Preliminary Results from the PrimEx-*eta* Experiment in Hall D at Jefferson Lab

Andrew Smith

for the PrimEx-*eta* group of the GlueX Collaboration

JLUO Annual Meeting 2026

Tuesday, June 23, 2026

Outline

I. **Introduction** – *What we're measuring and why*
   - Physics motivations, Conflicting experimental techniques

II. **Experimental Details** – *How we're measuring it*
   - Hall D at Jefferson Lab
   - Compton scattering as a reference process

III. **η Meson Photoproduction Cross section** – *Preliminary results*
   - Steps to extracting the radiative decay width

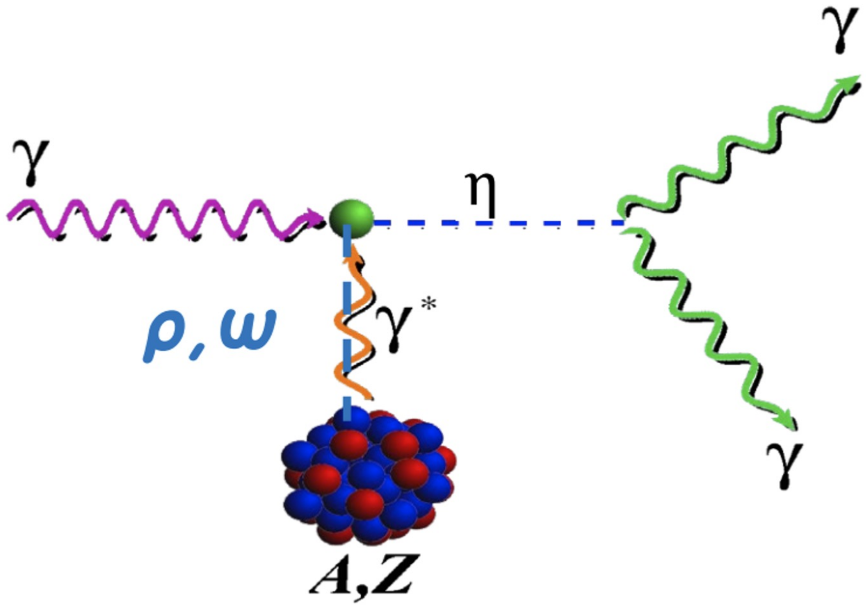
IV. **Outlook**

PrimEx-*eta* Experiment

Precision measurement of $\eta \rightarrow \gamma\gamma$ decay width via the Primakoff effect.

Decay proceeds via the *chiral anomaly*

- *Tests of symmetry breaking in low-energy QCD*



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

Larin *et al.*, *Science* **368**, 506-509 (2020). DOI:10.1126/science.aay6641

Physics Motivations – η-η' Mixing

Physical η, η' states are mixtures of singlet, octet states from SU(3) flavor symmetry breaking:

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \frac{1}{F} \begin{pmatrix} F_8 \cos\theta_8 & -F_0 \sin\theta_0 \\ F_8 \sin\theta_8 & F_0 \cos\theta_0 \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

$$F_{\eta\gamma\gamma} = \frac{1}{4\sqrt{3}\cos(\theta_0 - \theta_8)\pi^2} \left[\frac{\cos\theta_0}{F_8} - \frac{2\sqrt{2}\sin\theta_8}{F_0} \right]$$

$$F_{\eta'\gamma\gamma} = \frac{1}{4\sqrt{3}\cos(\theta_0 - \theta_8)\pi^2} \left[\frac{\sin\theta_0}{F_8} + \frac{2\sqrt{2}\cos\theta_8}{F_0} \right]$$

Precision measurements of η, η' decay widths provide insight to mixing angles

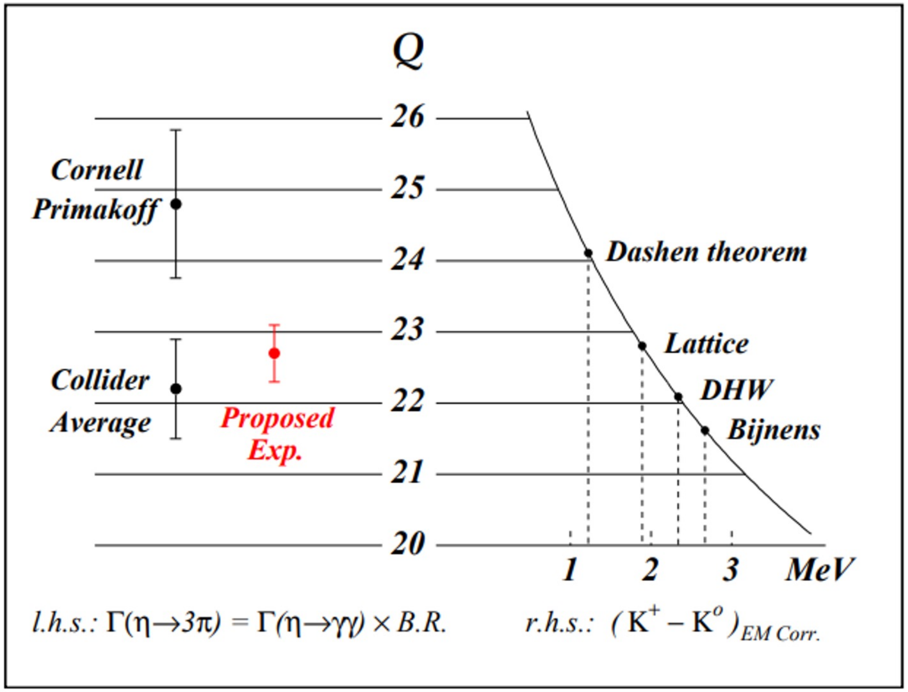
Physics Motivations – Light-Quark Mass Ratio

All other partial decay widths are known from two-photon width, plus branching ratios

$$\Gamma_{\eta\to 3\pi} = \Gamma_{\eta\to\gamma\gamma} \times \left(\frac{BR(\eta\to 3\pi)}{BR(\eta\to\gamma\gamma)}\right)$$

$$\mathcal{A}_{\eta\to\pi^+\pi^-\pi^0} \sim \frac{1}{Q^2}$$

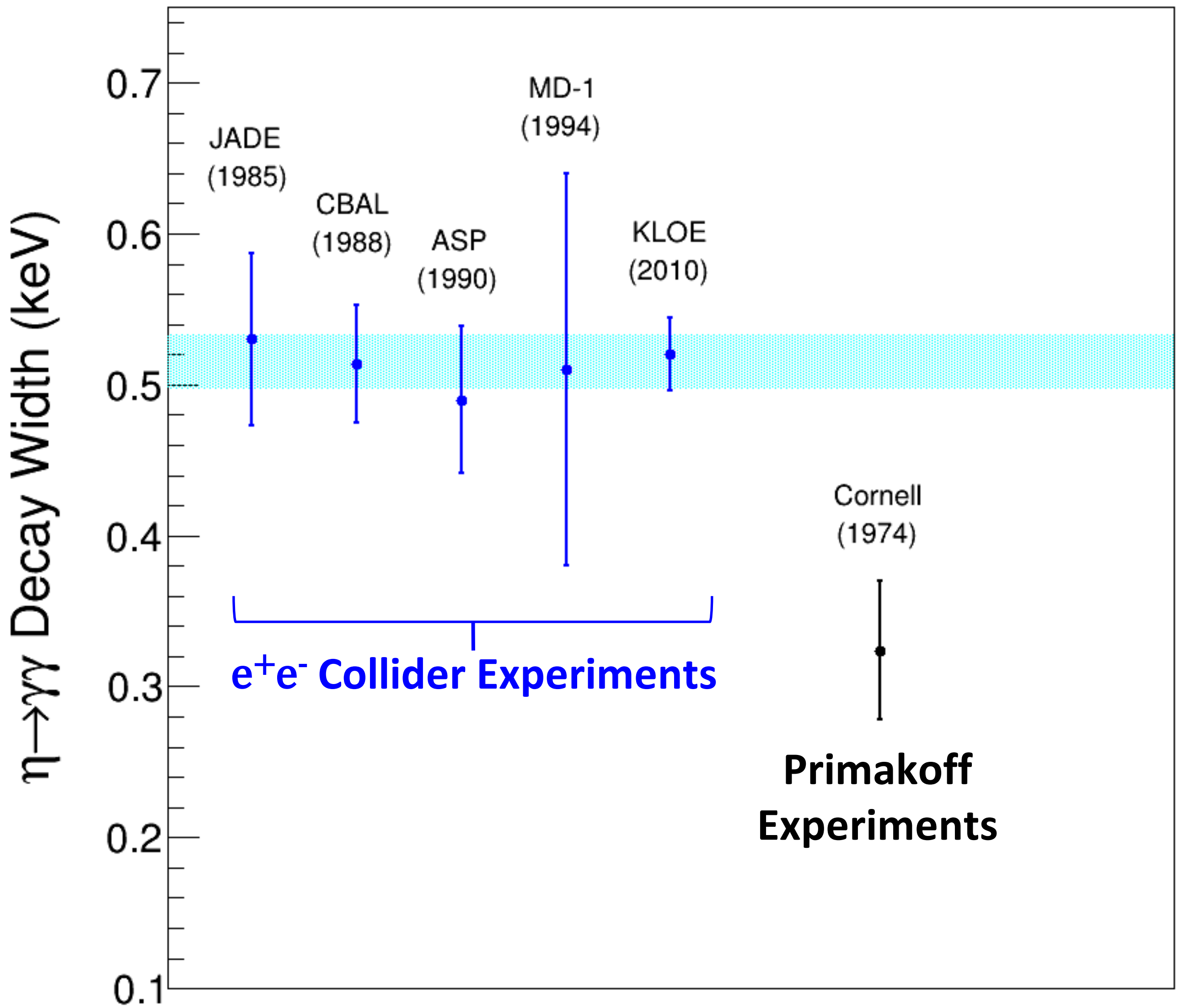
$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \hat{m} = \frac{m_u + m_d}{2}$$



H. Leutwyler, Phys. Lett. B374 (1996) 181

Precision measurement of $\Gamma_{\eta\to\gamma\gamma}$ → Model-independent extraction of light-quark mass ratio

Experimental Status of $\Gamma(\eta\rightarrow\gamma\gamma)$



PDG Average: $\Gamma(\eta\rightarrow\gamma\gamma)$ = 0.515 +/- 0.018 keV

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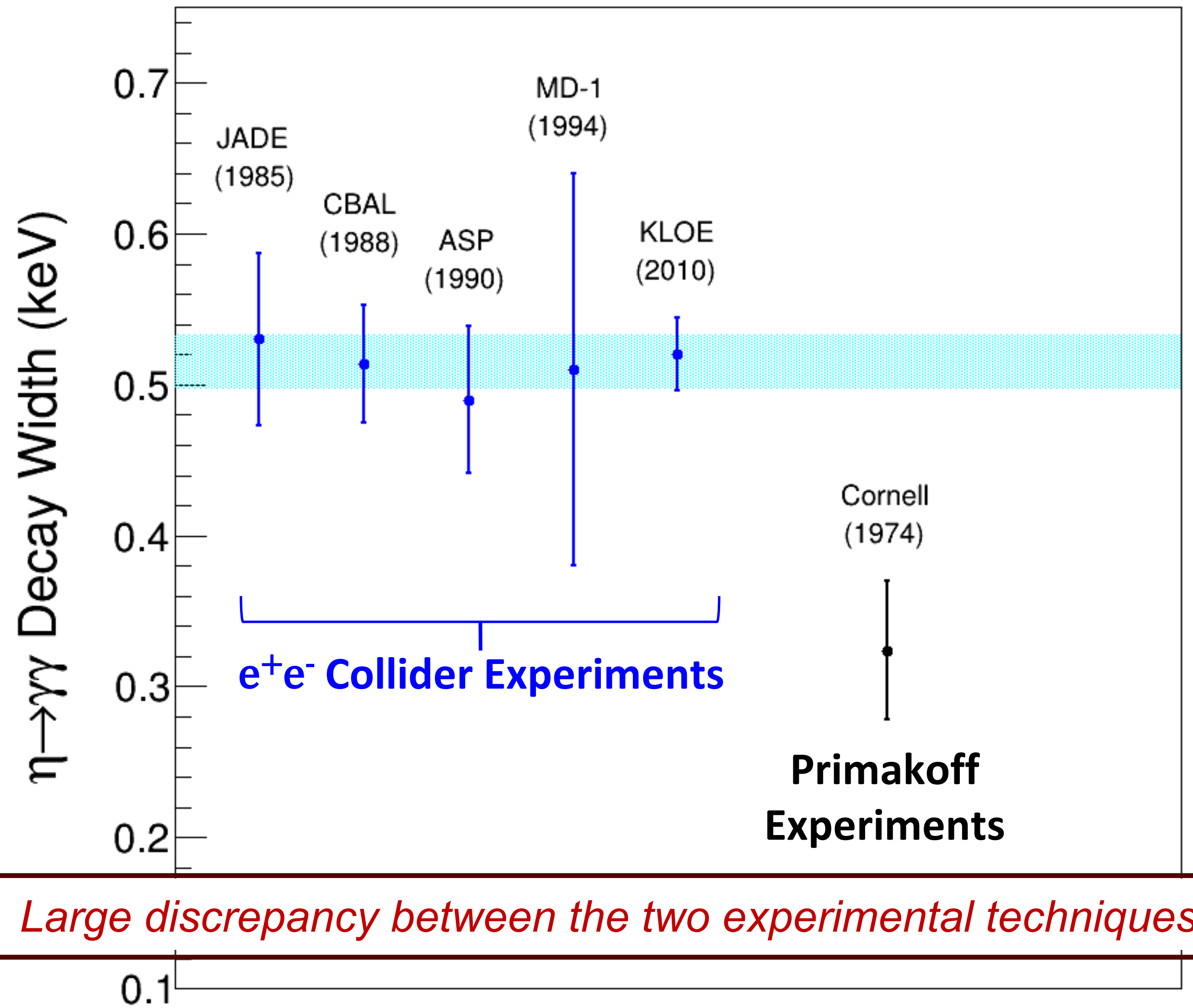

Large discrepancy between the two experimental techniques!

