Glimpsing one of Nature's Secrets: The π^0 Lifetime

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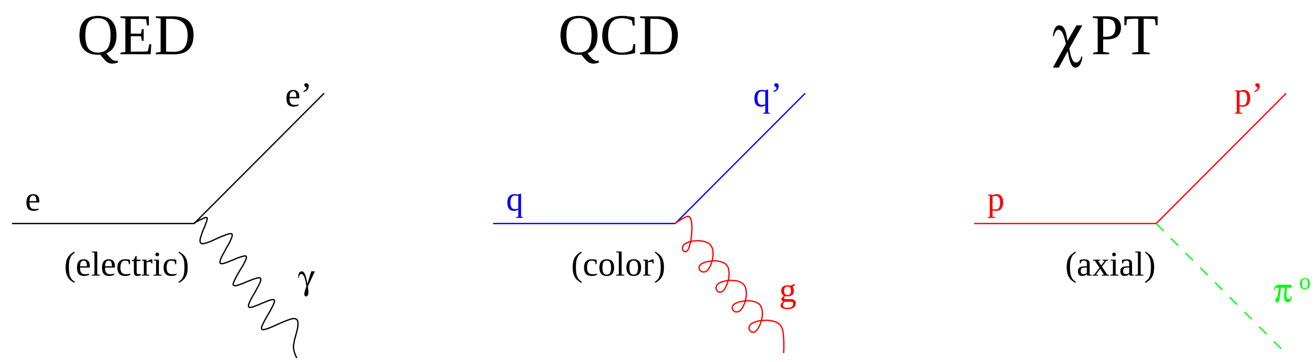
Outline

- Introduction and Physics Motivation
- Experimental Overview
- Calibration Reactions
  - Pair Production
  - Compton Scattering
- π^0 Analysis Details
- Final $\Gamma_{\pi^0 \to \gamma\gamma}$ Result
- Summary and Outlook

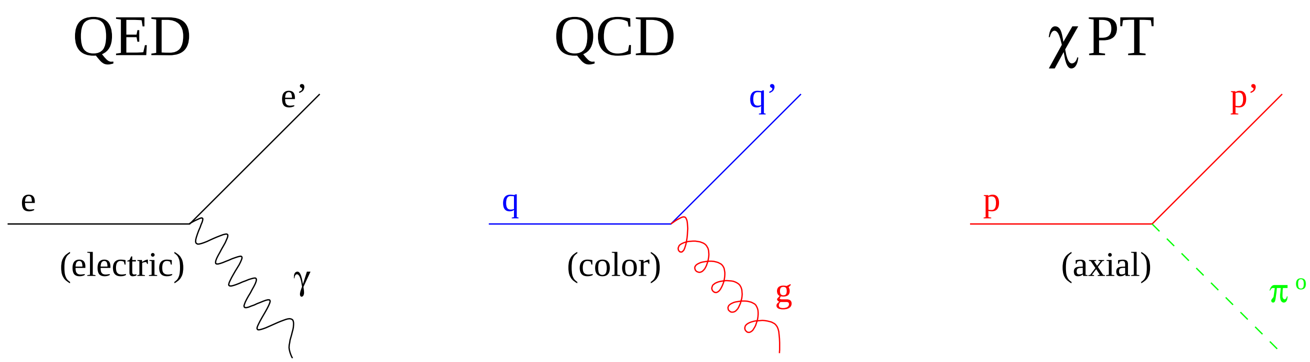
Intro: Examples of Charges and their Theories



- QED: Relativistic quantum field theory describing the interactions between electrically charged particles by photon exchange.
  →Very successful fundamental theory–can calculate all EM phenomenon to extremely high precision.

- QCD: Fundamental theory describing the interactions between color charged particles (quarks and gluons) which make up hadrons.
  →Difficult to prove–can only make quantitative, testable predictions using perturbative approach for high momentum transfer processes...Here the quark masses are neglected....

Intro: Examples of Charges and their Theories



- χPT: Effective (not fundamental) field theory describing the physics of QCD with light quark masses. It does this by replacing the quark/gluon interactions by a set of nucleon/pion interactions with strengths governed by the axial charge.

→Strengths and limitations under investigation: Uses perturbative expansion of exchange currents associated with the near massless three lightest quarks to make testable predictions about the structure of hadrons at low energies. .

Intro: Properties of the Neutral Pion (π^0)

- Lightest of all hadrons: mass = 264m_e (134.98MeV)
- Spin = 0 (boson)
- Decay channels: $\pi^0 \rightarrow \gamma\gamma$ (98.8%), $\pi^0 \rightarrow e^+e^-\gamma$ (1.1%)
- Composition: $(u\bar{u} - d\bar{d})/\sqrt{2}$
- Quantum numbers: $J^{PC} \equiv 0^{-+}$

$\longrightarrow$Total angular momentum J = S + L = 0 implies π^0 is a scalar (not changed by Lorentz transformations)

$\longrightarrow$Natural Parity P = (-), implies x$\rightarrow$ -x, mirror reversed ψ needs to be multiplied by -1 (means π^0 is a pseudoscalar).

$\longrightarrow$Charge Parity C = (+), implies meson unchanged under interchange of quark and antiquark ($q \rightarrow \bar{q}$); it is its own anti-particle.

Intro: Connection Between Decay Width and Lifetime

- In addition to other parameters, unstable particles are characterized. by their mass and mass uncertainty
- The mass uncertainty is called the “width” of the unstable particle and can be theoretically related to its lifetime (τ) via the Weisskopf - Wigner relation

Hand-Waving Explanation

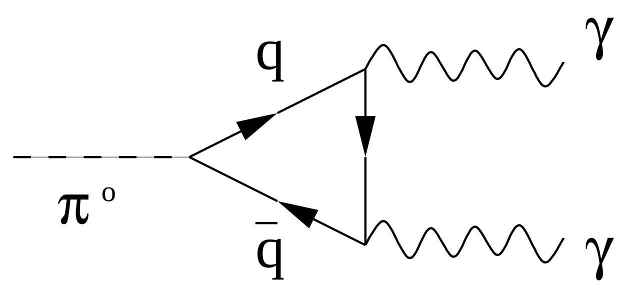
- Decay width $\Gamma = \hbar/\tau$ follows from the energy-time uncertainty principle $\Delta E \Delta t \leqq \hbar/2$
- The idea is this: If you observe a narrow mass peak (small energy uncertainty, ΔE), then its lifetime (Δt) can be relatively long, and vice versa
- So very short lifetimes can be determined by width measurements

