Meson Physics at JLab

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Outline

- Introduction of Physics
- PrimEx Primakoff Program
- JLab Eta Factory (JEF)
- Summary

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Open Questions in Modern Physics

- 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?

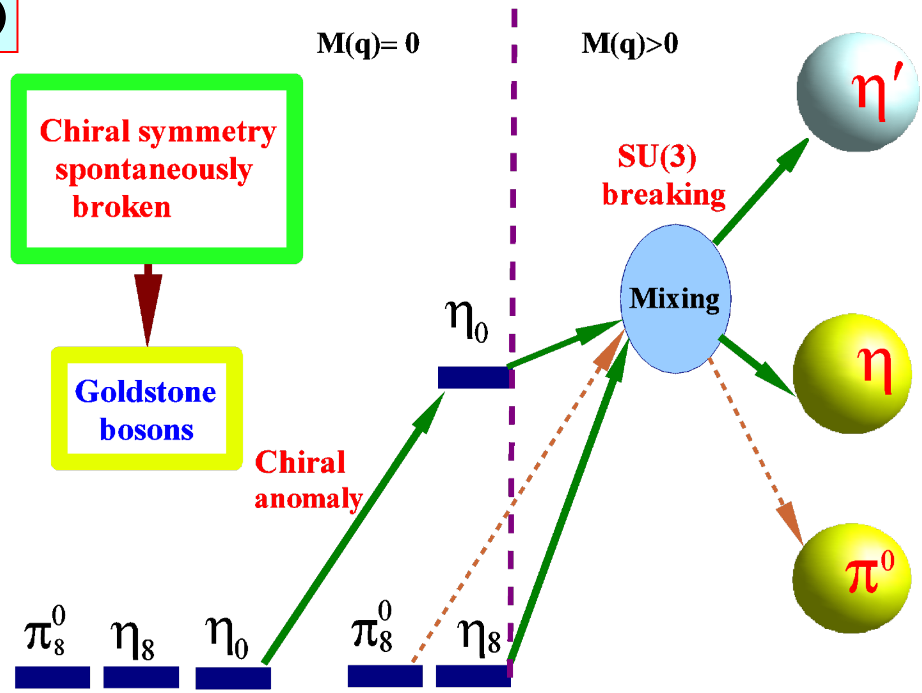
Light pseudoscalar mesons offer a sensitive tool to explore these fundamental questions.

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)
  - Non-zero mass of η_0
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- $SU_L(3)xSU_R(3)$ and SU(3) are explicitly broken:
  - GB are massive
  - Mixing of π^0, η, η'



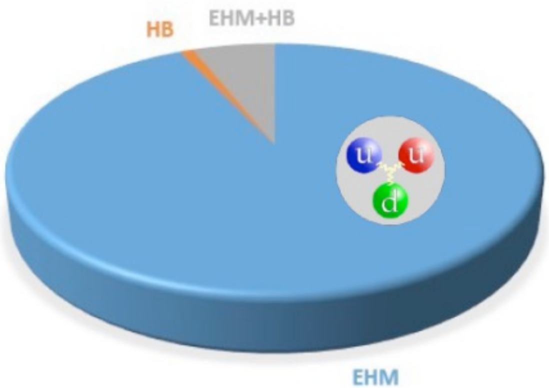
The π^0, η, η' system provides a rich laboratory to study the symmetry structure of confinement QCD.

What is the origin of visible mass?

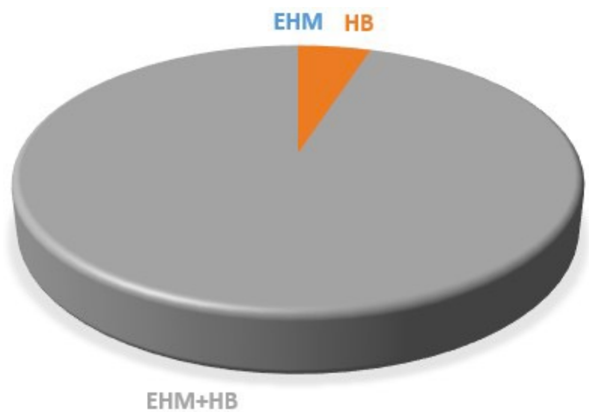
Mass-generating mechanisms:

- Higgs Boson (HB), alone is responsible for <2% of the visible mass in the universe.

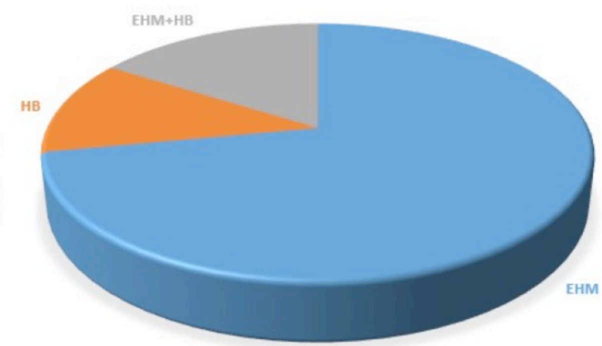
- Emergent Hadron Mass (EHM) and its constructive interference with Higgs-Boson (EHM+HB) account for >98% of the visible mass.



Proton mass budget



π^0 mass budget



η' mass budget

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

Complementary to proton, π^0 and η offers a unique opportunity to study the interference between two known mass generating mechanisms, while η' offers access to all three contributions due to chiral anomaly.

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

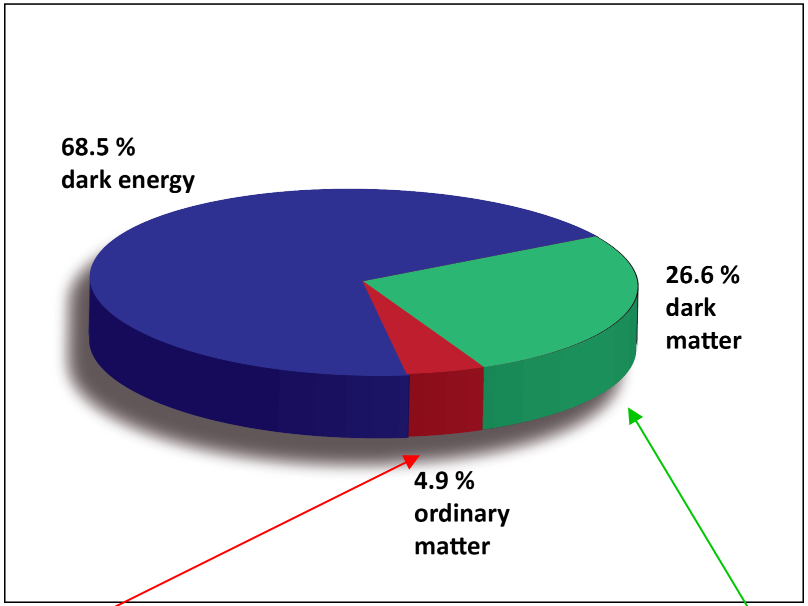
- QCD θ-term
- Examples: $\eta^{(\prime)} \to 2\pi$, $\eta^{(\prime)} \to \pi^+\pi^-\gamma^{(*)}, \cdots$
- Strong constraints from EDM measurements

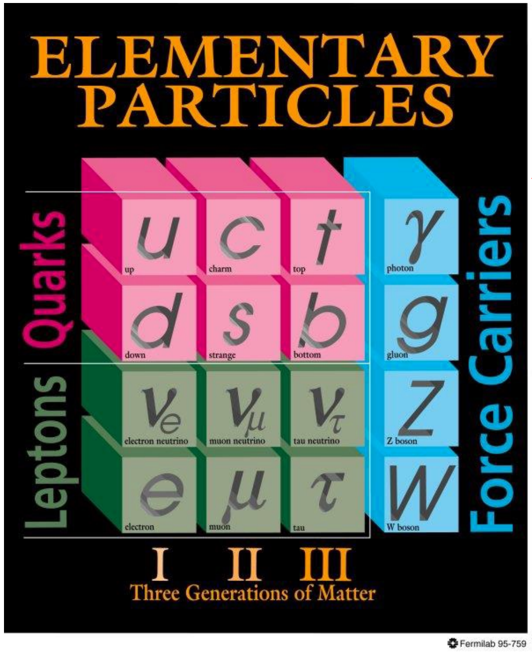
Class III: C-, CP-violation

- 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.

