The Jefferson Lab Eta Factory (JEF) experiment

Simon Taylor / JLab for the GlueX collaboration

- Physics channels involving η decays
- CEBAF and the GlueX detector
- Upgrade to standard GlueX equipment: $PbWO_4$ crystals
- Hardware status

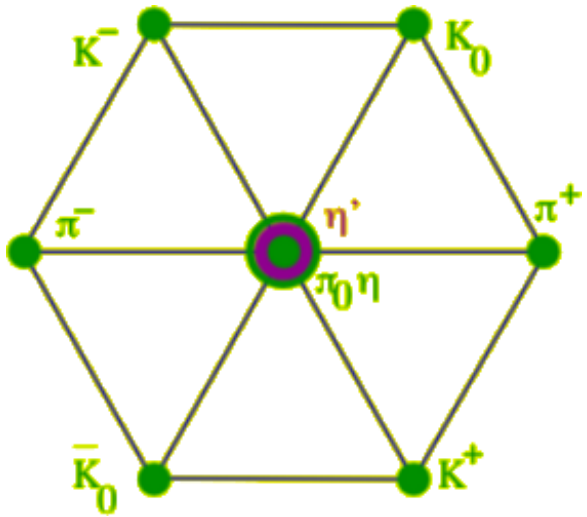
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

η as a probe for QCD and Beyond Standard Model physics

- Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  - Bridge our understanding of low-energy hadron dynamics and underlying QCD
- Decay width Γ_η=1.3 keV is narrow
  - Width << experimental resolution, aids in analysis
- Eigenstate of P, C, CP, and G: $I^G(J^{PC})=0^+(0^{-+})$
  - Study violations of discrete symmetries
- Decays are flavor-conserving reactions effectively free of SM backgrounds for new physics searches...



- Review article: L. Gan, et al., “Precision tests of fundamental physics with η and η′ mesons”, Phys.Rept. 945 (2022) 1-105 https://arxiv.org/abs/2007.00664

Physics channels

- Search for a leptophobic dark boson (*B*)
  - ~0.14 < M_B < ~0.55 GeV
  - $B \to \pi^0 \gamma$, ...
- Search for a dark scalar mediator (*S*)
  - $S \to \gamma\gamma$, ...
- Probe interplay of VMD and scalar resonances in Chiral Perturbation Theory → $O(p^6)$ LEC's in the chiral Lagrangian
- Directly constrain C-violating/Parity-conserving (CVPC) new physics
- Constrain the light quark mass ratio

Mode	Branching Ratio	Physics highlight
$\gamma + B'$	beyond SM	leptophobic dark boson
$\pi^0 2\gamma$	$(2.55 \pm 0.22) \times 10^{-4}$	χPT at $\mathcal{O}(p^6)$
$3\pi^0$	$(32.57 \pm 0.21)\%$	$m_u - m_d$
$\pi^+\pi^-\pi^0$	$(23.02 \pm 0.25)\%$	$m_u - m_d$, CV
3γ	$< 1.6 \times 10^{-5}$	CV, CPV

Branching ratios from P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

Light quark mass ratio

- Quark masses are fundamental QCD parameters
  - $\eta \to \pi^+\pi^-\pi^0$ provides direct way to constrain light quark masses and source term for isospin violation

- QCD Lagrangian: isospin violation amplitude *A* proportional to $m_u - m_d$

$$A = (m_u - m_d)A_1 + \alpha_{em} A_2$$

small

- Quark mass ratio: $Q^2 = \dfrac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \hat{m} = \dfrac{m_u + m_d}{2}$

- Decay width:

$$\Gamma(\eta \to 3\pi) \propto \int \mathrm{d}s\, \mathrm{d}u |\mathcal{A}_{\eta\to 3\pi}(s,t,u)|^2 \propto \frac{1}{Q^4}$$

F. Ambrosino, et al . JHEP 0805:006,2008

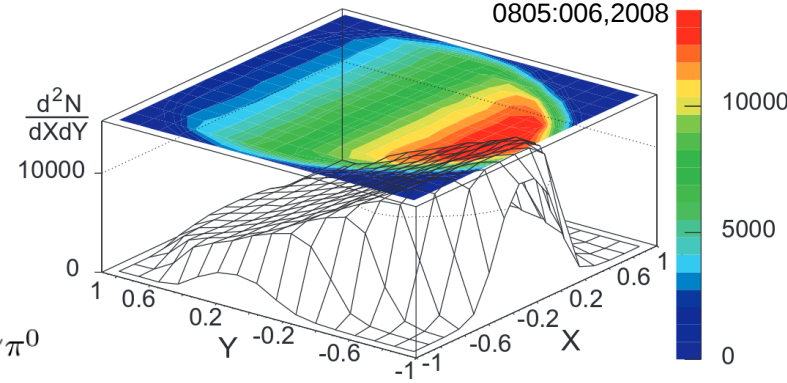
- Measure Dalitz distribution for $\eta \to \pi^+\pi^-\pi^0$

$$\Gamma(X,Y) \propto 1 + aY + bY^2 + dX^2 + fY^3 + hX^2Y + \cdots$$

$$X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta}$$

$$Y = \frac{3T_0}{Q_\eta} - 1$$

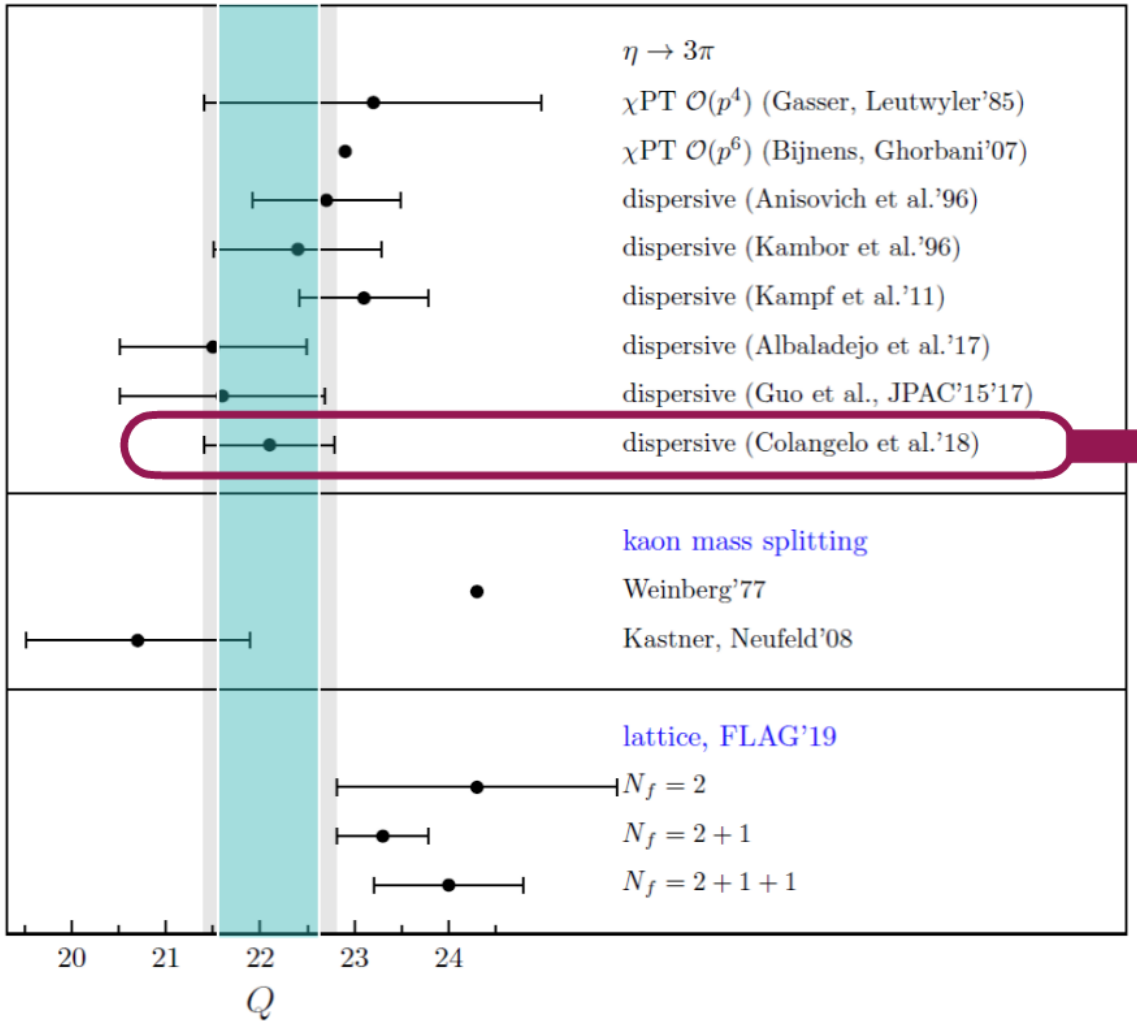
$$Q_\eta = m_\eta - 2m_{\pi^+} - m_{\pi^0}$$



