GlueX-II and JLab Eta Factory (JEF) PAC 48 Jeopardy

September 25, 2020

Representing the GlueX Collaboration
(L. Gan, Z. Papandreou, M. Shepherd, A. Somov, J. Stevens, S. Taylor)

The Proposals

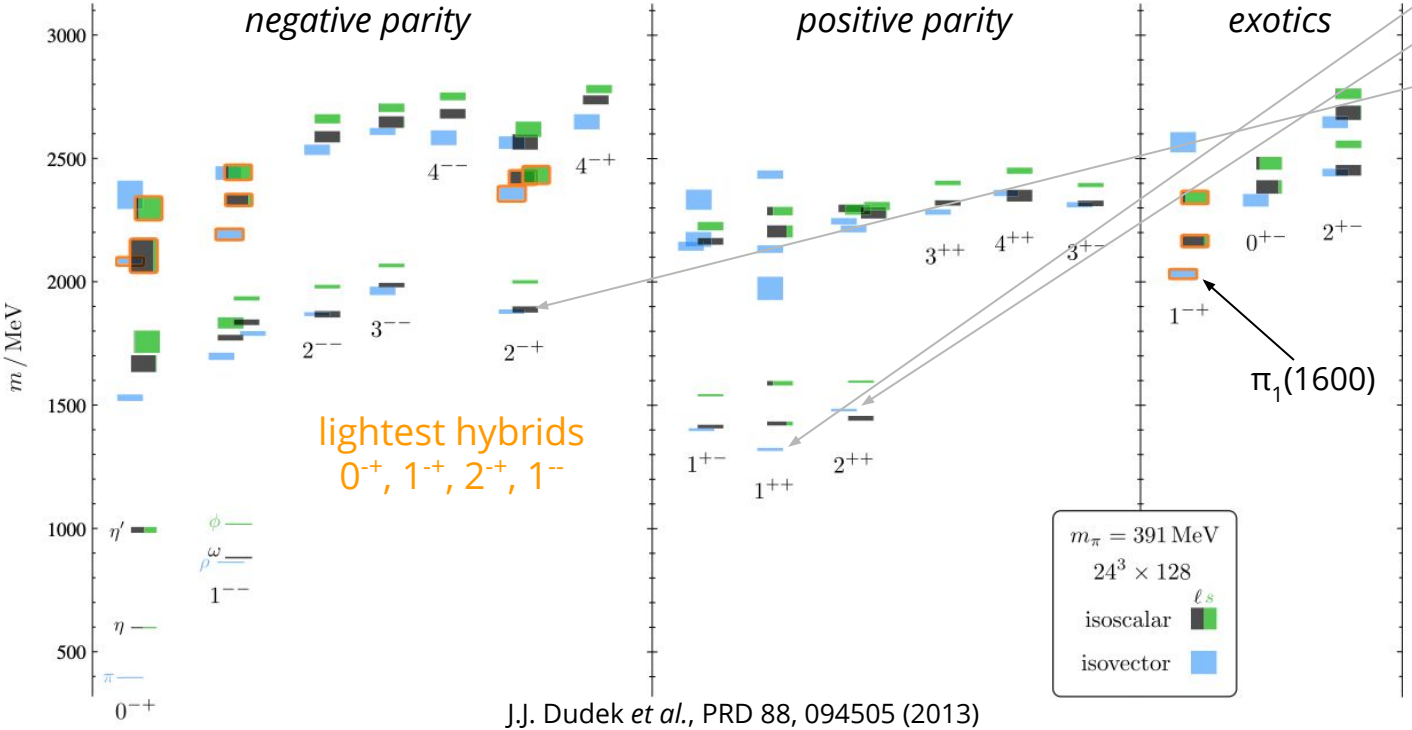
- **GlueX-II**: a extension of the GlueX spectroscopy program at high intensity (E12-13-003) and with enhanced particle identification (E12-12-002)
- **JEF**: a focus on rare and forbidden decays of $\eta^{(\prime)}$ mesons that is enabled by a high-resolution upgrade to the forward calorimeter
- PAC approved JEF to run concurrently with GlueX-II

Summer 2020

		Commissioning		Production		
Topic	Proposal Number	Approved	Completed	Approved	Completed	
GlueX II with DIRC	E12-12-002	20	14	200	38	+22 (estimated)
GlueX II	E12-13-003	0	0	200	38	+22 (estimated)
JEF	E12-12-002A	0	0	100	0	
Total Unique	-	20	14	200	38	+22 (estimated)

GlueX Goals and Tools

Search for a spectrum of hybrid mesons using amplitude analysis

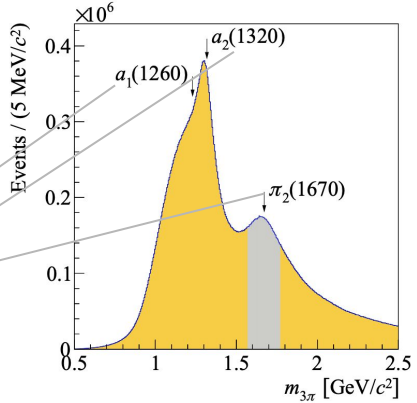


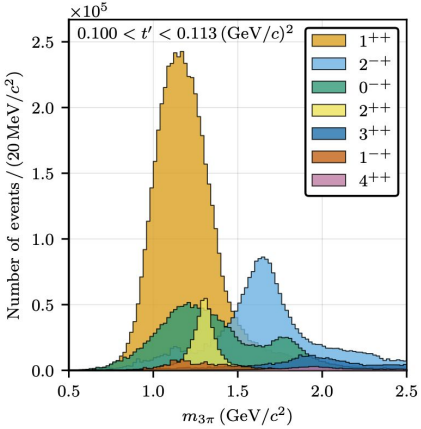
lightest hybrids
0^{-+}, 1^{-+}, 2^{-+}, 1^{--}

$\pi_1(1600)$

J.J. Dudek *et al.*, PRD 88, 094505 (2013)

$\pi^- p \to \pi^+ \pi^- \pi^- p$





COMPASS results reviewed in:
B. Ketzer, B. Grube, and D. Ryabchikov, PPNP 113, 103755 (2020).

