Precision Measurement of η Radiative Decay Width via the Primakoff Effect

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Outline

1. Physics motivation
2. How do we meaure?
3. Current status

Confinement QCD

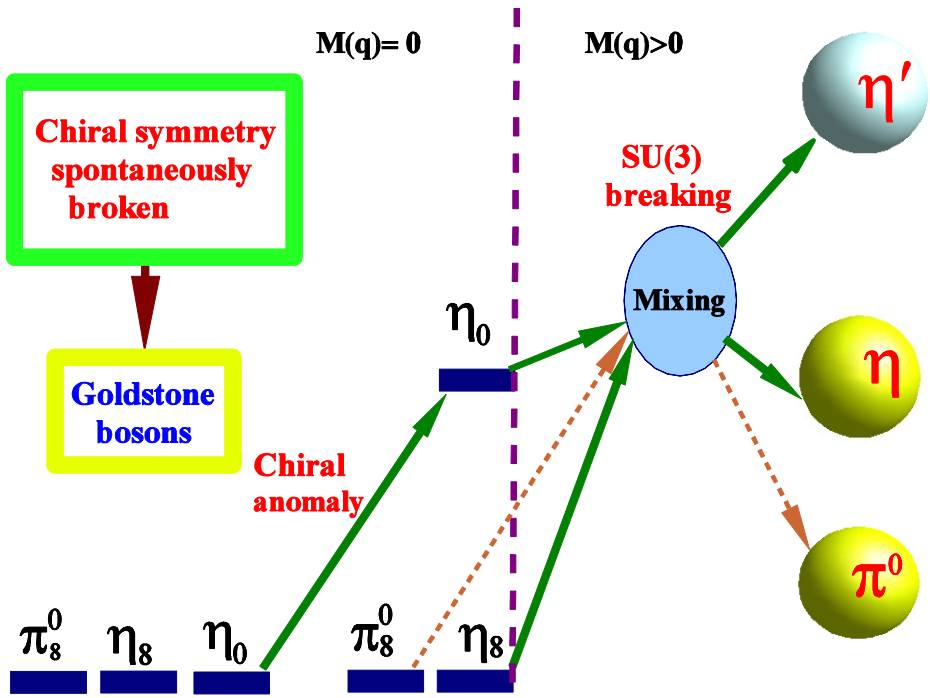
- Frontier of QCD
- Sensitive probe → symmetry test

QCD Symmetries and Light Mesons

QCD Lagrangian in Chiral limit ($m_q \rightarrow 0$) is invariant under:

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

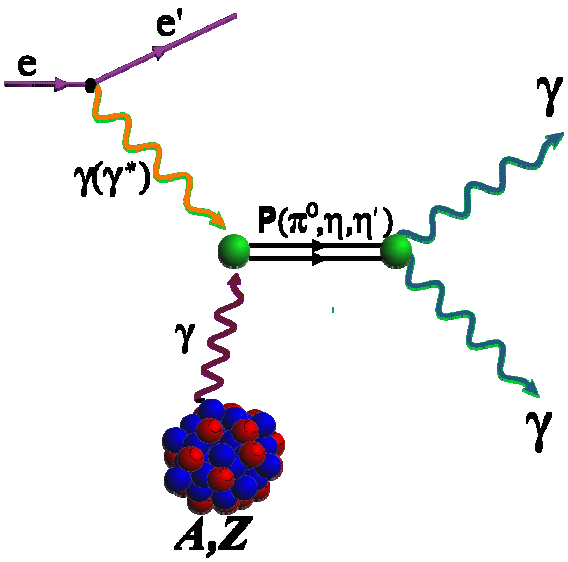
- Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously broken:
  - 8 Goldstone Bosons (π,K,η)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$, $\Gamma(\eta \rightarrow \gamma\gamma)$, $\Gamma(\eta' \rightarrow \gamma\gamma)$
  - Mass of η_0
- Massive quarks, SU(3) broken:
  - GB are massive
  - Mixing of π^0 η η'



The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

PrimEx Program at JLab

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



I. Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \rightarrow \gamma\gamma)$
3) $\Gamma(\eta' \rightarrow \gamma\gamma)$

Input to Physics:

- Test chiral symmetry and chiral anomalies
- Determine light quark mass ratio
- η-η' mixing angle

II. Transition Form Factors at low Q^2 (0.001-0.5 GeV^2/c^2):

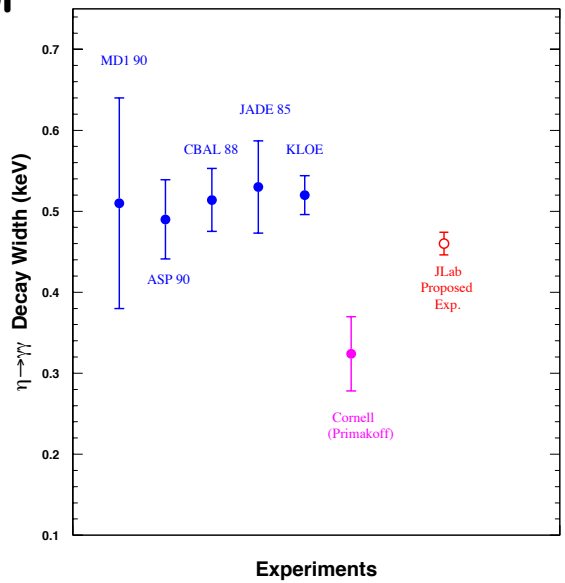
$F(\gamma\gamma^* \rightarrow \pi^0)$, $F(\gamma\gamma^* \rightarrow \eta)$, $F(\gamma\gamma^* \rightarrow \eta')$

Input to Physics:

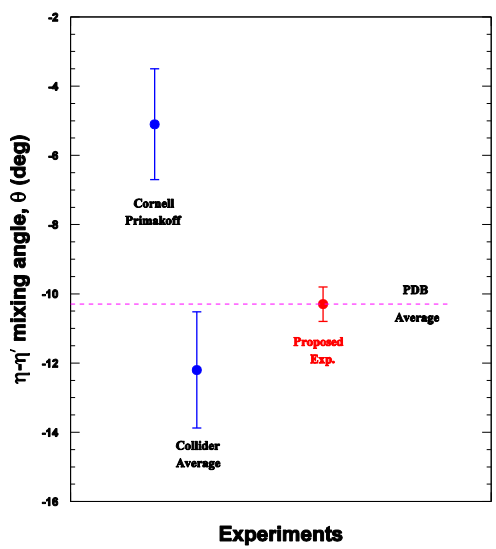
- π^0,η and η' electromagnetic interaction radii
- Is η' an approximate Goldstone boson?
- Muon g-2

Impact of $\Gamma(\eta\to\gamma\gamma)$ Measurement

1. Improve all decay widths in η-sector

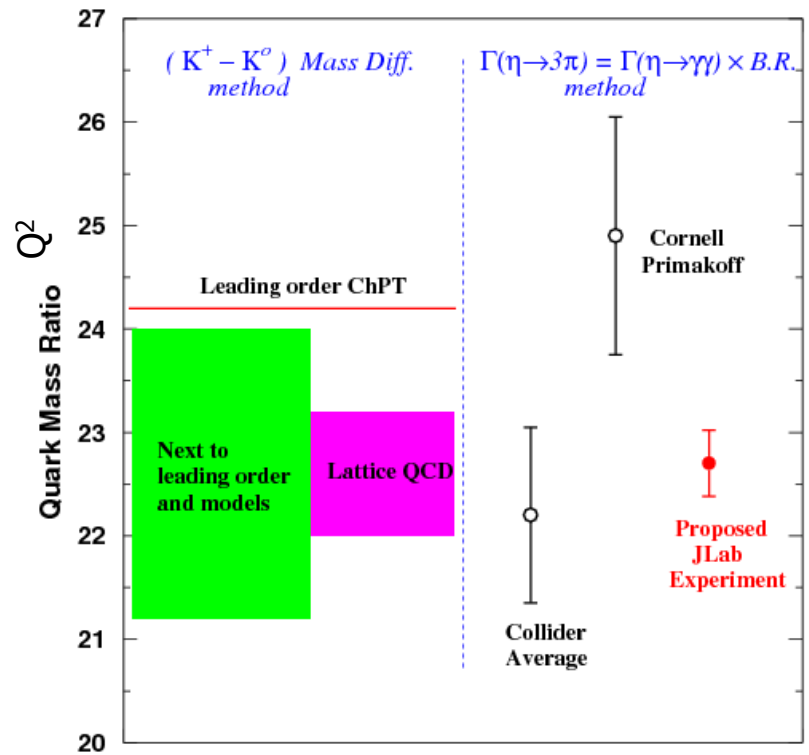


2. Extract η-η' mixing angle:



3. Determine light quark mass ratio:

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



H. Leutwyler Phys. Lett., B378, 313 (1996)

Input for Cabibbo Angle Determination

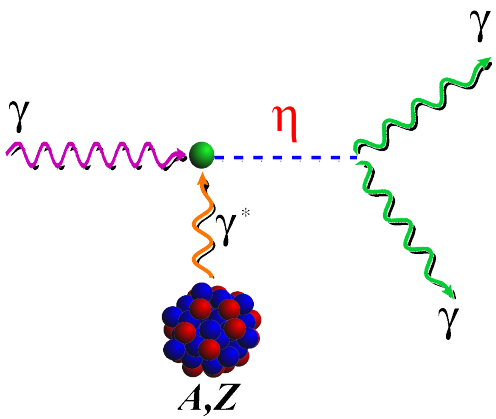
$$V_{us} = \sin(\theta_c)$$

- Light quark masses are input to extract V_{us} from kaon decays or hyperon decays.

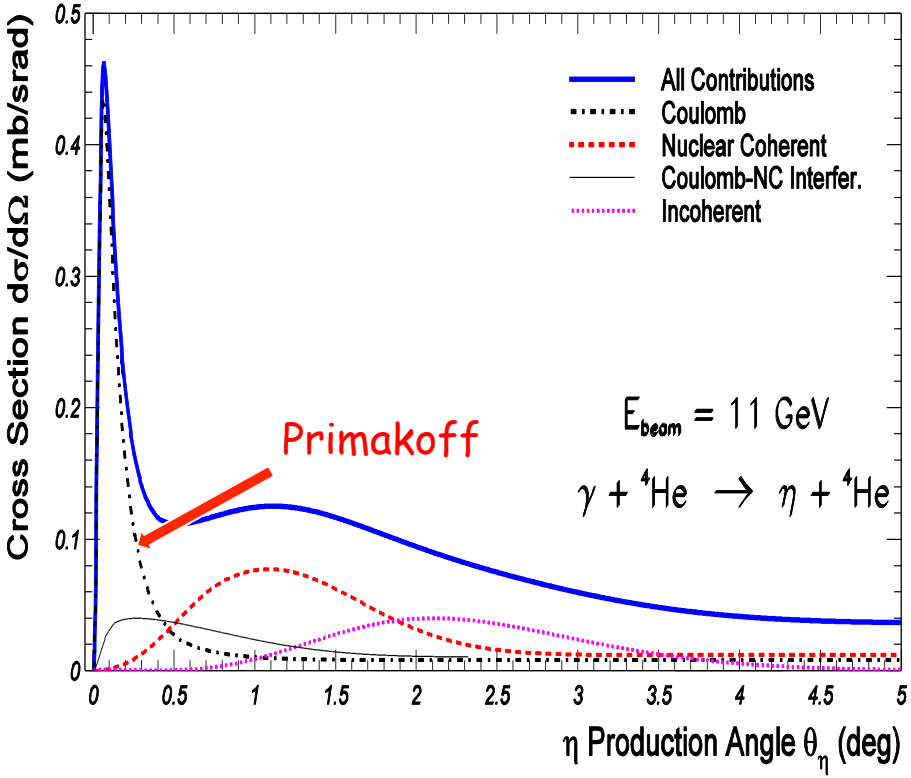
- V_{us} is a cornerstone for CKM unitarity test

