Tests of Fundamental Physics via Light Pseudoscalar Meson Decays

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Outline

- Introduction of Physics Motivation
- JLab Eta Factory (JEF)
- PrimEx Primakoff Program
- Summary

- Thanks for support by American NSF: PHY-2111181 and PHY2412800.
- GlueX Acknowledgements: gluex.org/thanks

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?

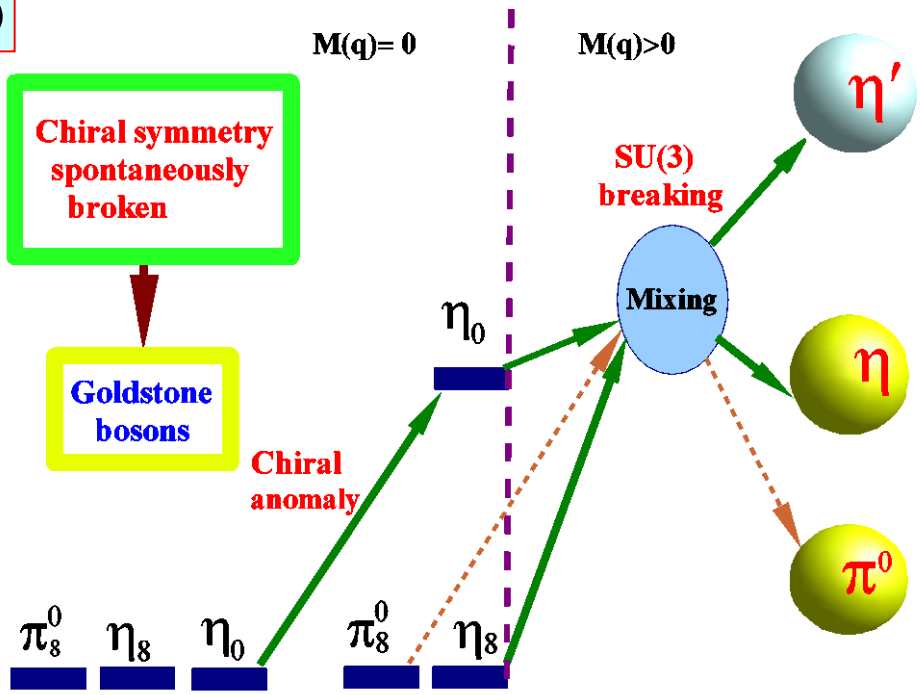
Light pseudoscalar mesons offer a sensitive tool to explore these fundamental questions.

What is the origin of QCD confinement?

- **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)
  - Non-zero mass of η_0
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- **$SU_L(3) \times SU_R(3)$ and SU(3) are explicitly broken:**
  - GB are massive
  - Mixing of π^0, η, η'

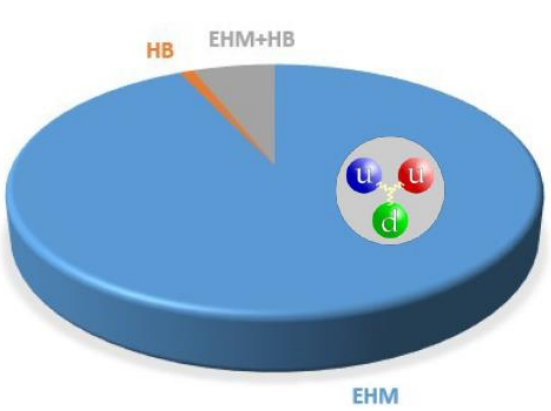


The π^0, η, η' system provides a rich laboratory to study the symmetry structure of confinement QCD.

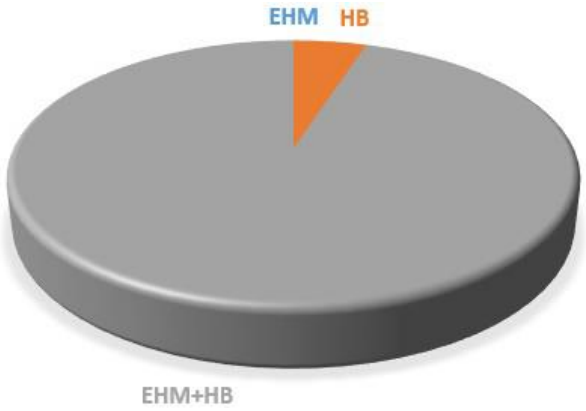
What is the origin of visible mass?

Mass-generating mechanisms:

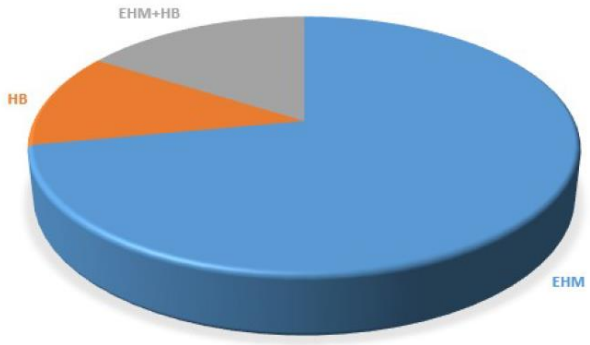
- Higgs Boson (HB), alone is responsible for <2% of the visible mass in the universe.
- Emergent Hadron Mass (EHM) and its constructive interference with Higgs-Boson (EHM+HB) account for >98% of the visible mass.



Proton mass budget



π^0 mass budget



η' mass budget

https://doi.org/10.1007/s00601-024-01924-2

Complementary to proton, π^0 and η offers a unique opportunity to the interference between two mass generating mechanisms, while η' offers access to all three contributions.

What are the causes of matter-antimatter asymmetry in the universe?

- "Sakharov conditions" for matter-antimatter asymmetry require simultaneous C and CP violations.

- C and CP are breaking in the weak interaction of SM. However, SM fails about ten orders of magnitude to explain the observed asymmetry.

- The π^0, η, η' mesons are among very few C eigenstates in nature, offering important probes for new sources of C- and CP-violations.

- SM CP-violating reactions are flavor-changing. The π^0, η, η' decays are flavor-conserving, effectively free of the SM background for BSM CP-violation searches.

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

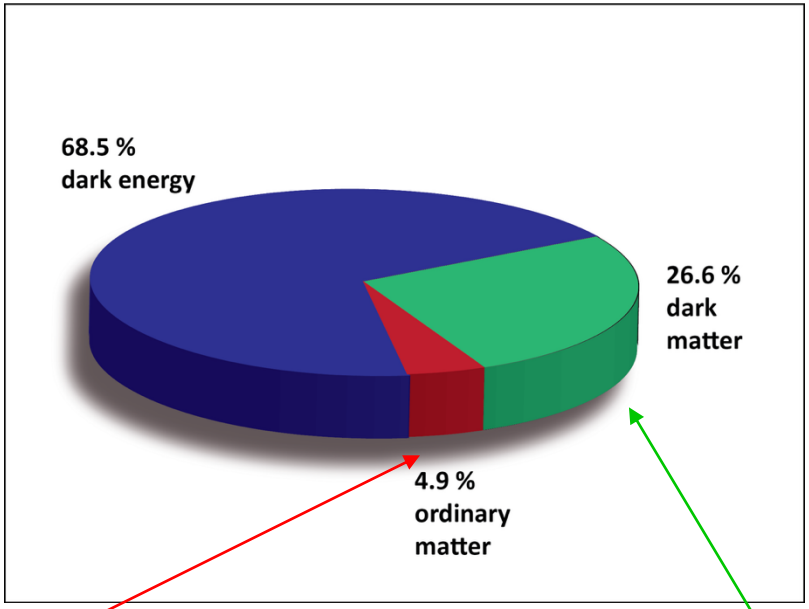
- QCD θ-term
- Examples: $\eta^{(\prime)} \to 2\pi$, $\eta^{(\prime)} \to \pi^+\pi^-\gamma^{(*)}, \cdots$
- Strong experimental constraints from EDM measurements

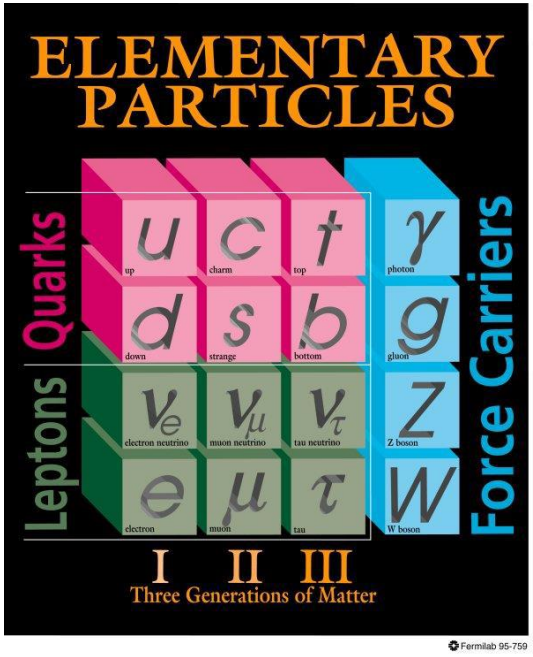
Class III: C-, CP-violation

- A new C- and T-violating, and P-conserving interaction was initially proposed in the 60th (Phys. Rev.,139, B1650); a significant theoretic progress has emerged in recent years (Phys.Rev.D,101(11):115038; Phys.Rev.D,110(5):055039; JHEP, 06:154, 2023)
- Examples: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to \pi^o\gamma^{(*)}$, $\eta^{(\prime)} \to \pi^0\pi^+\pi^-, \cdots$
- Electroweak radiative corrections mix class II and III, but much weaker EDM constraints.

