Status of the PrimEx-Eta Experiment in Hall D

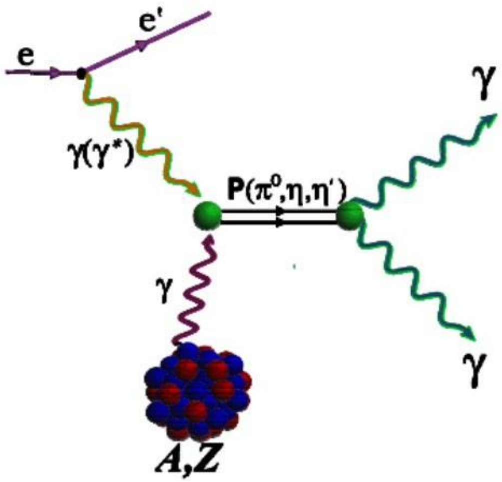
Drew Smith
on behalf of the GlueX Collaboration

JLab Users Group Meeting

Primakoff Program at JLab

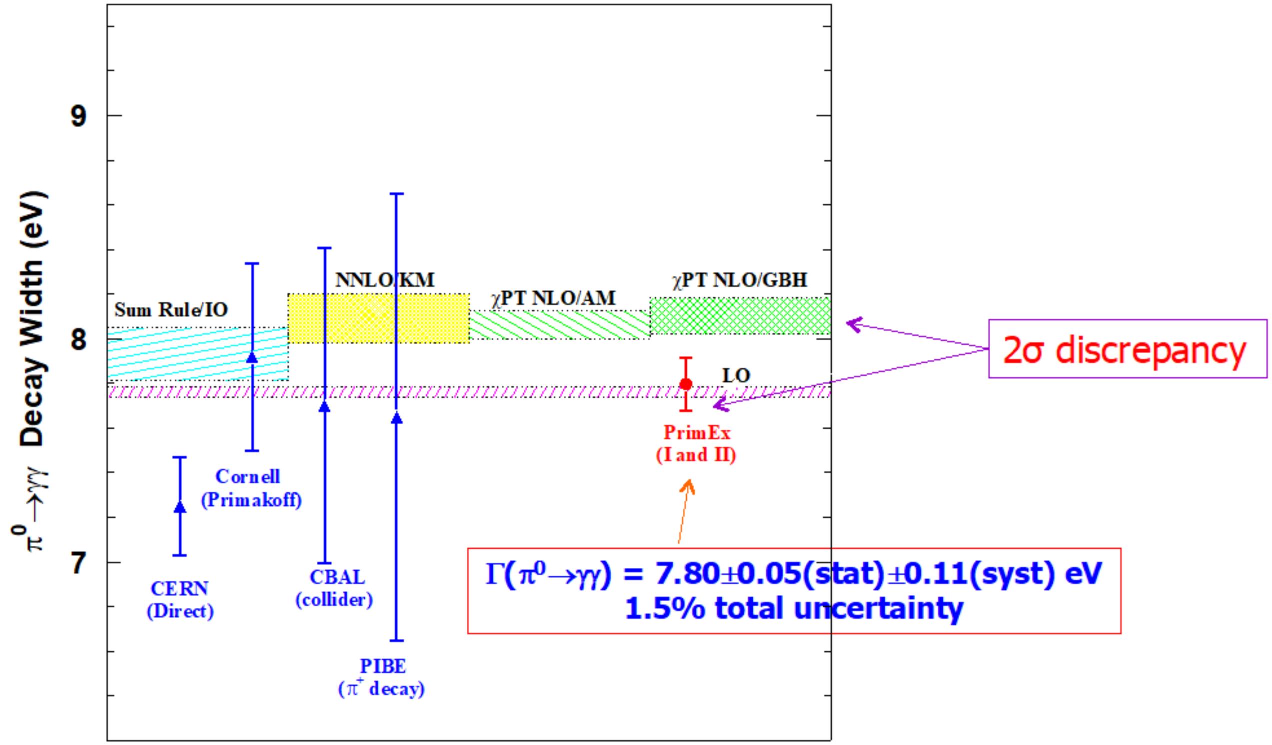
Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect:

a) Two-Photon Decay Widths
b) Transition Form Factors at Low Q^2 (0.001-0.5 GeV^2/c^2)



- The Primakoff reaction $\gamma\gamma \to \pi^+\pi^-$ is being used to measure the Charged Pion Polarizability (CPP) in Hall D [E12-13-008]

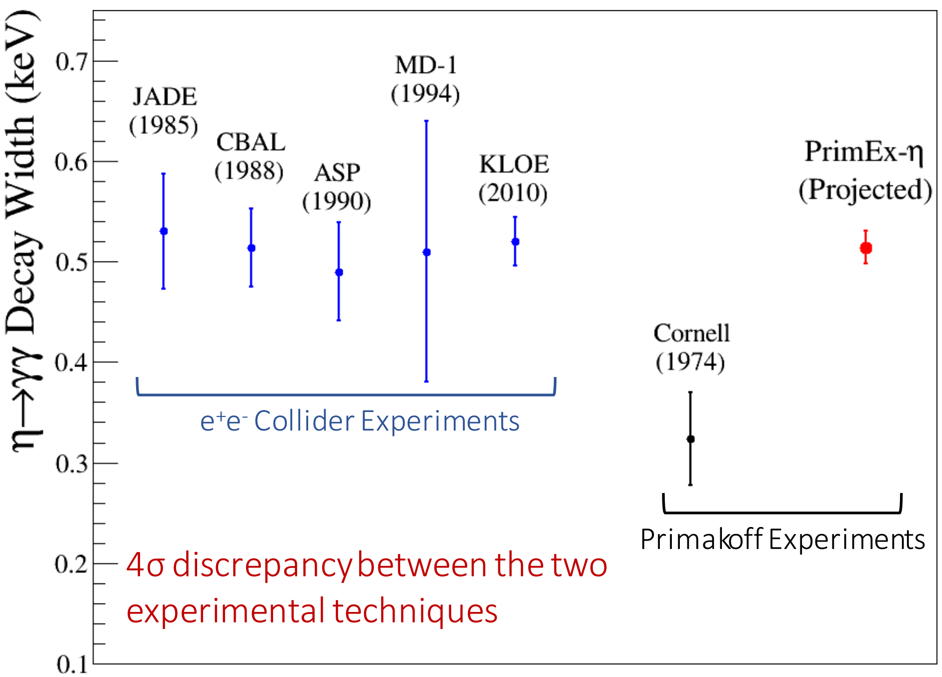
PrimEx-I and II in Hall B measured the $\pi^0 \to \gamma\gamma$ decay width with 1.5% total uncertainty.



I. Larin, et al. PRL 106, 162303 (2008)
I. Larin, Y. Zhang, A. Gasparian, L. Gan, et al. Science 368, 6490 (2020)

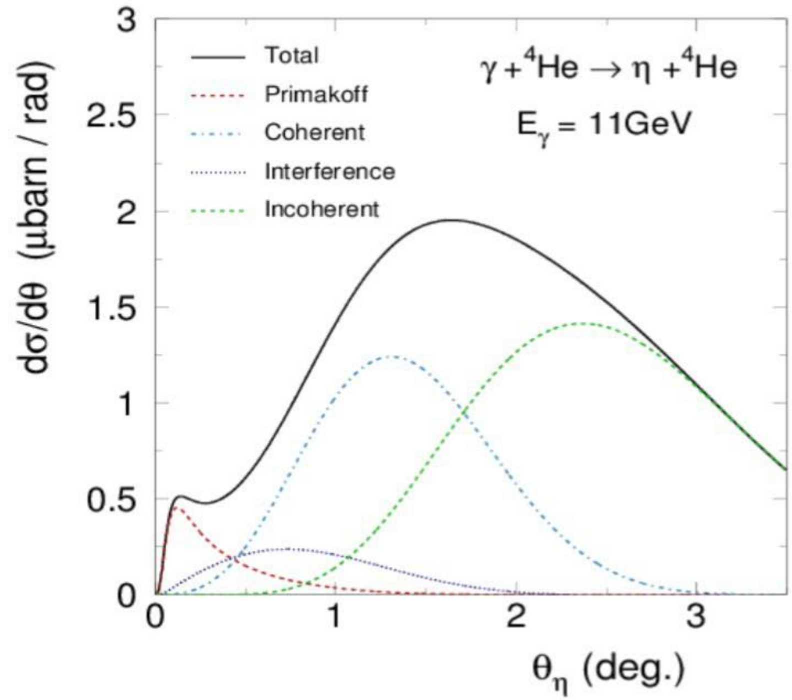
PrimEx-Eta Experiment

Precision measurement of the η meson radiative decay width via the Primakoff method



PDG Average: $\Gamma(\eta\rightarrow\gamma\gamma)$ = 0.51 ± 0.018 keV

Compton scattering from atomic electrons is simultaneously measured as a reference process.



