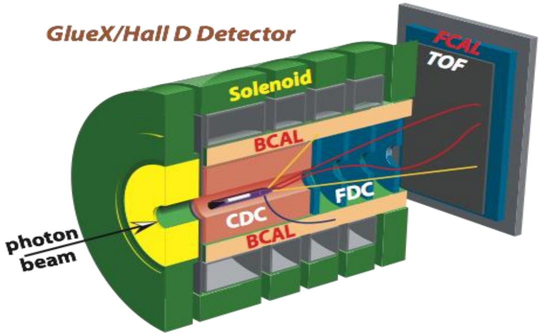
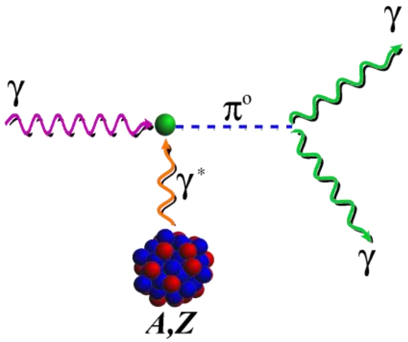




Precision Tests of Fundamental Symmetries via η and η′

A. Somov (Jefferson Lab)

(on behalf of the PrimEx working group)

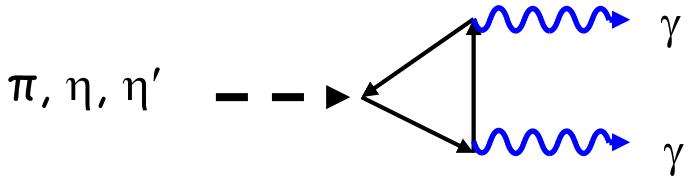
Jefferson Lab at 22 GeV Workshop, January 23 – 25, 2023

Outline

- Physics motivation
- Measurement of the $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ decay widths using Primakoff process
- Measure of the decay width $\Gamma(\eta \to \gamma\gamma)$ at 12 GeV: PrimEx - η experiment in Hall D
- Primakoff program in Hall D at 22 GeV
  - measurement of $\Gamma(\eta \to \gamma\gamma)$ decay width
  - measurement of $\Gamma(\eta' \to \gamma\gamma)$ decay width

Symmetries in QCD and Light Pseudoscalar Mesons

- $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $\eta' \to \gamma\gamma$ decays are associated with the Chiral anomaly



- Decay widths can be computed precisely in higer orders

- SU(3) and isospin breaking by the unequal quark masses induce mixing among π^0, η, and η'

π^0, η, η' mesons provides a rich laboratory to study the symmetry structure of QCD at CEBAF energies

Physics Motivation

➢ **Light quark mass ratio:**

- $\Gamma(\eta\to\gamma\gamma)$ obtained in PrimEx can be used to compute $\Gamma(\eta\to3\pi)$

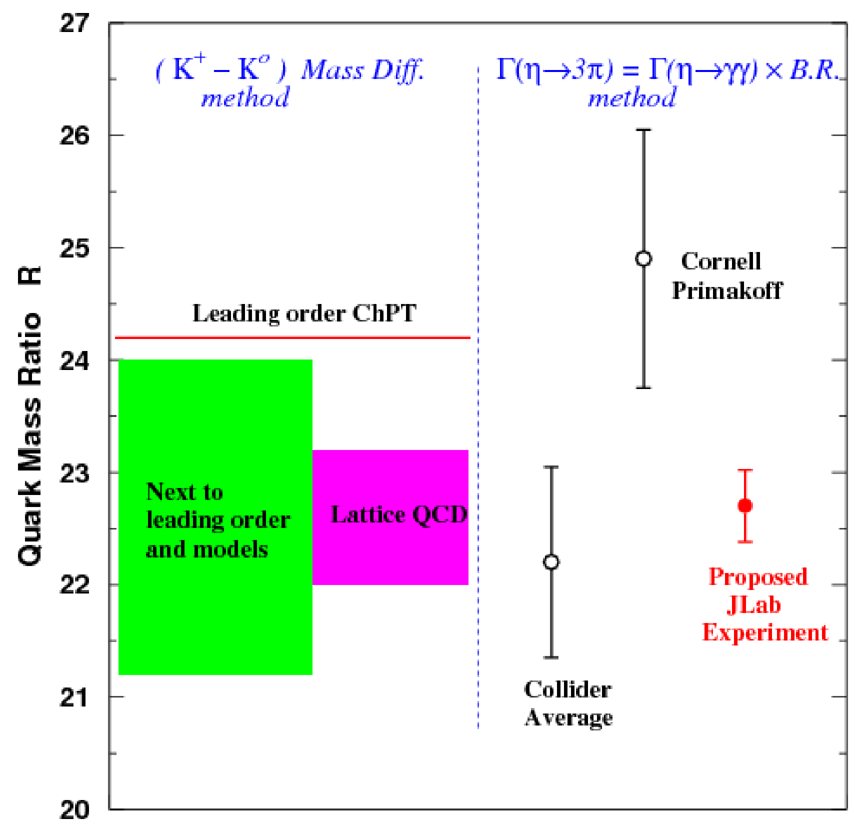
$$\Gamma(\eta\to3\pi)=\Gamma(\eta\to\gamma\gamma)\cdot BR(3\pi)\,/\,BR(\gamma\gamma)$$

Branching fractions are measured with good precision

- $\eta\to3\pi$ is forbidden by isospin symmetry. The quark mass ratio R can be extracted from the width $\Gamma(\eta\to3\pi)$

$$R^2 = \frac{m_s^2-\hat{m}^2}{m_d^2-m_u^2}, \qquad \text{where } \hat{m}=\frac{1}{2}(m_u+m_d)$$

