Primakoff Measurements of π^0, η, η' at JLab

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Outline

1. Introduction: low-Energy QCD symmetries and properties of light pseudoscalar mesons

2. Primakoff measurements of π^0, η, η':

   - Two-photon decay widths $\Gamma(P\rightarrow\gamma\gamma)$
   - Transition form factors $F(\gamma^*\gamma\rightarrow P)$

3. Summary

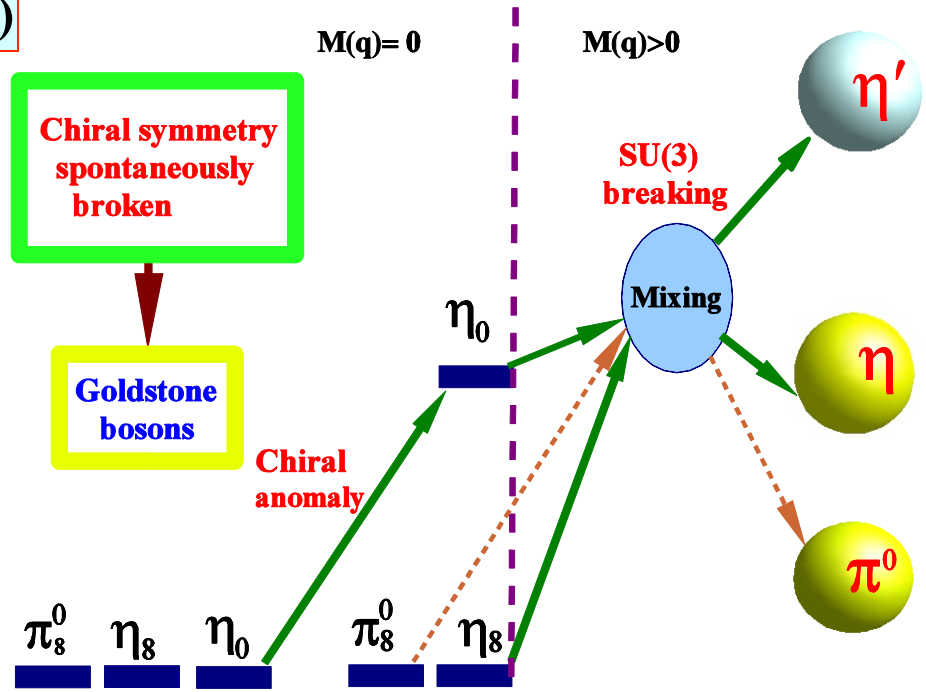
Thank to NSF for support of PHY-1812396

Low-Energy QCD Symmetries and Light Mesons

- **QCD Lagrangian in Chiral limit ($m_q \to 0$) 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 breaks to $SU(3)$**
  - 8 Goldstone Bosons (GB)
- **$U_A(1)$ is explicitly broken: (Chiral anomalies)**
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- **$SU_L(3) \times SU_R(3)$ and $SU(3)$ are explicitly broken:**
  - GB are massive
  - Mixing of π^0, η, η'



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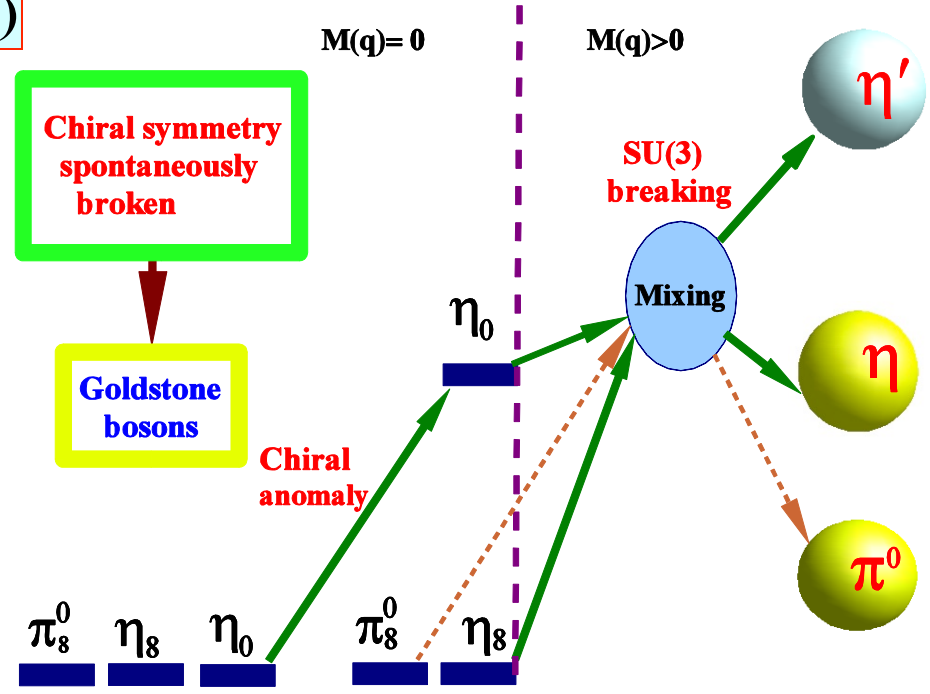
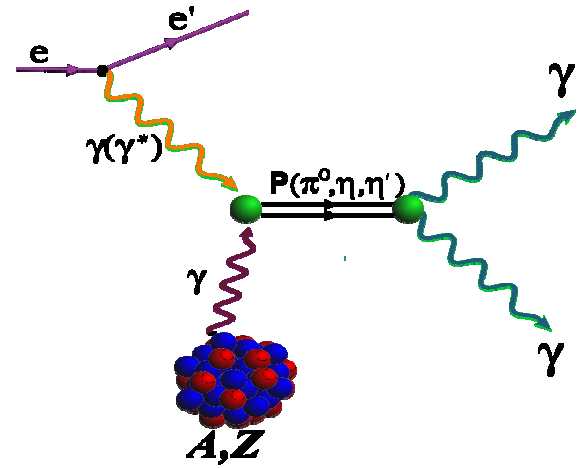


The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

Primakoff Program at JLab 6 & 12 GeV

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



a) 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:

- precision tests of Chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle

b) Transition Form Factors at Q^2 of 0.001-0.5 GeV^2/c^2:

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

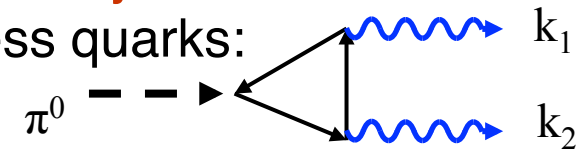
Input to Physics:

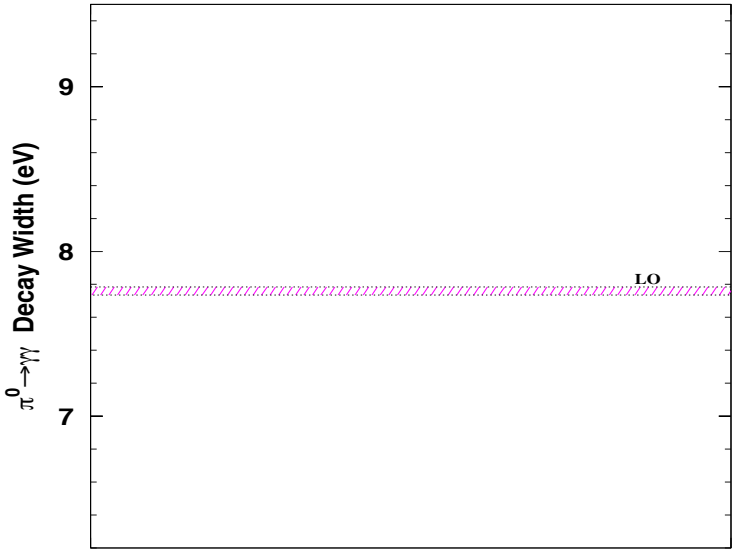
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$

Axial Anomaly Determines π^0 Lifetime

- $\pi^0 \rightarrow \gamma\gamma$ decay proceeds primarily via the chiral anomaly in QCD.
- The chiral anomaly prediction is exact for massless quarks:

$$\Gamma\left(\pi^0 \rightarrow \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.750 \pm 0.016\ eV$$





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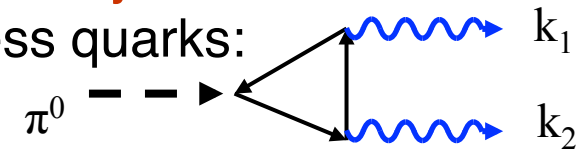

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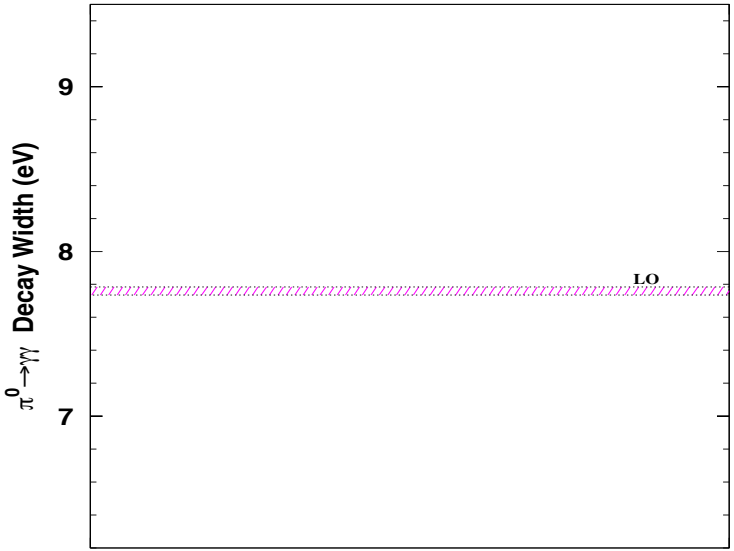

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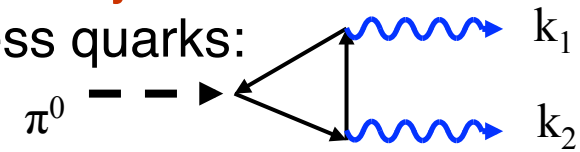

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    Calculations in NLO ChPT:

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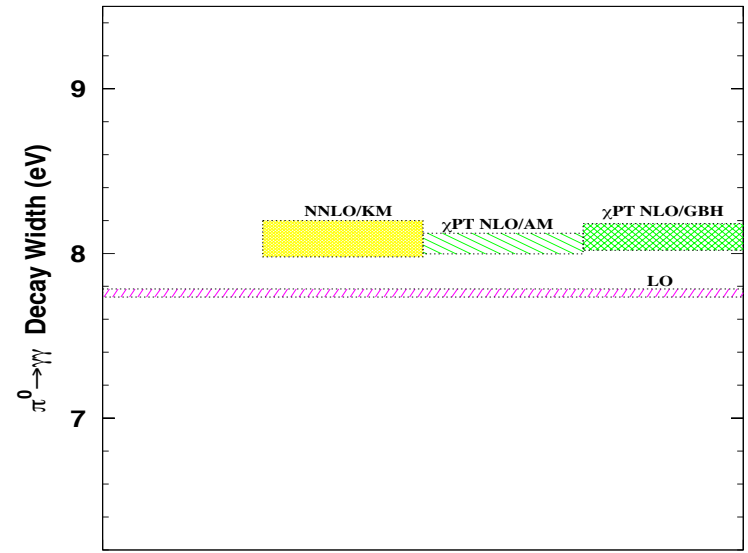

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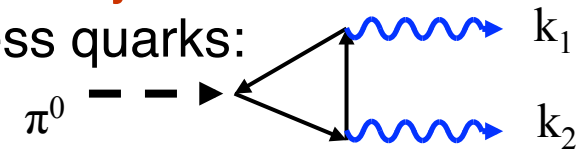

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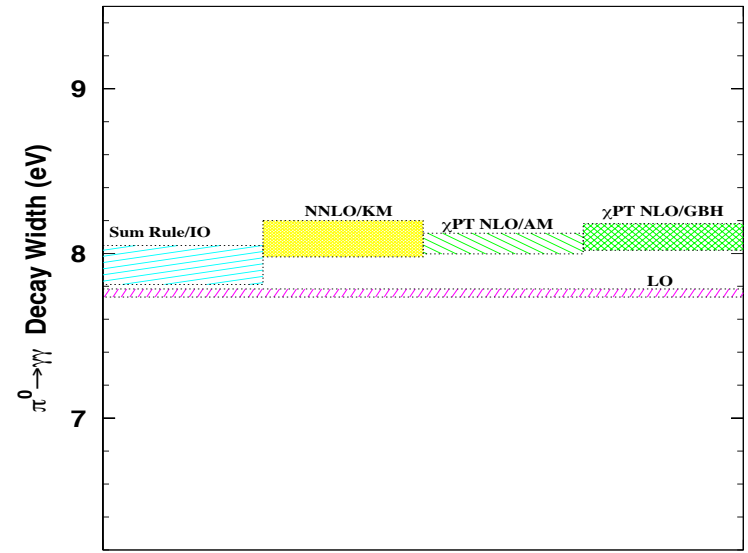

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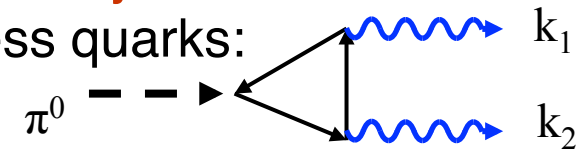

