The η and η' physics at JLab

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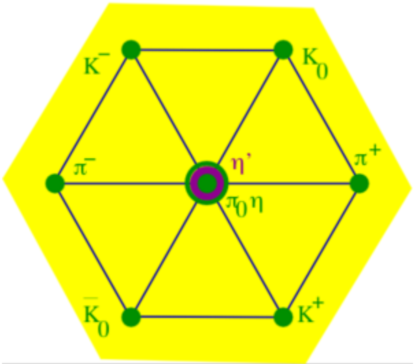
Outline

1. Overview of η and η' physics
2. Two experimental programs at JLab
   - Primakoff experiment
   - JLab Eta Factory (JEF) experiment
3. Summary

Why η is a unique probe for QCD and BSM physics?



- A Goldstone boson due to spontaneous breaking of chiral symmetry in QCD
  → η plays important role in bridging our understanding of low-energy hadron dynamics and underlying QCD

- All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width (Γ_η =1.3KeV compared to Γ_ω=8.5 MeV)
  → Enhanced sensitivity to the higher order contributions (by a factor of ~7000 compared to ω decays) for new physics search

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  → tests for C, CP

- All its additive quantum numbers are zero and its decays are flavor-conserving
  → effectively "free" of SM backgrounds for new physics search.

Rich η and η' Physics

Standard Model Tests:
- Chiral symmetry and anomalies
- Extract η-η' mixing angle and quark mass ratio
- Theory inputs to HLbL for $(g\text{-}2)_\mu$
- Scalar dynamics in ChPT

Fundamental Symmetry Tests:
- C, CP violations
- P, CP violations

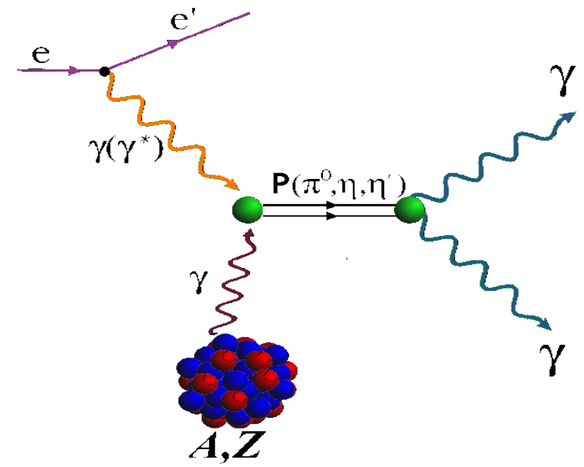
BSM Physic Searches:
- Vector bosons (B boson, dark photon and X boson)
- Dark scalars
- Pseudoscalars (ALPs)
- BSM weak decays

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[54]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [55]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

arXiv:2007.00664

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

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

Status of Primakoff Program at JLab 6 & 12 GeV

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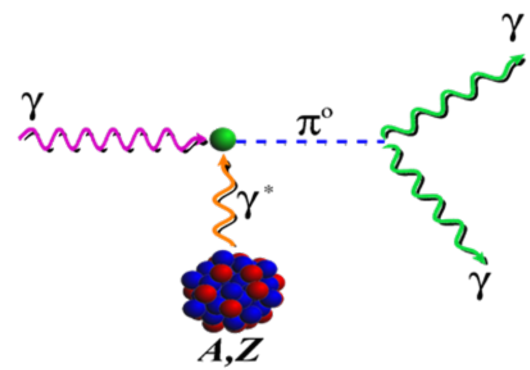

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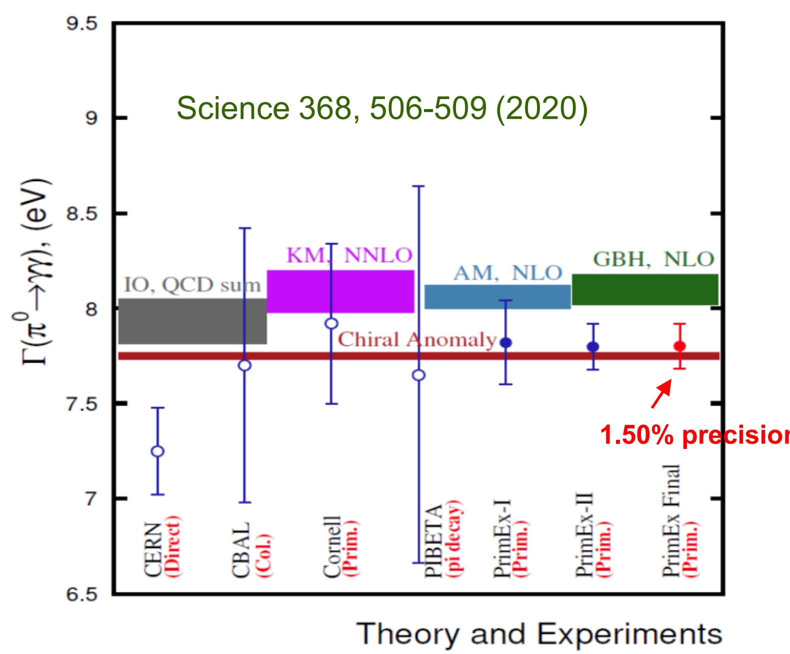

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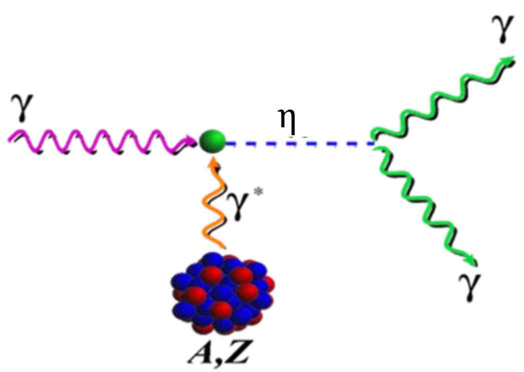


a) Two-Photon Decay Widths:

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

Input to Physics:

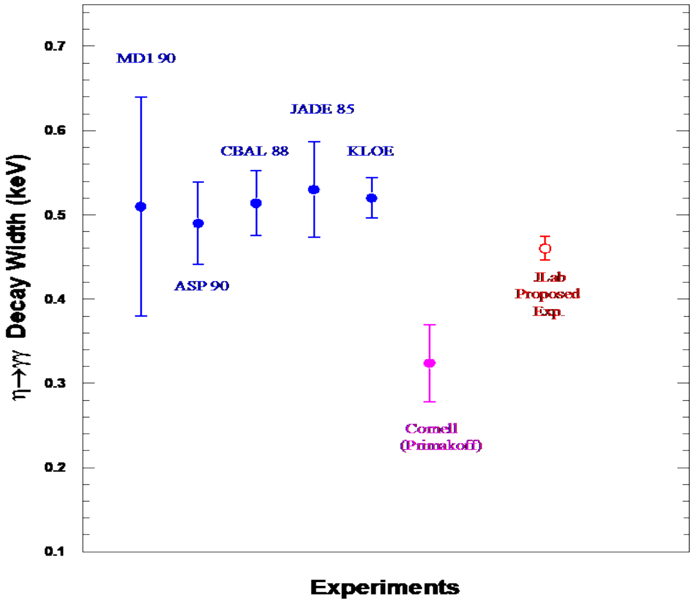
- precision tests of Chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle
- input to calculate HLbL in $(g-2)_\mu$

On-Going PrimEx-eta experiment

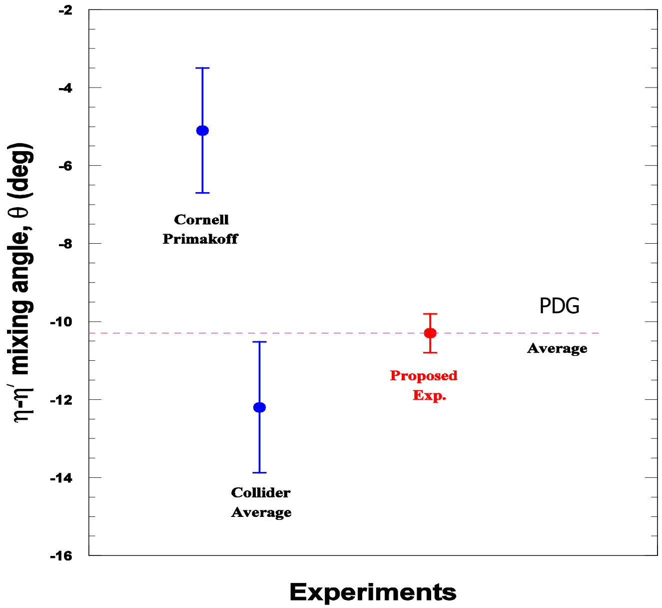
- Two data sets were collected in 2019 and in 2021.
- The third run started on Aug 18 until Dec 19, in 2022.

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

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



2. **Extract η-η′ mixing angle:**



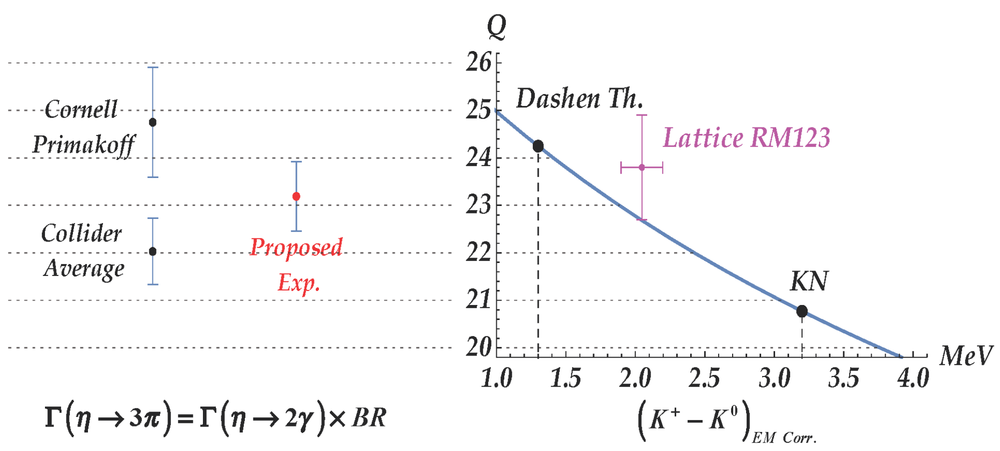
3. **Improve calculation of the η-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g\text{-}2)_\mu$**

