JLab Eta Factory (JEF) experiment

Presented by

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(Contributions from the collaboration)

The Jlab Eta Factory (JEF) is a GlueX endorsed experiment which is supported by the USDOE and NSF.

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Challenges in Physics at the 1Gev Scale

Confinement QCD

- Nature of QCD confinement
- Relation to dynamical chiral symmetry breaking

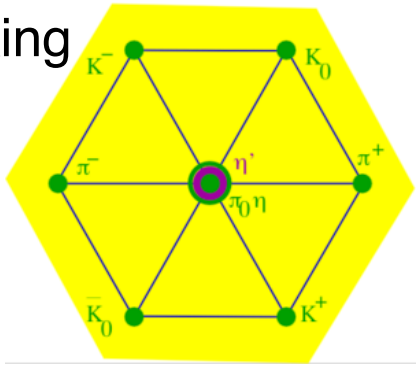
Physics Beyond the Standard Model (BSM)

- New sources of CP violation
- Dark matter
- Dark energy

η and η' decays provide sensitive probes to explore both fundamental issues

The η is a unique probe for QCD and BSM physics

- The η is a Goldstone boson due to spontaneous breaking of QCD chiral symmetry.
  - → The η is key to bridging the understanding of low-energy hadron dynamics and underlying QCD.



- Its strong and EM decays are forbidden in lowest order; it has a narrow decay width (Γ_η = 1.3KeV compared to Γ_ω= 8.5 MeV)
  - → Enhances higher-order contributions (factor of ~7000 compared to ω decays); sensitive to weakly interacting forces.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  - → η provides tests of fundamental symmetries through rare decays

- quantum numbers ~ the same as Higgs or vacuum (except for parity); decays are flavor-conserving
  - → effectively free of SM backgrounds in BSM searchs.

Rich η (η') Physics

Standard Model Tests:

- Chiral symmetry and anomalies
- Extract η-η' mixing angle
- Quark mass ratio
- Theory inputs to HLbL for $(g\text{-}2)_\mu$
- QCD scalar dynamics

Fundamental Symmetry Tests:

- C, CP violations
- P, CP violations
- Lepton flavor violations

BSM Physics in Dark Sector:

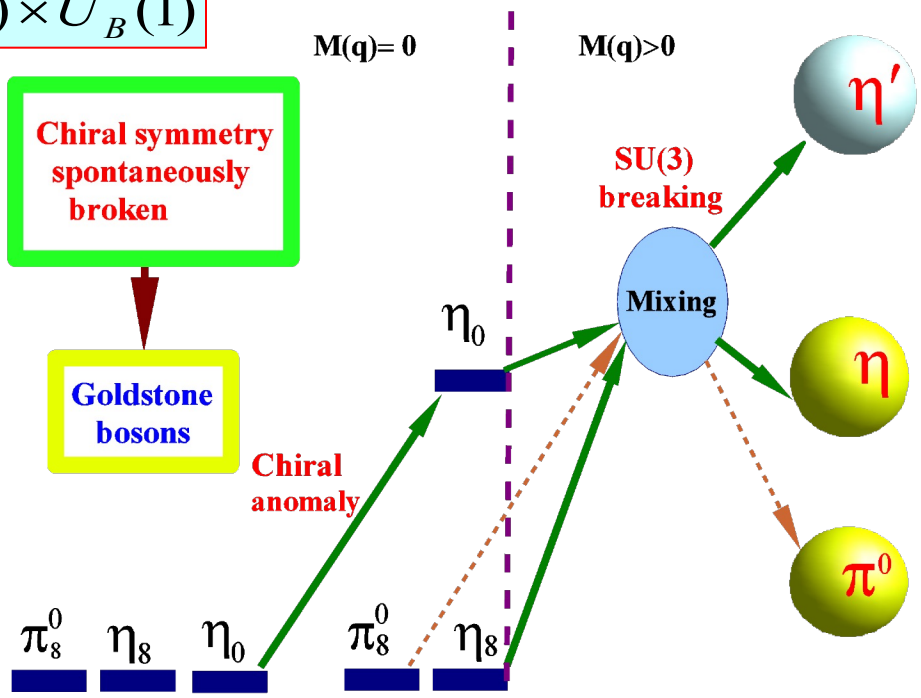
- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [54]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [55]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Phys. Rept. 945 (2022) 1-105

Low-Energy QCD Symmetries and Light Mesons

- **QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under group algebra:** $SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$
- **Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously breaks to $SU(3)$**
  - 8 Goldstone Bosons (GB)
- **$U_A(1)$ explicitly broken:**
  (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Non-zero mass of η_0
- **$SU_L(3) \times SU_R(3)$ and $SU(3)$ are explicitly broken:**
  - 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 QCD at low energies.

