JLab Eta Factory (JEF) Experiment

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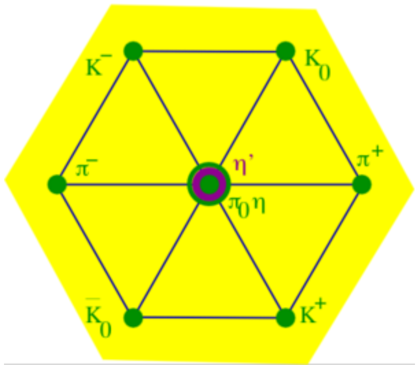
Outline

- Overview of η and η' Physics
- JLab Eta Factory (JEF) experiment and status
- 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

- Its quantum numbers are the same as Higgs or vacuum (except parity) and its decays are flavor-conserving
  ⟶ effectively free of SM backgrounds for new physics search.

Rich η (and η') Physics

Standard Model Tests:
- Chiral symmetry and anomalies
- Extract η-η' mixing angle and quark mass ratio
- Theory inputs to HLbL for $(g-2)_\mu$
- 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

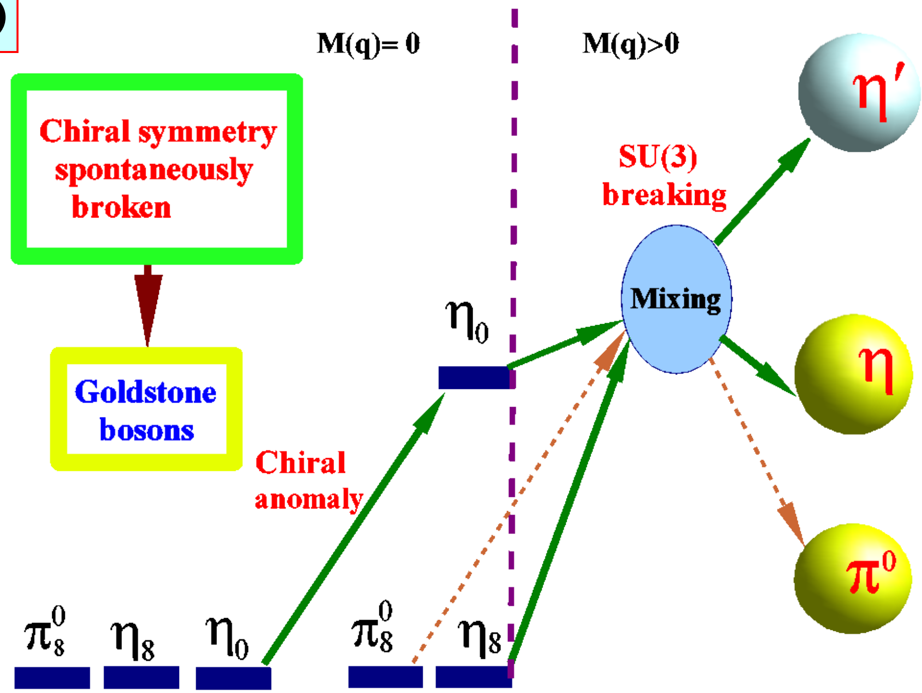
Phys. Rept. 945 (2022) 1-105

Low-Energy QCD Symmetries and Light Mesons

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

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

- **Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to SU(3)**
  - 8 Goldstone Bosons (GB)
- **$U_A(1)$ is 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
- **$SU_L(3)xSU_R(3)$ and SU(3) are explicitly broken:**
  - GB are massive
  - Mixing of π^0, η, η'



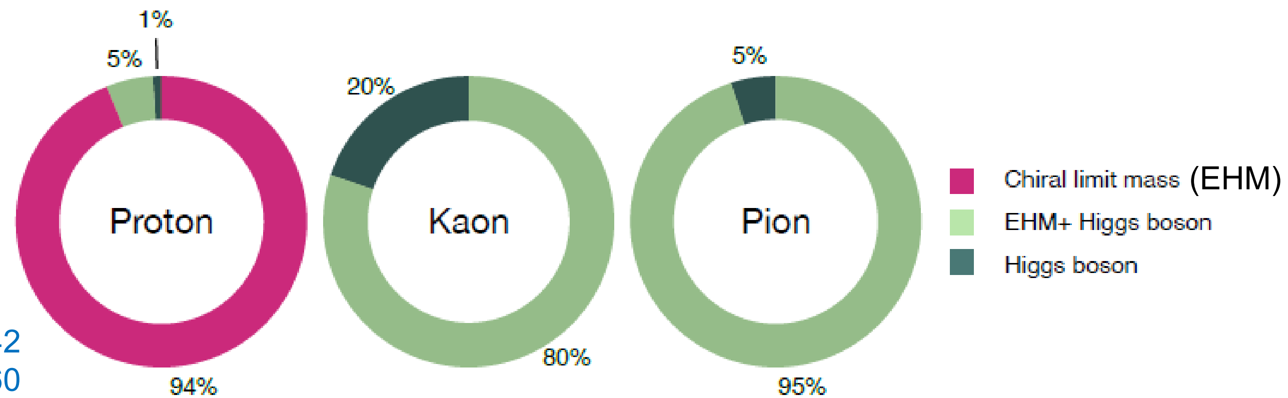
The π^0, η, η' system provides a rich laboratory to study the symmetry structure of confinement QCD.

What is the origin of visible mass?

Mass-generating mechanisms:

- Higgs boson, alone is responsible for <2% of the visible mass in the universe.

- Emergent Hadron Mass (EHM) and its constructive interference with Higgs-boson account for >98% of the visible mass.



Few Body Syst. 63 (2022) 2,42
Few Body Syst. 65 (2024) 2,60

Complementary to proton, pseudoscalar mesons offer a unique opportunity to study the interference between two known mass generating mechanisms.