Intro: History of π^0 Lifetime Experiments

- 1947: Pions ($\pi^{\pm}$) discovered in cosmic rays
- 1950: π^0 discovered in cosmic rays, $\pi^0 \rightarrow \gamma\gamma$ decay mode observed at Berkeley Cyclotron (lifetime to short to measure)
- Mean lifetime $\tau_{\pi^0} < 10^{-15}$ seconds established by 1957 from $K^+ \rightarrow \pi^0\pi^0$ emulsion experiment ($d_{\pi^0} < 0.5\mu$m)
- 1951: Primakoff effect ($\gamma\gamma^* \rightarrow \pi^0$) invented
- 1970-5: First experiments to use Primakoff effect to measure τ_{π^0}
- Particle Data Group (PDG) Book database established by 1988

Intro: History of π^0 Lifetime Theory

- The amplitude ($A_{\pi\gamma\gamma}$) for $\pi^0 \rightarrow \gamma\gamma = 0$ in the Chiral limit ($m_q \rightarrow 0$) according to theory of Partially Conserved Axial Current (PCAC)
- 1968: Adler,Bell, and Jaciw discover the axial anomaly (non-conservation of axial current)



$\rightarrow A_{\pi\gamma\gamma} = \alpha_{em}/\pi F_\pi$

$\rightarrow \Gamma_{\pi^0\rightarrow\gamma\gamma} = (m_\pi^3/64\pi)A_{\pi\gamma\gamma}^2 = 7.725\text{eV} \pm 0.5\%$

$\rightarrow \tau_{\pi^0} = 8.07 \times 10^{-17}$ s

$\rightarrow c\tau_{\pi^0} \sim 25$ nm

Intro: Anomalies in QCD

- Anomaly: When a symmetry of the classical theory is not present in the quantized version.
- In QCD, the anomaly is not anomalous, it is an essential part of the theory.
- For which processes does the anomaly occur?

$\rightarrow$ Define a multiplicative quantum number "natural parity" (P) = 1 for S, V, ... particles. P = -1 for PS, PV, ...

$\rightarrow$ An anomalous reaction changes the natural parity:

$\gamma\pi(P = -1) \longrightarrow \gamma\pi(P = -1)$ not anomalous
$\pi^0(P = -1) \longrightarrow \gamma\gamma(P = 1)$ anomalous
$\gamma\pi(P = -1) \longrightarrow \pi\pi(P = 1)$ anomalous

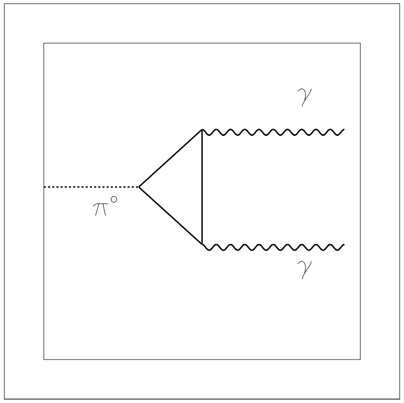
- All anomalous reactions are governed by the Wess-Zumino Lagrangian in χPT which permits transitions that violate certain symmetries.
- In the Chiral limit, the absolute rate of these reactions are predicted by QCD

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.



→In the leading order (chiral limit), the anomaly leads to the decay width:

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

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

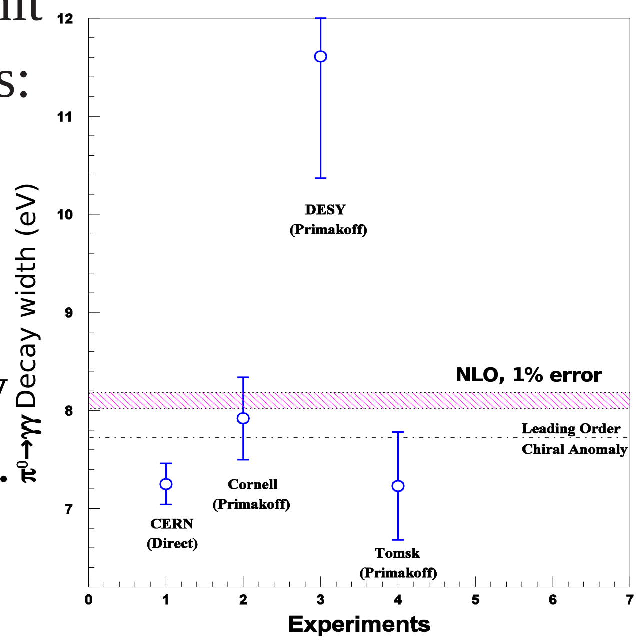
→ Current Particle Data Book value is 7.84 ± 0.56 eV

Physics Motivation

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

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

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



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

  $\longrightarrow$ 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)

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

○ 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 ⇒ too small to measure

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

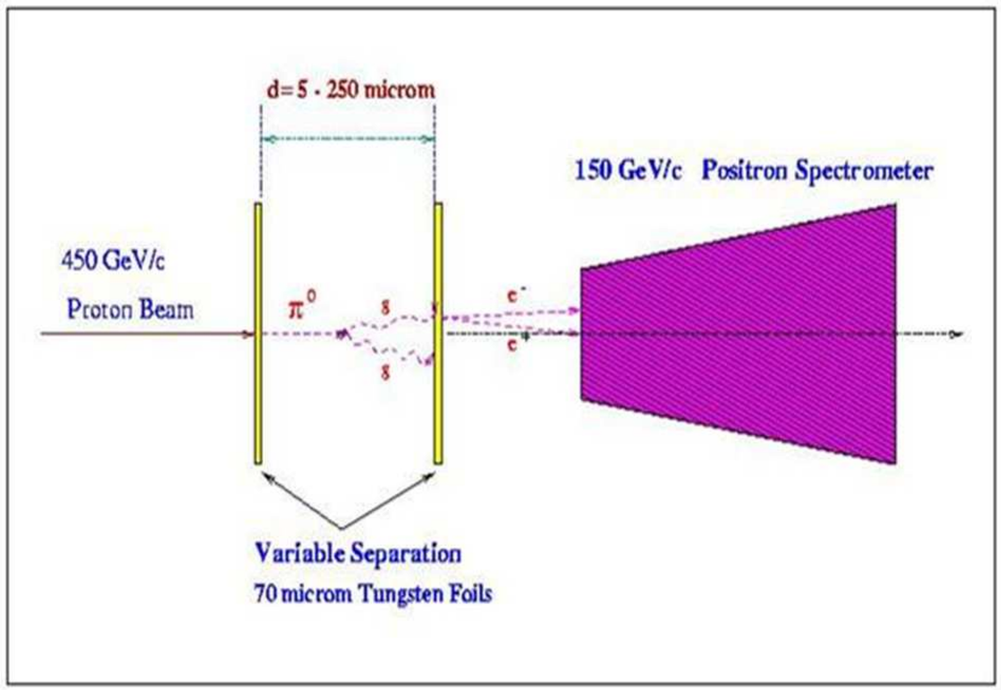
$$L = v\tau_{\pi^0} E/m \tag{2}$$

→ for E = 1000GeV, L∼ 100μm (very challenging experiment)