Class III has much weaker experimental constraint, offer an opportunity for new physics search in η/η’ decays.

BSM Physics in Dark Sector

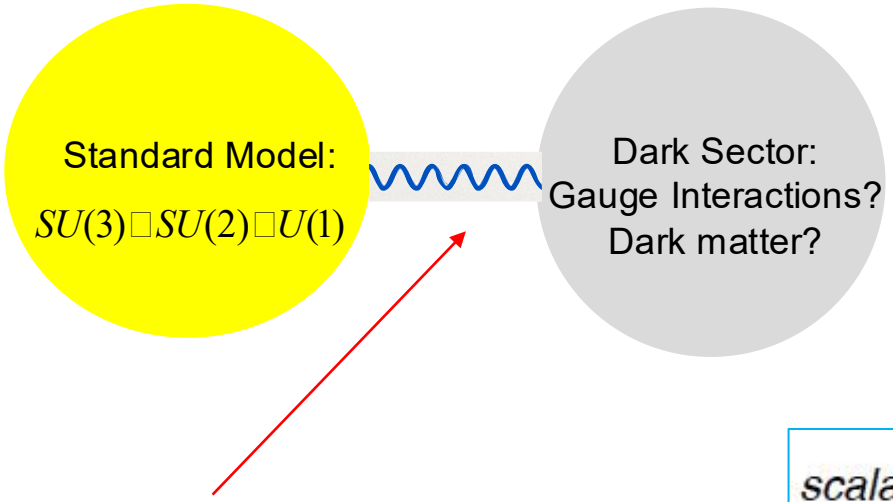




Dark Sector

- 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

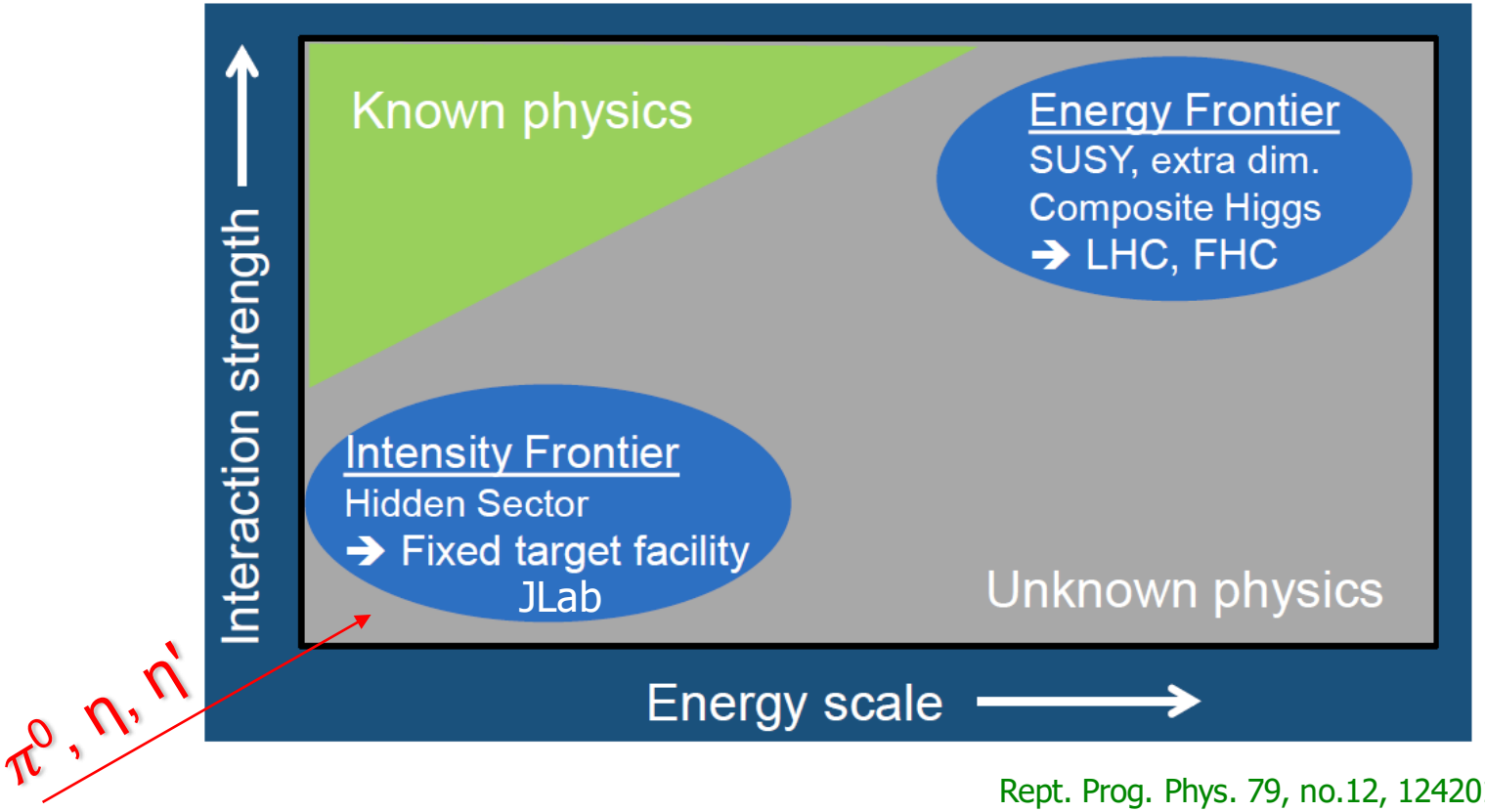
ALP $c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}$

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

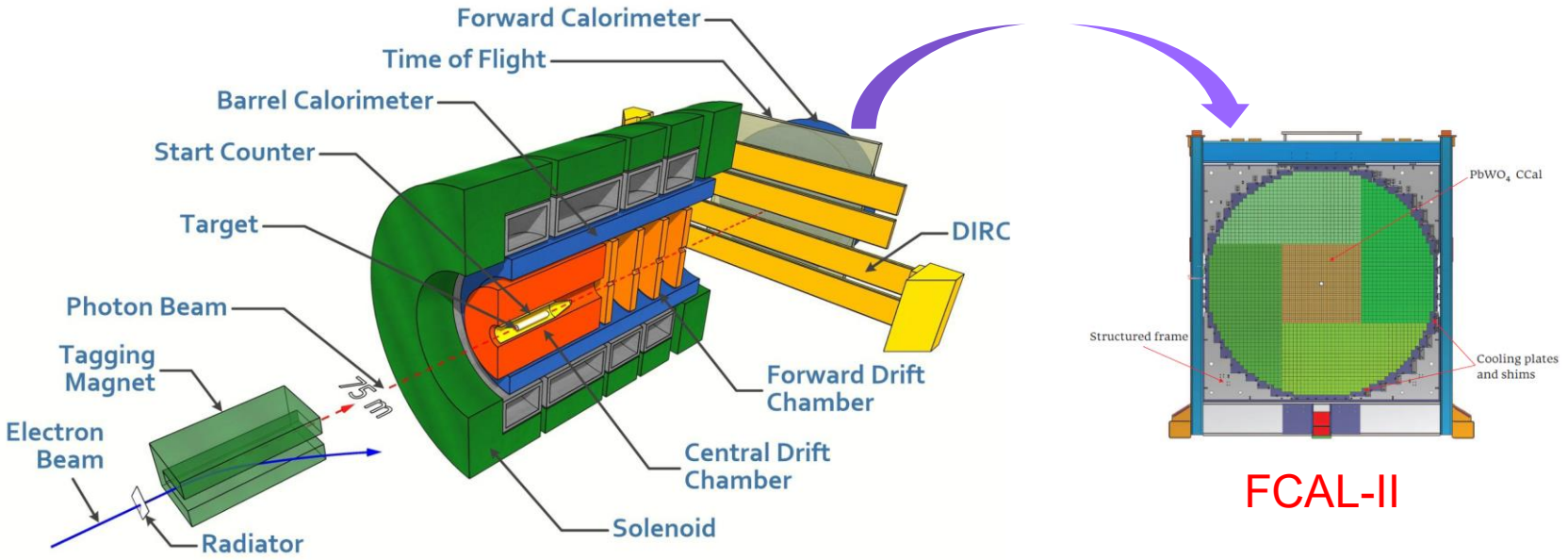
Landscape of BSM Physics Search



Rept. Prog. Phys. 79, no.12, 124201

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

JLab Eta Factory (JEF) Experiment at GlueX

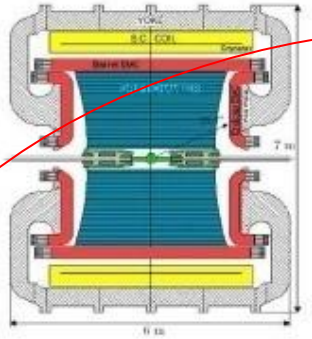


- Simultaneously produce η/η' on LH_2 target with 8.4-11.7 GeV tagged photon beam via $\gamma+p \rightarrow \eta/\eta'+p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity $PbWO_4$ insertion (FCAL-II) to detect multi-photons from the η/η' decays
- The GlueX detector will detect the charged products from the η/η' decays

