Pseudoscalar Mesons

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Outline

- Introduction
- PrimEx Primakoff program
- JLab Eta Factory (JEF)
- Summary

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Some Open Questions in Modern Physics

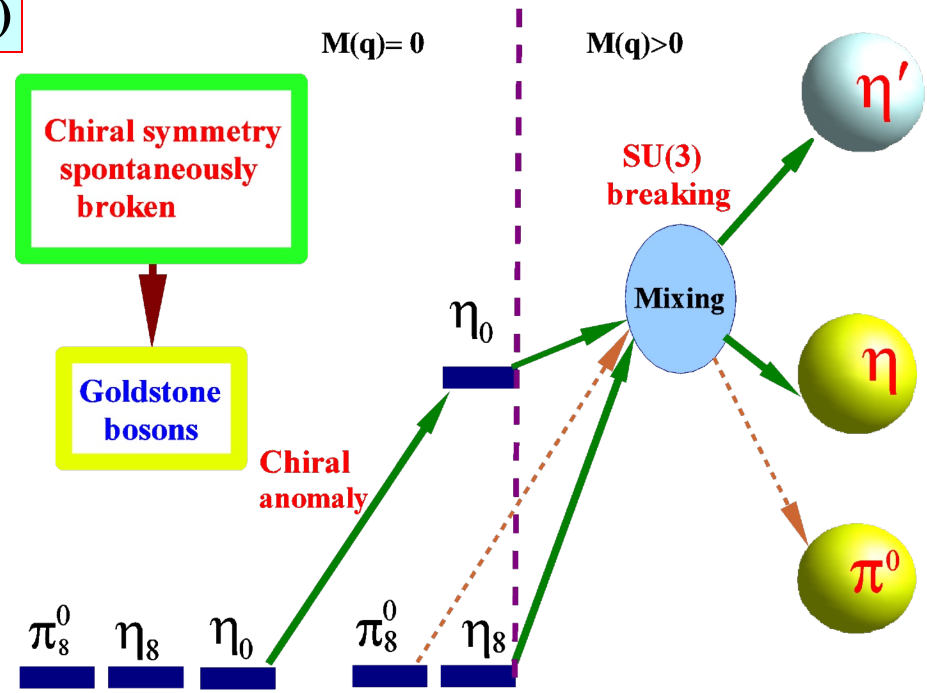
- What is the origin of QCD confinement?
- How did the visible mass emerge in the early universe?
- What is the cause of the matter-antimatter asymmetry in the universe?
- What is the nature of dark matter?

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

Low-Energy QCD Symmetries and Light Mesons

- QCD Lagrangian in Chiral limit ($m_q \rightarrow 0$) 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
  - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$, $\Gamma(\eta \rightarrow \gamma\gamma)$, $\Gamma(\eta' \rightarrow \gamma\gamma)$
- **$SU_L(3)xSU_R(3)$ 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 low-energy 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.

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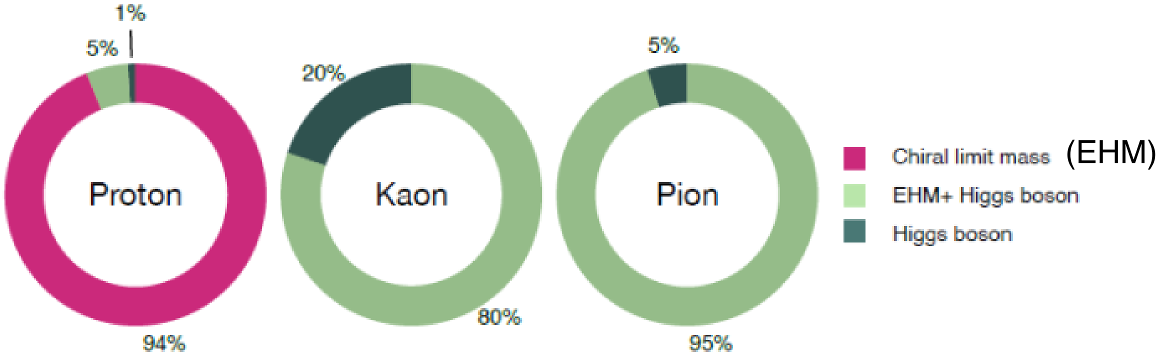


Complementary to proton, pseudoscalar mesons offer a unique opportunity to study the interference between two known mass generating mechanisms.

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: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^0\gamma^* \ldots$

❖ A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee Phys. Rev.,139, B1650 (1965)

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

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

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

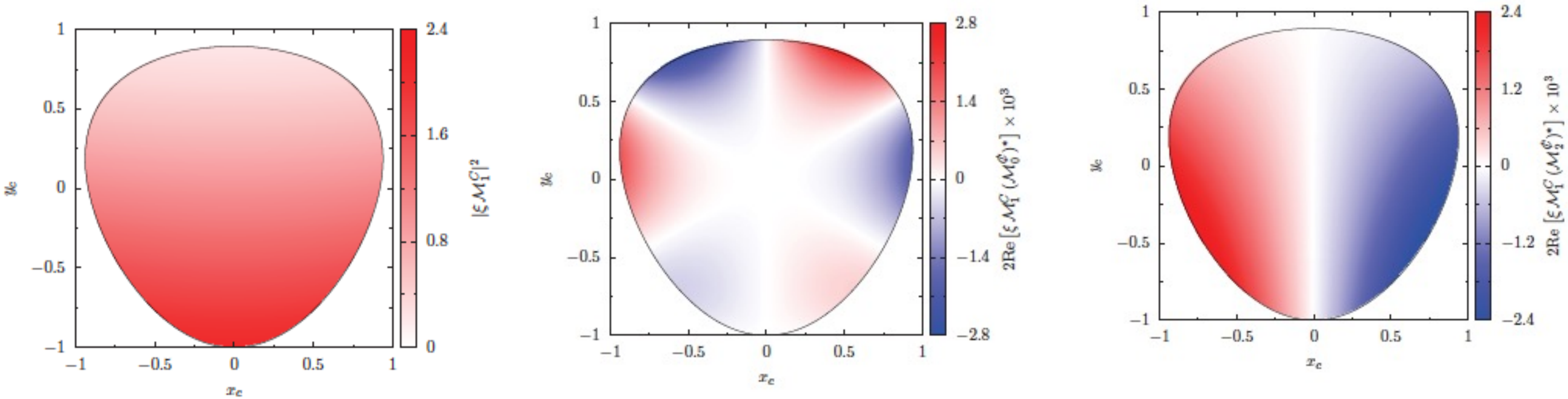
$\longrightarrow$ require helicity flip, actually dimension-8 in SMEFT

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

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

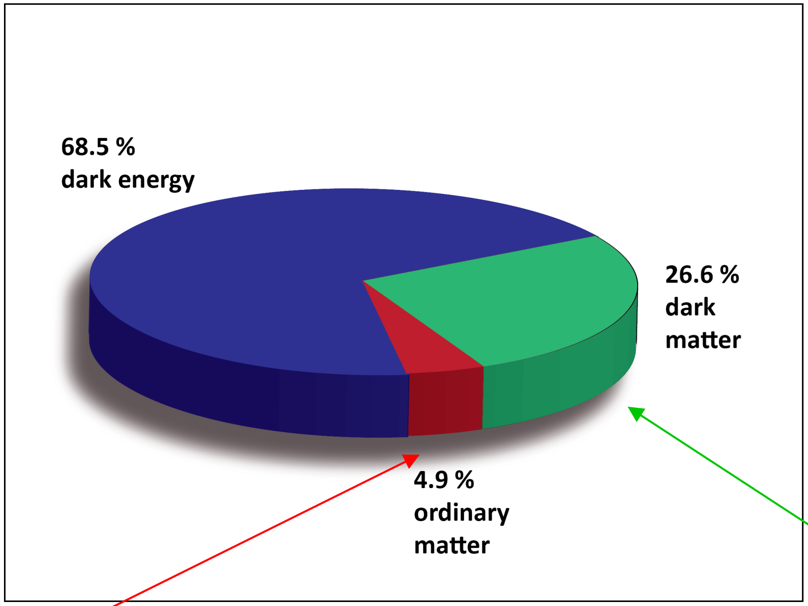
- Dalitz plot decomposition (central fit result)

