Probe Fundamental Symmetry and BSM Physics Via the Primakoff Effect

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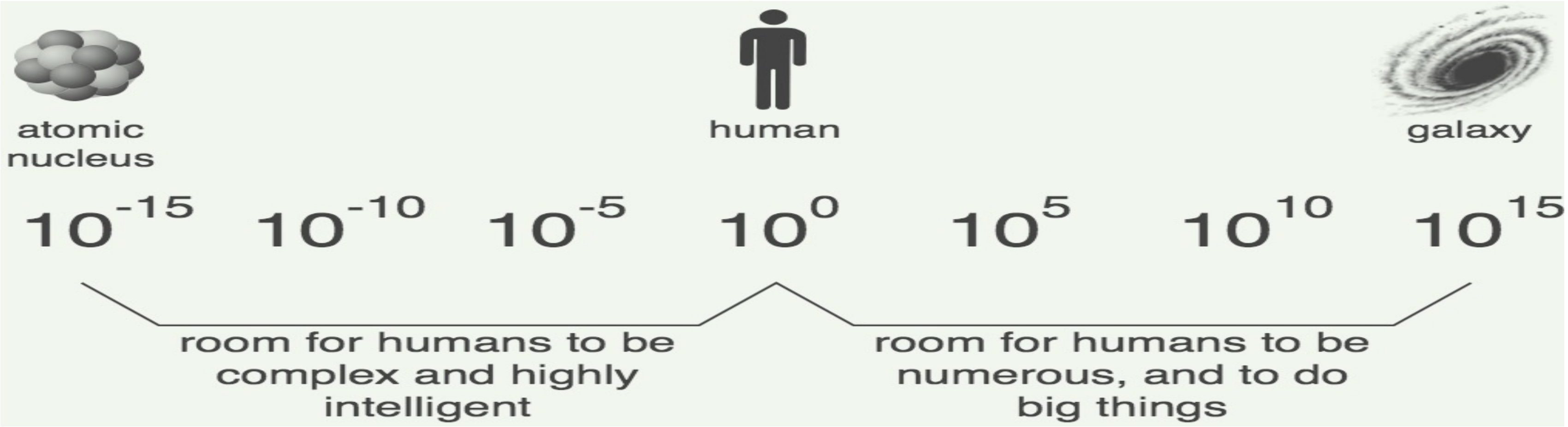
University of North Carolina Wilmington

Outline

- Introduction
- Current status of the PrimEx program at 6 & 12 GeV
- New opportunities at JLab 22 GeV
- Summary

Challenges in Physics



Low-energy QCD

- Nature of QCD confinement
- Origin of visible mass

New physics Beyond the Standard Model (BSM)

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

The Primakoff effect provides a great experimental tool to explore some fundamental issues in both areas.

What is the Primakoff Effect?

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

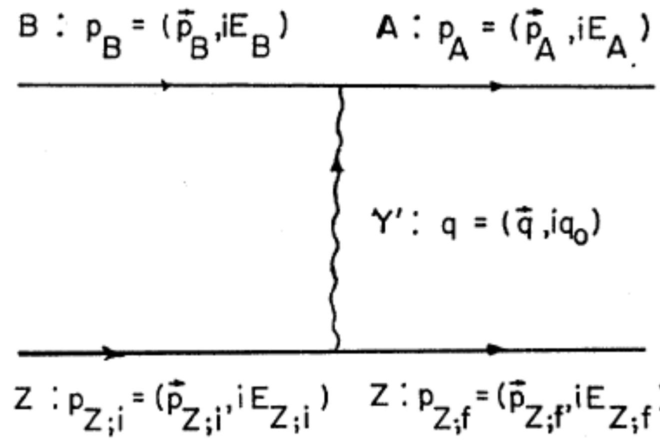
H. PRIMAKOFF†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

IT has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^0 spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

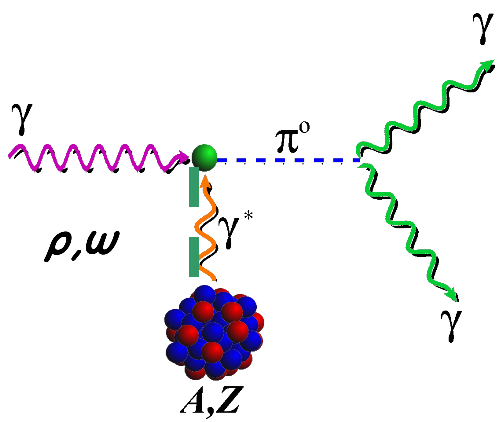
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi \mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of π^0),