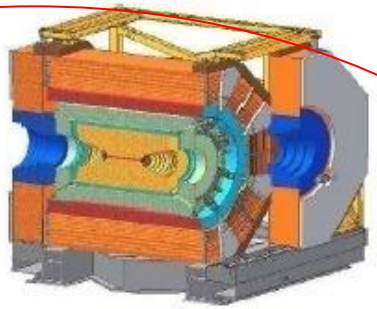
Global Experimental Efforts in η Decays

e^+e^- Collider

KLOE-2 at DAϕNE



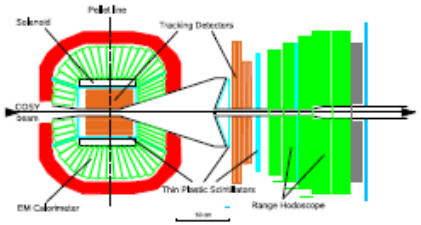
BESIII at BEPCII



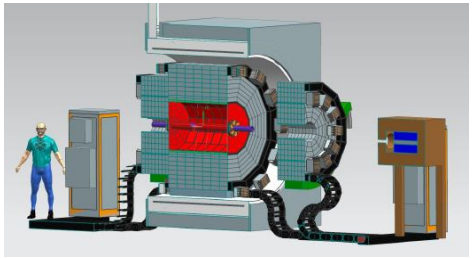
Fixed-target

hadroproduction

WASA at COSY

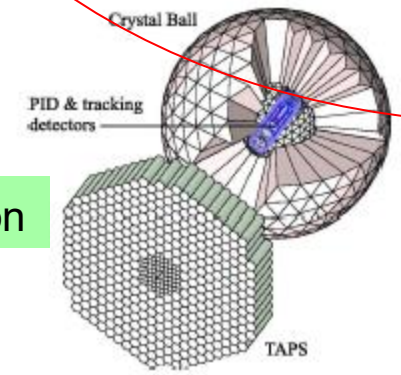


Proposed REDTOP

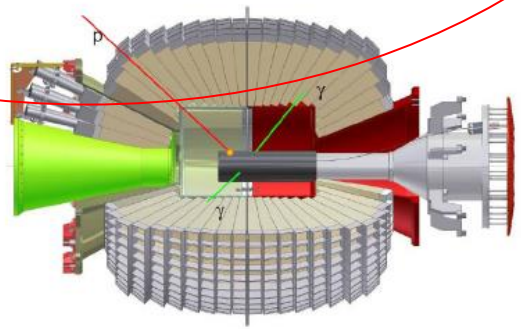


Photoproduction

Crystall Ball at MAMI

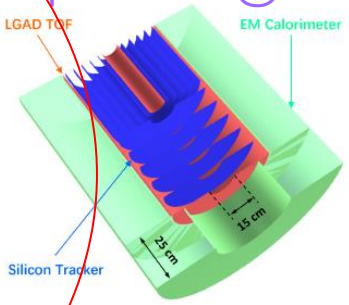


CBELSA/TAPS at ELSA



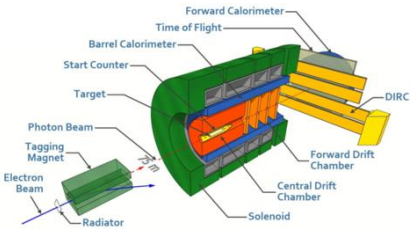
Low-energy

Proposed eta@HIAF



High-energy

JEF at JLab



Main JEF Physics Objectives

1. *Search for various gauge boson candidates in the MeV–GeV mass range, probing three out of four highly-motivated portals coupling the SM sector to the dark sector:*

Vector:

- A leptophobic vector boson (B') [53] coupling to baryon number.

$$\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma, \quad (0.14 < m_{B'} < 0.62 \text{ GeV})$$
$$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma, \quad (0.62 < m_{B'} < 1 \text{ GeV})$$

- A dark photon (or leptophilic vector boson) kinetically mixing with the SM photon [54, 55, 56, 57].

$$\eta, \eta' \to A'\gamma \to e^+e^-\gamma$$

Scalar: Search for hadrophilic [58, 59] scalar.

$$\eta, \eta' \to \pi^0 S \to \pi^0\gamma\gamma,\ \pi^0 e^+e^-, \quad (10 \text{ MeV} < m_S < 2m_\pi)$$
$$\eta, \eta' \to \pi^0 S \to 3\pi,\ \eta' \to \eta S \to \eta\pi\pi, \quad (m_S > 2m_\pi)$$

Axion-Like Particle (ALP): Search for light pseudoscalars [60, 61, 62, 63].

$$\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ \pi\pi e^+e^-$$

Phys. Rept. 945 (2022) 1-105, JEF-II proposal

Main JEF Physics Objectives (cont.)

2. *Explore new sources of C- and CP-violation by measuring* [33, 34, 35, 37]:

   - branching ratio of: $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$
   - charge-asymmetry in the Dalitz distributions of: $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$, $\eta' \to \eta\pi^+\pi^-$, $\eta^{(\prime)} \to \pi^0 e^+e^-$, $\eta^{(\prime)} \to e^+e^-\gamma$
   - the lepton charge asymmetry or pion charge asymmetry in $\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$

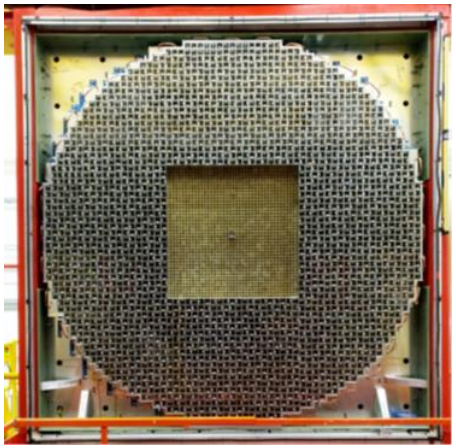
3. *Test low-energy QCD to*:

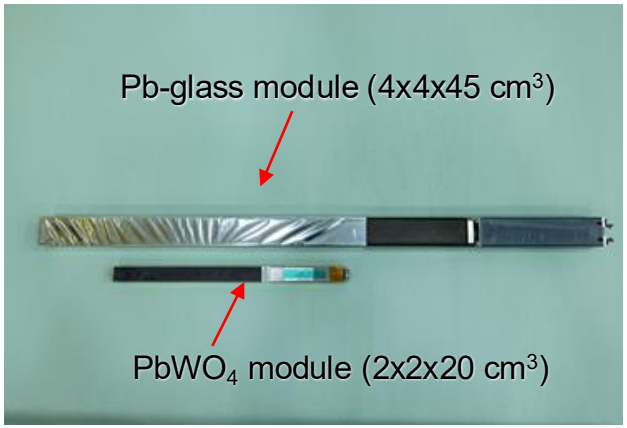
   - understand interplay of VMD and scalar dynamics in ChPT [17, 64] through $\eta^{(\prime)} \to \pi^0\gamma\gamma$
   - improve the light quark mass ratio [22] by $\eta \to 3\pi$
   - understand the origin of visible mass [25] and provide inputs to calculate the hadronic light-by-light in $g-2$ [24] via $\eta^{(\prime)} \to e^+e^-\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-e^+e^-$

Phys. Rept. 945 (2022) 1-105, JEF-II proposal

Status of the JEF Experiment

- A high granularity, high resolution $PbWO_4$ ECAL was successfully constructed for an upgraded FCAL-II.



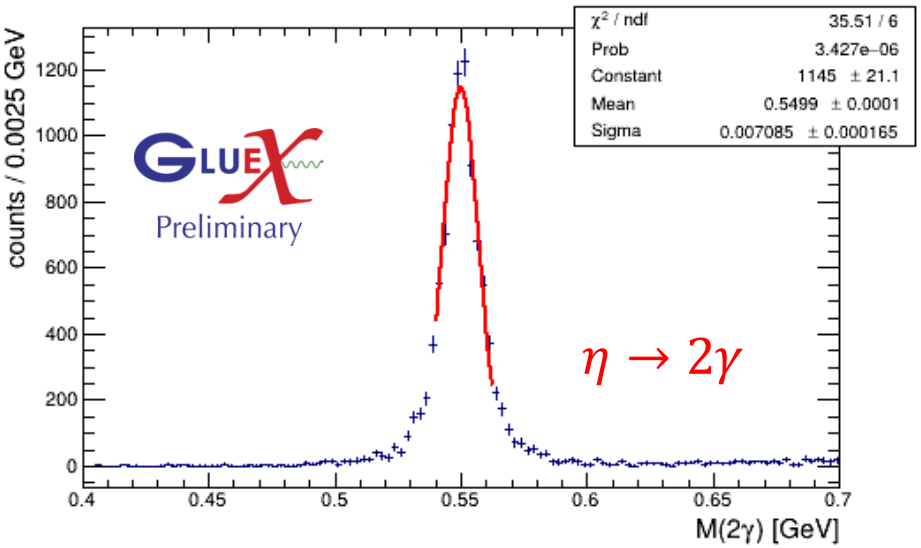


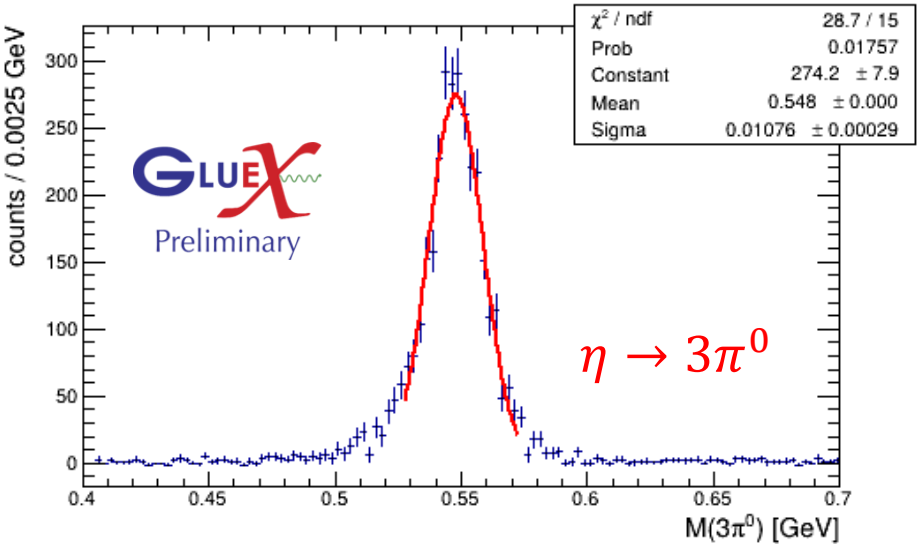
- About 75% JEF-I data was collected. The remaining data will be completed in 2026.