Key Physics Objectives

- **GlueX-II:** extend the hadron spectroscopy program of the GlueX experiment
  - improved statistical precision in key hybrid-search final states like η'π
  - improved purity in search for mesons and baryons containing strange quarks
  - a high-statistics multipurpose data set enables a broad physics program
    - discover and measure the quark flavor content of isoscalar hybrid mesons, compare with predictions from QCD
    - explore the spectrum of doubly-strange baryons
    - opportunistic physics, *e.g.*, J/ψ production [GlueX, PRL 123, 072001 (2019)]
- **JEF:** strong interaction and beyond the Standard Model physics enabled by access to rare neutral decays of η and η' mesons
  - precision determination of light quark mass ratio
  - validation of chiral perturbation theory
  - search for sub-GeV dark matter
  - search for new *C*-violating *P*-conserving processes, *e.g.*, $\eta \rightarrow \pi^0 e^+ e^-$, $\eta \rightarrow 3\gamma$

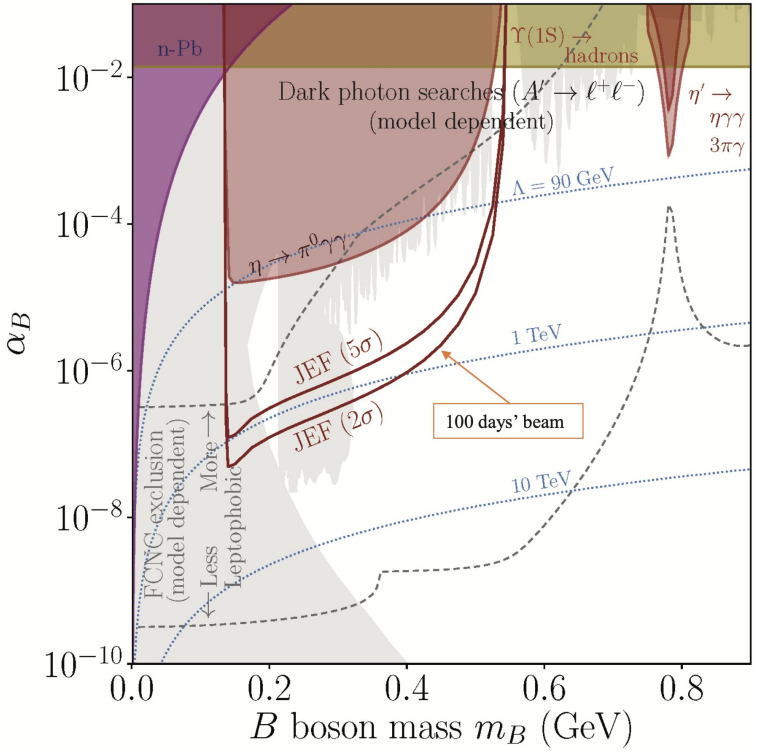
Scientific Importance

"Is there any new information that would affect the scientific importance or impact of the Experiment since it was proposed?"

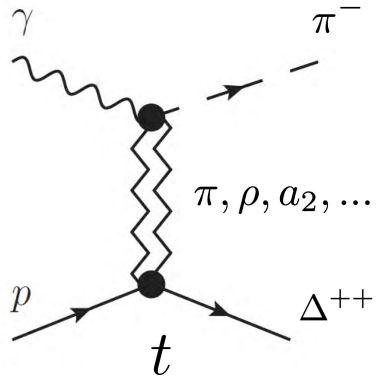
- GlueX-II
  - new results from JPAC + COMPASS and JPAC + Crystal Barrel provide a consistent picture of an isovector exotic hybrid $\pi_1(1600)$ coupling to $\eta(')\pi$: confirming in photoproduction and searching for the spectrum of hybrids is critical
  - theory development continues to mature: lattice results on couplings and validation of OZI-rule; enhanced modeling of photoproduction based on GlueX results
- JEF
  - laboratory detection of dark matter remains one of the most elusive and important goals of particle physics: JEF will extend this search in unique ways
  - while other experiments may have comparable statistics, JEF remains unique in η production kinematics, which is a critical aspect of background reduction in key rare channels like $\eta \rightarrow \pi^0\gamma\gamma$

Physics Beyond the Standard Model

- Model space for sub-GeV dark continues to be refined and expanded -- JEF will search for a variety of dark matter candidates:
  - leptophobic dark vector boson
  - dark photons or “leptophilic vector bosons”
  - hadrophilic scalar particles
  - axion-like light pseudoscalars
- DM search strategy: resolve narrow structures in invariant mass spectra in the decays
  - $\eta \rightarrow \pi^0\gamma\gamma$, $e^+e^-\gamma$, $\pi^0e^+e^-$, 3π, $\pi\pi\gamma\gamma$, $\pi\pi e^+e^-$
  - $\eta' \rightarrow \pi^0\gamma\gamma$, $\pi^+\pi^-\pi^0\gamma$, $e^+e^-\gamma$, 3π, $\eta\pi\pi$, $\pi\pi\gamma\gamma$, $\pi\pi e^+e^-$
- Additional thrust: search for *C*-violating η decays
- Requirement: high-resolution and high-granularity calorimeter