Transition Form Factor and $(g-2)_\mu$

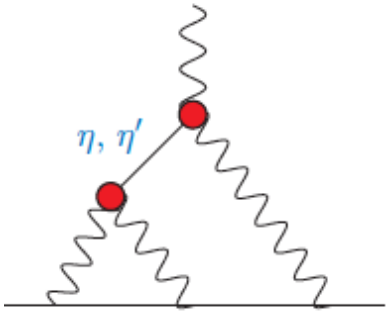
important hadronic light-by-light contribution:

$\eta^{(\prime)}$ pole terms

singly / doubly virtual
transition form factors (TFFs)

$F_{\eta^{(\prime)}\gamma^*\gamma^*}(q^2,0)$ and $F_{\eta^{(\prime)}\gamma^*\gamma^*}(q_1^2,q_2^2)$

normalisation fixed by WZW anomaly



HLbL

*WZW - Wess–Zumino–Witten

SM allowed $\eta \to \pi^0\gamma\gamma$

Rare window to probe interplay of VMD & scalar resonances in ChPT to calculate the chiral Lagrangian of $O(p^6)$

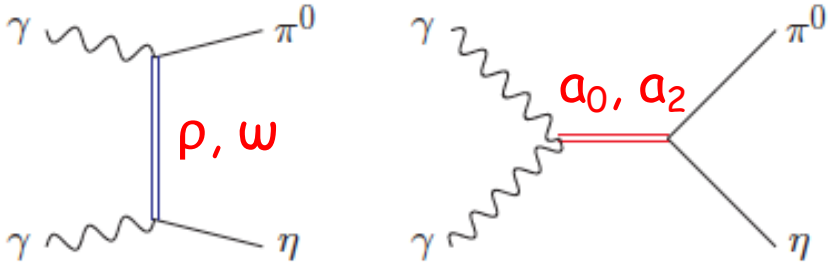
- Major contributions to $\eta \to \pi^0\gamma\gamma$ - two $O(p^6)$ counter-terms in chiral Lagrangian ➡ unique probe for high-order ChPT.

  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

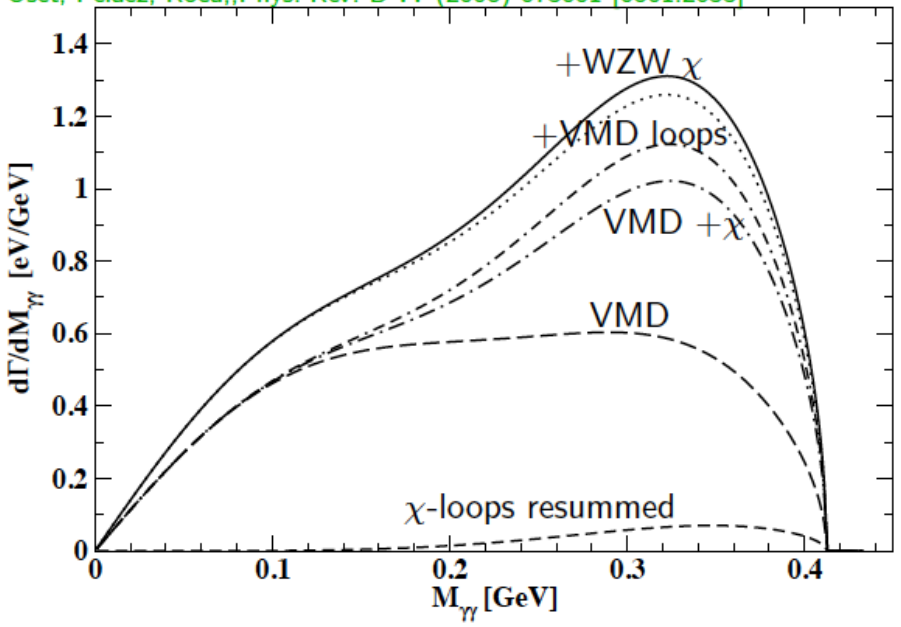
- Shape of Dalitz distribution sensitive to role of scalar resonances.

LEC's are dominated by resonances

Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael1989
Donoghue, Ramirez, Valencia 1989



Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]



Discrete Symmetries

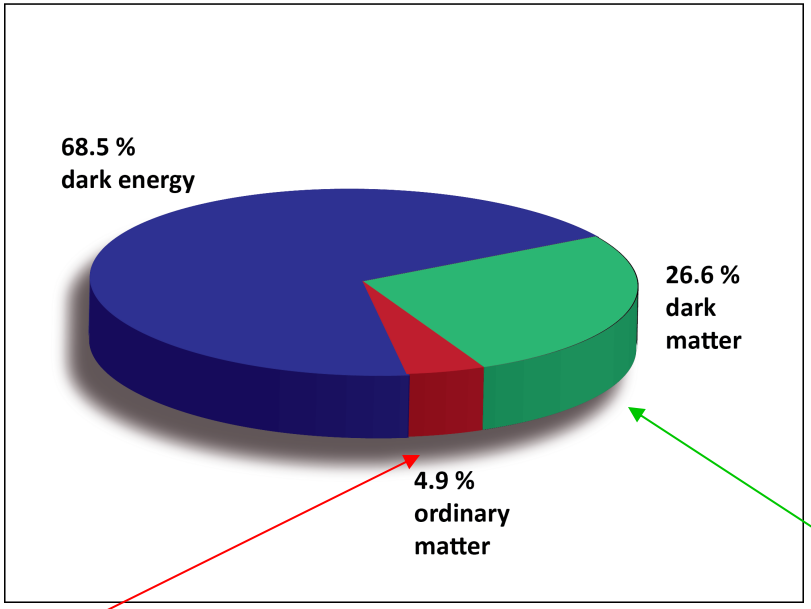
Class	Violated	Conserved	Interaction
0		C, P, T, CP, CT, PT, CPT	strong, electromagnetic
I	C, P, CT, PT	T, CP, CPT	(weak, with no KM phase or flavor-mixing)
II	P, T, CP, CT	C, PT, CPT	
III	C, T, PT, CP	P, CT, CPT	
IV	C, P, T, CP, CT, PT	CPT	weak

