The Primakoff Experimental Program at Jefferson Lab

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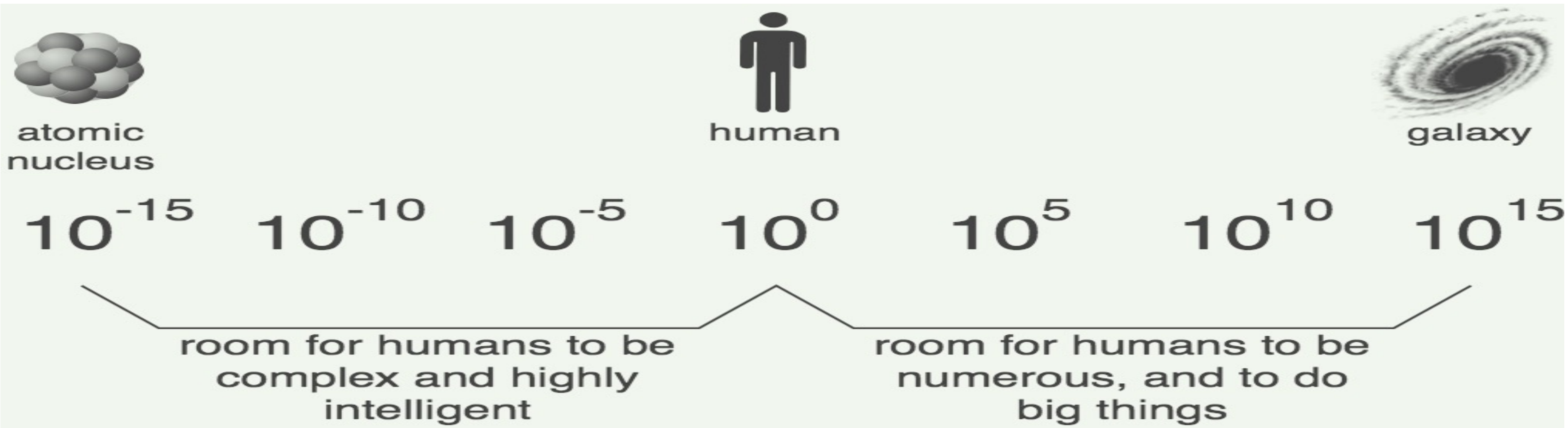
Outline

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

Two Challenges in Physics



Low-energy QCD

- Nature of QCD confinement
- How is the QCD confinement related to the chiral symmetry and symmetry breaking?

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?

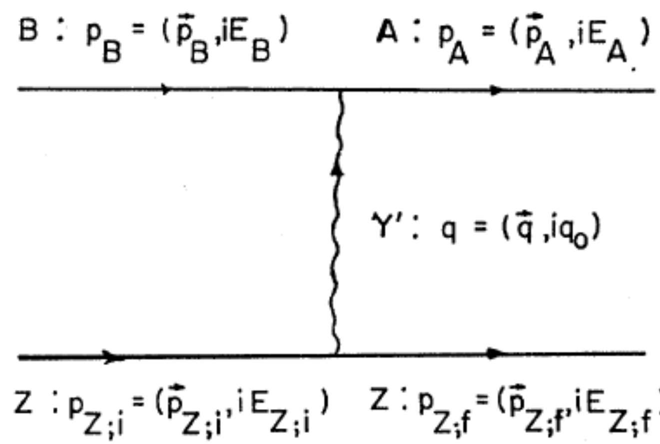
Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

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:

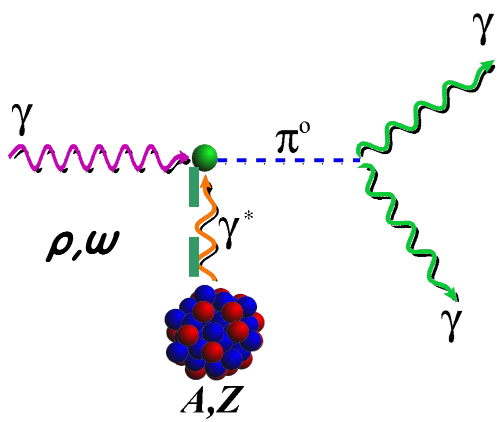
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

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



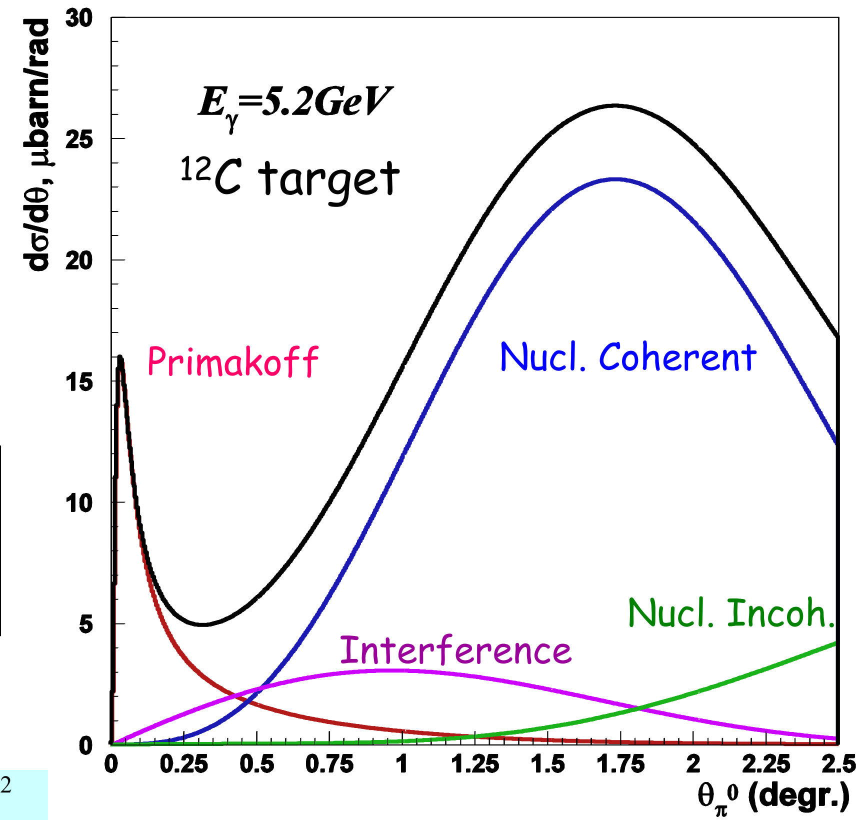
$$\frac{d\sigma_{\Pr}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$