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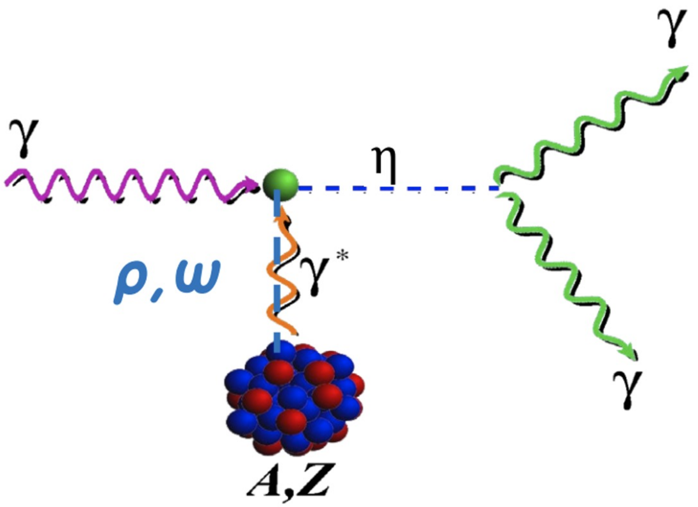
Primakoff Method

Precision measurement of $\eta \rightarrow \gamma\gamma$ decay width via the ***Primakoff method***.



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

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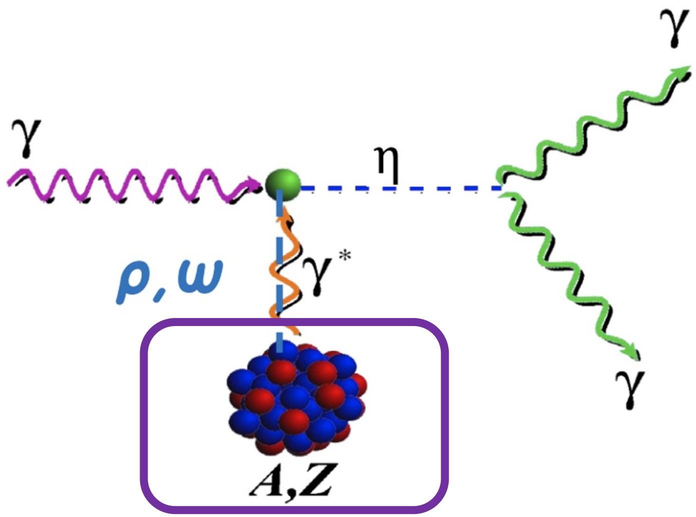

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Nuclear target: Liquid ^{4}He

- Well-known form factors
- Primakoff cross section ~Z^2

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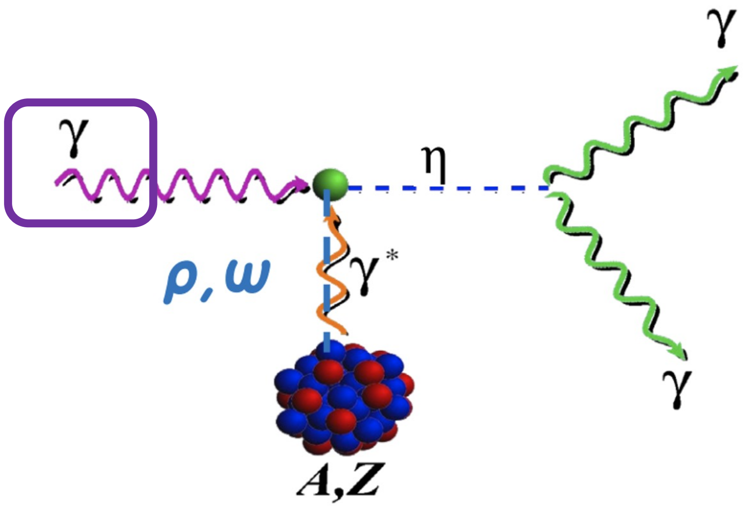

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Tagged photons:
6 GeV < E_γ < 11.3 GeV

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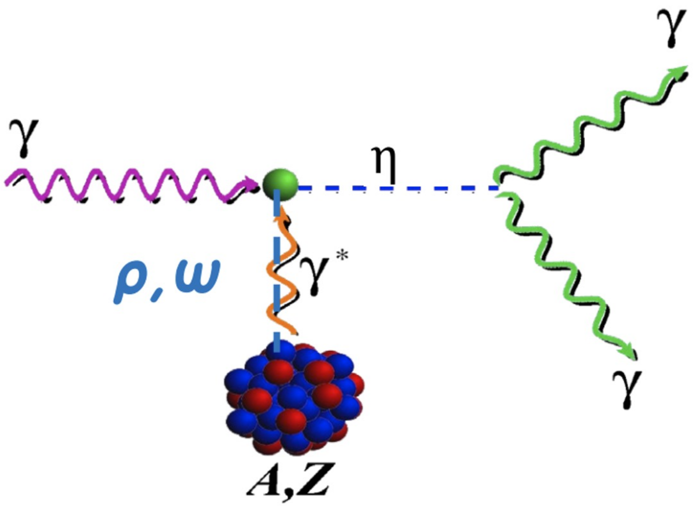

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Nuclear target: Liquid ^{4}He

- Well-known form factors
- Primakoff cross section ~Z^2

Tagged photons:

6 GeV < E_γ < 11.3 GeV

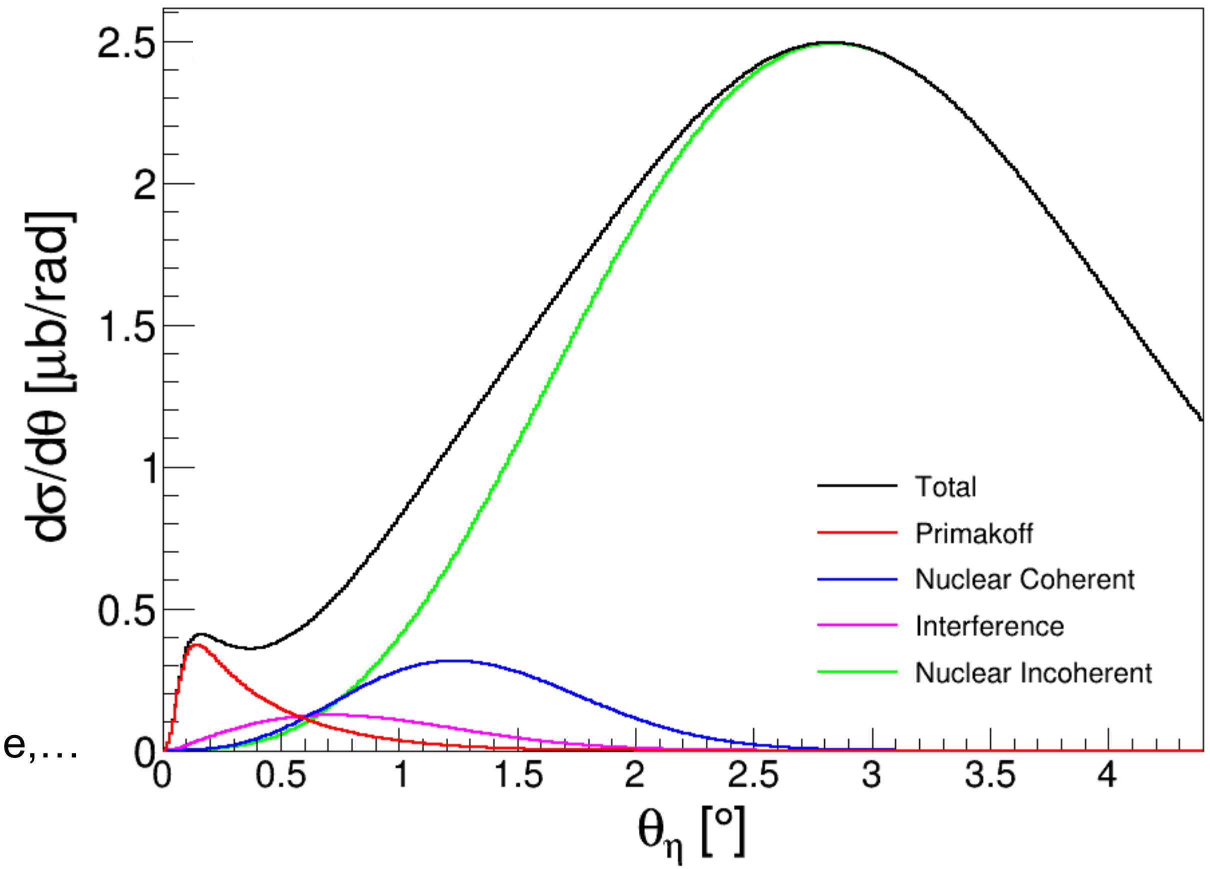
Integrated luminosity: 17.2 pb^{-1}

Primakoff Method

Challenge: *η mesons can also be produced via the strong interaction*

$$\gamma + {}^4\text{He} \rightarrow \eta + X$$

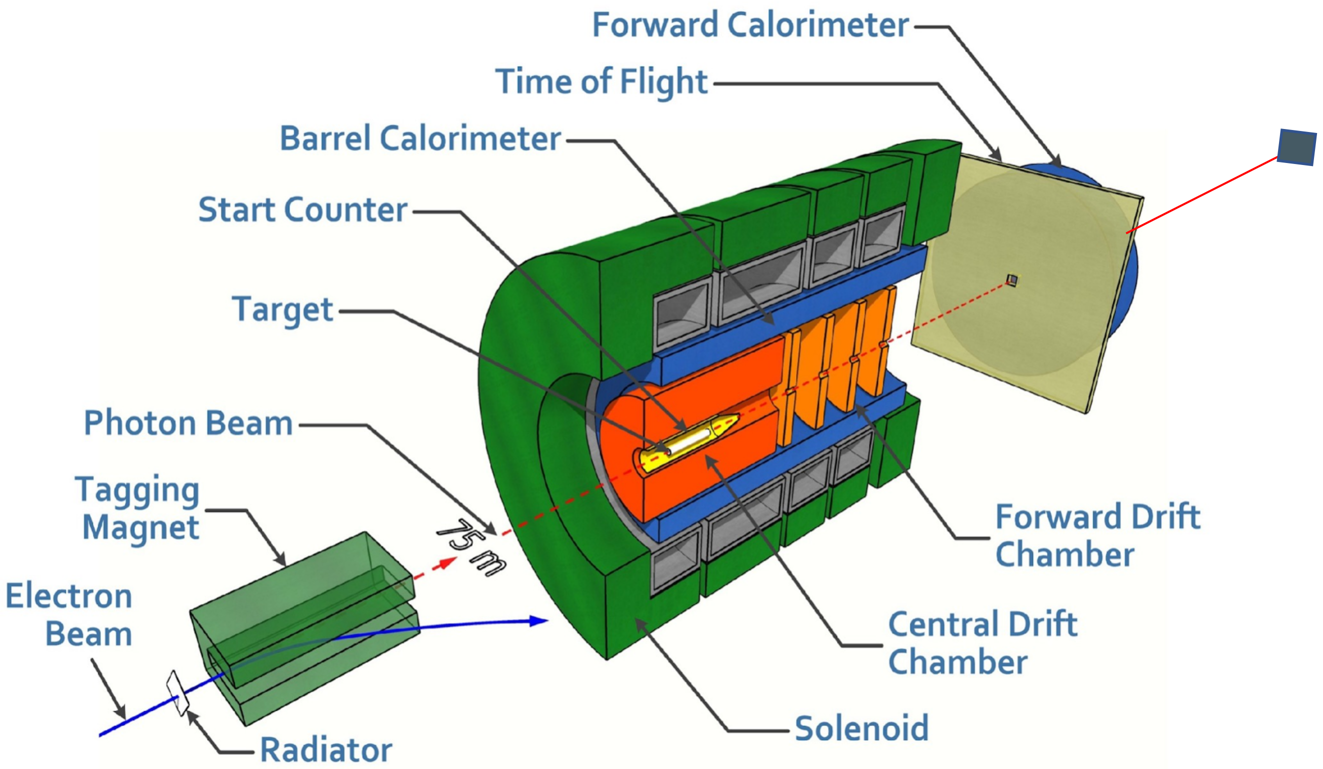
- *Primakoff*
  - $X = {}^4\text{He}$
  - $\theta_{peak} \sim \frac{m_\eta^2}{2E_\gamma}$
- *Nuclear Coherent*
  - $X = {}^4\text{He}$
  - $\theta_{peak} \sim \frac{2}{EA^{1/3}}$
- *Nuclear Incoherent*
  - $X = {}^4\text{He}'$, $p + {}^3\text{H}$, $n + {}^3\text{He}$,…
- *Interference*