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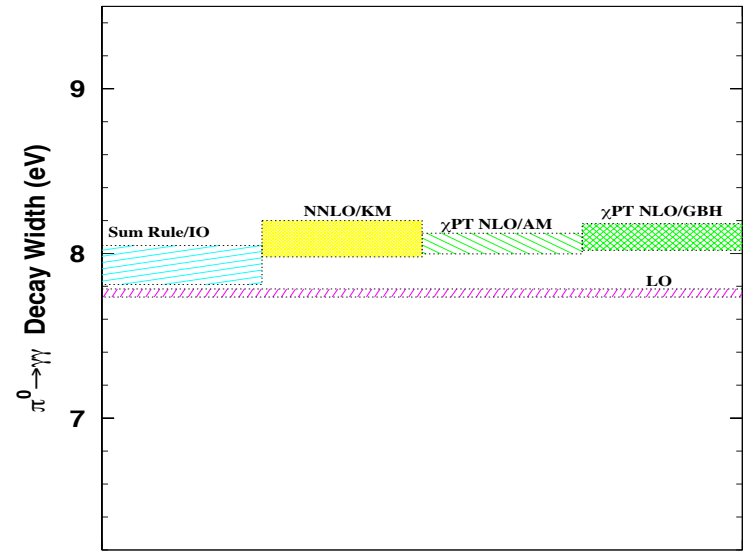

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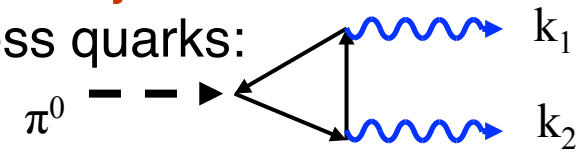

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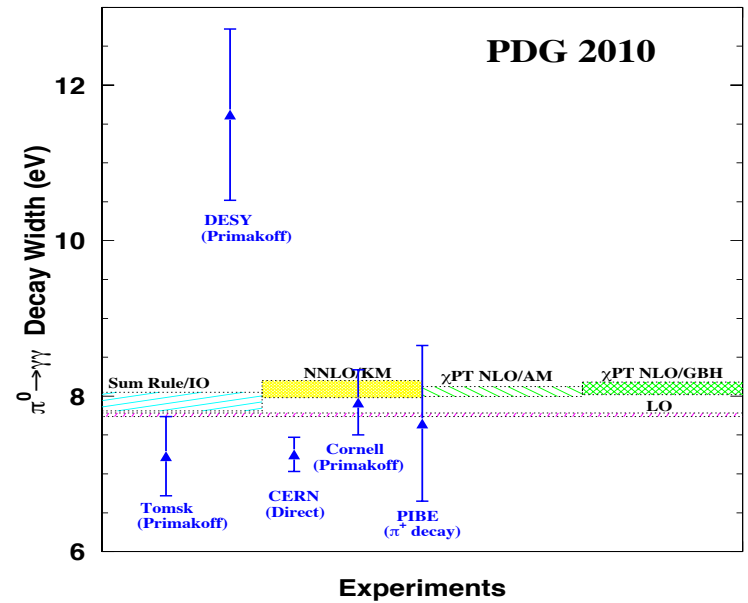

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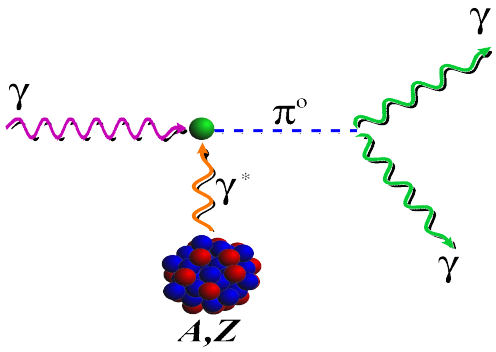
Primakoff Method



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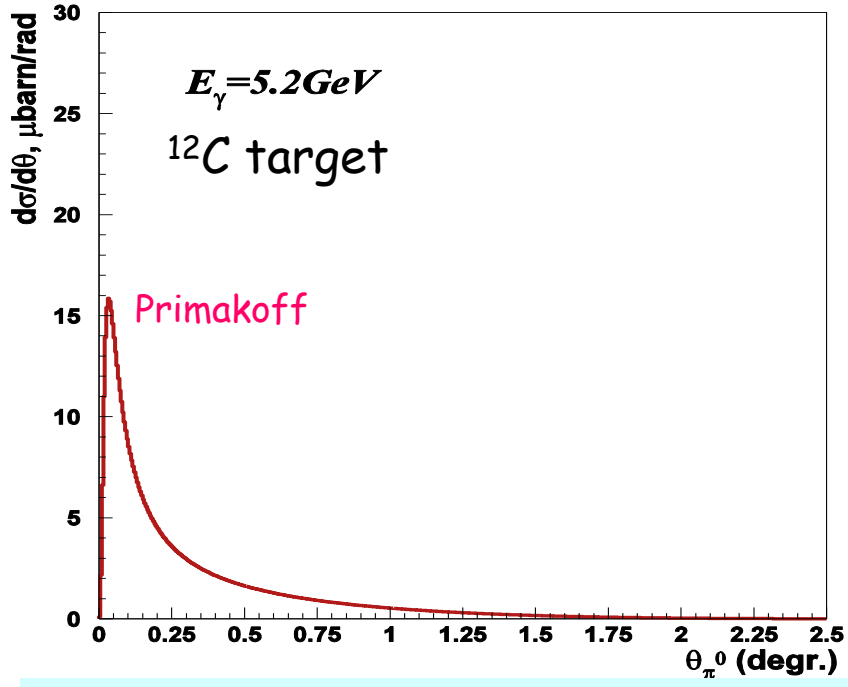

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- Beam energy sensitive:

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

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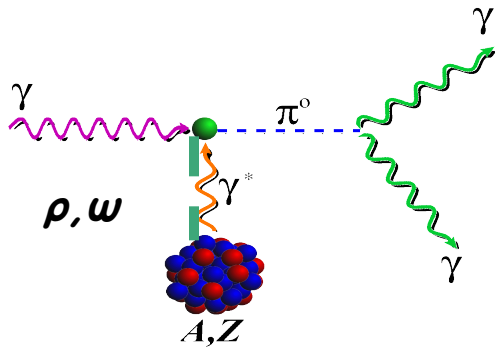

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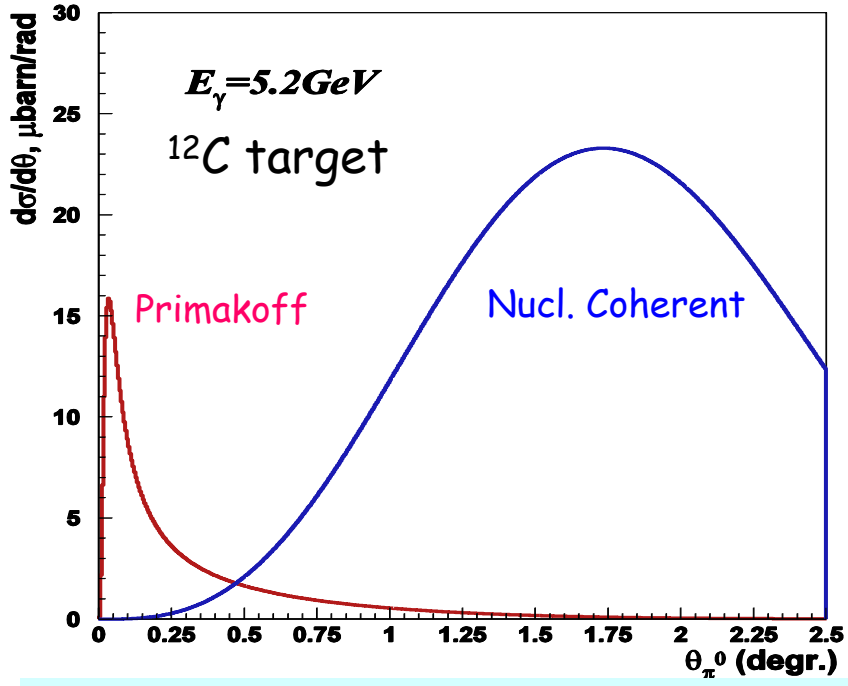

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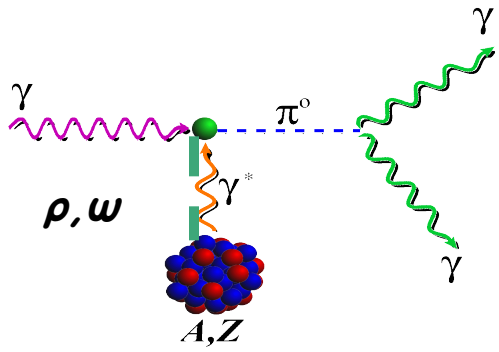

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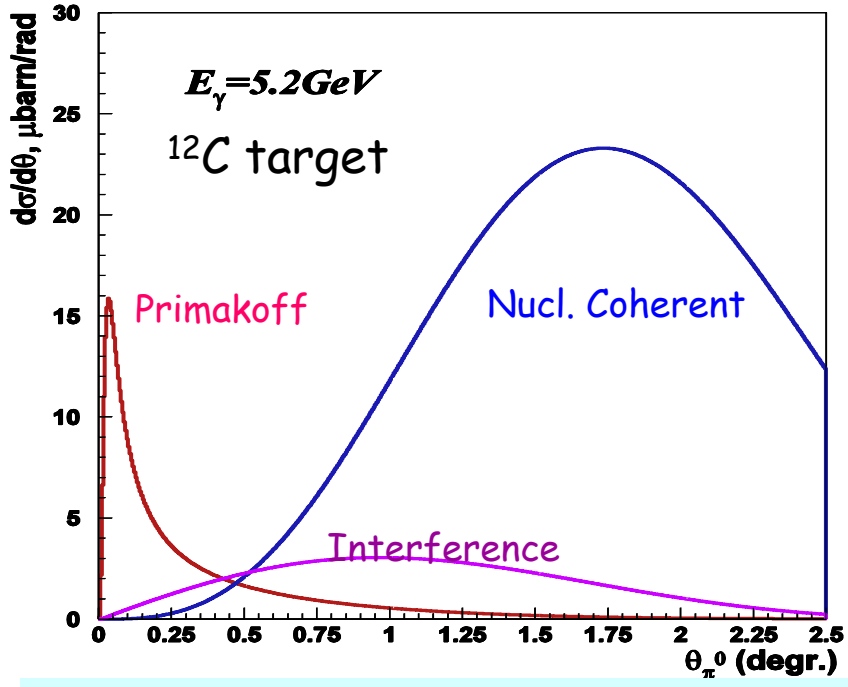

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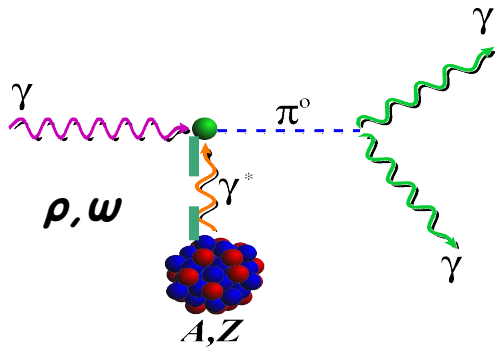

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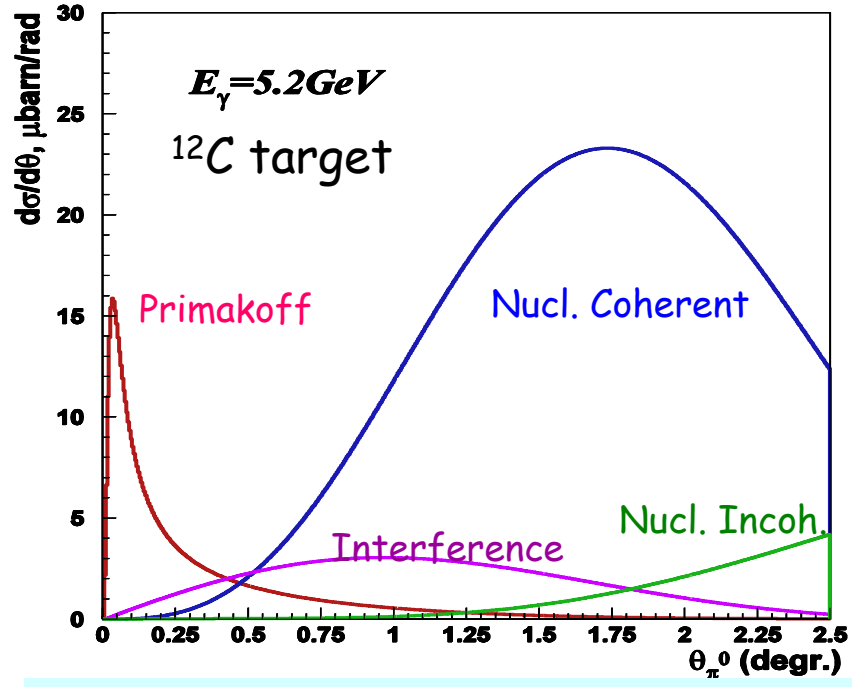

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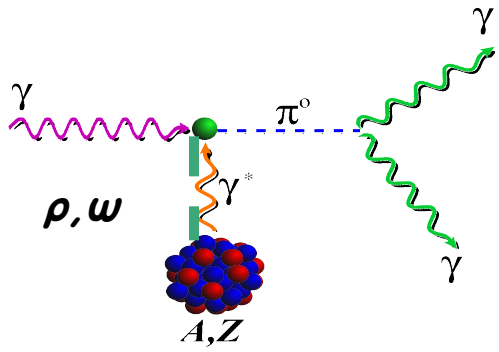

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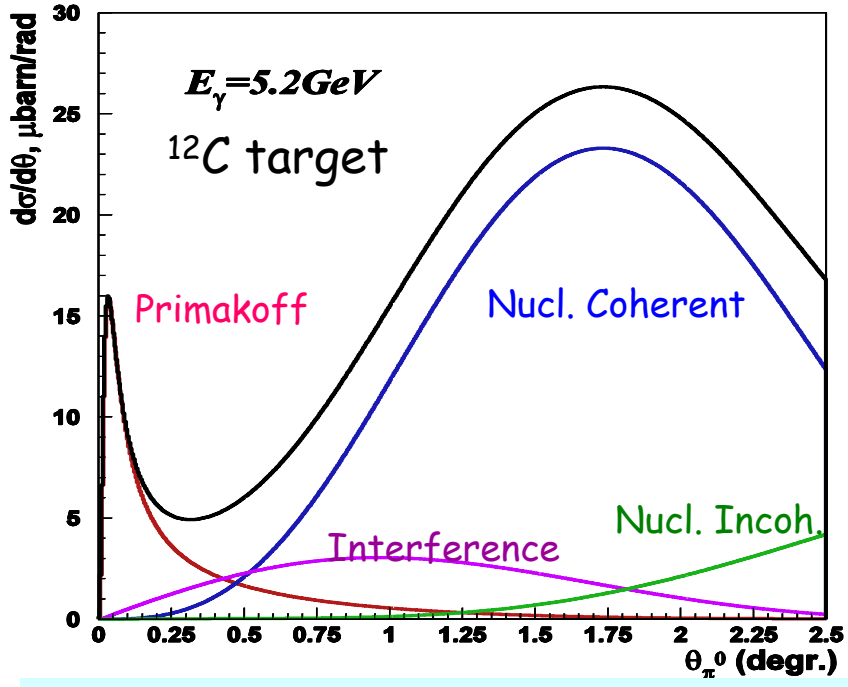
Challenge: Extract the Primakoff amplitude