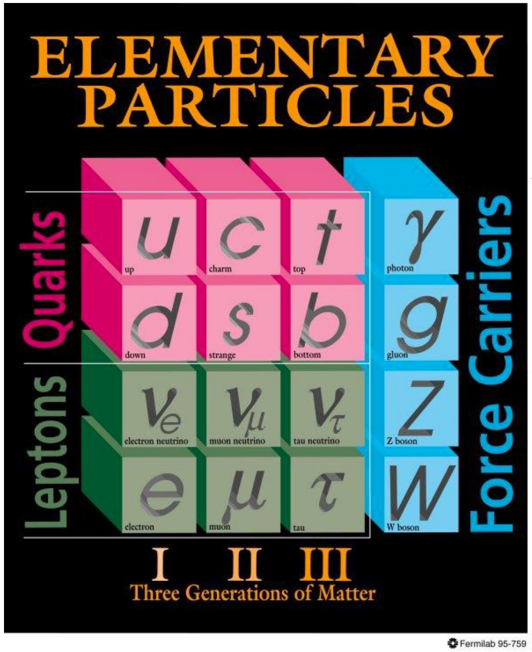
$$|\mathcal{M}_c|^2 \approx |\mathcal{M}_1^{C}|^2 + 2\mathrm{Re}\left[\mathcal{M}_1^{C}\,(\mathcal{M}_0^{\not{C}})^*\right] + 2\mathrm{Re}\left[\mathcal{M}_1^{C}\,(\mathcal{M}_2^{\not{C}})^*\right]$$



- $\mathcal{M}_0^{\not{C}}$ 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

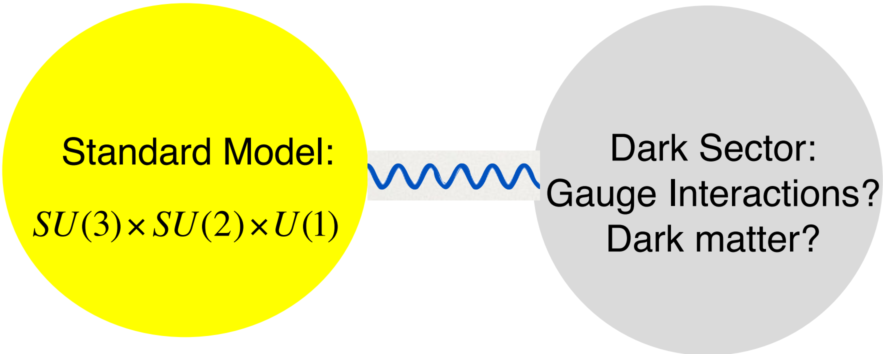




Dark Sector

- 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'