Extraction of radiative decay width from cross section is inherently model-dependent

Experimental Hall D

Elastic $\eta(\gamma\gamma)$ production: Two decay photons detected in Forward Calorimeter (FCAL) in coincidence with tagged beam photon



S. Adhikari *et al.*, Nucl. Instrum. & Meth. A**987**, 164807 (2021)

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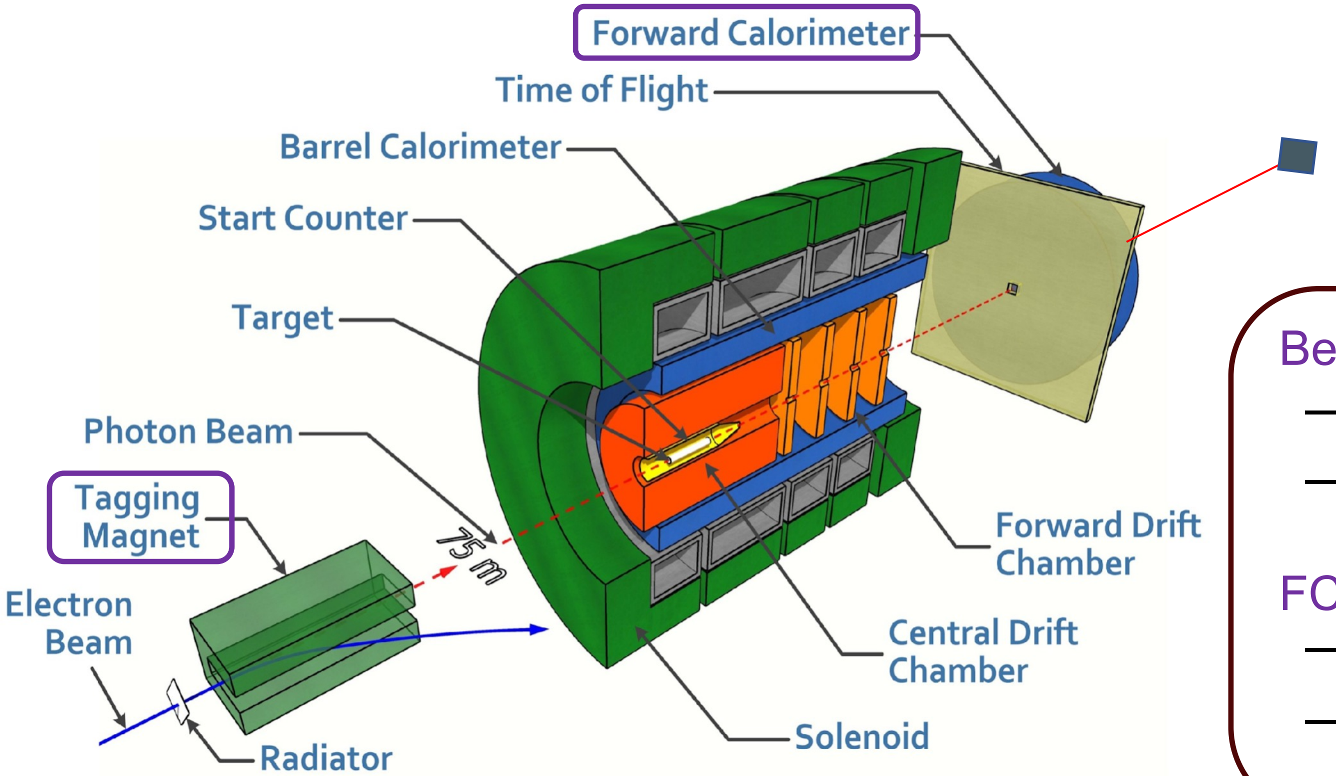

Beam Photon Tagger:

- $\frac{\sigma_E}{E} = (0.4 - 1.4)\%$
- $\sigma_t = 200$ ps

FCAL:

- $\theta = 1^\circ - 11^\circ$
- $\frac{\sigma_E}{E} = \left(\frac{6.2}{\sqrt{E}} \oplus 4.7\right)\%$

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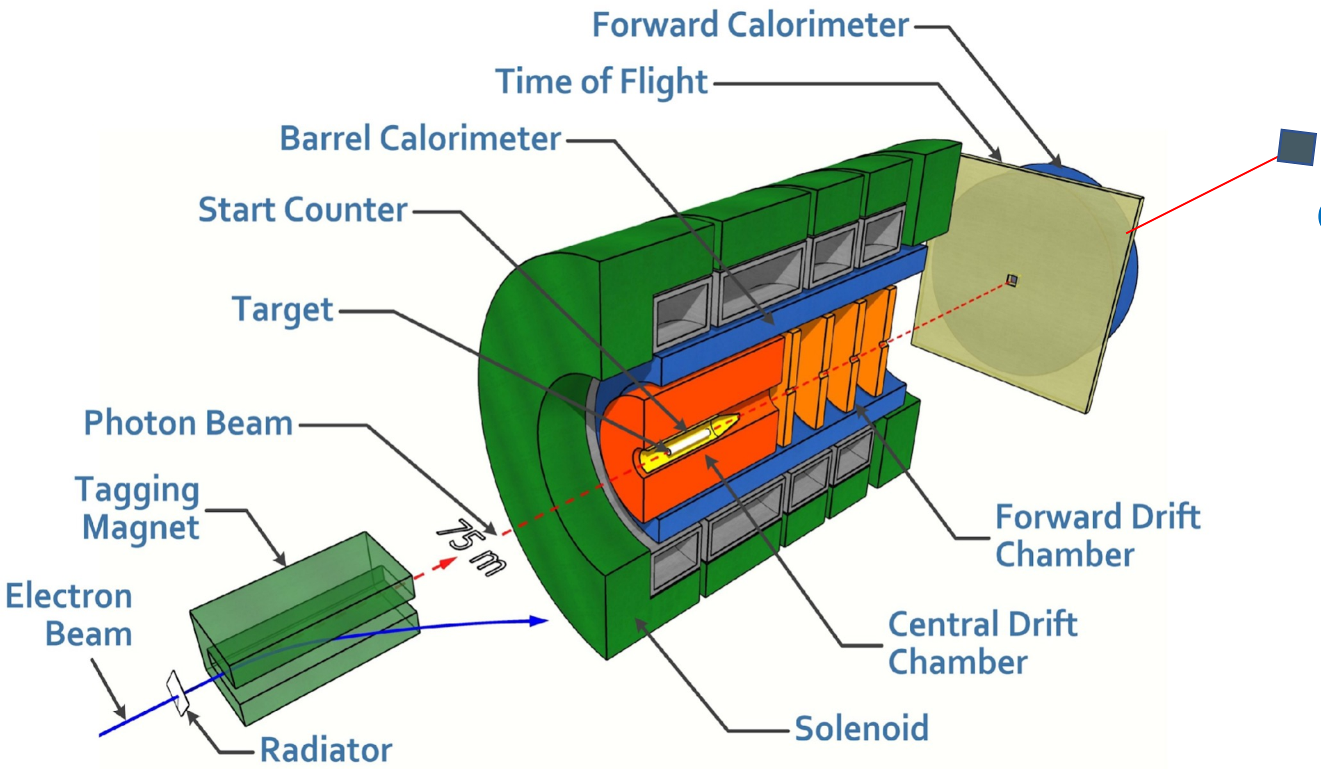
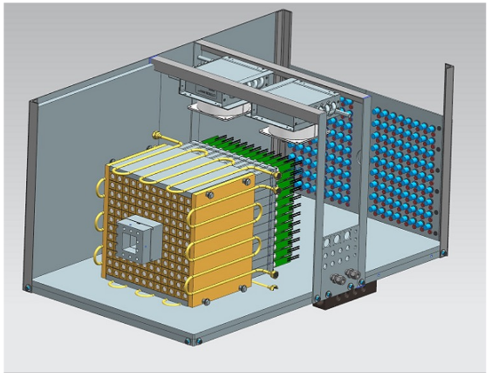


Compton Calorimeter

- $PbWO_4$ crystals
- $0.2^{\circ} < \theta < 0.6^{\circ}$



S. Adhikari *et al.*, Nucl. Instrum. & Meth. A**987**, 164807 (2021)

A. Asaturyan *et al.*, Nucl. Instrum. & Meth. A**1013**, 165683 (2021)

η Decay Modes

- $\eta \rightarrow \gamma\gamma$ Branching Ratio: (39.36±0.18)%
  - Acceptance ~50%
  - Simple final state → lower overall systematic uncertainty

- $\eta \rightarrow \pi^0\pi^0\pi^0(6\gamma)$ Branching Ratio: (32.57±0.21)%
  - Acceptance ~30%
  - Reduced background

- $\eta \rightarrow \pi^+\pi^-\pi^0(2\gamma)$ Branching Ratio: (23.02±0.30)%
  - Acceptance ~20%
  - Charged particles → vertex reconstruction
  - Additional systematics from tracking

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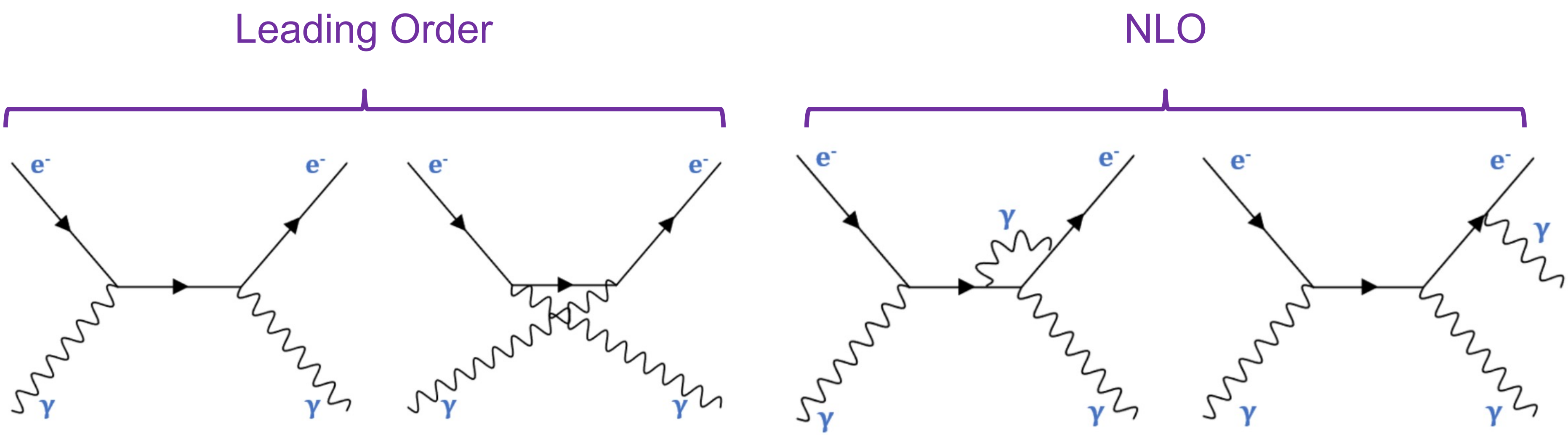
Compton Scattering Cross Section ($\gamma e^- \rightarrow \gamma e^-$)

