The **J**efferson Lab **E**ta **F**actory (JEF) experiment

Bill Briscoe

for the JEF Program in the

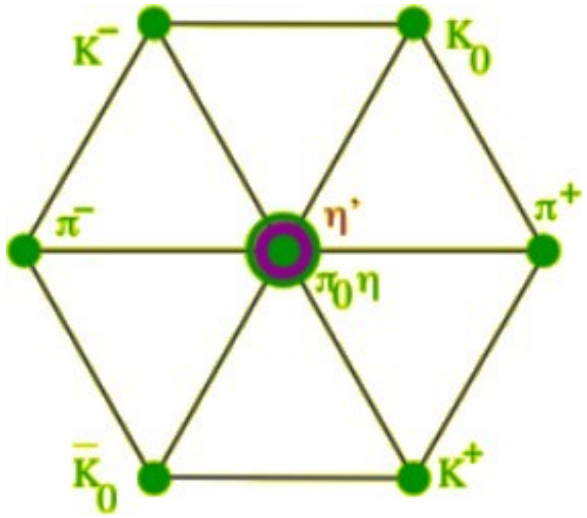
GlueX Collaboration

We will discuss:

- Quick overview of physics channels involving η decays
- CEBAF and the GlueX detector
- Upgrade to standard GlueX equipment: PbWO4 crystals

Thanks to Simon Taylor, Igal Jaegle, Alexander Somov and Liping Gan for material from previous reports

η – excellent probe for QCD and Beyond Standard Model physics



- Goldstone boson – spontaneous breaking of QCD chiral symmetry
  - Bridge our understanding of low-energy hadron dynamics and underlying QCD and
  - maybe answer some pending questions of status as GB
- Decay width Γ_η =1.3 keV is narrow
  - Width being less than the 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

Channels to be Explored by JEF

- Search for 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 VMD & scalar resonances in Chiral Perturbation Theory → $O(p^6)$ LEC's in the chiral Lagrangian
- Directly constrain C-violating/Parity-conserving (CVPC) → new physics
- Constrains 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 – fundamental QCD parameters
  - $\eta \to \pi^+\pi^-\pi^0$ – constrains light quark masses – source for isospin violation

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

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

← small – can be ignored in first order

- 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:

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

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

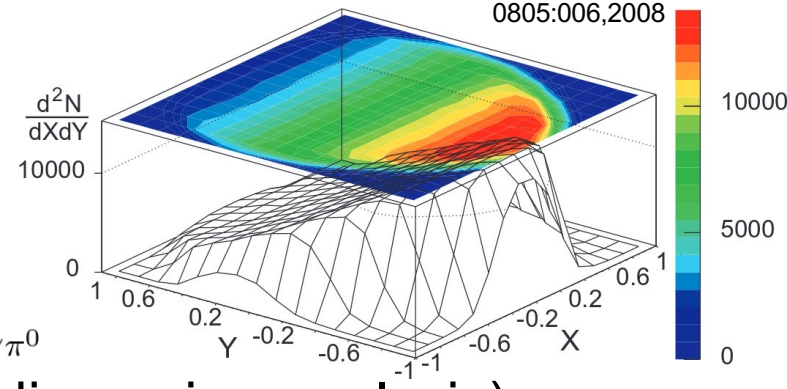
$$\Gamma(X,Y) \propto 1 + aY + bY^2 + dX^2 + fY^3 + hX^2Y + \cdots$$

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

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

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

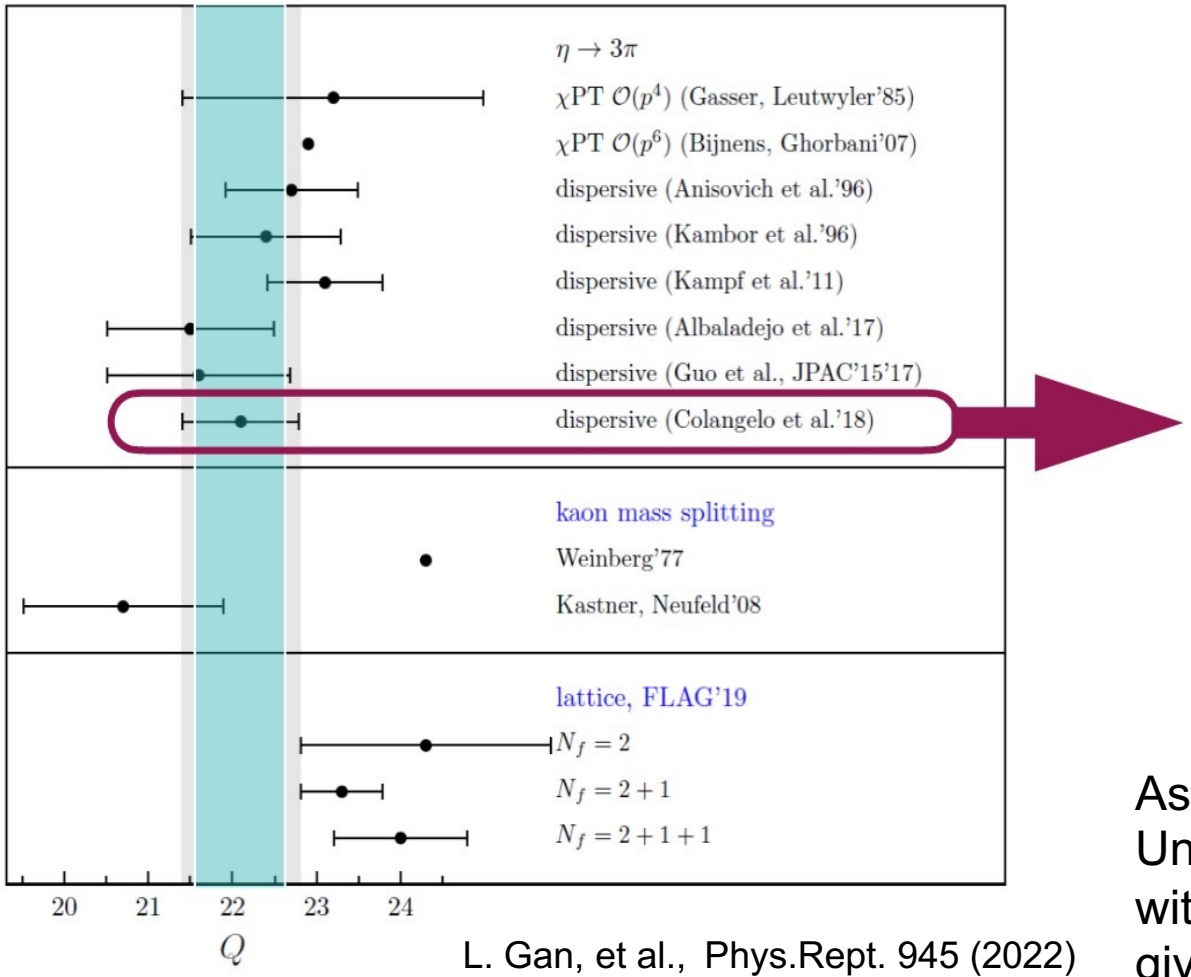
F. Ambrosino, et al . JHEP (feom KLOE) 0805:006,2008



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

Light quark mass ratio: current status

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

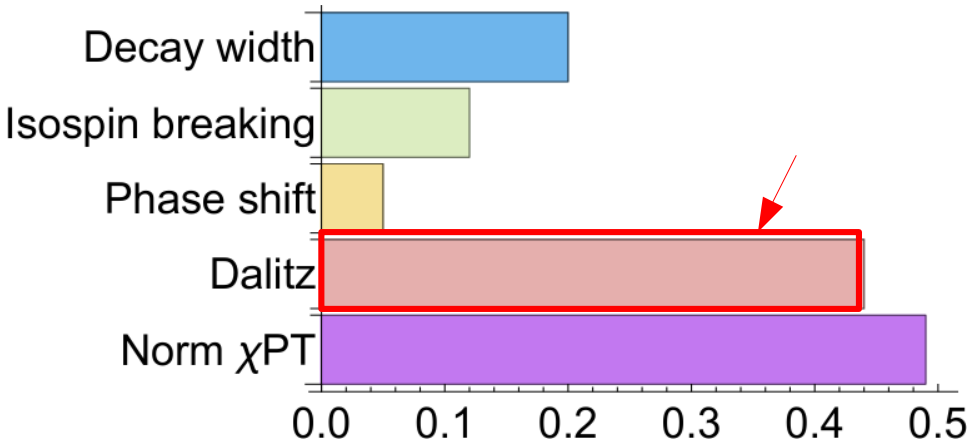


L. Gan, et al., Phys.Rept. 945 (2022)

- Amplitude:

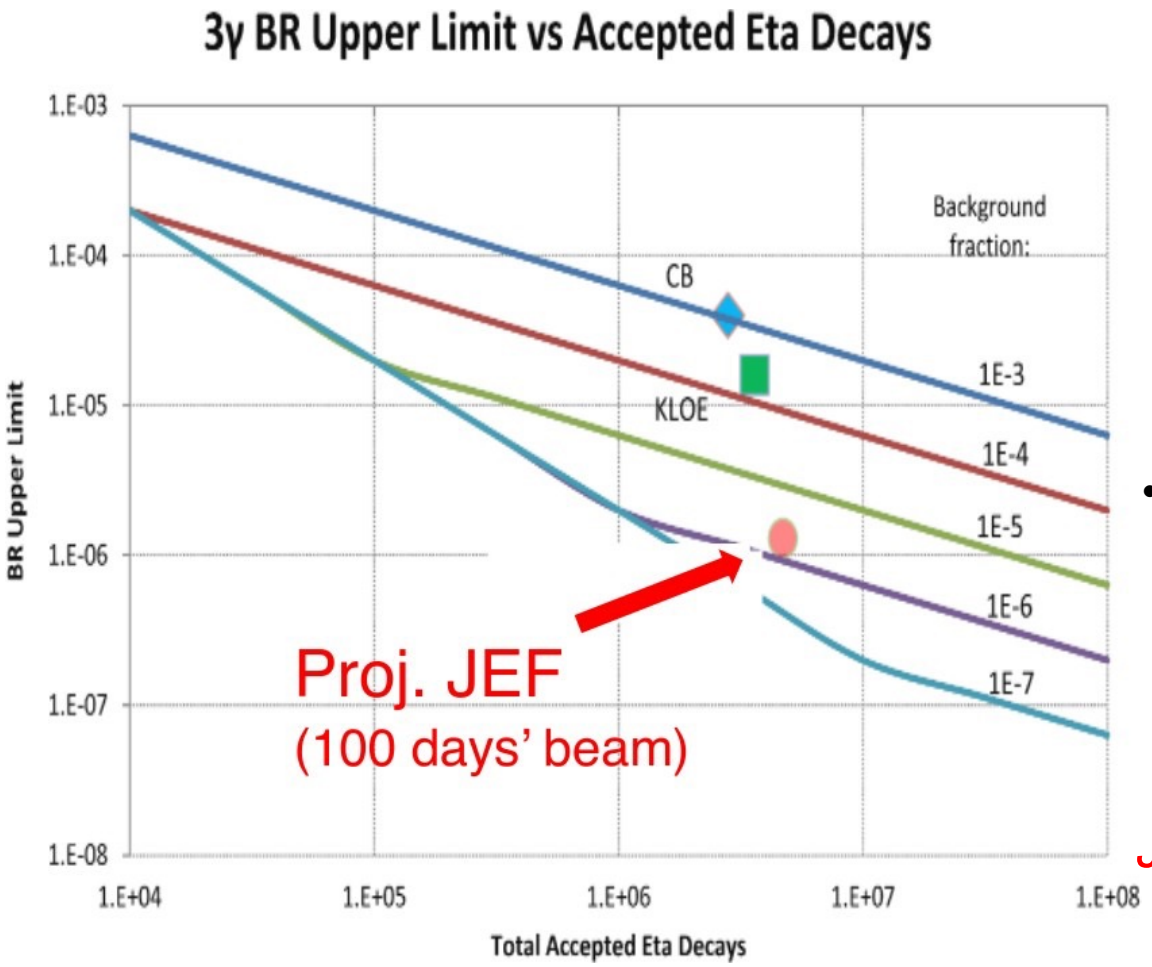
$$A = (m_u - m_d)A_1 + \alpha_{em}A_2, \quad \alpha_{em} \sim small$$

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



Assessment of uncertainties on quark mass double Ratio. Uncertainty of partial decay width dominated by total width with branching ratio B(η → π+π−π0) = Γ(η → π+π−π0)/Γη giving a negligible contribution (±0.067B).

C-violating/parity-conserving (CVPC) physics

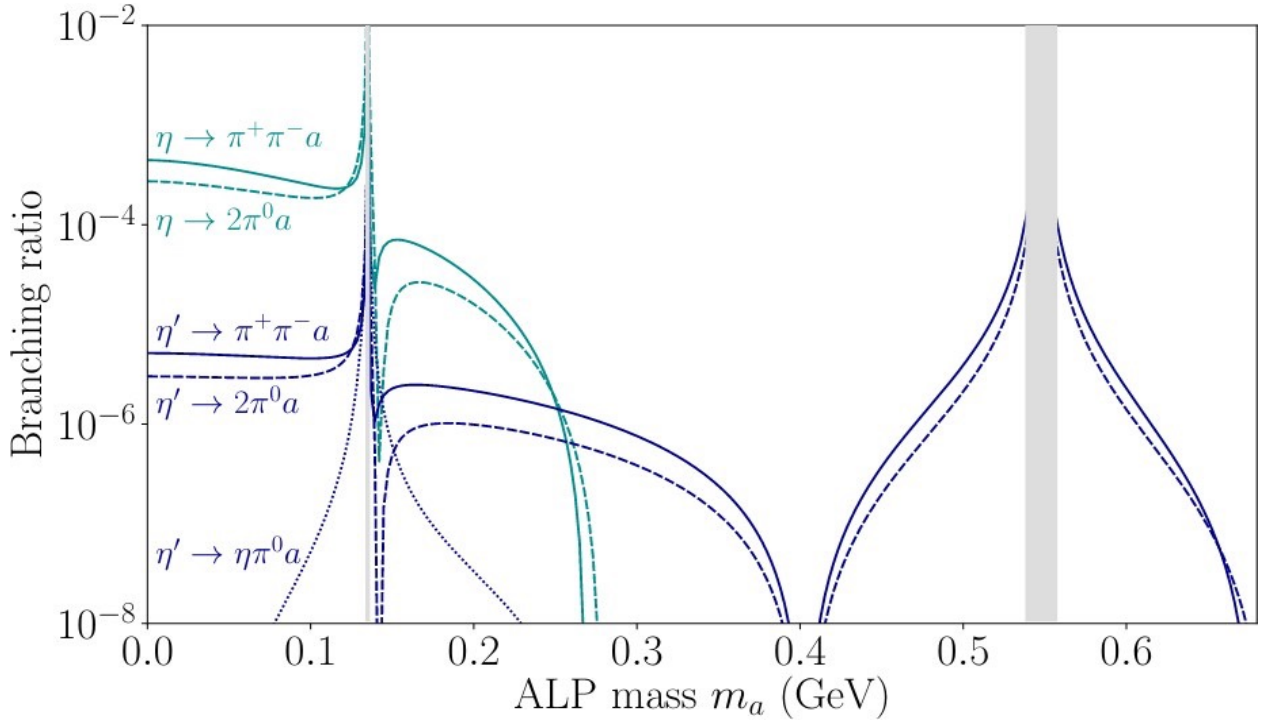


- C(ch conj) violation only in weak interactions.
- Strong and EM forces conserve C-parity.
- Focus on $\eta \to 3\gamma$:
  - Bernstein, Feinberg, and Lee: new C- and T-violating, P- conserving interaction Phys.Rev., 139, B1650(1965).
  - Theoretical estimate: $BR(\eta \to 3\gamma) < 10^{-2}$ Tarasov, 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: expects at least 1 order of magnitude better

Search for Axion-like particles (ALPs)

- Proposed light pseudoscalar (*a)* mediator between Standard Model and Dark Matter
- Dominant coupling to gluons
- BRs for ALP production in η decays (light blue) and η′ decays (dark blue), assuming no direct quark-ALP coupling.
- Channels include:
  η, η′ → $\pi^+\pi^-$a (solid) – *a*→γγ, e^+e^-, $\mu^+\mu^-$
  η, η′ → $2\pi^0$a (dashed) – *a*→$\pi^+\pi^-\gamma$, 3π ,
  η′ → ηπ^0a (dotted) – *a*→γγ, e^+e^-, $\mu^+\mu^-$
- BR scale as 1/ f_a^2 and ALP decay constant fixed to f_a = 10 GeV, equivalent to an effective mass scale ≈ 3 TeV.
- Regions around $m_a = M\pi^0$ and $m_a = M_\eta$ are shaded out - ALP–meson mixing angles become larger that 0.1



