JEF-II: an Extension of the JLab Eta Factory Experiment

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Outline

- Physics Motivation
- On-going JEF-I Experiment with GlueX-II
- Proposed JEF-II Run Group with GlueX-III
- Summary

What special about η/η′?

Property of η/η′:

- Quantum numbers: $I^G J^{PC} = 0^+ 0^{-+}$
  → excellent for symmetry tests
- Flavor-conserving decays
  → "free" of SM backgrounds for new physics
- LO strong and EM decays are forbidden.
  → sensitive for weak signals

Probe →

Open Questions:

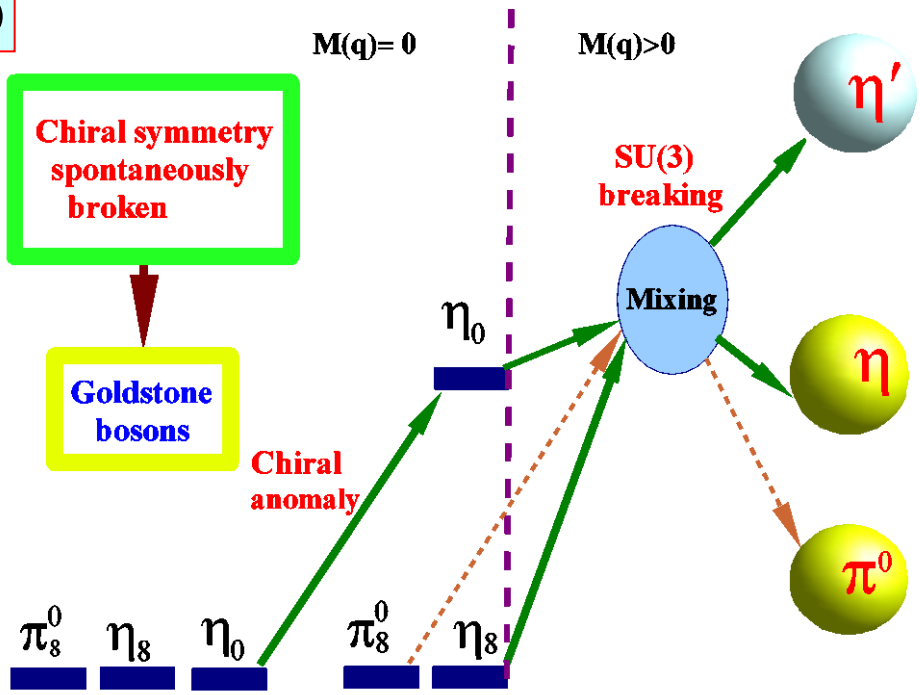
- What is the origin of QCD confinement?
- How did the visible mass emerge in the early universe?
- What is the cause of the matter-antimatter asymmetry in the universe?
- What is the nature of dark matter?

What is the origin of QCD confinement?

- **QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under:**

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

- **Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously breaks to SU(3)**
  - 8 Goldstone Bosons (GB)
- **$U_A(1)$ explicitly breaks:**
  (Chiral anomalies)
  - Non-zero mass of η_0
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- **$SU_L(3) \times SU_R(3)$ and SU(3) explicitly break:**
  - GB are massive
  - Mixing of π^0, η, η'

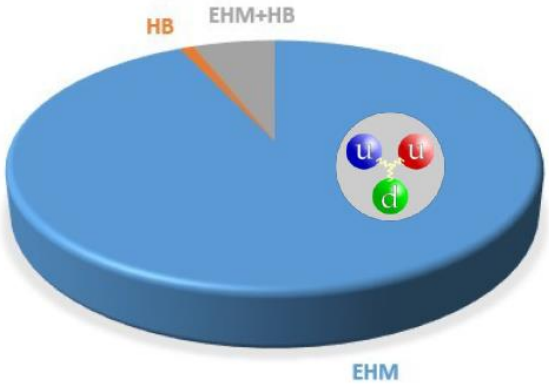


The π^0, η, η' system provides a rich laboratory to study the symmetry structure of confinement QCD.

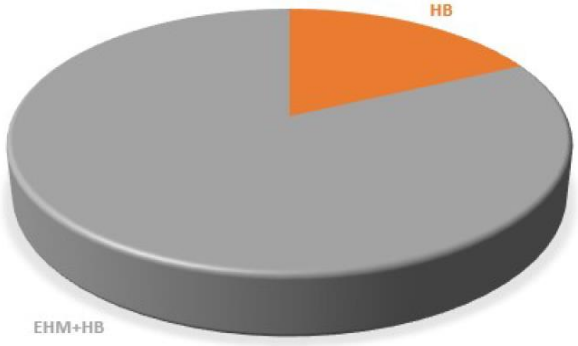
What is the origin of visible mass?

Mass-generating mechanisms:

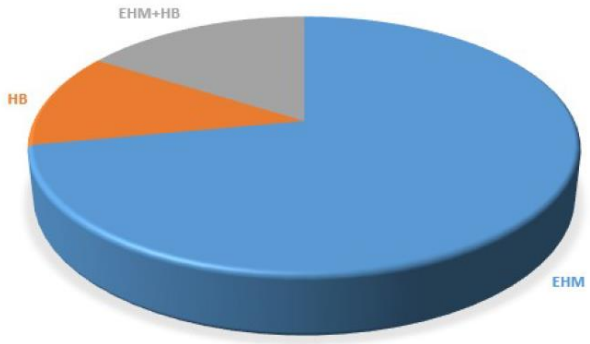
- Higgs Boson (HB) alone contributes <2% of the visible mass of universe.
- Emergent Hadron Mass (EHM) and its interference with Higgs-Boson (EHM+HB) account for >98%.



Proton mass budget



η mass budget



η' mass budget

https://doi.org/10.1007/s00601-024-01924-2

Complementary to proton, η offers a unique opportunity to the interference between two mass generating mechanisms, which can be studied by measuring transition form factor via $\eta \to e^+e^-\gamma$ or $\eta \to \pi^+\pi^-e^+e^-$

What are the causes of matter-antimatter asymmetry in the universe?

- "Sakharov conditions" for matter-antimatter asymmetry require simultaneous C and CP violations.

- C and CP are breaking in the weak interaction of SM. However, SM fails about ten orders of magnitude to explain the observed asymmetry.

