# The Primakoff Experimental Program at Jefferson Lab

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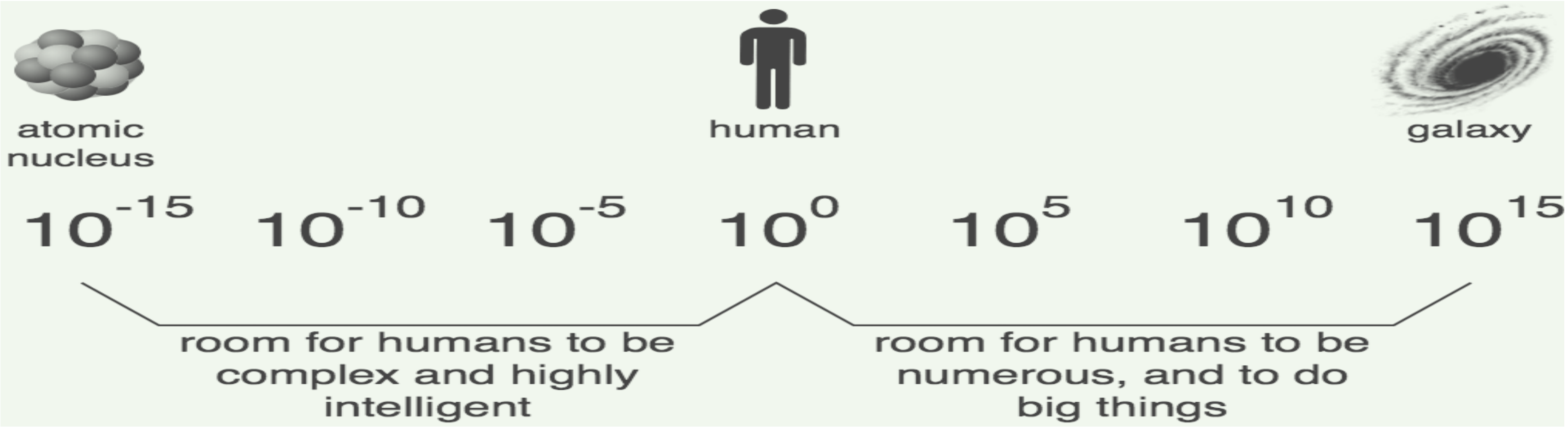
University of North Carolina Wilmington

## Outline

- Introduction
- Current JLab Primakoff program at 6 & 12 GeV
- New opportunities with future 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*

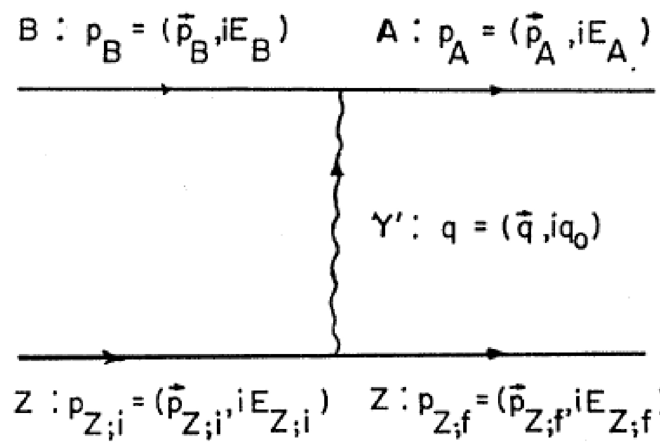
H. PRIMAKOFF†
*Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts*

January 2, 1951

IT has now been well established experimentally that neutral $\pi$-mesons ($\pi^0$) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero $\pi^0$ 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 $\pi^0$ wave field, $\varphi$, and the electromagnetic wave field, **E**, **H**, representable in the form:

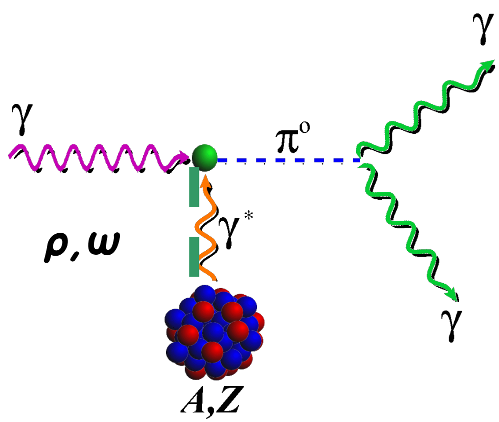
$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi \mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

Here $\varphi$ 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 $\pi^0$),

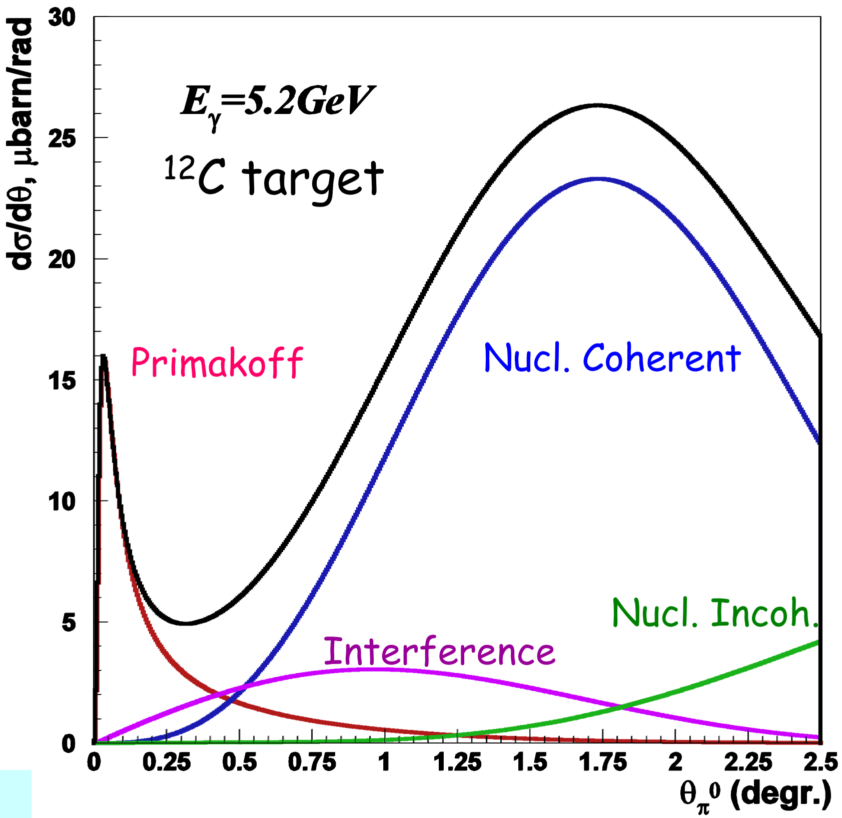



H. Primakoff, Phys. Rev. 81, 899 (1951)

# Distinguishable Features of 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:

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

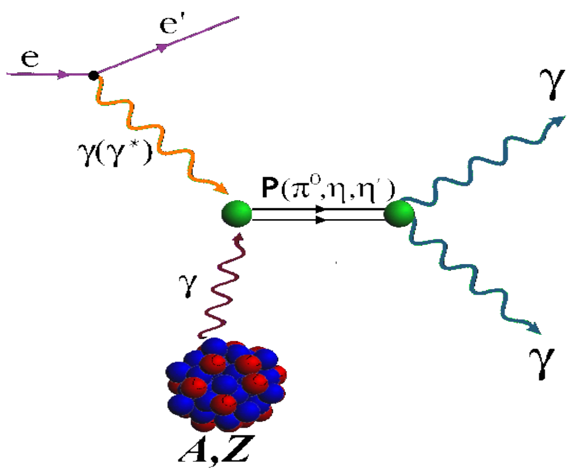
$$\langle\theta_{Pr}\rangle_{peak} \propto \frac{m^2}{2E^2} \quad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- Coherent process

