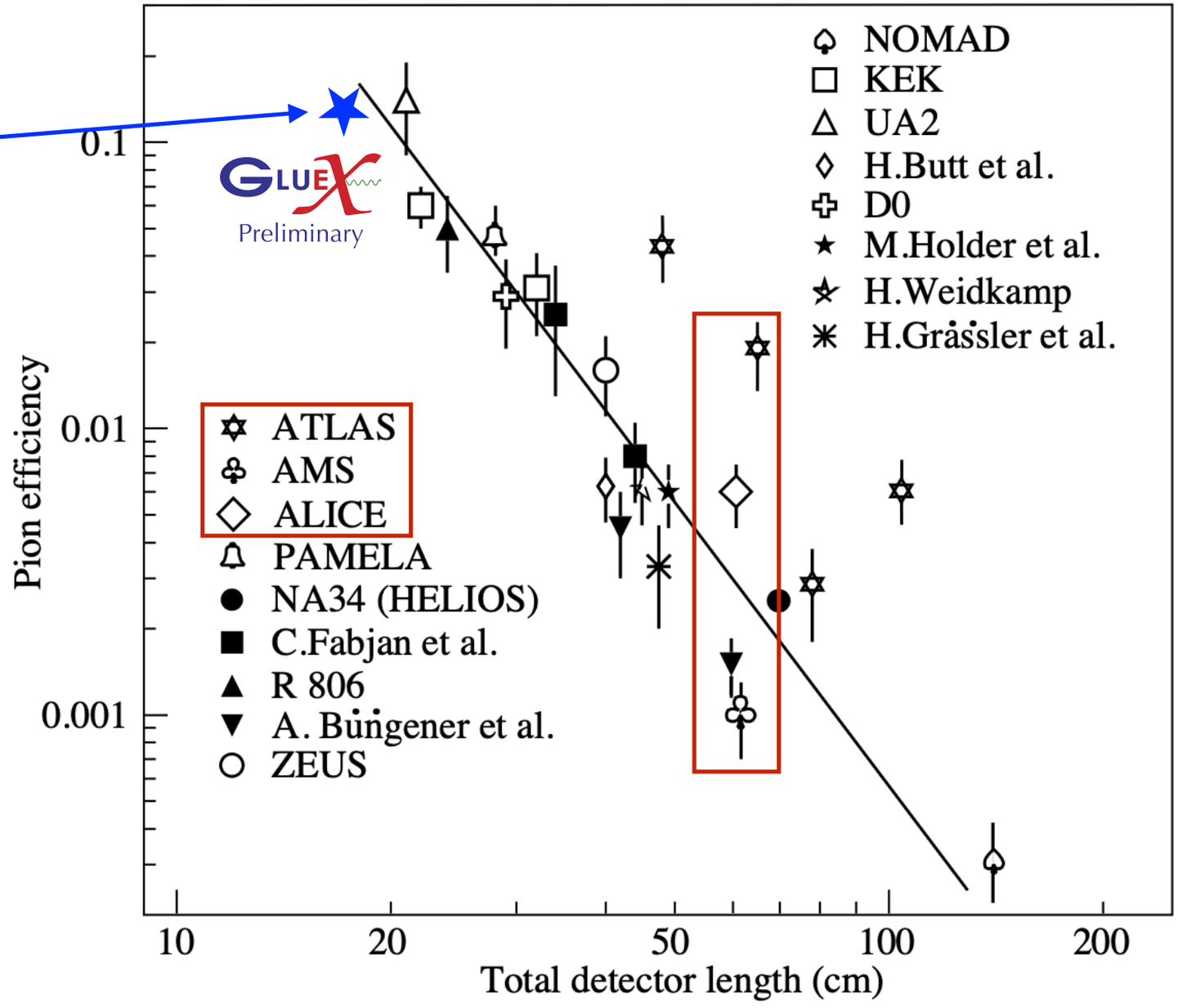
TRD Performance Comparison

TRD prototype performance



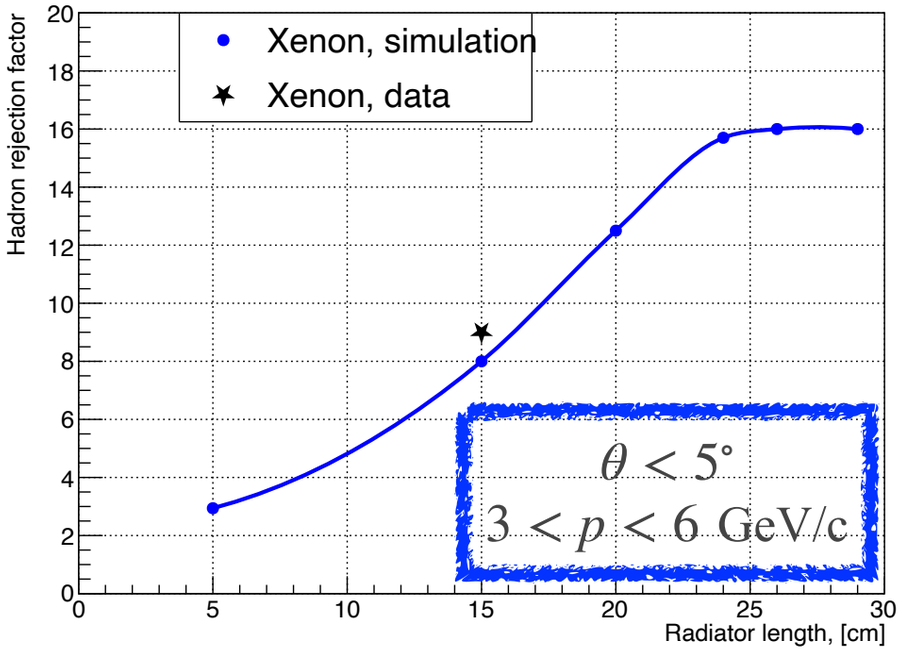
- Prototype achieved performance in-line with simulation and radiator length dependence: factor ~10 $\pi^{\pm}$ rejection at 90% $e^{\pm}$ efficiency
- 15 cm thick radiator chosen to minimize material upstream of calorimeter, while significantly improving di-lepton identification

PDG Particle Detectors at Accelerators
Historical TRD Performance for 90% $e^{\pm}$ effic.