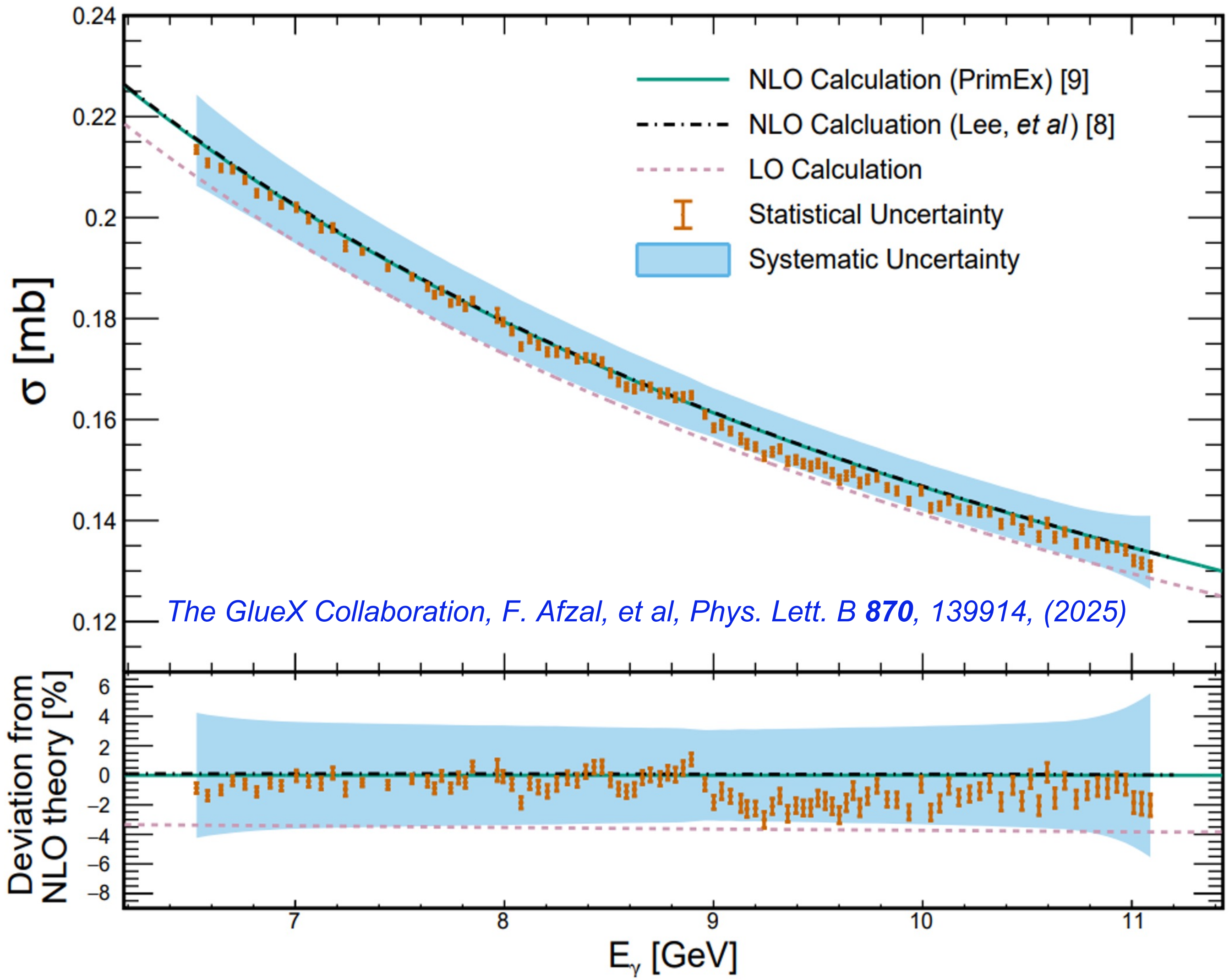


Compton scattering from atomic electrons is a well-known QED process to use as a reference:

- Assess forward-angle acceptance and luminosity systematics
- Monitor target density and detector performance throughout experiment

Compton Scattering Cross Section ($\gamma e^- \rightarrow \gamma e^-$)

Average combined uncertainty: 3.4%.



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$\eta \rightarrow \gamma\gamma$ Event Selection

- Two photons detected in Forward Calorimeter (FCAL) in coincidence with tagged beam photon

η→γγ Event Selection

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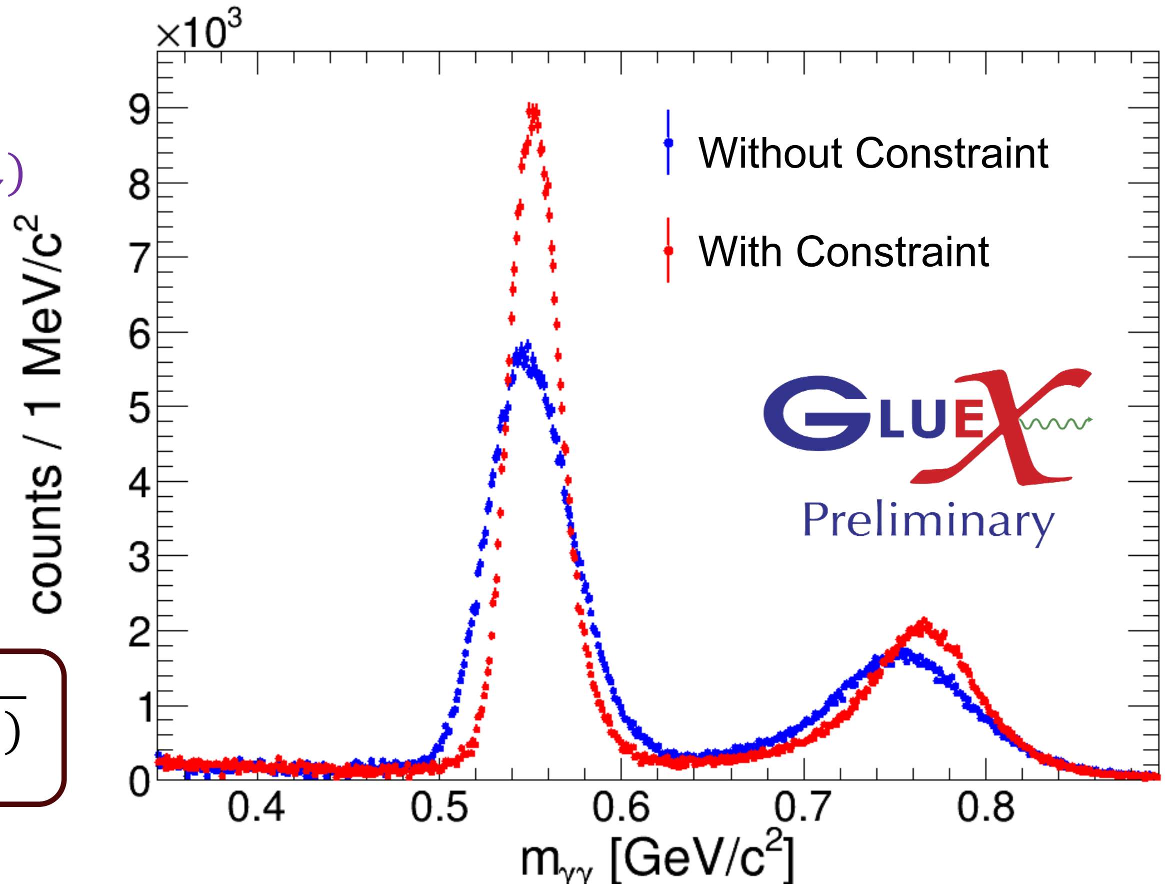
Energy-constraint applied to improve resolution and separate non-exclusive backgrounds:

$$E_i \rightarrow E_i' = E_i + \Delta E_i$$

$$E_1' + E_2' = E_\gamma - E_{recoil}\,(E_\gamma, \theta_{\gamma\gamma})$$

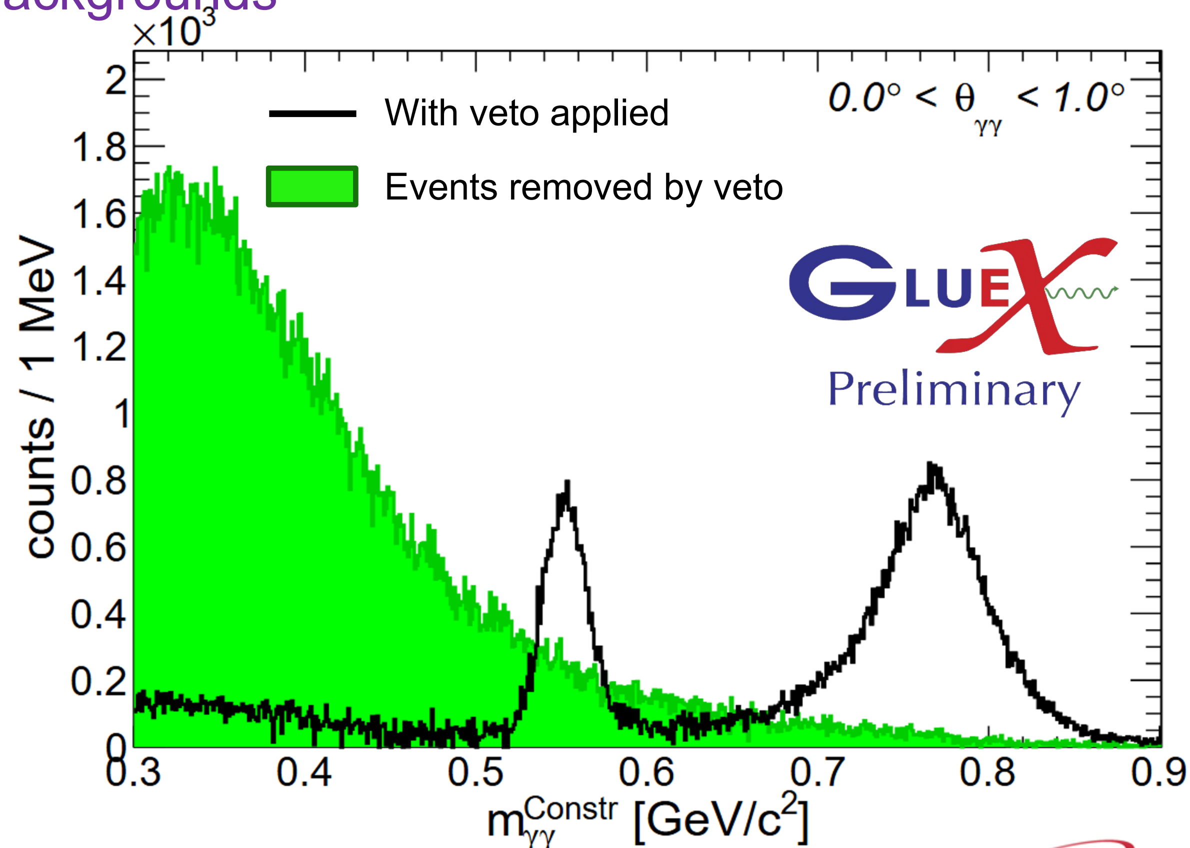
$$\frac{\Delta E_1}{\Delta E_2} = \frac{\sigma(E_1)}{\sigma(E_2)}$$

$$m_{\gamma\gamma}^{Constr} = \sqrt{2E_1'E_2'(1 - \cos\theta_{12})}$$



$\eta \rightarrow \gamma\gamma$ Event Selection

- Two photons detected in Forward Calorimeter (FCAL) in coincidence with tagged beam photon
- Time-of-Flight detector (TOF) upstream of FCAL used to reject charged particle backgrounds



$\eta \rightarrow \gamma\gamma$ Event Selection

- Two photons detected in Forward Calorimeter (FCAL) in coincidence with tagged beam photon
- Scintillating detector upstream of FCAL used to reject charged particle backgrounds (TOF)
- Barrel Calorimeter (BCAL) and scintillating paddles around target cell used to reject hadronic background channels

η→γγ Event Selection

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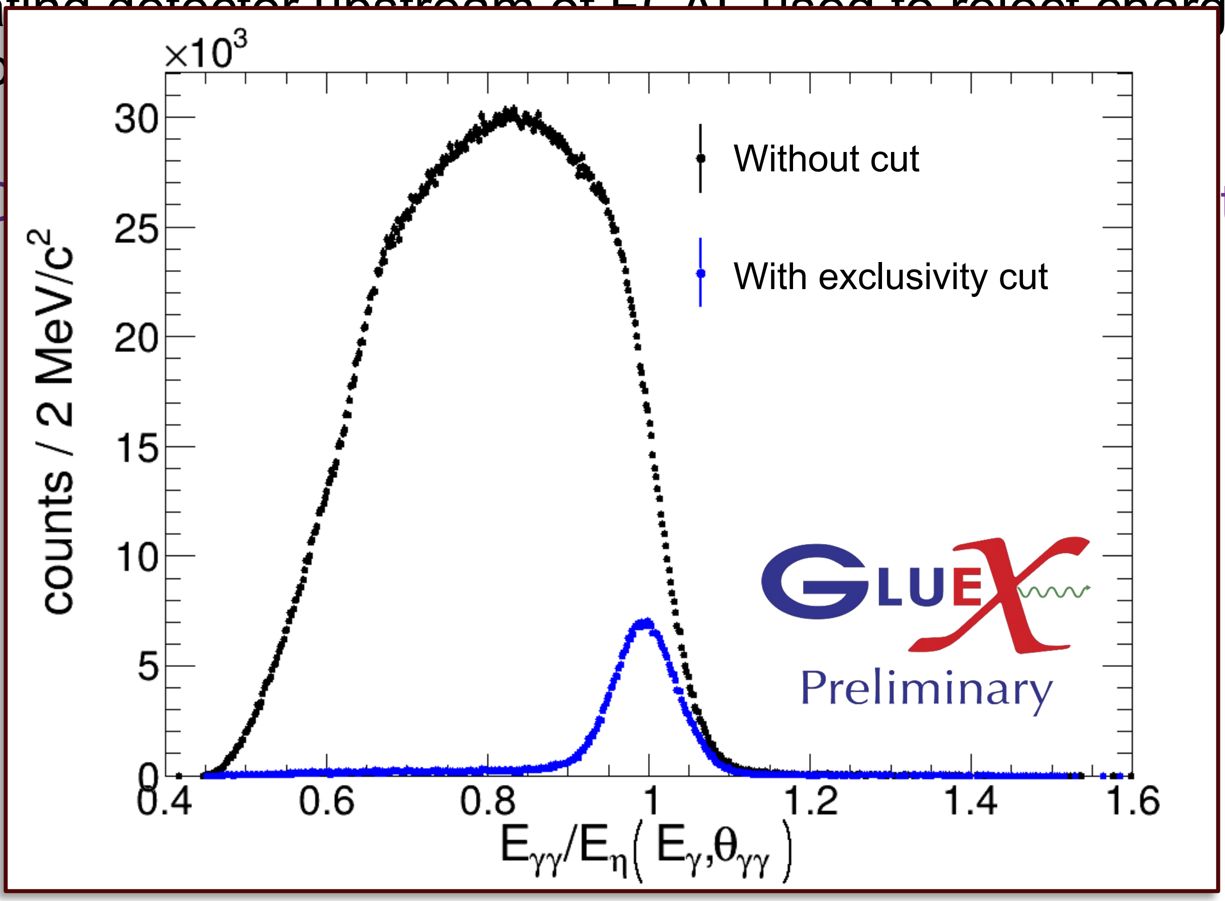
- Scintilla ... ged particle backgro ...
- Barrel C ... target cell used to ...