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

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

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

- Coherent process



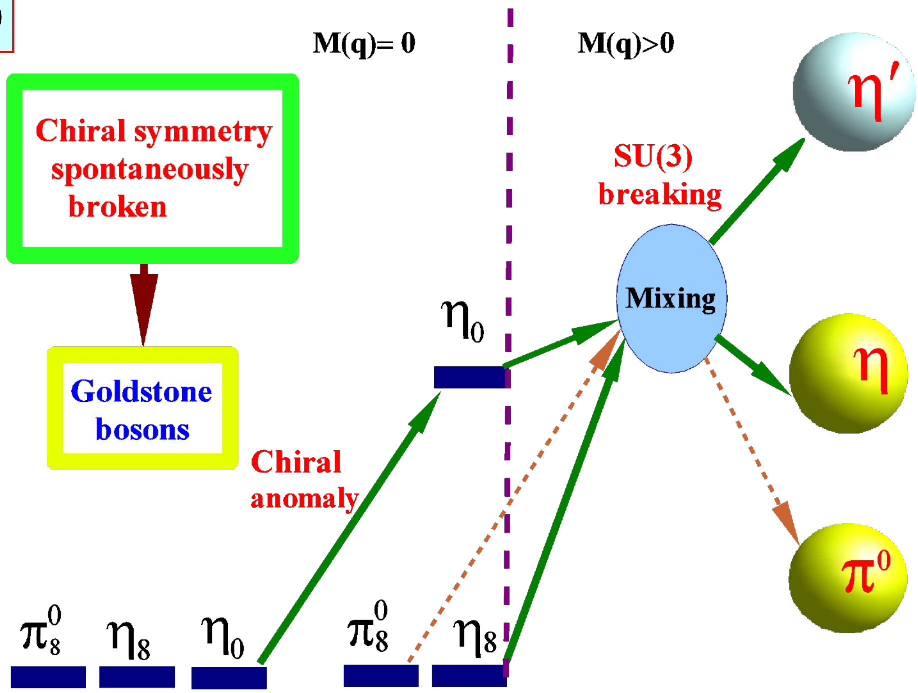
- The higher beam energy is, the higher Primakoff cross section and the better separation of Primakoff from the nuclear backgrounds.
- A higher beam energy is more important for more massive particle

Low-Energy QCD Symmetries and Light Mesons

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

$$\boxed{SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)}$$

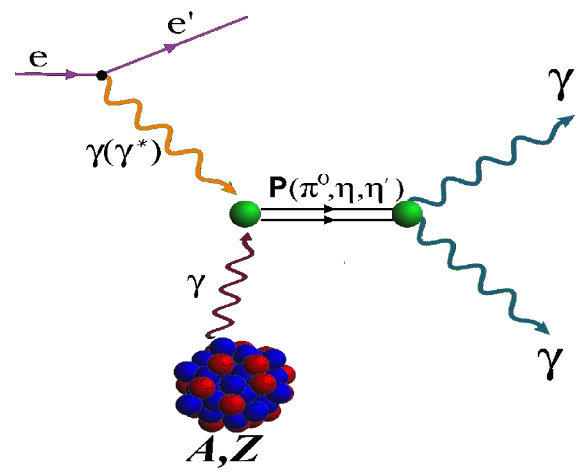
- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Non-zero mass of η_0
- $SU_L(3)xSU_R(3)$ and $SU(3)$ 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 QCD at low energies.

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

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 $(g-2)_\mu$

Status of Primakoff Program at JLab 6 & 12 GeV

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

- 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!

a) Two-Photon Decay Widths:

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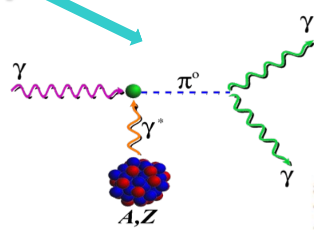

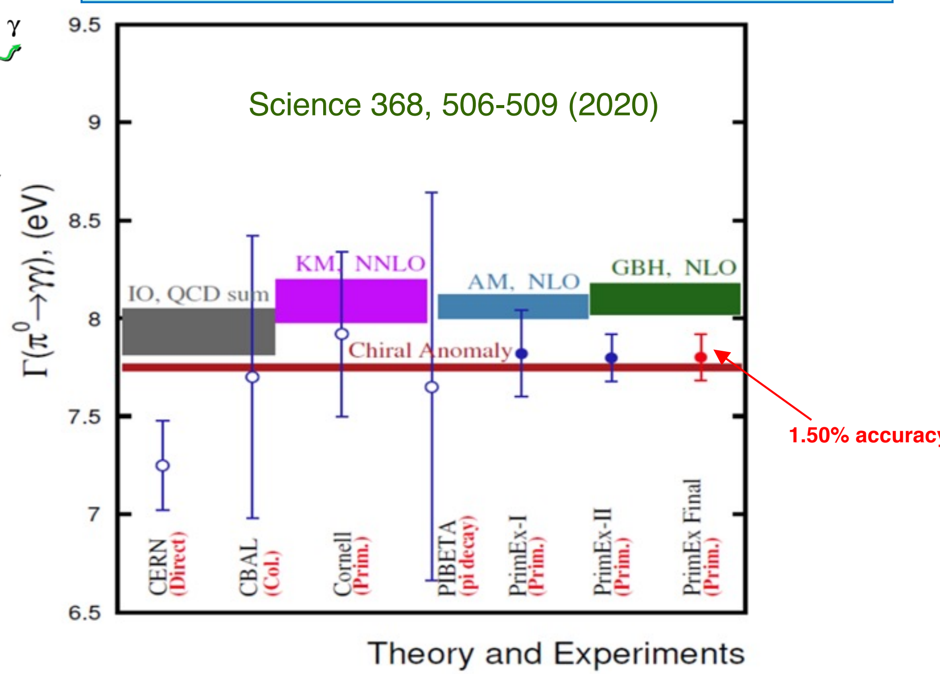

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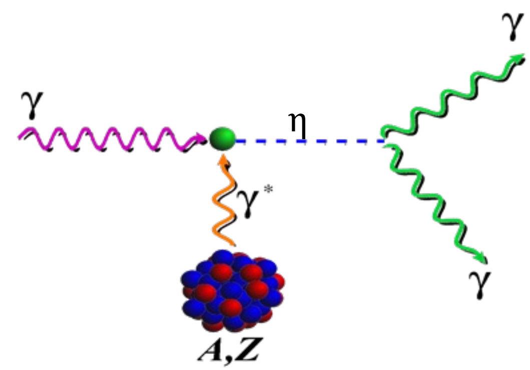
Status of Primakoff Program at JLab 6 & 12 GeV (cont.)

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

Input to Physics:

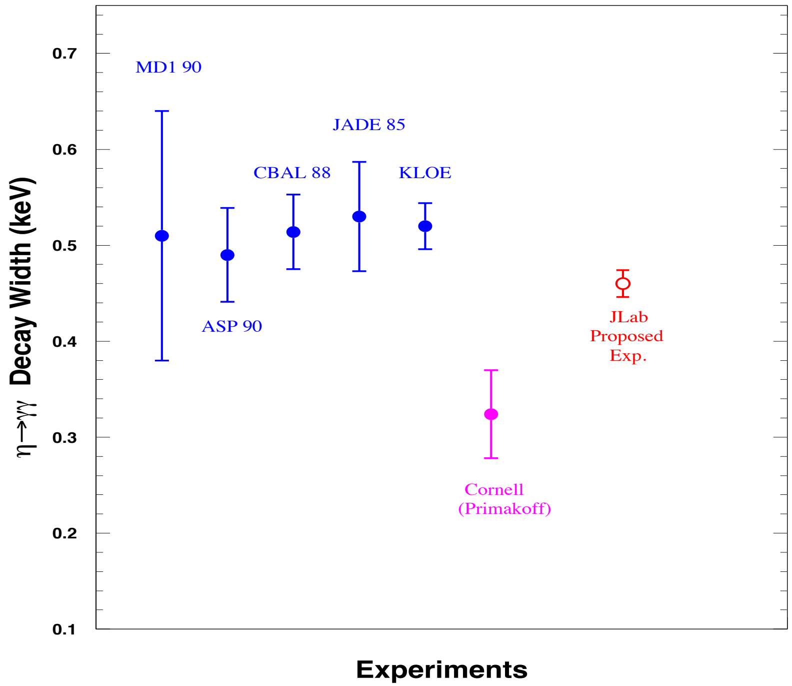
- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g\text{-}2)_\mu$