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Primakoff Method



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



Requirement:

- **Luminosity**
- **Beam energy**
- **Coherency**

Features of Primakoff cross section:

- Peaked at very small forward angle

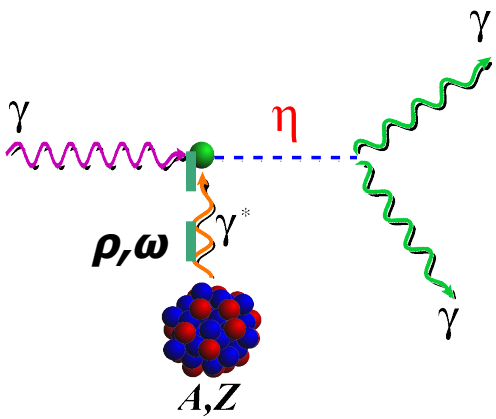
$$\langle \theta_{\Pr} \rangle_{peak} \propto \frac{m^2}{2E^2}$$

- Beam energy sensitive

$$\left\langle \frac{d\sigma_{\Pr}}{d\Omega} \right\rangle_{peak} \propto E^4, \int d\sigma_{\Pr} \propto Z^2 \log(E)$$

- Coherent process

Primakoff Method



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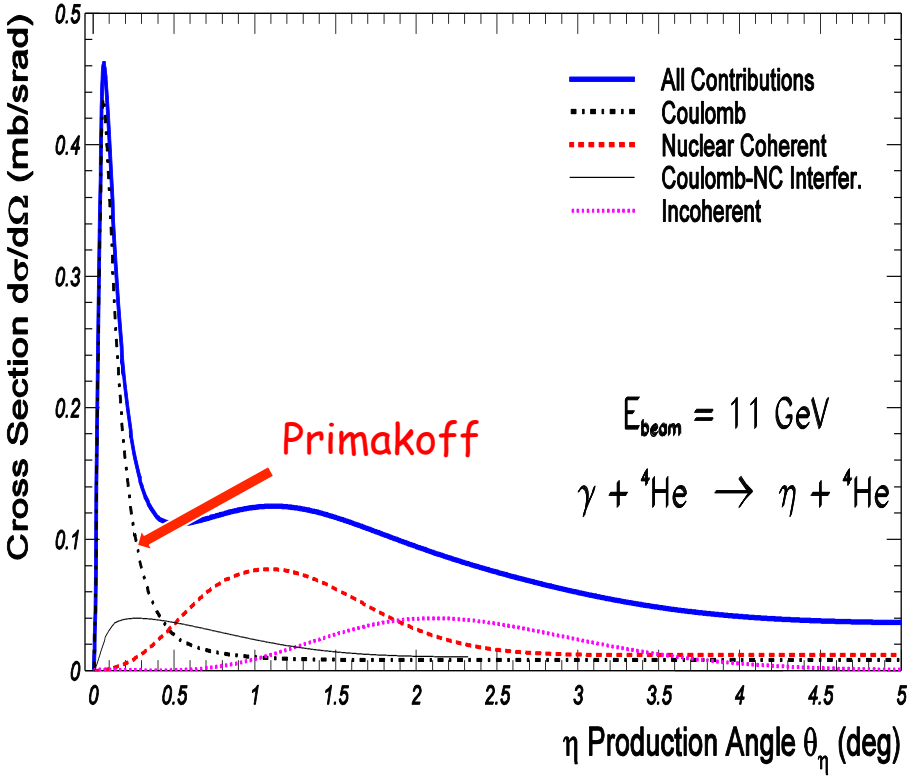

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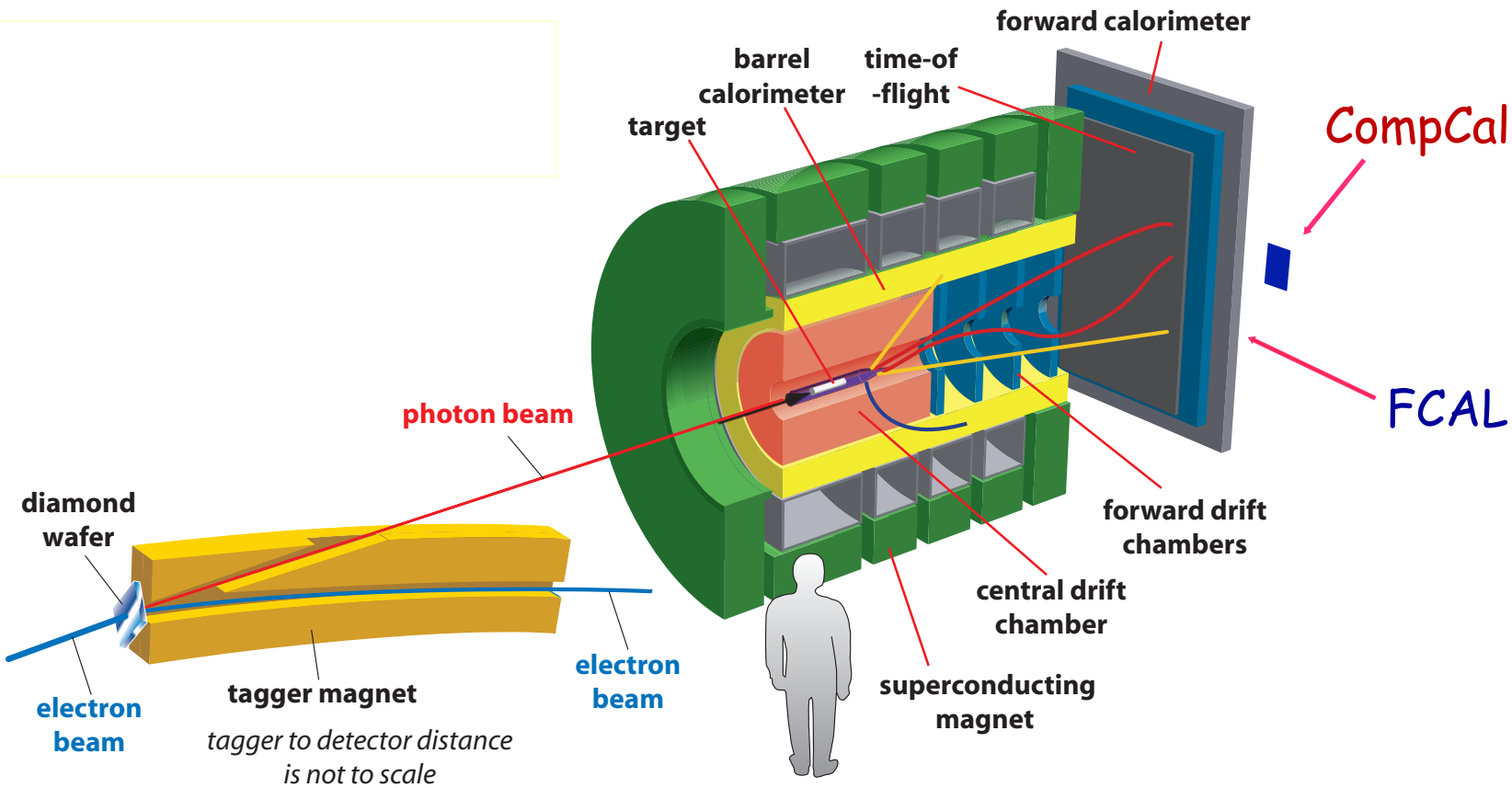
Experimental Setup in Hall D