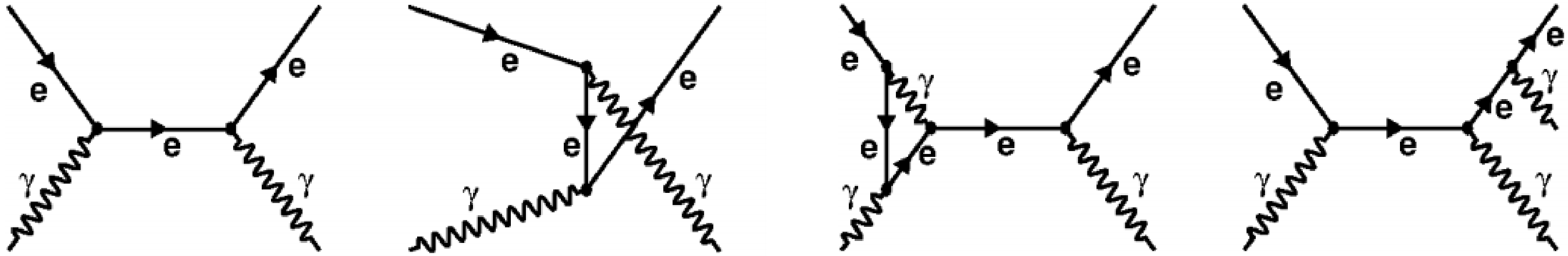
$$\frac{d\sigma_{Pr}}{d\Omega} = \boxed{\Gamma(\eta \rightarrow \gamma\gamma)} \frac{8\alpha Z^2}{m_\eta^3} \frac{\beta^3 E^4}{Q^4} |F_{em}(Q)|^2 \sin^2(\theta_\eta)$$

<u>Physical Motivations:</u>

- Address discrepancy in different experimental methods
- η – η’ mixing angles
- Light quark mass ratio

Compton Scattering in PrimEx-Eta

- Hall D has limited acceptance at far forward angles for precision cross section measurements.
- Compton scattering on the atomic electrons is a well-known QED process and can be used as a reference process to:
  - Verify overall systematics in absolute cross section measurement
  - Monitor changes in luminosity
  - Measure detection efficiency in the forward calorimeter
- Will provide first measurement of total Compton scattering cross section in the energy range 6-11 GeV.

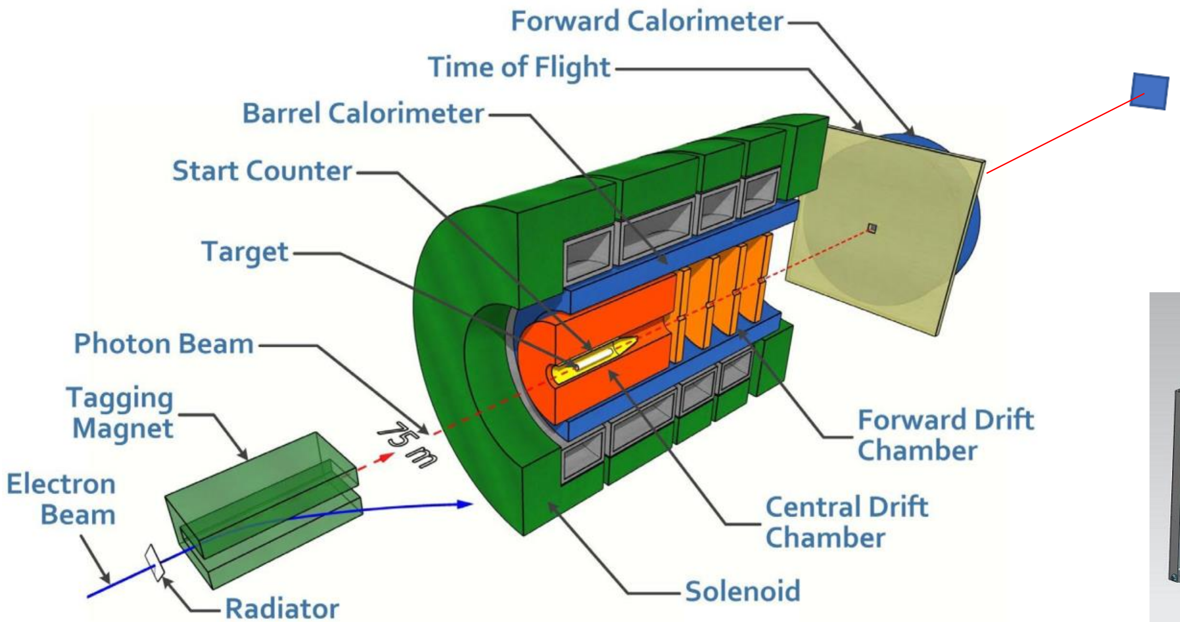


PrimEx-II Compton result (E_{γ} = 4.5 GeV – 5.5 GeV) [P. Ambrozewicz, L. Ye, I. Larin, et al. Phys Lett B 797 (2019) 134884]

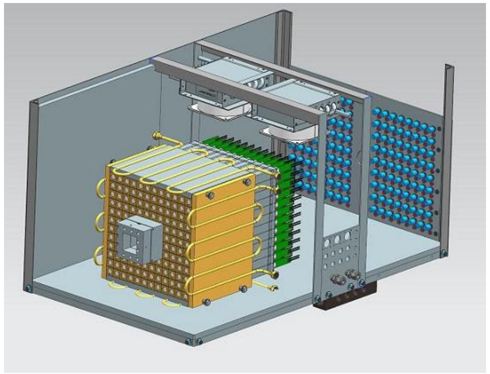
Hall D at Jefferson Lab

PrimEx-Eta uses the standard GlueX spectrometer with a few modifications:

- An aluminum radiator is used to produce an *unpolarized* Bremsstrahlung photon beam
- A new $PbWO_4$ calorimeter was inserted into the beamline to allow for detection of more forward angle particles (0.19° – 0.8°)



Compton Calorimeter
(12.1m from target)



