The π^0 Lifetime: Experimental Probe of the QCD Axial Anomaly

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Outline

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- Calibration Reactions
  - Pair Production
  - Compton Scattering
- π^0 Analysis Details
- Preliminary $\Gamma_{\pi^0 \to \gamma\gamma}$ Result
- Summary and Outlook

PrimEx Collaboration

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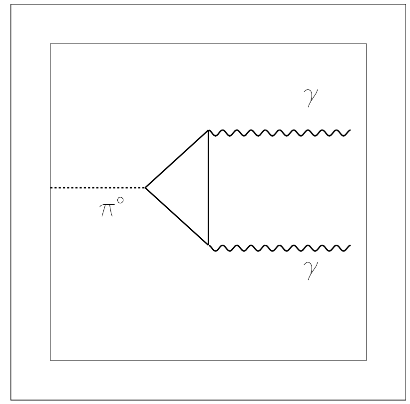
Physics Motivation

- π^0 decay rate is a fundamental prediction of 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 width:

$$\Gamma_{\pi^0\rightarrow\gamma\gamma} = \frac{\alpha^2 m_\pi^3}{64\pi^3 F_\pi^2} = 7.725 \pm 0.044 \text{ eV} \qquad (1)$$

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

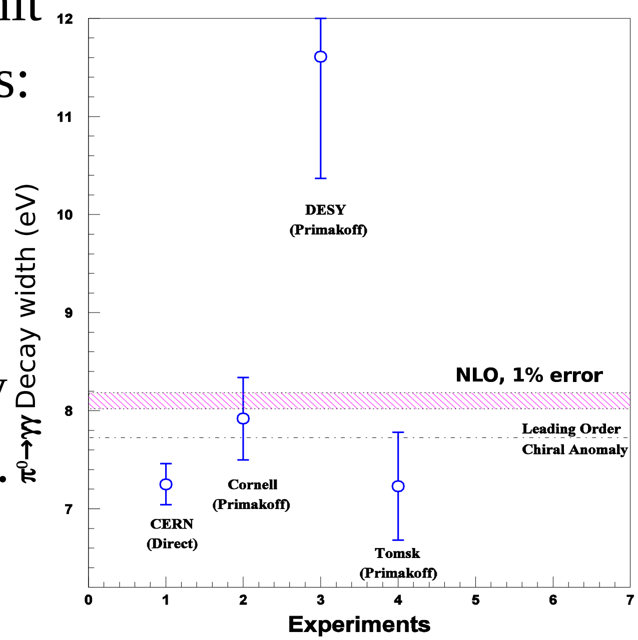
$\rightarrow$ Current Particle Data Book value is 7.84 ± 0.56 eV

Physics Motivation

- LO prediction exact in Chiral limit
- For $m_q \nrightarrow 0$, there are corrections:

  $\rightarrow$ Due to isospin sym-breaking ($m_u \neq m_d$), π^0, η and η' mixing induced.

  $\rightarrow$ Further corrections induced by terms in the Chiral Lagrangian.



- NLO prediction for the decay width is 8.10 eV $\pm$ 1%

  $\rightarrow$ Calc. using Chiral Perturbation Theory and $1/N_c$ expansion.

  J.L.Goity et al, Phys. Rev. D66, 076014 (2002); B.Moussallam, Phys. Rev. D51, 4939 (1995)

  $\rightarrow$ This is 4% higher than current experimental value!

$\circ$ A precision measurement of the π^0 decay width is needed.

CERN (Direct Method) Decay Length Measurement

→ $\tau_{\pi^0} \sim 1 \times 10^{-16}$ s $\Rightarrow$ too small to measure

→ Solution–Measure decay length of highly energetic π^0's:

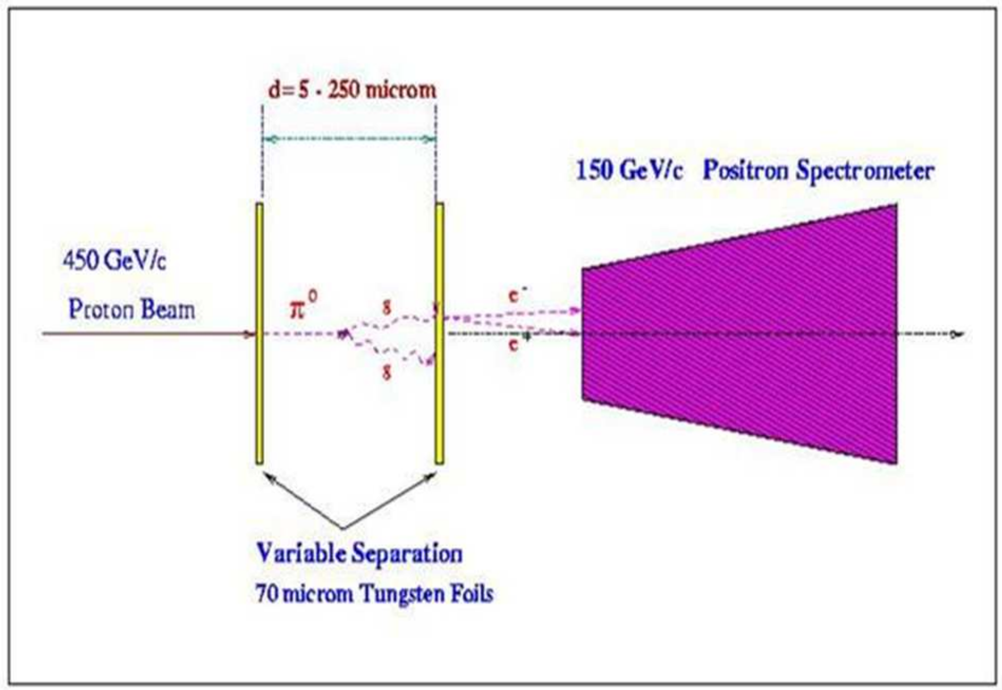
$$L = v\tau_{\pi^0} E/m \tag{2}$$

→ for E = 1000GeV, L$\sim$ 100μm (very challenging experiment)

→ Performed in 1984:
Used 450GeV protons

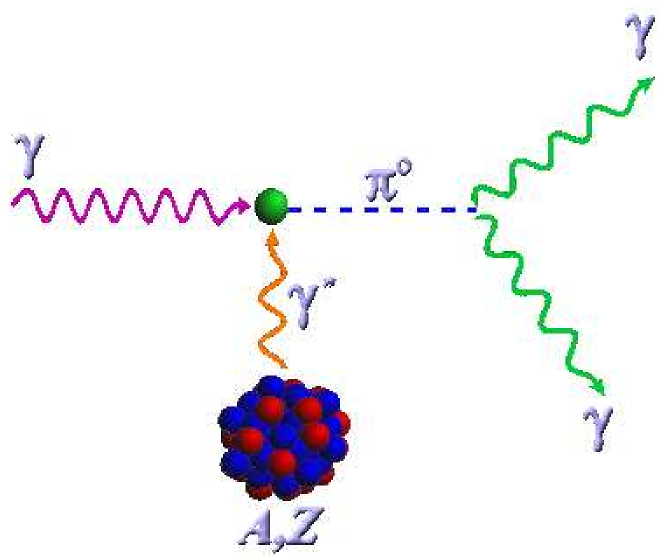
→ Result:
$\Gamma_{(\pi^0 \to \gamma\gamma)}$ = 7.34eV$\pm$3.1%

→ Dominant syst. error:
Uncertainty in E_{π^0} ($\pm$1.5%)



The 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.

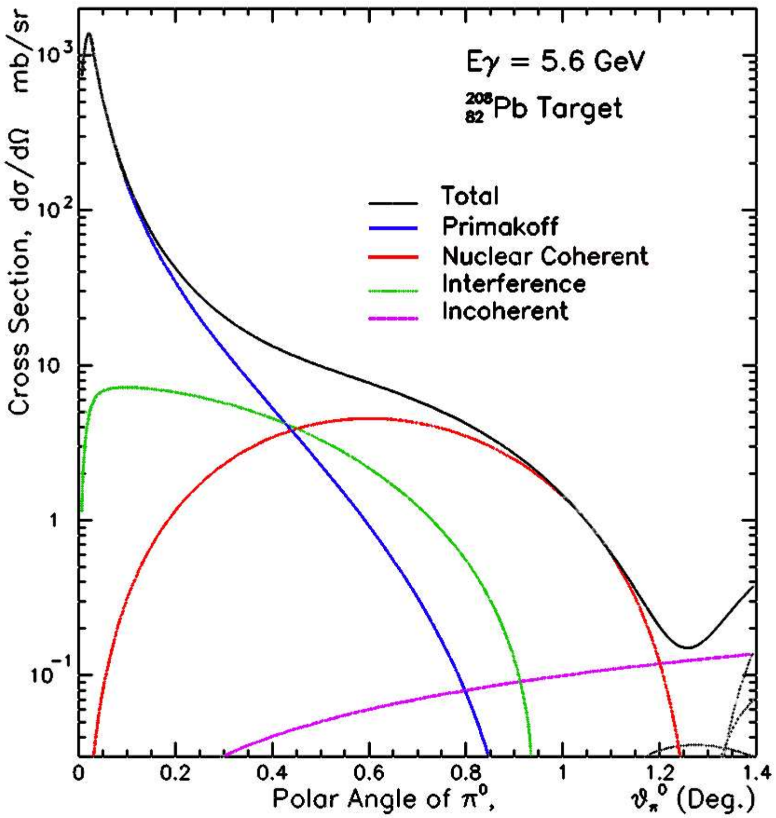


$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\to\gamma\gamma)} \frac{8\alpha_{em} Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |\tilde{F}_{em}(Q)|^2 sin^2\theta_\pi \qquad (3)$$

Full Cross Section Components

$$\frac{d\sigma_{\pi^0}}{d\Omega} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_C}{d\Omega} + \frac{d\sigma_I}{d\Omega} + 2\cdot\sqrt{\frac{d\sigma_P}{d\Omega}\cdot\frac{d\sigma_C}{d\Omega}}cos(\phi) \quad (4)$$

Primakoff Nucl.Coherent Incoherent Interference



Primakoff:

Proportional to Z^2,

peaked at $\theta_{\pi^0} = m^2_{\pi^0}/2E^2_\gamma$

Nuclear Coherent:

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

Nuclear Incoherent:

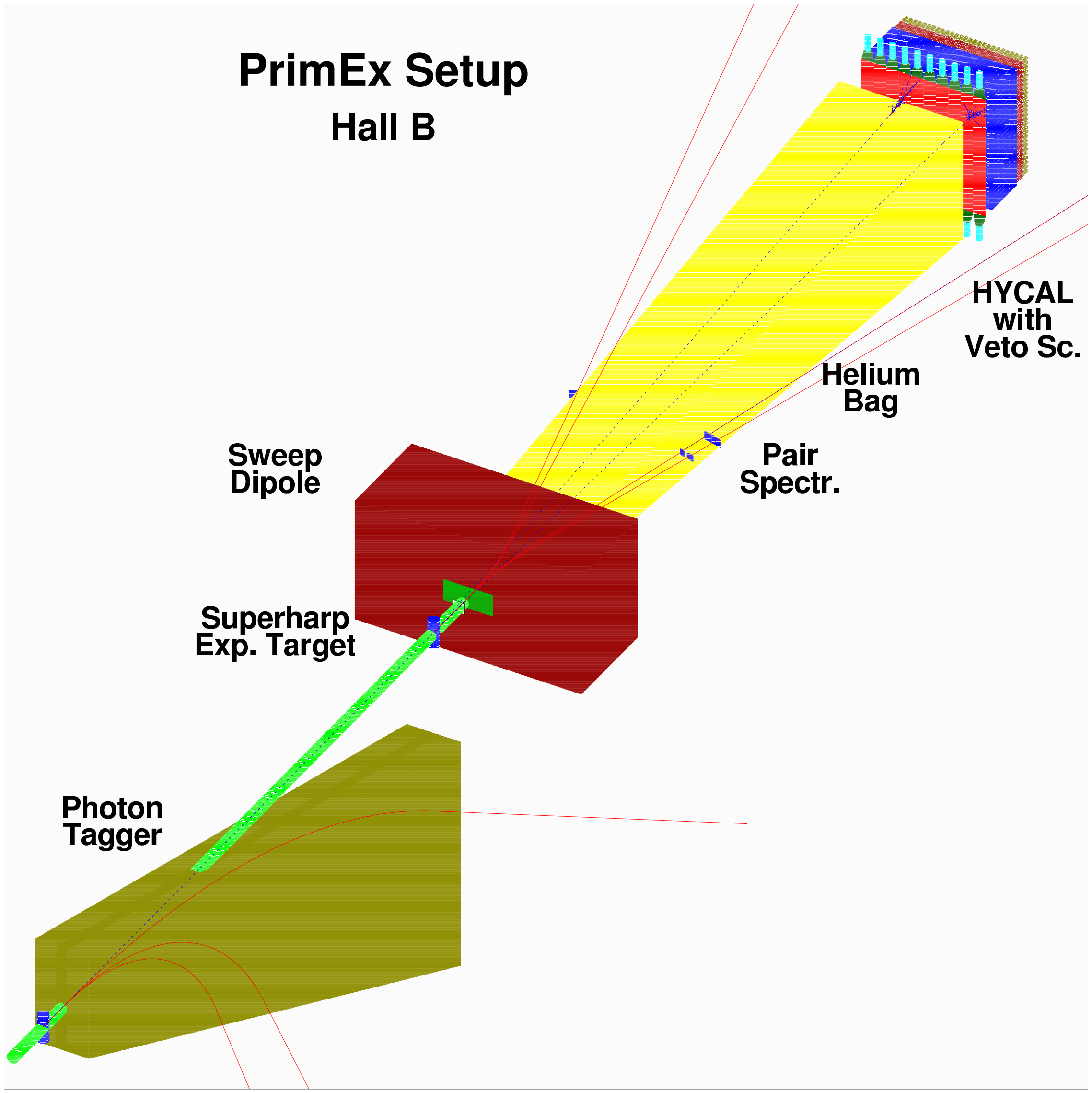
$$\frac{d\sigma_I}{d\Omega} = \xi A(1-G(Q))\frac{d\sigma_H}{d\Omega} \quad (6)$$

Interference:

Experiment Overview

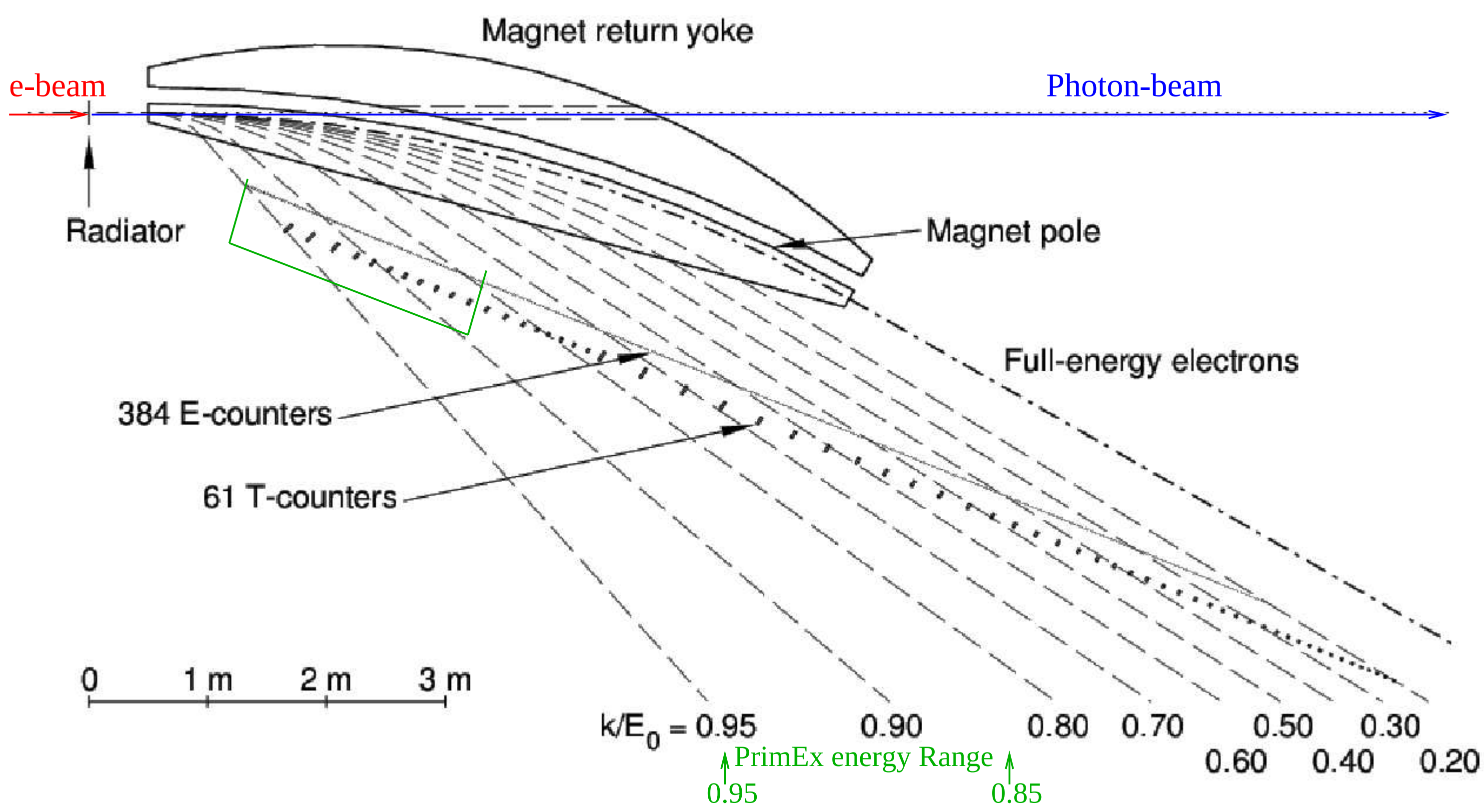
- Conducted at Jefferson Lab, Fall 2004
- Used 5.75 GeV continuous e^- beam and Hall B γ-tagging facility
- Tagged photons incident on 5%X_0 targets: ^{12}C and ^{208}Pb
- New PrimEx/Hall B calorimeter (HyCal), upstream of CLAS, designed to detect π^0 decay γ's
- Measured 3 physical processes (absolute cross sections): Primary - π^0 production, Secondary - Compton and e^+e^- pair production
- Improvements over previous experiments: Precision tagged γ flux and incident γ energy info, enhanced π^0 angular and mass resolution, and identification and subtraction of background event contamination

Experiment Overview



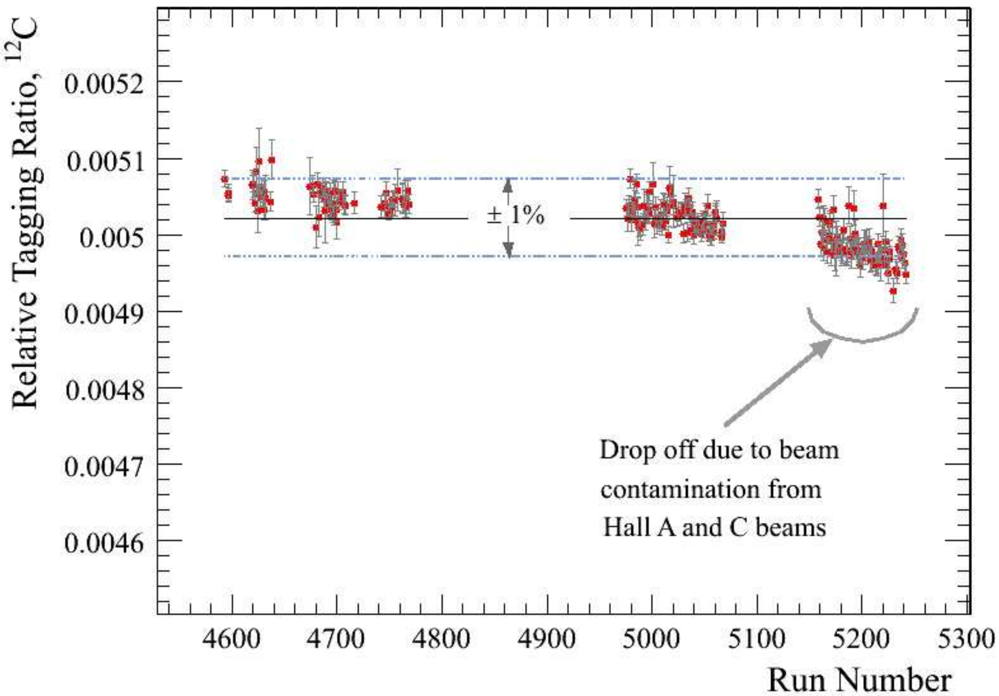
Hall B Photon Tagger

- 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 0.1% energy resolution and is capable of 50 MHz rates.