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

Precision Determination Light Quark Mass Ratio

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

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



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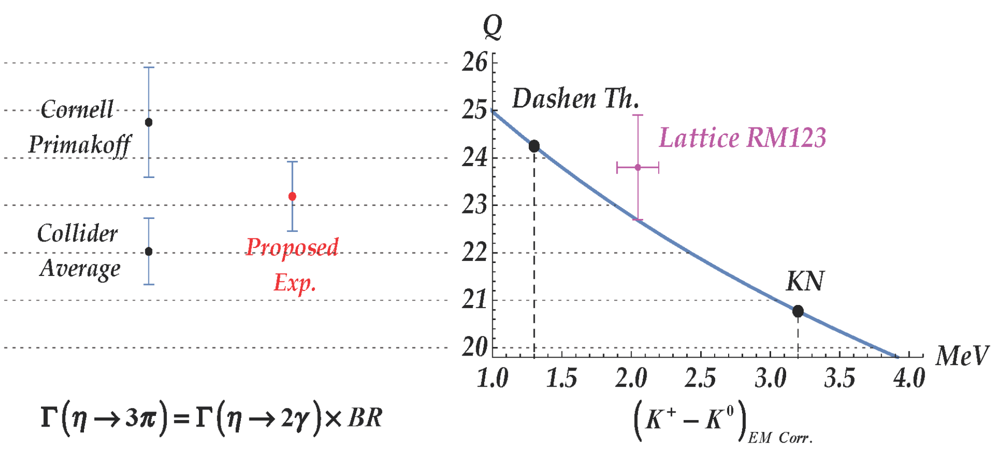

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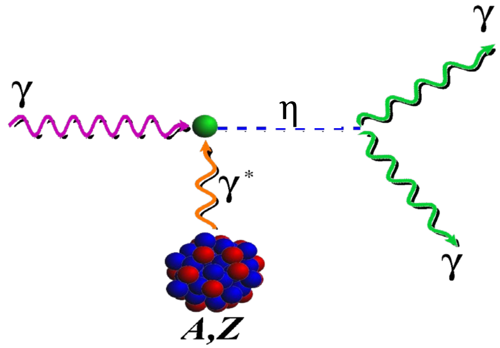
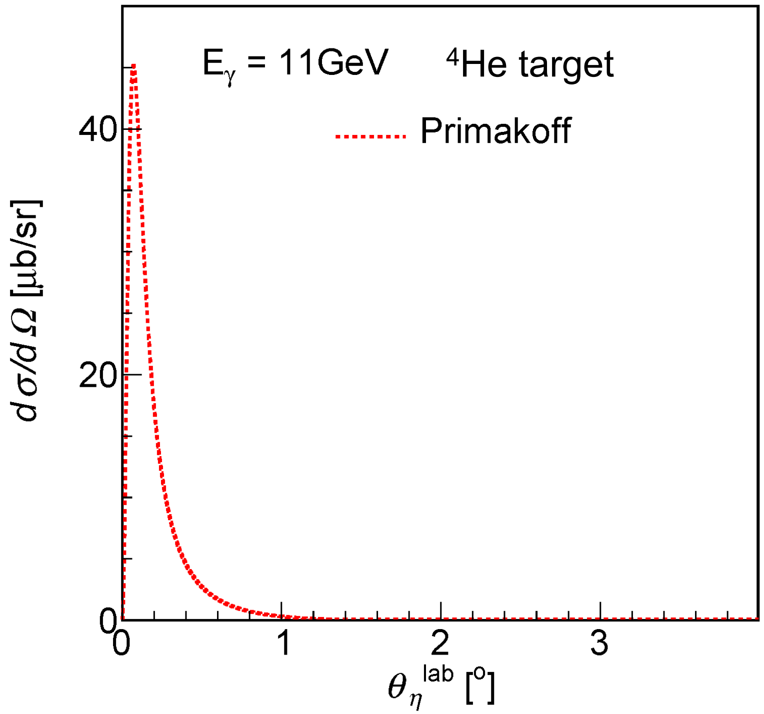
- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Primakoff Method



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



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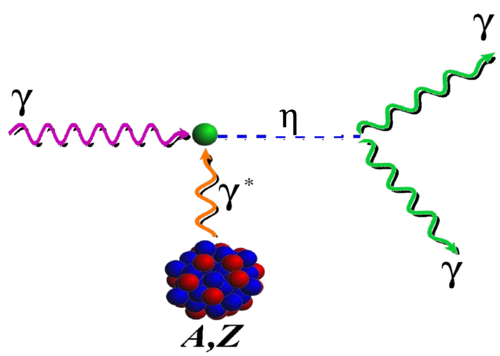

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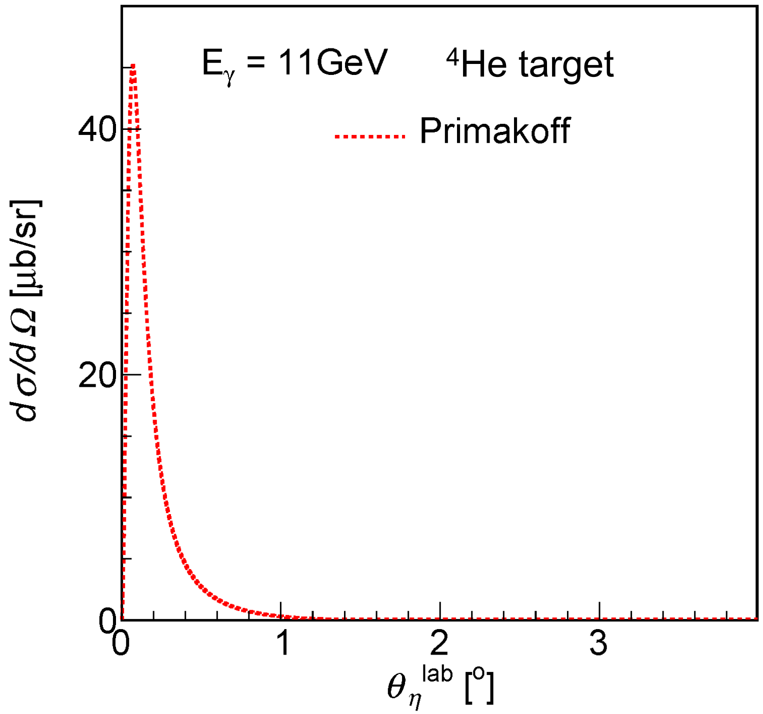


- Peaked at very small forward angle

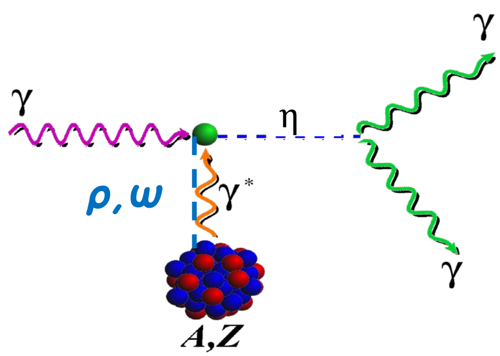
$$\langle \theta_{\mathrm{Pr}} \rangle_{peak} \propto \frac{m^2}{2E^2}$$

- Beam energy sensitive:

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

- Coherent process

Primakoff Method



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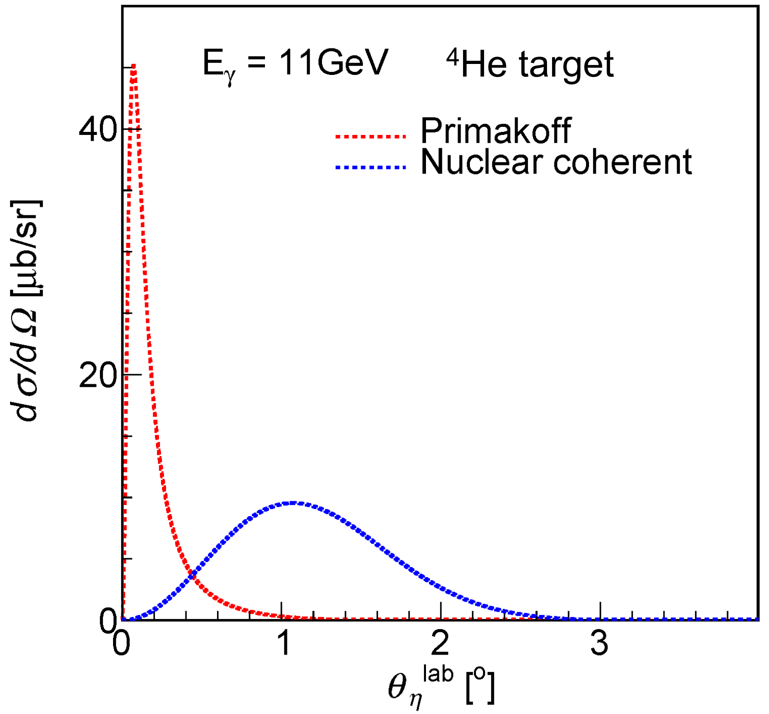

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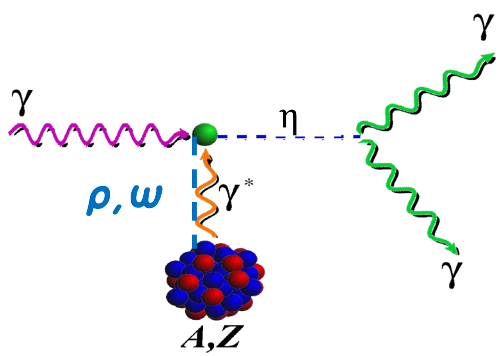