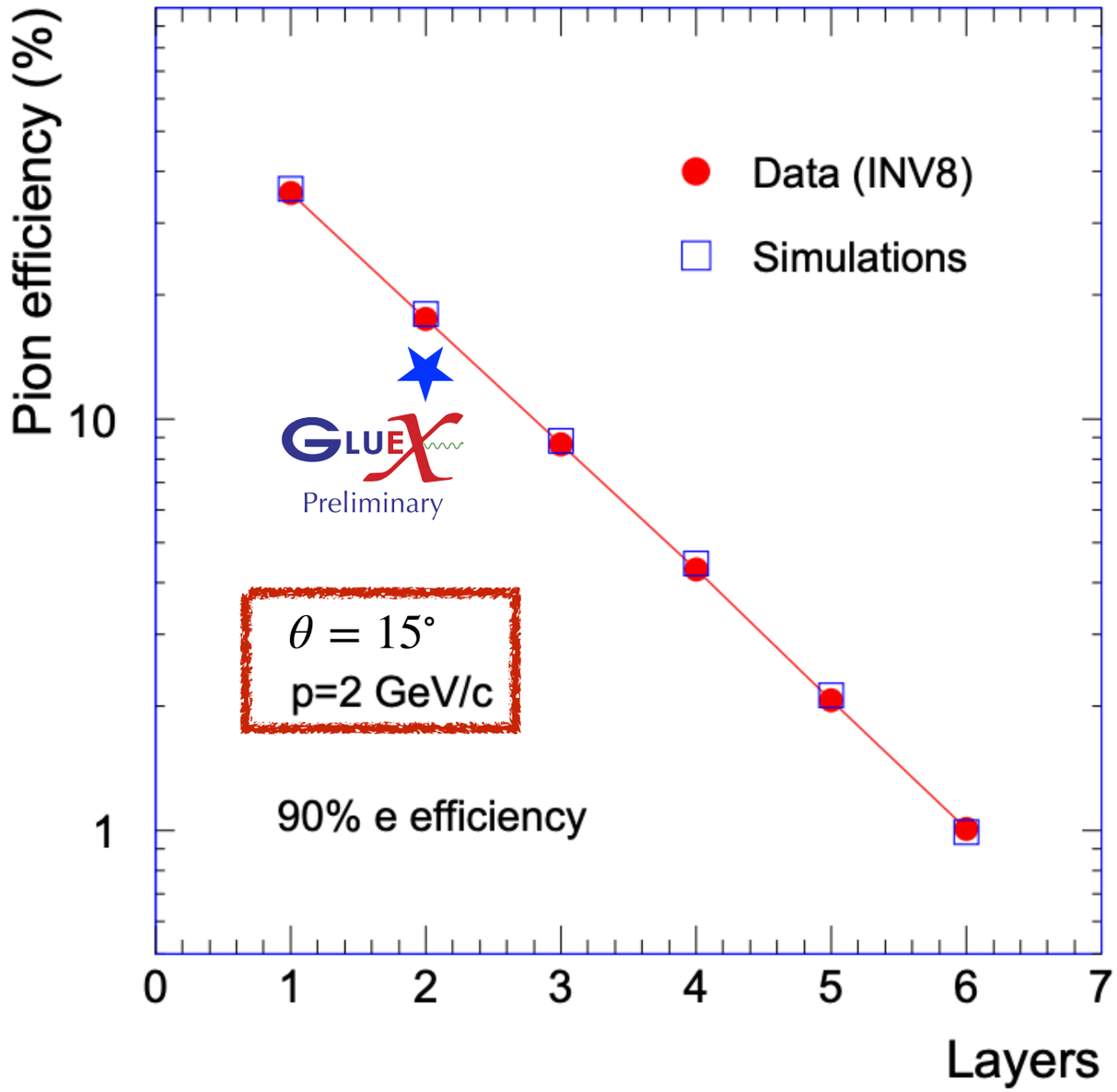


TRD Performance Comparison

TRD prototype performance



ALICE TRD Performance for 90% $e^{\pm}$ effic.
Prototype test: JPG 32 (2006)