H. Leutwyler PLB, 378,1996



Physics Motivation

- **Significantly improve all η decay widths in PDG**

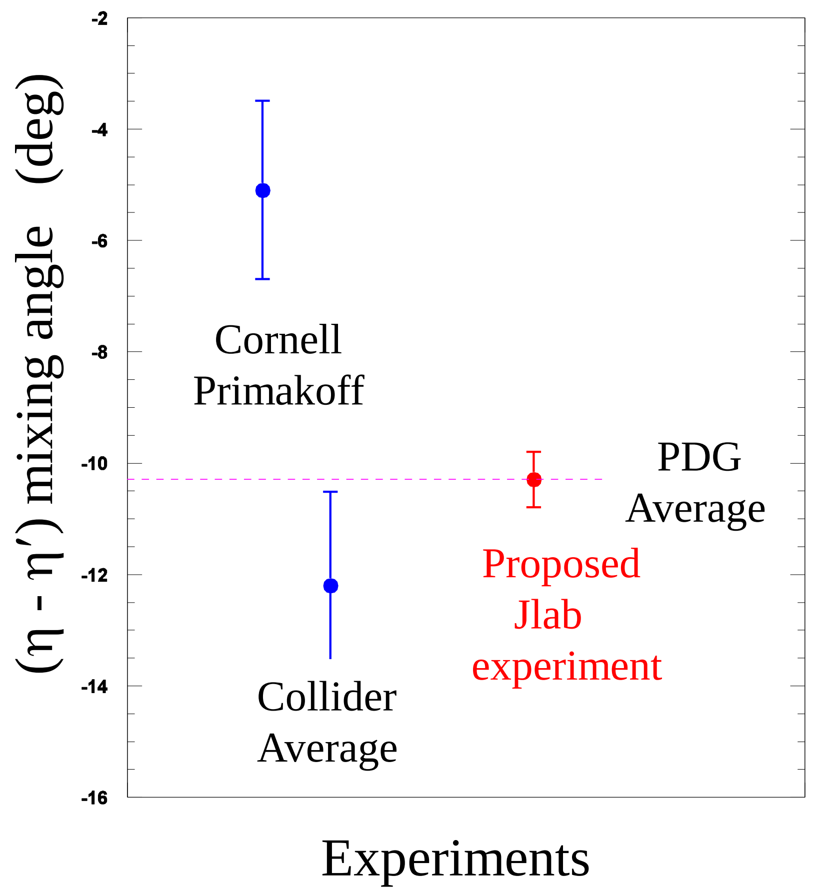
$$\Gamma(\eta\to X) = \Gamma(\eta\to\gamma\gamma)\cdot BR(X)\,/\,BR(\gamma\gamma)$$

- **(η - η′) mixing angle**

η→γγ and η′ →γγ are associated with chiral anomaly and should be analyzed together

$$\begin{pmatrix}\eta\\ \eta^{/}\end{pmatrix} = \begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}\eta_8\\ \eta_0\end{pmatrix}$$

relations involve decay constants and mixing angle



- Model dependent extraction of the mixing angle

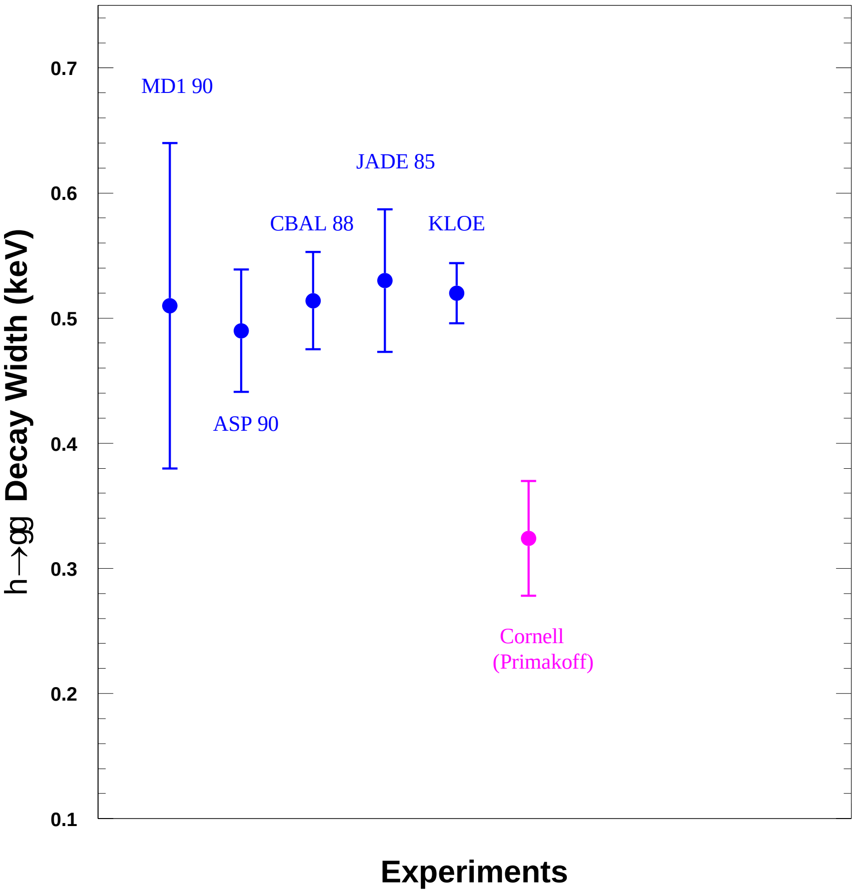
Measurements of $\Gamma(\eta\rightarrow\gamma\gamma)$

- The partial width $\Gamma(\eta\rightarrow\gamma\gamma)$ was derived from measurements

  - collider experiments in the reaction
    $e^+ e^- \rightarrow e^+ e^- \eta$

  - Primakoff production of η mesons

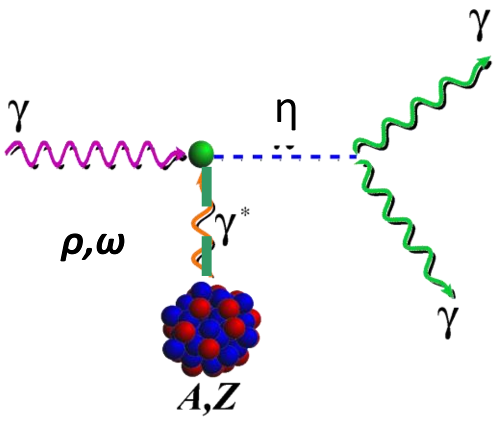
- Some disagreemnts between collider and Primakoff results

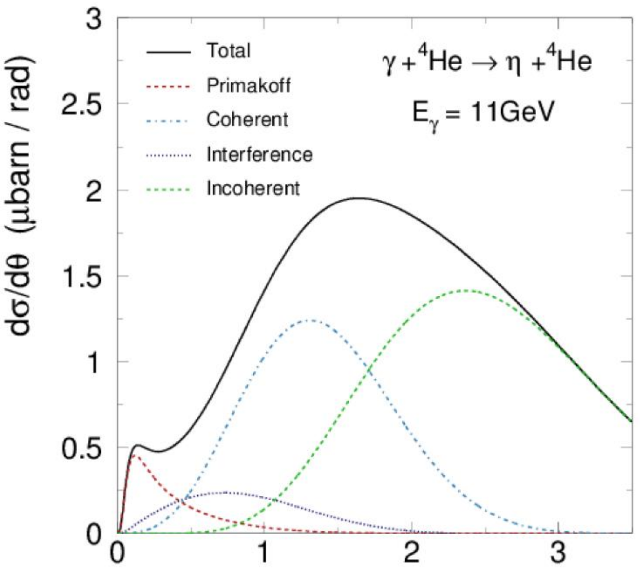


The PrimEx experiment in Hall D at Jefferson Lab has just finished data taking

Measure $\Gamma(\eta\rightarrow\gamma\gamma)$ using Primakoff process with the precision of 4 - 6 %
(work in progress)