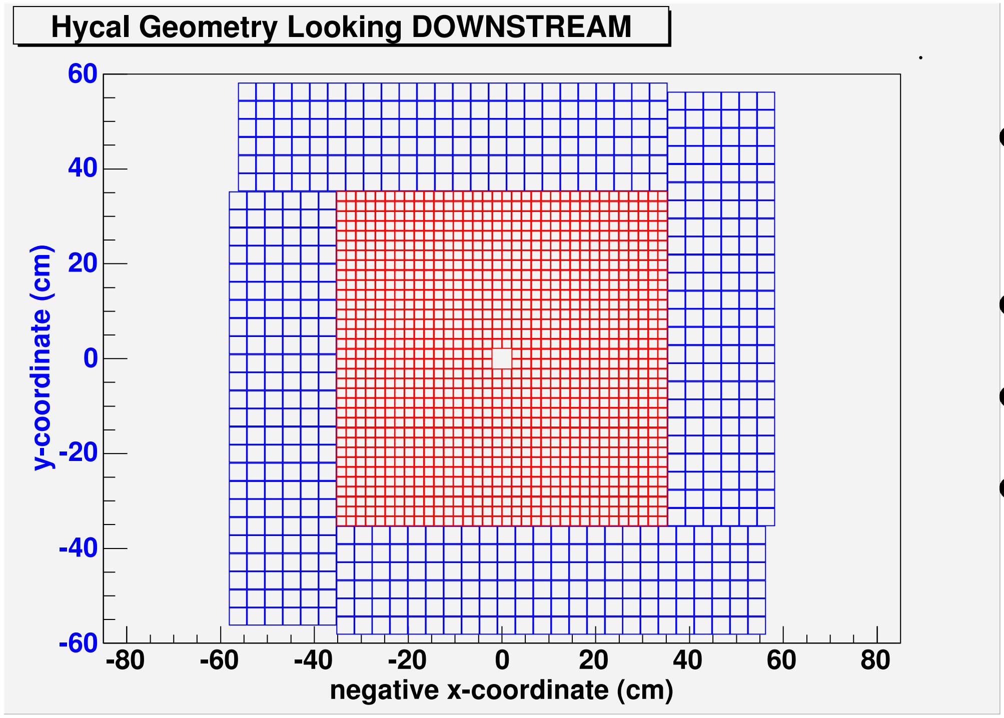


Photon Flux Control

- PrimEx achievement: Total uncertainty in photon flux = 1.1%.
- Number of tagged photons on target (N_γ) calibrated periodically using a Total Absorption Counter (TAC).
- Any drifts in the tagging ratio, occuring between calibration points, are monitored online with the e^+e^- pair spectrometer.



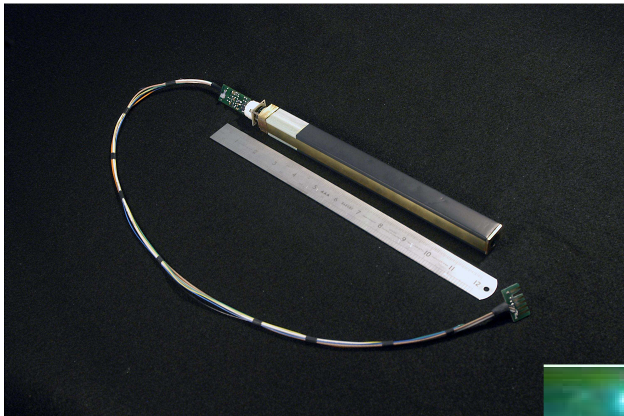
PrimEx Hybrid Calorimeter – "HyCal"

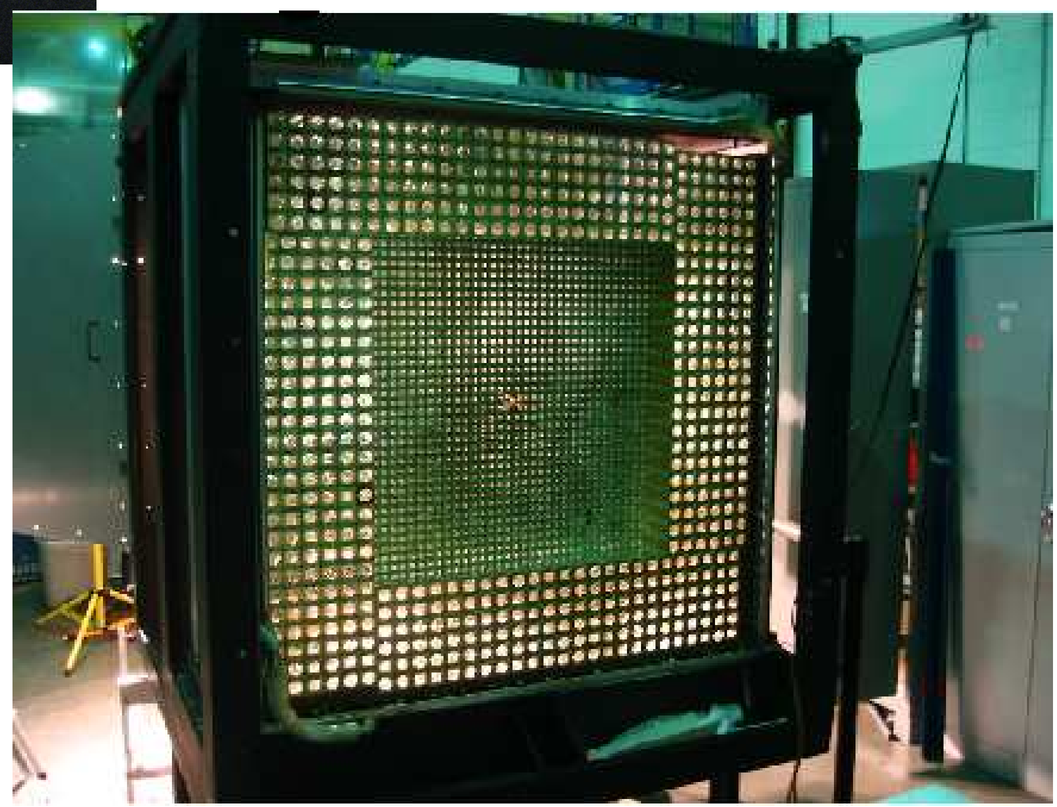


- Optimal performance/cost design
- 1.2 m ×1.2 m, 1728 channels
- 576 Lead-glass (outer layers)
- 1152 Lead-Tungstenate crystal (inner layers)

	Lead-glass	$PbWO_4$
Energy Res. ($\Delta E/E$)	3 – 5 %	1 – 2 %
Position Res. ($\Delta x,y$)	~ 5 mm	~ 1.5 mm
Angular Res. ($\Delta\theta_{\pi^0}$)	~ 675 μrad	~ 300 μrad

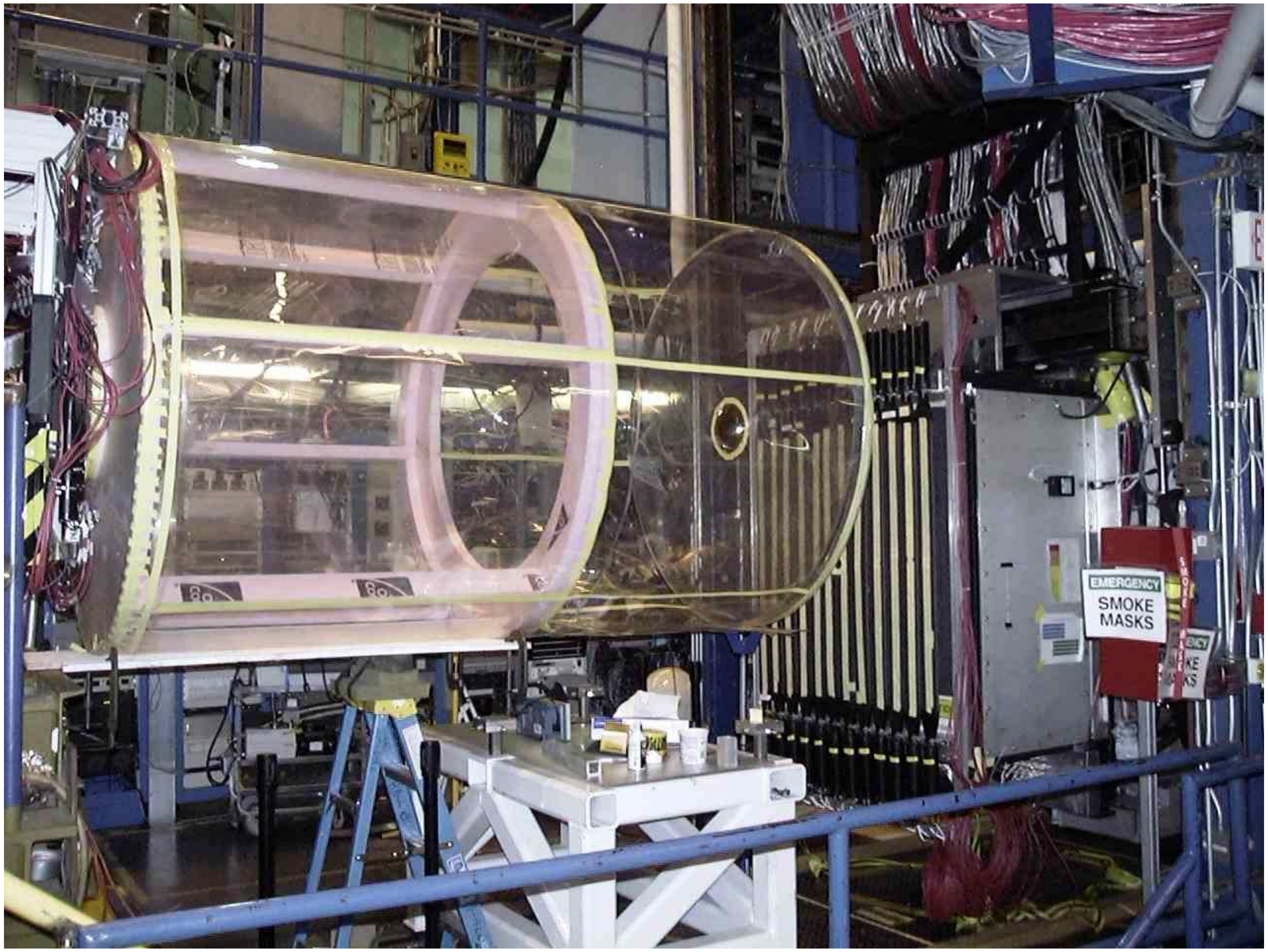
PrimEx Hybrid Calorimeter – "HyCal"