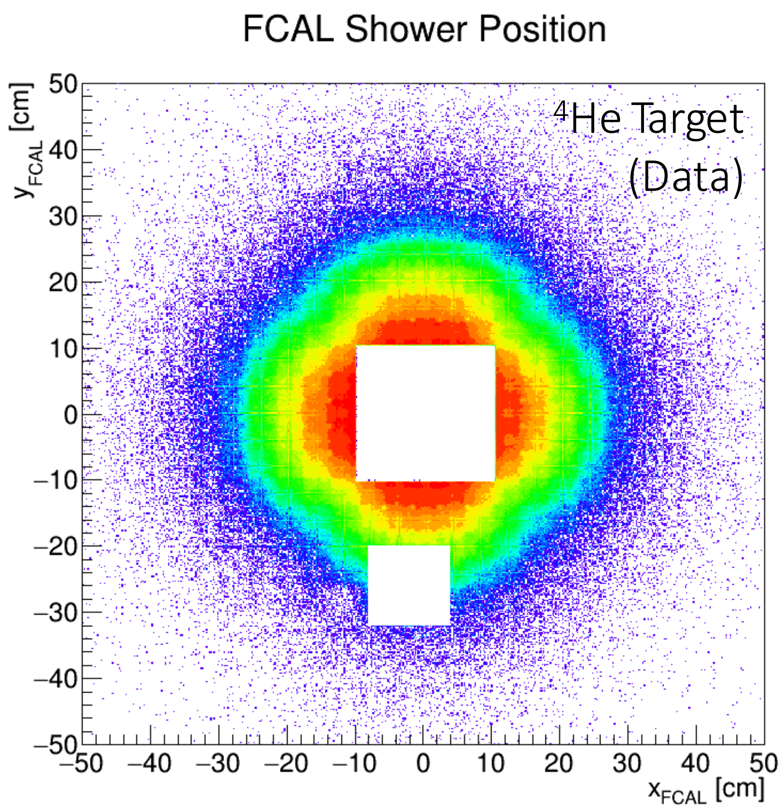
Current Status of PrimEx-Eta Experiment

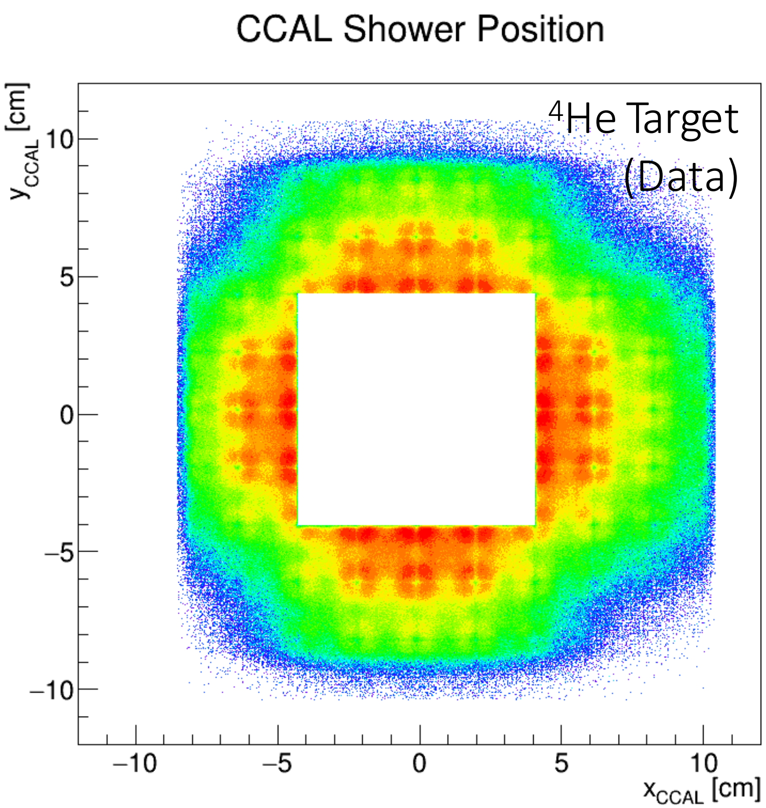
- Phase I of data collected in Spring 2019.
  - Electron beam energy: 11.2 GeV
  - Solenoid magnetic field turned OFF (→ no tracking detectors used)
- Phase II of data collected in Fall 2021.
  - Electron beam energy: 10.0 GeV
  - Solenoid magnetic field turned ON for most of the run
- Phase III scheduled for Aug-Oct 2022.
  - Expected beam energy: ~11.5 GeV
  - Solenoid magnet will be turned ON

- So far, we have 50% of the total statistics on tape, with the rest expected to be collected during Phase III.
- Most of the data was collected on the liquid ^{4}He target.
  - Some "calibration" runs were collected on a solid, ^{9}Be target.

Compton Scattering Event Selection

Compton scattering events are measured by detecting one particle in the Forward Calorimeter (FCAL) and one particle in the Compton Calorimeter (CCAL) in coincidence with the beam photon.

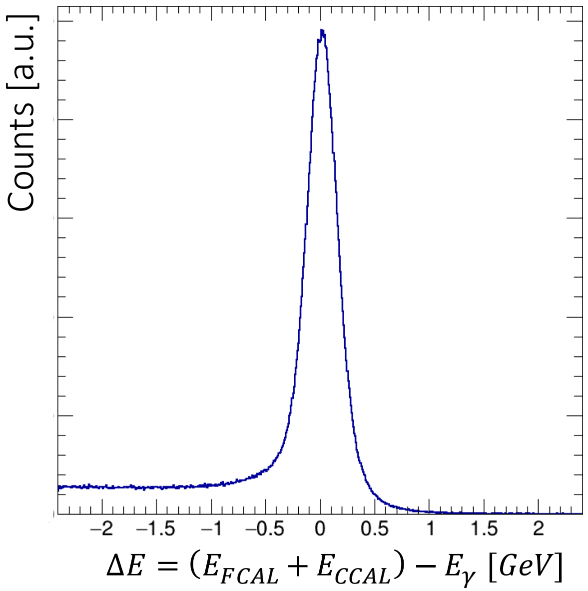




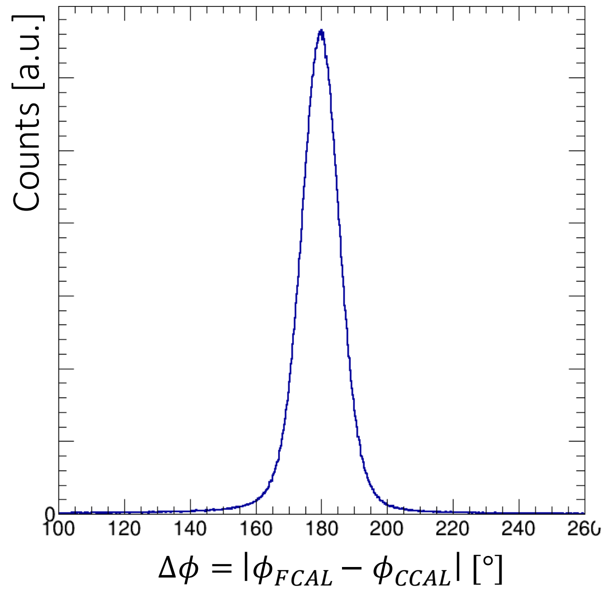
Note difference in axis scales: Particles detected by the CCAL pass through the beam hole in the FCAL.

Compton Scattering Signal ($\gamma e^- \rightarrow \gamma e^-$)