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

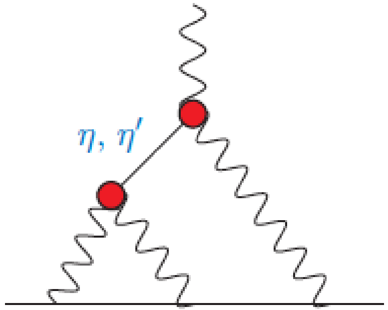
important hadronic light-by-light contribution:

$\eta^{(\prime)}$ 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

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

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

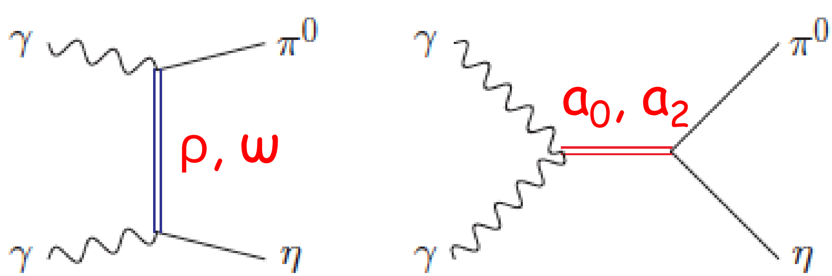
◆ The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian ➡ an unique probe for the high order ChPT.

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

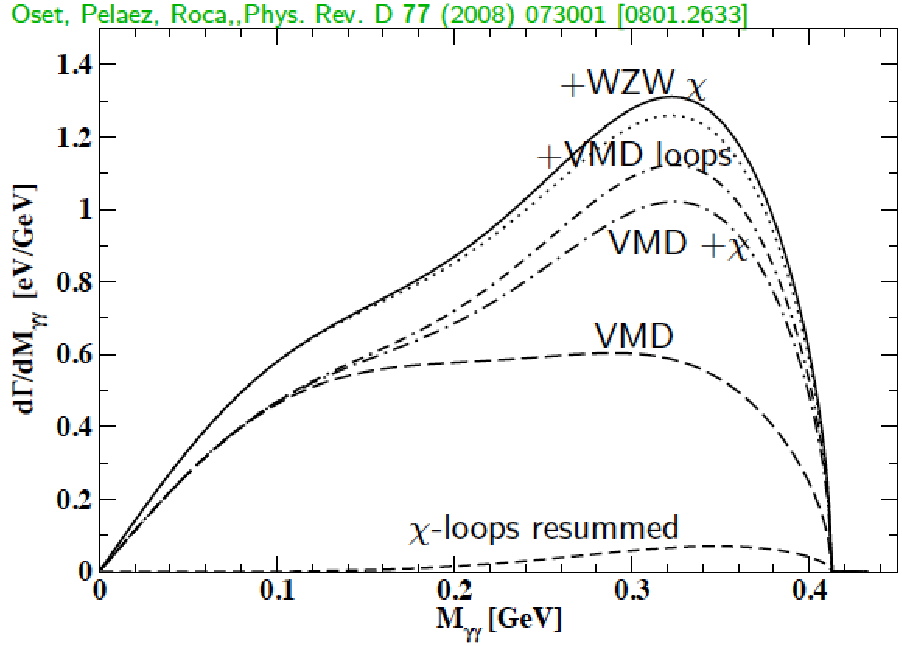
◆ Shape of Dalitz distribution is sensitive to the role of scalar resonances.

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]



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 constraints from EDM measurements with a few exceptions

Class III: C-, CP-violation

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee, but little theoretic progress until very recent. Phys. Rev.,139, B1650 (1965)
- Examples: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^o\gamma^{(*)}, \cdots$
- 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 decays.

Class II: P-, CP-Violation via Strange-Quark-Muon Operators

- new class of *CP*-tests in — Sánchez-Puertas 2019

$$\eta \to \mu^+\mu^- , \quad \eta \to \mu^+\mu^-\gamma , \quad \eta \to \mu^+\mu^- e^+ e^-$$

$$\eta \to \pi^0 \mu^+\mu^- \qquad \eta \to \pi^+\pi^-\mu^+\mu^-$$

E. Royo

Zillinger, BK, Sánchez-Puertas

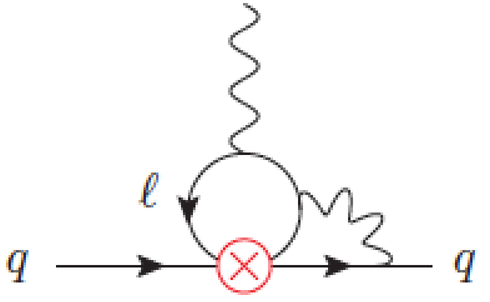
- quark–lepton four-fermion operators (scalar–pseudoscalar):

$$\mathcal{L}_{\text{eff}} = \frac{1}{2v^2} \text{Im}\, c^{2222}_{\ell edq} \Big[(\bar{\mu}\mu)(\bar{s} i\gamma^5 s) - (\bar{\mu} i \gamma^5 \mu)(\bar{s}s) \Big] + [u\text{-},\, d\text{-quarks}]$$

- EDMs only generated at two loops

  constraint for strange quarks weakest:

$$|\text{Im}\, c^{2222}_{\ell edq}| < 0.04$$

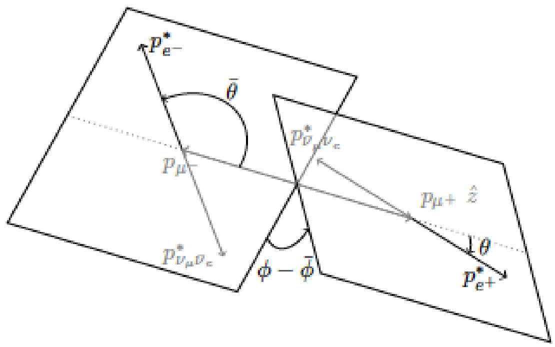


- Offer good opportunities for P-, CP-violation tests in the eta-sector.

Class II: P-, CP-Violation via Scalar Operators (cont.)

- μ-polarization asymmetry in $\eta^{(\prime)} \to \mu^+u^-$, $\eta^{(\prime)} \to \gamma\mu^+u^-$, $\eta^{(\prime)} \to \pi^0\mu^+u^-$

  JHEP 01, 031 (2019)
  hep-ph/0202002



$$A_L = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N}$$

$$A_\times = \frac{N(\sin\Phi > 0) - N(\sin\Phi < 0)}{N}$$

- Angular asymmetry in decay planes:

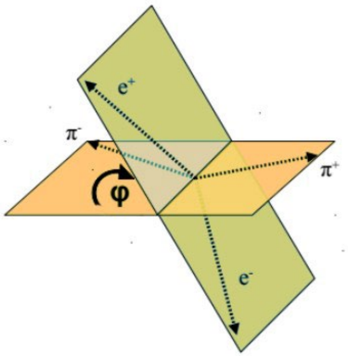
$\eta^{(\prime)} \to \mu^+u^-e^+e^-$

$$A_{sin\Phi cos\Phi} = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$

$$A_{sin\Phi} = \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)}$$

$\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}$$



Class III: C- and CP-Violation

- $\eta^{(\prime)}$ are $C = +1$ eigenstates: opportunity to test C-violation!