- Dalitz plot parameters (*a*, *b*, *d*, ...): compute from theory (χPT, dispersion analysis)

Light quark mass ratio: current status

- Quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \hat{m} = \frac{m_u + m_d}{2}$

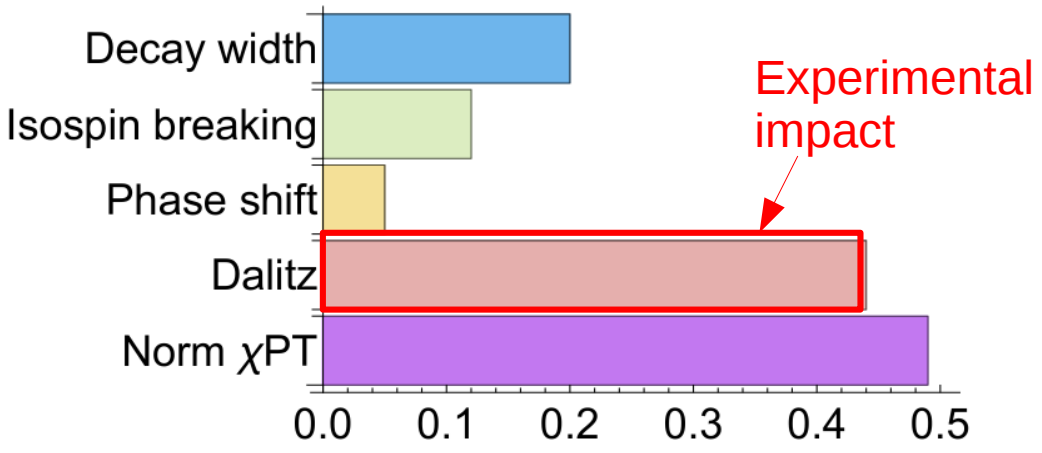


- Amplitude:

$$A = (m_u - m_d)A_1 + \alpha_{em}A_2, \quad \alpha_{em} \sim small$$

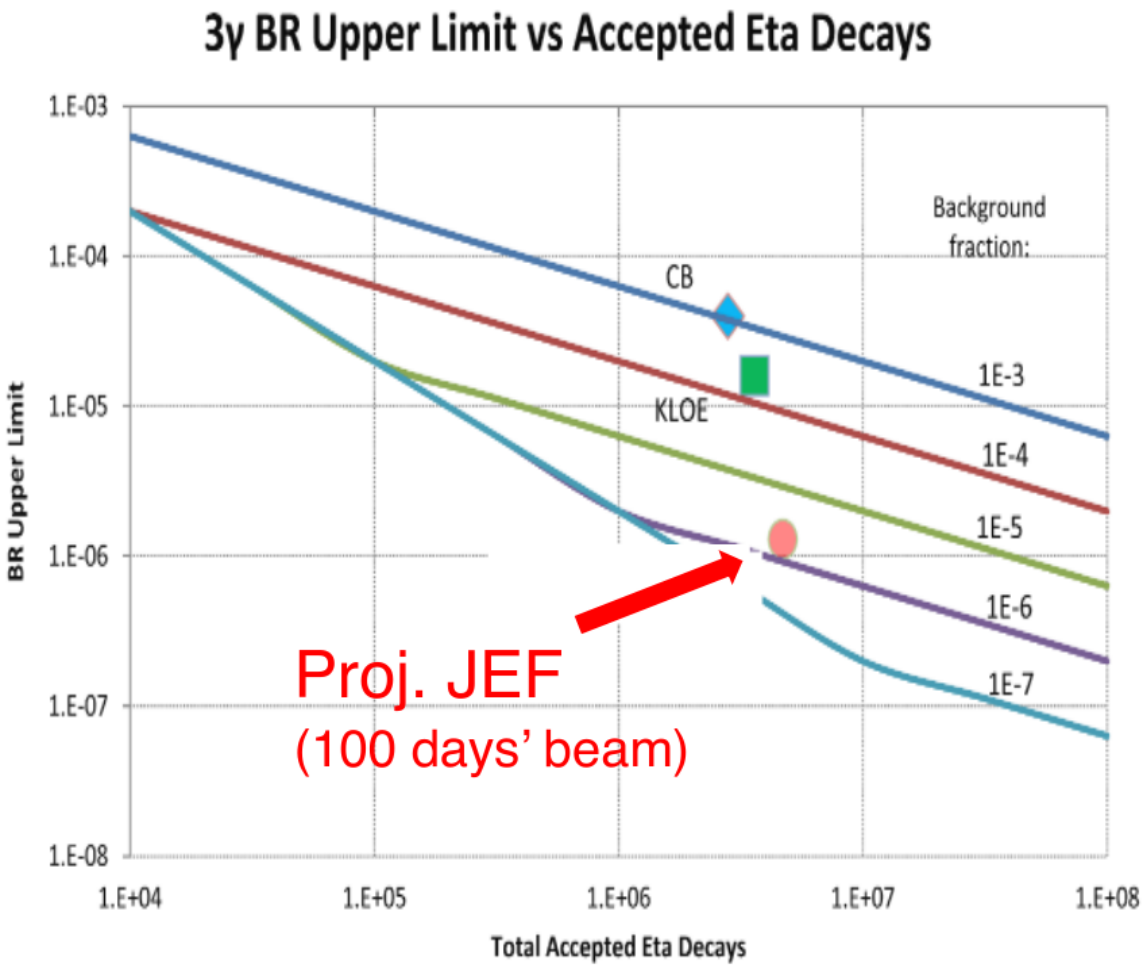
$$\Gamma(\eta \to 3\pi) \propto \int ds\, du |\mathcal{A}_{\eta\to 3\pi}(s,t,u)|^2 \propto \frac{1}{Q^4}$$

- Uncertainties in quark mass ratio:



L. Gan, et al., Phys.Rept. 945 (2022)

C-violating/parity-conserving (CVPC) physics

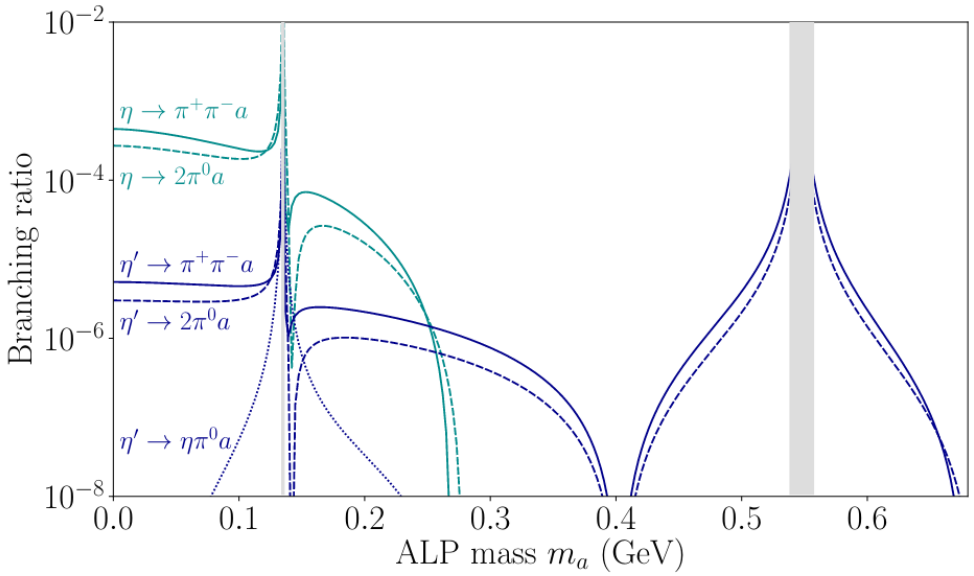


- C(charge conjugation)-violation known only in weak interactions
- Strong and EM forces conserve C-parity
- Focus on $\eta \to 3\gamma$:
  - Bernstein, Feinberg, and Lee: new C- and T-violating, P-conserving interaction
    Phys.Rev., 139, B1650(1965)
  - Theoretical estimate: $BR(\eta \to 3\gamma) < 10^{-2}$
    Tarasov, Sov.J.Nucl.Physics.,5,445(1967)
  - SM scale: $BR(\eta \to 3\gamma) < 10^{-19}$ via P-violating weak interaction
    P. Herczeg, Production and Decay of Light Mesons Proc. Int. Workshop, Paris, France, ed P Fleury (1988) p16
  - Current upper limit: $BR(\eta \to 3\gamma) < 1.6 \times 10^{-5}$
    P.A. Zyla et al., Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

JEF: expect improvement by 1 order of magnitude….