- Prototype achieved performance in-line with simulation and radiator length dependence: factor ~10 $\pi^{\pm}$ rejection at 90% $e^{\pm}$ efficiency
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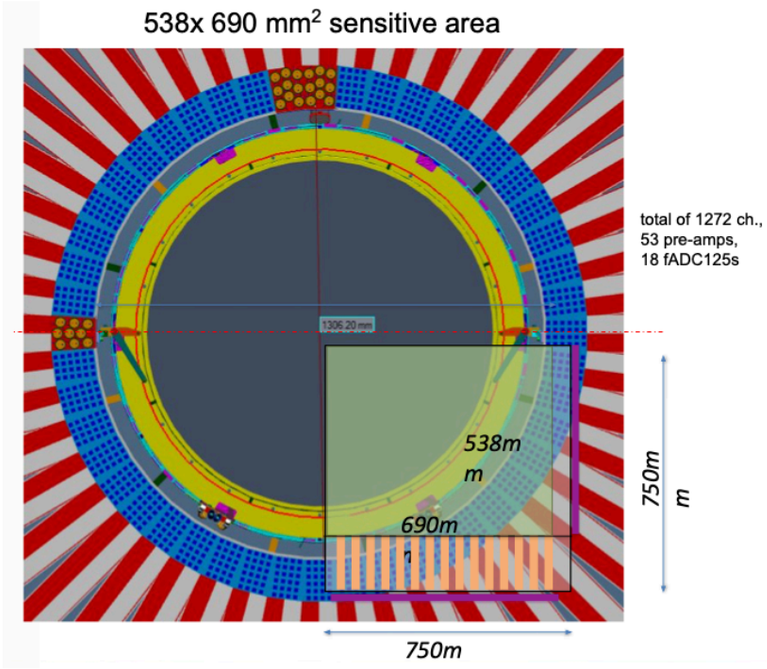
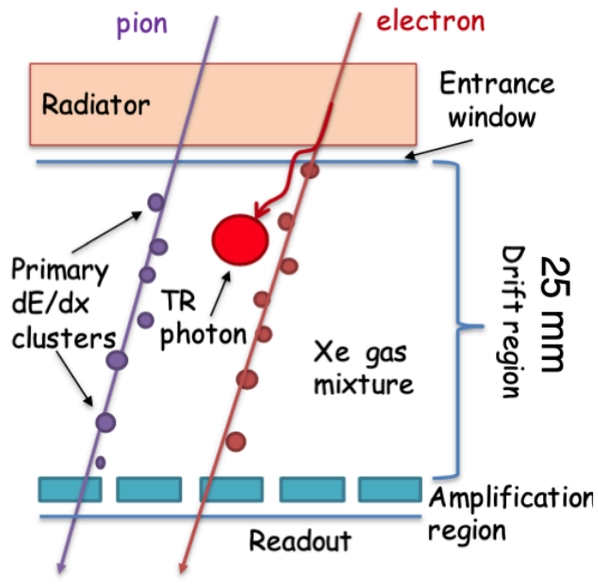
TRD: why GEMs?





- TRD signal with conventional wire-chamber (e.g. ALICE) significantly degraded by spaced-charge for low incident angle tracks
- GlueX TRD covers $\theta < 11^{\circ}$, requiring a GEM chamber to maintain pion rejection
- GEM prototype demonstrated required performance for small incident angles

ALICE TRD: Space-charge Issue
Prototype test: NIM A 525 (2004)