Channel	Branching ratio	Note
$\eta \to 3\gamma$	$< 1.6 \times 10^{-5}$	
$\eta \to \pi^0\gamma$	$< 9 \times 10^{-5}$	Violates angular momentum conservation or gauge invariance
$\eta \to \pi^0 e^+ e^-$	$< 7.5 \times 10^{-6}$	C, CP-violating as single-γ process
$\eta \to \pi^0 \mu^+ \mu^-$	$< 5 \times 10^{-6}$	C, CP-violating as single-γ process
$\eta \to 2\pi^0\gamma$	$< 5 \times 10^{-4}$	
$\eta \to 3\pi^0\gamma$	$< 6 \times 10^{-5}$	

- example ops.: Khriplovich 1991; Ramsey-Musolf 1999; Kurylov et al. 2001

$$\frac{1}{\Lambda^3}\bar{\psi}_f\gamma_5 D_\mu\psi_f\,\bar{\psi}_{f'}\gamma^\mu\gamma_5\psi_{f'} + \text{h.c.}\,, \qquad \frac{1}{\Lambda^3}\bar{\psi}_f\sigma_{\mu\nu}\lambda_a\psi_f G_a^{\mu\lambda}F_\lambda^\nu$$

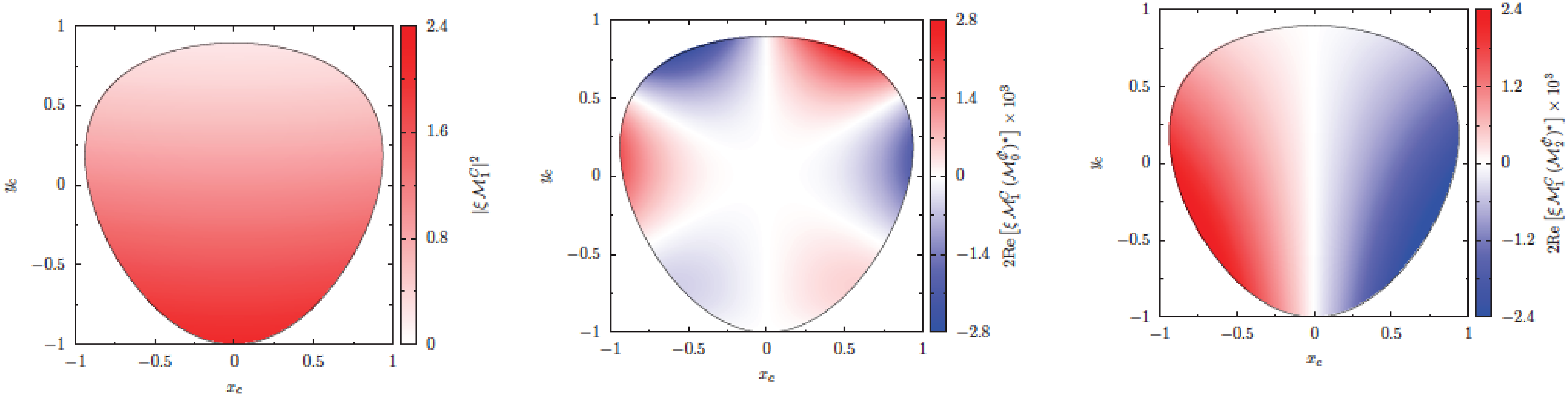
$\longrightarrow$ require helicity flip, actually dimension-8 in SMEFT

- electroweak radiative corrections mix class II and class III still weaker EDM constraints

Class III: C- and CP-Violation in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$, $\eta' \to \pi^+\pi^-\eta$

- Dalitz plot decomposition (central fit result)

$$|\mathcal{M}_c|^2 \approx |\mathcal{M}_1^{C}|^2 + 2\mathrm{Re}\left[\mathcal{M}_1^{C}\left(\mathcal{M}_0^{\not{C}}\right)^*\right] + 2\mathrm{Re}\left[\mathcal{M}_1^{C}\left(\mathcal{M}_2^{\not{C}}\right)^*\right]$$