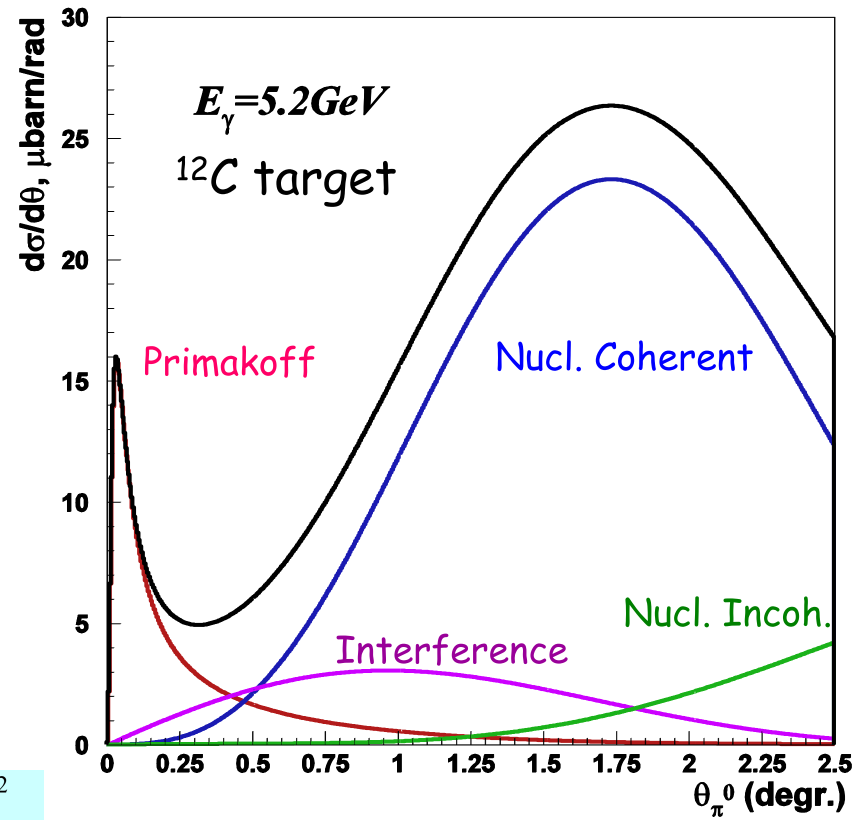


H. Primakoff, Phys. Rev. 81, 899 (1951)

Distinguishable Features of Primakoff Effect



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



- 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

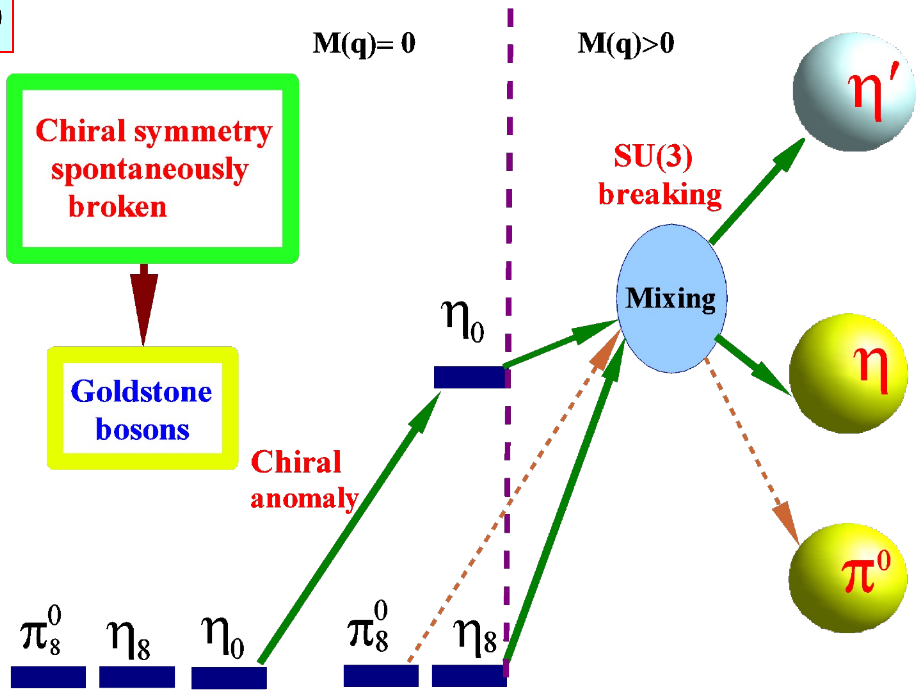
- The higher beam energy is, the higher Primakoff cross section and the better separation of Primakoff from the nuclear backgrounds.
- A higher beam energy is more important for more massive particle

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 QCD at low energies.

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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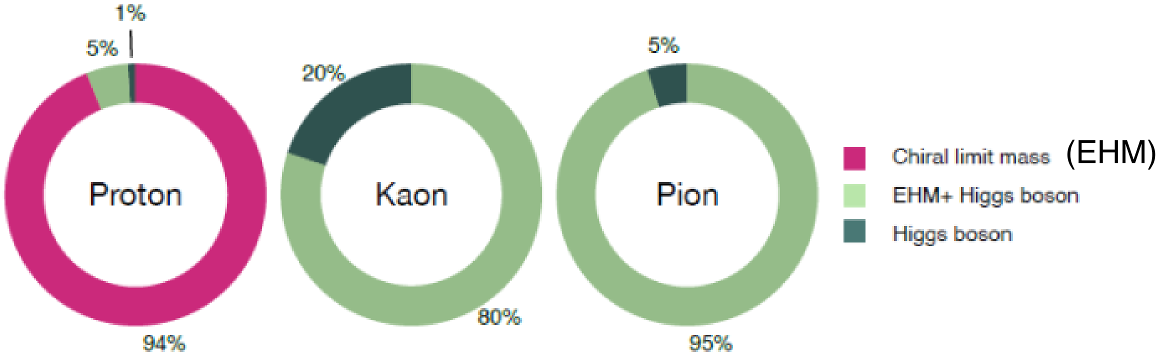
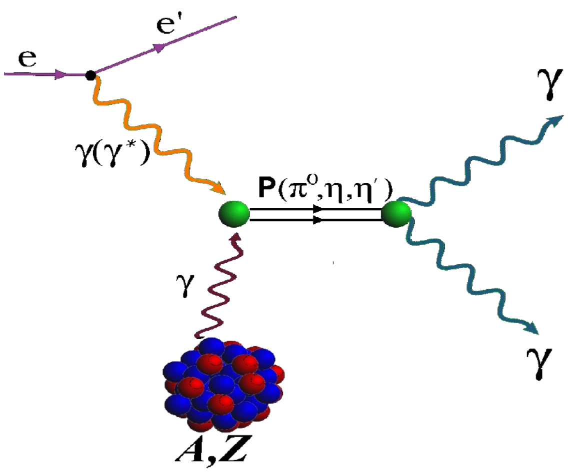


Complementary to proton, pseudoscalar mesons offer a unique opportunity for the interference between two known mass generating mechanisms.

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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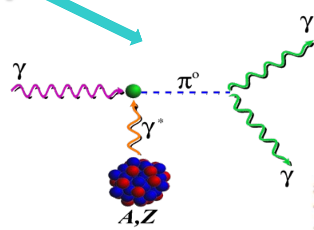


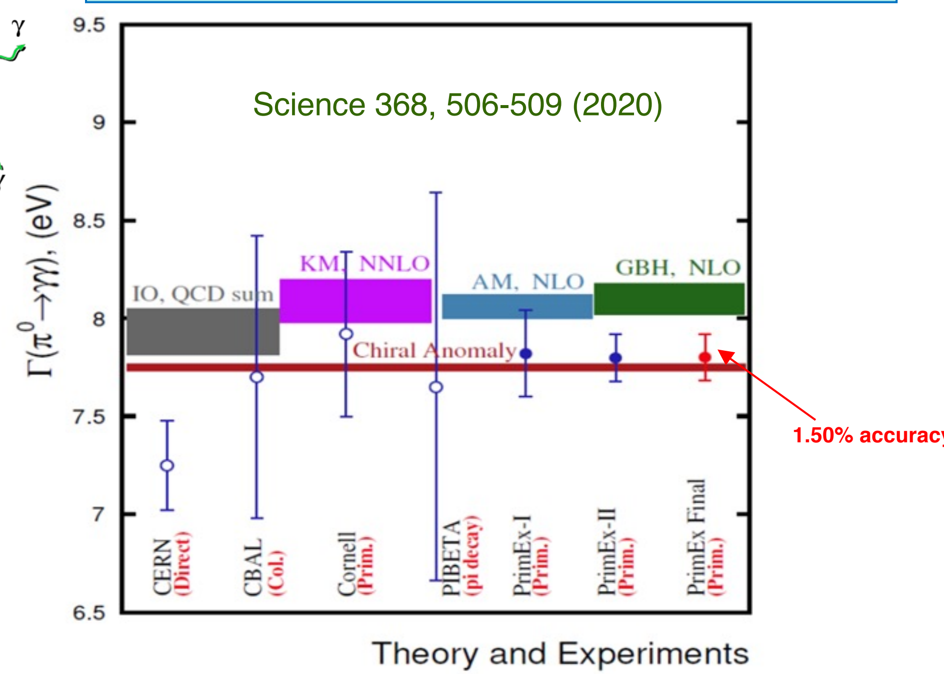
Input to Physics:

- 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:

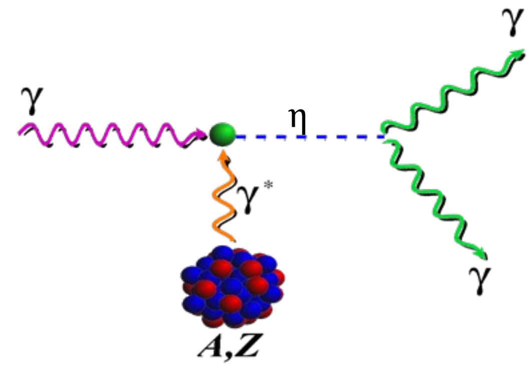
$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{m_{\pi^0}^3 \alpha^2 N_c^2}{576\pi^3 F_{\pi^0}^2} = 7.750 \pm 0.016\, eV$$

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

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

Input to Physics:

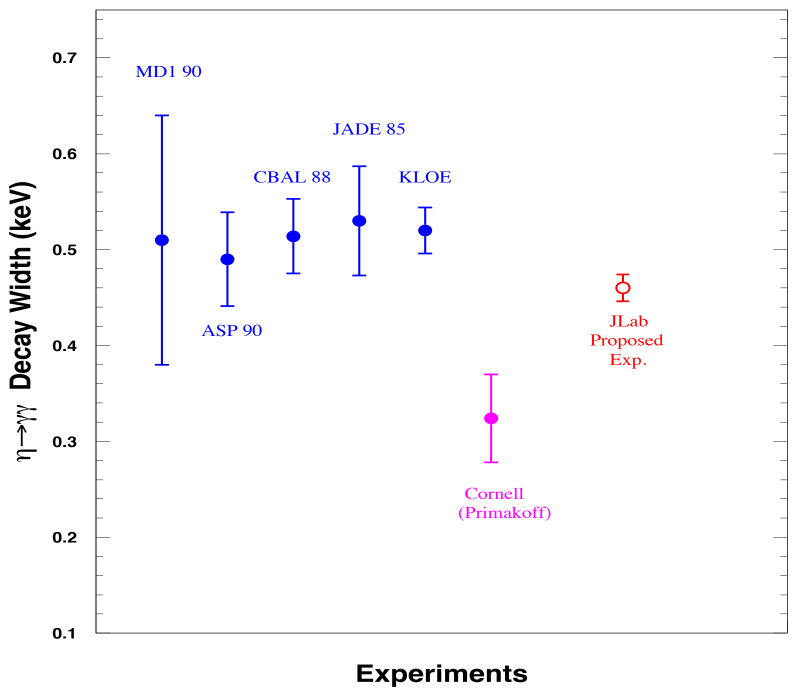
- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g\text{-}2)_\mu$

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:

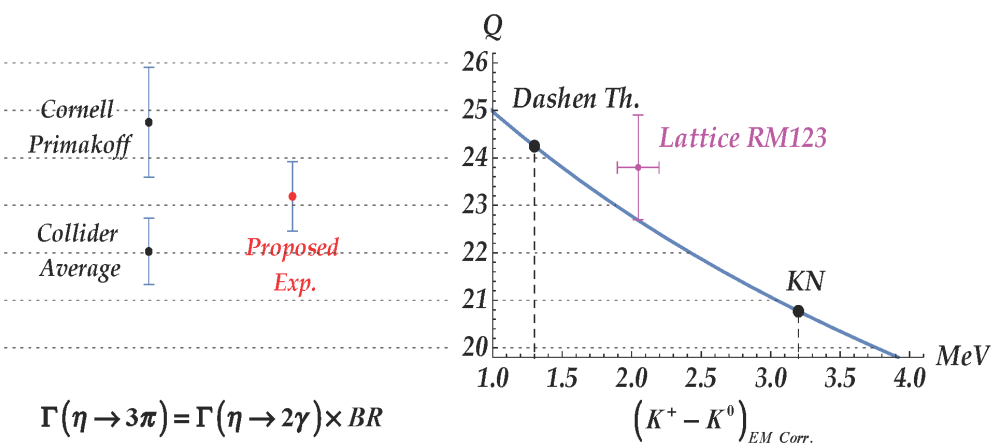


- **Extract η-η' mixing angle**
- **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**
- **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

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

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



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

Phys. Rept. 945 (2022) 1-105

Precision Determination Light Quark Mass Ratio

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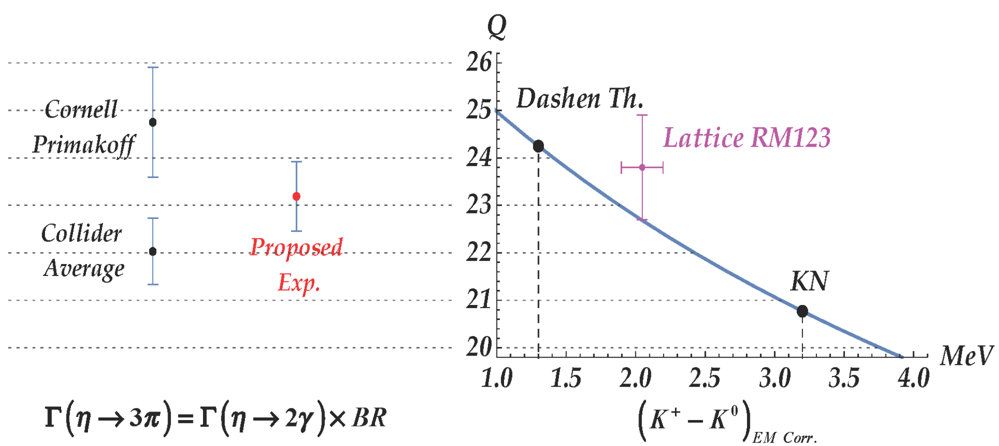