On-Going PrimEx-eta experiment

- 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:

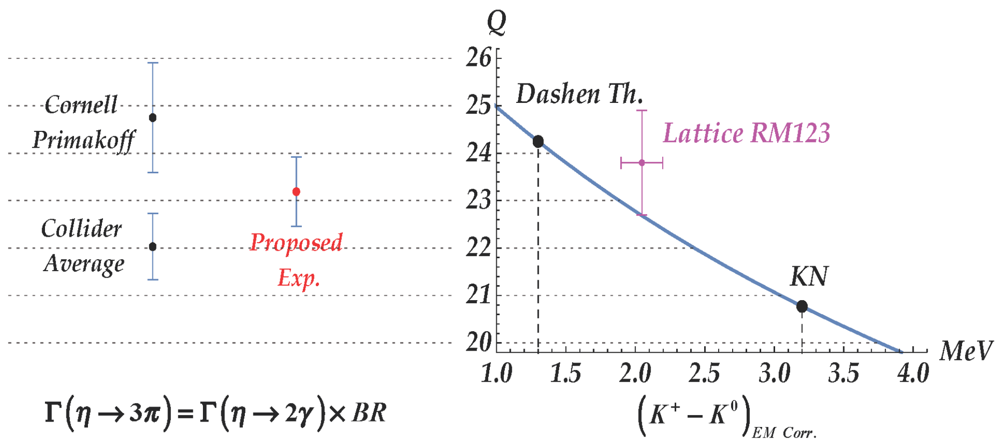


- **Extract η-η' mixing angle**
- **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**
- **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

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

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



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

Phys. Rept. 945 (2022) 1-105

Precision Determination Light Quark Mass Ratio

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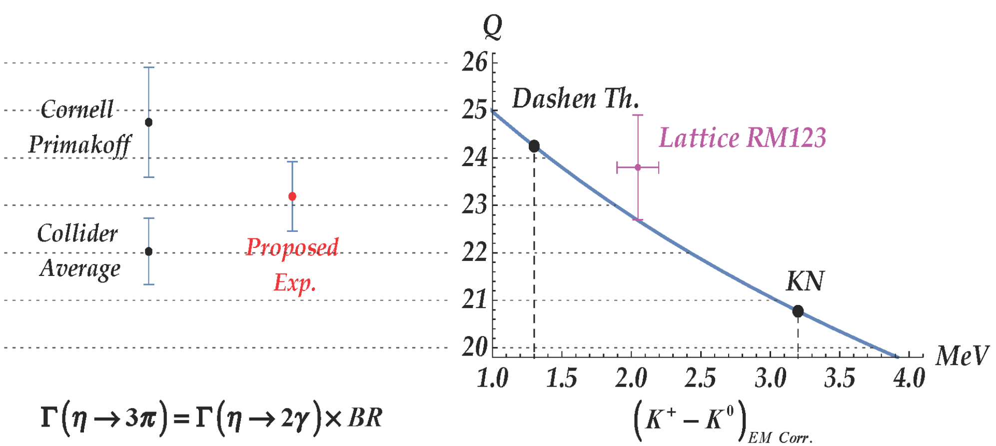

