π^0 Lifetime Measurement

Dustin E. McNulty
PrimEx Collaboration
MIT/Jlab
mcnulty@jlab.org

April 8, 2005

π^0 Lifetime Measurement

- Introduction: Physics Motivation and Goals

  QCD Axial Anomaly

  Quark Mass Effects

- Pion Photoproduction Cross section

  Primakoff

  Nuclear Coherent

  Incoherent

- Experimental Overview

- Analysis Status

PrimEx Collaboration

Spokesperson
Spokesperson and contact person

A. Afanasev [p], A. Ahmidouch [m], M. Alexanian [u], A. Asratyan [i], I. Aznauryan [x], K. Baker [f], J. Ball [a], A.M. Bernstein [k], T. Black [u], W. Briscoe [e], J.P. Chen [p], O. Chernyshov [i], M. Christy [f], E. Chudakoff [p], E. Clinton [t], P.L. Cole [v], H. Crannell [b], D. Dale [s], S. Danagoulian [m], G. Davidenko [i], A. Dolgolenko [i], M. Dugger [a], G. Dzyubenko [i], H. Egiyan [p], K. Egiyan [x], M. Elaasar [o], R. Ent [p], A. Evdokimov [i], A.I. Fix [q], M. Gabrielyan [s], L. Gan [u], **A. Gasparian [m]**, S. Gevorgyan [x], A. Glamazdin [j], J. Goity [f], Yu. Goncharenko [h], V. Goryachev [i], P. Gueye [f], V. Gyurjyan [p], R. Hakobyan [b], D. Hasell [k], J. He [g], R. Hicks [t], M. Hollister [u], B. Hu [s], M. Ito [p], C. Jackson [m], A. Kamenskii [i], C. Keppel [f], A. Ketikyan [x], M. Khandaker [l], W. Korsch [s], S. Kowalski [k], M. Kubantsev [i], V. Kubarovsky [h], I. Larin [i], D. Lawrence [t], C. Li [c], Z. Liu [c], S. Lu [c], A. Margaryan [x], V. Matveev [i], A. Meschanin [h], B. Milbrath [d], R. Minehart [w], R. Miskimen [t], S. Mtingwa [m], A. Nathan [r], A. Omelaenko [j], E. Pasyuk [a], A. Petrosyan [x], V. Punjabi [l], B.G. Ritchie [a], C. Salgado [l], V. Semyachkin [i], A. Shahinyan [x], Y. Sharabian [p], A. Sitnikov [i], E. Smith [p], D. Sober [b], L. Soloviev [h], B. Stevens [w], R. Suleiman [k], L. Tang [f], A. Teymurazyan [s], V.A. Tryasuchev [q], J. Underwood [m], A. Vasiliev [h], V. Verebryusov [i], V. Vishnyakov [i], H. Voskanyan [x], J. Yuan [c], L. Yuan [f], J. Zhou [c], S. Zhou [c], X. Zhu [c], P. Zolnierczuk [s]

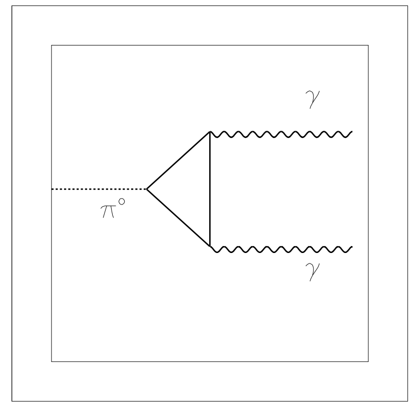
[a] Arizona State University, Tempe, AZ
[b] Catholic University of America, Washington, DC
[c] Chinese Institute of Atomic Energy, Beijing, China
[d] Eastern Kentucky University, Richmond, KY
[e] George Washington University, Washington, DC
[f] Hampton University, Hampton, VA
[g] Institute for High Energy Physics, Chinese Academy of Sciences, Beijing, China
[h] Institute for High Energy Physics, Protvino, Moscow region, Russia
[i] Institute for Theoretical and Experimental Physics, Moscow, Russia
[j] Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[k] Massachusetts Institute of Technology, Cambridge, MA
[l] Norfolk State University, Norfolk, VA
[m] North Carolina A&T State University, Greensboro, NC
[n] North Carolina Central University, Durham, NC
[o] Southern University at New Orleans, New Orleans, LA
[p] Thomas Jefferson National Accelerator Facility, Newport News, VA
[q] Tomsk Polytechnical University, Tomsk, Russia
[r] University of Illinois, Urbana, IL
[s] University of Kentucky, Lexington, KY
[t] University of Massachusetts, Amherst, MA
[u] University of North Carolina at Wilmington, Wilmington, NC
[v] University of Texas at El Paso, El Paso, TX
[w] University of Virginia, Charlottesville, VA
[x] Yerevan Physics Institute, Yerevan, Armenia

Physics Motivation

- π^0 decay rate is a fundamental prediction of confinement scale QCD.

Chiral Anomaly

Presence of closed loop triangle diagram results in nonconserved axial vector current, even in the limit of vanishing quark masses.



$\rightarrow$In the leading order (chiral limit), the anomaly leads to the decay amplitude:

$$A_{\pi^0 \to \gamma\gamma} = \frac{\alpha_{em}}{4\pi F_\pi} \varepsilon_{\mu\nu\rho\sigma} k^\mu k'^\nu \varepsilon^{*\rho} \varepsilon^{*\sigma}, \quad (1)$$

or the reduced amplitude,

$$A_{\gamma\gamma} = \frac{\alpha_{em}}{4\pi F_\pi} = 0.02513 \text{ GeV}^{-1} \quad (2)$$

where $F_\pi = 92.42 \pm 0.25$ MeV is the pion decay constant.