- A new run-group proposal (JEF-II) was developed and would add a factor of 4 more statistics.

JEF-I Data Quality Check

- Analyzed a small subset of data





- Extracted $BR(\eta \to 3\pi^0)/BR(\eta \to 2\gamma)$

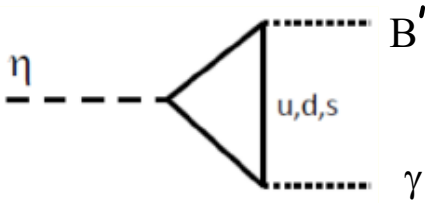
Measured	PDG
0.85 ± 0.02(stat)	0.827 ± 0.007

Quality of the JEF-I data looks promising

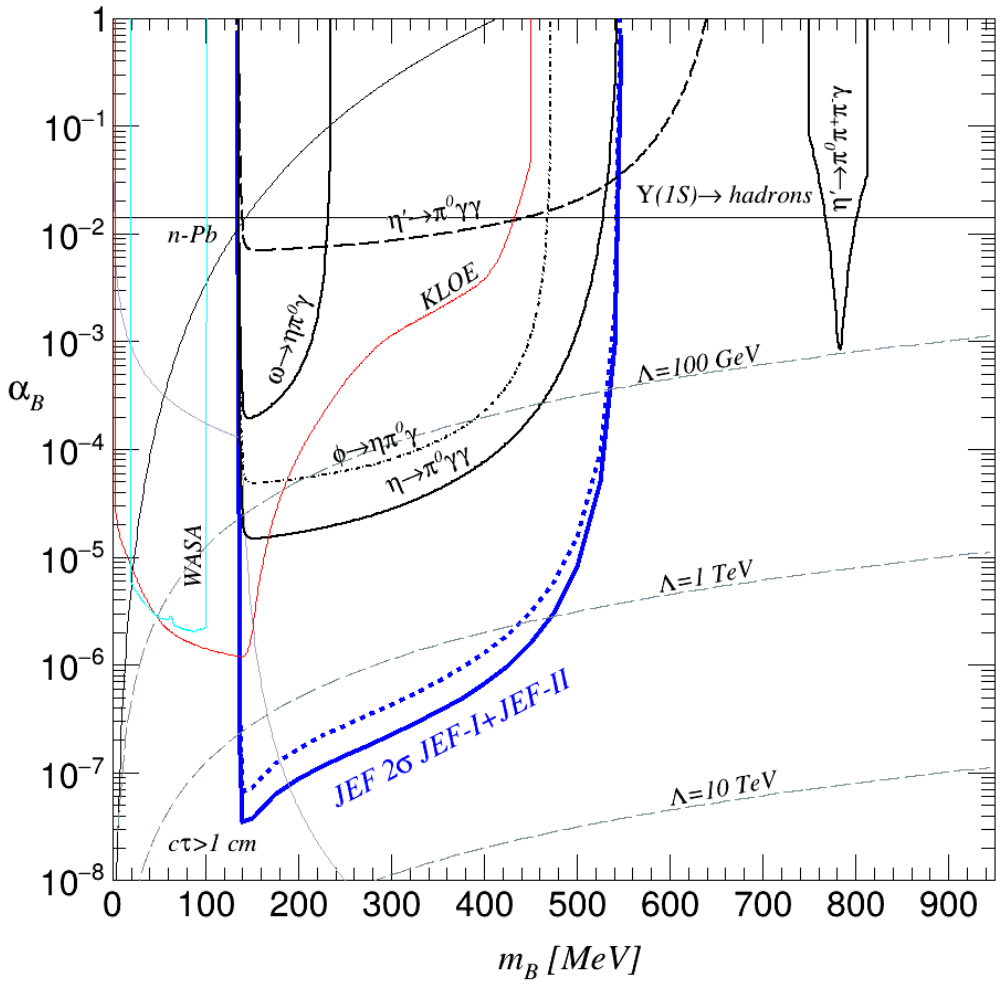
Projected JEF Experimental Reach for B′

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

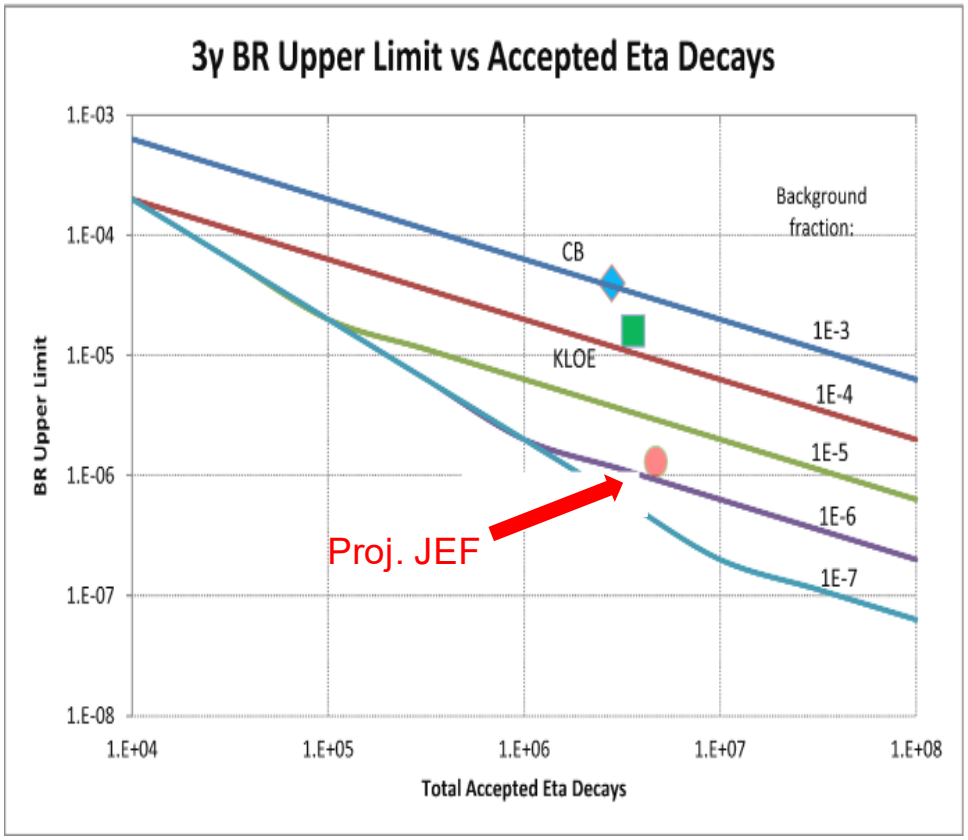
$\eta \rightarrow B'\gamma \rightarrow \pi^0\gamma\gamma$