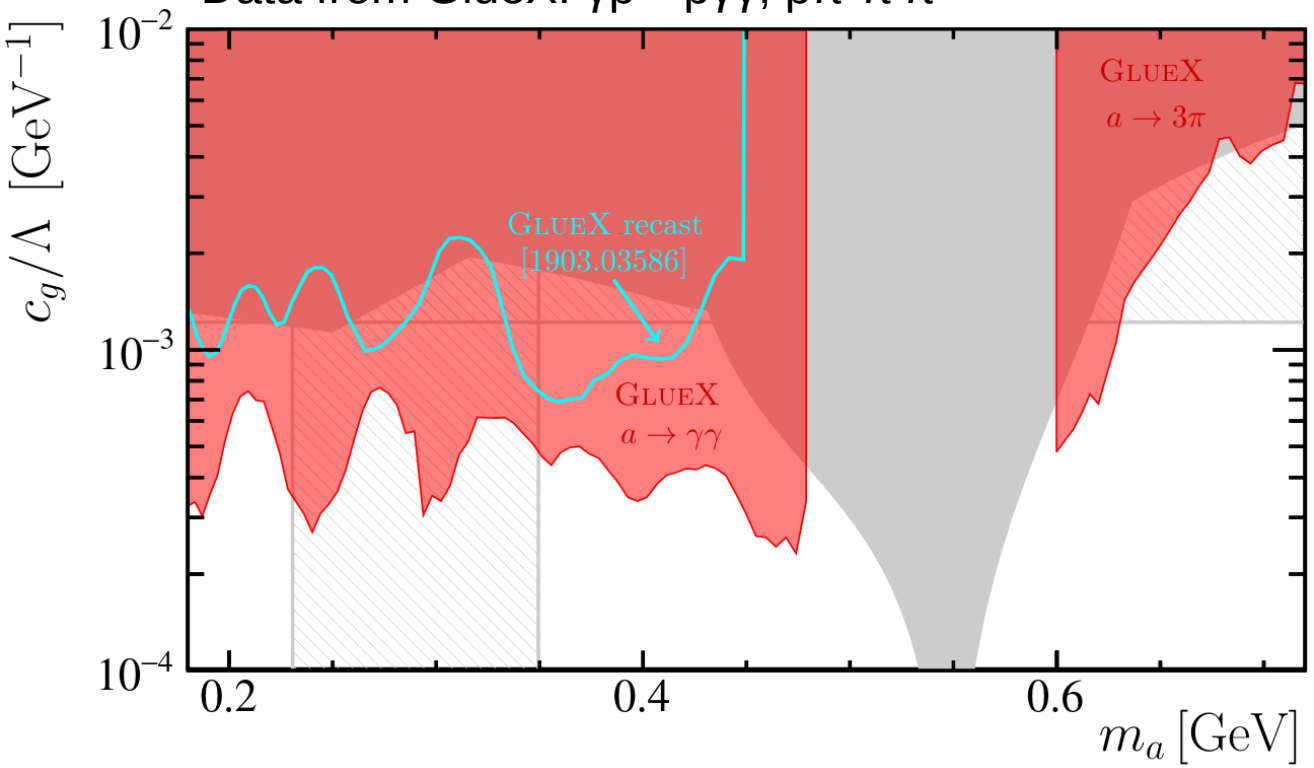
Search for axion-like particles (ALPs)

- Proposed light pseudoscalar (*a*) mediators between Standard Model and Dark Matter
  - Dominant coupling to gluons
- Search channels:
  - $\eta(') \to \pi\pi a$, where $a \to \gamma\gamma$, e^+e^-, $\mu^+\mu^-$
  - $\eta' \to \pi\pi a$, where $a \to \pi^+\pi^-\gamma$, 3π
  - $\eta' \to \eta\pi^0 a$, where $a \to \gamma\gamma$, e^+e^-, $\mu^+\mu^-$



L. Gan, et al., Phys.Rept. 945 (2022)

Data from GlueX: $\gamma p \to p\gamma\gamma$, $p\pi^+\pi^-\pi^0$



Phys.Rev.D 105 (2022) 5, 052007

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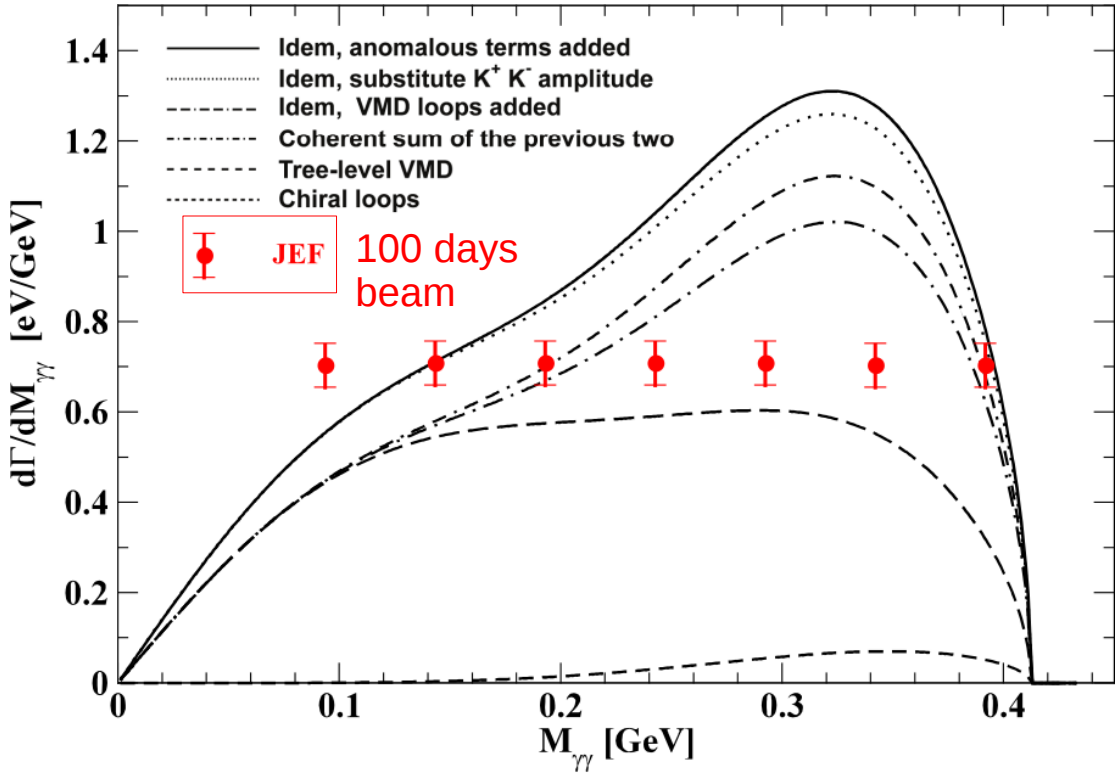
Rare decay: $\eta \to \pi^0 \gamma\gamma$

- Unique probe for high order Chiral Perturbation Theory (χPT)
  - Tree level amplitudes $O(p^2)$ and $O(p^4)$ vanish
  - First sizeable contributions to $\eta \to \pi^0 \gamma\gamma$: two $O(p^6)$ counter-terms in chiral Lagrangian

    Ametller, Bijnens, Bramon, and Cornet, Phys. Lett., B276, 185 (1992)

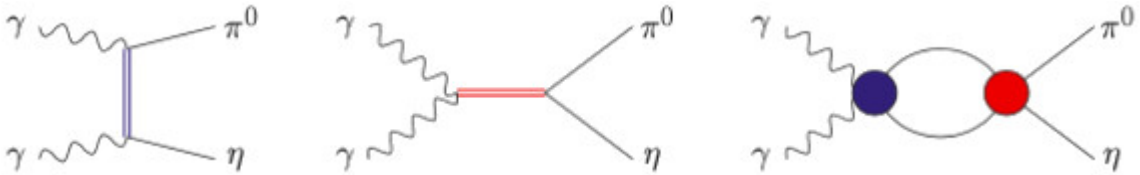
  - Access two Low Energy Constants



E. Oset, J.R. Pelaez, and L. Roca, Phys.Rev.D77:073001,2008

- Shape of Dalitz distribution ($M_{\gamma\gamma}$) sensitive to role of scalar resonances

Gasser, Leutwyler 1984; Ecler, Gasser, Pich, de Rafael 1989; Donoghue, Ramirez, Valencia 1989



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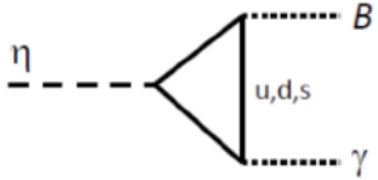
Portal to dark sector: *B*-boson

- Leptophobic vector *B* coupling to baryon number
- *B*-boson production:

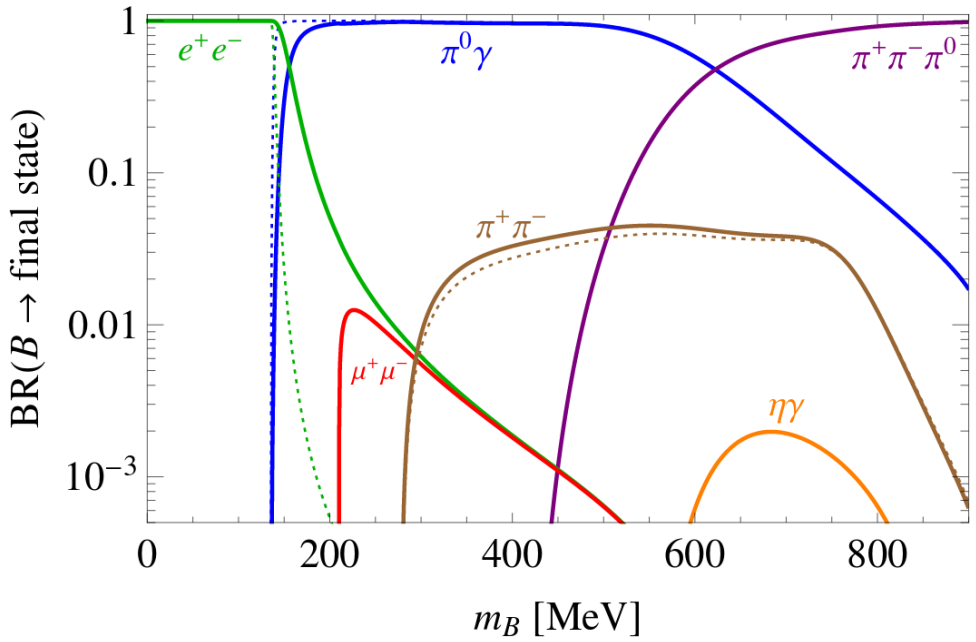
  A.E. Nelson, N. Tetradis,
  Phys. Lett., B221, 80 (1989)

  $\eta \rightarrow B\gamma$ decay ($m_B < m_\eta$)

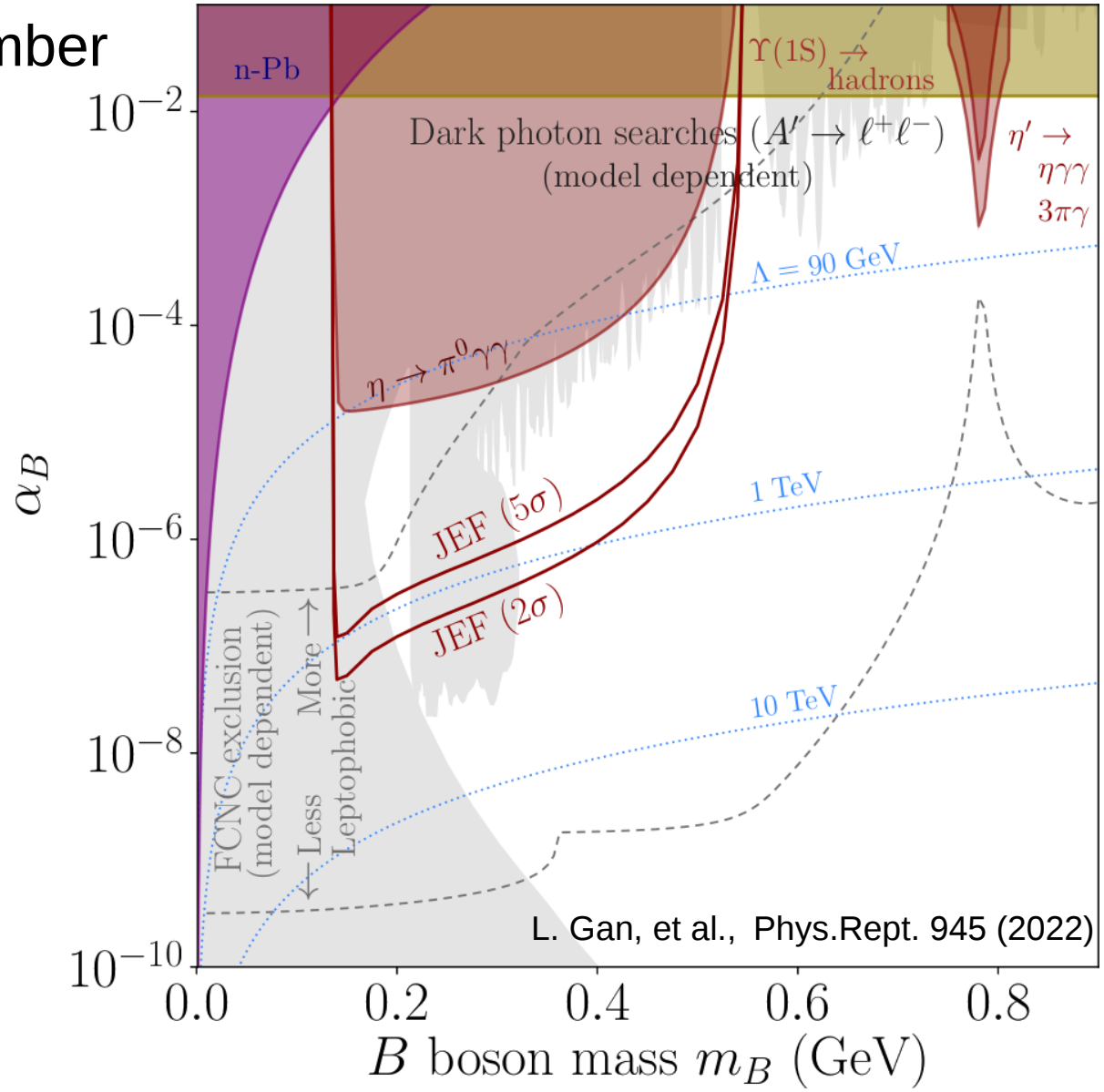


Triangle diagram

- Look for signals in $\eta \rightarrow \gamma B \rightarrow \gamma(\pi^0\gamma)$



S. Tulin, Phys.Rev. D89, 14008 (2014)

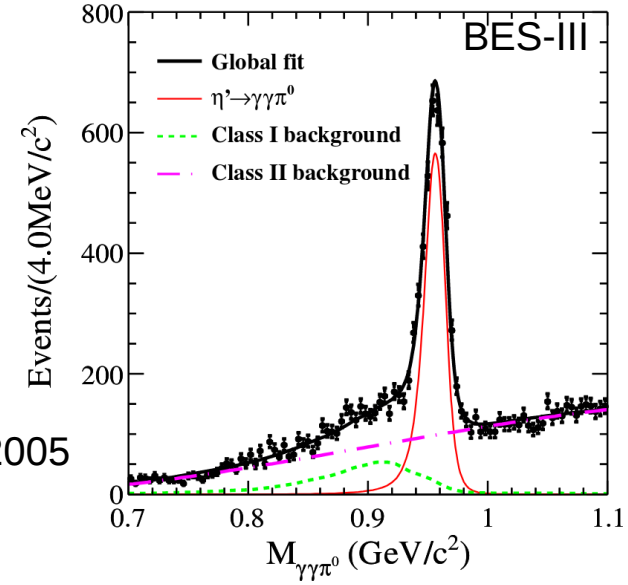


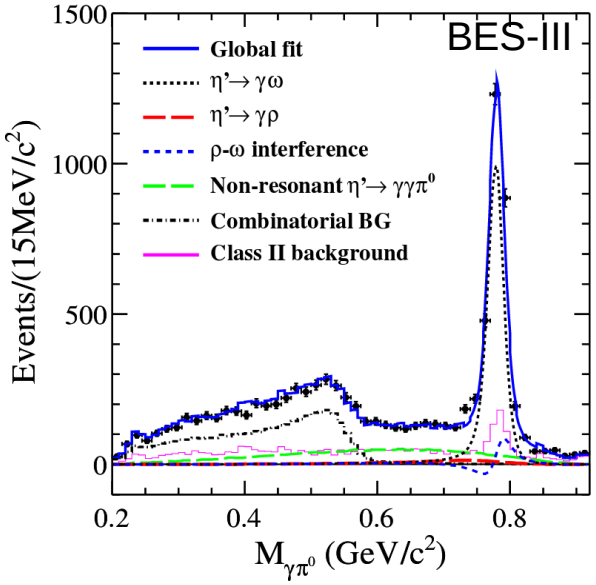
L. Gan, et al., Phys.Rept. 945 (2022)

Extension to $\eta' \to \pi^0\gamma\gamma$

- Recent BES-III measurement[1]:
  - Non-resonant contribution measured for first time
  - BR(inclusive) = 3.20±0.07(stat)±0.23(sys))×10^{-3}
  - BR(non-resonant) = (6.16±0.64(stat)±0.67(sys))×10^{-4}