$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to 2\gamma) \times BR$

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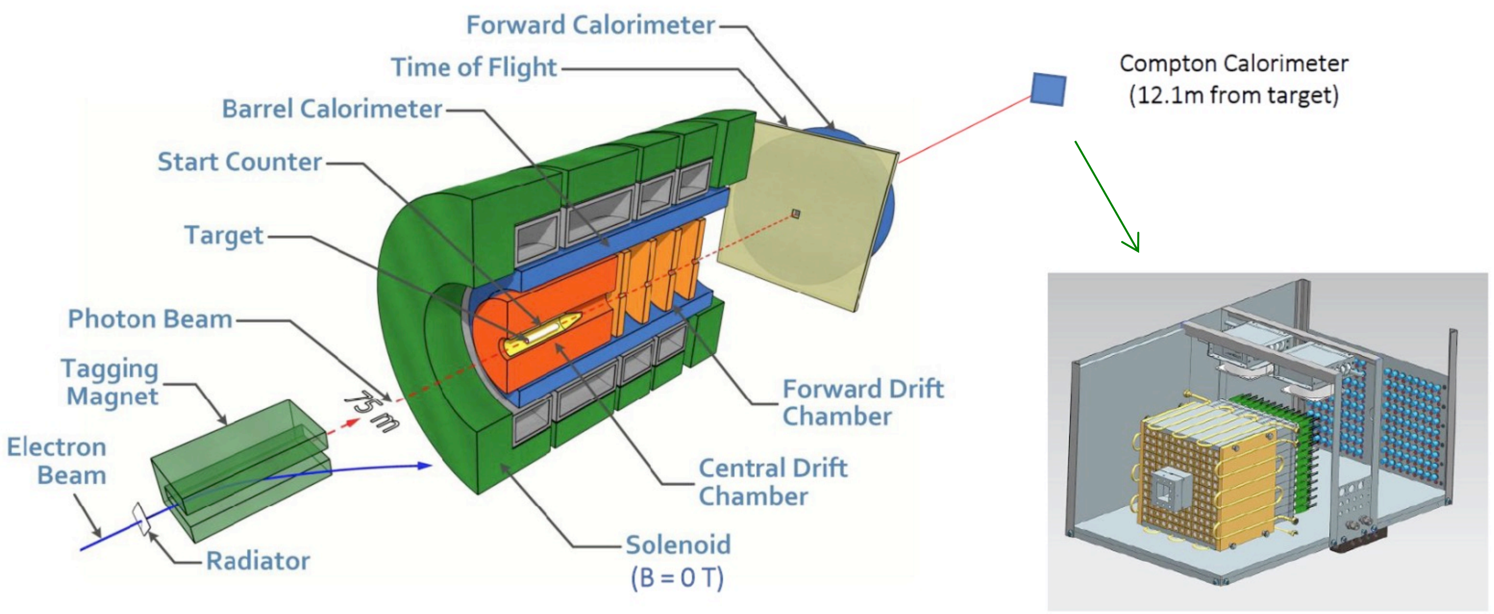
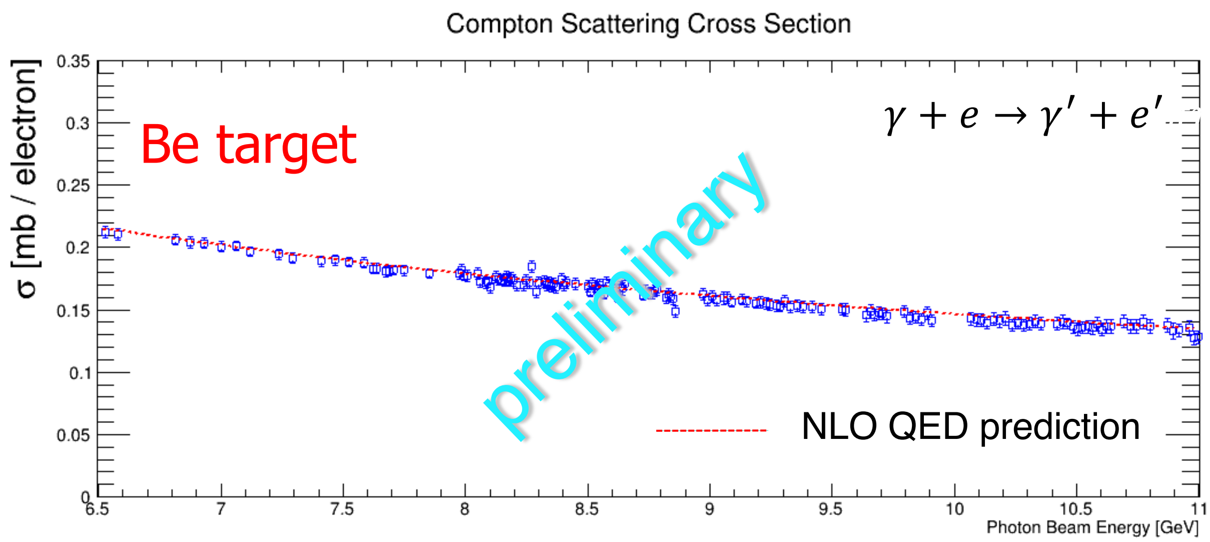
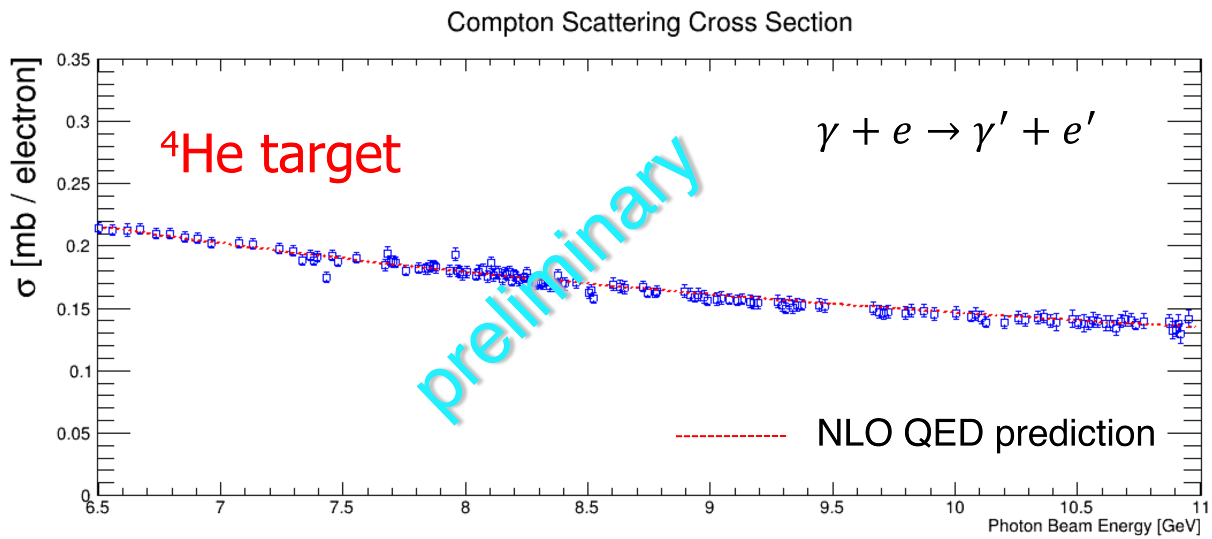
PrimEx-eta Experiment on $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D



- 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.

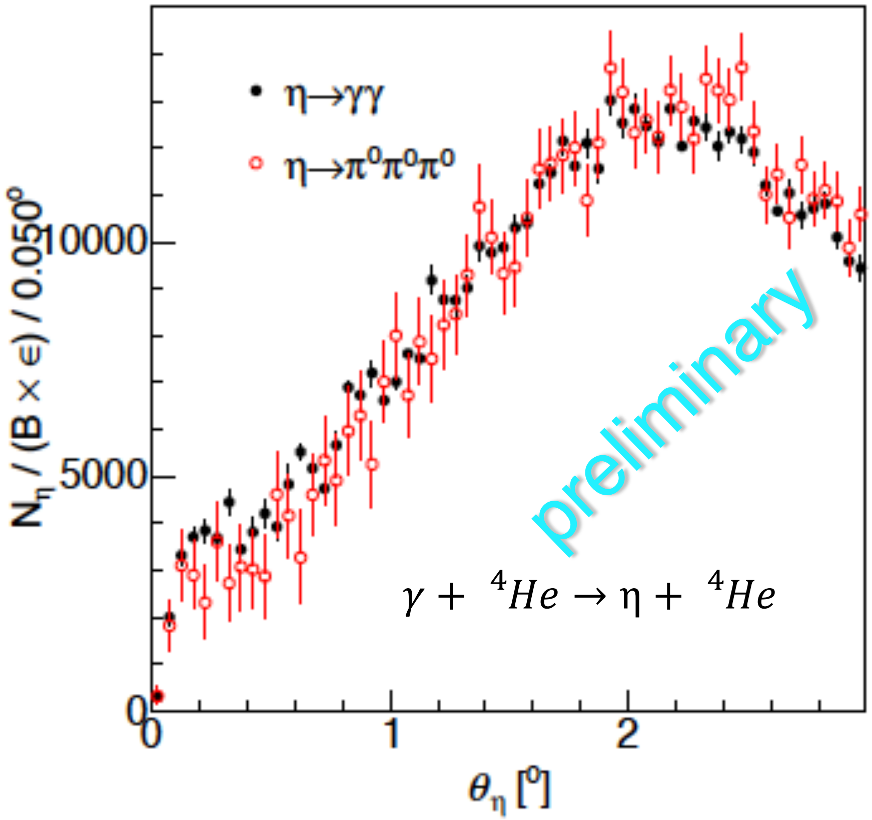
Control Systematics with Compton Scattering

