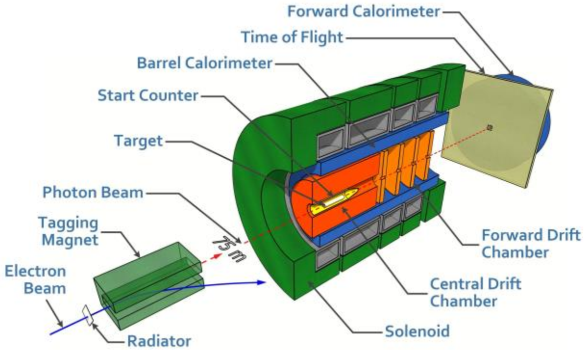
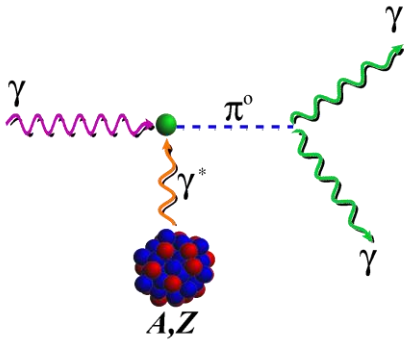


Jefferson Lab



Status of the PrimEx -η Experiment at Jefferson Lab

A. Somov Jefferson Lab

on behalf of the PrimEx working group

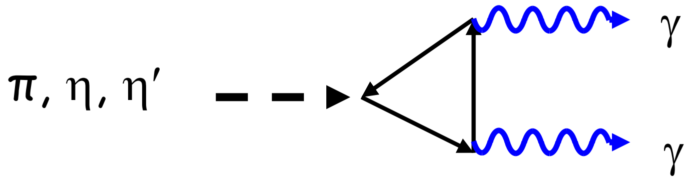
The 11th International Workshop on Chiral Dynamics
Ruhr University Bochum, Germany
August 26-30, 2024

Outline

- Physics motivation
- Primakoff program at Jefferson Lab
- GlueX detector in Hall D
- Measurement of the radiative decay width of η using GlueX detector
- Future plans

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 higher 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

Decay Width of η Mesons : Physics Motivation

- **Light quark mass ratio:**

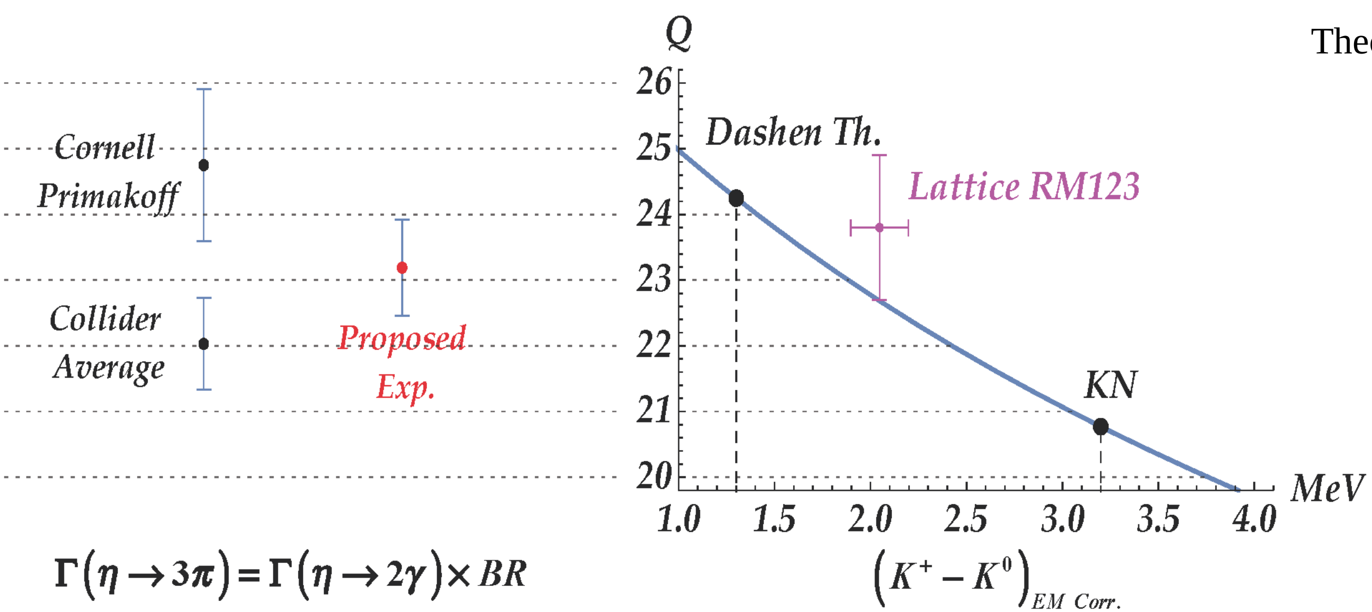
$\eta\rightarrow 3\pi$ forbidden by isospin symmetry:

$\Gamma(\eta\rightarrow 3\pi) \sim |A|^2 \sim Q^{-4}$

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

$\Gamma(\eta\rightarrow 3\pi)=\Gamma(\eta\rightarrow\gamma\gamma)\cdot BR(3\pi) / BR(\gamma\gamma)$

Phys. Rept. 945 (2022) 1-105



Theoretical calculations:

$$Q^2 \sim \frac{M_K^2}{M_\pi^2}\,\frac{M_K^2 - M_\pi^2}{(M_{K^0}^2 - M_{K^+}^2)_{QCD}}$$

Uncertainties in EM contributions to $M_{K^0}^2 - M_{K^+}^2$

Physics Motivation

➢ **(η - η') mixing angle**

- *SU(3)* symmetry breaking induces mixing between the *SU(3)* states

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

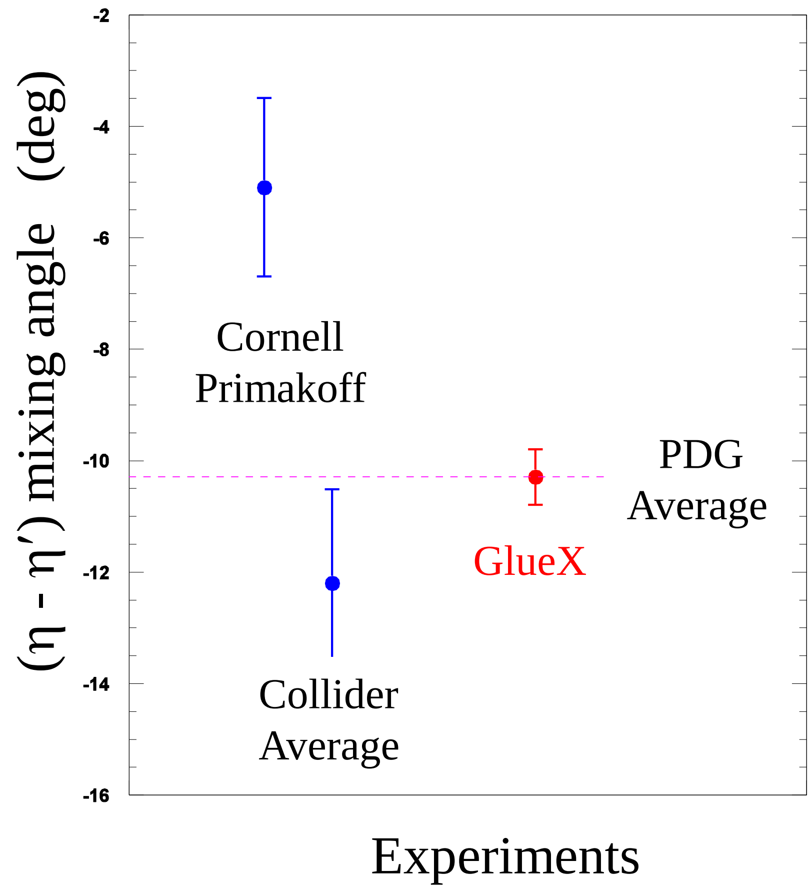
- The mixing angle θ can be determined using measured decay widths $\Gamma(\eta^{(\prime)} \to \gamma\gamma)$ and NLO corrections to decay constant

- Important to analyze together decays $\eta^{(\prime)} \to \gamma\gamma$ and $\eta \to \gamma\gamma$

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

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

L. Goity and al. PRD 66 (2002) 076014



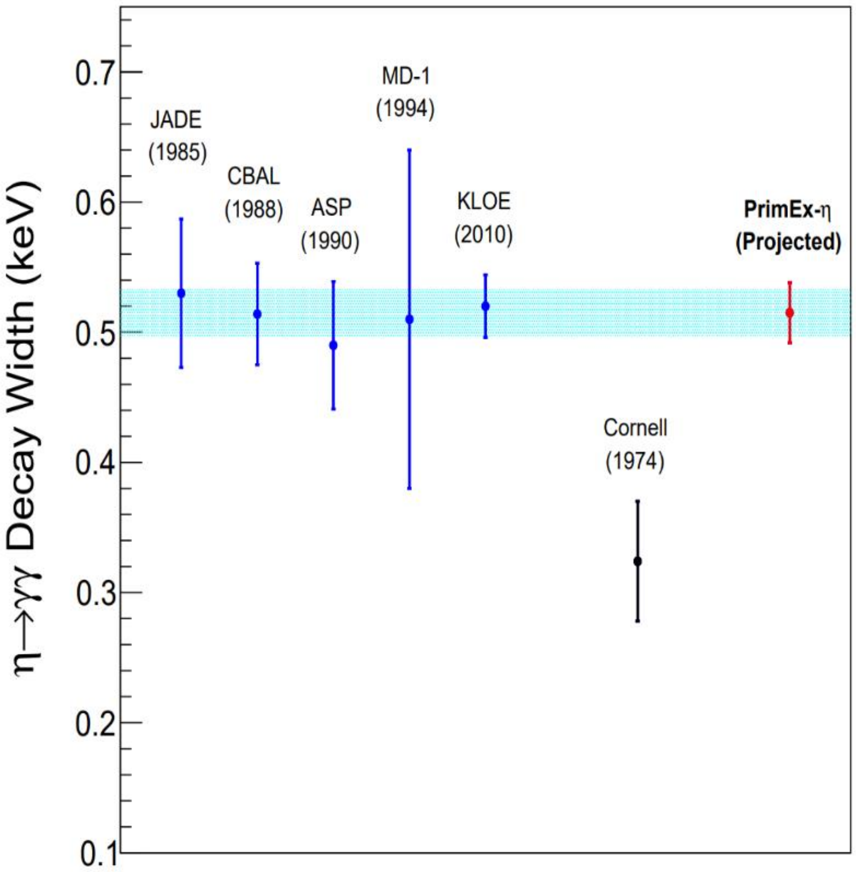
Measurements of $\Gamma(\eta\to\gamma\gamma)$

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

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

  - Primakoff production of η mesons

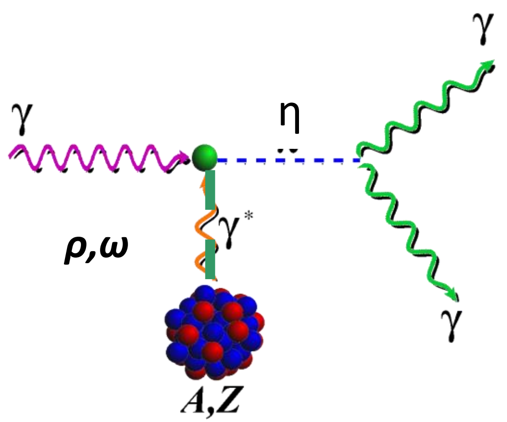
- Some disagreements between collider and Primakoff results