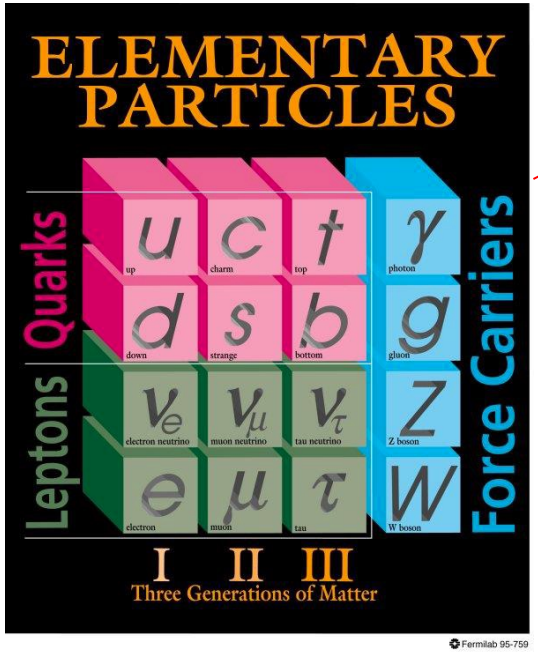
- class II: *P*-, *CP*-violation
  - ▷ QCD θ-term; in general: electric dipole moments
  - ▷ $\eta^{(\prime)}$ decay examples: $\eta^{(\prime)} \to 2\pi$, $\eta^{(\prime)} \to \pi^+\pi^-\gamma^{(*)}$
- class III: *C*-, *CP*-violation
  - ▷ far less discussed; in SMEFT, start at dimension 8 only
  - ▷ $\eta^{(\prime)}$ decay examples: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^0\gamma^* \ldots$

Class III has weaker experimental constraint, offer an opportunity for new physics search.

n.b. - Kobayashi–Masakawa (KM)

BSM Physics in Dark Sector

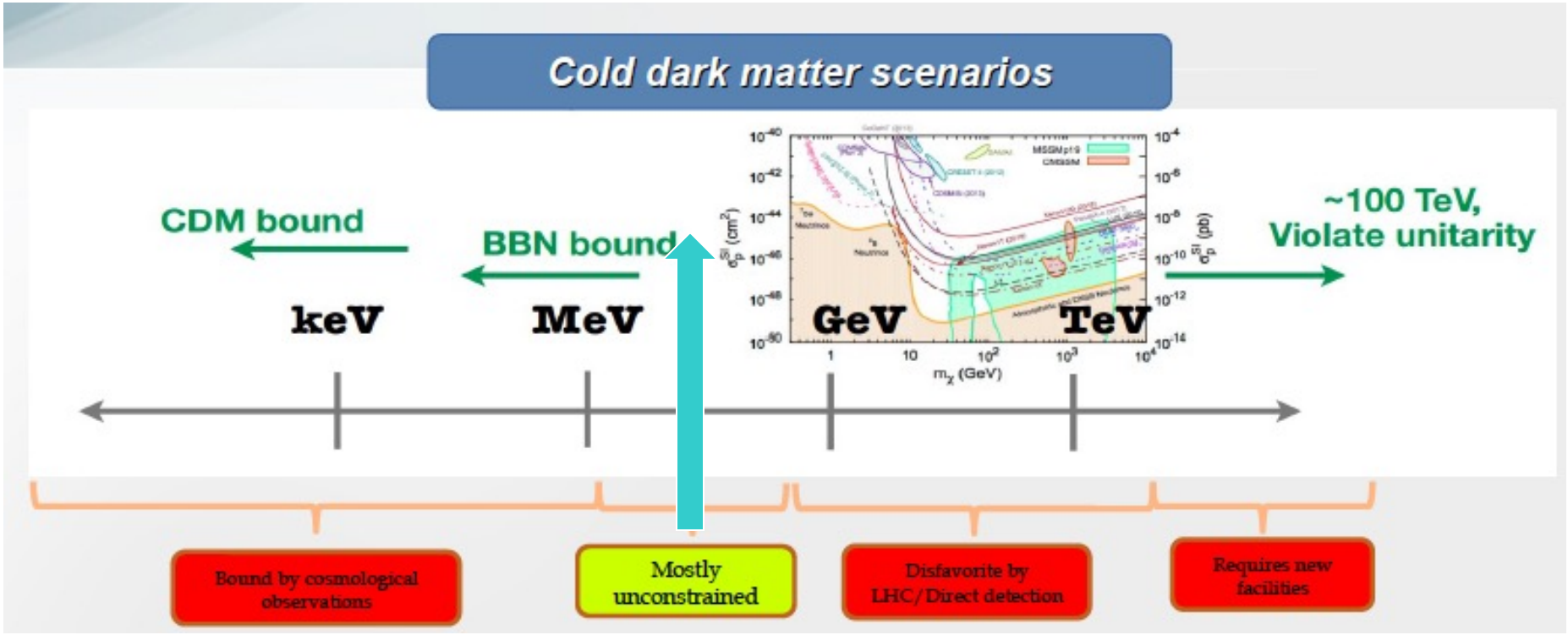




Dark Sector

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

Where to Search in the Dark Sector?