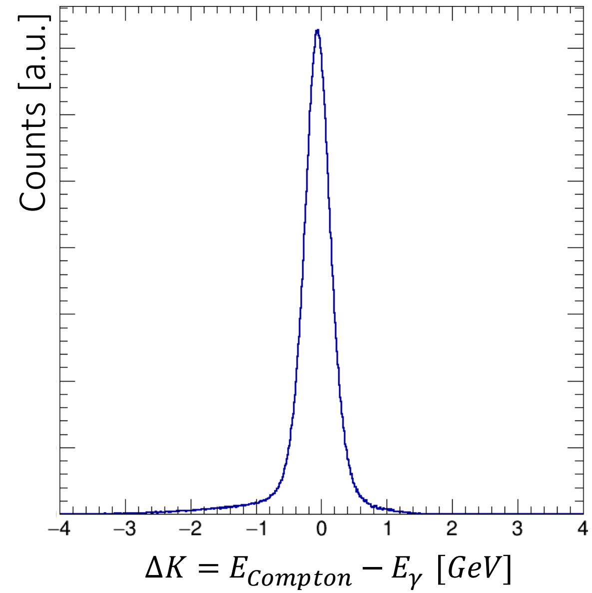
Elasticity



Coplanarity



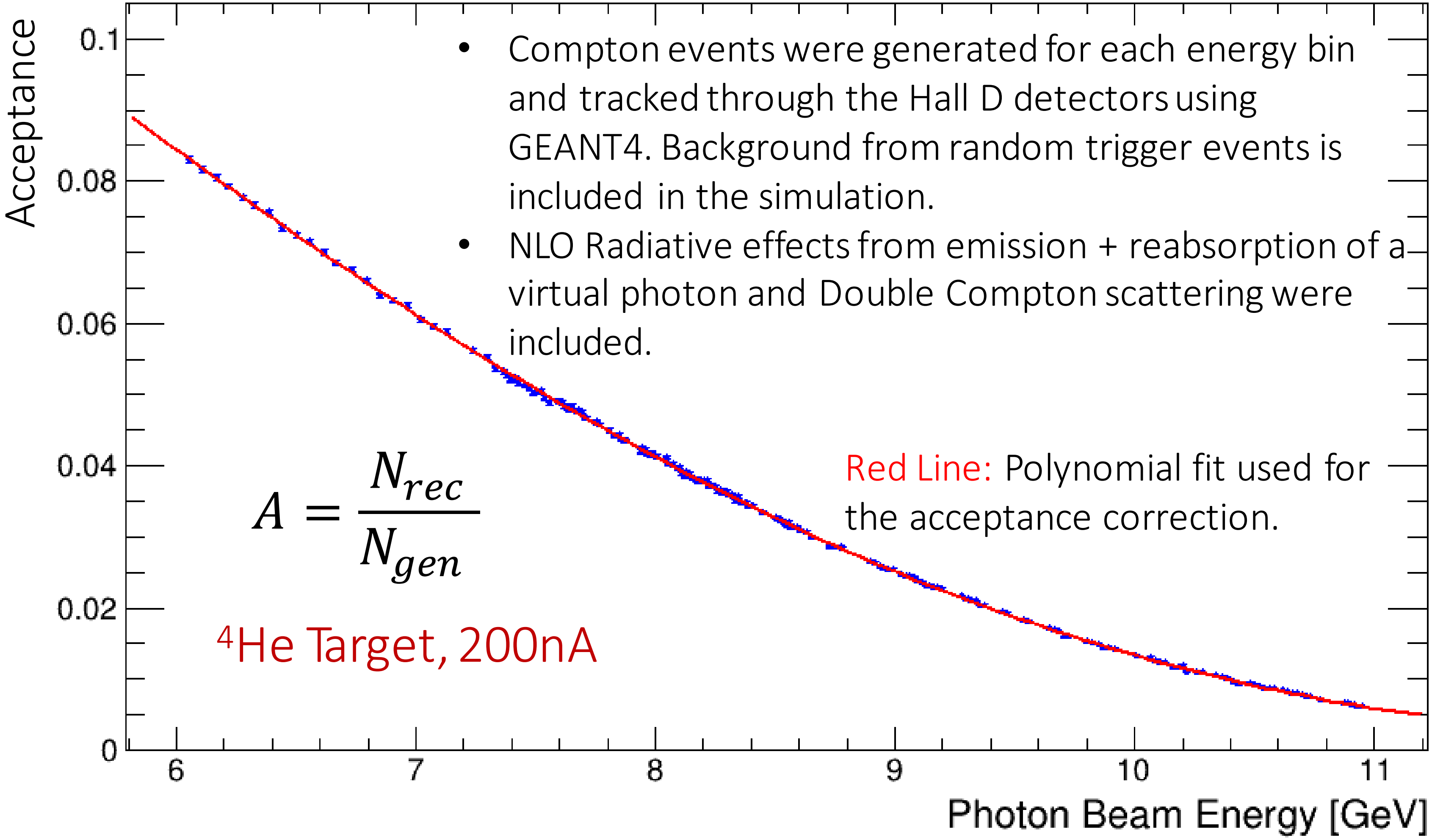
Kinematic Energy Difference



$$E_{Compton} = \sum_{i=1}^{2} \frac{1}{\frac{1}{E_\gamma} + \frac{1}{m_e}(1 - \cos(\theta_i))}$$

- ❑ 5σ cuts are applied to each distribution to select Compton events, and the yield is extracted from a fit to the Kinematic Energy Difference (ΔK) distribution

Compton Acceptance



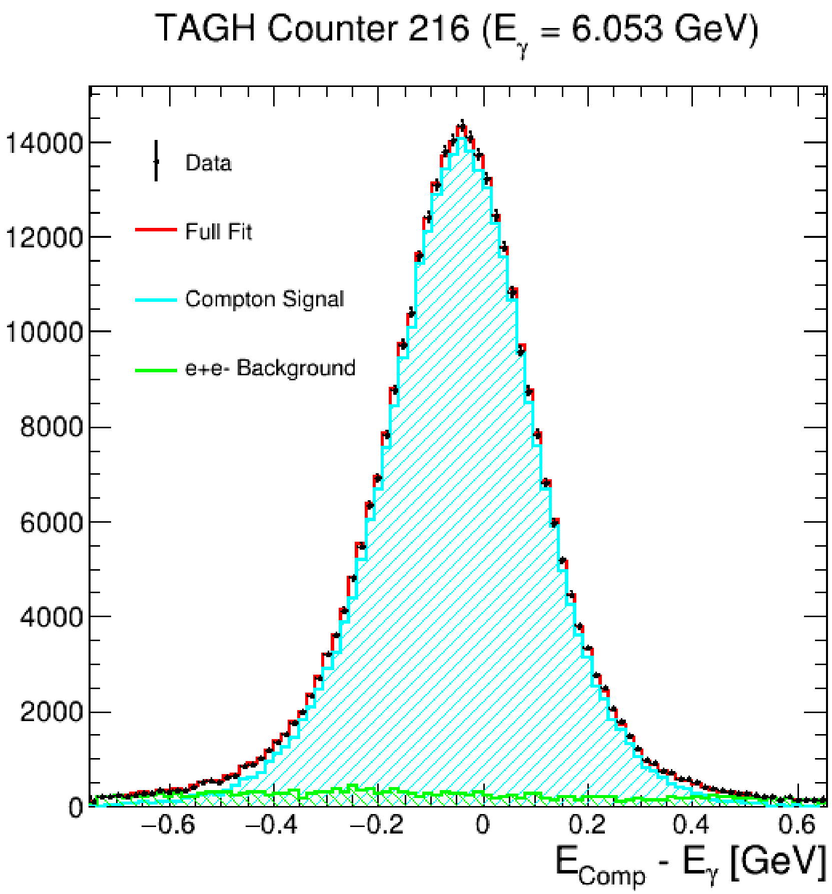
- Compton events were generated for each energy bin and tracked through the Hall D detectors using GEANT4. Background from random trigger events is included in the simulation.
- NLO Radiative effects from emission + reabsorption of a virtual photon and Double Compton scattering were included.

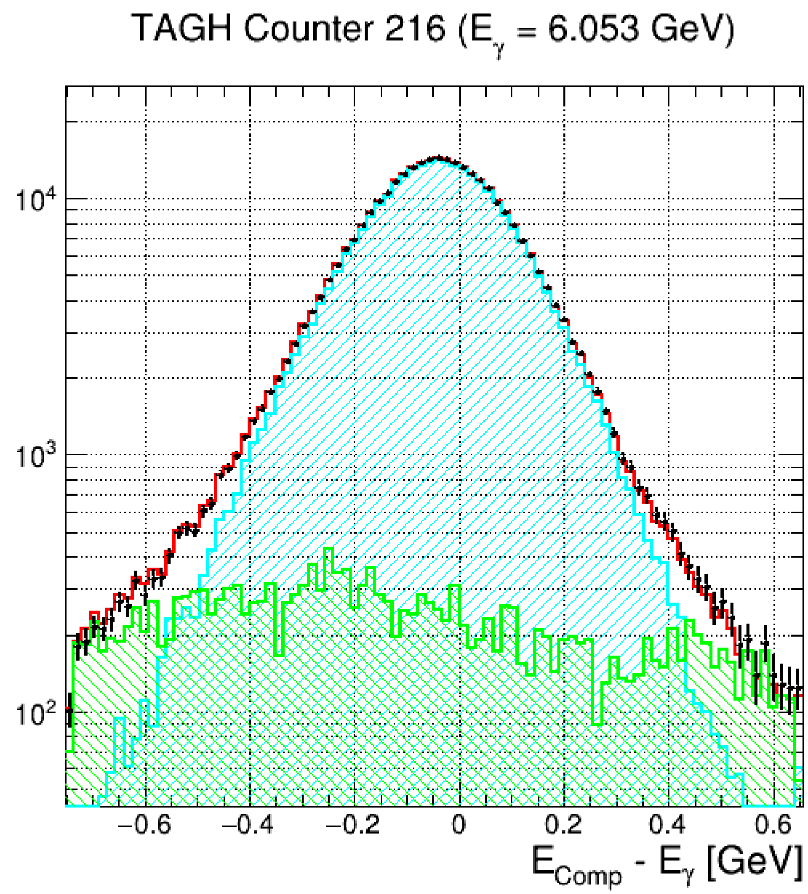
$$A = \frac{N_{rec}}{N_{gen}}$$

Red Line: Polynomial fit used for the acceptance correction.