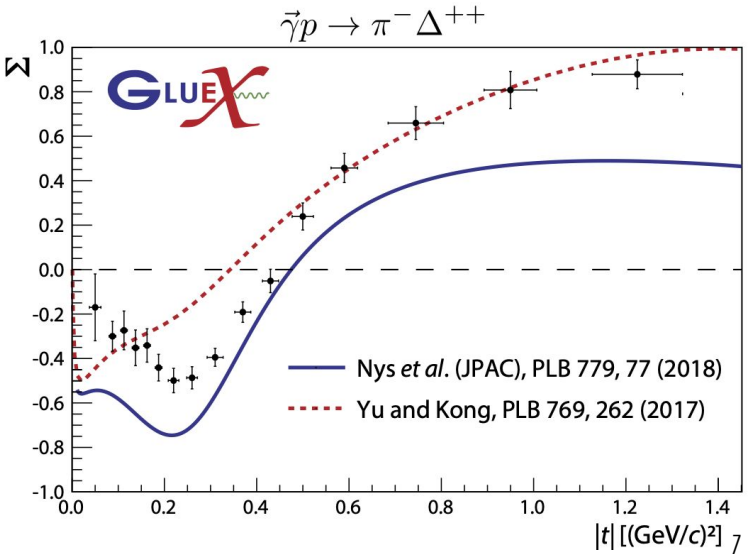
Reaction Phenomenology



Initial GlueX results for beam asymmetry constrain photoproduction models

- $\gamma p \rightarrow (\pi^0,\eta,\eta')p$ [*PRC 95, 042201 (2017); PRC 100, 052201 (2019)*]
- $\gamma p \rightarrow K^+\Sigma$ [*PRC 101, 065206 (2020)*]
- $\gamma p \rightarrow \pi^-\Delta^{++}$ [*arXiv:2009.07326*]

Production mechanism of mesons depends on momentum transfer → high statistics is needed to extract resonance production in bins of *t*



Final State Survey

Table from the GlueX-II proposal to PAC 42.

lattice calculations [3]. Those final states marked with a dagger (†) are ideal for experimental exploration because there are relatively few stable particles in the final state or moderately narrow intermediate resonances that may reduce combinatoric background. (We consider η, η', and ω to be stable final state particles.)

	Approximate Mass (MeV)	J^{PC}	Total Width (MeV) PSS	IKP	Relevant Decays	Final States
π_1	1900	1^{-+}	80 – 170	120	$b_1\pi^\dagger$, $\rho\pi^\dagger$, $f_1\pi^\dagger$, $a_1\eta$, $\eta'\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	60 – 160	110	$a_1\pi$, $f_1\eta^\dagger$, ~~$\pi(1300)\pi$~~	~~4π~~, ~~$\eta 4\pi$~~, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	100 – 220	170	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K^*K^\dagger$	~~$KK\pi\pi^\dagger$~~, $KK\pi^\dagger$, $KK\omega^\dagger$
b_0	2400	0^{+-}	250 – 430	670	$\pi(1300)\pi$, $h_1\pi$	4π
h_0	2400	0^{+-}	60 – 260	90	$b_1\pi^\dagger$, $h_1\eta$, $K(1460)K$	$\omega\pi\pi^\dagger$, $\eta 3\pi$, $KK\pi\pi$
h_0'	2500	0^{+-}	260 – 490	430	$K(1460)K$, $K_1(1270)K^\dagger$, $h_1\eta$	$KK\pi\pi^\dagger$, $\eta 3\pi$
b_2	2500	2^{+-}	10	250	$a_2\pi^\dagger$, $a_1\pi$, $h_1\pi$	4π, $\eta\pi\pi^\dagger$
h_2	2500	2^{+-}	10	170	$b_1\pi^\dagger$, $\rho\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2600	2^{+-}	10 – 20	80	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K_2^*K^\dagger$	~~$KK\pi\pi^\dagger$~~, $KK\pi^\dagger$

NB: new results from HadSpec on exotic π_1 decays in lattice QCD just this week: arXiv:2009.10034

Final State Survey

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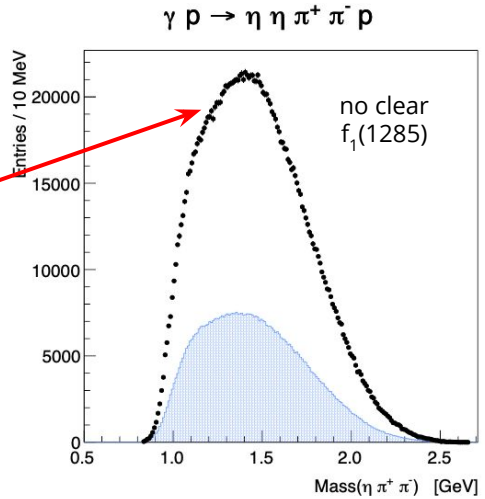
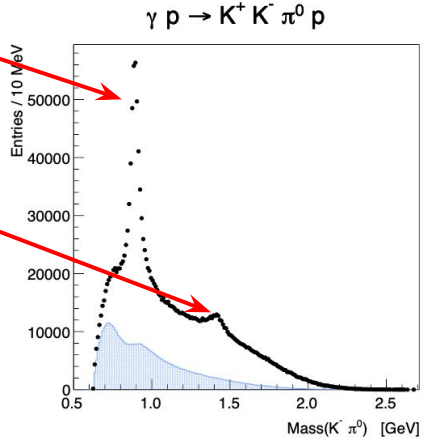
b_2	2500	2^{+-}	10	250	$a_2\pi^\dagger$, $a_1\pi$, $h_1\pi$	4π, $\eta\pi\pi^\dagger$
h_2	2500	2^{+-}	10	170	$b_1\pi^\dagger$, $\rho\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2600	2^{+-}	10 – 20	80	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K_2^*K^\dagger$	$KK\pi\pi^\dagger$, $KK\pi^\dagger$