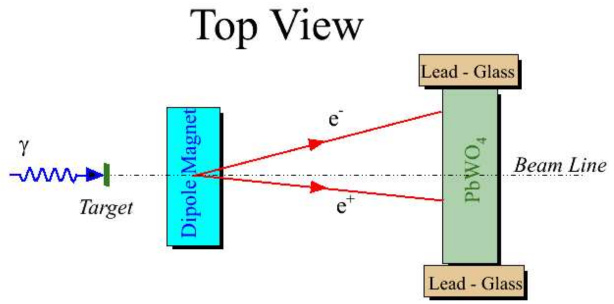


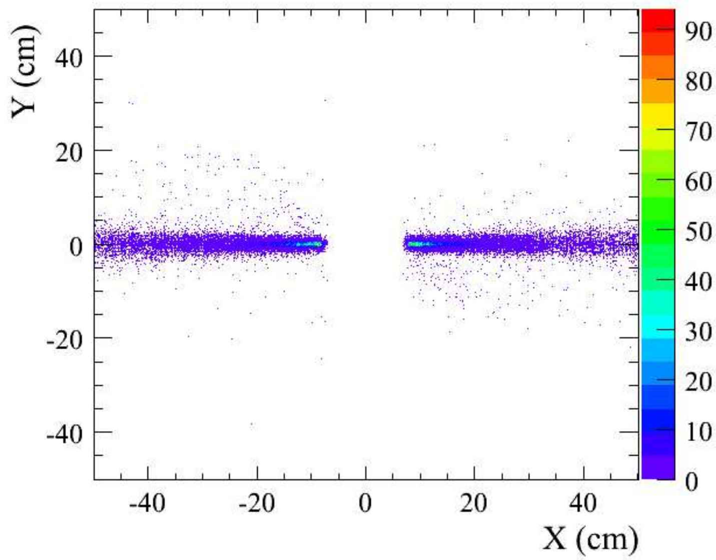
HyCal Calibration

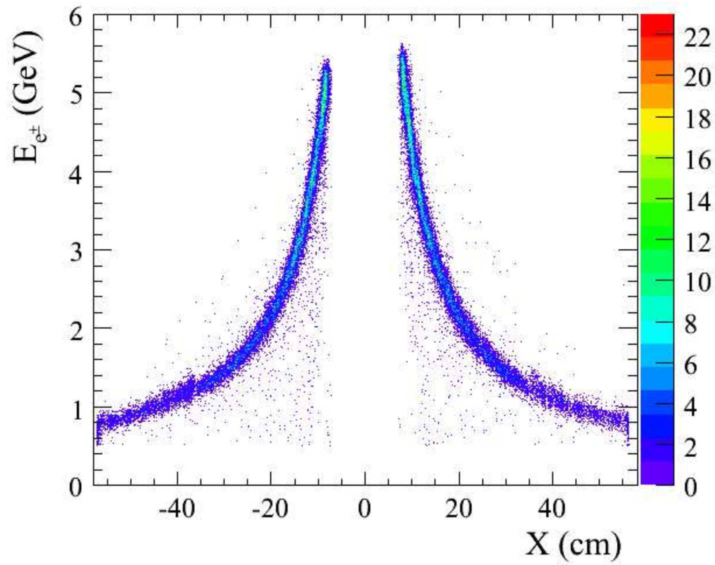
- Full x,y motion allowed each ch. to be scanned through tagged γ beam.
- Performed at both the beginning and end of the experiment.



Calibration Reactions: $e^+ e^-$ Pair Production



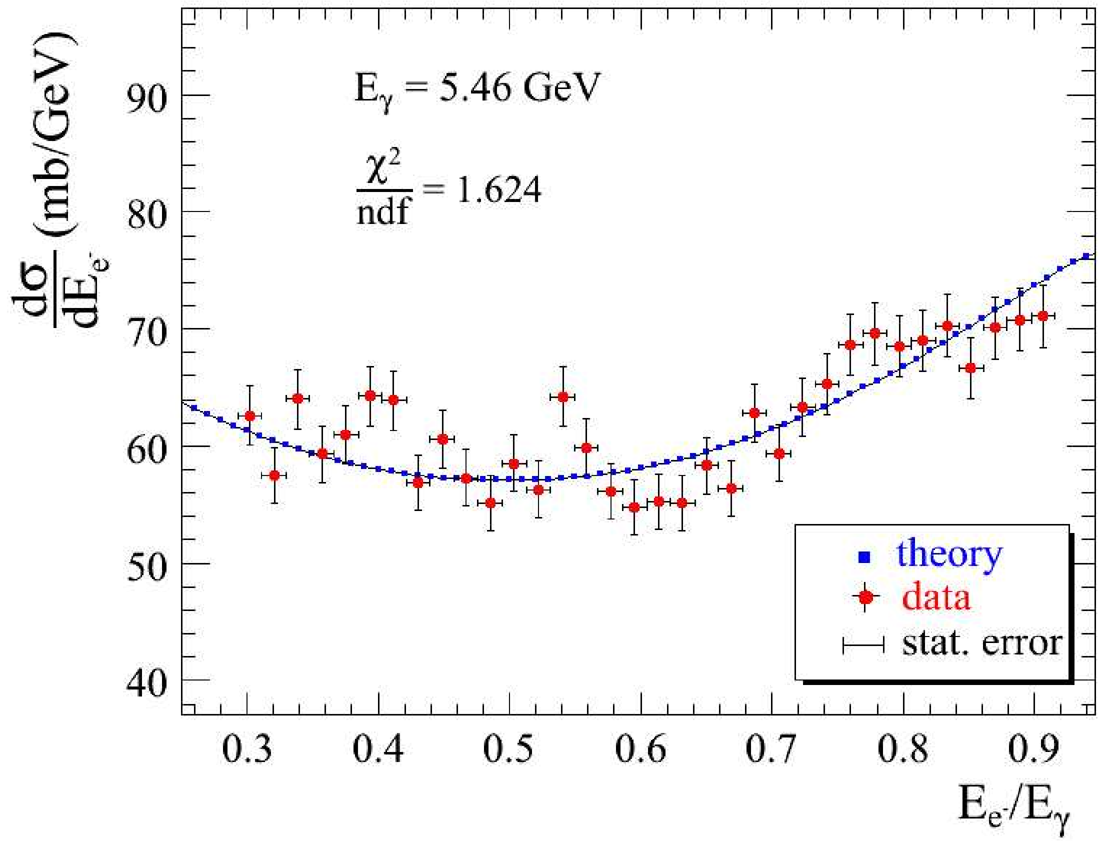




Calculation of Pair Production Cross Section at PrimEx Kinematics

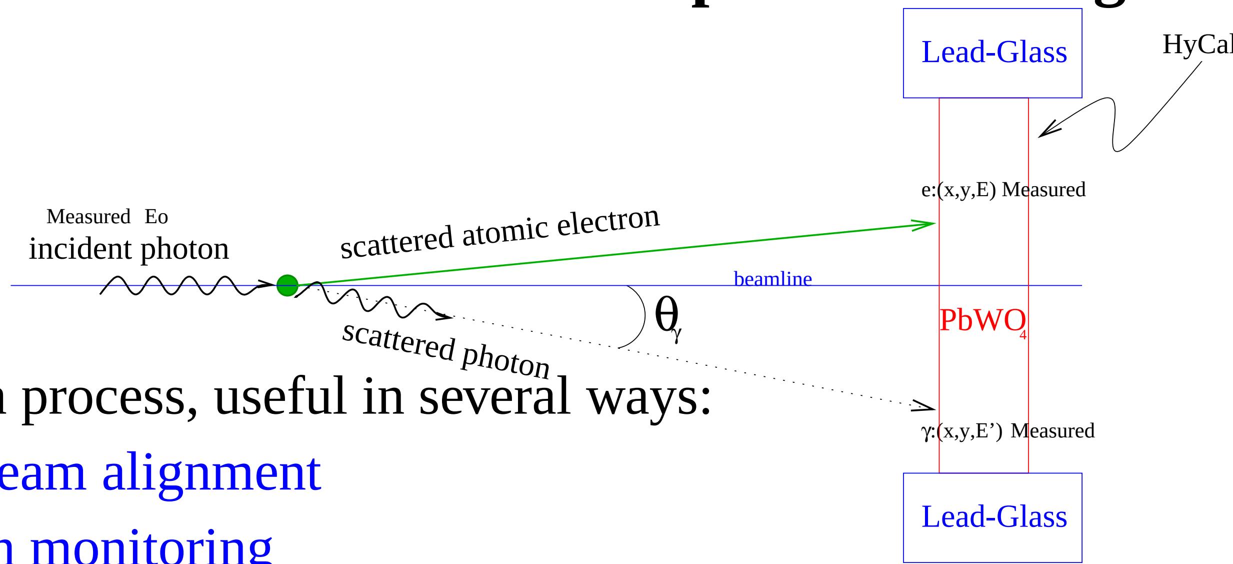
- Bethe-Heitler mechanism of pair production on the nucleus with screening effects due to atomic electrons and Coulomb distortion
- Pair production off atomic electrons, considering excitation of all atomic states and correlation effects due to the presence of other electrons and the nucleus
- Radiative corrections (of order α/π) (i) virtual photon loops and (ii) real photon process like $\gamma + A \rightarrow e^{+} + e^{-} + A + \gamma$
- Nuclear incoherent contribution, $\gamma + p \rightarrow e^{+} + e^{-} + p$
- Nuclear coherent contribution (VCS), $\gamma + A \rightarrow \gamma^{*} + A \rightarrow e^{+} + e^{-} + A$