BSM Physics in Dark Sector

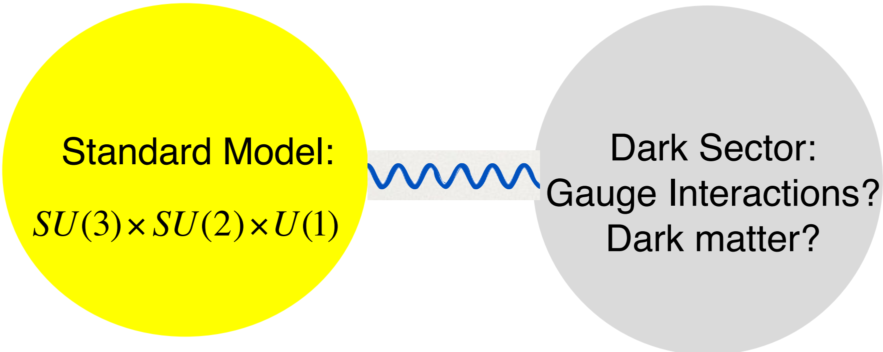




Dark Sector

- 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

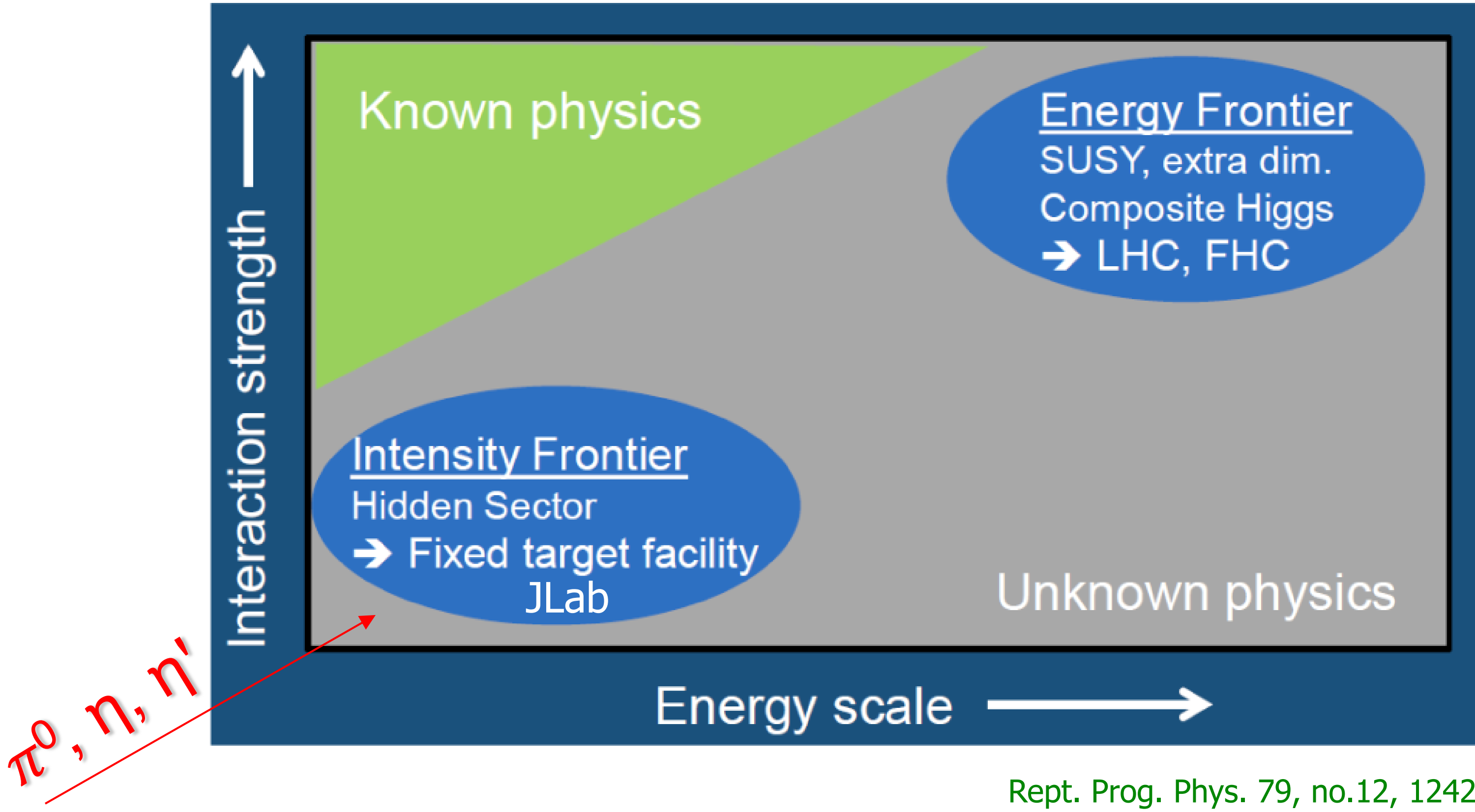
ALP $c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$