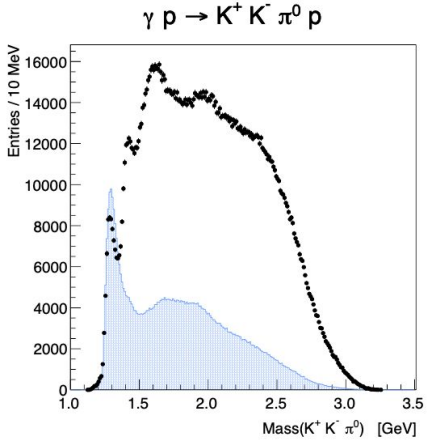
reconstruct >50 reactions at once to guide priorities for future analysis

$p\pi^0\pi^0$, $p\pi^0\pi^0\pi^0$, $p\pi^+\pi^-$, $p\pi^+\pi^-\pi^0$, $p\pi^+\pi^-\pi^0\pi^0$, $p\pi^+\pi^-\pi^0\pi^0\pi^0$, $p\pi^+\pi^+\pi^-\pi^-$, $p\pi^+\pi^+\pi^-\pi^-\pi^0$, $p\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$, $p\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$, pK_SK_S, $pK_SK_S\pi^0$, $pK_SK_S\pi^0\pi^0$, $pK_SK_S\pi^+\pi^-$, $pK^-K_S\pi^+$, $pK^-K_S\pi^+\pi^0$, $pK^-K_S\pi^+\pi^0\pi^0$, $pK^-K_S\pi^+\pi^+\pi^-$, $pK^+K_S\pi^-$, $pK^+K_S\pi^-\pi^0$, $pK^+K_S\pi^-\pi^0\pi^0$, $pK^+K_S\pi^+\pi^-\pi^-$, pK^+K^-, $pK^+K^-\pi^0$, $pK^+K^-\pi^0\pi^0$, $pK^+K^-\pi^0\pi^0\pi^0$, $pK^+K^-\pi^+\pi^-$, $pK^+K^-\pi^+\pi^-\pi^0$, $pK^+K^-\pi^+\pi^-\pi^0\pi^0$, $pK^+K^-\pi^+\pi^+\pi^-\pi^-$, $p\pi^0\eta$, $p\pi^0\pi^0\eta$, $p\pi^+\pi^-\eta$, $p\pi^+\pi^-\pi^0\eta$, $p\pi^+\pi^-\pi^0\pi^0\eta$, $p\pi^+\pi^+\pi^-\pi^-\eta$, $pK_SK_S\eta$, $pK^+K^-\eta$, $p\eta\eta$, $p\pi^0\eta\eta$, $p\pi^+\pi^-\eta\eta$, $p\pi^+\pi^-\pi^0\eta\eta$, $\Lambda K_S\pi^+$, $\Lambda K_S\pi^+\pi^0$, $\Lambda K_S\pi^+\pi^+\pi^-$, ΛK^+, $\Lambda K^+\pi^0$, $\Lambda K^+\pi^+\pi^-$, $\Lambda K^+\pi^+\pi^-\pi^0$, $\Lambda K_S\pi^+\eta$, $\Lambda K_S\pi^+\pi^0\eta$, $\Lambda K^+\eta$, $\Lambda K^+\pi^0\eta$, $\Lambda K^+\pi^+\pi^-\eta$