The Primakoff Method



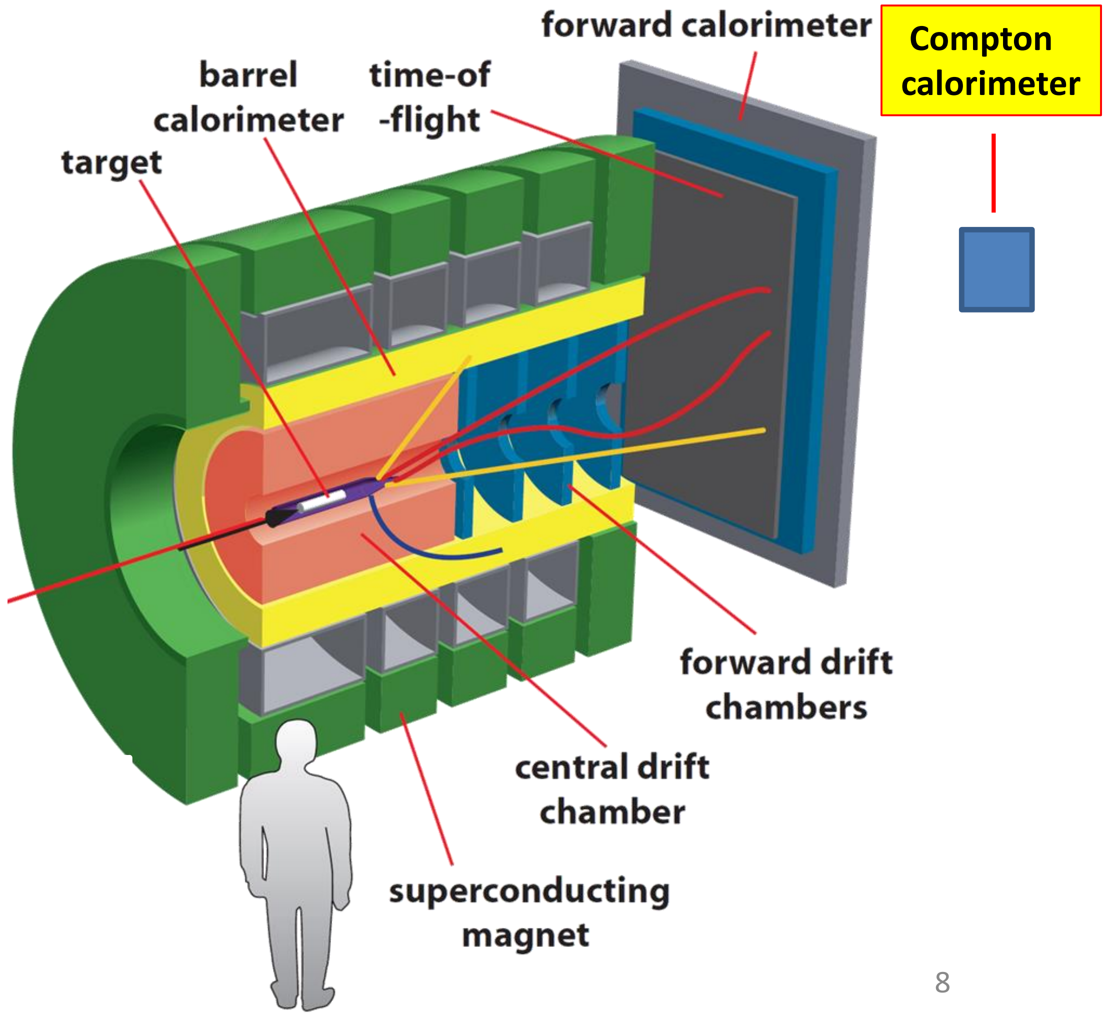


$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$

- Extract decay width Γ(η→γγ) from the measured cross section dσ/dΩ
  - Use low A targets LHe_4 to control:
    - coherency
    - contributions from nuclear processes

PrimEx – η Experiment in Hall D

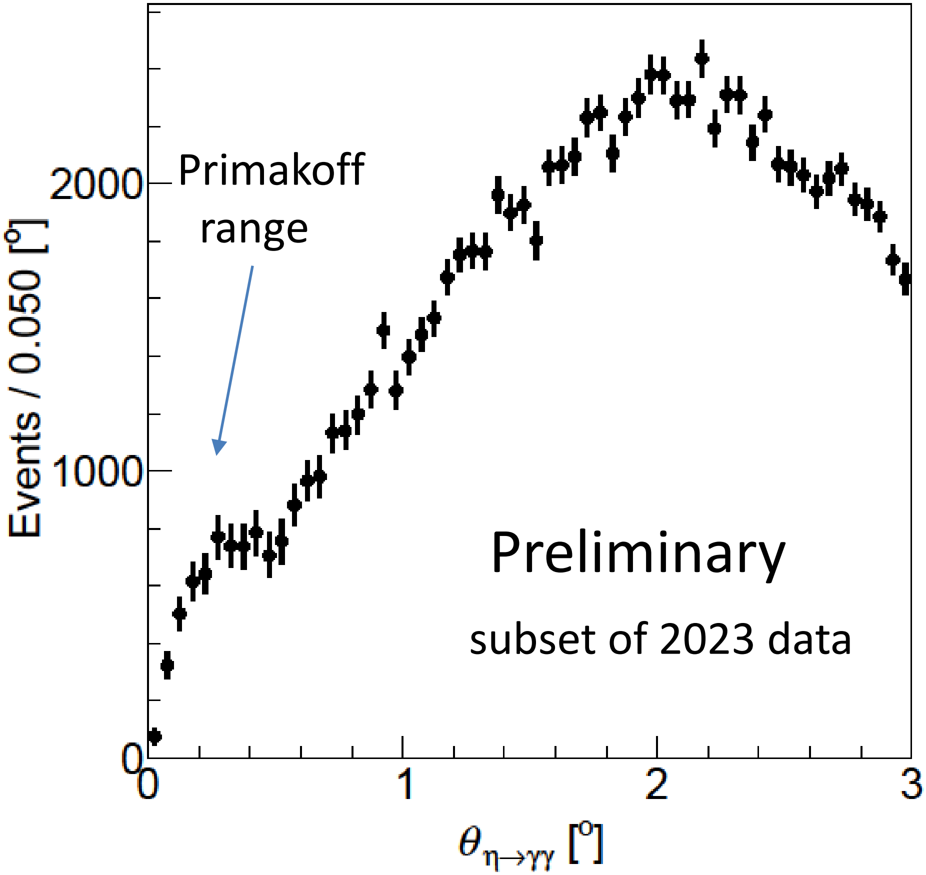
- New liquid He and Be targets
- New Compton Calorimeter
- Use Compton events for:
  - absolute luminosity normalization
    (Be target)
  - stability monitoring
    (He target)
- Solenoid field switched off
  for the first run period
- 3 sets of data collected at different beam energies:
  11.2 GeV, 10 GeV, and 11.6 GeV
- Reconstruct η mesons using decays:
  $\eta \to \gamma\gamma$ ($\eta \to 3\pi$)



The PrimEx – η Experiment

I. Jaegle

Polar angle distribution of $\gamma\gamma$
(background subtracted)