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

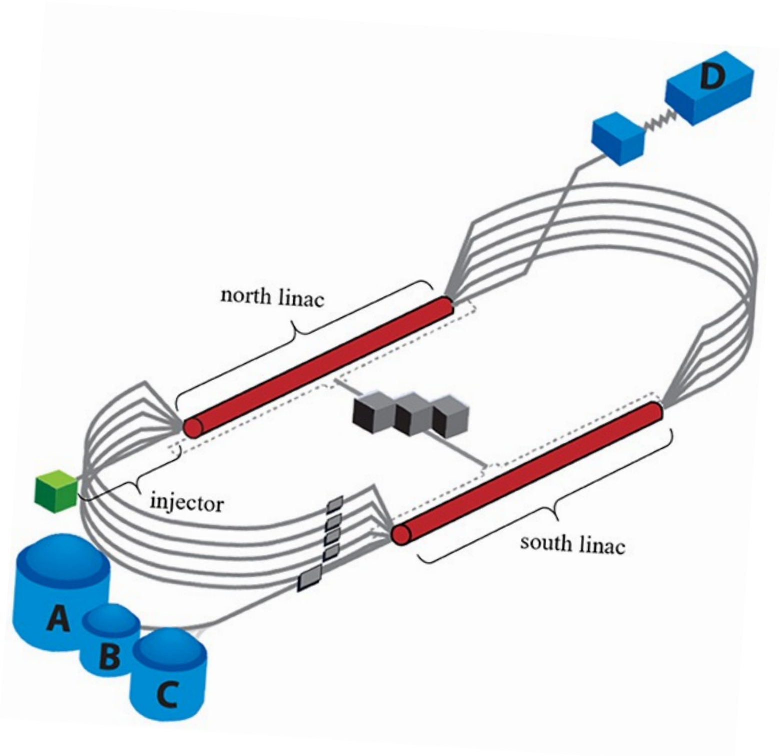
Landscape of BSM Physics Search



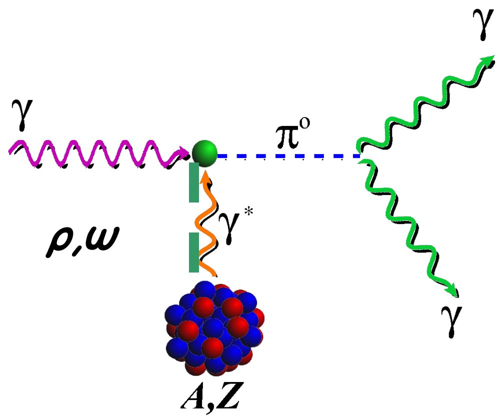
Rept. Prog. Phys. 79, no.12, 124201

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

Jefferson Lab



Primakoff Effect



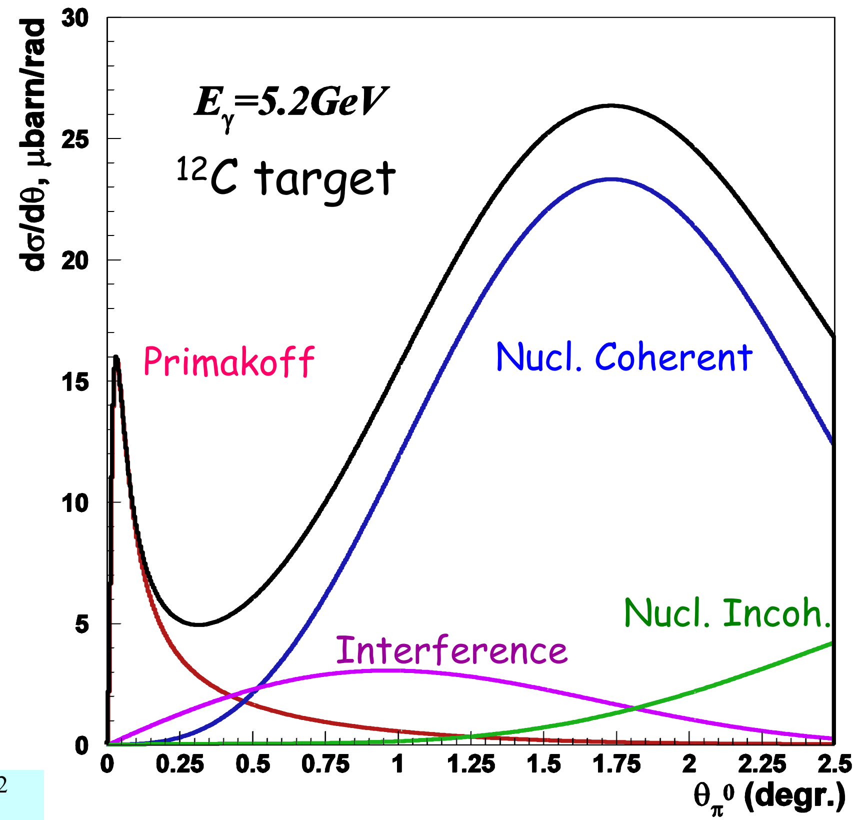
$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$

- Peaked at very small forward angle: $\langle\theta_{Pr}\rangle_{peak} \propto \frac{m^2}{2E^2}$
- Beam energy sensitive:

$$\left\langle\frac{d\sigma_{Pr}}{d\Omega}\right\rangle_{peak} \propto \frac{E^4}{m^3}, \int d\sigma_{Pr} \propto \frac{Z^2}{m^3}\log E$$

$$\langle\theta_{Pr}\rangle_{peak} \propto \frac{m^2}{2E^2} \quad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- Coherent process

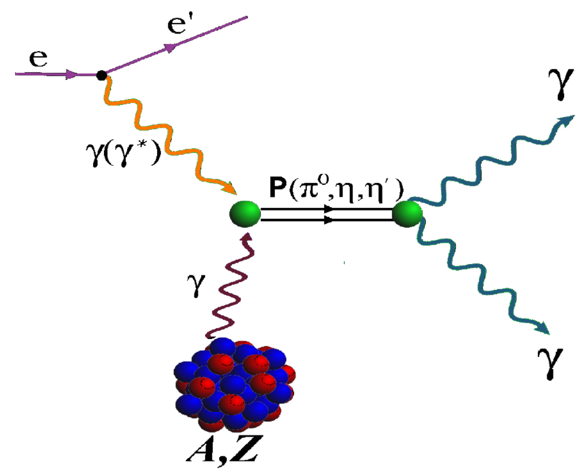


- The higher beam energy is, the higher Primakoff cross section and the better separation of Primakoff from the nuclear backgrounds.

- A higher beam energy is more important for more massive particle

PrimEx Primakoff Program at JLab 6 & 12 GeV

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect



a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \to \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \to \gamma\gamma)$
3) $\Gamma(\eta' \to \gamma\gamma)$

<u>Input to Physics:</u>

- precision tests of chiral symmetry and anomalies
- light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g-2)_\mu$
- origin of the visible mass

b) Transition Form Factors at Q^2 of 0.001-0.3 GeV^2/c^2:

$F(\gamma\gamma^* \to \pi^0)$, $F(\gamma\gamma^* \to \eta)$, $F(\gamma\gamma^* \to \eta')$

<u>Input to Physics:</u>

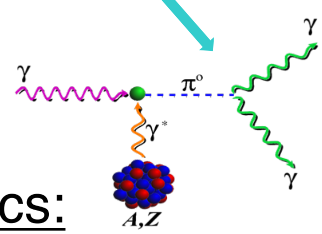
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$
- origin of the visible mass

Status of Primakoff Program at JLab 6 & 12 GeV

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect

a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \to \gamma\gamma)$ @ 6 GeV (in Hall B)
2) $\Gamma(\eta \to \gamma\gamma)$
3) $\Gamma(\eta' \to \gamma\gamma)$



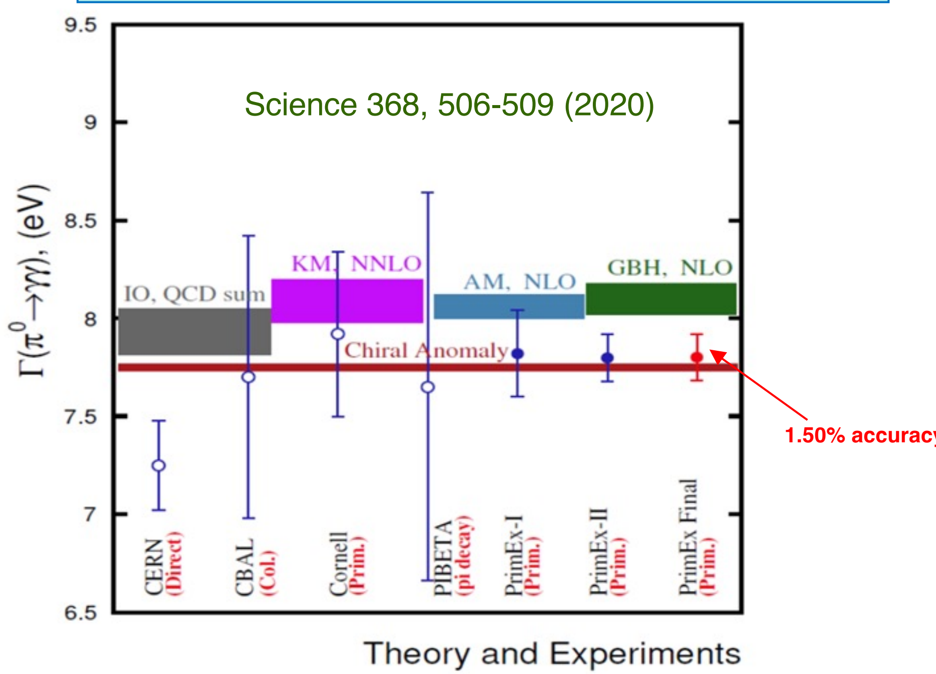
Input to Physics:

- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g-2)_\mu$

- The chiral anomaly prediction is exact for massless quarks:

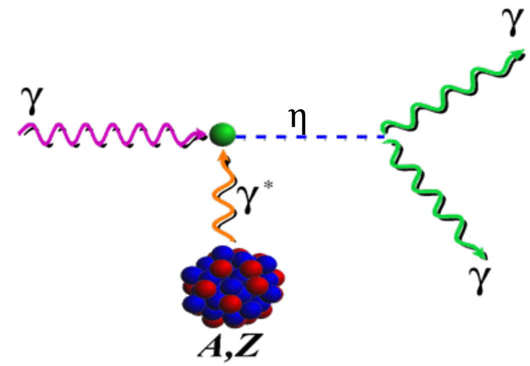
$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{m^3_{\pi^0}\alpha^2 N_c^2}{576\pi^3 F^2_{\pi^0}} = 7.750 \pm 0.016\, eV$$

- $\Gamma(\pi^0 \to \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders!



Status of Primakoff Program at JLab 6 & 12 GeV (cont.)

