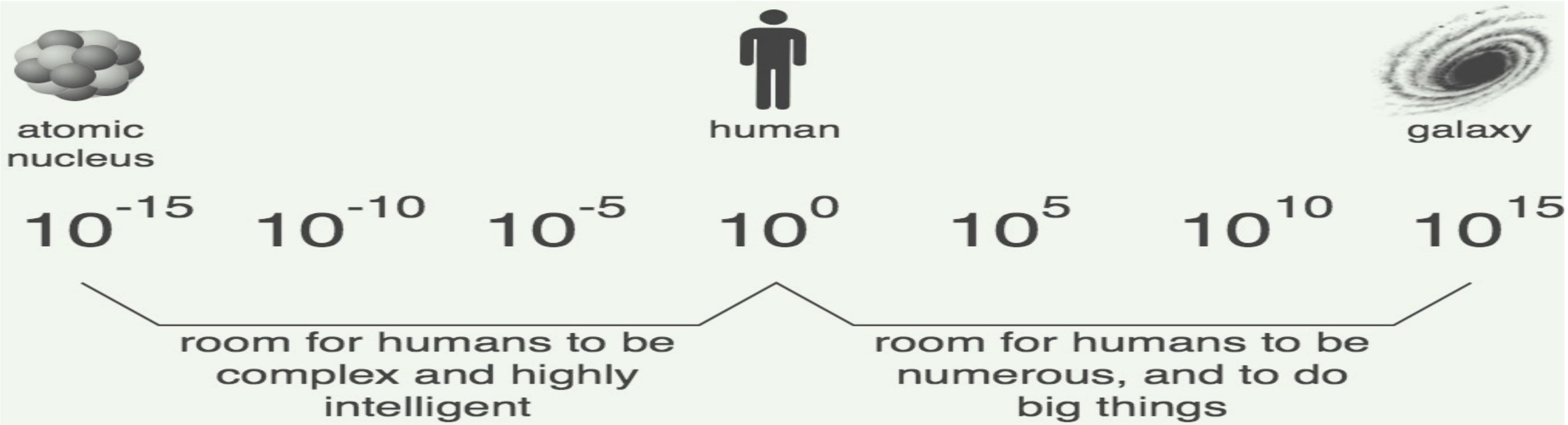
Probe Fundamental Symmetries and BSM Physics via the Primakoff Effect

Liping Gan
University of North Carolina Wilmington

Outline

- Introduction
- Current JLab Primakoff program at 6 & 12 GeV
- New opportunities with future 20-24 GeV upgrade
- Summary

Challenges in Physics



Confinement QCD

- Nature of QCD confinement
- Its relationship to the dynamical chiral symmetry breaking

New physics beyond the Standard Model (SM)

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

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

What is the Primakoff Effect?

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

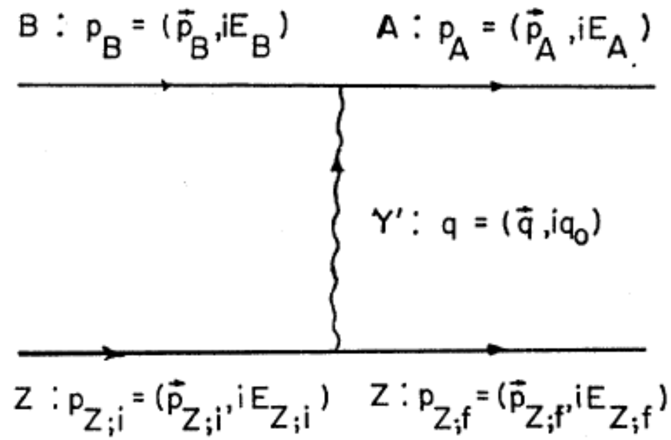
H. PRIMAKOFF†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

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, $\mathbf{E}$, $\mathbf{H}$, representable in the form:

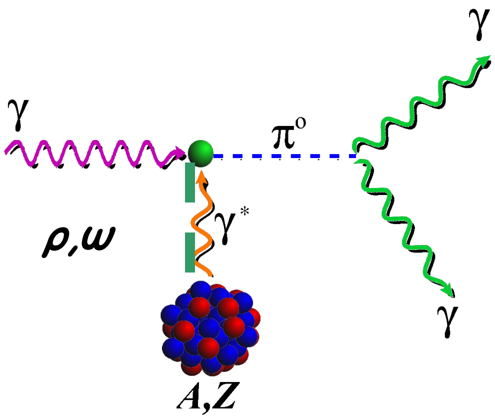
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

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),

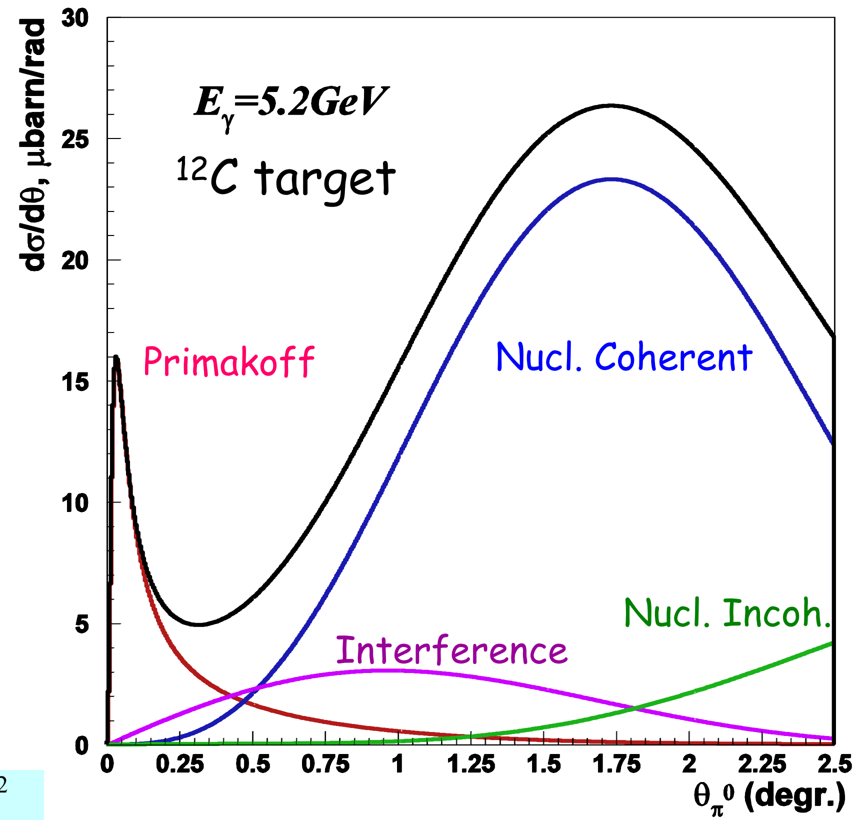


H. Primakoff, Phys. Rev. 81, 899 (1951)

Distinguishable Features of Primakoff Effect



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



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

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

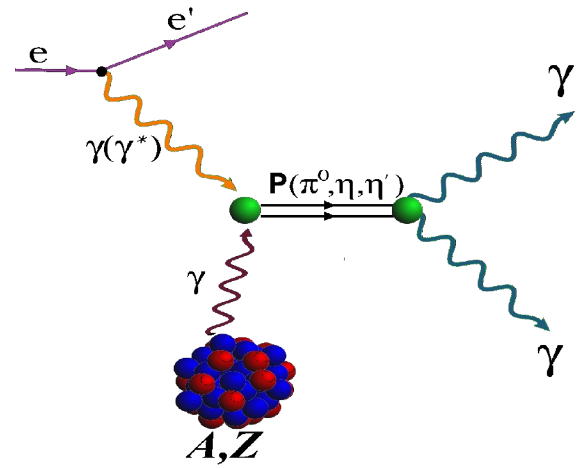
$$\boxed{\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \quad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}}$$