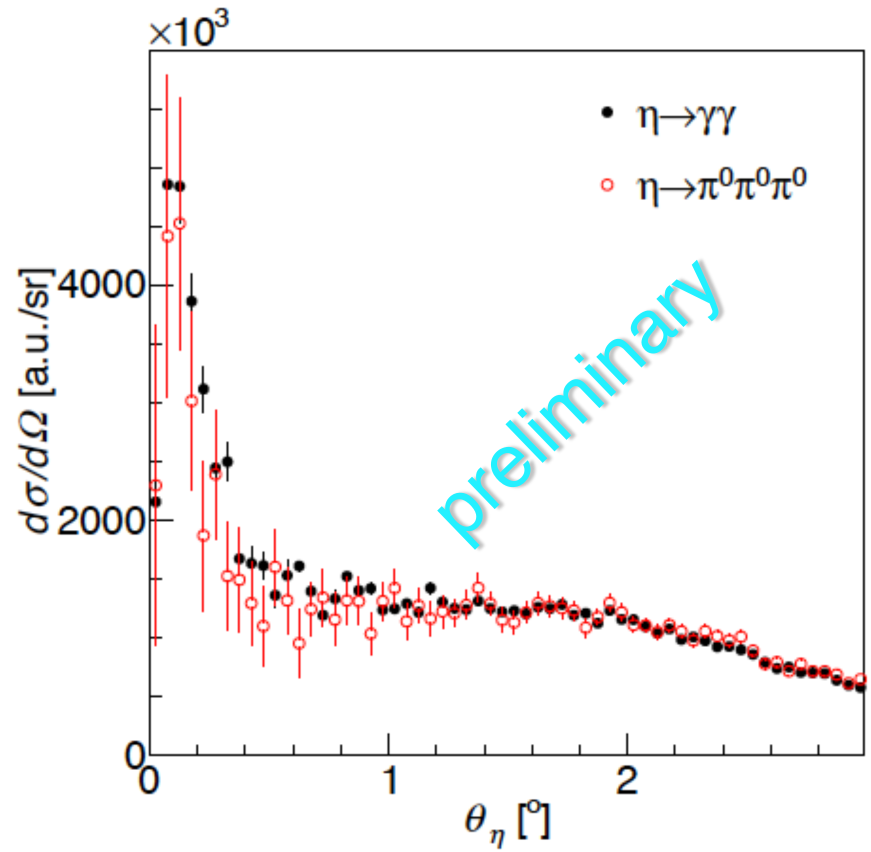




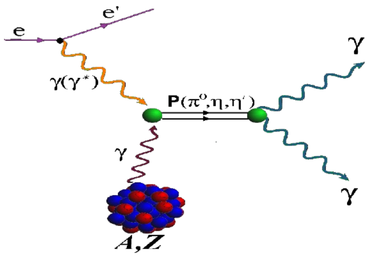
Preliminary Results on the η Distributions

Normalized η Yield
(phase III data)

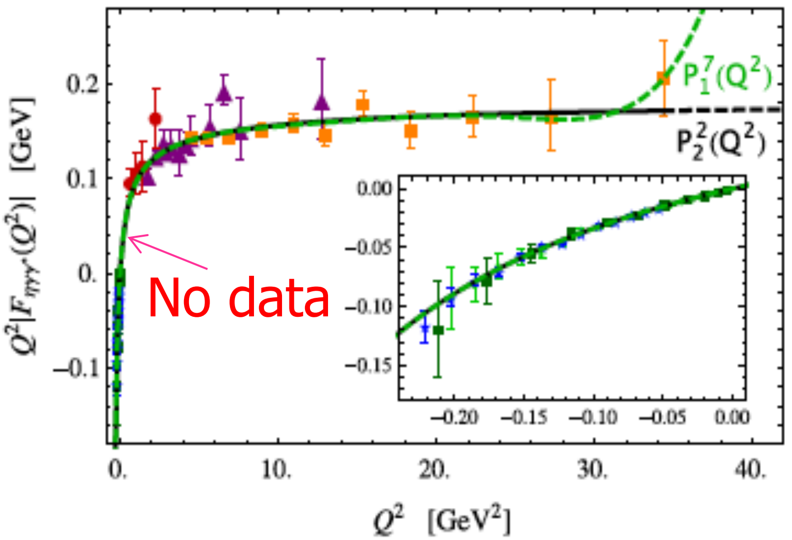




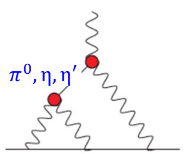
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

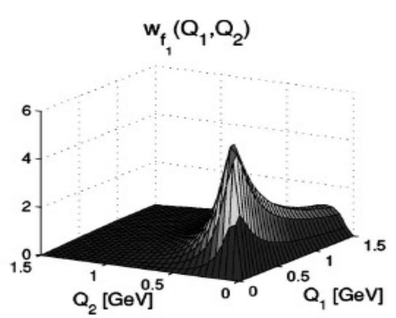


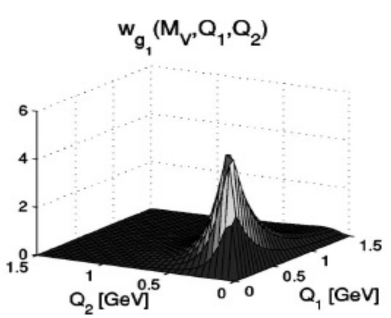
- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^* P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



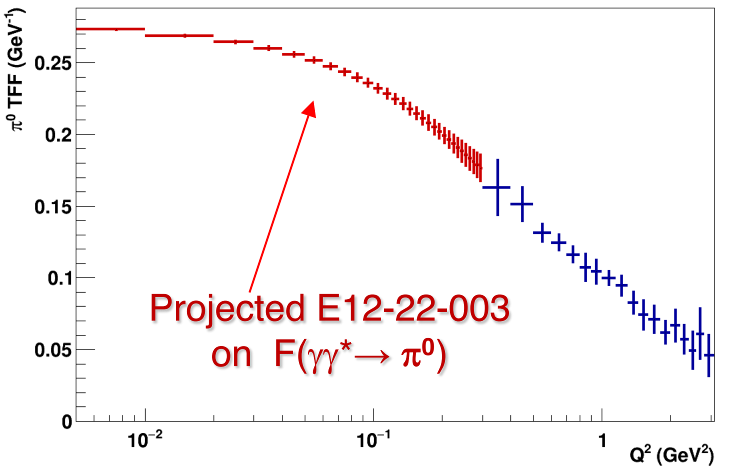
- Input for hadronic light-by-light calculations in muon (g-2)







Phys.Rev.D65,073034



New opportunities with JLab 22 GeV Upgrade

1. The first π^0 Primakoff production off an electron target.

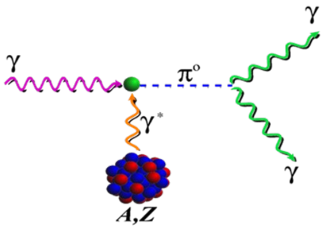
2. Improve the precisions of η/η' Promakoff production off nuclear targets.