Physics Motivation

The $\pi^0 \rightarrow \gamma\gamma$ decay width predicted by this amplitude is

$$\Gamma_{\pi^0 \rightarrow \gamma\gamma} = m_\pi^3 \frac{|A_{\gamma\gamma}|^2}{64\pi} = 7.725 \pm 0.044 \text{ eV} \qquad (3)$$

$\rightarrow$Current Particle Data Book value is 7.84 ± 0.56 eV

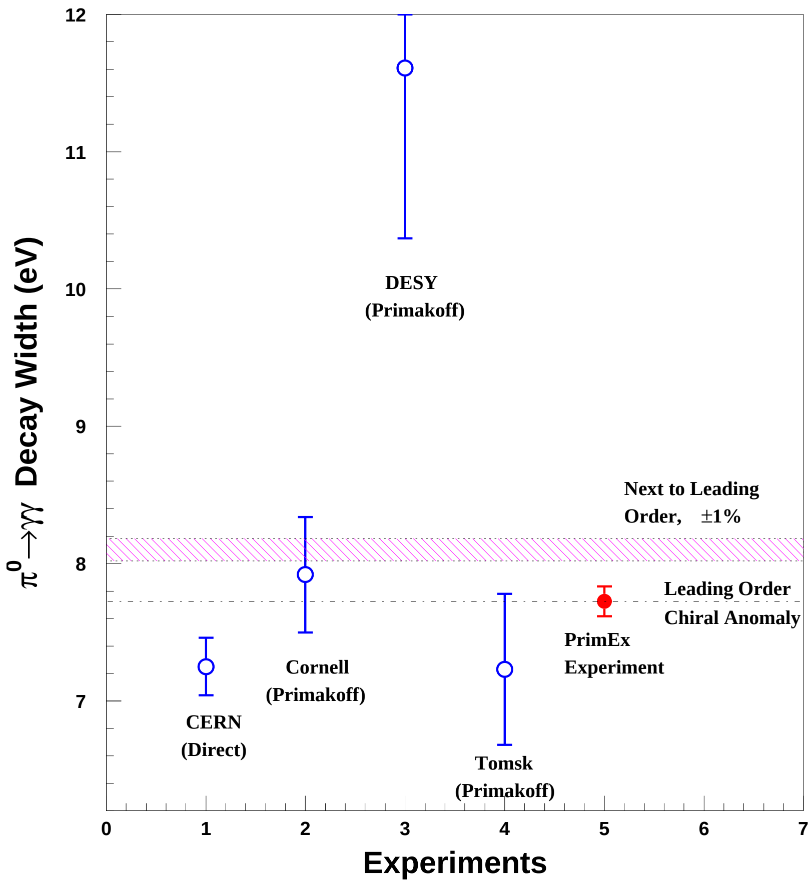
The above result for the decay amplitude is exact in the chiral limit, however, for non-vanishing quark masses there are corrections to this amplitude.

$\rightarrow$Next to Leading Order prediction for the decay width is $8.10 \text{ eV} \pm < 1\%$

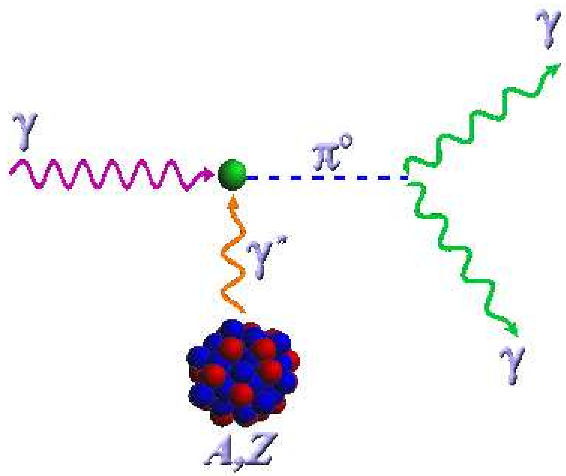
This is 4% higher than current experimental value.

Physics Goal

- Use the Primakoff effect to measure $\Gamma_{\pi^0 \to \gamma\gamma}$ to within 1.5% uncertainty



Primakoff Effect



- π^0 photoproduction from Coulomb field of nucleus.
- Equivalent production ($\gamma\gamma^* \to \pi^0$) and decay ($\pi^0 \to \gamma\gamma$) mechanism implies Primakoff cross section proportional to π^0 lifetime.
- Primakoff π^0 produced at very forward angles.

Primakoff Cross Section

$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\to\gamma\gamma)} \frac{8\alpha_{em}Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{em}(Q)|^2 sin^2\theta_\pi \tag{4}$$

- $\Gamma_{(\pi^0\to\gamma\gamma)}$ is the pion decay width $\propto \frac{1}{lifetime}$.
- α_{em} is fine structure constant, and Z is the atomic # of target nuclei.
- m, β, θ_π are the mass, velocity and production angle of the pion.
- E is the energy of incoming photon.
- Q is the momentum transfer to the nucleus.
- $F_{em}(Q)$ is the nuclear electromagnetic form factor.

Nuclear Coherent

$$\frac{d\sigma_C}{d\Omega} = C \cdot A^2 |F_N(Q)|^2 sin^2\theta_\pi \qquad (5)$$

- A is the nucleon number.
- $\sqrt{C} sin\theta_\pi$ is the spin independent part of the neutral meson photoproduction amplitude on a single nucleon.
- $F_N(Q)$ is the form factor for nuclear matter distribution in the target nucleus.