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect



a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \to \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \to \gamma\gamma)$
3) $\Gamma(\eta' \to \gamma\gamma)$

$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\eta^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q^2)|^2 \sin^2\theta_\eta$$

Input to Physics:

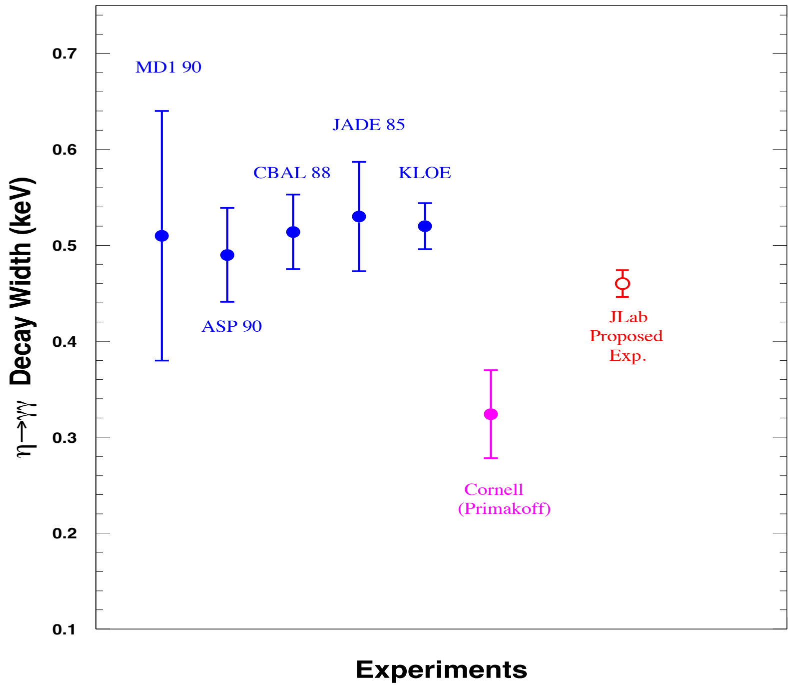
- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g\text{-}2)_\mu$

On-Going PrimEx-eta experiment (in Hall D)

- A full data set was completed via three run periods in 2019, 2021 and 2022.
- Data analysis is in progress.

Physics for $\Gamma(\eta\rightarrow\gamma\gamma)$ Measurement

Resolve long standing discrepancy between previous collider and Primakoff measurements:

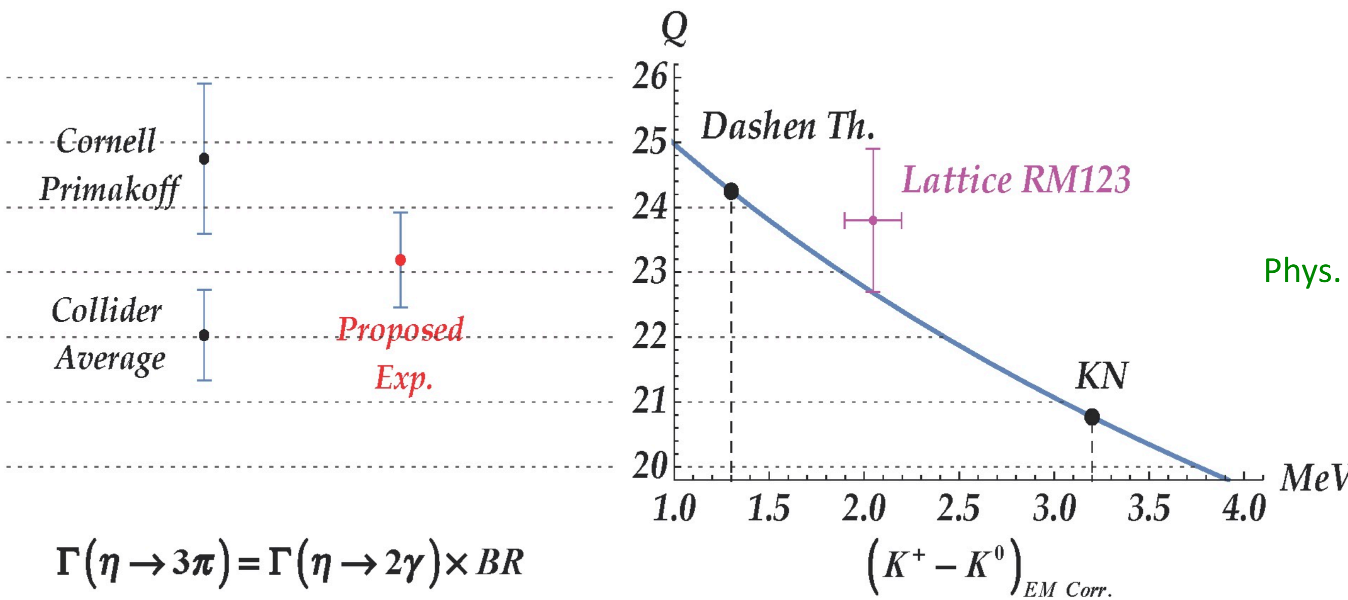


- **Extract η-η′ mixing angle**
- **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**
- **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$

- $\eta \to 3\pi$ decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em} A_2$
- α_{em} is small
- Amplitude: $A(\eta \to 3\pi) = \frac{1}{Q^2} \frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$



$$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to 2\gamma) \times BR$$

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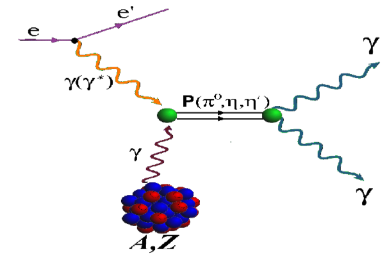
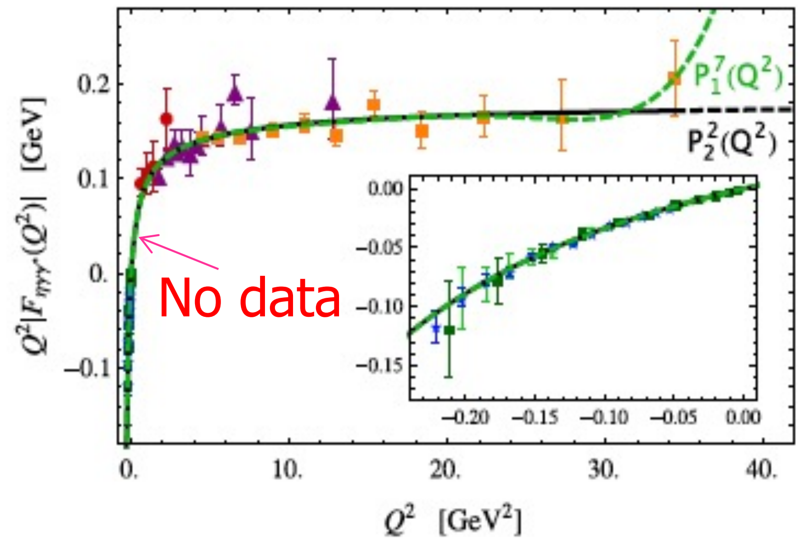
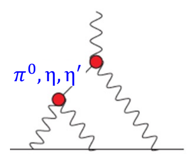
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

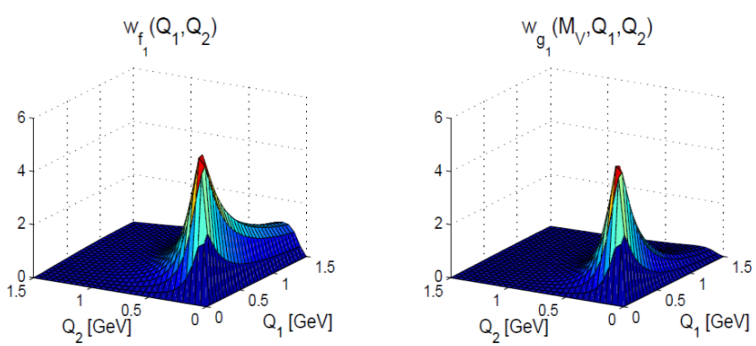


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian

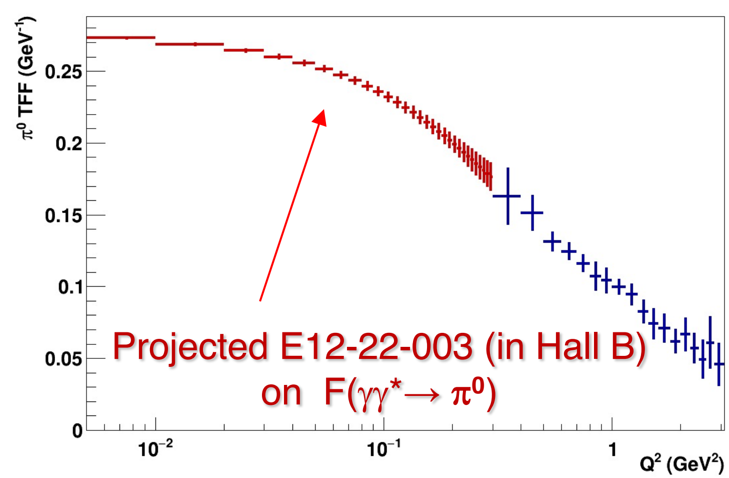


- Input for hadronic light-by-light calculations in muon (g-2)





Phys.Rev.D65,073034



New opportunities with JLab 22 GeV Upgrade

1. The first π^0 Primakoff production off an electron target to measure $\Gamma(\pi^0 \to \gamma\gamma)$ and $F(\gamma\gamma^* \to \pi^0)$.