- Analysis is ongoing

- Expected precision on Γ ($\eta\to\gamma\gamma$)
  4 – 6 %

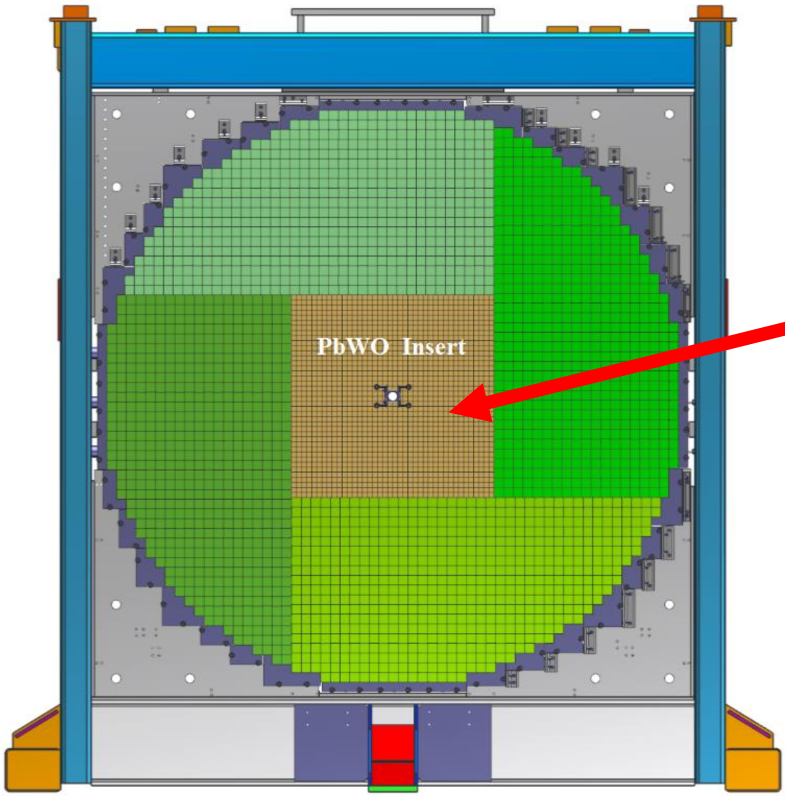
  - dominated by systematics
  - large background from beamline
  - finite detector resolution
    (under study)

Improvements (for future experiments):

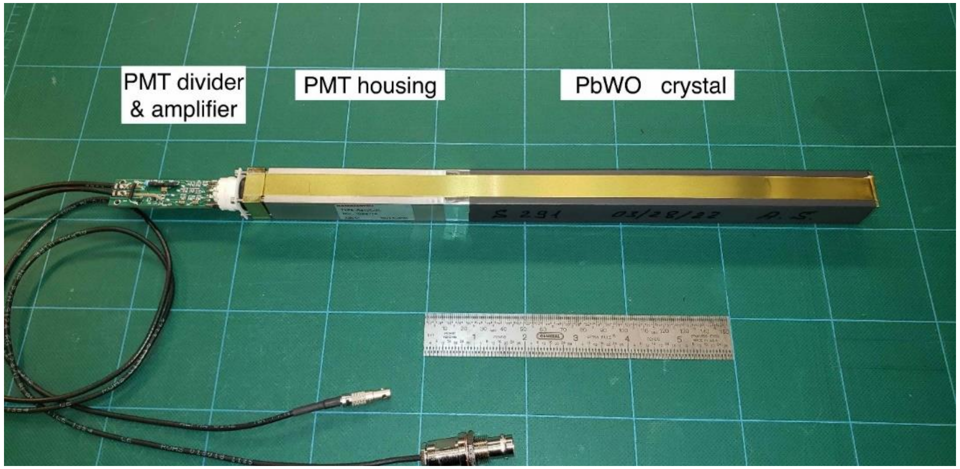
- calorimeter upgrade (FCAL2)
- reduce beamline material
- increase beam energy
- use heavier targets

Forward Calorimeter Upgrade (FCAL2)

Forward Calorimeter



$PbWO_4$ module



- Install an array of 40 x 40 $PbWO_4$ modules in the inner part of the FCAL
  (replace lead glass modules)

  - 2 cm x 2 cm x 20 cm $PbWO_4$
  - 4 cm x 4 cm x 45 cm lead glass

- A factor of 4 better detector granularity
  - significantly improve shower separation

- Improves the energy and position resolutions by about a factor of 2

Why 22 GeV ?

- Primakoff cross sections increases with energy

$\sigma(E = 20\text{ GeV}) \ / \ \sigma(E = 10\text{ GeV}) \ \sim \ 1.5$

- Better separation of Primakoff from hadronic processes:

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

- Better energy, mass, and angular resolution of reconstructed η mesons at large energies

- Smaller momentum transfer (t) at larger energies $q_L \sim (m^2 / 2E)$, $q_T \sim 4 E E_\eta \sin^2(\theta/2)$

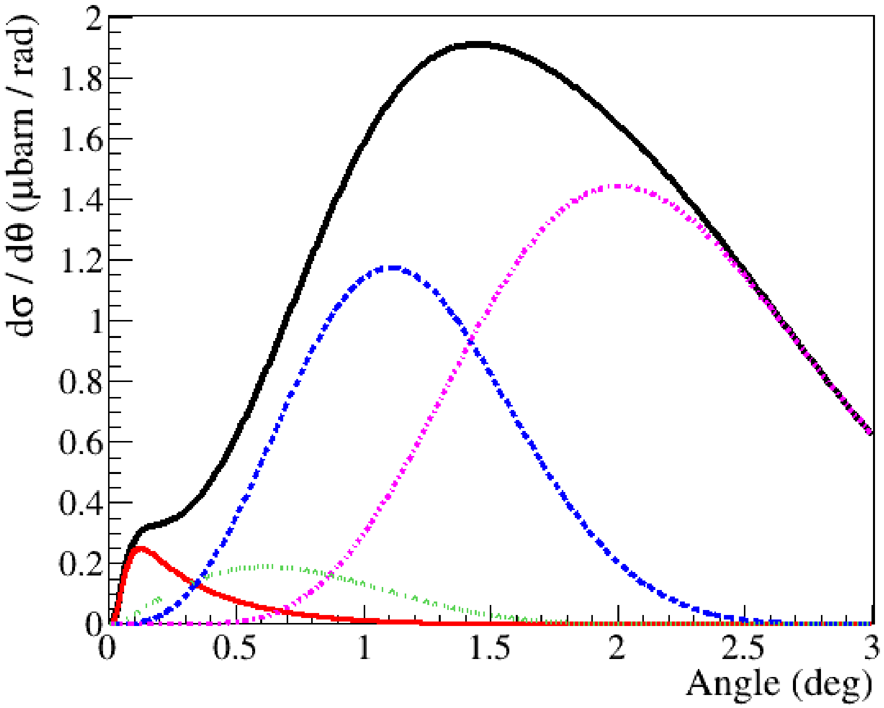
  - consider to use heavier targets (feedback from theorist)
  - smaller contribution from hadronic background