Incoherent

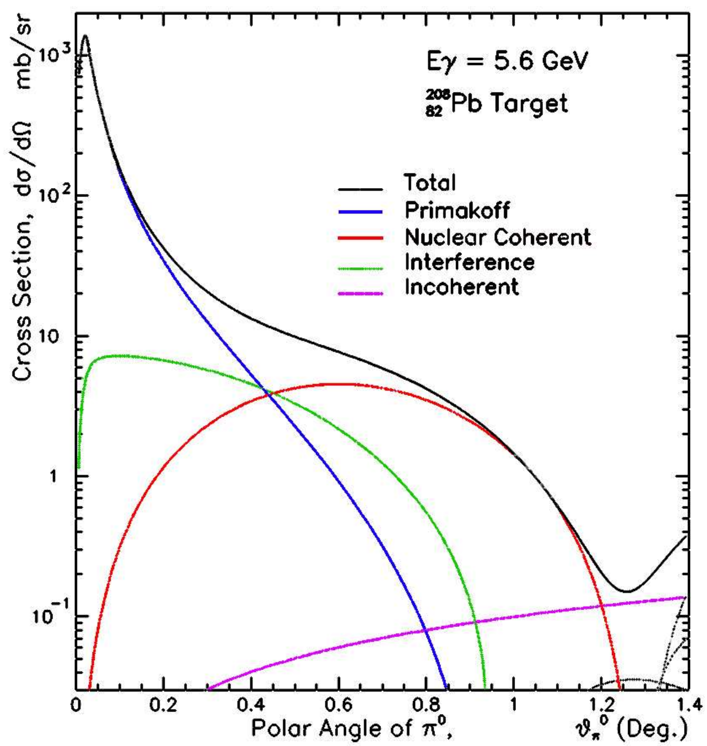
$$\frac{d\sigma_I}{d\Omega} = \xi A(1 - G(Q)) \frac{d\sigma_H}{d\Omega} \tag{6}$$

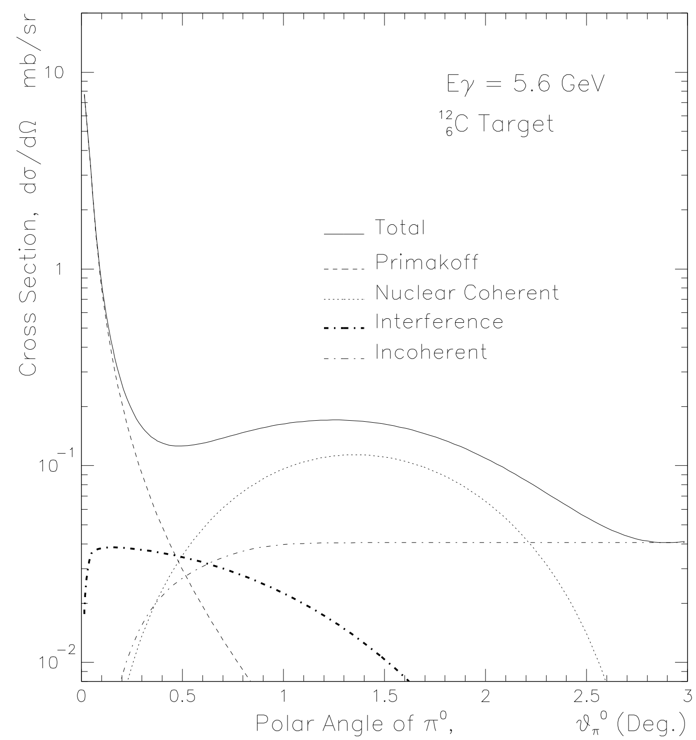
- ξ is the absorption factor for the incoherently produced pions.
- $1 - G(Q)$ ia a factor which reduces the cross section at small momentum transfer.
- $\frac{d\sigma_H}{d\Omega}$ is the π^0 photoproduction cross section on a single nucleon.

Full Cross Section

$$\frac{d\sigma}{d\Omega_\pi} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_C}{d\Omega} + \frac{d\sigma_I}{d\Omega} + 2\cdot\sqrt{\frac{d\sigma_P}{d\Omega}\cdot\frac{d\sigma_C}{d\Omega}}\cos(\phi) \qquad (7)$$