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

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

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

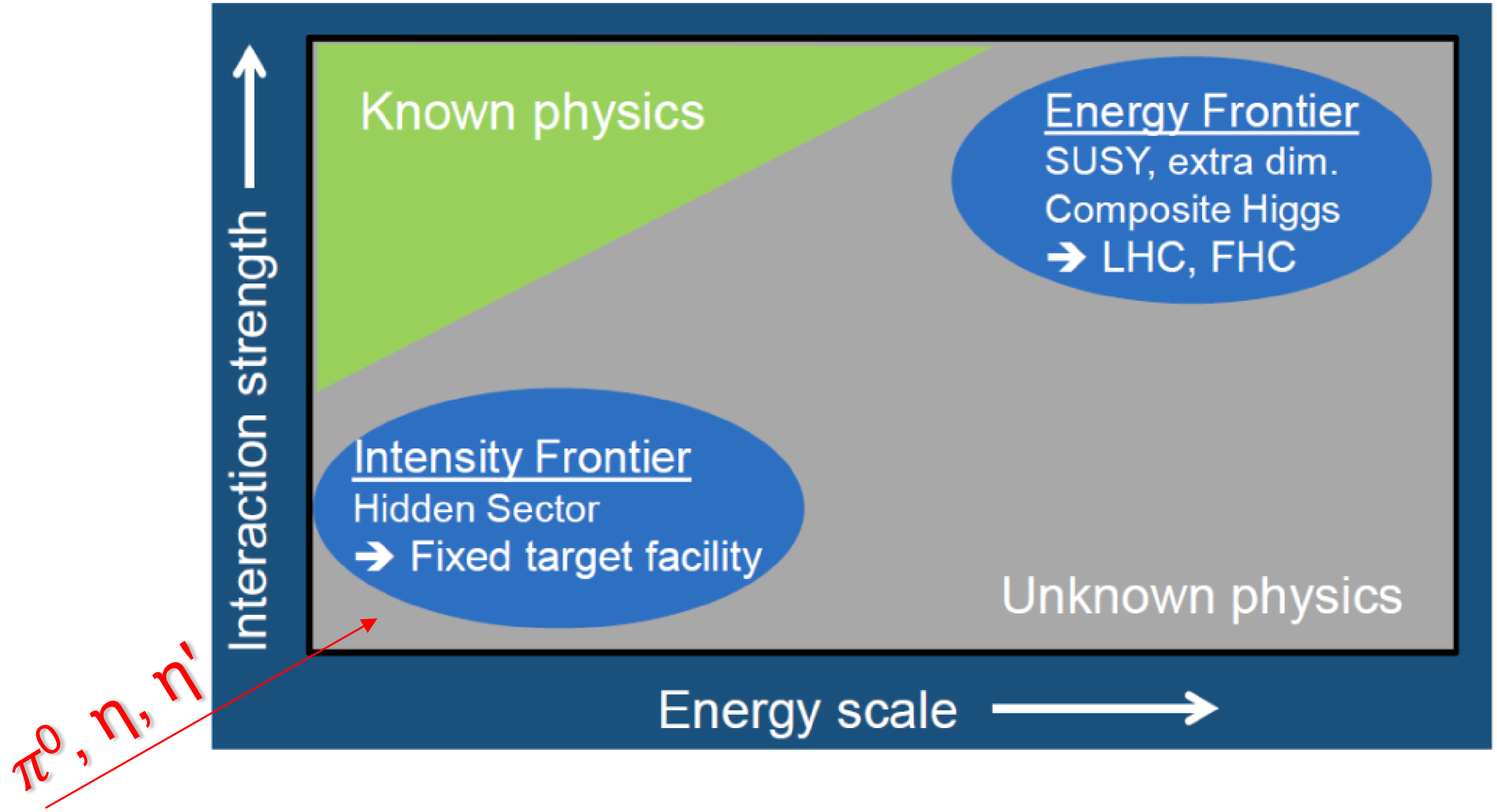
Fermion: $\eta \to \pi^0 H$,

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

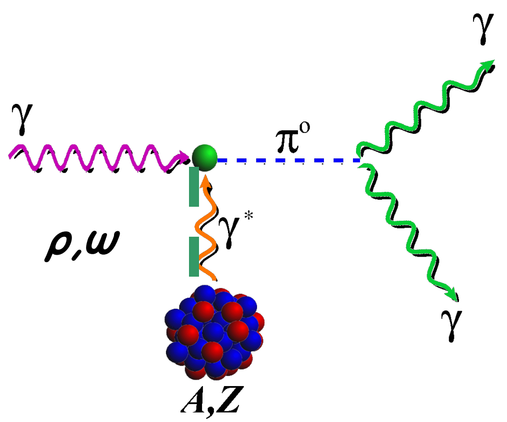
Landscape of BSM Physics Search



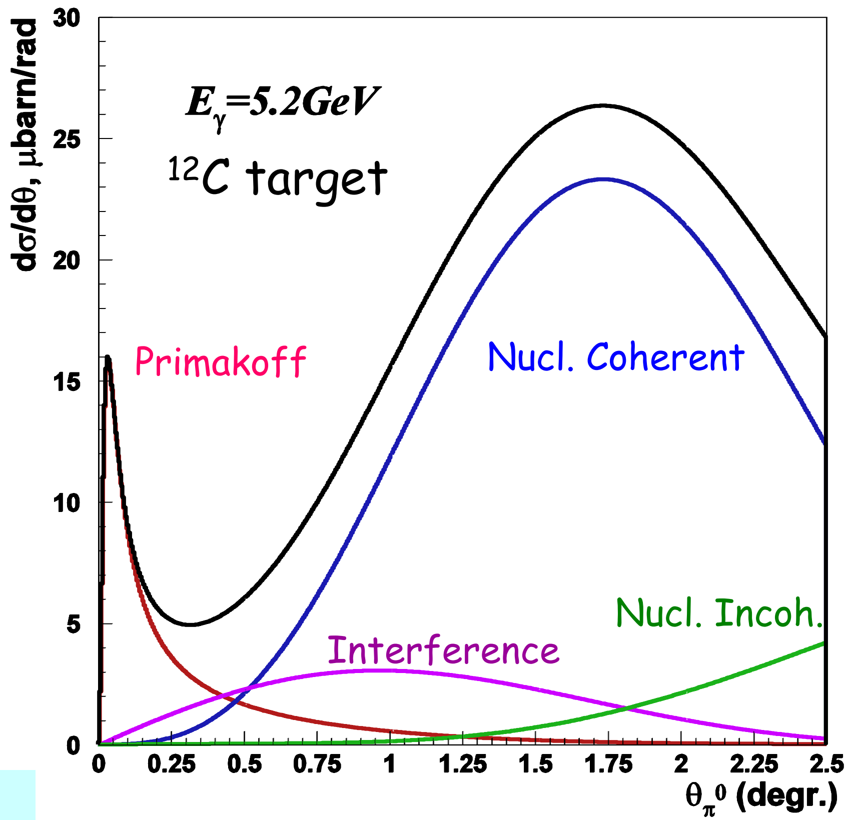
arXiv:1504.04855

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

Primakoff Effect



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



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

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

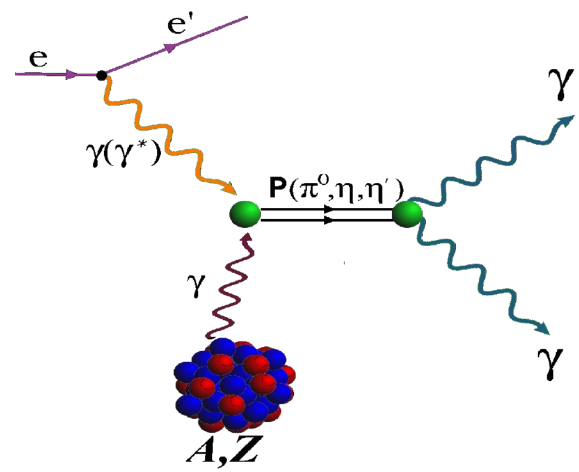
$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \quad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- 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) $\Gamma(\eta'\to\gamma\gamma)$

Input to Physics:

- 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:

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

Input to Physics:

- 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:

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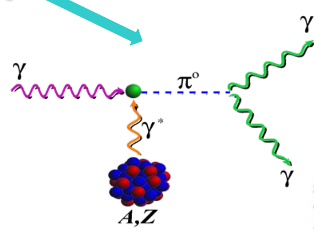


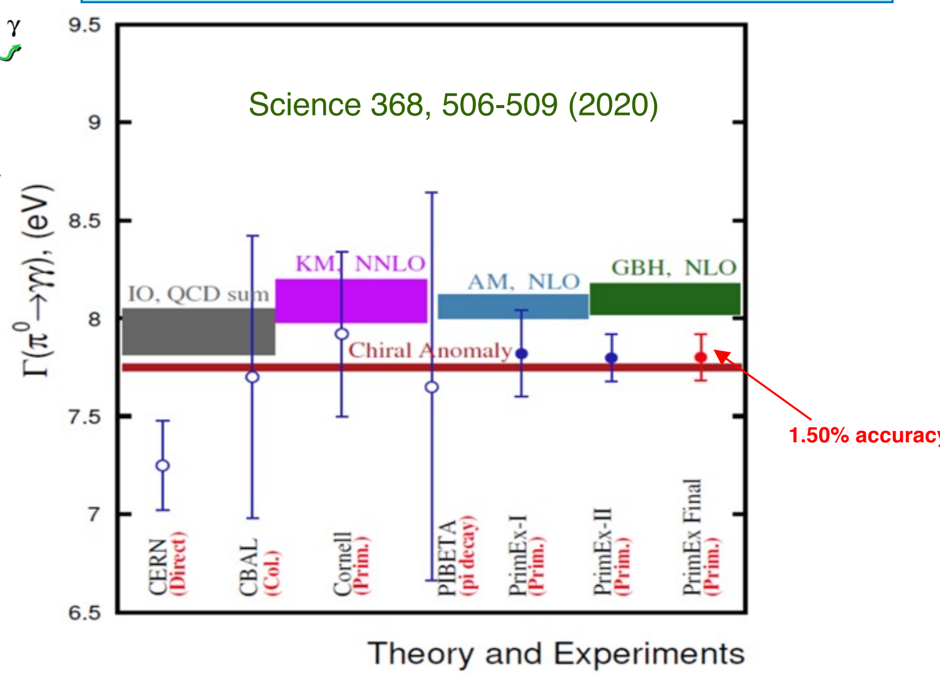
Input to Physics:

- 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:

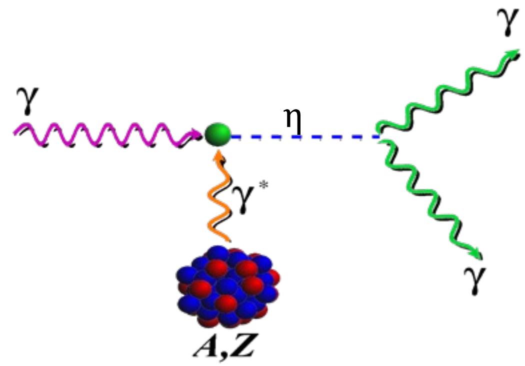
$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{m_{\pi^0}^3 \alpha^2 N_c^2}{576\pi^3 F_{\pi^0}^2} = 7.750 \pm 0.016\, eV$$

- $\Gamma(\pi^0 \to \gamma\gamma)$ 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



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

a) Two-Photon Decay Widths:

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Input to Physics:

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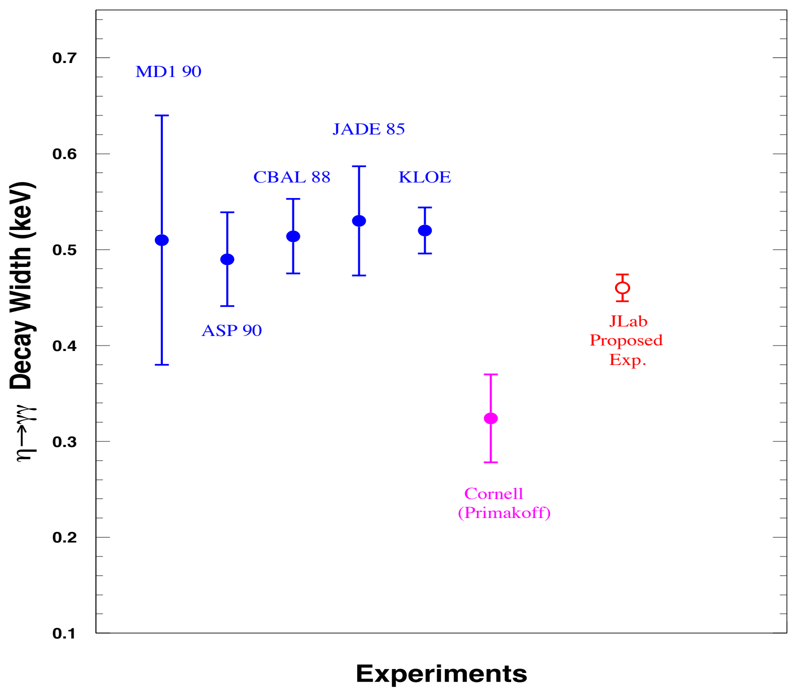
- η-η' mixing angle
- input to calculate HLbL in $(g-2)_\mu$

On-Going PrimEx-eta experiment

- Three data sets were collected 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:

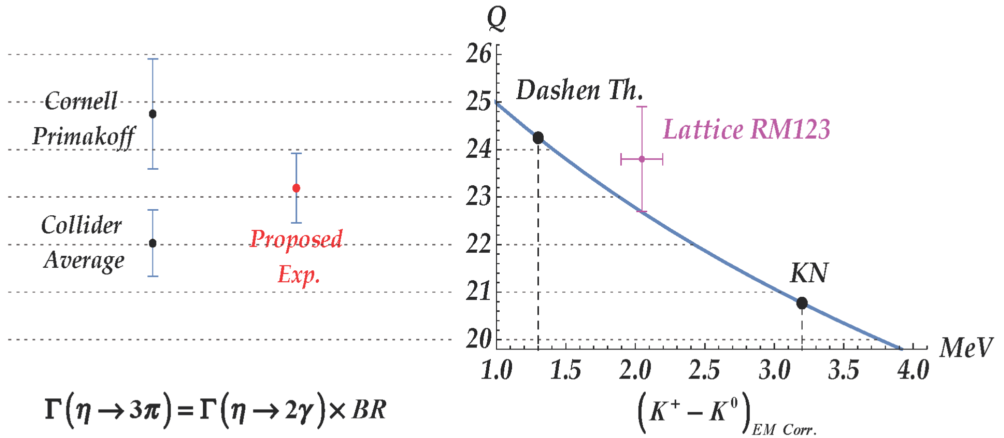


- **Extract η-η′ mixing angle**
- **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**
- **Improve all partial decay widths in the η-sector**