projected GlueX-II scale factor: 10x-15x more data



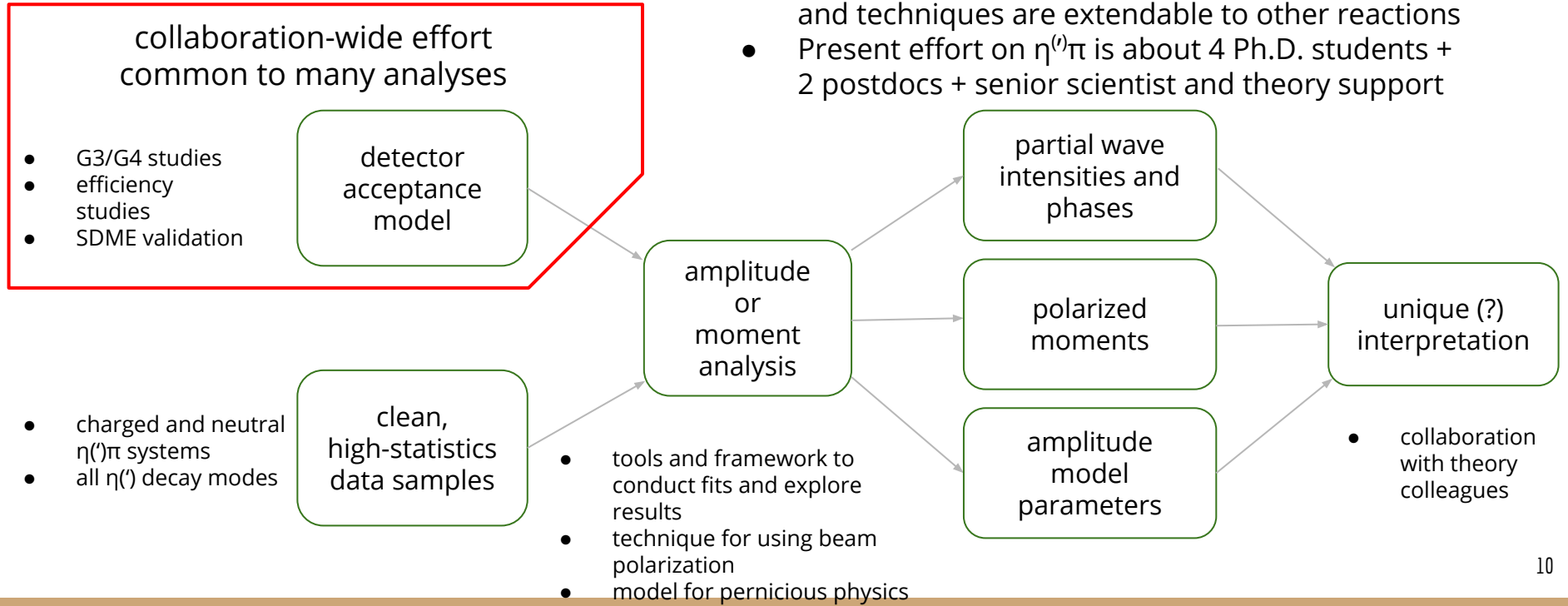




Clear K* and K_2* with interesting structure in the KKπ mass that needs further analysis.

A strategy for exotic hybrid searches in $\eta^{(\prime)}\pi$

- Typical amplitude analysis workflow -- framework and techniques are extendable to other reactions
- Present effort on $\eta^{(\prime)}\pi$ is about 4 Ph.D. students + 2 postdocs + senior scientist and theory support

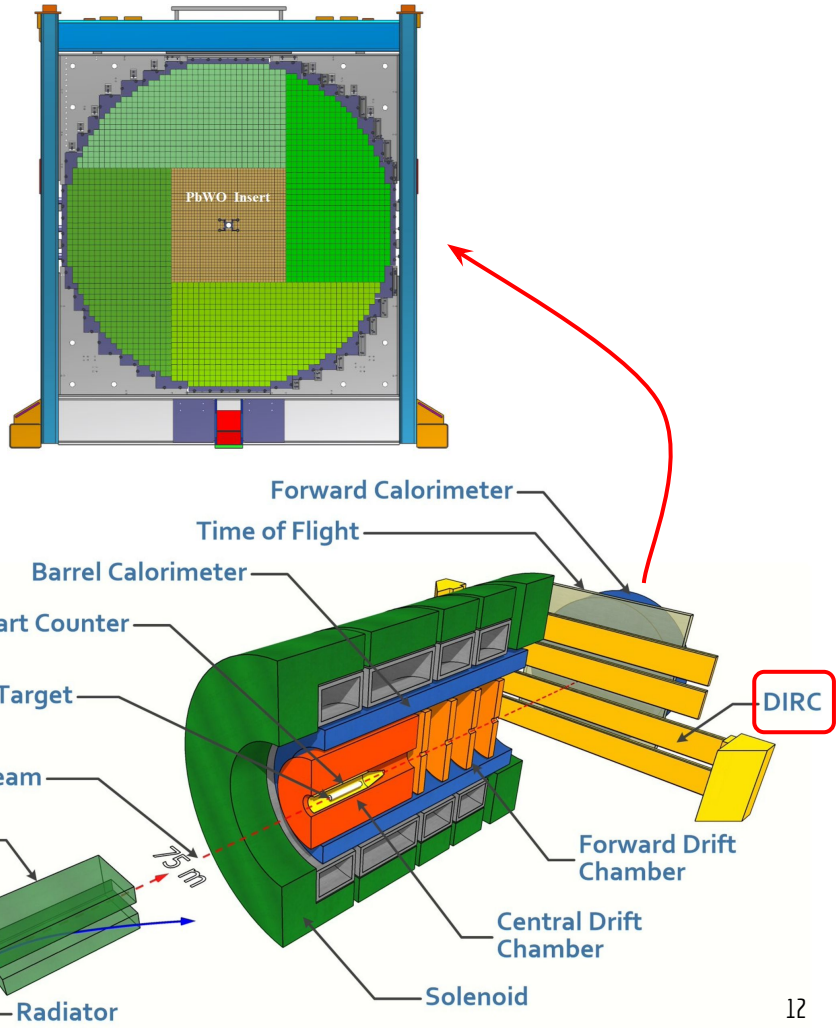


Summary of Motivation and Analysis Readiness

- The motivation for the GlueX-II and JEF programs is as strong if not stronger than it was when these initiatives were developed
  - convergence of data + phenomenology + lattice QCD: key contributions from GlueX
  - physics beyond the Standard Model with JEF: direct searches for dark matter and new C-violating processes while constraining low-energy strong interaction physics
- The GlueX-II and JEF programs use all existing analysis infrastructure that is supported, maintained, and organized by the GlueX Collaboration
  - detector and analysis complexity requires a standardized approach
    - workflow that is scalable to tens of PB of raw data and reconstruction tasks that consume well over 100M CPU-hours
  - years (decades?) of effort invested in software and data analysis technology
    - robust multi-threaded analysis framework; offsite HPC data reconstruction; MC simulation on the Open Science Grid and Compute Canada; standardized event selection and understanding of systematic uncertainties; GPU-accelerated amplitude analysis; detector specific calibration and data quality monitoring techniques; ...
  - strong partnership with JPAC and theory community

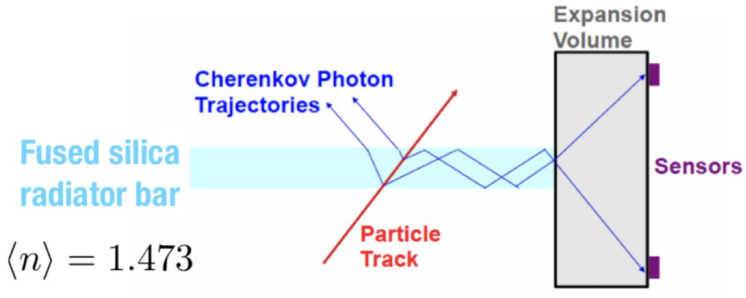
Detector upgrades enhance discovery potential

Hall D beamline, baseline GlueX detector, and reconstruction performance is documented in arXiv:2005.14272 (submitted to Nuclear Instruments and Methods).