[1]Phys. Rev. D 96, 012005

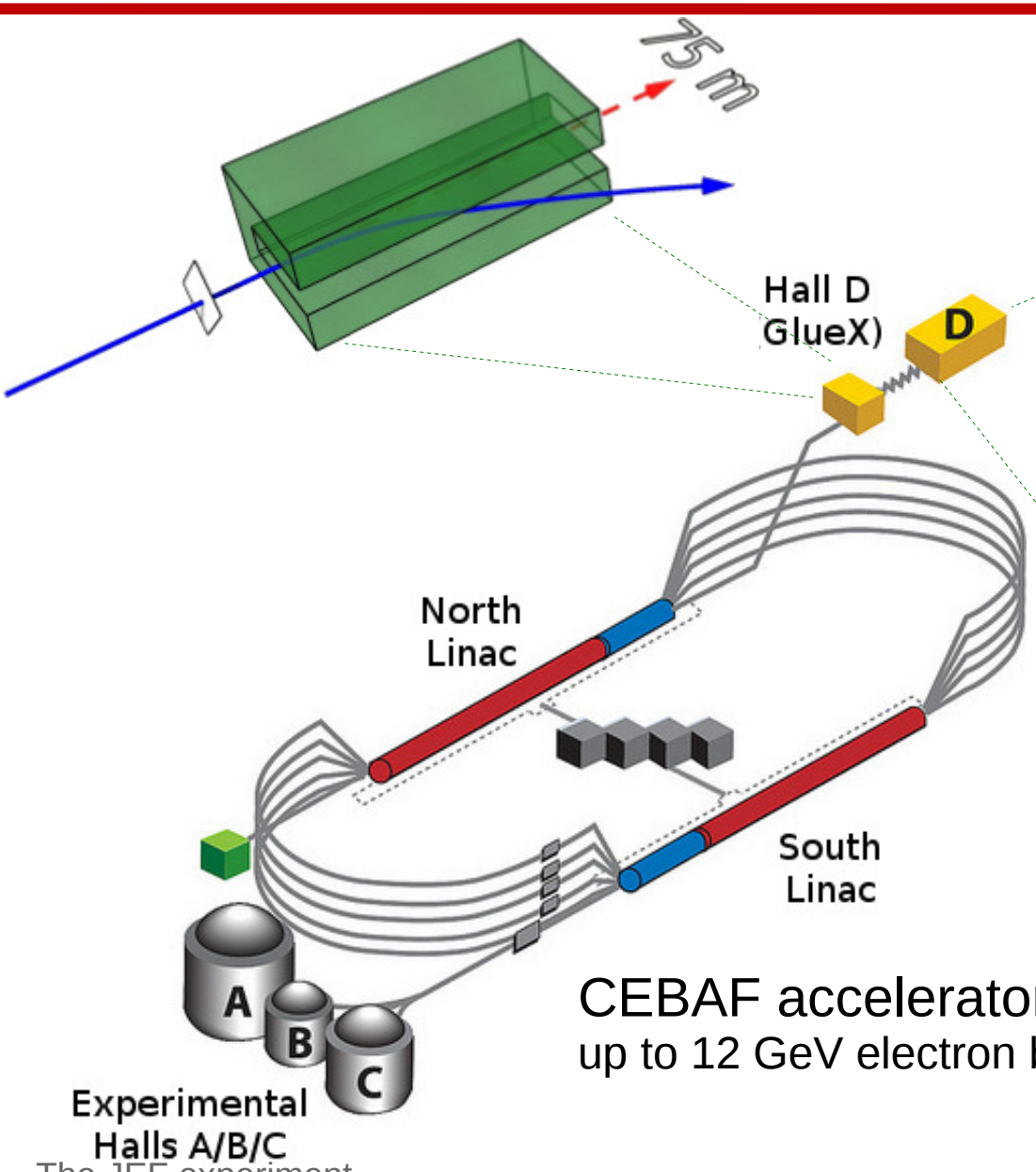




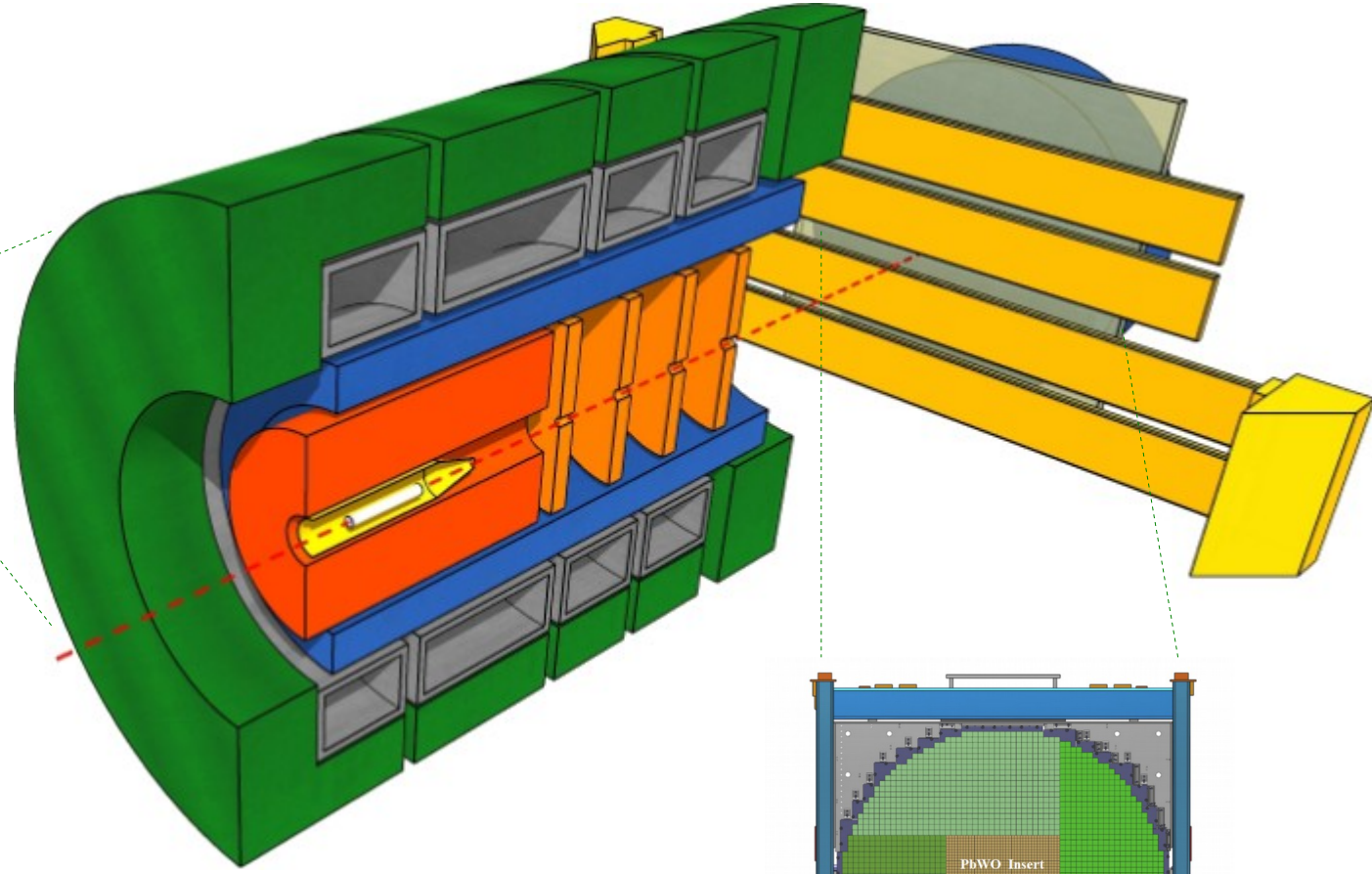
- Recent theory developments: Balytzkyi, arXiv:1811.01402
  - VMD + (Chiral Perturbation theory or Linear sigma model) (highly suppressed)
  - Result $\Gamma(\eta' \to \pi^0\gamma\gamma)$=1.6-3.0 keV disagrees with BESIII result $\Gamma(\eta' \to \pi^0\gamma\gamma) \approx$0.64 keV

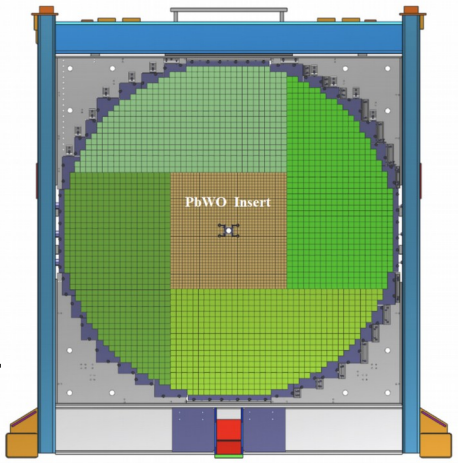
- **Potential to increase mass range for *B* search**