^{4}He Target, 200nA

Yield Extraction





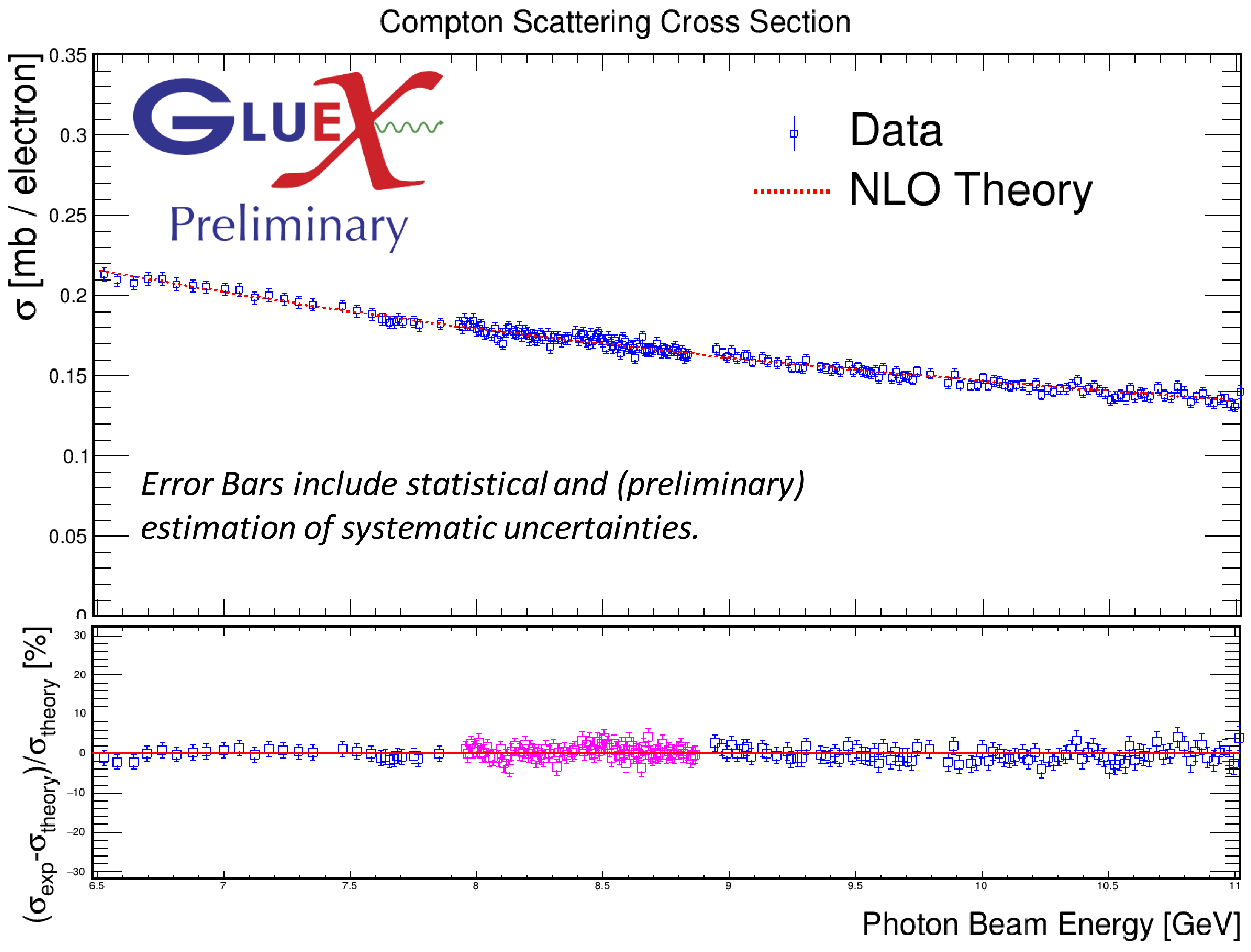
The signal is fit with a combination of the Compton signal, pair production background, and random background using ROOT's TFractionFitter class.

Systematic Uncertainty Analysis

The following independent sources contribute to the overall systematic uncertainty in the cross section:

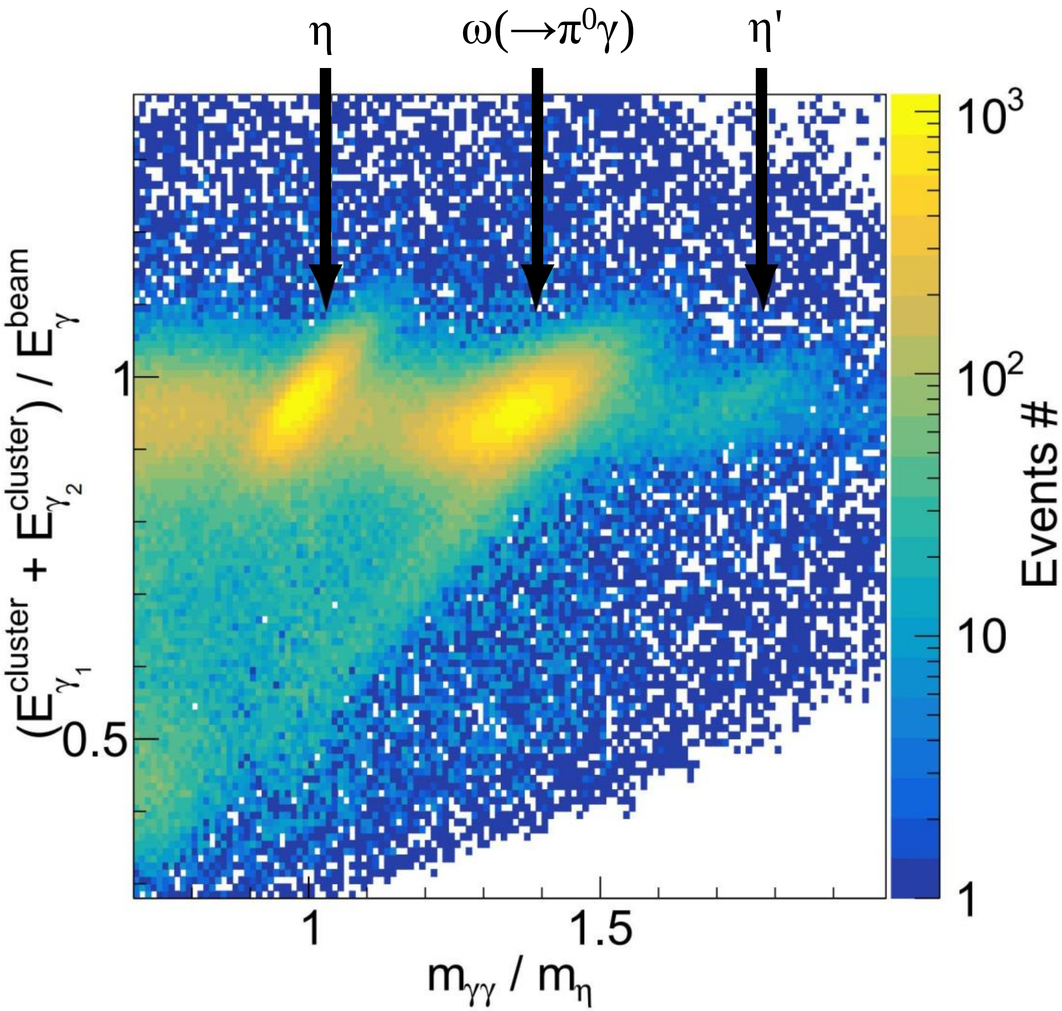
- ❑ Luminosity (photon flux + target density)
- ❑ Acceptance
- ❑ Photon absorption
- ❑ Event selection / cut stability
- ❑ Signal/background separation

- Statistical Uncertainty $< 1\%$ for all energy bins.
- Total systematic uncertainty ranges from 2% at 6 GeV to 4% at 11 GeV.
  - Dominant source of uncertainty is elasticity cut