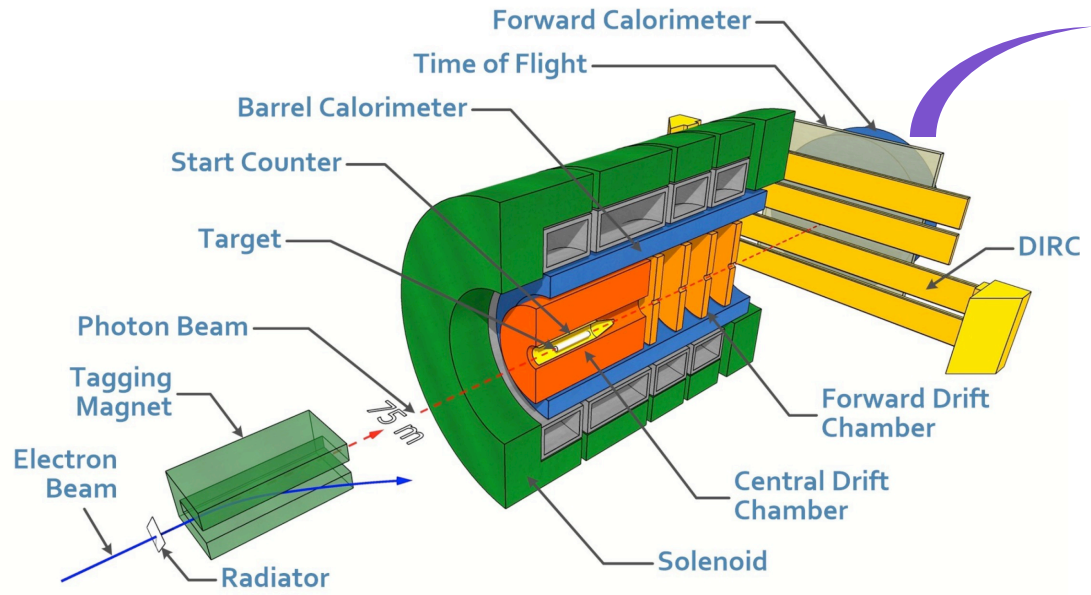


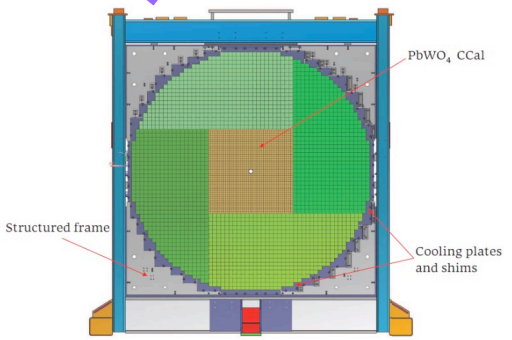
Sub-GeV region represents a good discovery opportunity

BBN - big bang nucleosynthesis

CDM - cold dark matter

JLab Eta Factory (JEF) Experiment





FCAL-II

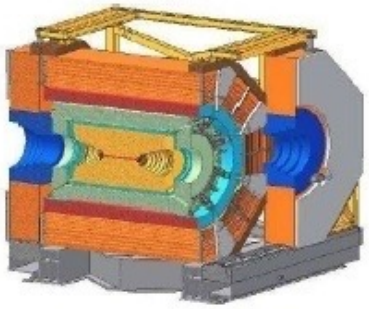
- Simultaneously produce η/η' on LH_2 target with 8.4-11.7 GeV tagged photon beam via $\gamma+p \rightarrow \eta/\eta'+p$ so decay products get forward boost.
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector.
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η/η' decays.
- The GlueX detector will detect charged products from the η/η' decays

