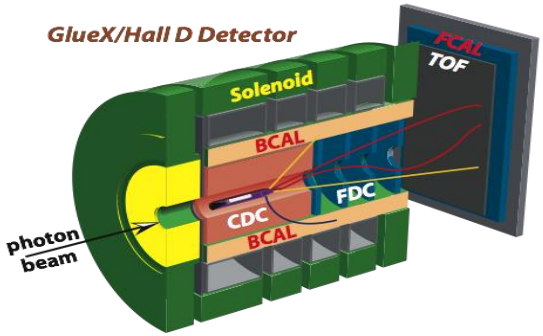
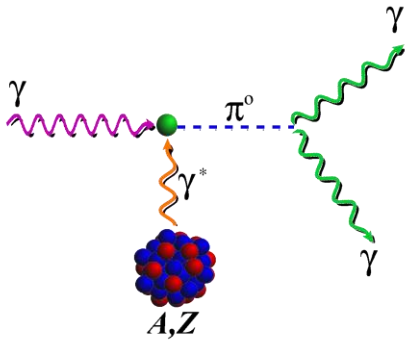


Jefferson Lab



η Decay Program at GlueX

A. Somov (Jefferson Lab)

for the GlueX Collaboration

HADRON 2019, August 18, 2019, Guilin, China

- Primakoff production of η mesons
- Study rare decays of η mesons

Outline

- PrimEx η experiment with the GlueX detector to measure the width $\Gamma(\eta \rightarrow \gamma\gamma)$ using Primakoff process

  - collected about 30 % of data in Spring 2019

  - the experiment complements the Primakoff program at Jefferson Lab (see talk by L. Gan about measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ in Hall B)

- Study rare decays of eta mesons

  - future GlueX experiment (approved)

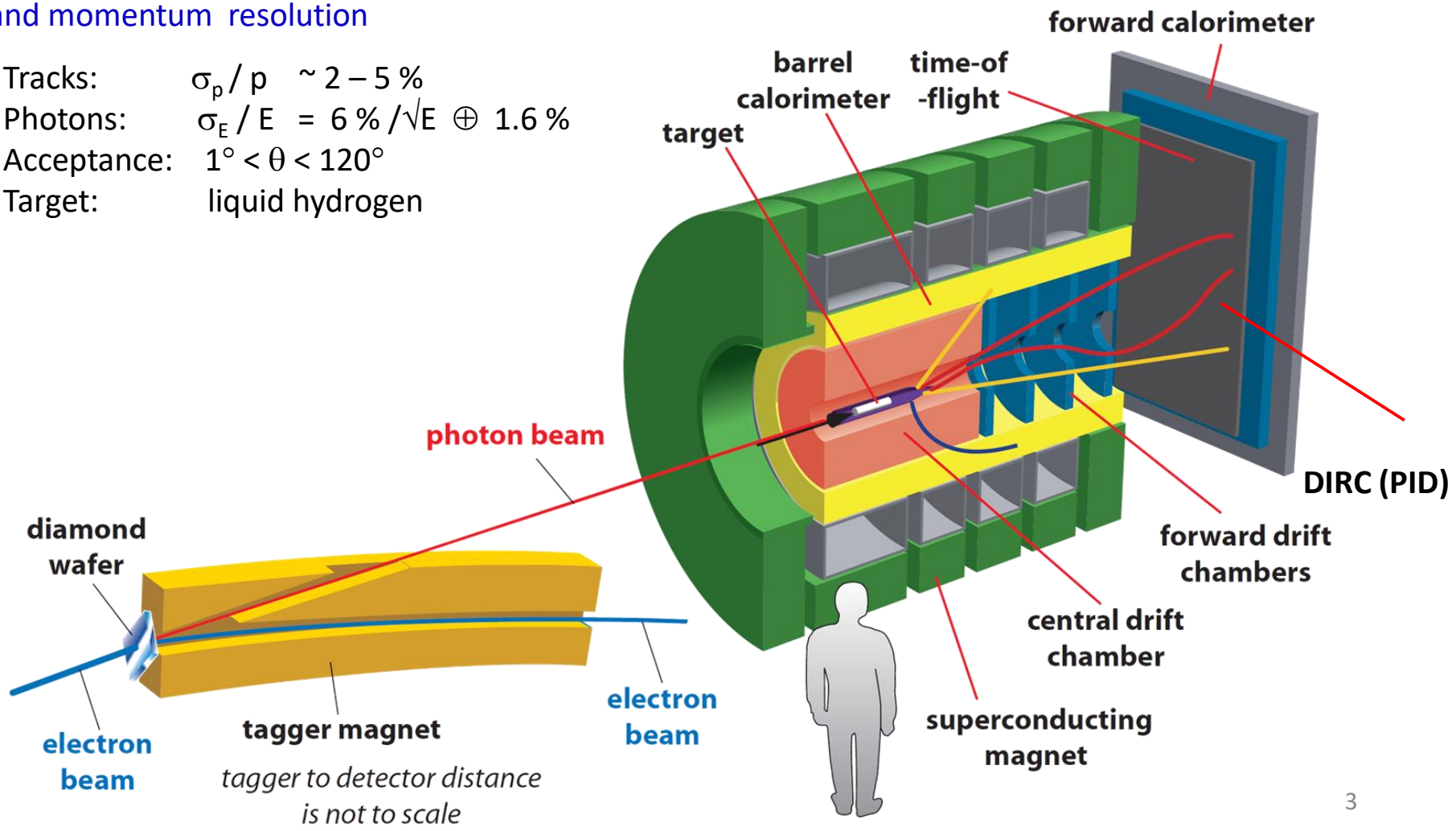
  - require upgrade of the GlueX forward calorimeter

GlueX Detector

see talks by M.Shepherd, D.Mack, S. Dobbs

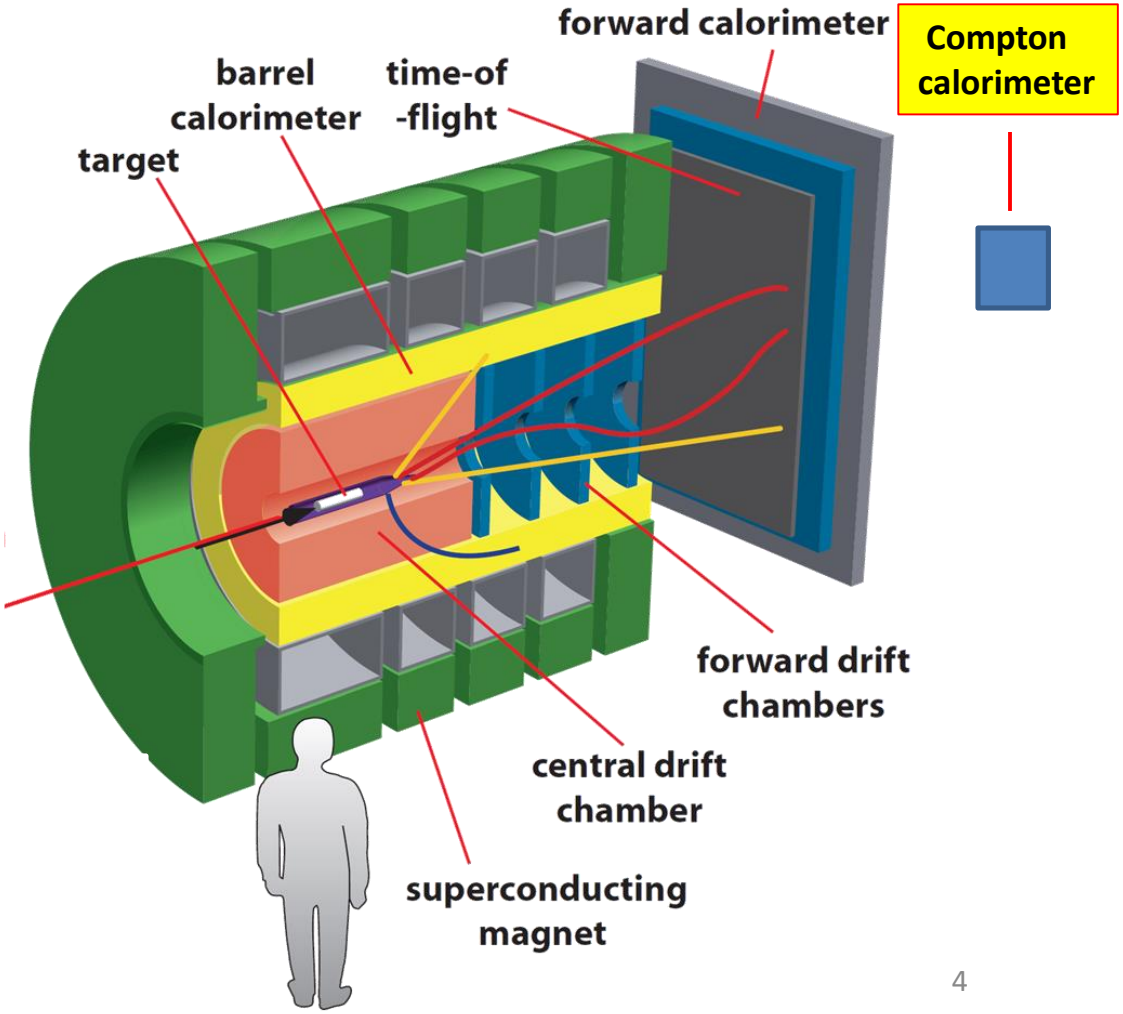
- Optimized to detect multi-particle final states
- Hermetic, large/uniform acceptance for charged and neutral particles, good energy and momentum resolution

Tracks: σ_p / p ~ 2 – 5 %
Photons: σ_E / E = 6 % /$\sqrt{E}$ $\oplus$ 1.6 %
Acceptance: $1° < \theta < 120°$
Target: liquid hydrogen