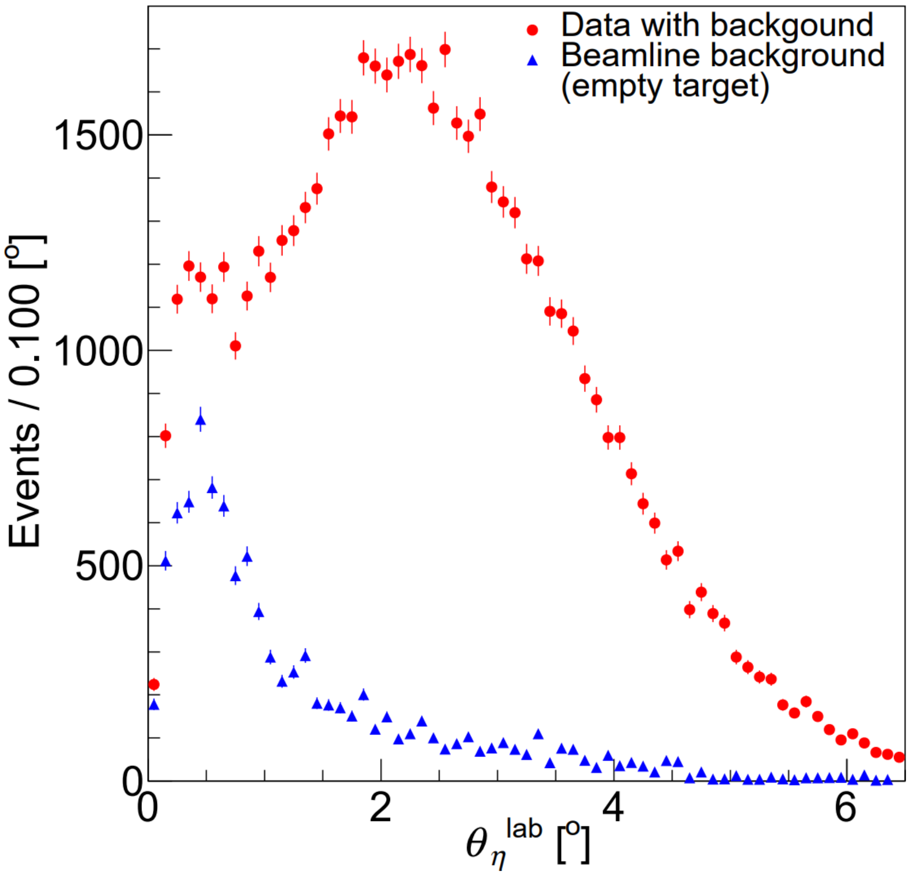
Compton Scattering Cross Section
GlueX
Preliminary
Data
NLO Theory
Error Bars include statistical and (preliminary) estimation of systematic uncertainties.
σ [mb / electron]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
(σexp-σtheory)/σtheory [%]
30
20
10
0
−10
−20
−30
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
Photon Beam Energy [GeV]

$\eta \to \gamma\gamma$ Event Selection

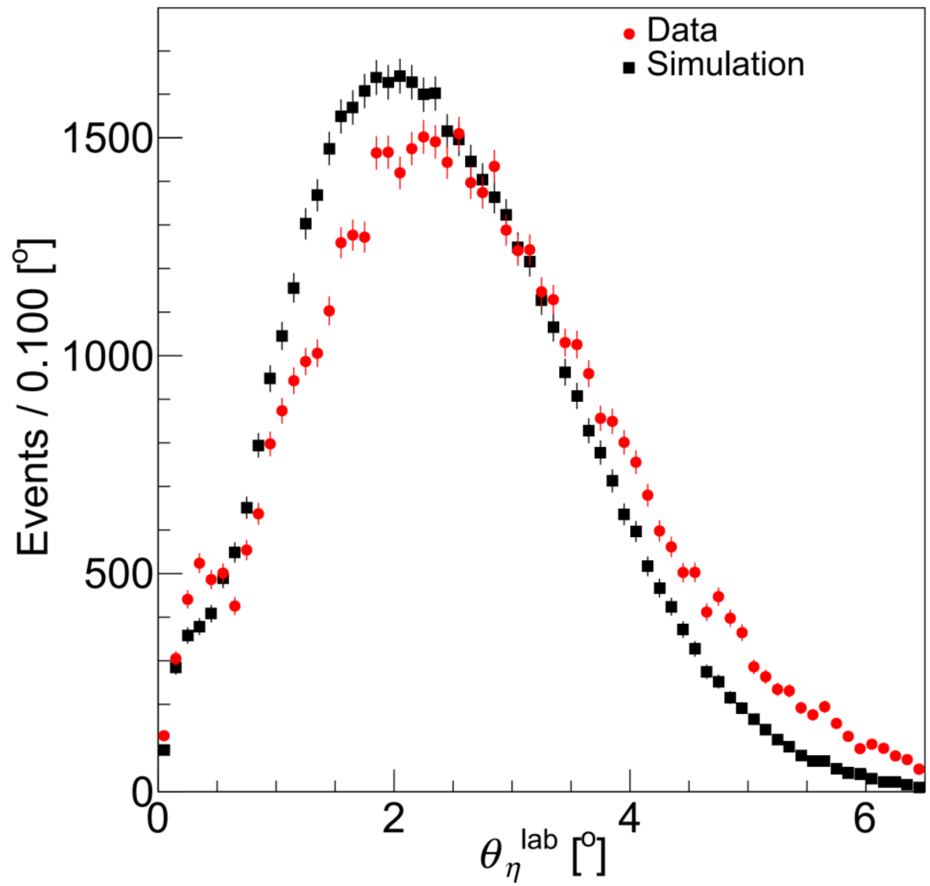


- Both final state photons are detected by the Forward Calorimeter.
- The Barrel Calorimeter is used to veto hadronic background.
- The Time-of-Flight scintillators are used to veto charged particle background.
- An elasticity cut is applied between the two measured photons and the initial photon beam.

