Primakoff Production Overview

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Outline

- the original idea and some history
- real Primakoff production processes
- virtual Primakoff production processes
- next generation Primakoff experiments
- summary

A Short Review of $\pi^0 \rightarrow \gamma\gamma$: "Discovery"

- ✓ 1938: Yukawa postulates a neutral meson based on observations of charge independence of the NN force
- ✓ 1940: Sakata estimates $t \approx 10^{-16}$ s for the π^0 lifetime from PP loop diagram
- ✓ 1948: Oppenheimer suggests π^0 decays are responsible for gamma backgrounds in high altitude cosmic rays
- ✓ 1950: π^0 discovered at Berkeley Cyclotron

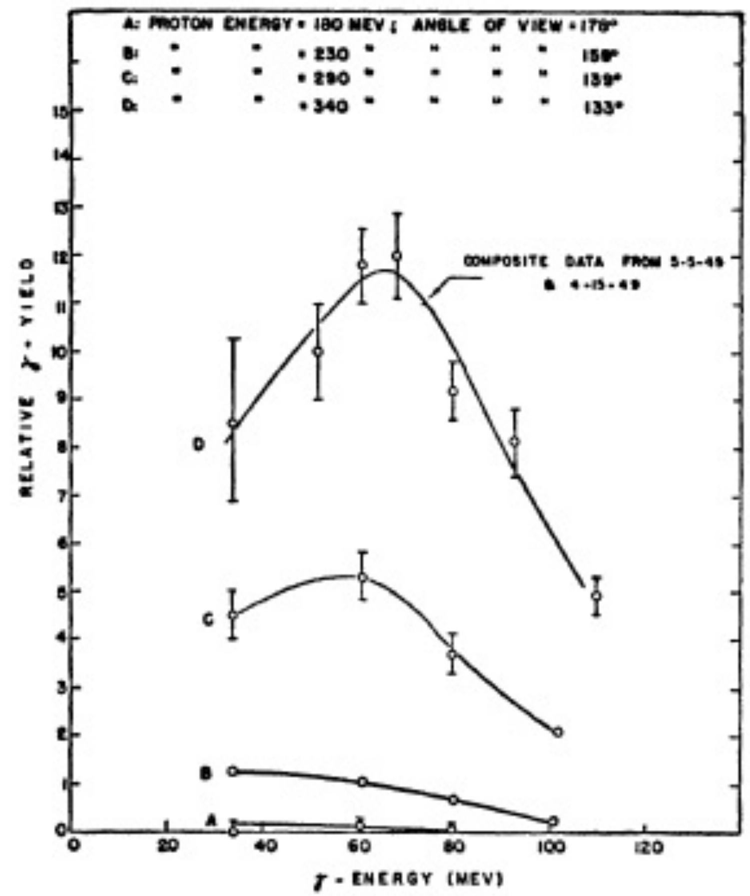

FIG. 4a. Relative gamma-yield from ½-in. carbon target at various proton energies.

The Original Idea

- Phys. Rev. 81, 899, 1951

Walter and Barratt[1] examined and identified the absorption spectra of Li_2, Na_2, K_2, Rb_2, Cs_2, LiK, LiRb, LiCs, NaK, NaRb, NaCs, KRb, RbCs, and KCs.

The identification of a NaLi molecule is complicated by the existence of Na_2 and Li_2 band systems in the regions of the visible, near infrared and ultraviolet. Since the probability of molecular formation is a function of the product of the concentration of the atoms involved, it seemed possible that one component of a sodium-lithium mixture might be held at a low vapor pressure and the other at a high vapor pressure to increase the probability of observing the NaLi molecule.

In our experiment the lithium metal was placed in an absorption cell constructed of nickel and having water-cooled quartz windows. A nickel side tube was connected to the absorption cell to contain the sodium. Heating units were arranged around the absorption cell and side tube to control the temperature of the sodium and lithium metals independently.

The lithium metal was maintained at 850°C. A series of absorption spectrograms was then taken with the sodium at temperatures of 435, 460, 485, and 510°C, respectively. A similar procedure was used for maintaining constant high sodium with increasing lithium vapor pressures.

The results of this experiment confirm the previous work of Walter and Barratt. No bands attributable to a NaLi molecule were observed in the region 3000 to 8000A. No explanation is available, particularly as it is the only member not observed of the complete set of binary molecular systems obtainable with the alkali metals.

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‡ Now at South Dakota State College, Brookings, South Dakota.
1 J. M. Walter and S. Barratt, Proc. Roy. Soc. (London) **A119**, 257 (1928).

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

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January 2, 1951

IT has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^0 spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \qquad (1)$$

Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of π^0), and η is a dimensionless constant determined by the decay mechanism.[4]

One can obtain η immediately (by a first-order perturbation calculation) in terms of the mean life, τ, of a neutral π-meson at rest, *viz.*:[5]

$$\tau^{-1} = \pi^2\eta^2\mu c^2/2\hbar. \qquad (2)$$

The effective interaction of Eq. (1) can now be used for a calculation of the probability of the inverse process: π^0 production in photon-photon collisions, or, for the calculation of the probability of the more interesting process: π^0 production in the collision of a photon with an external, approximately static electric field; e.g., the Coulomb field of a (slowly recoiling) nucleus. The total cross section σ for this last process is, from a first-order perturbation treatment of Eq. (1), proportional to η^2; i.e., to τ^{-1}; one obtains[6]

$$\sigma \approx 32\pi^2\frac{\hbar/\mu c}{c\tau}Z\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{\mu c}\right)^2\frac{4}{3}\left(\frac{\hbar\kappa}{\mu c}\right)^3, \quad \text{for} \quad \hbar\kappa \ll \hbar k \approx \mu c \qquad (3)$$

$$\sigma \approx 32\pi^2\frac{\hbar/\mu c}{c\tau}Z^2\left(\frac{e^2}{\hbar c}\right)\left(\frac{\hbar}{\mu c}\right)^2, \quad \text{for} \quad R(k-\kappa) \approx \frac{(2Z)^{\frac{1}{3}}}{2}\frac{\mu c}{\hbar k} \ll 1. \qquad (4)$$

In Eqs. (3) and (4), $\hbar k$, $\hbar\kappa = \hbar k[1-(\mu c/\hbar k)^2]^{\frac{1}{2}}$ are, respectively, the momenta of the incident photon and produced neutral π-meson; the angular distribution of the mesons is strongly collimated about the direction of the incident photon if $\hbar k \gg \mu c$. In deducing Eq. (3), it has been supposed that the nuclear protons remain approximately at rest during time intervals of the order of several periods of the incident electromagnetic wave [since $v_{\text{proton}} \approx \frac{1}{5}c$ and $(ck)^{-1} \lesssim \hbar/\mu c^2$], and that the probability of finding any pair of protons a distance r apart is proportional to $\exp(-r/R)$, where $R \approx \hbar(2Z)^{\frac{1}{3}}/\mu c$ is the nuclear radius. It is seen from Eqs. (3) and (4) that the electric fields of the Z protons contribute "coherently" to the π^0 production, once the photon energy exceeds $\frac{1}{2}(2Z)^{\frac{1}{3}}\mu c^2$.

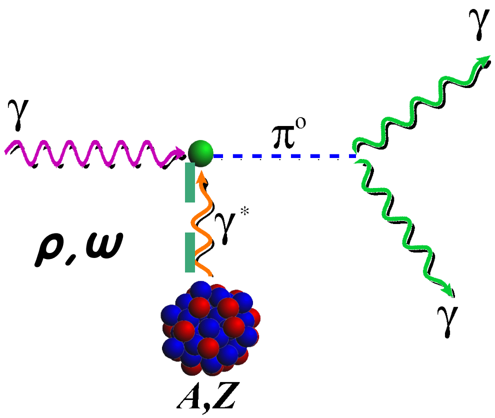
Thus, if τ is less than, say, 10^{-17} sec, Eq. (4) indicates that a Z^2 term should be observable in the total cross section for production of neutral π-mesons in photon-nucleus collisions. Since no such term has so far been experimentally detected,[7] one can set a very rough lower limit on τ: $\tau > 5\times10^{-16}$ sec. An approximate upper limit of 5×10^{-14} sec seems to be indicated by cosmic-ray data.[8]

* Assisted by the joint program of the ONR and AEC.
† On leave from Washington University, St. Louis, Missouri.
1 Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950); Panofsky, Aamodt, Hadley, and Phillips, Phys. Rev. **80**, 94 (1950).
2 C. N. Yang, Phys. Rev. **77**, 243 (1950); D. C. Peaslee, Helv. Phys. Acta **23**, 845 (1950); we exclude the possibility of the π^0 spin being >1.
3 J. Steinberger, Phys. Rev. **76**, 1180 (1949), and other references quoted there.
4 Marshak, Tamor, and Wightman, Phys. Rev. **80**, 765, 766 (1950); K. Brueckner, Phys. Rev. **79**, 641, 187 (1950).
5 The mechanism of π^0 decay via interaction with virtual proton anti-proton pairs gives, if for example γ_5 coupling is used between the meson and nucleon wave fields, $\tau^{-1} = (\mu c^2/16\pi^2\hbar)(\mu e^2/M\hbar c)^2(g^2/\hbar c)$ (reference 3), so that in this case, $\eta = (\mu/8^{\frac{1}{2}}\pi^2 M)(g^2/\hbar c)^{\frac{1}{2}}(e^2/\hbar c)$.
6 Another possible process predicted from Eq. (1) involves the one-photon decay of a π^0 in an external (nuclear) electric field. If τ' is the mean life of this decay, one obtains (with N as the number of nuclei per unit volume, and using Eq. (4))

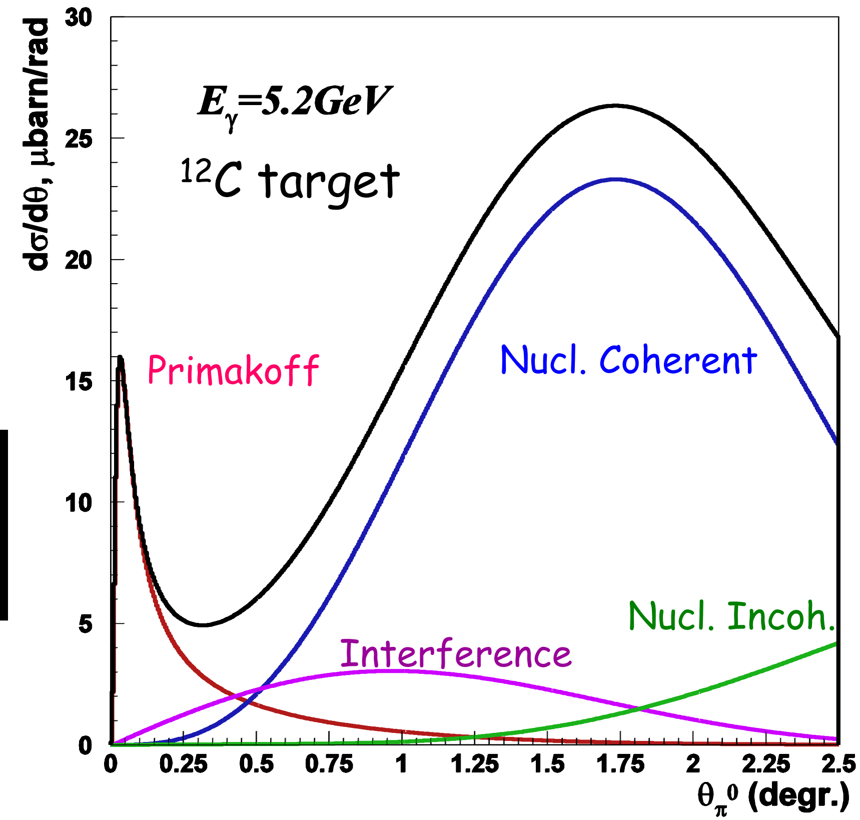
$$\tau/\tau' = \tau c N\sigma 2k^2[\kappa^4+(\mu c\kappa/\hbar)^2]^{-\frac{1}{2}} \approx 64\pi^2 Z^2(e^2/\hbar c)(\hbar/\mu c)^3 N \ll 1.$$

7 Observations of Steinberger, Panofsky, and Steller quoted by R. F. Mozley, Phys. Rev. **80**, 493 (1950).
8 Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).