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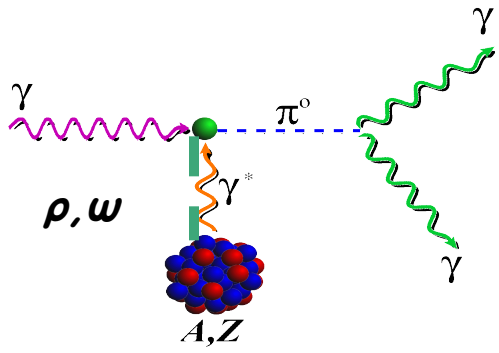

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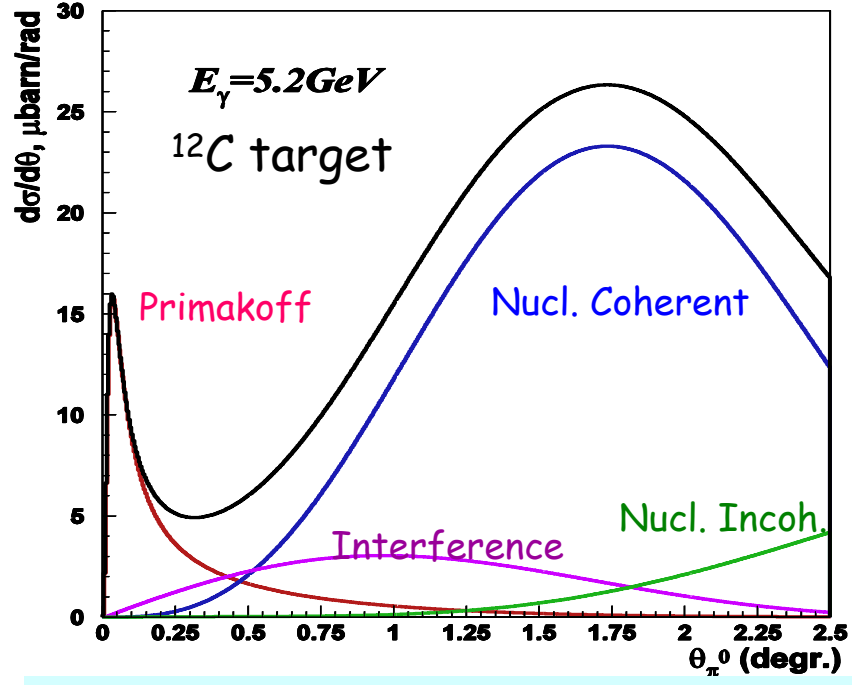

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Requirement:

- **Photon flux**
- **Beam energy**
- **π^0 production angle resolution**
- **Compact nuclear target**

- Peaked at very small forward angle

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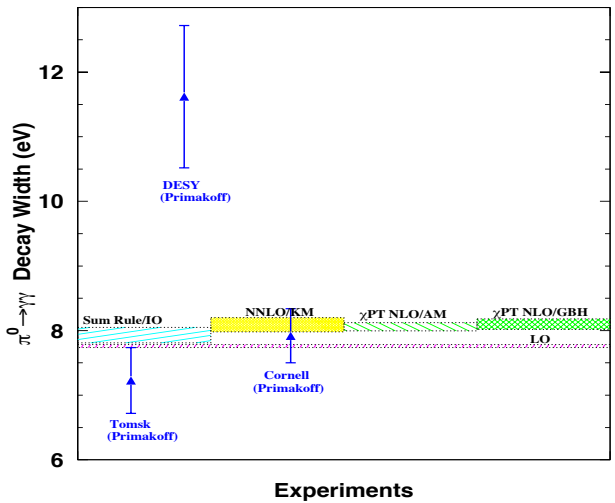
Previous Primakoff Experiments

- DESY (1970) (N.C.,66A,243)
  Untagged bremsstrahlung beam,
  $E\gamma$: about 1.5 and 2.5 GeV
  Targets: C, Zn, Al, Pb
  Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$=(11.7±1.2) eV (10%)
- Tomsk (1970) (Sov.Phys.JETP,30, 1037)
  Untagged bremsstrahlung beam
  $E\gamma$~1.1 GeV
  Target: Pb
  Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$=(7.23±0.51) eV (7.1%)
- Cornell (1974) (PRL,33,1400)
  Untagged bremsstrahlung γ beam
  $E\gamma$: about 4 and 6 GeV
  Targets: Be, Al, Cu, Ag, U
  Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$=(7.92±0.42) eV (5.3%)

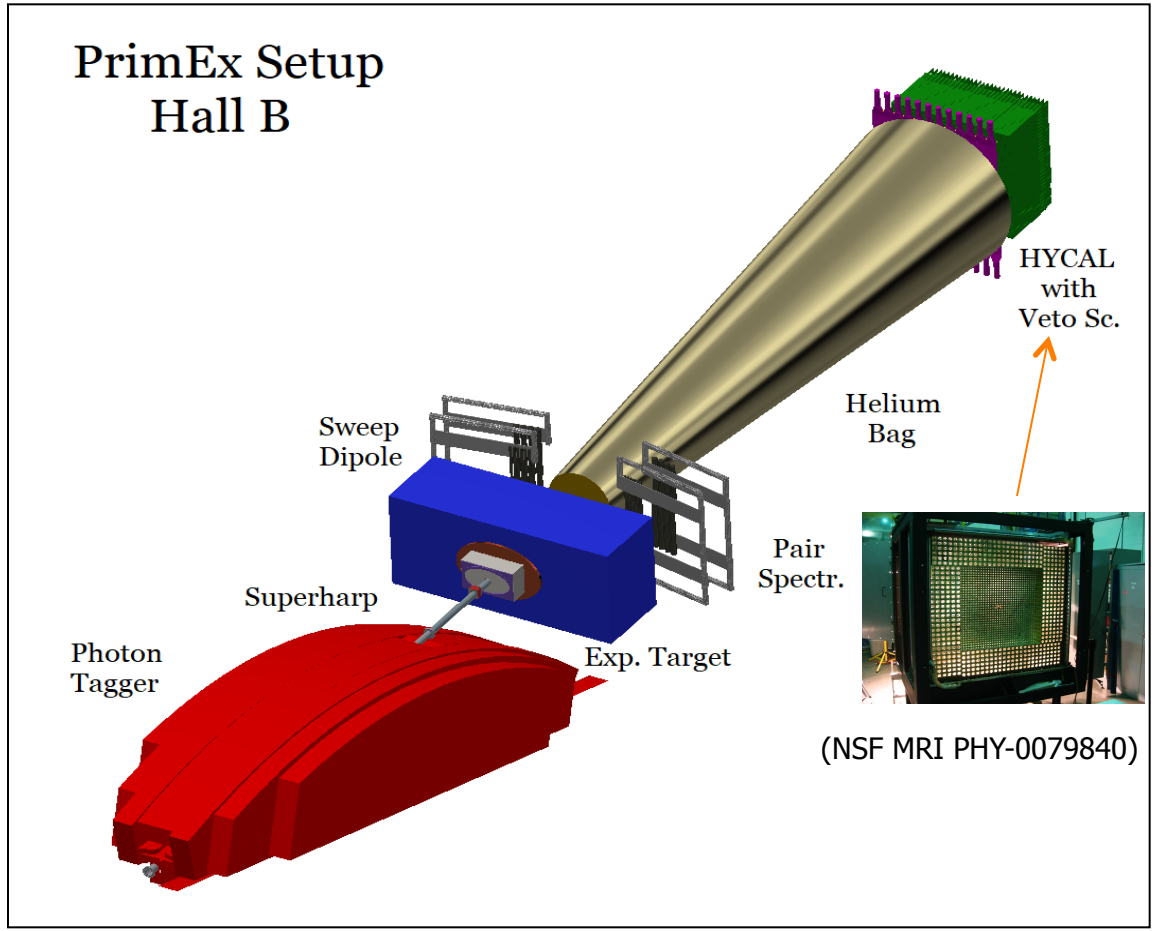


All these experiments used

1. Untagged bremsstrahlung photon beam
2. Conventional Pb-glass calorimeter
3. Earlier theoretical calculations

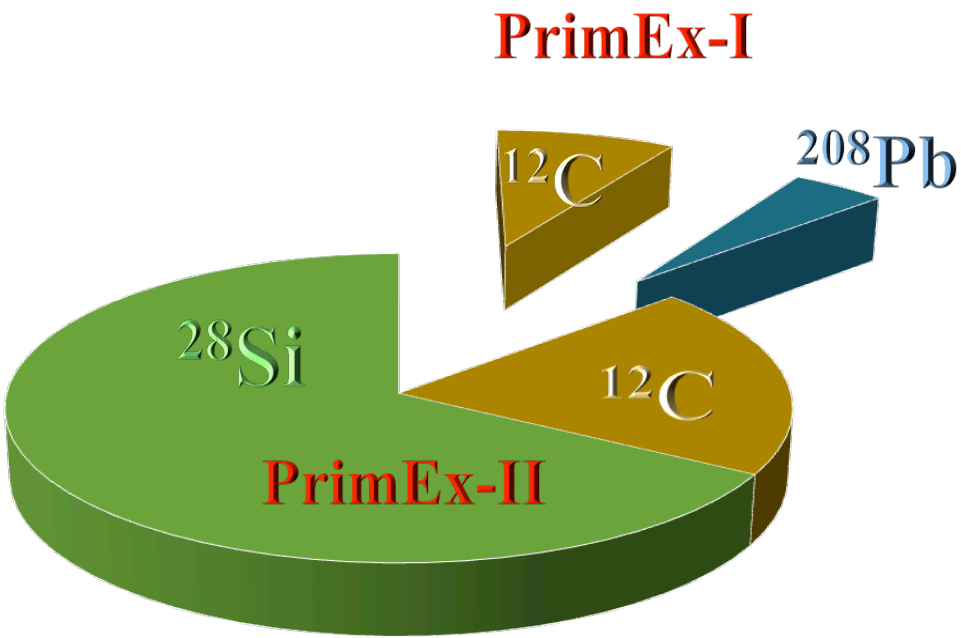
PrimEx Experimental Setup in Hall B

- Hall B high resolution, high intensity photon tagging facility
- A pair spectrometer for photon flux control at high beam intensities
- New high resolution hybrid multi-channel calorimeter (HyCal)



(NSF MRI PHY-0079840)

Two Experiments on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$: PrimEx I & II



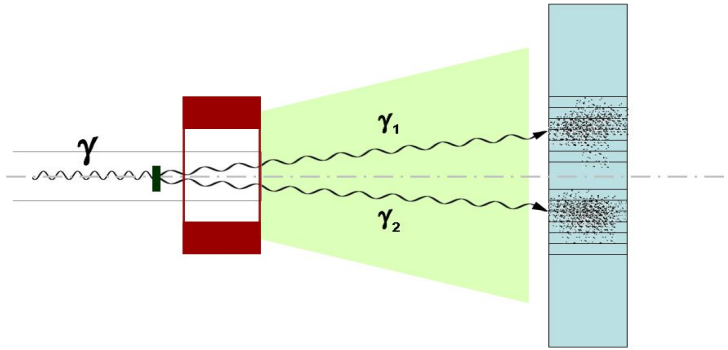
- PrimEx I was performed on ^{12}C and ^{208}Pb targets Published in 2011.
  PRL 106, 162303 (2011)

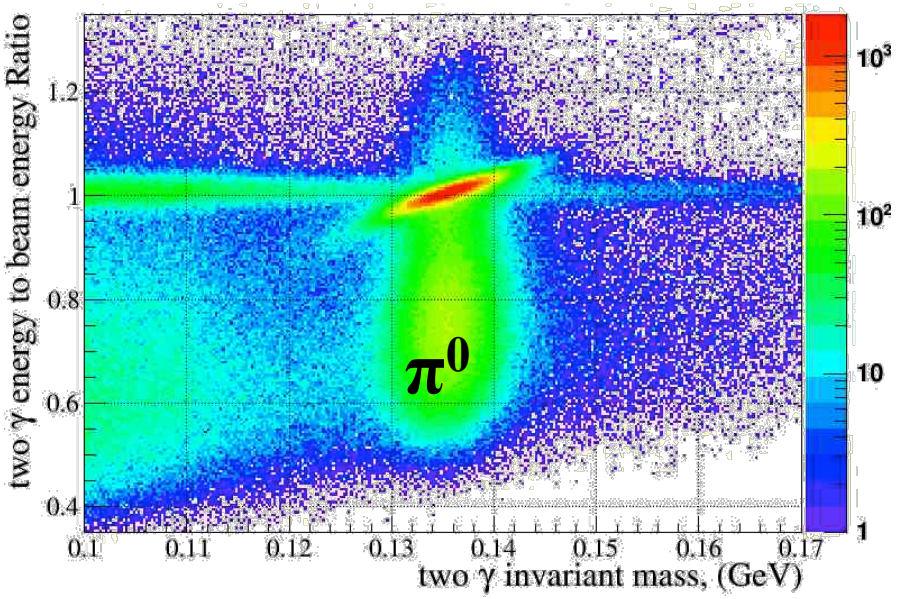
- PrimEx II was performed on ^{12}C and ^{28}Si targets. Published in 2020
  Science 368, 506 (2020)