$$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to 2\gamma) \times BR$$

- 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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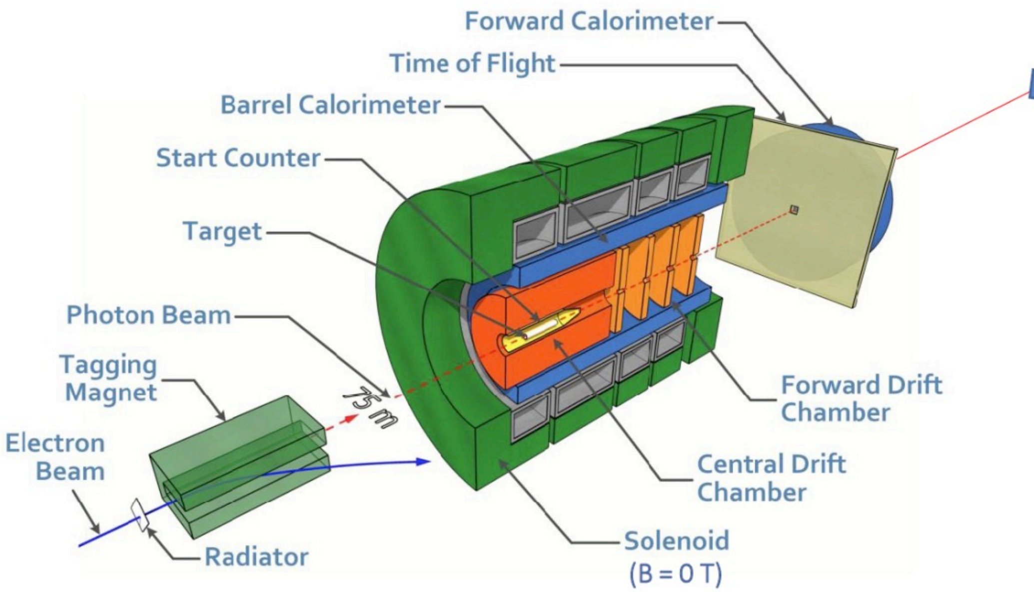
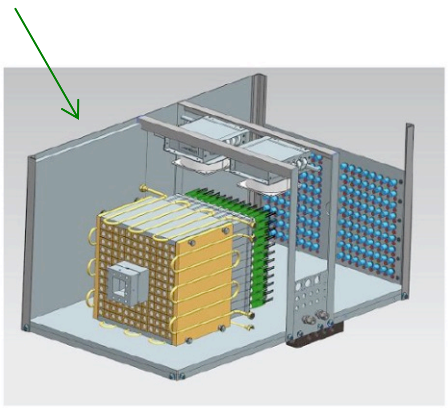
PrimEx-eta Experiment on $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D



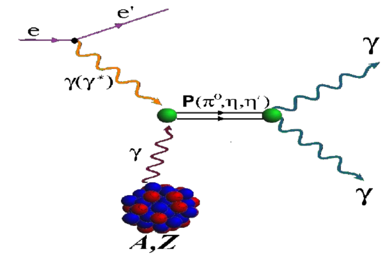


- Tagged photon beam (~8.0-11.7 GeV).
- Pair spectrometer and a TAC detector for the photon flux control.
- A liquid ^{4}He target (~4% R.L.)
- The η decay photons are detected by Forward Calorimeter (FCAL); the charged decay particles of η are detected by the GlueX spectrometer.
- CompCal and FCAL to measure Compton scattering off atomic electron for control of overall systematics.

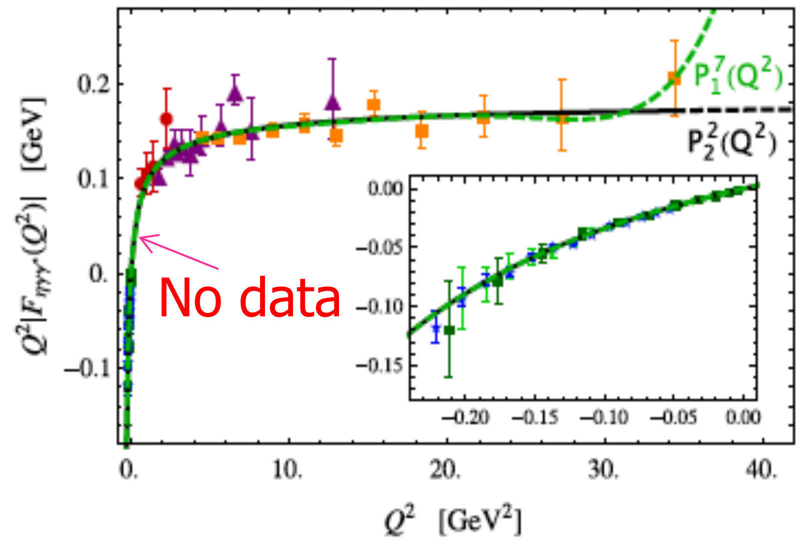
Data collection is completed, and data analysis has been in progress

(For more detail, see I. Jaegle's talk in the second afternoon session today)

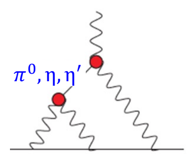
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

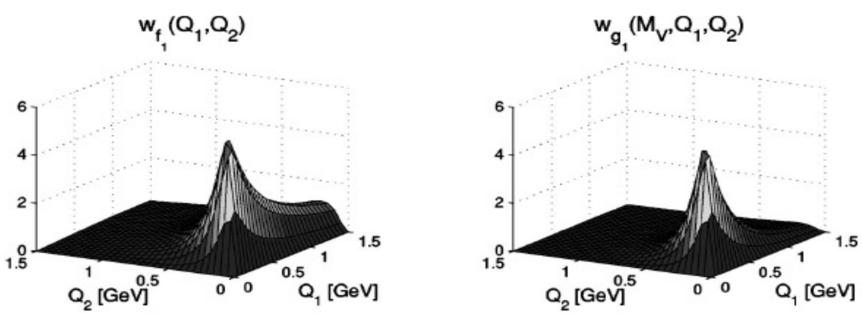


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian

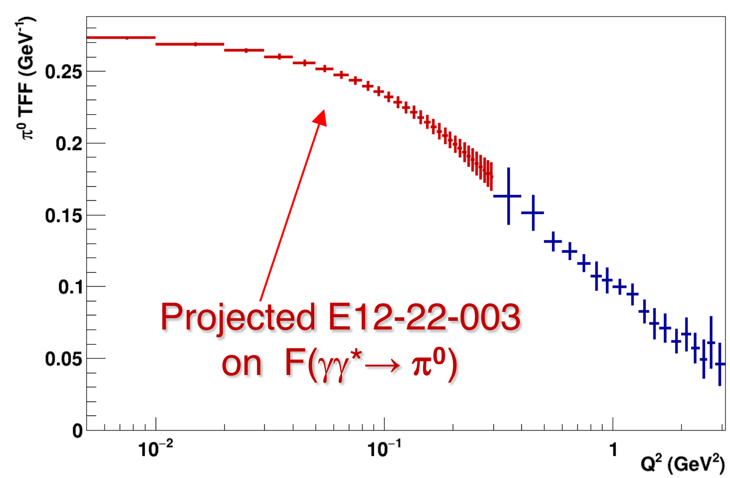


- Input for hadronic light-by-light calculations in muon (g-2)





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 $F(\gamma\gamma^* \to \pi^0)$.