Primakoff η Production at 10 GeV and 20 GeV

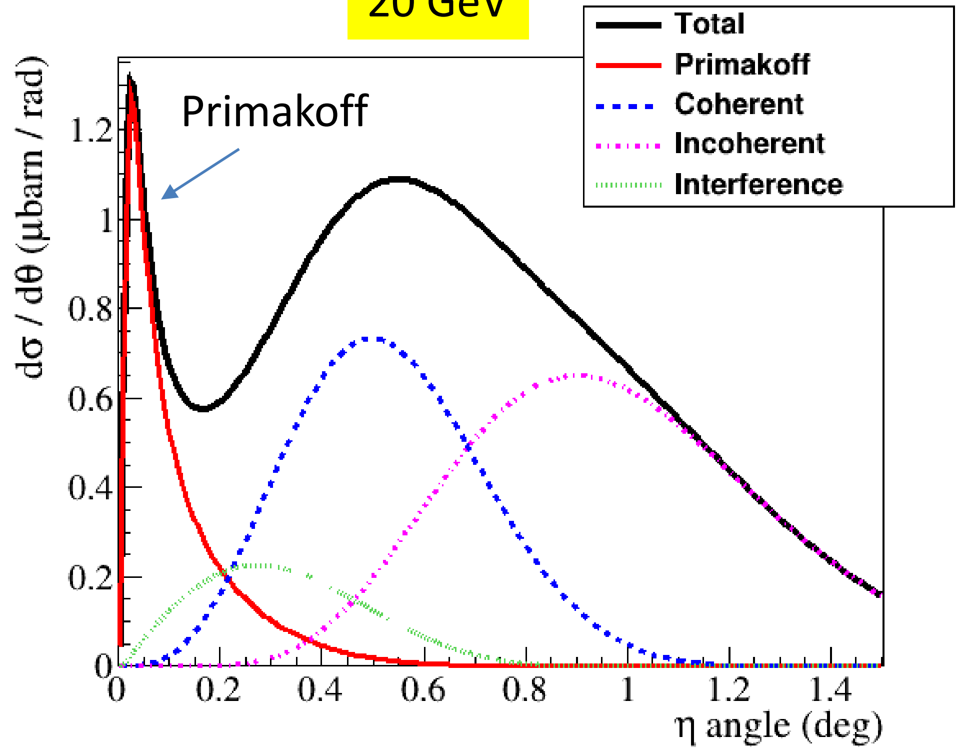
Differential cross sections

He4 target

10 GeV



20 GeV

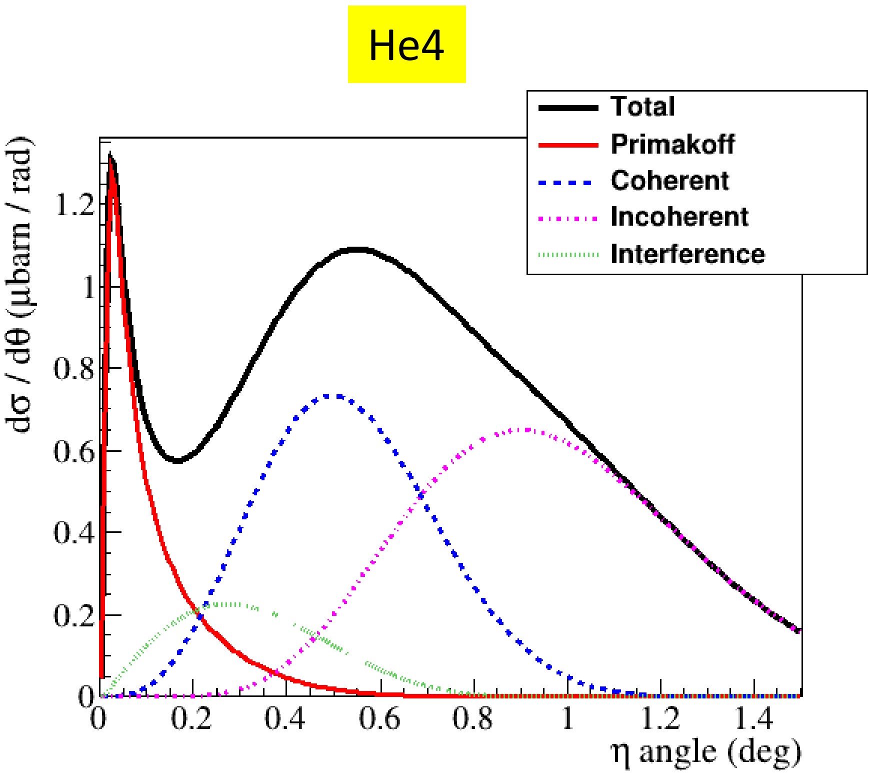


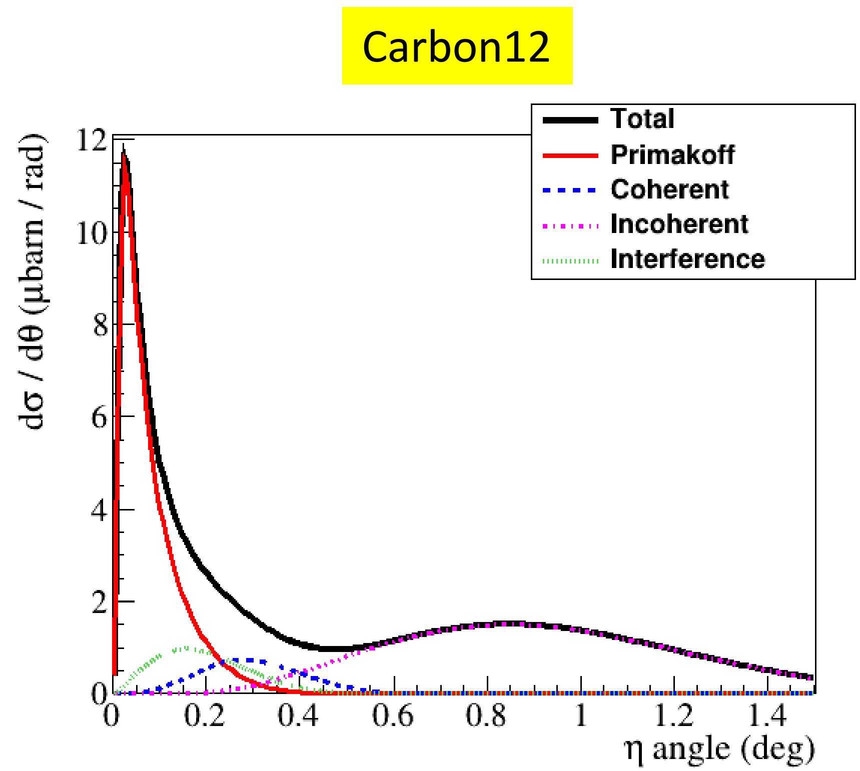
Significantly larger Primakoff peak at 20 GeV