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



Projected JEF for C- and CP-Violation Search



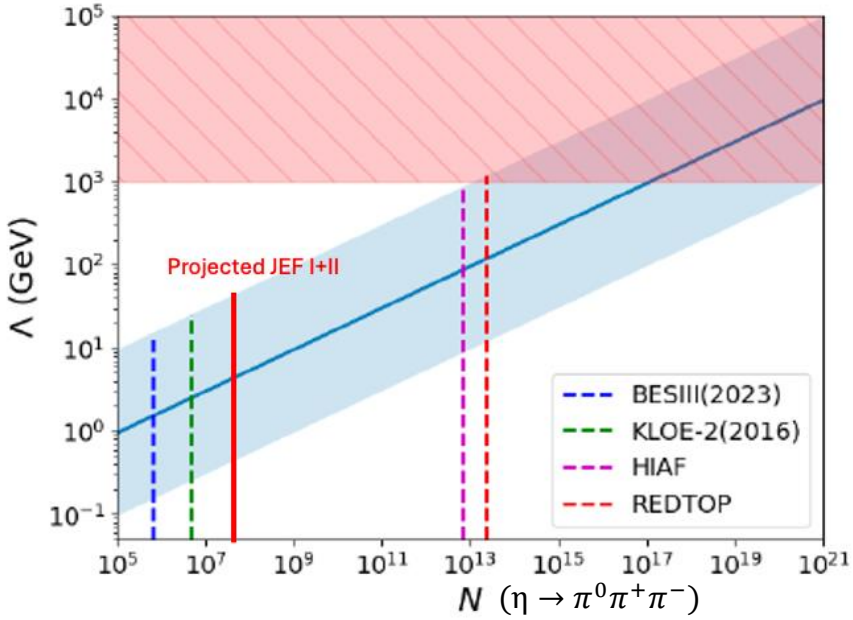


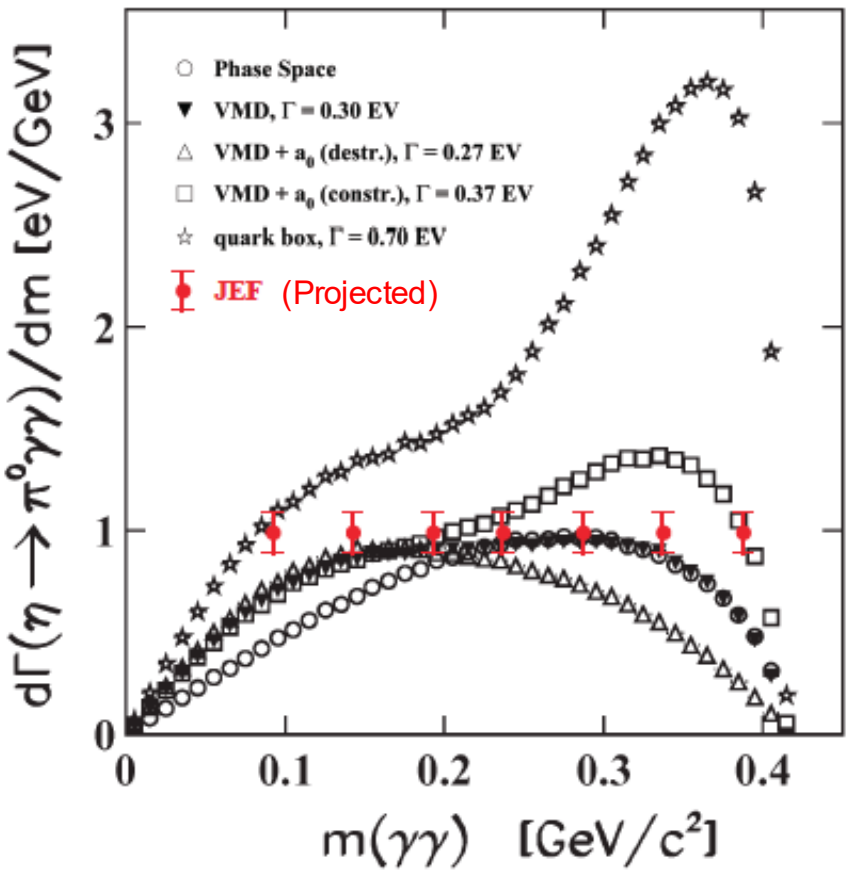
Fig. from Phys. Rev. D, 110(5):055039

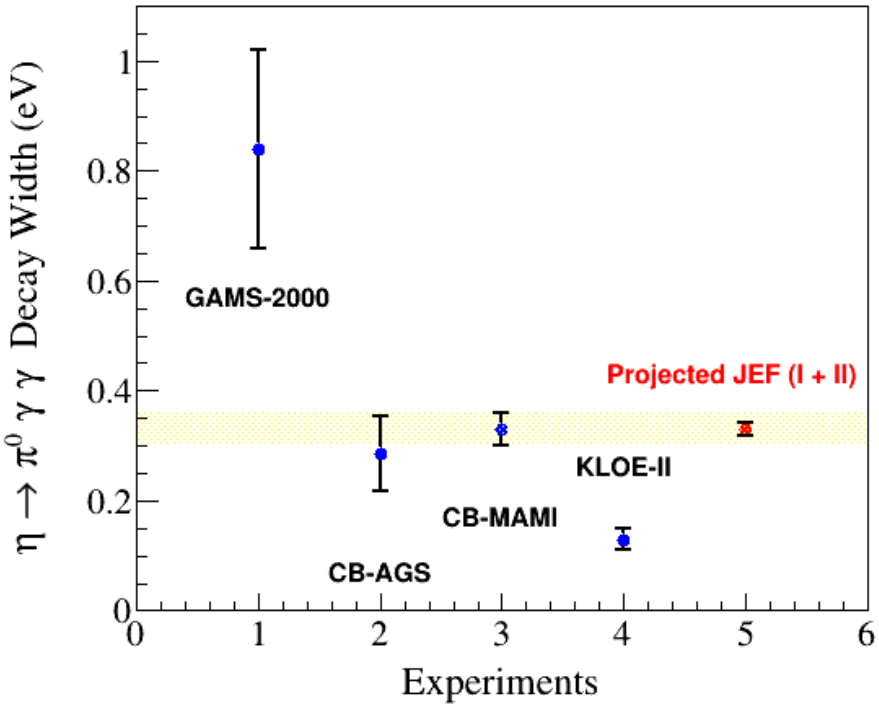
Tighten the constraint on new CVPC physics by:

- improve BR upper limit for $\eta \to 3\gamma$ by ~1 order of magnitude
- increase world data size of $\eta \to \pi^0\pi^+\pi^-$ by ~1 order of magnitude

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

J.N. Ng and D.J. Peters, Phys. Rev. D47, 4939





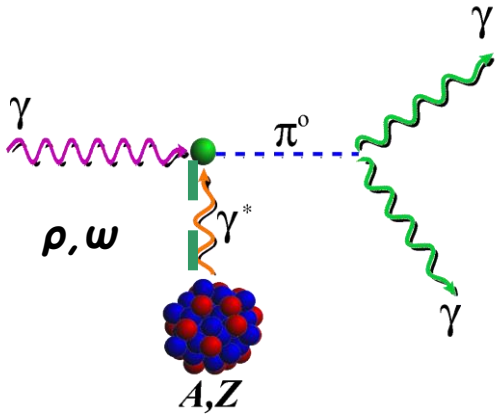
A rare window to probe interplay of VMD & scalar resonance in ChPT

We measure both BR and Dalitz distribution

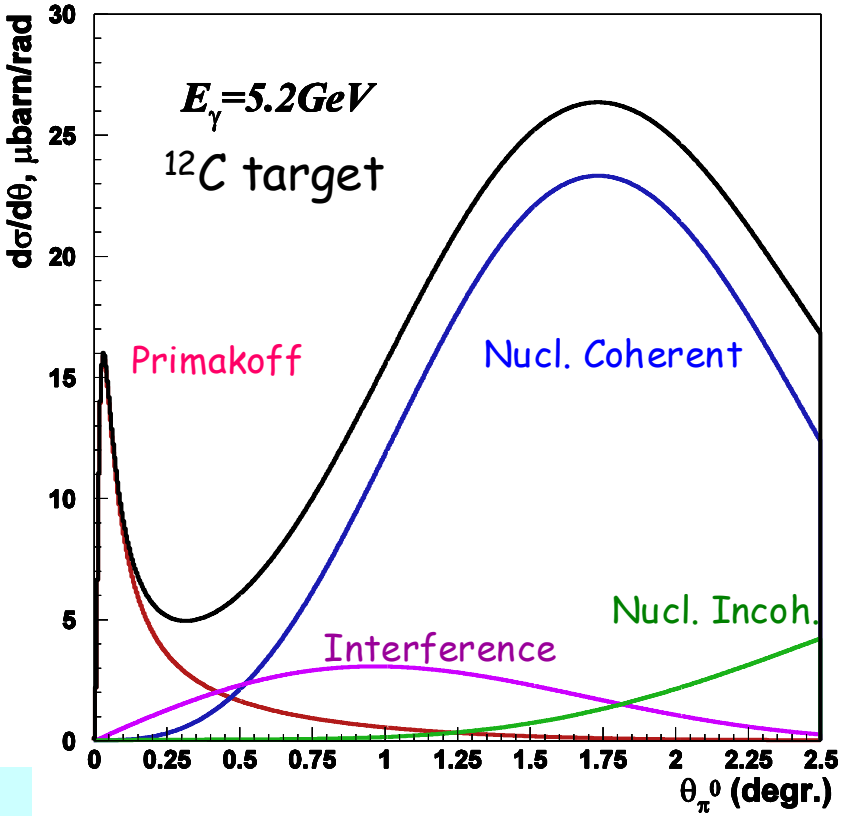
- model-independent determination of two LEC's of the $O(p^6)$ counter- terms
- probe the role of scalar dynamics.

J. Bijnens, talk at AFCI workshop

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:

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

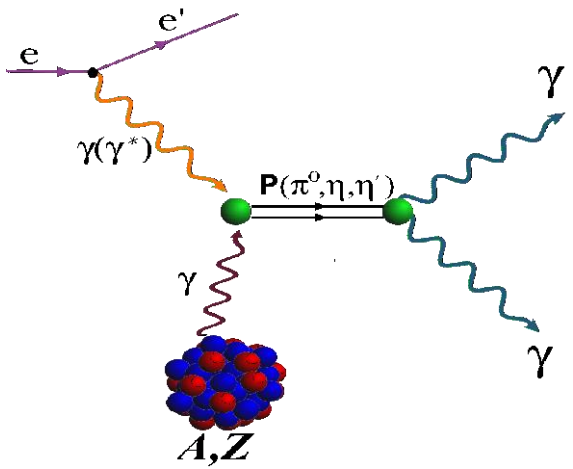
$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \quad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E\,\square A^{1/3}}$$

- 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

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



a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \to \gamma\gamma)$
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 $(g-2)_\mu$

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

Primakoff Program at JLab

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

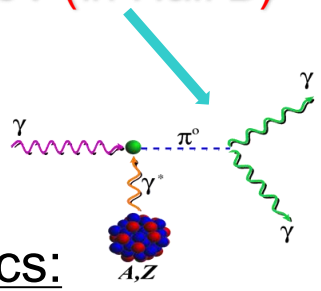
- The chiral anomaly prediction is exact for massless quarks:

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

- $\Gamma(\pi^0 \to \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders!