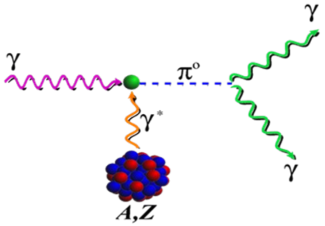
2. Improve the precisions of η/η' Promakoff production off nuclear targets.

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:

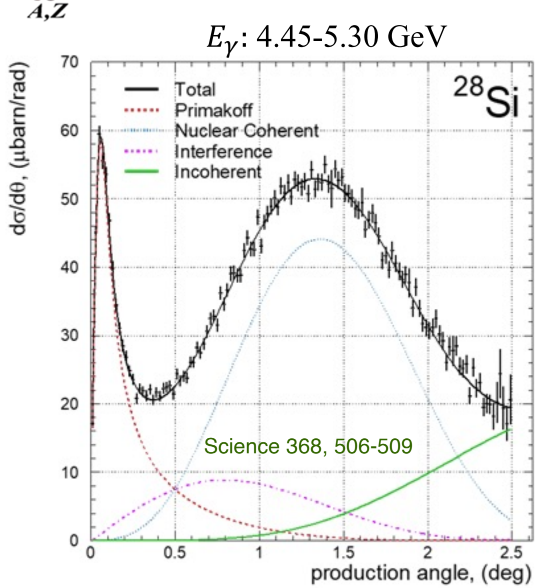
$$H^+H(\varepsilon S + \lambda S^2) \qquad c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$$

Advantages of the π^0 Primakoff Production off an Electron

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

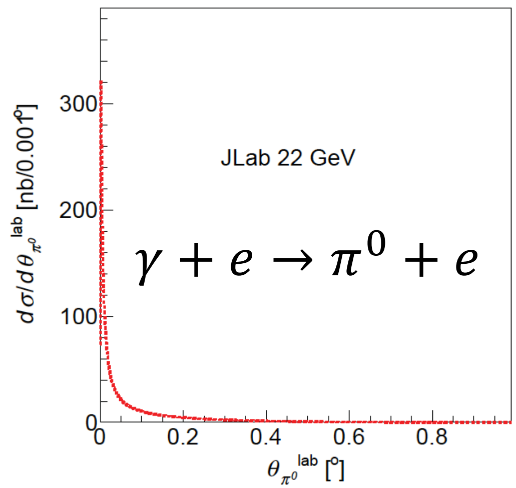


$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$



Advantages of an electron target:

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



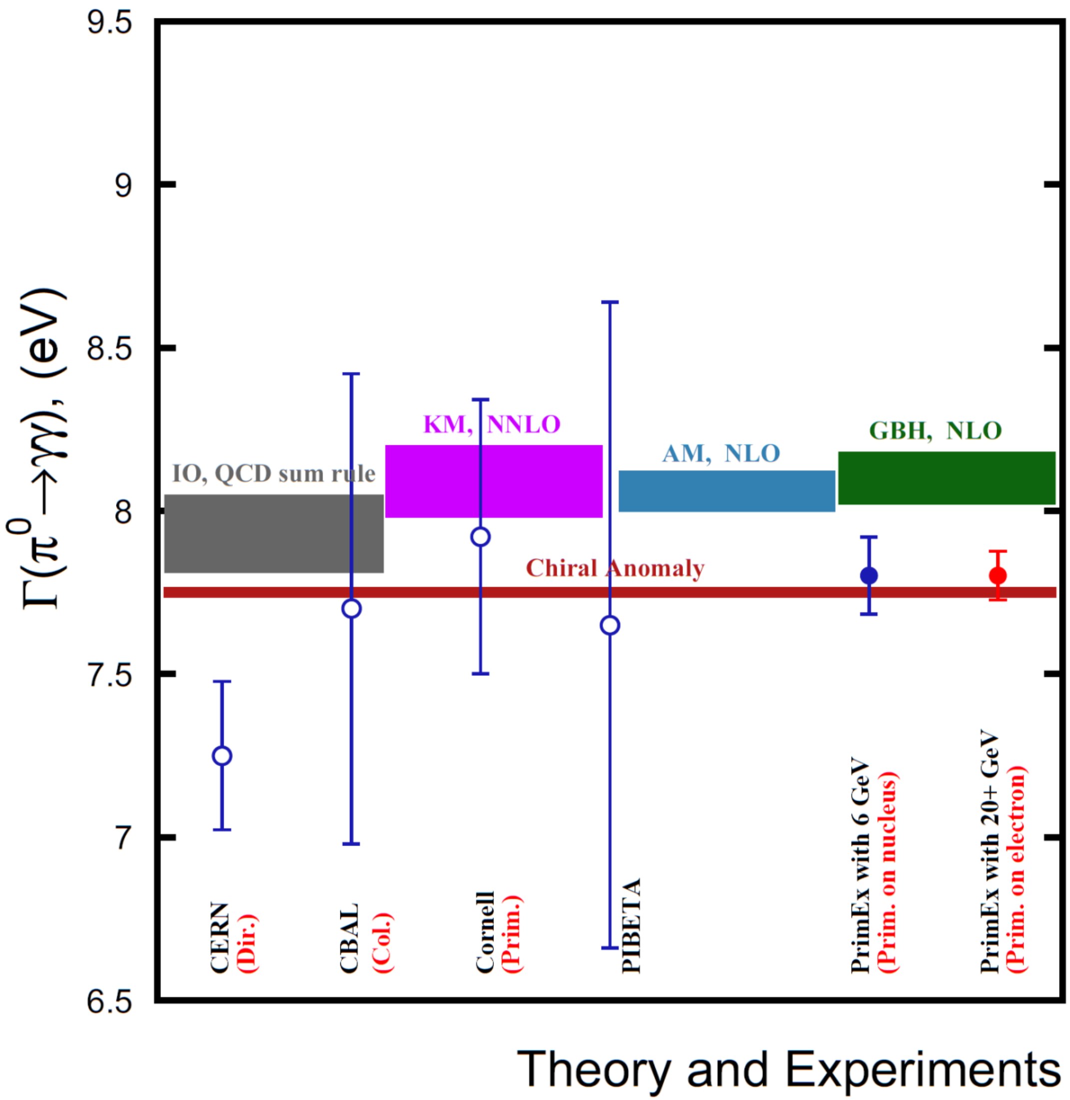
$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