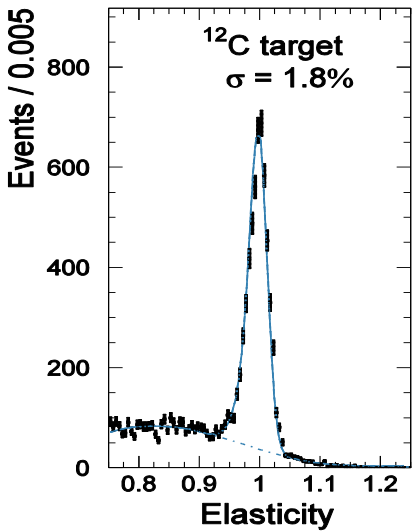
π^0 Event selection

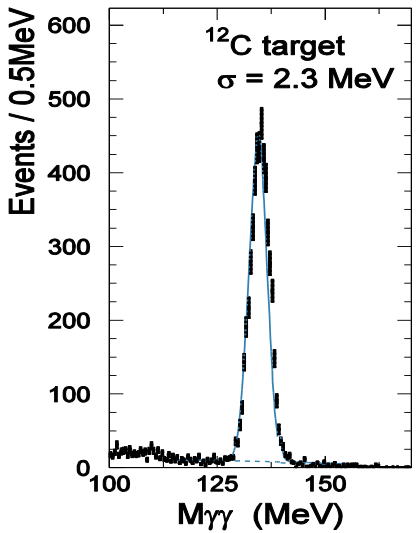
We measure:

- incident photon: $E\gamma$ and time
- Two decay photons:
  - $E\gamma_1$, $E\gamma_2$ and time
  - X,Y positions of decay photons





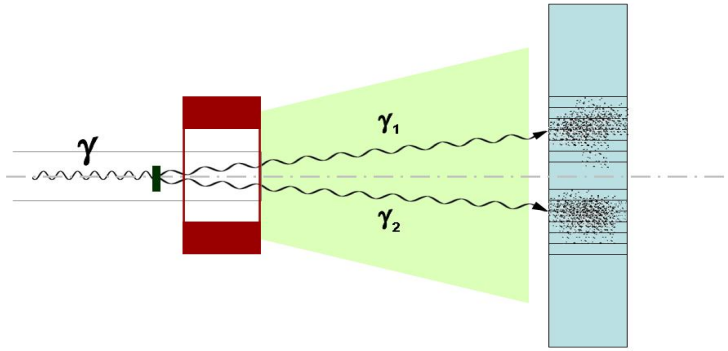


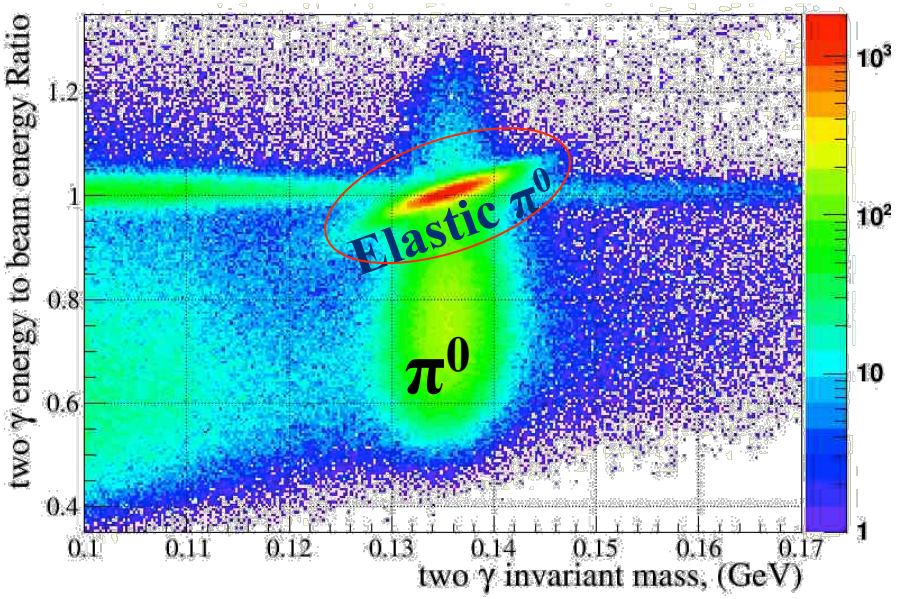


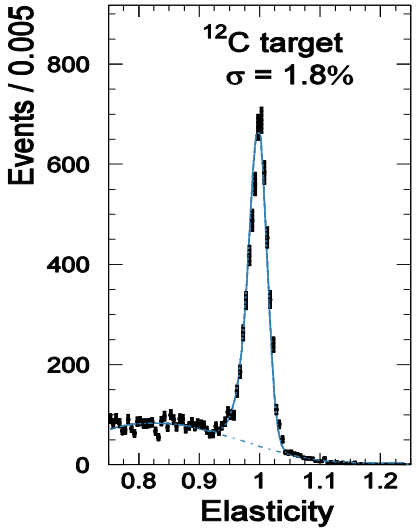
π^0 Event selection

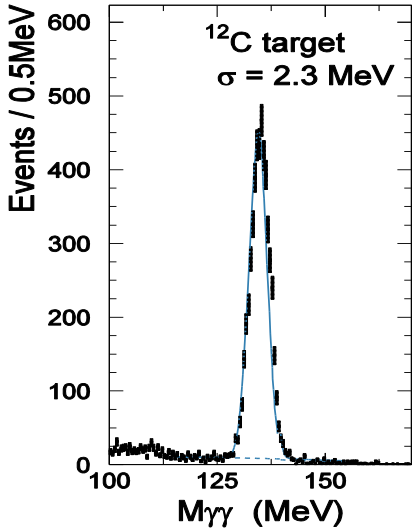
We measure:

- incident photon: $E\gamma$ and time
- Two decay photons:
  - $E\gamma_1$, $E\gamma_2$ and time
  - X,Y positions of decay photons





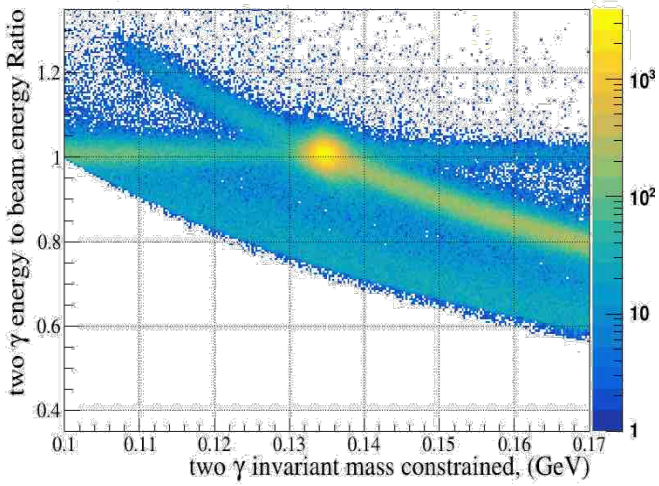


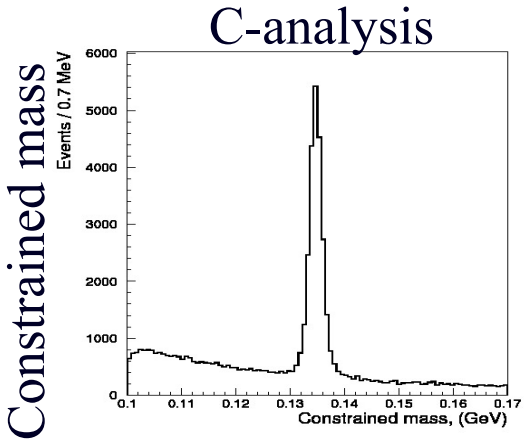


Two Methods for π^0 yield extraction

- **Energy Constrained mass analysis (C)**

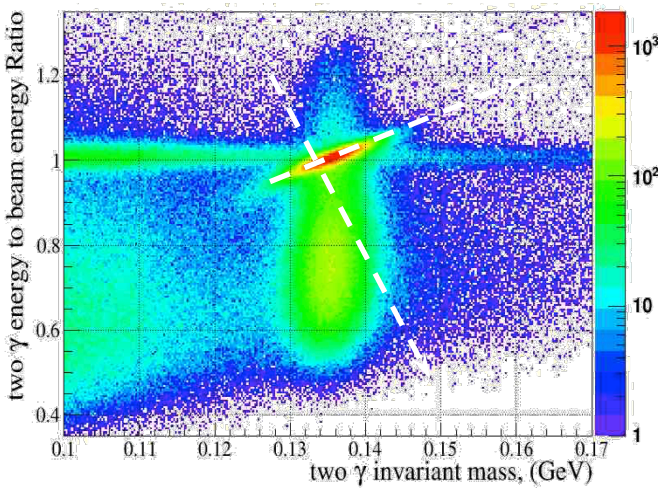
  by I. Larin, Umass

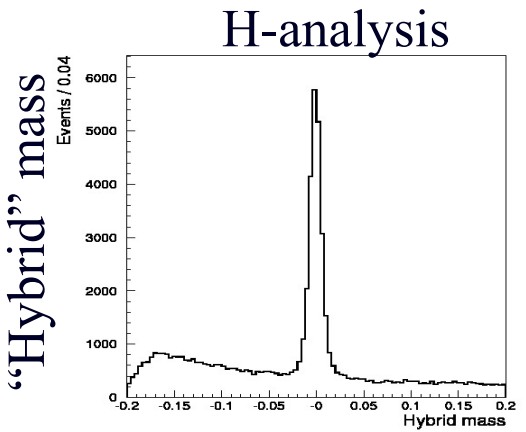




- **Hybrid mass analysis (H)**

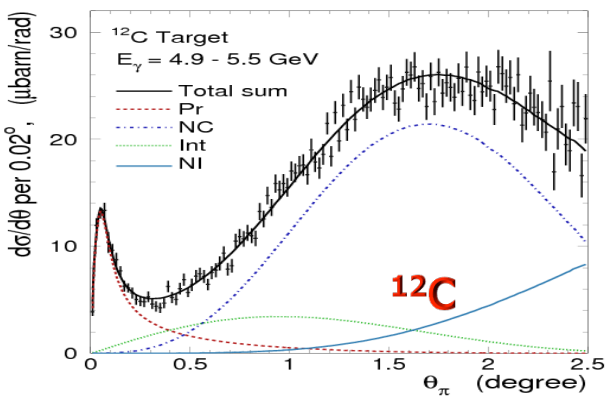
  by Y. Zhang, Duke Univ.

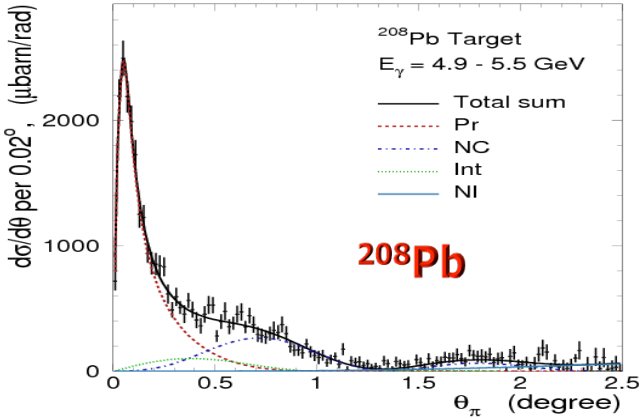




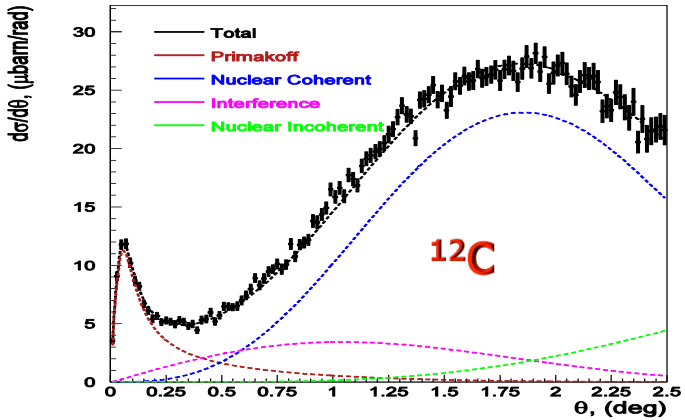
Differential Cross Sections

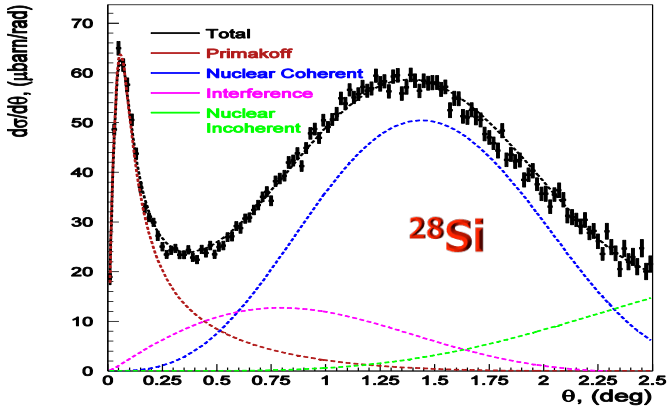
PrimEx I:





PrimEx II:



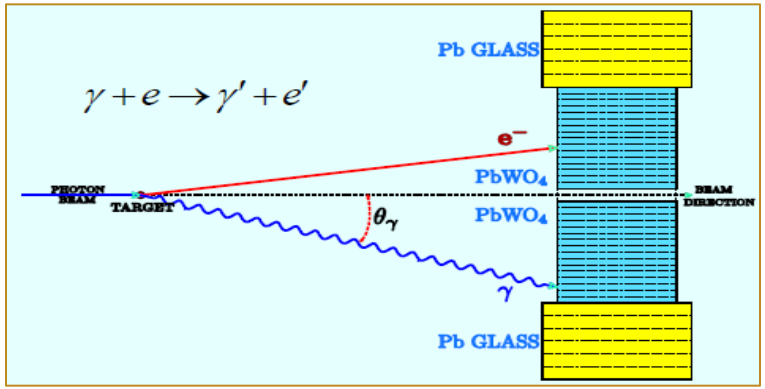


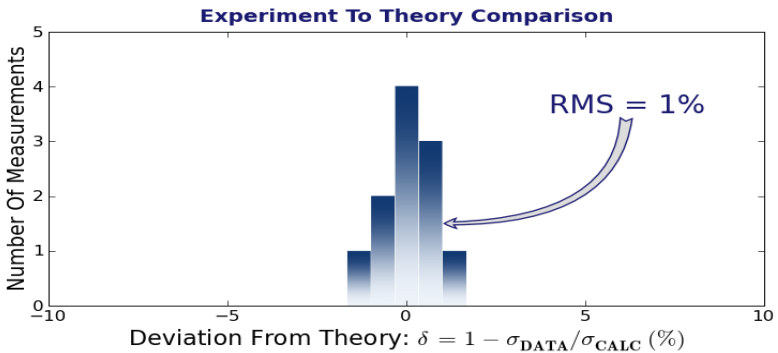
Fitting data with new theoretical calculations to extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

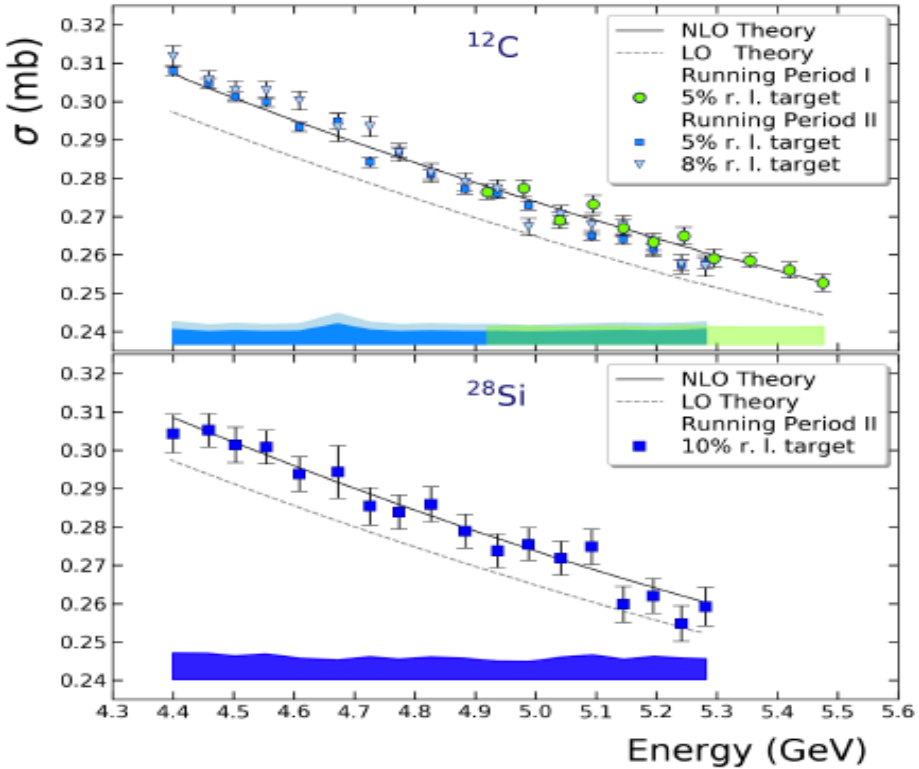
Phys.Rev. C80, 055201 (2009); Phys.Part.Nucl.Lett.,9,3 (2012)

Verification of Overall Experimental Systematics with Compton Scattering

Phys.Lett. B797 (2019) 4884



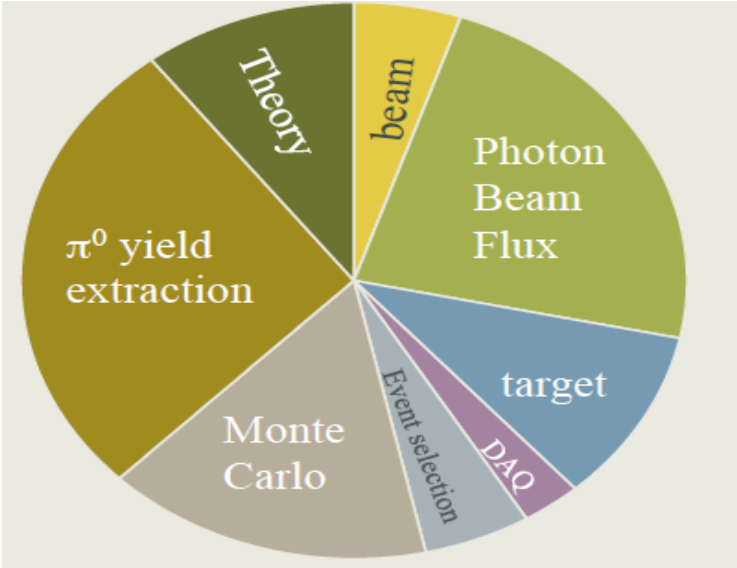




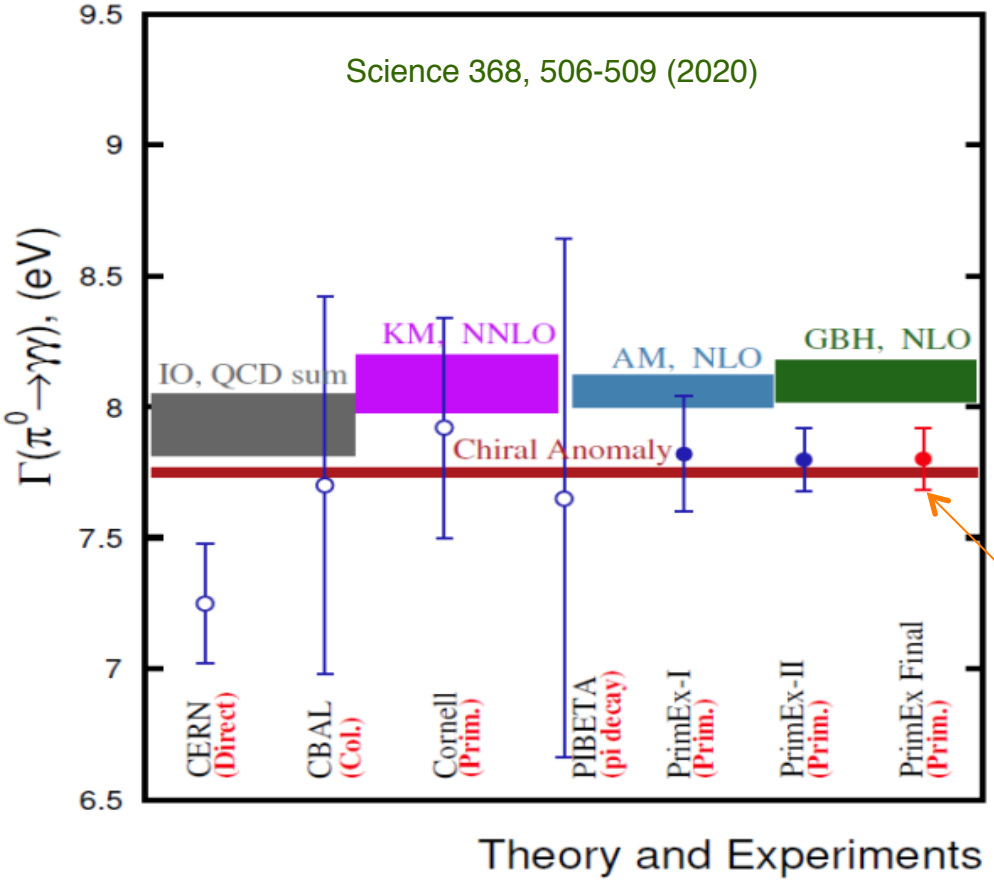
Systematic uncertainties of measured cross section are controlled at 1.5%

Uncertainties of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

Item	PrimEx-II
Beam parameters	0.2%
Photon flux	0.8%
Target	0.3%
DAQ	0.1%
Event selection	0.2%
Monte-Carlo simulation	0.6%
Yield extraction	1.0%
Photoproduction theory parameters	0.4%
Systematics	**1.5%**
Statistical	0.7%
Total	**1.6%**

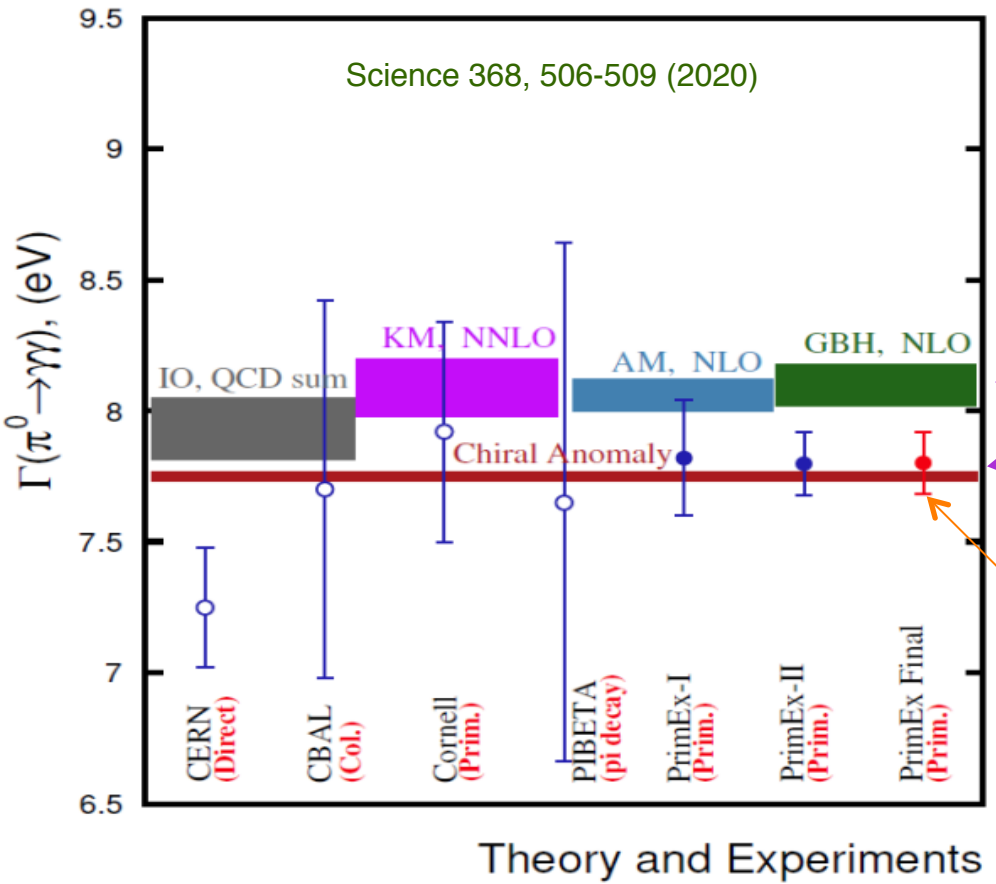


PrimEx Final Result



$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.802±0.052(stat)±0.105(syst) eV
1.50% total uncertainty

Final PrimEx Result

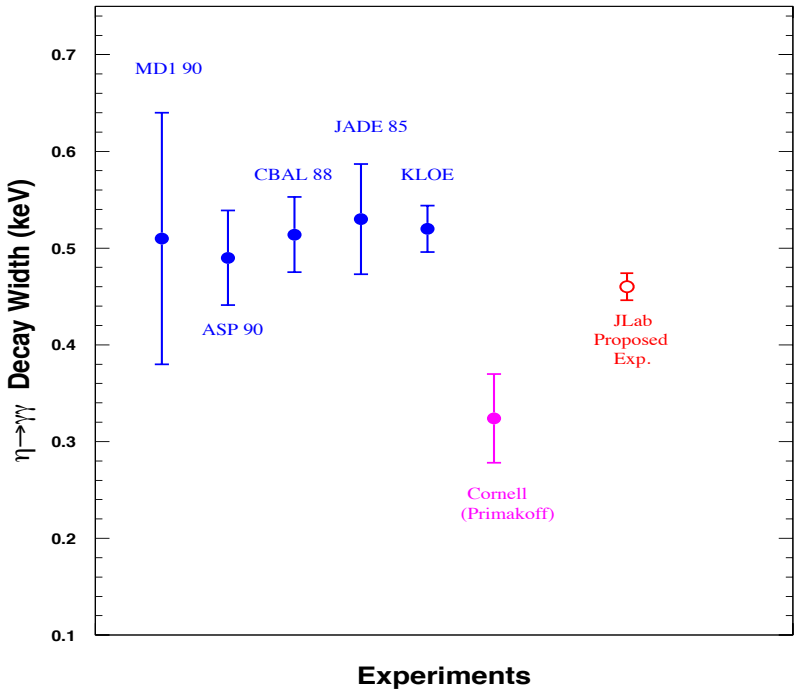


2σ discrepancy

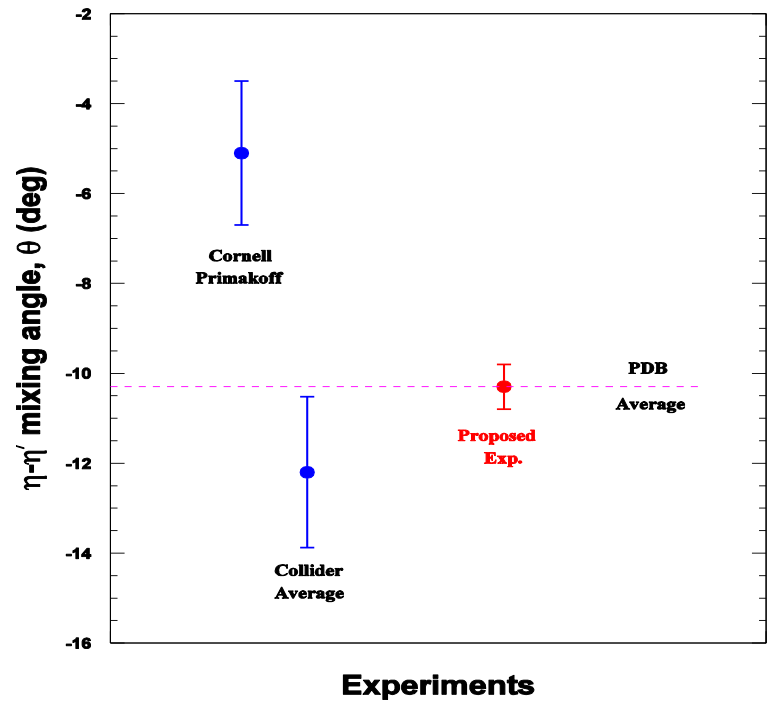
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.802±0.052(stat)±0.105(syst) eV
1.50% total uncertainty