→ Performed in 1984:
Used 450GeV protons

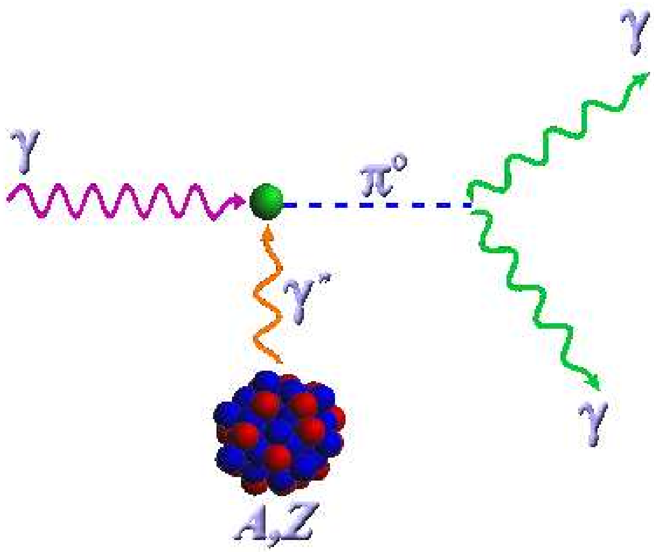
→ Result:
$\Gamma_{(\pi^0 \to \gamma\gamma)}$ = 7.34eV±3.1%

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



The Primakoff Effect

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

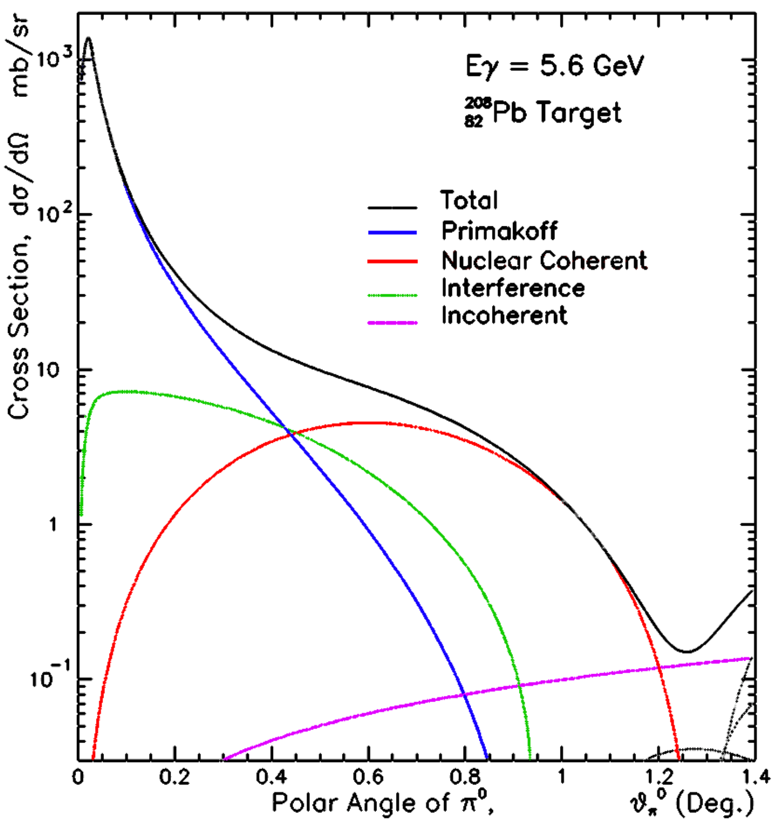


$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\rightarrow\gamma\gamma)}\frac{8\alpha_{em}Z^2}{m^3}\frac{\beta^3E^4}{Q^4}|\tilde{F}_{em}(Q)|^2 sin^2\theta_\pi \quad (3)$$

Full Cross Section Components

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

Primakoff Nucl.Coherent Incoherent Interference



Primakoff:

Proportional to Z^2,

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

Nuclear Coherent:

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

Nuclear Incoherent:

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

Interference:

PrimEx Collaboration

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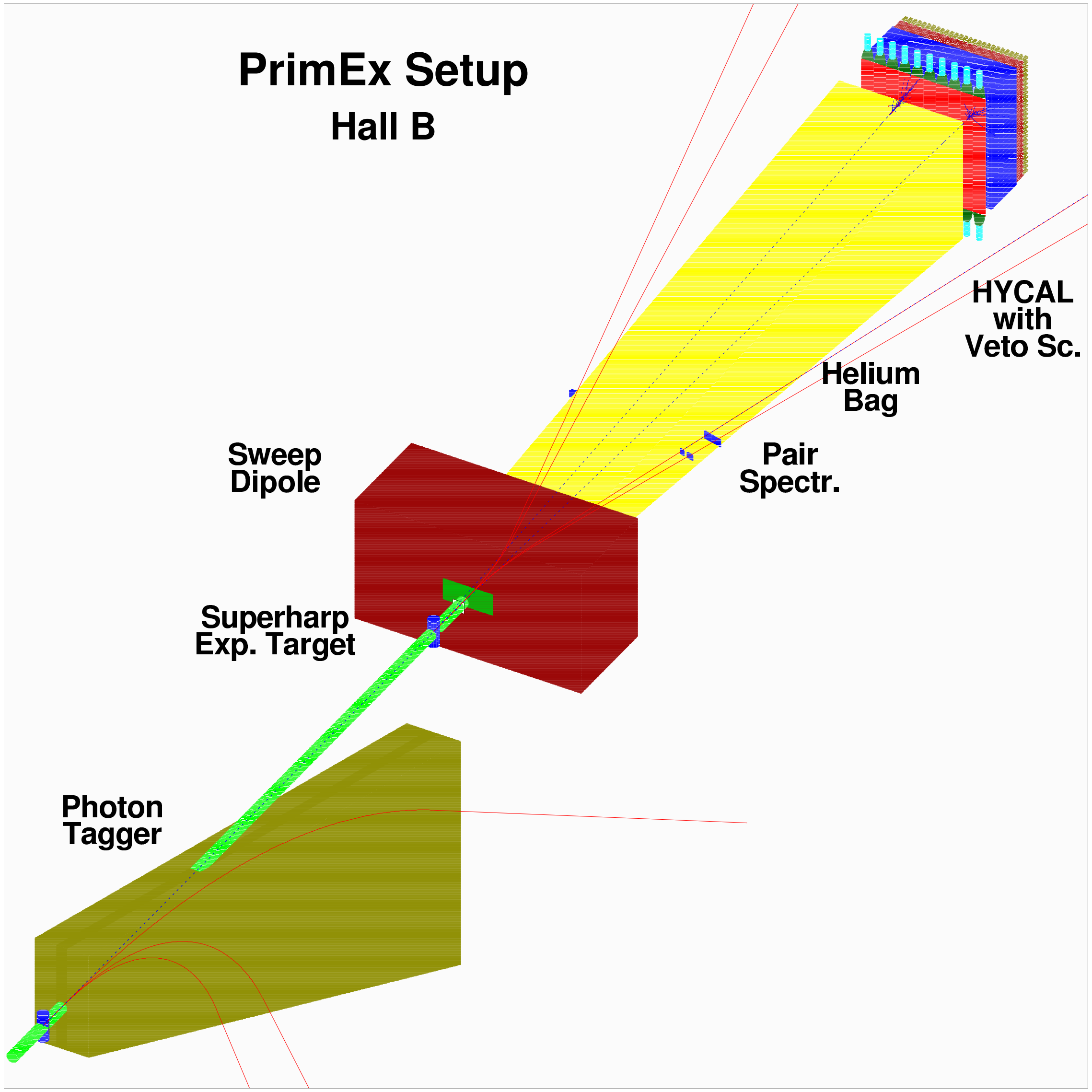
Experiment Overview