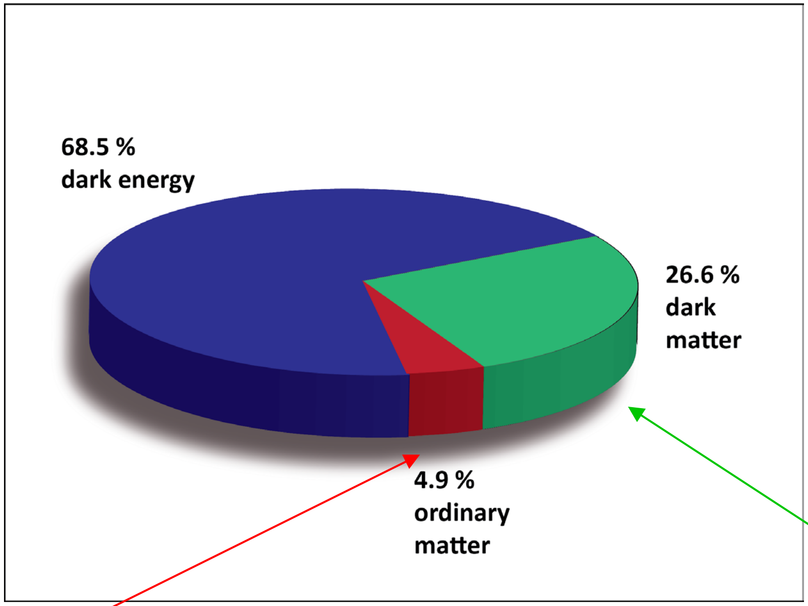


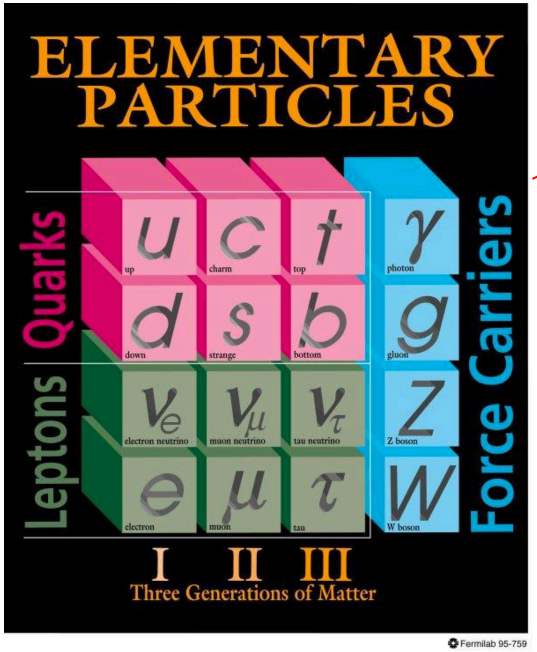
- $\mathcal{M}_0^{\not{C}}$ and $\mathcal{M}_2^{\not{C}}$ lead to different interference patterns

- CP-violation from these processes is not bounded by EDM.

- Complementary to nEDM searches even in the case of T and P odd observables, since the flavor structure of the η is different from the nucleus

BSM Physics in Dark Sector

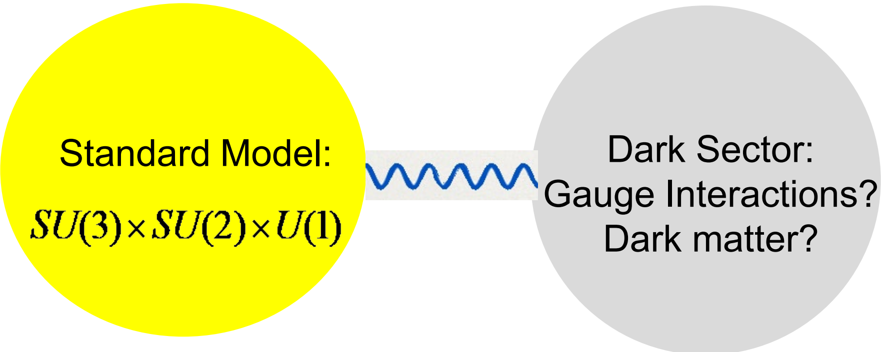




Dark Sector

- 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'

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

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

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

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

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

Portals:

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

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

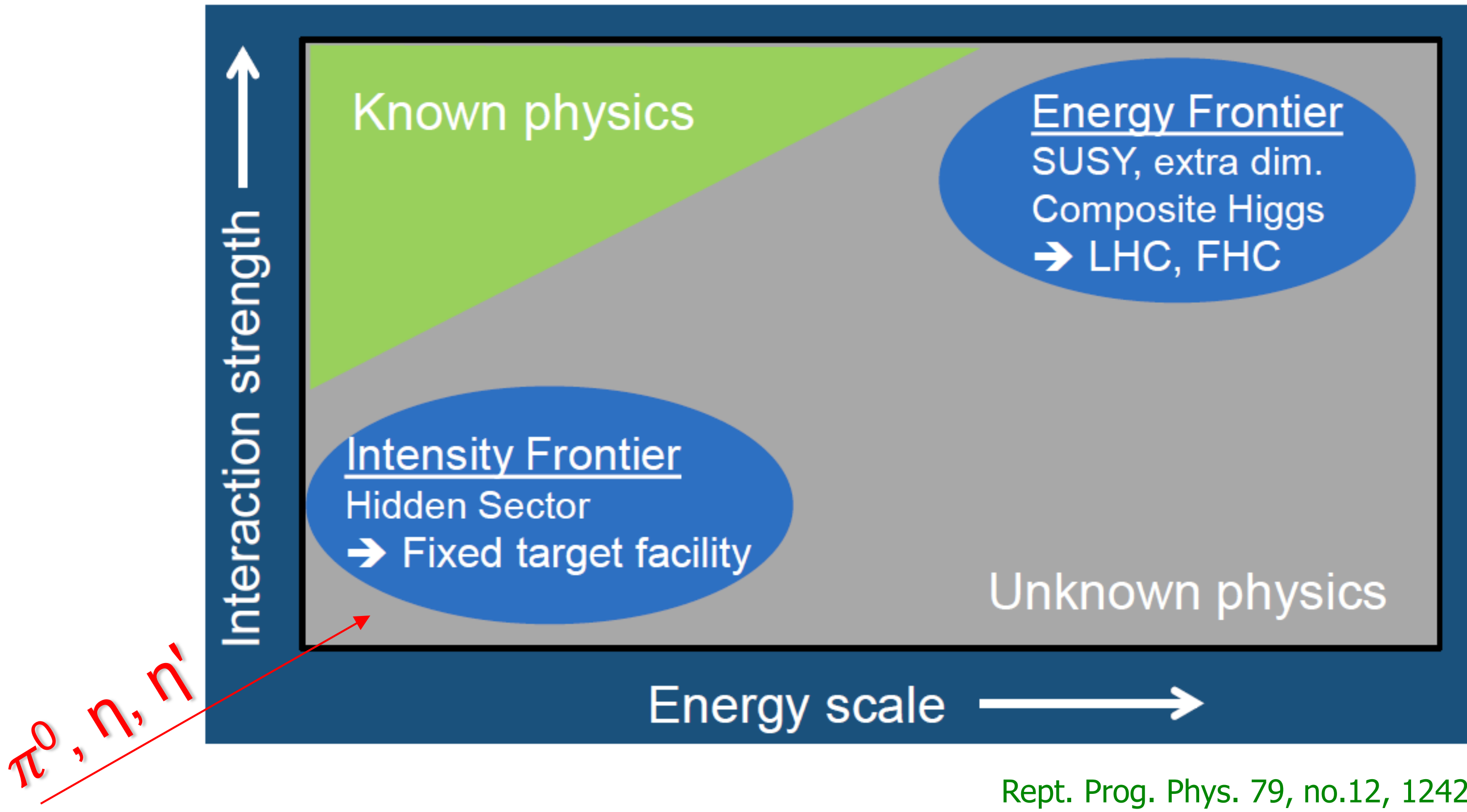
Fermion ξLHN

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

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



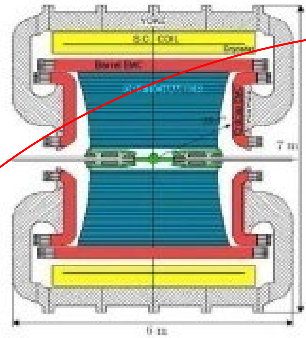
Rept. Prog. Phys. 79, no.12, 124201

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

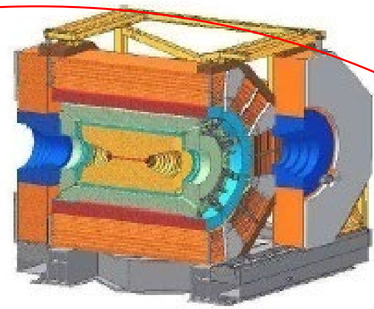
Global Experimental Efforts in η Decays

e⁺e⁻ Collider

KLOE-2 at DAφNE

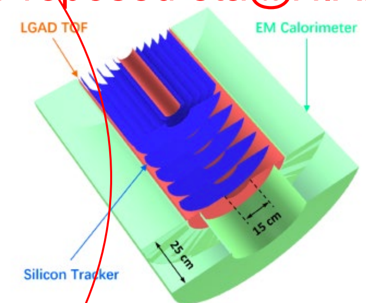


BESIII at BEPCII



Low-energy

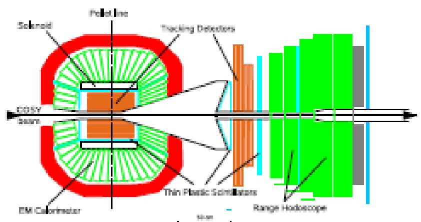
Proposed eta@HIAF



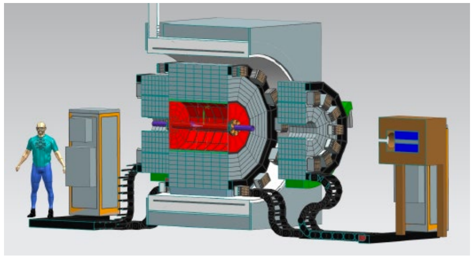
Fixed-target

hadroproduction

WASA at COSY

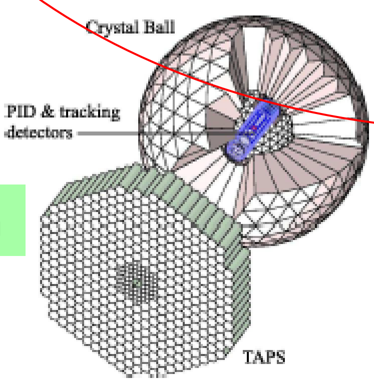


Proposed REDTOP

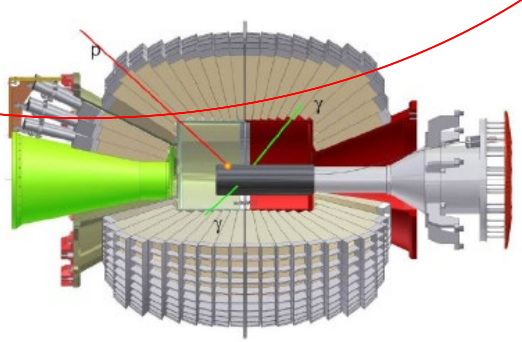


High-energy

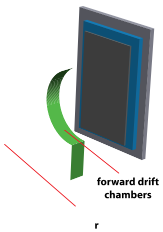
Crystall Ball at MAMI



CBELSA/TAPS at ELSA

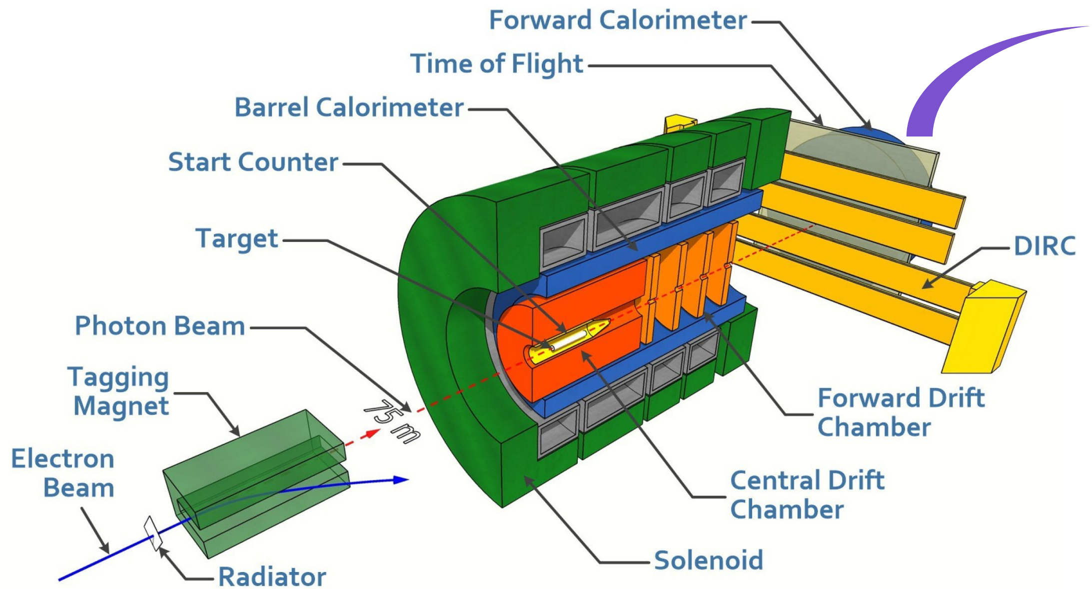


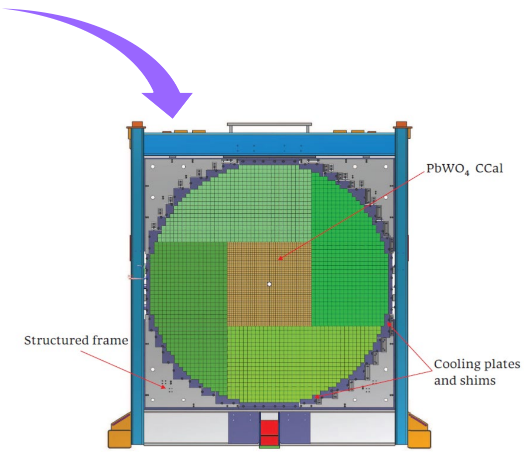
JEF at JLab



Photoproduction

JLab Eta Factory (JEF) Experiment





FCAL-II

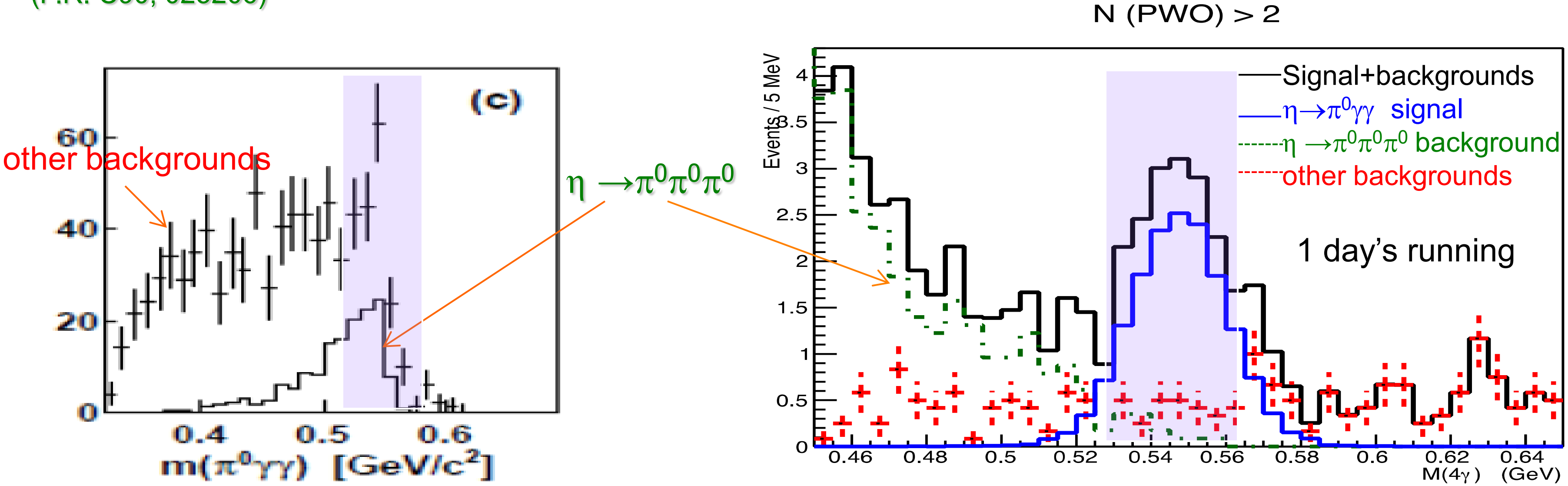