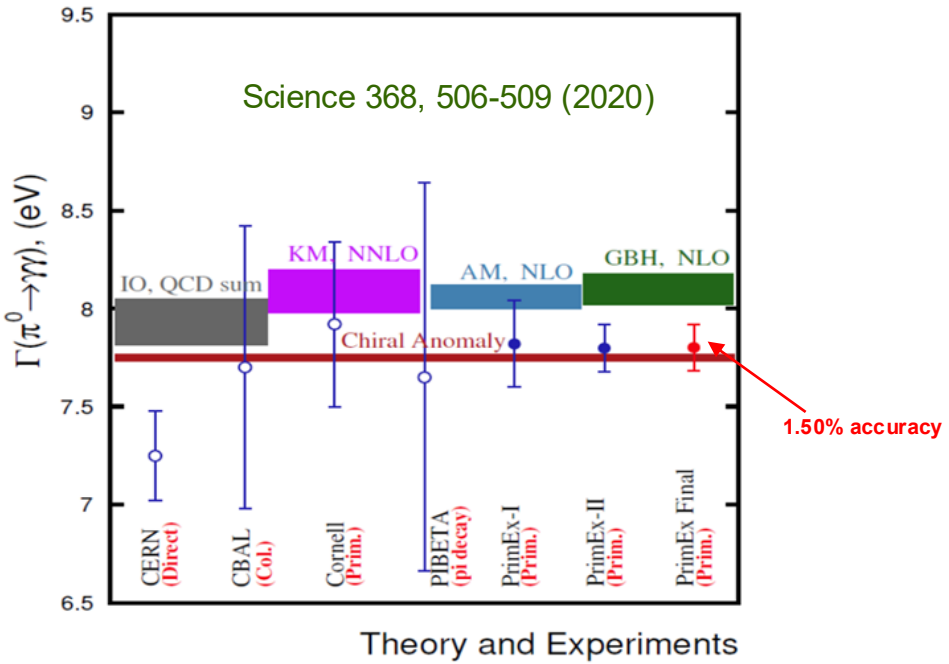
a) Two-Photon Decay Widths:

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



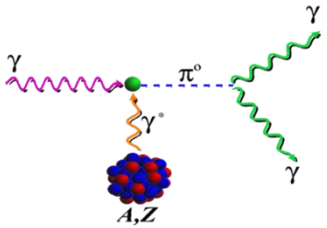
Input to Physics:

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



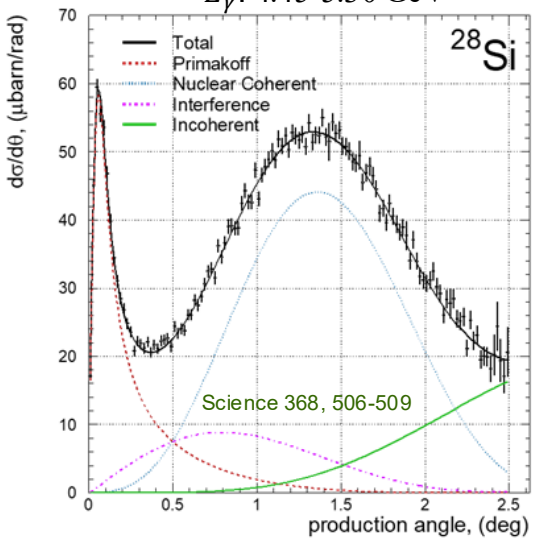
Advantages of an Electron Target

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



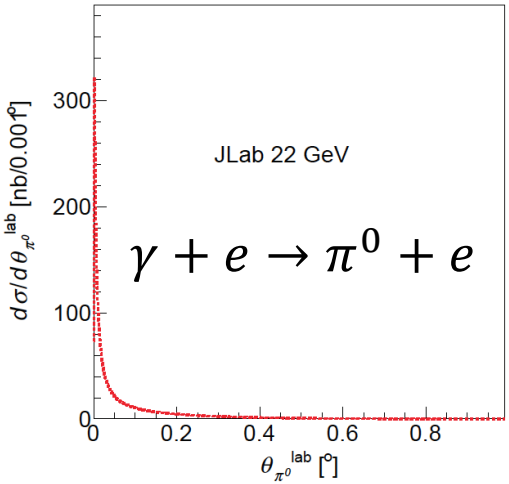
$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha Z^2}{m_\pi^3}\frac{\beta^3 E^4}{Q^4}\left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$

E_γ: 4.45-5.30 GeV



Advantages of an electron target:

- Eliminate all nuclear backgrounds
- No form factor for electron
- Recoiled electron detection



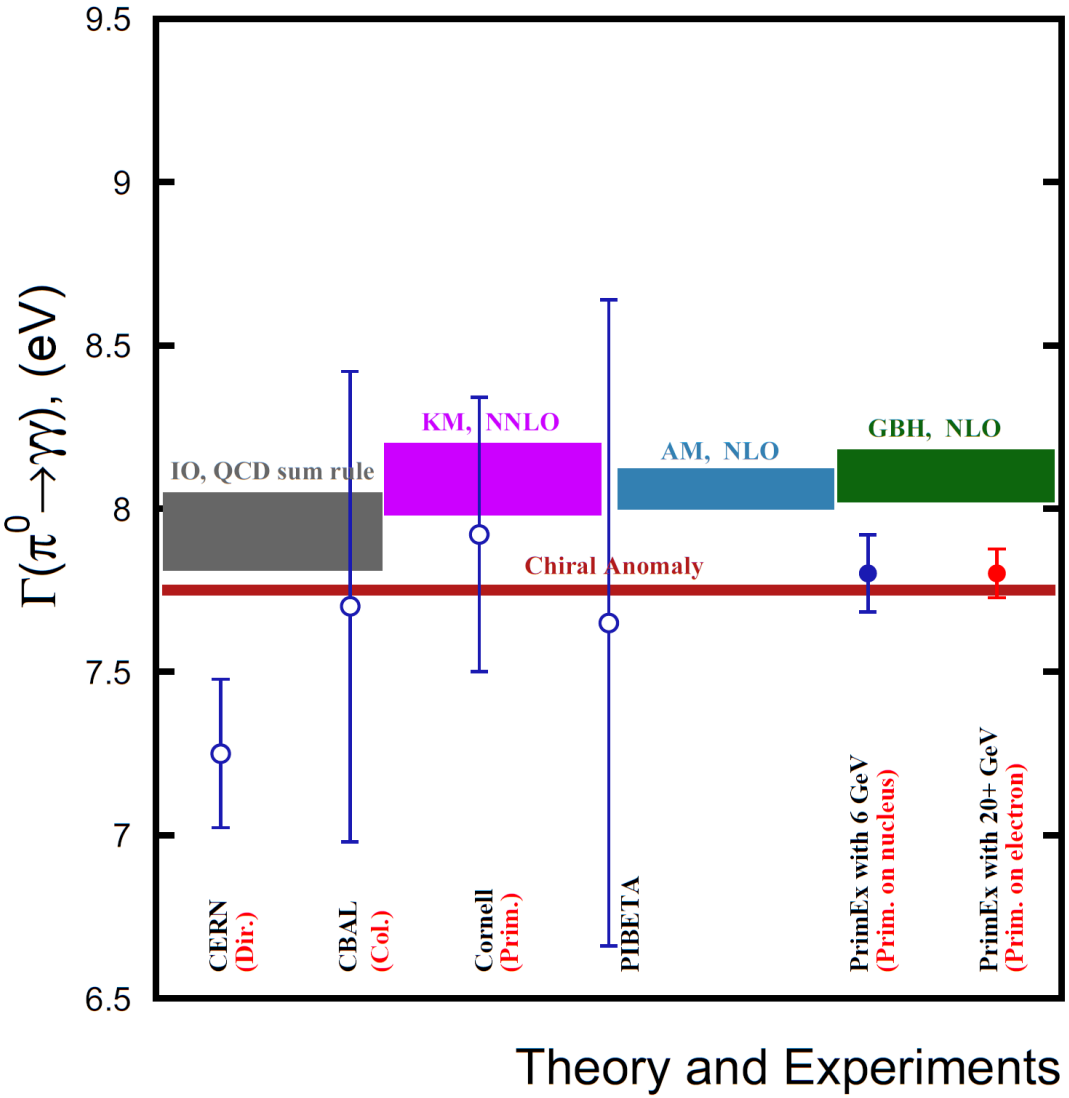
$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha}{m_\pi^3}\frac{\beta^3 E^4}{Q^4}\sin^2\theta_\pi$$

Main challenges for the nuclear target:

- Nuclear backgrounds
- Form factor of nucleus
- No recoil detection

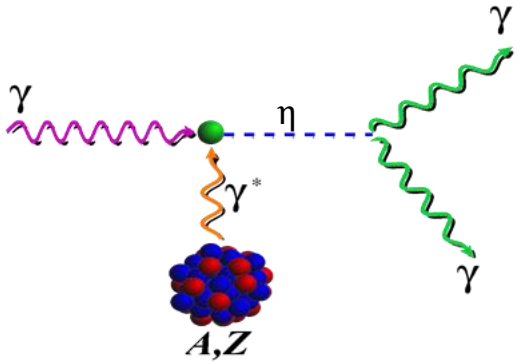
Measurement	Reaction	E_{th} (GeV)
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$	$\gamma + e \rightarrow \pi^0 + e$	18.0
$F(\gamma^*\gamma \rightarrow \pi^0)$	$e + e \rightarrow \pi^0 + e + e$	18.1