- larger Primakoff cross section and better separation of the signal and backgrounds

Simulation performed in the framework provided by S. Gevorgyan

Primakoff η: He4 and Carbon Targets



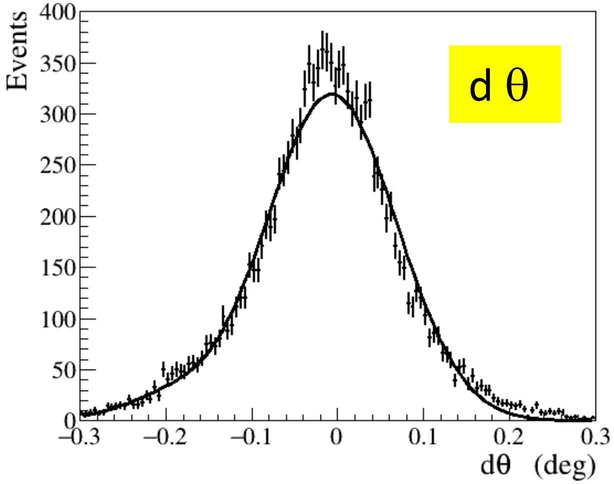


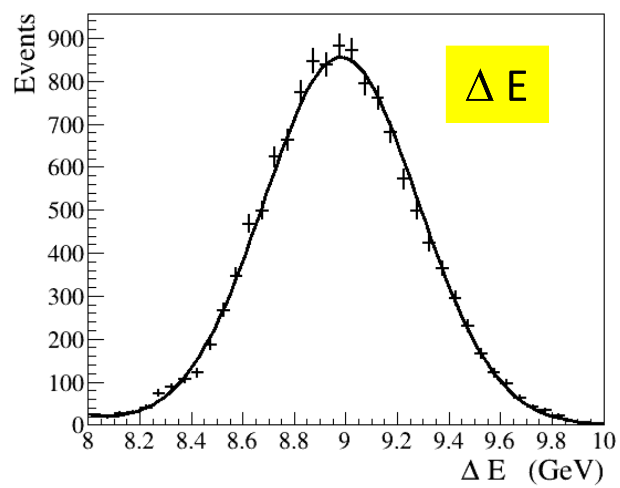
- Advantages of Carbon target:
  - large Primakoff cross section (scales as Z^2)
  - much smaller empty target background for $\eta \to \gamma\gamma$ decay mode

- Need feedback from theorists regarding using C target

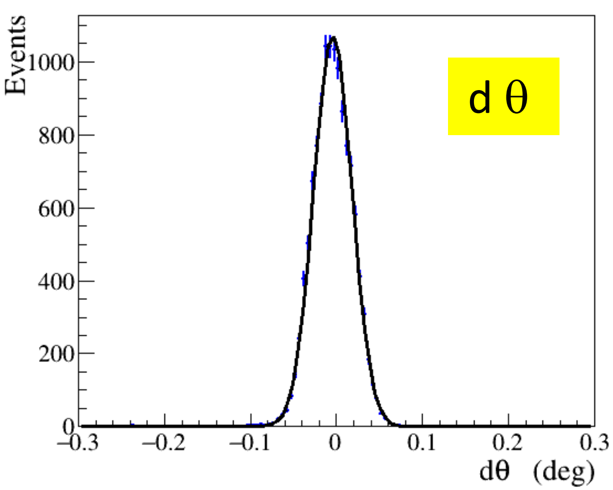
Primakoff η: Monte Carlo Simulation

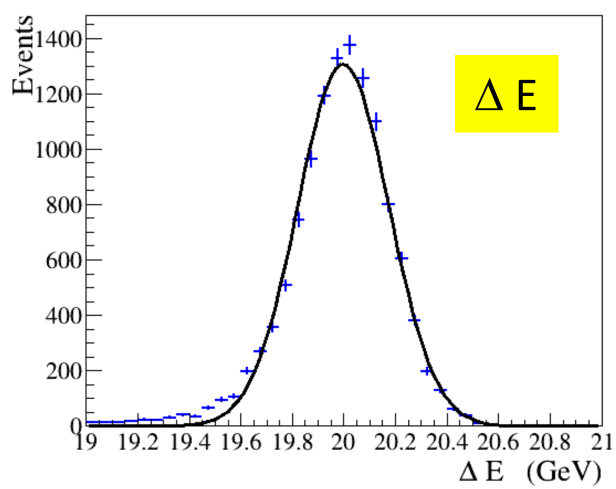
Geant simulation of Primakoff reaction: **$\gamma + He \rightarrow He + \eta,\ \ \eta \rightarrow \gamma\gamma$**





FCAL @ 10 GeV





FCAL2 @ 20 GeV

Primakoff η: Monte Carlo Simulation

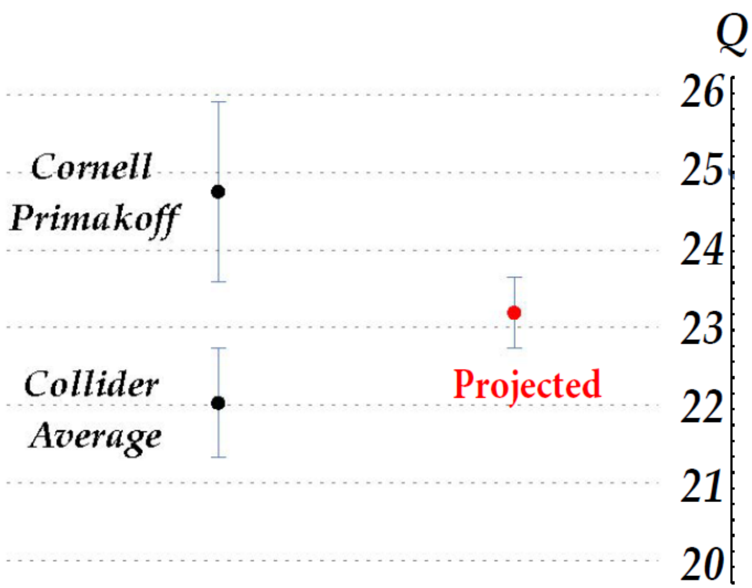
	9 GeV (FCAL)	20 GeV (FCAL2)
Mass Resolution	23 MeV	**12 MeV**
Energy Resolution	300 MeV	**180 MeV**
Angular Resolution	0.08°	**0.02°**
Reconstruction Efficiency	30 %	**25 %**

- Significantly better mass, energy, and angular resolution at 20 GeV with the FCAL2
- Similar reconstruction efficiency of $\eta \rightarrow \gamma\gamma$ at 9 GeV and 20 GeV

  - large FCAL2 acceptance at small angles

Projected Errors on Quark Mass Ratio

- Expect to measure the decay width of $\eta \to \gamma\gamma$ with an accuracy of 2 – 3 %