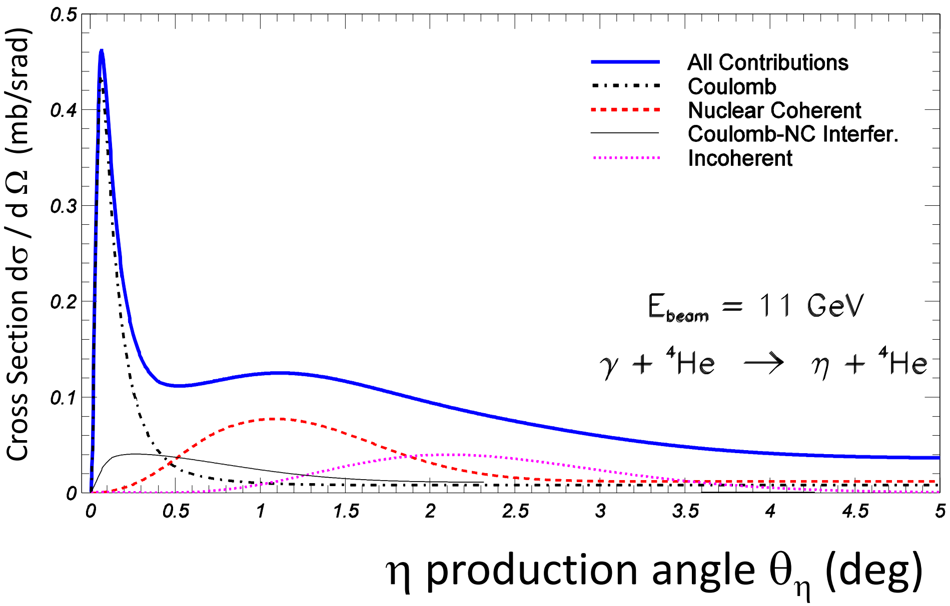
New measurement of the decay width using Primakoff process PrimEx - η experiment at Jefferson Lab

Initial goal for uncertainties 3.2 %, more likely be 6 – 9 %

The Primakoff Method

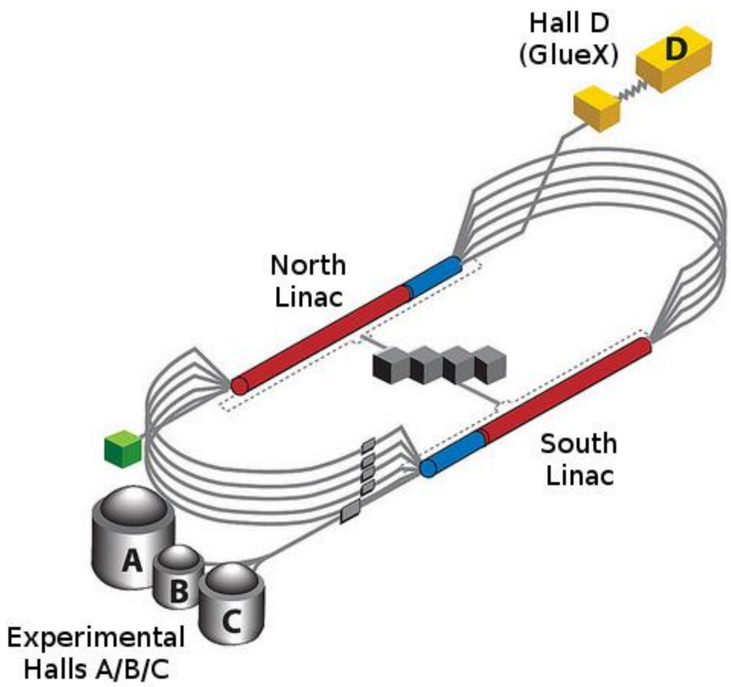


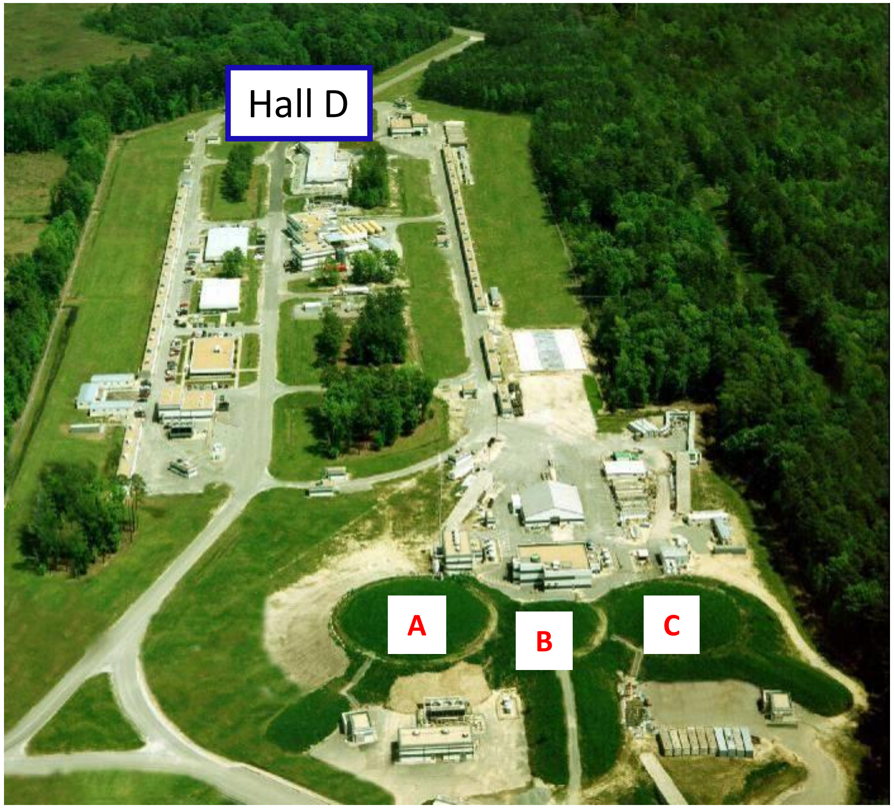
$$\frac{d\sigma_{\mathrm{Pr}}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\eta^3} \frac{\beta^3 E^4}{Q^4} \left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\eta$$



- Measure differential cross section dσ/dΩ
- Contributions from:
  - signal Coulomb
  - nuclear coherent (incoherent)
  - interference between signal and coherent
  - other hadronic background
- Distribution shapes are computed or measured
- Free parameters in the fit:
  - normalizations, interference phase

Jefferson Lab

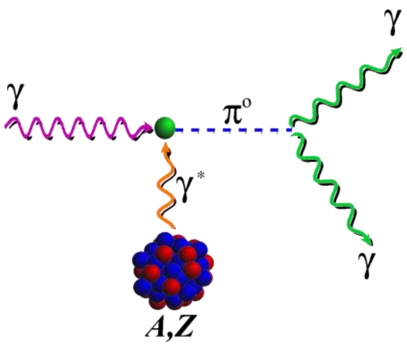




- CEBAF energy upgrade from 6 GeV to 12 GeV
- Four experimental halls: A, B, C, and D
- Hall D constructed in 2016
  - beam of linearly polarized photons

Pimakoff Program at Jefferson Lab

I) Determination of two photon decay widths:



$\Gamma(\pi^0 \to \gamma\gamma)$ PrimEx I, II experiment in Hall B at 6 GeV

$\Gamma(\eta \to \gamma\gamma)$ PrimeEx-η experiment in Hall D at 12 GeV

$\Gamma(\eta' \to \gamma\gamma)$

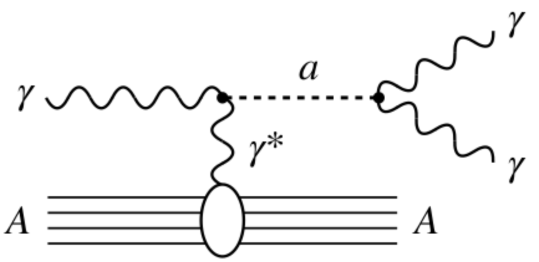
- test Chiral symmetry and anomaly, extract light quark mass ratio, determine η - η′ mixing angle

II) Measuring the charged and neutral pion polarizability

- Primakoff production of $\pi^+ \pi^-$ and $\pi^0 \pi^0$ (see talk by R. Miskimen)
- Hall D, polarized photon beam (collected data in 2022)

III) Search for axion-like particles through nuclear Primakoff production

- APL predominantly couple to photons, with an effective ALP-photon interaction $\mathcal{L}_{\rm eff} \supset \frac{1}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$
- portal to probe beyond-SM physics (dark sector)
- Search for ALP in Hall D *Phys.Lett.B 855 (2024) 138790*

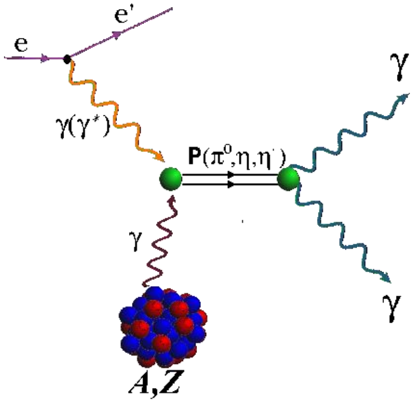


Pimakoff Program at Jefferson Lab

(see talk by L. Gan)

IV) Measure transition form factors at low Q^2 (0.001 – 0.5 GeV^2/c^2) with an electron beam

$F(\gamma\gamma^* \to \pi^0)$, $F(\gamma\gamma^* \to \eta)$, $F(\gamma\gamma^* \to \eta')$



- new experiment in Hall B (in preparation)
- π^0 electromagnetic transition radius, input for hadronic calculations in muon (g-2)

V) Extension of the Primakoff program for the Jefferson's Lab energy upgrade to 22 GeV

- Primakoff production off π^0 of an electron (detect recoil electron)
- Improve measurements of η / η'

Measurement of π^0 Decay Width

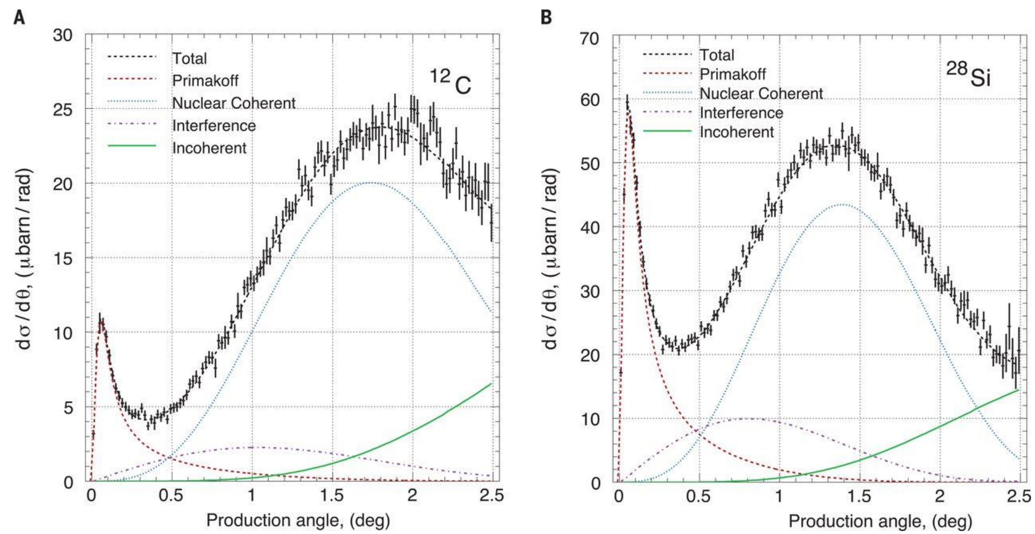
- Two experiments in Hall B in 2004 and 2010 using 6 GeV tagged photon beam