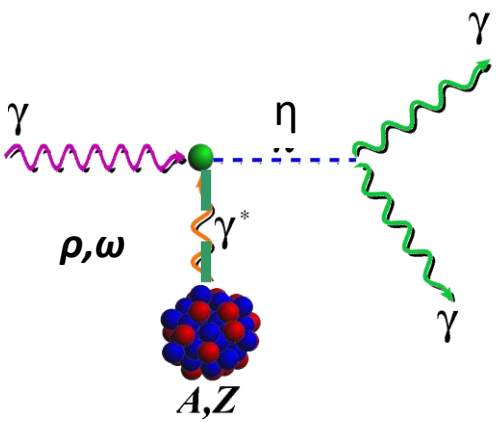


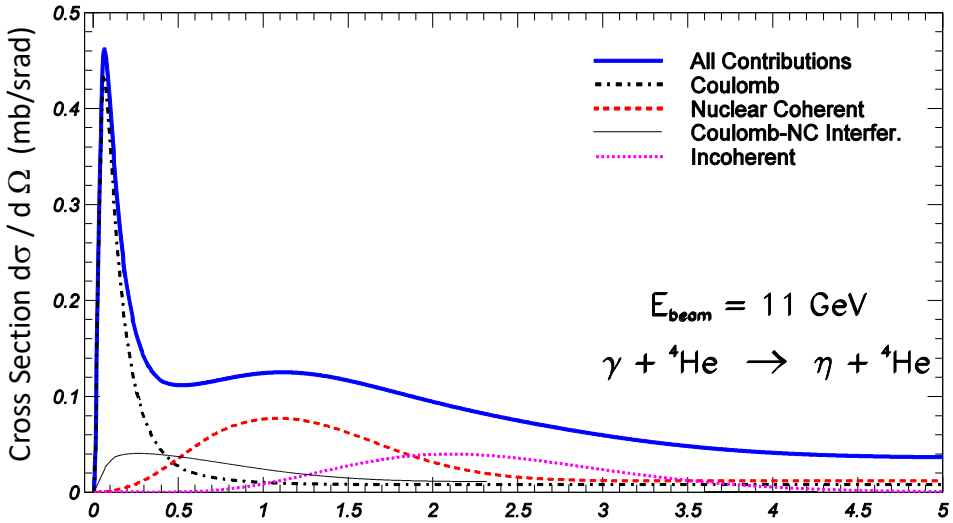
Primakoff η Experiment

- 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
- Beam energy range if interest
  9 GeV – 11.2 GeV
- Collected 30 % of the total statistics in Spring 2019 using LHe target



The Primakoff Method





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

- Extract decay width $\Gamma(\eta\to\gamma\gamma)$ from the measured cross section $d\sigma/d\Omega$
- Use low A targets LH_2 and LHe_4 to control:
  - coherency
  - contributions from nuclear processes

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

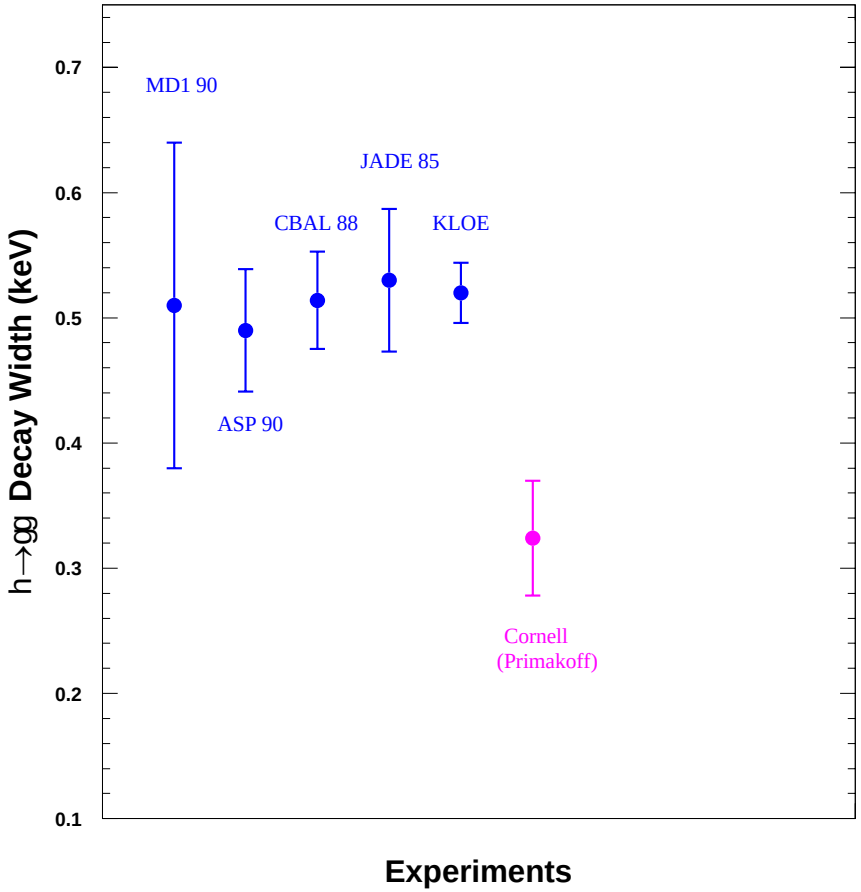
- The partial width $\Gamma(\eta \to \gamma\gamma)$ was derived from measurements

  - collider experiments in the reaction

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

  - Primakoff production of η mesons

- Some disagreemnts between collider and Primakoff results



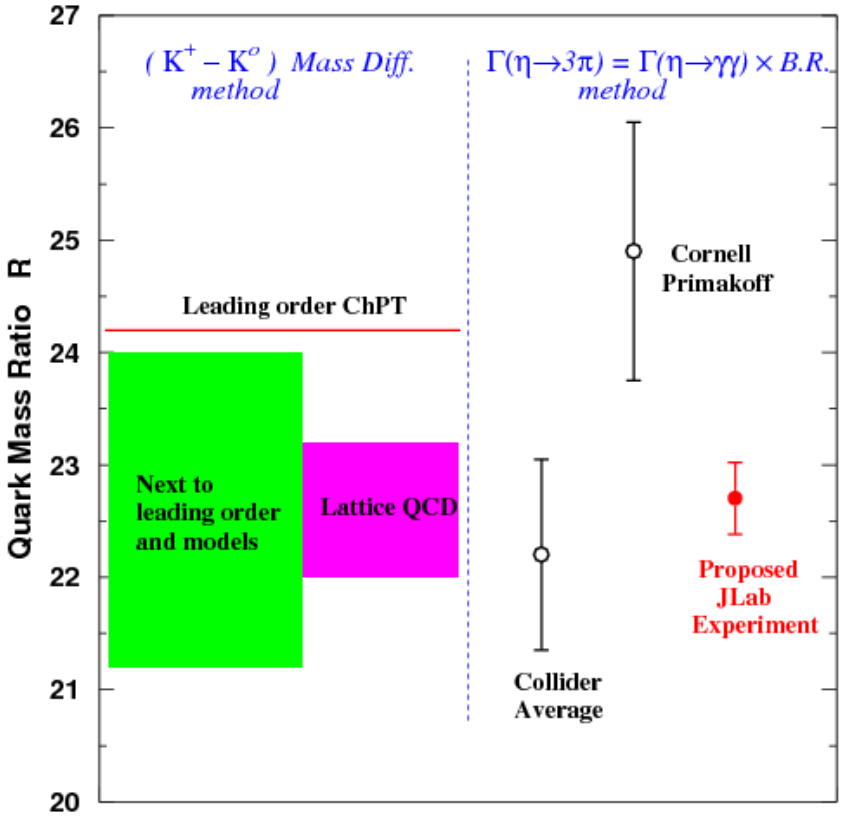
New PrimEx experiment in Hall D at Jefferson Lab

Measure $\Gamma(\eta \to \gamma\gamma)$ using Primakoff process with the precision of 3.2%

Physics Motivation

- **Light quark mass ratio:**

H. Leutwyler PLB, 378,1996



- $\Gamma(\eta\to\gamma\gamma)$ 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 $\Gamma(\eta\to3\pi)$