Pair Production Preliminary Result



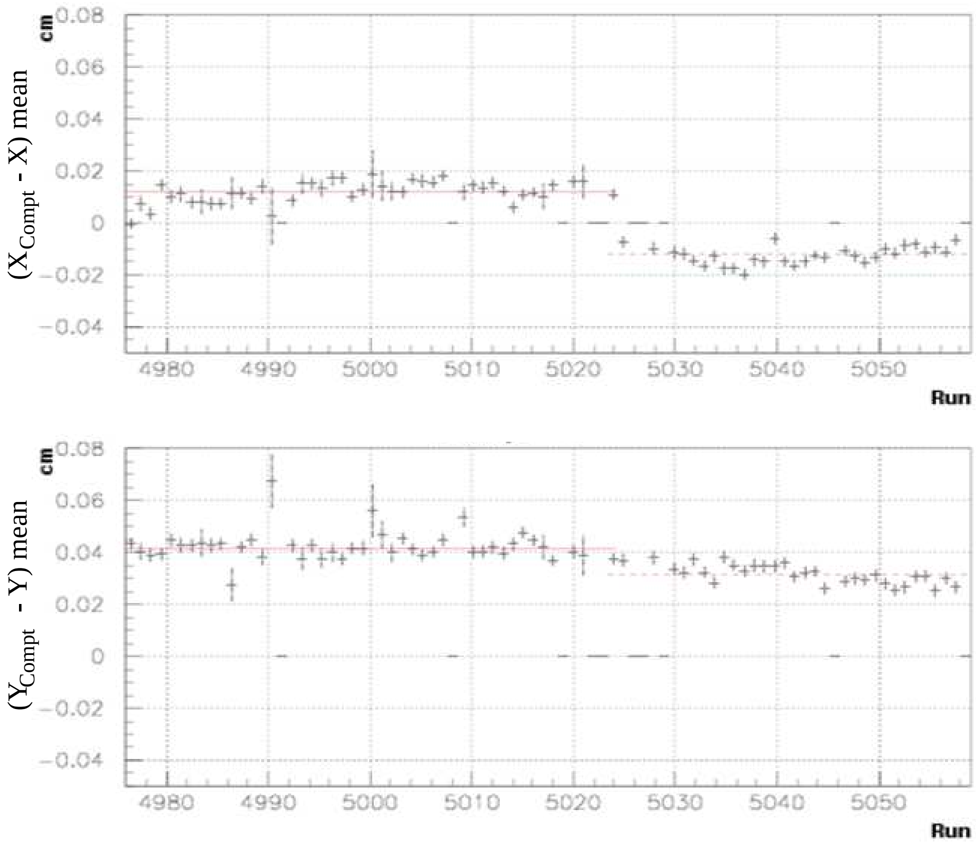
- Agreement with theory at $\sim 2.5\%$ level
- Work in progress to reduce systematic errors to $1 - 2\%$ level

Calibration Reactions: Compton Scattering



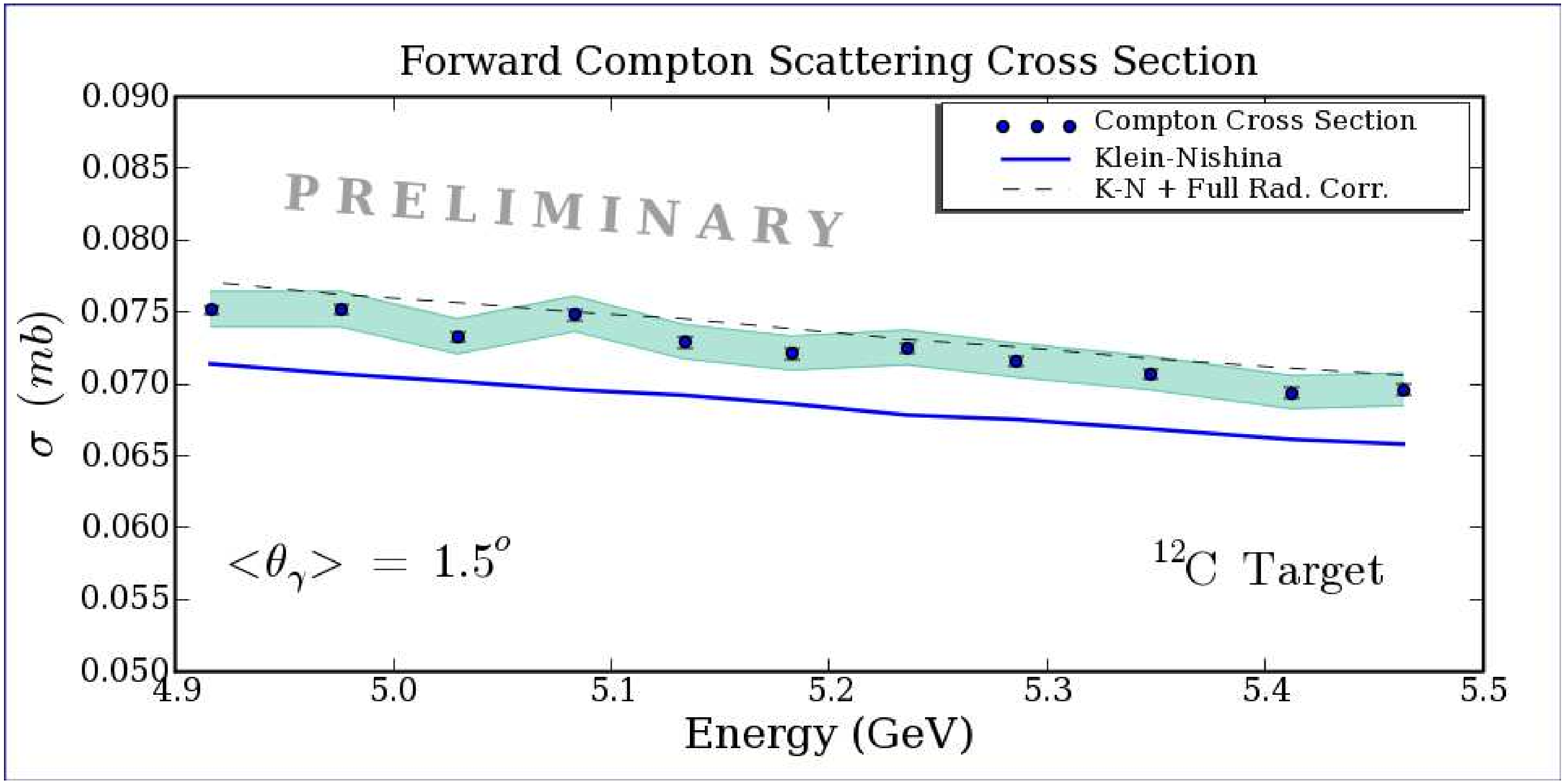
- A well known process, useful in several ways:
  - $\rightarrow$ Detector/beam alignment
  - $\rightarrow$ HyCal gain monitoring
  - $\rightarrow$ Overall check of PrimEx setup to measure absolute cross sections
    - ◦ Dedicated "Double-Arm" Compton Runs:
      - $\rightarrow$ Performed on a weekly basis, $B_{PS} = 0$, $I_{beam} \sim 5 - 10$ nA
      - $\rightarrow$ Both e^- and scattered photon detected in HyCal
      - $\rightarrow$ Compton Cross Section Measured: ^{12}C and 0.5%X_0 ^{4}Be
    - ◦ "Single-Arm" Compton Data:
      - $\rightarrow$ Dominant Source of Events in π^0 production dataruns
      - $\rightarrow$ $B_{PS} \sim 2$ T, $I_{beam} \sim 100$ nA, only scattered photon detected

Beam Alignment Monitoring using Single-Arm Compton



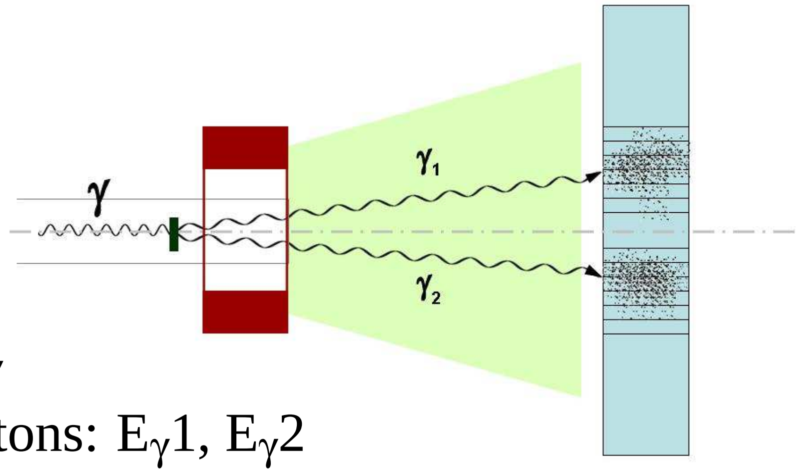
- Only scattered γ measured
- $X \equiv$ reported HyCal coord
- $X_{Compt} \equiv$ calc. (x,y) from Hycal E and Compton kin.
- If beam alignment perfect: $(X_{Compt}\text{-}X) = 0$
- Technique tracks alignment at 0.1 mm level
- Jump in X correlated with beamline BPM