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:

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

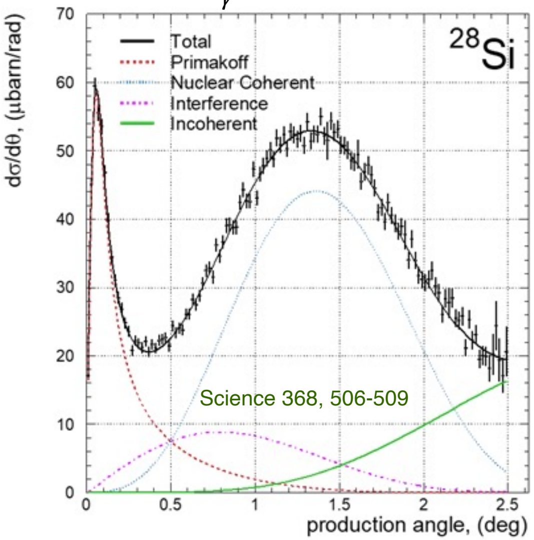
Advantages of the π^0 Primakoff Production off an Electron

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



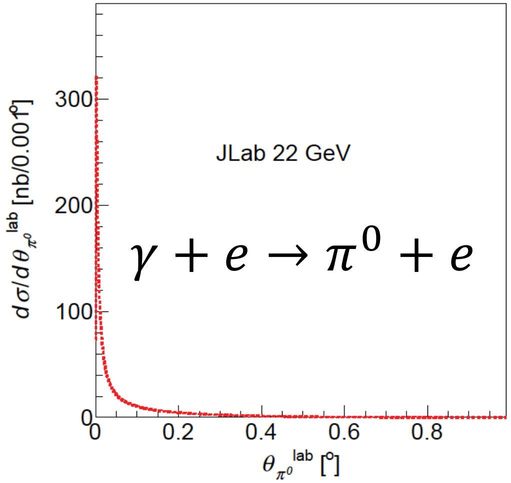
$$\frac{d\sigma_{\text{Pr}}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$

E_γ: 4.45-5.30 GeV



Advantages of an electron target:

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



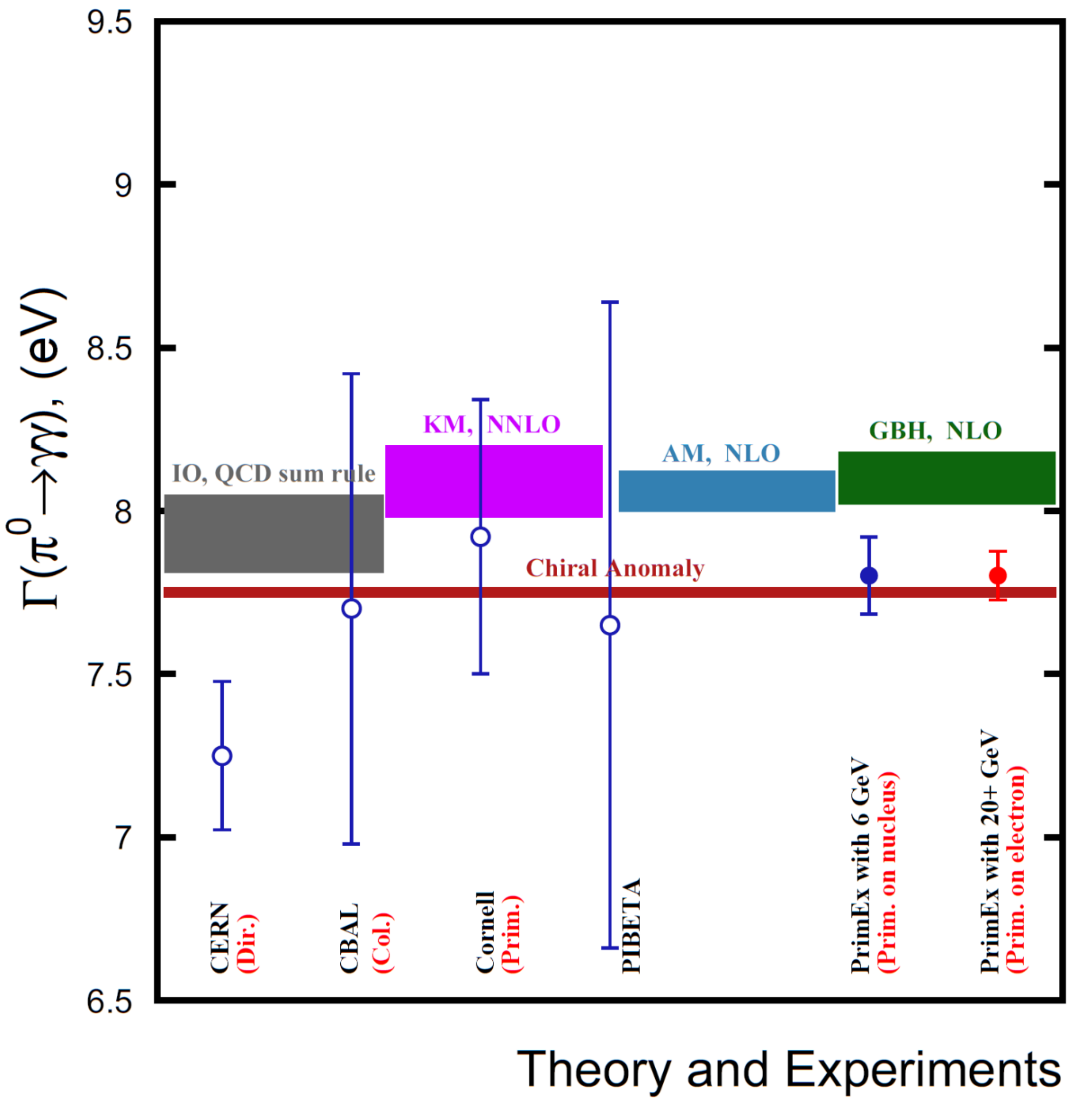
$$\frac{d\sigma_{\text{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

Main challenges for the nuclear target:

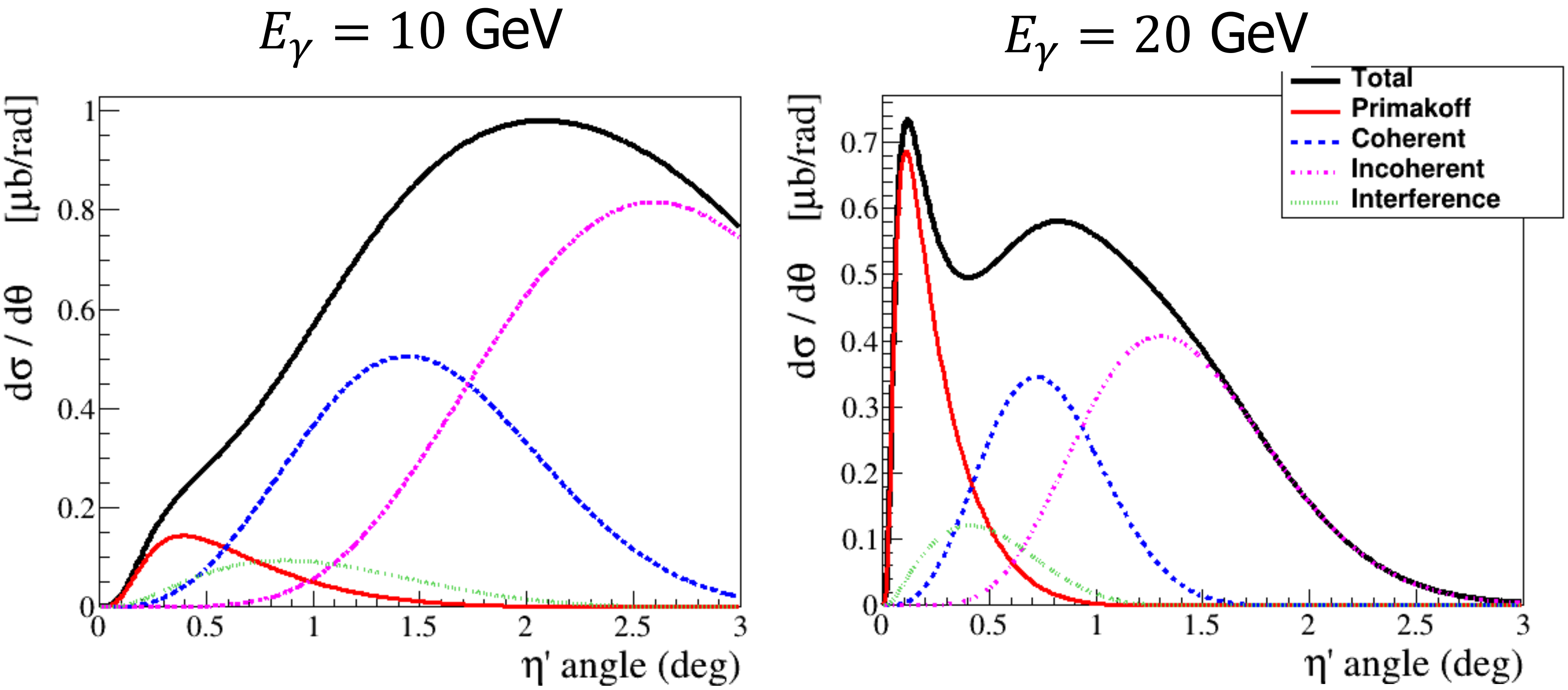
- Nuclear backgrounds
- Nuclear effects
- No recoil detection