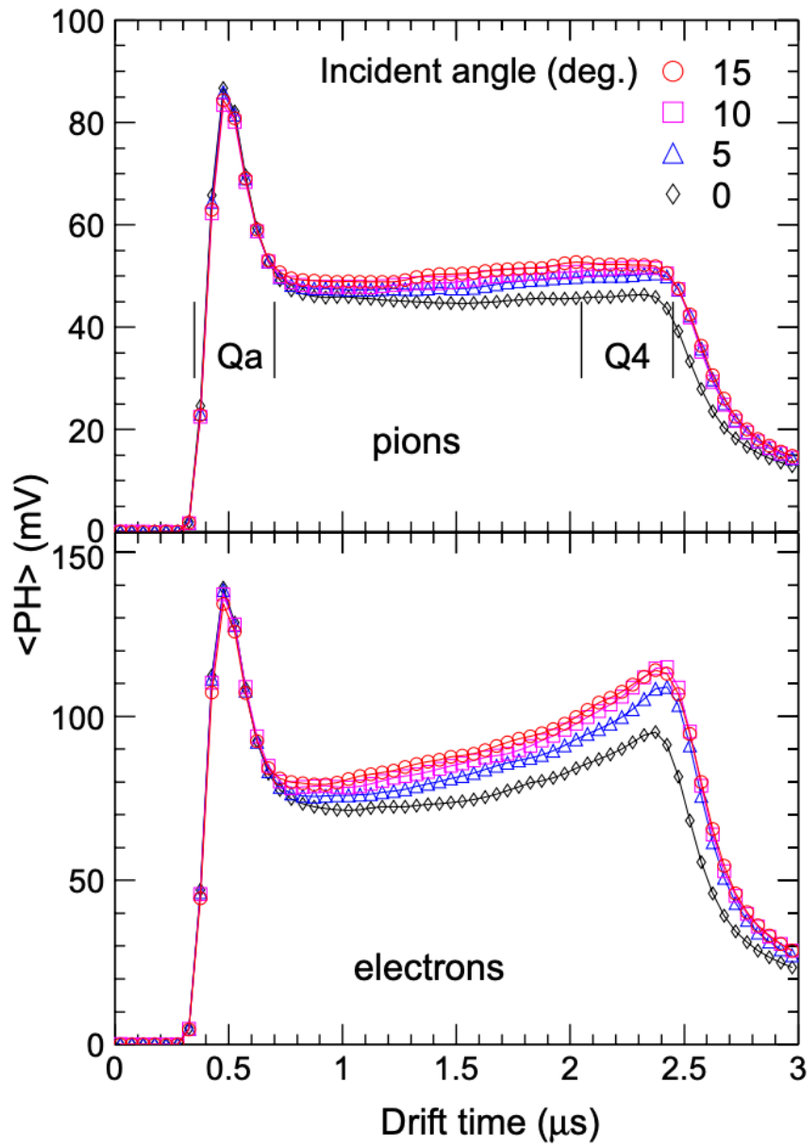


Fig. 3. Average pulse height as a function of drift time, for different incident angles. Upper panel: pions, lower panel: electrons. The gas gain used for these measurements was 3900.

Questions from PAC readers

Q1: Can you please give details on the schedule for the full detector production. We would like to see the final results of the small detector test and understand when and how the full detector will be realized. Is this "minimal configuration" enough?

The small prototype detectors (10x10 cm^2) have been tested with electrons in the Pair Spectrometer and downstream of the GlueX solenoid in Hall D during separate run periods. They were exposed to electrons and pions, respectively, in these two configurations (see the answer to question 4). We have started testing the large-scale (¼ of the full detector) prototype (see the next answer). All the estimations in the proposal assume using this ¼ scale prototype.

Once the performance of the ¼ scale prototype is evaluated (expected by spring of 2025) we plan to start the production of the full detector, taking into account possible modifications and improvements. Detailed schedule includes:

- Design of the full detector - April-June 2025
- Procurement of long-term items (GEM foils and readout boards from CERN) - June 2025
- Design of the tools needed for the production - July-August 2025
- Production of all the frames and tools needed for the production - September-December 2025
- Assembling of the detector and performing initial tests step-by-step during the assembly - January-May 2026
- Final tests of the assembled detector (HV tests, gas tightness, cosmics tests) June-July 2026
- Delivery of the detector and installation in Hall D - August-November 2026
- December 2026 - ready for commissioning

Based on the experience with the production of the ¼ scale prototype and other large GEM detectors,the full detector can be manufactured in less than two years.

The ¼ scale prototype can be used with existing electronics, however using the spare flash ADC125 modules. In parallel we are working towards implementing new readout electronics, based on the OpenVPX system (designed and tested at Juelich Forschungszentrum). The new electronics needed for the full detector is expected to be ready by the end of 2025, while we will have the first prototypes in the coming months this year. We are also working on building a recirculating gas system. An initial prototype of the system has been built and we plan to evaluate its performance together with experts from the ATLAS TRT detector. Finally, during the tests of the large-scale prototype, we evaluated the quality of the radiator material used at HERMES (that we have on-site) in producing transition radiation, and found it compatible with the best radiators we have used so far.

Questions from PAC readers

Q2: Is it worthwhile to pursue any measurements before the TRD is fully implemented into GLUEX?