Compton Cross Section Preliminary Result



- Total estimated error: 2.5% (dominated by photon flux 1.5%)
- Work in progress to reduce systematic errors to 2% level

Analysis Details: π^0 Event Selection



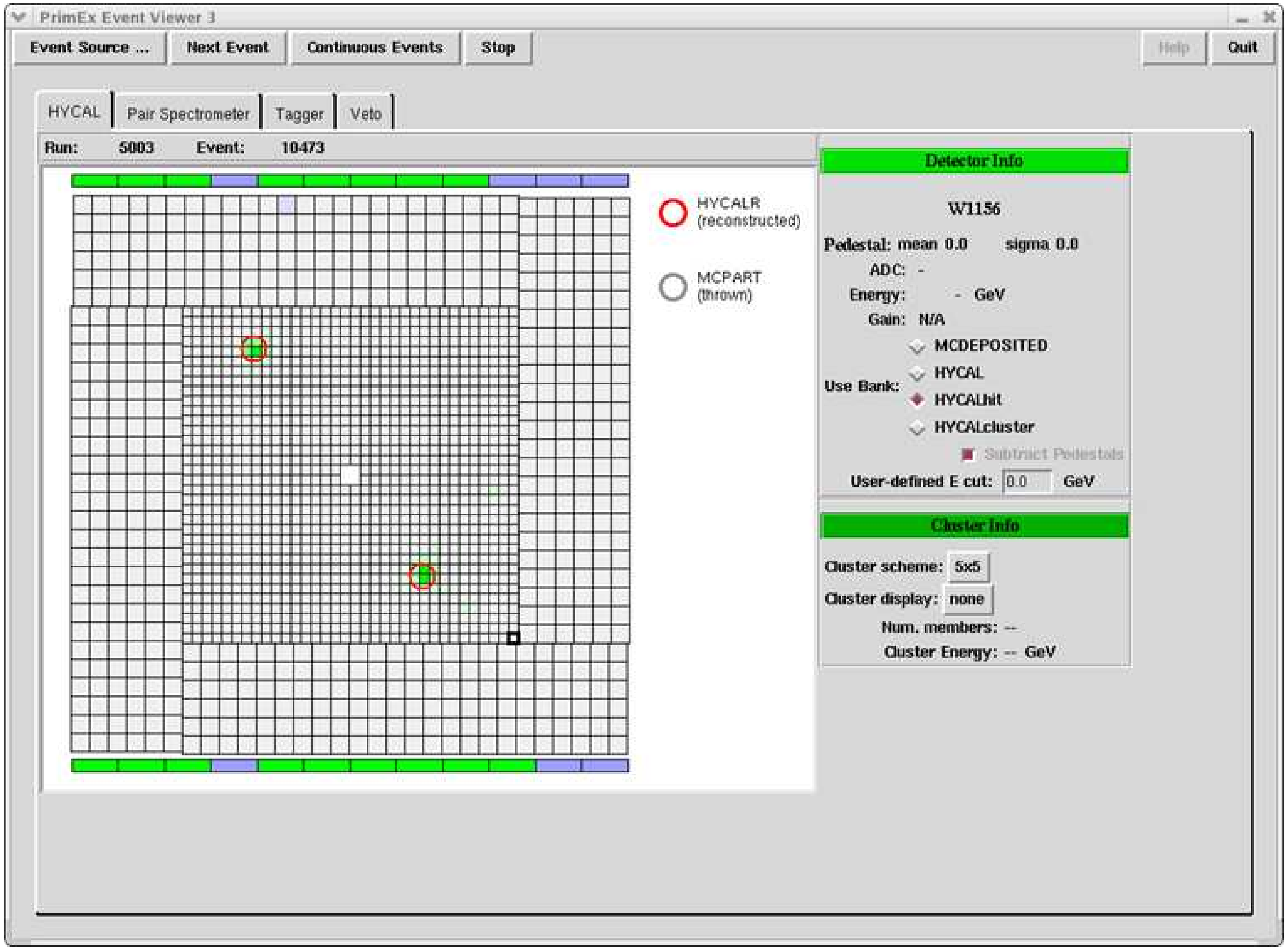
We measure:

- → initial photon energy: E_γ
- → energies of decayed photons: $E_\gamma 1$, $E_\gamma 2$
- → X,Y positions of decayed photons

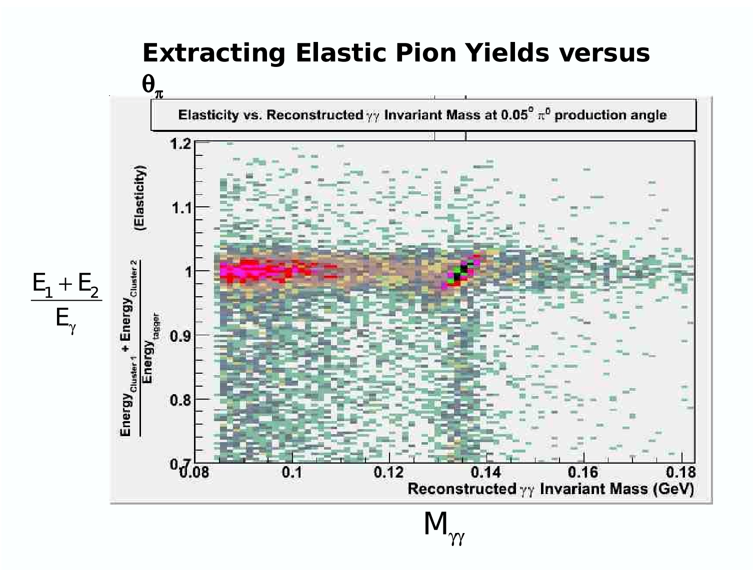
Kinematical constrains:

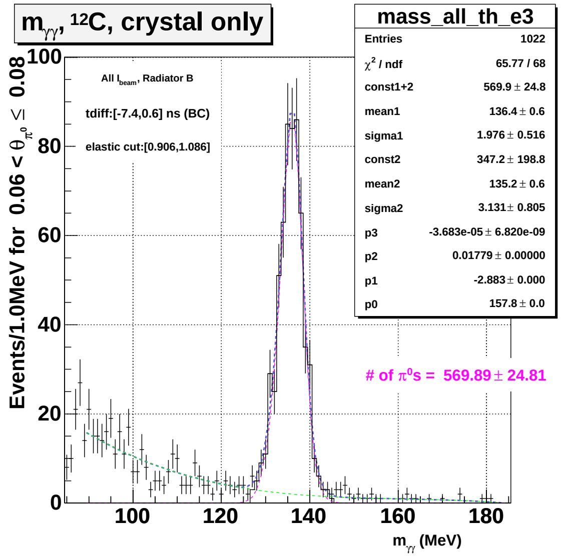
- → Conservation of energy
- → Conservation of momentum
- → $m_{\gamma\gamma}$ invariant mass

