The JLab Eta Factory (JEF) Experiment

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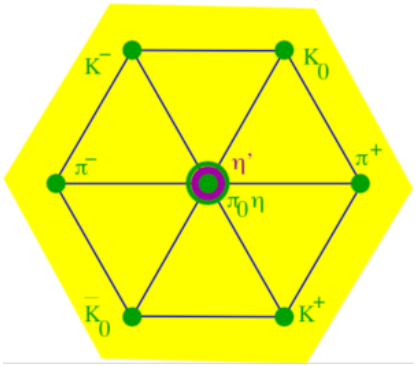
Outline

1. Introduction to the JEF experiment
   - Why η/η' is interesting?
   - Experimental approach
   - Physics objectives and sensitivities
2. Current status
3. Summary

Why η is a unique probe for QCD and BSM physics?

- A Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  - → η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD

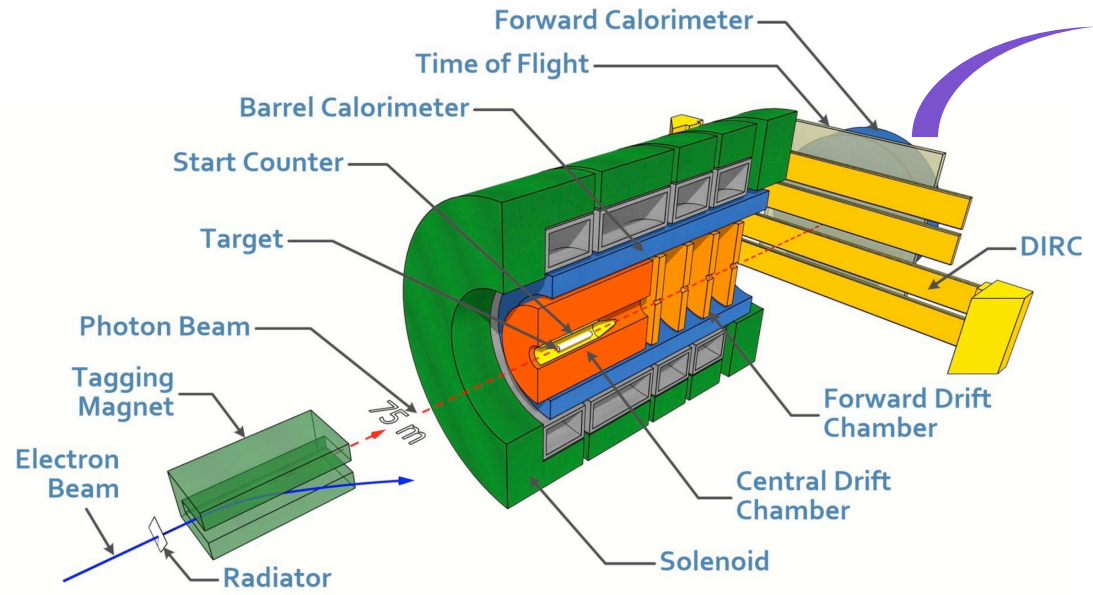


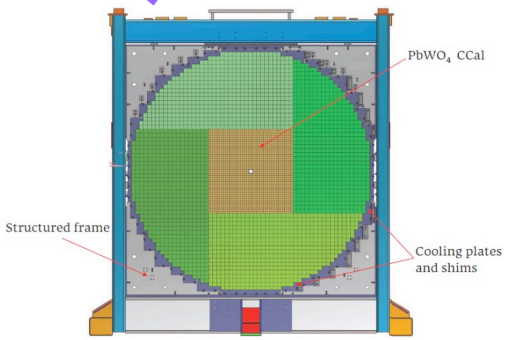
- All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width (Γ_η =1.3KeV compared to Γ_ω=8.5 MeV)
  - → Enhance the higher order contributions (by a factor of ~7000 compared to ω decays). Sensitive to weakly interacting forces.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  - → tests for C, CP

- All its additive quantum numbers are zero and its decays are flavor-conserving
  - → effectively free of SM backgrounds for new physics search.