Primakoff Nucl.Coherent Incoherent Interference

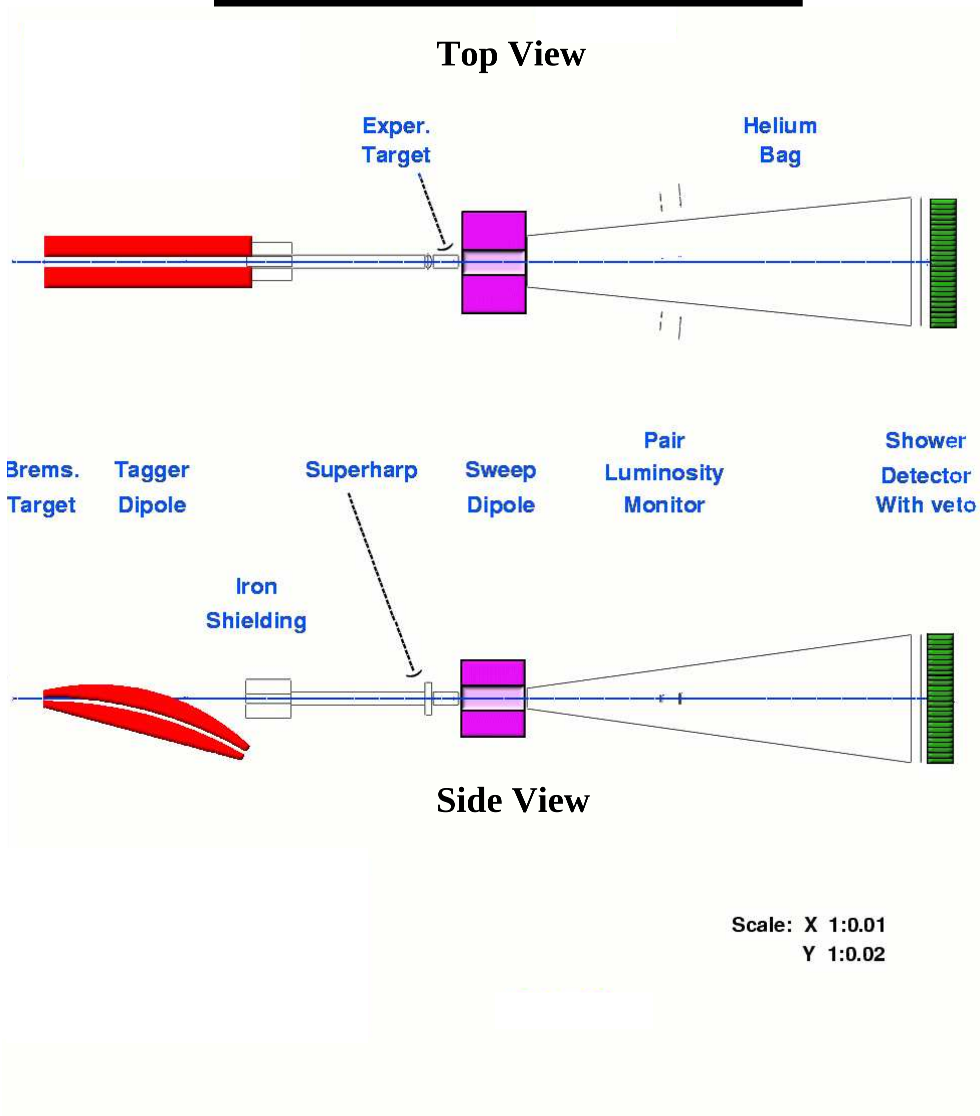




Experiment Overview

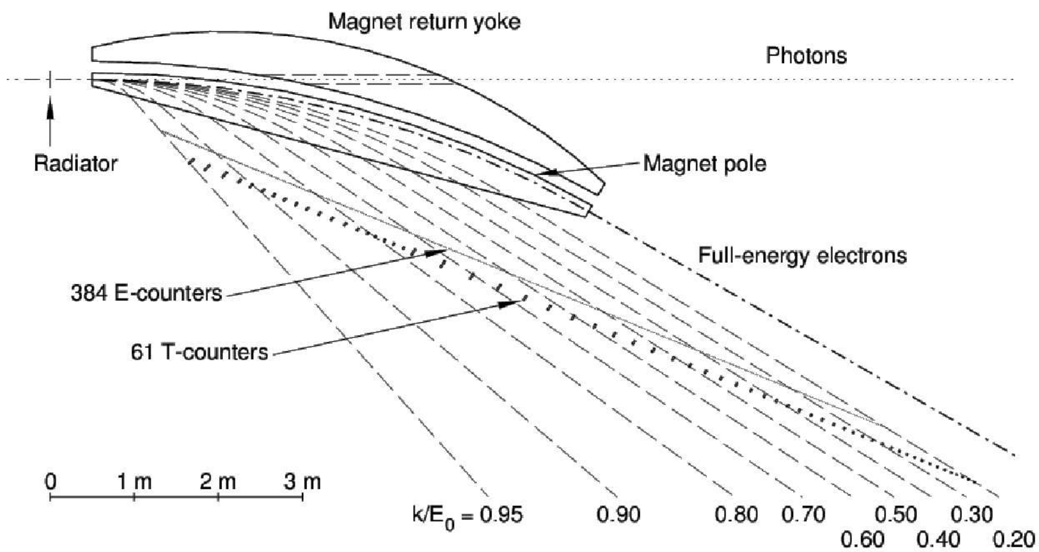
- Tagged photons of energy 4.9 - 5.5 GeV were used to measure the absolute cross section of π^0 photoproduction from two nuclei–^{12}C and ^{208}Pb.
- Pion invariant mass and production angle were reconstructed by detecting the two π^0 decay photons in a highly segmented calorimeter centered on the beamline.
- Number of tagged photons on target was calibrated using a Total Absorption Counter (TAC) and monitored with an e^+e^- pair spectrometer.

Experiment Layout



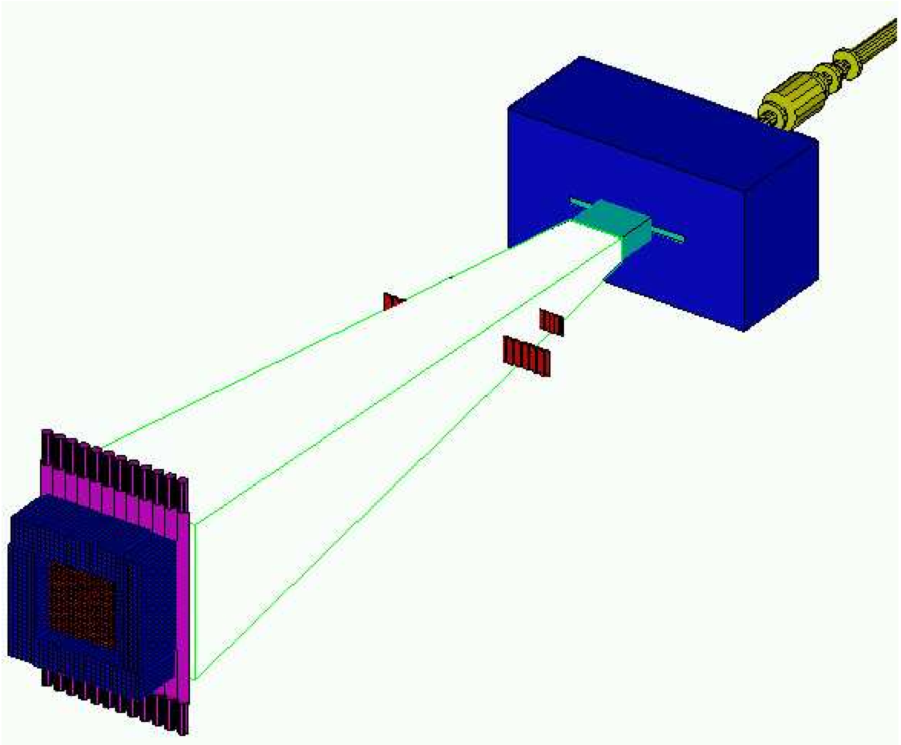
Photon Tagger

- Single dipole magnet combined with a hodoscope containing two planar arrays of plastic scintillators to detect energy-degraded electrons from a thin bremsstrahlung radiator.
- Tagger has energy resolution of 0.1% and is capable of 50 MHz rates