Real Primakoff Production



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



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

$$\left(\frac{d\sigma_{\text{Pr}}}{d\Omega}\right)_{peak} \propto E^4$$

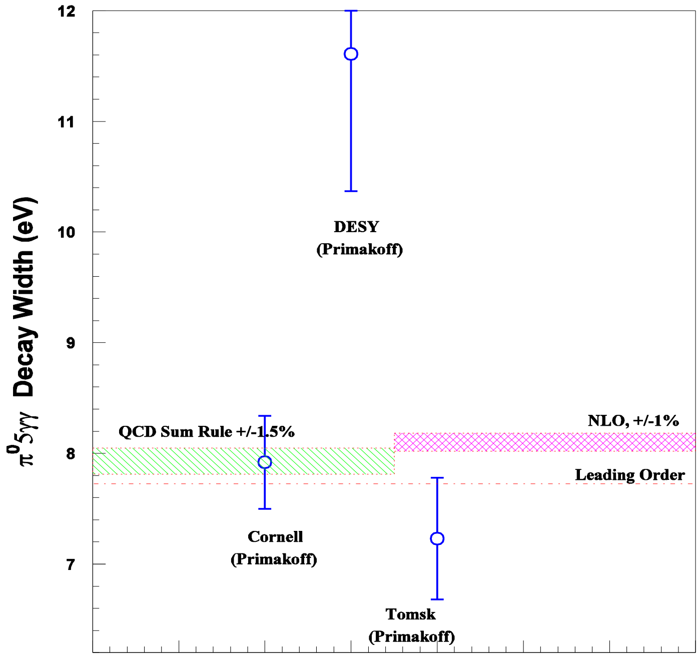
$$\int d\sigma_{\text{Pr}} \propto Z^2 \log(E)$$

Challenge:

Extract the Primakoff amplitude

$\pi^0 \to \gamma\gamma$ Primakoff Experiments Before PrimEx

- DESY (1970)
  - bremsstrahlung γ beam, $E\gamma$=1.5 and 2.5 GeV
  - Targets C, Zn, Al, Pb
  - Result: $\Gamma(\pi^0 \to \gamma\gamma)$=(11.7±1.2) eV ±10.%
- Cornell (1974)
  - bremsstrahlung γ beam $E\gamma$=4 and 6 GeV
  - targets: Be, Al, Cu, Ag, U
  - Result: $\Gamma(\pi^0 \to \gamma\gamma)$=(7.92±0.42) eV ±5.3%



- All previous experiments used:
  - Untagged bremsstrahlung γ beam
  - Conventional Pb-glass calorimetry

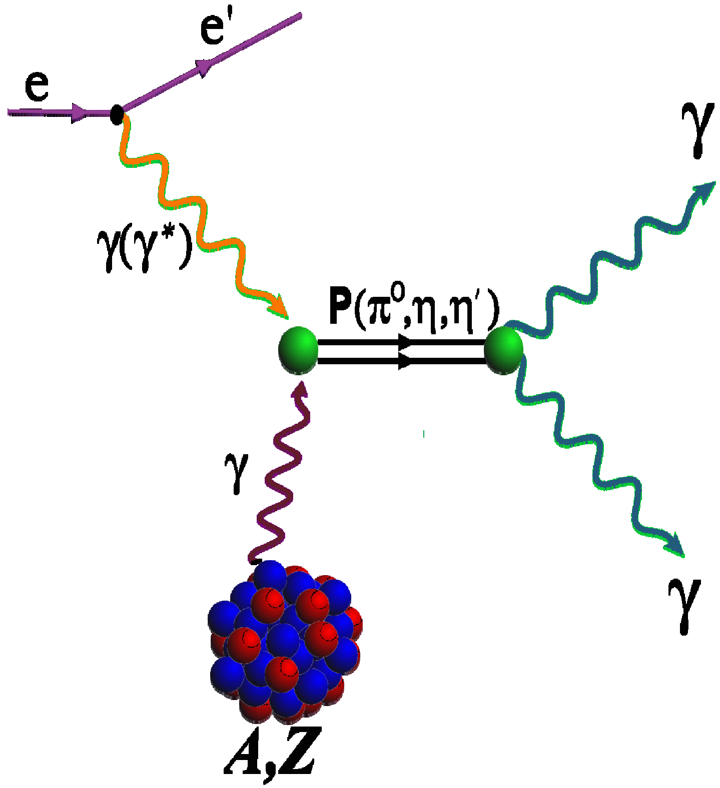
The PrimEx Project at JLab
(second generation Primakoff experiments)

Experimental program

Precision measurements of:

- Two-Photon Decay Widths:
  $\Gamma(\pi^0 \rightarrow \gamma\gamma)$, $\Gamma(\eta \rightarrow \gamma\gamma)$, $\Gamma(\eta' \rightarrow \gamma\gamma)$

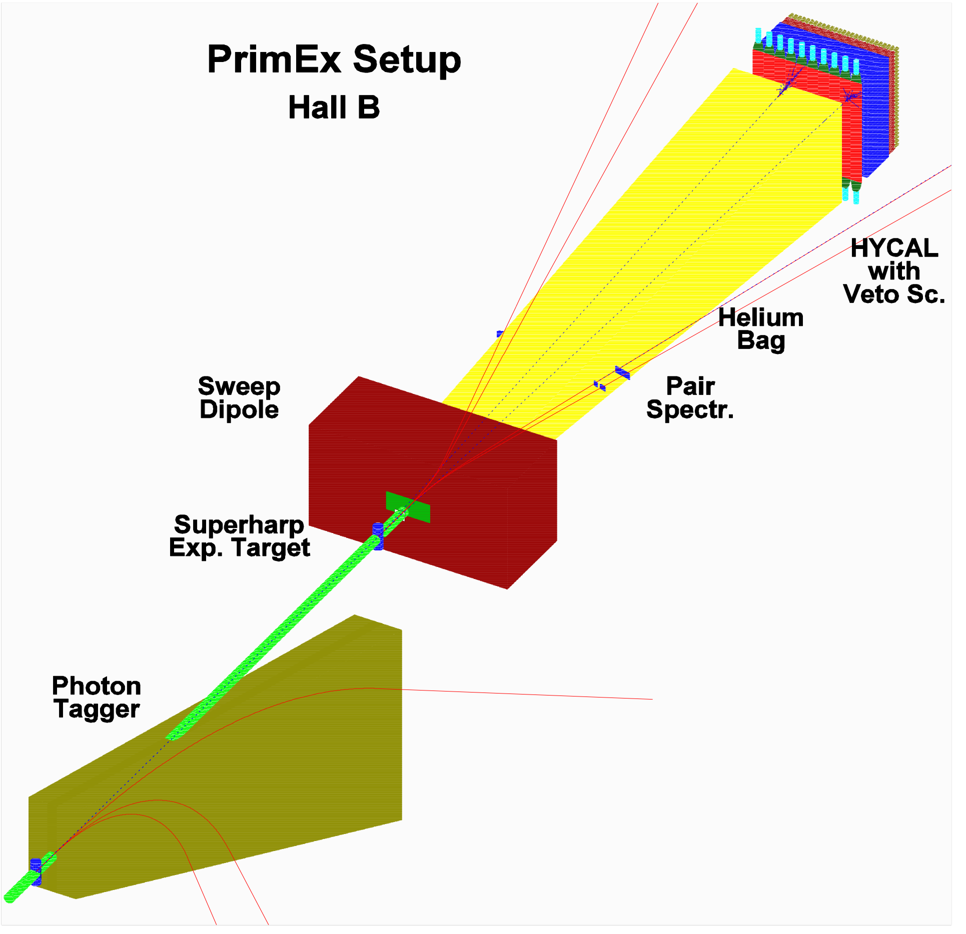
- Transition Form Factors at low Q^2 (0.001-0.5 GeV^2/c^2):
  $F(\gamma\gamma^* \rightarrow \pi^0)$, $F(\gamma\gamma^* \rightarrow \eta)$,
  $F(\gamma\gamma^* \rightarrow \eta')$