JLab Eta Factory (JEF) Experiment





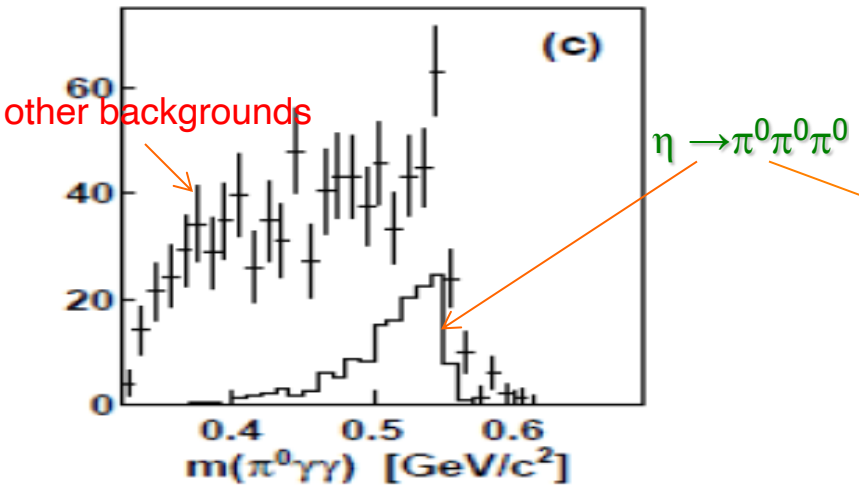
FCAL-II

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

Uniqueness of JEF Experiment

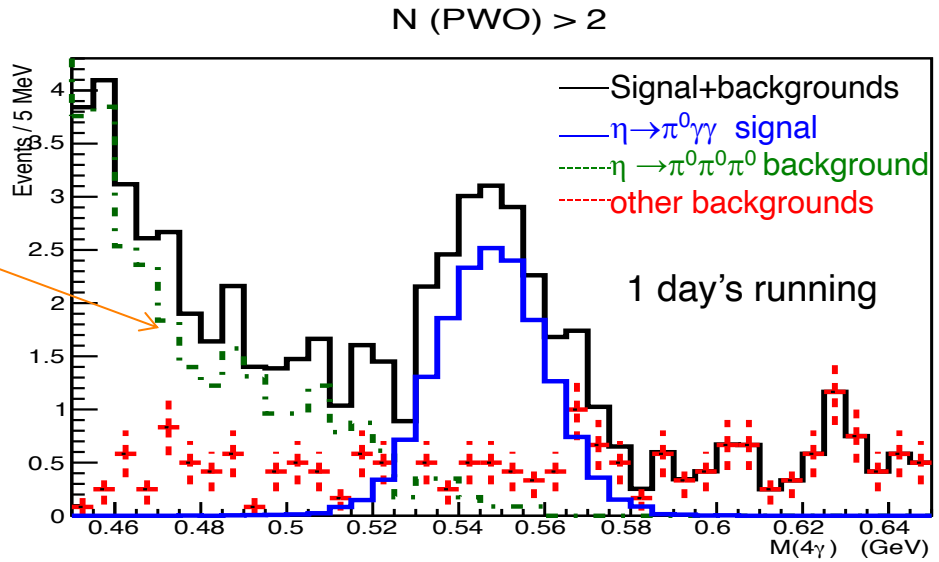
1. Highly suppressed background comparing to all other experiments:
   a) η/η′ energy boost; b) FCAL-II; c) exclusive detections

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV)
(P.R. C90, 025206)



$\eta \rightarrow \pi^0\pi^0\pi^0$

JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV)



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
   (~5x10^7 per 100 days)

Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

Experiment	**Total η**	**Total η'**
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim 3 \times 10^7$ (p+d), $\sim 5 \times 10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim 10^7$	$\sim 5 \times 10^7$