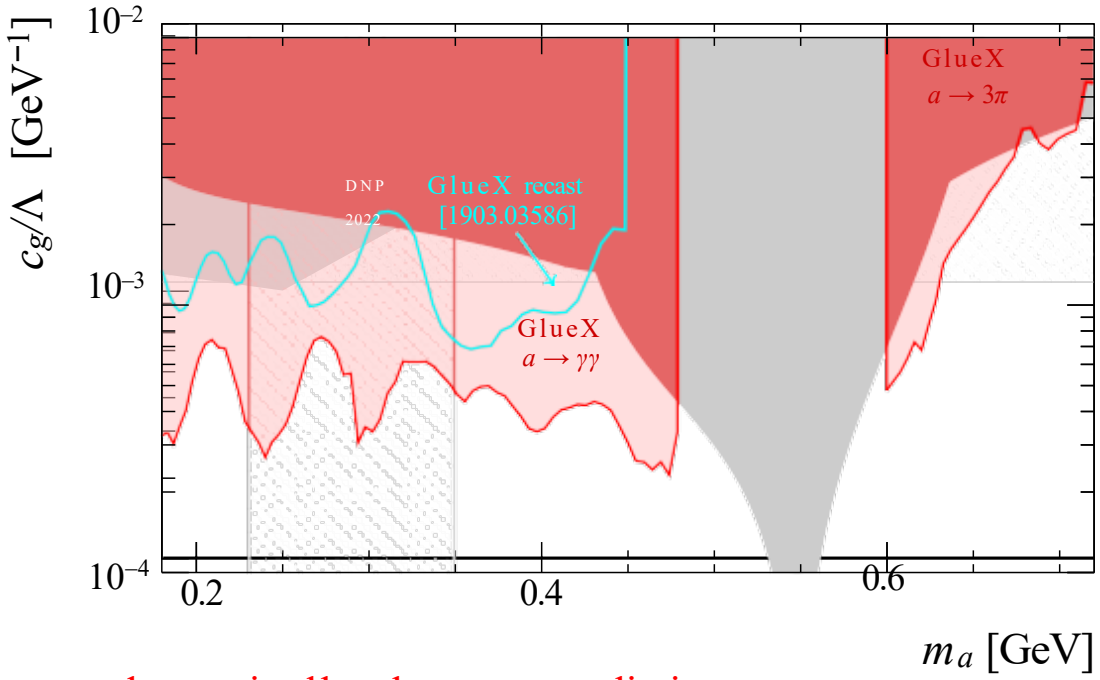
L. Gan, et al., Phys.Rept. 945 (2022)

GlueX limit on ALP coupling to gluons

$\gamma p \rightarrow ap$, $L = 170\ \mathrm{pb}^{-1}$

Y. Yang et al – PRD 105, 052007 (2022) - arxiv:2109.13439

$a \rightarrow \gamma\gamma$ $a \rightarrow \pi^+\pi^-\pi^0$



Improve dramatically the current limit

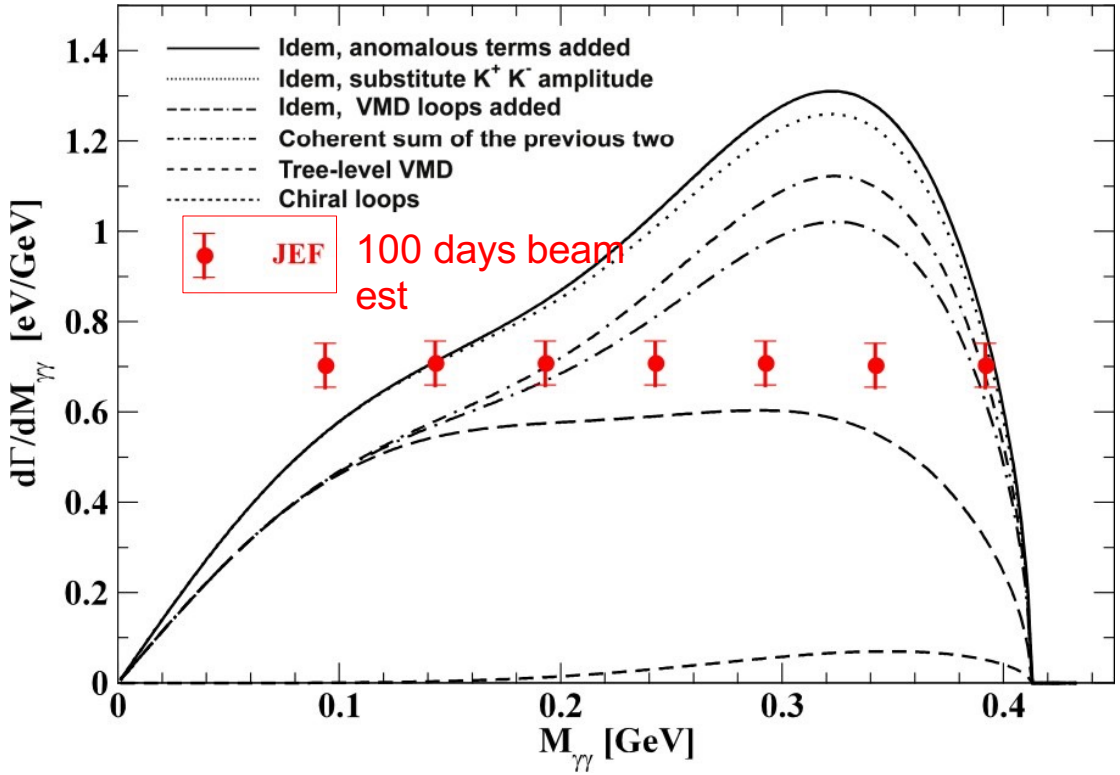
Results from (red) this search compared to the (gray) previous bounds from LEP, φ and η' decays, and the (cyan line) GlueX limits recast. In addition, limits obtained from kaon decays and the B-meson lifetime, which have $O(1)$ uncertainties induced by the unknown UV physics, are shown as hashed regions.

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

- Unique probe for high order Chiral Perturbation Theory (cPT)
  - 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)

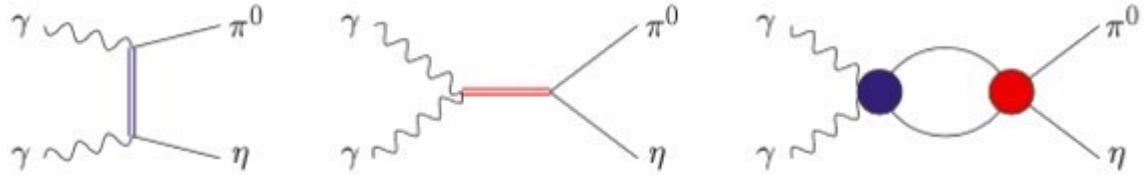
  - Access two Low Energy Constants



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

- Shape of Dalitz distribution (M_{gg}) sensitive to role of scalar resonances

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

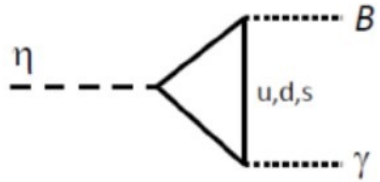


Portal to dark sector: *B*-boson

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

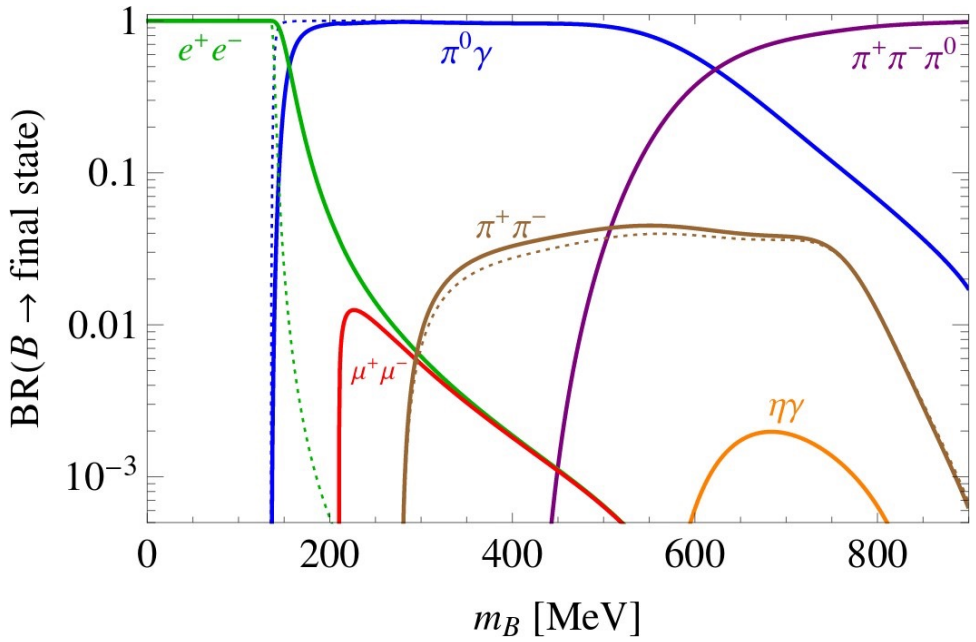
  A.E. Nelson, N. Tetradis,
  Phys. Lett., B221, 80 (1989)