Test of Chiral Symmetry and Anomalies via the Primakoff Effect

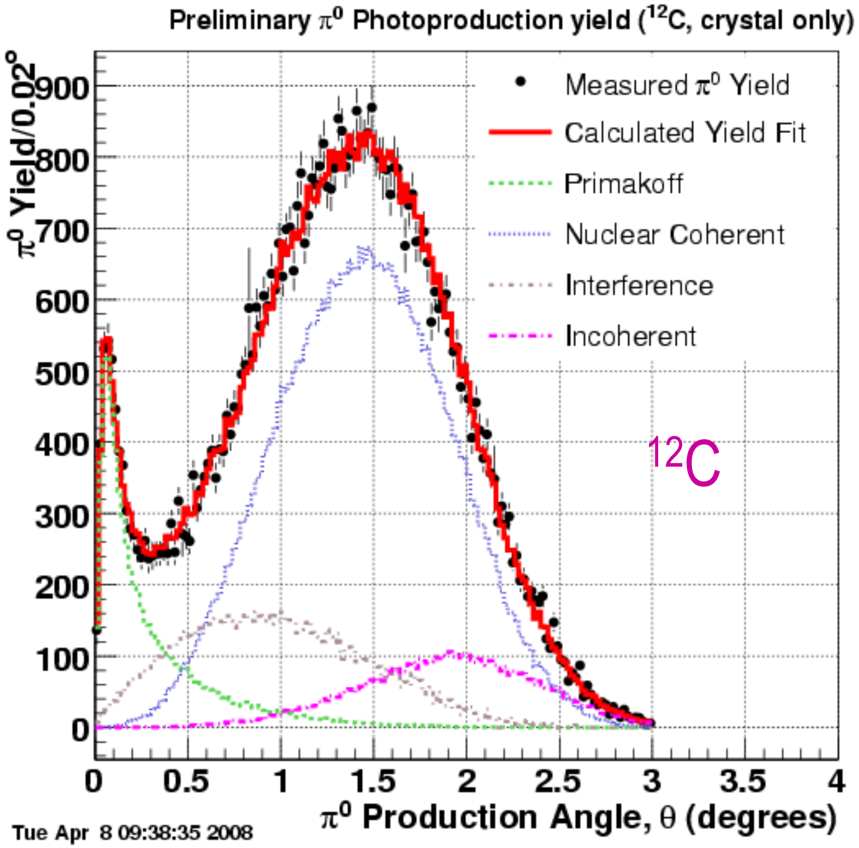
The PrimEx-I Experiment in Hall B

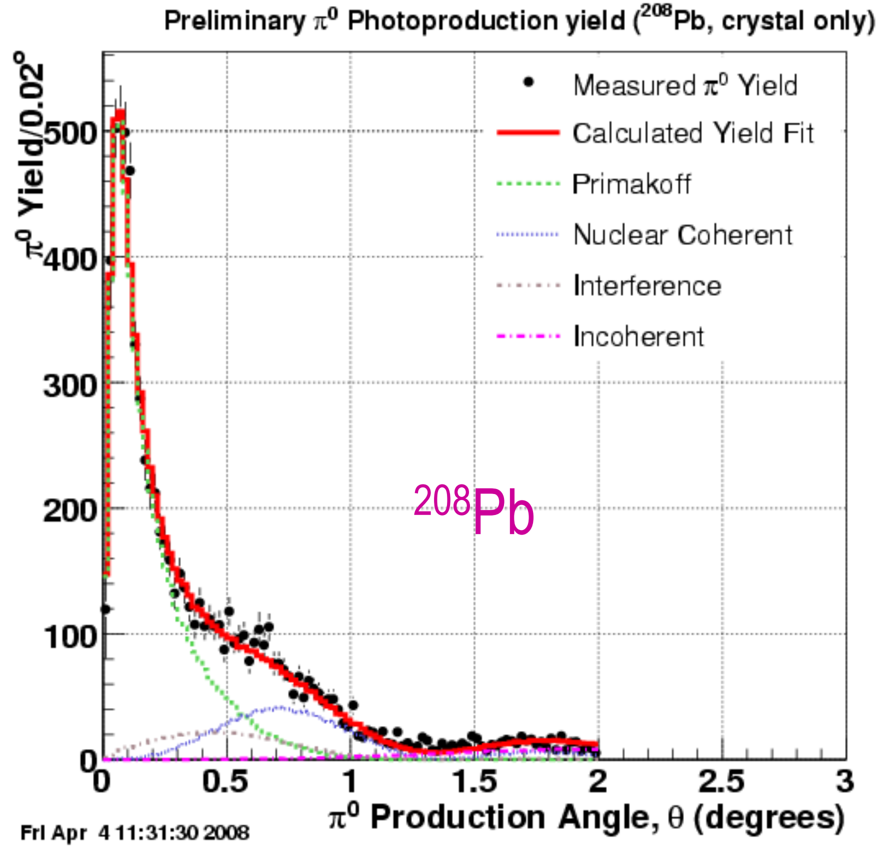
- Requirements of Setup:
  - **high angular resolution (~0.5 mrad)**
    - high resolutions in calorimeter
    - small beam spot size (‹1mm)
  - **Background:**
    - tagging system needed
  - **Particle ID for (γ-charged part.)**
    - veto detectors needed



- ✓ JLab Hall B high resolution high intensity photon tagging facility
- ✓ New high resolution hybrid multi-channel calorimeter (HYCAL)
- ✓ New pair spectrometer for photon flux control at high intensities

Experimental Distributions





PrimEx-I Result and the PDG status Before 2014

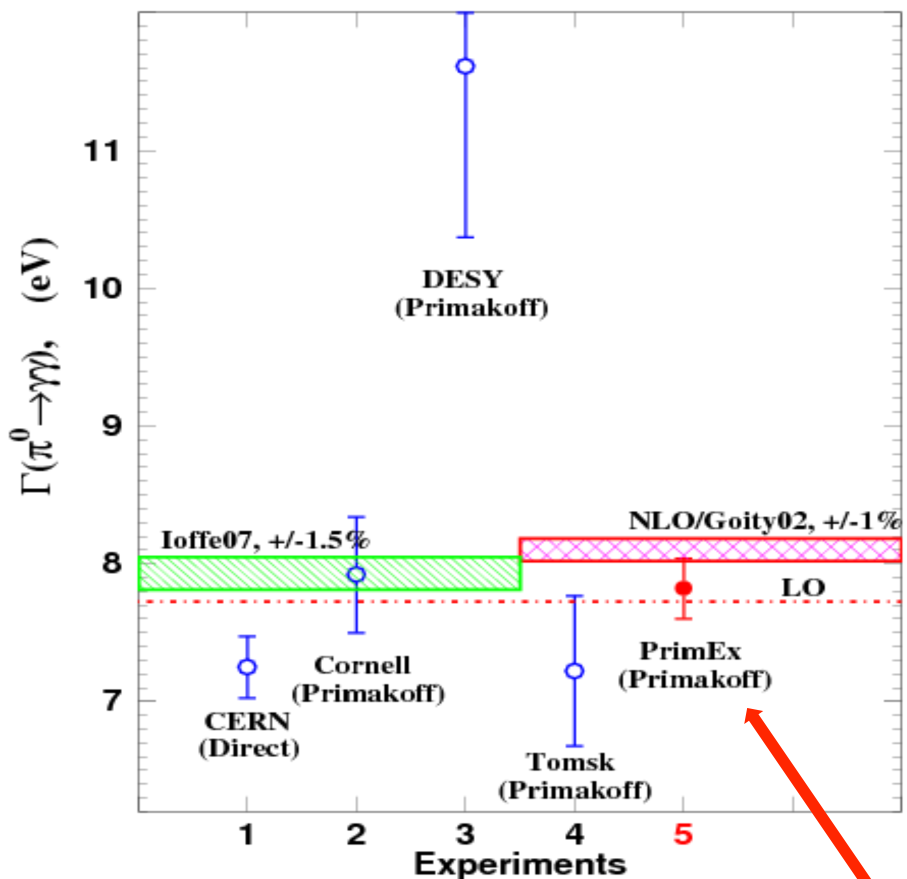
- ✓ **PrimEx-I achieved 2.8% precision (total):**

  $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.82 eV ±1.8% (stat) ±2.1% (syst.)

  (I. Larin, et al. PRL 106, 162303, 2011)

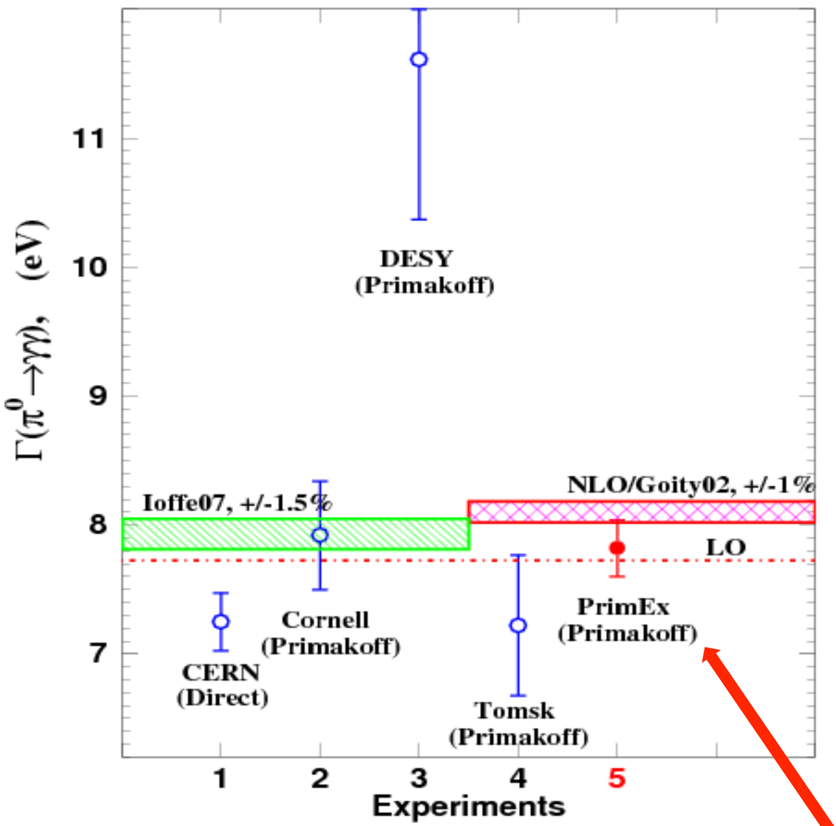
- ➢ **Task for PrimEx-II:**
  to achieve 1.4% precision:

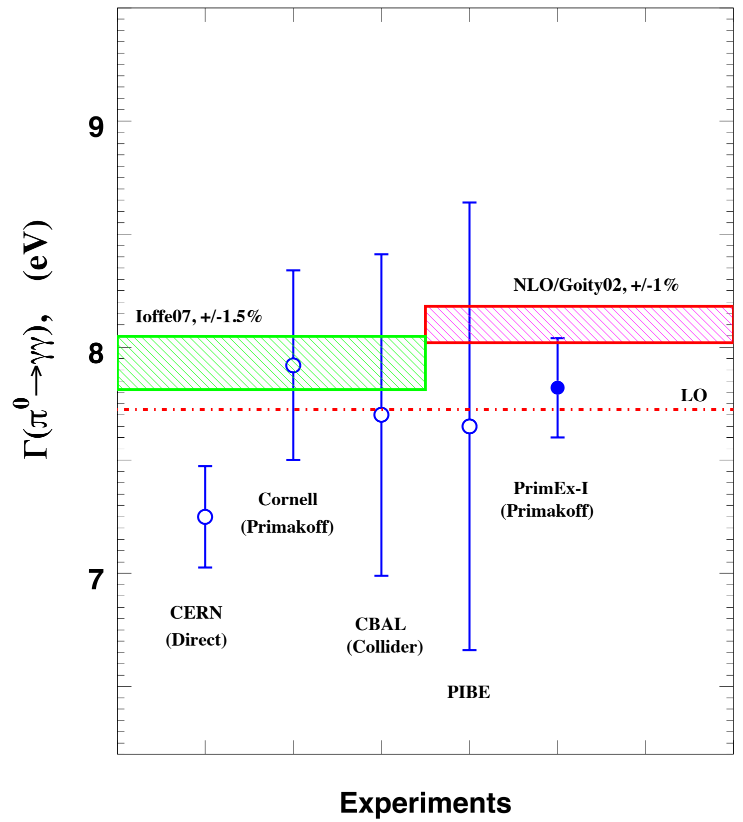
  Projected errors:
  ±0.5% (stat.) ±1.3% (syst.)