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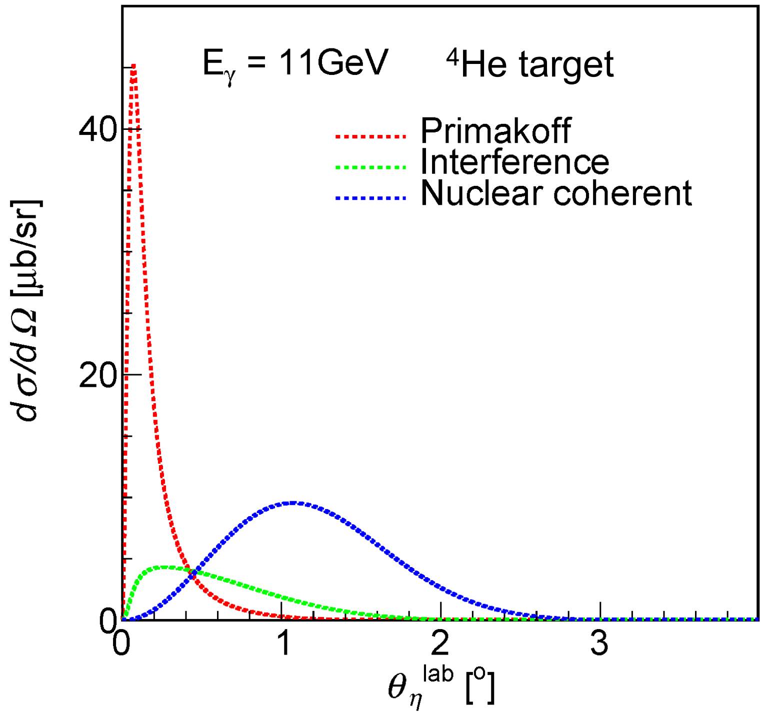

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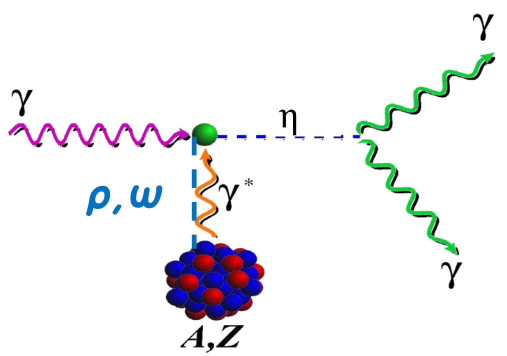

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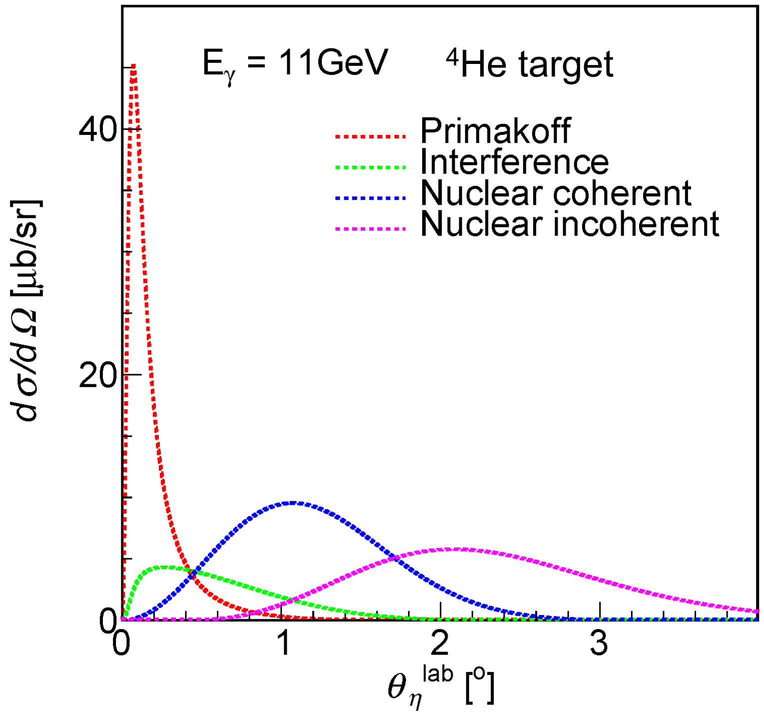

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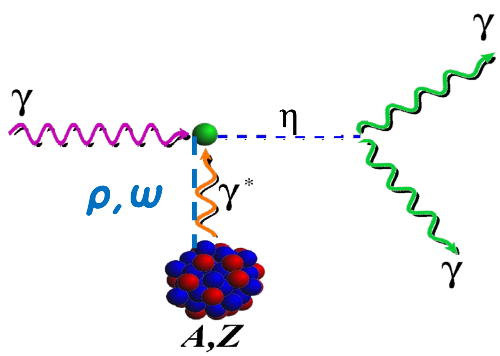

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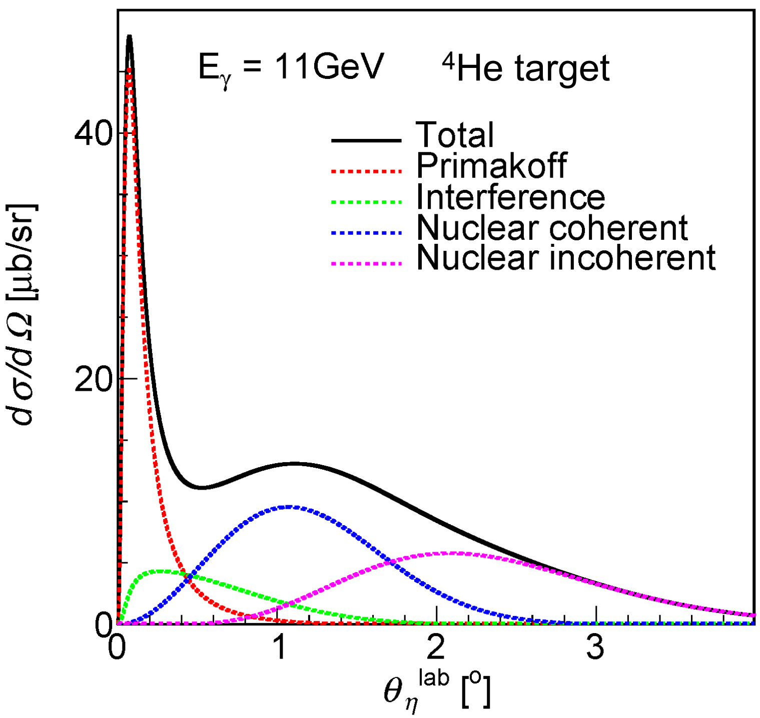

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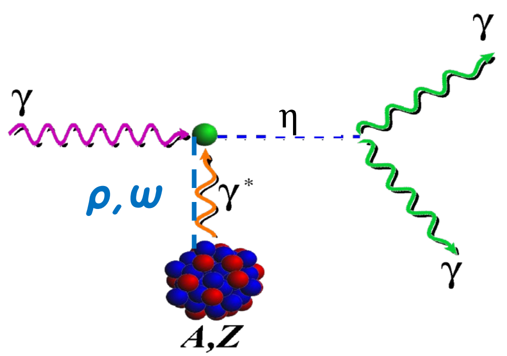

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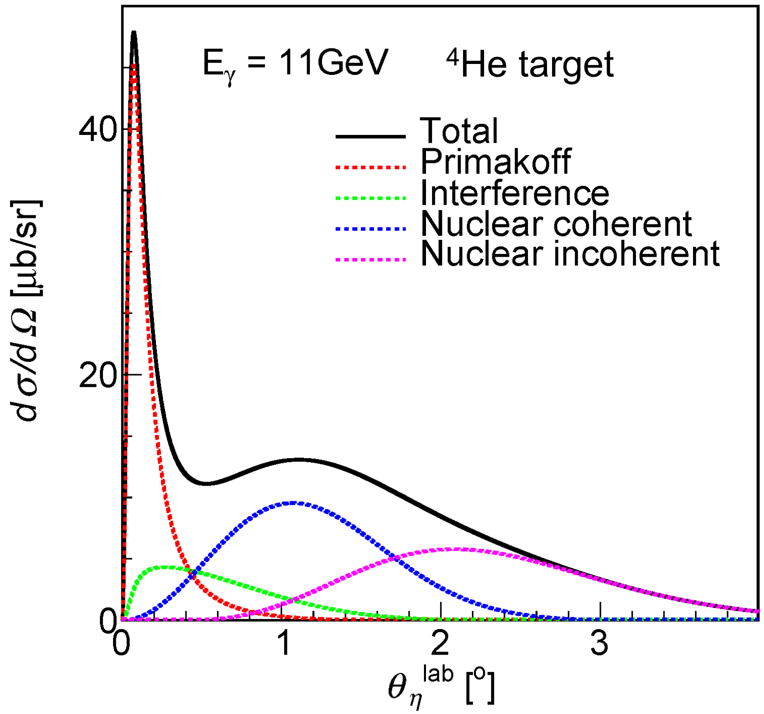

Requirement:

- Photon flux
- Beam energy
- Compact nuclear target

- Peaked at very small forward angle

$$\langle \theta_{Pr} \rangle_{peak} \propto \frac{m^2}{2E^2}$$

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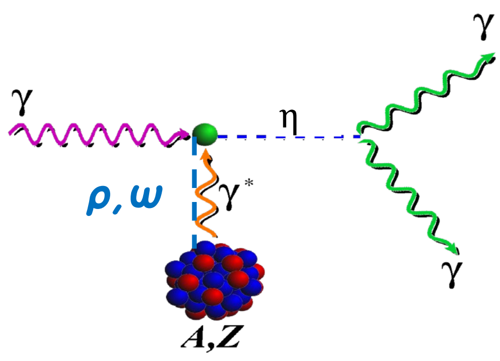

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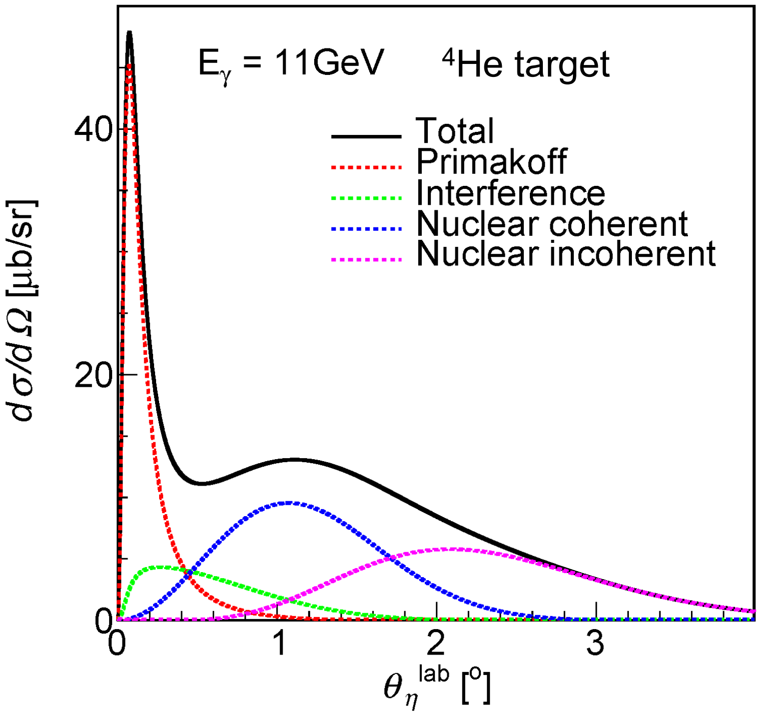