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

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

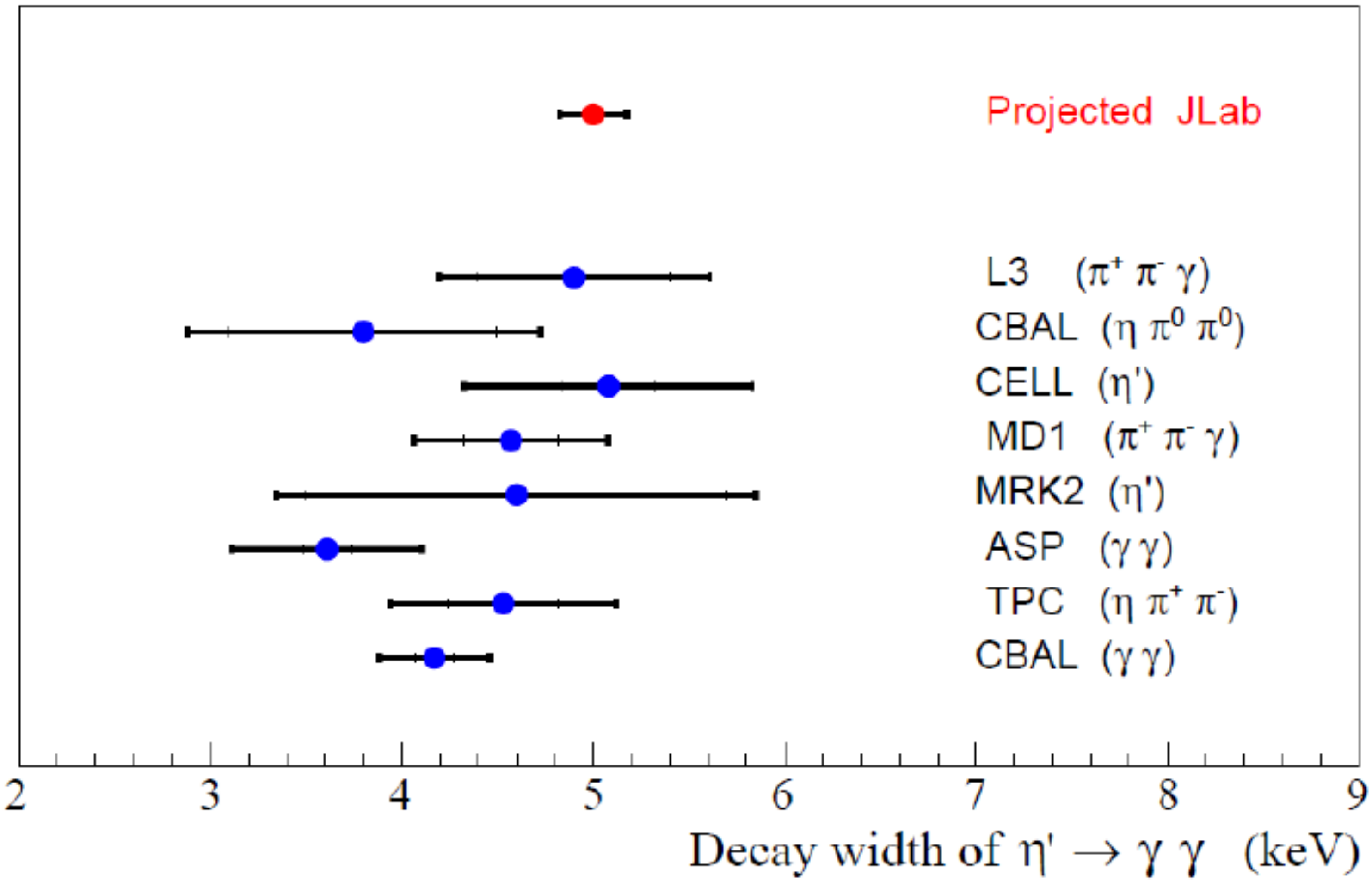


Improve Primakoff Measurements of η/η' with nuclear targets

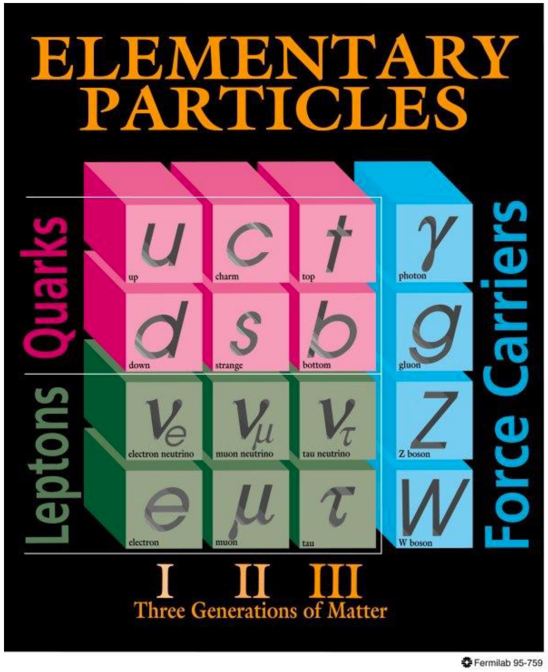


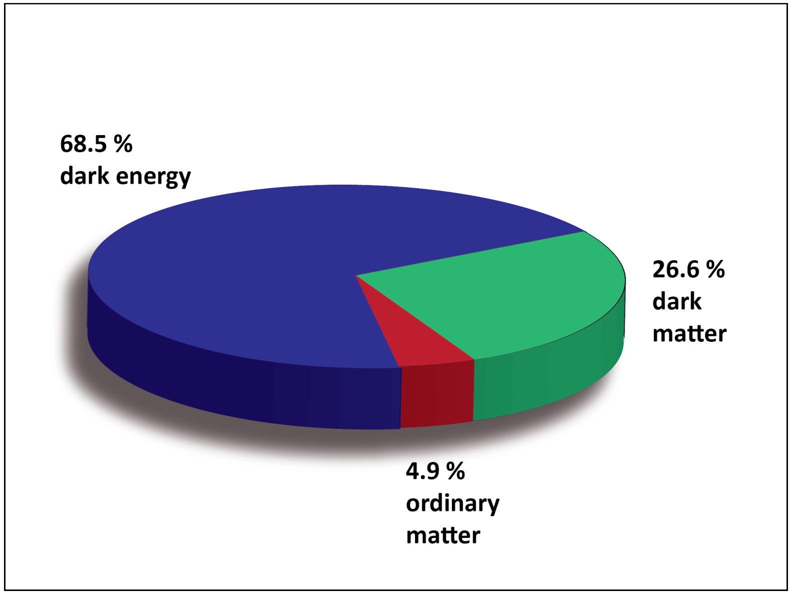
$$\gamma + {}^4He \rightarrow \eta' + {}^4He$$