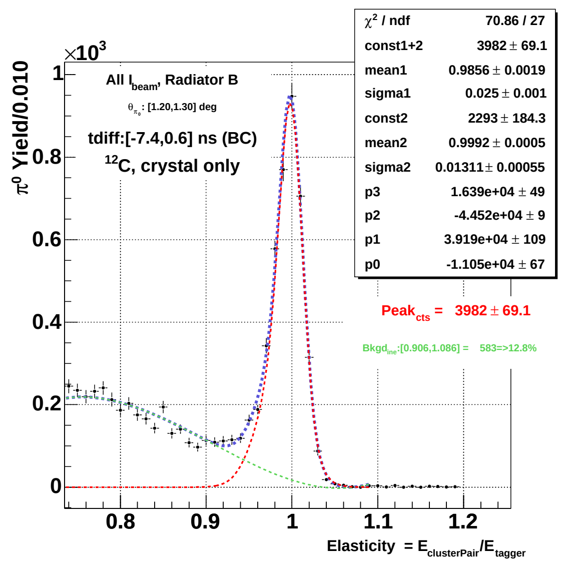
Analysis Details: π^0 Event Selection



Analysis Details: π^0 Yield Extraction

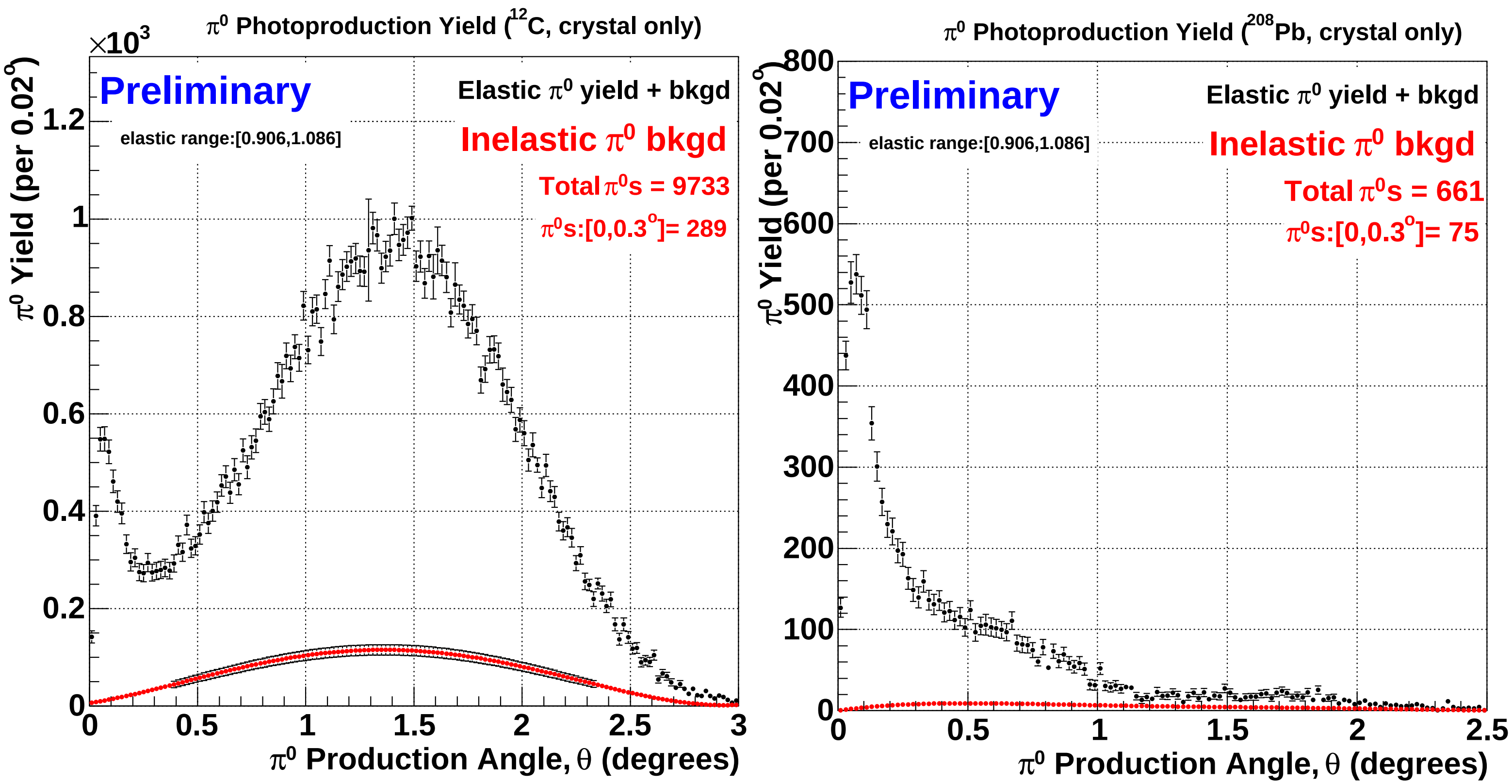




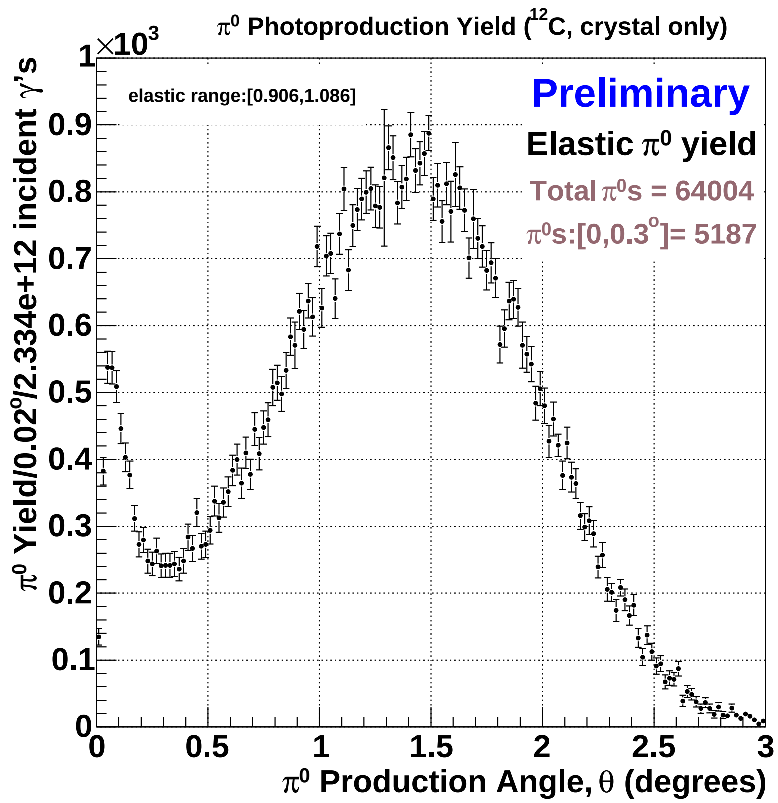


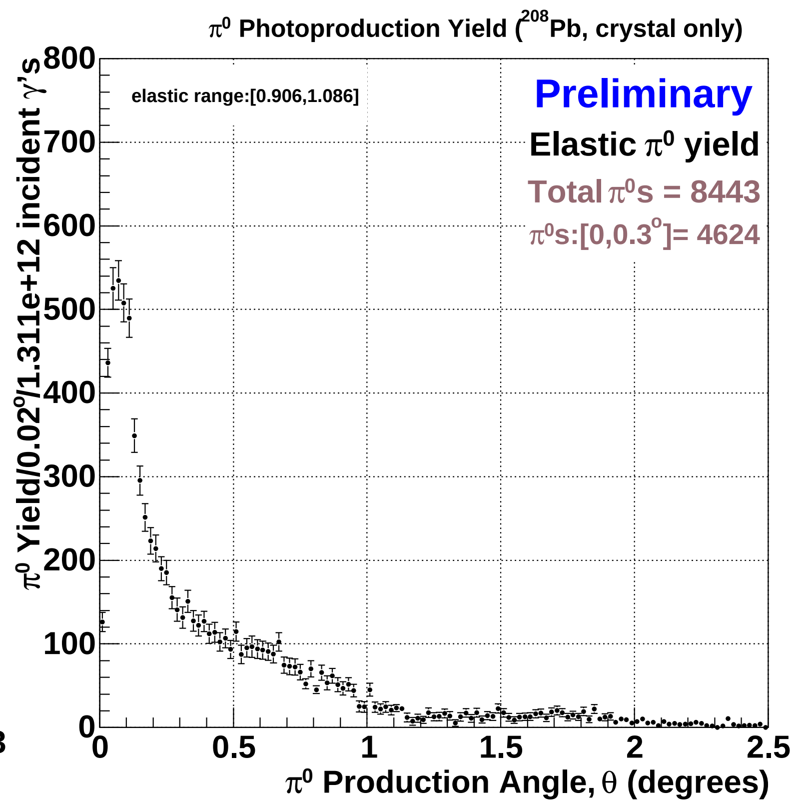
- For each θ_{π^0} bin, apply elastic cut and form $m_{\gamma\gamma}$ distributions; perform fit and extract peak counts = uncorrected yield.
- Correct for inelastic bkgd by evaluating π^0 elasticity distribution explicitly for each θ_{π^0}; evaluate inelastic bkgd under the elastic peak using fit and subtract from yield.

Analysis Details: Yield Result for ^{12}C and ^{208}Pb



Yield Results for ^{12}C and ^{208}Pb





Analysis Details: $\Gamma_{\pi^0\to\gamma\gamma}$ Determination

- Convert Yield to Cross Section.

$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = \frac{N^{yield}_{\pi^0}(\theta_{\pi^0})}{N_\gamma \times N_t \times \varepsilon_{\pi^0}(\theta_{\pi^0}) \times \Delta\theta_{\pi^0}} \quad (7)$$

$\rightarrow$ where $N_\gamma \equiv$ # of γ's on target (uncertainty $\sim$ 1.1%).

$\rightarrow$ where $N_t \equiv$ target atoms/cm^2 (thickness mapped to $\sim$ 0.05%).

$\rightarrow$ where $\varepsilon_{\pi^0} \equiv$ experimental acceptance (uncertainty $\sim$ 0.6%).

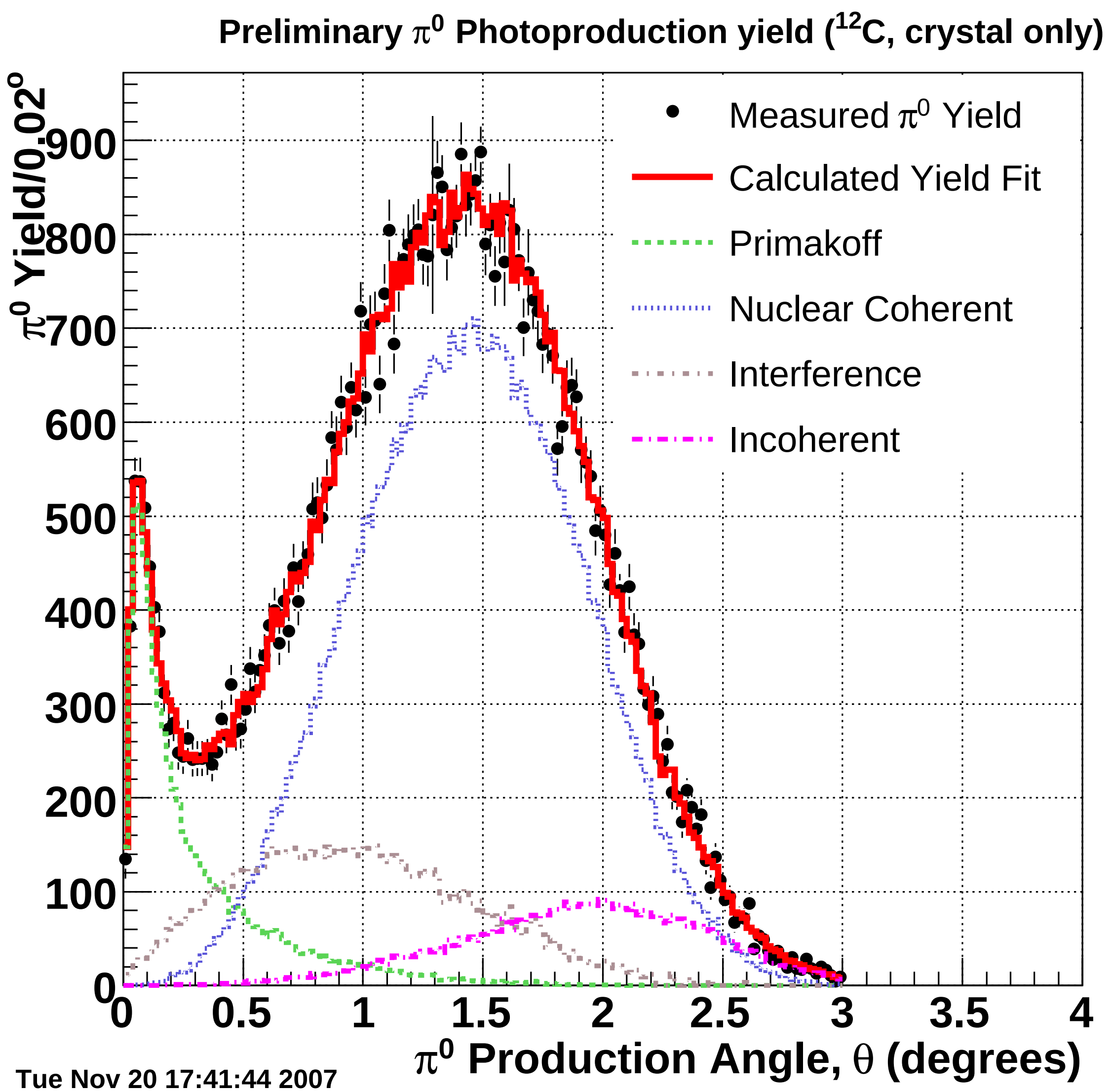
- Fit experimental data with parameterization:

$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = b_p\frac{d\sigma_P}{d\Omega} + b_c\frac{d\sigma_N}{d\Omega} + b_i\frac{d\sigma_I}{d\Omega} + 2cos\phi\sqrt{b_p b_c \frac{d\sigma_P}{d\Omega}\frac{d\sigma_C}{d\Omega}} \quad (8)$$

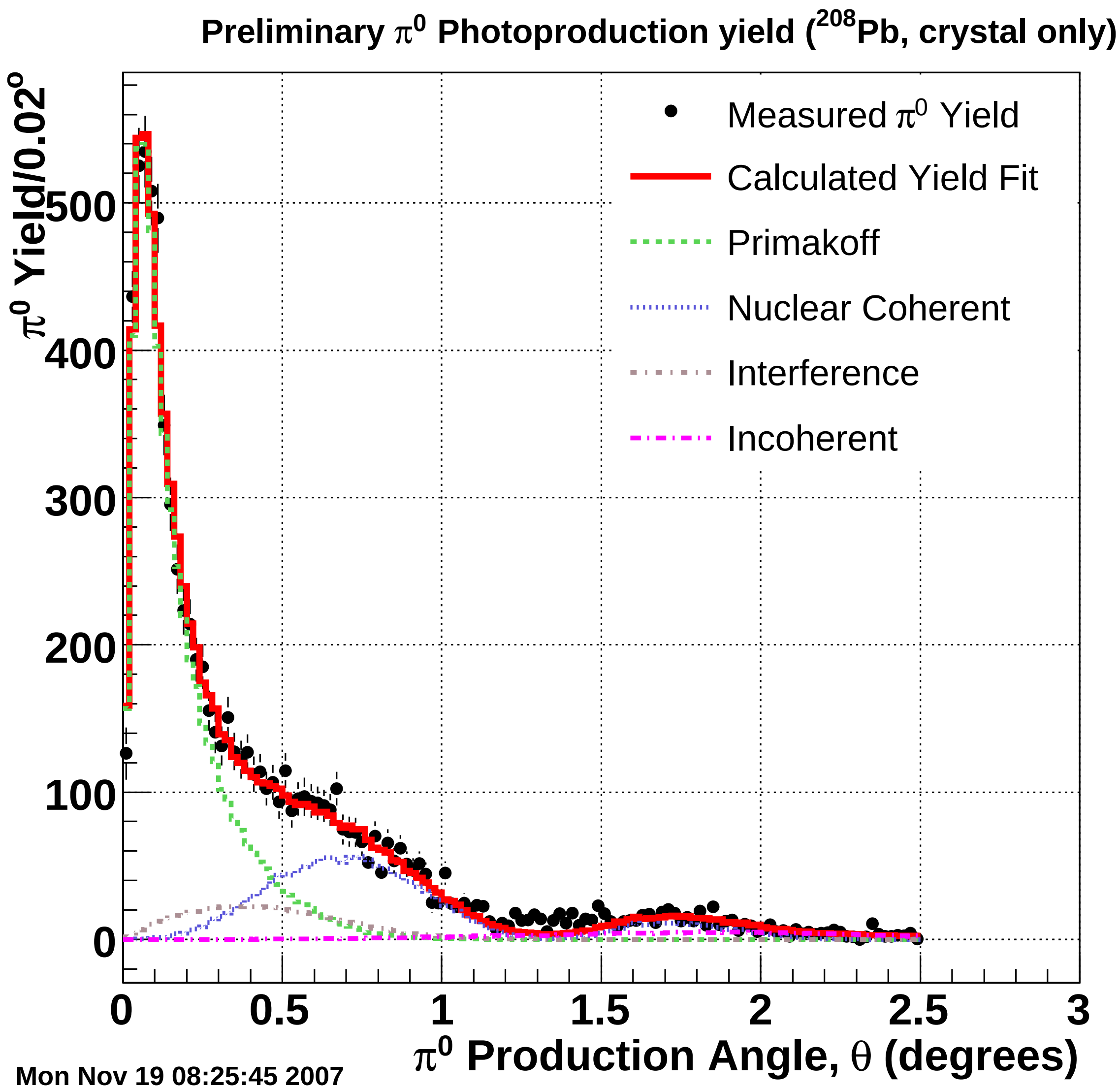
$\rightarrow$ where the parameter $b_p = \Gamma_{\gamma\gamma}$

∘ Vary the four parameters (b_p, b_c, b_i, and ϕ) and minimize χ^2.

^{12}C Target Yield Fit



^{208}Pb Target Yield Fit

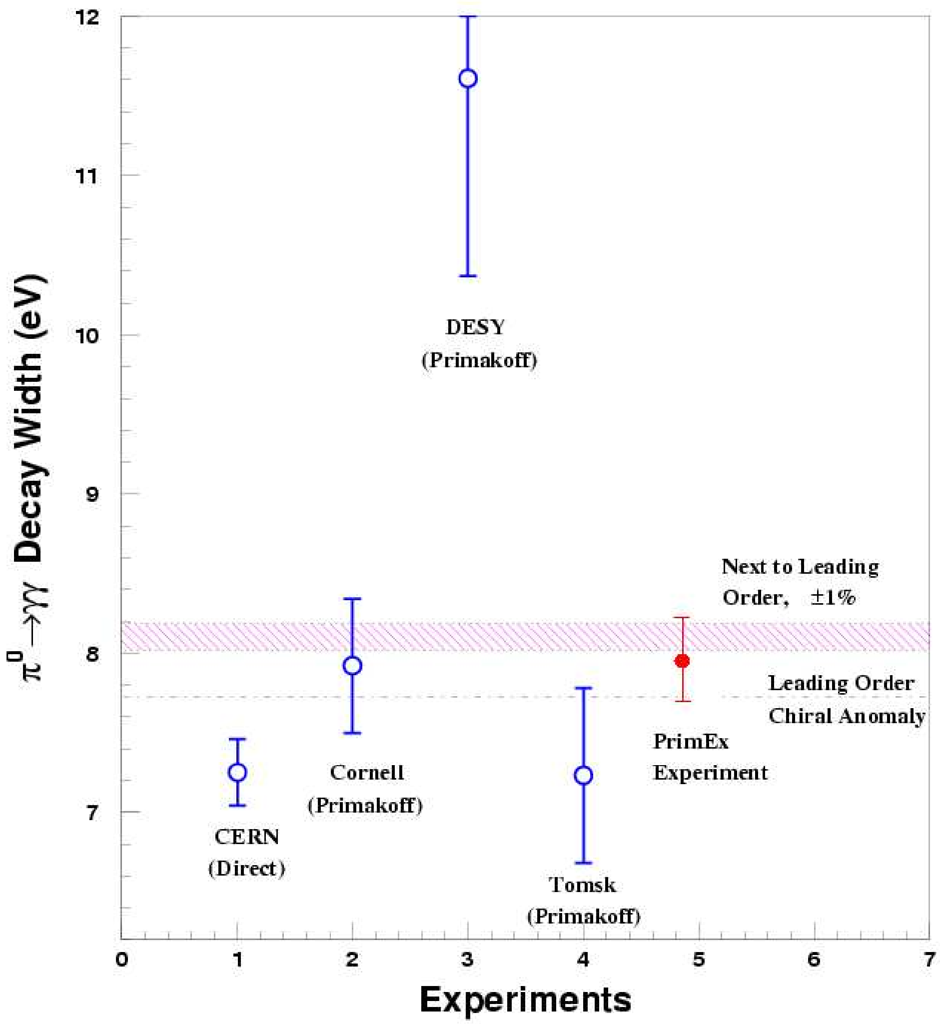


Systematic Error Table and Yield Fit Result

$m_{\gamma\gamma}$ fits + inelast bkgd corr.	$\pm$1.0
Inelastic bkgd shape uncert.	$\pm$0.75
Photon flux	$\pm$1.1
Incoherent XS shape uncert.	$\pm$1.3
Nuclear coh. XS energy dep.	$\pm$0.04
Detection/Recon efficiency	$\pm$0.5
Fiducial Acceptance	$\pm$0.3
Event Selection	$\pm$1.0
Target thick. + branch ratio	$\pm$0.06
Tagged Photon Energy	$\pm$0.1
Total Systematic	$\pm$2.4%

Prelim. Result: $\Gamma_{\pi^0\to\gamma\gamma} = 7.93\text{eV} \pm 1.6\%(\text{stat}) \pm 2.4\%(\text{syst})$

$\Gamma_{\pi^0 \to \gamma\gamma}$ Preliminary Result



Summary and Outlook

- High Quality precision π^0 photoproduction data on ^{12}C and ^{208}Pb targets using $4.9 \leq E_\gamma^{tagged} \leq 5.5$ GeV has been collected and analyzed by the PrimEx Collaboration.
- Preliminary cross section results from studied calibration reactions e^+e^- production and Compton scattering are both in excellent agreement with theory (at the $2-3\%$ level).
- All three ∼independent π^0 analysis groups have achieved very consistent results.
- The preliminary π^0 partial width result from this analysis: $\Gamma_{\pi^0 \to \gamma\gamma} = 7.93\text{eV} \pm 1.6\%(\text{stat}) \pm 2.4\%(\text{syst})$.
- The mean lifetime: $(8.20 \pm 0.24) \times 10^{-17}$ s
- Preliminary $\Gamma_{\pi^0 \to \gamma\gamma}$ results from both targets in excellent agreement.
- Continued work on reducing systematic error and finalizing results.