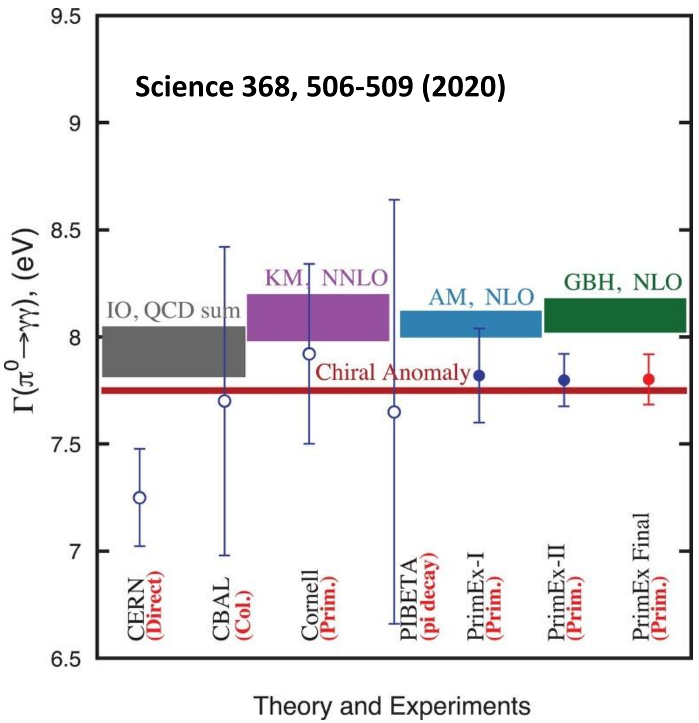
- Nuclear targets:

^{12}C, ^{208}Pb, and ^{28}Si

Science 368 (2020) 6490, 506-509

Phys.Rev.Lett. 106 (2011) 162303





- The chiral anomaly can be exactly calculated for massless quarks

- Combined measurements from two PrimEx runs

$\Gamma(\pi^0 \to \gamma\gamma) = 7.802 \pm 0.052(\text{stat.}) \pm 0.105(\text{syst.})$ eV

- The decay width was measured with the total uncertainty of 1.5 %

Measurement of $\eta \to \gamma\gamma$ Decay Width

Challenges of the measurement

- Small cross section, increases with the energy $\sigma_{prim} \sim \log(E)$
- η mass is a factor of 4 larger than π^0

  - larger momentum transfer (nuclear excitations, control coherency)
- Large overlap between Primakoff and hadronic processes

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

use a low-A target (LHe_4)
measurement at high beam energy, $E_\gamma > 8$ GeV

General requirements to the experiment:

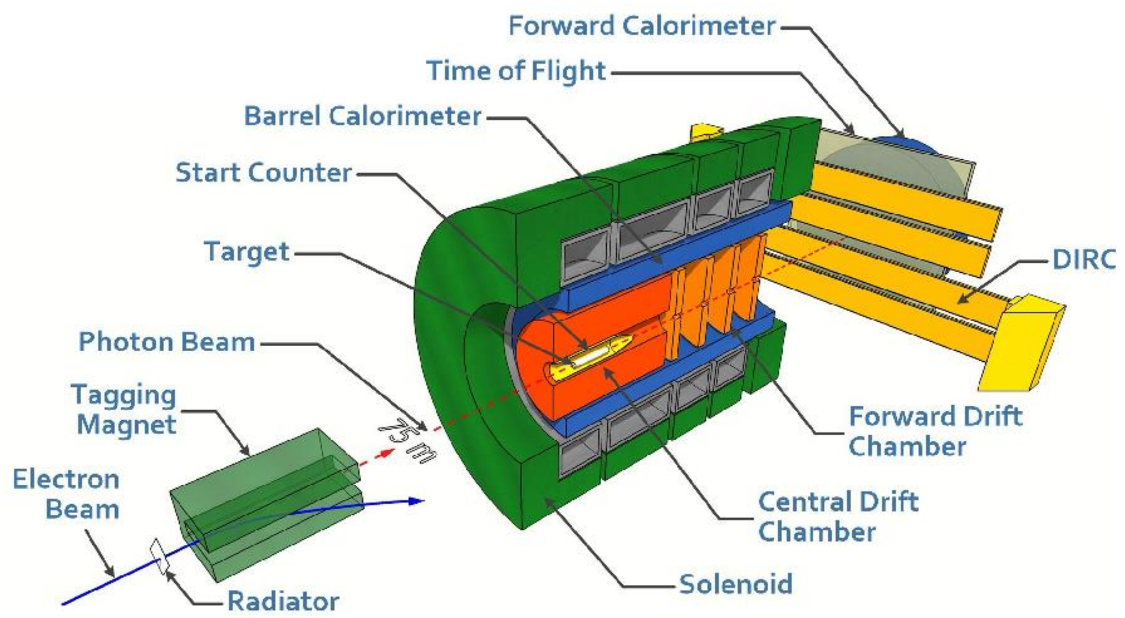
- Good angular resolution for reconstructed η mesons
- Precise measurements of luminosity

GlueX Detector in Hall *D* at Jefferson Lab

Photons: $\sigma_E / E \sim 6\% / \sqrt{E} \oplus 2.0\%$

Nucl. Instrum. Meth. A 987, 164807 (2021)

Tracks: $\sigma_p / p \sim 2 - 5\%$ **Acceptance:** $1° < \theta < 120°$

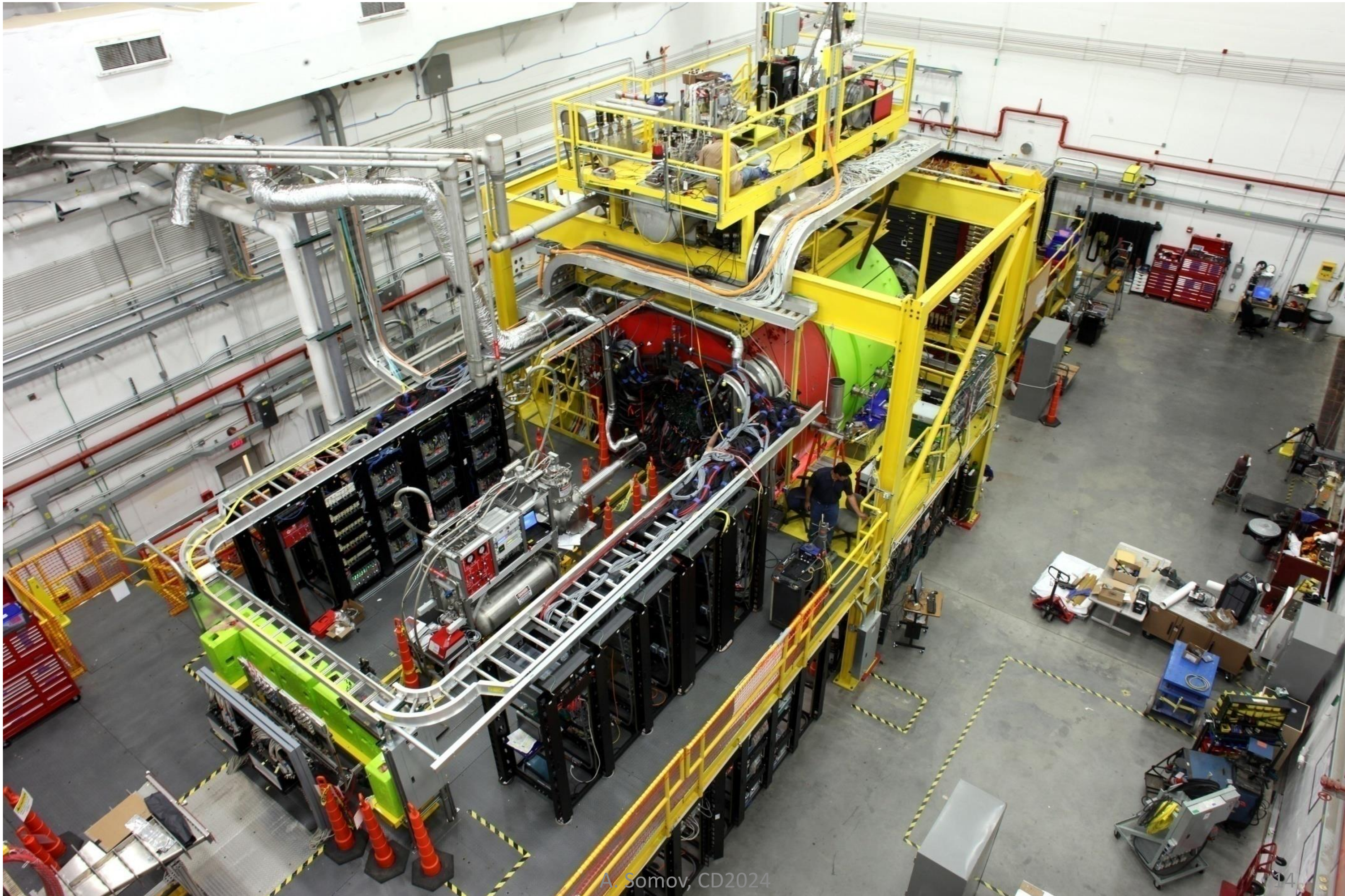


Experiments:

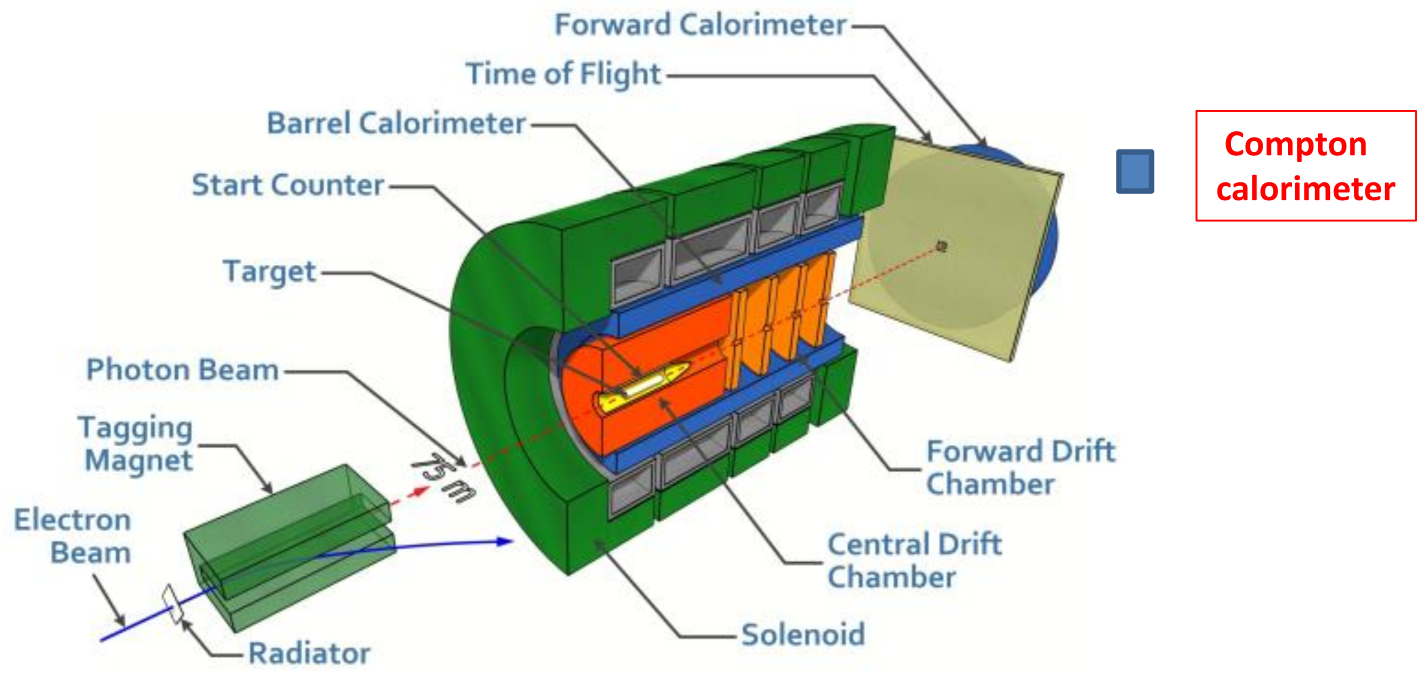
- Search for mesons with exotic quantum numbers
- Study of meson and baryon decays to strange final states
- Measurement of η radiative decay width via the Primakoff effect
- Measurement of pion polarizability
- Study short range correlations
- Study $\eta^{(')}$ decays (JEF)
- Measurement of high energy contribution to the GDH sun rule
- Strange hadron spectroscopy with KL beam

- Beam of tagged photons with the energy of up to 12 GeV, linear polarization (produced by CEBAF electrons via the bremsstrahlung process)
- The detector design is optimized to detect multi-particle final states
- The detector was commissioned in 2016. Several experiments have been carried out since then

GlueX Detector



PrimEx – η Experiment in Hall D



- New liquid ^{4}He and Be targets
- New Compton Calorimeter

- Use Compton scattering reaction for:
  - absolute luminosity normalization (Be target)
  - stability monitoring (^{4}He target)
- Reconstruct η mesons using decays:
  $\eta \to \gamma\gamma$ ($\eta \to 3\pi$)

PrimEx – η Experiment

- Three sets of data collected at different beam energies

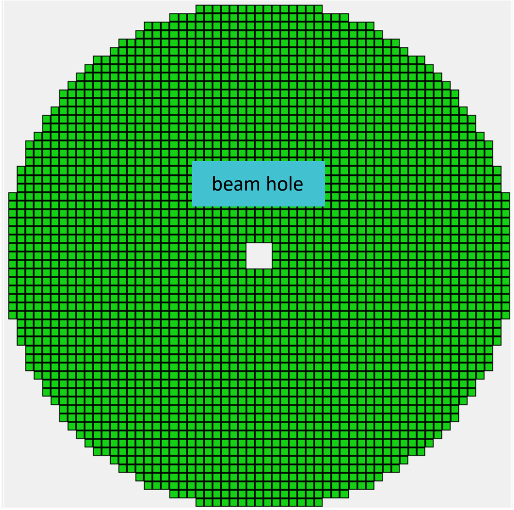
	Phase I	Phase II	Phase III
Year	2019	2021	2022
E_{beam}	11.2	10.0	11.6
Luminosity	6 pb^{-1}	2 pb^{-1}	~ 15 pb^{-1}
Magnetic field	OFF	OFF (most runs)	ON

~ 5 months of data taking in total

- $\eta \rightarrow \gamma\gamma$ decays are reconstructed in the forward calorimeter

- 2800 lead glass modules (taken from E852 experiment at BNL)
  - lead glass block size: 4 cm x 4 cm x 45 cm
- The energy resolution: $\frac{\sigma(E)}{E}(\%) = \frac{6.2}{\sqrt{E}} \oplus 4.7$
- Acceptance: $0.6° < \theta < 11°$
- Beam hole in the middle of the detector: 12 cm x 12 cm
  - place Compton calorimeter downstream the beam to improve coverage in the forward direction

Forward Calorimeter



Compton Calorimeter

Nucl. Inst. Meth. A 1013 (2021) 165683

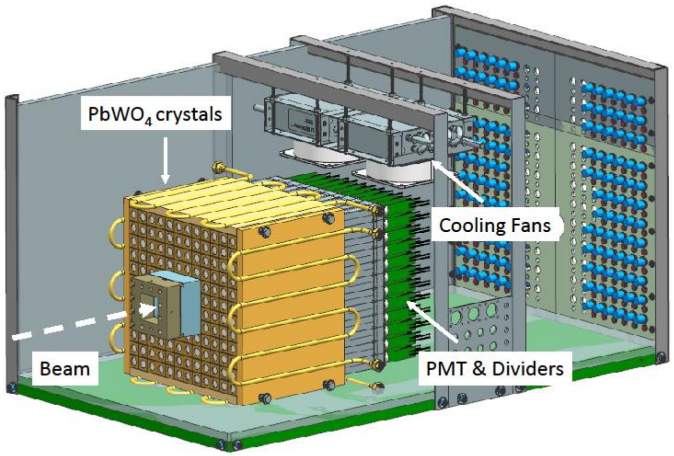
- Allows to reconstruct forward-directed Compton scattering events

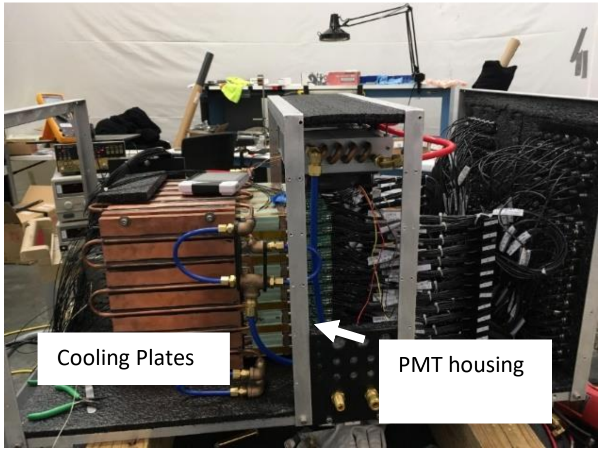
- Covers a beam hole in the GlueX forward lead glass calorimeter
  - increase angular acceptance of the detector to $\theta_{MIN} > 0.1$

- Consists of an array of 12 x 12 modules of $PbWO_4$ scintillating crystals, 2 cm x 2 cm x 20 cm with a beam hole of 2 x 2 modules

- Positioned on a movable platform
  - each module was inserted into the photon beam for energy calibration

- Integrated into the GlueX trigger. Reconstruct Compton scattering events during GlueX production
  - monitor density of the liquid ^{4}He target and overall detector stability





Compton Scattering

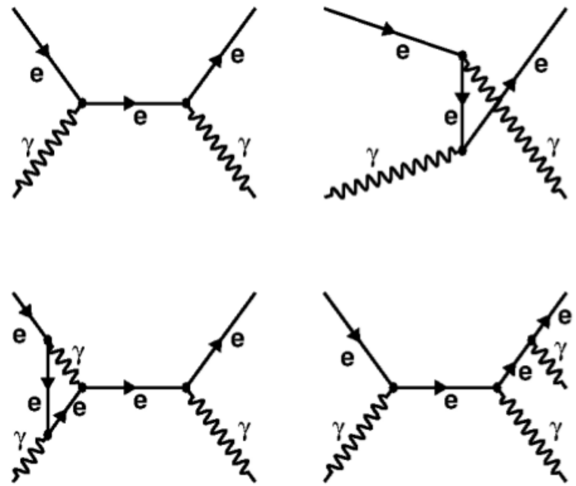
A. Smith

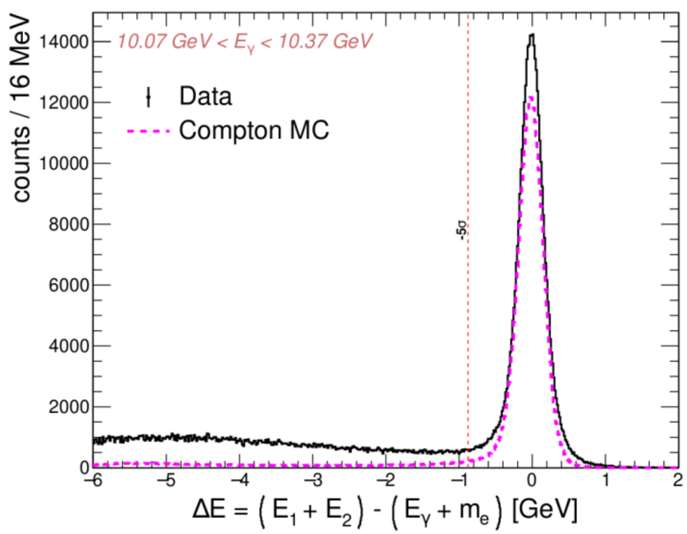
- Differential cross section at leading order (Klein-Nishina)

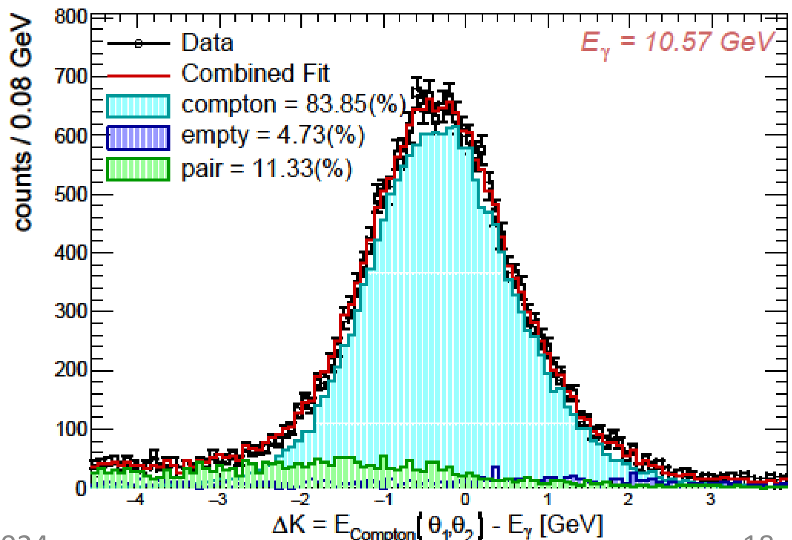
$$\frac{d\sigma_{KN}}{d\Omega_\gamma} = \frac{r_e^2}{2}\frac{1}{[1+E_0(1-\cos\theta_\gamma)^2]}\left[1+\cos^2\theta_\gamma+\frac{E_0^2(1-\cos\theta_\gamma)^2}{1+E_0(1-\cos\theta_\gamma)}\right]$$