- Coherent process

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

Primakoff Program at JLab 6 & 12 GeV with Nuclear Targets

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:

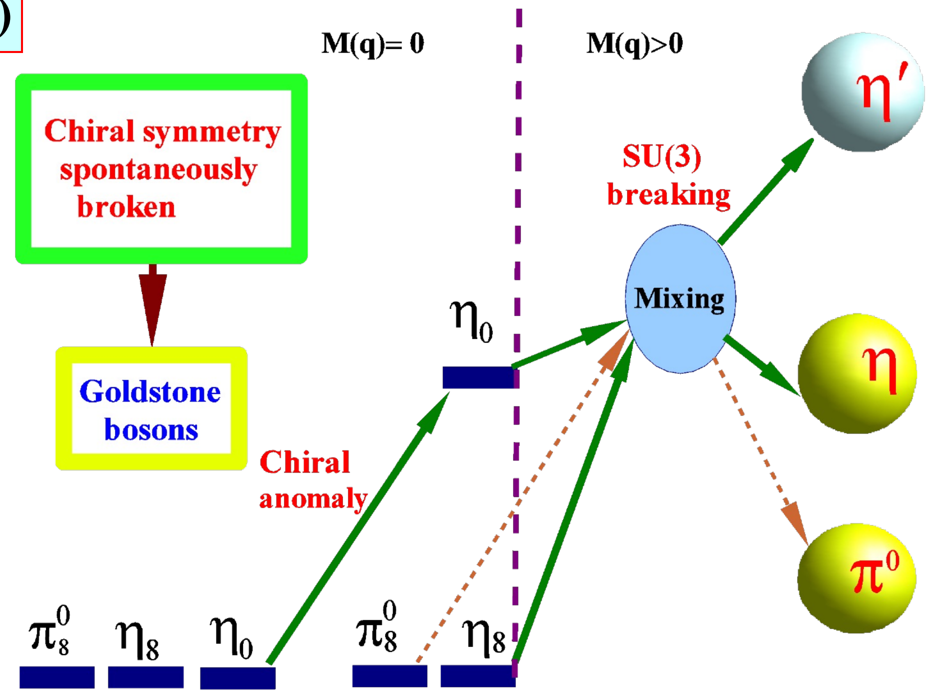
- π^0, η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$

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.

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:

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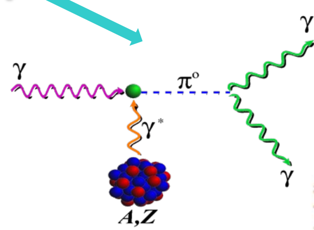
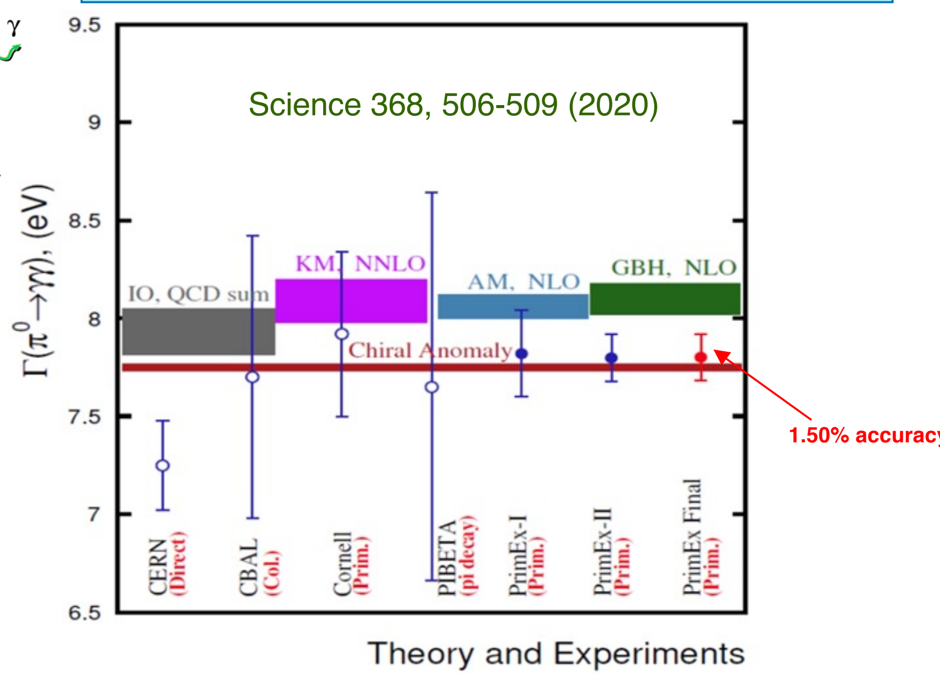


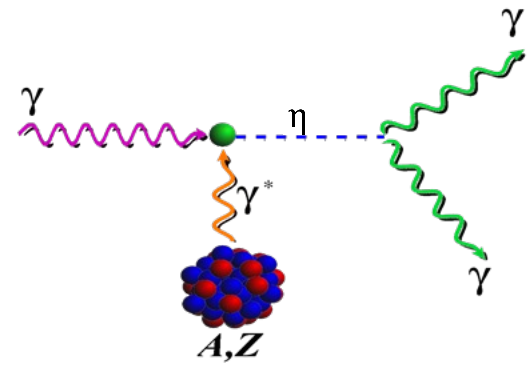


Input to Physics:

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

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
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Input to Physics:

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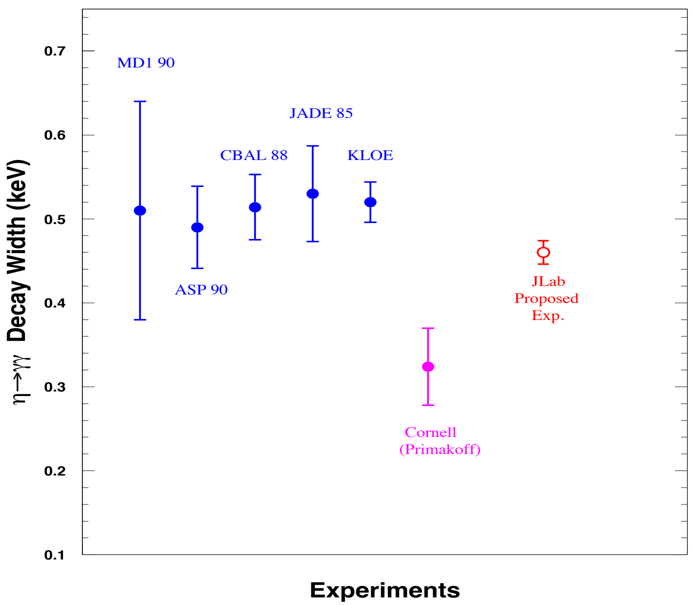
On-Going PrimEx-eta experiment

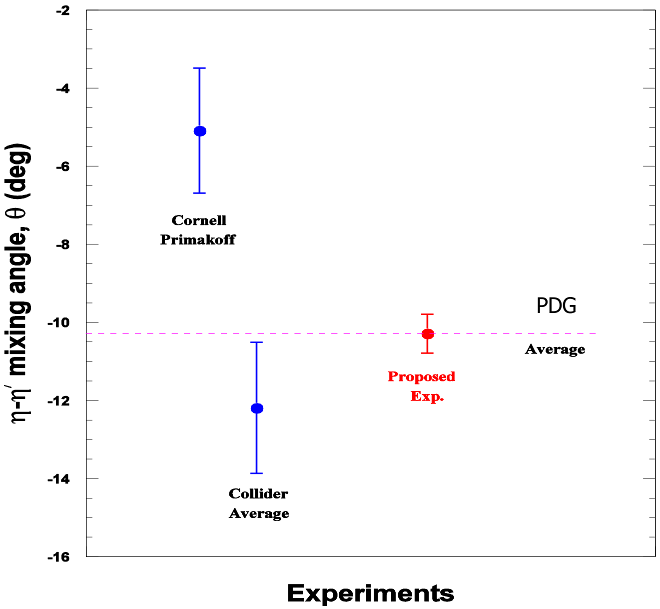
- Two data sets were collected in 2019 and in 2021.
- The third run started on Aug 18 until Dec 19, in 2022.