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



Primakoff Program at JLab (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) $\Gamma(\eta \to \gamma\gamma)$ @ 12 GeV
3) $\Gamma(\eta' \to \gamma\gamma)$

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

Input to Physics:

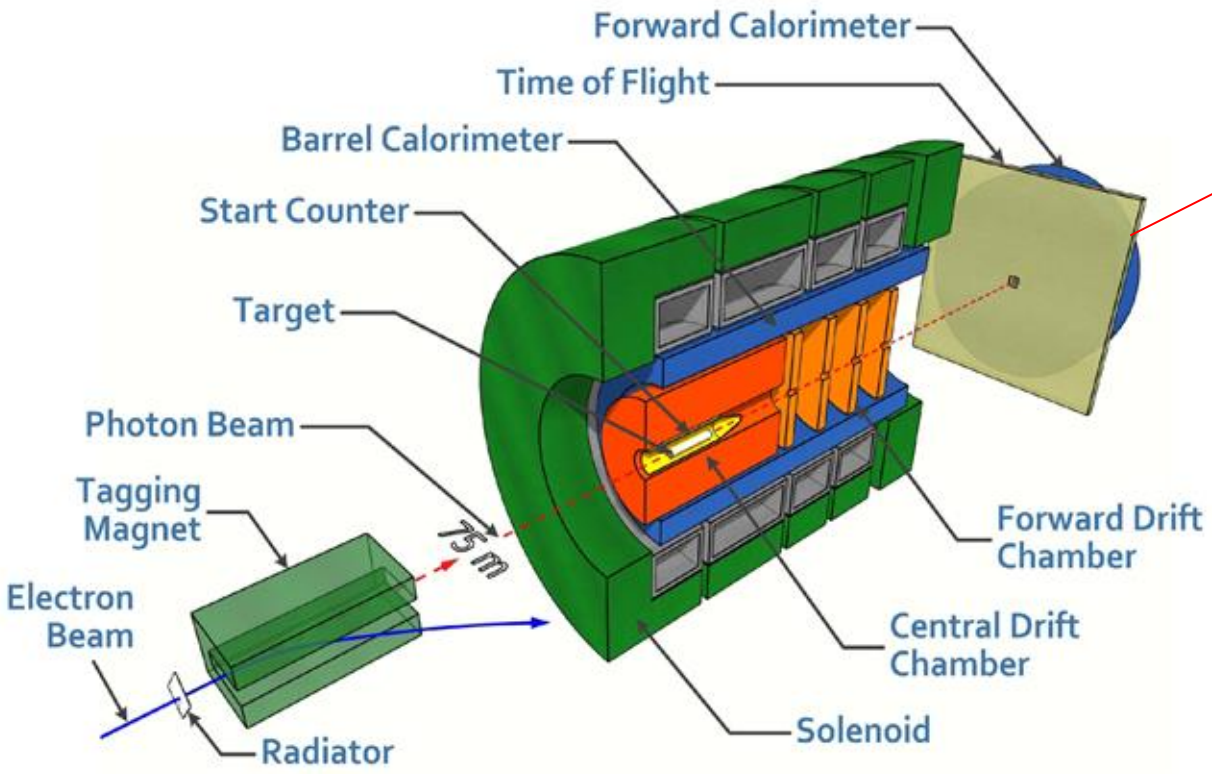
- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g\text{-}2)_\mu$

On-Going PrimEx-eta experiment (in Hall D)

- A full data set was collected by the end of 2022.
- A preliminary result has been extracted.

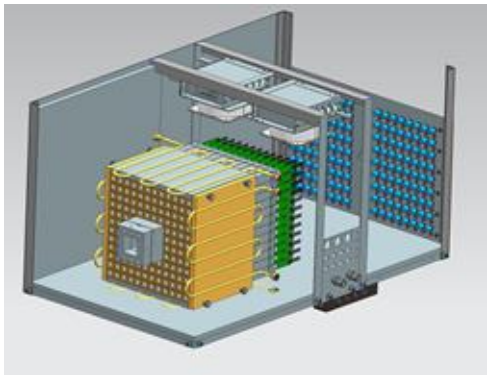
Primex-eta Experiment in Hall D

$\eta(\gamma\gamma)$ production: Two decay photons detected in original Forward Calorimeter (FCAL) in coincidence with tagged beam photon