- Two-body kinematics
- Main background from $e^{\pm}$ pairs

leading order (top)





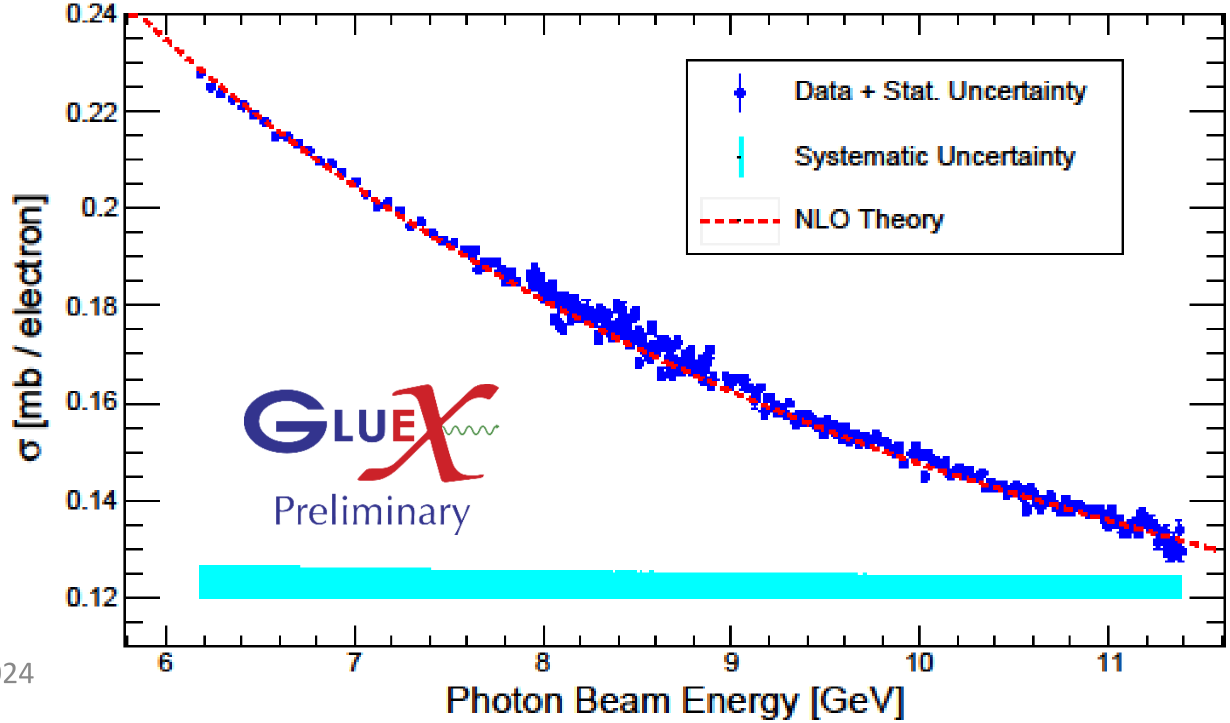


Compton Cross Section

A. Smith

- First cross section measurement in the range between 6 GeV and 11.5 GeV
  - previously measured for beam energies 4.4-5.3 GeV *Phys.Lett.B 797 (2019)*
- Journal paper under preparation
- Measurement are dominated by systematic uncertainties (3.6 %)
- "Good" agreement with NLO calculations *Phys.Rev.Lett. 126 (2021) 21, 211801*

Cross section measured on Be target (preliminary)

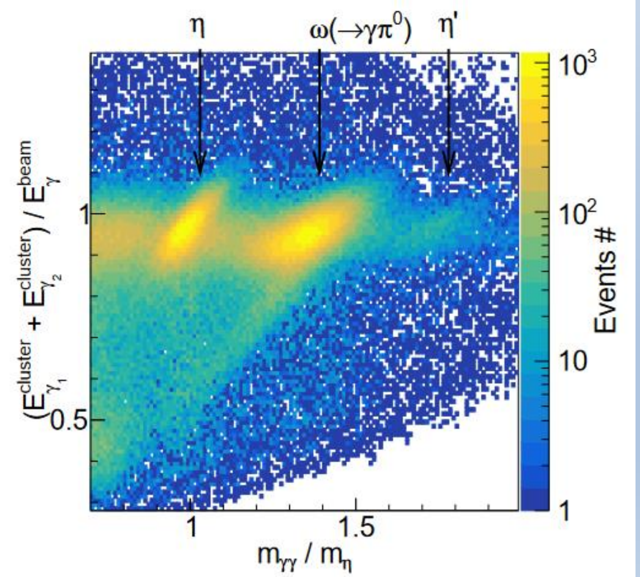


Status of the $\eta \to \gamma\gamma$ Analysis

A. Smith & I. Jaegle

Event selection:

- Two photons in the forward calorimeter originating from the same beam bunch
- Use time-of-flight detector to veto charged tracks
- Use barrel calorimeter to veto on hadronic background
- Elasticity requirement, $E^1_\gamma + E^2_\gamma$ - E_{BEAM} < 1 GeV

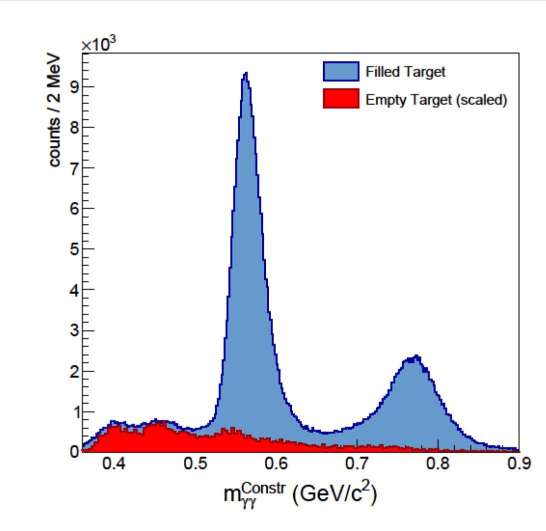


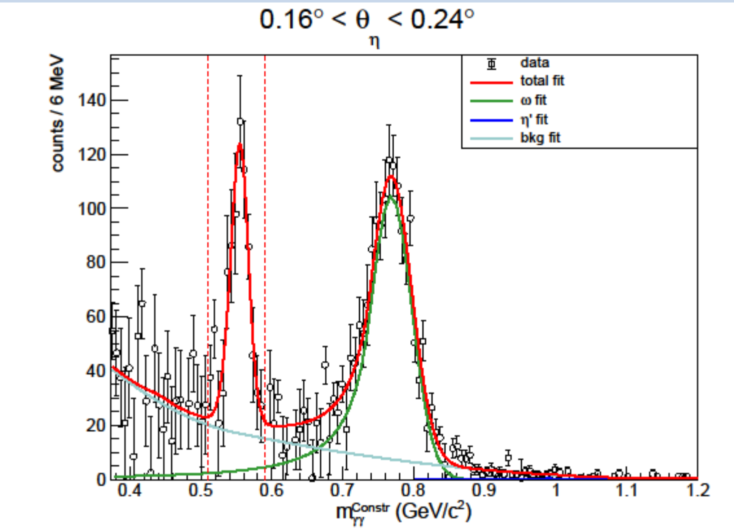
Clear selection of η candidates (large background)

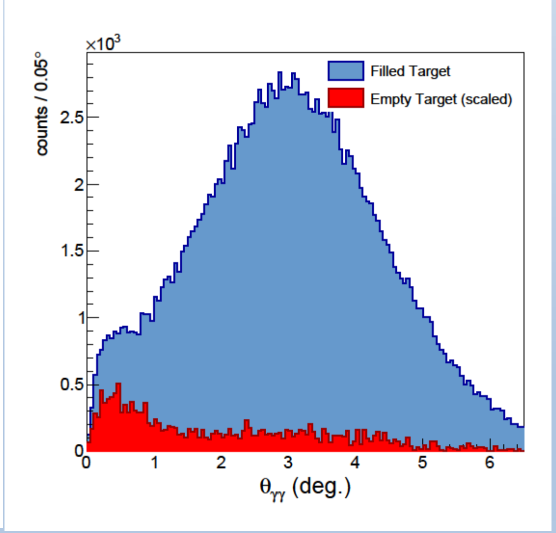
Status of the $\eta \to \gamma\gamma$ Analysis

- Beamline background from electromagnetic pair production downstream the target
  - peaking at small angles
  - collected large empty-target data sample to subtract

- Bin in the production angle, determine yield of η candidates for each bin from the lineshape distribution





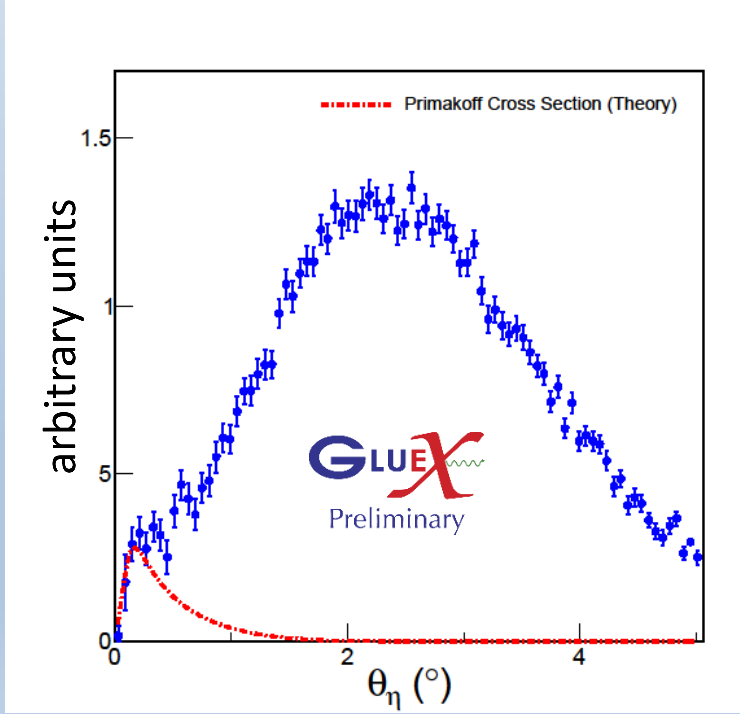


Angular Yield of $\eta \rightarrow \gamma\gamma$

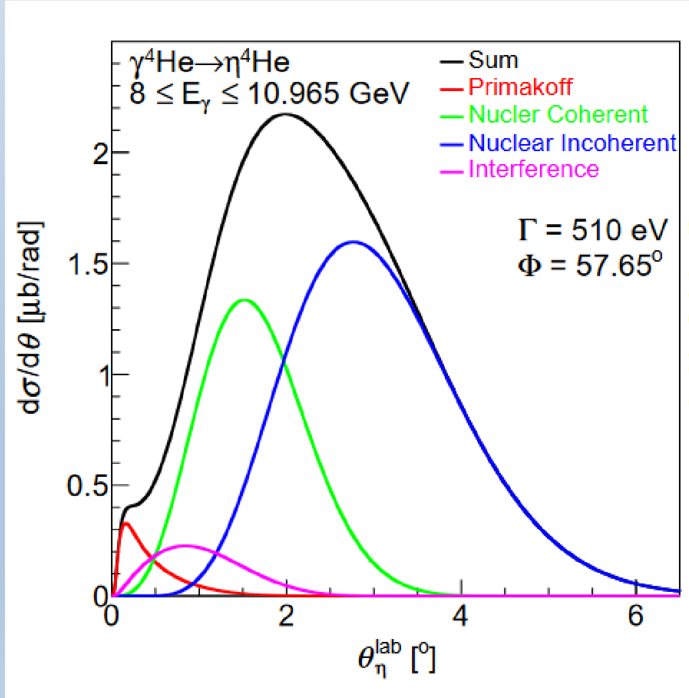
A. Smith & I. Jaegle

- Analysis of PrimEx Phase I data
  L ~ 6 pb^{-1} (about 25% of the full data set)
- Angular resolution of $\eta \rightarrow \gamma\gamma$ decays is about 1 mrad