- The η/η' are among very few C eigenstates in nature, offering important probes for new sources of C- and CP-violations.

Discrete Symmetries

Class	Violated	Conserved	Interaction
0		C, P, T, CP, CT, PT, CPT	strong, electromagnetic
I	C, P, CT, PT	T, CP, CPT	(weak, with no KM phase or flavor-mixing)
II	P, T, CP, CT	C, PT, CPT	
III	C, T, PT, CP	P, CT, CPT	
IV	C, P, T, CP, CT, PT	CPT	weak

Class II: P-, CP-violation

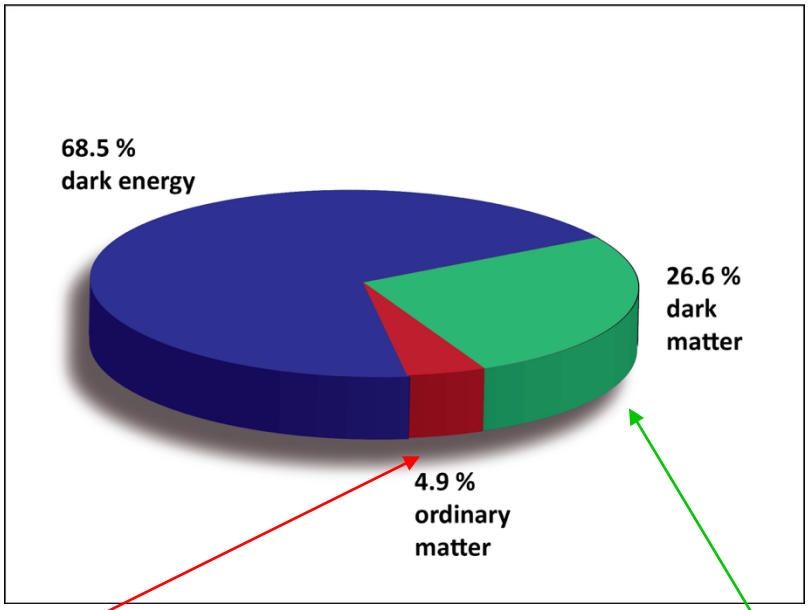
- QCD θ-term
- Examples: $\eta^{(\prime)} \to 2\pi$, $\eta^{(\prime)} \to \pi^+\pi^-\gamma^{(*)}, \cdots$
- Strong experimental constraints from EDM measurements

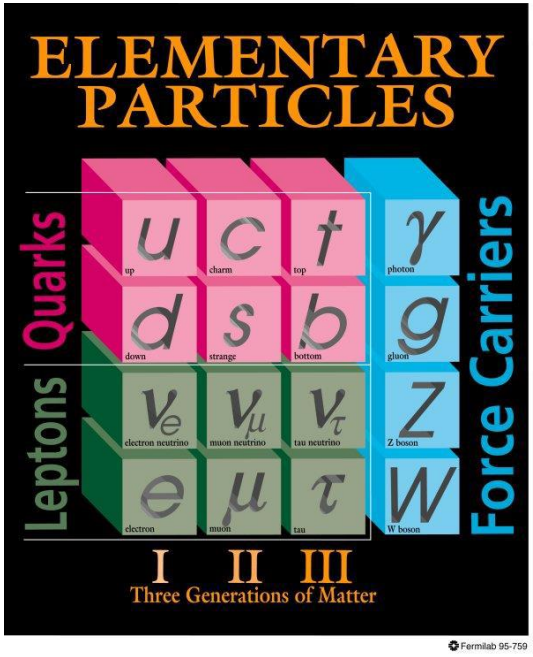
Class III: C-, CP-violation

- A new C- and T-violating, and P-conserving interaction was initially proposed in the 60th (Phys. Rev.,139, B1650); a significant theoretic progress has emerged in recent years (Phys.Rev.D,101(11):115038; Phys.Rev.D,110(5):055039; JHEP, 06:154, 2023)
- Examples: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^o\gamma^{(*)}$, $\eta^{(\prime)} \to \pi^0\pi^+\pi^-, \cdots$
- Electroweak radiative corrections mix class II and III, but much weaker EDM constraints.

Class III has much weaker experimental constraint, offer an opportunity for new physics search in η/η’ decays.

BSM Physics in Dark Sector

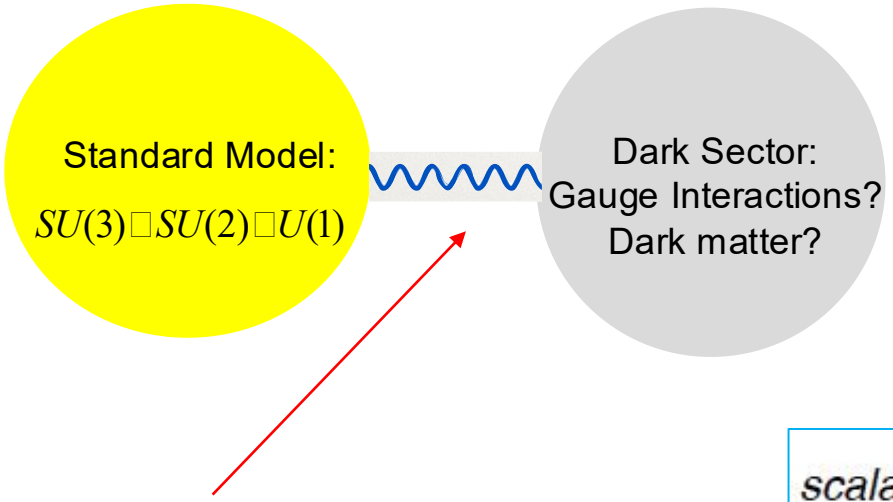




Dark Sector

- New gauge forces, bosons and fermions beyond SM.
- The stability of dark matter can be explained by the dark charge conservation.