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

1. **Resolve long standing discrepancy between previous collider and Primakoff measurements:**



2. **Extract η-η' mixing angle:**



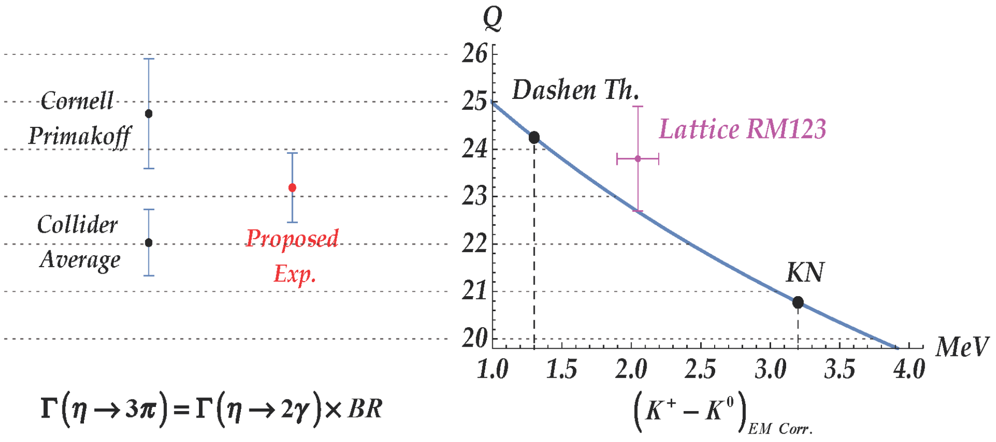
3. **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**

4. **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

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

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



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

Phys. Rept. 945 (2022) 1-105

Precision Determination Light Quark Mass Ratio

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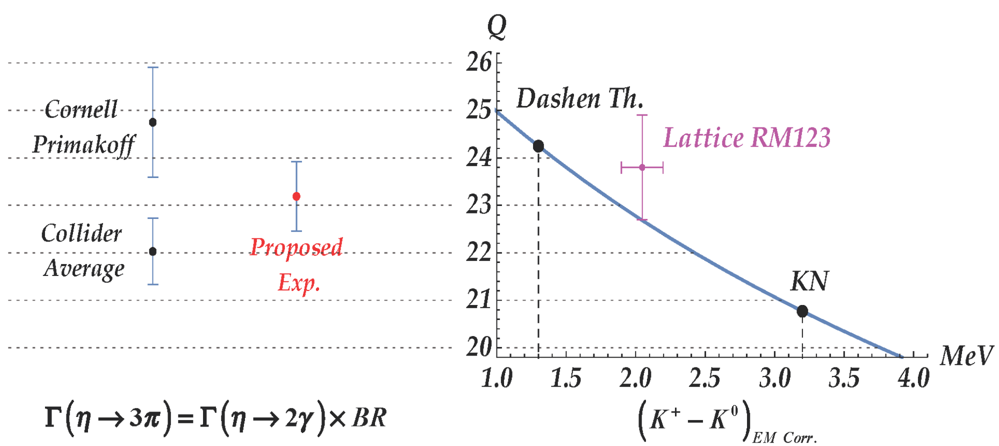

$\Gamma(\eta \rightarrow 3\pi) = \Gamma(\eta \rightarrow 2\gamma) \times BR$

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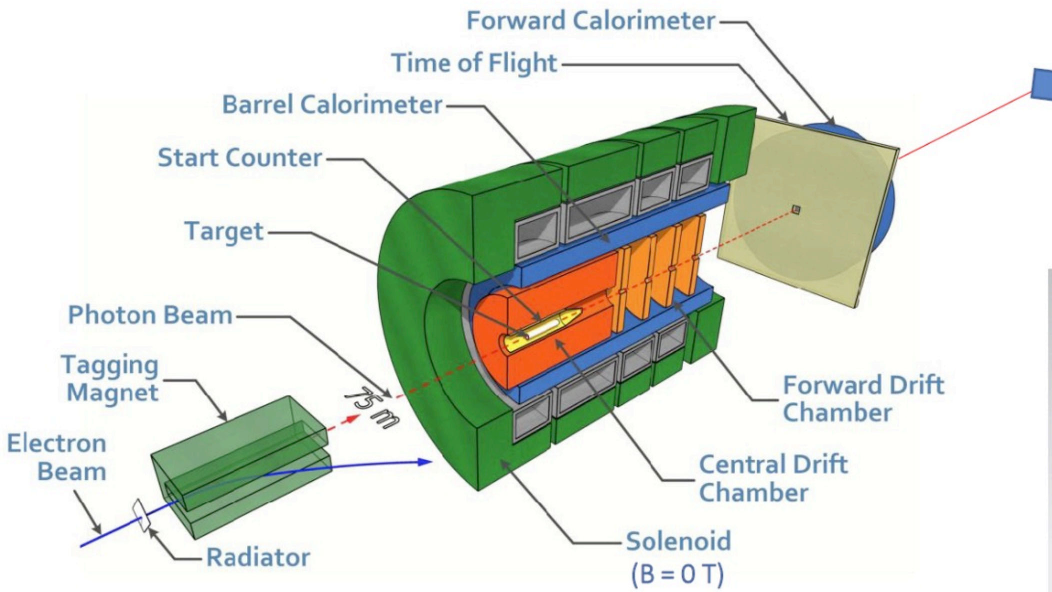
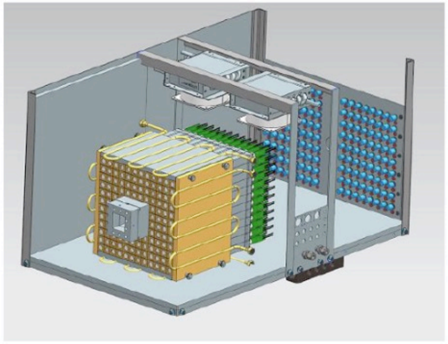
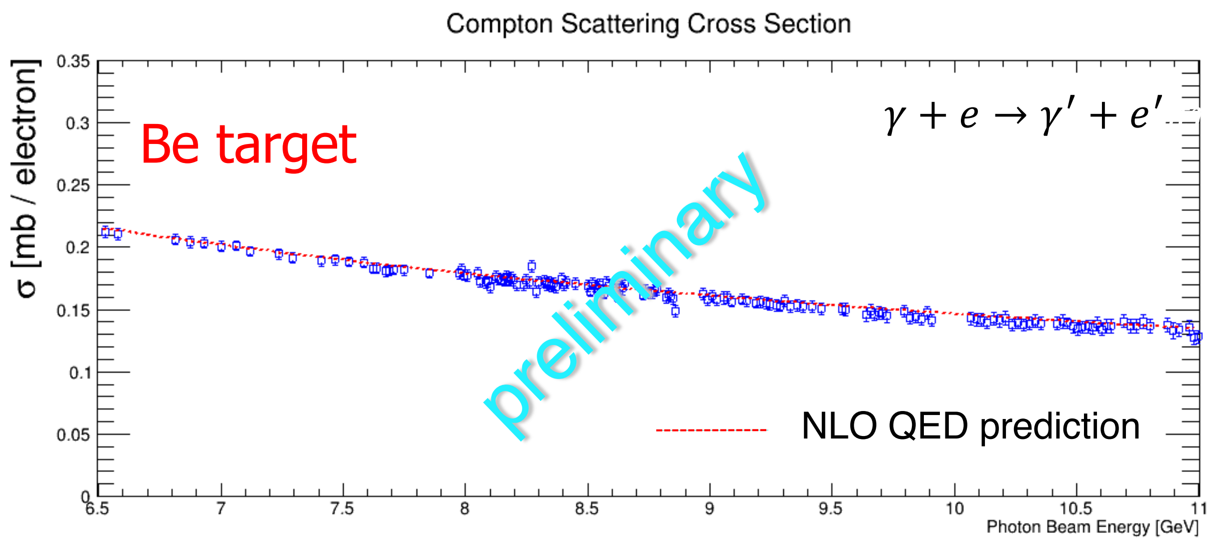
PrimEx-eta Experiment on $\Gamma(\eta\to\gamma\gamma)$ in Hall D