- The higher beam energy is, the higher Primakoff cross 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

## Precision measurements of electromagnetic properties of $\pi^0$, $\eta$, $\eta'$ 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
- $\eta$-$\eta'$ 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:

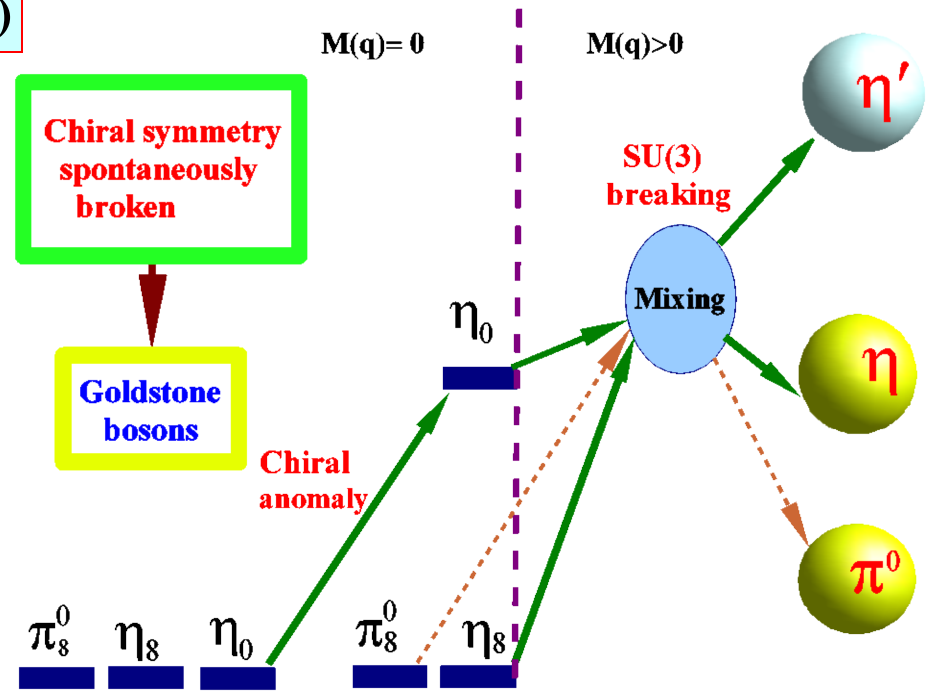
- $\pi^0$,$\eta$ and $\eta'$ electromagnetic interaction radii
- is the $\eta'$ an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$

# Low-Energy QCD Symmetries and Light Mesons

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

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

- Chiral symmetry $SU_L(3) \times SU_R(3)$ 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 $\eta_0$
- $SU_L(3) \times SU_R(3)$ and SU(3) are explicitly broken:
  - GB are massive
  - Mixing of $\pi^0$, $\eta$, $\eta'$




**The $\pi^0$, $\eta$, $\eta'$ 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 $\pi^0$, $\eta$, $\eta'$ 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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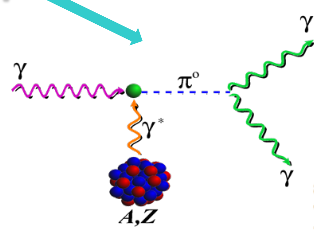
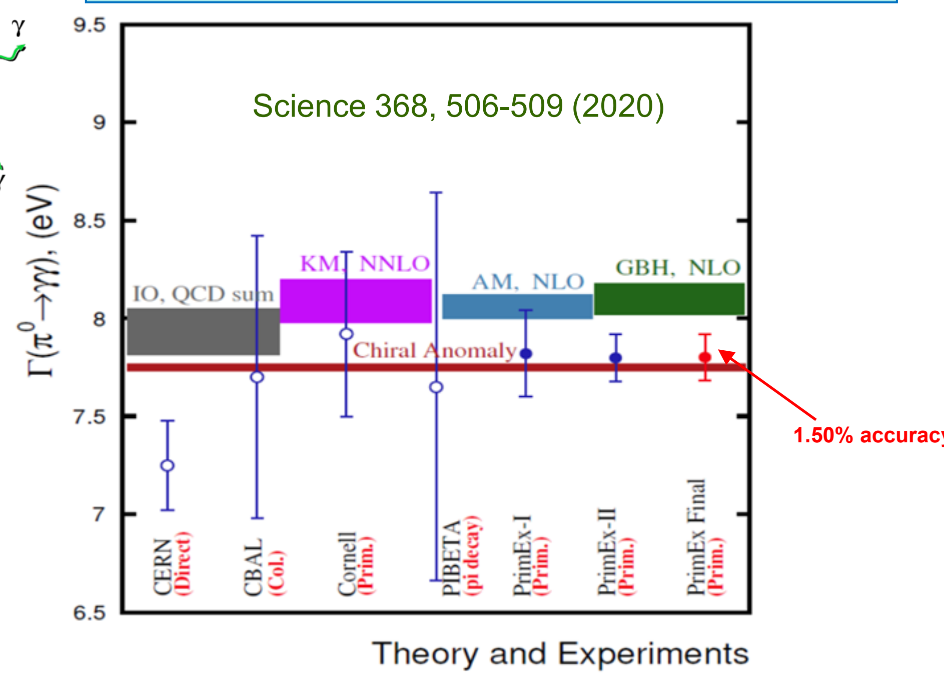


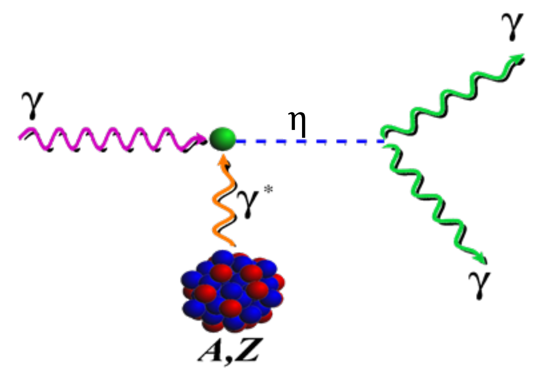




<u>Input to Physics:</u>

- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- $\eta$-$\eta'$ 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 $\pi^0$, $\eta$, $\eta'$ via Primakoff effect




**a) Two-Photon Decay Widths:**

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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
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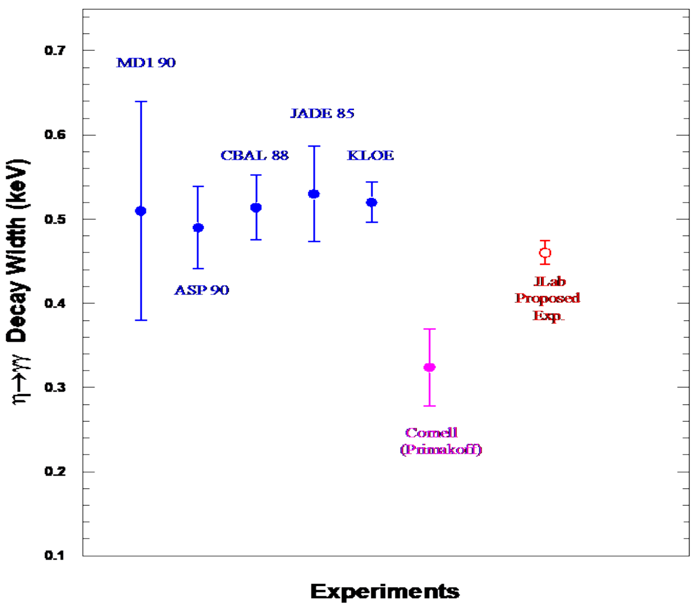
- input to calculate HLbL in $(g-2)_\mu$