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Tagged photon beam

- Peaked at very small forward angle

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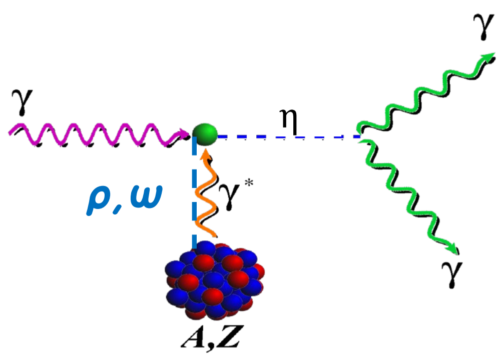

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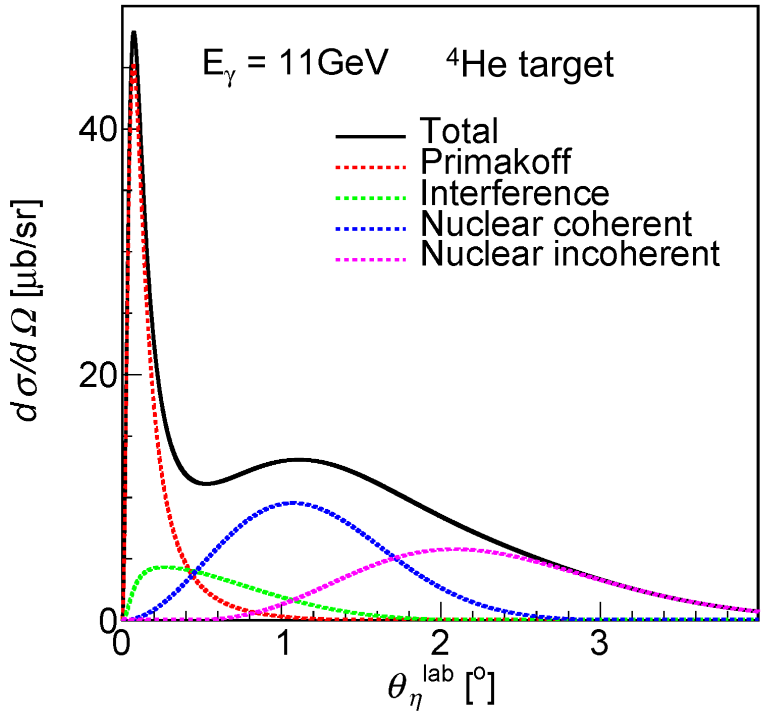

Requirement:

- Photon flux
- Beam energy

Tagged photon beam

- Compact nuclear target

^{4}He target

- Peaked at very small forward angle

$$\langle\theta_{\text{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2}$$

- Beam energy sensitive:

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- Coherent process

Experimental Challenges

Compared to π^0:

- η mass is a factor of 4 larger
- smaller Primakoff cross section

$$\left\langle \frac{d\sigma_{\mathrm{Pr}}}{d\Omega} \right\rangle_{peak} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

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

- larger momentum transfer (coherency, form factors, FSI,…)

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1. Higher beam energy
2. Light targets

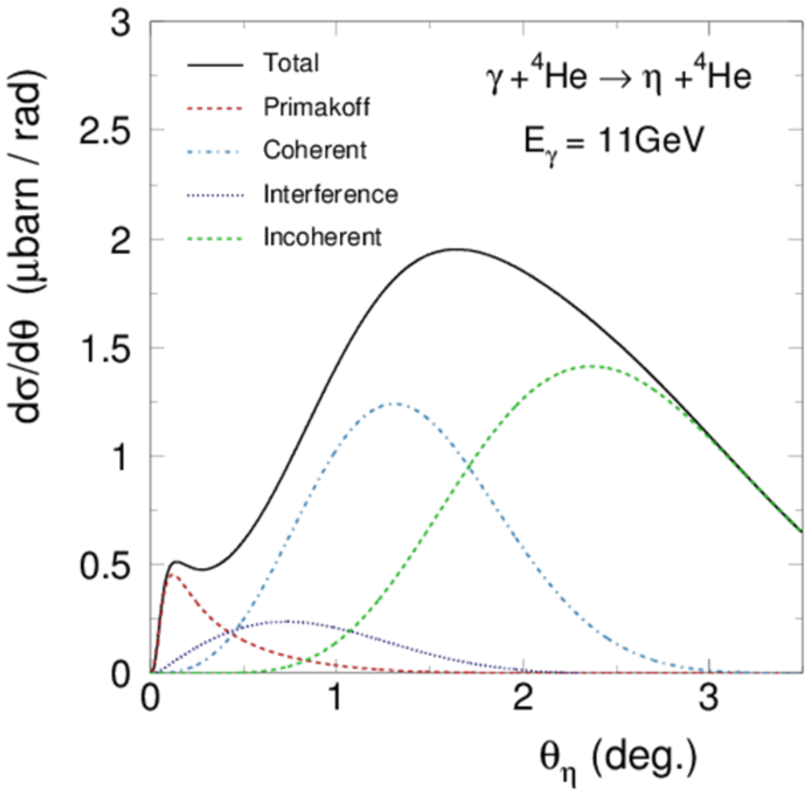
Advantage of Light Targets

Low A targets to control:

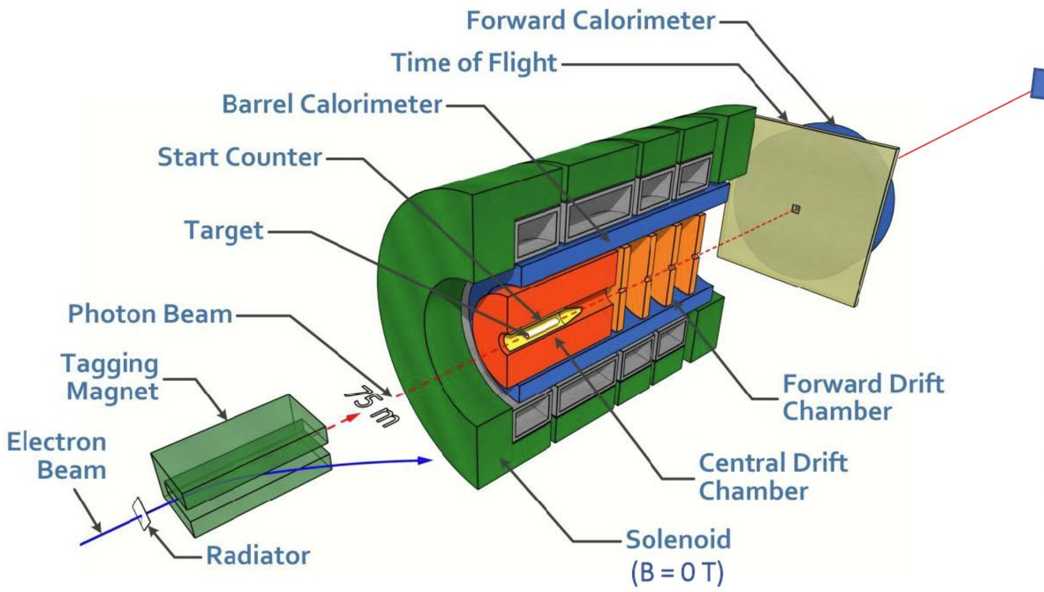
- Coherency: compact nucleus
- Separate background

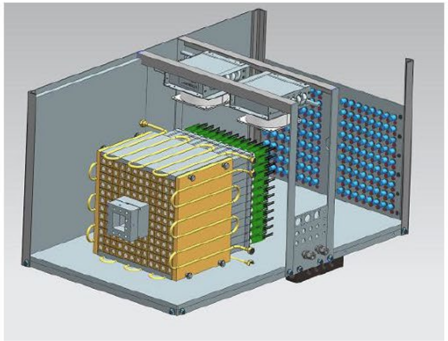
$$\langle \theta_{Pr} \rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \langle \theta_{NC} \rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- Well known form factors



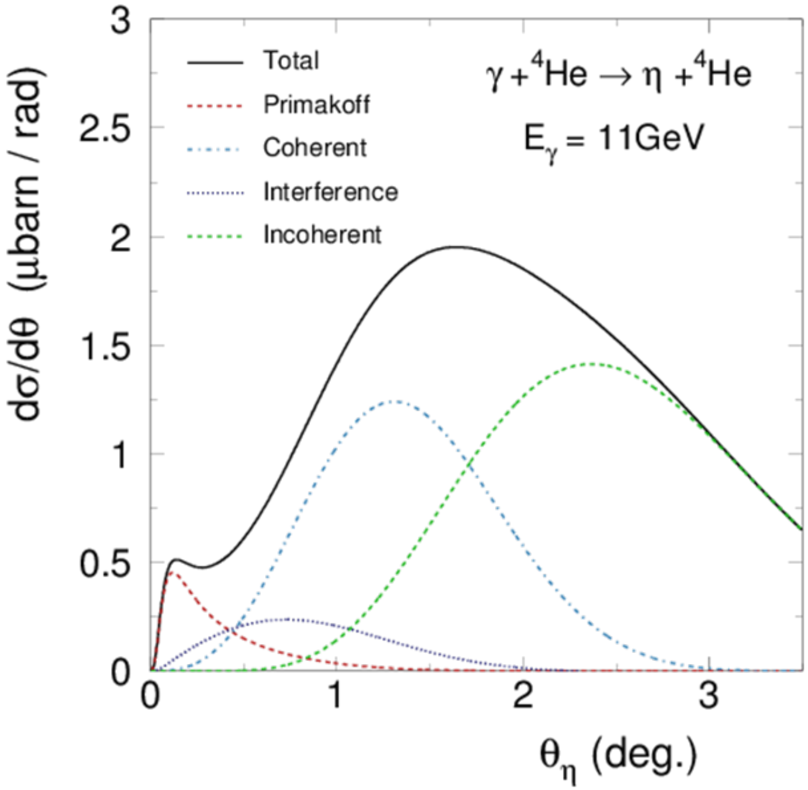
PrimEx-eta Experiment on $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D





- 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.)
- Forward Calorimeter (FCAL) detects the η decay photons; the GlueX spectrometer will detect the charged particles from the η decays.
- CompCal and FCAL to measure electron Compton scattering for control of overall systematics.