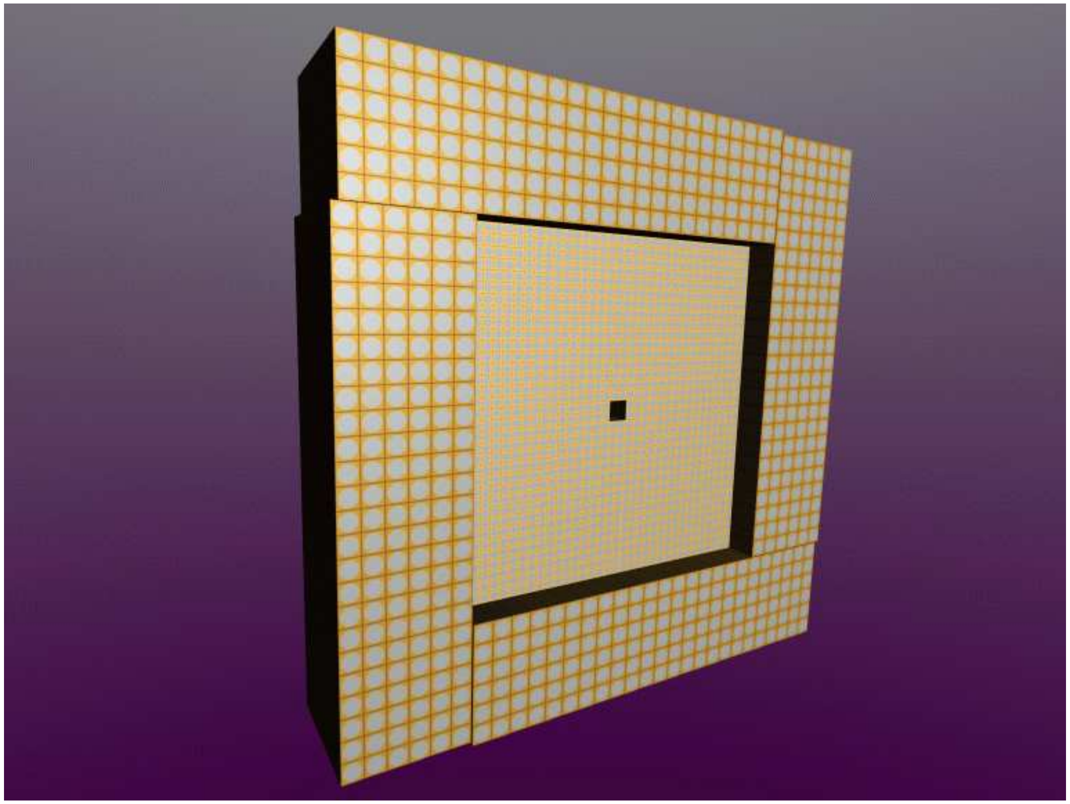


Pair Spectrometer

- Uses the physics target as the e^+e^- pair converter.
- Large dipole sweep magnet bends pairs into a series of plastic scintillator telescopes.



Hybrid Calorimeter – "HyCal"