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

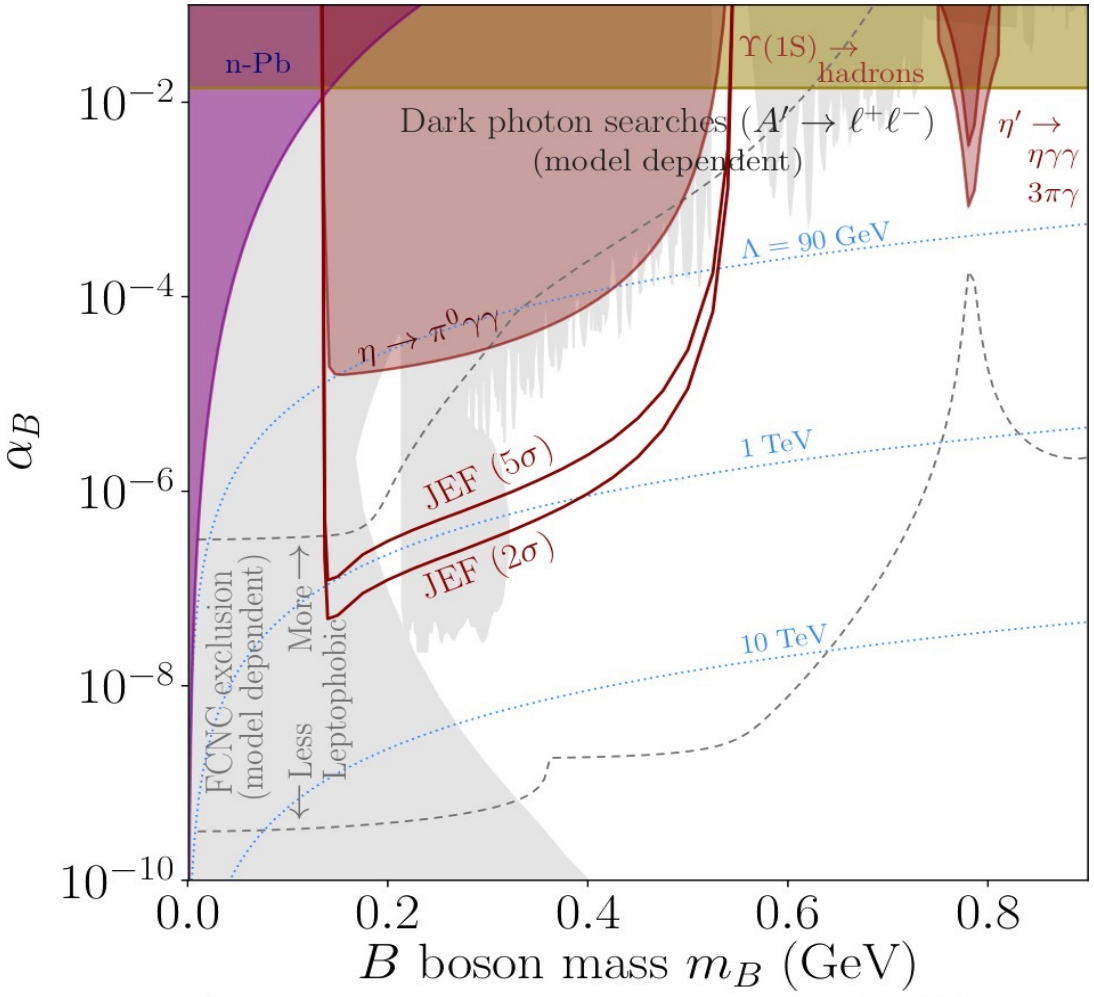


Triangle diagram

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



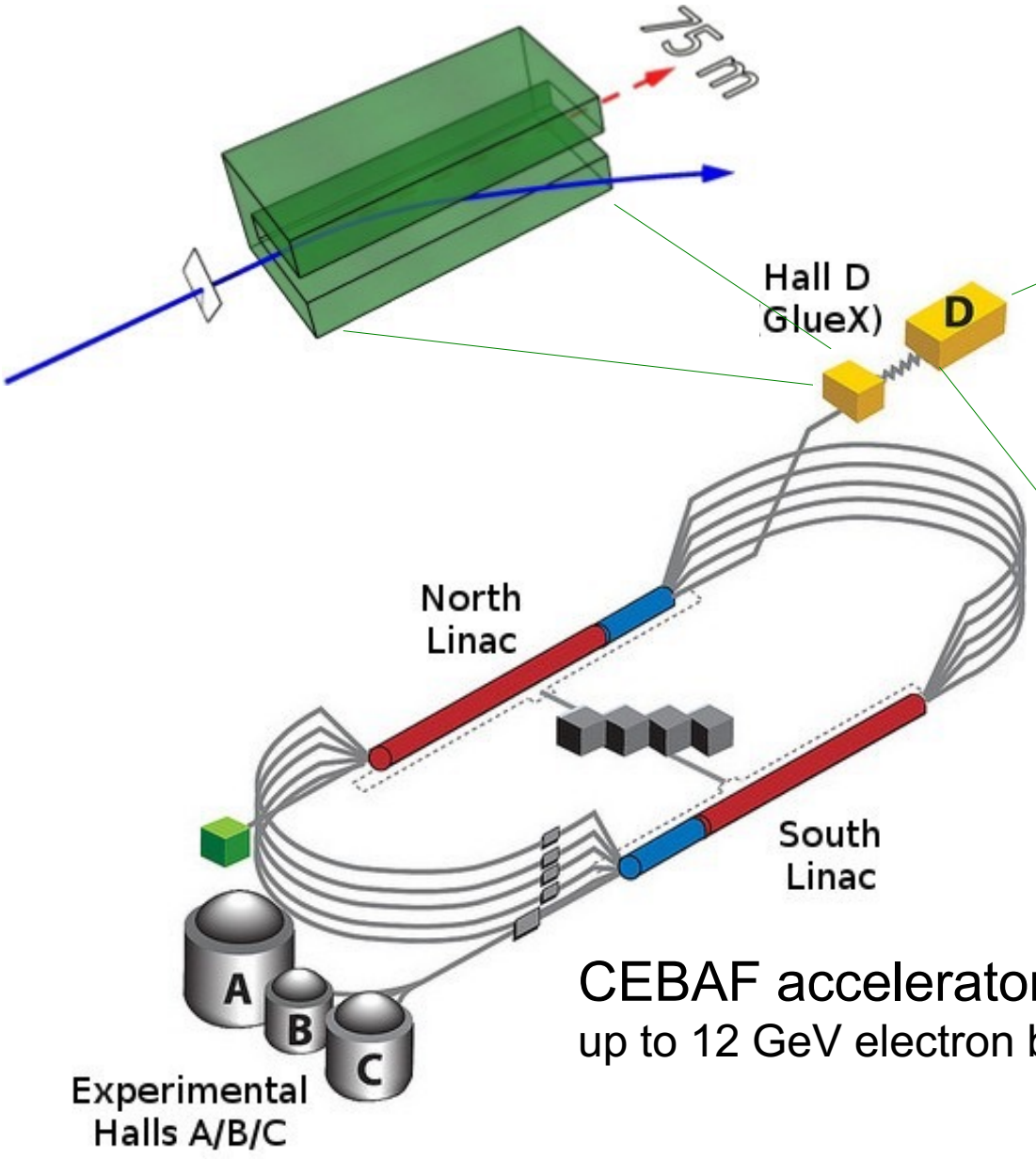
S. Tulin, Phys.Rev. D89, 14008 (2014)