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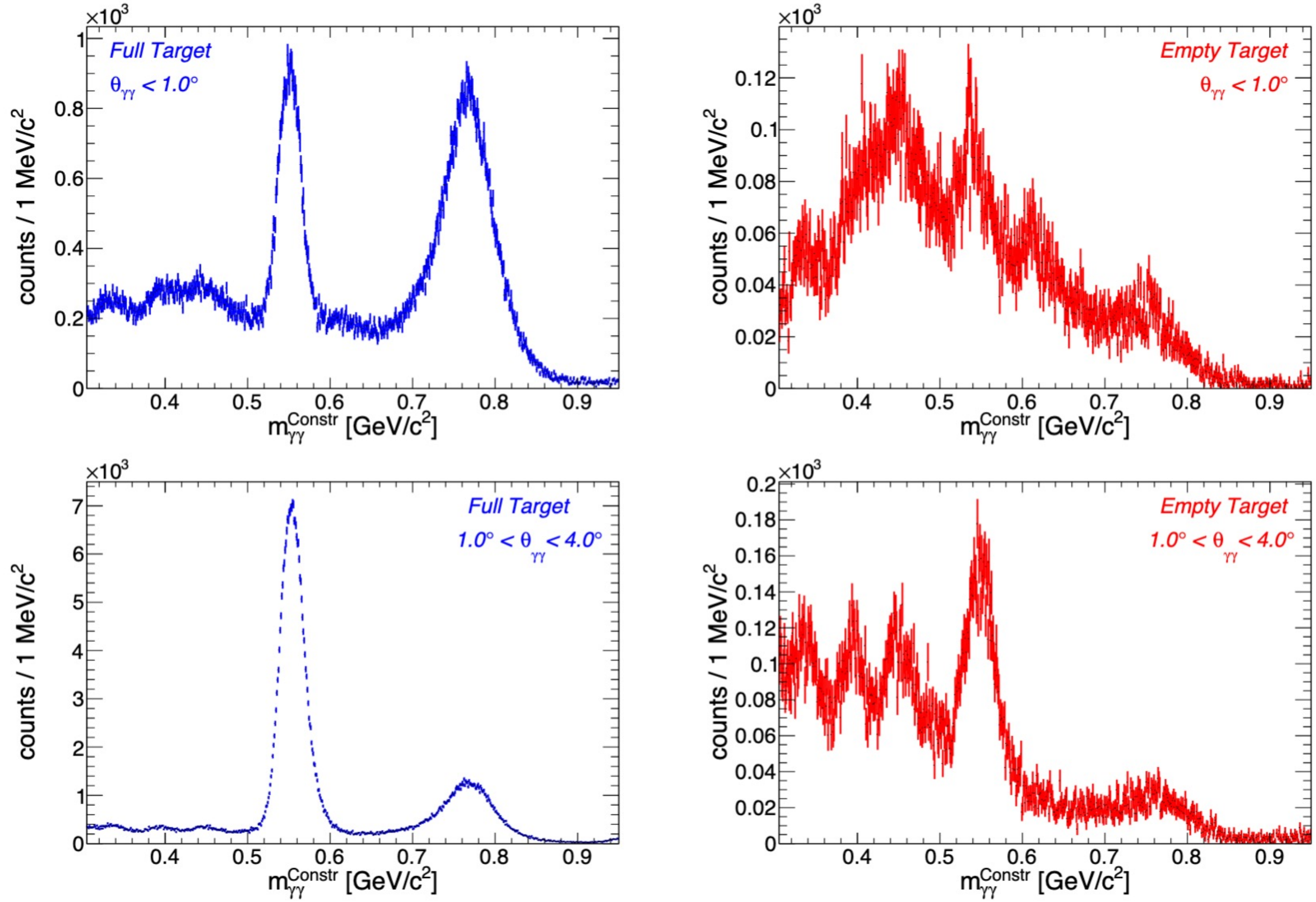
- Barrel Calorimeter (BCAL) and scintillating paddles around target cell used to reject hadronic background channels
- *Agnostic* approach to recoil particle detection:
  - Keep events with recoil nucleons (incoherent production)
  - Unable to detect Helium-4 nucleus from coherent process

Empty Target Data

30% of experiment time was spent with liquid Helium evaporated and pumped out of cell

- *Some residual Helium gas remained inside cell*

This data can be used to subtract background originating outside of target



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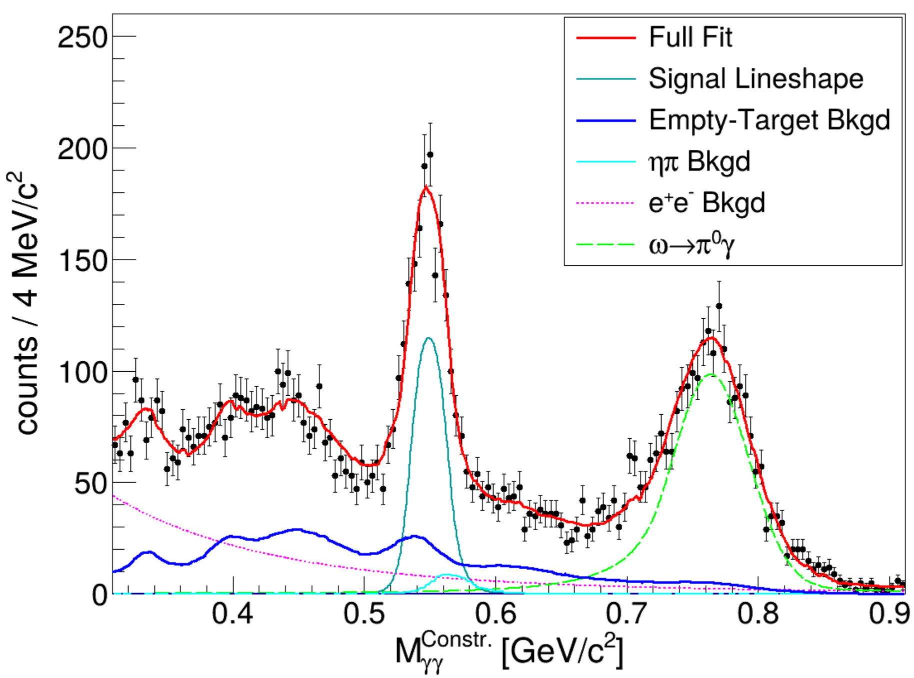
η→γγ Decay Channel

Yield extracted by simultaneous fits to "empty" and full target data sets

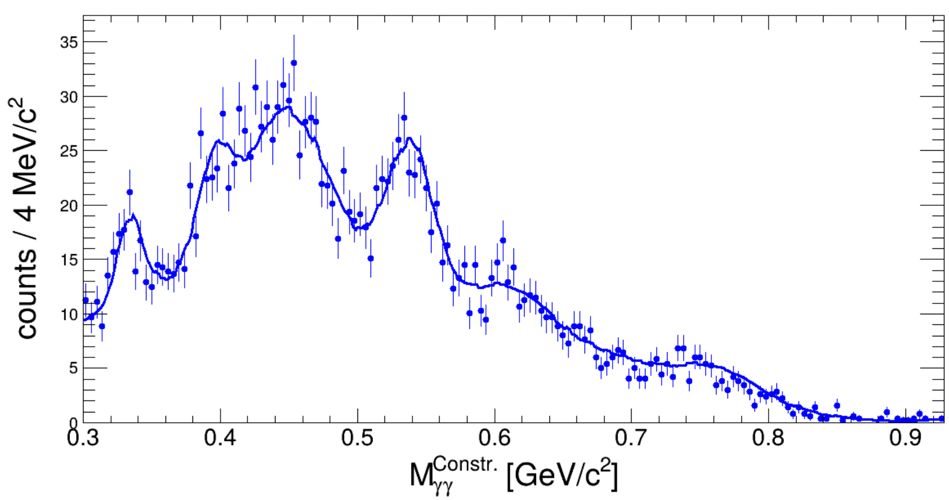
Additional backgrounds from:

- $\eta\pi,\ \eta\pi\pi$
- $\omega \to \pi^0\gamma$
- e^+e^- Pair production

Full Target



Empty Target



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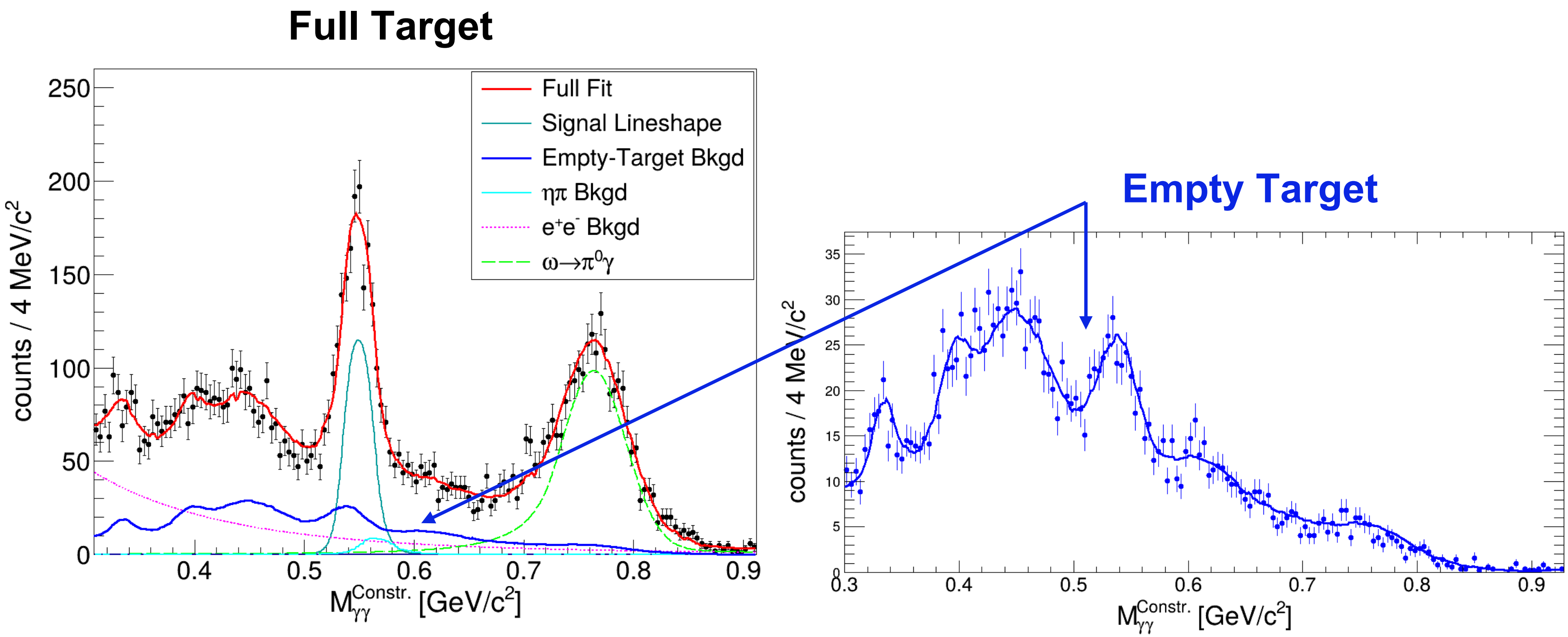