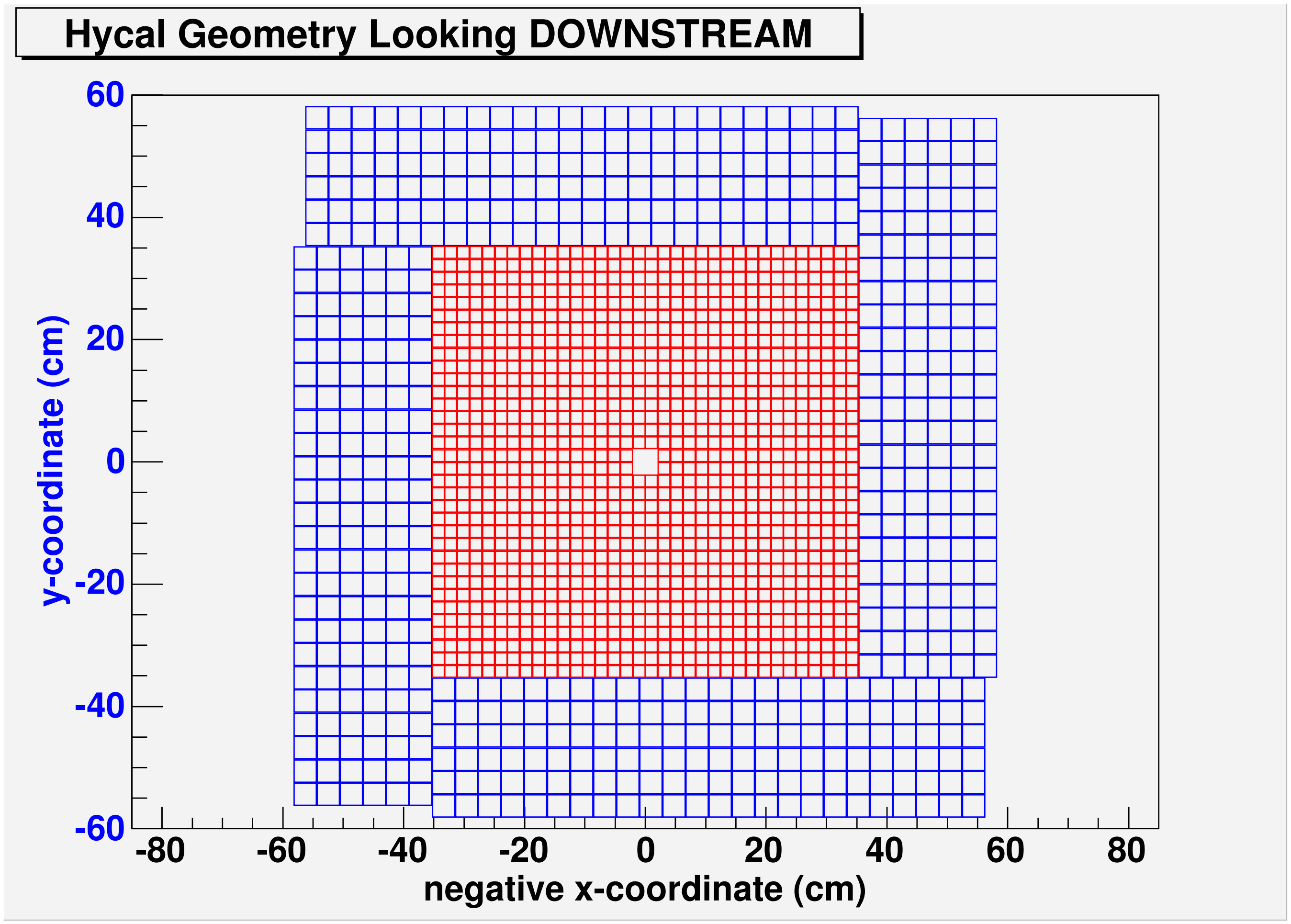


- 1.2 m ×1.2 m, 1728 channel electromagnetic shower calorimeter with Lead-glass outer layers and high resolution Lead-Tungstenate inner layers.

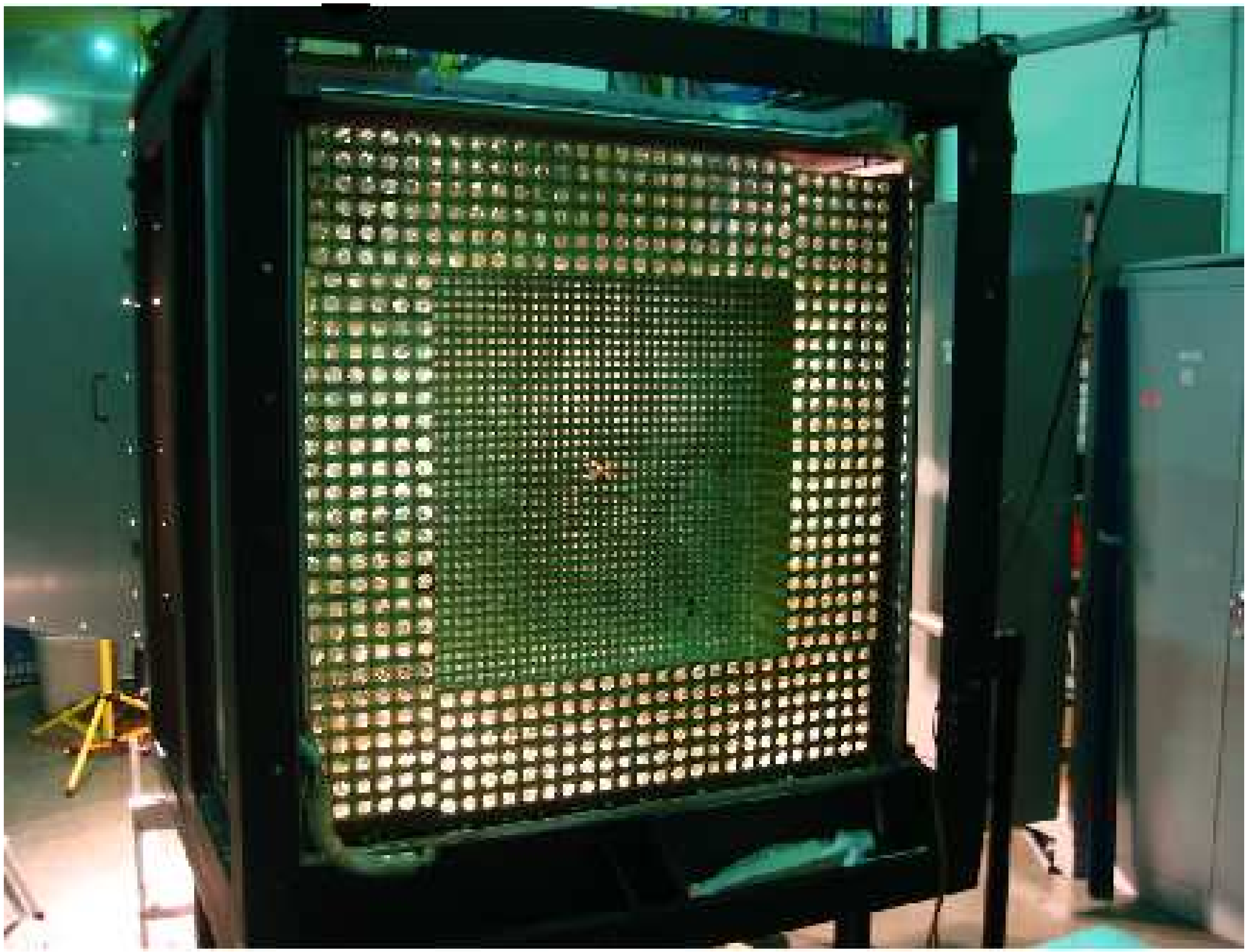
HyCal Specifications

	Lead-glass (outer)	$PbWO_4$ (inner)
Mechanism	Čerenkov	Scintillator
Block dimensions	$3.80 \times 3.80 \times 45$ cm^3	$2.05 \times 2.05 \times 20$ cm^3
Number of blocks	576	1152
Density	3.85 g/cm^3	8.28 g/cm^3
Moliere Radius	3.6 cm	2.0 cm
Radiation Length	2.7 cm	0.89 cm
Energy Res.	$3-5$ %	$1-2$ %
Position Res.	~ 5 mm	~ 2 mm
Angular Res.	~ 675 μrad	~ 270 μrad