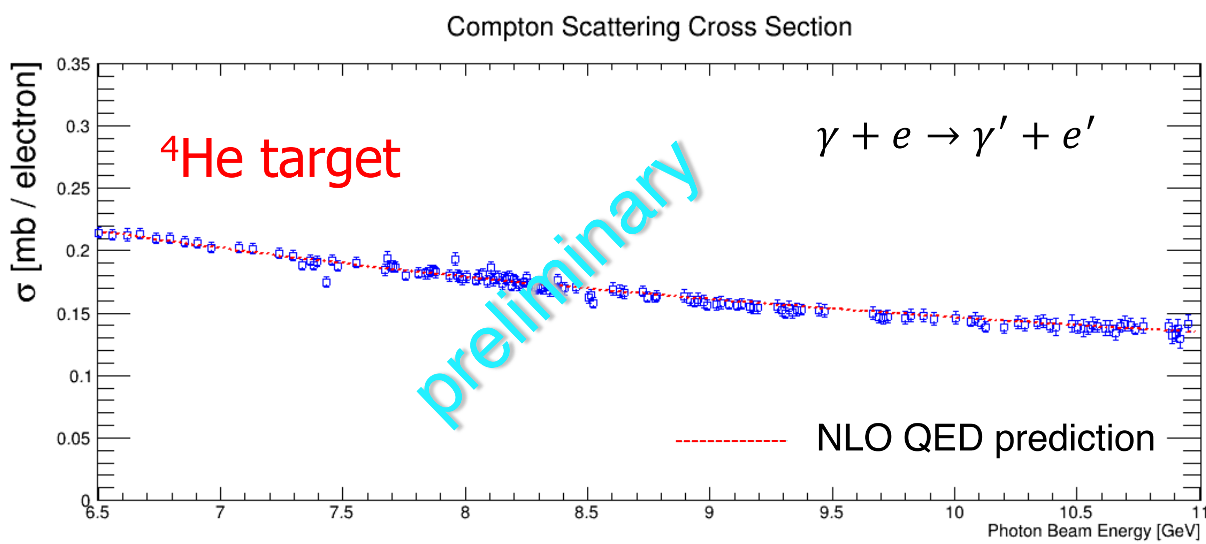




- Tagged photon beam (~8.0-11.7 GeV).
- Pair spectrometer and a TAC detector for the photon flux control.
- Liquid Hydrogen (3.5% R.L.) and ^{4}He targets (~4% R.L.)
- The η decay photons are detected by Forward Calorimeter (FCAL); the charged decay particles of η are detected by the GlueX spectrometer.
- CompCal and FCAL to measure Compton scattering off atomic electron for control of overall systematics.

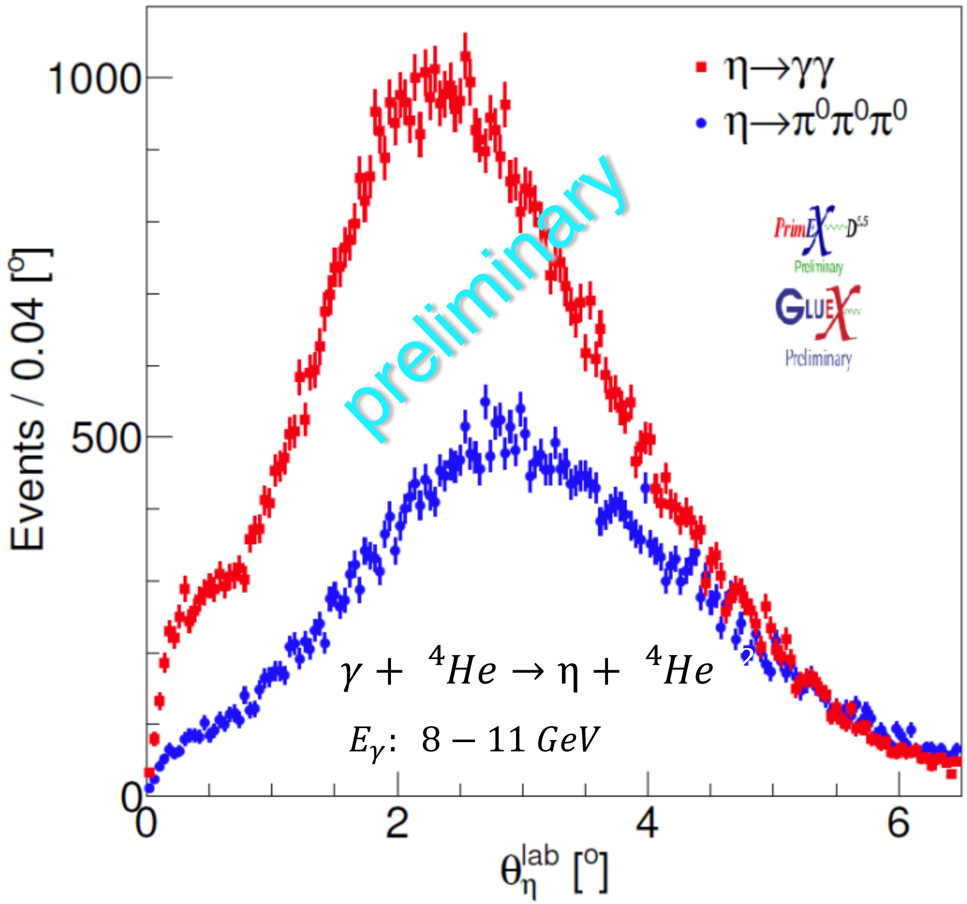
Control Systematics with Compton Scattering