Portals Coupling SM and Dark Sector



vector:

- Leptophobic vector B'

$$\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma, \ (0.14 < m_{B'} < 0.62 \text{ GeV});$$
$$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma, \ (0.62 < m_{B'} < 1 \text{ GeV}).$$

- X boson or dark photon: $\eta, \eta' \to X\gamma \to e^+e^-\gamma$

scalar S: $\eta \to \pi^0 S \to \pi^0\gamma\gamma, \ \pi^0 e^+e^-, \ (10 \text{ MeV} < m_S < 2m_\pi);$
$\eta, \eta' \to \pi^0 S \to 3\pi, \ \eta' \to \eta S \to \eta\pi\pi, \ (m_S > 2m_\pi).$

Portals:

vector $\kappa B^{\mu\nu} V_{\mu\nu}$

Scalar $H^+H(\varepsilon S + \lambda S^2)$

Fermion ξLHN

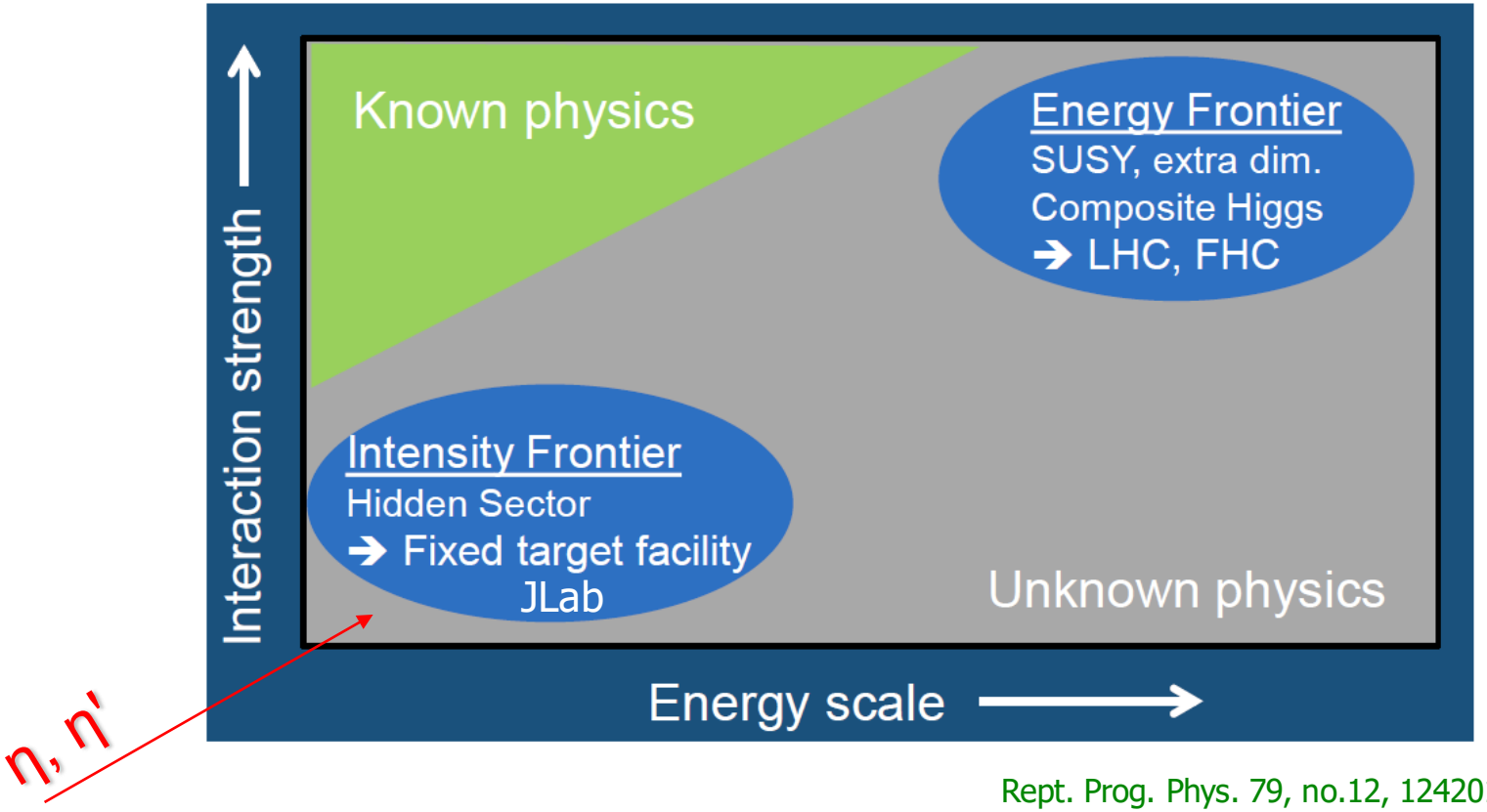
ALP $c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$

Fermion: $\eta \to \pi^0 H,$
$with\ H \to \nu N_2,\ N_2 \to h' N_1,\ h' \to e^+e^-$

Axion-Like Particles (ALP): $\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \ \pi\pi e^+e^-$

Phys. Rept. 945 (2022) 1-105, arXiv:2207.06905, arXiv:2203.07651

Landscape of BSM Physics Search

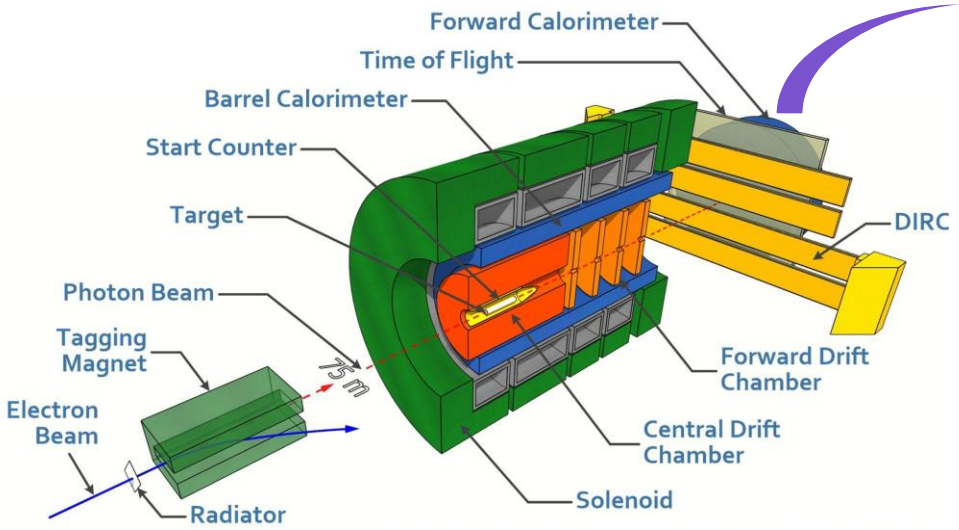


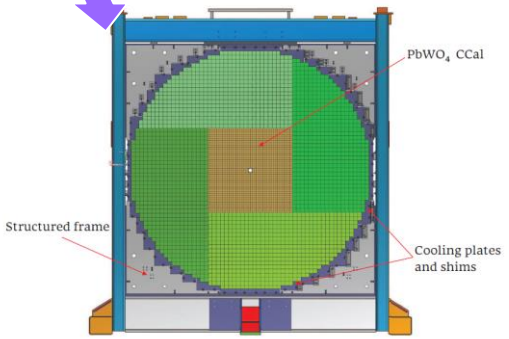
Rept. Prog. Phys. 79, no.12, 124201

Complementary to other experiments, pseudoscalar mesons offer unique sensitivity for sub-GeV new physics that are flavor-conserving and light quark-coupling.