$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$, PDG Status Before and After the PrimEx-I Experiment



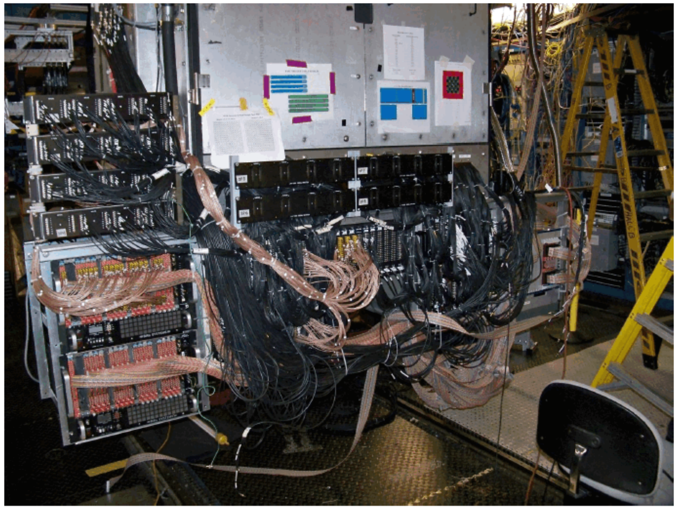


$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.82 \pm 0.14(\text{stat}) \pm 0.17(\text{syst})$ eV
2.8% total uncertainty

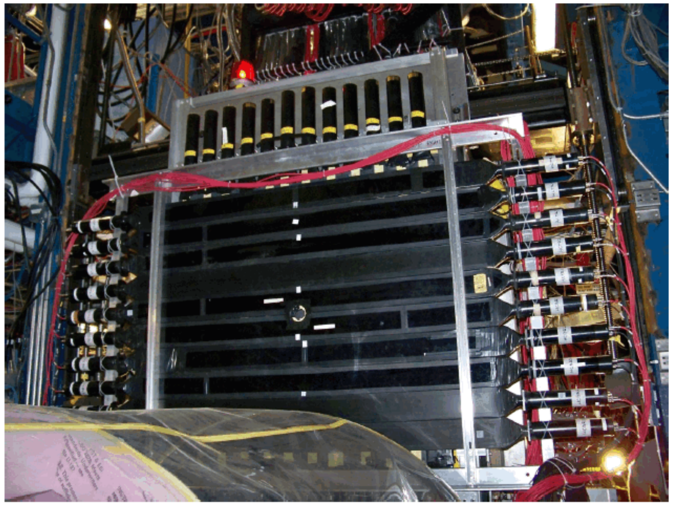
- ✓ PDG average on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ improved by factor of 2

Second Primakoff Experiment (PrimEx-II in Hall B, 2010)

- Statistics:
  - ✓ double the target thickness (10% R.L.)
  - ✓ Increase DAQ speed to 5 kHz (factor of 5 gain)
  - ✓ accept twice more tagged photon energy interval



- Systematics:
  - ✓ Add more timing information in HyCal
  - ➢ (~500 TDC channels)
  - ✓ Improve PID (add horizontal veto counters)
  - ✓ Improve photon beam line
  - ✓ Take more "empty target" data
  - ✓ Measure HyCal detection efficiency
  - ✓ get data for new ^{28}Si target.

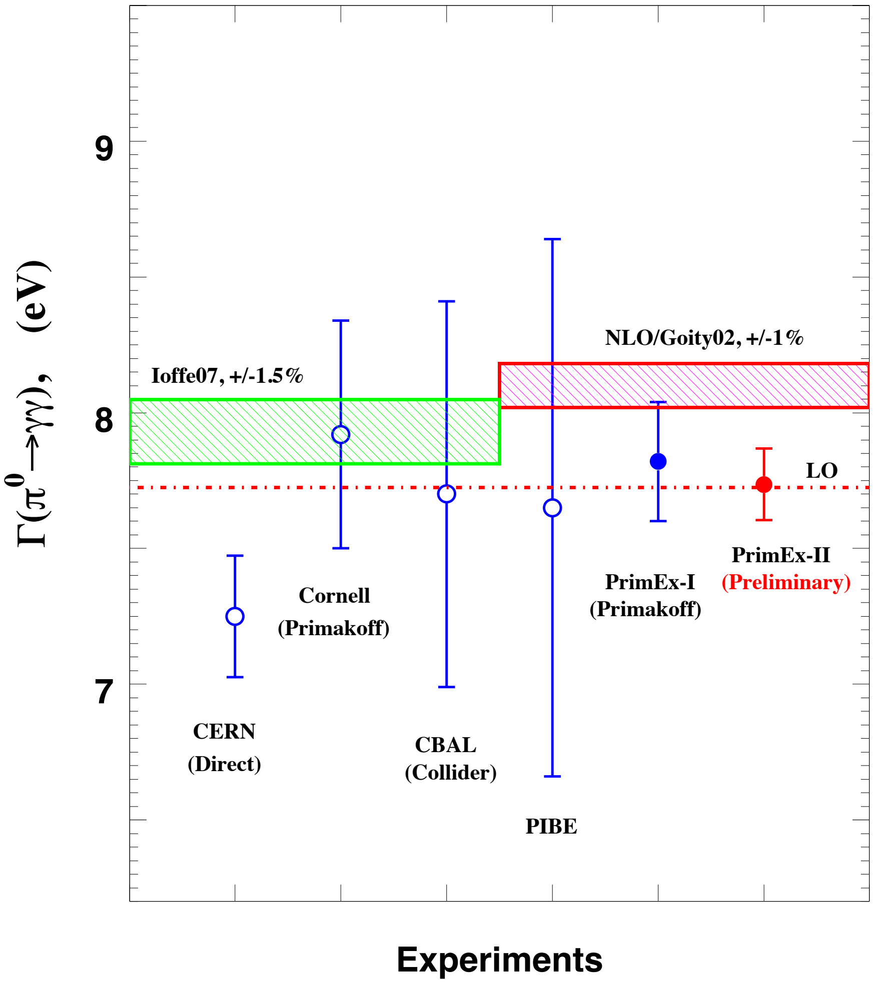


Preliminary Result from the PrimEx-II Experiment

- Results from the first group
  - (ITEP Moscow/China)
  - are presented (Preliminary).

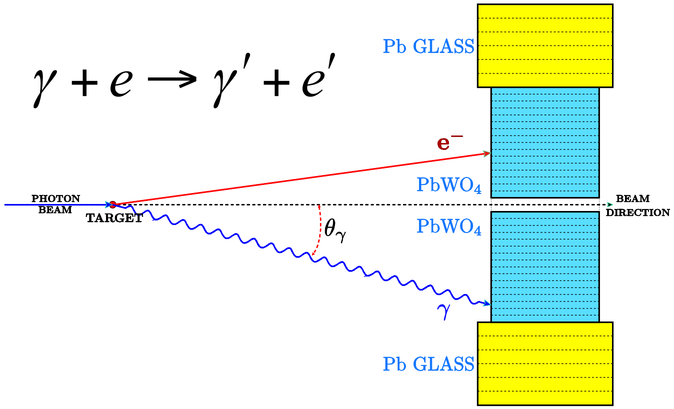
- $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.74 ± 0.06(stat.) ± 0.12(syst.) eV
- 1.7% total uncertainty

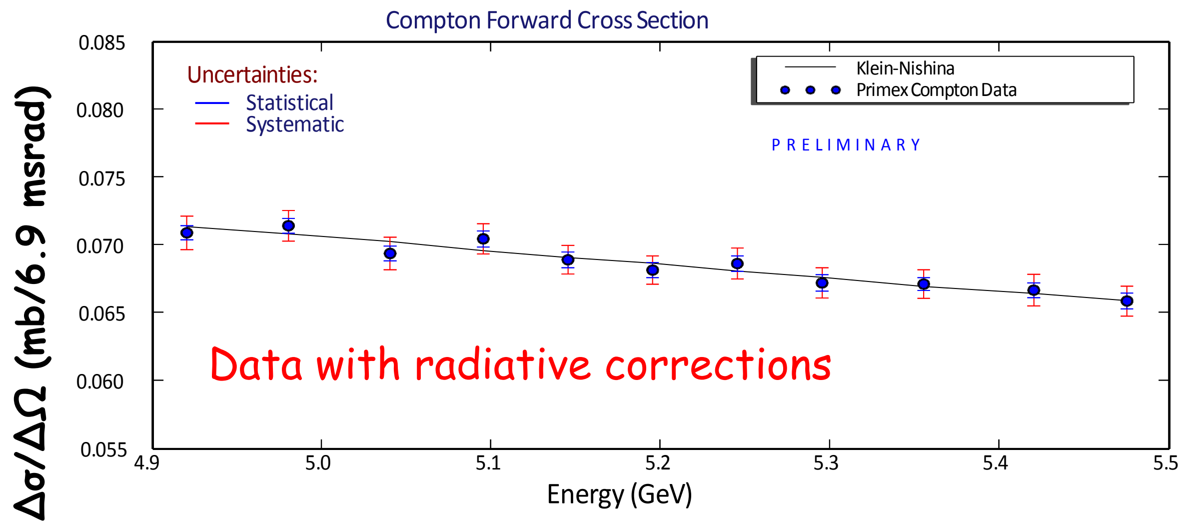
- Results from the second group
  - (Duke University)
  - are expected soon.

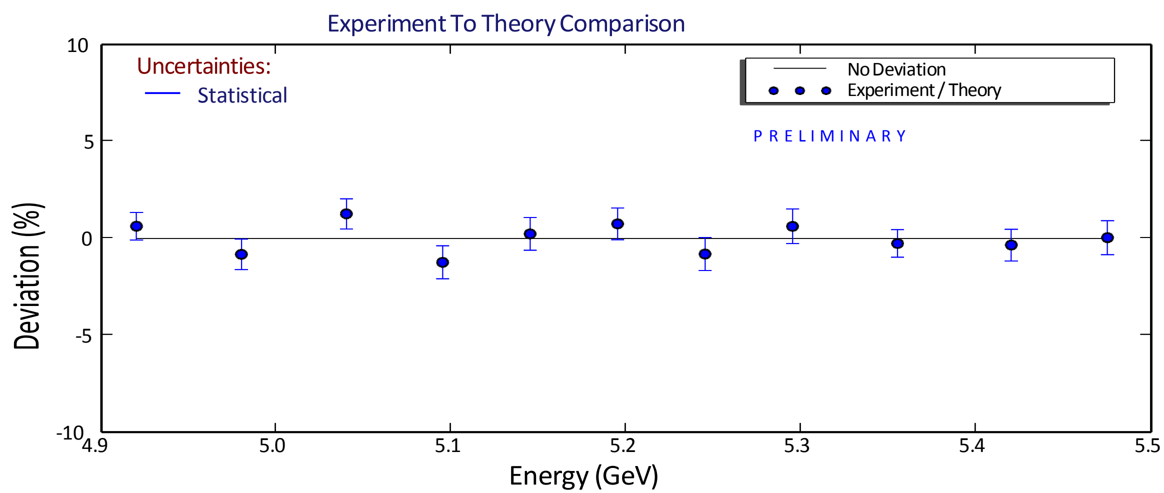


Verification of Overall Systematics: Compton Cross Section

$$\gamma + e \rightarrow \gamma' + e'$$







- **Average stat. error: 0.6%**
- **Average syst. error: 1.2%**
- **Total error: 1.3%**