$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$

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

Measurement of $\eta' \rightarrow \gamma\gamma$ Decay Width

Measurements of $\eta' \to \gamma\gamma$ Decay Width

- η' width was measured in several collider experiments using reaction

$$e^+ e^- \to e^+ e^- \eta'$$

F. Butler, et.al., PRD Vol 42, 5, 1990

Experiment	$\Gamma_{\eta' \to \gamma\gamma}$ (keV)	Mode	Reference
Mark II (SPEAR)	$5.8 \pm 1.1 \pm 1.2$	$\rho\gamma$	1
JADE	$5.0 \pm 0.5 \pm 0.9$	$\rho\gamma$	2
CELLO	$5.4 \pm 1.0 \pm 0.7$	$\rho\gamma$	3
PLUTO	$3.80 \pm 0.26 \pm 0.43$	$\rho\gamma$	4
TASSO	$5.1 \pm 0.4 \pm 0.7$	$\rho\gamma$	5
JADE	4.0 ± 0.9	$\gamma\gamma$	6
Crystal Ball	$5.0 \pm 0.6 \pm 0.8$	$\gamma\gamma$	7
TPC/2γ	$4.5 \pm 0.3 \pm 0.7$	$\rho\gamma$	8
ARGUS	$3.76 \pm 0.13 \pm 0.47$	$\rho\gamma$	9
Crystal Ball	$4.6 \pm 0.4 \pm 0.6$	$\eta\pi^0\pi^0$	10
Mark II (PEP)	$4.61 \pm 0.32 \pm 0.57$	$\rho\gamma$	This paper
Mark II (PEP)	$4.37 \pm 0.62 + 0.96 - 0.94$	$\eta\pi^+\pi^-$	This paper
Mark II (PEP)	$4.60 \pm 0.49 + 0.65 - 0.95$	$\pi^+\pi^-\pi^+\pi^-$	This paper

  - no background associated with a nuclear target
  - relatively large uncertainties on luminosity

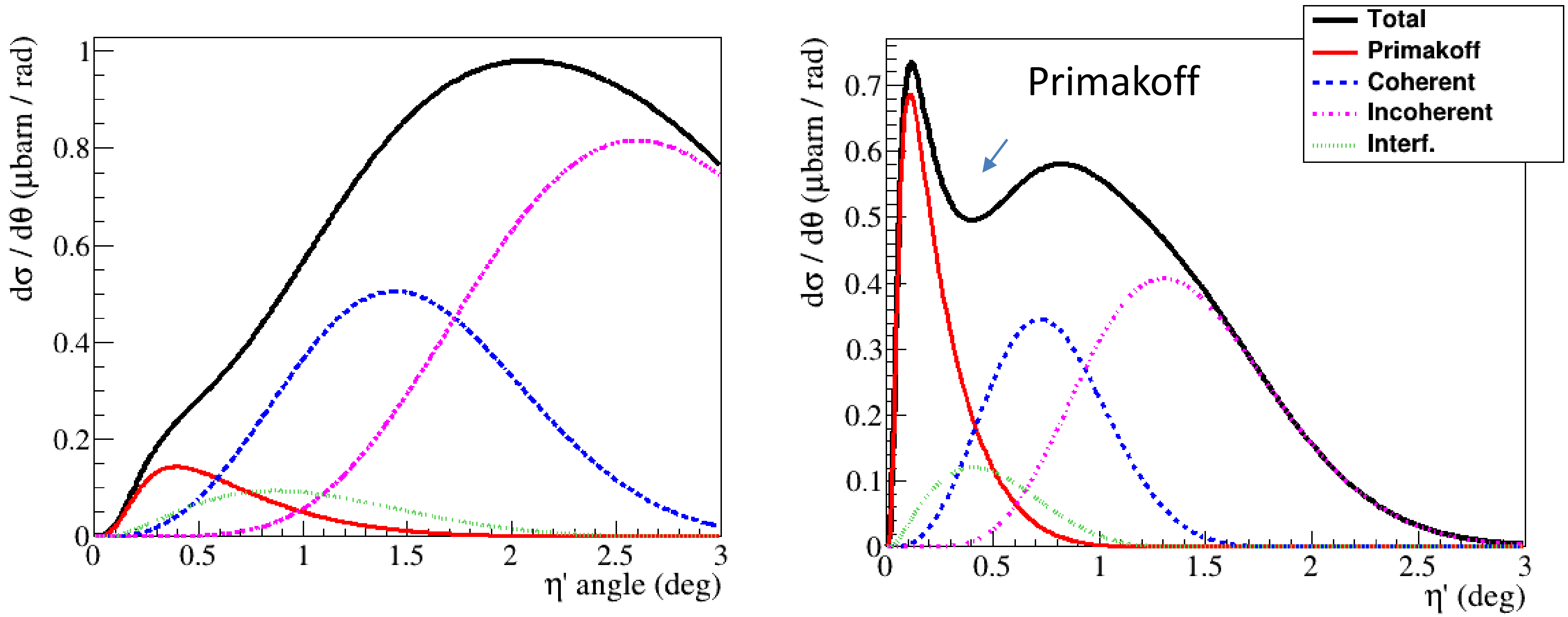
- No Primakoff measurement of the $\eta' \to \gamma\gamma$ decay width has been performed so far