Efficiency corrected yield



Theoretical predictions (S. Gevorkyan)



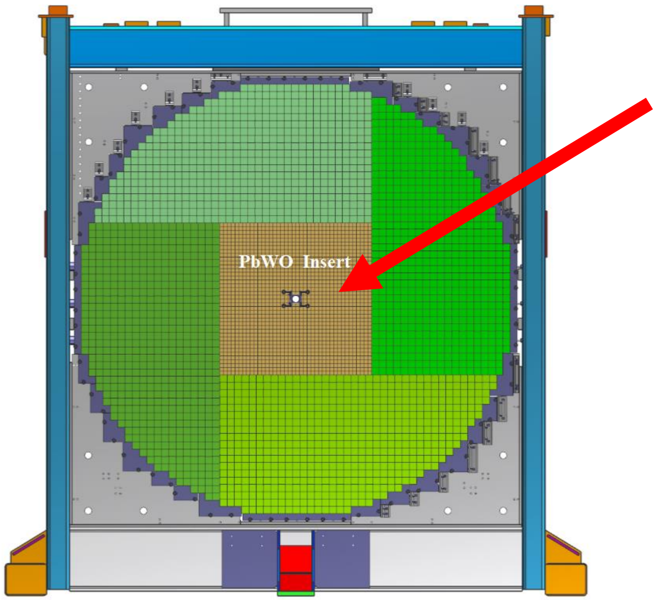
Future Plans

Extension of the Primakoff Program with the GlueX Detector

- Upgrade of the GlueX forward calorimeter
- Optimization of the detector beam line for Primakoff measurements
- Study feasibility of using heavier nuclear targets. Measurement of the decay width of η'
- Prospects of Primakoff measurements after Jefferson Lab energy upgrade to 22 GeV

Lead Tungstate Eta Calorimeter (ECAL)

- Upgrade the GlueX forward lead glass calorimeter with high-granularity high-resolution lead tungstate scintillating crystals
- Required by Jefferson Lab Eta Factory Experiment (see talk by L. Gan)
- Significantly improve reconstruction of photons in the forward direction



- ECAL consists of an array of 40 x 40 $PbWO_4$ (1596) modules

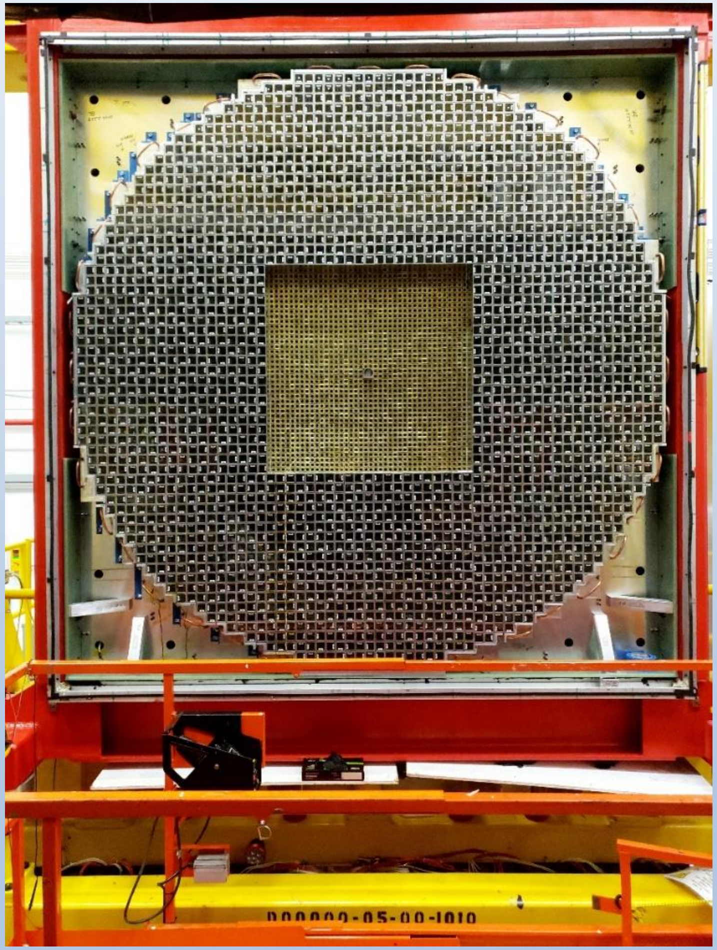
  - 2 cm x 2 cm x 20 cm $PbWO_4$ crystal
  - 4 cm x 4 cm x 45 cm lead glass block

Lead Glass & $PbWO_4$ modules

- A factor of 4 better detector granularity
  - significantly improve shower separation
- Improves the energy and position resolutions by about a factor of 2

Installation of the ECAL

October 6, 2023



- Started construction of ECAL $PbWO_4$ modules in 2022
- Detector installation completed in October 2023
- ECAL is currently under commissioning.
- GlueX run with the ECAL is scheduled for January 2025

Feasibility of Using Heavy Targets for Measurement of $\eta \to \gamma\gamma$ Decay Width

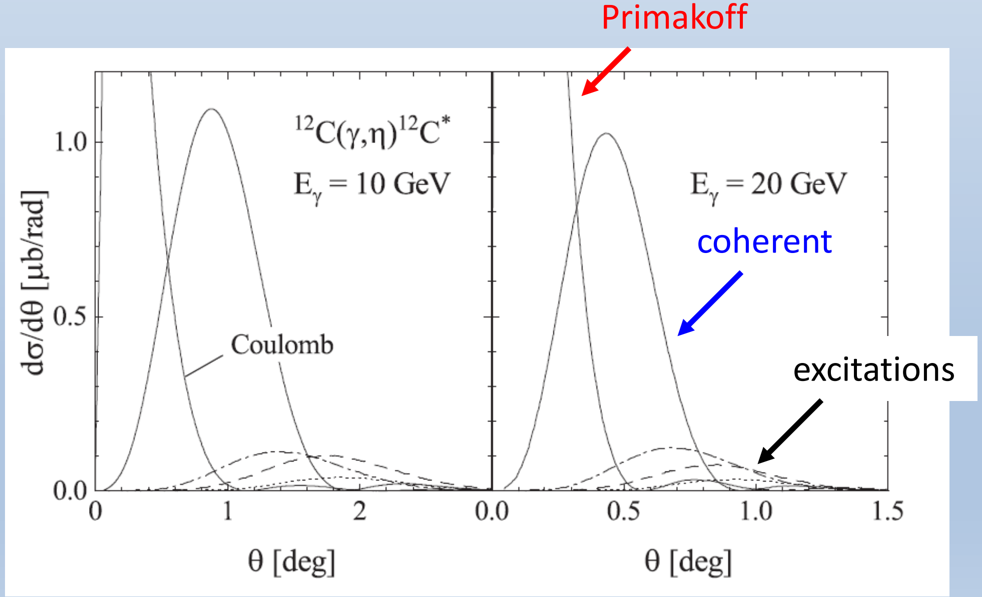
- Primakoff cross section $\sim Z^2$. Relatively large momentum transfer, have to consider nuclear excitations (coherency of the reaction)

- Calculations by A. Fix for coherent and incoherent photoproduction of

$$\gamma + {}^{12}C \to \eta + {}^{12}C^*$$

with various excitation levels

Phys. Rev. C 108, 044607 (2023)



Primakoff Program at 22 GeV

- Primakoff cross sections increases with energy

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

- 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

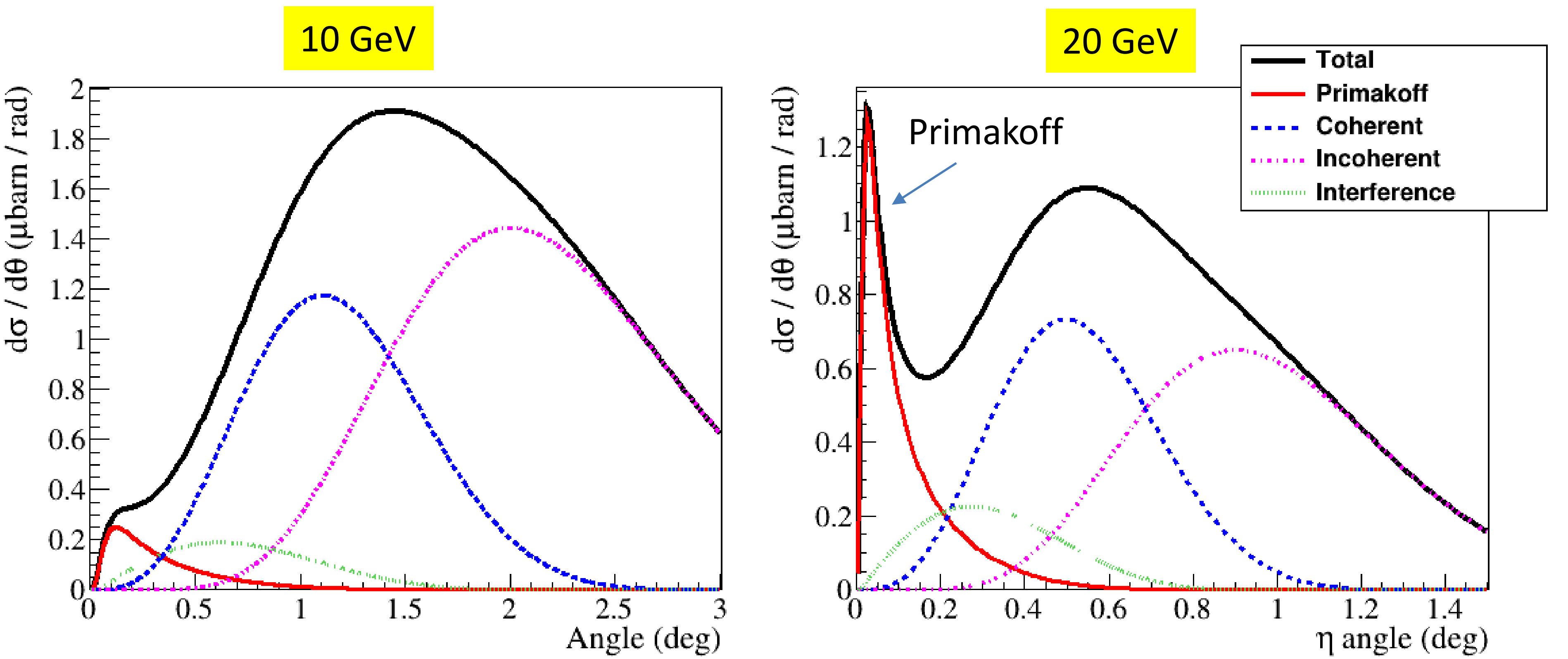
  $q_L\ \sim\ (m^2 / 2\ E)$,
  $q_T\ \sim\ 4\ E\ E_\eta \sin^2(\theta/2)$