Main challenges for the nuclear target:

- Nuclear backgrounds
- Nuclear effects
- No recoil detection

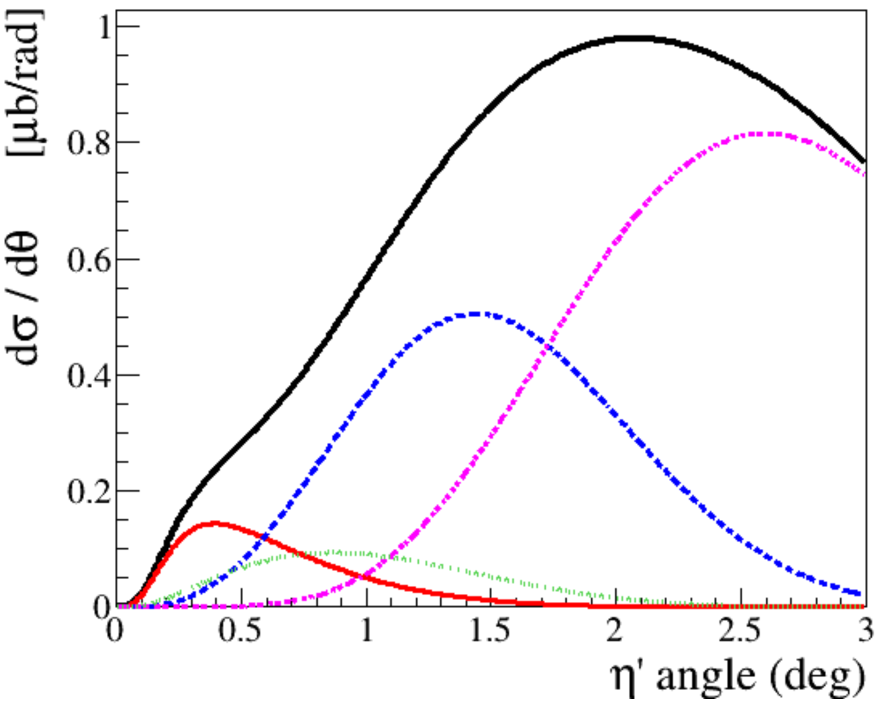
Measurement	Reaction	E_{th} (GeV)
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$	$\gamma + e \rightarrow \pi^0 + e$	18.0
$F(\gamma^*\gamma \rightarrow \pi^0)$	$e + e \rightarrow \pi^0 + e + e$	18.1