Physics for $\Gamma(\eta \rightarrow \gamma\gamma)$ Measurement

1. **Resolve long standing discrepancy between collider and Primakoff measurements:**



2. **Extract η-η' mixing angle:**



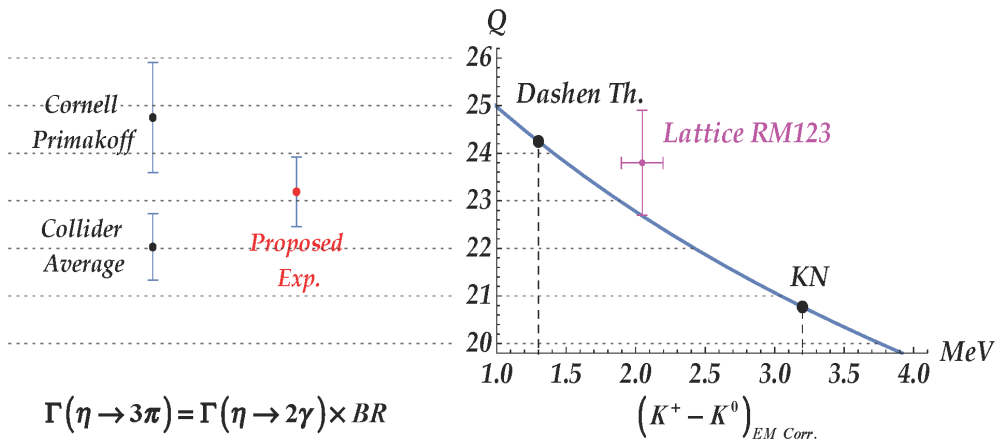
3. **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

A clean probe for quark mass ratio:

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

- $\eta \to 3\pi$ decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em} A_2$
- α_{em} is small
- Amplitude: $A(\eta \to 3\pi) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$



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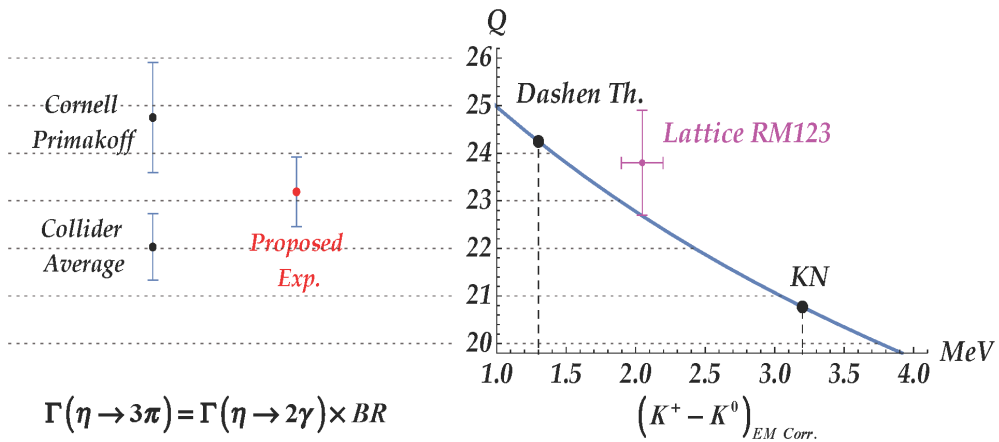

- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

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

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, …)

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

→

1. Higher beam energy
2. Light targets

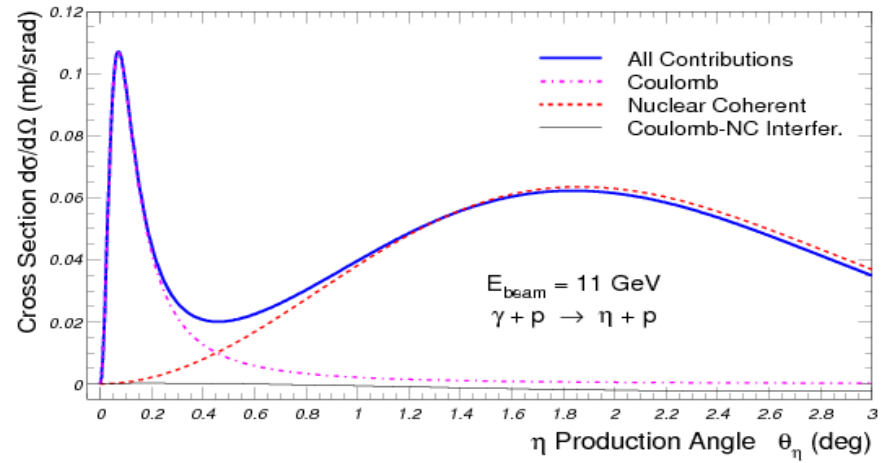
Advantage of Light Targets

Low A targets to control:

- Coherency: compact nucleus
- Separate background

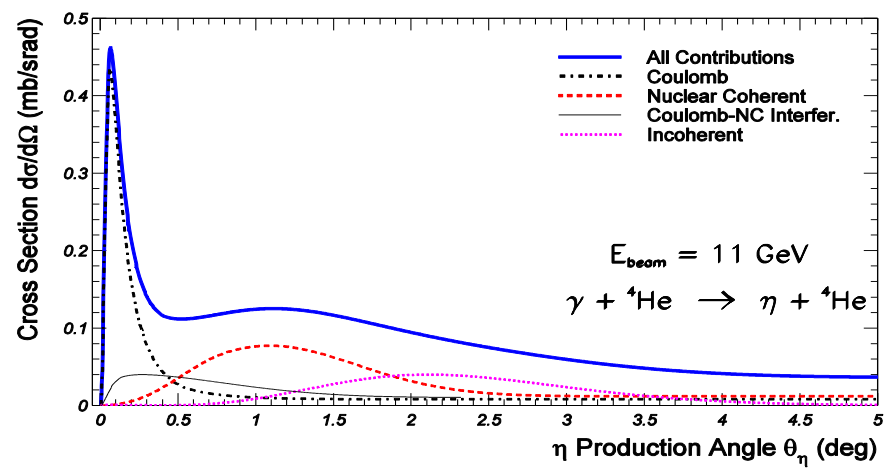
$$\langle \theta_{\mathrm{Pr}} \rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \langle \theta_{NC} \rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- Well known form factors



Hydrogen:

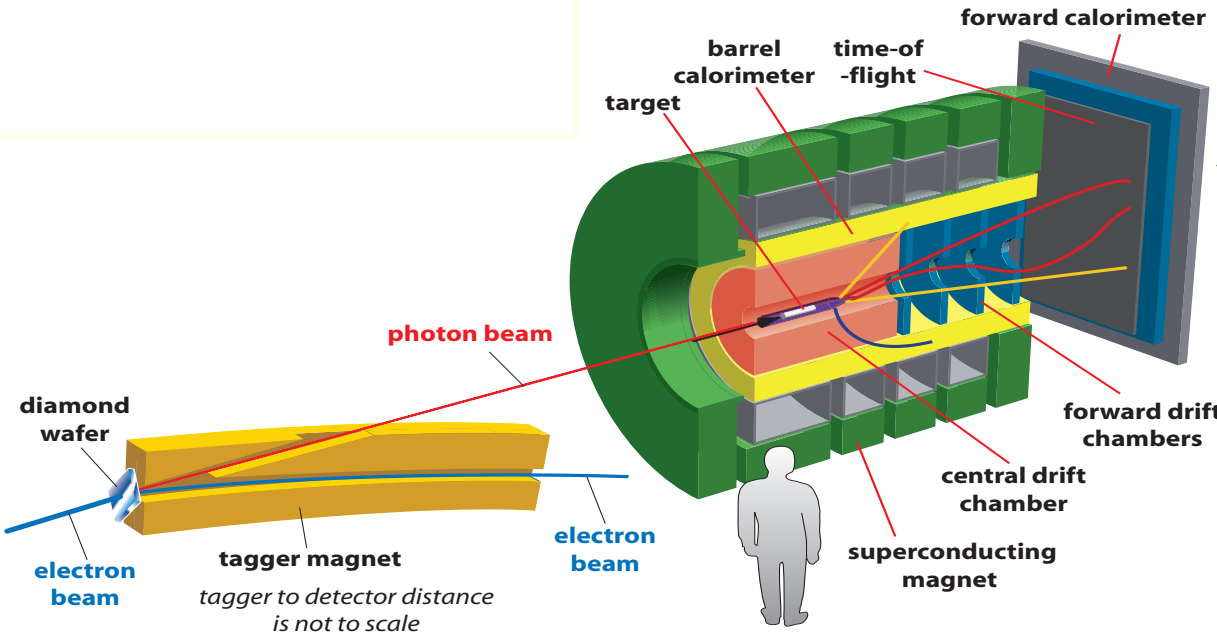
- No inelastic hadronic contribution
- No nuclear final state interactions



^{4}He:

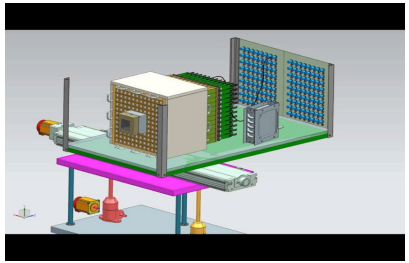
- Higher Primakoff cross section: $\sigma_{\mathrm{Pr}} \propto Z^2$

Measurement of $\Gamma(\eta \rightarrow \gamma\gamma)$ in Hall D at 12 GeV



FCAL

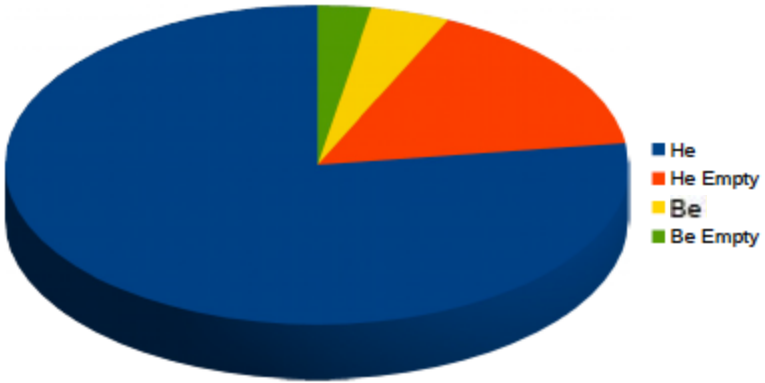
CompCal



- Tagged photon beam (~9.0-11.7 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.

Status of PrimEx-eta

- A engineering run with a new CompCal in fall 2018
- The first production run:
  Feb 22 - April 15, 2019.
  (~70k exclusive $\eta \rightarrow \gamma\gamma$ events on ^{4}He)
- Second run is scheduled for 2021

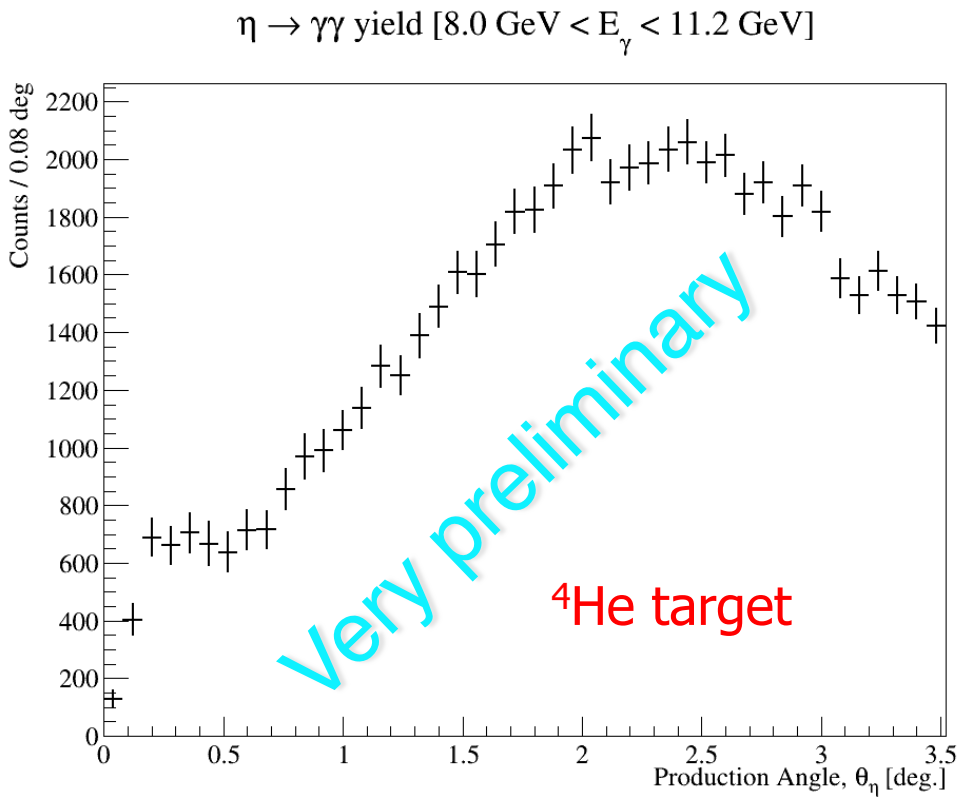


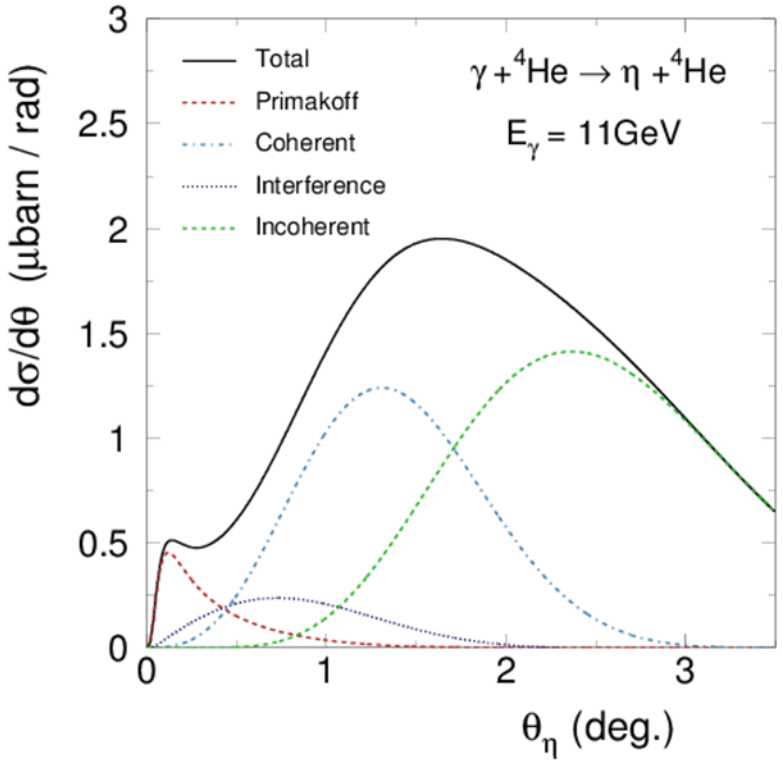
Time Spent on each Target during Spring-2019