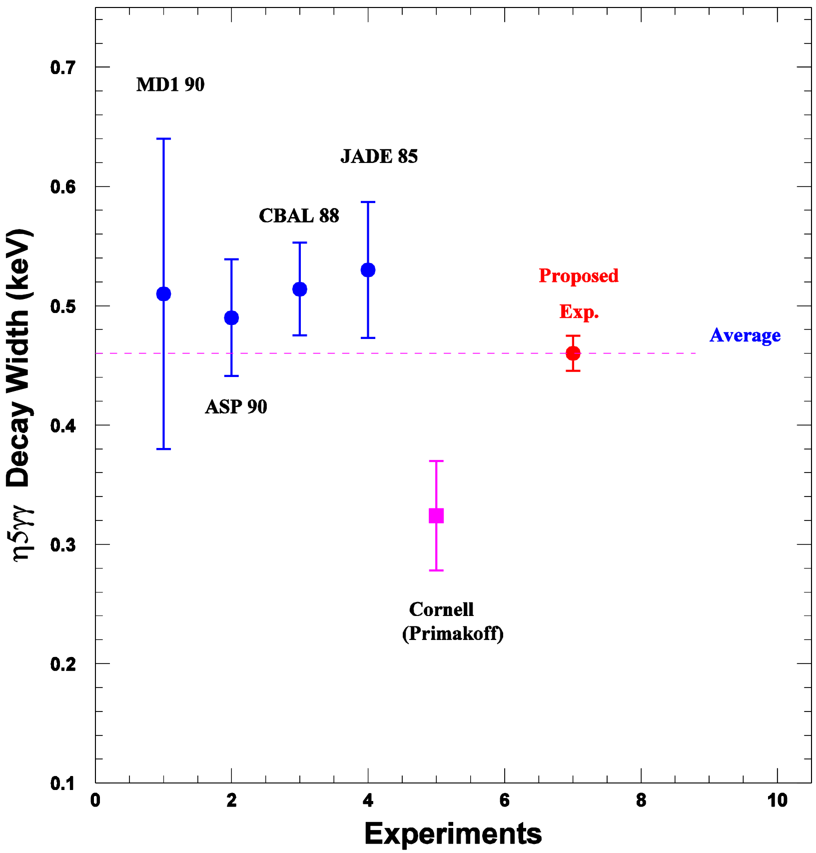
✓ **Cross sections in agreement with theory at the percent level**

$\eta \to \gamma\gamma$ Decay Width Experiment with GlueX

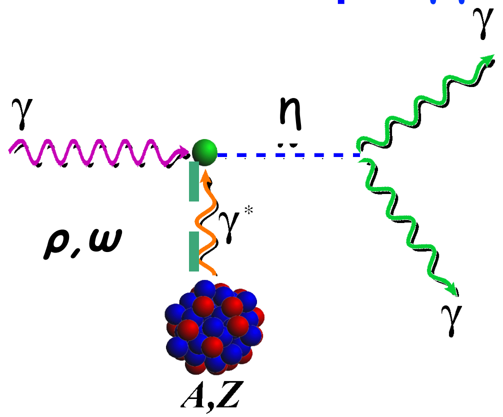
- To perform a new Primakoff type experiment with a precision of 3.2% using standard GlueX setup including the photon tagger and FCAL.

- Potentially solve collider/Primakoff discrepancy
- Improve (η - η') mixing angle
- most model independent determination of the light quark mass ratio
- Change whole decay widths of η-sector in PDG

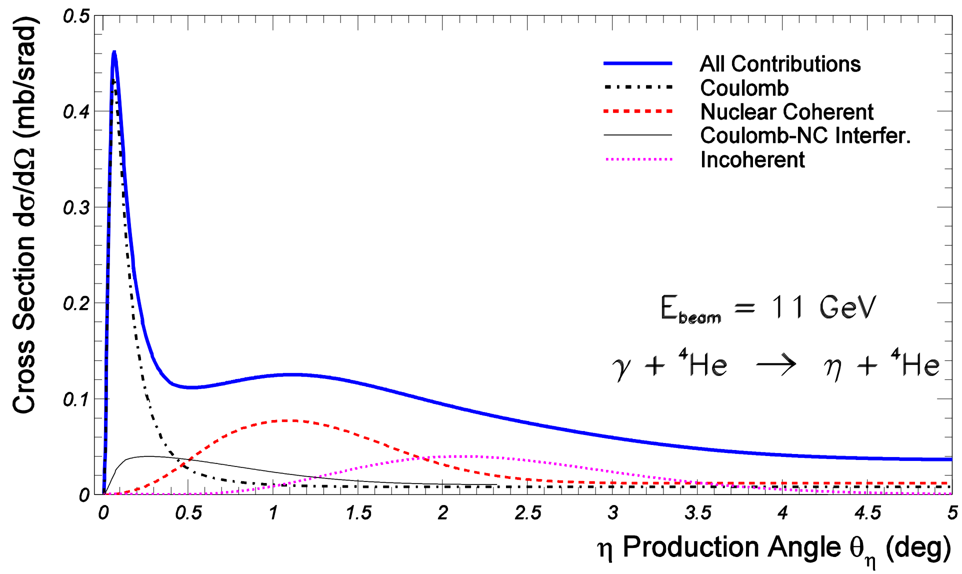
$\Gamma(\eta \to X) = \Gamma(\eta \to \gamma\gamma) * BR(X) / BR(\gamma\gamma)$



$\eta\to\gamma\gamma$ Decay Width Experiment with GlueX



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



- Difficulties of $\eta\to\gamma\gamma$ experiment:
  - η mass factor of 4 larger than π^0;
  - cross section is smaller;
  - larger overlap between Primakoff and hadronic processes;

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

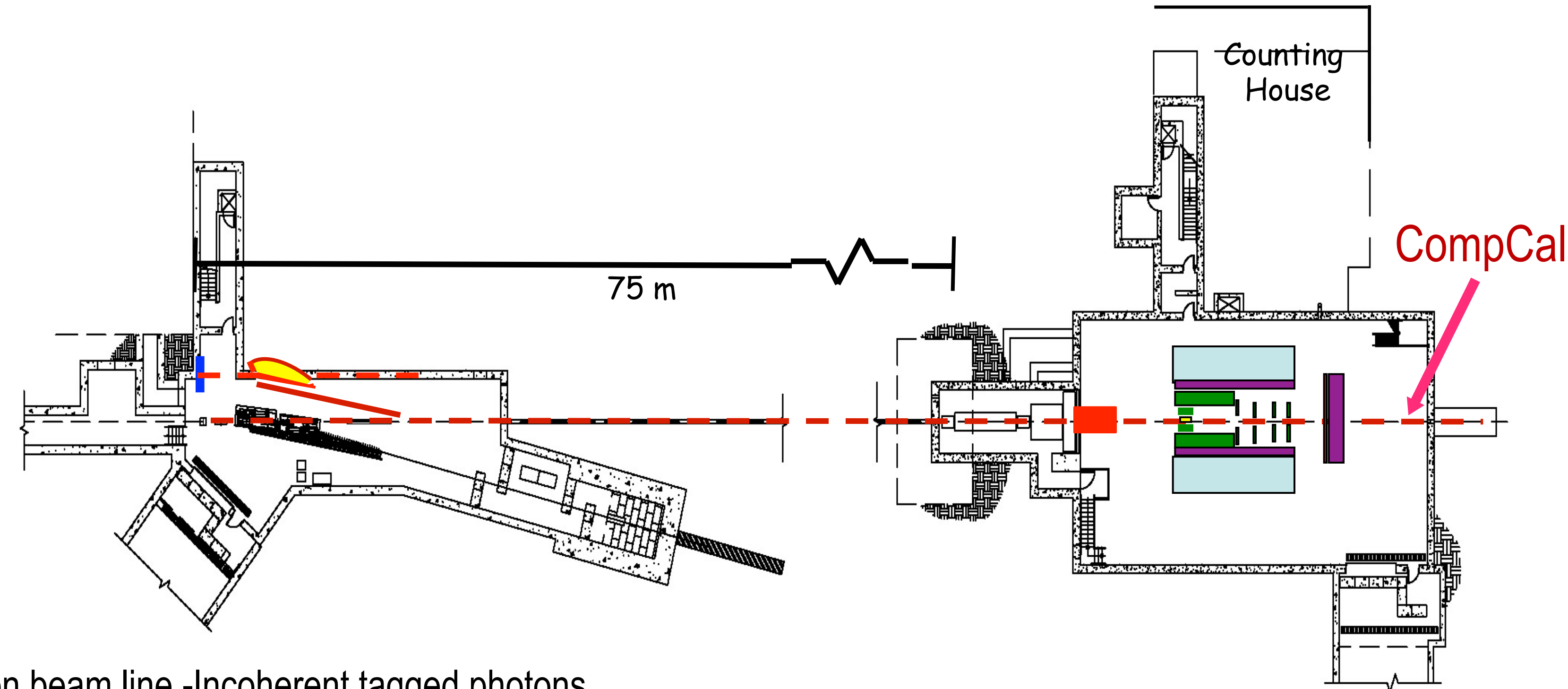
  - larger momentum transfer: (coherency, form factors, FSI,…)

Challenge: Separate Primakoff amplitude from hadronic processes.

We propose to use LH2 and LHe4 targets to address all those issues.

The Experimental Setup in Hall D

- We proposed to use GlueX standard setup for this measurement:



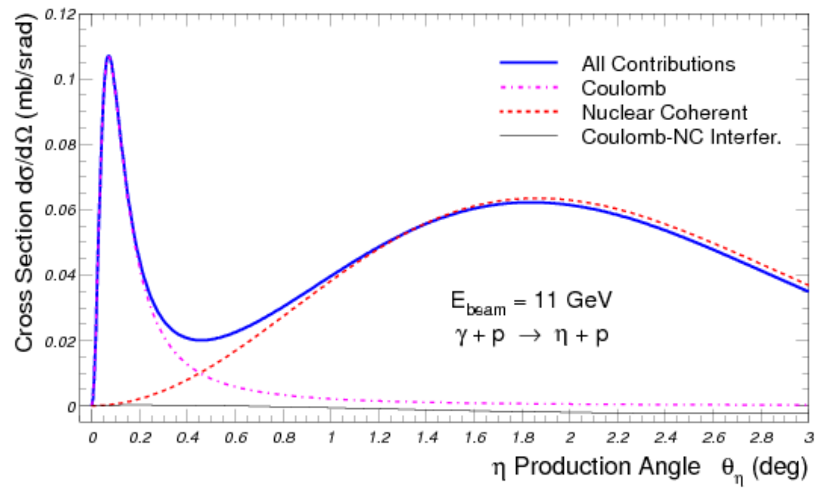
- Photon beam line -Incoherent tagged photons
- Pair spectrometer
- Solenoid detectors (for background rejection)
- 30 cm LH2 and LHe4 targets (~3.6% r.l.)
- Forward tracking detectors (for background rejection)
- Forward Calorimeter (FCAL) for $\eta \rightarrow \gamma\gamma$ decay photons
- Add CompCal detector for overall control of systematics

Advantages of the Proposed Targets

- Precision measurements require low A targets to control:
  - coherency
  - contributions from nuclear processes

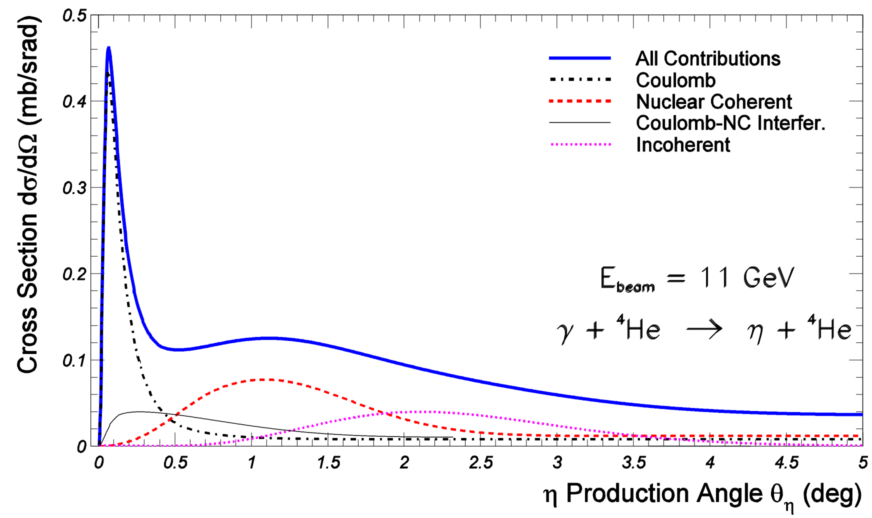
- **Hydrogen:**
  - ✓ no inelastic hadronic contribution
  - ✓ no nuclear final state interactions
  - ✓ proton form factor is well known
  - ✓ better separation between Primakoff and nuclear processes
  - ✓ new theoretical developments of Regge description of hadronic processes