HyCal Geometry



HyCal



Data Collection

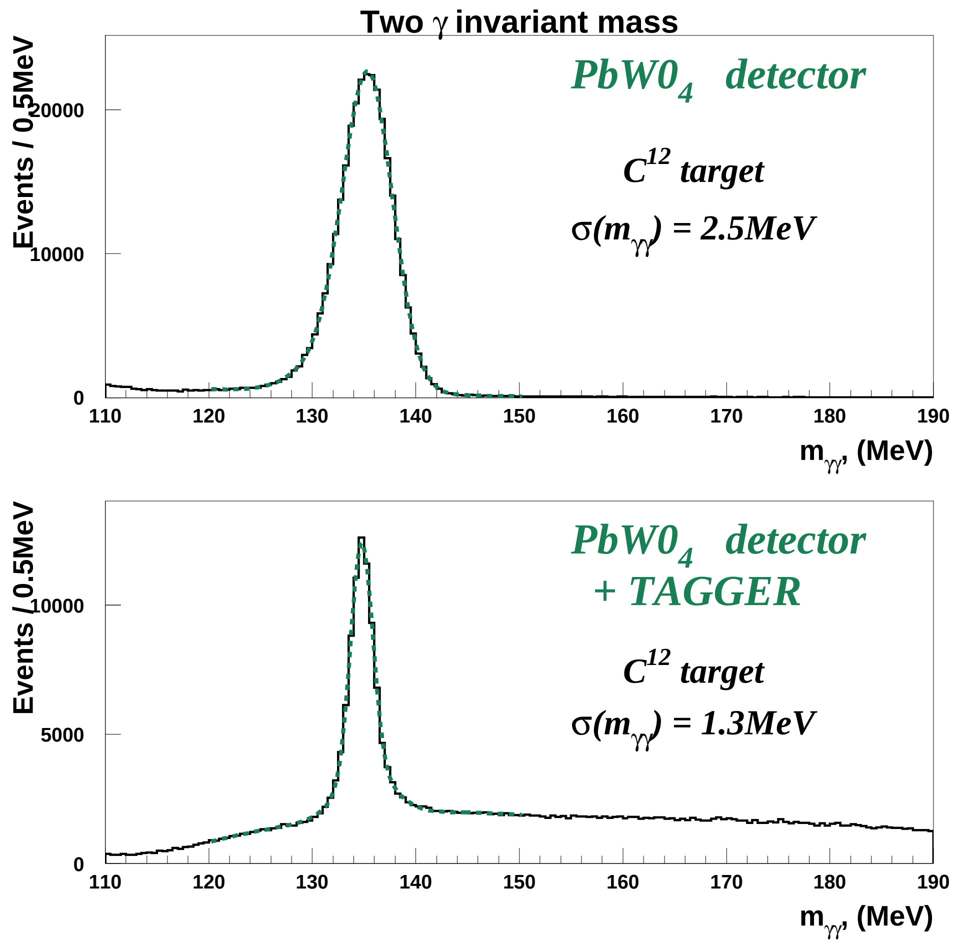
- HyCal Calibration: “snake” scan before and after experiment (for gain alignment and energy calibration)
- Periodic TAC/luminosity runs–measure absolute tagging efficiency for photon flux determination
- Periodic Compton runs (to measure absolute Compton coss section)–used for systematic studies of experimental setup (detector/beam alignment, π^0 yield normalization, and Hycal gain drift monitoring).
- π^0 photoproduction from 5% χ_0 ^{12}C and ^{208}Pb targets using $\sim$ 100 nA e-beam current which generated $\sim$ 5 MHz tagged photon rate. DAQ event readout triggered by HyCal total ADC sum in coincidence with tagger hodoscope hit (produced a rate of $\sim$ 1.2 kHz)

Data Analysis

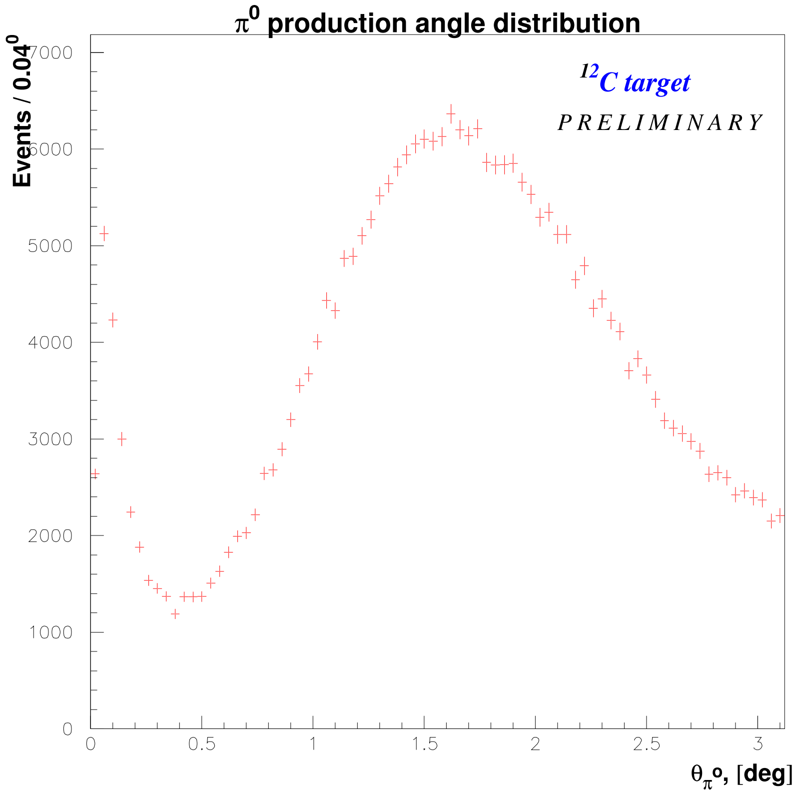
statistical	0.4%
target thickness (atoms/cm^2)	0.7%
photon flux	1.0%
π^o detector acceptance and misalignment	0.4%
background subtraction	0.2%
beam energy	0.2%
distorted form factor calculation errors	0.3%
total	1.4%