  - 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



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

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

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

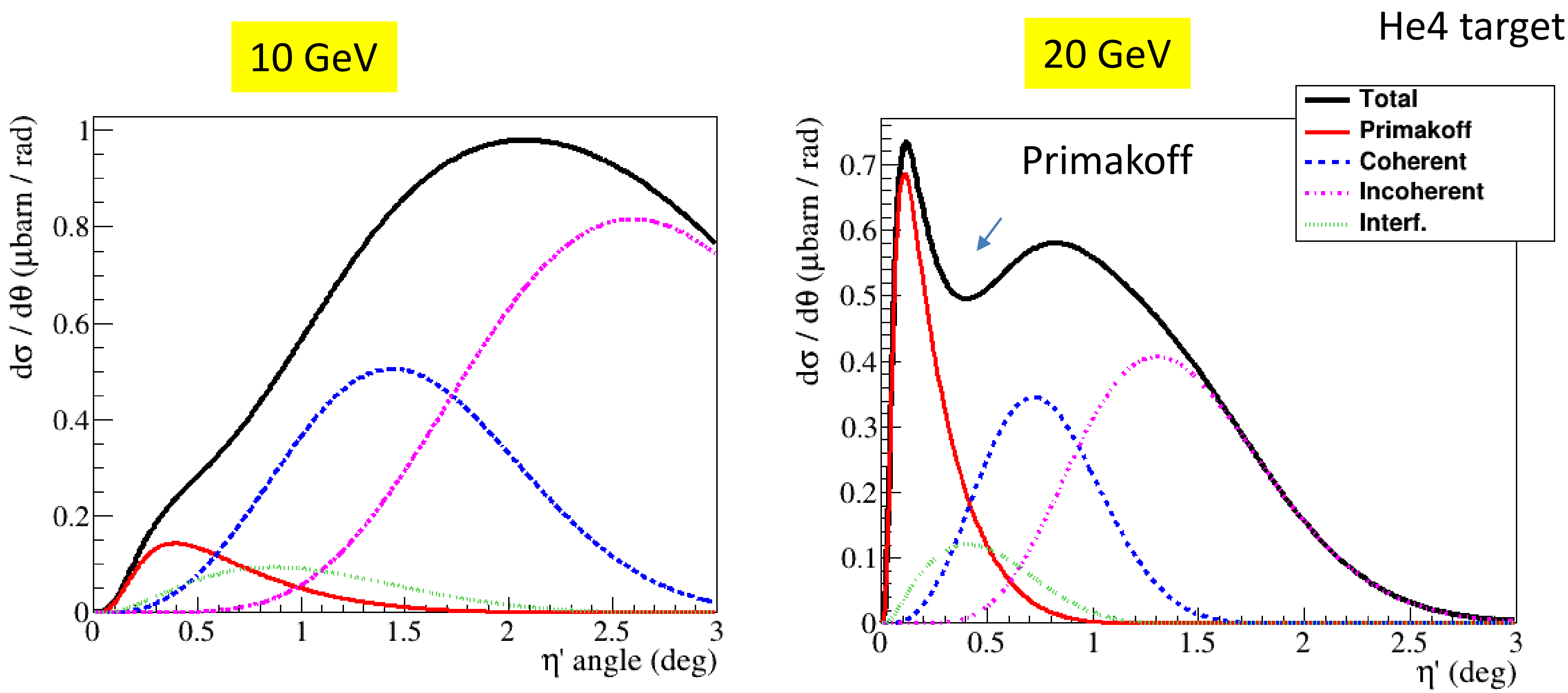
$$e^+ e^- \to e^+ e^- \eta'$$

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

$\Gamma(\gamma\gamma)$	Exp	Mode
$4.17 \pm 0.1 \pm 0.27$	L3	$\pi^+\pi^-\gamma$
$4.53 \pm 0.29 \pm 0.27$	CBAL	$\eta\pi^0\pi^0$
$3.61 \pm 0.13 \pm 0.48$	CELL	$\rho^0\gamma$, $\eta\pi^+\pi^-$
$4.6 \pm 1.1 \pm 0.6$	MD1	$\pi^+\pi^-\gamma$
$4.57 \pm 0.25 \pm 0.44$	MRK2	$\rho^0\gamma$, $\eta\pi^+\pi^-$
$5.08 \pm 0.24 \pm 0.71$	ASP	$\gamma\gamma$
$3.8 \pm 0.7 \pm 0.6$	TPC	$\eta\pi^+\pi^-$
$1.00 \pm 0.08 \pm 0.10$	CBAL	$\gamma\gamma$

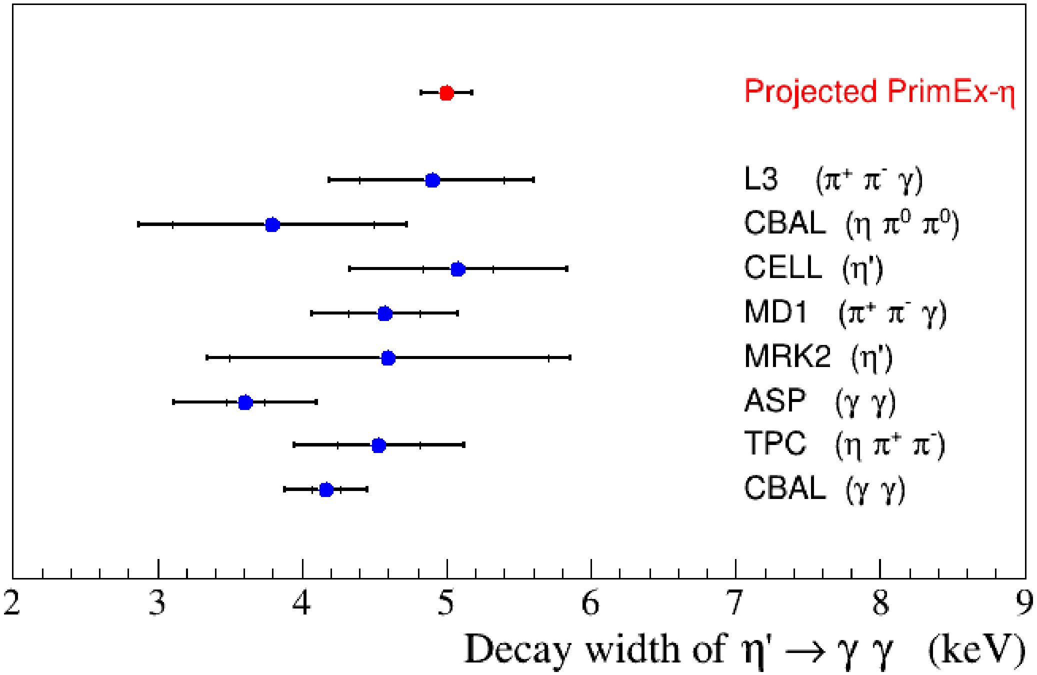
- No Primakoff measurement of the $\eta' \to \gamma\gamma$ decay width has been performed so far

Primakoff η′ Production at 10 GeV and 20 GeV



- Difficult to extract Primakoff η′ signal on He target at 10 GeV
- More 'prominent' Primakoff peak at 20 GeV
- Currently study feasibility to use ^{12}C target
  - Primakoff cross section ~ Z^2
  - have to consider nuclear excitations

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



- Run conditions: photon flux in the beam energy range 19 –21 GeV: 2×10^7 γ / sec, 6 % R.L. C 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

- Measurement of the radiative decay width of η mesons with the GlueX detector is a part of the Primakoff program at Jefferson Lab, which was initiated by the measurement of the decay width of π^0 meson in 2004

- The PrimEx-*η* experiment in Hall D completed collecting experimental data on a liquid ^{4}He target in 2022

    - Calibration of the acquired data set and data analyses are currently ongoing

    - The first publication of the Compton scattering cross section is under collaboration review.

- We are studying the feasibility of extending the Primakoff measurements of the η decay width using heavier targets and performing the first measurements of the η' decay width. The current upgrade of the GlueX forward calorimeter will significantly improve the photon detection capabilities.

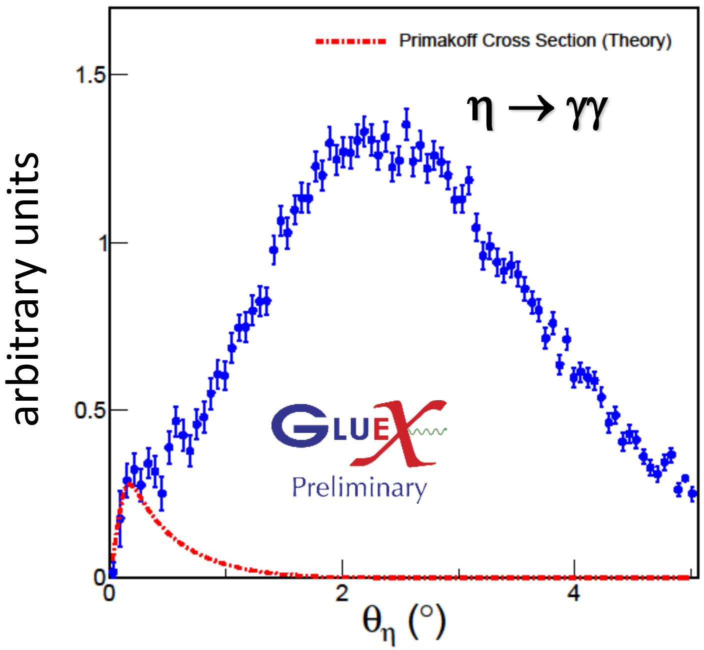
- The Primakoff physics program can be naturally extended to future experiments after a possible Jefferson Lab beam energy upgrade to 22 GeV.