J.M. Laget, Phys. Rev. C72, (2005)
A. Sibirtsev, et al. hep-ph/0902.1819 (2009)



- **^{4}He:**
  - ✓ higher Primakoff cross section
  - ✓ the most compact nucleus
  - ✓ form factor well known
  - ✓ new theoretical developments for FSI

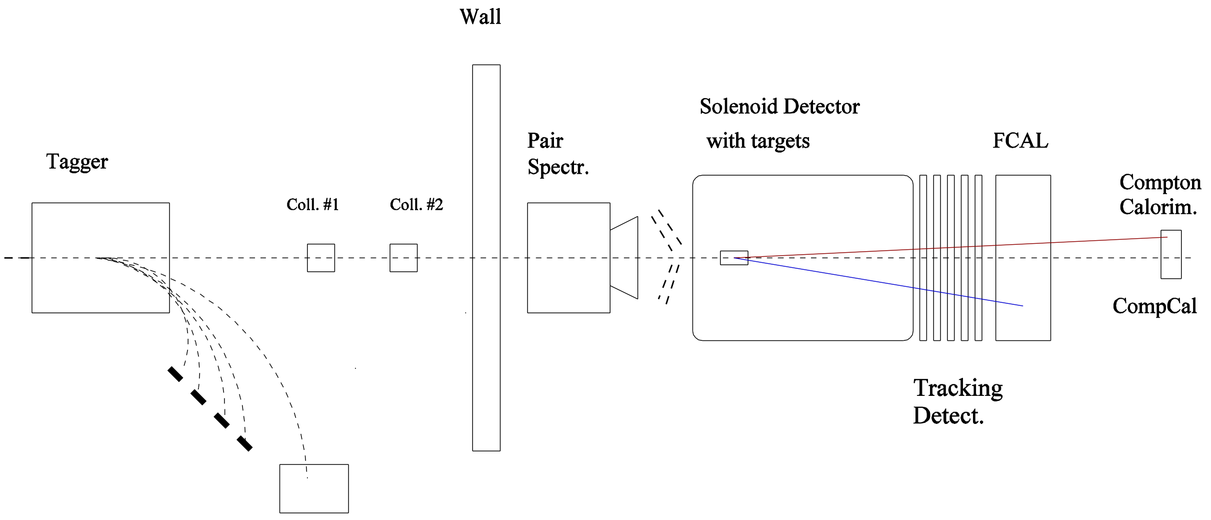
S. Gevorkyan et al., Phys. Rev. C 80, 2009



Control of Overall Systematics: Compton Cross Section Measurement

- Forward Compton cross section will be measured by new CompCal detector in combination with FCAL

$$\gamma + e \rightarrow \gamma' + e'$$



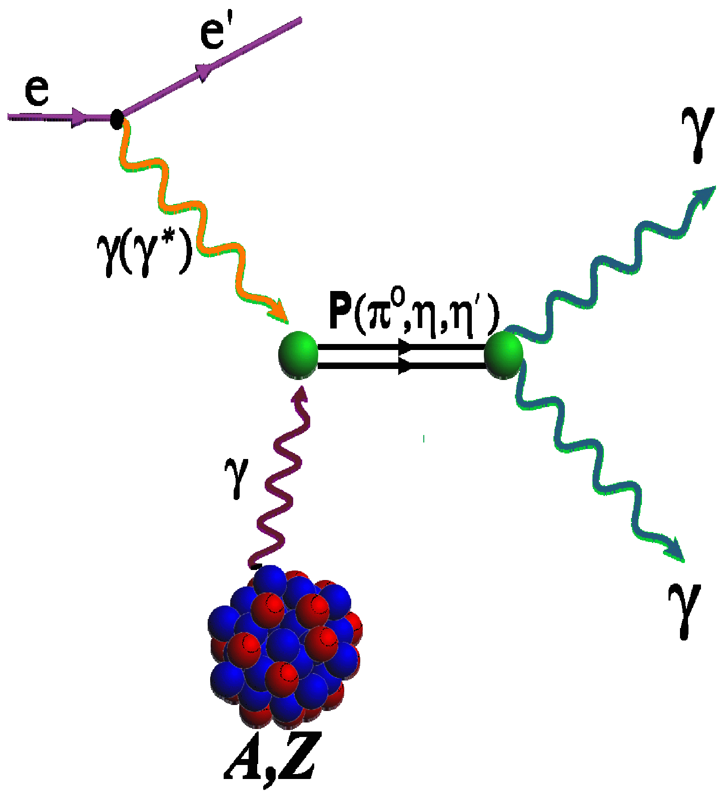
- CompCal calorimeter:
  10x10 (20x20 cm^2) $PbWO_4$ crystal detector

Virtual Primakoff Production:
(second generation Primakoff experiments)

Experimental program

Precision measurements of:

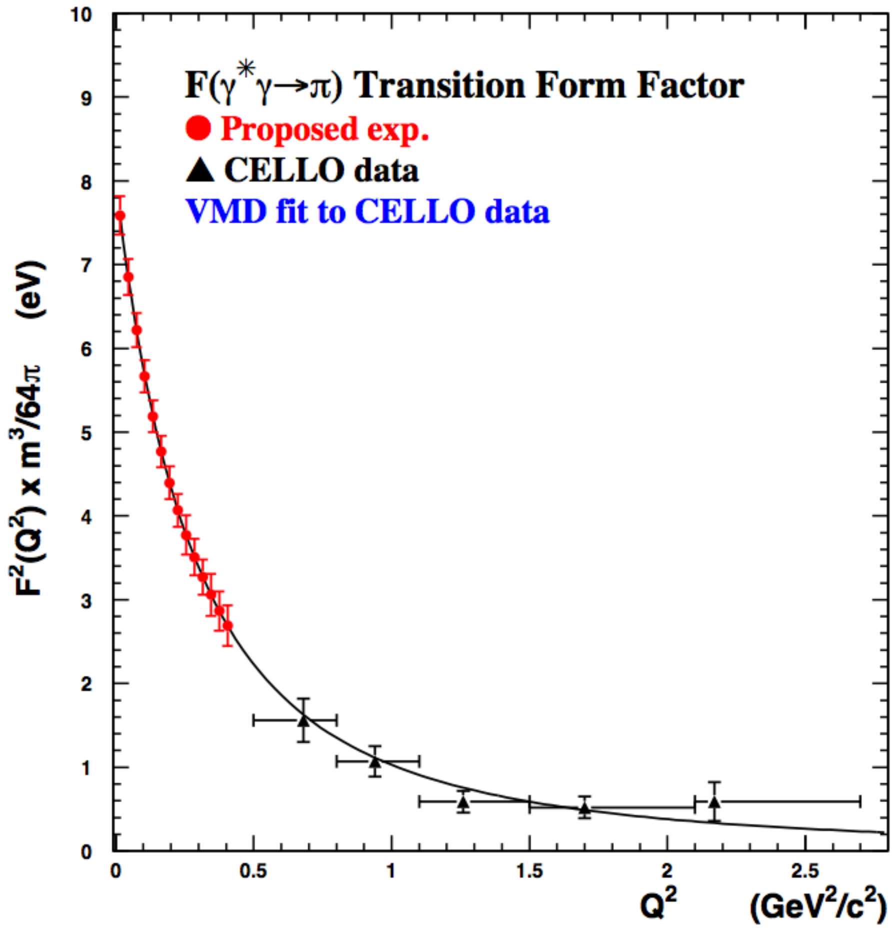
- Transition Form Factors at low Q^2 (0.001-0.5 GeV^2/c^2): $F(\gamma\gamma^* \rightarrow \pi^0)$, $F(\gamma\gamma^* \rightarrow \eta)$, $F(\gamma\gamma^* \rightarrow \eta')$



Test of Chiral Symmetry and Anomalies via the Primakoff Effect

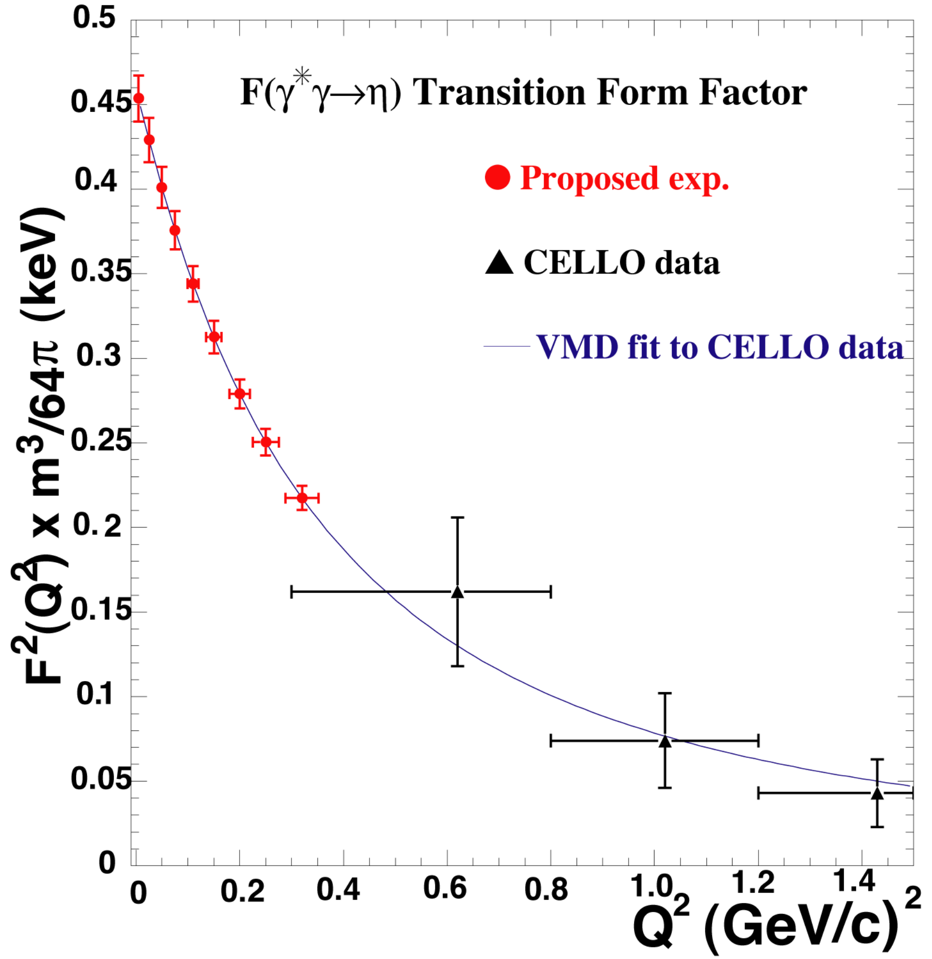
$F(\gamma\gamma^* \to \pi^0)$ Transition Form Factor

Work in progress for a new proposal



F(γγ* →η) Transition Form Factor

Work in progress for a new proposal



Third Generation Primakoff Experiments
(future Primakoff experiments)

- Primakoff production on atomic electrons:

$$e^- + e^- \rightarrow e^- + \pi^0 + e^-$$

Or:

$$\gamma + e^- \rightarrow \pi^0 + e^-$$

Requires: $E\gamma > E_{threshold}$ (~ 20 GeV)

✓ No hadronic contributions !