CEBAF and the GlueX detector



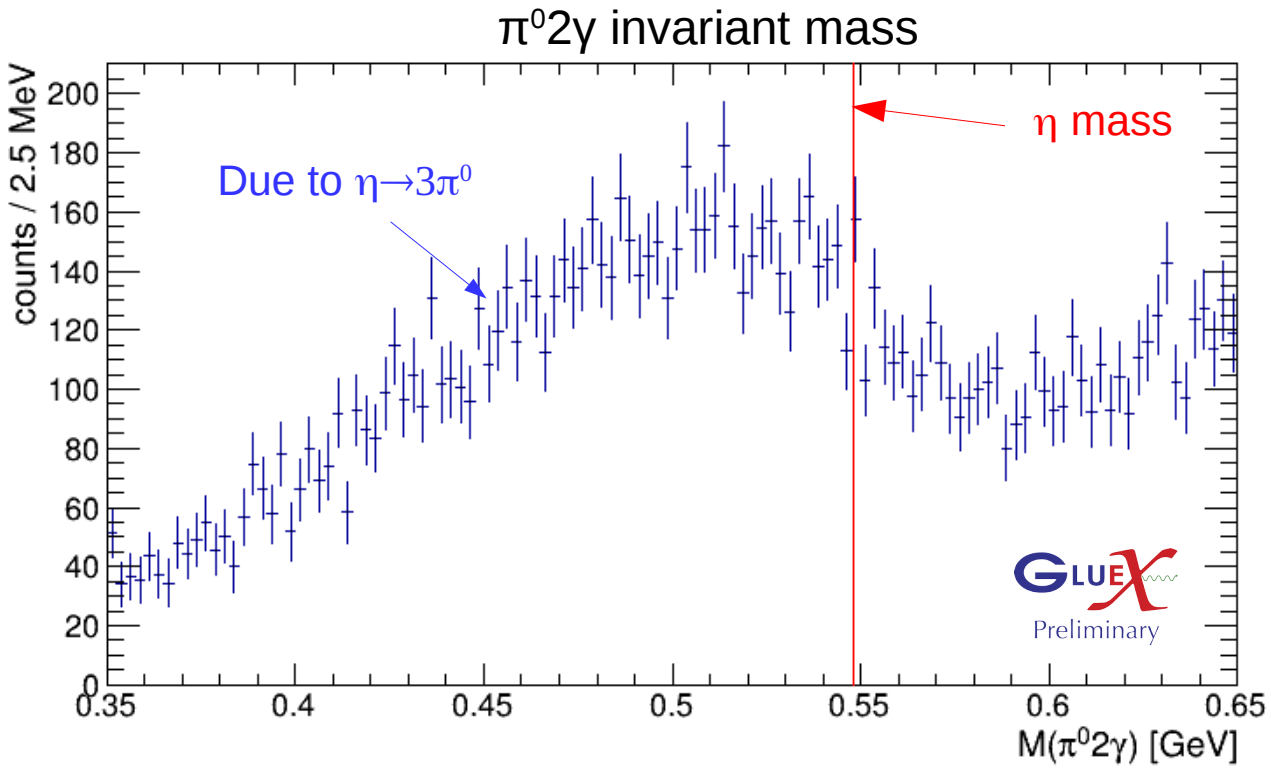
CEBAF accelerator:
up to 12 GeV electron beam





Forward
Calorimeter

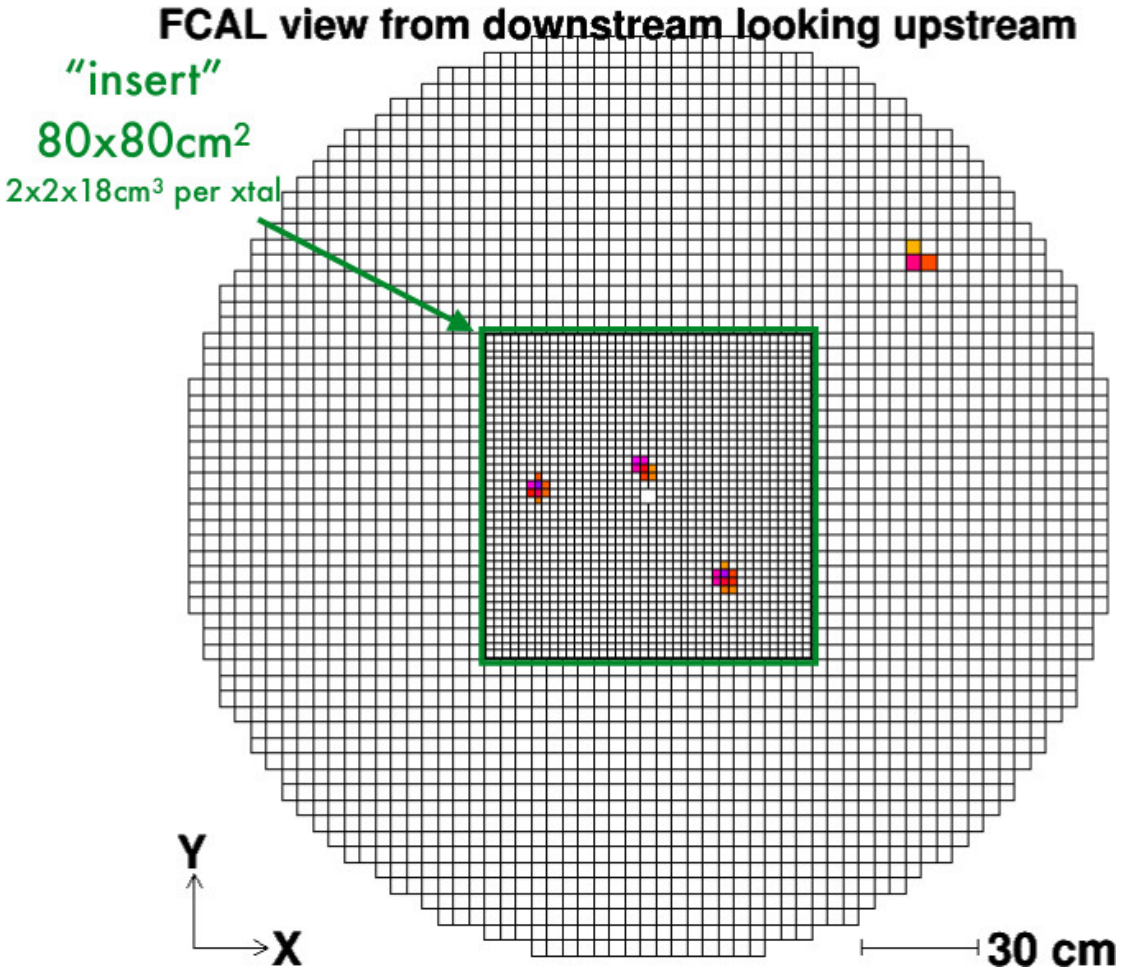
First look at $\gamma p \rightarrow p\pi^0\gamma\gamma$



- Subset of GlueX Phase I data
- Branching ratio is very small: BR=2.55x10^{-4}
- Significant source of background for $\eta \rightarrow \pi^0\gamma\gamma$:
  - $\eta \rightarrow 3\pi^0$ with missing/merged photons

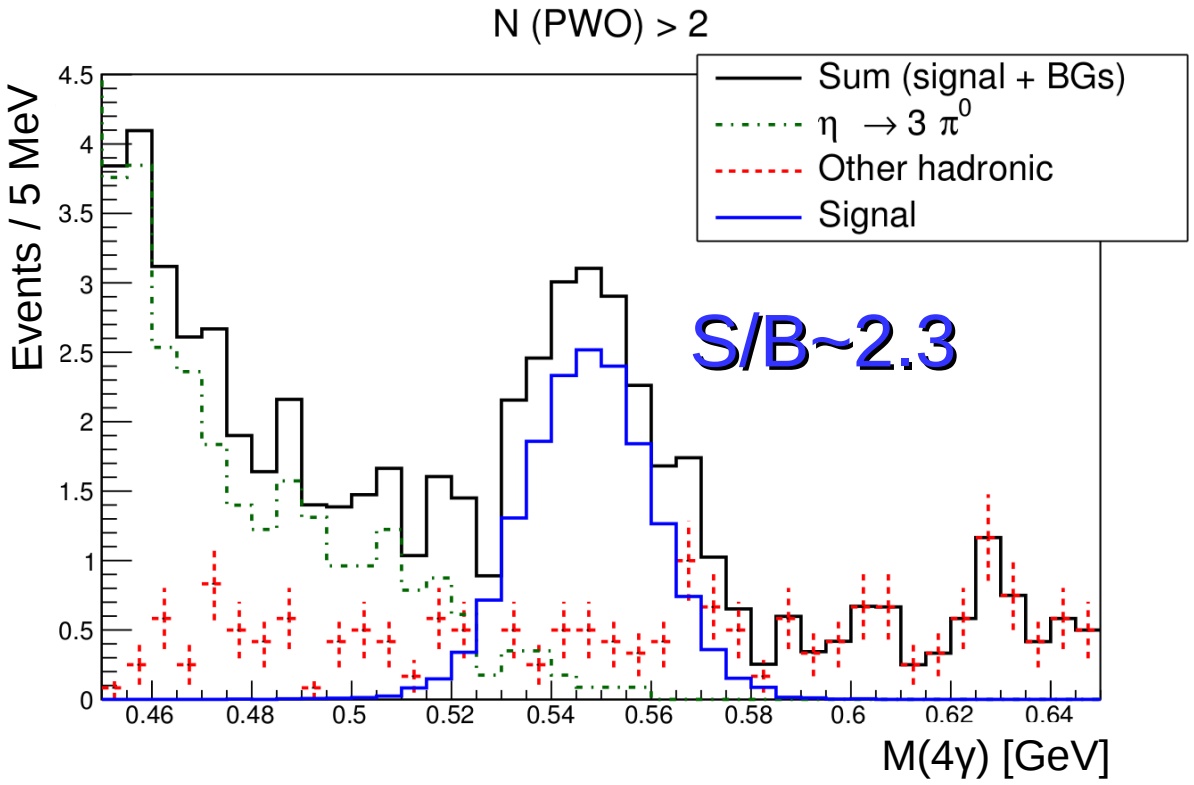
Resolution of Forward Calorimeter (FCAL) not sufficient to resolve rare decay channel...