JLab Eta Factory (JEF-I) Experiment at GlueX

(approved for 100 PAC days running in parallel with GlueX-II)





FCAL-II

- Simultaneously produce η/η' with 8-11.7 GeV tagged photon beam via $\gamma+p \rightarrow \eta/\eta'+p$
- Reduce non-coplanar backgrounds by detecting recoil protons
- Upgraded Forward Calorimeter with High resolution, high granularity $PbWO_4$ insertion (FCAL-II) to detect multi-photons from the η/η' decays
- Charge particles from the η/η' decays are detected by GlueX detector

Global Experimental Efforts in η Decays

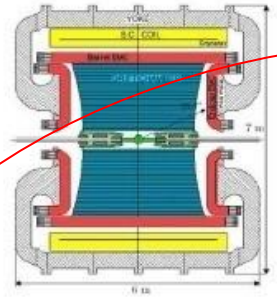
e^+e^- Collider

Fixed-target

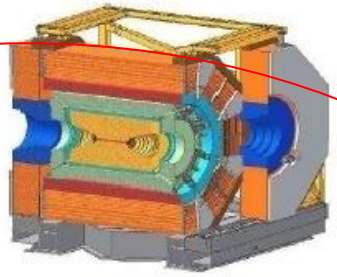
hadroproduction

Photoproduction

KLOE-2 at DAϕNE

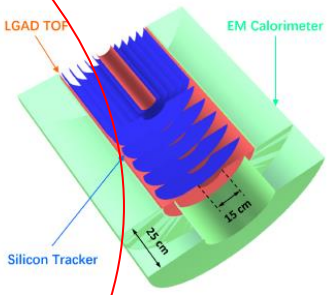


BESIII at BEPCII

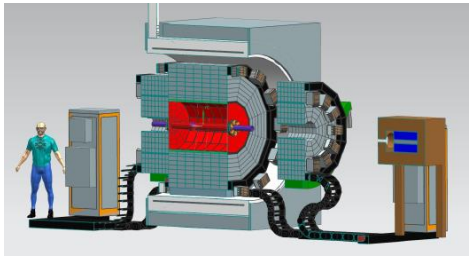


Low-energy

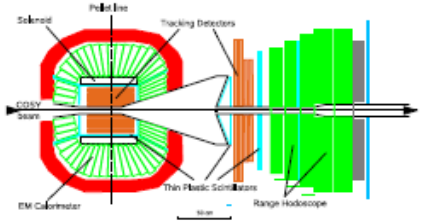
Proposed eta@HIAF



Proposed REDTOP

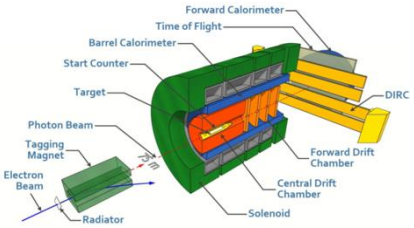


WASA at COSY

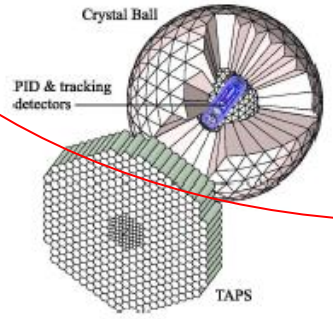


High-energy

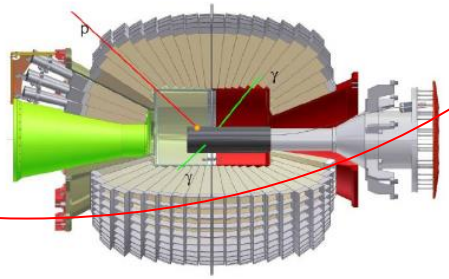
JEF at JLab



Crystall Ball at MAMI



CBELSA/TAPS at ELSA



High energy η/ η′ & the upgraded FCAL-II for JEF offer two orders of magnitude background suppression in the rare neutral decay mode

Main JEF Physics Objectives

1. *Search for various gauge boson candidates in the MeV–GeV mass range, probing three out of four highly-motivated portals coupling the SM sector to the dark sector:*

Vector:

- A leptophobic vector boson (B') [53] coupling to baryon number.

$$\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma, \quad (0.14 < m_{B'} < 0.62 \text{ GeV})$$
$$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma, \quad (0.62 < m_{B'} < 1 \text{ GeV})$$

- A dark photon (or leptophilic vector boson) kinetically mixing with the SM photon [54, 55, 56, 57].

$$\eta, \eta' \to A'\gamma \to e^+e^-\gamma$$

Scalar: Search for hadrophilic [58, 59] scalar.

$$\eta, \eta' \to \pi^0 S \to \pi^0\gamma\gamma,\ \pi^0 e^+e^-, \quad (10 \text{ MeV} < m_S < 2m_\pi)$$
$$\eta, \eta' \to \pi^0 S \to 3\pi,\ \eta' \to \eta S \to \eta\pi\pi, \quad (m_S > 2m_\pi)$$

Axion-Like Particle (ALP): Search for light pseudoscalars [60, 61, 62, 63].

$$\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ \pi\pi e^+e^-$$

Phys. Rept. 945 (2022) 1-105, JEF-II proposal

Note: the red box highlights the priority channel, in response to Chris Polly's (PAC reader) questions.

Main JEF Physics Objectives (cont.)