How to measure η?



Reconstruct η via three decay channels:

(1) $\eta \to \gamma\gamma \ (B.R. = 39.41\%)$

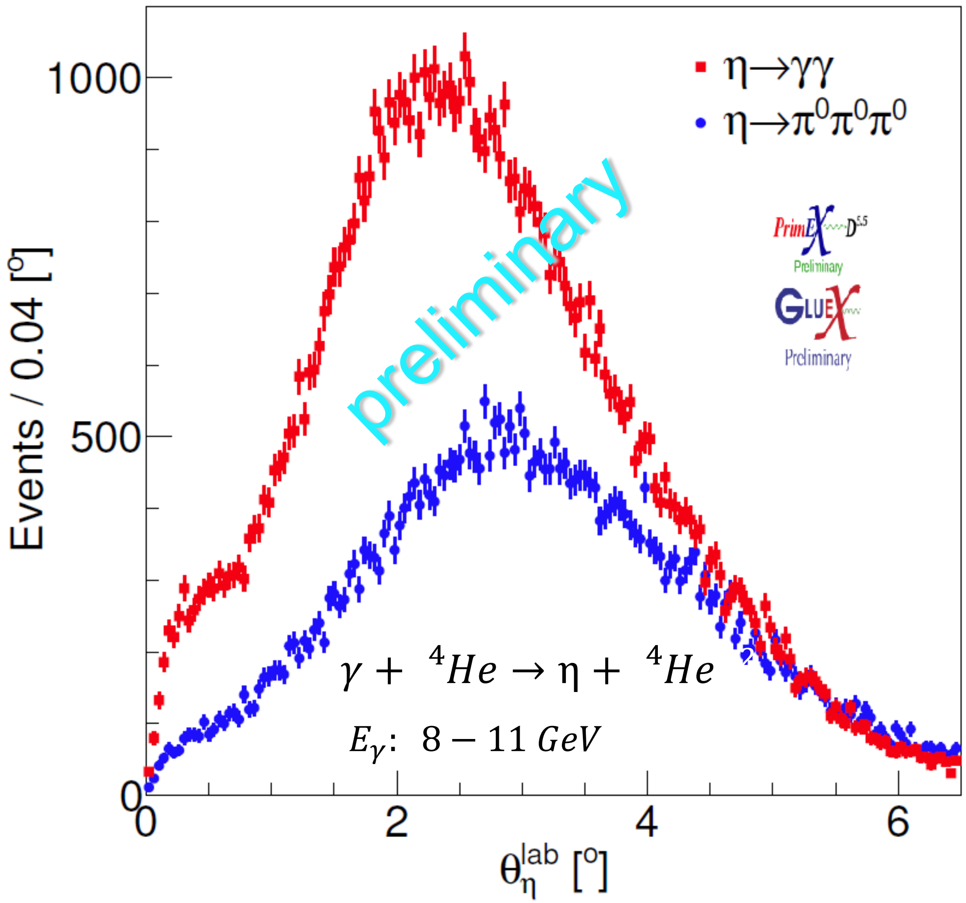
(2) $\eta \to 3\pi^0 \ (B.R. = 32.69\%)$

(3) $\eta \to \pi^+\pi^-\pi^0 \ (B.R. = 22.92\%)$

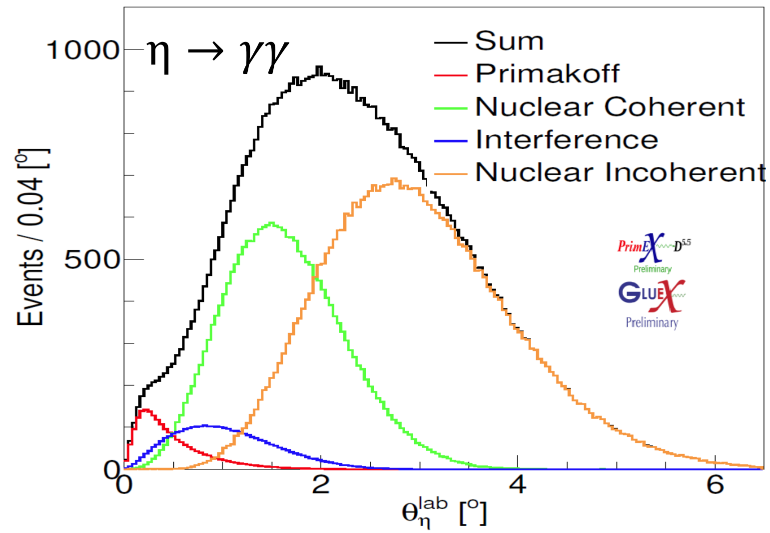
Measure the $\gamma + {}^4He \to \eta + {}^4He$ cross section via three η decay channels to control experimental systematics

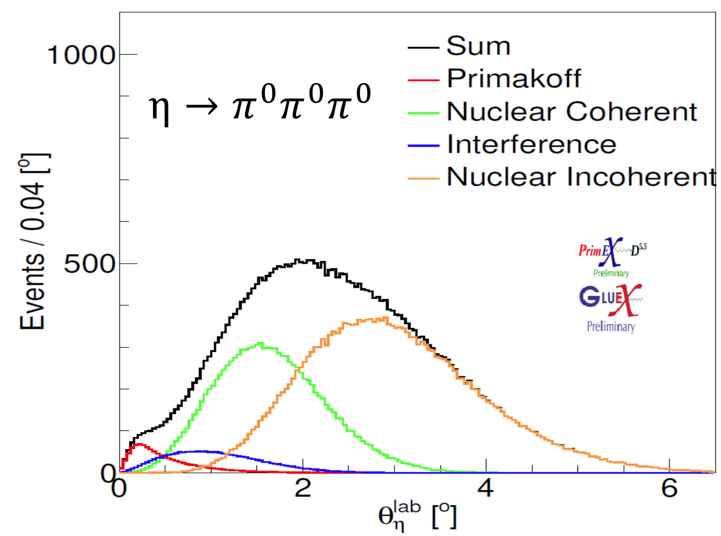
Preliminary Results on the η Yield

η Yield from phase I data:



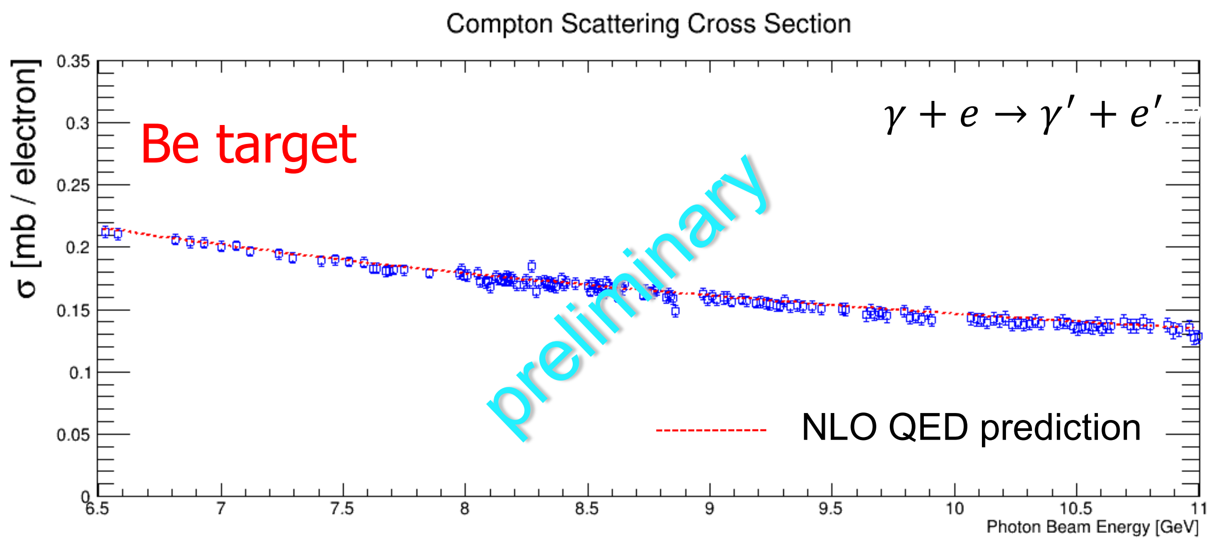
Simulations:

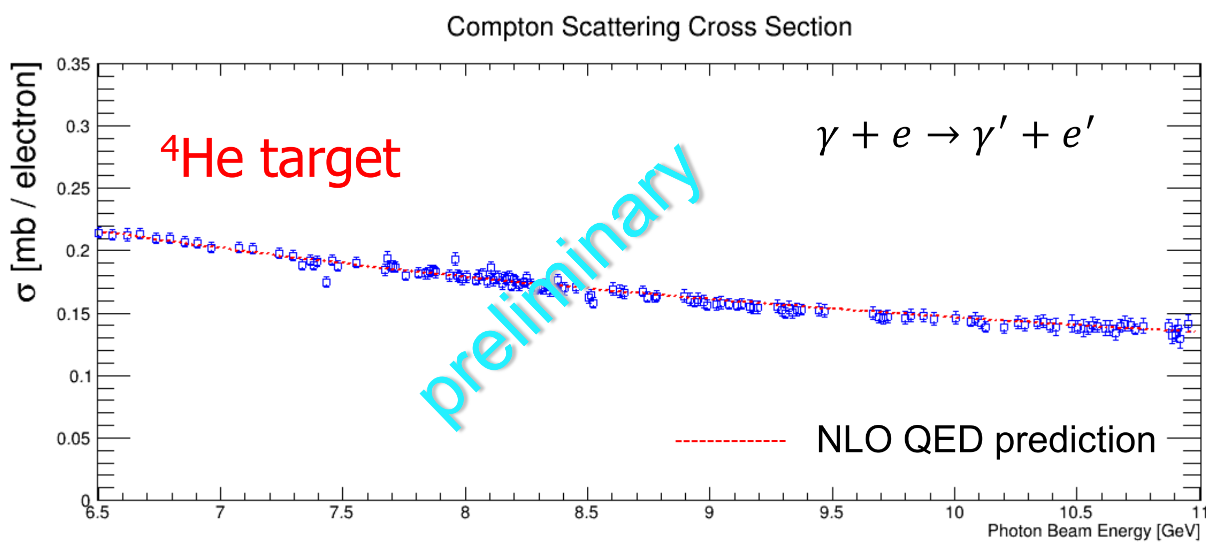




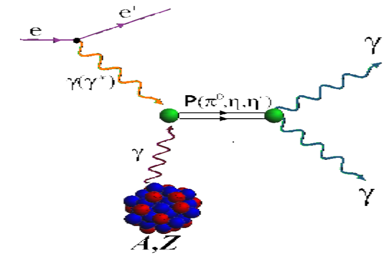
More details presented by Igal Jaegle, **Y07.00003**