Forward Calorimeter upgrade: $PbWO_4$ insert



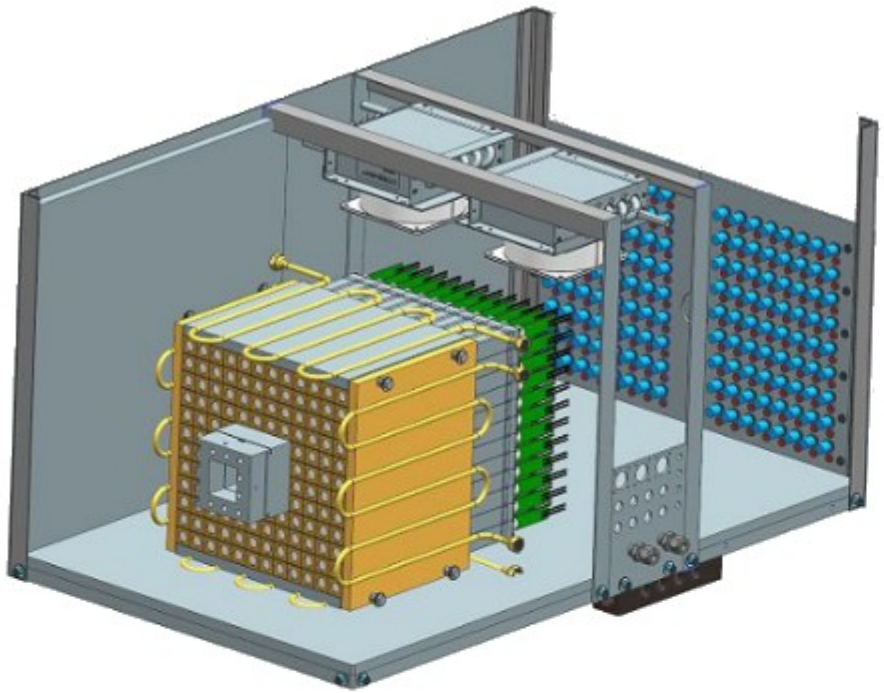
Simulated $\eta \rightarrow \pi^0 \gamma\gamma$ event

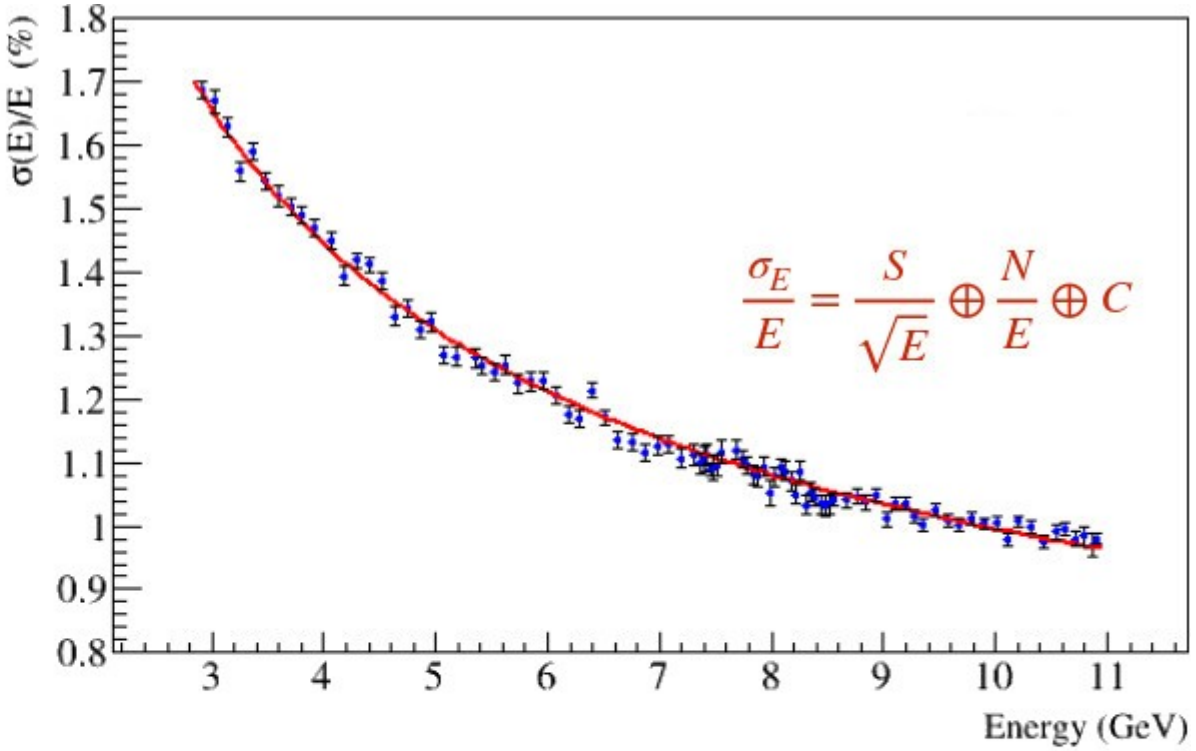
- Results of simulation for 1 day of running
  - Beam energy range: 8.4-11.7 GeV, intensity $N_\gamma \sim 1\times10^8$/s
  - Signal: $\eta \rightarrow \pi^0 \gamma\gamma$



Jefferson Lab

Lead tungstate calorimeter prototype





- Prototype: 12x12 $PbWO_4$ array
  - Successfully tested and used for the PrimEx-η experiment in 2019 and in fall 2021
  - NIM article:
    https://doi.org/10.1016/j.nima.2021.165683

ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

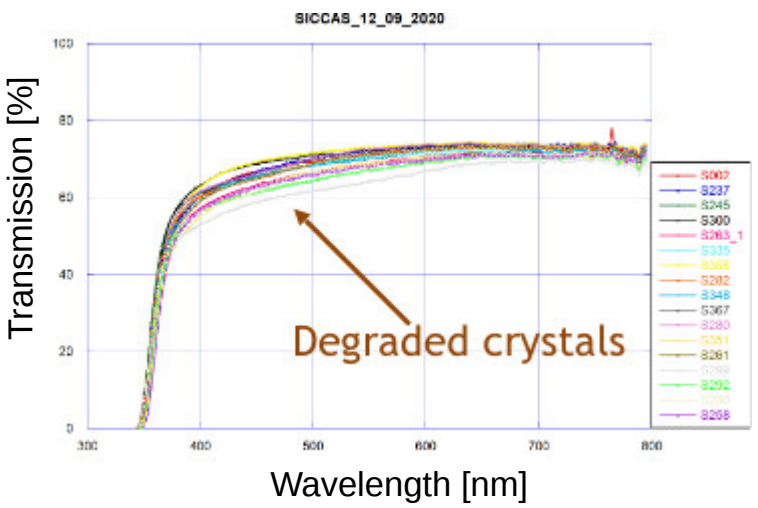
Available online 24 July 2021, 165683

In Press, Journal Pre-proof

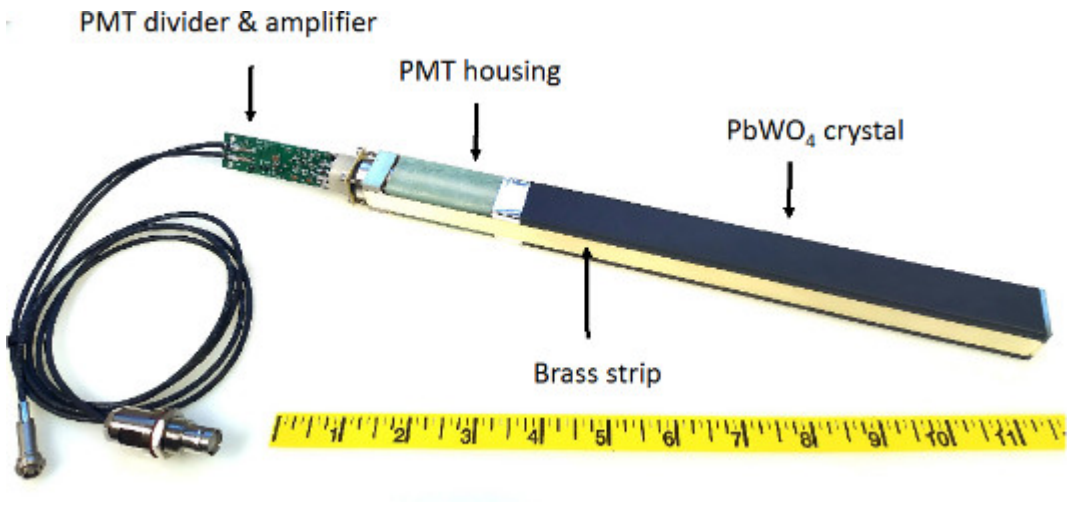
Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab ☆