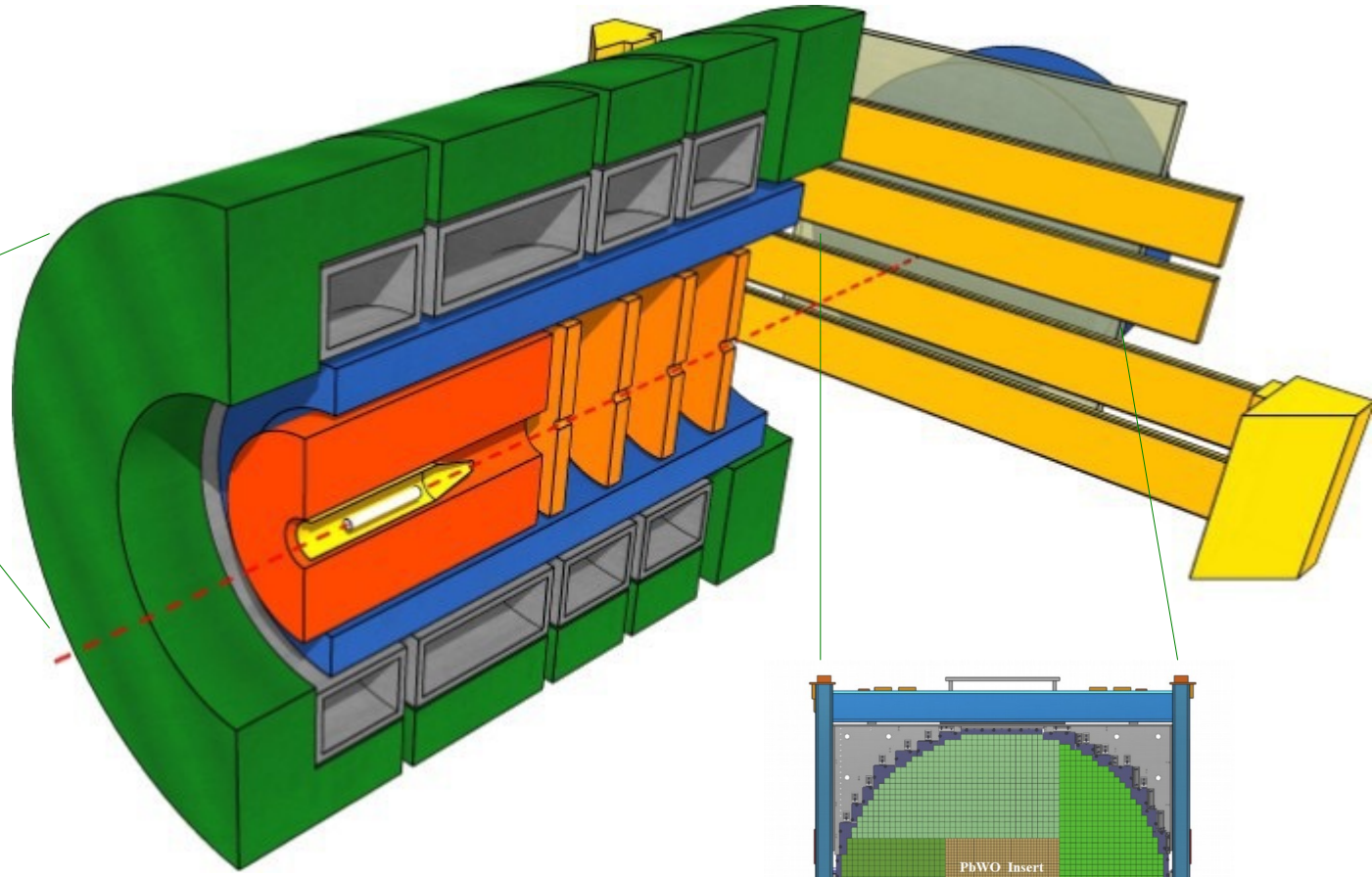
JEF Competitive – 100 day estimate

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

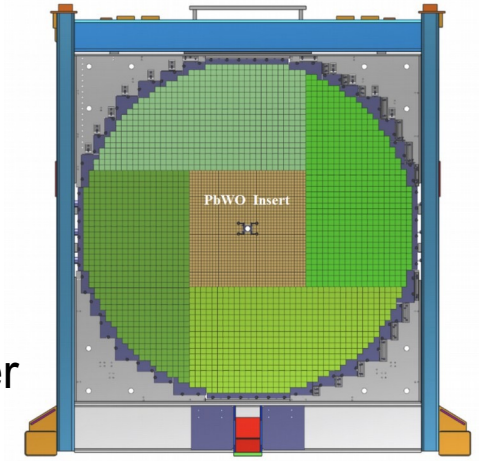
CEBAF and the GlueX detector



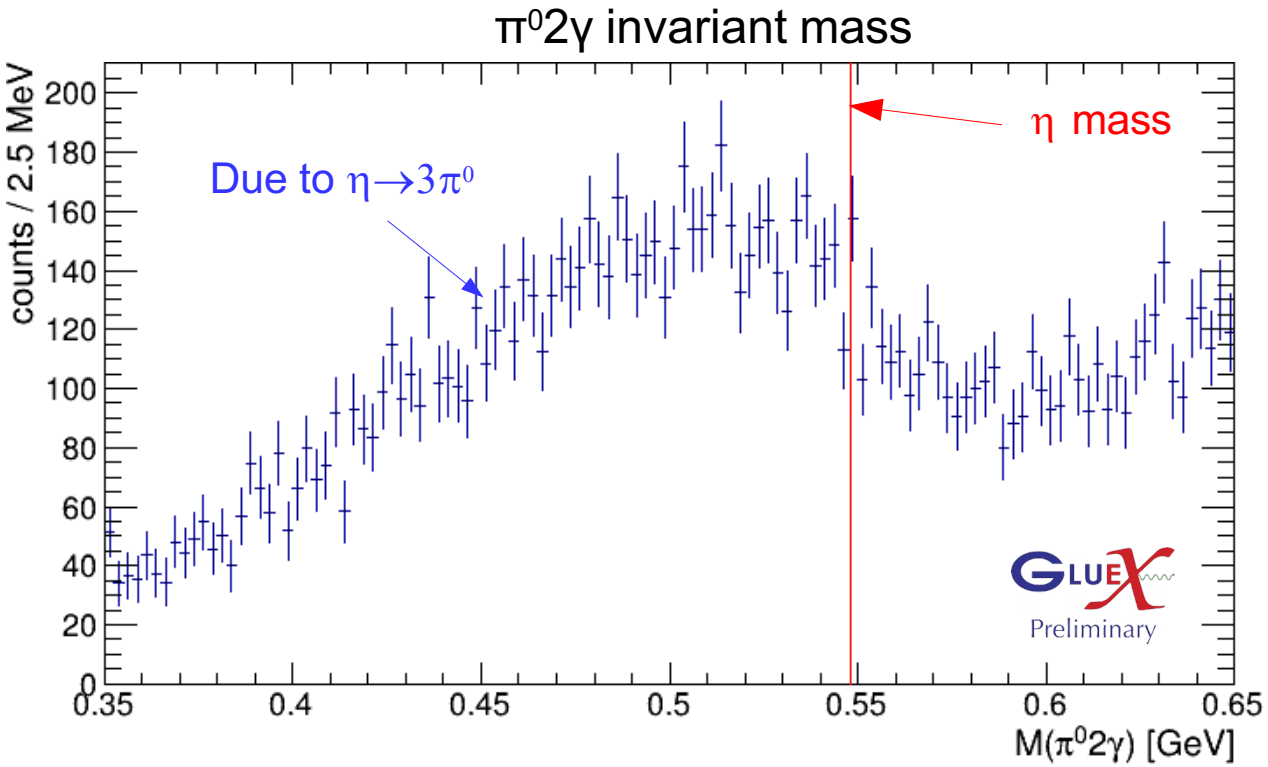
CEBAF accelerator:
up to 12 GeV electron beam