World Competition in η Decays

e^+e^- Collider

KLOE-2 at DAϕNE

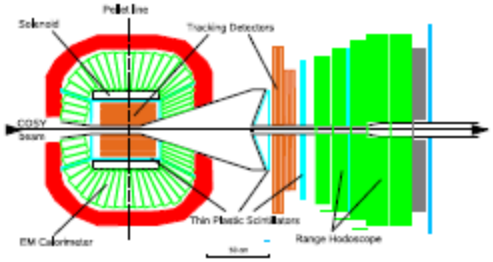
BESIII at BEPCII



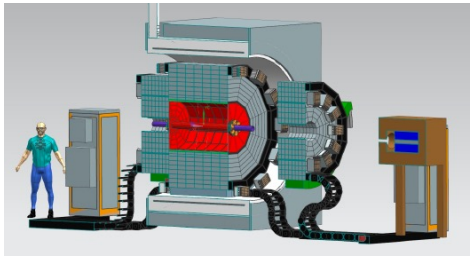
Fixed-target

hadroproduction

WASA at COSY

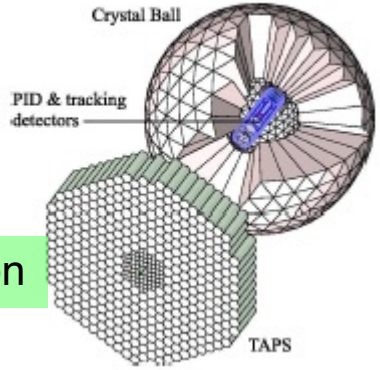


Proposed REDTOP

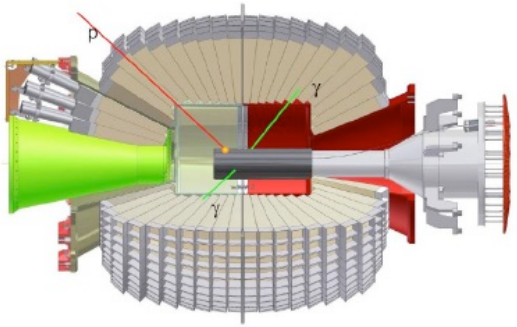


Photoproduction

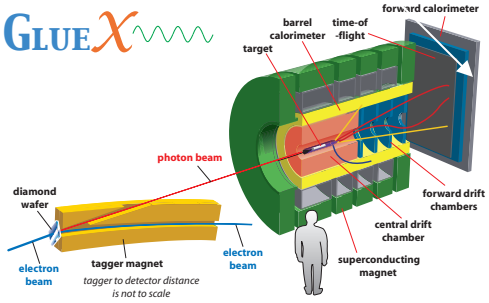
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



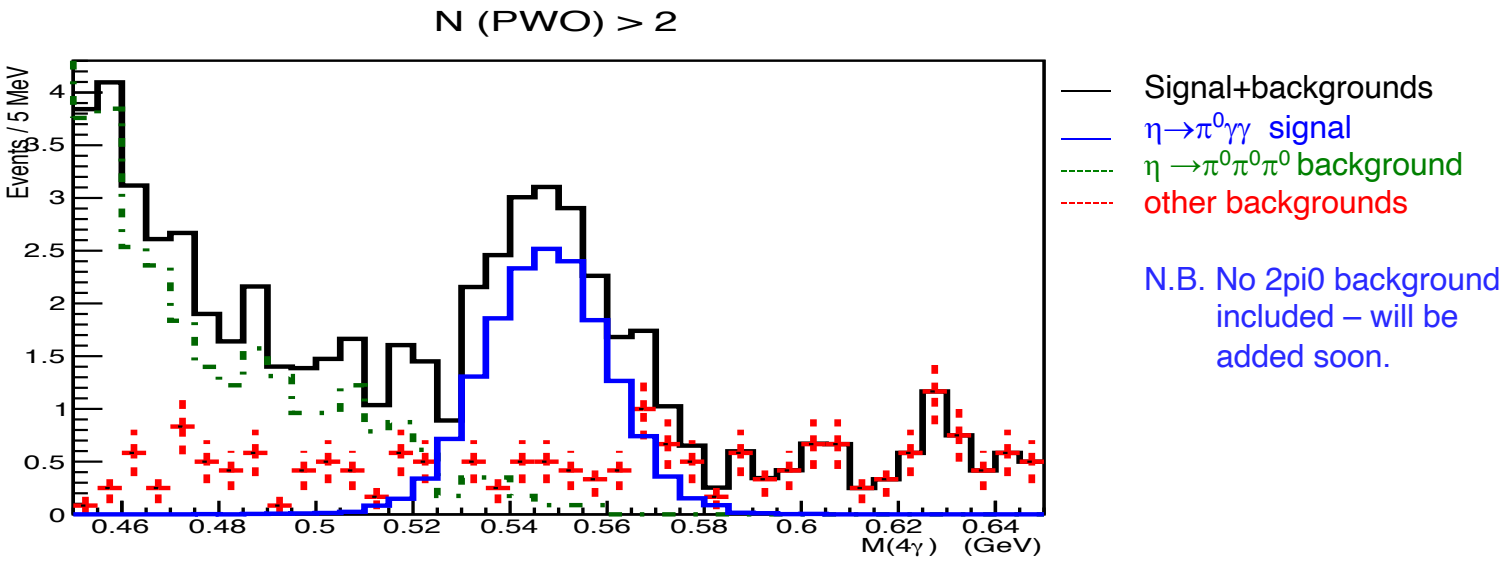
JEF at JLab



Uniqueness of JEF Experiment

1. Large background suppression compared to other experiments:
   a) η/η′ energy boost; b) FCAL-II; c) exclusive detections

JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV) 1 day's running



2. Capability of running in parallel with GlueX and other experiments in Hall D
   → high-statistics data set

3. Simultaneously produce tagged η and η' with similar rates

Estimated Design Production Rate

JEF for 100 days of beam:

	η	η′
Tagged mesons	~5 x 10^7	~ 5 x 10^7

Previous Experiments:

Experiment	Total η	Total η′
CB at AGS	10^7	-
CB MAMI-B	2x10^7	-
CB MAMI-C	6x10^7	10^6
WASA-COSY	~3x10^7 (p+d), ~5x10^8 (p+p)	-
KLOE-II	3x10^8	5x10^5
BESIII	~10^7	~5x10^7

JEF offers a competitive η/η′ production rate with cleaner backgrounds.
New estimates are in progress using more up to date cross sections.