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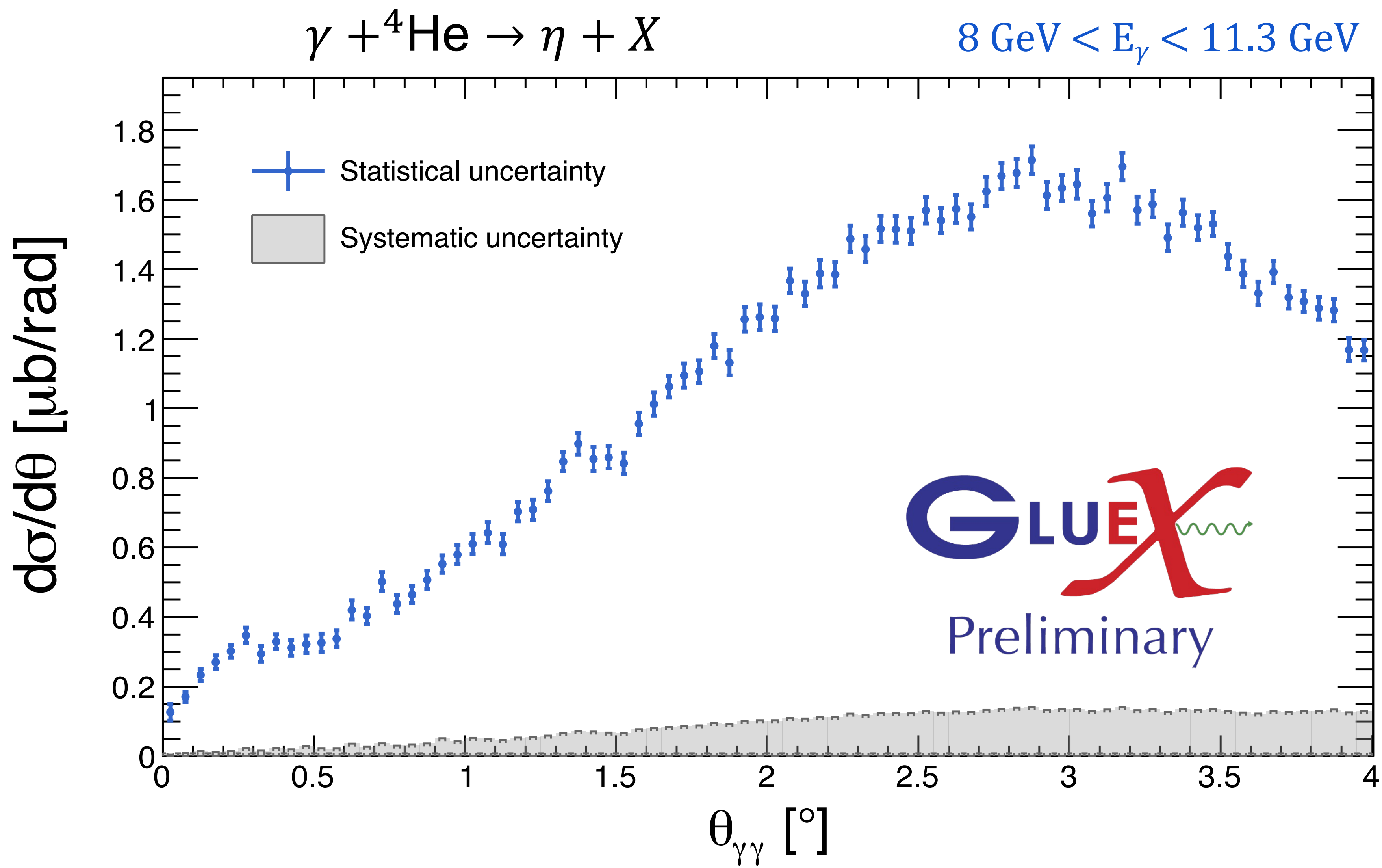
Preliminary Results - Cross Section



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Decay Width Extraction

Fit measured angular yield distribution with theoretical calculations convolved with experimental resolution and acceptance

$$\frac{dN}{d\theta_{rec}} = \Gamma_{Int} \cdot t \cdot \epsilon \cdot \sum_{i,\theta} \left[w_i \cdot M(i, \theta, \theta_{rec}) \cdot \frac{d\sigma}{d\theta}(i, \theta, \vec{\beta}) \right]$$

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- w_i: Fraction of photon flux in energy bin, i
- $M(i, \theta, \theta_{rec})$: Angular acceptance and resolution matrix
- $\frac{d\sigma}{d\theta}(i, \theta, \vec{\beta})$: Theoretical calculation for energy bin, i, angle, θ, and model parameters, $\vec{\beta}$

Model Calculations

S. Gevorkyan, *et al*, Phys. Rev. C **80,** 055201 (2009)

$$\frac{d\sigma}{d\Omega} = \left|T_{Prim} + e^{i\phi} T_{Coh}\right|^2 + \frac{d\sigma_{Inc}}{d\Omega}$$

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- $T_{Coh} = A\left(\vec{h}\cdot\vec{q}\right)f_p(0)\,F_S(q,\Delta)$

Elementary production amplitude on nucleon: $f_p(q) = f_p(0)\left(\vec{h}\cdot\vec{q}\right)e^{-\frac{a_p q}{2}}$

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Form factors corrected for initial and final-state interactions

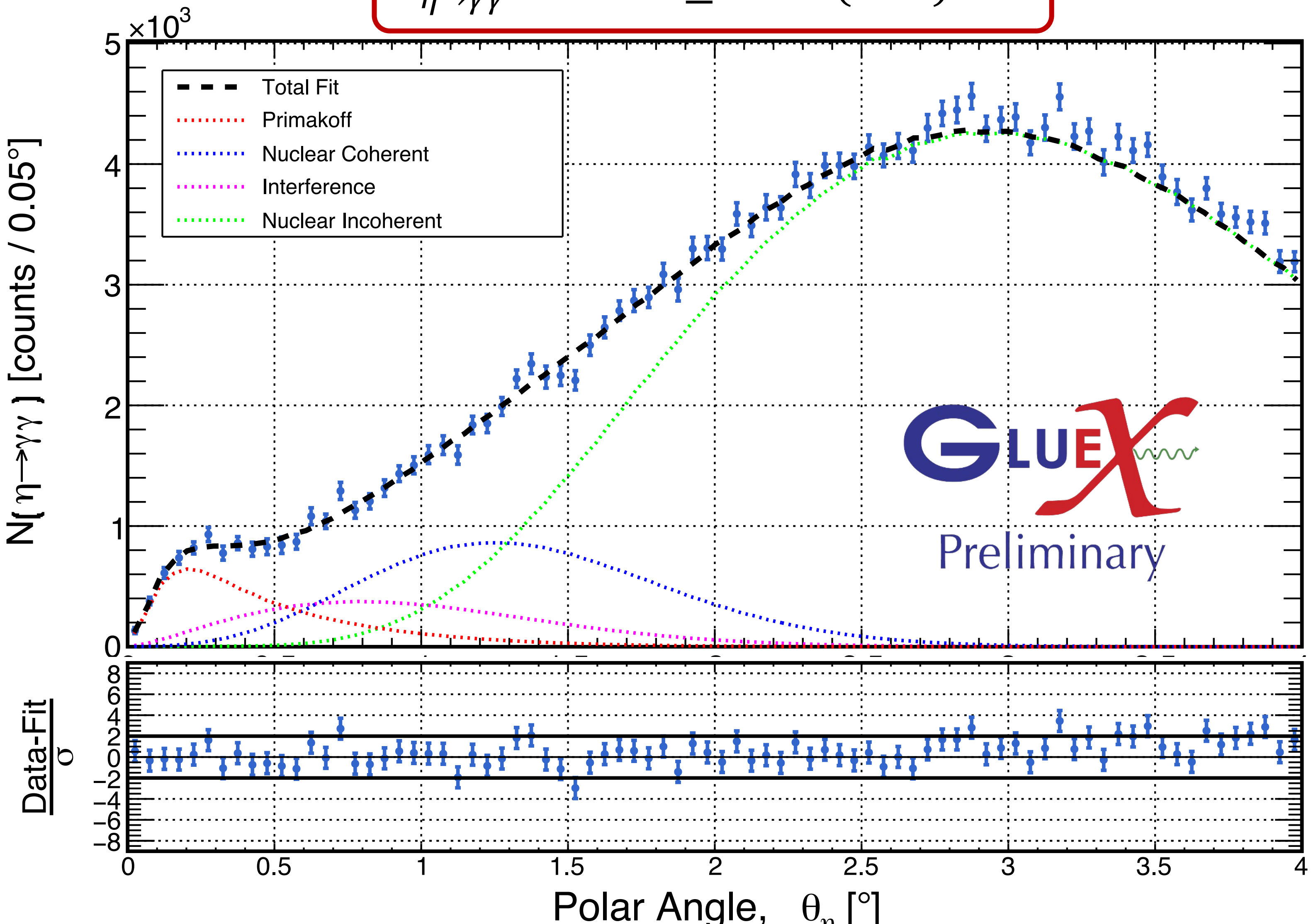
Elementary production amplitude on nucleon: $f_p(q) = f_p(0)\left(\vec{h}\cdot\vec{q}\right)e^{-\frac{a_p q}{2}}$

- $\frac{d\sigma_{Inc}}{d\Omega}$: *Includes free-nucleon cross section combined with Pauli-blocking suppresion factor and final state interactions using framework of Glauber Theory*

Decay Width Extraction

$$\Gamma_{\eta\to\gamma\gamma} = 0.431 \pm 0.021(stat)\ keV$$

$$\chi^2/ndf = 1.24$$



Uncertainty Breakdown

Source	Uncertainty (%)
Event Selection	2.20
Yield Extraction	1.42
Acceptance	1.06
Luminosity	2.07
Model Dependence	4.50
Total Systematic	5.70
Statistical	4.80
Total	**7.45**

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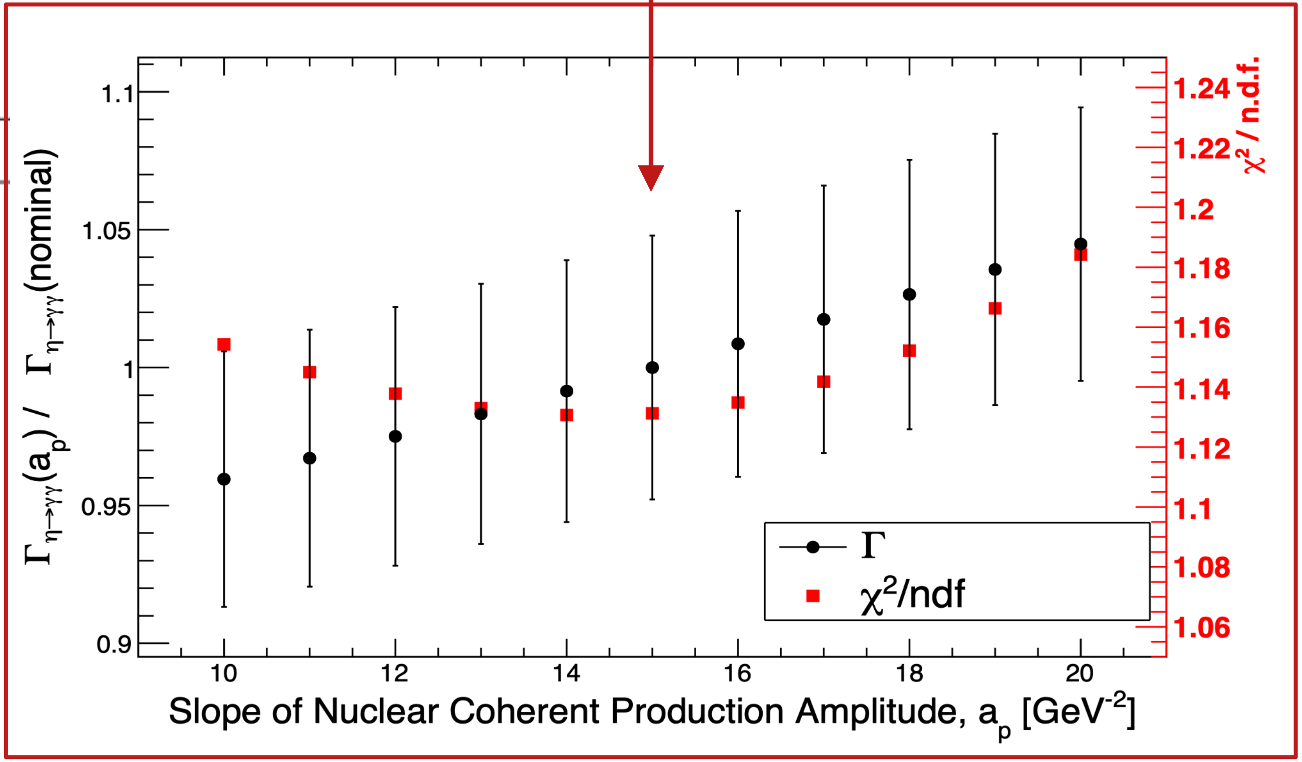
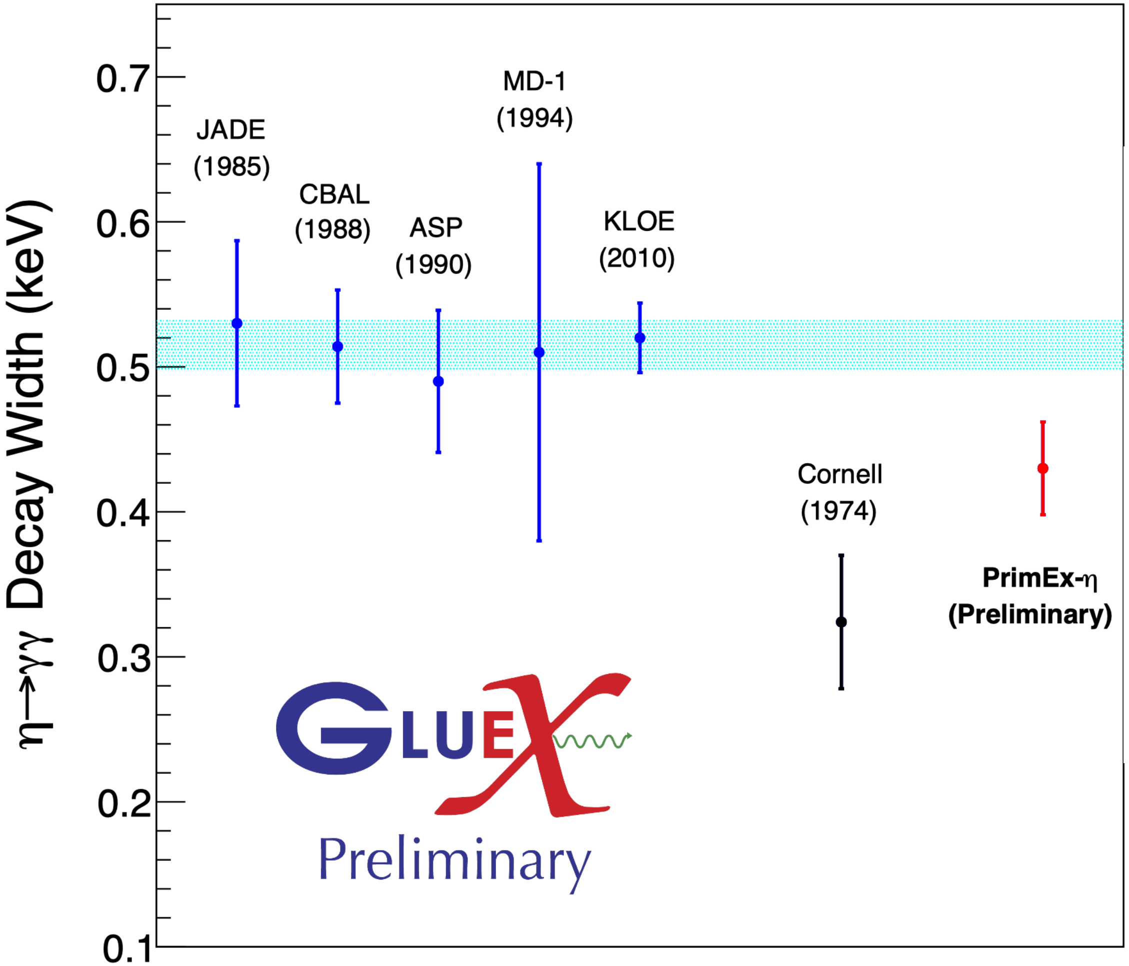
Primarily due to uncertainty in slope of elementary production amplitude:



Updated Status of Experimental Results



- PDG:
  $\Gamma_{\eta\to\gamma\gamma} = 0.515 \pm 0.018$ keV
- PrimEx-*eta*:
  $\Gamma_{\eta\to\gamma\gamma} = 0.431 \pm 0.032$ keV

$$N_\sigma = \frac{\left|\Gamma^{PDG}_{\eta\to\gamma\gamma} - \Gamma^{PrimEx}_{\eta\to\gamma\gamma}\right|}{\sqrt{\sigma^2_{PDG} + \sigma^2_{PrimEx}}} = 2.3$$

Summary

The η meson photoproduction cross section was measured at forward angles from a Helium-4 target for the first time

Preliminary extraction of decay width → Competitive uncertainty with collider experiments

Largest source of systematic uncertainty is from uncertainty on slope of elementary production amplitude

Internal (GlueX) review underway, publication soon to follow

GlueX Acknowledgements: gluex.org/thanks

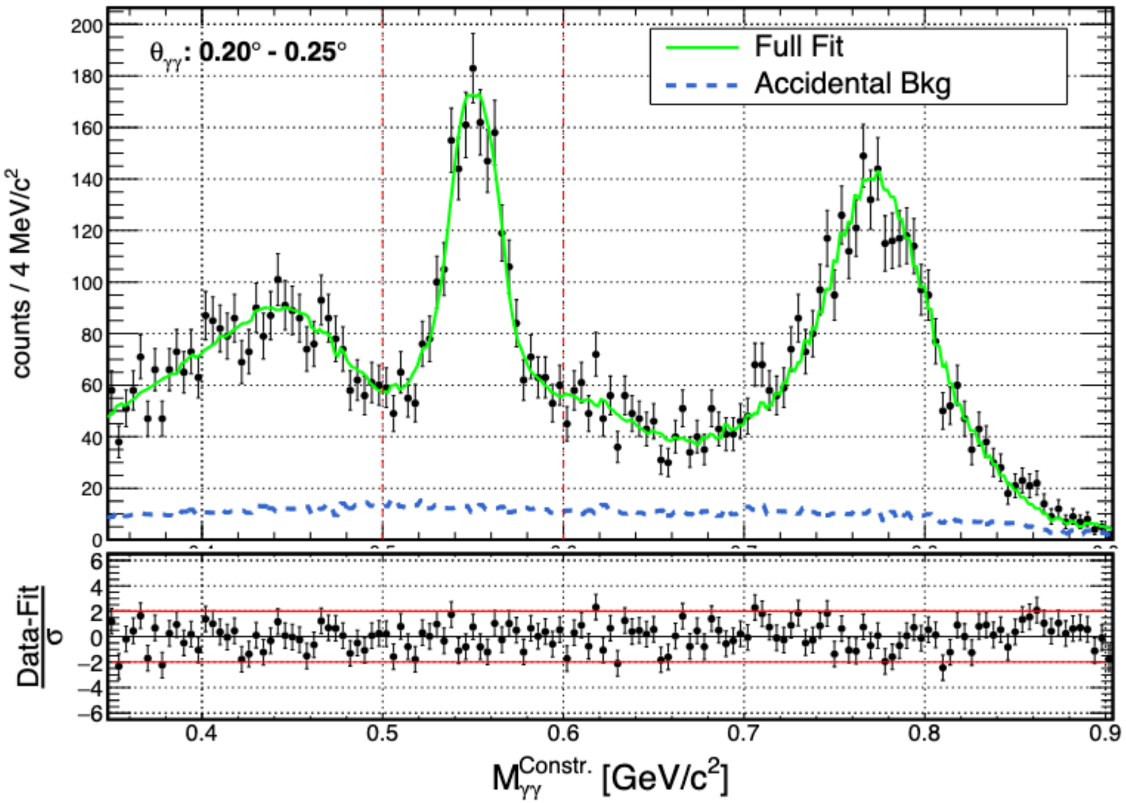
Event Selection Systematics

Source	Variation	Uncertainty (%)
FCAL Fiducial Cut	$N_{\text{layers}} = 2.0 \to 3.0$	1.7%
FCAL Extra Energy (E_{min})	0 – 100 MeV	0.2%
FCAL Photon Energy Cut (E_{good})	300 – 700 MeV	0.5%
Elasticity Cut	$\pm 3\sigma \to \pm 7\sigma$	0.7%
TOF Veto Distance Cut	8.0 cm $\to$ 12.0 cm	0.4%
TOF Veto Timing Cut	0.8 ns $\to$ 1.5 ns	0.2%
BCAL/SC Veto	Nominal vs. loosened	0.9%
Total (Event Selection)		2.2%

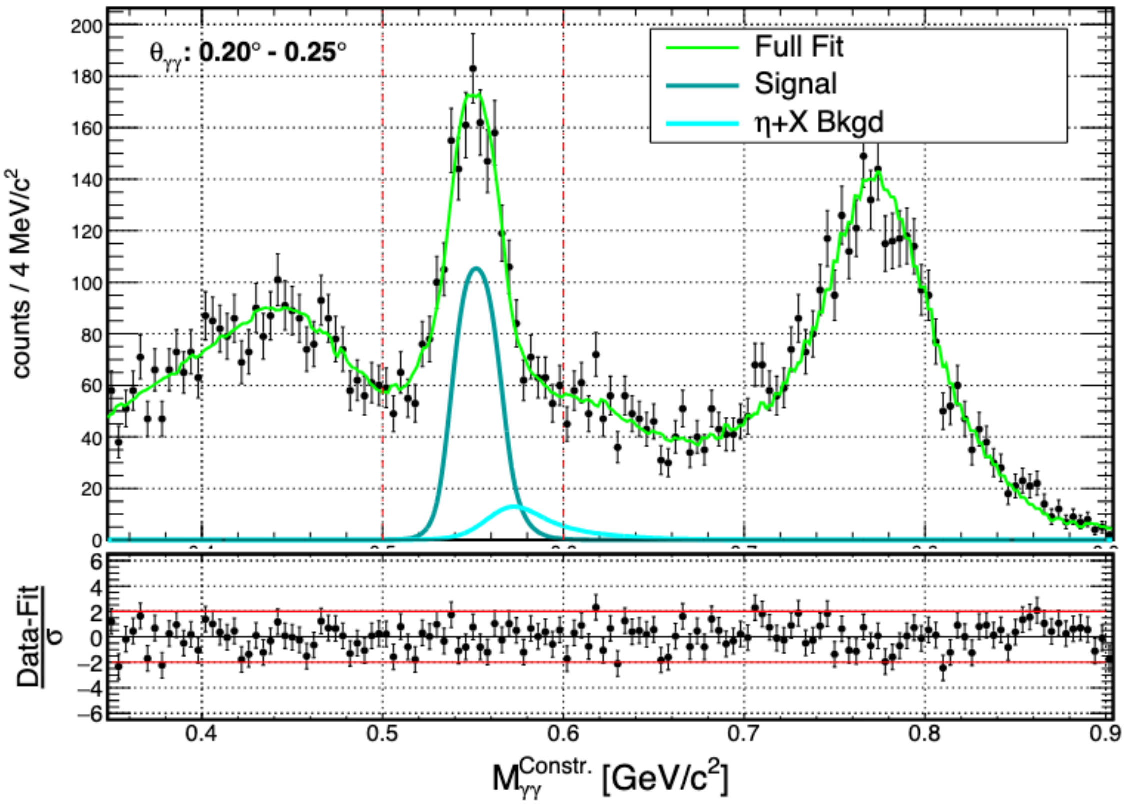
Dominant source of systematic uncertainty from FCAL fiducial cut

- i.e. how much of the region surrounding the beam hole is excluded

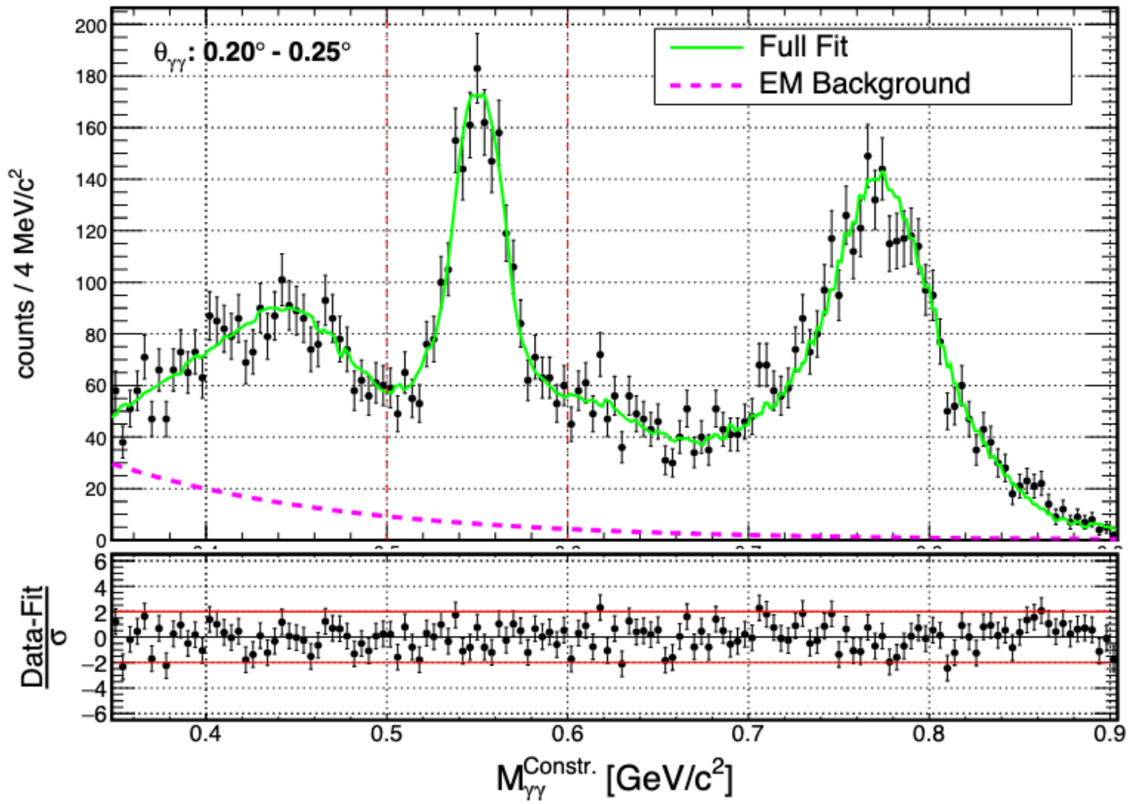
Yield Extraction - Example Fit Result ($0.20° < \theta_{\gamma\gamma} < 0.25°$)