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

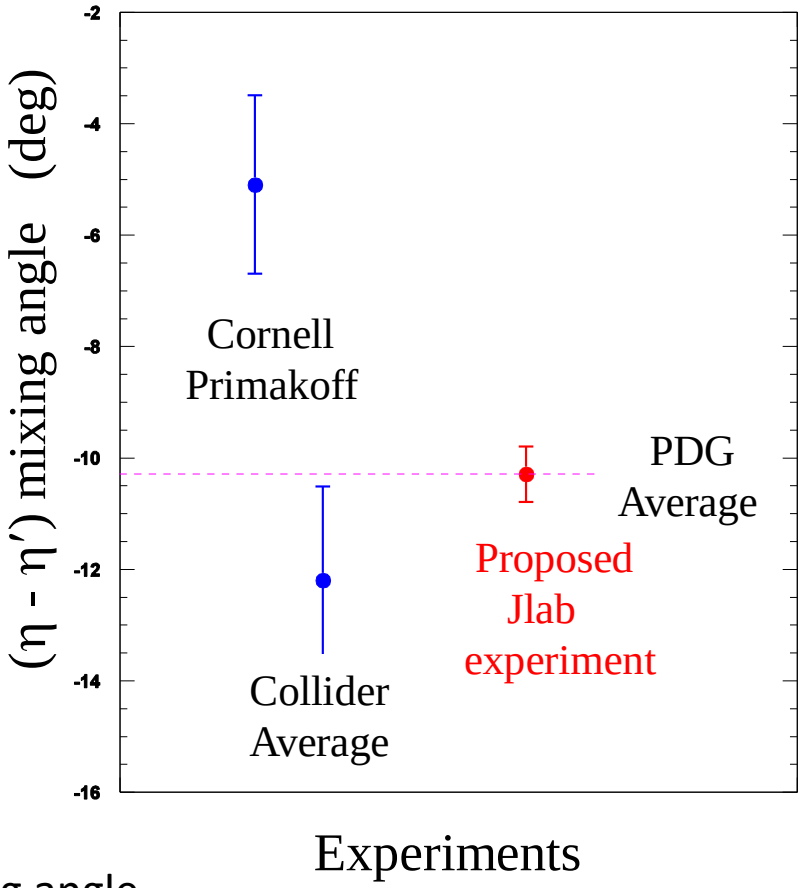
Physics Motivation

- **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**

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

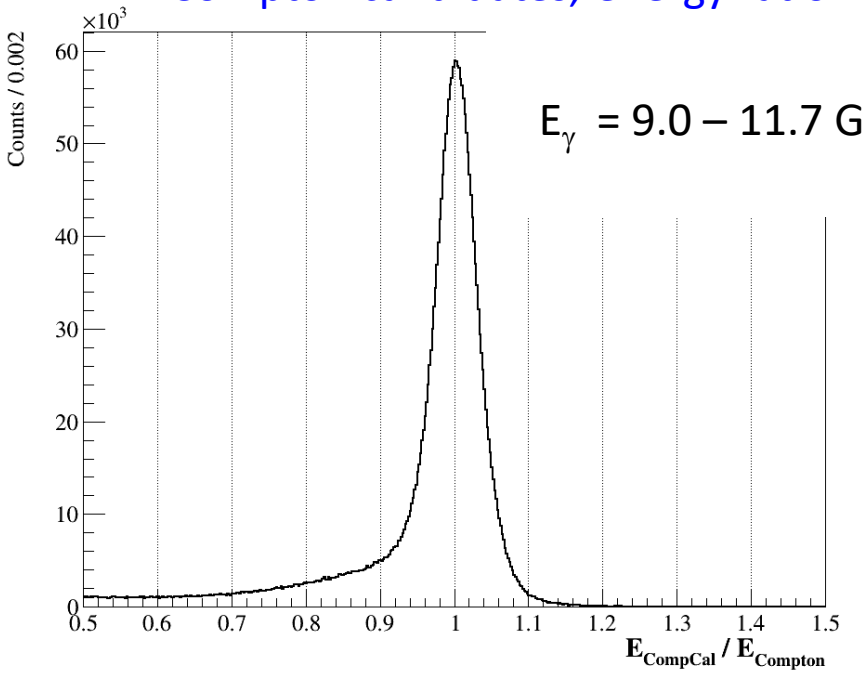


- Model dependent extraction of the mixing angle
- Uncertainty in the Γ(η'→γγ) has less impact on the angle extraction

Reconstruction of Compton Events

- Measure Compton $\gamma + e \rightarrow \gamma + e$ cross section in the forward direction during physics production runs
- Monitor target thickness and beam flux during production runs (rate of reconstructed events ~ 30 Hz)
- Use Compton for the cross section normalization

Compton candidates, energy ratio



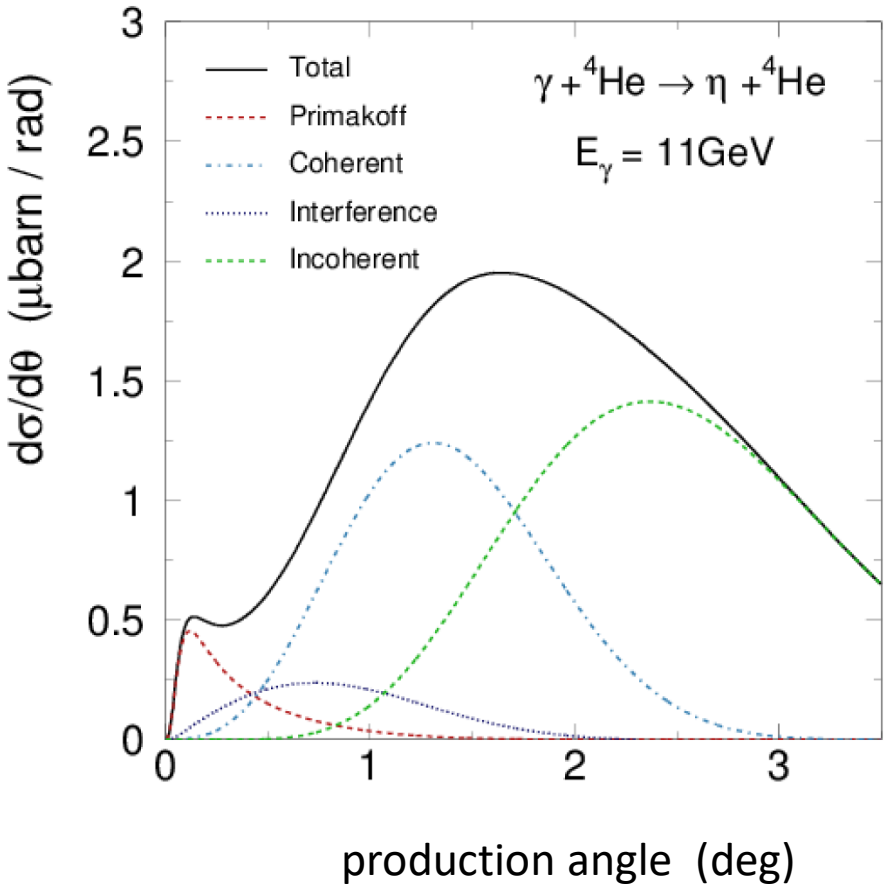
E_γ = 9.0 – 11.7 GeV

- Install Compton calorimeter behind forward calorimeter

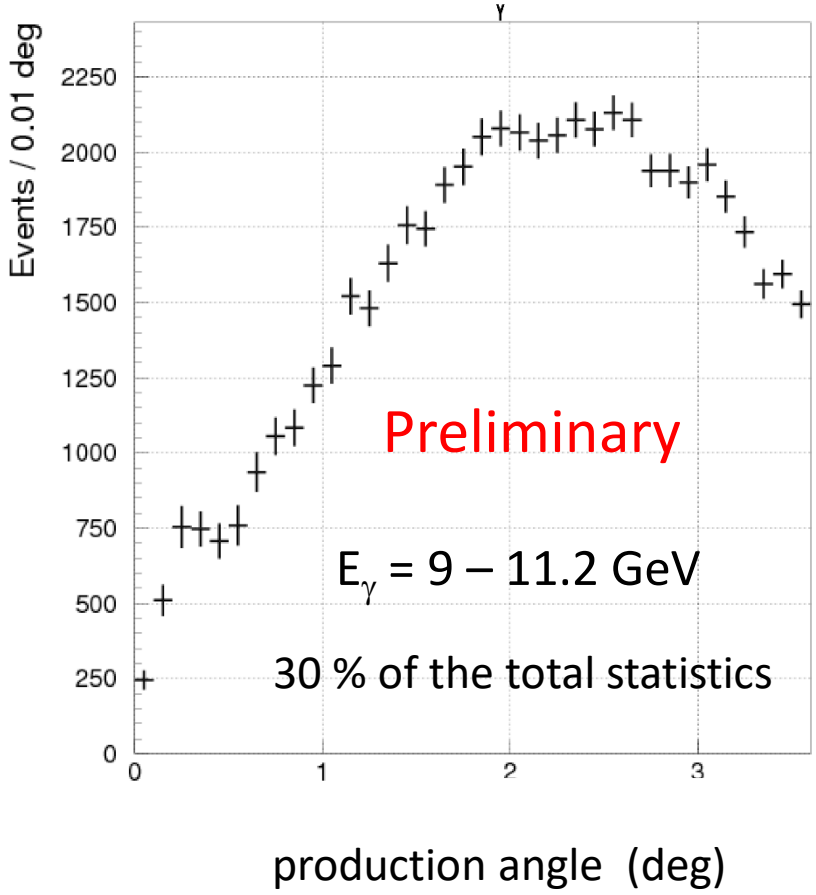
  - 12x12 (24 x 24 cm^2) $PbWO_4$ crystals

$\eta \rightarrow \gamma\gamma$ Angular Distribution

MC predictions

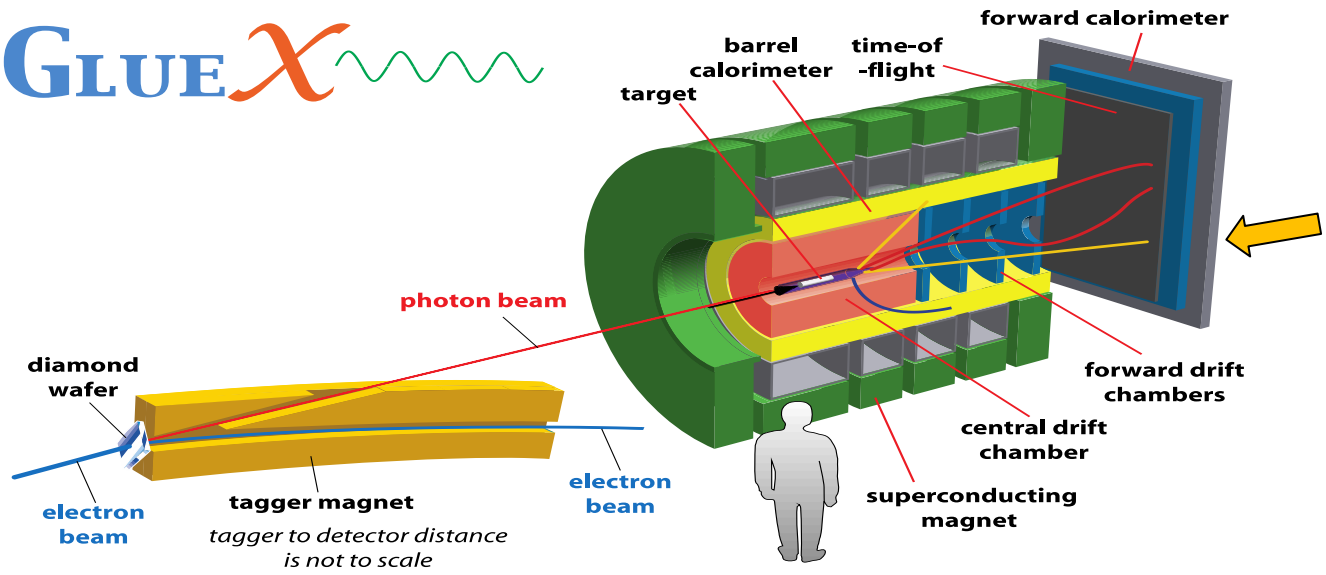


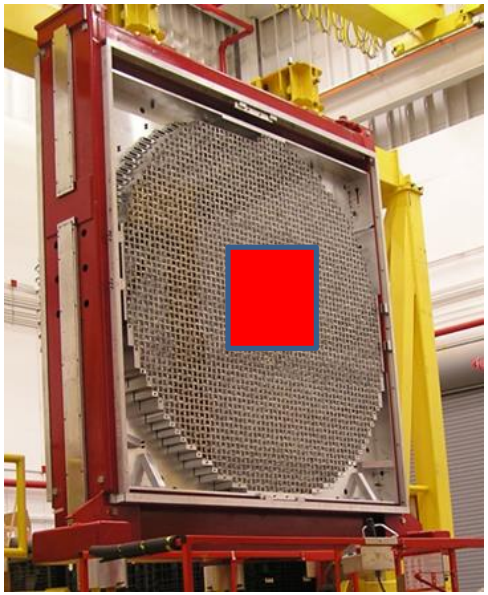
He target, Spring 2019



GlueX Upgrade

FCAL





- Upgrade the inner part of the lead glass Forward Calorimeter with the $PbWO_4$ crystals (**FCAL-II**)