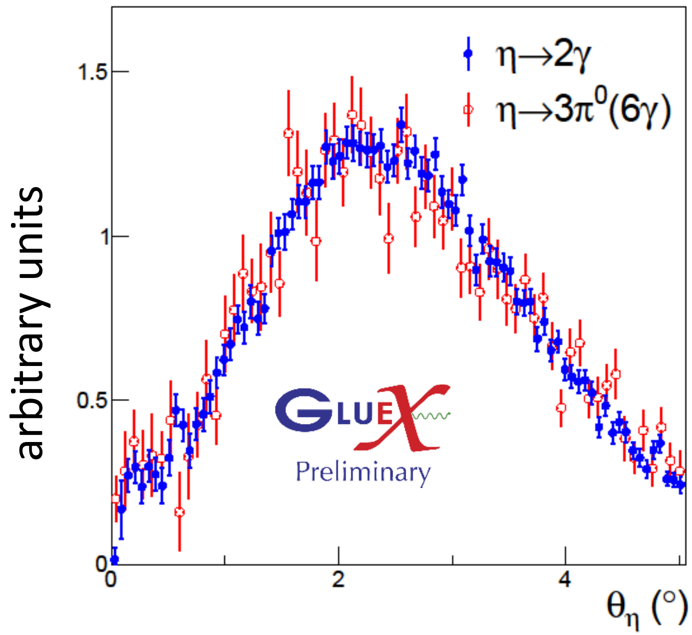
Backup Slides

Angular Yield of $\eta \rightarrow \pi^0\pi^0\pi^0$

A. Smith & I. Jaegle

- Analysis of PrimEx Phase I data
  L $\sim$ 6 pb^{-1} (about 25% of the full data set)





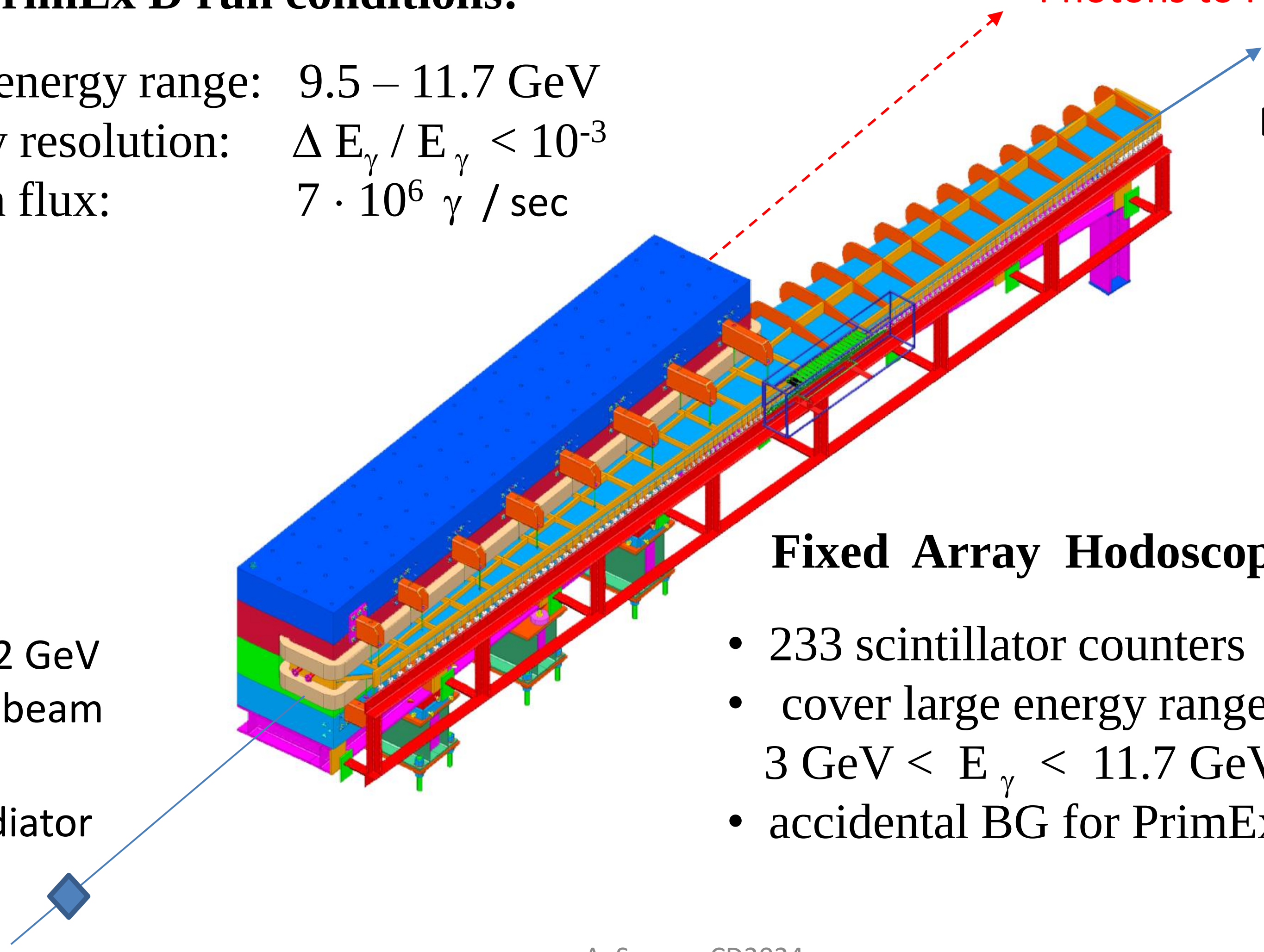
Analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$ channel is ongoing
 - most runs with the magnetic field in the PrimEx 3 phase, the trigger was also adjusted

Tagged Photon Beam

Measure energy of each beam photon by detecting a bremsstrahlung electron

PrimEx D run conditions:

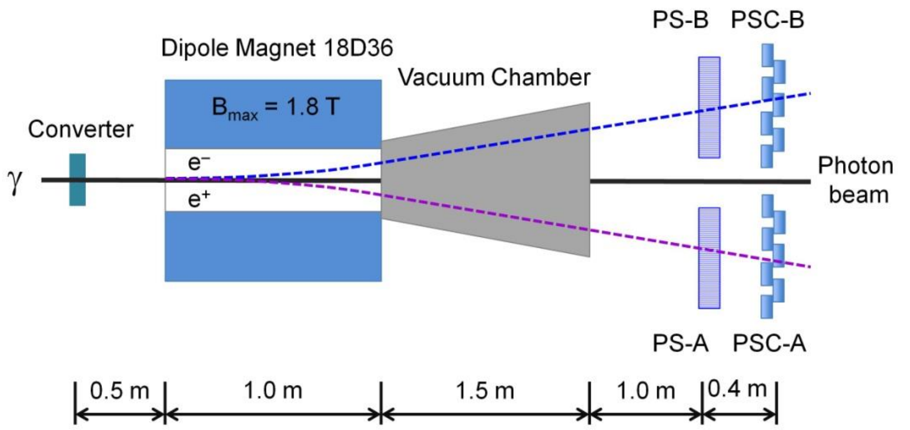
Beam energy range: 9.5 – 11.7 GeV
Energy resolution: $\Delta E_\gamma / E_\gamma < 10^{-3}$
Photon flux: $7 \cdot 10^6\ \gamma$ / sec



Fixed Array Hodoscope

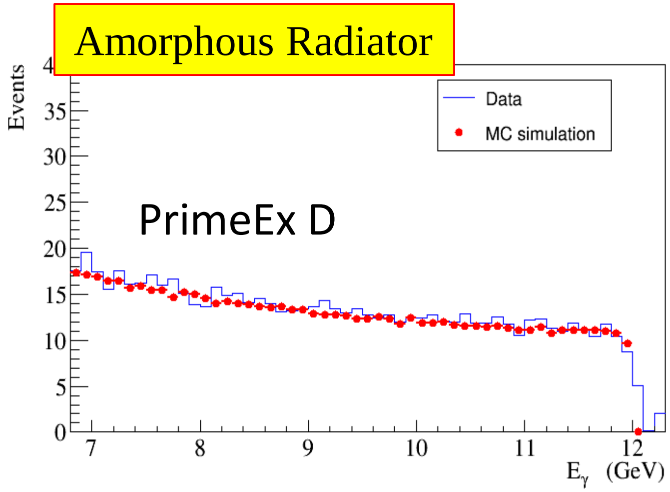
- 233 scintillator counters
- cover large energy range
  3 GeV < E_γ < 11.7 GeV
- accidental BG for PrimEx D < 4 %

Photon Flux Measurements with Pair Spectrometer



Two layers of scintillator detectors:

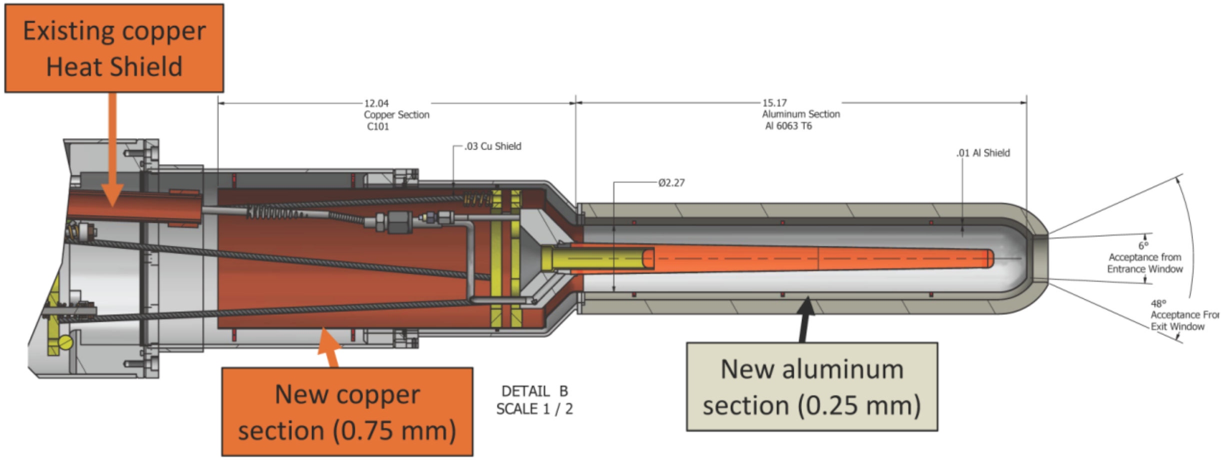
- Reconstruct the energy of a beam photon by detecting $e^{\pm}$ pairs ($6 < E_{\gamma} < 12$ GeV)



Monitor the photon flux with the precision < 1 %

PrimeEx D Targets

- liquid H_2 target (3.6 % R.L.): standard GlueX target
- liquid He target (4.0 % R.L.): modify GlueX target
  add heat shield around the target cell



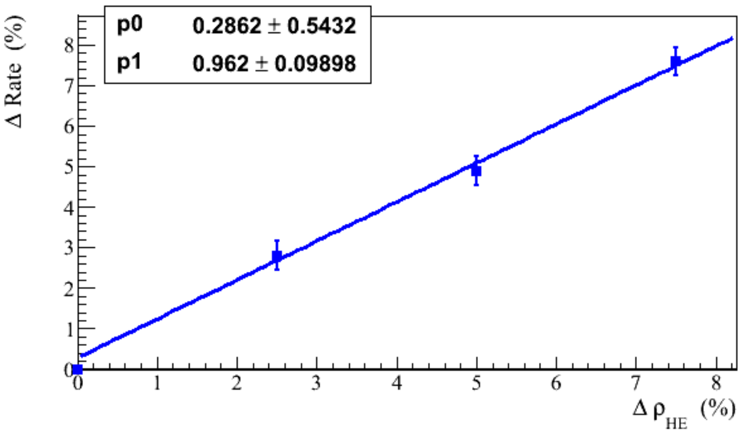
- Be target: Luminosity calibration using Compton process

Target Density Monitor

- Short term stability control:

  - photon beam flux provided by the PS
  - rates in the Start Counter (ST) and Time-of-Fight (TOF) wall

ST rate dependence on the target density



ST consists of 30 paddles surrounding the target

ST rate for production runs: 250 kHz / paddle

Coincidence of hits between the ST and TOF
(2 x 2 bars in TOF at R = 30 cm & one ST paddle)
1.5 kHz

- Long term stability control:

  - monitor using Compton process; expected rate in the photon range of interest is about 30 Hz