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

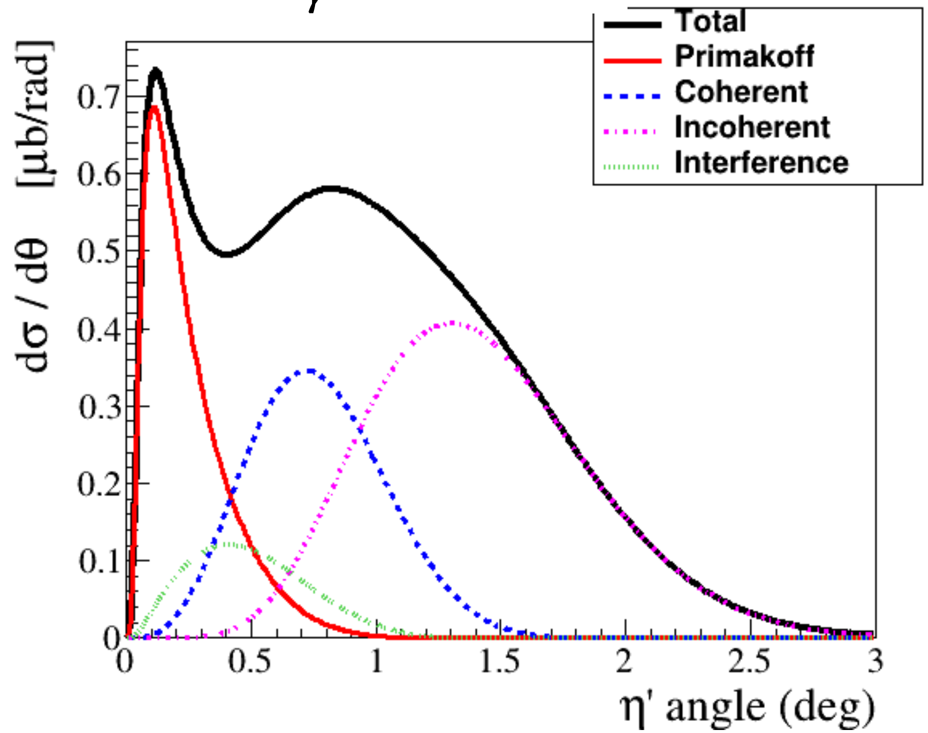


Improve Primakoff Measurements of η/η' with nuclear targets

$E_\gamma = 10$ GeV

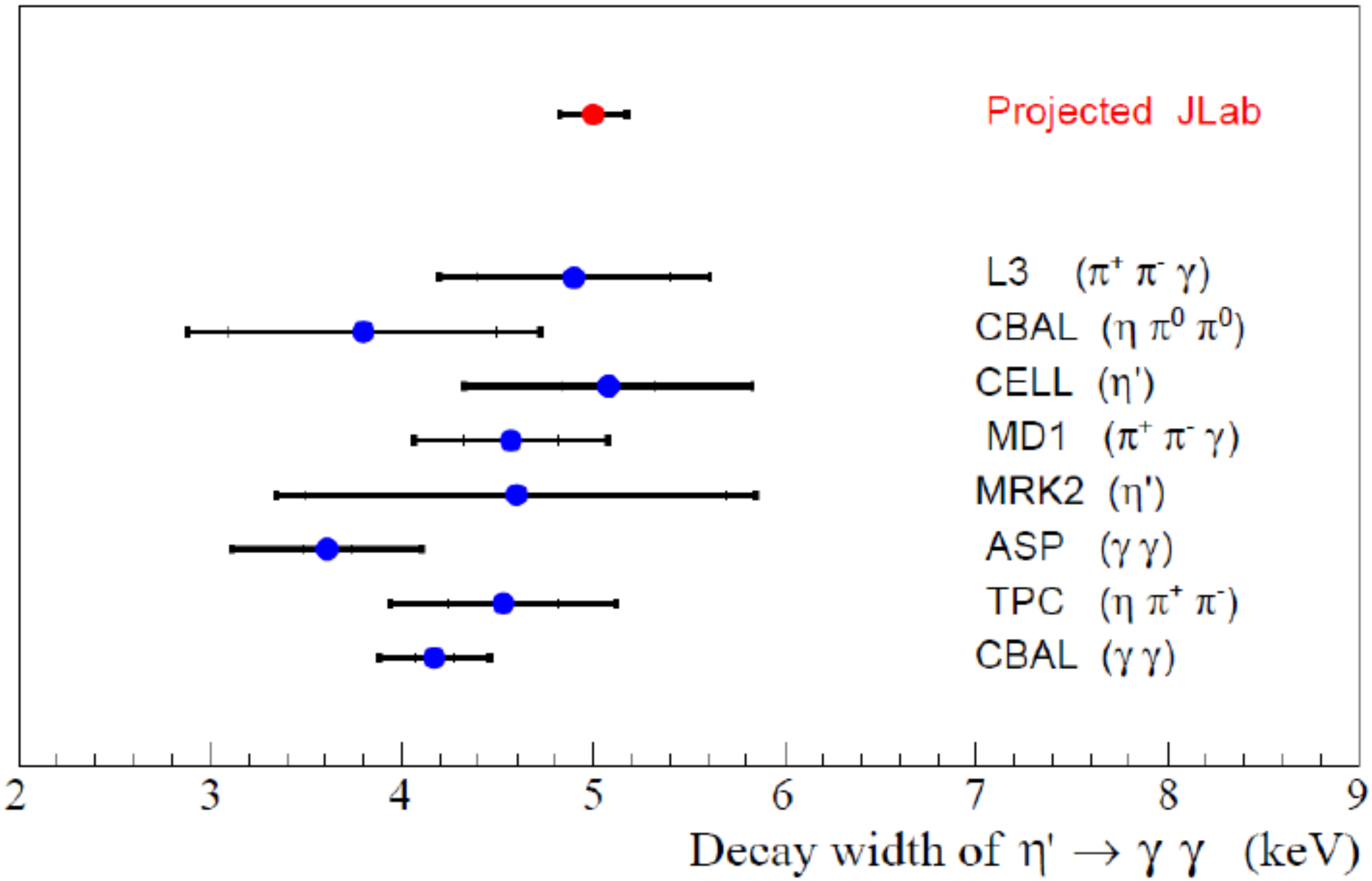


$E_\gamma = 20$ GeV

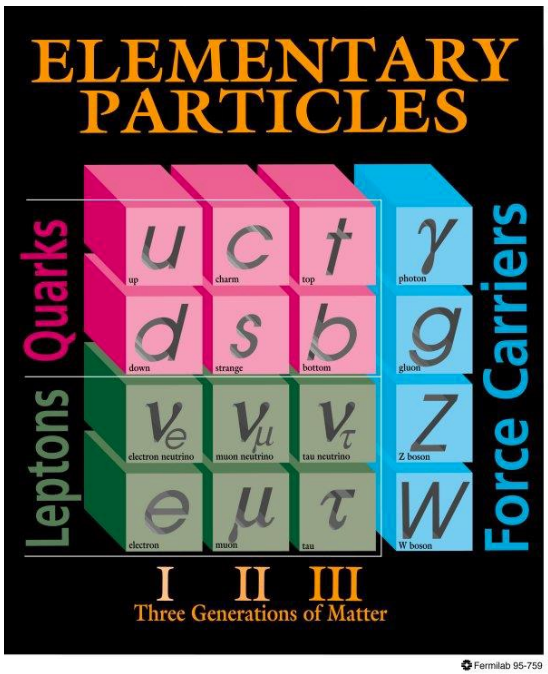


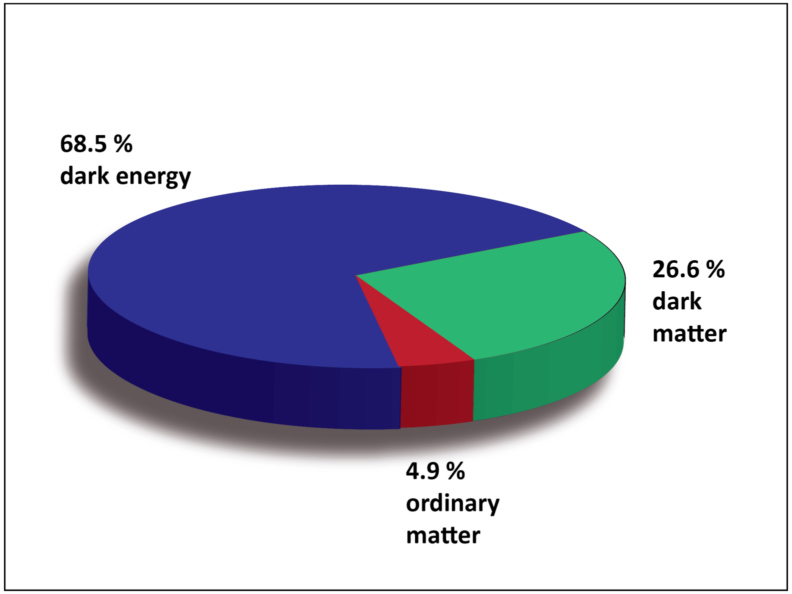
$$\gamma + {}^4He \rightarrow \eta' + {}^4He$$