Main JEF Physics Objectives

1. **Search for sub-GeV hidden bosons**

vector:

- Leptophobic vector *B '*

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

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

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

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

2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

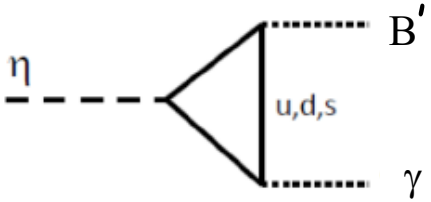
3. **Precision tests of low-energy QCD:**
   - Interplay of VMD & scalar dynamics in ChPT: $\eta \to \pi^0\gamma\gamma$ $\eta' \to \pi^0\gamma\gamma$
   - Transition Form Factors of $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

4. **Improve the quark mass ratio via Dalitz distributions of $\eta \to 3\pi$**

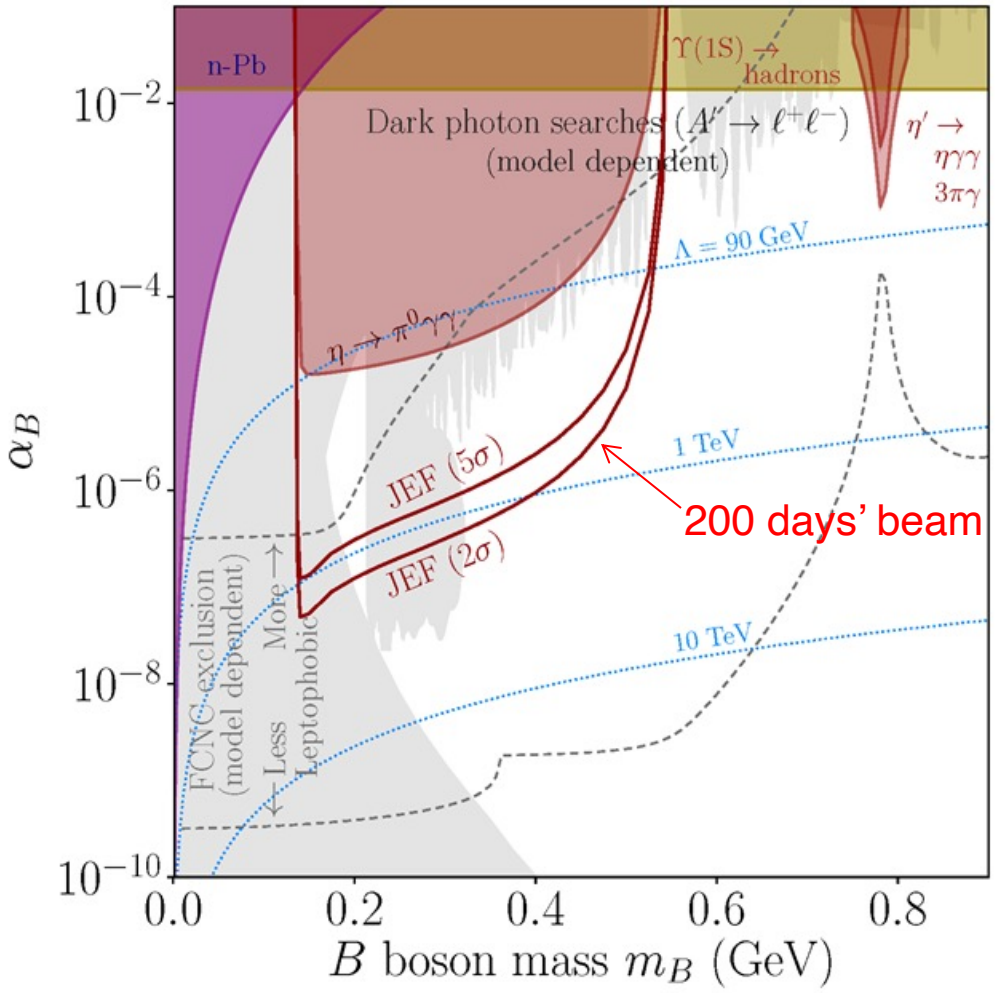
Preliminary Estimate of JEF Experimental Reach for B′

Search for leptophobic dark B' boson coupled to baryon number; complementary to searches for a dark photon