- significantly improve detection of multi-photons from η decays
- allow to study rare decays such as $\eta \rightarrow \pi^0\gamma\gamma$ in the $\gamma + p \rightarrow \eta + p$ reaction using a beam of tagged photons with the energy between 9 – 11.7 GeV

Jefferson Lab Eta Factory (JEF)

JEF Project Overview

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[112]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$		2

Main physics goal:

1. Probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian
2. Search for a dark boson (B)
3. Directly constrain CVPC new physics
4. Constrain the light quark mass ratio

Impact of $\eta \to \pi^0\gamma\gamma$ measurements on ChPT

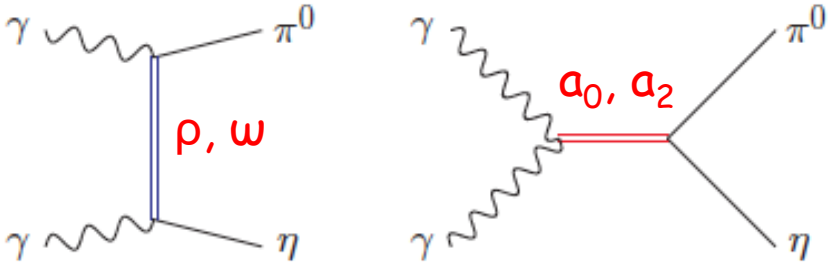
- Unique probe for the high order ChPT: the major contributions to $\eta \to \pi^0\gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian

  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

- Study contribution of scalar resonances in calculation of $O(p^6)$ low-energy constants (LEC) in the chiral Lagrangian

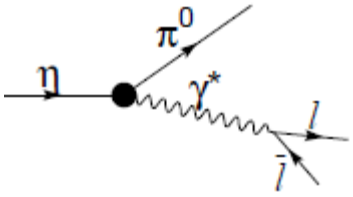
- Shape of Dalitz distribution is sensitive to the role of scalar resonances

Higher order LEC's are dominated by resonances
Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael1989; Donoghue, Ramirez, Valencia 1989

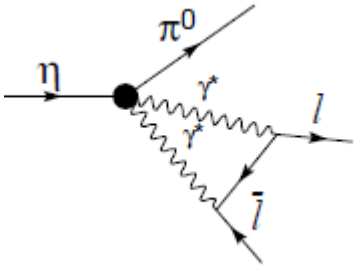


- A cross-check of LEC's with different processes

C and CP violating



C and CP conserving background

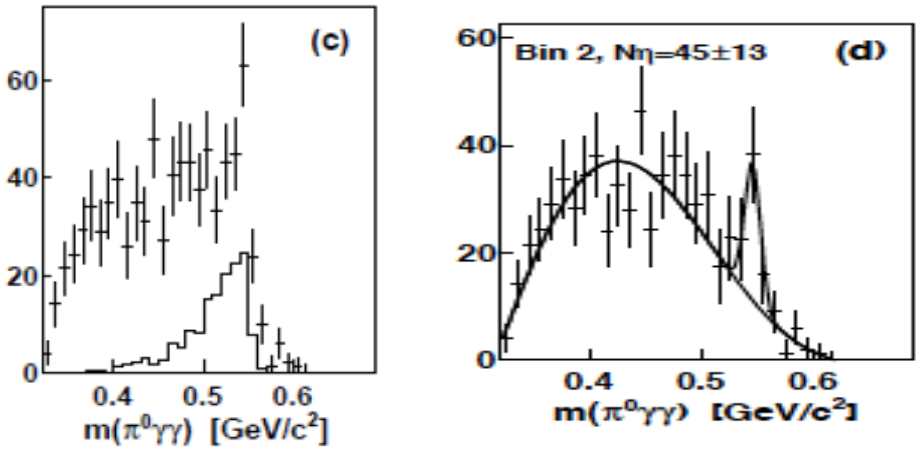


J.N. Ng, et al., Phys. Rev., D46, 5034 (1992)

Measurements of $\eta \rightarrow \pi^0\gamma\gamma$

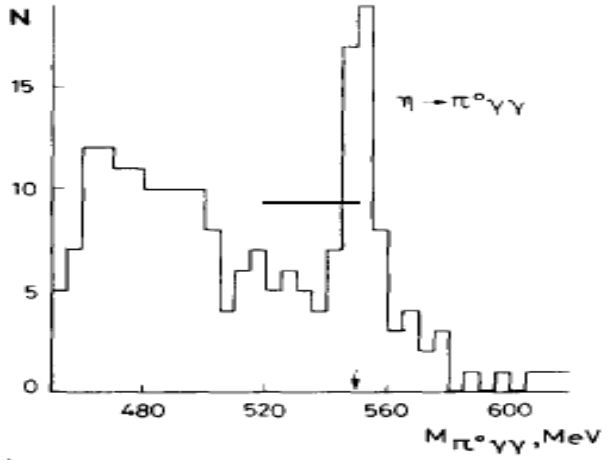
A2 at MAMI (Phys.Rev. C90, 025206,2014)

$\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV)



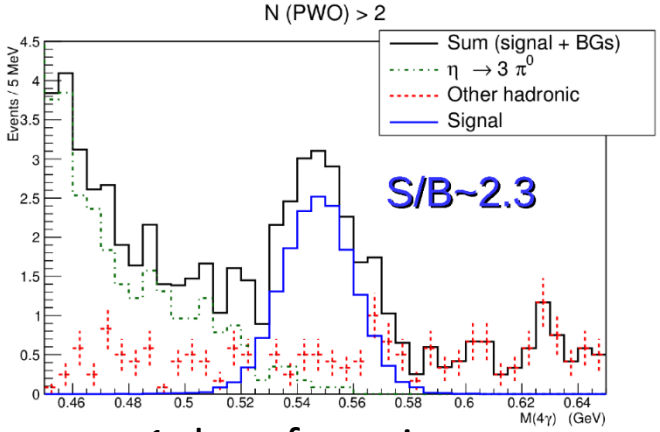
GAMS (Z. Phys. C25,225, 1985)

$\pi p \rightarrow \eta p$ (E_π= 30 GeV)



JEF (proposed)

$\gamma p \rightarrow \eta p$ (E_γ = 9-11.7 GeV)

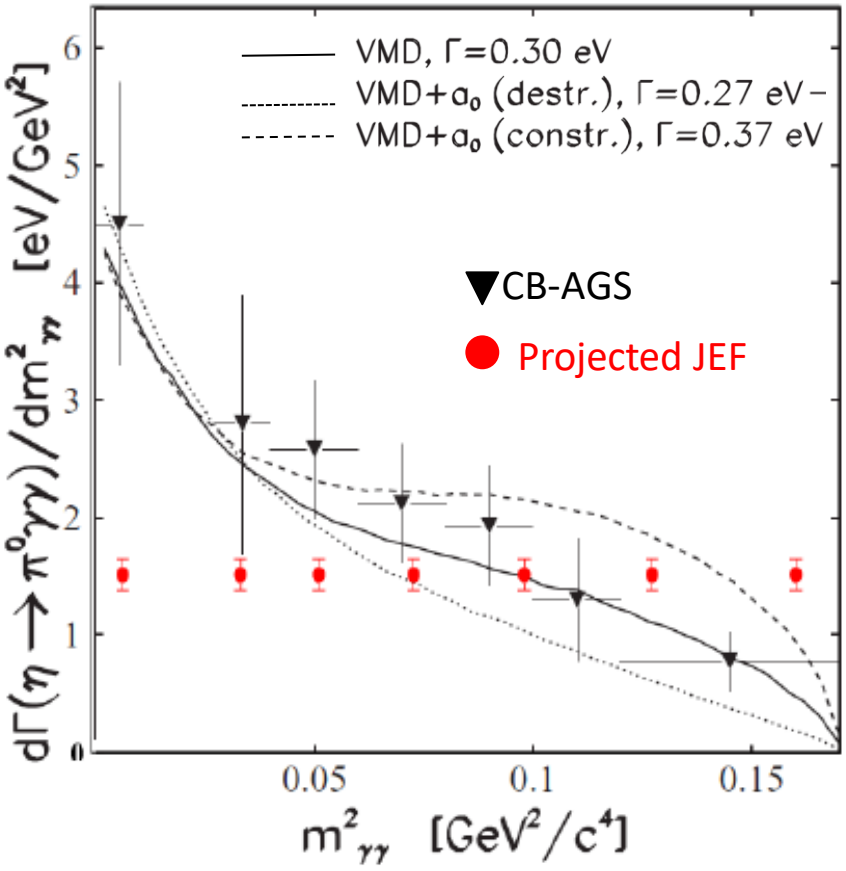


1 day of running

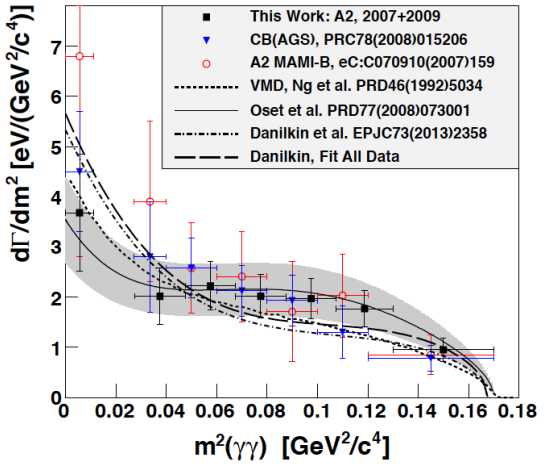
- Smaller background with η energy boost
- Large statistics