Control Systematics with Compton Scattering

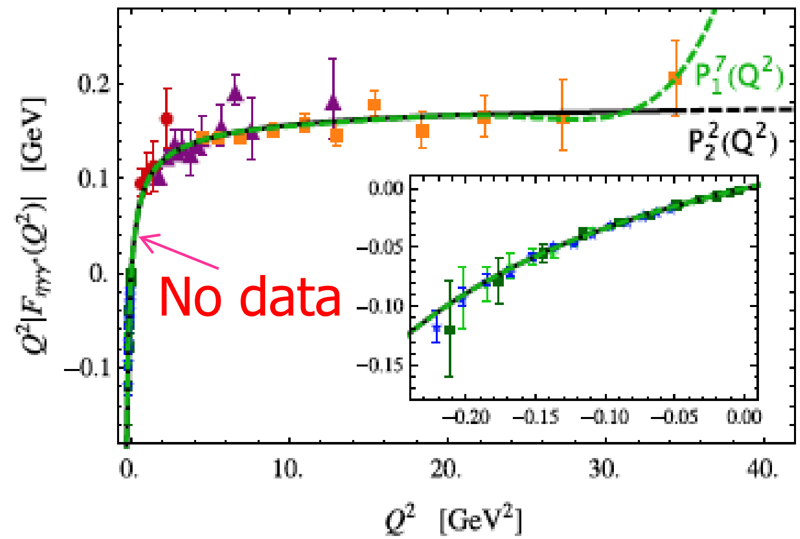




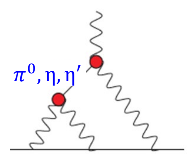
Space-Like Transition Form Factors
(Q^2 : 0.001-0.3 GeV^2/c^2)

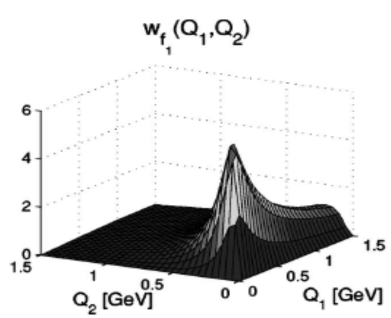


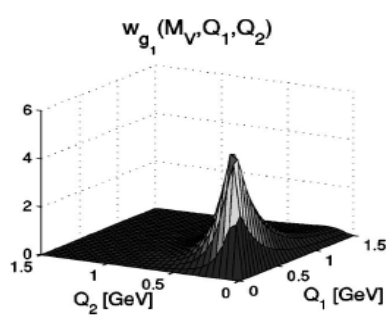
- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



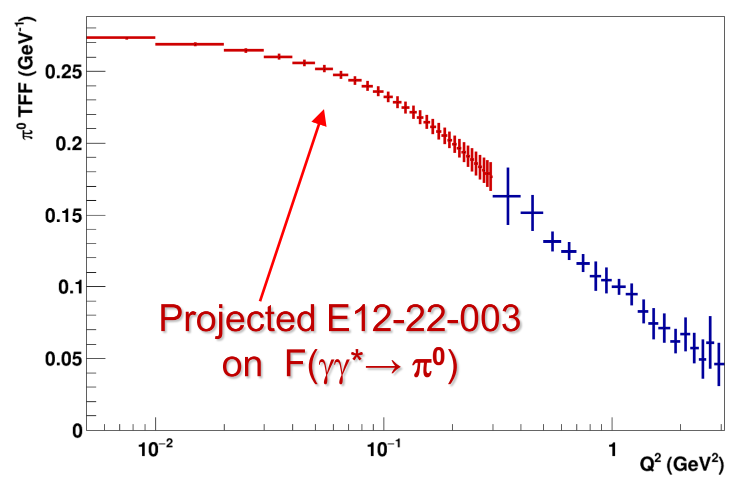
- Input for hadronic light-by-light calculations in muon (g-2)







Phys.Rev.D65,073034



Space-Like Transition Form Factors
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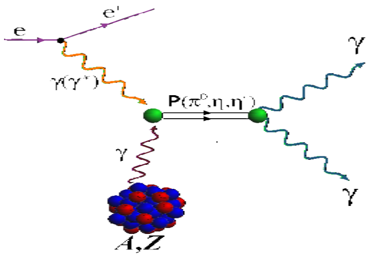

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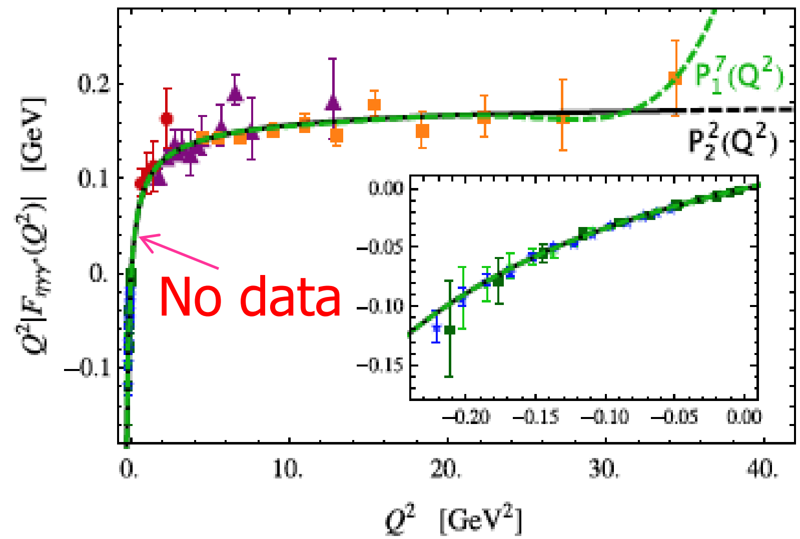

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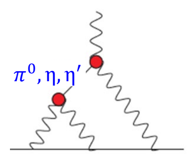
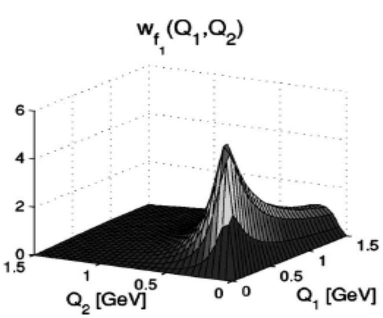
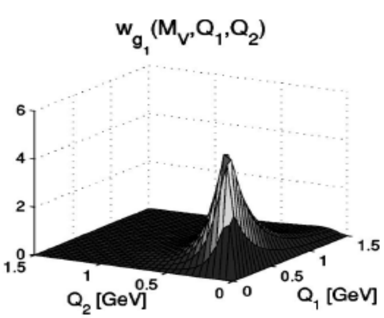
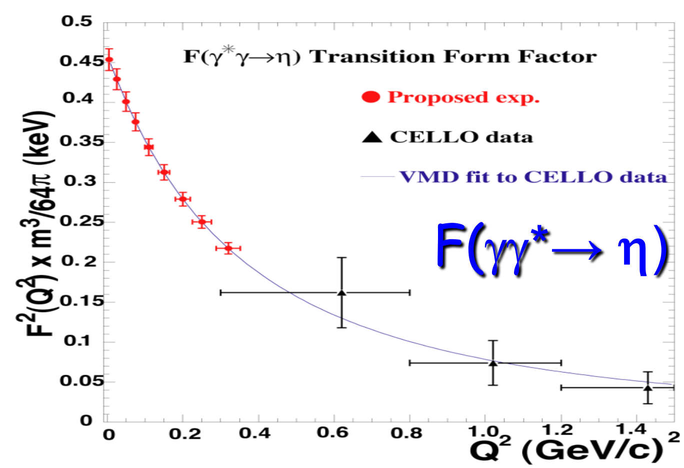


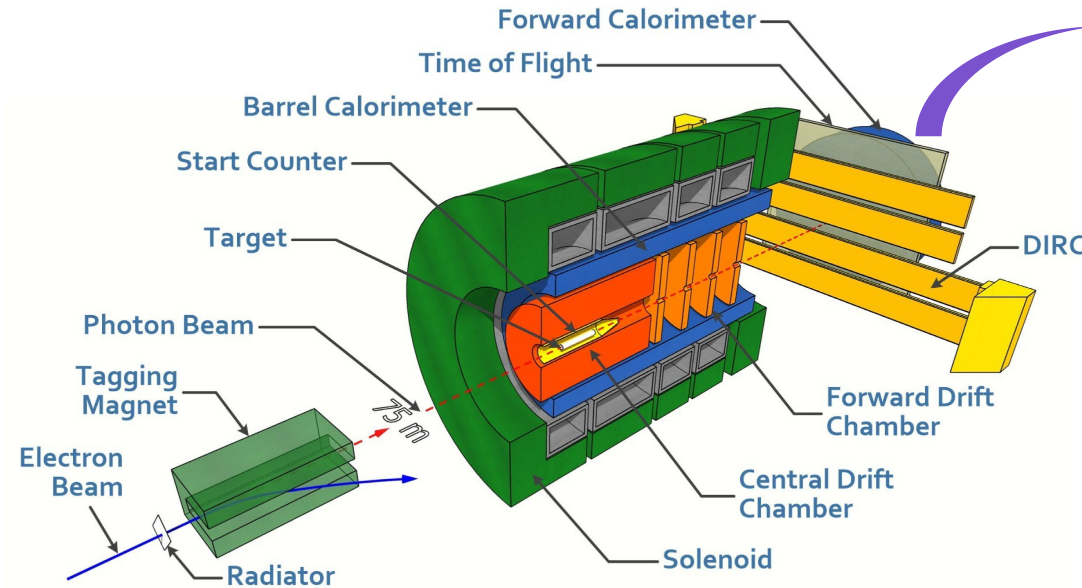


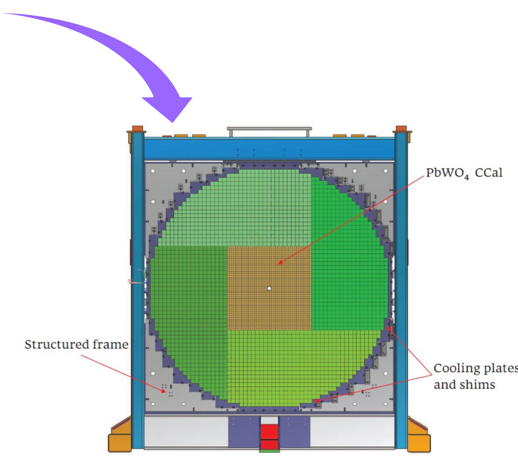


Phys.Rev.D65,073034



JLab Eta Factory (JEF) Experiment





FCAL-II

- Simultaneously produce η/η' on LH_2 target with 8.4-11.7 GeV tagged photon beam via $\gamma+p \to \eta/\eta'+p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO 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

Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim3\times10^7$ (p+d), $\sim5\times10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim10^7$	$\sim5\times10^7$

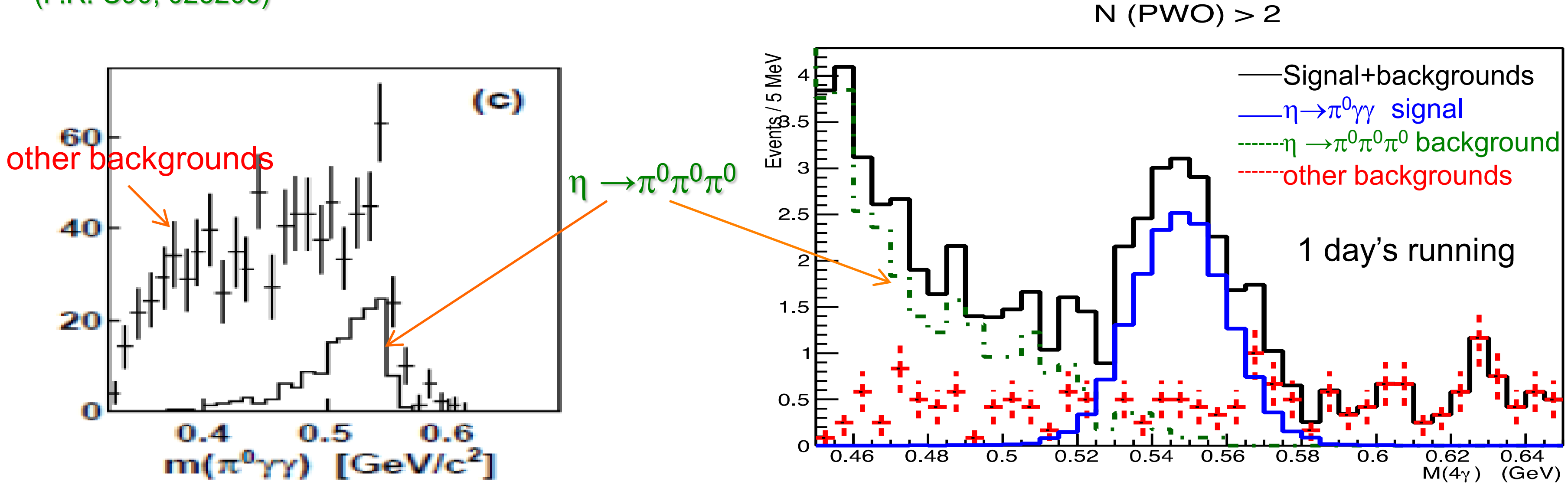
JEF offers a competitive η/η' factory

Uniqueness of JEF Experiment

1. Highly suppressed background in decay channels:
   a) η/η′ energy boost; b) an upgraded calorimeter (FCAL-II)

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV) (P.R. C90, 025206)

JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV)



2. Simultaneously produce tagged η and η' with similar rates (~5x10^7 per 100 beam days)

Main JEF Physics Objectives

1. **Search for sub-GeV hidden bosons**

   vector:

   - Leptophobic vector *B '*

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

   - Hidden or dark photon: $\eta, \eta' \to X\gamma \to e^+e^-\gamma$.

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

   Axion-Like Particles (ALP): $\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ \pi\pi e^+e^-$

2. **Directly constrain CVPC new physics:** $\eta^{(\prime)} \to 3\gamma$, $\eta^{(\prime)} \to 2\pi^0\gamma$, $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$

3. **Precision tests of low-energy QCD:**
   - Interplay of VMD & scalar dynamics in ChPT: $\eta \to \pi^0\gamma\gamma$ $\eta' \to \pi^0\gamma\gamma$
   - Time-like Transition Form Factors of $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

4. **Improve the quark mass ratio via Dalitz distributions of $\eta \to 3\pi$**

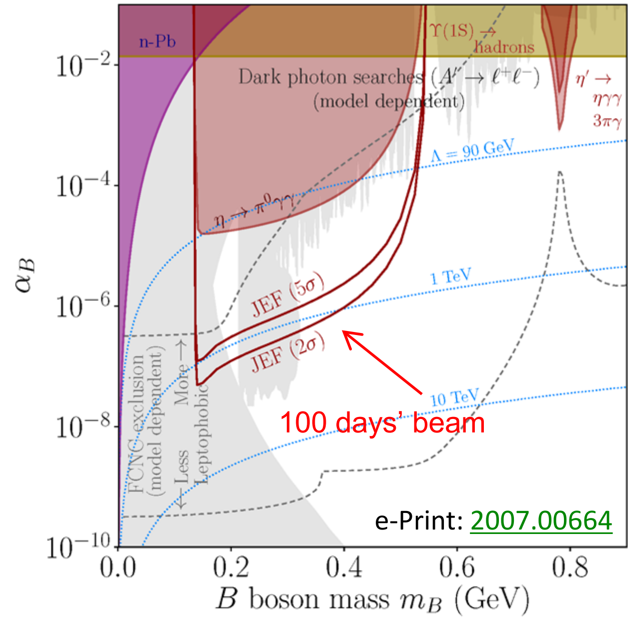
A Key Channel: $\eta\to\pi^0\gamma\gamma$

- **Search for sub-GeV gauge bosons**
  - A leptophobic vector B':

    $\eta\to\gamma B'$, $B'\to\pi^0\gamma$ — PL, B221, 80; PR,D89,114008

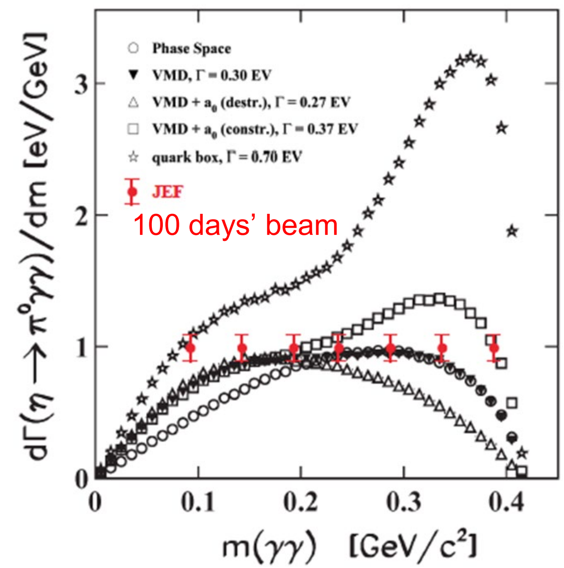
  - An scalar S:

    $\eta\to\pi^0 S$, $S\to\gamma\gamma$ — PR,D100,095020; Nucl.Phy.B,114638



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

PR,C78,015206



Search for CVPC Interaction via $\eta\to 3\gamma$

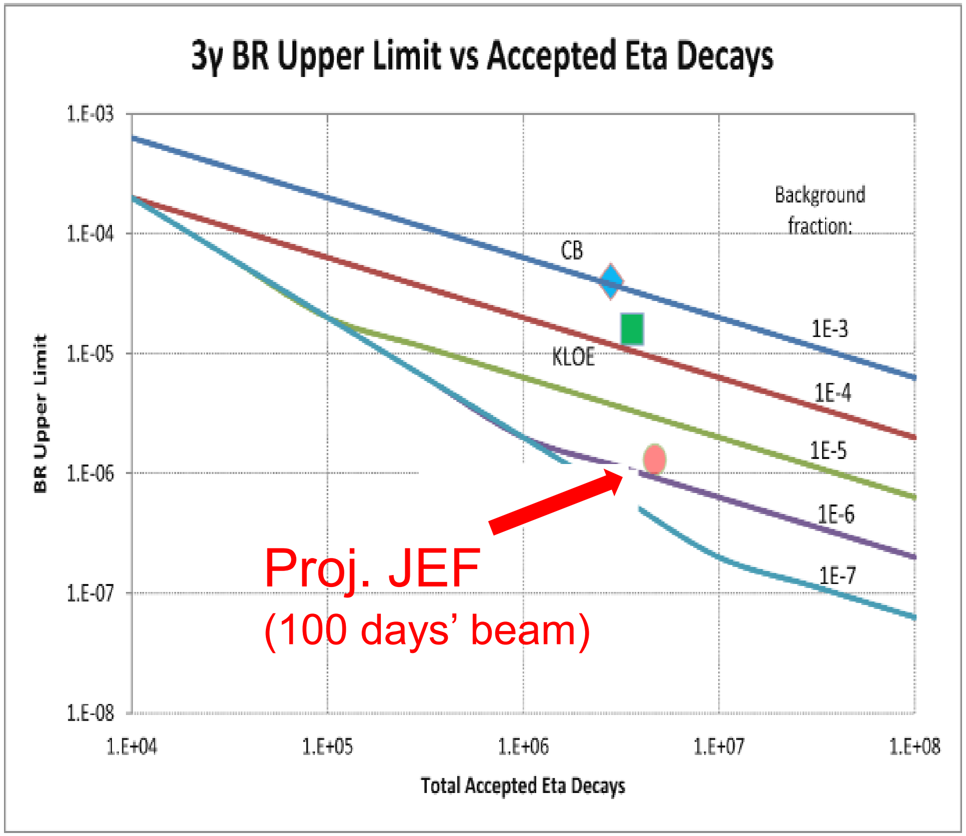
- SM contribution: BR($\eta\to 3\gamma$) <10^{-19} via P-violating weak interaction.