**On-Going PrimEx-eta experiment**

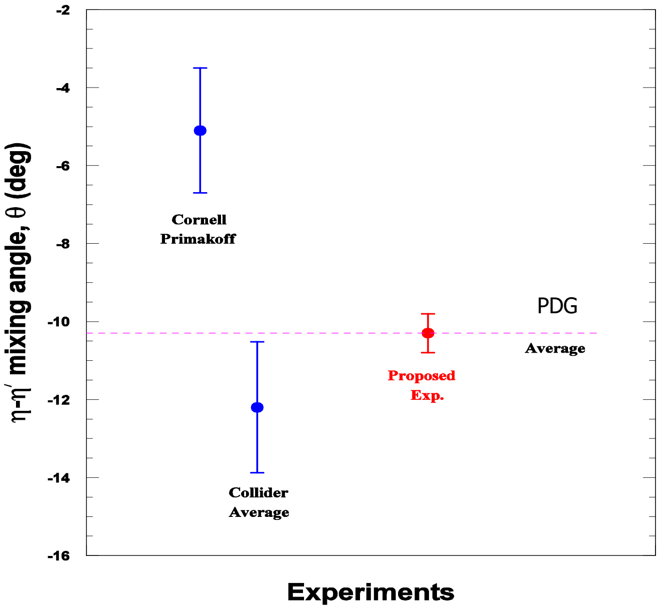
- Two data sets were collected in 2019 and in 2021.
- The third run started on Aug 18 until Dec 19, in 2022.

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

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




2. **Extract $\eta$-$\eta'$ mixing angle:**



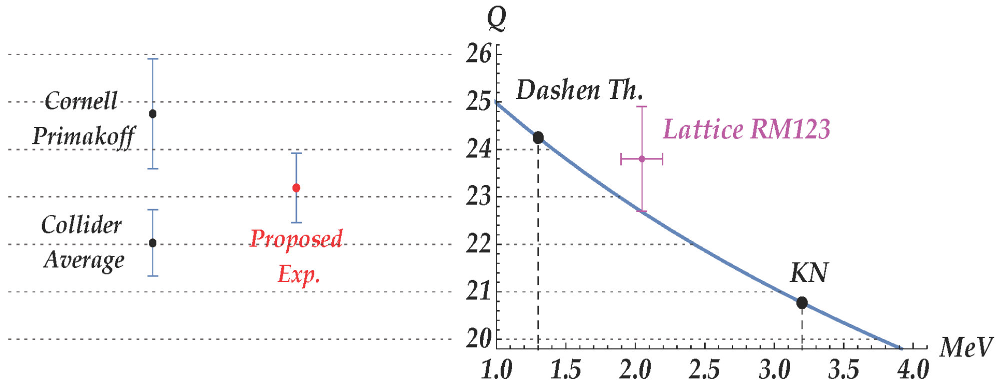

3. **Improve calculation of the $\eta$-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g-2)_\mu$**

4. **Improve all partial decay widths in the $\eta$-sector**

# Precision Determination Light Quark Mass Ratio

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

- $\eta \to 3\pi$ decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em} A_2$
- $\alpha_{em}$ 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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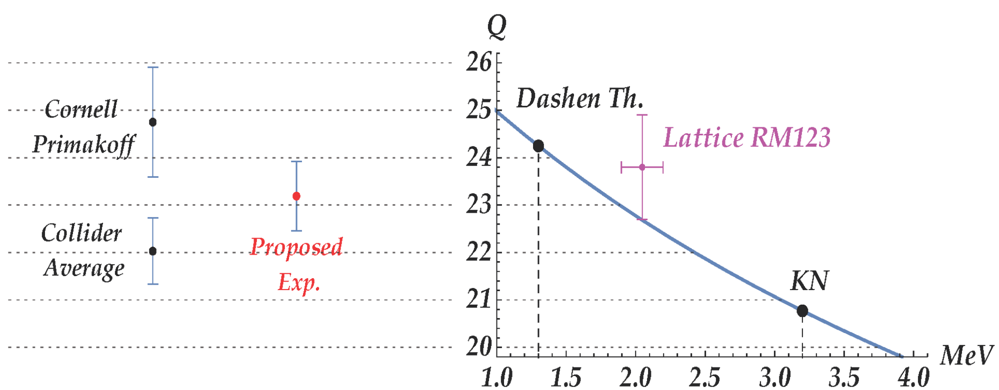