Proposed PrimEx Error Budget

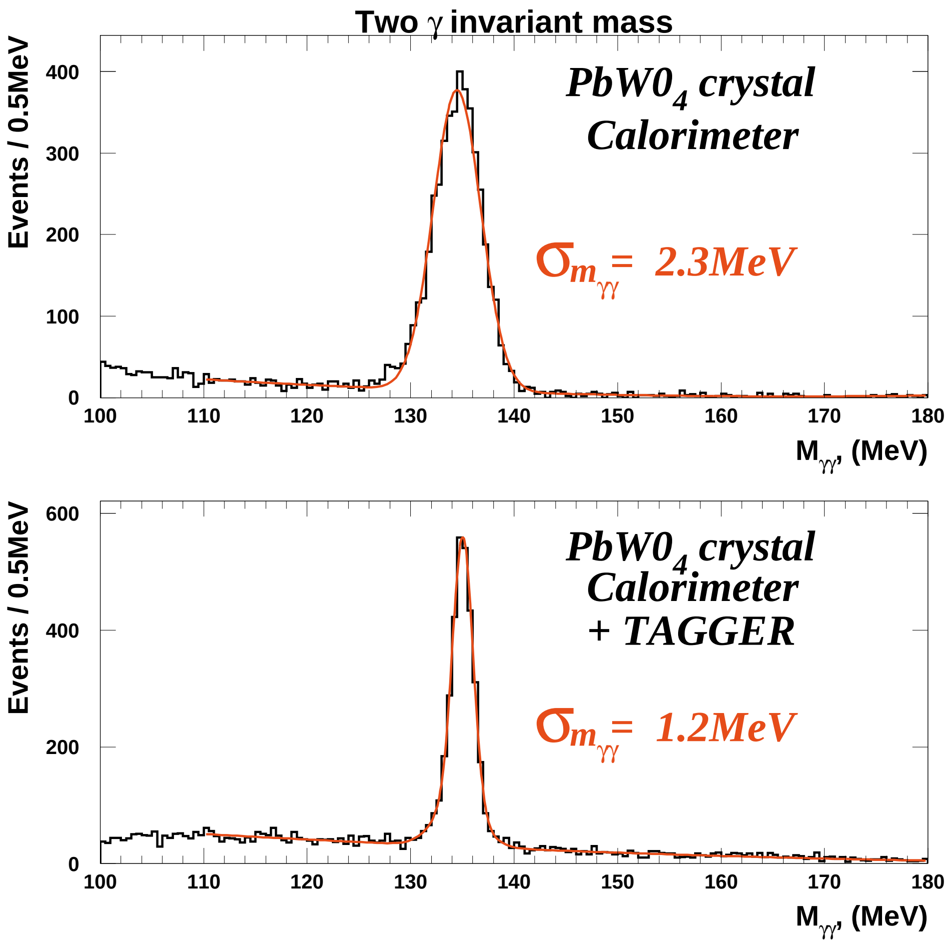
Analysis STatus: ^{12}C: $\gamma\gamma$ Invariant Mass



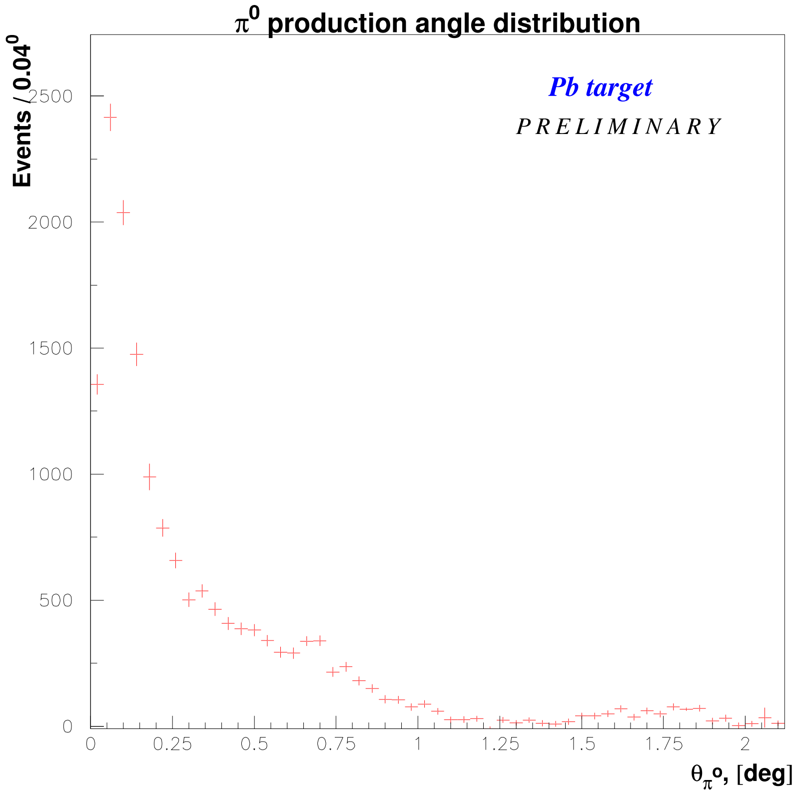
Preliminary Results: ^{12}C: $dn/d\theta_{\pi}$



Analysis Status: ^{208}Pb: $\gamma\gamma$ Invariant Mass



Preliminary Results ^{208}Pb: $dn/d\theta_{\pi}$



Summary

- This has been a progress report on a very challenging experiment.
- Primakoff π^0 statistics in hand: $\sim$ 25k events for Carbon, $\sim$ 12k for Lead.
- Continued analysis is ongoing: photon flux, refinement of energy calibration and position resolution, systematic studies.