- Tagged photon beam (~9.5-11.7 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- Liquid Hydrogen (3.5% R.L.) and ^{4}He targets (~4% R.L.)
- Forward Calorimeter (FCAL) detects the $\eta \rightarrow \gamma\gamma$ decay photons
- CompCal and FCAL to measure electron Compton scattering for control of overall systematics.

Experimental Challenges

Compared to π^0:

- η mass is a factor of 4 larger
- smaller cross section

$$\left\langle \frac{d\sigma_{\mathrm{Pr}}}{d\Omega} \right\rangle_{peak} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

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

- larger momentum transfer (coherency, form factors, FSI,…)

→

1. Higher beam energy
2. Light targets

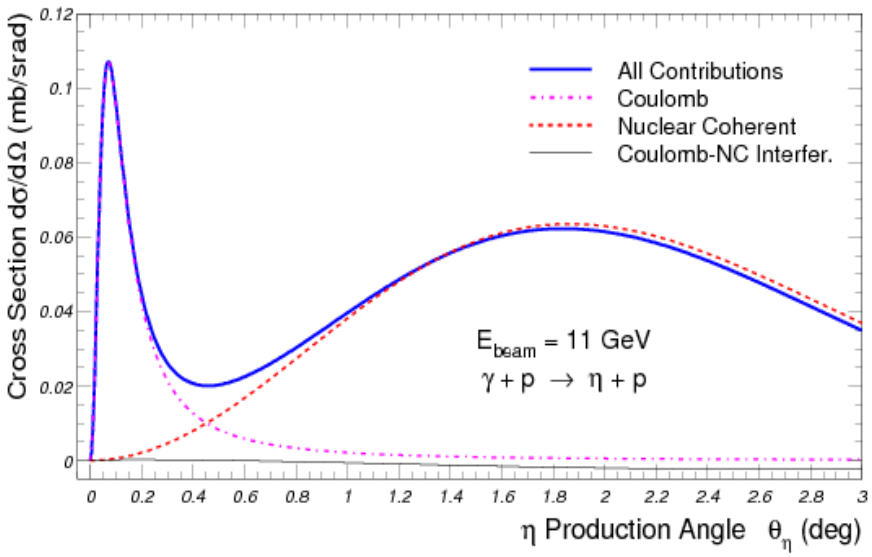
Advantage of Light Targets

Low A targets to control:

- Coherency: compact nucleus
- Separate background

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

- Well known form factors

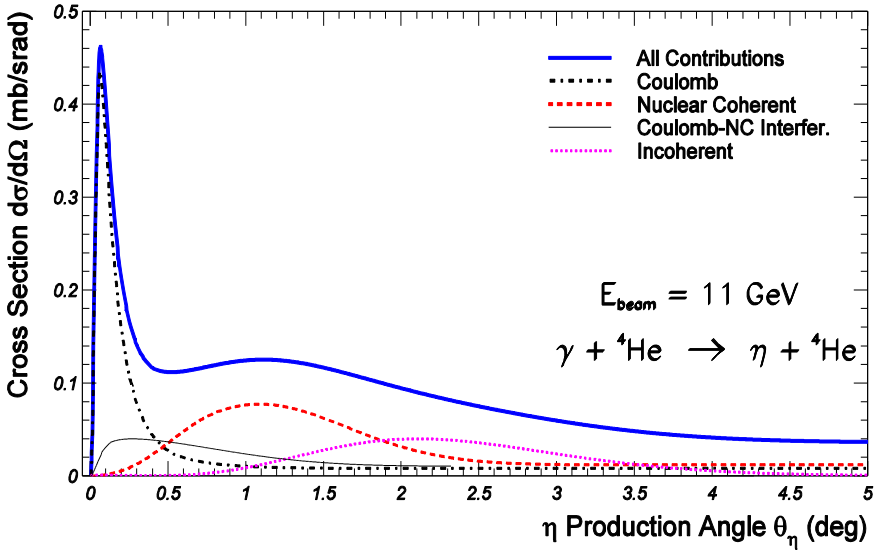


Hydrogen:

- No inelastic hadronic contribution
- No nuclear final state interactions

^{4}He:

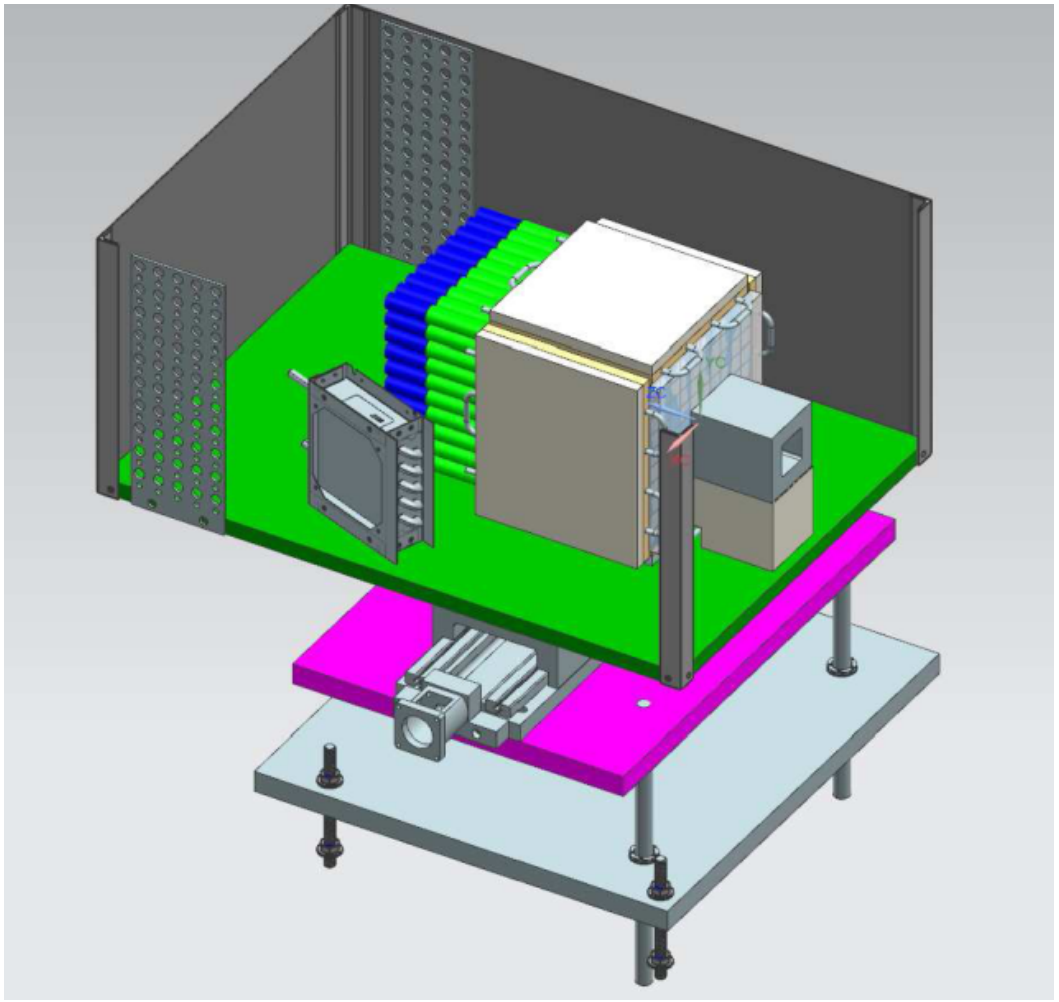
- Higher Primakoff cross section: $\sigma_{\mathrm{Pr}} \propto Z^2$

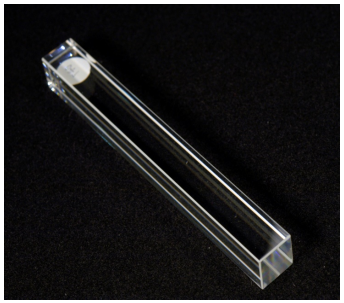


Current Status

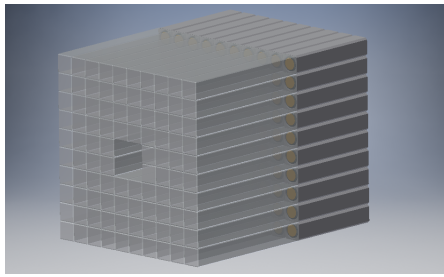
- Recently passed the Experiment Readiness Review and is recommended for 2018 beam request.
- CompCal Calorimeter
- Liquid ^{4}He target