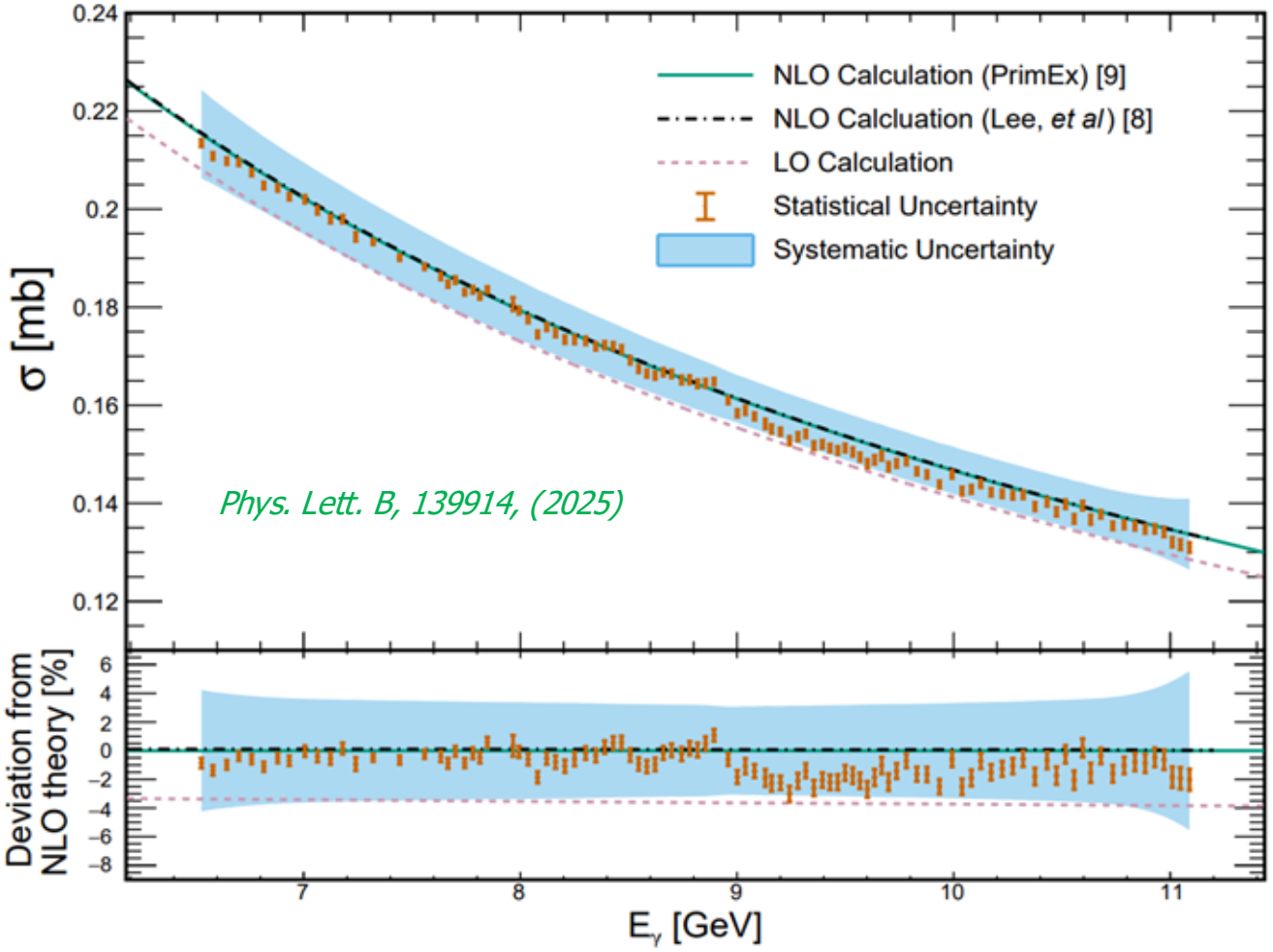
Compton Calorimeter

- $PbWO_4$ crystals
- $0.2° < \theta < 0.6°$



Jefferson Lab

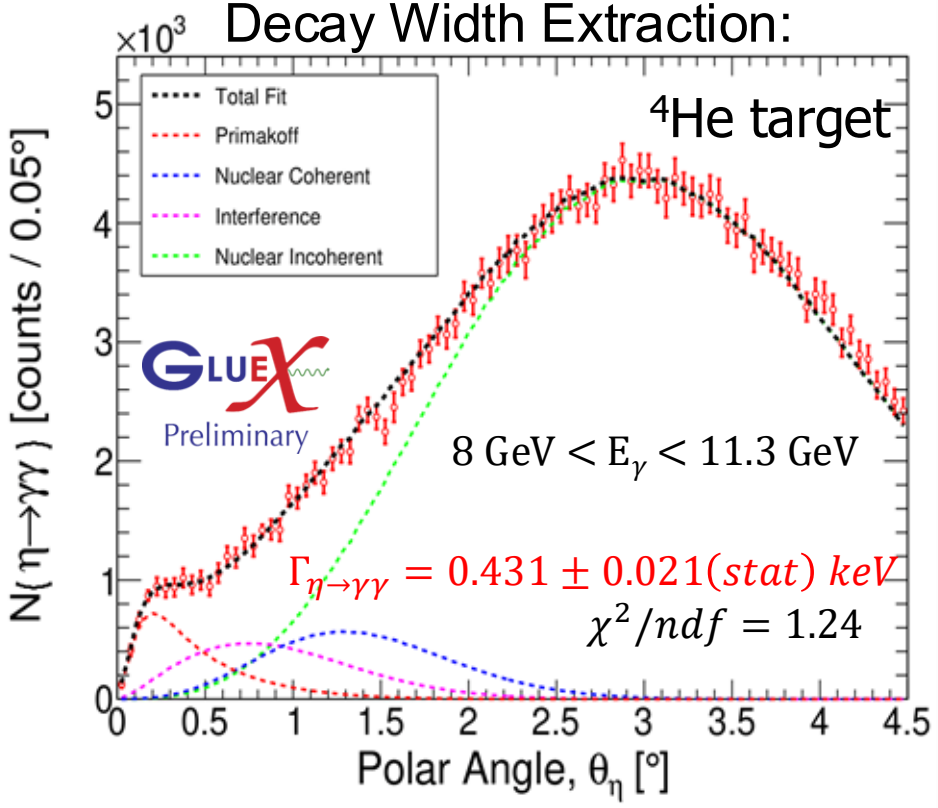
Published Compton Cross Section ($\gamma e^- \rightarrow \gamma e^-$)

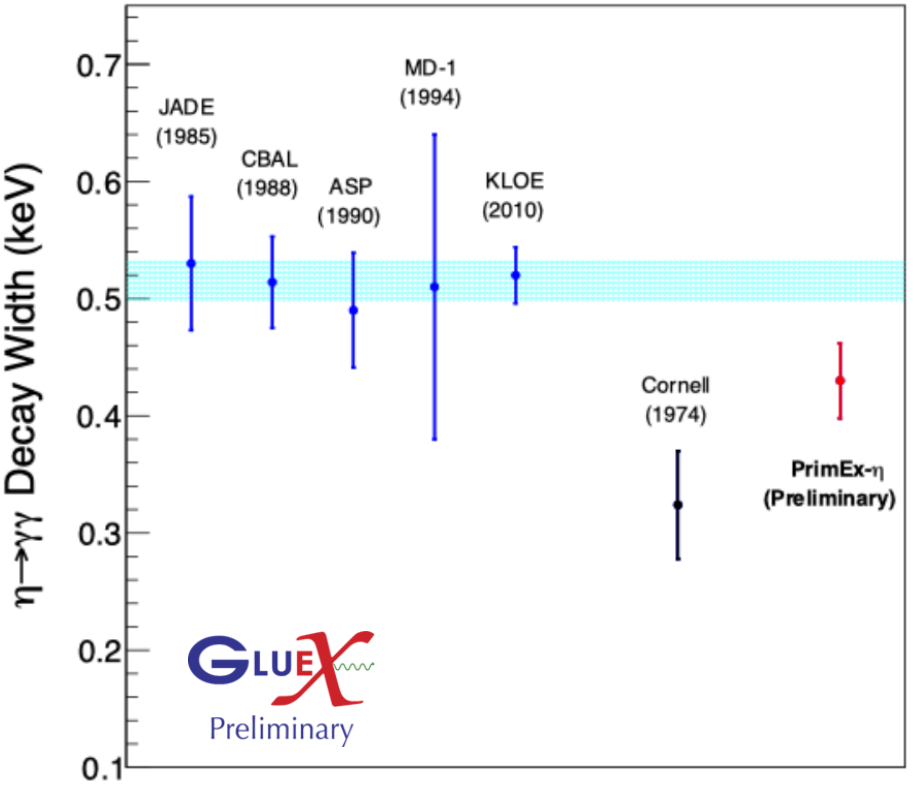


Average combined uncertainty per energy bin: 3.4%.

Preliminary PrimEx-eta Result

Decay Width Extraction:



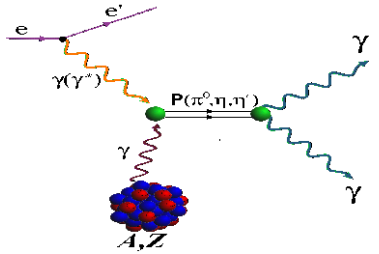


Source	Uncertainty (%)
Event Selection	2.20
Yield Extraction	1.42
Acceptance	1.06
Luminosity	2.07
Model Dependence	4.50
Total Systematic	5.70
Statistical	4.80
Total	**7.45**

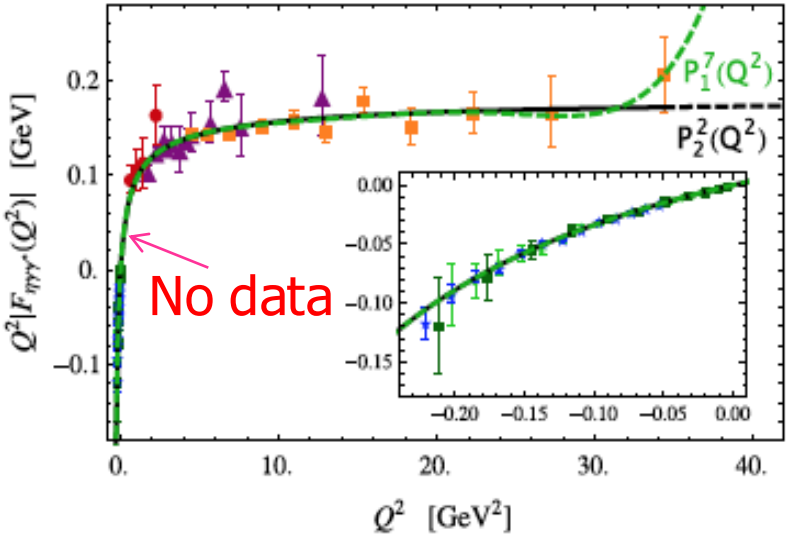
PrimEx-η preliminary result:

- lies between previous collider and Primakoff results
- ~2.3**σ** below the collider average.

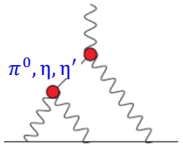
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

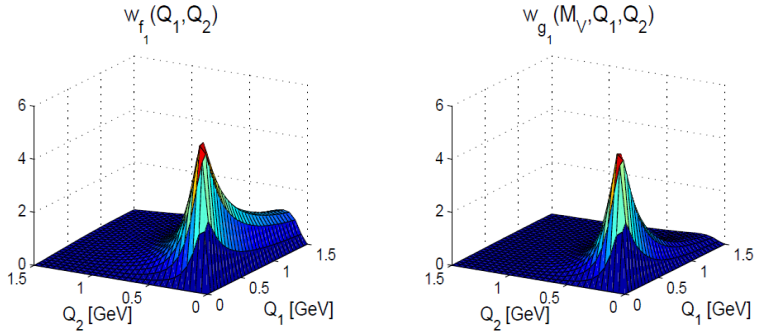


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



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





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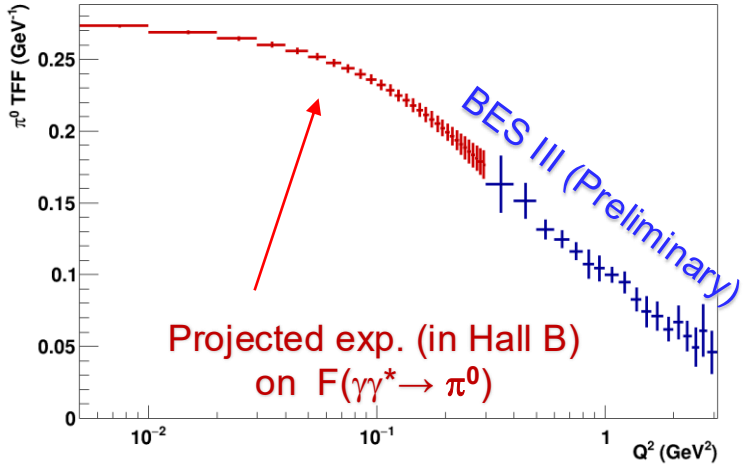

Summary

- Light pseudoscalar mesons offer a sensitive probe to test the standard model and to search for new physics beyond.

- The JEF-I experiment: 75% data was collected and remaining data will be completed in 2026, with the upgraded FCAL-II. Future JEF-II will add a factor of 4 statistics.
  - ✓ Search for sub-GeV hidden bosons: vector, scalar, and ALP
  - ✓ Directly constrain CVPC new physics
  - ✓ Precision tests of low-energy QCD: light quark mass ratio; the role of scalar dynamics in ChPT; transition form factors of η/η' to understand the origin of visible mass and to calculate HLbL contributions in $(g\text{-}2)_\mu$

- 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.
  - ✓ A preliminary result of $\Gamma(\eta \to \gamma\gamma)$ was extracted and the final publication is in progress.
  - ✓ A new experiment on $F(\pi^0 \to \gamma^* \gamma)$ off a nuclear target is on the way.

  future JLab 22 GeV upgrade will offer new opportunities
  - ✓ New generation of Primakoff experiments on $\Gamma(\pi^0 \to \gamma\gamma)$ 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.