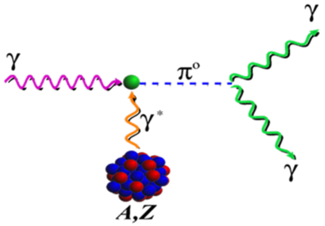
2. Improve the precisions of η/η' Promakoff production off nuclear targets.

3. Search for new sub-GeV gauge bosons (scalars and pseudoscalars) via the Primakoff production:
   - Strong CP and Hierarchy problems
   - $(g-2)_\mu$ and puzzle of proton charge radius
   - Portals coupling SM to the dark sector:

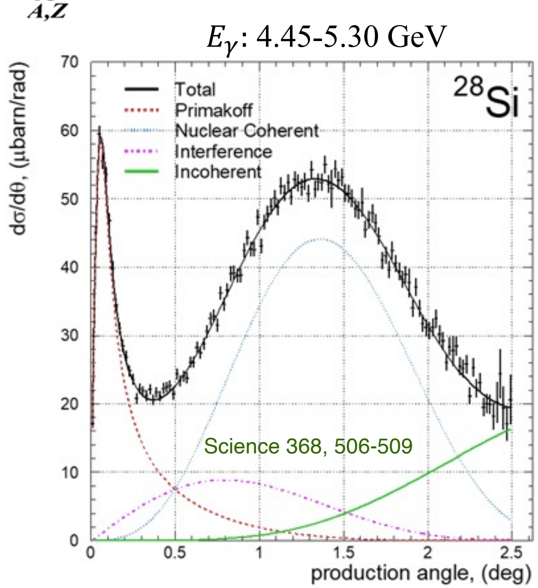
$$H^+H(\varepsilon S + \lambda S^2) \qquad c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$$

Advantages of the π^0 Primakoff Production off an Electron

PrimEx-II: $\gamma + {}^{28}Si \rightarrow \pi^0 + {}^{28}Si$

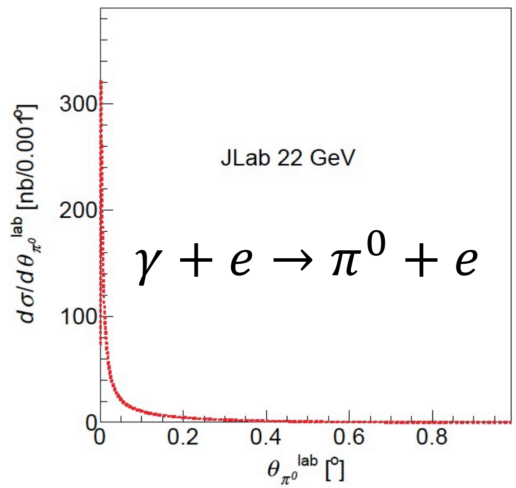


$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$



Advantages of an electron target:

- Eliminate all nuclear backgrounds
- A point-like electron target to eliminate nuclear effects
- Recoiled electron detection



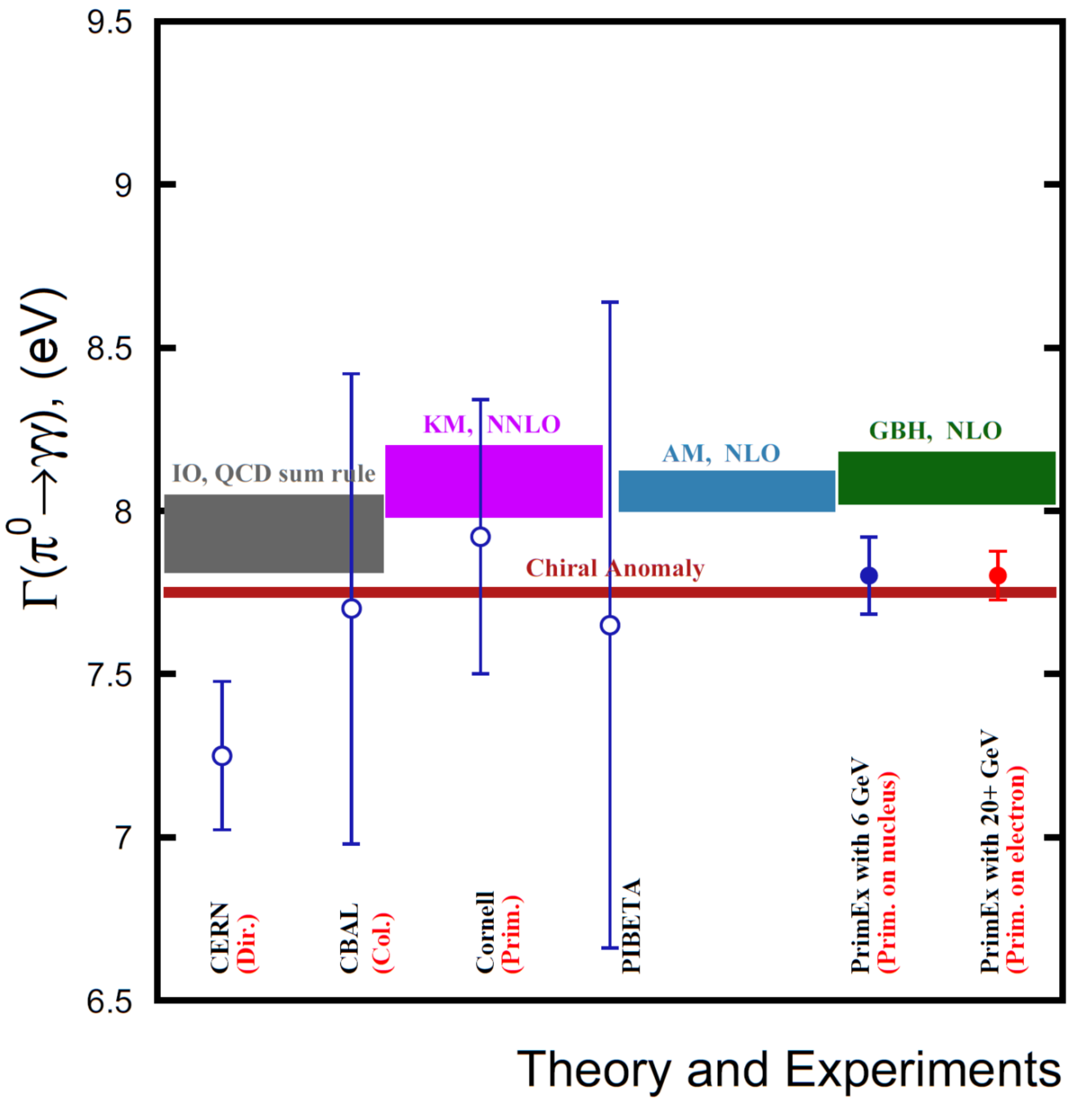
$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

Main challenges for the nuclear target:

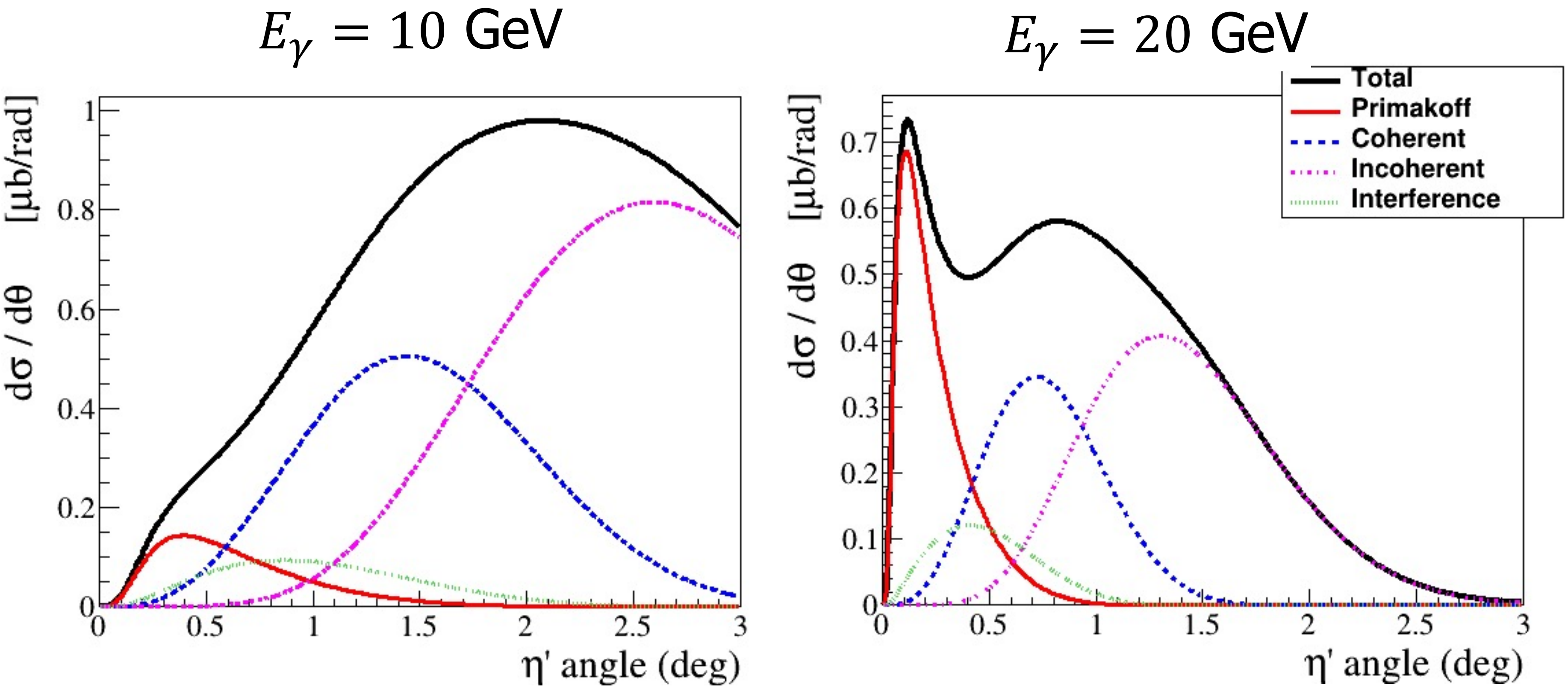
- Nuclear backgrounds
- Nuclear effects
- No recoil detection

Measurement	Reaction	E_{th} (GeV)
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$	$\gamma + e \rightarrow \pi^0 + e$	18.0
$F(\gamma^*\gamma \rightarrow \pi^0)$	$e + e \rightarrow \pi^0 + e + e$	18.1

Projected $\Gamma(\pi^0 \to \gamma\gamma)$ at JLab 22 GeV with an Electron Target

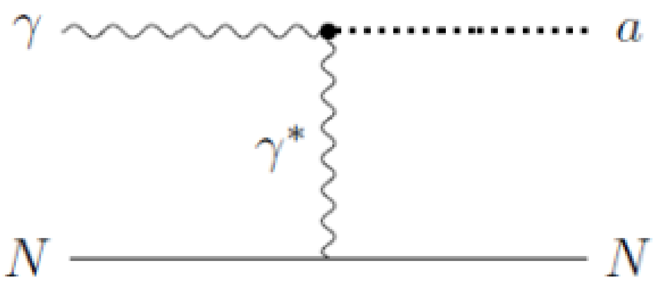


Improve Primakoff Measurements of η/η' with nuclear targets



$$\gamma + {}^4He \rightarrow \eta' + {}^4He$$

Search for sub-GeV Scalar and Pseudoscalar via Primakoff Effect



$$\mathcal{L}_{\text{eff}} \supset \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$\frac{d\sigma_{Pr}}{d\Omega} \sim \frac{c_\gamma^2 \alpha Z^2}{8\pi\Lambda^2} \cdot \frac{\beta^3 E^4}{Q^4} \cdot |F_{e.m.}(Q)|^2 sin^2\theta_a$$

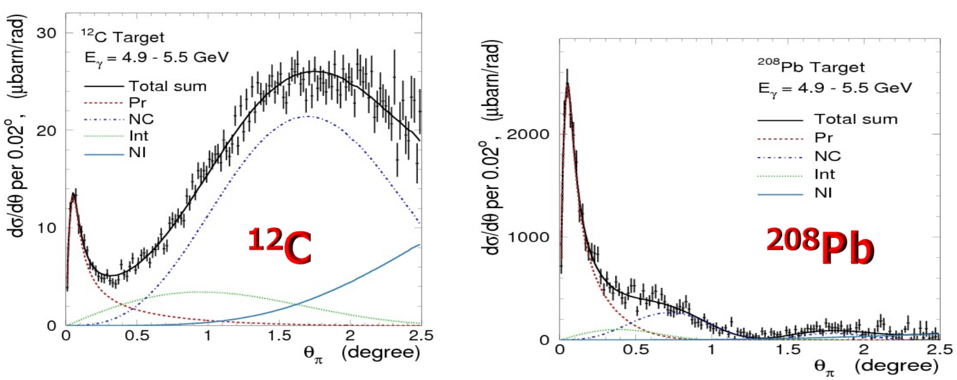
The Primakoff signal dominates in the forward angles

↓

Minimizing the QCD backgrounds

Favorable experimental condition:

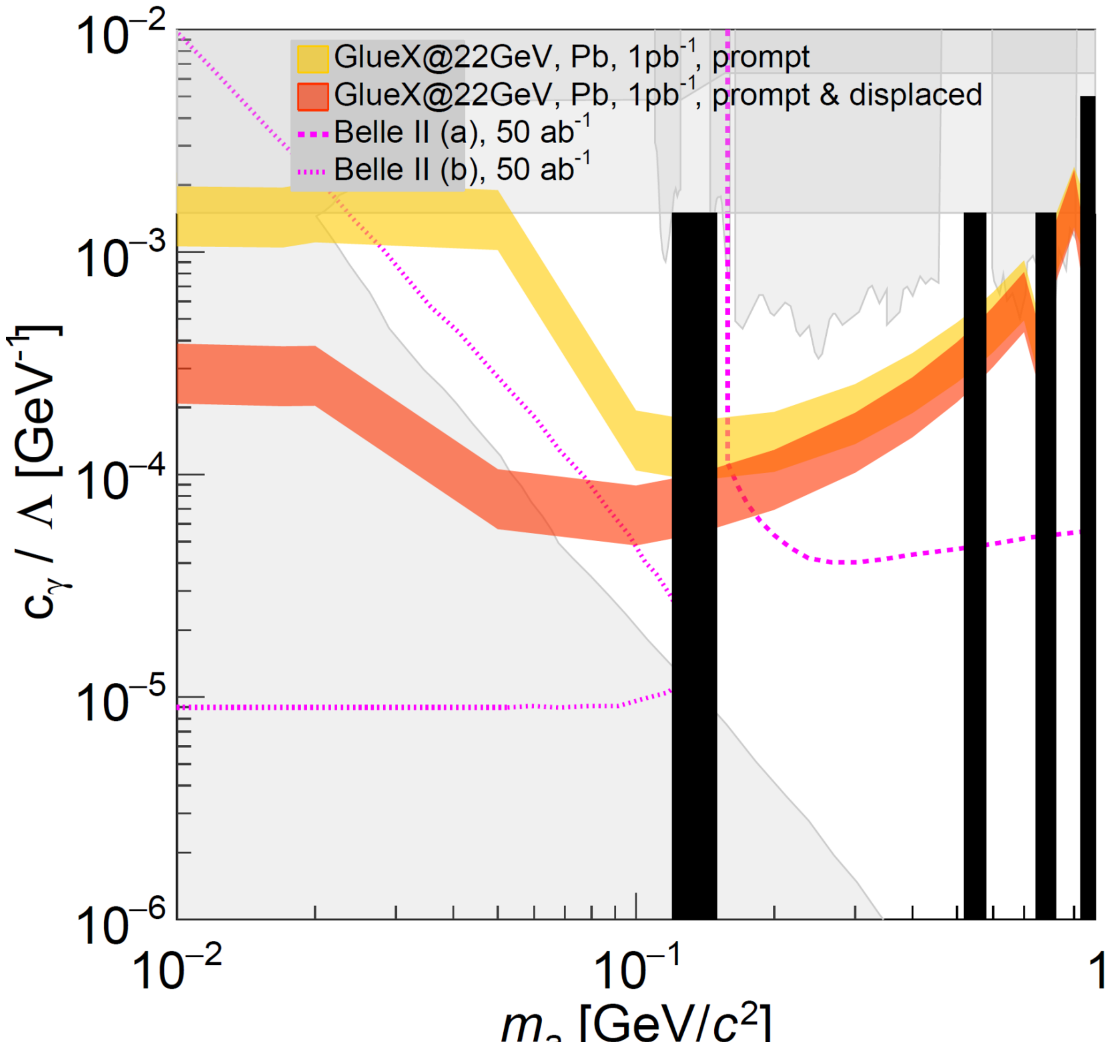
- A high energy beam
- A high Z nuclear target