Forward
Calorimeter



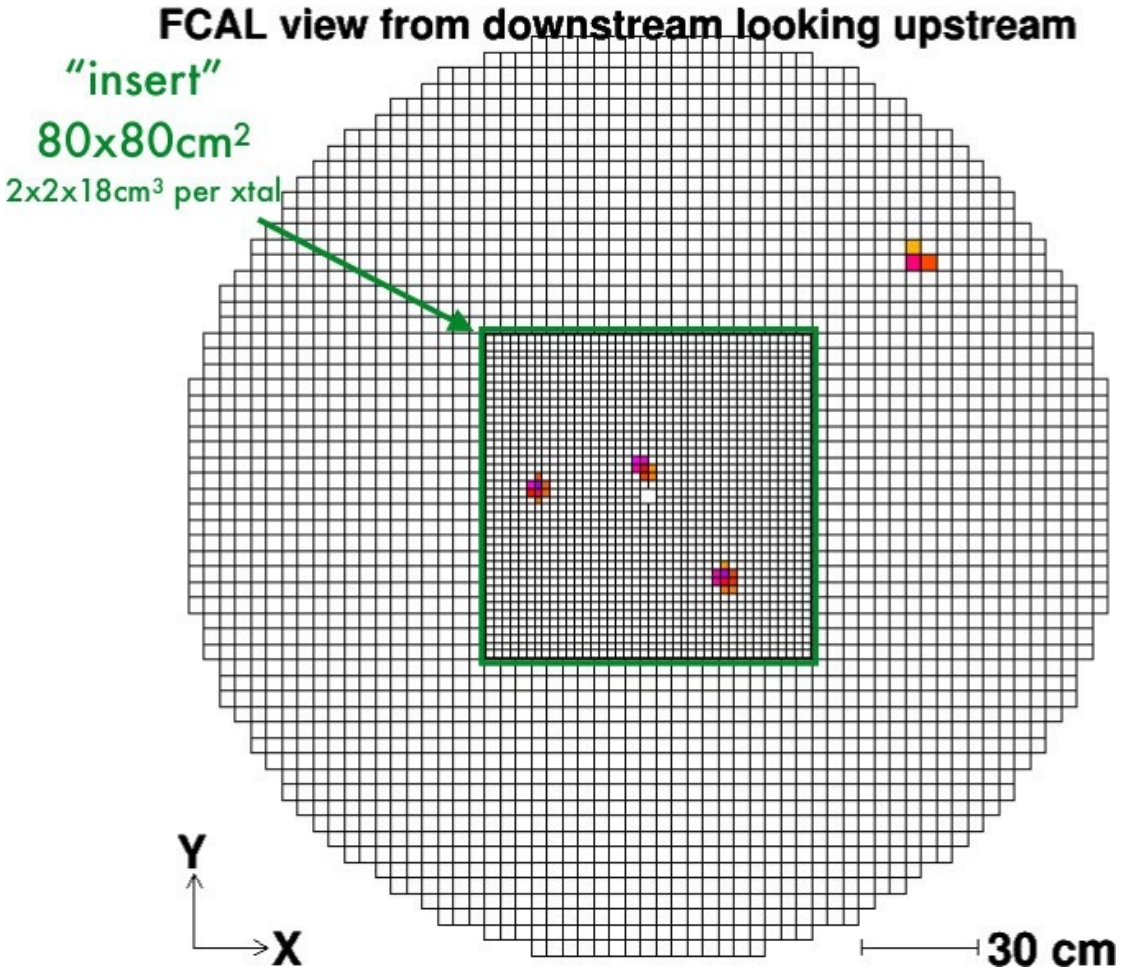
First look at $\gamma p \rightarrow p\pi^0\gamma\gamma$



- 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

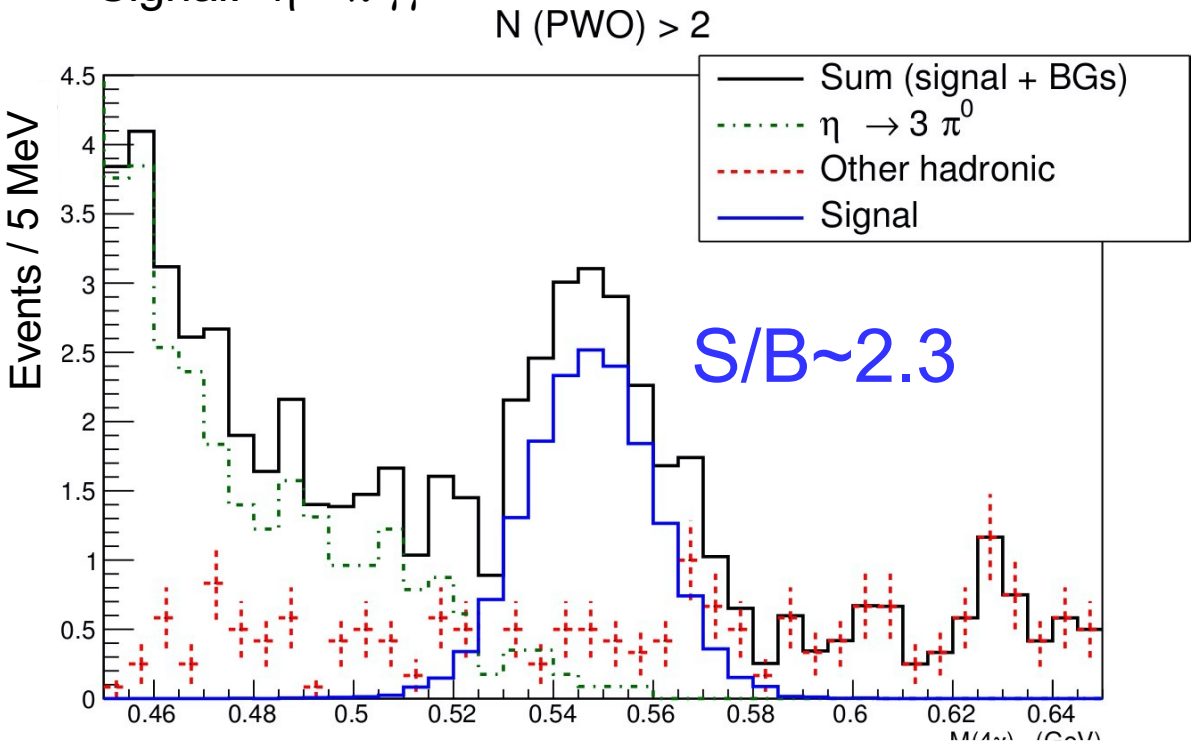
Resolution of Forward Calorimeter (FCAL) not sufficient to resolve rare decay channel...