CompCal Calorimeter





2.05x2.05x20 cm^3

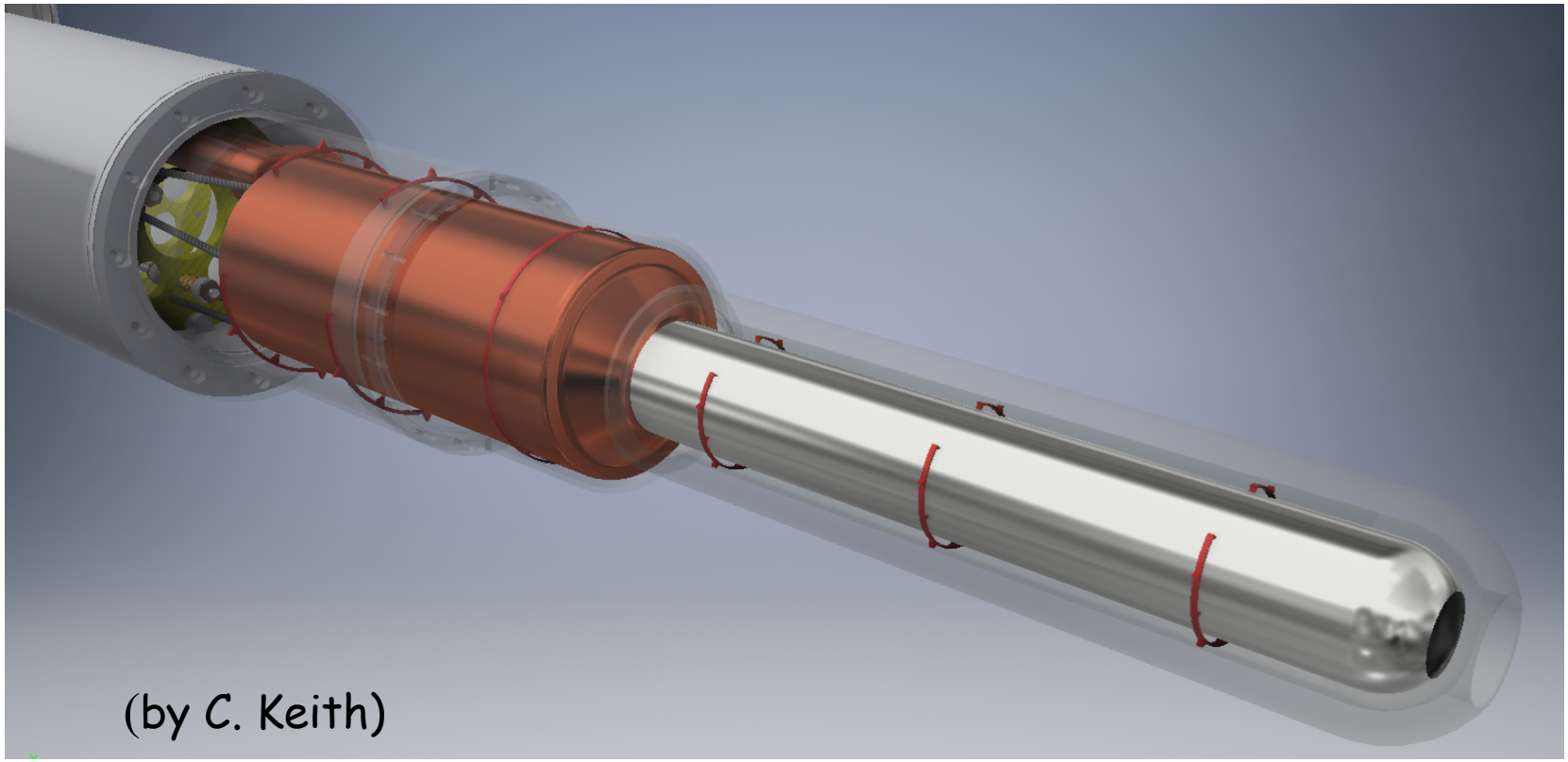


1. 96 of PWO crystal modules coupled to Hamamatsu R4125HA PMTs (from NPS in Hall C)

2. Central 2x2 crystals are removed for beam to pass through

- Engineering design is done
- Calorimeter will be ready by Aug 2018.

Liquid ^{4}He Target



The existing cryotarget in Hall D with a new, two-piece heat shield:

- A 0.75 mm copper upstream of target cell
- A 0.25 mm aluminum surrounding the cell

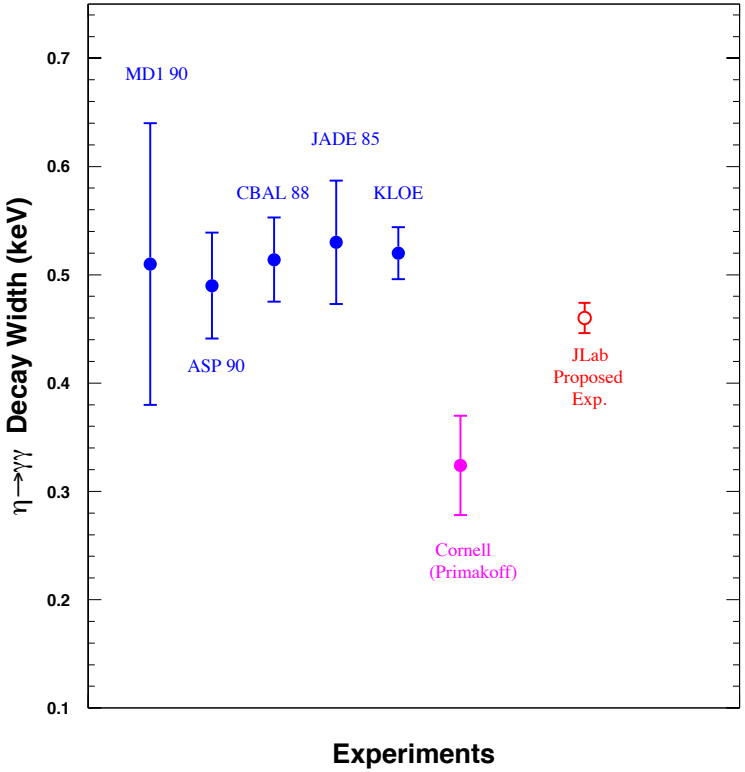
Beam Time

	Days
Setup calibration, checkout	2
Tagger efficiency, TAC runs	1
Liquid ^{4}He target run	30
LH_2 target run	40
Empty target run	6
Total	**79**

Estimated Error Budget

Systematical uncertainties:

Contributions	Estimated Error
Luminosity	1.2%
Background subtraction	2.0%
Event selection	1.7%
Acceptance and misalignment	0.5%
Beam energy	0.2%
Detection efficiency	0.5%
Branching ratio (PDG)	0.51%
Total Systematic	**3.0%**



Total uncertainty:

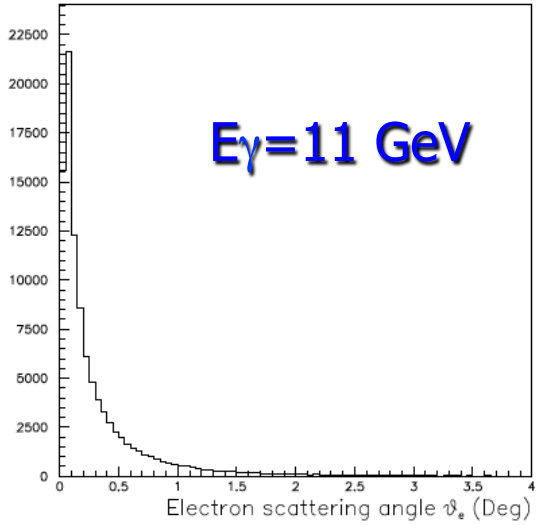
Statistical	1.0%
Systematic	3.0%
Total	**3.2%**