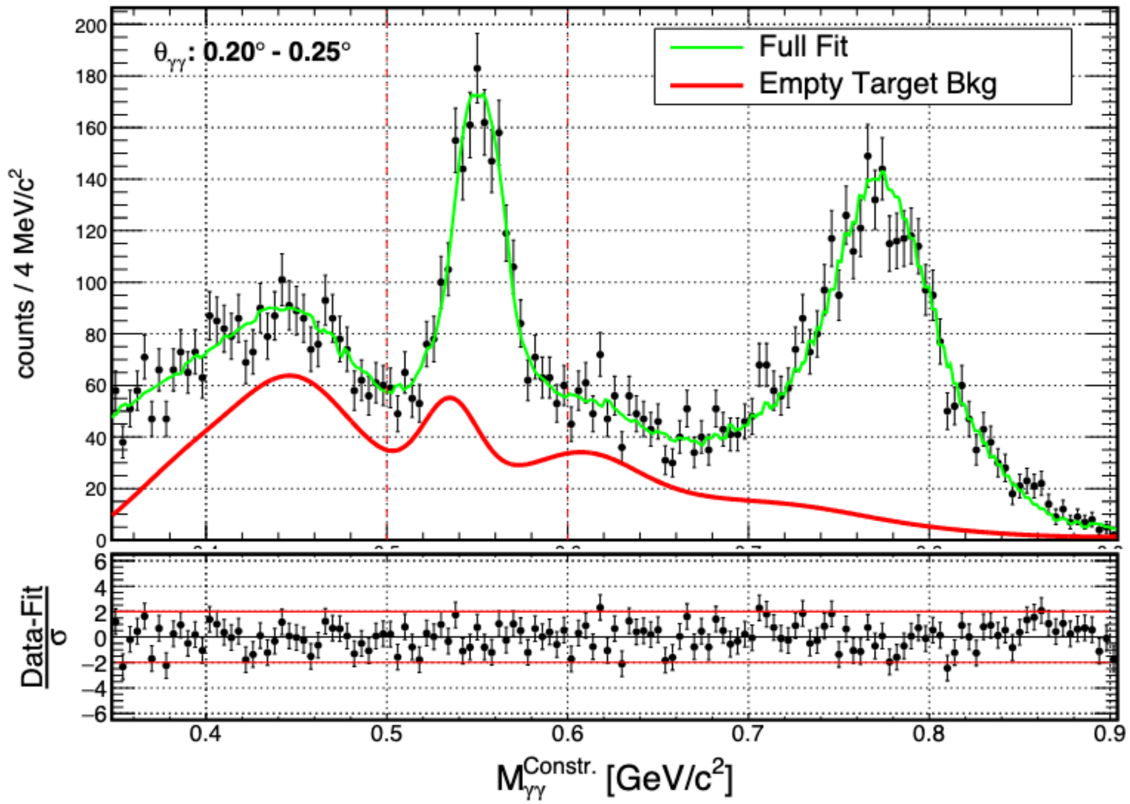
Yield Extraction - Example Fit Result $(0.20^\circ < \theta_{\gamma\gamma} < 0.25^\circ)$



Yield Extraction - Example Fit Result ($0.20° < \theta_{\gamma\gamma} < 0.25°$)



Yield Extraction - Example Fit Result ($0.20^\circ < \theta_{\gamma\gamma} < 0.25^\circ$)



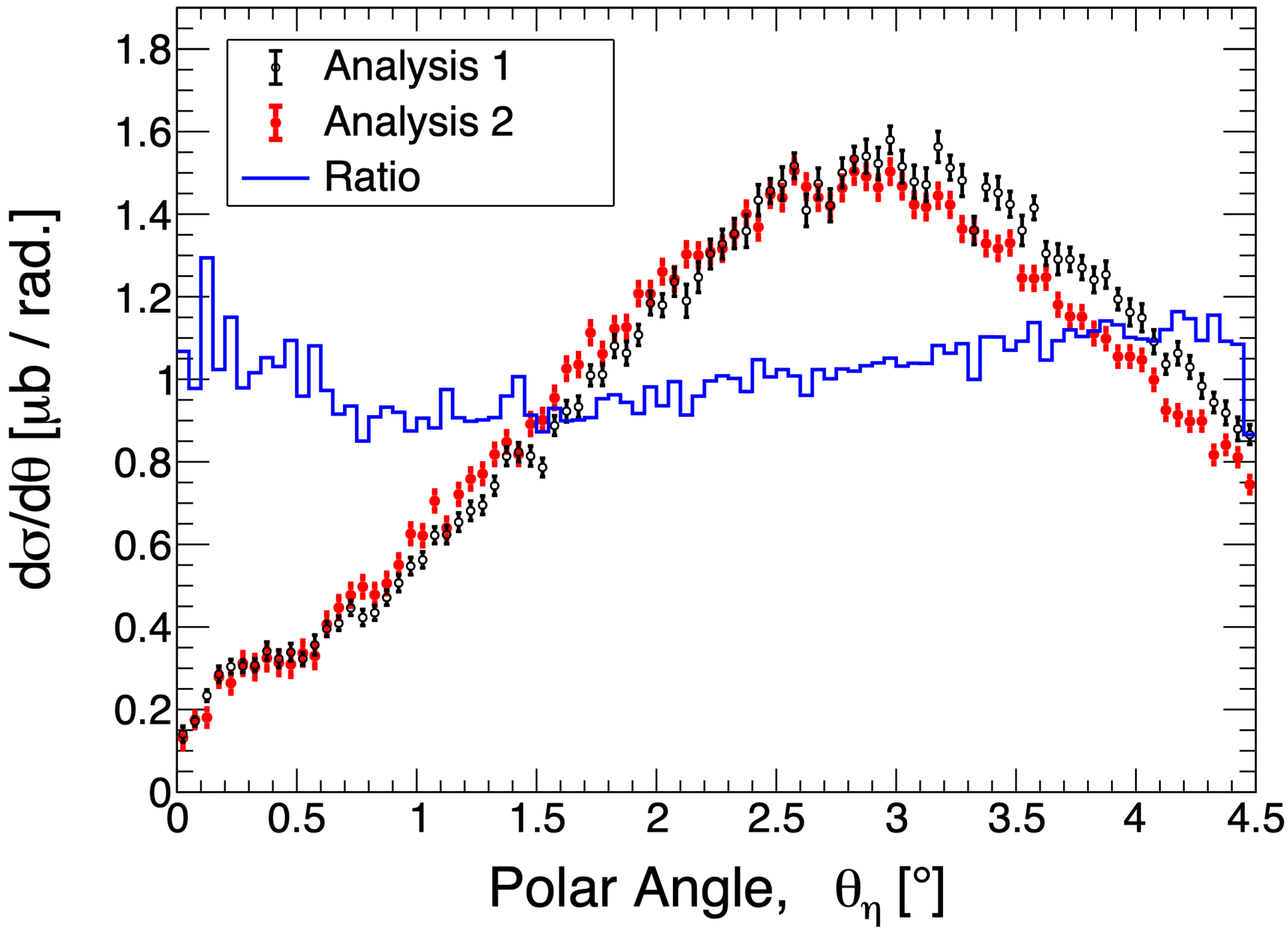
Model Inputs

Parameter	Nominal Choice	Alternate Variations
$\rho(r)$	AV18 [1]	HO, SOG [2]
$\rho_{ch}(r)$	SOG [2]	HO, 3PF [2]
a_p	15 GeV^{-2}	10–20 GeV^{-2}
$\sigma_{\eta N}$	20 μb [3]	15–25 μb
a_s	7 GeV^{-2}	4–10 GeV^{-2}
w	0.25	0.0–0.5

- Slope of elementary production amplitude is in general different for protons and neutrons.
- In Coherent photoproduction off nucleus, only isoscalar contribution contributes:
  - Slope of isoscalar amplitude larger than $|t_s + t_v|$ or $|t_s - t_v|$, but poorly constrained from experiment

Cross-Check: Independent Analysis Results

Second, independent analysis performed with different technique
→ Results consistent within experimental uncertainties

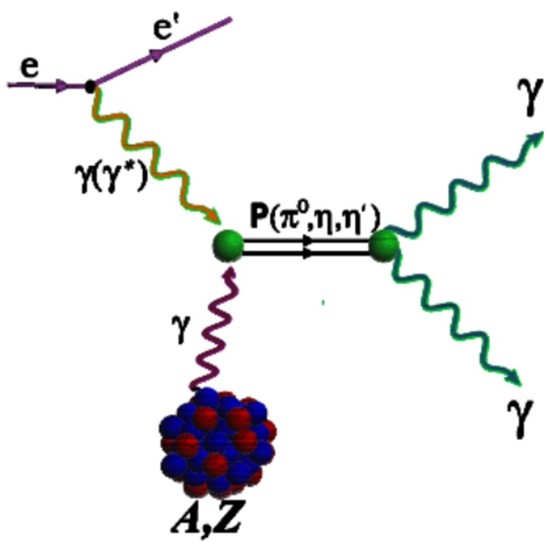


Jefferson Lab

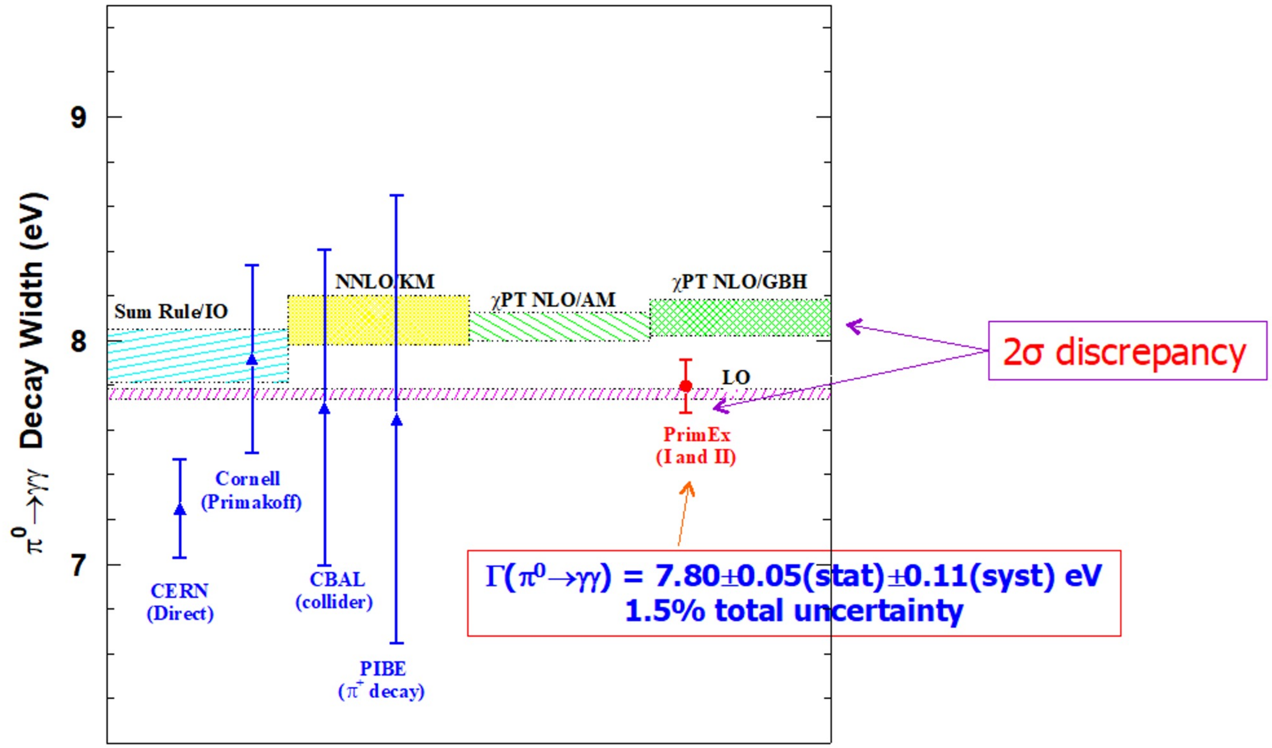
Primakoff Program at JLab

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

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



PrimEx-I and II in Hall B measured the $\pi^0 \rightarrow \gamma\gamma$ 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)

Cornell Primakoff Measurement

A. Browman *et al*., Phys. Rev. Letts., 32, (1974) 1067