Angular Distribution of η→γγ Decay

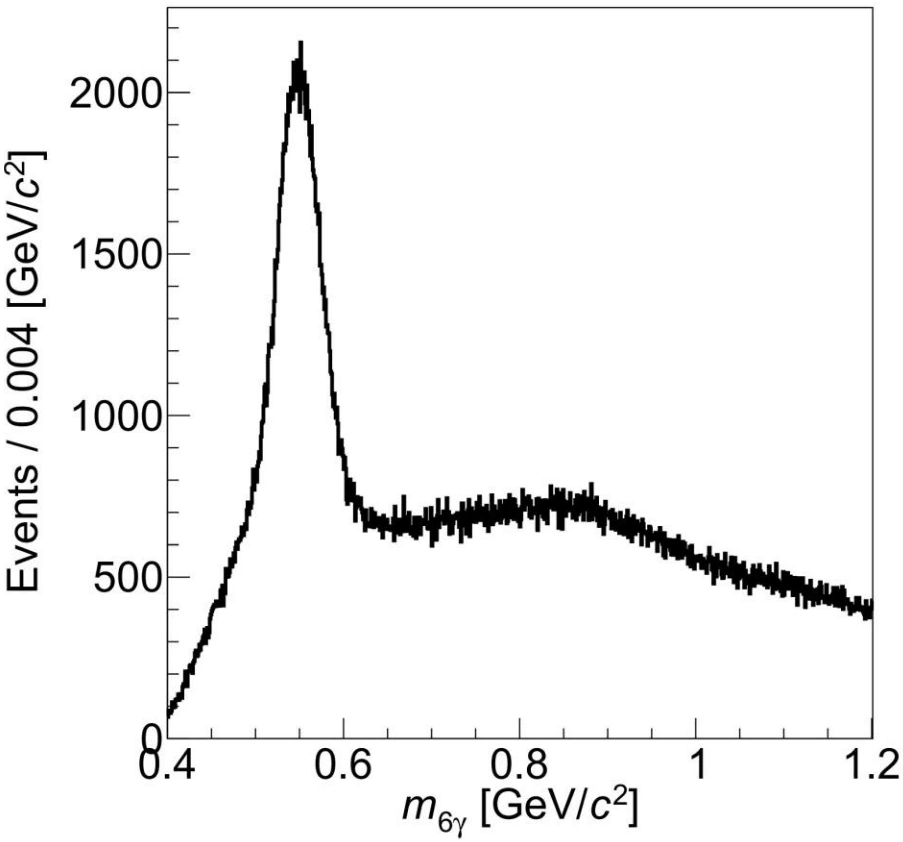


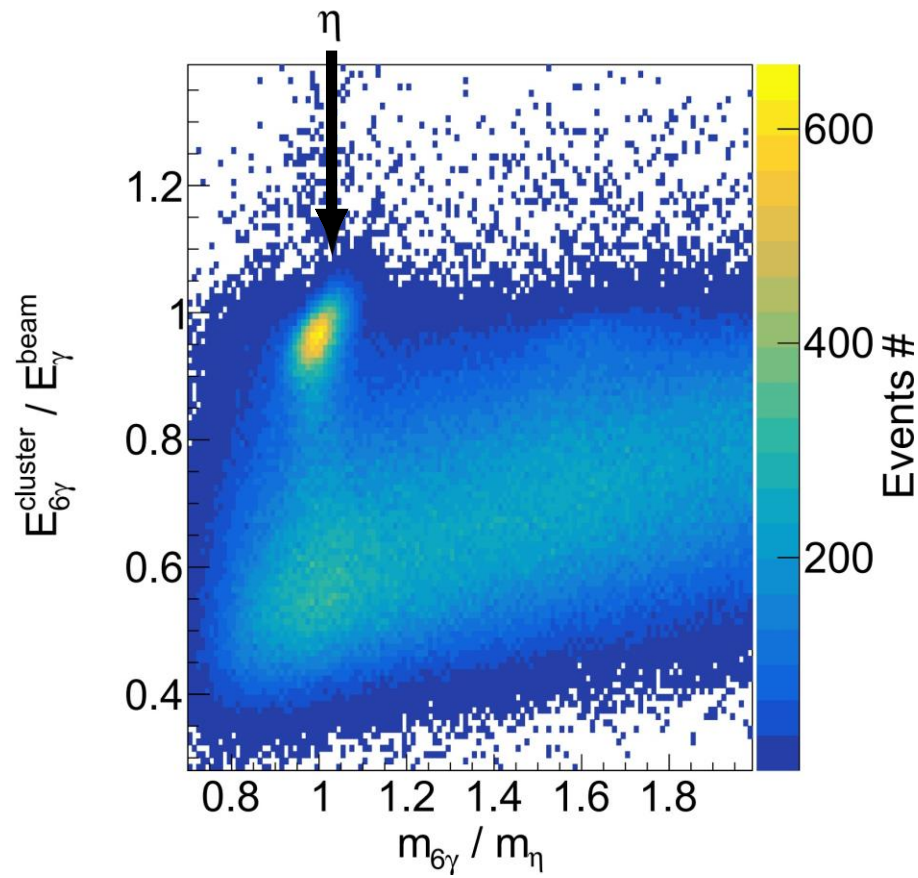
Empty Target Background Subtracted



- $\gamma\, {}^4He \rightarrow \eta\, {}^4He$ events are simulated assuming the average PDG value for $\Gamma(\eta\rightarrow\gamma\gamma)$ and the interference angle between Primakoff and Nuclear Coherent production mechanisms.
- Background due to beamline elements is much larger than originally anticipated, introducing additional uncertainty in the decay width extraction.

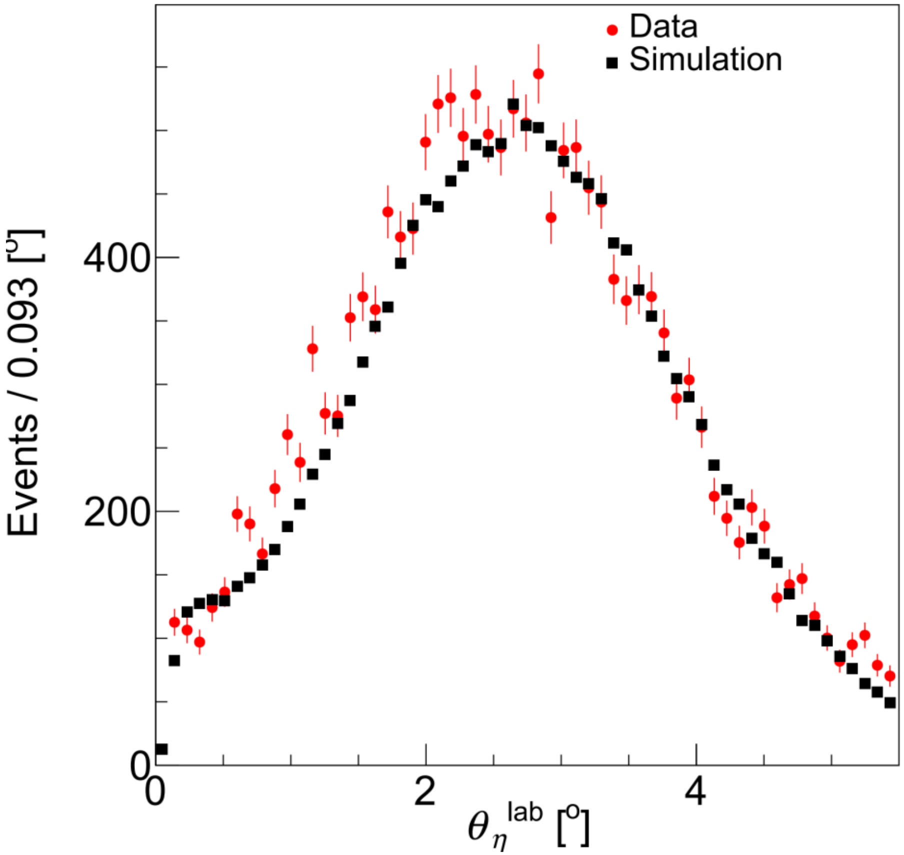
$\eta \to 3\pi^0$ Decay Channel





The beamline background present in the $\eta \to \gamma\gamma$ channel analysis is almost completely gone from the $3\pi^0$ channel.

$\eta \rightarrow 3\pi^0$ Decay Channel (Angular Distribution)



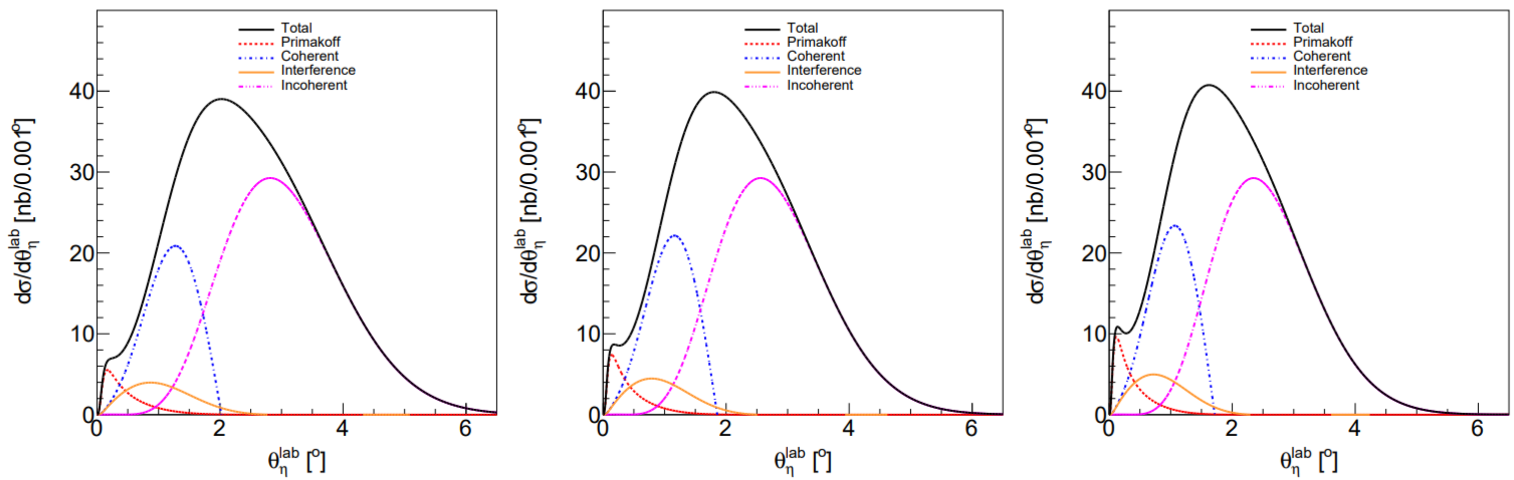
- The shape of the measured angular distribution closely matches expectation from MC.
- A combined fit can be performed using both decay channels to reduce uncertainty in decay width extraction.