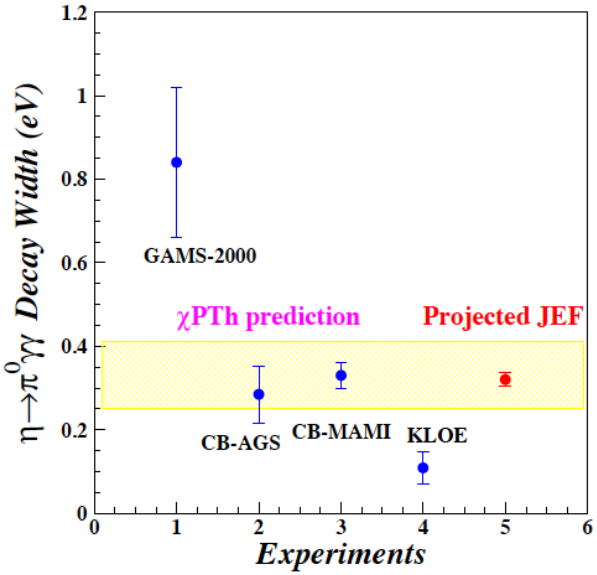
Projections for $\eta \to \pi^0\gamma\gamma$ Decay

Prakhov et al., Phys. Rev. C78, 015206 (2008)



A2 at MAMI arXiv:1405.4904, 2014





Constrain contribution of scalar resonances in the calculation of $O(p^6)$ low-energy constants

Search for B boson

- Dark leptophobic B-boson

$$L = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu + \ldots$$

- Arises from a new gauge baryon symmetry $U(1)_B$

Early studies by Lee and Yang, Phys.Rev.,98 (1955) 1501; Okun, Yad.Fiz., 10 (1969) 358,

- Unified genesis of baryonic and dark matter

- the $m_B < m_p$ region is strongly constrained by long-range forces search exp. ; the $m_B > 50 GeV$ has been investigated by the collider experiments

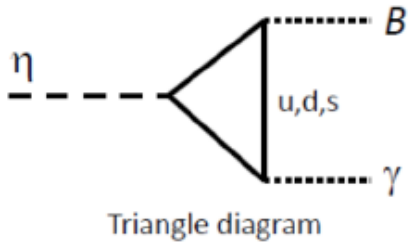
- GeV-scale domain is poorly constrained

discovery opportunity!

Search for B-boson in η decay

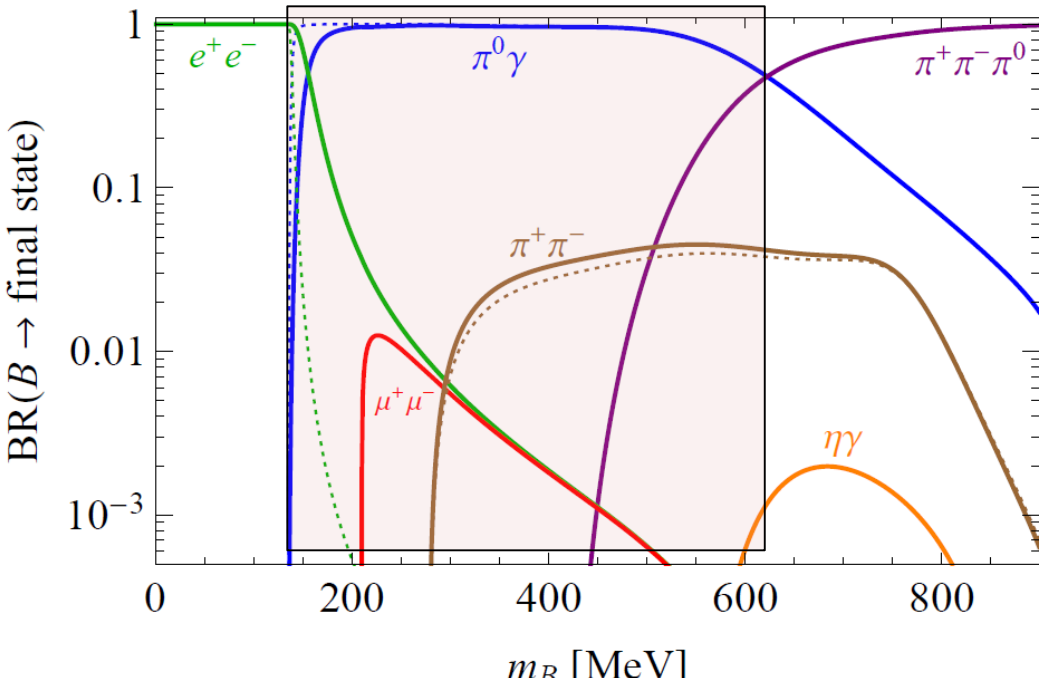
B production: A.E. Nelson, N. Tetradis, Phys. Lett., B221, 80 (1989)

$\eta \rightarrow B\gamma$ decay ($m_B < m_\eta$)



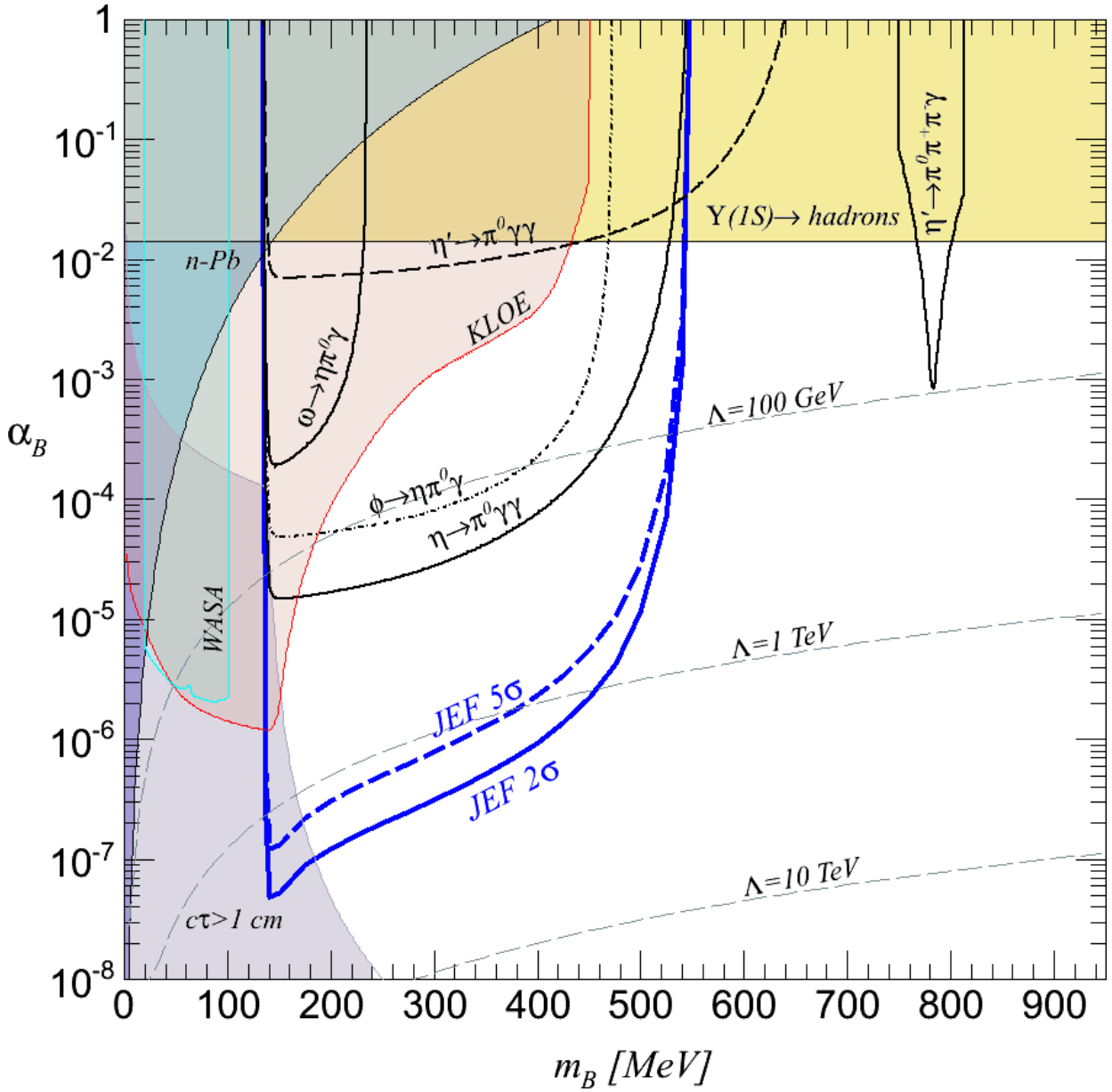
Triangle diagram

B decay: $B \rightarrow \pi^0\gamma$ in 140-600 MeV mass range



S. Tulin, Phys.Rev.,D89, 14008 (2014)

JEF Experimental Reach ($\eta \to B\gamma \to \pi^0\gamma\gamma$)



A stringent constraint on the leptophobic B-boson in 140-550 MeV range

Summary

- The GlueX detector provides a unique capability to perform a precision measurement of the η radiative decay width using Primakoff reaction