$\Gamma(\eta \rightarrow 3\pi) = \Gamma(\eta \rightarrow 2\gamma) \times BR$

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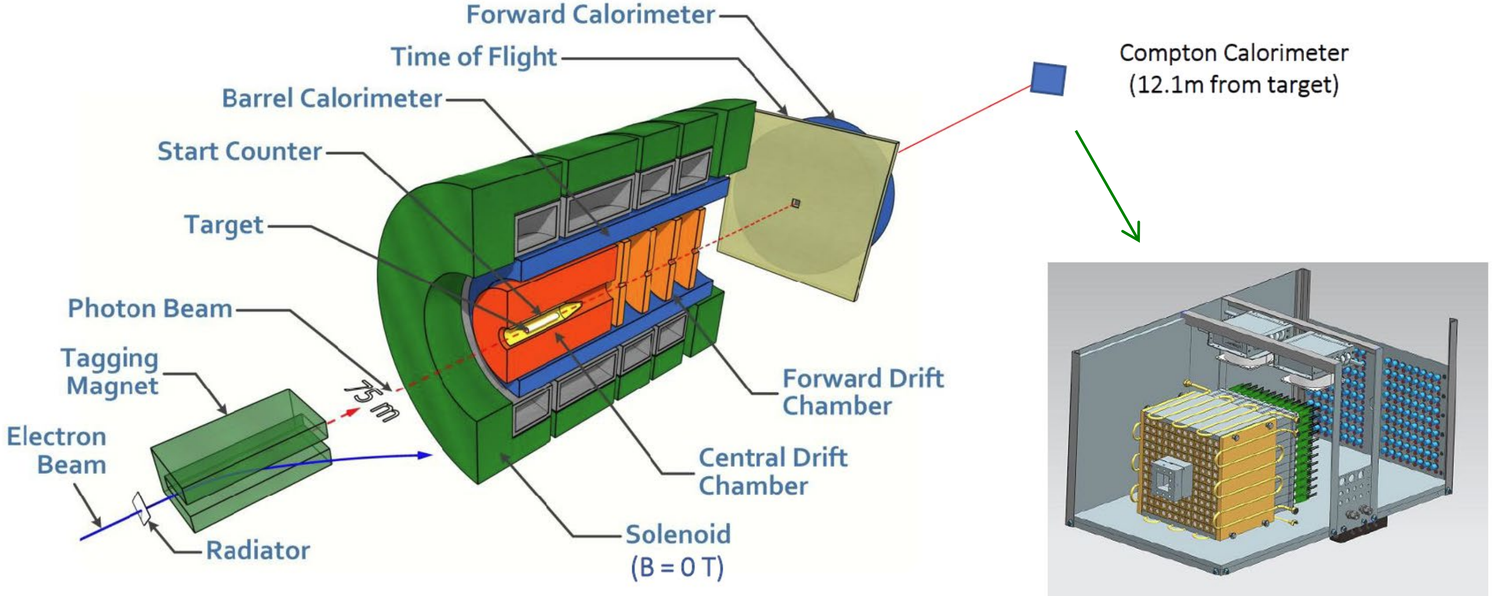
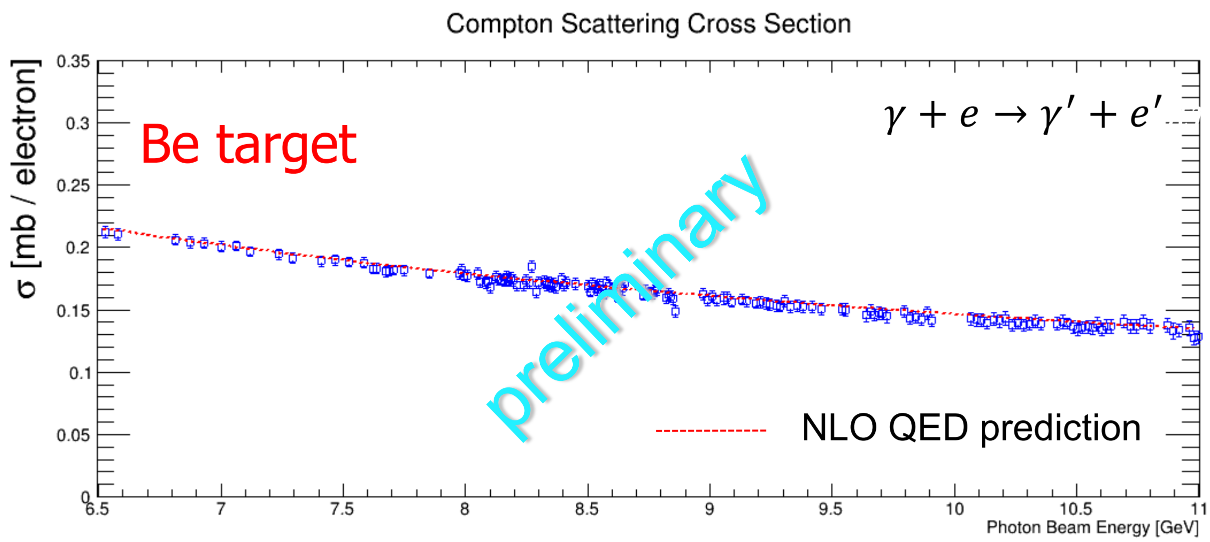
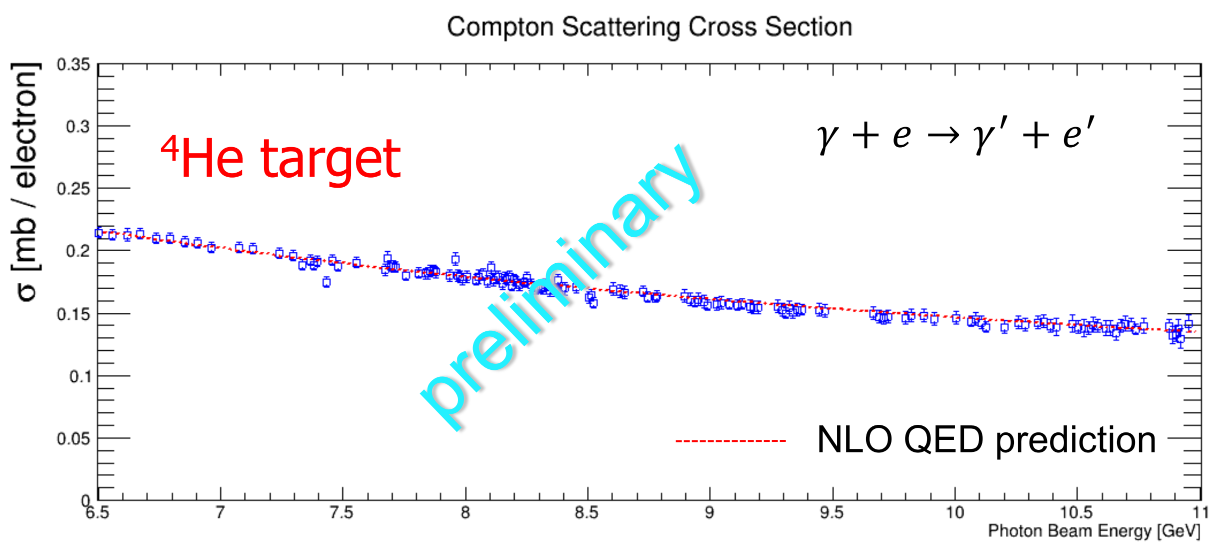
# PrimEx-eta Experiment on $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D




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

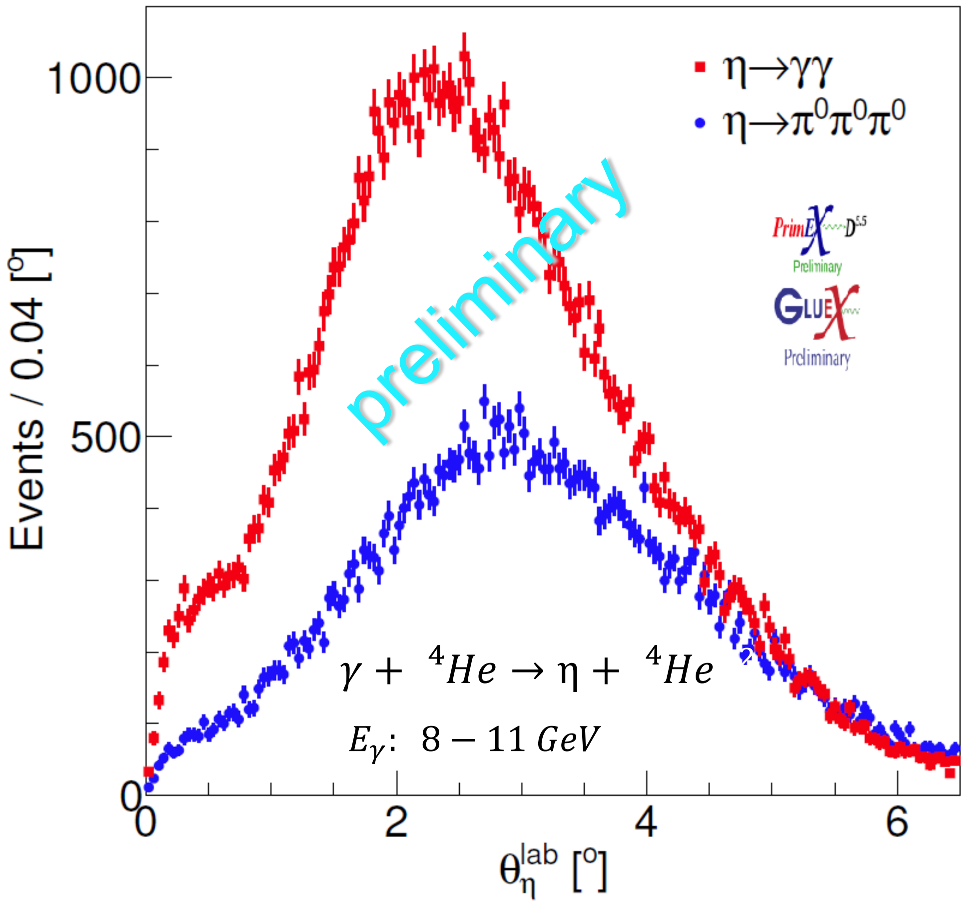
# Control Systematics with Compton Scattering