Hardware status

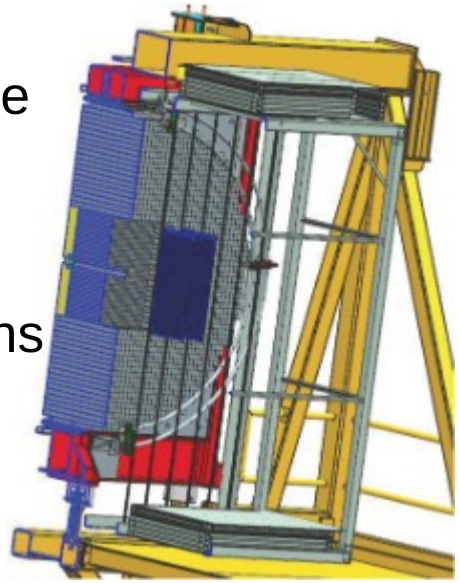
- $PbWO_4$ crystal Quality Assurance:
  - Surface, clarity, color, dimensions, light transmission, light yield



- Module assembly



- Fabrication and Installation
  - Finalizing engineering design for frame
  - Finalizing design of crystal cooling system
  - Modules ready for installation in 2023
  - Planned installation duration: 6 months

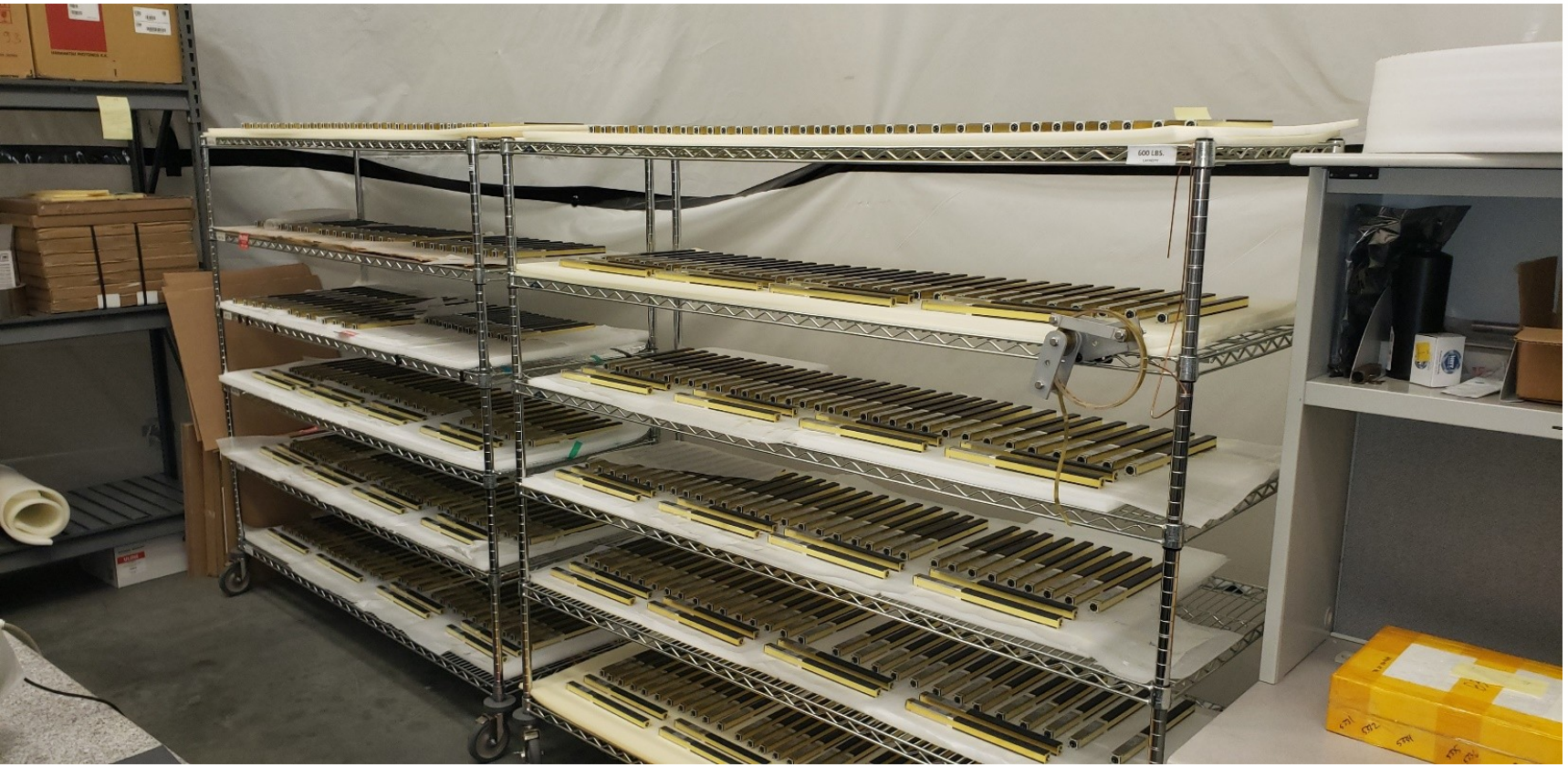


Module fabrication

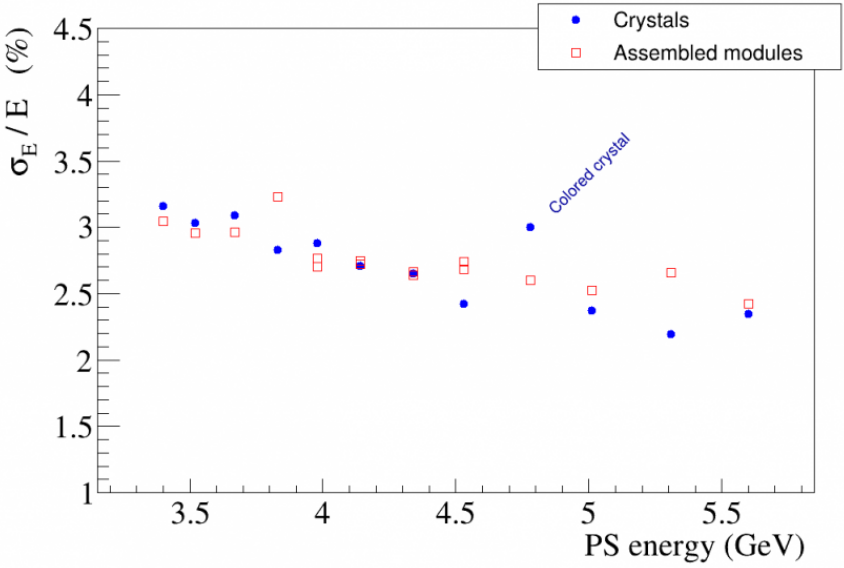
- Enormous progress due to help from undergraduate students from GWU, Lamar University, Northern VA Community College, and UNCW

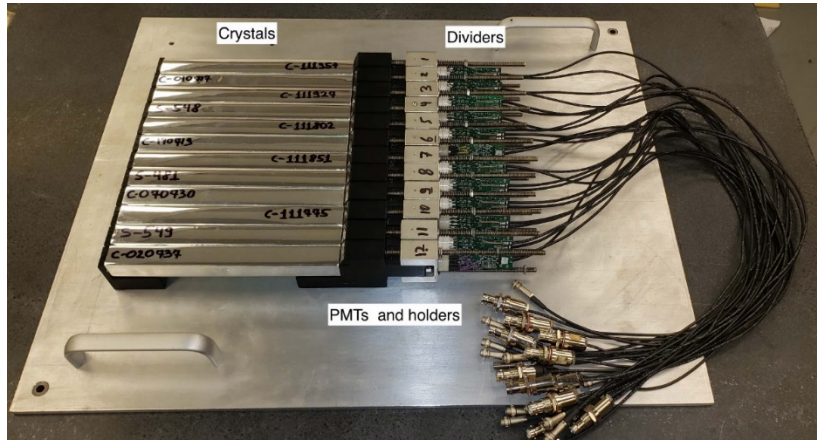
Fabricated modules

- Significant progress: **1206** / 1596 modules have been fabricated!



Energy resolution of a single crystal





Jefferson Lab

Summary and outlook

- η decays allow access to many interesting physics channels:
  - Testing the role of scalar dynamics in chiral perturbation theory for $\eta \to \pi^0 \gamma\gamma$
  - Searching for dark sector B-boson
  - Searching for CVPC interactions
  - Measurement of light quark mass ratio
- Rare decay channel requires upgrade to Forward Calorimeter
  - Shipments of $PbWO_4$ crystals coming to JLab
  - Quality assurance procedures in place
  - Modules under construction
- Data taking with upgraded Forward Calorimeter expected in 2024

http://www.gluex.org/thanks.html

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.