Forward Calorimeter upgrade: $PbWO_4$ insert

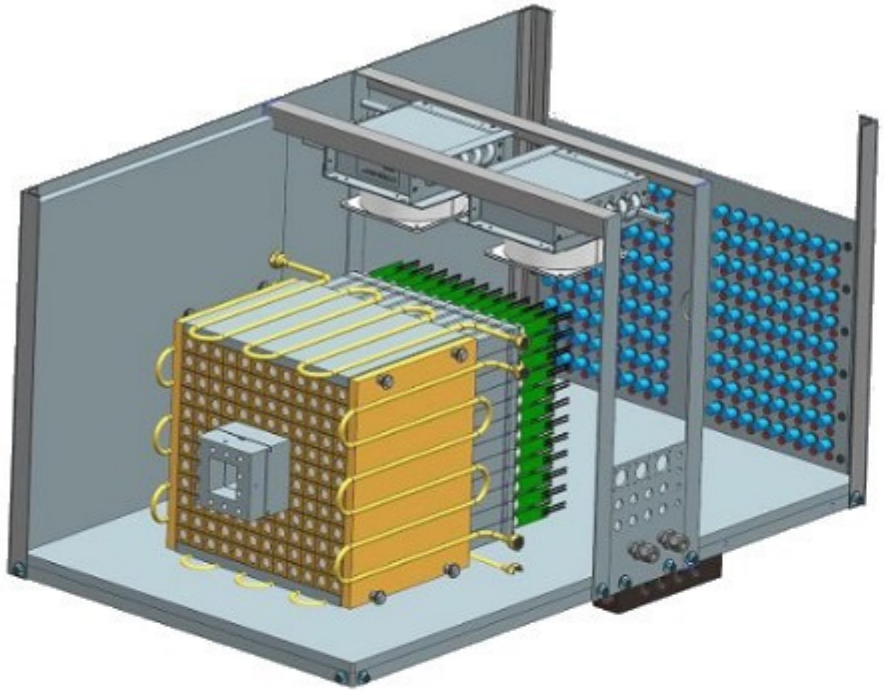


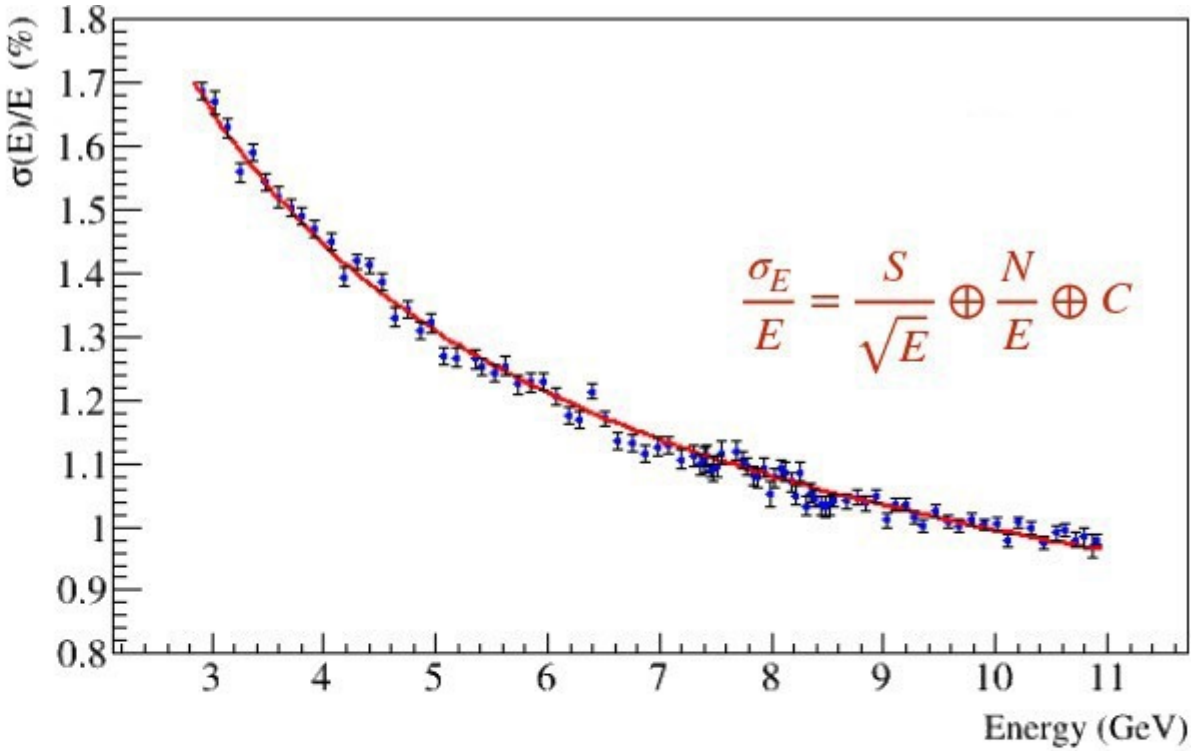
Simulated $\eta \to \pi^0\gamma\gamma$ event

- Results of simulation for 1 day of running
  - Beam energy range: 8.4-11.7 GeV, intensity $N\gamma \sim 1x10^8$/s
  - Signal: $\eta \to \pi^0\gamma\gamma$



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

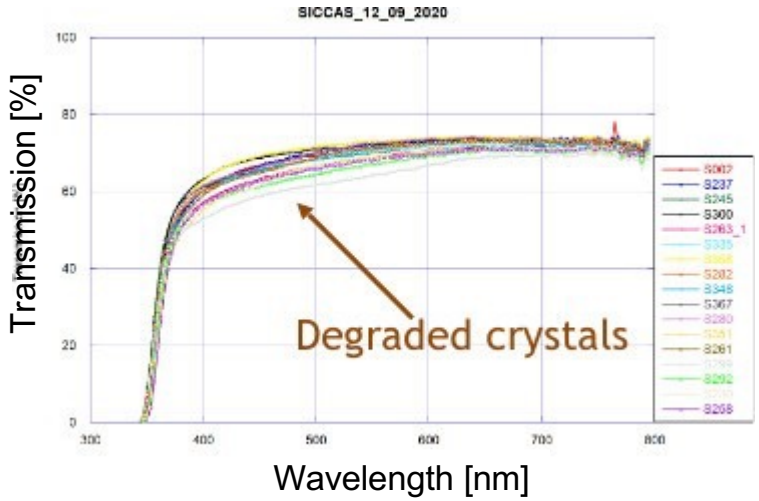
Available online 24 July 2021, 165683

In Press, Journal Pre-proof

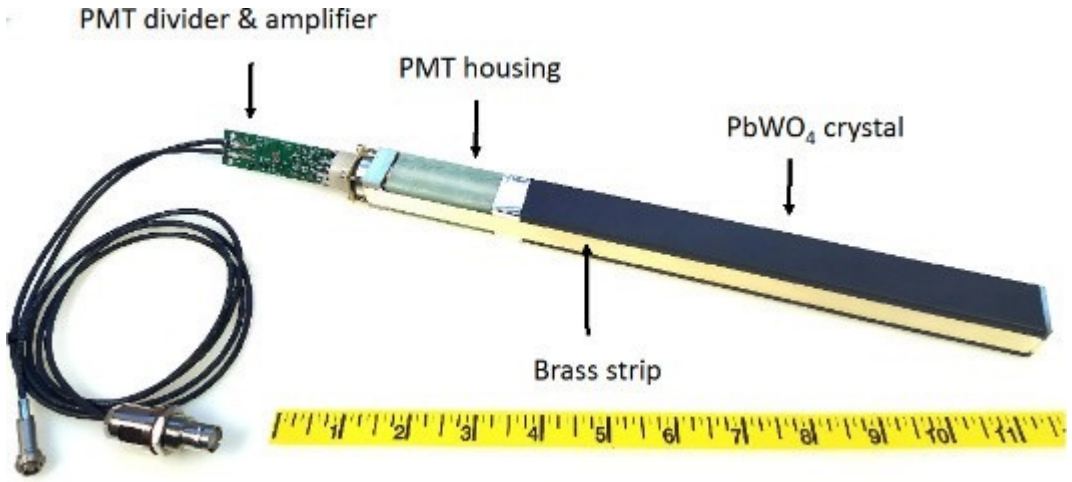
Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab ☆

Hardware status

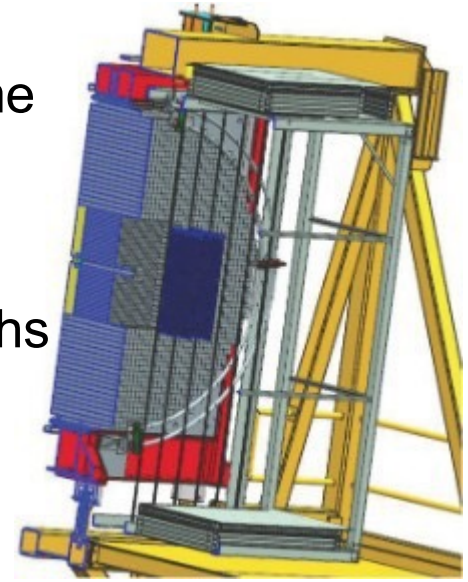
- $PbWO_4$ crystal Quality Assurance:
  - Surface, clarity, color, dimensions, light transmission, light yield