Summary

- Primakoff production is an effective mechanism to measure electromagnetic properties of the pseudoscalar mesons with high precisions.

- A rich and comprehensive experimental program has been developed at JLab to measure radiative decay widths and transition form factors at very low Q^2 for the light pseudoscalar mesons: π^0, η, η'

- Two PrimEx experiments are already performed in Hall B to extract the $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ decay width with a percent level precision.

- The $\eta \rightarrow \gamma\gamma$ decay width experiment is approved for Hall D with the GlueX experimental setup.

- Active work is in progress for the next experimental proposals at JLab..

The End

Physics Outcome from New $\eta \to \gamma\gamma$ Experiment

- **Light quark mass ratio:**

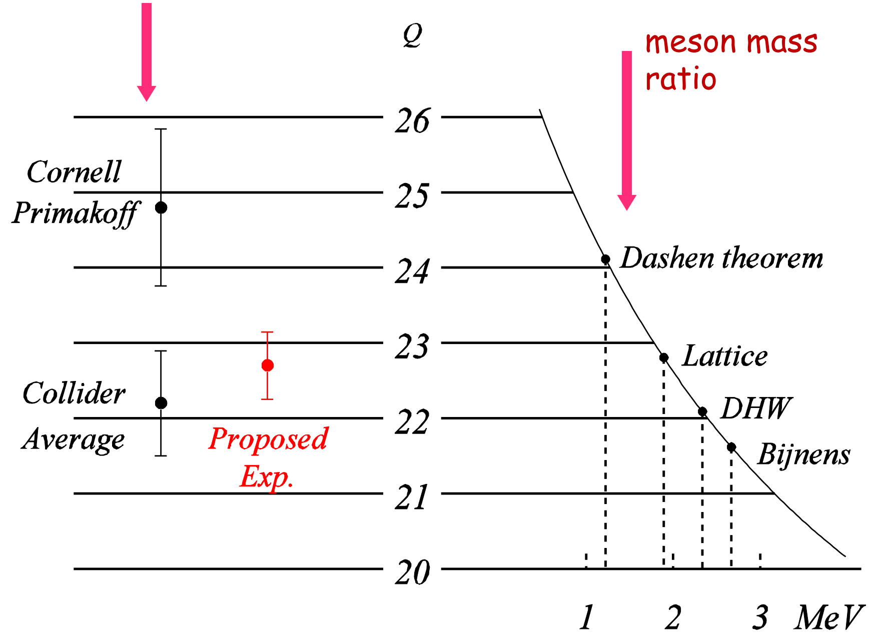
$\eta \to 3\pi$ **forbidden** by isospin symmetry, therefore:

$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$ with:

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

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

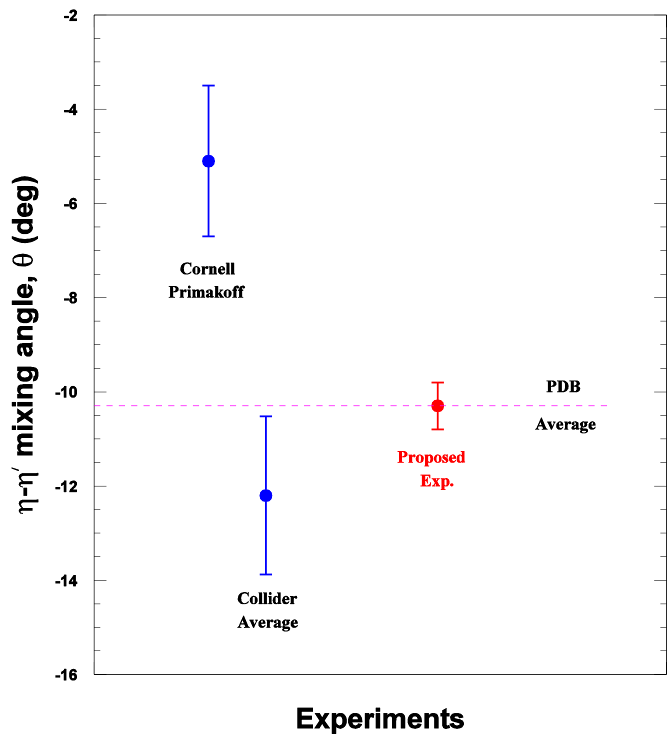
$(K^+ - K^0)_{e.m.}$



$(m_{K^0} - m_{K^+})_{e.m.}$ Corr.

H. Leutwyler PLB, 378,1996

- **(η - η') mixing angle:**



Modifications from Nominal GlueX Running

- **The Hall D/GlueX apparatus will be used in the following settings:**
  - ***Incoherent tagged bremsstrahlung photon beam:***
    (~10^{-4} r.l. amorphous Au radiator, I_e ~ 0.2 μA)
    - ✓ better stability at endpoint energy spectrum
    - ✓ less sensitive to radiation
  - ***5.0 mm diameter beam collimator:***
    vs. 3.4 mm at 75 m from tagger
    - ✓ better photon flux stability (within 1%)
    - ✓ double the tagging efficiency (from ~15% to ~30%)
  - ***Solenoid field off*:**
    - ✓ precision measurement of forward Compton cross section for overall control of systematics
- **This configuration requires dedicated run.**

Experimental Methods: Decay Length Measurement (Direct Method)

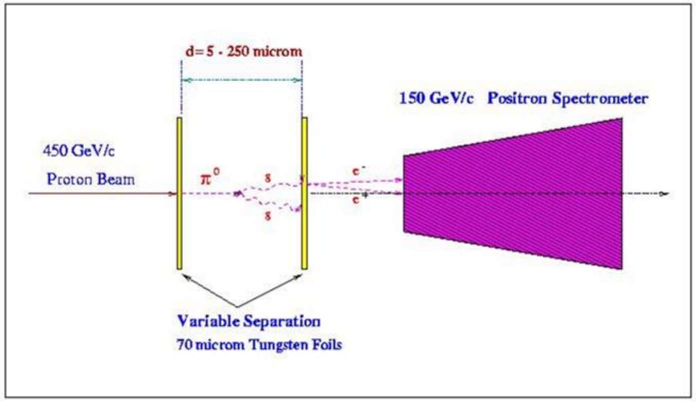
- Measure π^0 decay length distribution

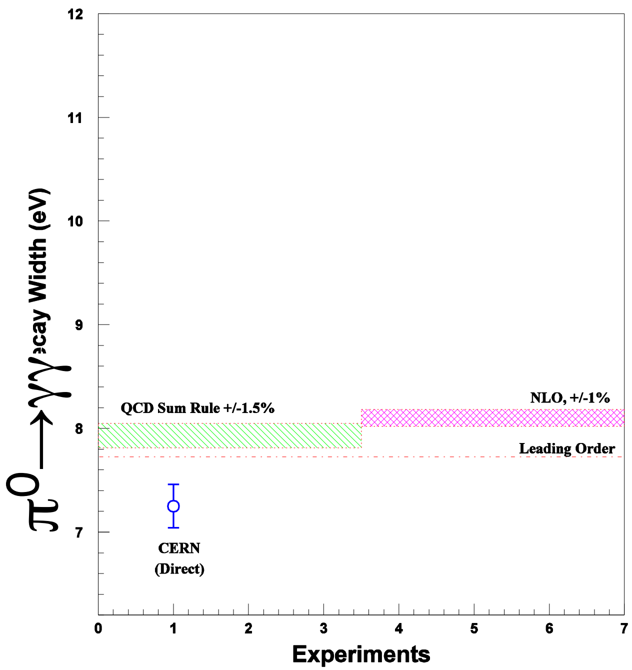
- $\tau_\pi \sim 1\times10^{-16}$ sec $\Rightarrow$ too small to measure

solution: Create energetic π^0 's,
$L = v\tau_\pi E_\pi / m_\pi$

But, for E= 1000 GeV, L_{mean} ~ 100 μm
very challenging experiments

1984 CERN experiment:
P=450 GeV proton beam
Two variable separation (5-250μm) foils
Result:
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.34eV±3.1% (total)





- Major limitations of method
- unknown P_{π^0} spectrum
- needs higher energies for improvement

$\pi^0 \to \gamma\gamma$ decay width (Theory)

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

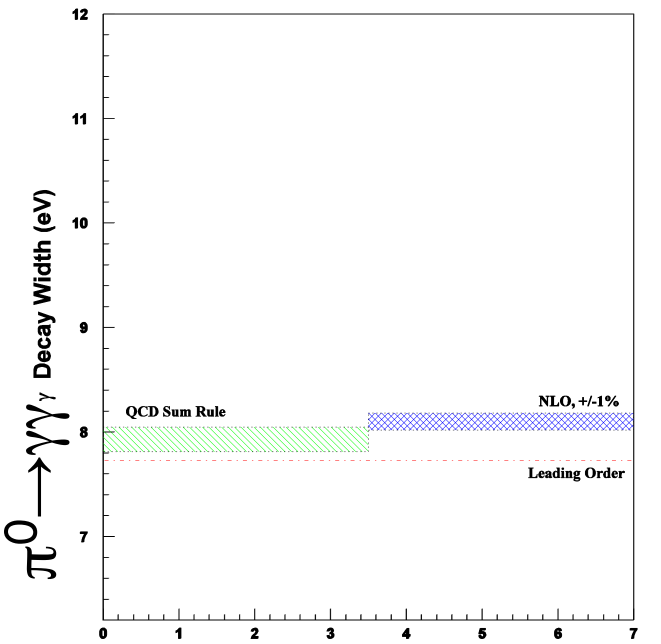
$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.725\ eV$$

- Corrections to the chiral anomaly prediction:
  (u-d quark masses and mass differences)
  Calculations in NLO ChPT:
  (J. Goity, at al. Phys. Rev. D66:076014, 2002)
  $\Gamma(\pi^0 \to \gamma\gamma) = 8.10\text{eV} \pm 1.0\%$

~4% higher than LO, uncertainty: less than 1%

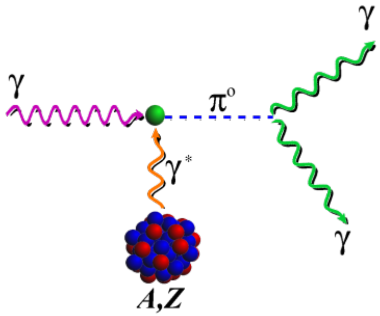
- Recent calculations in QCD sum rule:
  (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)
  - $\Gamma(\eta \to \gamma\gamma)$ is only input parameter
  - π^0-η mixing included