The large-scale prototype (¼ of the full detector) has been tested recently in the Hall D Pair Spectrometer arm but using Krypton instead of Xenon. Even so, the response of the detector with/without radiator was similar to the results with the small prototypes filled with Xenon. We plan to perform tests of the large-scale prototype downstream of the solenoid in the coming run.

The answer to the question is “yes” – the projections in the proposal are based on having only this ¼ scale prototype installed. Therefore the proposed program can begin with this version of the TRD and transition to the full detector when it becomes available. (Some measurements, like the chi_cJ cross sections, have unique kinematics that can be used to suppress background and do not require the TRD.)

Q3: What is the output of the Carnegie Mellon University internal review committee?

We assume this refers to the internal review committee that was appointed by the Collaboration Board Chair, Naomi Jarvis from Carnegie Mellon. The members of that committee were Garth Huber (U. Regina), Werner Boeglin (Florida International U.), and Beijiang Liu (Institute for HEP in Beijing). We will provide a PDF with the concluding report of the internal review committee that was communicated to the GlueX Collaboration. We would like to note that the report and the proposal you have comes at the end of the review process. There was significant discussion and some revision of the proposal through the internal review.

Finally, the GlueX Collaboration voted positively to endorse the proposal, which was communicated to the PAC in a letter from Matt Shepherd on behalf of the Collaboration.

(The committee report is in the Document Database here.)

Questions from PAC readers

Q4: When talking about the TRD, the separation of e/pi should be better quantified.

From the studies with small prototypes, exposed to electrons and pions in separate runs, we found a pion suppression factor of 10 at 90% electron detection efficiency. MC simulation of the transition radiation in the radiator and absorption in the Xenon gas gives very similar results. Tests with mixed electron/pion beams have been performed at Fermilab, however the quality of the beam didn't allow to extract pure enough samples of electrons and pions.

Q5: Why are you talking about to "run concurrently" when the other mentioned proposals are just LoIs?