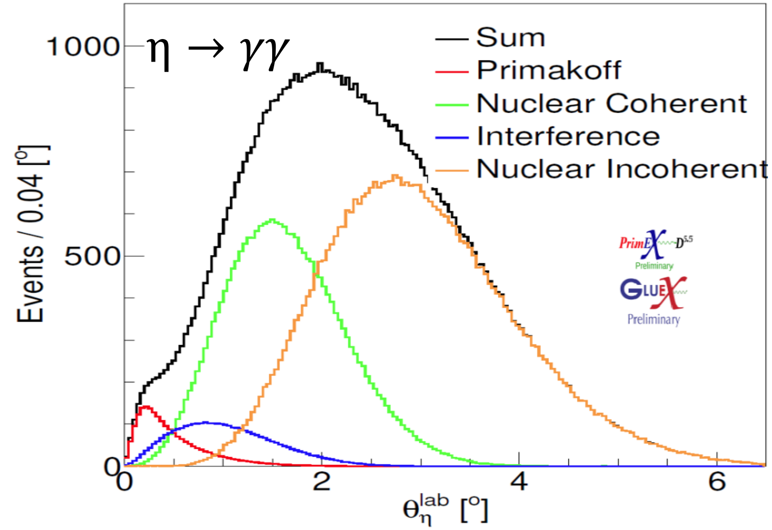


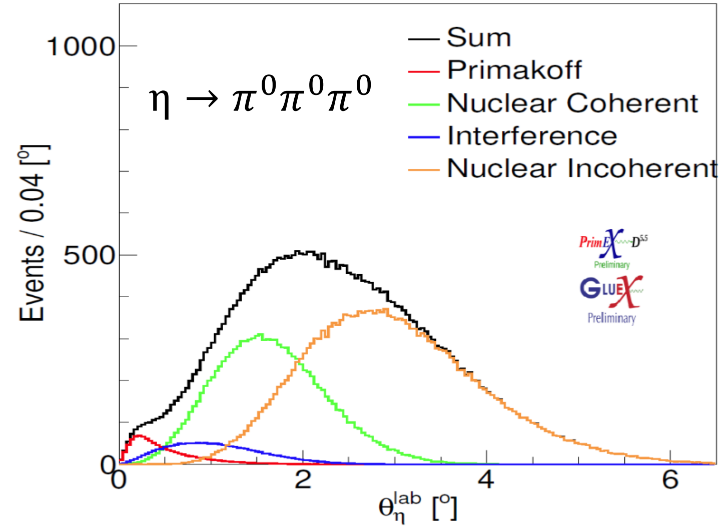
Preliminary Results on the η Yield

η Yield from phase I data:

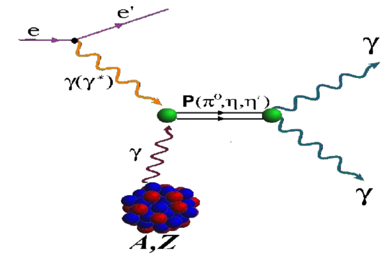


Simulations:

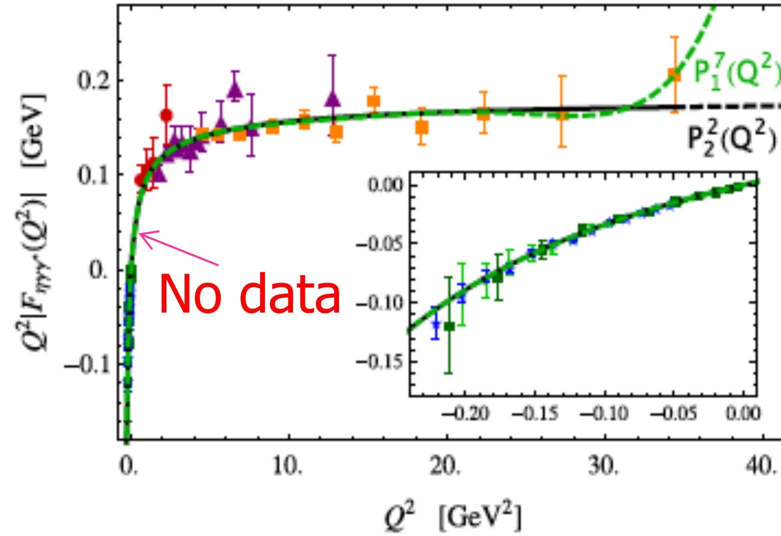




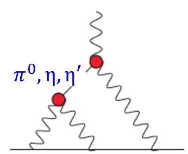
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

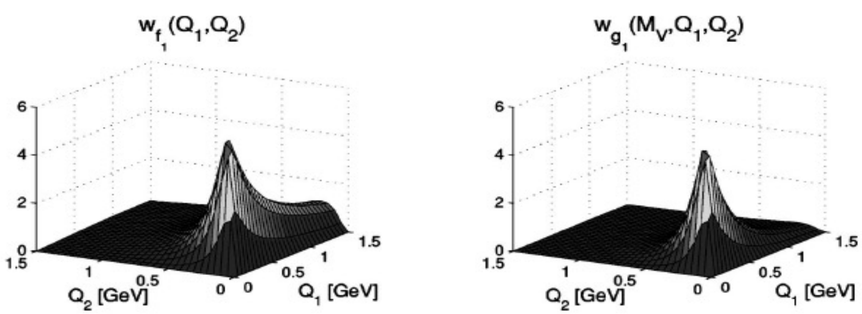


- Direct measurement of slopes
  - Interaction radii:
    $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian

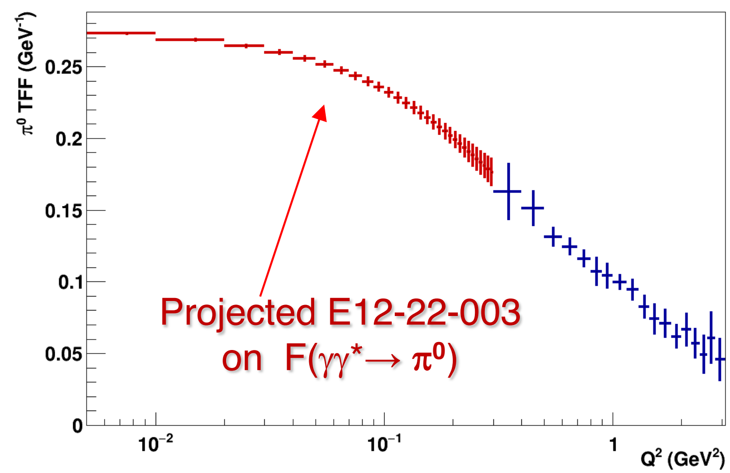


- Input for hadronic light-by-light calculations in muon (g-2)