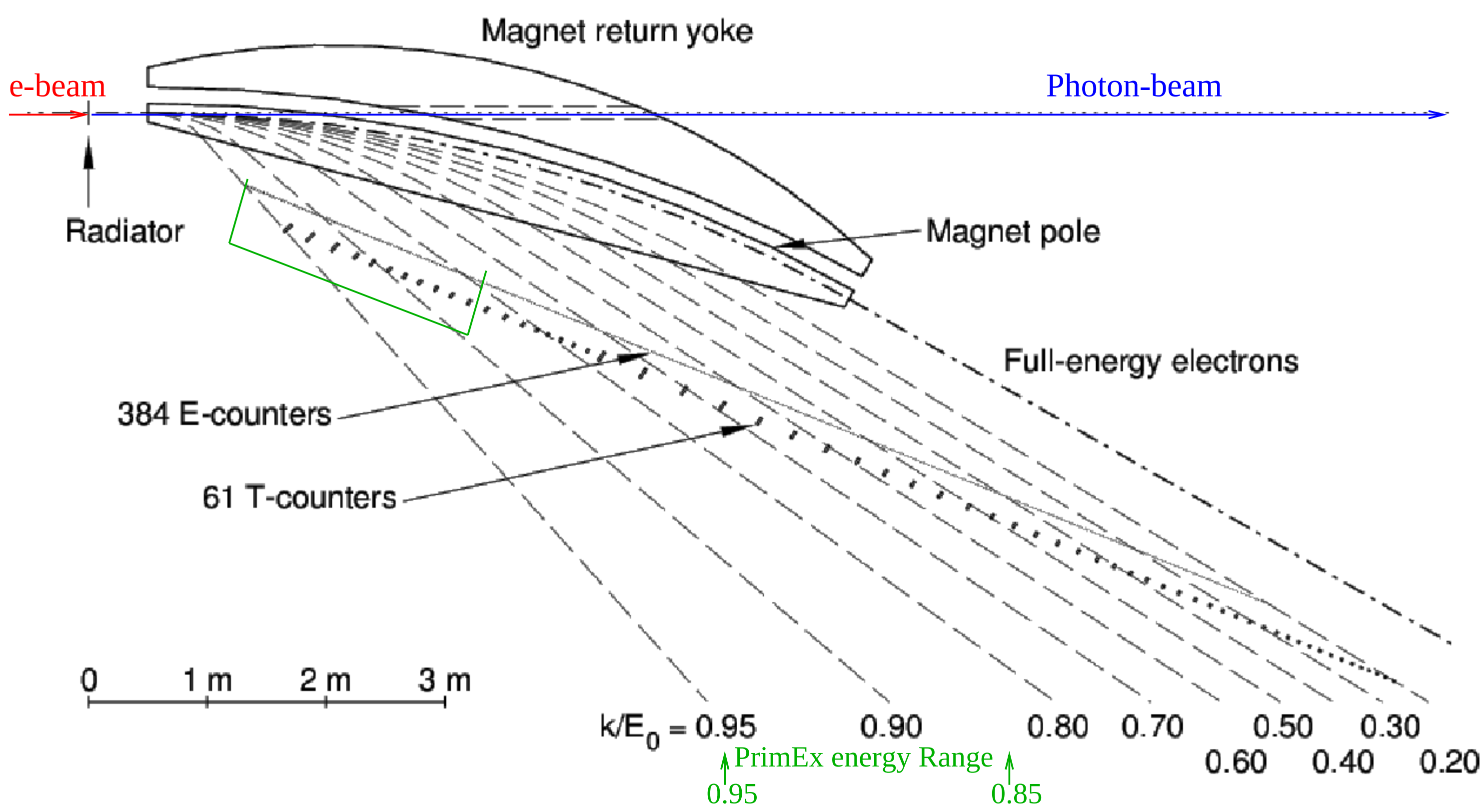
- Conducted at Jefferson Lab, Fall 2004
- Used 5.75 GeV continuous e^- beam and Hall B γ-tagging facility
- Tagged photons incident on $5\%X_0$ targets: ^{12}C and ^{208}Pb
- New PrimEx/Hall B calorimeter (HyCal), upstream of CLAS, designed to detect π^0 decay γ's
- Measured 3 physical processes (absolute 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