- Simultaneously produce η/η' on LH_2 target with 8.4-11.7 GeV tagged photon beam via $\gamma + p \rightarrow \eta/\eta' + p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity $PbWO_4$ insertion (FCAL-II) to detect multi-photons from the η/η' decays
- The GlueX detector will detect the charged products from the η/η' decays

Uniqueness of JEF Experiment

1. Two-orders of magnitude background suppression comparing to the other experiments in rare neutral decays:
   a) η/η′ energy boost; b) FCAL-II; c) recoil detections

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV) JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV)

(P.R. C90, 025206)



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

3. Simultaneously produce tagged η and η' with similar rates ($\sim 5\times10^5$ per day)

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

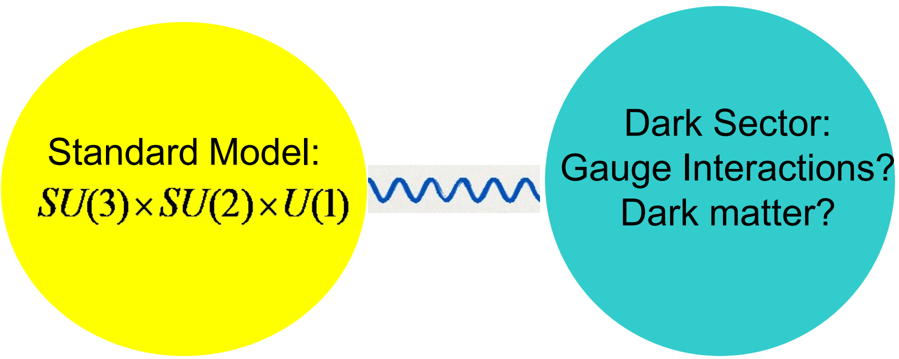
2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

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 light quark mass ratio via Dalitz distributions of $\eta \to 3\pi$**

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

fermion ξLHN

- **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)

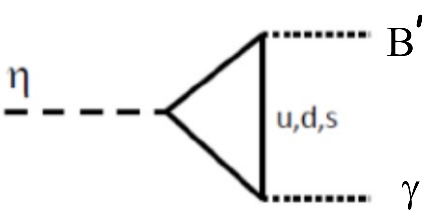
2. Confinement QCD:

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

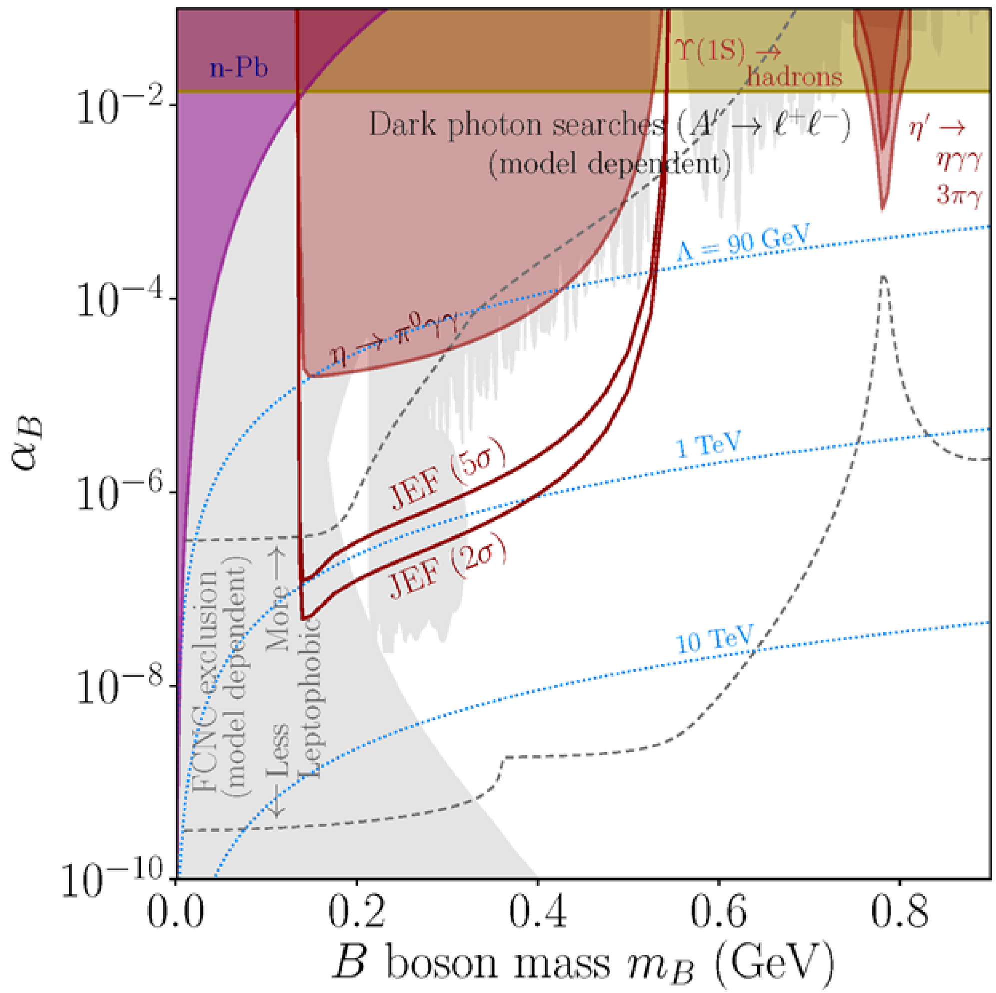
JEF Experimental Reach for B′

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

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

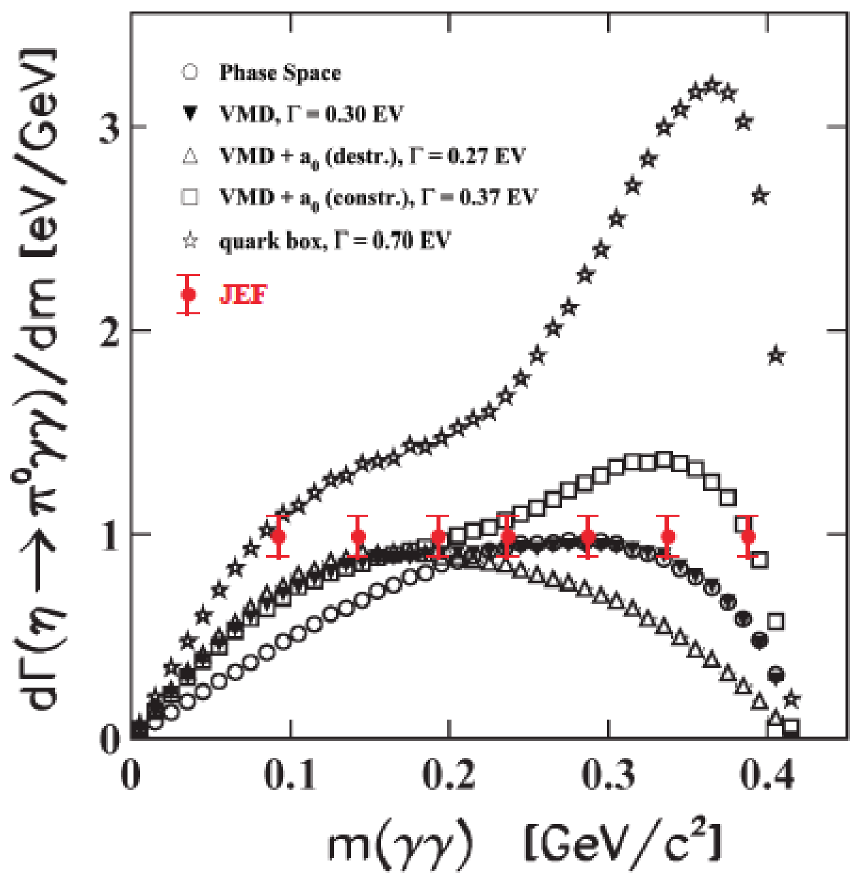


PL, B221, 80 (1989)
PR,D89,114008

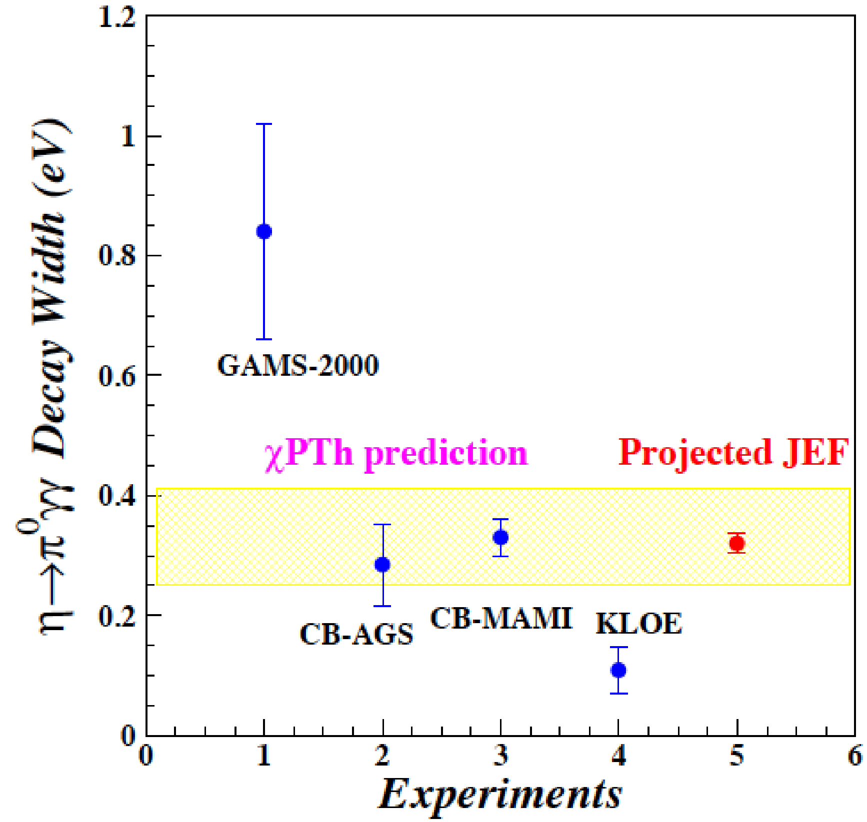


Projected JEF on SM Allowed $\eta\to\pi^0\gamma\gamma$

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

J. Bijnens, talk at AFCI workshop

Test Charge Conjugation Invariance

- C is 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

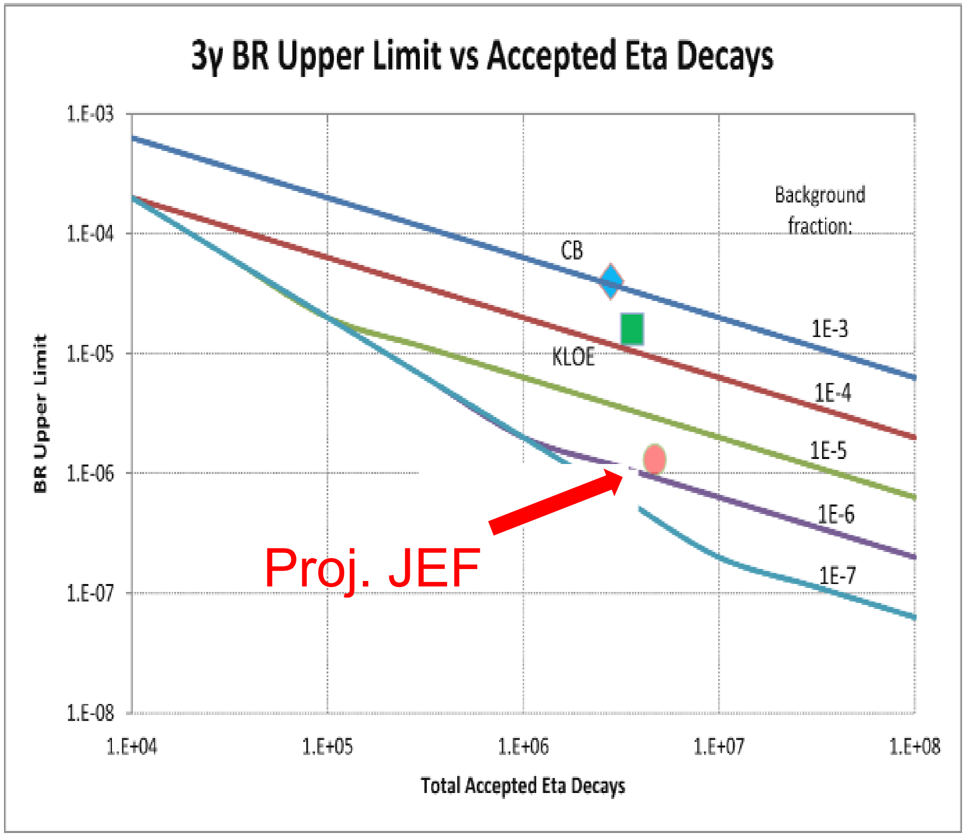
<table>
<tr><th>Mode</th><th>Branching Ratio (upper limit)</th><th>No. γ's</th></tr>
<tr><td>3γ</td><td>$< 1.6 \cdot 10^{-5}$</td><td rowspan="2">3</td></tr>
<tr><td>$\pi^0\gamma$</td><td>$< 9 \cdot 10^{-5}$</td></tr>
<tr><td>$2\pi^0\gamma$</td><td>$< 5 \cdot 10^{-4}$</td><td rowspan="2">5</td></tr>
<tr><td>$3\gamma\pi^0$</td><td>Nothing published</td></tr>
<tr><td>$3\pi^0\gamma$</td><td>$< 6 \cdot 10^{-5}$</td><td rowspan="2">7</td></tr>
<tr><td>$3\gamma 2\pi^0$</td><td>Nothing published</td></tr>
</table>