Phys.Rev.D65,073034

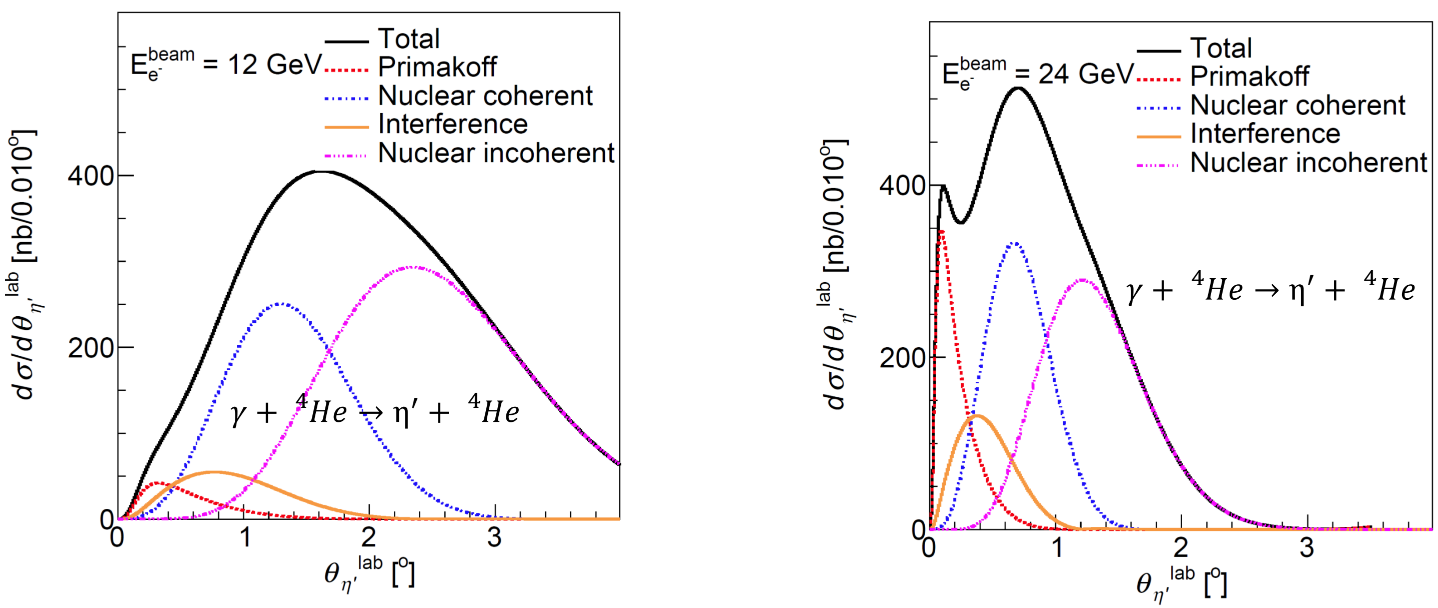


Enhancement with a 24 GeV Beam

Higher Primakoff cross section: $\left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{peak} \propto \frac{E^4}{m^3}$ $\int d\sigma_{\mathrm{Pr}} \propto \frac{Z^2}{m^3}\log(E)$

Better separation of Primakoff from nuclear processes:

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



A 24 GeV beam will significantly enhance the measurements of decay width $\Gamma(\eta'\rightarrow\gamma\gamma)$, the transition form factors $F(\eta\rightarrow\gamma^*\gamma)$ and $F(\eta'\rightarrow\gamma^*\gamma)$.

New opportunities with JLab 24 GeV Upgrade

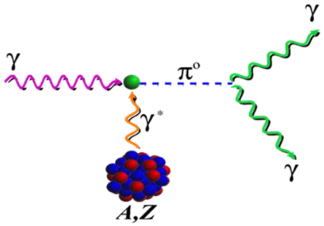
1. Precision measurement of decay width $\Gamma(\pi^0 \to \gamma\gamma)$ and transition form factor $F(\pi^0 \to \gamma^*\gamma)$ via the Primakoff effect off an atomic electron target.

2. 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:

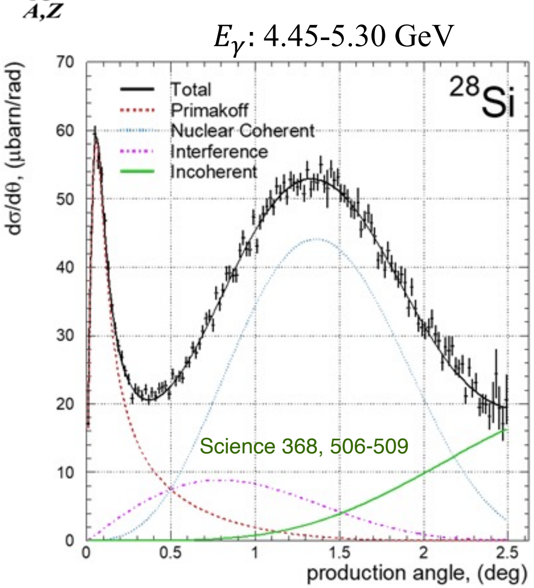
$$H^+H(\varepsilon S + \lambda S^2) \qquad c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$$

Advantages of the π^0 Primakoff Production off an Electron

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

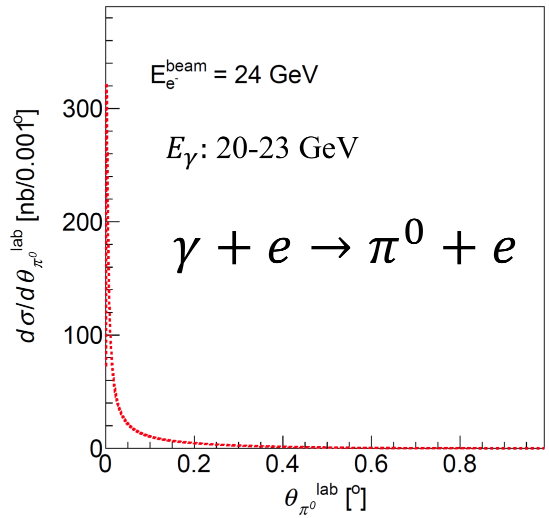


$$\frac{d\sigma_{Pr}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$



Advantages of an electron target:

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



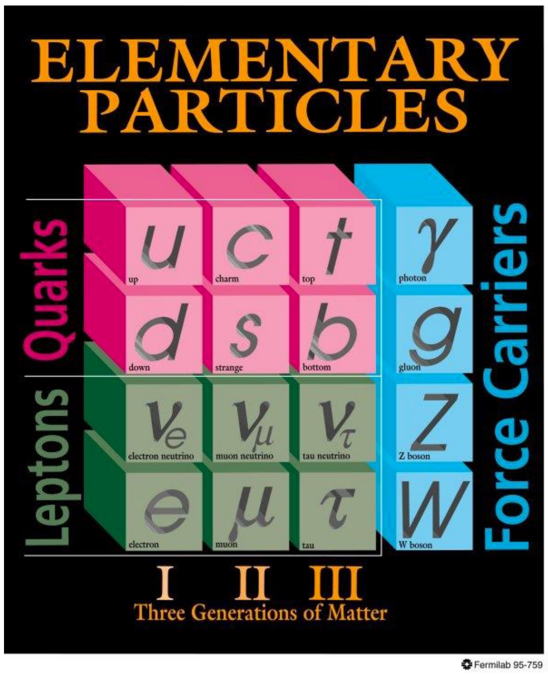
$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

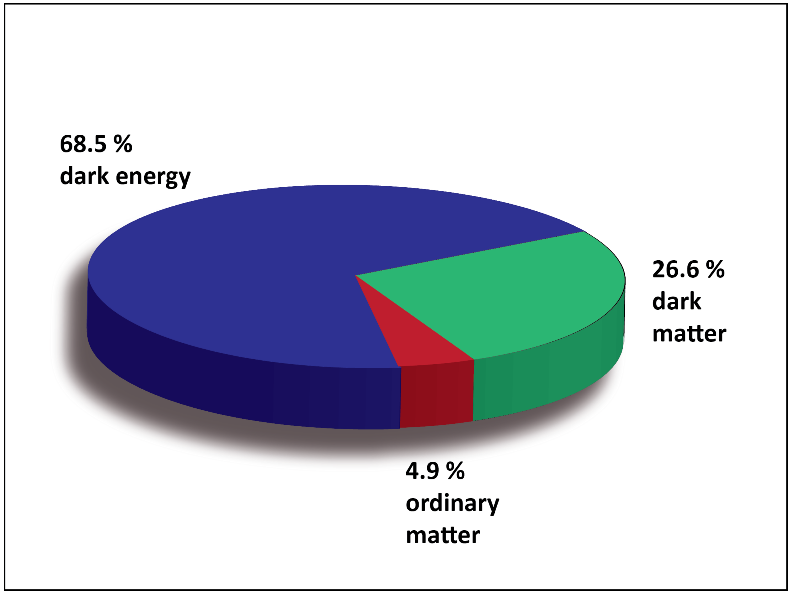
Main challenges for nuclear targets:

- 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

BSM Physics in Dark Sector

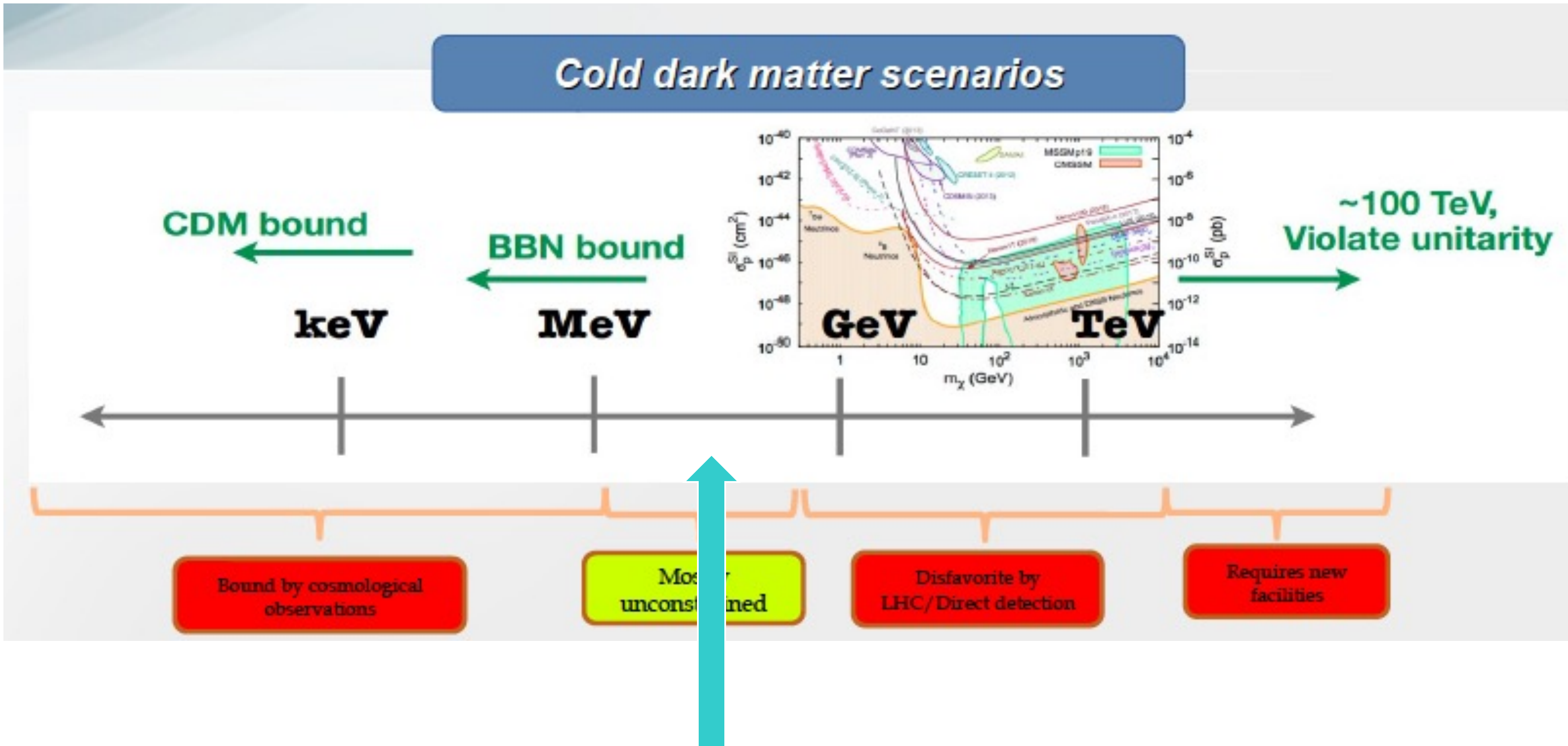




Dark Sector

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

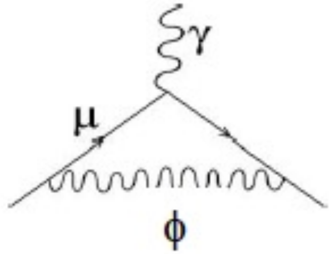
Where to Search for Dark Matter?

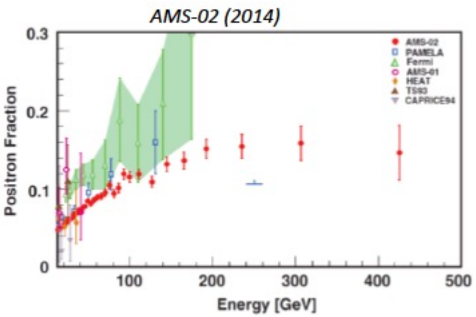


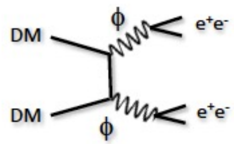
Sub-GeV region represents a good discovery opportunity

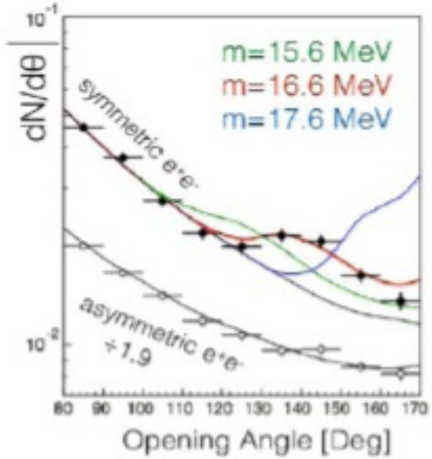
Motivation for sub-GeV New Physics

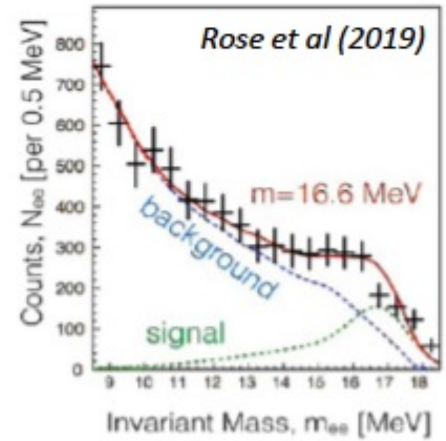
$(g\text{-}2)_\mu$ anomaly
Pospelov (2008)



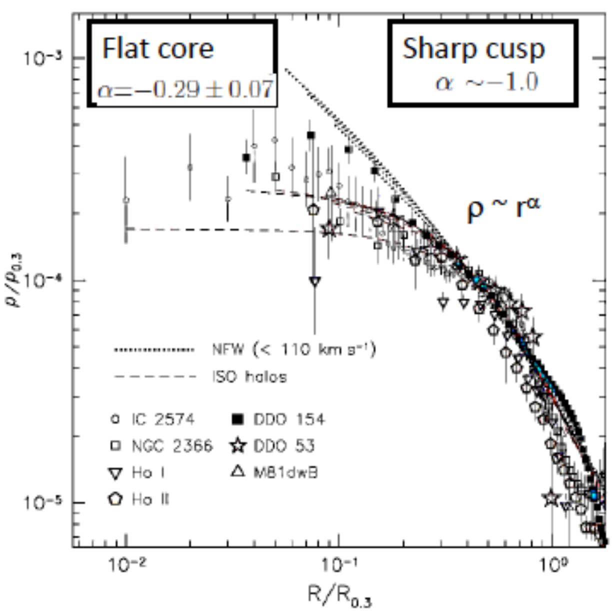


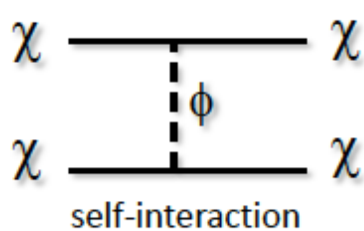


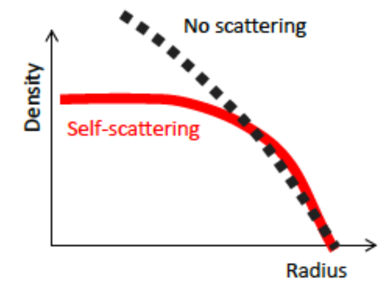




THINGS (dwarf galaxy survey) - Oh et al. (2011)