- Module assembly

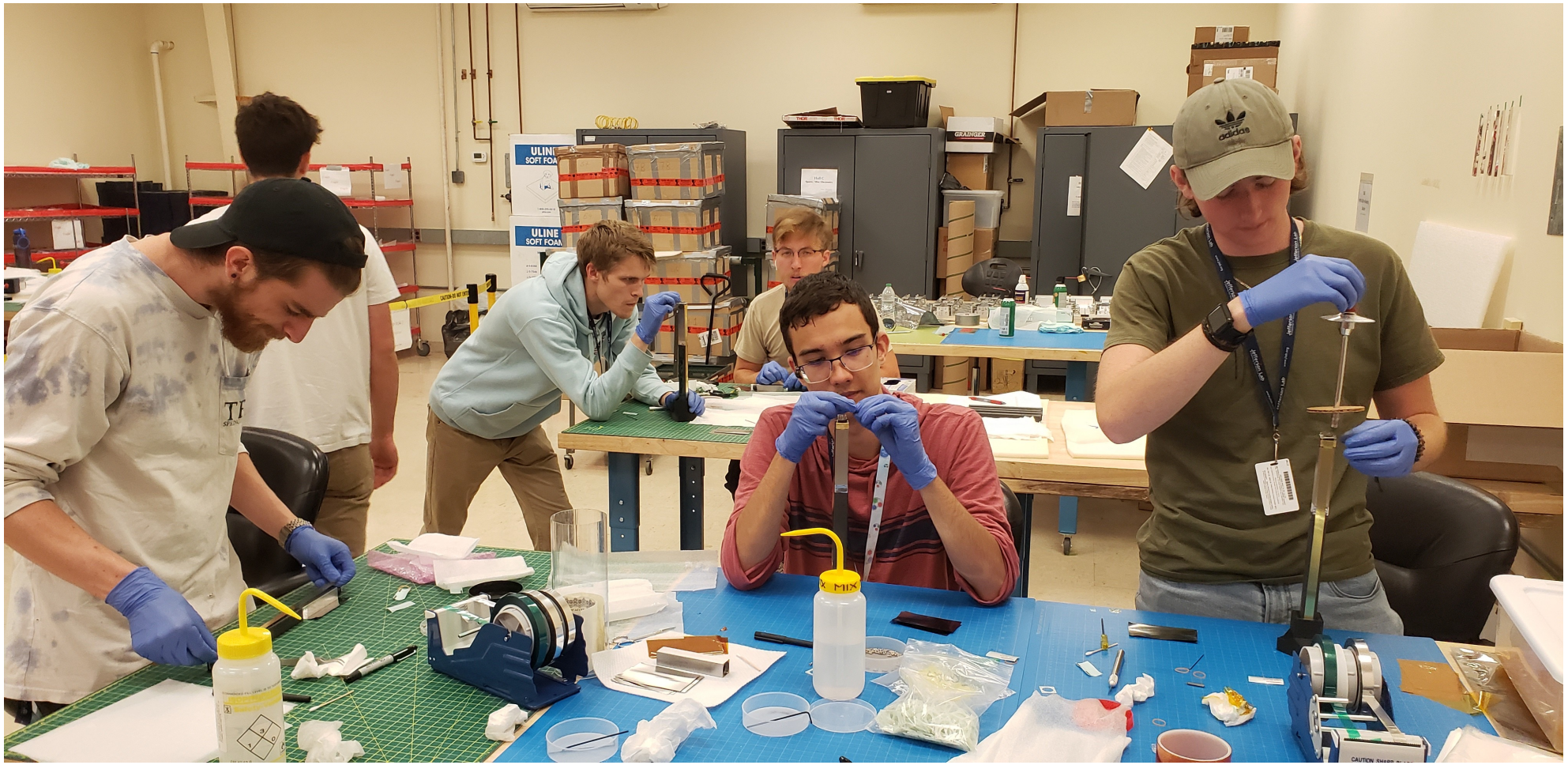


- Fabrication and Installation
  - Finalizing engineering design for frame
  - Finalizing design of crystal cooling system
  - Modules ready for installation
  - Planned installation duration: 6 months



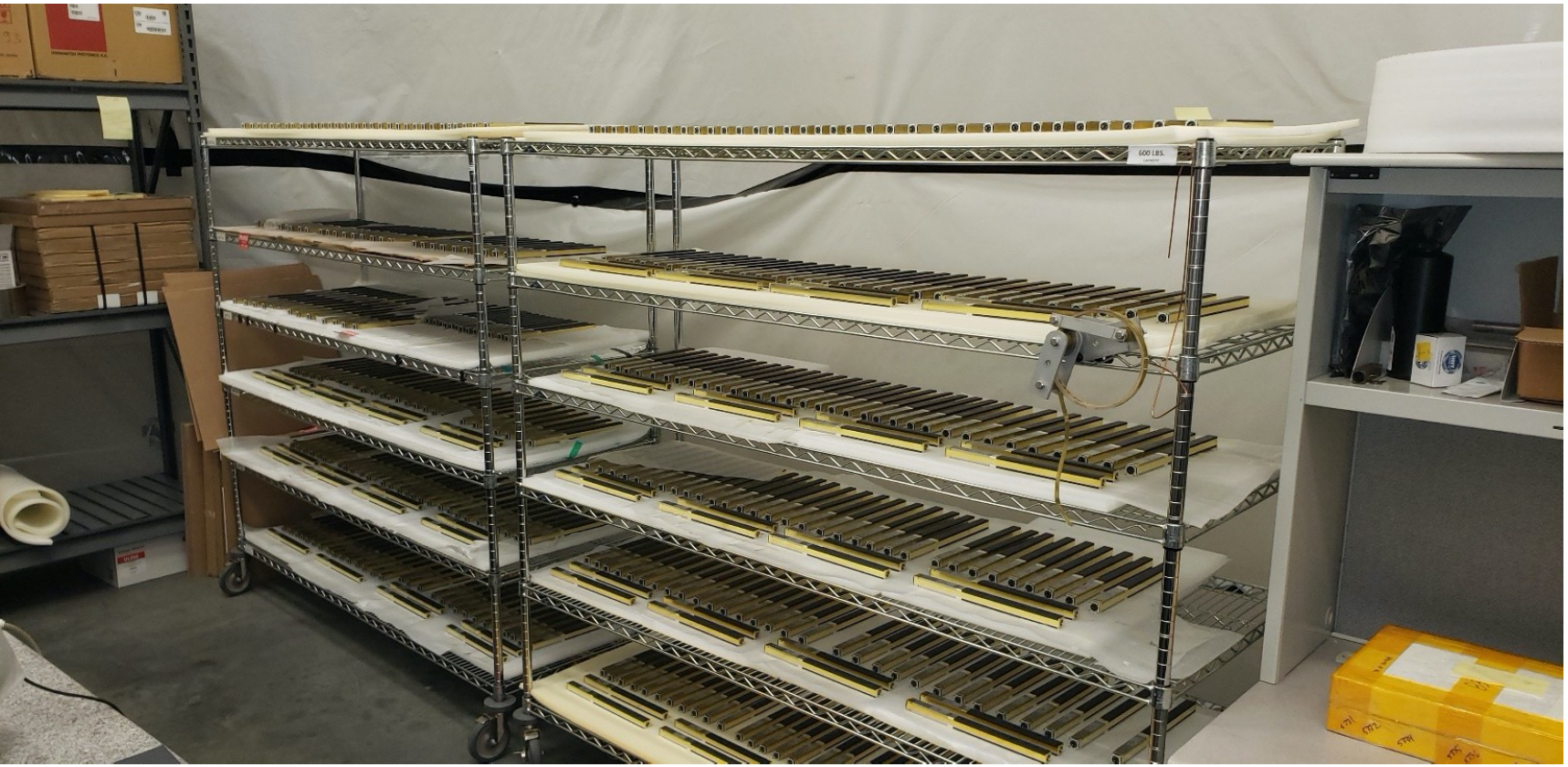
Module fabrication

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

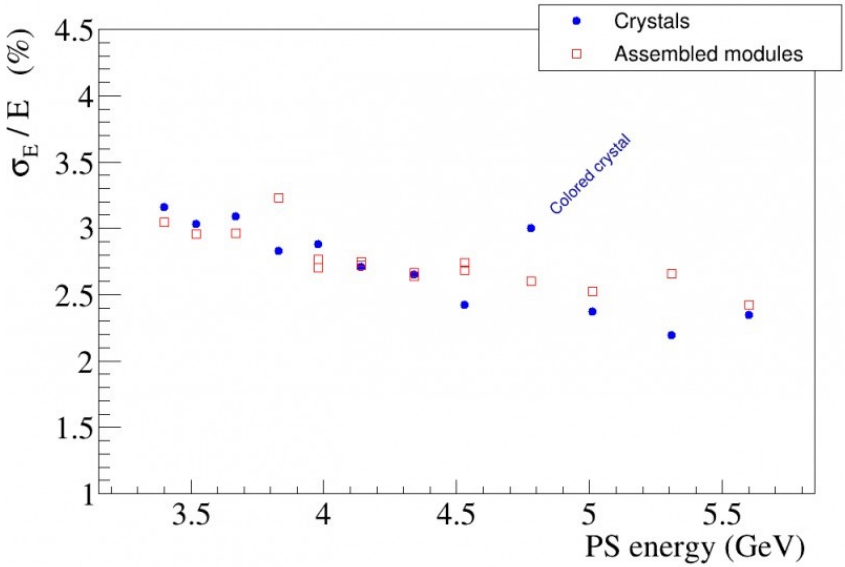


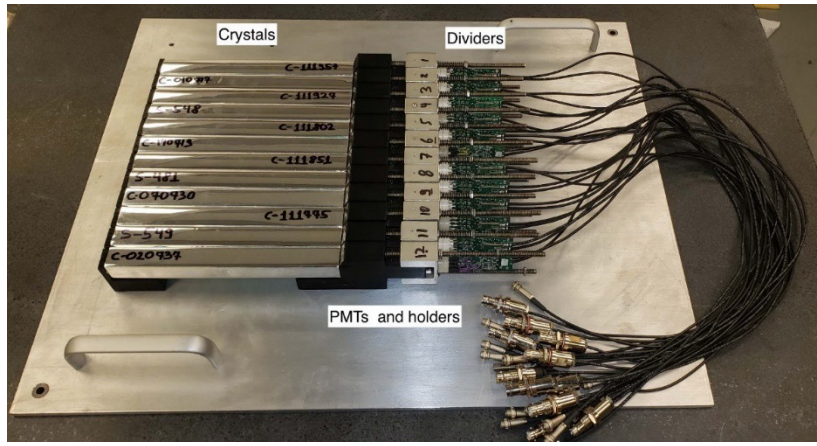
Fabricated modules

- Significant progress: **all 1596 modules have been fabricated!**



Energy resolution of a single crystal





Summary and outlook

- η decays allow access to many interesting physics channels:
  - Testing 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 required upgrade to Forward Calorimeter
  - All $PbWO_4$ crystals at JLab
  - Quality assurance in progress
  - Module construction complete
- Data taking with upgraded Forward Calorimeter expected in 2024

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

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