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: $A(\eta \to 3\pi) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$



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Precision Determination Light Quark Mass Ratio

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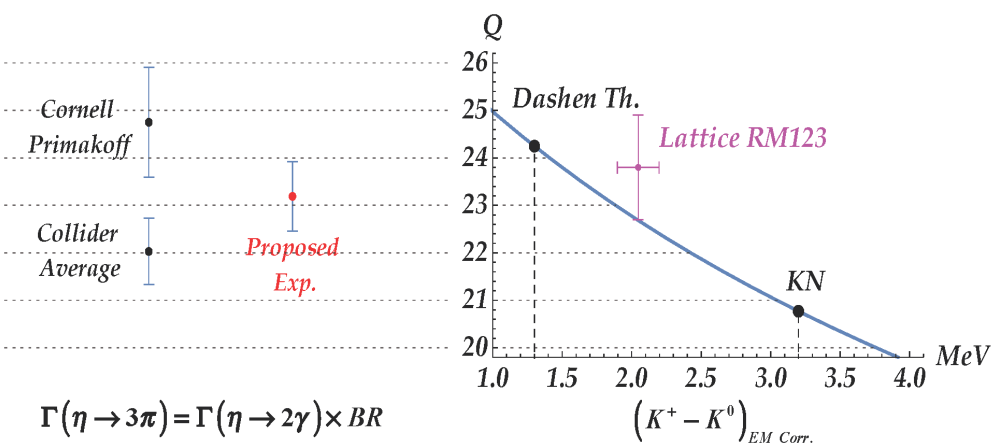

$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to 2\gamma) \times BR$

- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

  $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

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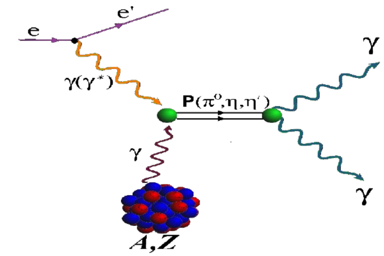
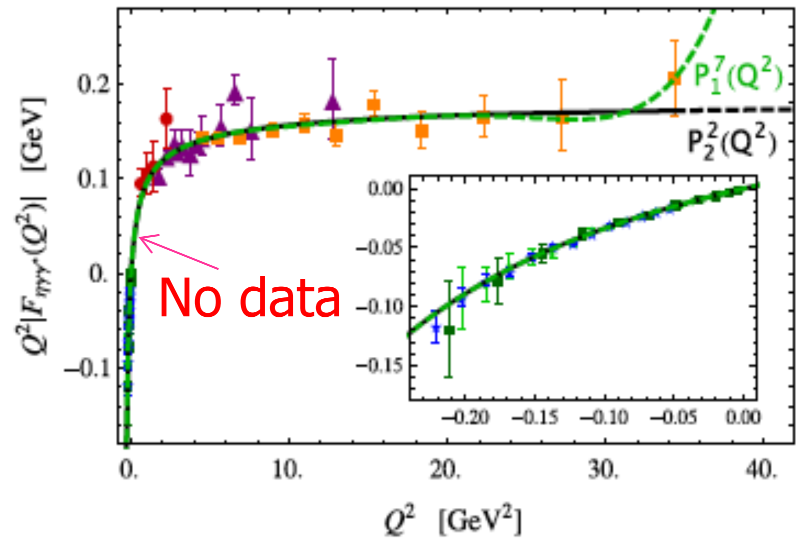
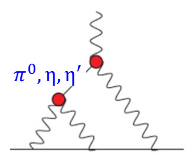
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

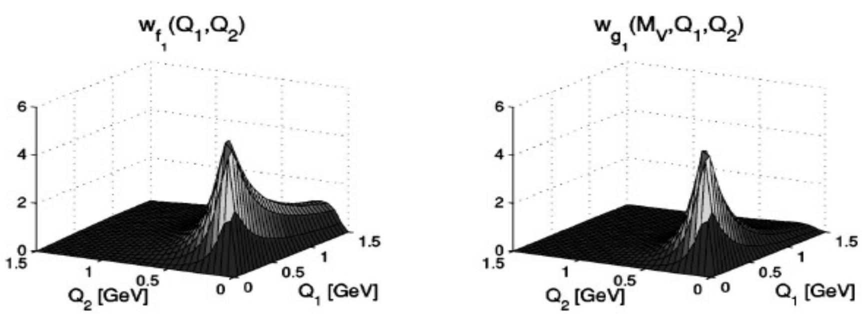


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1\text{-}1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



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





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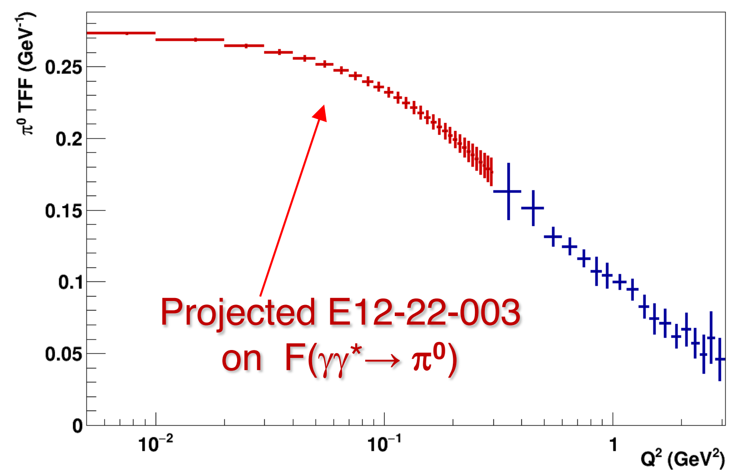


New opportunities with JLab 22 GeV Upgrade

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

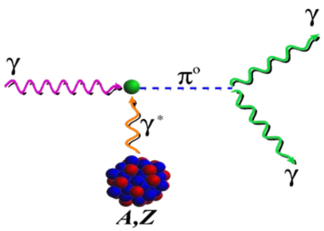
2. Improve the precisions of η/η' Promakoff production off nuclear targets.

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:

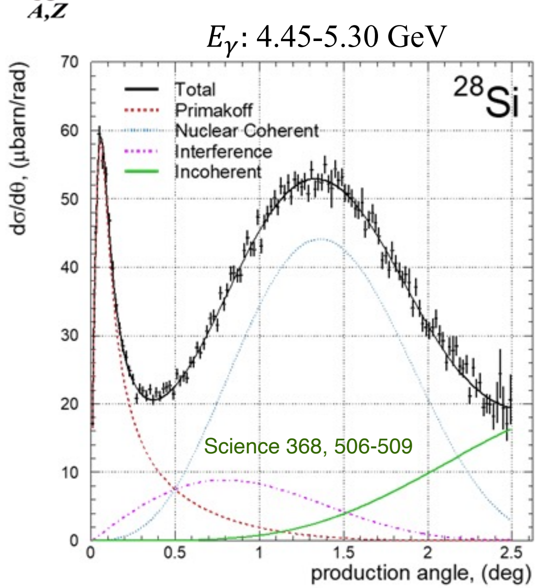
$$H^+ H(\varepsilon S + \lambda S^2) \qquad c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$$

Advantages of the π^0 Primakoff Production off an Electron

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

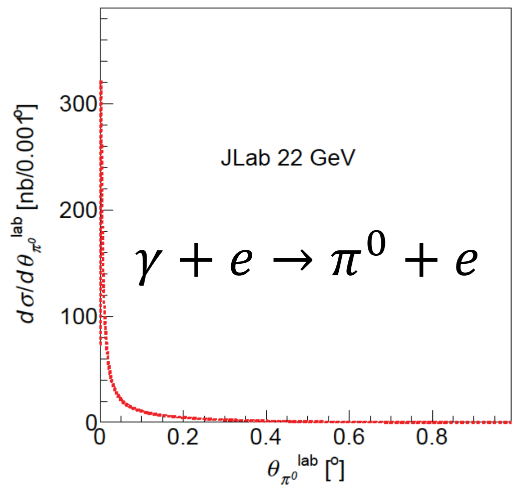


$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$



Advantages of an electron target:

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



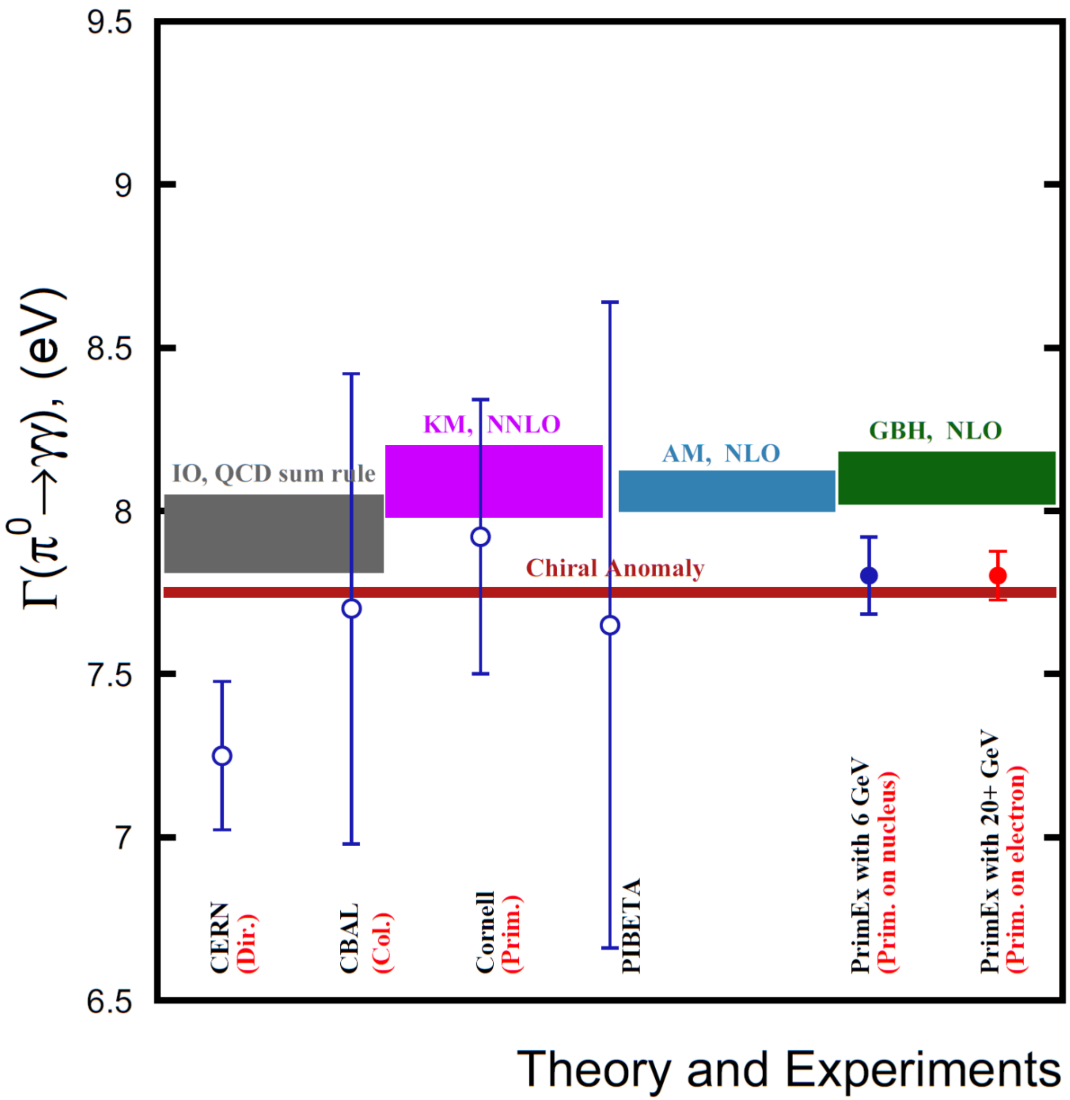
$$\frac{d\sigma_{\rm Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

Main challenges for the nuclear target:

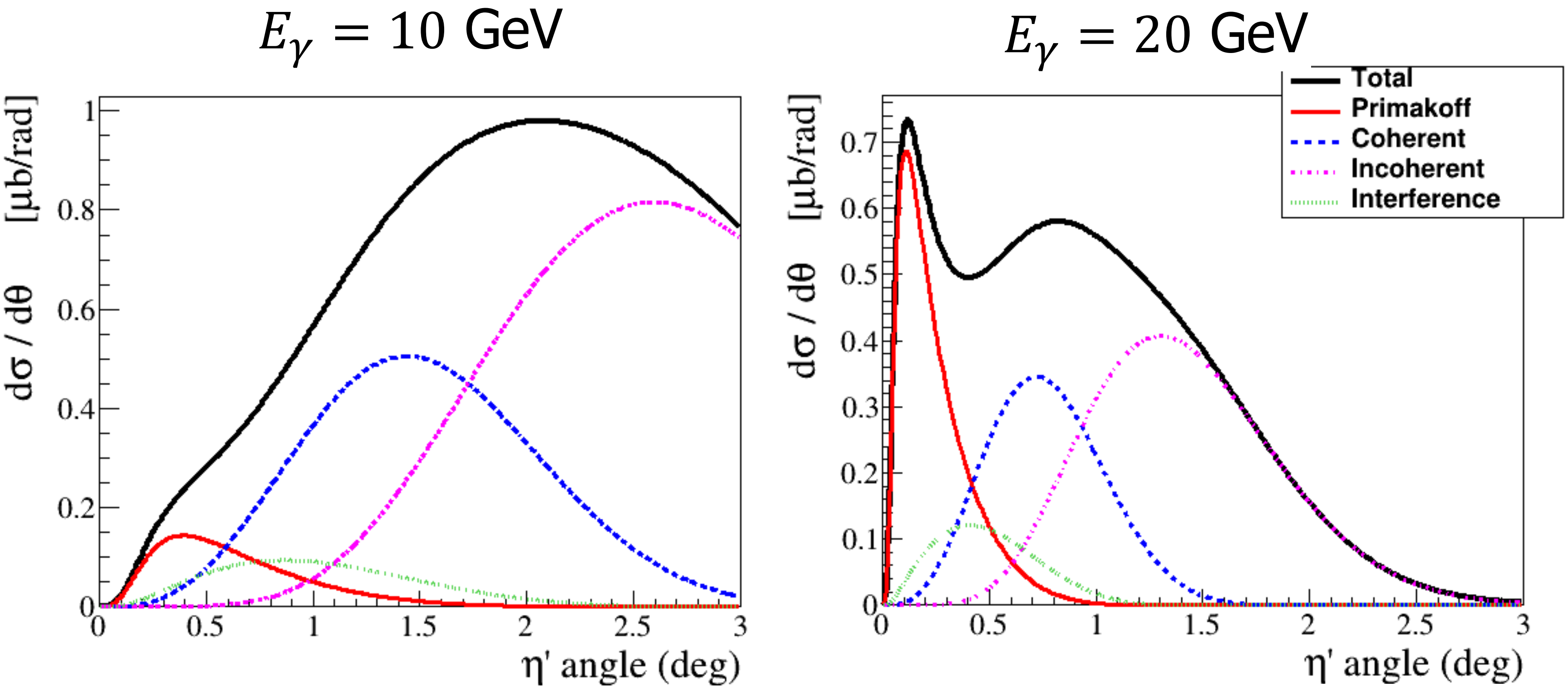
- Nuclear backgrounds
- Nuclear effects
- No recoil detection