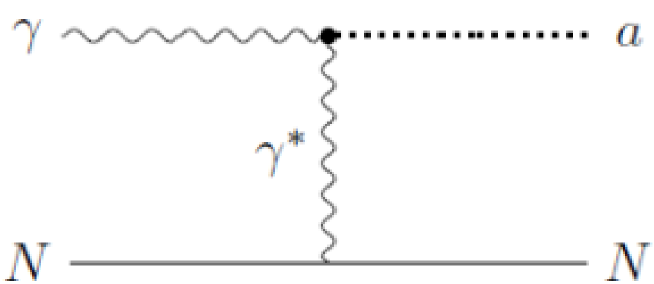




Self-interactions solve core-vs-cusp
Particles get scattered out of dense halo centers

If these anomalies are interpreted in terms of new physics, all point to new forces with mediator particles in the MeV–GeV mass range!

Search for New Scalar and Pseudoscalar via Primakoff Effect



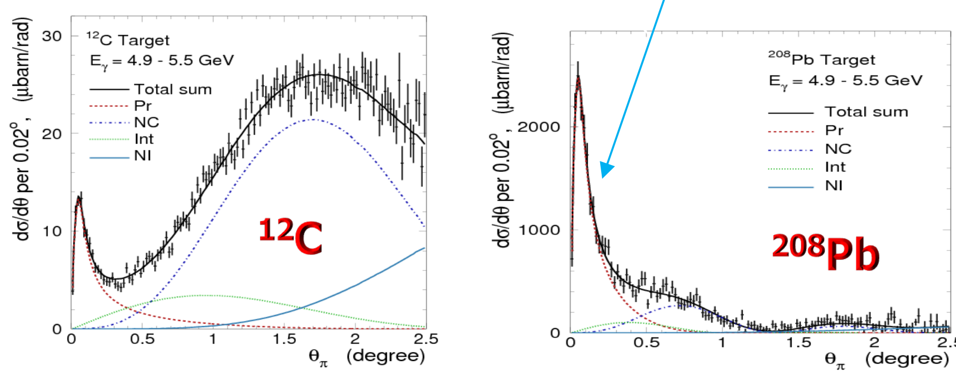
Favorable experimental condition:

- A high energy beam
- A high Z nuclear target

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

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

Improve by more than two-orders of magnitudes with a 20+ GeV beam



Search for resonant peaks of $e^+e^-, \gamma\gamma, \pi\pi, \pi\pi\pi$ in the forward angles where the Primakoff effect dominates

PrimEx I

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 $\Gamma(\eta \to \gamma\gamma)$ is nearly completed
  - ✓ The future 24 GeV beam will greatly enhance measurements of more massive particles, such as η'.

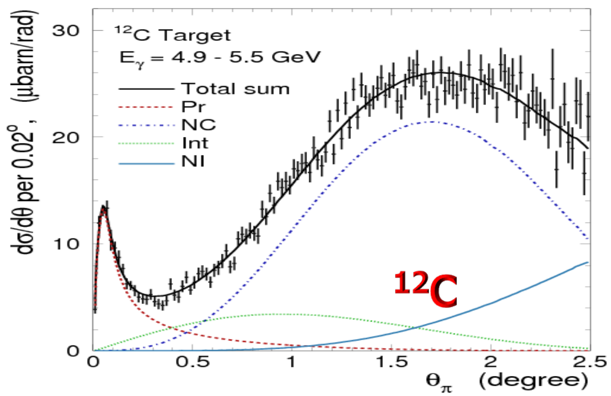
- A 24 GeV beam will offer new opportunities for the Primakoff physics:

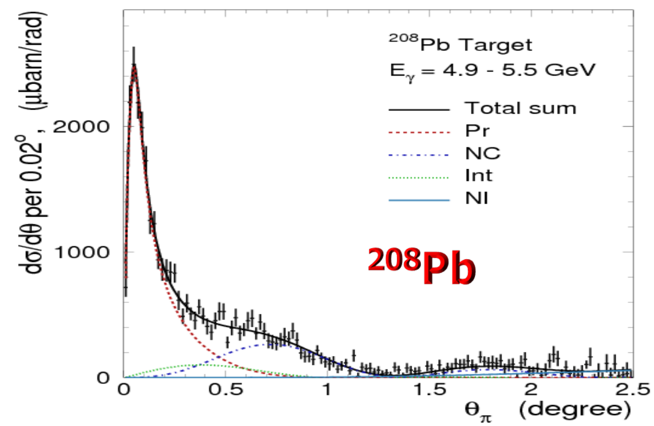
  - ✓ New generation of Primakoff experiments on $\Gamma(\pi^0 \to \gamma\gamma)$ and $F(\pi^0 \to \gamma^*\gamma)$ off an atomic electron target.
  - ✓ Search for new sub-GeV gauge bosons (scalars and pseudoscalars).

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

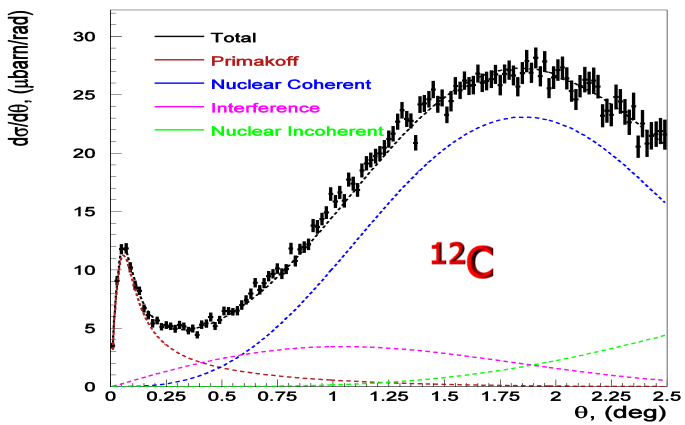
Differential Cross Sections

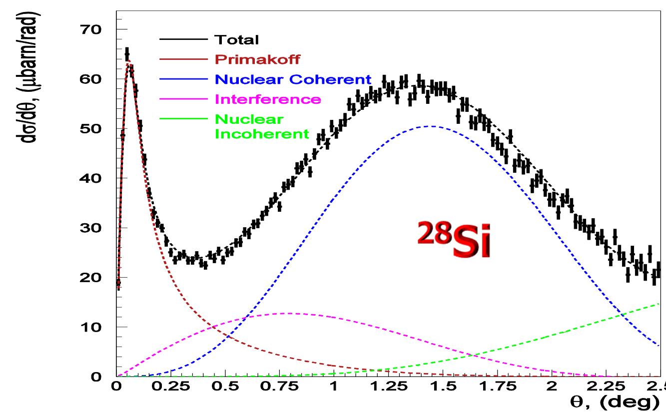
PrimEx I:





PrimEx II:





Fitting data with new theoretical calculations to extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

Phys.Rev. C80, 055201 (2009); Phys.Part.Nucl.Lett.,9,3 (2012)