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

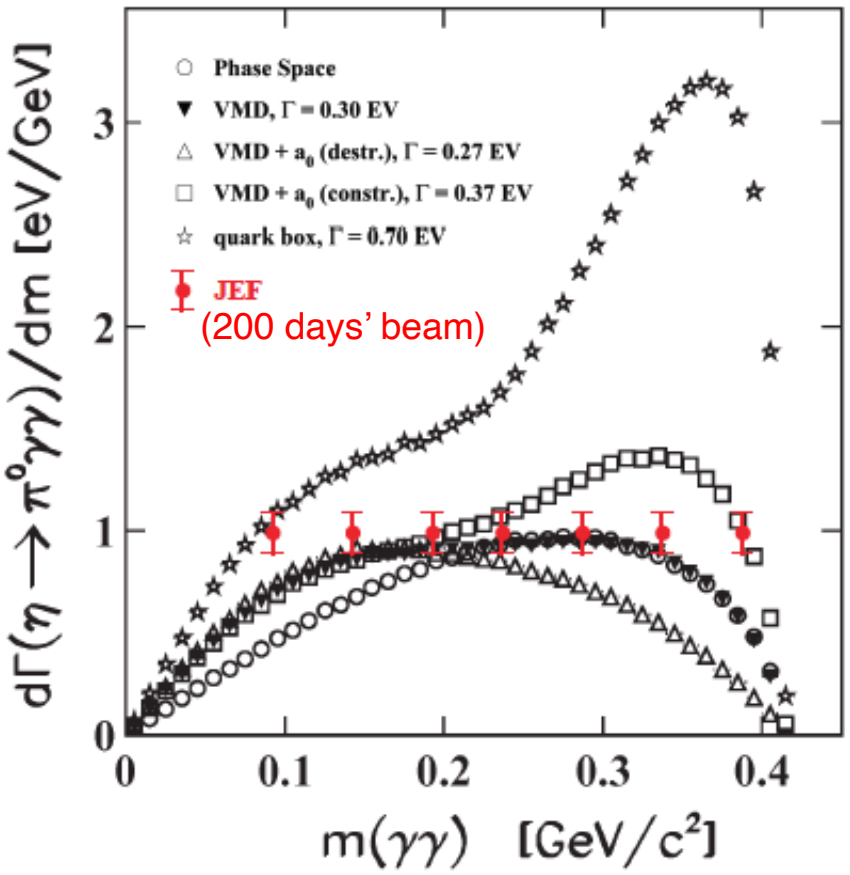


PL, B221, 80 (1989)
PR,D89,114008

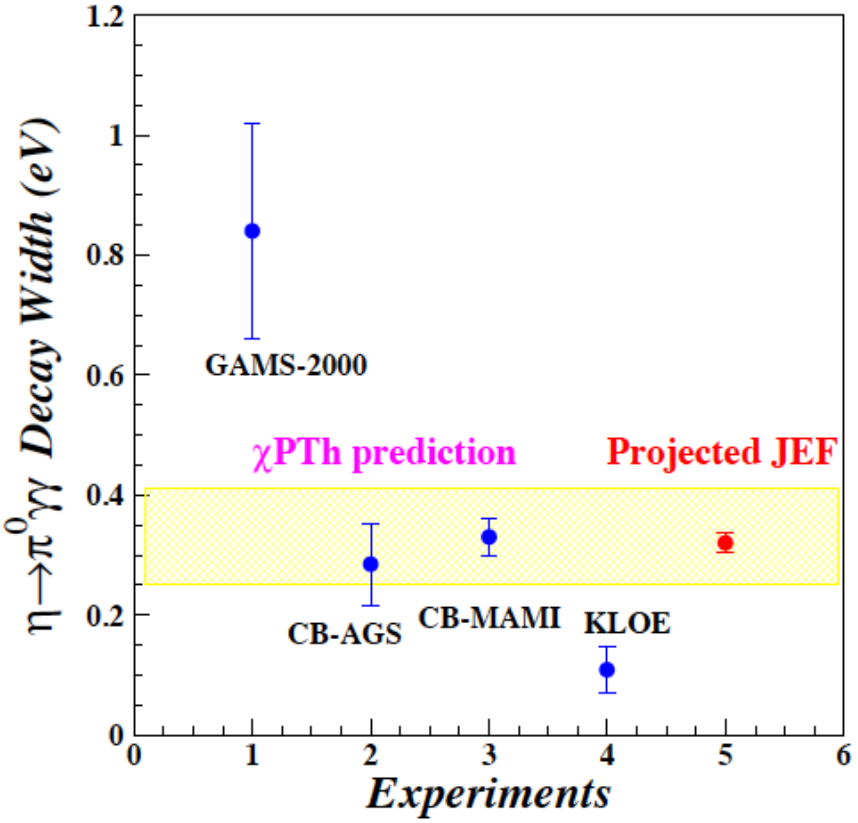


Projected* JEF on SM Allowed $\eta \to \pi^0\gamma\gamma$

J.N. Ng and D.J. Peters, Phys. Rev. D47, 4939



χPTh by Oset et al., Phys. Rev. D77, 073001



We measure both BR and Dalitz distribution

- model-independent determination of two LEC's of the $O(p^6)$ counter-terms
- probe role of scalar resonances to calculate other unknown $O(p^6)$ LEC's