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee

  Phys. Rev.,139, B1650 (1965)

- A calculation due to such new physics by Tarasov suggests: BR($\eta\to 3\gamma$)< 10^{-2}

  Sov.J.Nucl.Phys.,5,445 (1967)

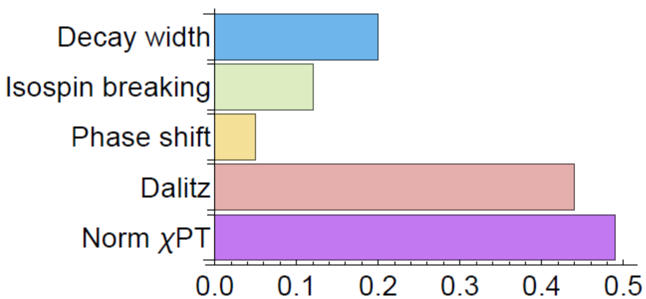


Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

Improve Quark-Mass Ratio via $\eta\to3\pi$ Dalitz Distributions

- A clean probe for quark mass ratio: $Q^2 = \dfrac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\quad \hat{m} = \dfrac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \dfrac{1}{Q^2}\dfrac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\dfrac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$

- Uncertainties in quark mass ratio



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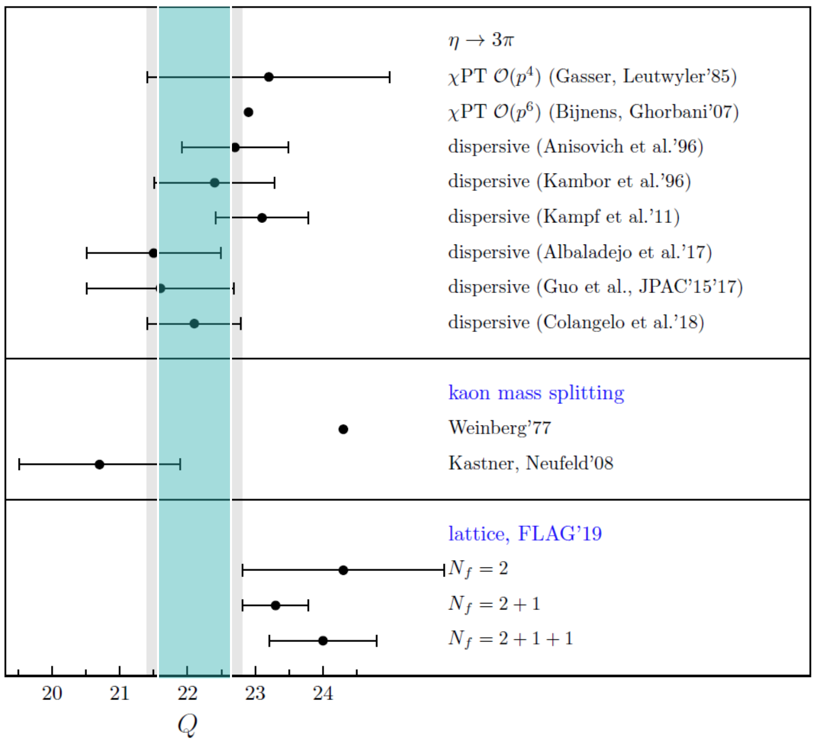
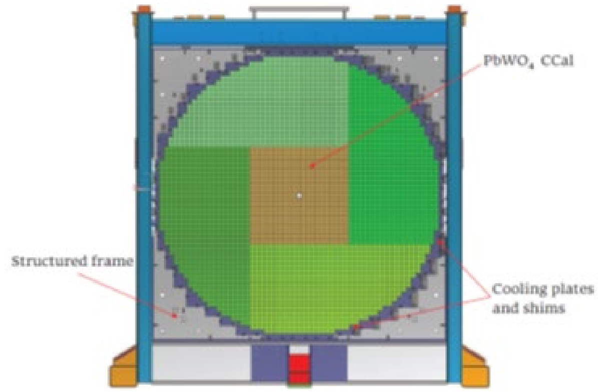


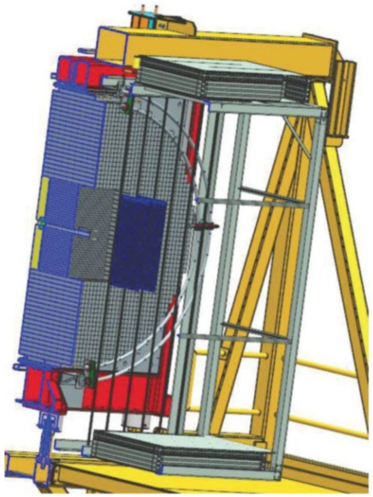
Current Status of the JEF Experiment

1. Non-rare decay data has been collecting with the GlueX spectroscope experiment since 2016.

2. A PWO insert to upgrade FCAL is under construction.

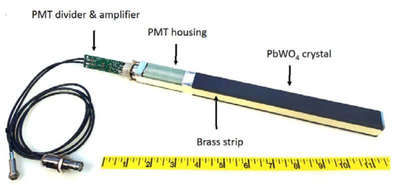
   - Mass production of 1600 PWO modules is on-going.
   - Engineering design for calorimeter frame is finalized.
   - Installation of the PWO insert is scheduled for 2023.





3. Rare decay data with FCAL-II is expected in 2024.

PWO module
(2x2x20 cm^3)



Undergraduate workforce

Summary

- The JLab η/η' decay measurements offer a rich physics program:
  - Precision tests of Standard Model: Chiral symmetry and anomalies; inputs to HLbL in $(g-2)_\mu$ calculation; improve the light quark mass and η-η' mixing angle; scalar dynamics in ChPT
  - Search for sub-GeV hidden bosons: vectors, scalars, and ALPs
  - Fundamental symmetries tests: directly constrain CVPC new physics

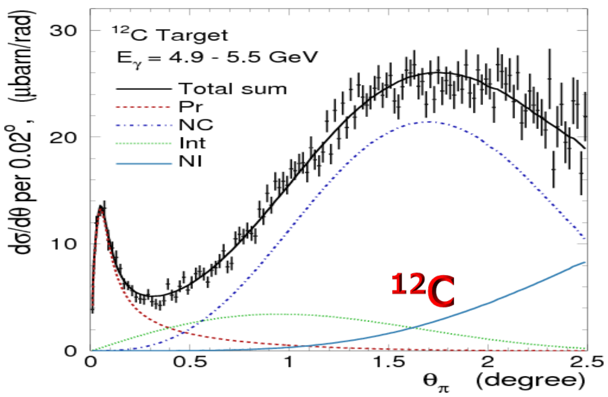
- The PrimEx-eta experiment on $\Gamma(\eta\rightarrow\gamma\gamma)$ will complete data collection by end of 2022.

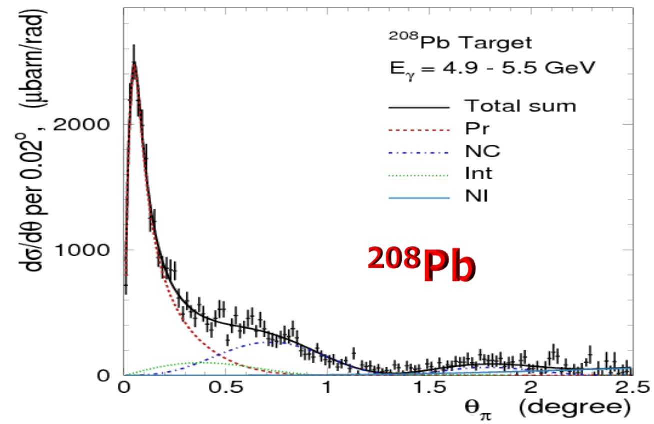
- The JEF experiment will measure η and η' decays simultaneously, with two orders of magnitude background reduction in the rare neutral modes compared to other facilities. Upgrade of Forward calorimeter with a PWO insert is currently under construction. JEF run will be expected in 2024.

Thanks for support by NSF PHY-1812396 and PHY-211181

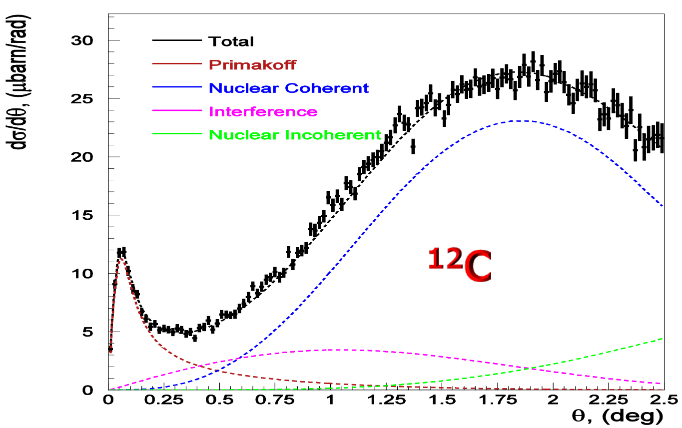
Differential Cross Sections

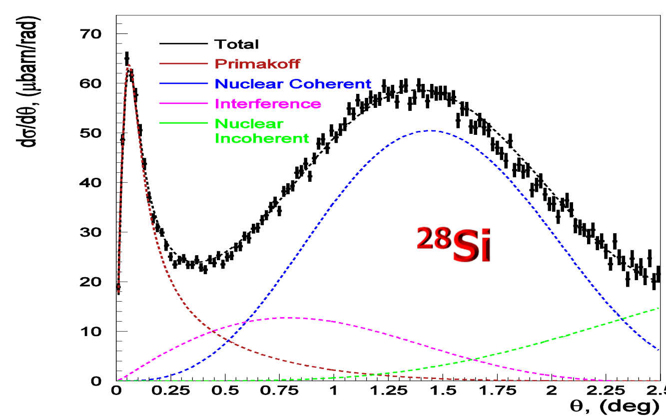
PrimEx I:





PrimEx II:





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

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