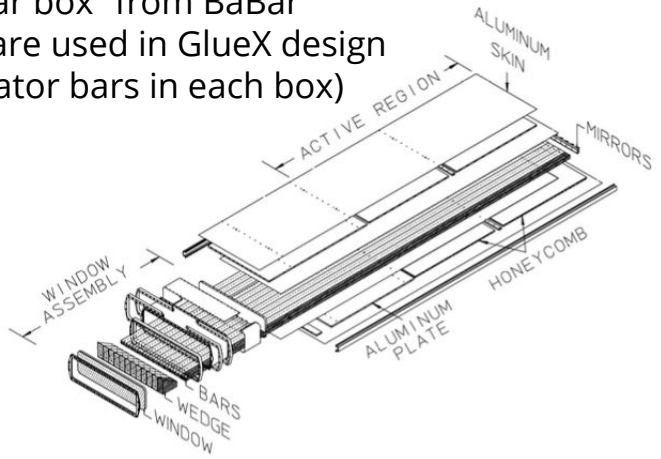


A DIRC for GlueX-II

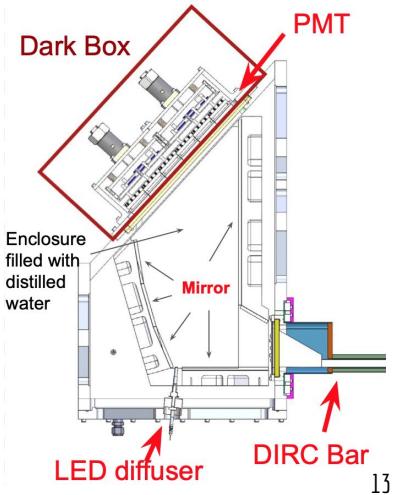
- Goal: 3σ π/K separation up to 3.7 GeV/c
- Use ⅓ of BaBar DIRC fused silica radiators
- New optical camera and front-end readout based on Multi-Anode PMTs (used in Hall B)
- Project cost: $1.8M
- Installation completed in 2019; commissioning now underway



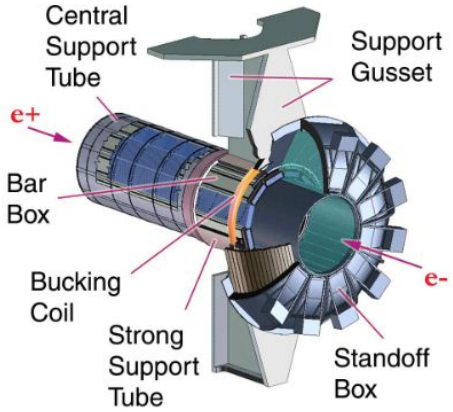
5-m long “bar box” from BaBar
four boxes are used in GlueX design
(twelve radiator bars in each box)



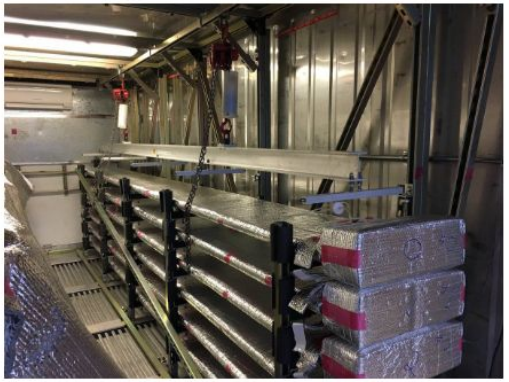
Top view of the
“optical box”
two bar boxes are
inserted into each
of two optical boxes
in the GlueX design.



BaBar DIRC Detector



DIRC Bar Box Storage at SLAC



On the Road in New Mexico

A long and very, very careful drive

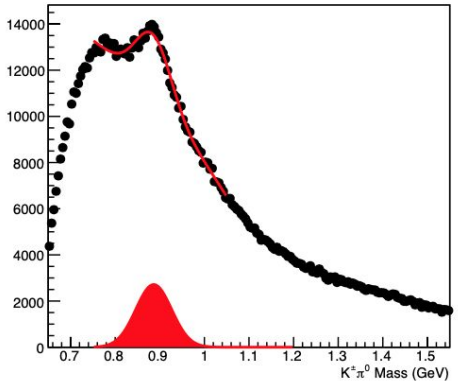
3000 miles later at JLab

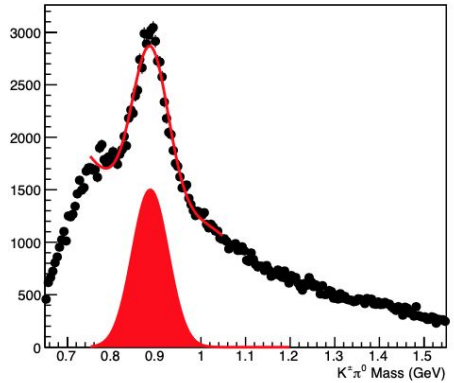
DIRC Bar Box in Hall D

We moved one bar box first in November 2017, and then repeated the entire process, moving the remaining three boxes in one trip in May 2018.