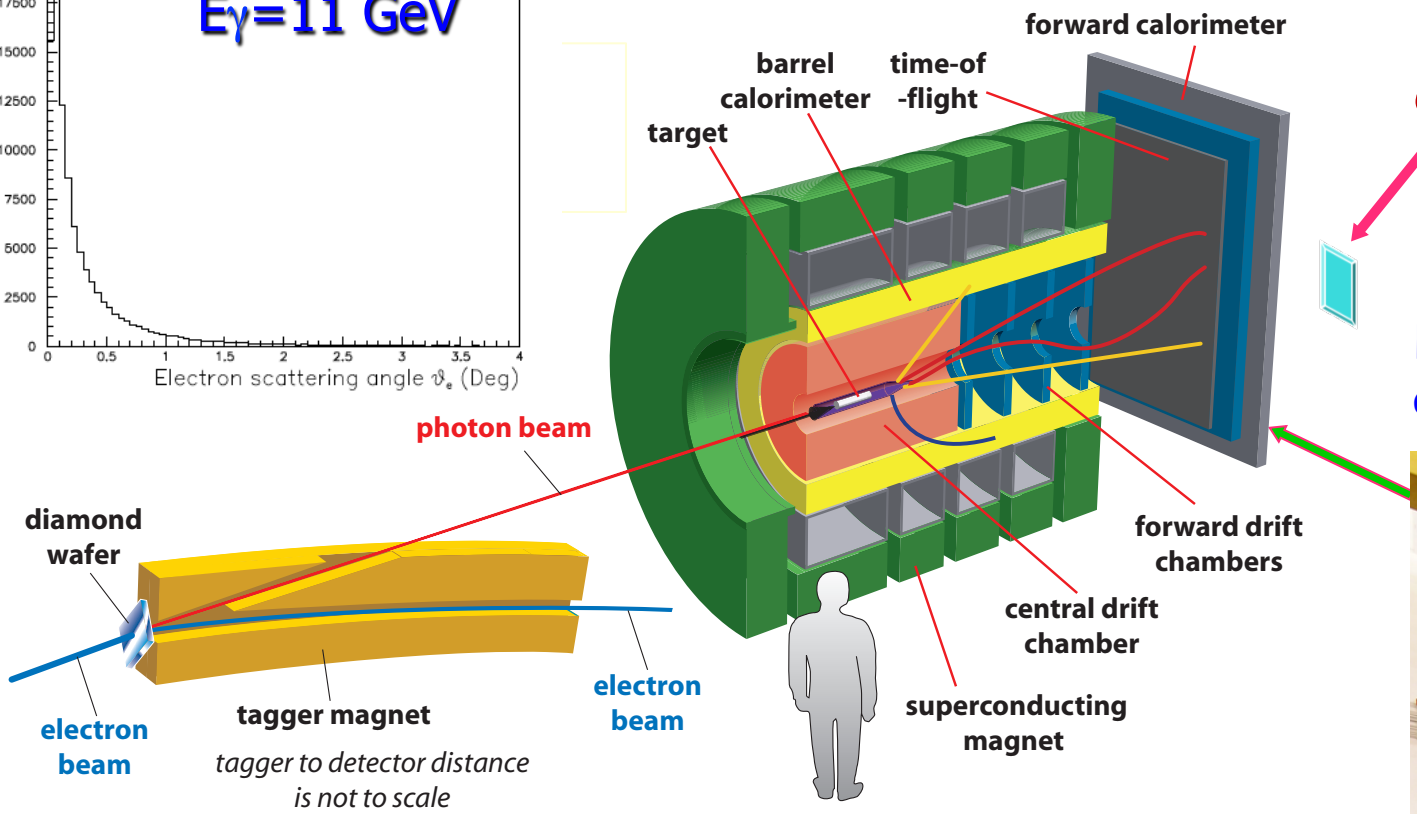
Summary

- A precision measurement of $\Gamma(\eta \rightarrow \gamma\gamma)$ is developed.
- Experiment is preparing to run in 2018.
- Physics impact:
  - Improve all decay widths in the η-sector of PDG
  - Quark mass ratio
  - Mixing angle of η-η'
  - Input for V_{us} determination and CKM unitarity test

This project is supported by NSF PHY-1506303 award.

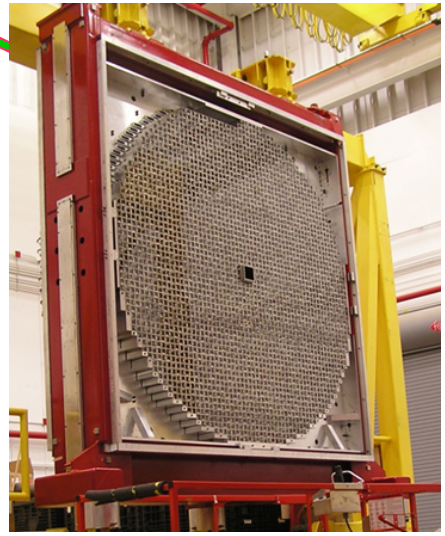
Control Systematics with Compton Scattering ($\gamma+e\rightarrow\gamma'+e'$)





CompCal

FCAL has no acceptance for $\theta < 1^{o}$

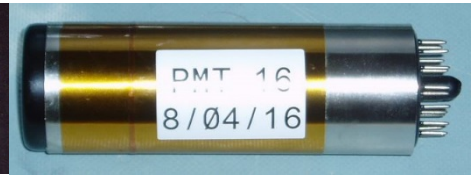


CompCal is needed for systematics control:

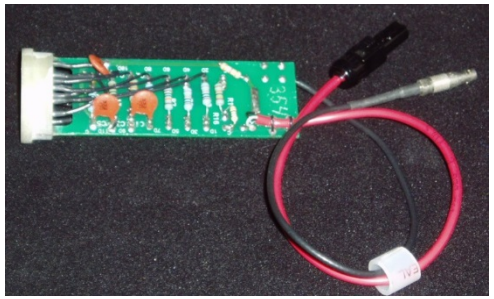
- Luminosity
- Monitoring the experimental stability

CompCal Prototype (25 lead glass assembly)

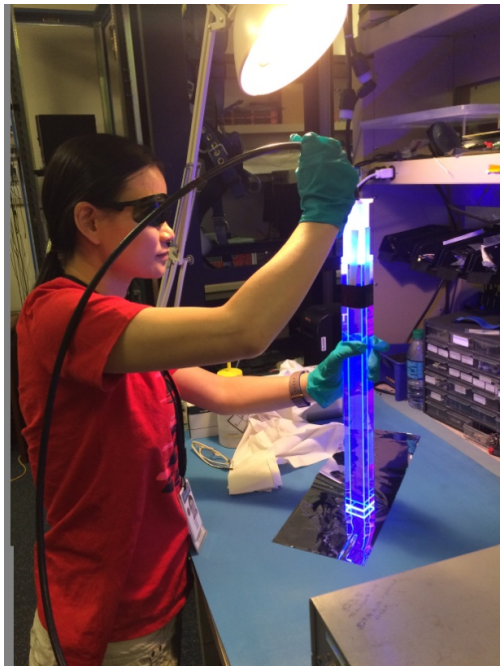
lead glass (4 cm x 4 cm x 45 cm)

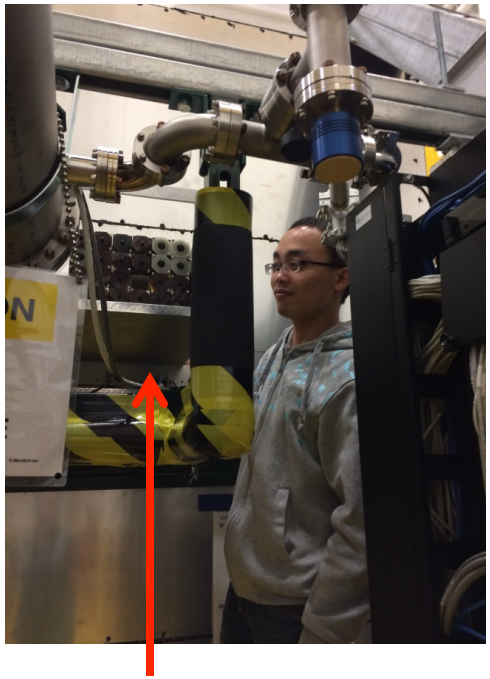


FEU 84 PMT



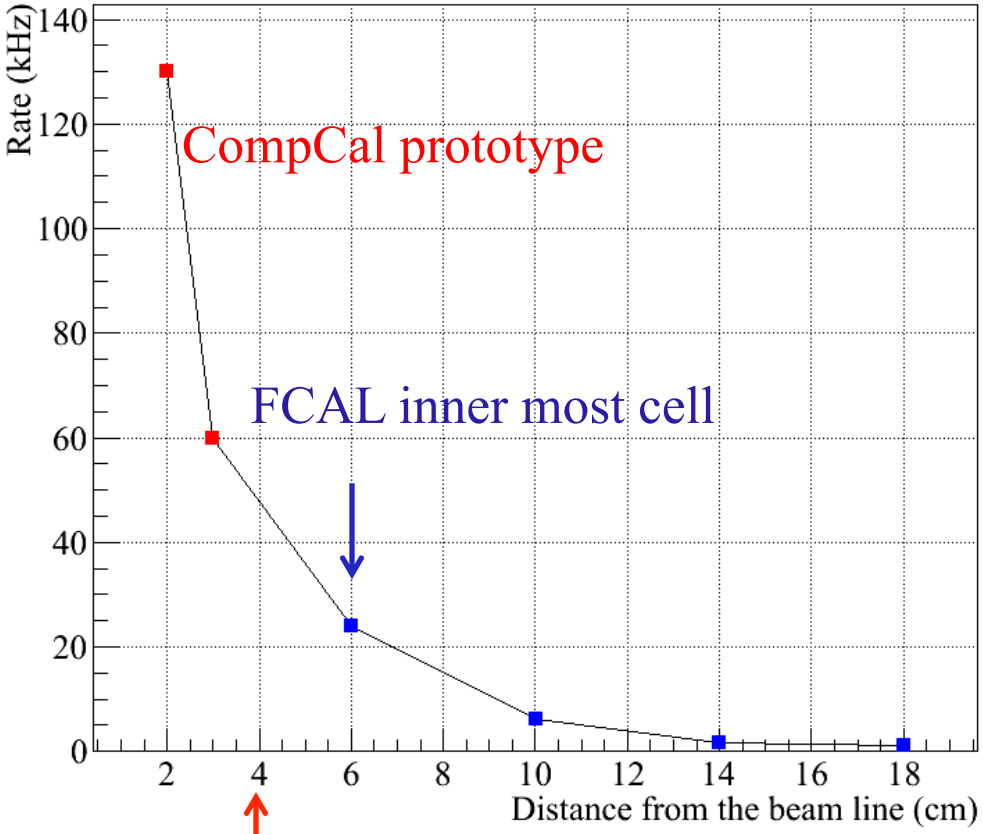
HyCal divider (passive)





Prototype assembly

CompCal Prototype Beam Test Result



Active area of CompCal
(4 cm from the beam)

- Measure counter rate at different distances from the beam line.

  - use the same thresholds as FCAL
  - magnetic field was turned on
  - CompCal was not calibrated

- Estimated rate of the CompCal (PWO) counter $R \leq R^{FCAL}_{INNER}$