Expected Precision for $\eta \to \gamma\gamma$ Decay Width

Toy MC was used to estimate the statistical uncertainty in the decay width ($\Gamma_{\eta\to\gamma\gamma}$) extraction from each decay channel.

$$\frac{d\sigma_T}{d\Omega} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_{NC}}{d\Omega} + 2\sqrt{\frac{d\sigma_P}{d\Omega}\frac{d\sigma_{NC}}{d\Omega}}\cos(\phi) + \frac{d\sigma_{NI}}{d\Omega}$$

$E_{e^-} = 10$ GeV $\quad$ $E_{e^-} = 11$ GeV $\quad$ $E_{e^-} = 12$ GeV



- Combining results from all 3 Phases and using 3 decay channels in the fit, the expected statistical error on the resulting decay width ($\Gamma_{\eta\to\gamma\gamma}$) is 3.85%.
  - 5.06% if only $\eta \to \gamma\gamma$ channel is used
  - 3.90% if both $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$ channels are used
- Most additional sources of systematic uncertainties are controlled by the Compton scattering analysis and are expected to be below 3%.

Conclusion

- 50% of data has been collected for the PrimEx-Eta experiment, with the remainder scheduled to be collected later this year.
- Compton scattering analysis shows strong agreement between measured cross section and NLO theory calculation.
  - Systematic uncertainties are being finalized but are expected to be around 2-4%.
  - We hope to publish these results soon.
- Extraction of the η meson decay width is underway.
  - Large beamline background is seen in $\eta \to \gamma\gamma$ channel
  - Combined fit of 3 dominant decay channels will reduce statistical uncertainty on decay width to <4%.

- Acknowledgements: gluex.org/thanks

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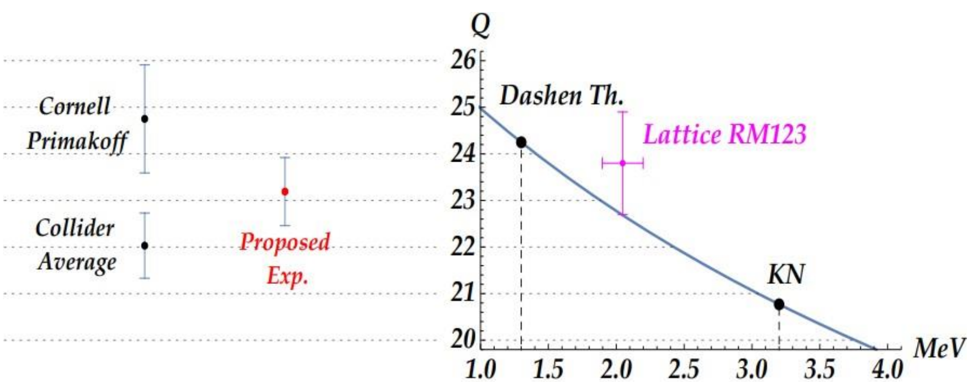
Backup Slides

Physics Motivations

Light-Quark Mass Ratio

- Improvement to $\Gamma(\eta \rightarrow \gamma\gamma)$ will reduce uncertainties to all other decay branching ratios
- $\eta \rightarrow 3\pi$ decays provide insight to the mass difference between light quarks

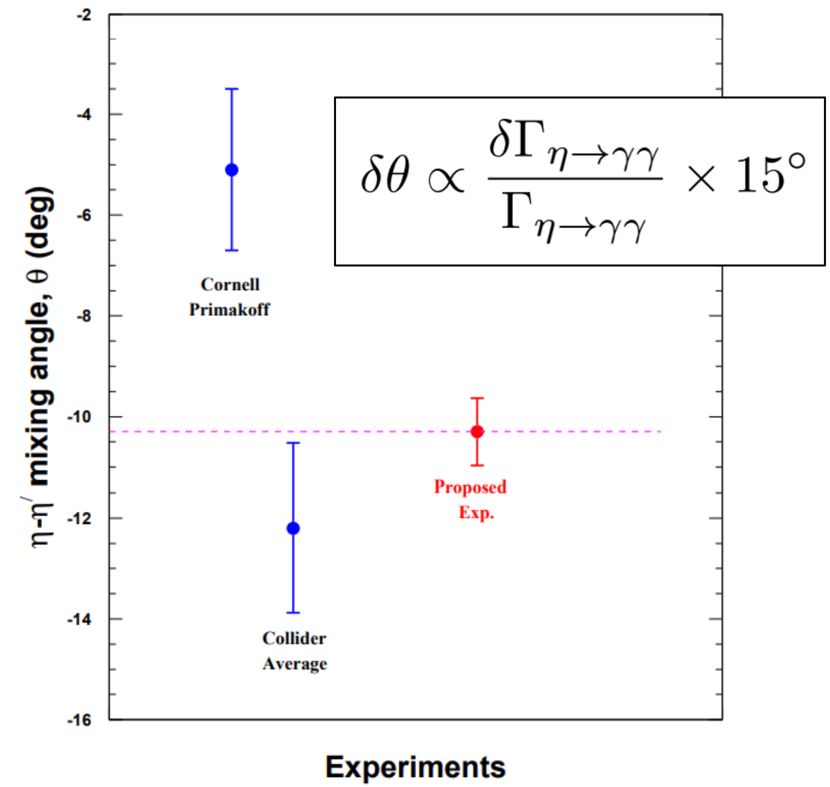
$$\boxed{Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}}$$



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

L. Gan, B. Kubis, E. Passemar, S. Tulin. arXiv:2007.00664 [hep-ph] (2020)

η-η′ Mixing Angle



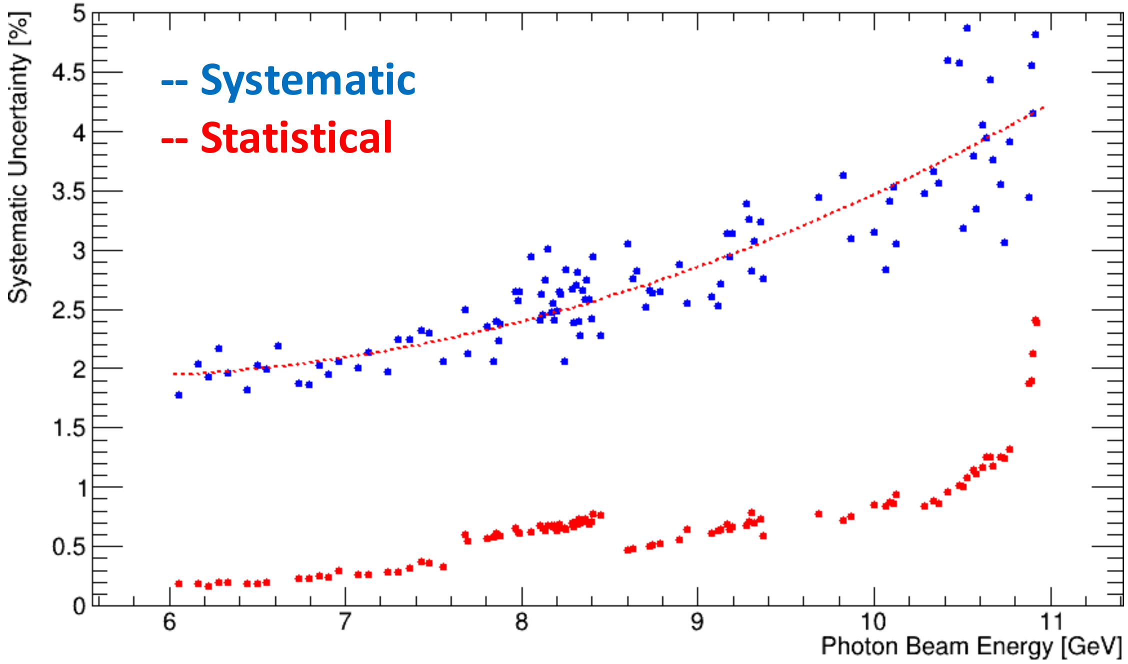
$$\boxed{\delta\theta \propto \frac{\delta\Gamma_{\eta\to\gamma\gamma}}{\Gamma_{\eta\to\gamma\gamma}} \times 15^\circ}$$

J.L. Goity, A.M. Bernstein and B.R. Holstein, Phys. Rev. D66 (2002) 076014

Compton Systematic Uncertainties

- Remaining systematics studies:
  - Uncertainty from photon flux and He target density
  - Uncertainty due to Signal to background separation

Combined Systematic Uncertainty (Not final)



Compton Acceptance (Field ON/OFF)