- The measurements are essential for testing the Chiral symmetries and anomaly and will be used for the extraction of fundamental properties such as the light quark mass ratio, and the η - η' mixing angles

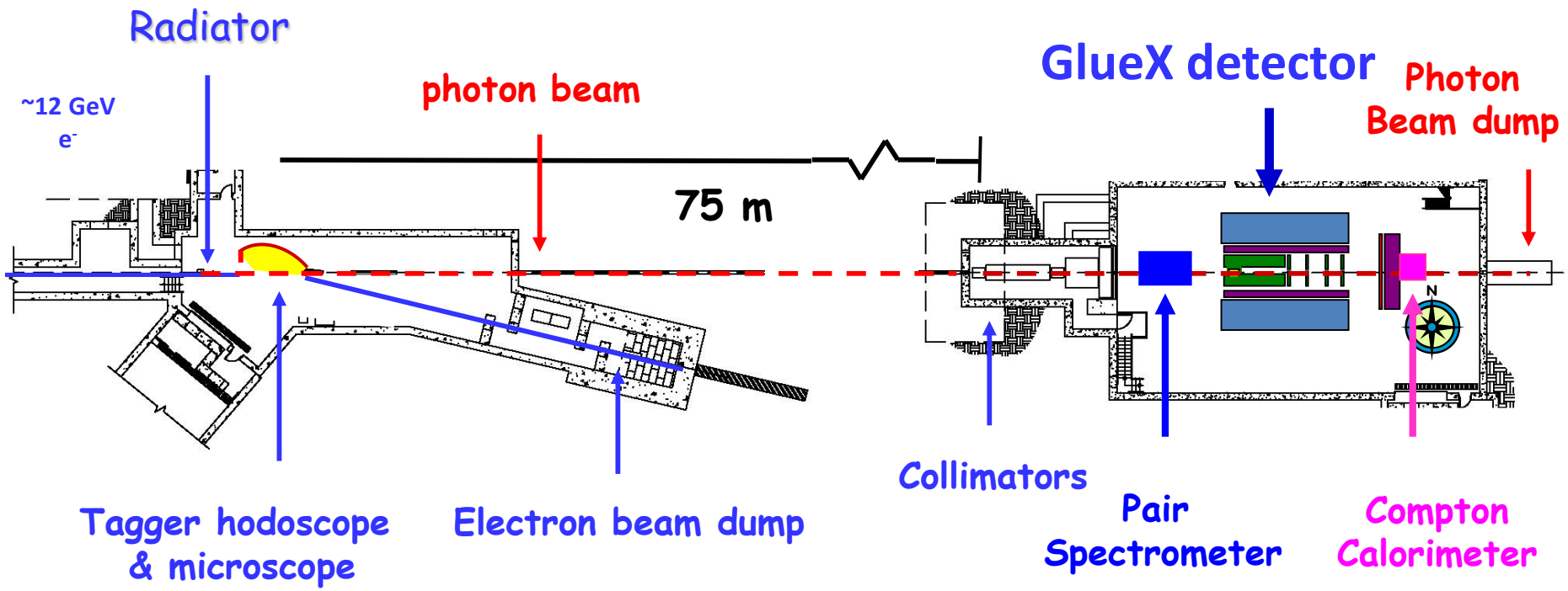
- The PrimEx η experiment collected about 30 % of required data in Spring 2019

- Future upgrade of the GlueX calorimeter will provide an opportunity to study rare decays of η mesons

  - Test the role of scalar dynamics in ChPT through $\eta \to \pi^0\gamma\gamma$
  - Probe a leptophobic dark B-boson in 140 - 550 MeV range via $\eta \to B\gamma \to \pi^0\gamma\gamma$

Hall D Photon Beam Line

Use standard Hall D beam line equipment for PrimEx D



Pair Spectrometer: measure/monitor photon flux

Compton Calorimeter (new): monitor target thickness and detector stability

Tagged Photon Beam

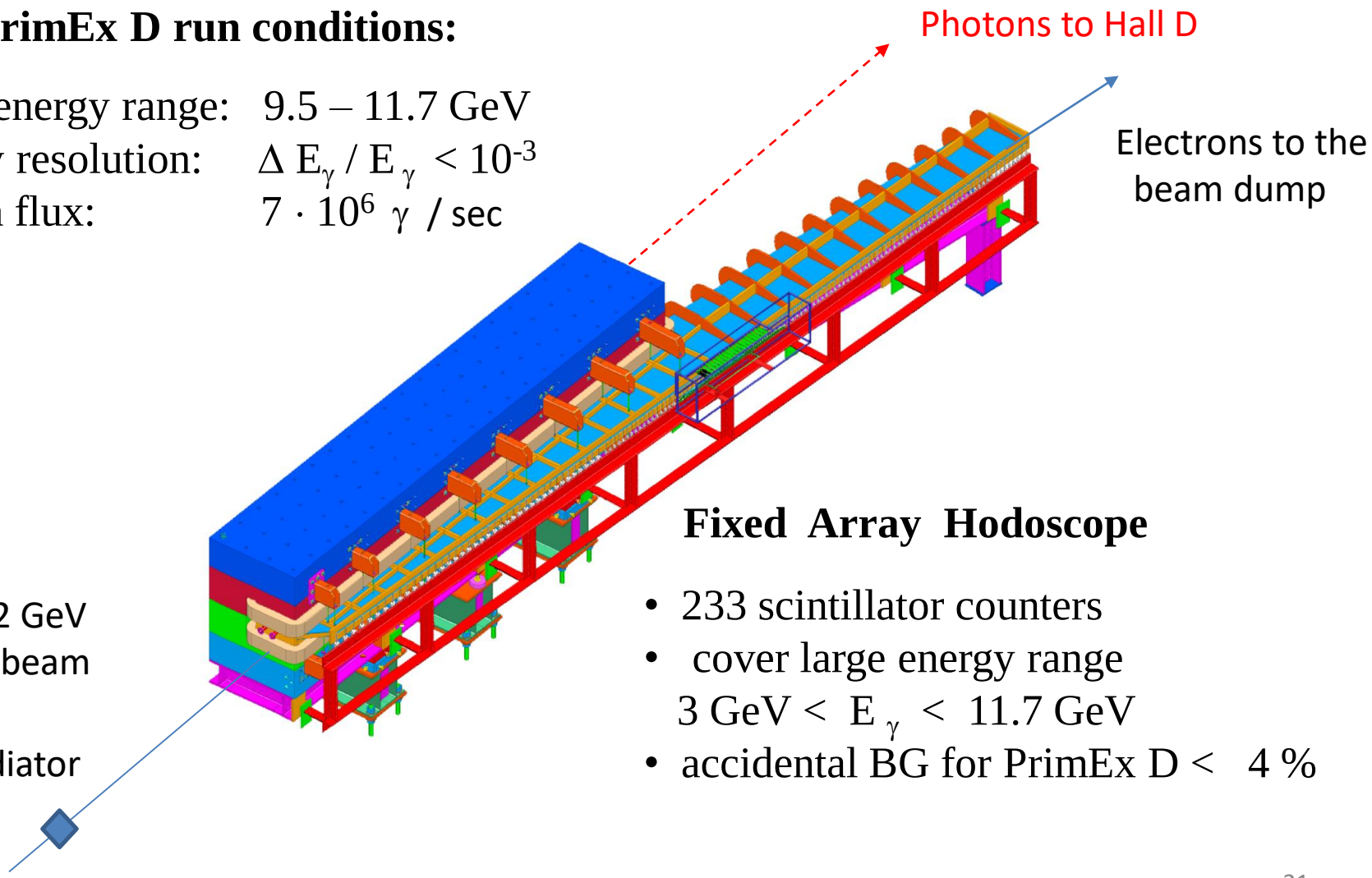
Measure energy of each beam photon by detecting a bremsstrahlung electron

PrimEx D run conditions:

Beam energy range: 9.5 – 11.7 GeV

Energy resolution: $\Delta E_\gamma / E_\gamma < 10^{-3}$

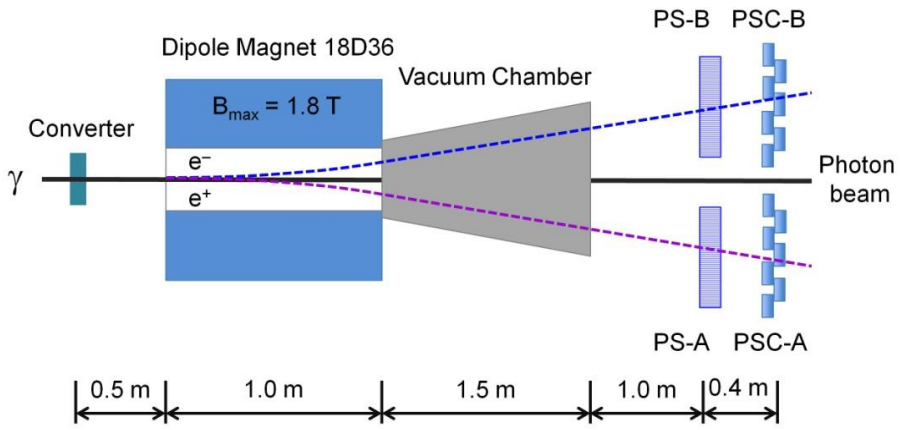
Photon flux: $7 \cdot 10^6$ γ / sec



Fixed Array Hodoscope

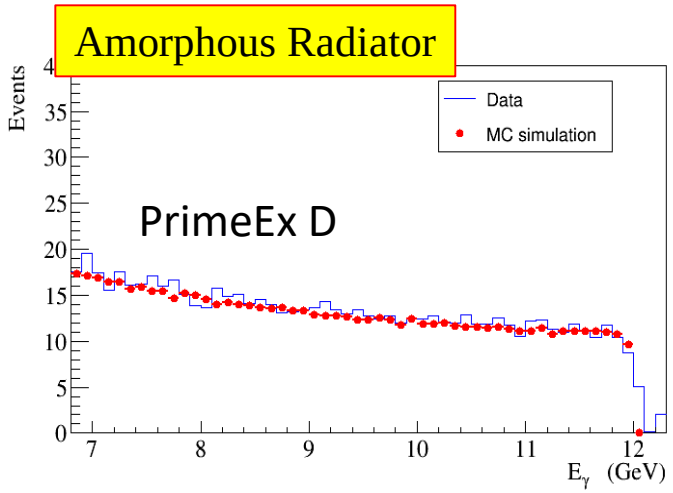
- 233 scintillator counters
- cover large energy range
  3 GeV < E_γ < 11.7 GeV
- accidental BG for PrimEx D < 4 %