PrimEx I

Phys.Rev.Lett. 106 (2011) 162303

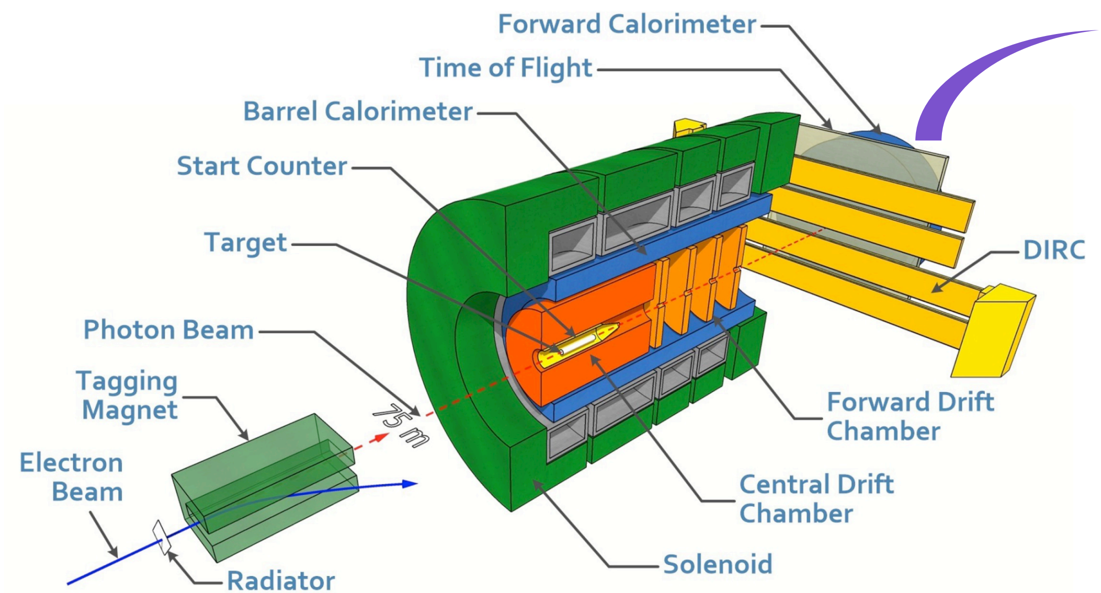
Projected Reach for a ALP at JLab 22 GeV

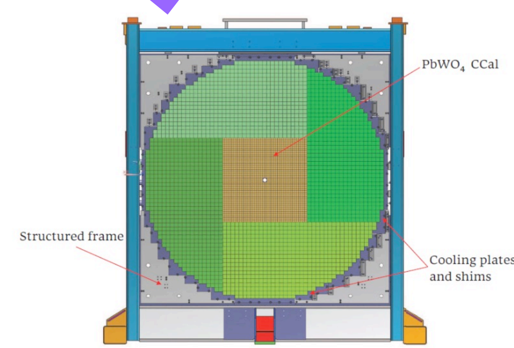


$$\gamma + Pb \rightarrow a + Pb$$

$$a \rightarrow \gamma\gamma$$

JLab Eta Factory (JEF) Experiment at GlueX





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

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

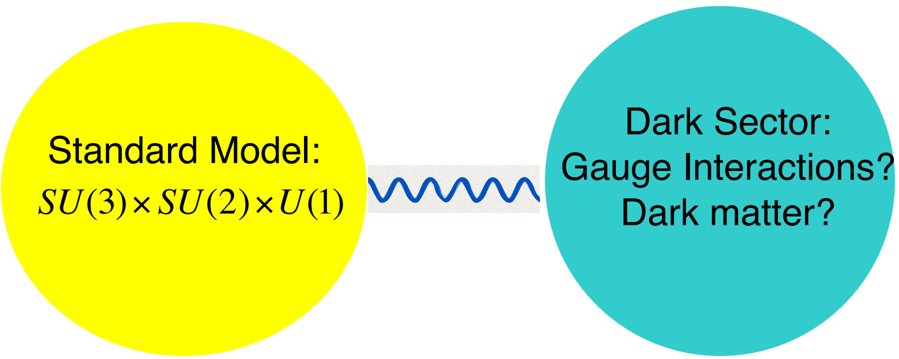
Axion-Like Particles (ALP): $\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \ \pi\pi e^+e^-$

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

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 $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$
   - Improve the light quark mass ratio via Dalitz distributions: $\eta \to 3\pi$

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 $\xi L H N$

- **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)

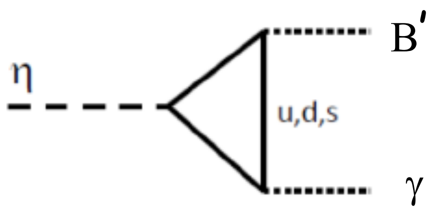
2. Confinement QCD:

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

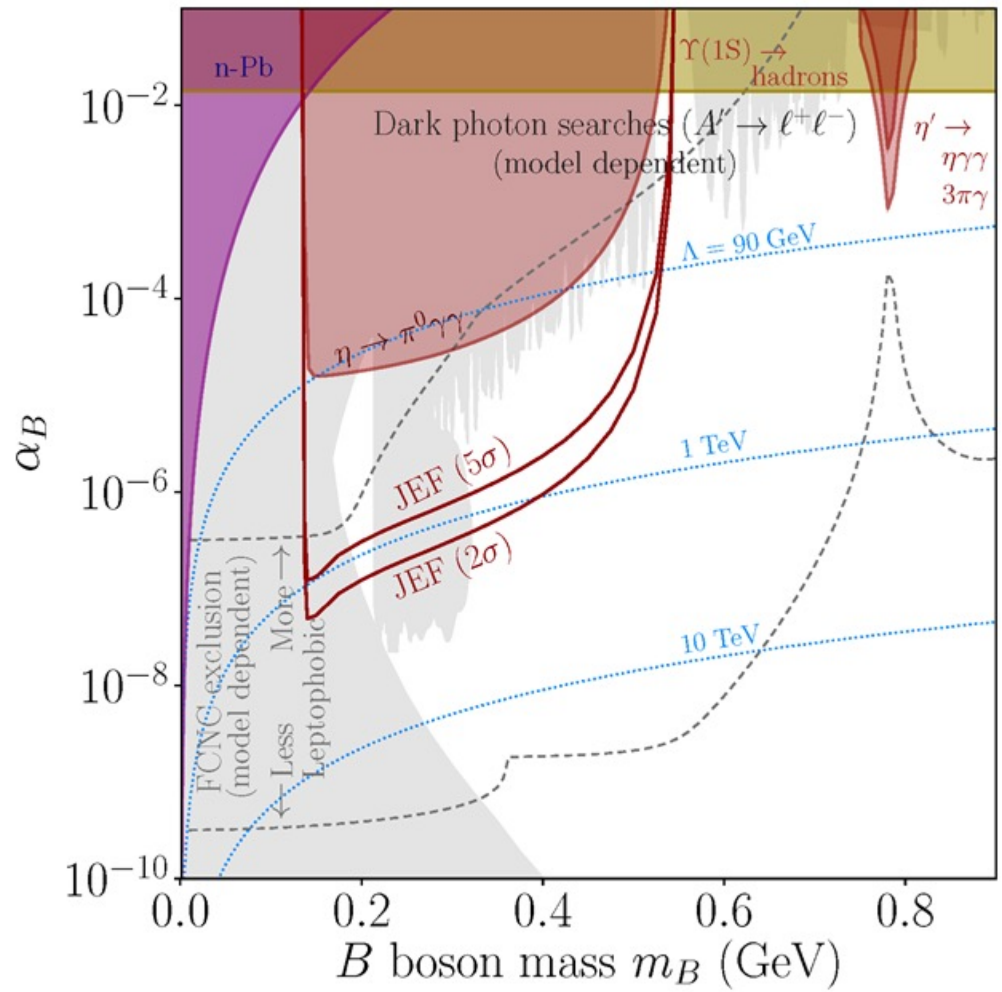
JEF Experimental Reach for B′

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

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

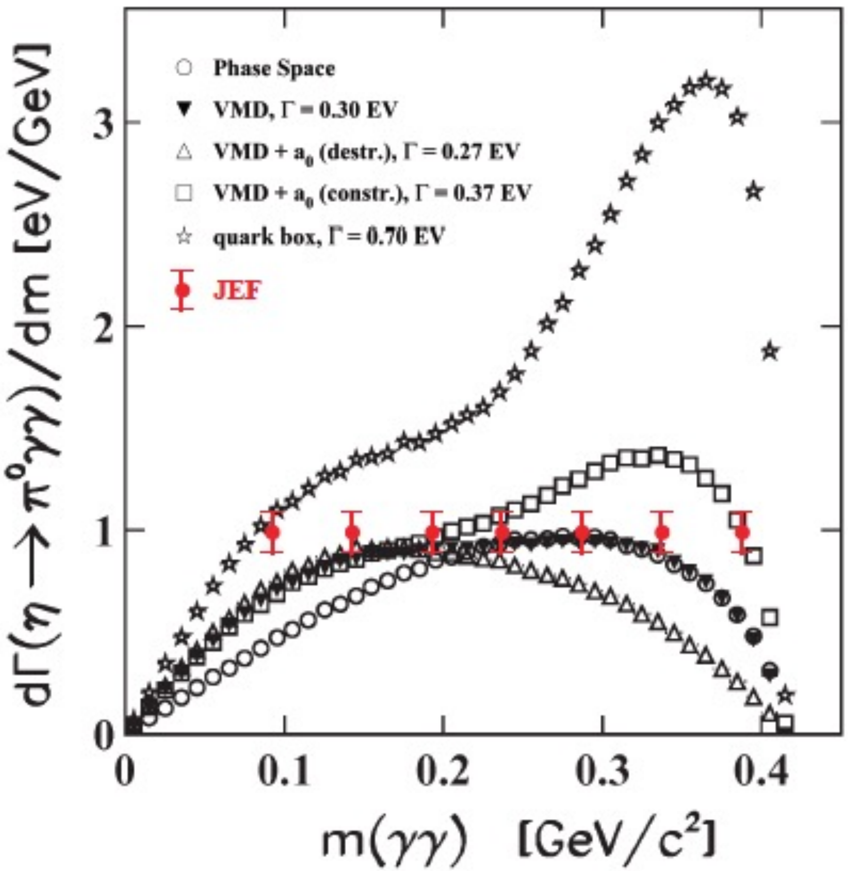


PL, B221, 80 (1989)
PR,D89,114008

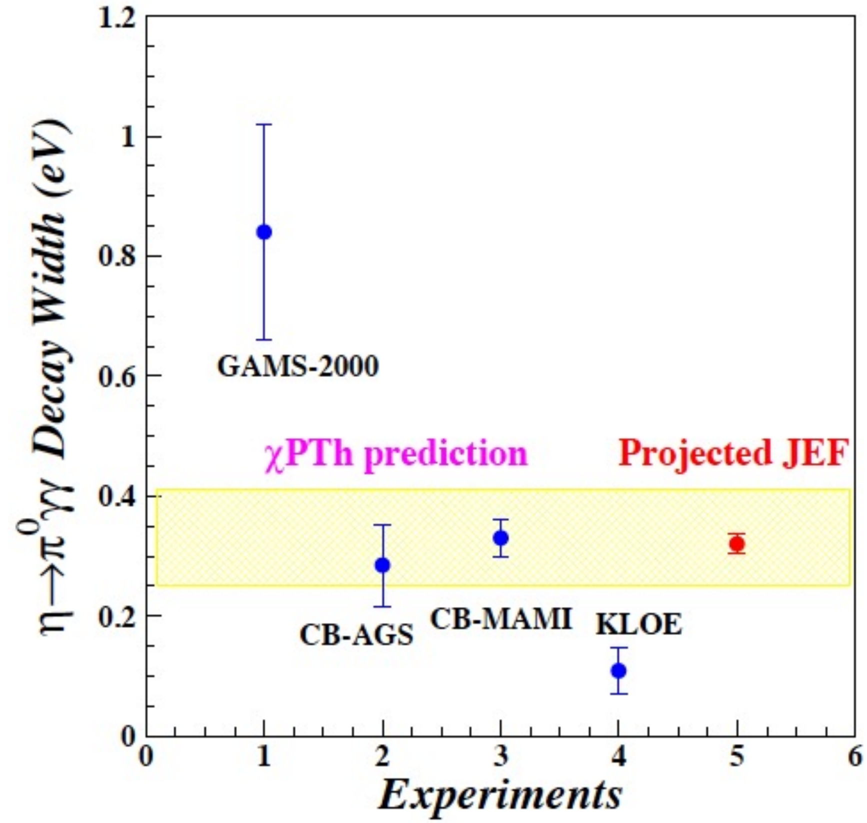


Projected JEF on SM Allowed $\eta\to\pi^0\gamma\gamma$

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

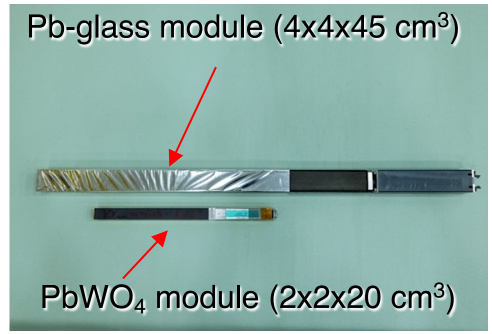
- ◆model-independent determination of two LEC's of the $O(p^6)$ counter- terms
- ◆probe the role of scalar resonances to calculate other unknown $O(p^6)$ LEC's

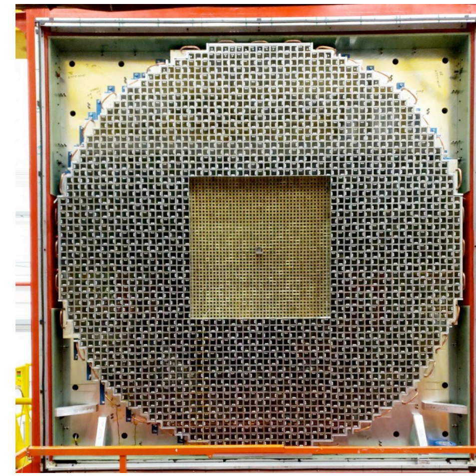
J. Bijnens, talk at AFCI workshop

Status of the JEF Experiment

1. Developed 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 is completed in the end of 2024.
- Over 40 undergraduate students from 11 institutes were trained by involving in this project.





Undergraduate workforce

2. Commissioning of FCAL-II was successfully done in April 2025 and data production for physics is currently in progress.

Summary

- Light pseudoscalar mesons offer a sensitive probe to test fundamental symmetries and to search for new physics beyond the standard model.

- PrimEx Primakoff program

  has been in progress @ 6&12 GeV

  ✓ The published PrimEx result on the π^0 lifetime provides a stringent test of low-energy QCD.

  ✓ Data collection on $\Gamma(\eta \rightarrow \gamma\gamma)$ was completed in 2022 and data analysis is in progress.

  ✓ A new experiment on $F(\pi^0 \rightarrow \gamma^* \gamma)$ off a nuclear target is on the way.

  future JLab 22 GeV upgrade will offer new opportunities

  ✓ New generation of Primakoff experiments on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ and $F(\gamma^*\gamma \rightarrow \pi^0)$ off an atomic electron target.

  ✓ Improve measurements of more massive particles, such as η and η', off nuclear targets.

  ✓ Search for new sub-GeV gauge bosons (scalars and pseudoscalars).

- The JEF experiment has been taking data since April 2025 using newly upgraded FCAL-II calorimeter with a PbWO4 insert.

  ✓ 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; transition form factors of η/η' to calculate HLbL contributions in $(g\text{-}2)_\mu$