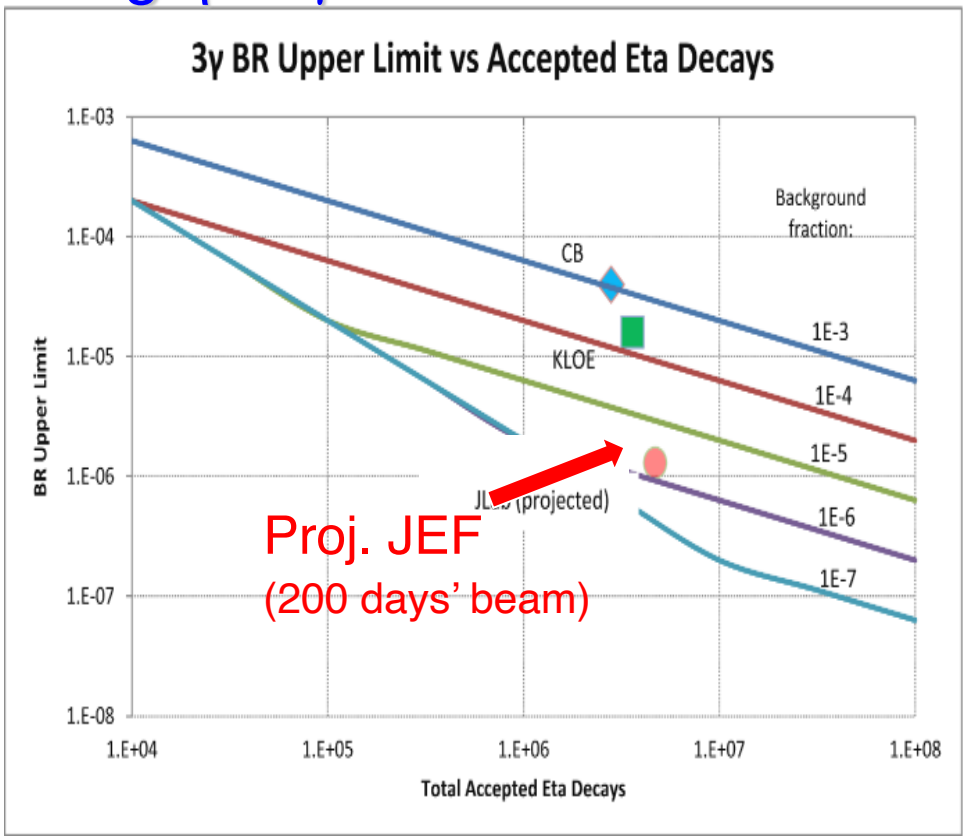
* N.B. New estimated projections are underway and will be ready for proceedings

Estimated Experimental Improvement on C-violating $\eta \to 3\gamma$

- SM contribution:
  BR($\eta \to 3\gamma$) $<10^{-19}$ via P-violating weak interaction.

- A calculation due to new physics by Tarasov suggests:
  BR($\eta \to 3\gamma$)$< 10^{-2}$

  Sov.J.Nucl.Phys.,5,445 (1967)



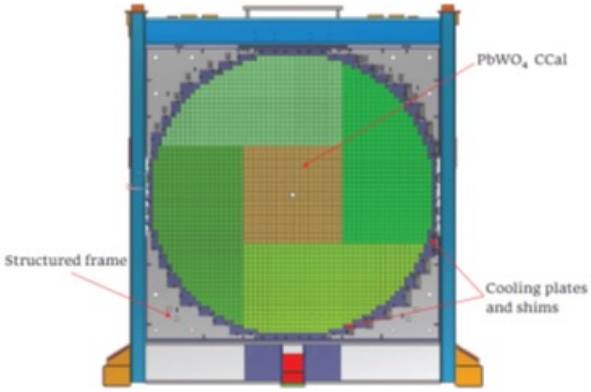
Aim to Improve BR upper limit by about an order of magnitude to tighten constraint on CVPC physics

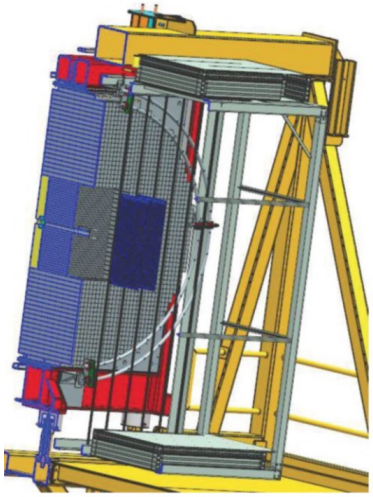
Current Status of the JEF Experiment

1. Non-rare decay data has been collecting with GlueX since 2016.

2. Upgraded FCAL-II with new PWO insert.

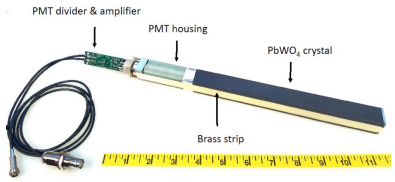
   - Production of the 1600 PWO modules is complete.
   - Installation into the upgraded FCAL-II is almost complete.
   - Testing in progress and will be completed this fall (2024).





3. Rare decay data with FCAL-II expected in Spring 2025.

PWO module ($2x2x20\ cm^3$)



Undergraduate workforce

Summary

- 12 GeV tagged photon beam with GlueX offers a unique η/η' factory to test SM and search for new BSM physics, with background reduction in the neutral rare decay mode.
- New estimated projections are underway and will be ready for proceedings
- Simultaneously measure η/η' decays with physics goals to:
  - Search for sub-GeV hidden bosons: vector, scalar, and ALP
  - Directly constrain new CVPC physics
  - Precision tests of low-energy QCD: role of scalar dynamics in ChPT; transition form factors of η/η' to calculate HLbL contributions in $(g\text{-}2)_\mu$
  - Improve light quark mass ratio via $\eta \to 3\pi$, $\eta' \to 3\pi$
- Data collection for non-rare decays on-going with GlueX since 2016.
- Rare decays require upgraded FCAL-II with PWO insert.
- Installation almost complete & testing in progress; complete Fall 2024.
- Data taking starts in Spring 2025.

- Scan for acknowledgments