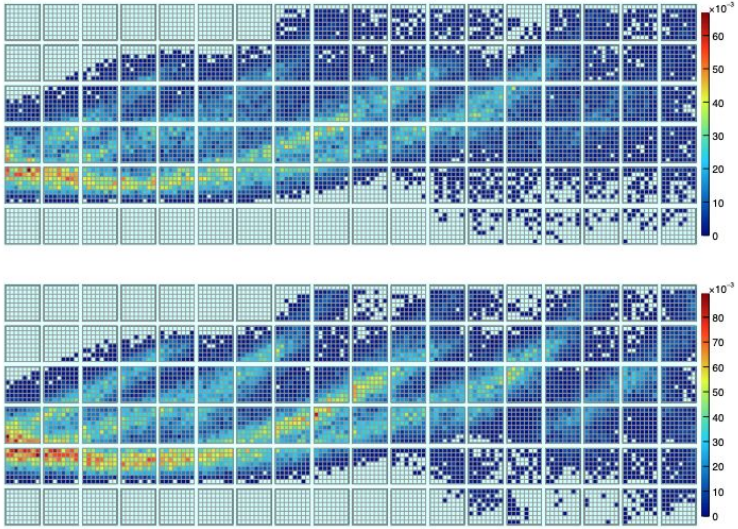
DIRC Performance

- Design performance achieved in some regions of phase space
- Anticipate that high-statistics data acquired in 2020 will be essential in refining reconstruction and calibration to maximize performance





Preliminary: improved *K** purity (right vs. left) by using DIRC to identify the charged kaon (no kinematic fitting)



DIRC Cherenkov photon occupancy on the MAPMT plane for $\pi^{\pm}$ tracks in data (top) and GEANT simulation (bottom).

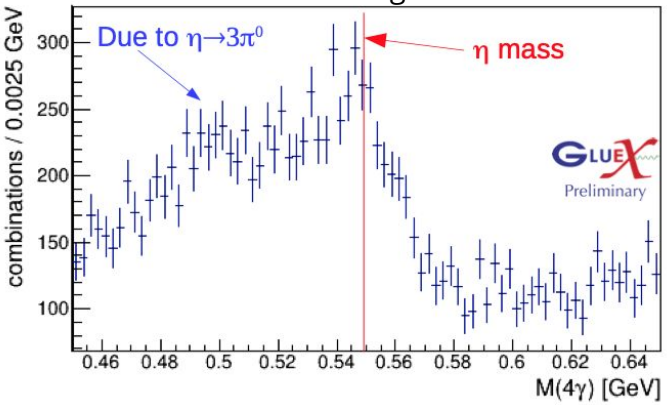
JEF Calorimeter Upgrade

- Calorimeter insert key features
  - factor of 2 improvement in both energy and position resolution
  - factor of 4 more granularity
  - factor of 10 more radiation resistance
  - improved angular coverage near beam hole
- Goal: 50 x 50 array of 2 cm x 2 cm x 20 cm $PbWO_4$ crystals
  - external funding (via NSF MRI) pending
- Procurements underway for 1600 modules
  - 1000 crystals ordered; 200 delivered; QA ongoing
    - two vendors: CRYTUR and SICCAS
  - 500 Hamamatsu R4125 PMTs delivered so far
  - readout electronics and high voltage for 1600 channels has been ordered

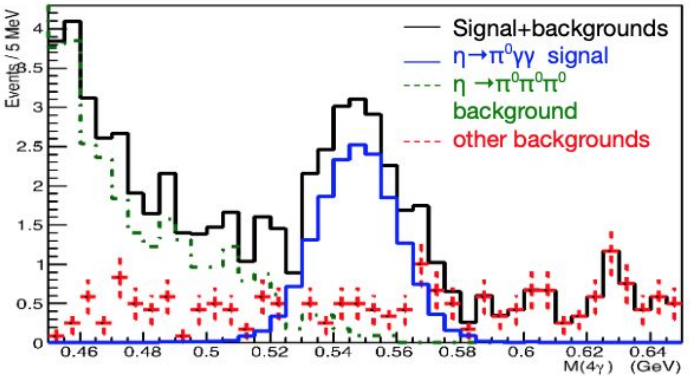
Key decay: $\eta \rightarrow \pi^0\gamma\gamma$

[$BF(\eta \rightarrow \pi^0\gamma\gamma) = 2.6 \times 10^{-4}$]