2. *Explore new sources of C- and CP-violation by measuring* [33, 34, 35, 37]:

   - branching ratio of: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$
   - charge-asymmetry in the Dalitz distributions of: $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$, $\eta' \to \eta\pi^+\pi^-$, $\eta^{(\prime)} \to \pi^0 e^+e^-$, $\eta^{(\prime)} \to e^+e^-\gamma$
   - the lepton charge asymmetry or pion charge asymmetry in $\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$

3. *Test low-energy QCD to*:

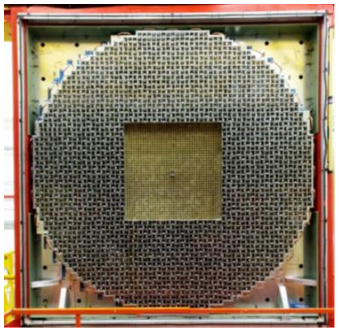
   - understand interplay of VMD and scalar dynamics in ChPT [17, 64] through $\eta^{(\prime)} \to \pi^0\gamma\gamma$
   - improve the light quark mass ratio [22] by $\eta \to 3\pi$
   - understand the origin of visible mass [25] and provide inputs to calculate the hadronic light-by-light in $g-2$ [24] via $\eta^{(\prime)} \to e^+e^-\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$

Phys. Rept. 945 (2022) 1-105, JEF-II proposal

Status of the JEF-I Experiment

- A $PbWO_4$ ECAL was constructed and its performance achieved the design goal ⟶ 4 publications

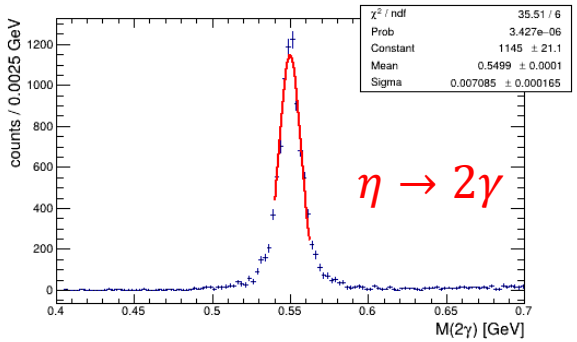
  Nucl. Instrum. Meth. A 1013, 165683; *EPJ Web Conf.* 320, 00058; Opt.Eng. 65, 054107; Nucl.Instrum.Meth.A 1088, 171523

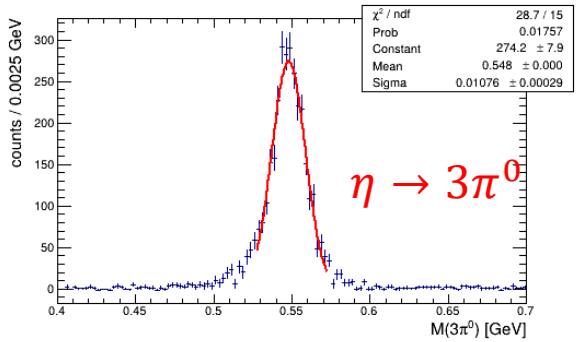


FCAL-II

- 75% JEF-I data was collected with FCAL-II and the remaining data will be completed in 2026.

- Quality of JEF-I data looks promising and matches expectations from simulation used for JEF-II projections.





Extract $\frac{BR(\eta \to 3\pi^0)}{BR(\eta \to 2\gamma)}$:

Measured	PDG
0.85 ±0.02(stat)	0.827 ±0.007

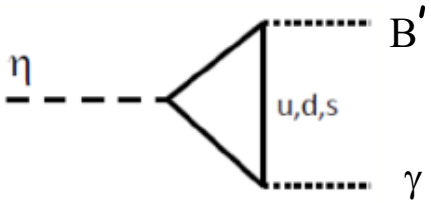
Proposed JEF-II

- Expand the JEF program as a run-group with GlueX-III to add a factor of 4 statistics:
  - 200 PAC days
  - ~$2 \times 10^8\ \gamma/s$ ($E_\gamma = 8 - 12\ GeV$) tagged photon beam
- No equipment changes to GlueX-III
- Endorsed by GlueX Collaboration.

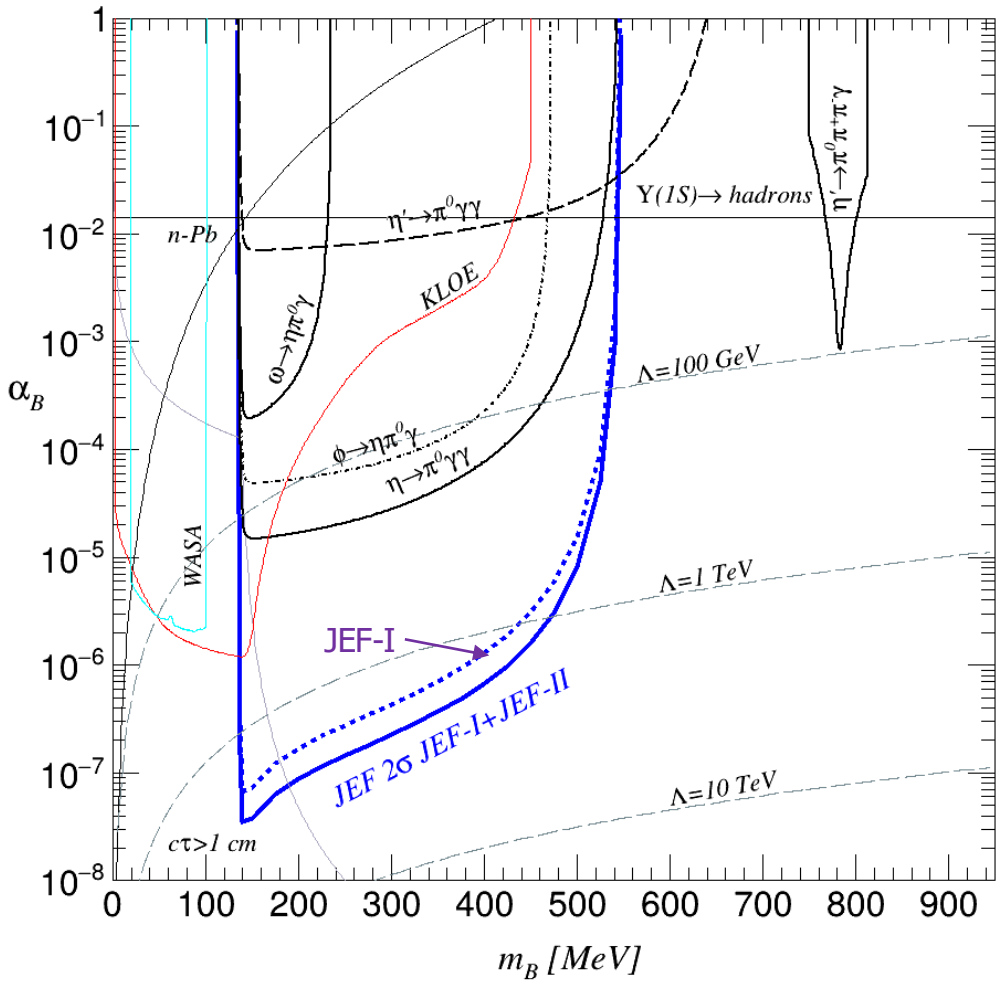
Highest-Priority Deliverables of JEF-II (response to Chris)