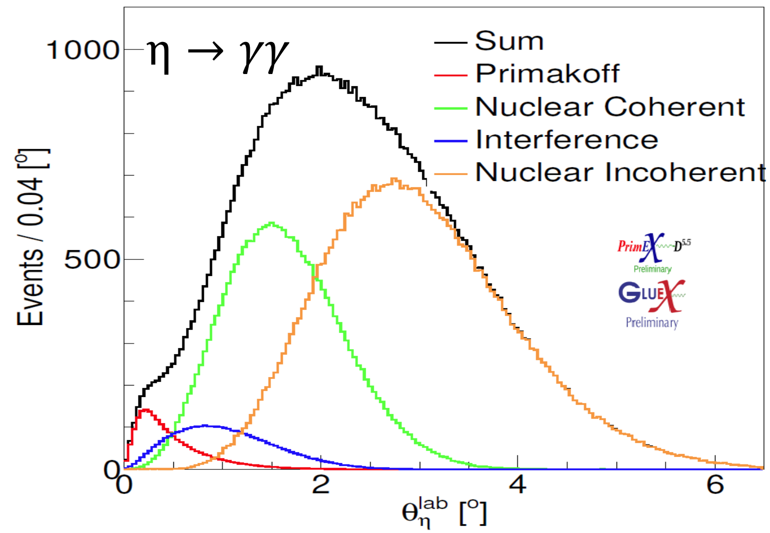



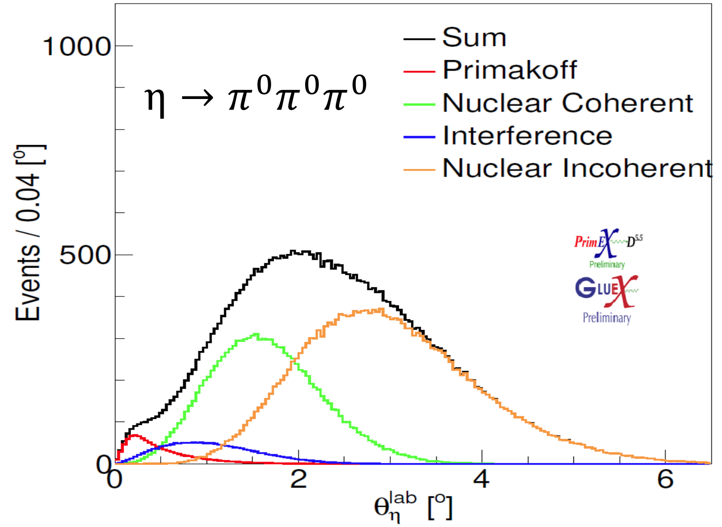
# Preliminary Results on the η Yield

η Yield from phase I data:

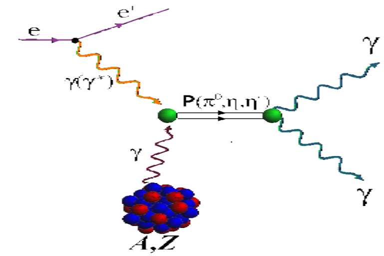



Simulations:

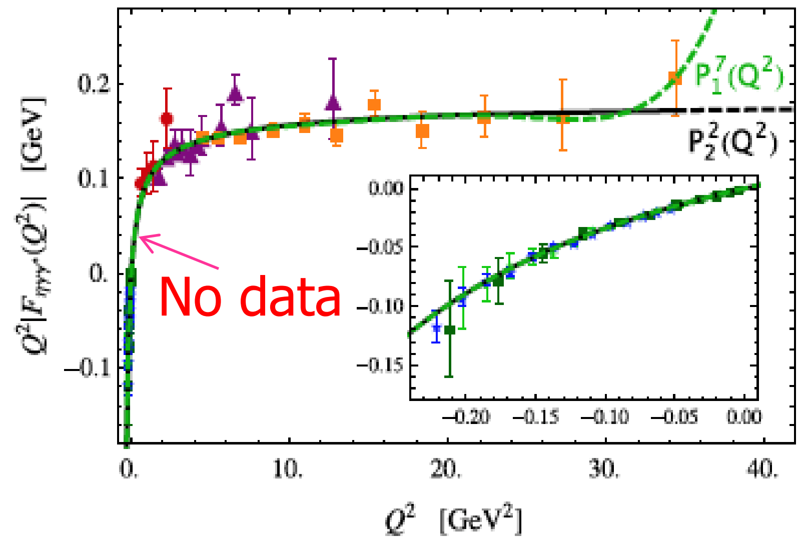


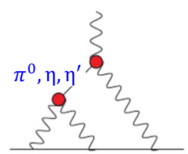
# Space-Like Transition Form Factors
## ($Q^2$ : 0.001-0.3 $GeV^2/c^2$)

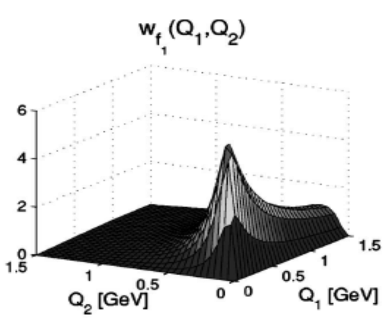


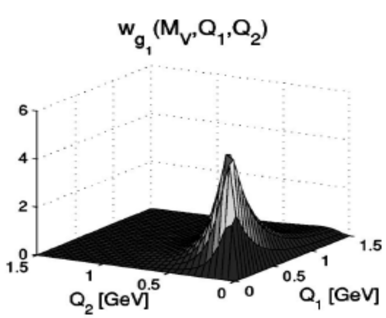

- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large $N_c$ predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



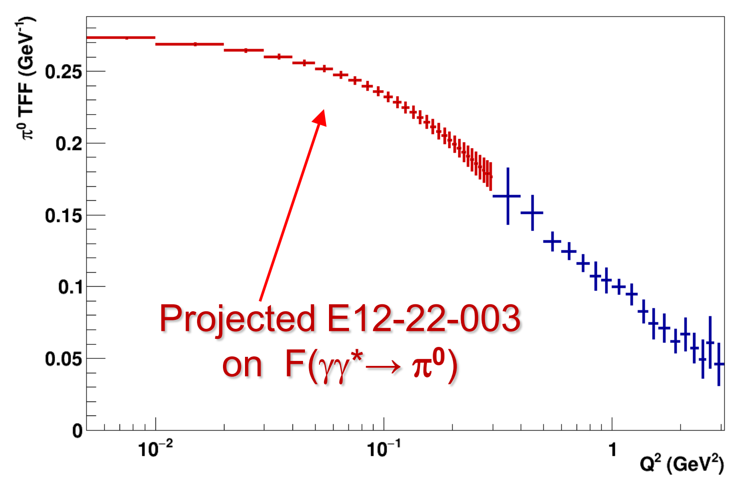

- Input for hadronic light-by-light calculations in muon (g-2)