JEF offers a competitive η/η' factory

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

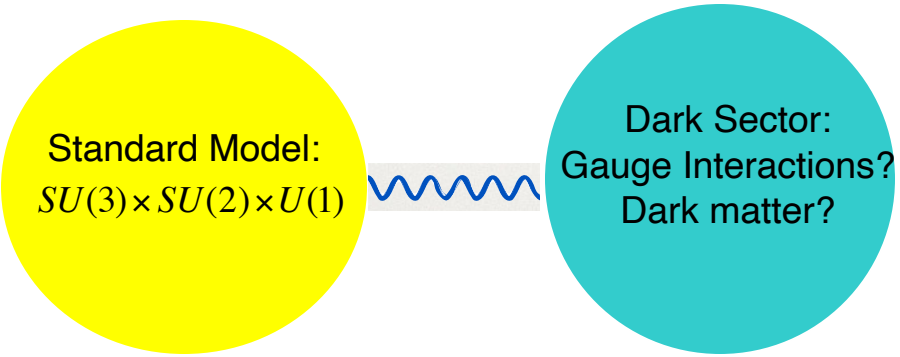
2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

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 $\eta \to 3\pi$**

Example of a Key Channel: $\eta \to \pi^0\gamma\gamma$

1. New physics:



Portal: $(n=4)$

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

scalar $H^{+}H(\varepsilon S+\lambda S^{2})$

- **Search for sub-GeV gauge bosons**
  - A leptophobic vector B′:
    $\eta \to \gamma B'$, $B' \to \pi^0\gamma$ **PR,D89,114008**
  - An electrophobic scalar Φ′:
    $\eta \to \pi^0\Phi'$, $\Phi' \to \gamma\gamma$

PRL 117,101801 (2016); PL B740,61(2015)

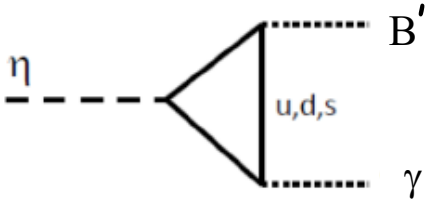
2. Confinement QCD:

- **A rare window to probe interplay of VMD & scalar resonance in ChPT**

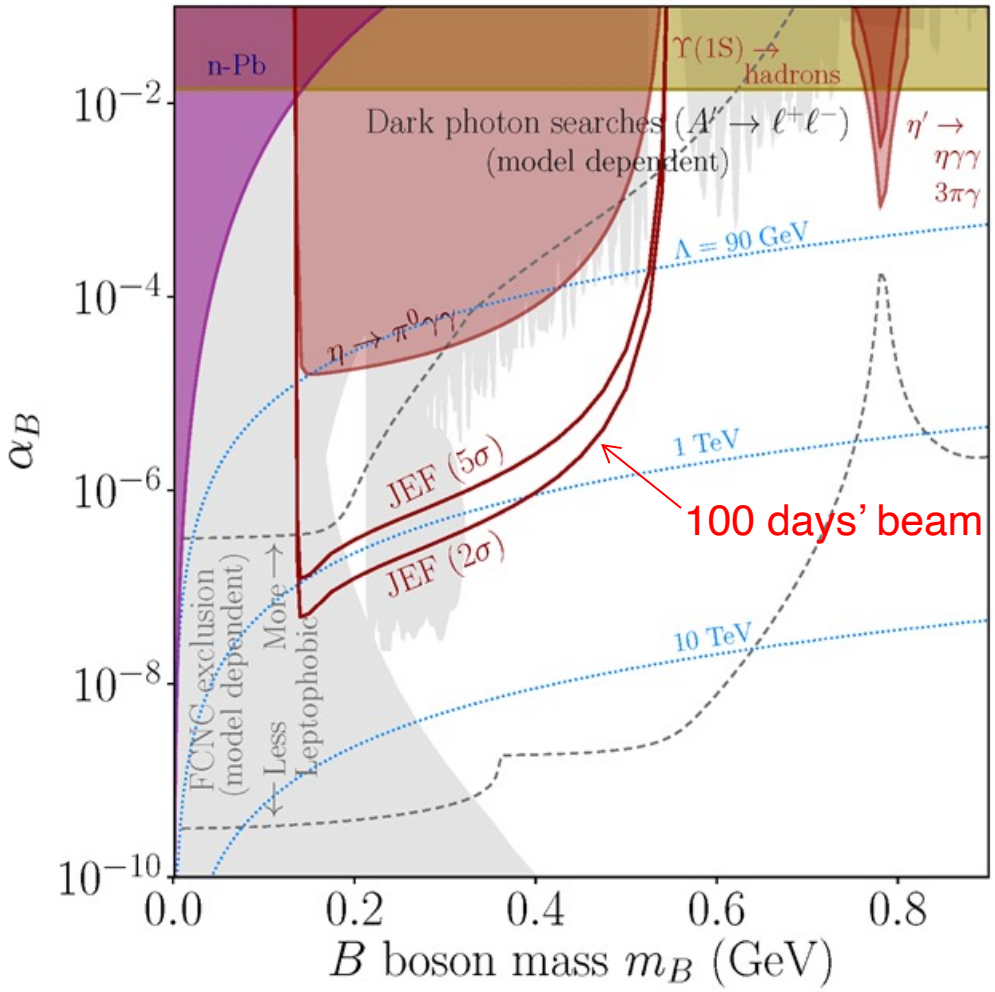
JEF Experimental Reach for B′

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



Impact of the SM allowed $\eta \to \pi^0\gamma\gamma$ measurement

➡ A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate O(p^6) LEC's in the chiral Lagrangian

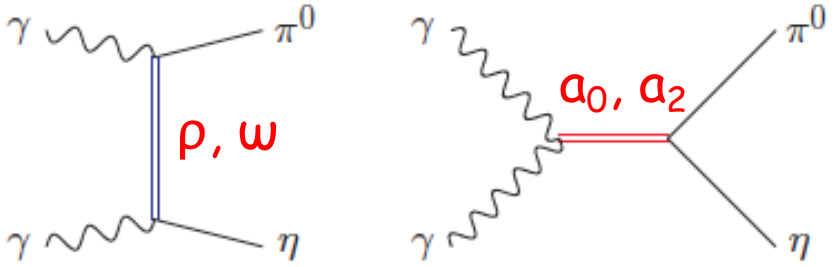
- The major contributions to $\eta \to \pi^0\gamma\gamma$ are two O(p^6) counter-terms in the chiral Lagrangian ➡ an unique probe for the high order ChPT.

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

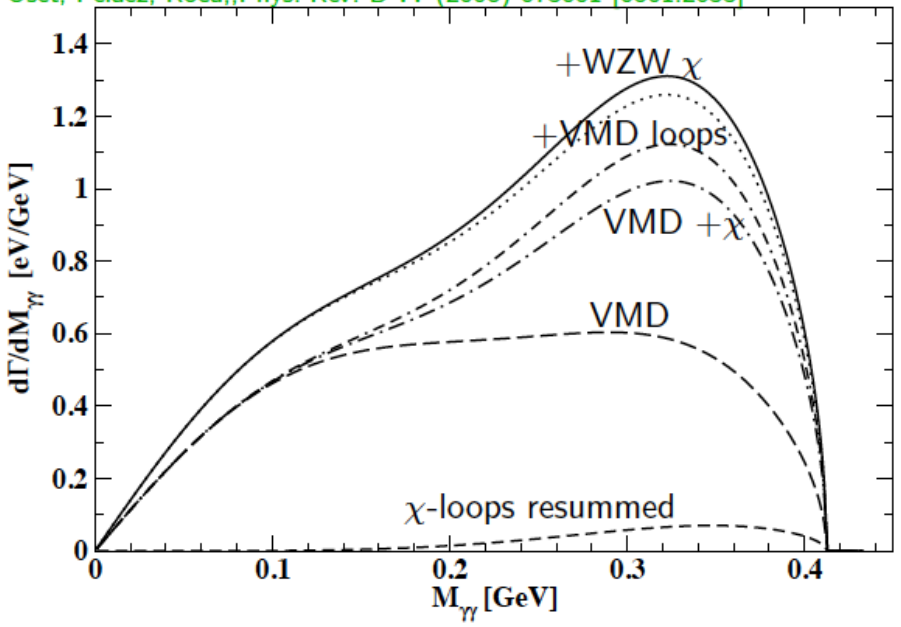
- Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by resonances