A search for a leptophobic dark B' boson coupled to baryon number is complementary to ongoing searches for a dark photon

$\eta \rightarrow B'\gamma \rightarrow \pi^0\gamma\gamma$



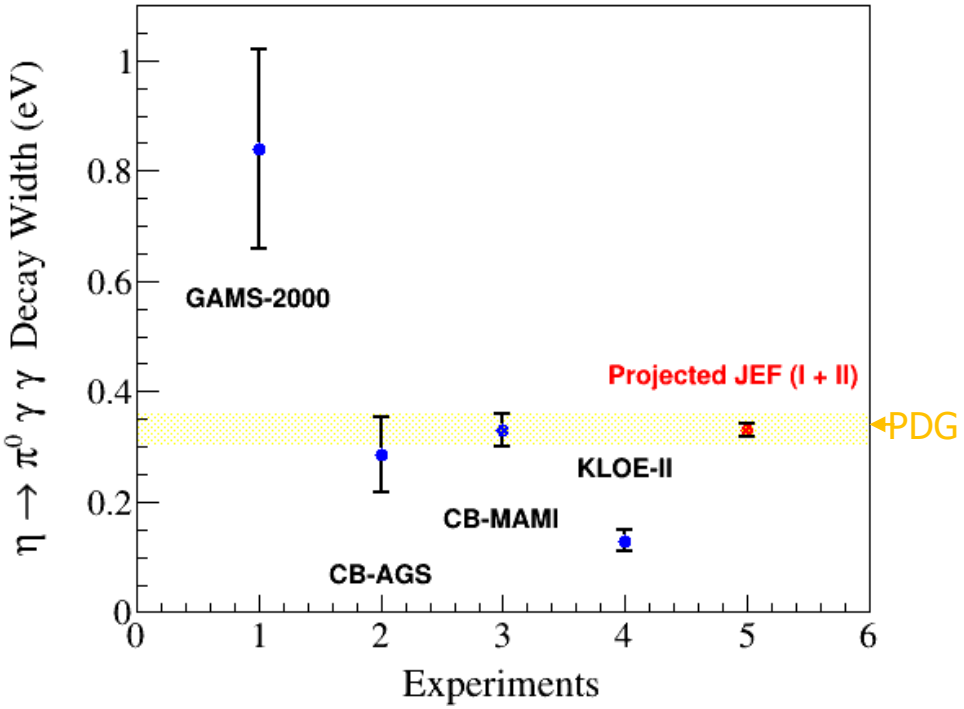
PL, B221, 80 (1989)
PR,D89,114008



Test SM Allowed $\eta \to \pi^0\gamma\gamma$

A rare window for NNLO ChPT:

- probe interplay of vector, scalar and tensor dynamics
- access $O(p^6)$ counter-terms



Recent theory predictions:

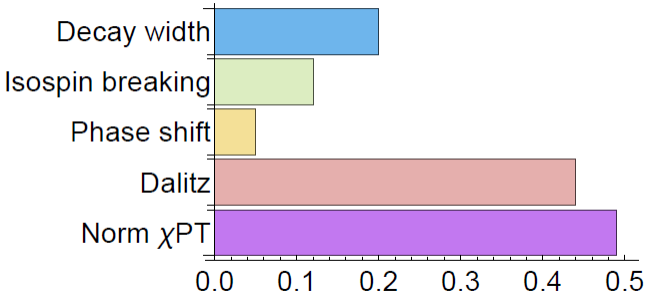
- $Phys.Rev.,D77,073001(2008)$
  $\Gamma = 0.33 \pm 0.08\ eV$
- $Phys.Rev.,D102,034026(2020)$
  $\Gamma = 0.18 \pm 0.01\ eV$
- $Phys.Rev.,D112,114009\ (2025)$
  $\Gamma = 0.154 \pm 0.022\ eV$

Note: The JEF projection is based on PDG BR($\eta \to \pi^0\gamma\gamma$). Even in the case KLOE-II was right so that the actual yield became smaller, JEF-II will ensure us to have a competitive precision.