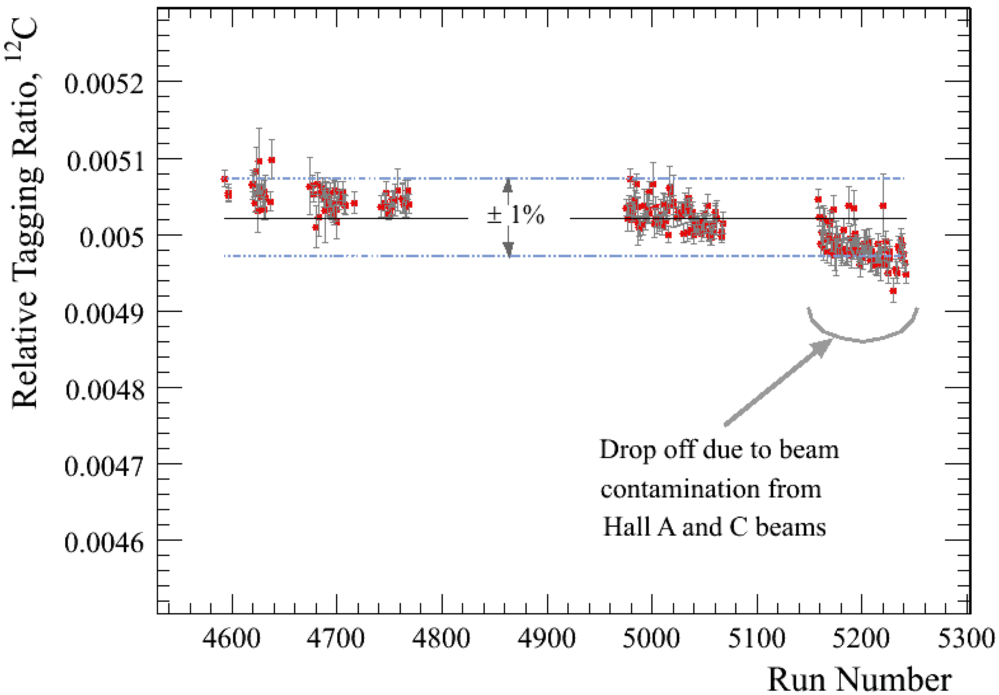
Hall B Photon Tagger

- 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.

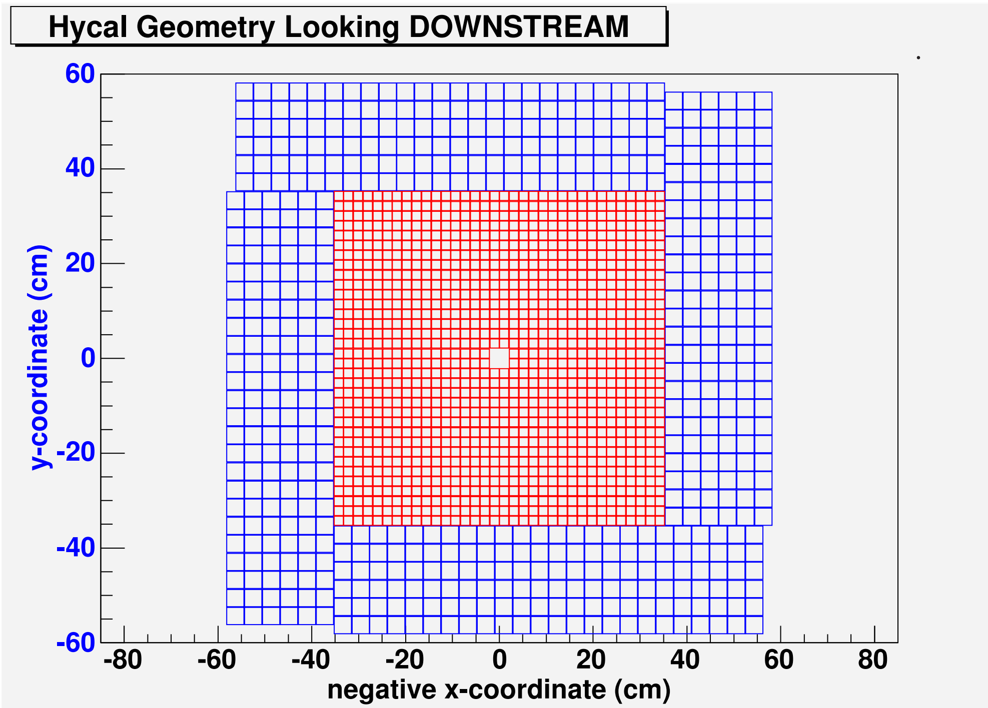


Photon Flux Control

- PrimEx achievement: Total uncertainty in photon flux = 0.98%.
- Number of tagged photons on target (N_γ) calibrated periodically using a Total Absorption Counter (TAC).
- Any drifts in the tagging ratio, occurring between calibration points, are monitored online with the e^+e^- pair spectrometer.



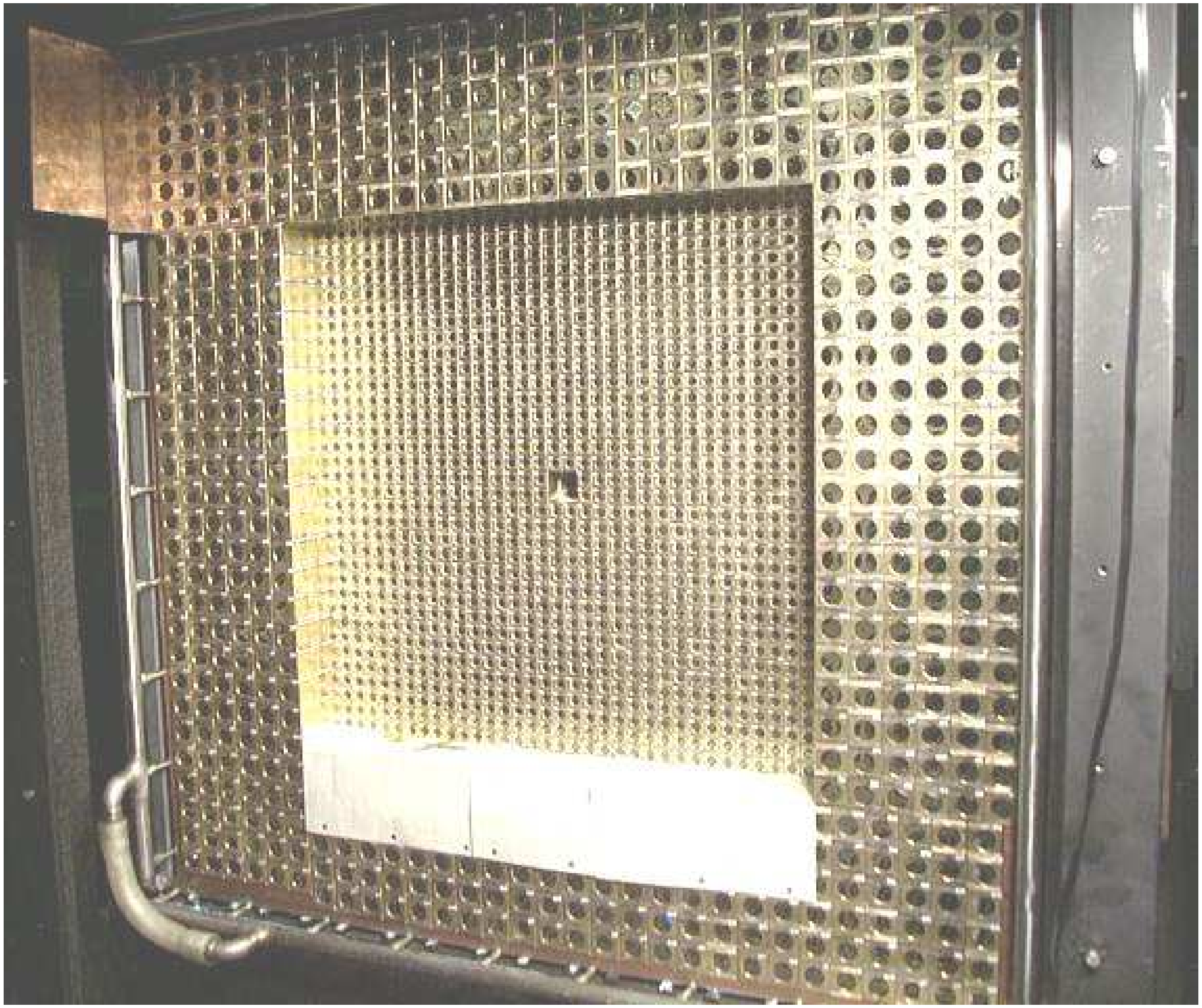
PrimEx Hybrid Calorimeter – “HyCal”