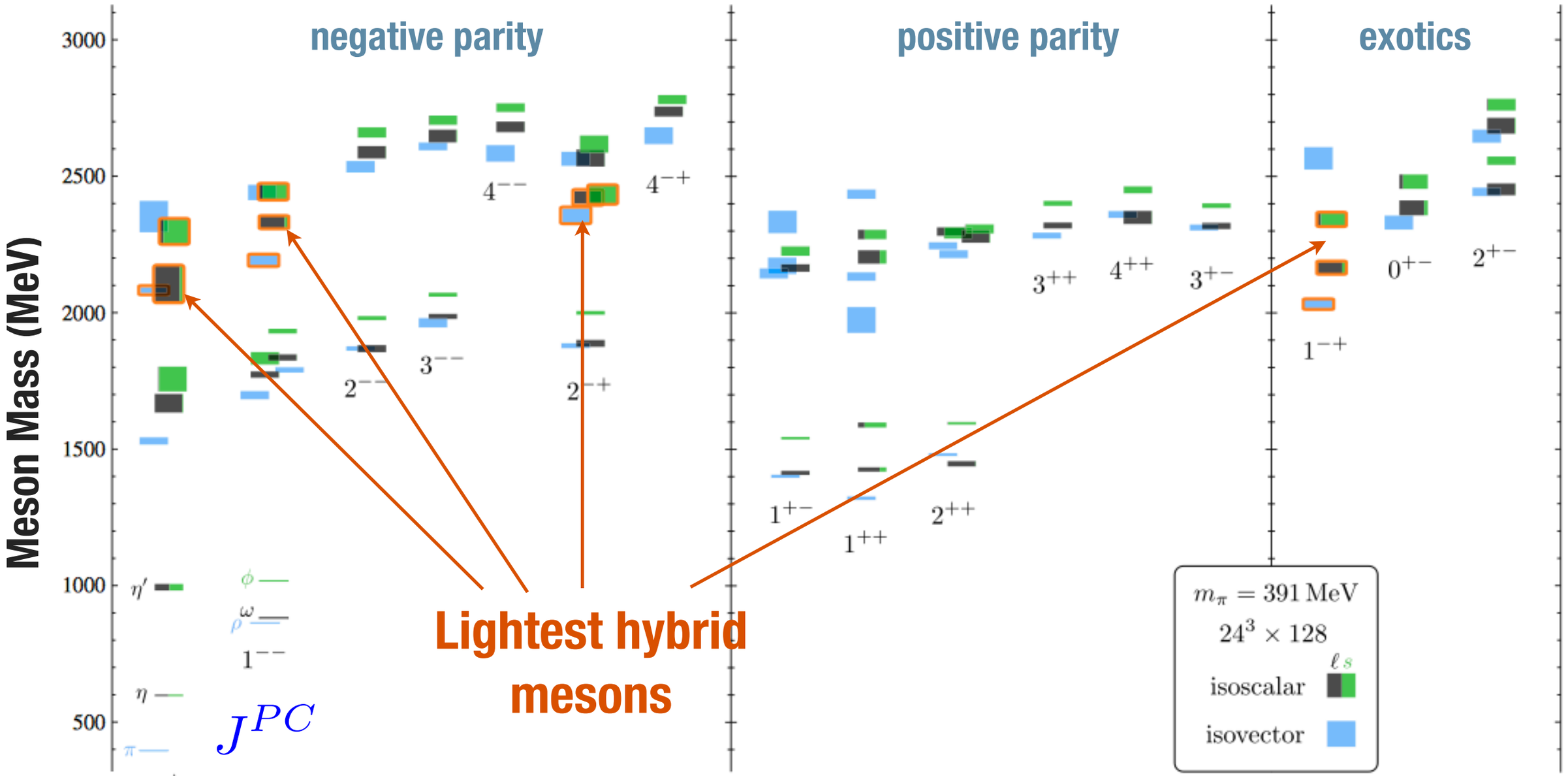
We submitted two separate LoI's to PAC 51 last year. One LoI was focused on the development of the TRD and the second LoI was focused on a broad program of running GlueX at high intensity. The PAC 51 report comments for both LOI-12-23-007 and LOI12-23-010 had the suggestion: "It could be helpful if the programs described here were able to run concurrently with the one described in…" the other LOI. Hence we have combined them into the proposal that you are reviewing now.

Q6: Fig. 1: Are you really suggesting to be able to disentangle the curves?

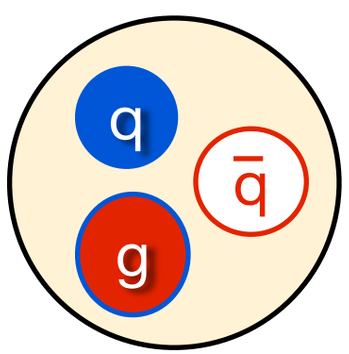
The curves illustrate successively more complex models where couplings to 1 (red) or 2 (green) open channels are significant and ultimately the presence of a resonance (orange) cannot be excluded by the data. The more complex models can be smoothly tuned to recover the simpler models by setting coupling constants to zero. A goal of the measurement is to attempt to establish the significance of coupled-channel effects. This would be done by showing the simplest model (blue curve) is inadequate to describe the data and there is statistically significant evidence for non-zero couplings to other open channels. If this were the case, then these effects influence the factorization assumptions used to interpret the data in the context of measuring the gravitational form factors. We will never be able to rule out the complex models as the parameters can be tuned to smooth the curves. We can only show that these complexities are not necessary to describe the data.