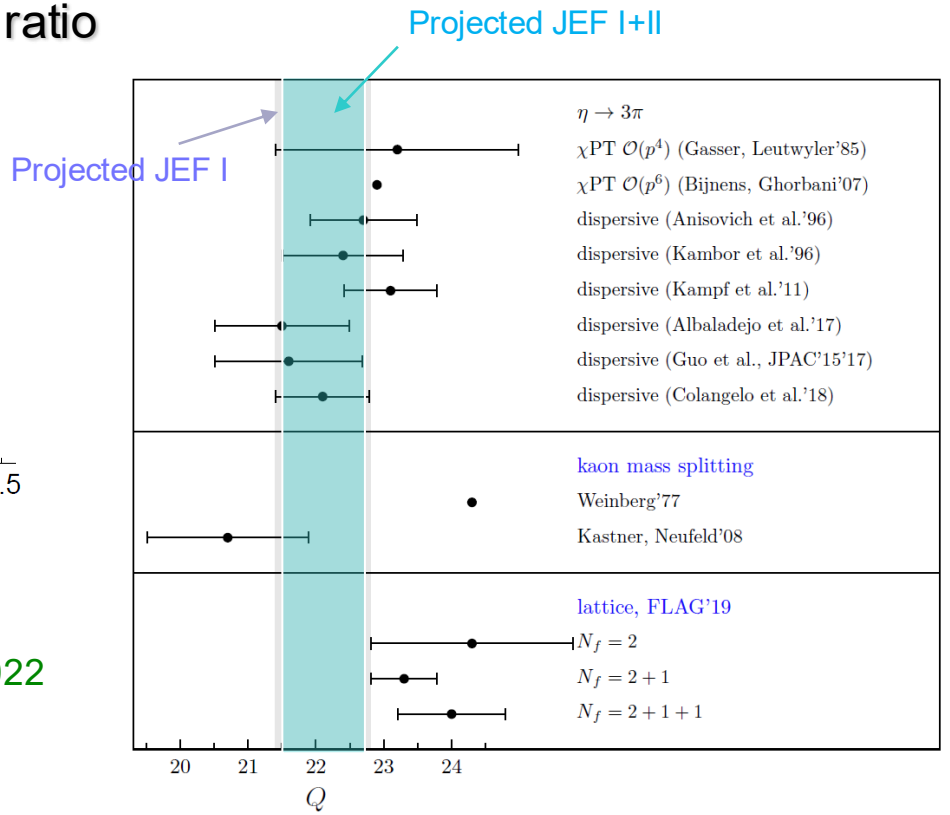
Improve Quark-Mass Ratio via $\eta \to 3\pi$

- A clean probe for quark mass ratio: $Q^2 = \dfrac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\quad \hat{m} = \dfrac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em} A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \dfrac{1}{Q^2}\dfrac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\dfrac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$

- Uncertainties in quark mass ratio



Phys. Rept., 945:2191, 2022



Search for C- and CP-Violation via $\eta \to \pi^0\pi^+\pi^-$

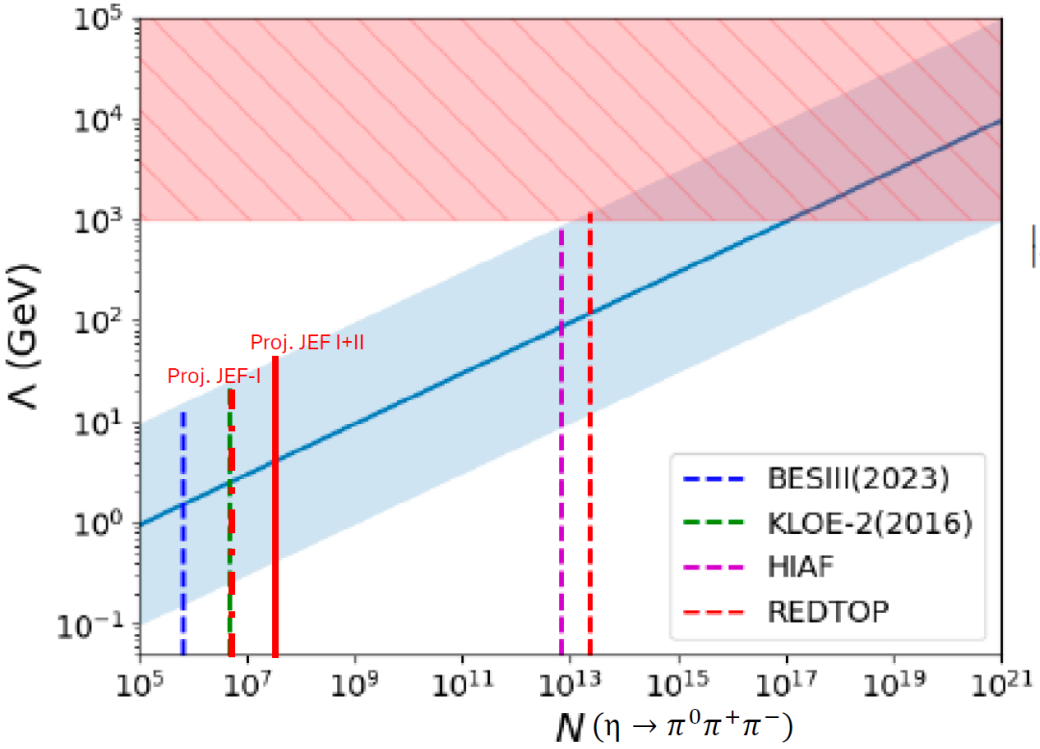
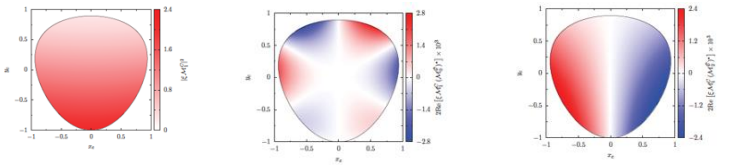


Fig. from Phys. Rev. D, 110(5):055039 (2024)

Dalitz plot Decomposition:

$$|\mathcal{M}_c|^2 \approx |\mathcal{M}_1^C|^2 + 2\mathrm{Re}\left[\mathcal{M}_1^C\,(\mathcal{M}_0^{\mathcal{C}})^*\right] + 2\mathrm{Re}\left[\mathcal{M}_1^C\,(\mathcal{M}_2^{\mathcal{C}})^*\right]$$



JEF will tighten the constraint on new CVPC physics by increasing the size of world data for $\eta \to \pi^0\pi^+\pi^-$

Run Configurations

GlueX-III/JEF-II has two differences from GlueX-II/JEF-I:

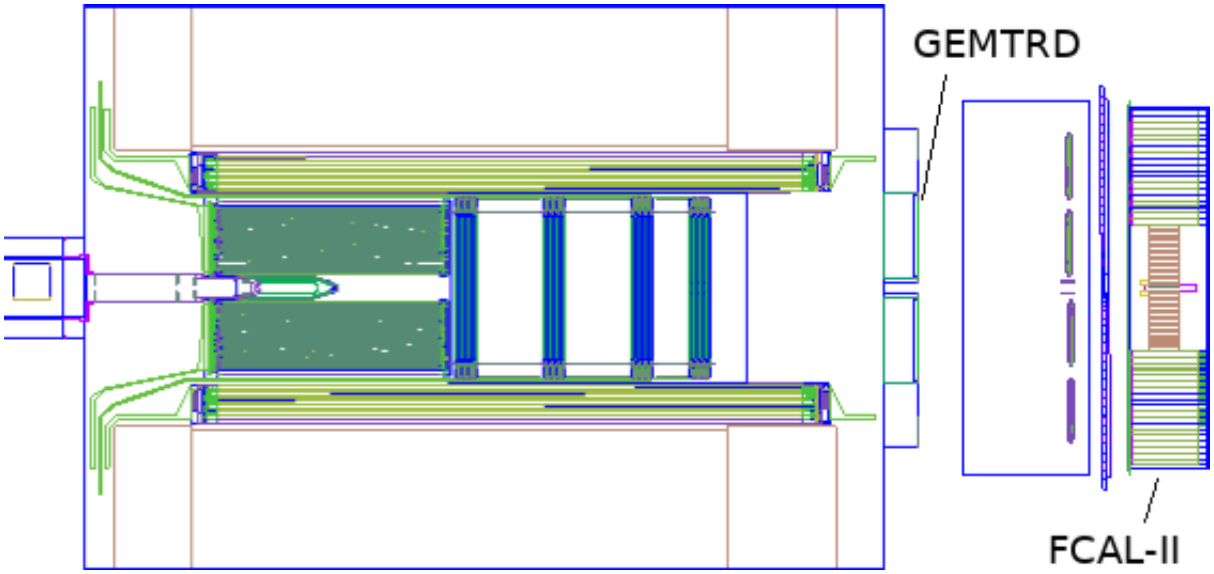
1. A new GEMTRD upstream of FCAL-II

   - beneficial to separate lepton from pion, example $\eta \to \pi^+\pi^- e^+ e^-$
   - increase conversion background for neutral decays, example $\eta \to \pi^0\gamma\gamma$

2. A factor of two higher beam intensity

   - improve production rate
   - increase accidental background

Simulation of High Intensity Run with JEF-II



Decay channel	ε(JEF-I)	ε(JEF-II)
$\pi^0\gamma\gamma$	0.238	0.163
2γ	0.4	0.31

Reduced efficiencies for JEF-II will be compensated by 4x increase in eta production.

Highlight of JLab Review Report

TAC report comments:

"GlueX-III is approved to run at a higher luminosity and with an additional detector, GEMTRD. This detector will increase the background for the reaction of interest of JEF. The JEF-II proposal studied this effect and found it acceptable. "

Theory report comments:

- "The pitch is straightforward and compelling." …
- "The catch is that the constructed ECAL ended up at 40 × 40 rather than the originally approved 50 × 50 (budget), …. The combined JEF-I+JEF-II dataset recovers that lost ground and pushes past it"…
- "the theory side is quite active right now,"…
- Some suggestions to the collaboration in preparation for data-taking and data analysis.

Summary

- The η/η' mesons offer sensitive probes to test the standard model and to search for new physics beyond.

- JEF-I was approved to run with GlueX-II for 100 days, requiring an upgraded FCAL-II:
  - ✓ Search for sub-GeV hidden bosons: vector, scalar, and ALP
  - ✓ Directly constrain CVPC new physics
  - ✓ Precision tests of low-energy QCD: light quark mass ratio; the role of scalar dynamics in ChPT; the origin of visible mass, and the hadronic HLbL contributions in $(g\text{-}2)_\mu$

- FCAL-II upgrade with a $PbWO_4$ ECAL was accomplished. 75% of JEF-I date was collected. The remaining data will be completed in 2026.

- Proposed JEF-II is a run group with GlueX-III. It adds 4x statistics for η/η' to enhance experimental sensitivities. No changes to the GlueX-III setup.

- JEF-II is endorsed by GlueX Collaboration.

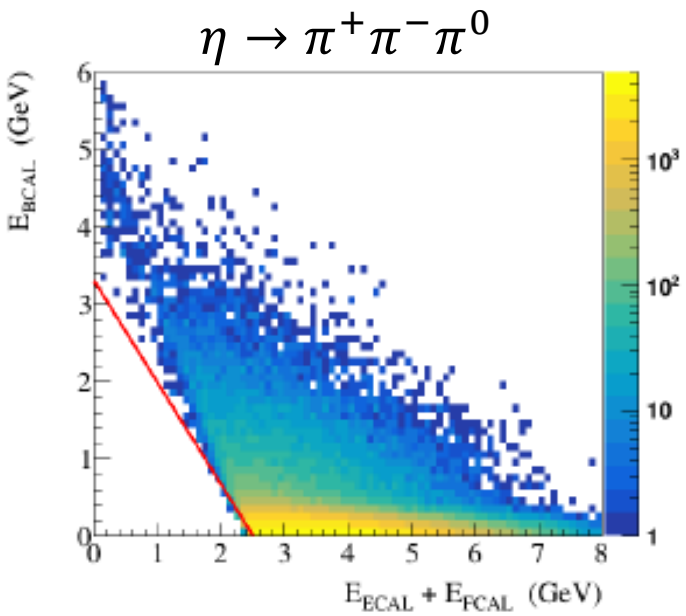
Manpower for JEF Project

- Support from GlueX collaboration

  Statement by the collaboration Spokesperson (Justin Stevens):“This endorsement signifies a commitment by 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.”

- Key member institutes in the JEF working group
  - University of North Carolina Wilmington
  - Jefferson Lab
  - University of Regina
  - University of George Washington
  - Wuhan University
  - China University of Geosciences
  - Chinese High Energy Institute
  - Shandong University (new member, needs Collaboration approval)
  - Shandong University of Technology (new member, needs Collaboration approval)

Level-I Trigger for GlueX-III



$$\frac{E_{\mathrm{ECAL}} + E_{\mathrm{FCAL}}}{2.5\ \mathrm{GeV}} + \frac{E_{\mathrm{BCAL}}}{3.3\ \mathrm{GeV}} > 1,$$

- To maintain the trigger rate at ~50 kHz, the energy threshold for FCAL-II and BCAL will be increased by factors of 3.5 and 2 respectively, compared to GlueX-II.
- Such trigger condition has negligible impact on the decay channels that are dominated by the electromagnetic particles in the final states.
- For the decay channel like $\eta \to \pi^+\pi^-\pi^0$

GlueX-II	GlueX-III	
$\epsilon_{\eta\to 3\pi}$	$\epsilon_{\eta\to 3\pi}$	$\epsilon_{\eta\to 3\pi+\mathrm{pileup}}$
100	73	96

No show-stopper for JEF priority channels