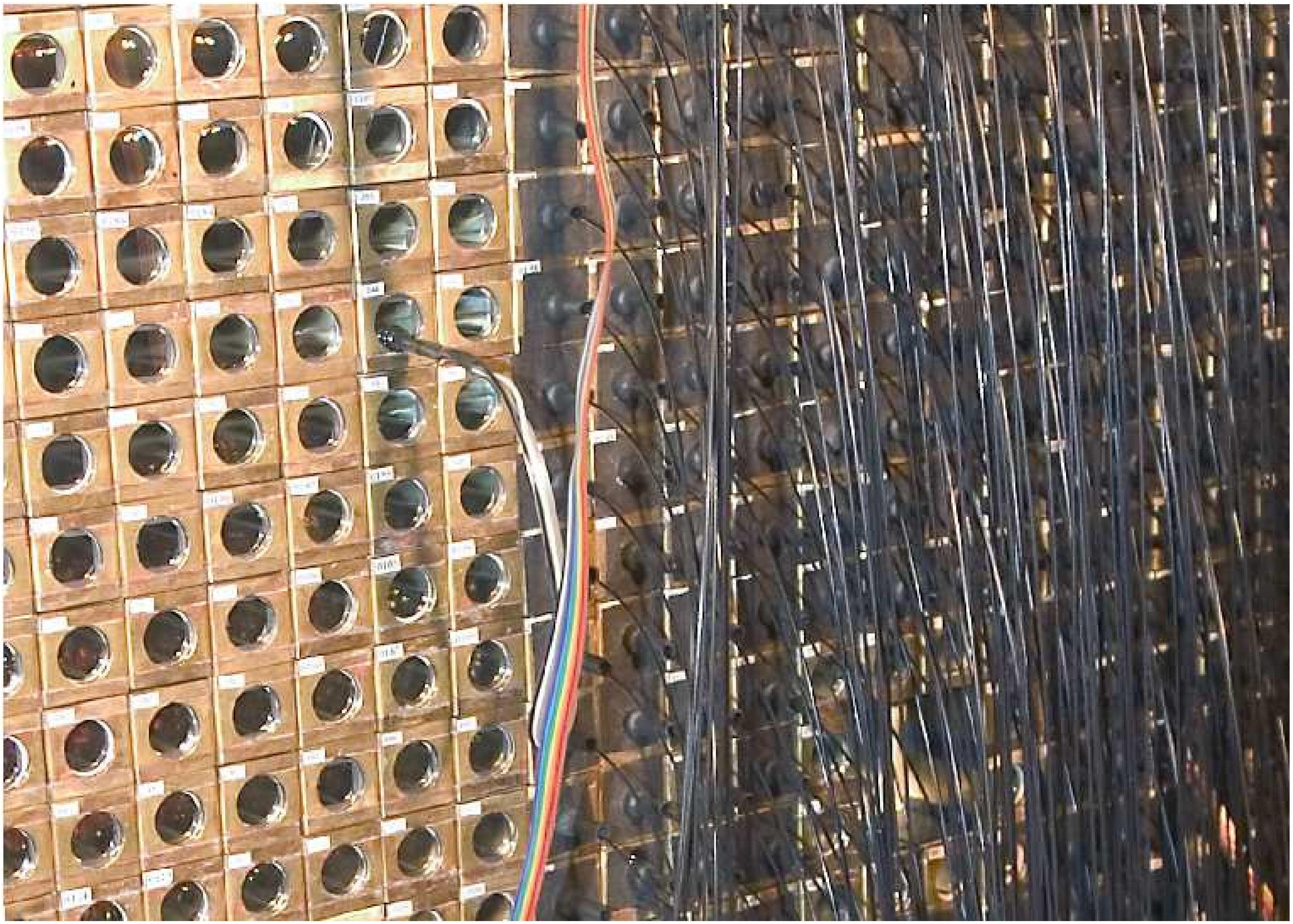
- Optimal performance/cost design
- 1.2 m $\times$1.2 m, 1728 channels
- 576 Lead-glass (outer layers)
- 1152 Lead-Tungstenate crystal (inner layers)