Phys.Rev.D65,073034

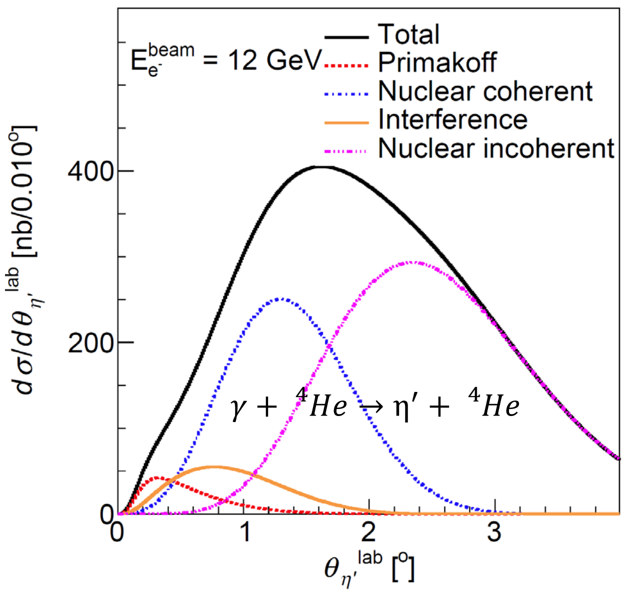


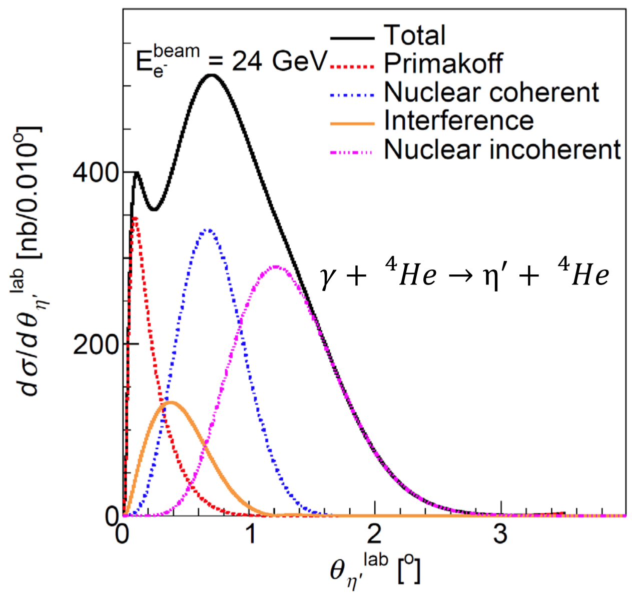
# Improvement with a 24 GeV Beam

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

Better separation of Primakoff from nuclear processes:

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




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

# New opportunities with JLab 24 GeV Upgrade

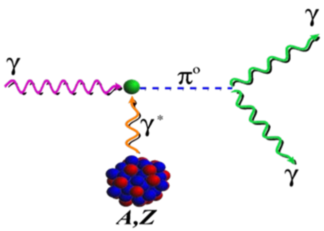
1. Precision measurement of decay width $\Gamma(\pi^0 \to \gamma\gamma)$ and transition form factor $F(\pi^0 \to \gamma^*\gamma)$ via the Primakoff effect off an atomic electron target.

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 $\pi^0$ Primakoff Production off an Electron

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

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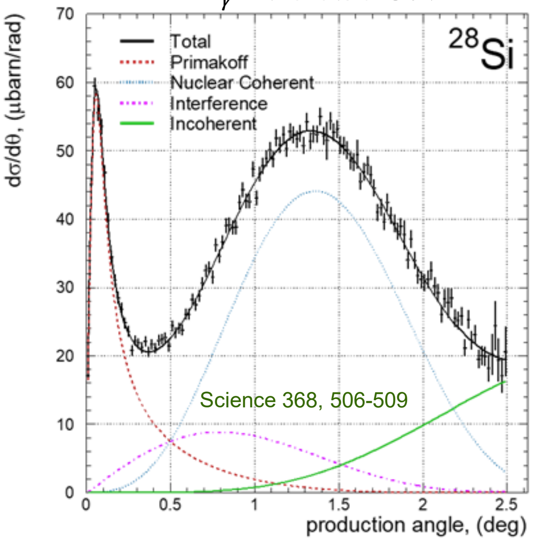
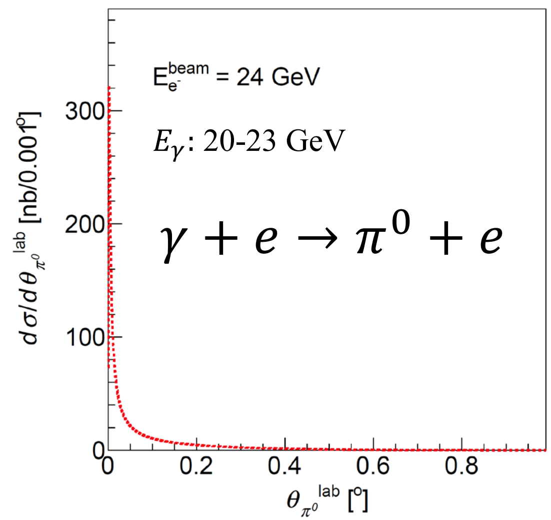
$E_\gamma$: 4.45-5.30 GeV




Advantages of an electron target:

- Eliminate all nuclear backgrounds
- Point-like target
- Recoiled electron detection



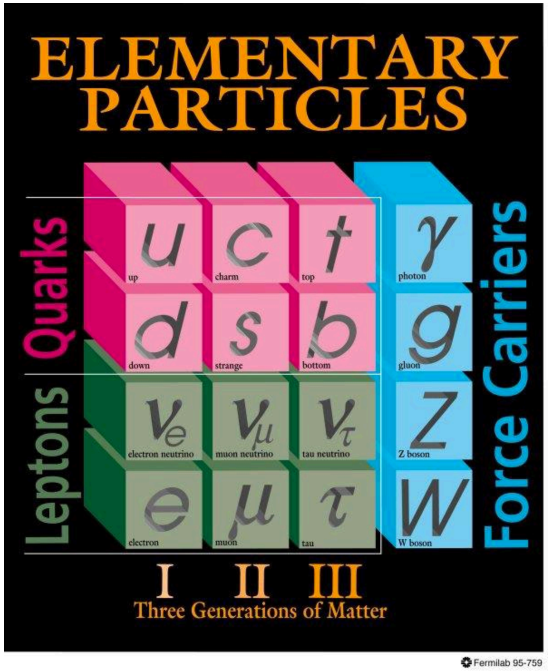

$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \sin^2\theta_\pi$$

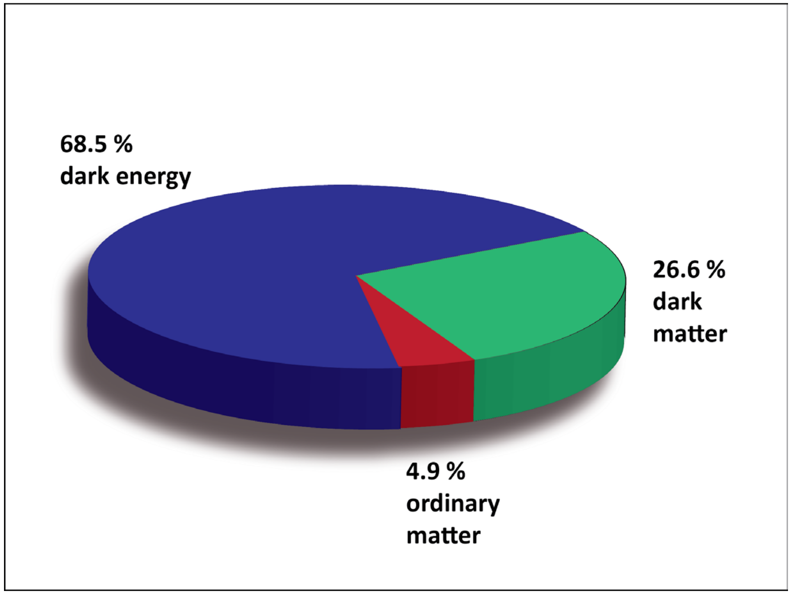
Main challenges for the nuclear target:

- Nuclear backgrounds
- Nuclear charge form factor
- 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

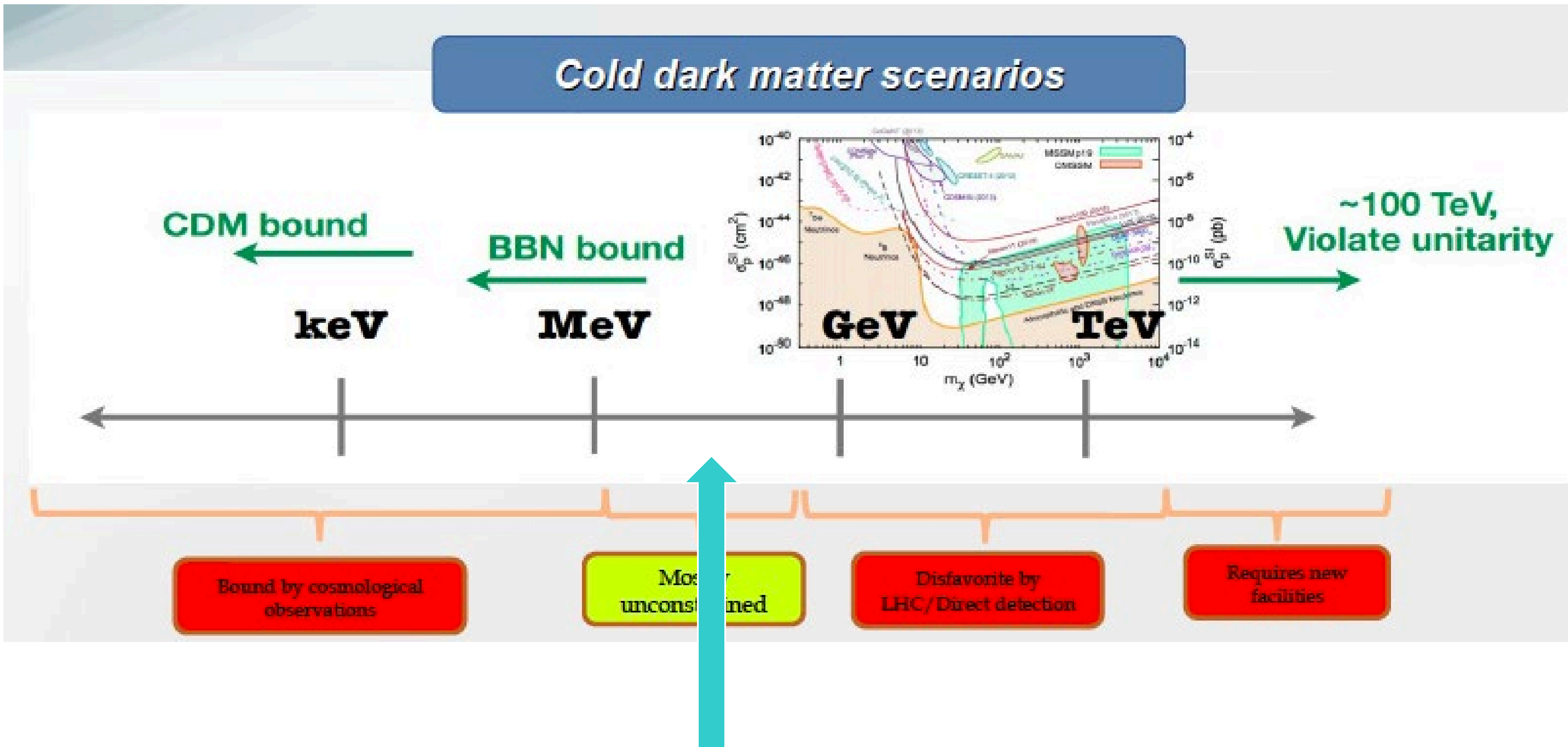



## Dark Sector

- 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?

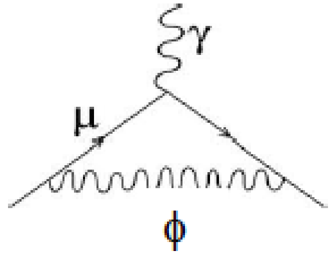


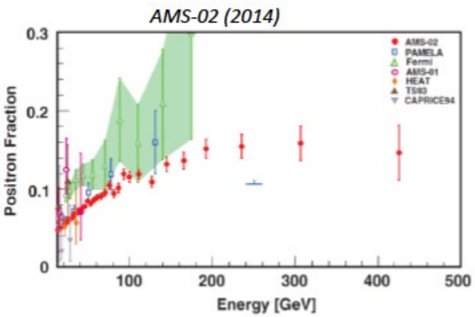

Sub-GeV region represents a good discovery opportunity

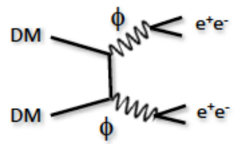
# Motivation for sub-GeV New Physics

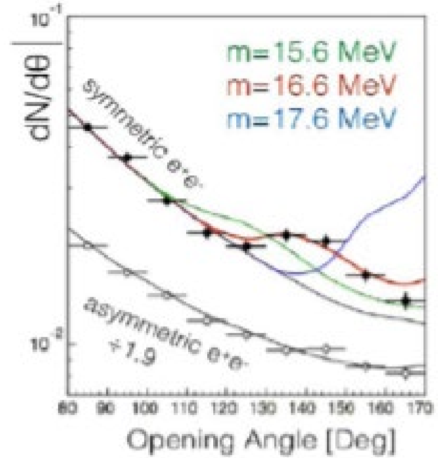
$(g\text{-}2)_\mu$ anomaly

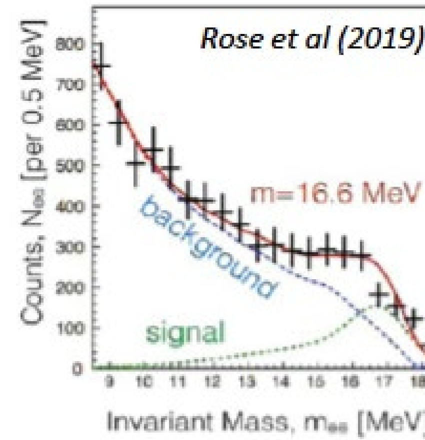
*Pospelov (2008)*



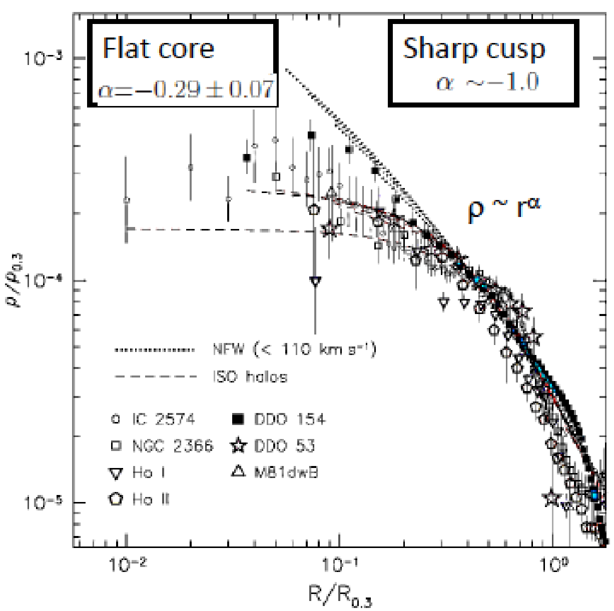



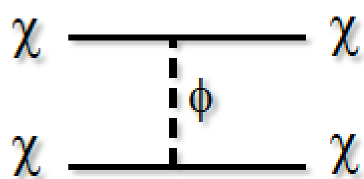



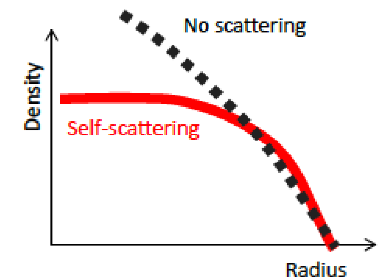




THINGS (dwarf galaxy survey) - Oh et al. (2011)