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 %

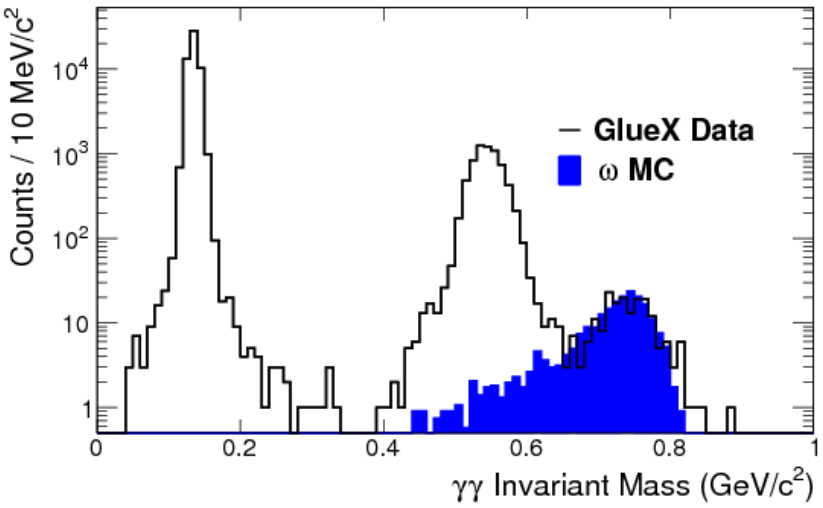
Reconstruction of $\gamma + p \rightarrow 2\gamma + p$

Forward Lead Glass Calorimeter

$$\frac{\sigma_E}{E} = \frac{6}{\sqrt{E}} \oplus 2.0 \quad (\%) \qquad \sigma_{X,Y} = \frac{6.4\ mm}{\sqrt{E}}$$

- Angular coverage $2° < \theta < 11°$
- 2800 lead-glass F8-00 blocks: 4 x 4 x 45 cm^3
- FEU84-3 PMTs and Cockroft-Walton bases

- Reconstructed $\gamma + p \rightarrow \gamma + \gamma + p$ events



Reconstruction of Primakoff η

Event selection and resolutions:

- Two clusters in the FCAL. Invariant mass consistent with η, σ_M ~ 19 MeV
- Match time between the tagger hit (beam time) and FCAL to reduce accidentals
- Energy conservation in the reaction (elasticity), σ_E ~ 270 MeV
- Angular resolution of reconstructed η mesons ~1 mrad
- Acceptance and reconstruction efficiency ~ 70 %

Background from other hadronic interactions:

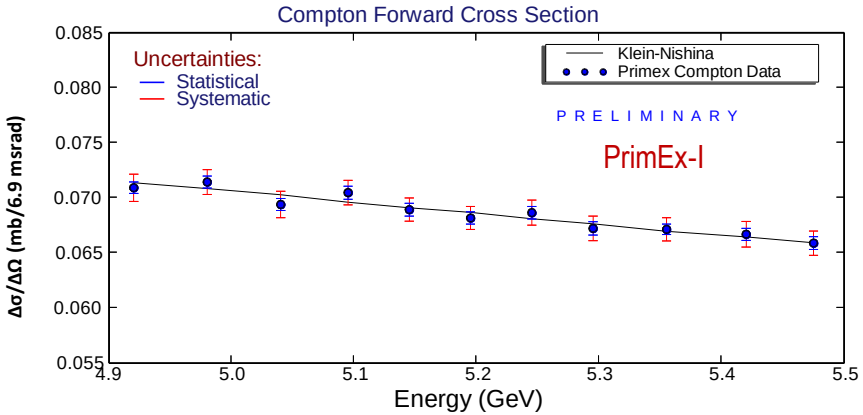
- $\gamma p \rightarrow p \eta \pi^0$
- $\gamma p \rightarrow n \eta \pi^+$
- $\gamma p \rightarrow p \pi^0 \gamma$

- studied using Pythia event generator
- use GlueX sub-detectors to veto/suppress
- background level: ~3%, will be measured and subtracted

Control of Overall Systematics

- Install CompCal calorimeter behind FCAL
  - 10x10 (20 x 20 cm^2) $PbWO_4$ crystals

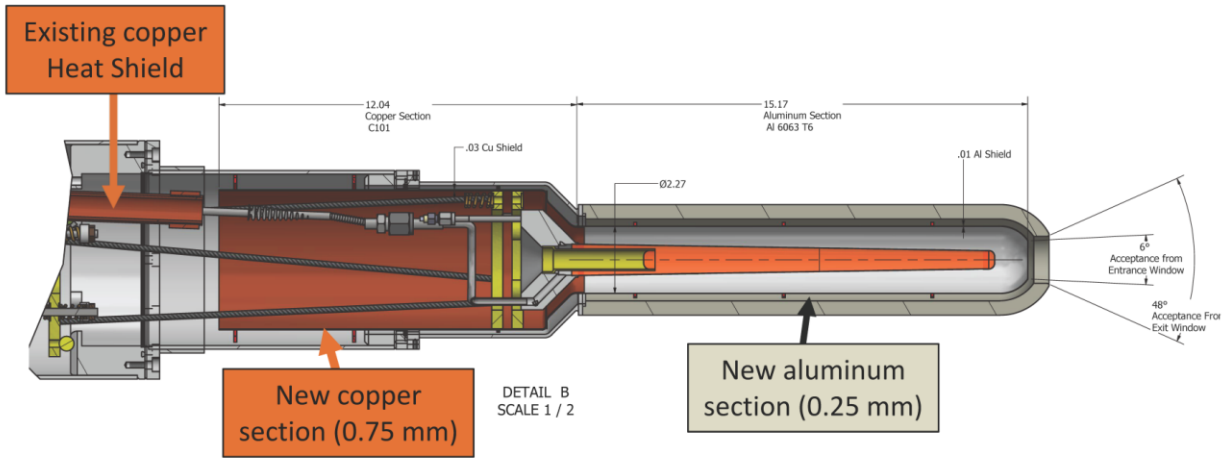
- Measure Compton $\gamma + e \rightarrow \gamma + e$ cross section in the forward direction using CompCal and FCAL



- Measure and monitor target thickness and beam flux during production runs (rate of reconstructed events – 30 Hz)

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

Beam Time and Statistics

- **Total cross section**

LH2 for $\theta_\eta = (0 - 5)^0$

σ = 61.4 nb (~2% is Primakoff process)

- **Reconstructed events:**

~ 260 Primakoff η events/day

LH2 target run	40 days
LHe4 target run	30 days
Empty target run	6 days
Tagger efficiency, TAC runs	1 days
Setup calibration and checkout	2 days
Total	79 days

1% statistical error for Primakoff events for each target

Estimated Error Budget

- **Systematical errors:**
  (added quadratically)

Contributions	Estimated Error
Luminosity	1.2%
Background subtraction	2.0%
Event selection	1.7%
Acceptance, misalignment	0.5%
Beam energy	0.2%
Detection efficiency	0.5%
Branching ratio (PDG)	0.66%
Total Systematic	**3.02%**

- **Total estimated error:**
  (added quadratically)

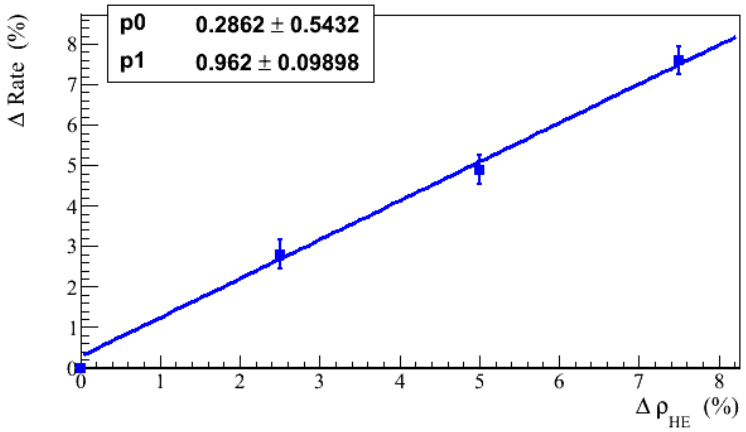
Statistical error	1.0%
Systematic error	3.02%
Total Error	**3.2%**

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

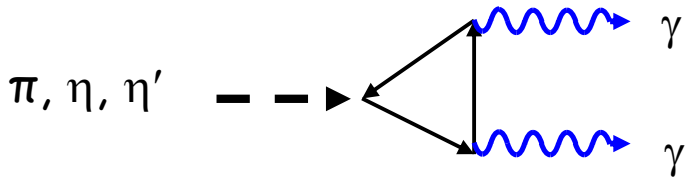
Coincidence of hits between the ST and TOF
(2 x 2 bars in TOF at R = 30 cm & one ST paddle)
1.5 kHz

- Long term stability control:

  - monitor using Compton process; expected rate in the photon range of interest is about 30 Hz (see Liping's talk)

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

The Primakoff Method

- Separate Primakoff amplitude from hadronic processes:

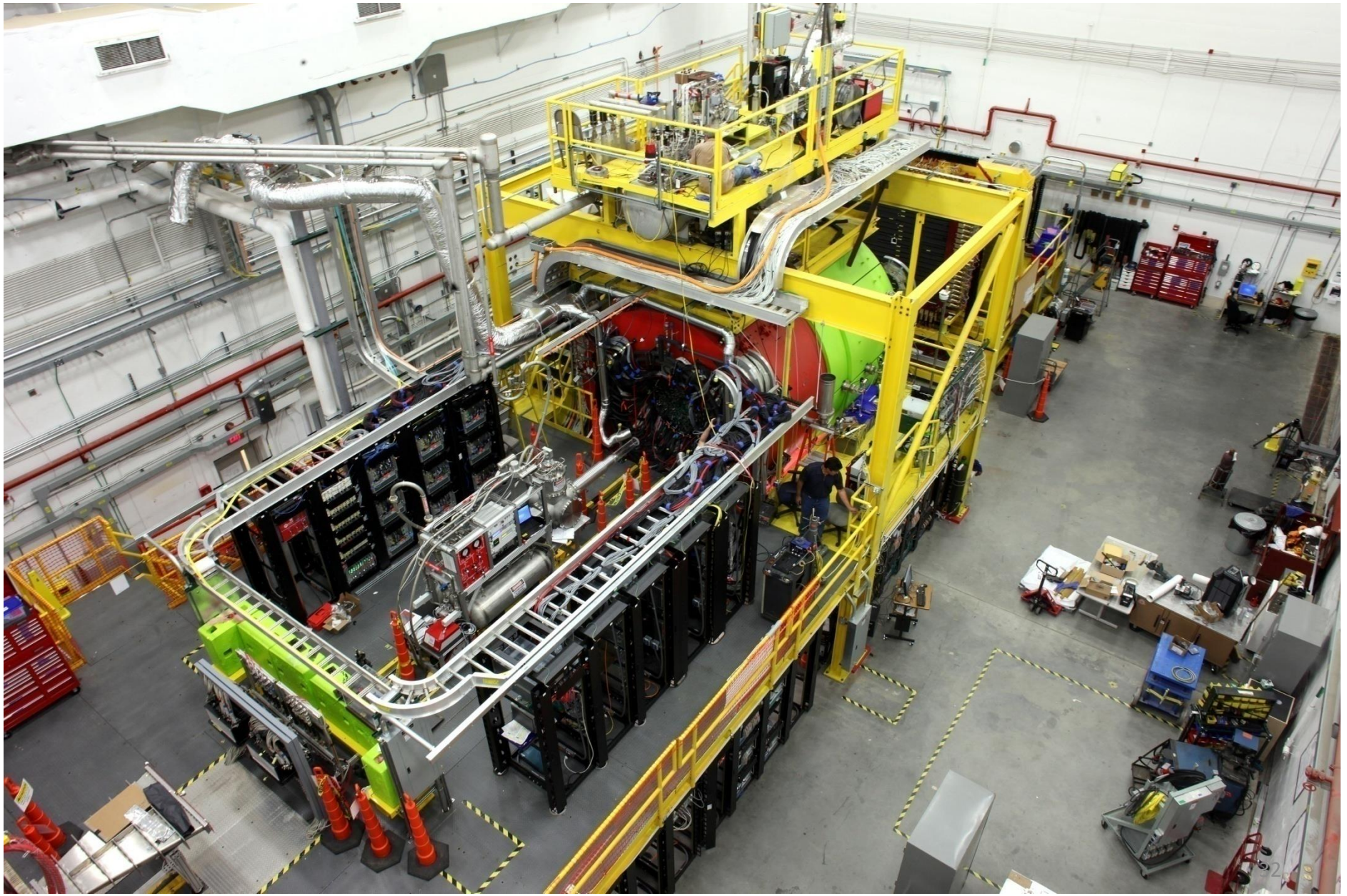
$$\langle \theta_{\mathrm{Pr}} \rangle_{peak} \propto \frac{m^2}{2 \cdot E^2} \qquad \theta_{NC} \propto \frac{2}{E \cdot A^{1/3}}$$

- Use low A targets LH_2 and LHe_4 to control:
  - coherency
  - contributions from nuclear processes

Requirements to the experiment:

- good angular resolution for reconstructed η mesons
- precise measurements of luminosity

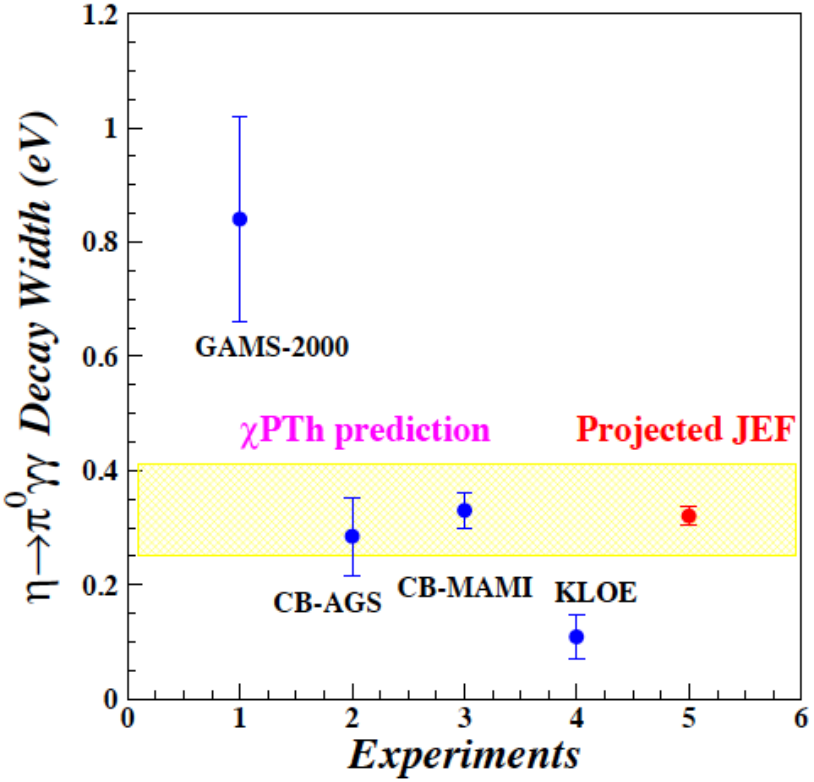
GlueX Detector



$\eta \to \pi^0\gamma\gamma$: Partial Decay Width

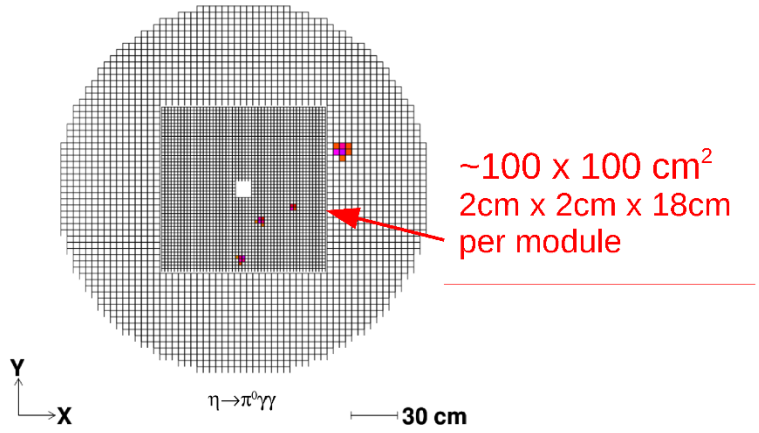
Theory	$\Gamma(\eta \to \pi^0\gamma\gamma)$ (eV)
χPTh, $\mathcal{O}(p^2)$	0
χPTh, $\cdots + \mathcal{O}(p^4)$	0.004
χPTh, $\cdots + \mathcal{O}(p^6)$	0.42 ± 0.20
χPTh, $\cdots + \mathcal{O}(p^6)$	0.47
χPTh, ENJL, $\cdots + \mathcal{O}(p^6)$	0.58 ± 0.30
χPTh, ENJL, $\cdots + \mathcal{O}(p^6)$	$0.27^{+0.18}_{-0.07}$
VMD	0.30 ± 0.15
Q box	0.70
χPTh, $\cdots + \mathcal{O}(p^6)$	0.44 ± 0.09
unitarized χPTh	0.47 ± 0.10
unitarized χPTh	0.33 ± 0.08

Experiments After 1980



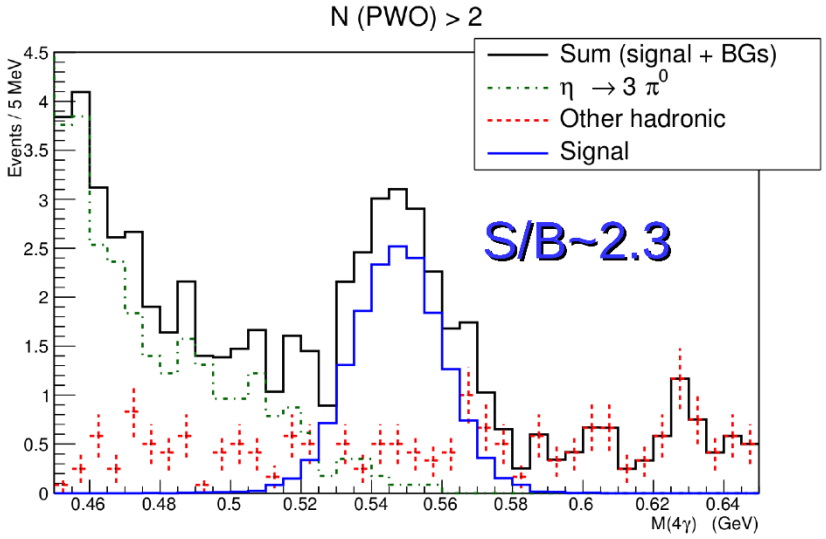
χPTh by Oset et al., Phys. Rev. D77, 07300 (2008)
arXiv:08801 (2013)

Upgrade of the Forward Calorimeter



- Replace inner part of the lead glass calorimeter by PWO crystals

Property	Improvement factor
Energy σ	2
Position σ	2
Granularity	4
Radiation-resistance	10



MC simulation:

- Reconstructed $\eta \to \pi^0\gamma\gamma$ events during 1 day of taking data