data with existing calorimeter

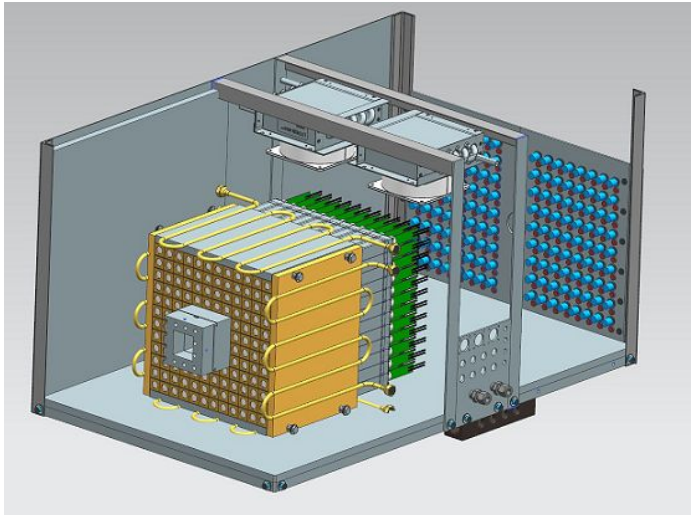


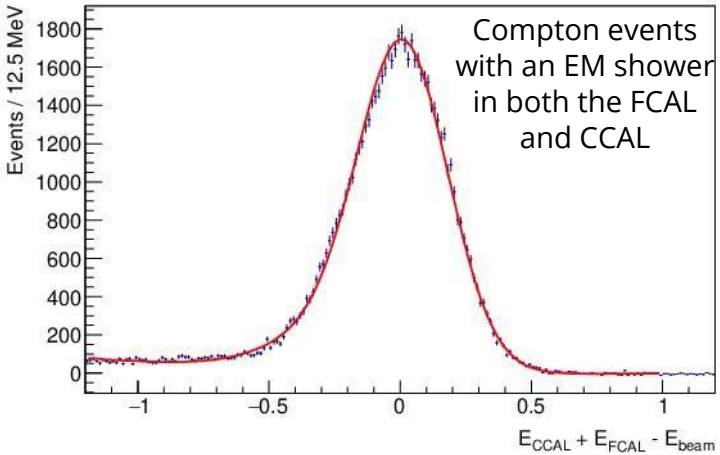
simulation with upgraded calorimeter



$PbWO_4$ Experience

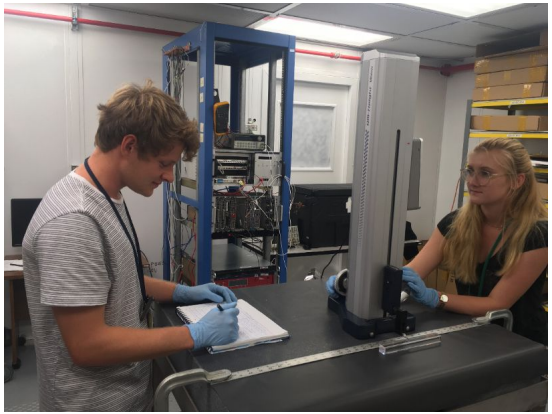
- Insert for JEF informed by construction and operation of the Hall B Hybrid Calorimeter
- In collaboration with Hall C (NPS) we built and successfully operated a “Compton Calorimeter” (CCAL) for Spring 2019 PrimEx-η run in Hall D
  - 140 $PbWO_4$+PMT modules of the same design
  - important for prototyping active PMT base design
  - observe clean Compton events
  - comparable resolution to Hall B HyCal
- Continued testing of modules in Hall D throughout recent runs
  - using energy-tagged e^+ and e^-



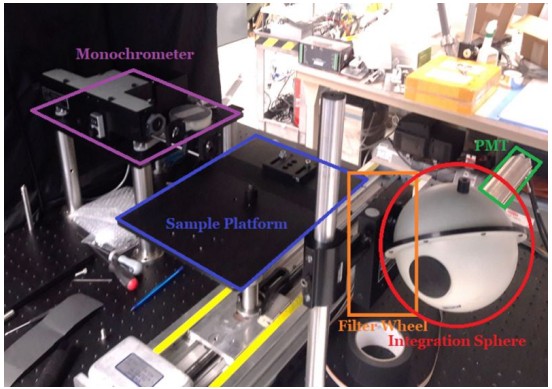


Testing of $PbWO_4$ Crystals

checking dimensions of crystals



light transmission measurement

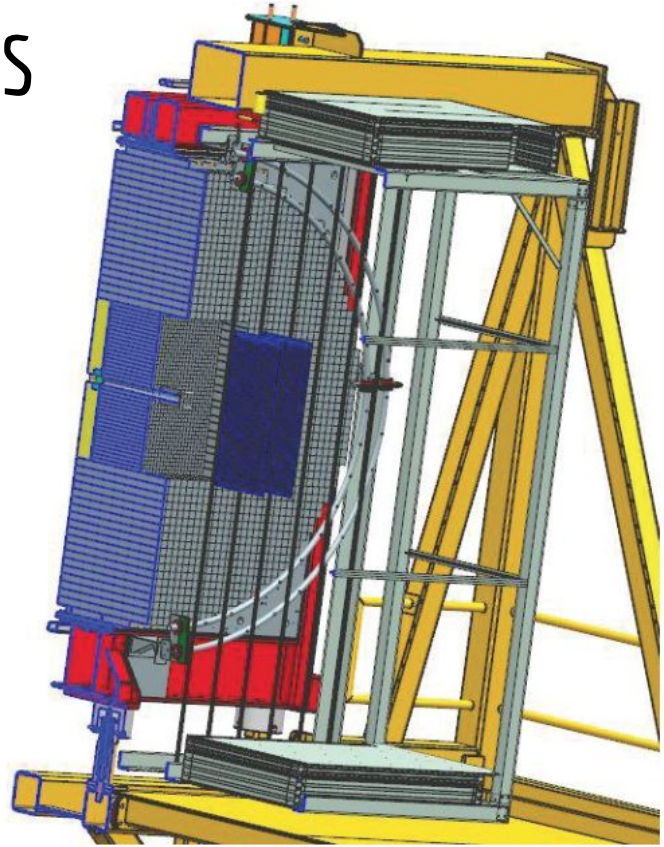


light yield measurement with radioactive source

full module testing using the Hall D pair spectrometer

Fabrication and Installation Plans

- Mass production of modules expected to begin soon
  - module mechanical design is complete
  - finalizing PMT base design
- Finalizing engineering design for frame
  - stacking procedure and alignment
  - cable management and dark room
  - water cooling system
  - beam hole support
- Anticipate that modules will be ready for installation in 2023
- Planned installation duration: 6 months



from Tim Whitlatch

Summary

- GlueX-II and JEF expand the initial baseline GlueX physics program
  - spectroscopy through decays to strange particles
  - enhanced program of searching for physics beyond the Stand Model
- Key detector upgrades completed and underway
  - successful installation of DIRC to provide enhanced kaon identification
  - beginning the construction phase of a high-resolution calorimeter insert to enable new studies of η(‘) meson decay
    - best estimate: completion of calorimeter upgrade in 2023
  - *together: over a decade of R&D, design, and construction effort at a cost of several million dollars*
- About 60 of the 200 approved PAC days are completed as of this week
  - request: complete the proposed running for the two programs as approved by the PAC
  - we will submit a request to the PAC for additional beam time as necessary to achieve the scientific objectives of the GlueX-II and JEF programs