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

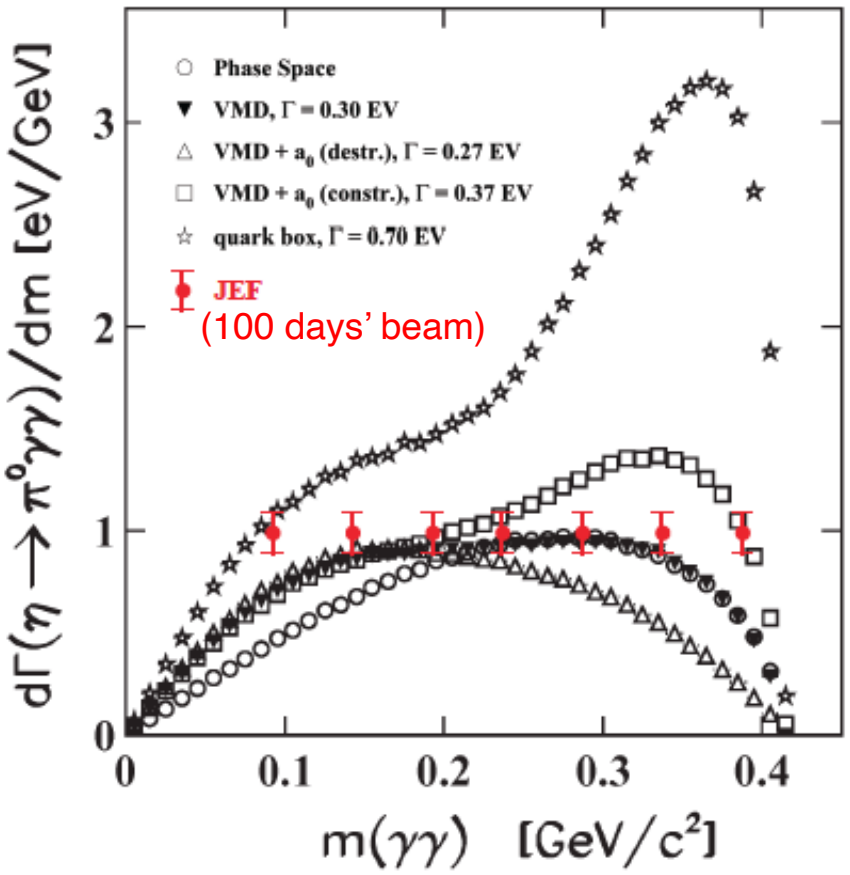


Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

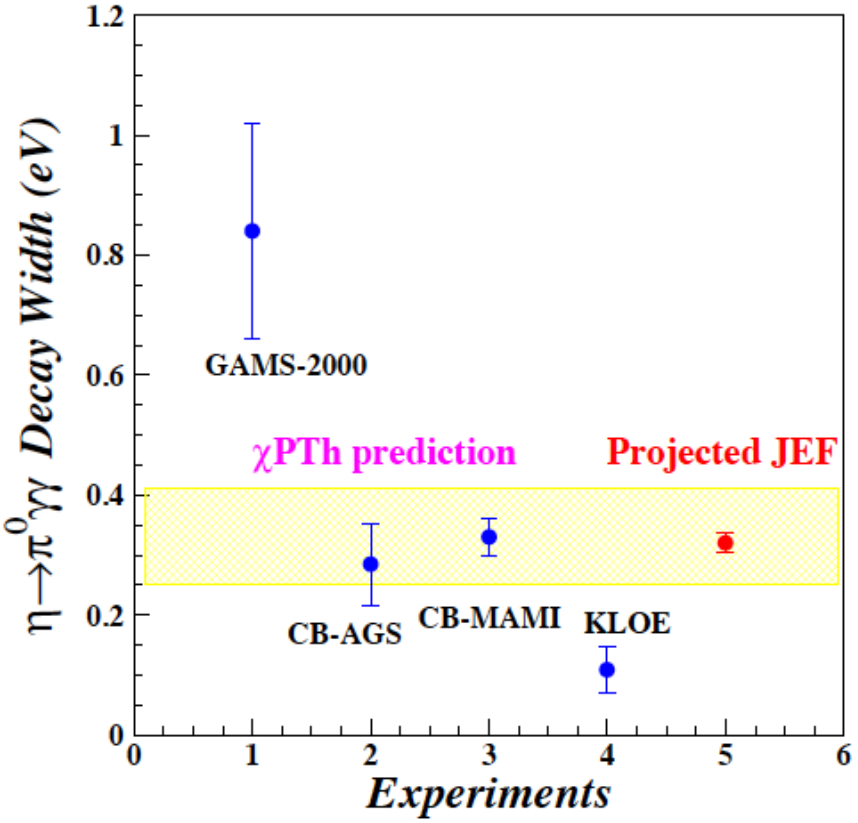


Projected JEF on SM Allowed $\eta \to \pi^0\gamma\gamma$

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 the role of scalar resonances to calculate other unknown O(p^6) LEC's

J. Bijnens, talk at AFCI workshop

Test Charge Conjugation Invariance

- Maximally violated in the weak force and is well tested.