  $\Gamma(\pi^0 \to \gamma\gamma) = 7.93\text{eV} \pm 1.5\%$

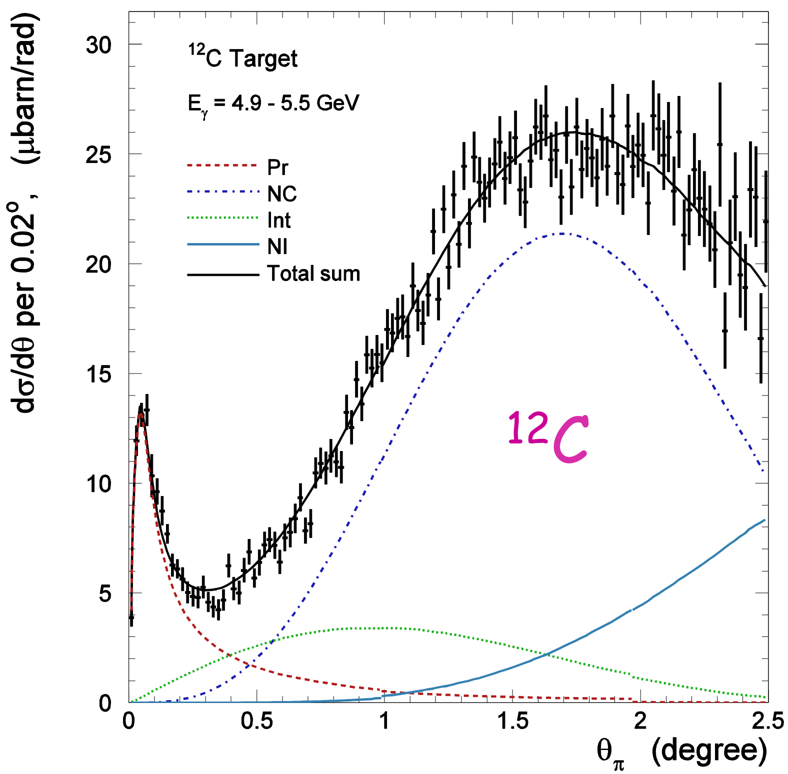


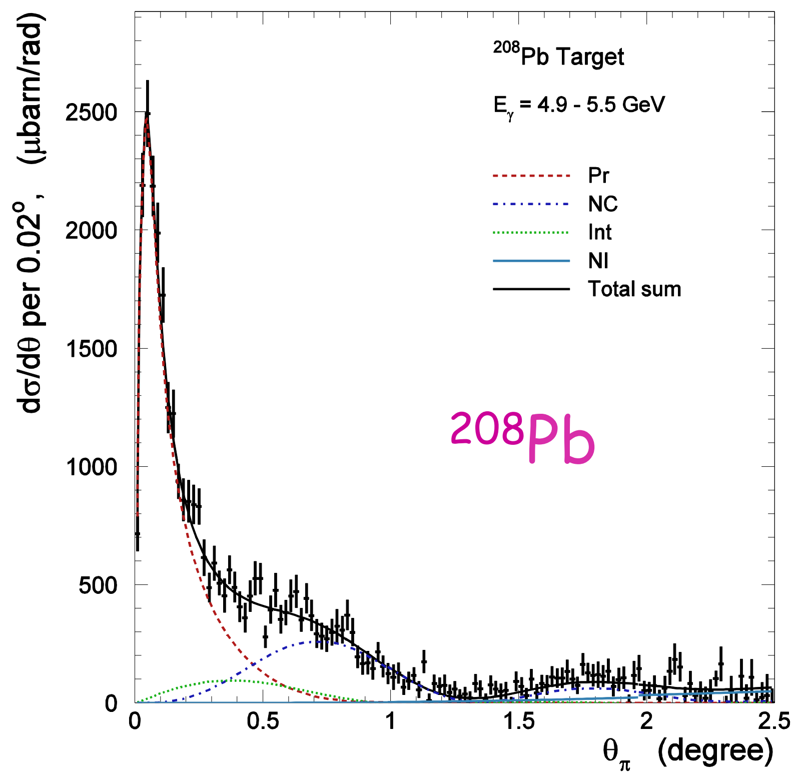
- Precision measurements of $\Gamma(\pi^0 \to \gamma\gamma)$ at the percent level will provide a stringent test of a fundamental prediction of QCD.

Results from PrimEx-I Experiment



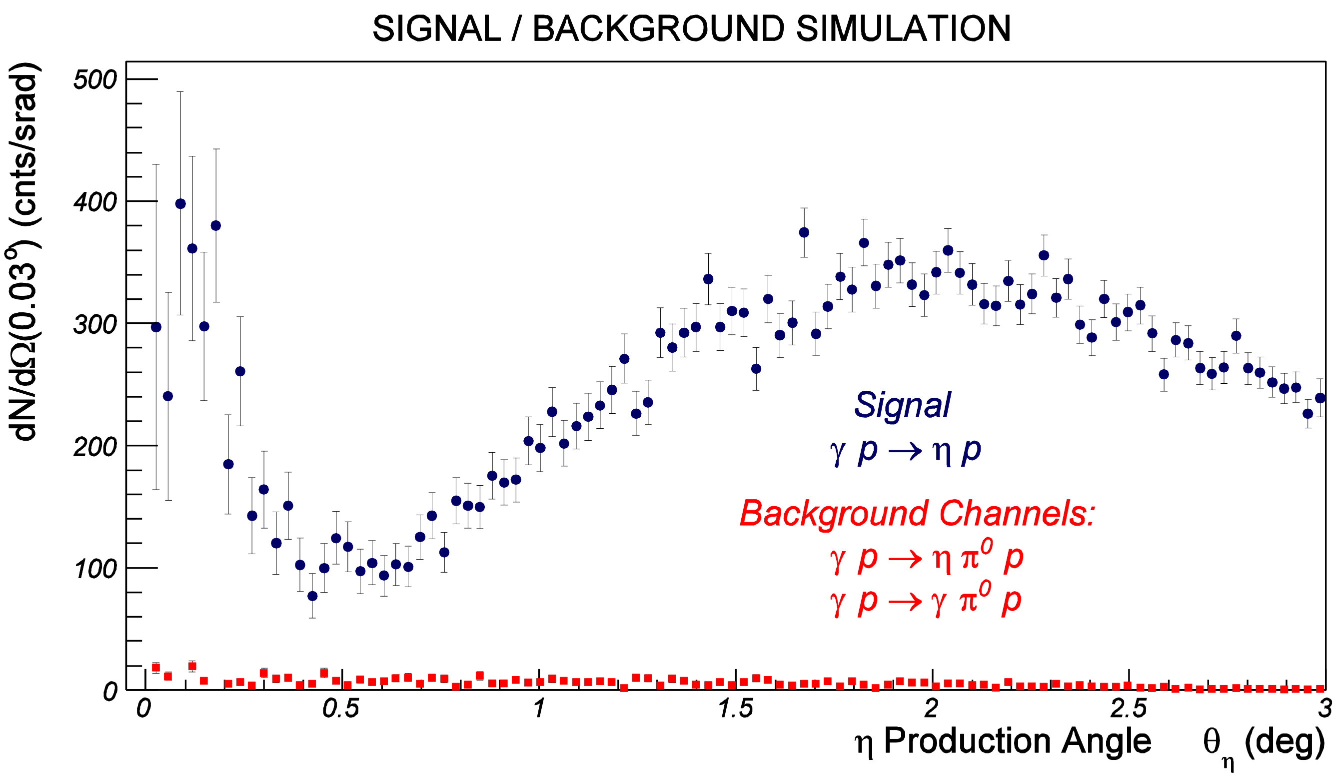
- Nuclear targets: ^{12}C and ^{208}Pb;
- 6 GeV Hall B tagged beam;
- experiment performed in 2004





Physics Background

- Monte Carlo simulation with Hall D/GlueX GEANT and Pythia generator



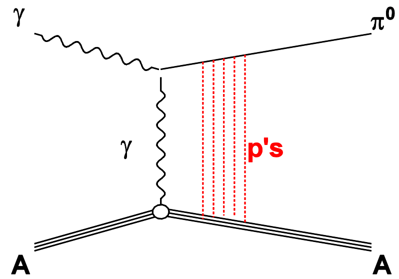
- event selection criteria are applied for both signal and background.
- other GlueX detectors (BCAL, …) are critical for background suppression.
- remaining background level: ~3%, will be subtracted off-line.

π^0 Forward Photoproduction off Complex Nuclei: (theoretical models)

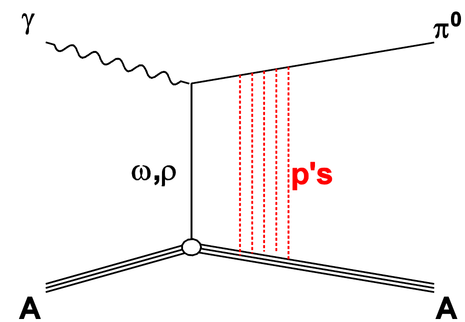
- Coherent Production $\gamma + A \rightarrow \pi^0 + A$

Leading order processes:

(with absorption)



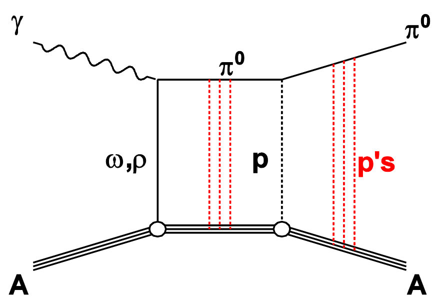
Primakoff



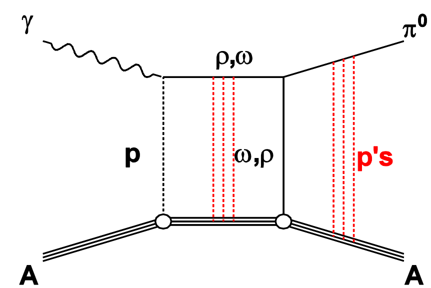
Nuclear coherent

Next-to-leading order:

(with absorption)



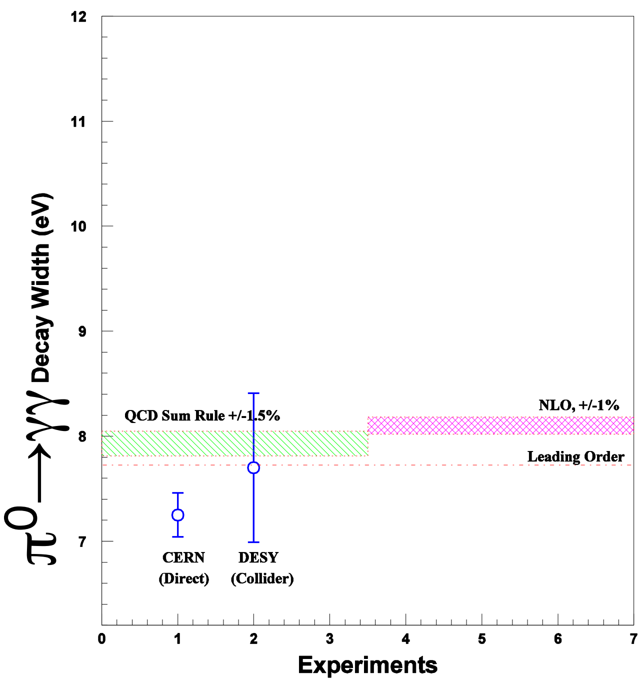
π^0 rescattering



Photon shadowing

e^+e^- Collider Experiment

- Experiment at DORIS II @ DESY
  - $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0 \to e^+e^-\gamma\gamma$
  - e^+, e^- scattered at small angles (not detected)
  - only $\gamma\gamma$ detected
  - Results:
    $\Gamma(\pi^0 \to \gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV ($\pm$ 10.0%)



- Not included in PDG average

- Major limitations of method:
  - unknown q^2 for $\gamma^*\gamma^*$
  - knowledge of luminosity