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

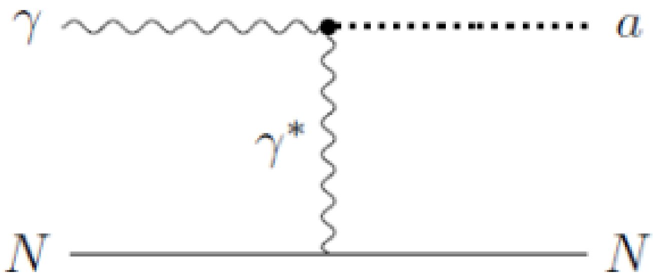


Improve Primakoff Measurements of η/η' with nuclear targets



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

Search for sub-GeV Scalar and Pseudoscalar via Primakoff Effect

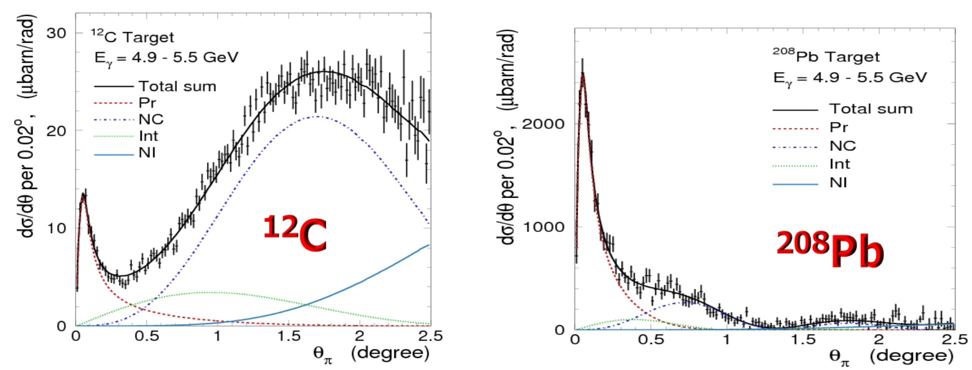


$$\mathcal{L}_{\text{eff}} \supset \frac{c_\gamma}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Favorable experimental condition:

- A high energy beam
- A high Z nuclear target

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

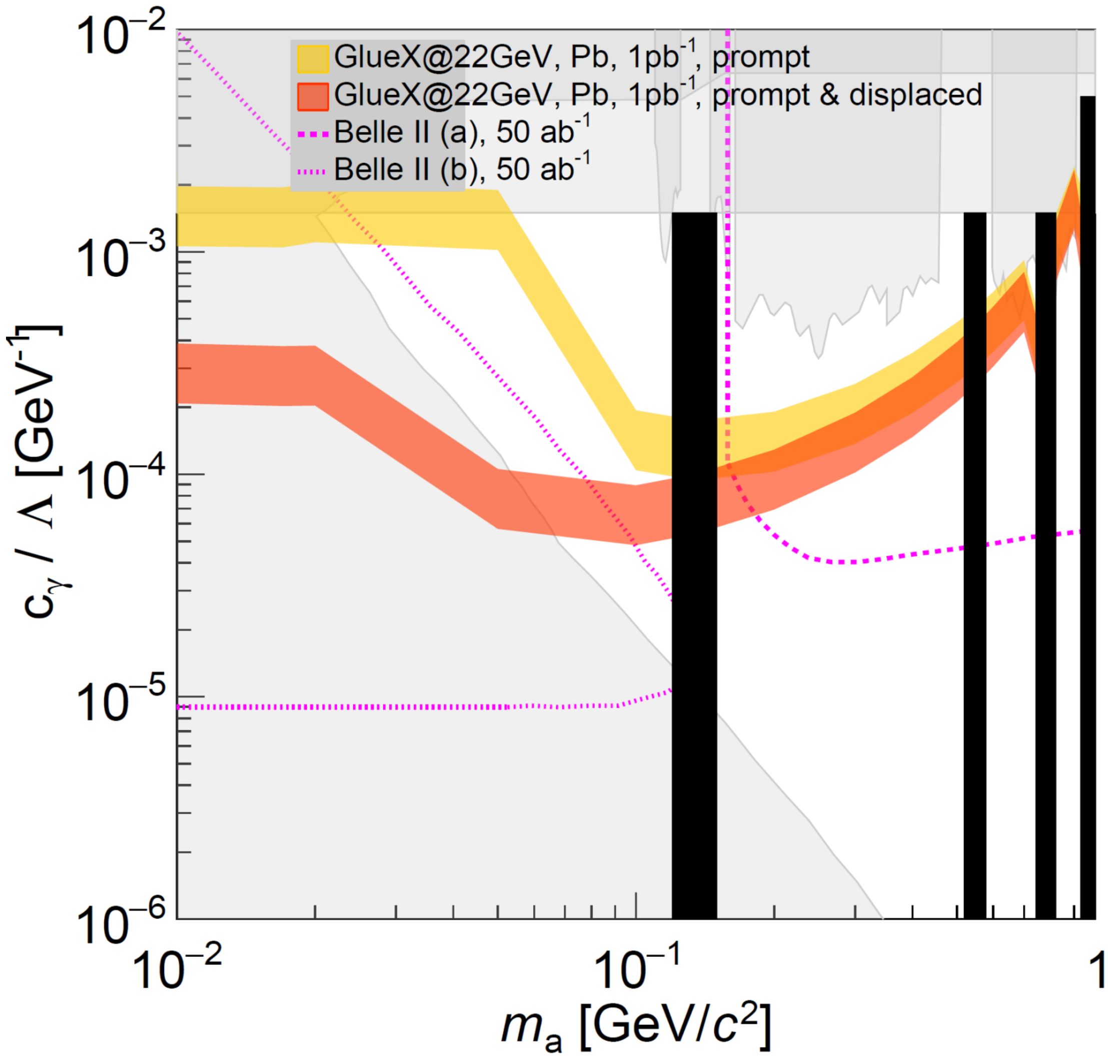


The Primakoff signal dominates in the forward angles

Minimizing the QCD backgrounds

PrimEx I

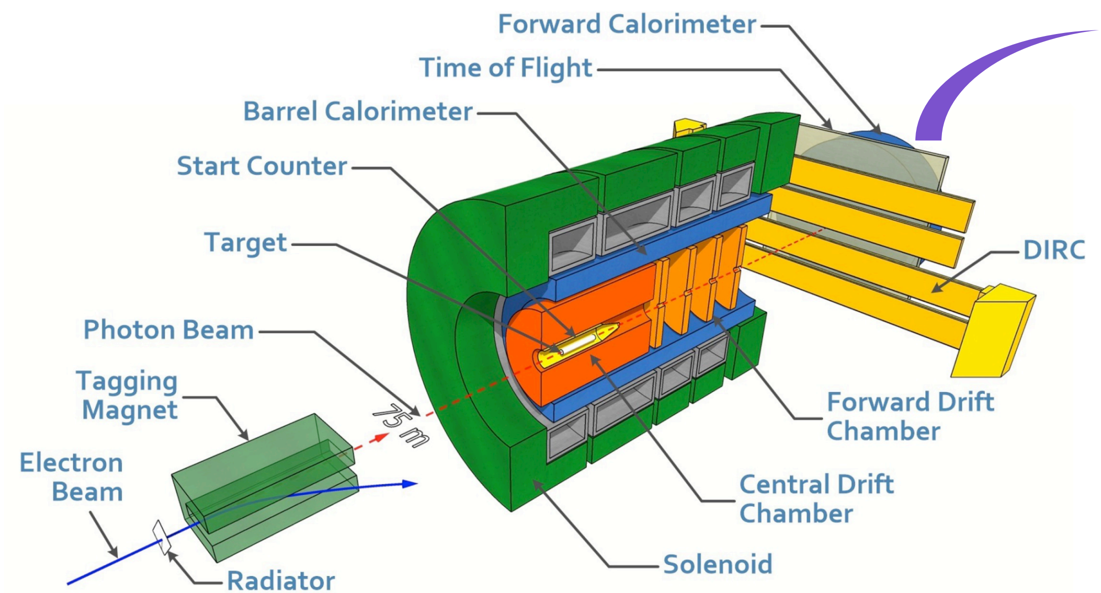
Projected Reach for a ALP at JLab 22 GeV