- Assumed in SM for electromagnetic and strong forces, but **it is not experimentally well tested**

(current direct constraint: $\Lambda \geq 1$ GeV)

C Violating η neutral decays

Mode	Branching Ratio (upper limit)	No. γ's
3γ	$< 1.6 \cdot 10^{-5}$	3
$\pi^0\gamma$	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

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

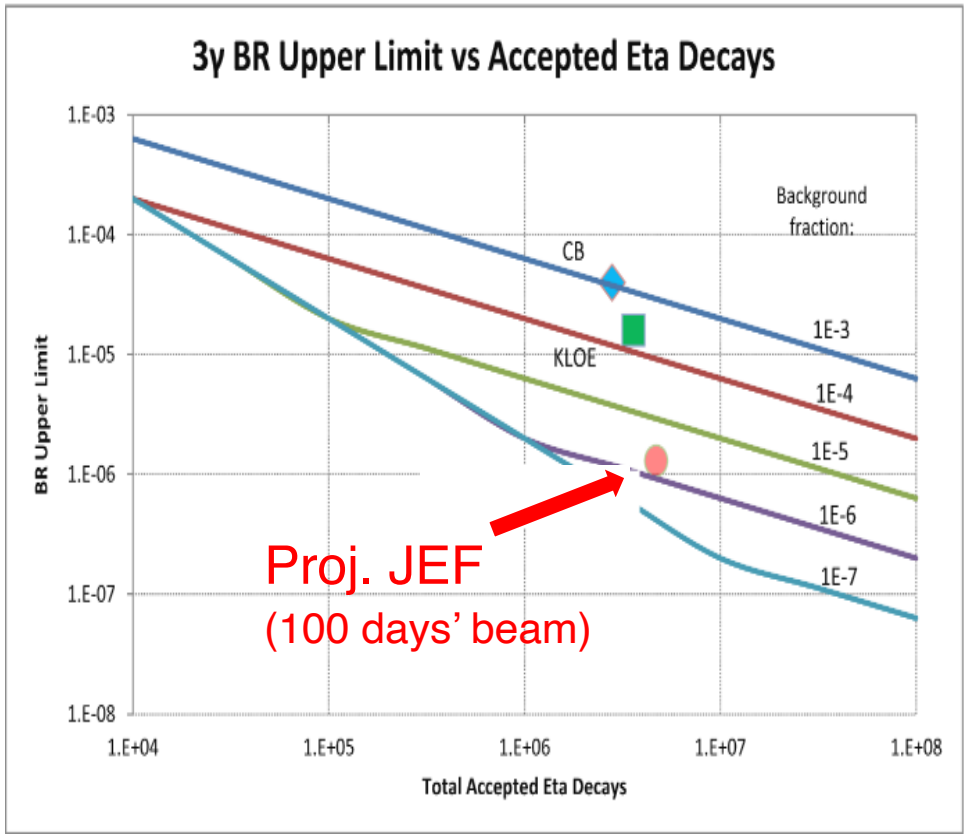
- SM contribution:
  BR($\eta \to 3\gamma$) $<10^{-19}$ via P-violating weak interaction.