Offer Frist Primakoff Measurement on $\Gamma(\eta' \rightarrow \gamma\gamma)$



BSM Physics in Dark Sector

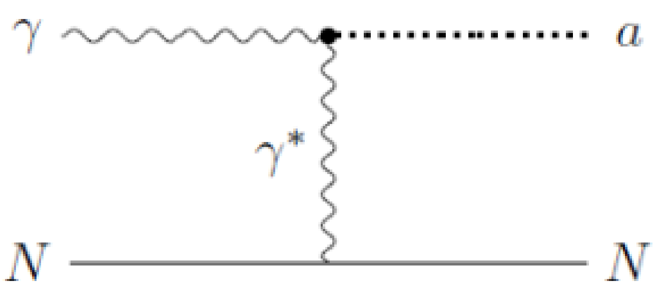




Dark Sector

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

Search for sub-GeV Scalar and Pseudoscalar via Primakoff Effect



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

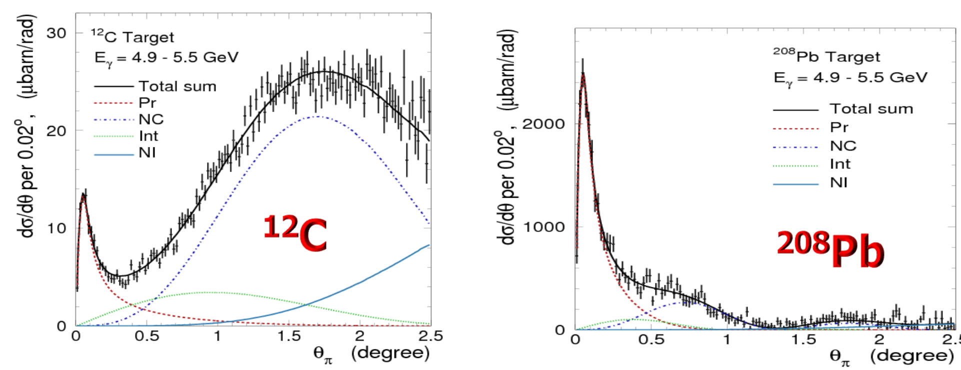
$$\frac{d\sigma_{Pr}}{d\Omega} \sim \frac{c_\gamma^2 \alpha Z^2}{8\pi\Lambda^2} \cdot \frac{\beta^3 E^4}{Q^4} \cdot |F_{e.m.}(Q)|^2 sin^2\theta_a$$

The Primakoff signal dominates in the forward angles

Minimizing the QCD backgrounds

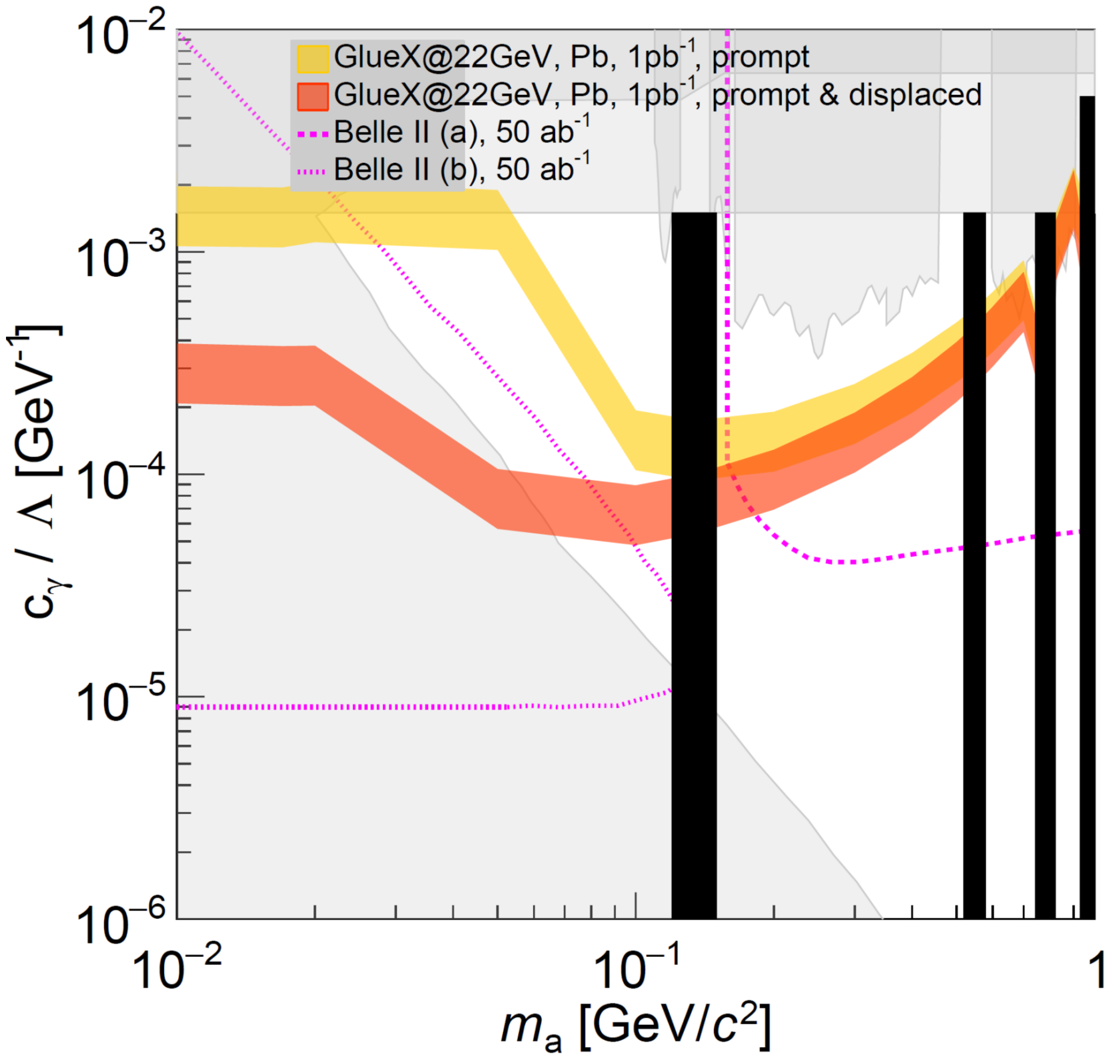
Favorable experimental condition:

- A high energy beam
- A high Z nuclear target



PrimEx I

Projected Reach for a ALP at JLab 22 GeV



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

$$a \rightarrow \gamma\gamma$$

Summary

- The distinguishable features of Primakoff effect make it a great experimental tool for fundamental symmetry tests and BSM physics searches.

- The current JLab Primakoff program at 6&12 GeV has been in progress.

  - ✓ The published PrimEx result on the π^0 lifetime provides a stringent test of low-energy QCD.
  - ✓ Data collection on $\Gamma(\eta \to \gamma\gamma)$ was completed in 2022 and data analysis is in progress.
  - ✓ A new experiment on $F(\pi^0 \to \gamma^* \gamma)$ off a nuclear target is on the way.

- JLab 22 GeV upgrade will offer new opportunities for the Primakoff physics:

  - ✓ New generation of Primakoff experiments on $\Gamma(\pi^0 \to \gamma\gamma)$ and $F(\gamma^*\gamma \to \pi^0)$ 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).

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