Lattice QCD

had spec **Dudek et al. PRD 88 (2013) 094505**



Lightest hybrid mesons



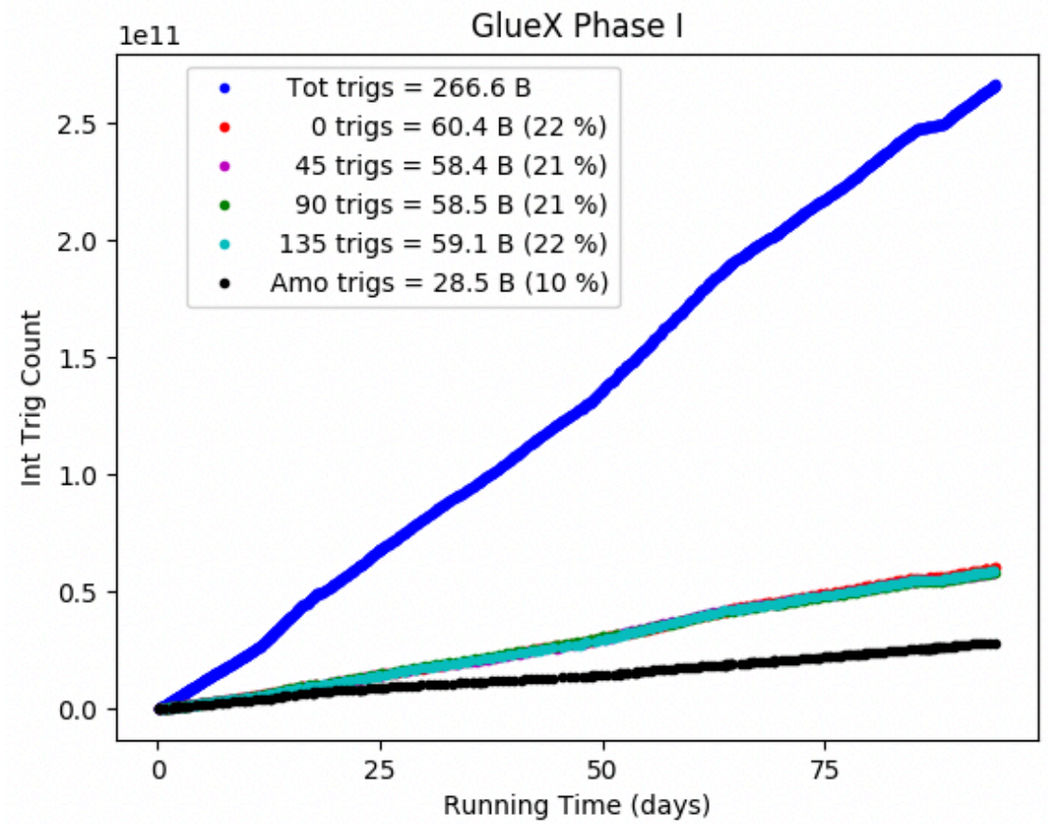
- Hybrid meson: excited gluonic field coupled to $q\bar{q}$ pair
- "Exotic" J^{PC}: not simple $q\bar{q}$ from the non-rel. quark model

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} \ldots$$

GlueX datasets

- **GlueX-I:** completed in 2018, full dataset under analysis
- **GlueX-II:** doubled beam intensity
  - π/K identification added in 2020 with DIRC detector
  - $PbWO_4$ calorimeter upgrade underway ready for 2024
- Completed Primakoff expts.: PrimEx-η, Pion Polarizability
- Future program with increased intensity, polarized target, etc.

GlueX-I dataset: 2017-2018
250 B events and ~3 PB of data



Approximate GlueX-I Yields

$\rho(770)$	200M	$\eta\pi$	2M
$\omega(782)$	40M	$\omega\pi$	10M
$\phi(1020)$	2M	J/ψ	2k

Extending hybrid program with GlueX-III

- Many studies will still be statistics-limited after GlueX I+II are completed, focus on rare production or decay
  - Establish the π_1 and its production mechanism, with unique sensitivity to photocouplings
  - Search for exotic hybrid nonet, including $\eta_1^{(\prime)} \to \eta^\prime\eta$ candidate observed at BESIII and hybrid kaon partners