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)



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

Status of the JEF Experiment

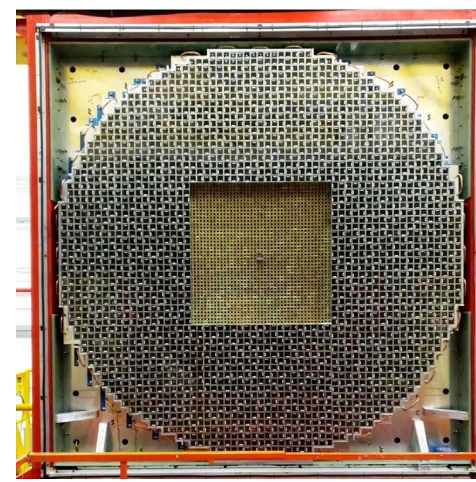
1. Development of an upgraded FCAL-II with a $PbWO_4$ insert.

- 1596 $PbWO_4$ modules are developed to replace ~400 Pb-glass modules.
- Installation of the upgraded FCAL-II has been on-going since Mar 2023 and will be completed by the end of 2024.
- Over 40 undergraduate students from 11 institutes were trained by involving in this project.

Undergraduate workforce

Summer 2023

Oct 6, 2023



2. Commissioning of FCAL-II and data taking with FCAL-II are scheduled to start in Jan 2025.

Summary

- Decays of η/η' mesons provide a unique flavor-conserving laboratory to test low-energy QCD and to search for the BSM physics.

- The JLab Eta Factory (JEF) experiment will start data collection in Jan 2025 using newly upgraded FCAL-II calorimeter with a $PbWO_4$ insert.

- The global experimental efforts at different kinematics and via different production mechanisms will be important for controlling the experimental systematics.

Thanks for support by NSF PHY-1812396 and PHY-2111181