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

HyCal Assembly – Support Frame and Cooling System

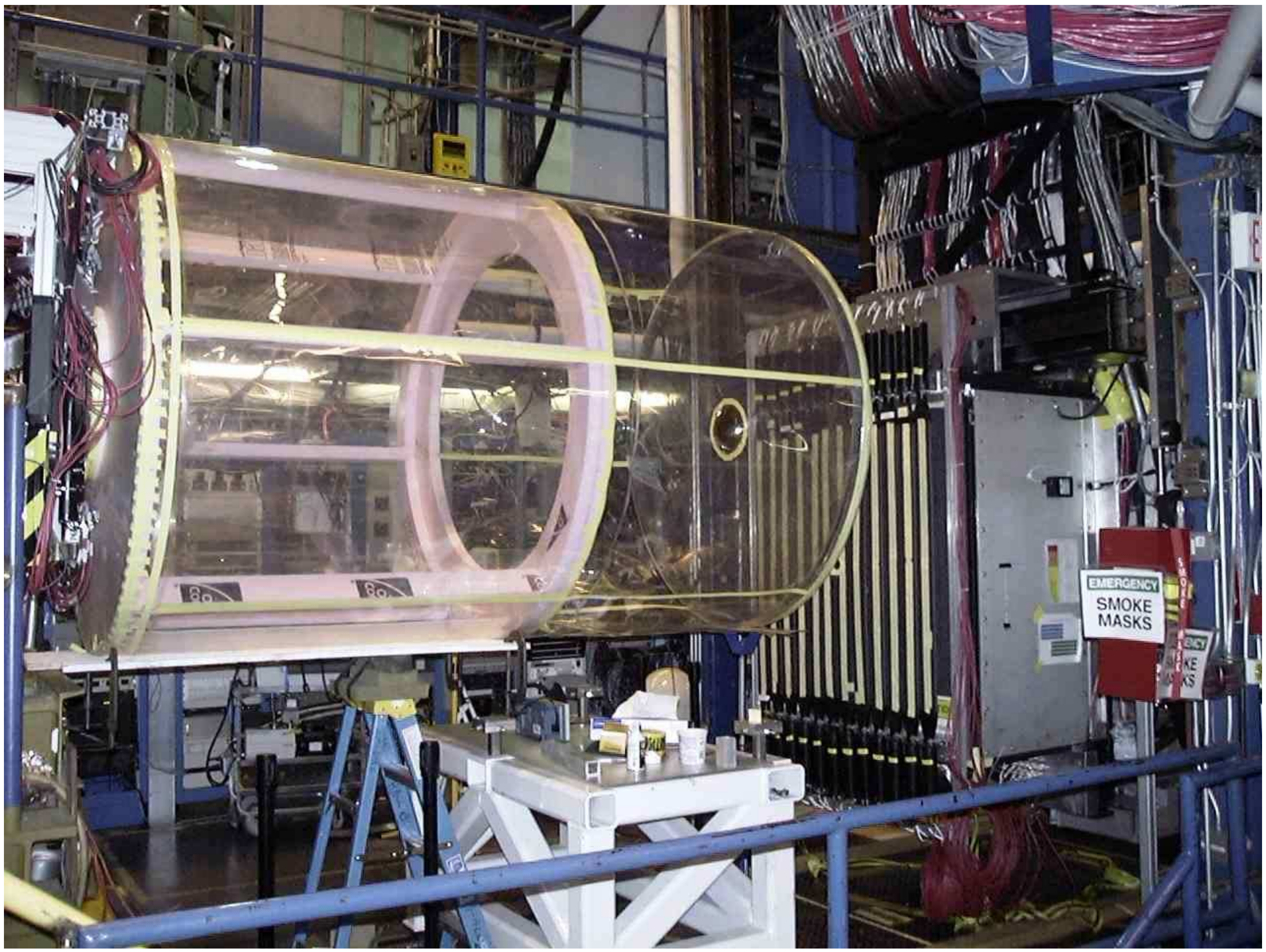


HyCal Assembly – Light Monitoring System

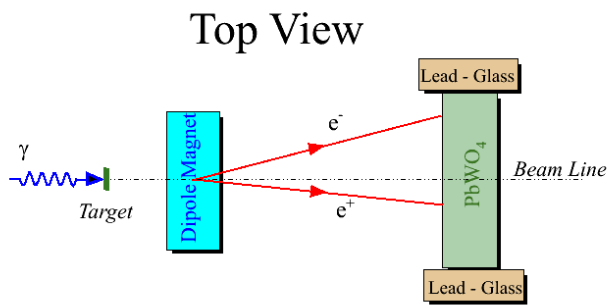


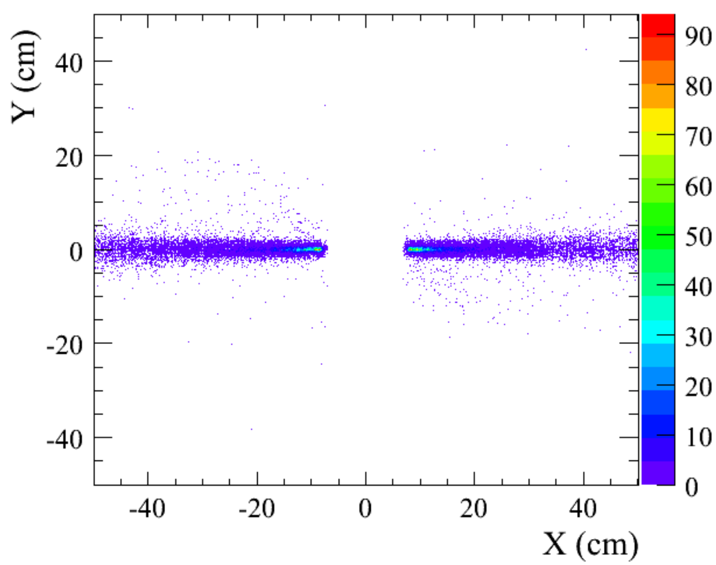
HyCal Calibration –"Snake Scans"

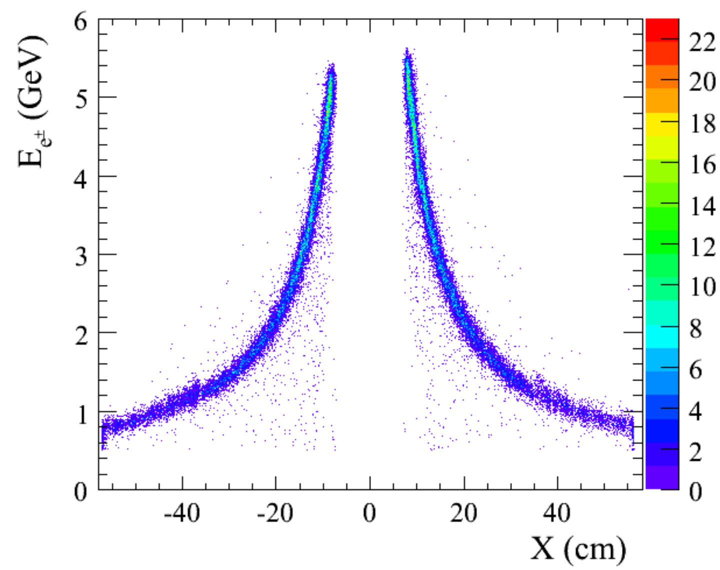
- Full x,y motion allowed each ch. to be scanned through tagged γ beam.
- Performed at both the beginning and end of the experiment.