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



BSM Physics in Dark Sector

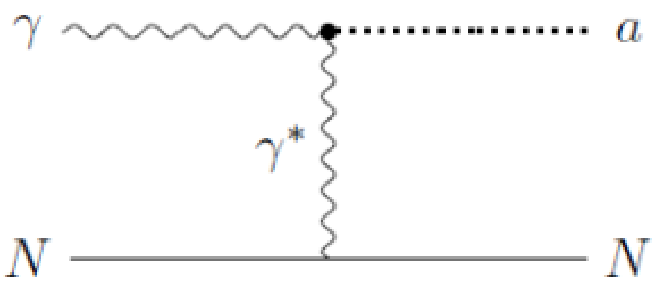




Dark Sector

- 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



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

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

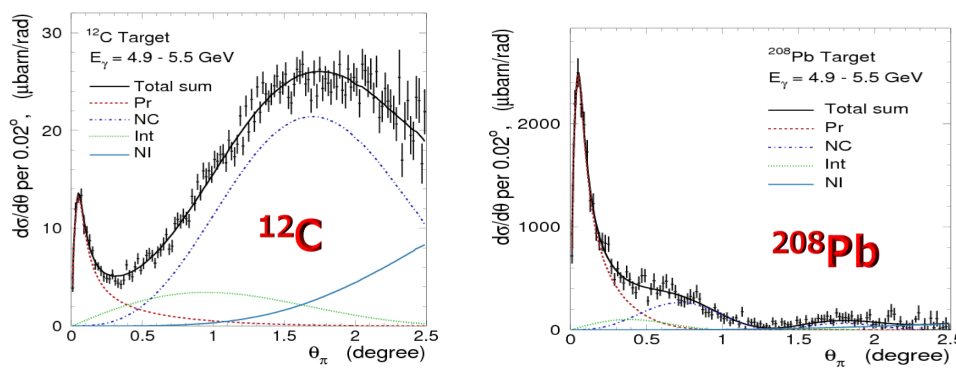
Favorable experimental condition:

- A high energy beam
- A high Z nuclear target

The Primakoff signal dominates in the forward angles

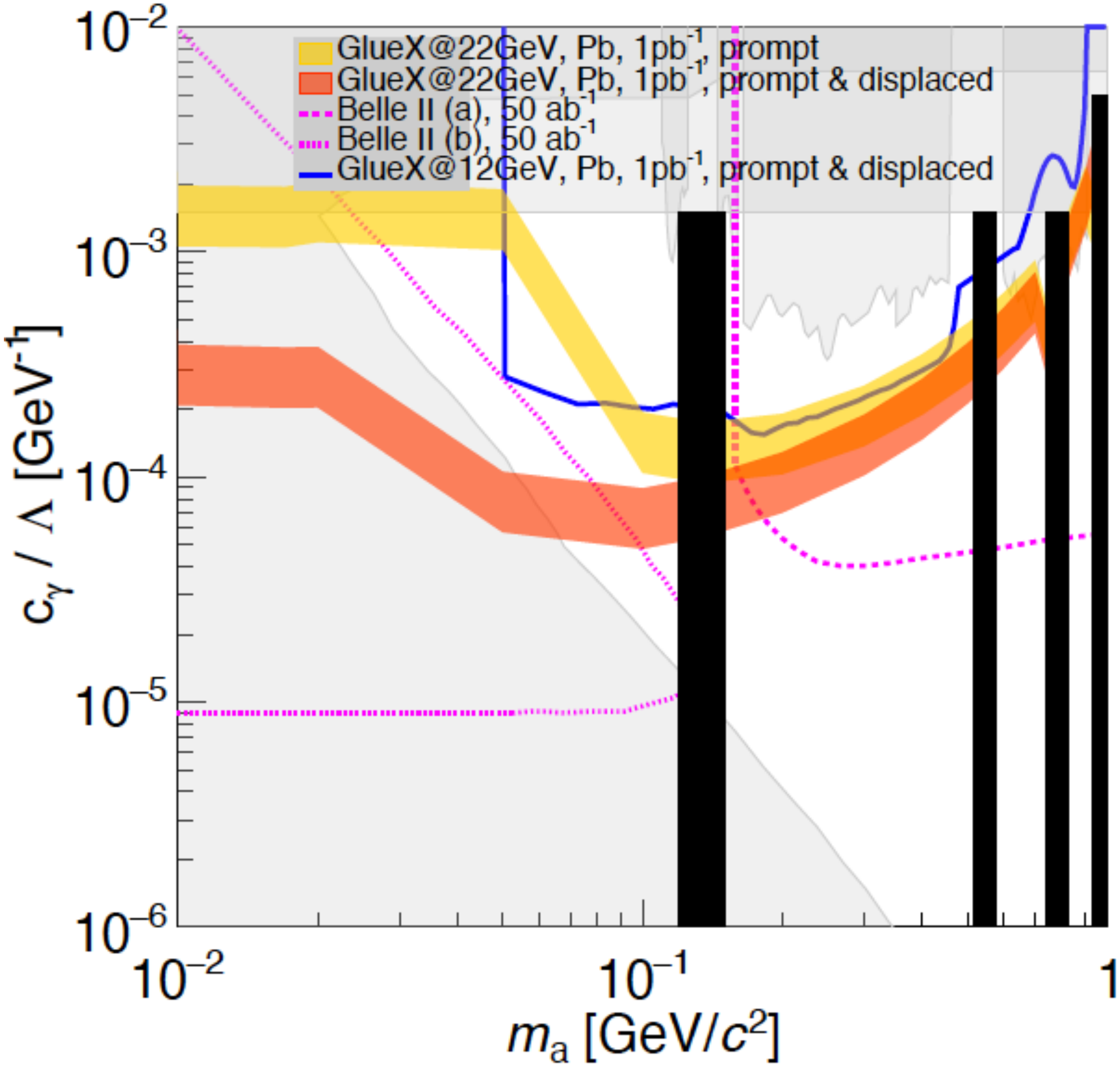
↓

Minimizing the QCD backgrounds



PrimEx I

Projected Reach for a ALP at JLab 22 GeV



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

$$a \rightarrow \gamma\gamma$$

Summary

- The distinguishable features of Primakoff effect make it a great experimental tool for SM 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 $F(\pi^0 \to \gamma^*\gamma)$ 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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