self-interaction

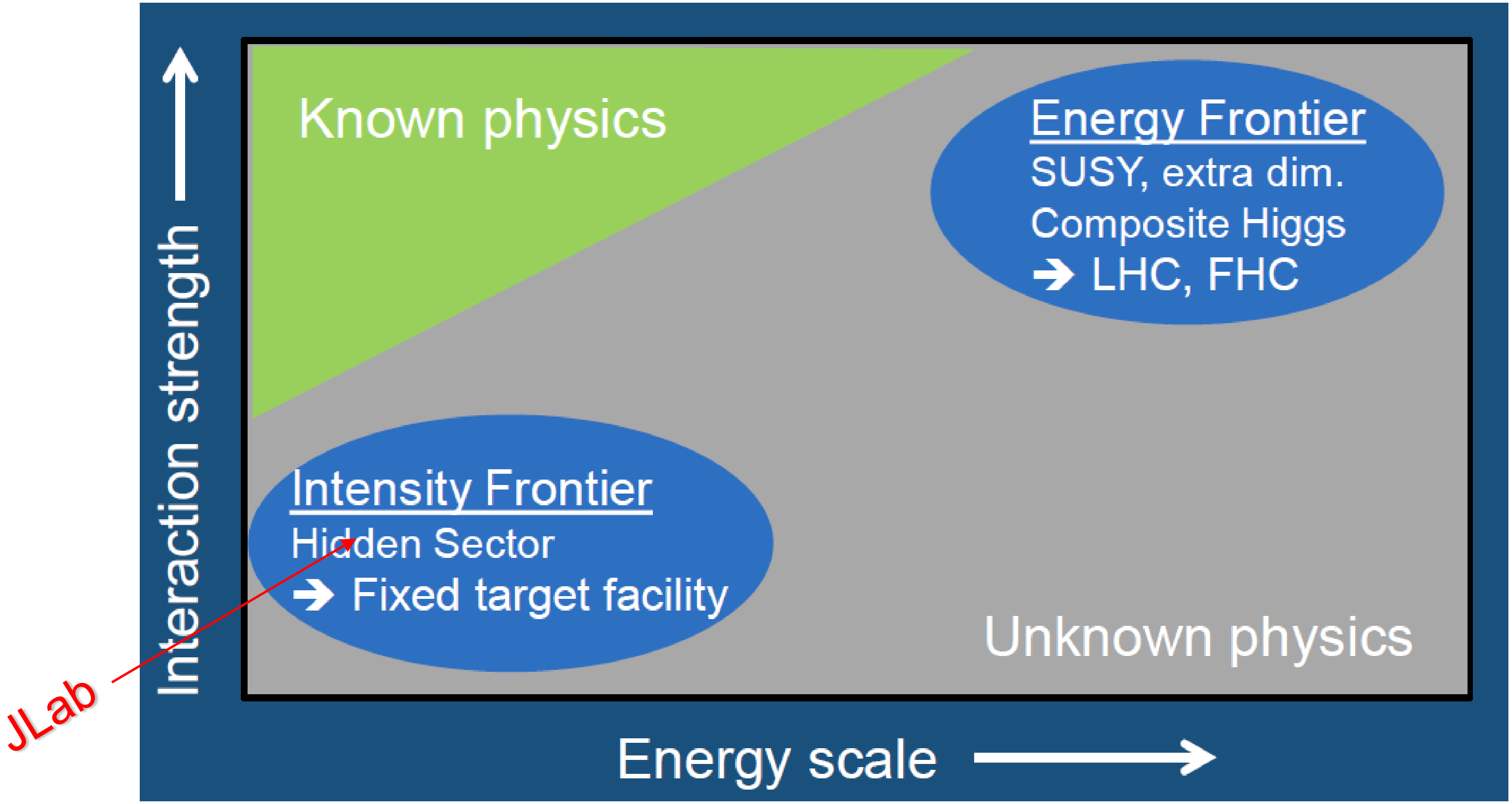



**Self-interactions solve core-vs-cusp**

*Particles get scattered out of dense halo centers*

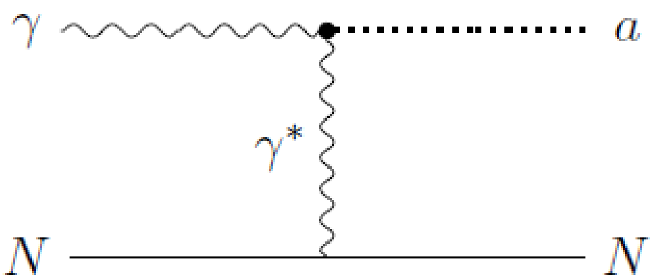
If these anomalies are interpreted in terms of new physics, all point to new forces with mediator particles in the MeV–GeV mass range!

# Landscape of BSM Physics Search




arXiv:1504.04855

# Search for New Scalar and Pseudoscalar via Primakoff Effect




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

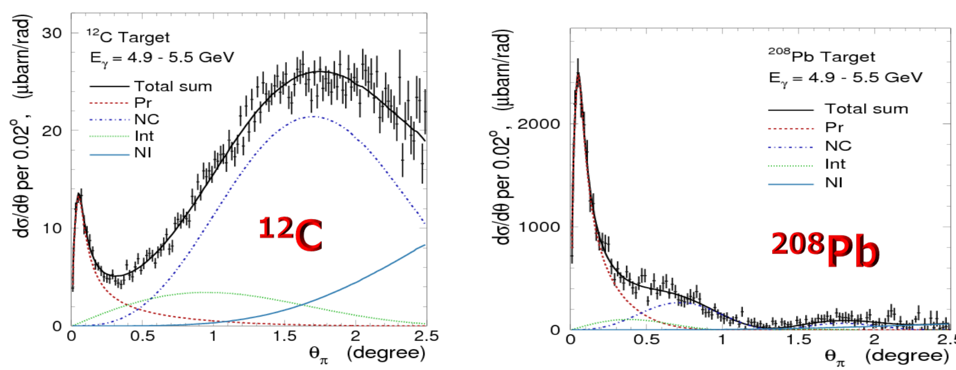
$$\frac{d\sigma_{Pr}}{d\Omega} \sim \frac{c_\gamma^2 \alpha Z^2}{8\pi\Lambda^2} \cdot \frac{\beta^3 E^4}{Q^4} \cdot |F_{e.m.}(Q)|^2 sin^2\theta_a$$

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

# 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 $\pi^0$ lifetime provides a stringent test of low-energy QCD. The future 24 GeV beam will greatly improve 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 electron target.
  - ✓ Search for new sub-GeV gauge bosons (scalars and pseudoscalars).

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