Primakoff η′ Production at 10 GeV and 20 GeV

He4 target

10 GeV

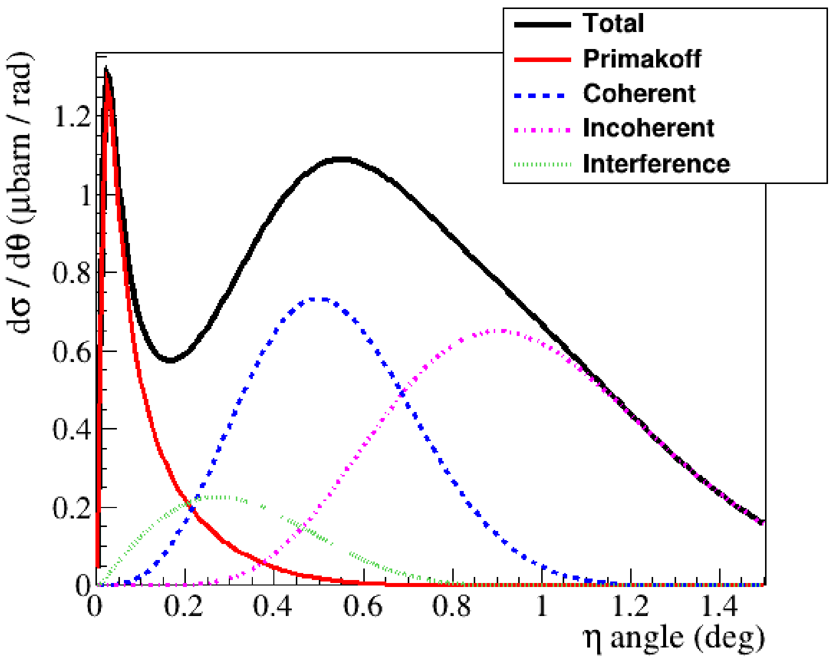
20 GeV



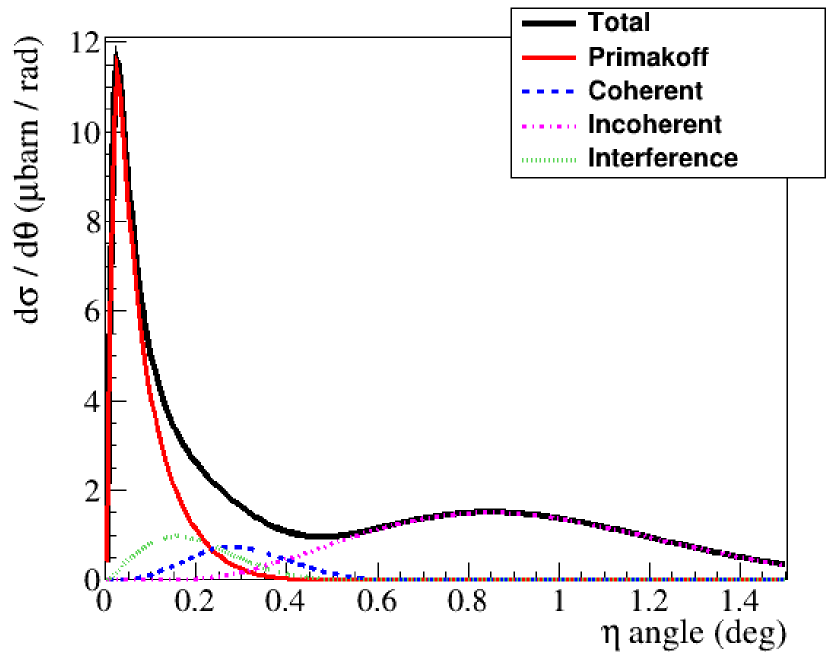
- Difficult to extract Primakoff η′ signal on He target at 10 GeV
- More ‘prominent’ Primakoff peak at 20 GeV

Primakoff η′: He4 and Carbon Targets

He4



Carbon



- Primakoff cross section ~ Z^2

Main Decay Modes of η'

Decay	BR (%)	Uncertainty on BR (%)	Preferred modes
$\eta' \to \gamma\gamma$	2.2	3.6	+
$\eta' \to \pi^+\pi^-\gamma$	29	2.0	
$\eta' \to \pi^0\pi^0\eta$			
$\eta \to \gamma\gamma$	8.5	3.7	+
$\eta \to \pi^+\pi^-\pi^0$	4.9	3.9	
$\eta \to \pi^0\pi^0\pi^0$	7.0	3.8	
$\eta' \to \pi^+\pi^-\eta$			
$\eta \to \gamma\gamma$	17	1.7	+
$\eta \to \pi^+\pi^-\pi^0$	9.9	2.0	+
$\eta \to \pi^0\pi^0\pi^0$	14	1.8	

momentum resolution

Several decay channels can be considered for the analysis

Reconstruction of Primakoff η'

$$\eta' \to \gamma\gamma$$

	9 GeV (FCAL)	20 GeV (FCAL2)
Mass Resolution	40 MeV	**23 MeV**
Energy Resolution	310 MeV	**205 MeV**
Angular Resolution	0.1°	**0.03°**
Reconstruction Efficiency	43 %	**45 %**

improved by a factor of 3

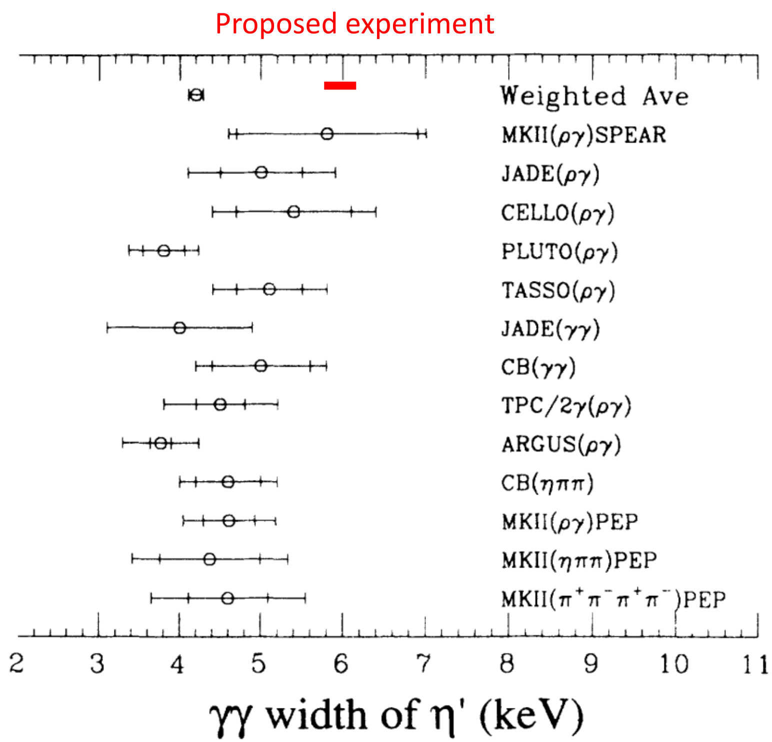
$$\eta' \to \pi^+ \pi^- \eta \quad (\eta \to \gamma\ \gamma)$$

	9 GeV (FCAL)	20 GeV (FCAL2)
Mass Resolution	30 MeV	**20 MeV**
Energy Resolution	310 MeV	**500 MeV**
Angular Resolution	0.12°	**0.05°**
Reconstruction Efficiency	24 %	**12 %**

poor momentum resolution of tracks, consider to apply kinemat. constr.

Note: no kinematics constraints applied

Expected Uncertainties on the $\eta' \to \gamma\gamma$ Decay Width



Simple estimates:

- η' Primakoff cross section on Carbon ~14 nb
- photon flux in the beam energy range 19 –21 GeV: $2\text{x}10^7$ γ / sec, 6 % R.L. target
- stat error on the Primakoff yield for $\eta' \to \pi\pi\eta$ $(\gamma\,\gamma)$ is about 3.5% for 20 days of data taking

Summary

- The energy upgrade of the Jefferson Labs facility to 22 GeV will allow for the extension of the Primakoff experimental program in Hall D, which is currently under development

  - we expect significantly improve recent measurements of the PrimEx-eta experiment of the η differential cross sections at forward angles. The expected precision on the η width is about 2 - 3 %.

  - we expect to perform the first measurement of the η' radiative decay width via the Primakoff effect, which will complement the existing results from the collider experiments. The η' decay width will be measure with an accuracy of about 3.5 %

- This result is essential for determinations of the fundamental QCD parameters, such as the ratio of light quark masses and the $\eta - \eta'$ mixing angle, and will provide an important test of chiral symmetry breaking in QCD