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee

  Phys. Rev.,139, B1650 (1965)

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

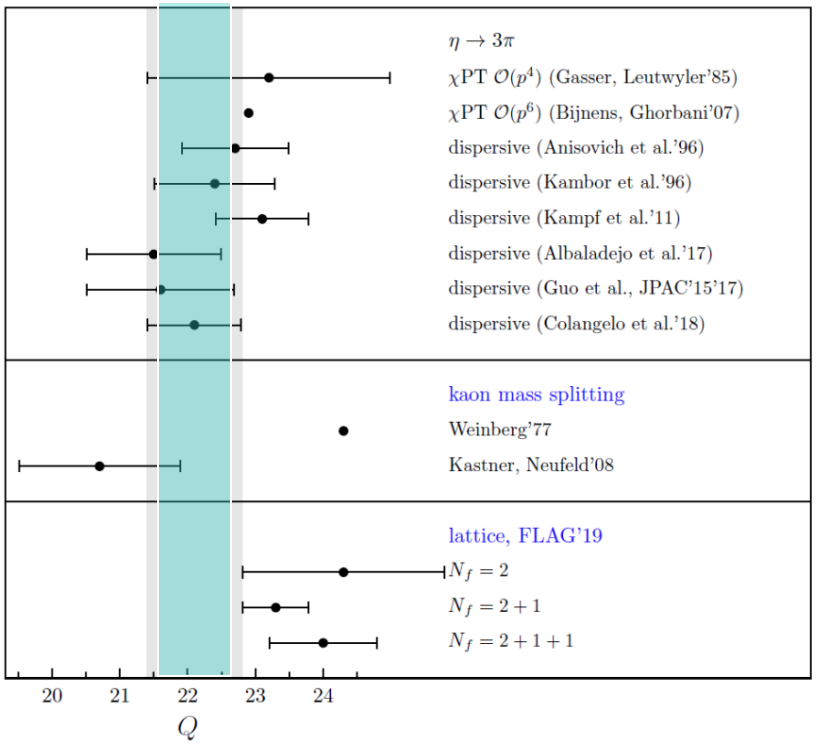
  Sov.J.Nucl.Phys.,5,445 (1967)



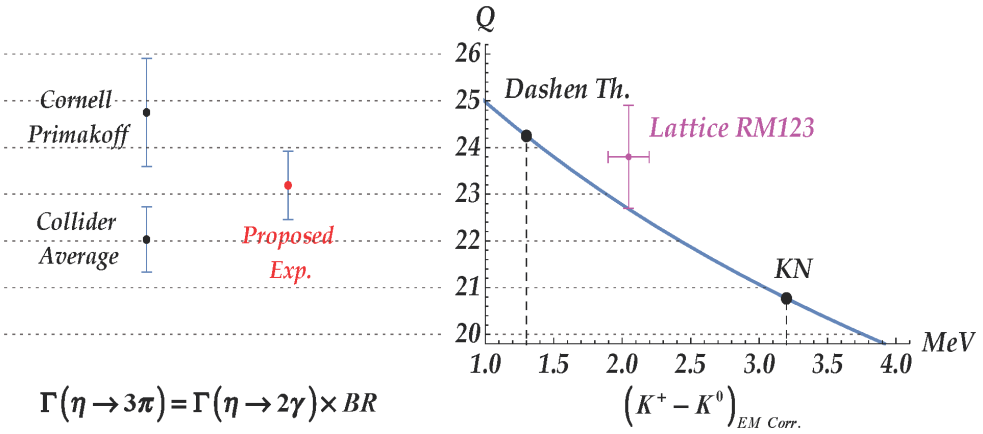
Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