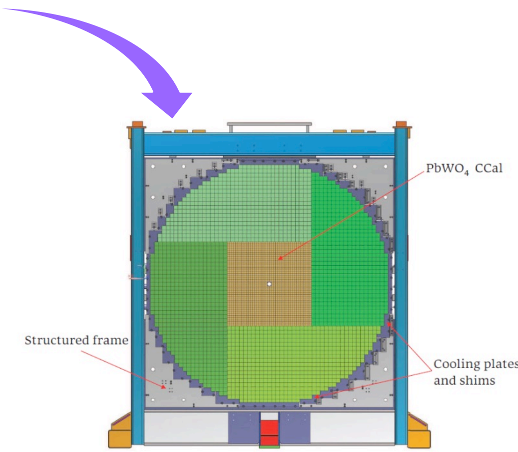


$$\gamma + Pb \rightarrow a + Pb$$

$$a \rightarrow \gamma\gamma$$

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

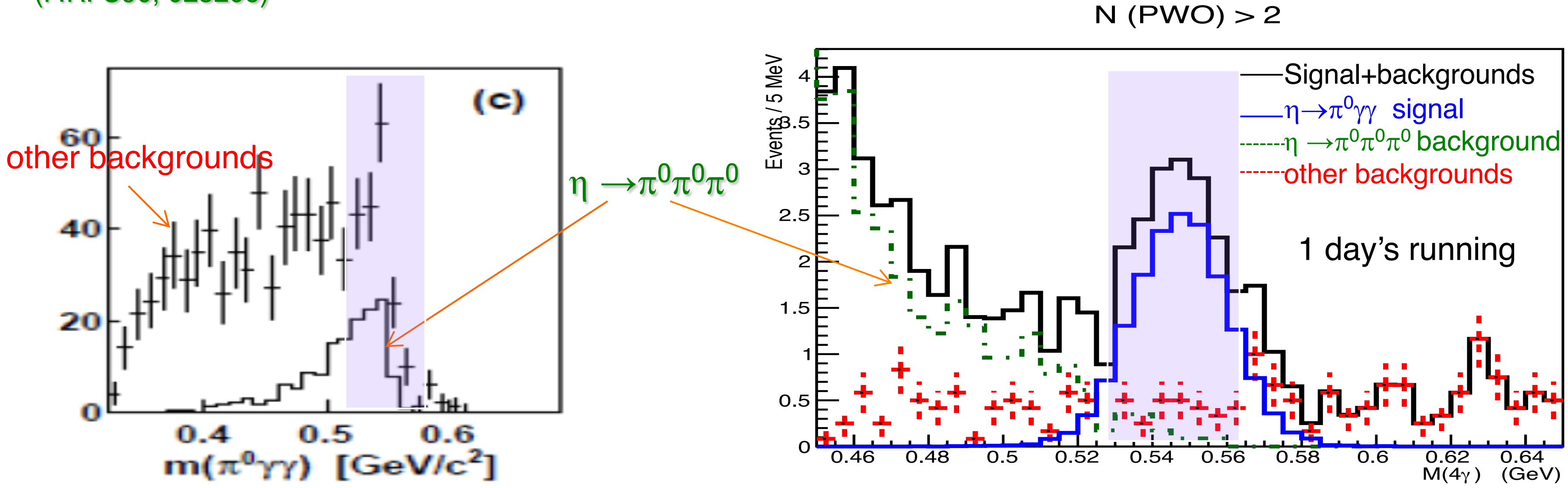
Uniqueness of JEF Experiment

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: $\gamma p \to \eta p$ (E_γ=1.5 GeV) JEF: $\gamma p \to \eta p$ (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 (~5x10^5 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): $\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \ \pi\pi e^+e^-$

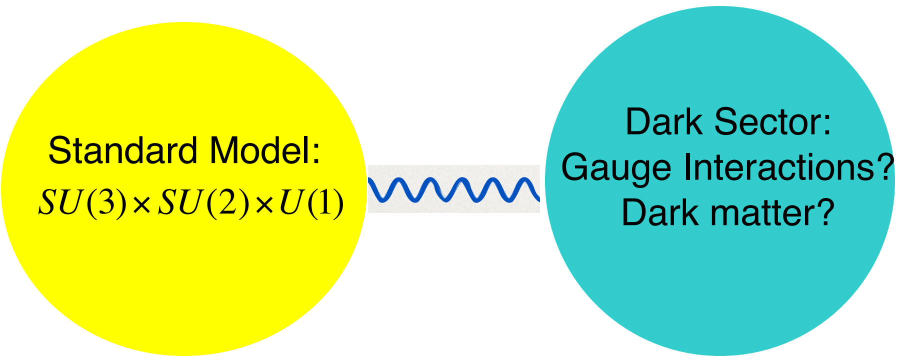
2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

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)

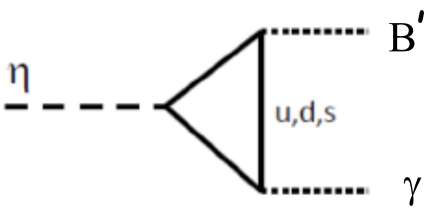
2. Confinement QCD:

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

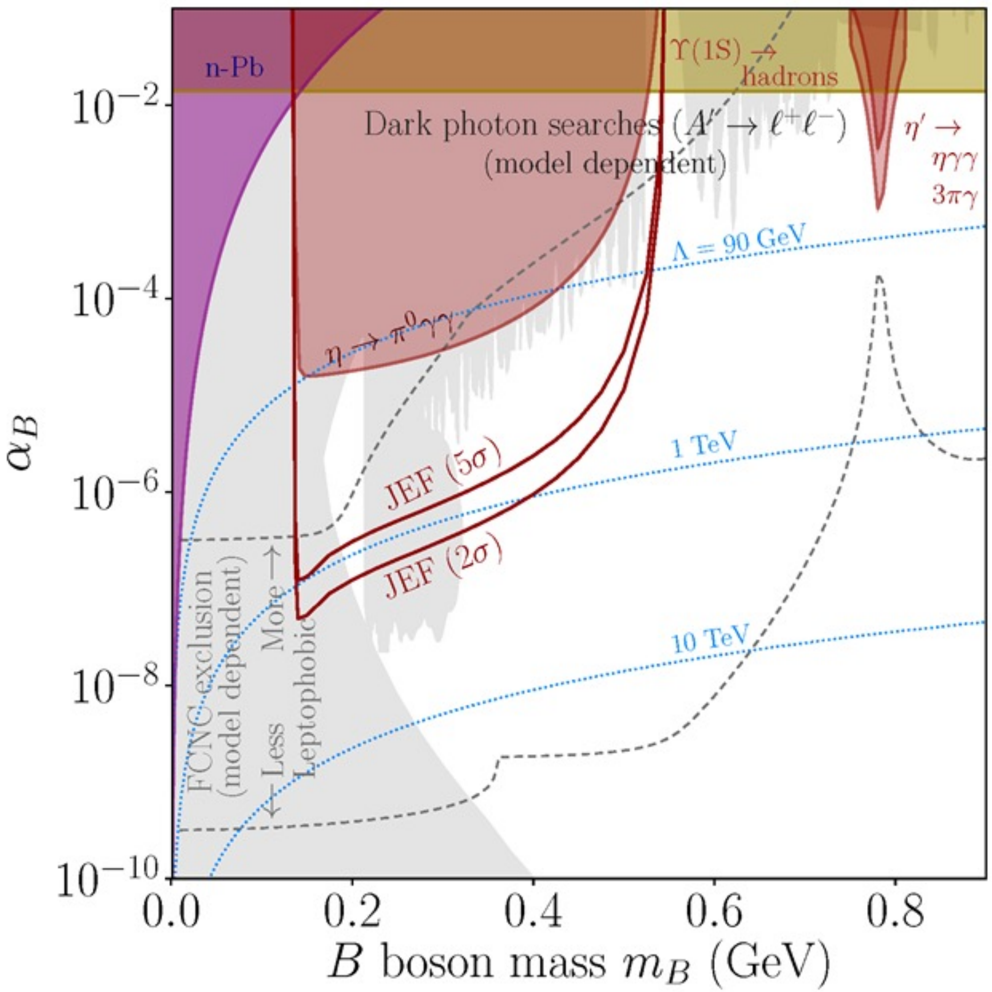
JEF Experimental Reach for B′

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

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

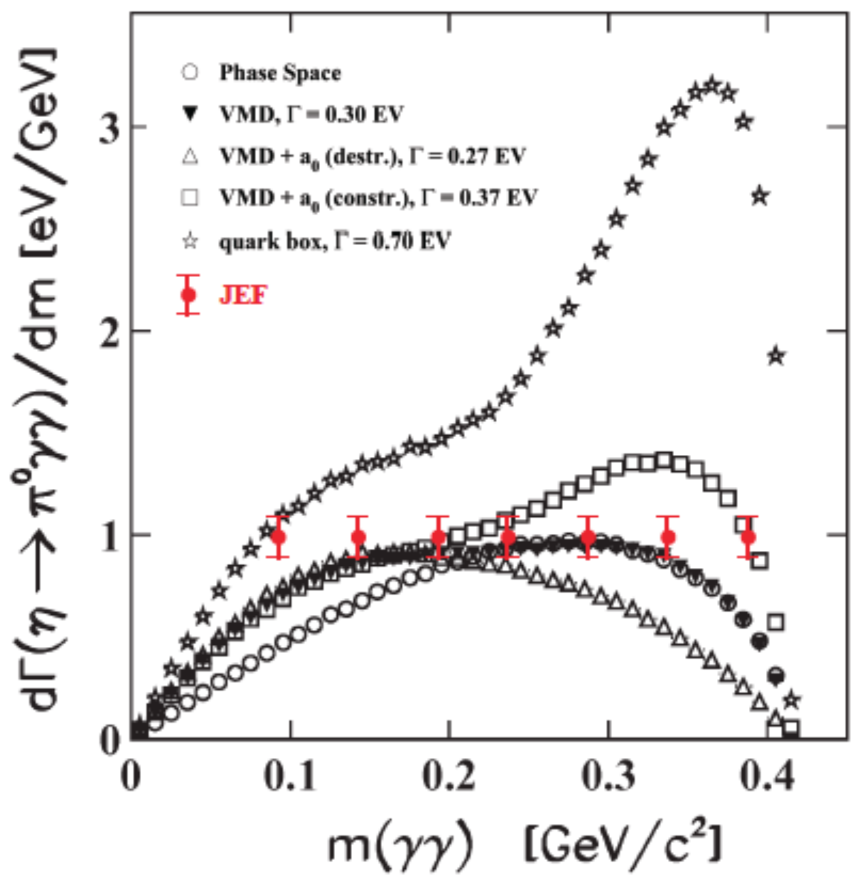


PL, B221, 80 (1989)
PR,D89,114008

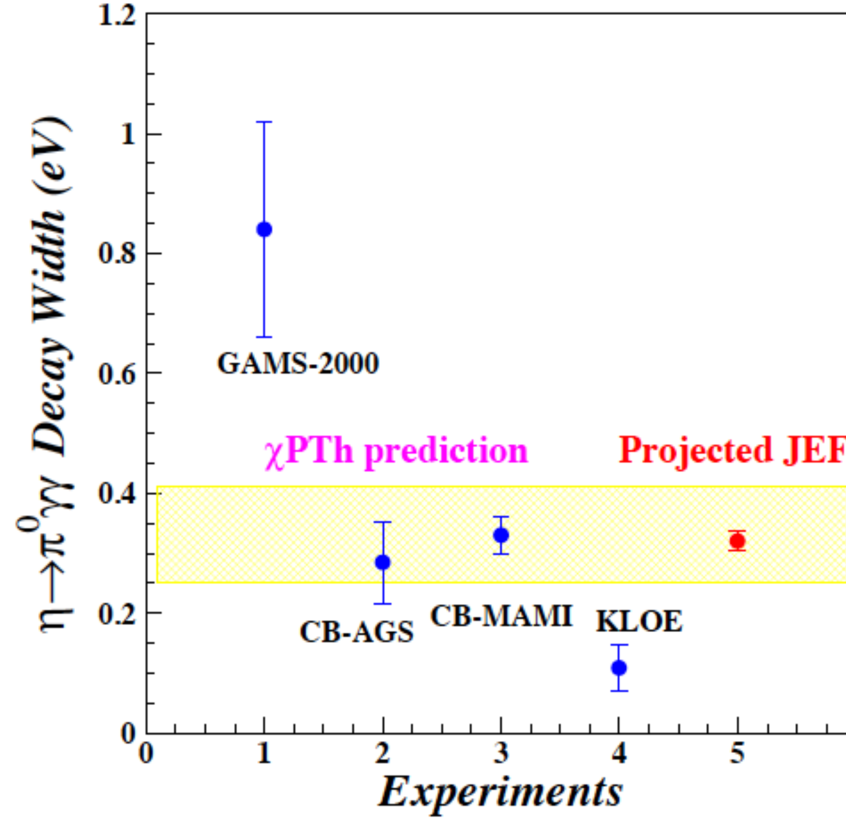


Projected JEF on SM Allowed $\eta\to\pi^0\gamma\gamma$

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

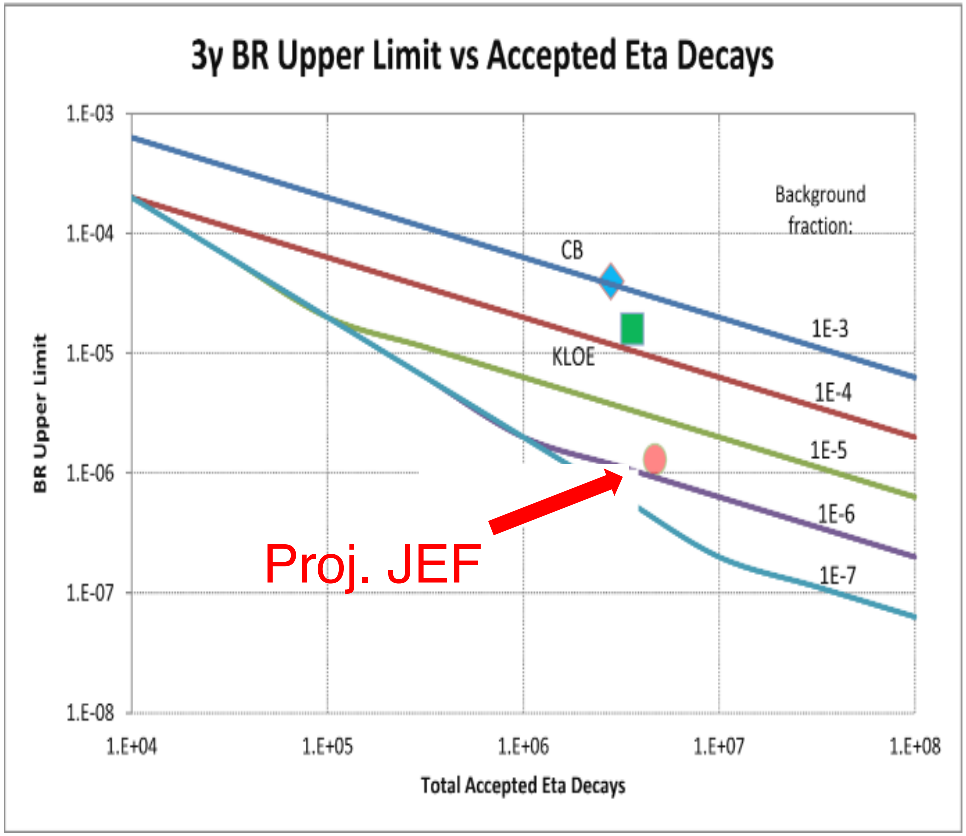
Mode	Branching Ratio (upper limit)	No. γ's
3γ	$< 1.6 \cdot 10^{-5}$	3
$\pi^0\gamma$	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

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

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

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

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

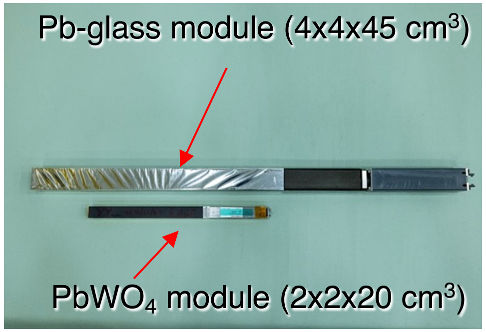


Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

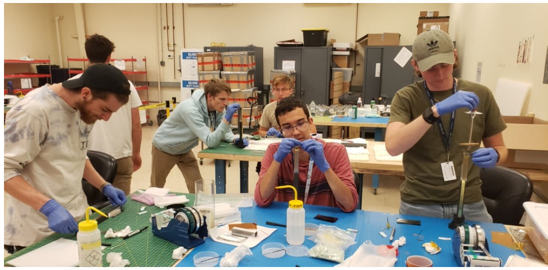
Status of the JEF Experiment

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.

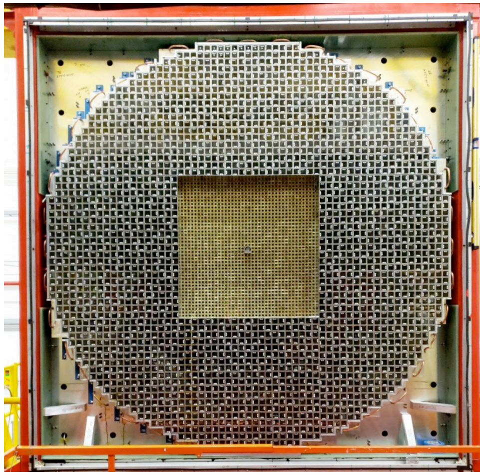


Undergraduate workforce



Summer 2023

Oct 6, 2023



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

Summary

- 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 will start data collection in Jan 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: the role of scalar dynamics in ChPT; transition form factors of η/η' to calculate HLbL contributions in $(g\text{-}2)_\mu$