	Approved PAC 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**

~50% data on ^{4}He was collected in 2019

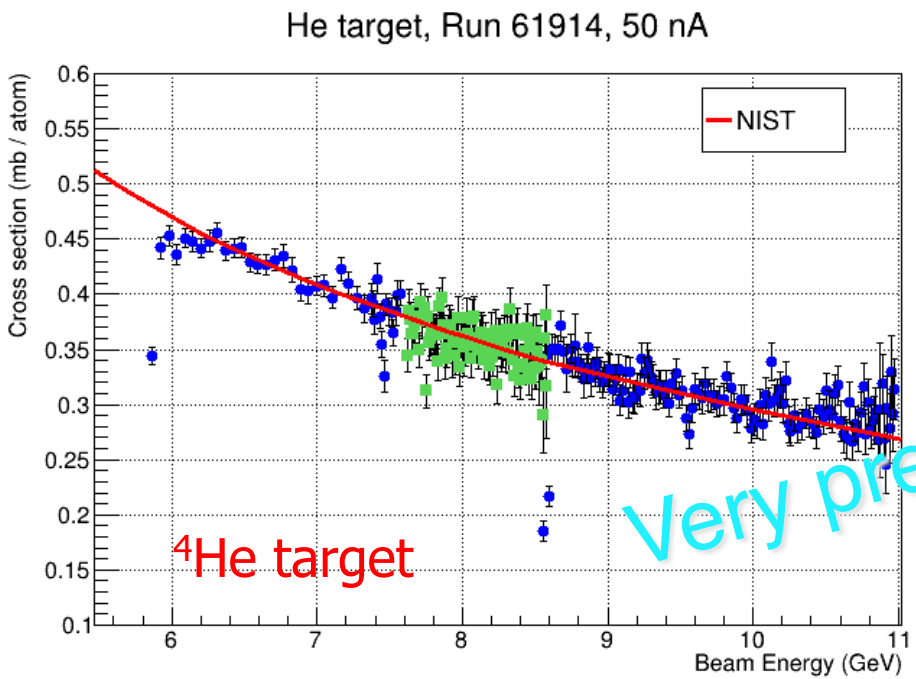
Preliminary Result



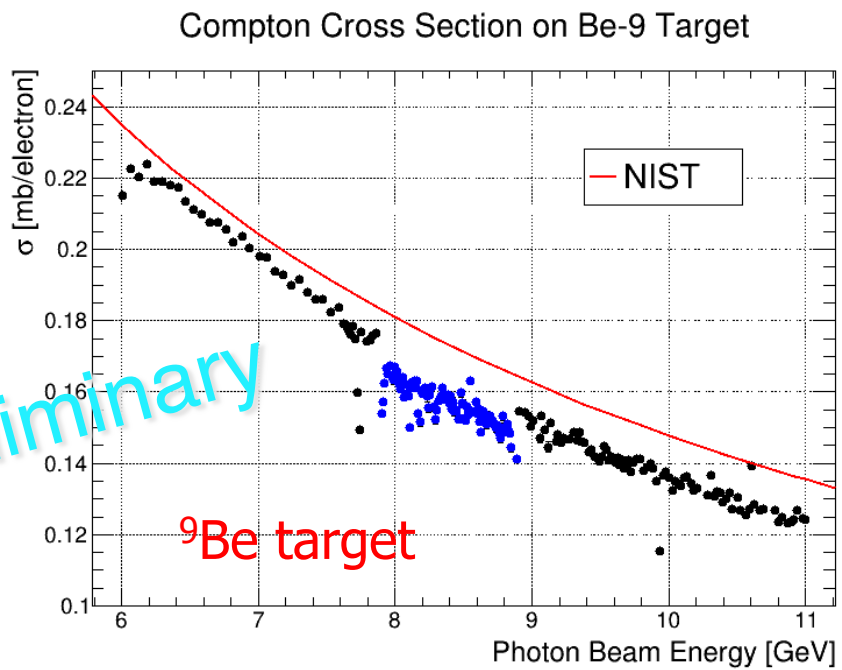


(By D. Smith)

Compton Cross Section



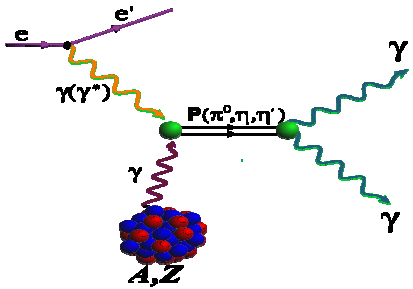
(By S. Somov)



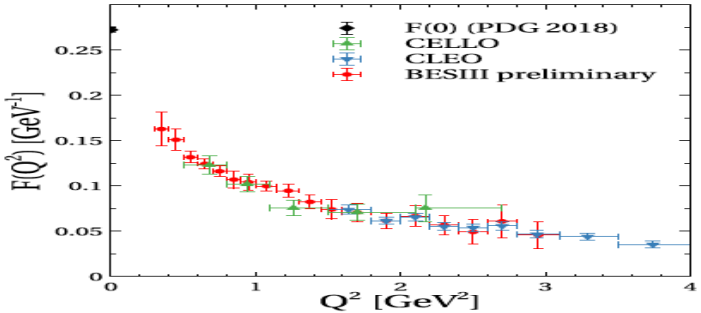
(By D. Smith)

Statistical errors only

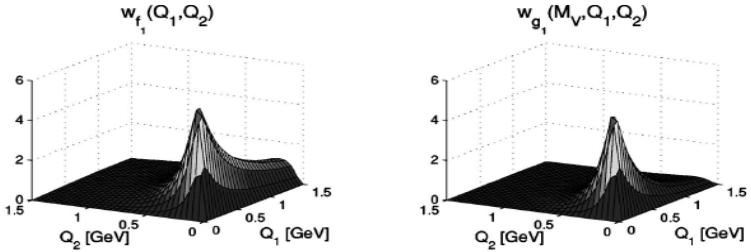
Space-Like Transition Form Factors $F(\gamma\gamma^* \to p)$ (at low Q^2 : 0.001-0.5 GeV^2/c^2)



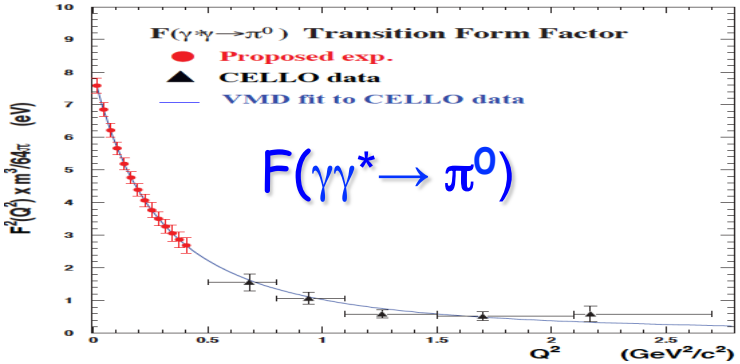
- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^* P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



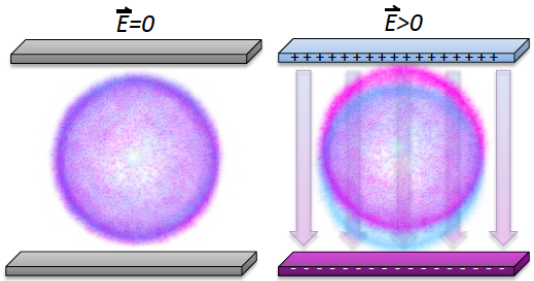
- Input for hadronic light-by-light calculations in $(g-2)_\mu$



Phys.Rev.D65,073034

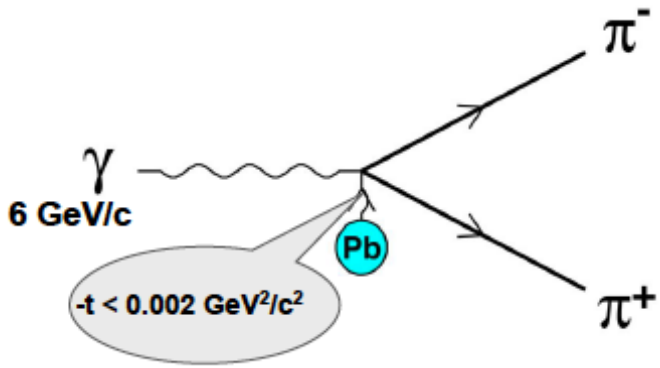


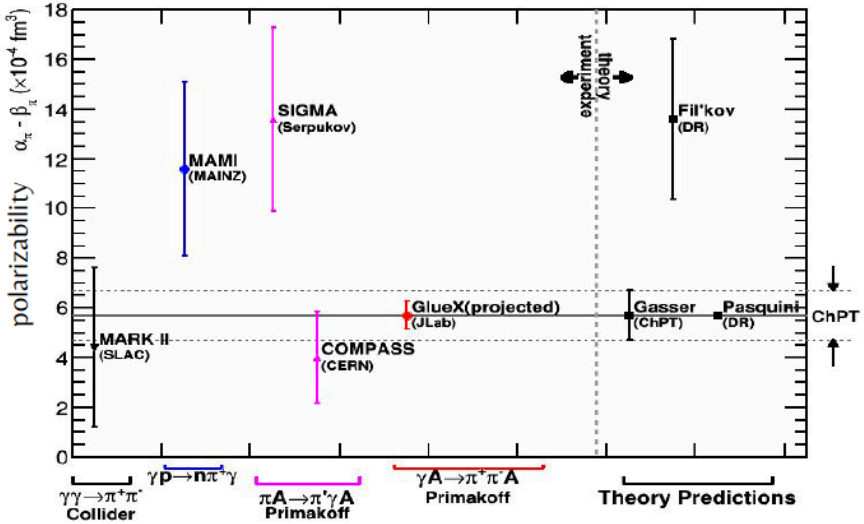
Charged and neutral pion polarizability measurements in Hall D



$\vec{p} = -\alpha\vec{E}$

$\vec{\mu} = \beta\vec{H}$





- A approved experiment (E12-13-008) to measure the charged pion polarizability (α_π-β_π) at ~10% precision.
- New proposal to PAC48 for the first measurement of the neutral pion polarizability at a level of 41%.

Summary

- **A comprehensive Primakoff program has been developed at JLab to measure $\Gamma(p \rightarrow \gamma\gamma)$ and $F(\gamma\gamma^* \rightarrow p)$ (p represents π^0, η and η') to test the confinement QCD symmetries.**
  - precision tests of chiral symmetry and anomalies
  - light quark mass ratio and η-η' mixing angle
  - π^0,η and η' electromagnetic interaction radii
  - Inputs to calculate HLbL for $(g-2)_\mu$
- **Two experiments on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ were performed in Hall B.**

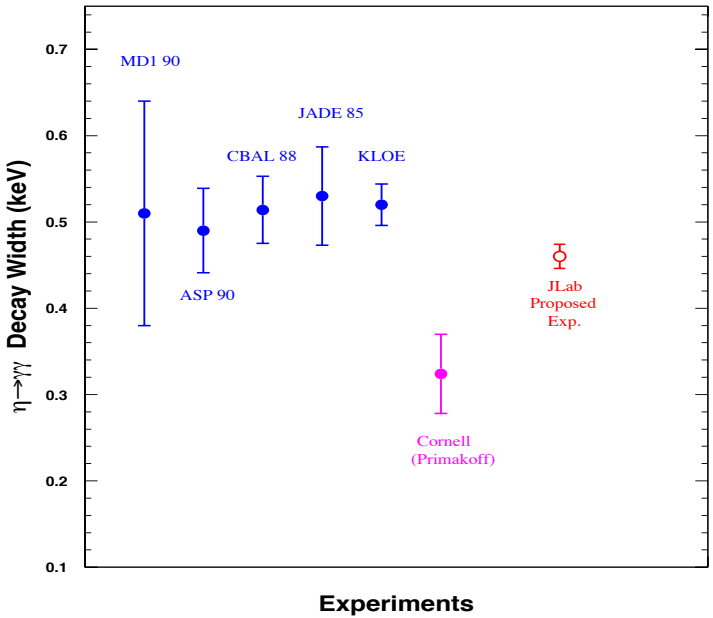
  Final result: $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.802 \pm 0.052(\text{stat}) \pm 0.105(\text{syst})$ eV
  1.50% total uncertainty

  Science 368, 506 (2020)
- **PrimEx-eta experiment for $\Gamma(\eta \rightarrow \gamma\gamma)$: the first run was performed in spring 2019 in Hall D; the second run is scheduled for 2021.**
- **A LOI for the π^0 transition form factor to PAC48.**

Projected Error Budget of $\Gamma(\eta \rightarrow \gamma\gamma)$

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:

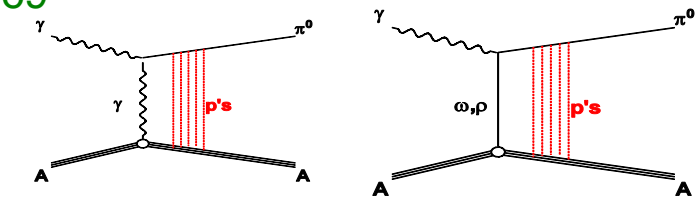
Statistical	1.0%
Systematic	3.0%
Total	**3.2%**

Theoretical Calculations

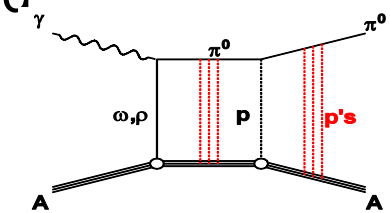
Coherent Production $\gamma+A\rightarrow\pi^0+A$

- 1964, G. Morpurgo, Neuovo Cimento, 31, 569
  - ✓ Strong absorption for outgoing pion in uniform nuclear density

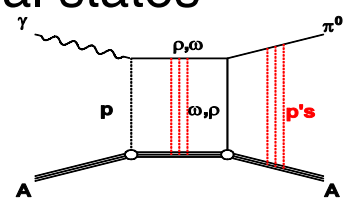
    Used for Tomsk and DESY Primakoff Exp.