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

- A clean probe for quark mass ratio: $Q^2 = \dfrac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\qquad \hat{m} = \dfrac{m_u + m_d}{2}$
  - Decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \dfrac{1}{Q^2}\dfrac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\dfrac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$
- JEF will improve the quark-mass ratio via measurement of $\eta \to 3\pi$ Dalitz distributions



Further improvement by PrimEx-eta to measure $\Gamma(\eta \to \gamma\gamma)$



Phys.Rept. 945 (2022) 1-105

Current Status of the JEF Experiment

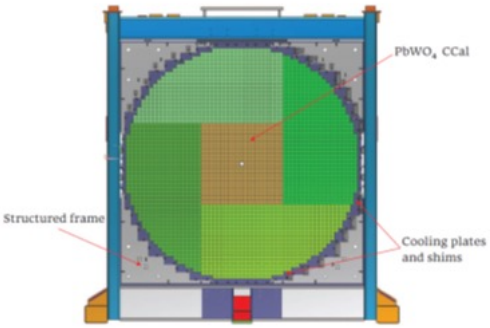
1. JEF was approved in 2017

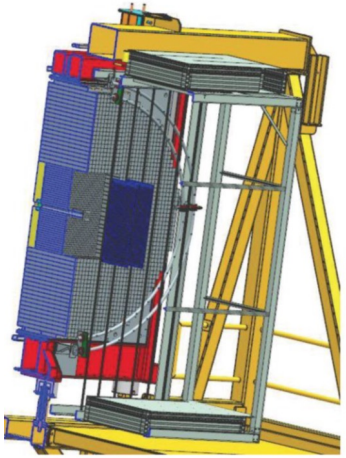
2. A PWO insert to upgrade FCAL is under construction:

   - Constructed a 12x12 array of PWO prototype calorimeter and successfully tested and used for the PrimEx-eta experiment in 2019, 2021
   - Mass production of 1600 Modules (2x2x20 cm^3) is on-going.
   - Engineering design for calorimeter frame is finalized
   - Installation of the PWO insert is anticipated in 2023

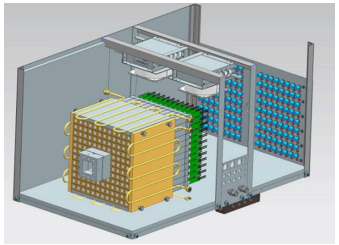
3. Data taking is expected in 2024

4. More beam time will be requested in 2023

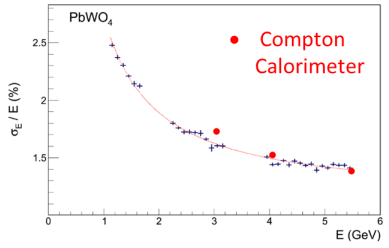




prototype calorimeter



prototype test result



Summary

- 12 GeV tagged photon beam with GlueX setup offers a unique η/η' factory to test SM and search for new BSM physics, with two orders of magnitude in background reduction in the neutral rare decay modes compared to other facilities.

- Simultaneously measure η/η' decays with main physics goals of:

  - Search for sub-GeV hidden bosons: vector, scalar, and ALP
  - Directly constrain CVPC new physics
  - Precision tests of low-energy QCD: the role of scalar dynamics in ChPT; transition form factors of η/η' to calculate HLbL contributions in $(g-2)_\mu$
  - Improve the light quark mass ratio via $\eta \to 3\pi$, $\eta' \to 3\pi$

- Data collection for non-rare decays has been on-going with the GlueX experiment since 2016.

- The rare decays require an upgraded FCAL-II with a PWO insert that is currently under construction. Data taking will be expected in 2024.

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