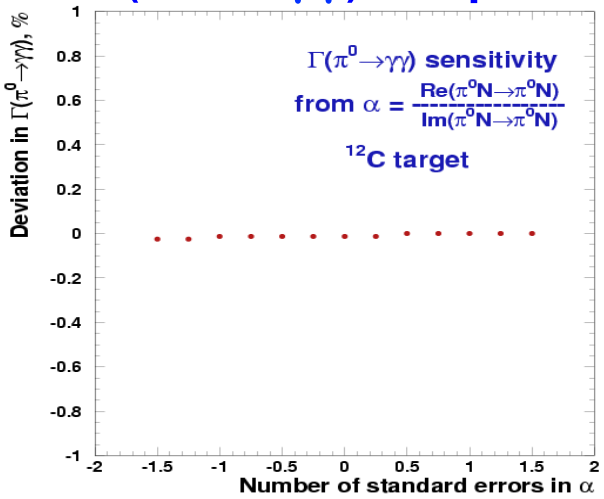
- 1972, G. Faldt, Nucl. Phys. B43, 591
  - ✓ Strong absorption in a nucleus for both incident and produced particles
  - ✓ final state pion re-scattering in nucleus
  - ✓ corrections for light nuclei Used for Cornell exp.

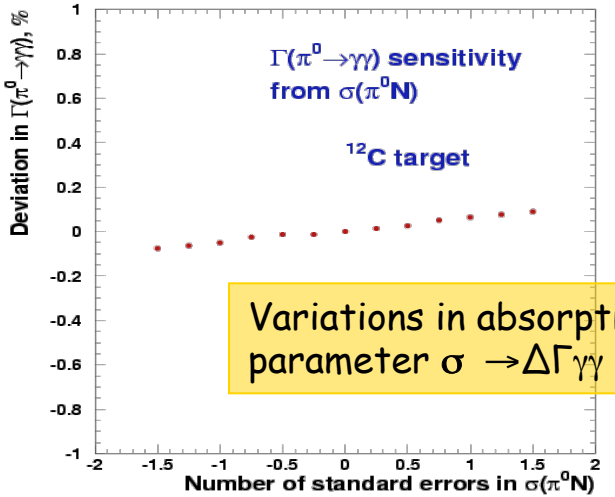


- 2009, S. Gevorkyan *et. al.*, Phys.Rev. C80, 055201, PrimEx note #85
  - ✓ Strong absorption in a nucleus for initial and final states
  - ✓ the final state pion re-scattering in nucleus
  - ✓ corrections for light nuclei
  - ✓ photon shadowing effect
  - ✓ Pion form factor Used for PrmEx

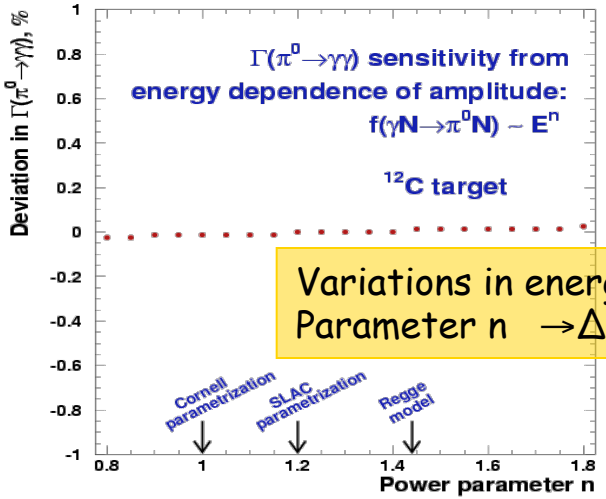


$\Gamma(\pi^0 \to \gamma\gamma)$ dependence on model parameters

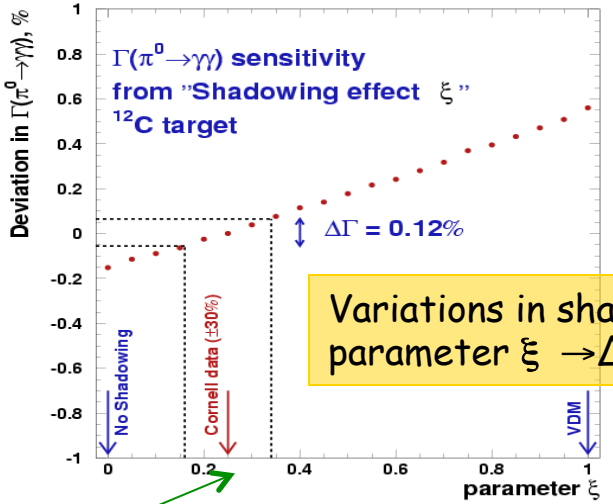




Variations in absorption parameter σ $\to \Delta\Gamma_{\gamma\gamma} < 0.06\%$



Variations in energy dependence Parameter n $\to \Delta\Gamma_{\gamma\gamma} < 0.04\%$



Variations in shadowing parameter ξ $\to \Delta\Gamma_{\gamma\gamma} < 0.06\%$

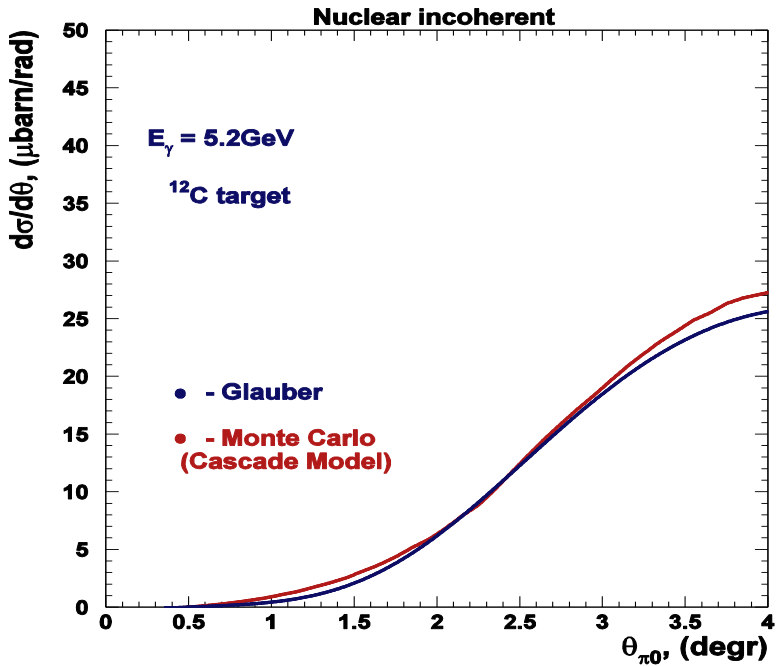
Phys. Rev. Lett. 28, 1344 (1972)

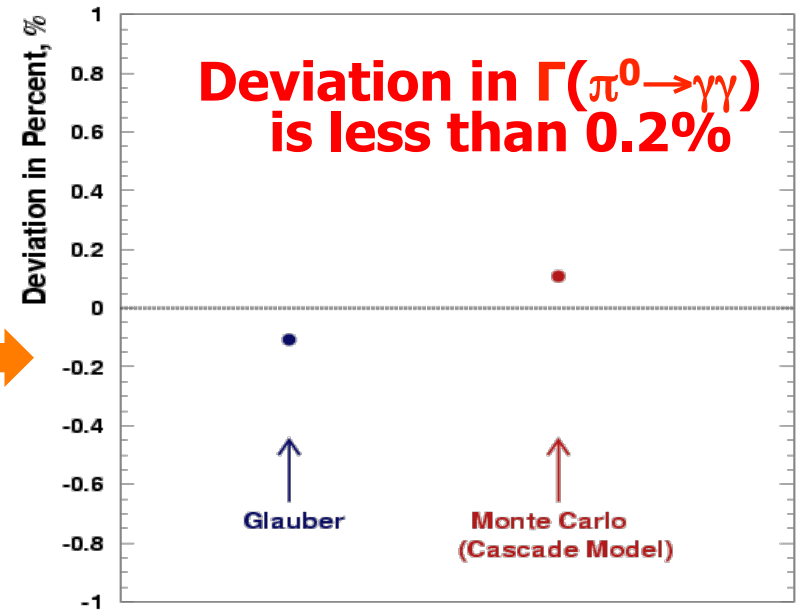
Theoretical Calculation (cont.)

Incoherent Production $\gamma + A \rightarrow \pi^0 + A'$

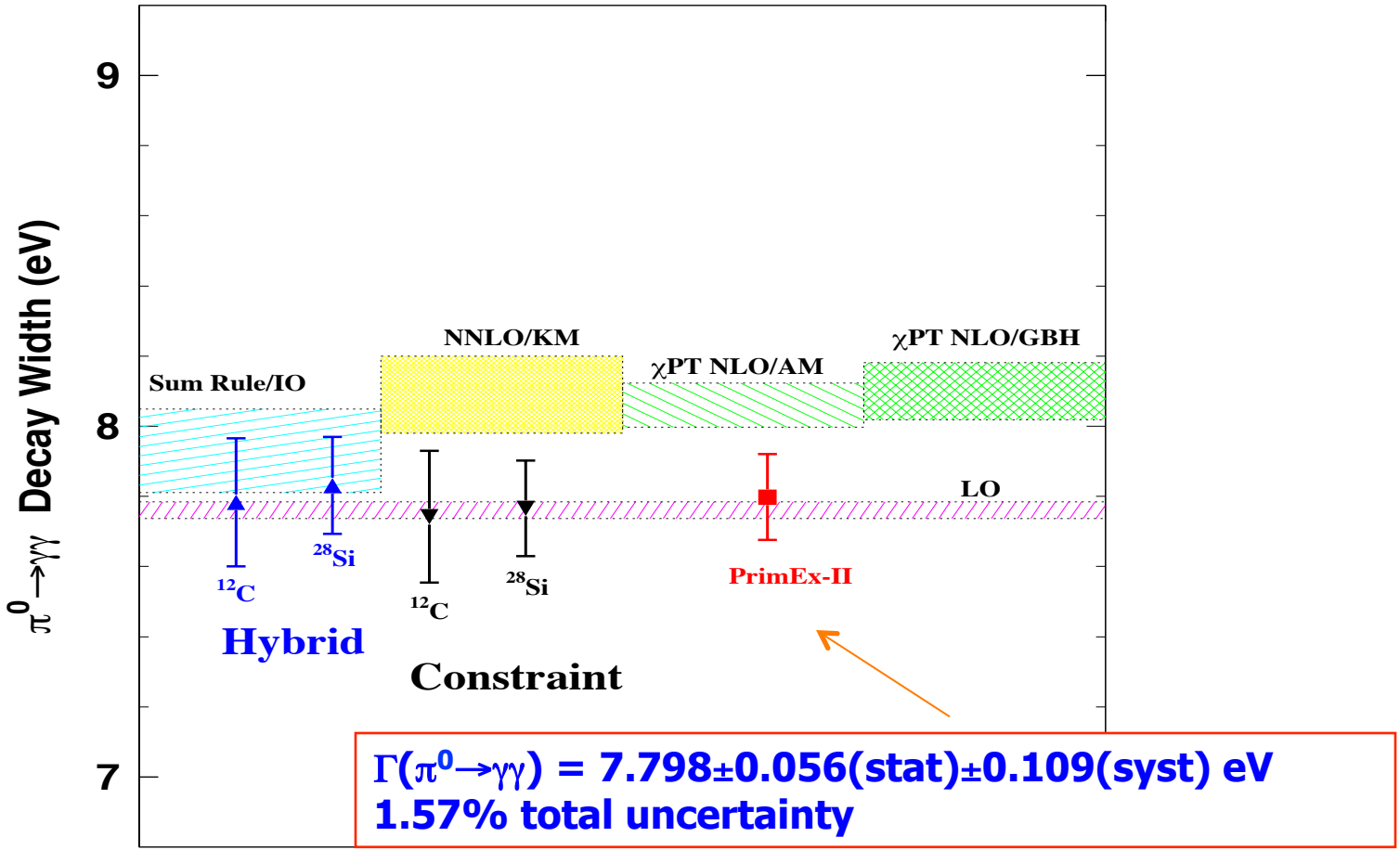
Two independent approaches:

- Glauber theory, Phys.Part.Nucl.Lett.,9,3 (2012)
- Cascade Model, Phys.Rev.Lett.,101, 012301 (2008)





PrimEx-II Result



Analysis Results