Calibration Reactions: e^{+} e^{-} Pair Production



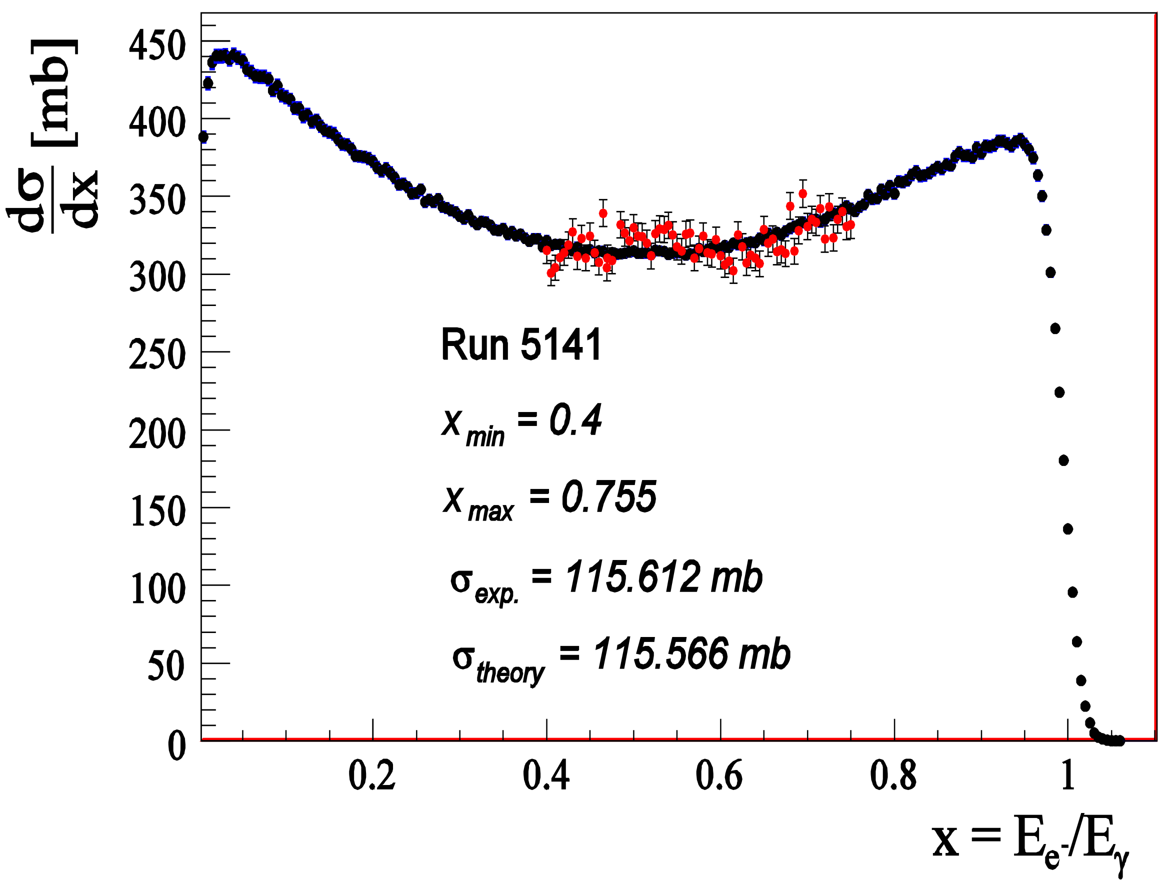




Calculation of Pair Production Cross Section at PrimEx Kinematics

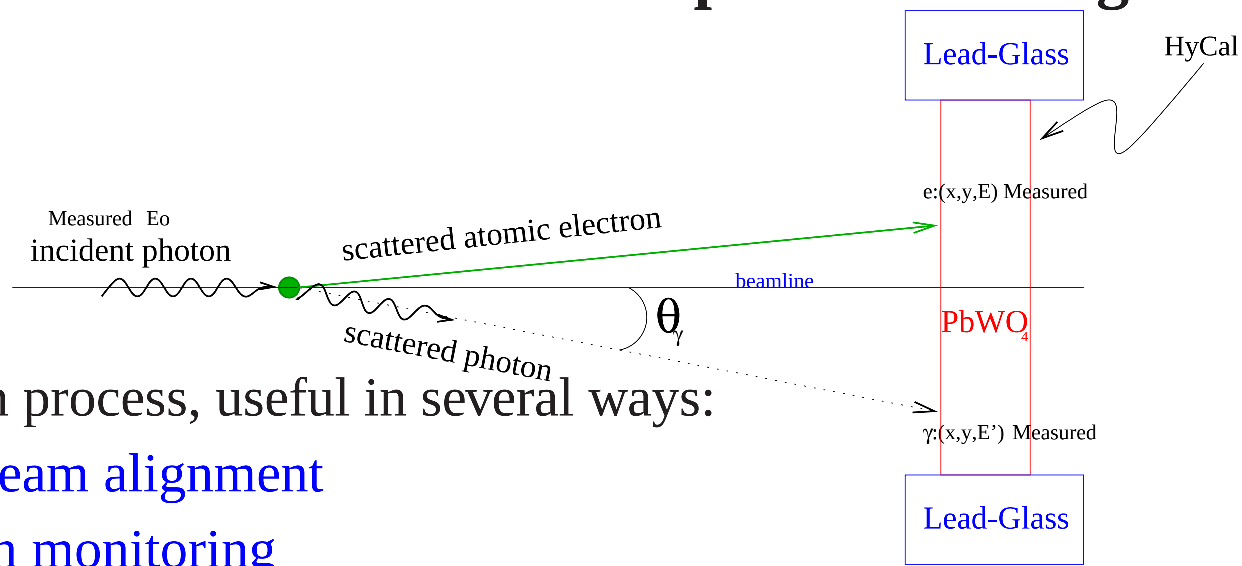
- Bethe-Heitler mechanism of pair production on the nucleus with screening effects due to atomic electrons and Coulomb distortion
- Pair production off atomic electrons, considering excitation of all atomic states and correlation effects due to the presence of other electrons and the nucleus
- Radiative 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



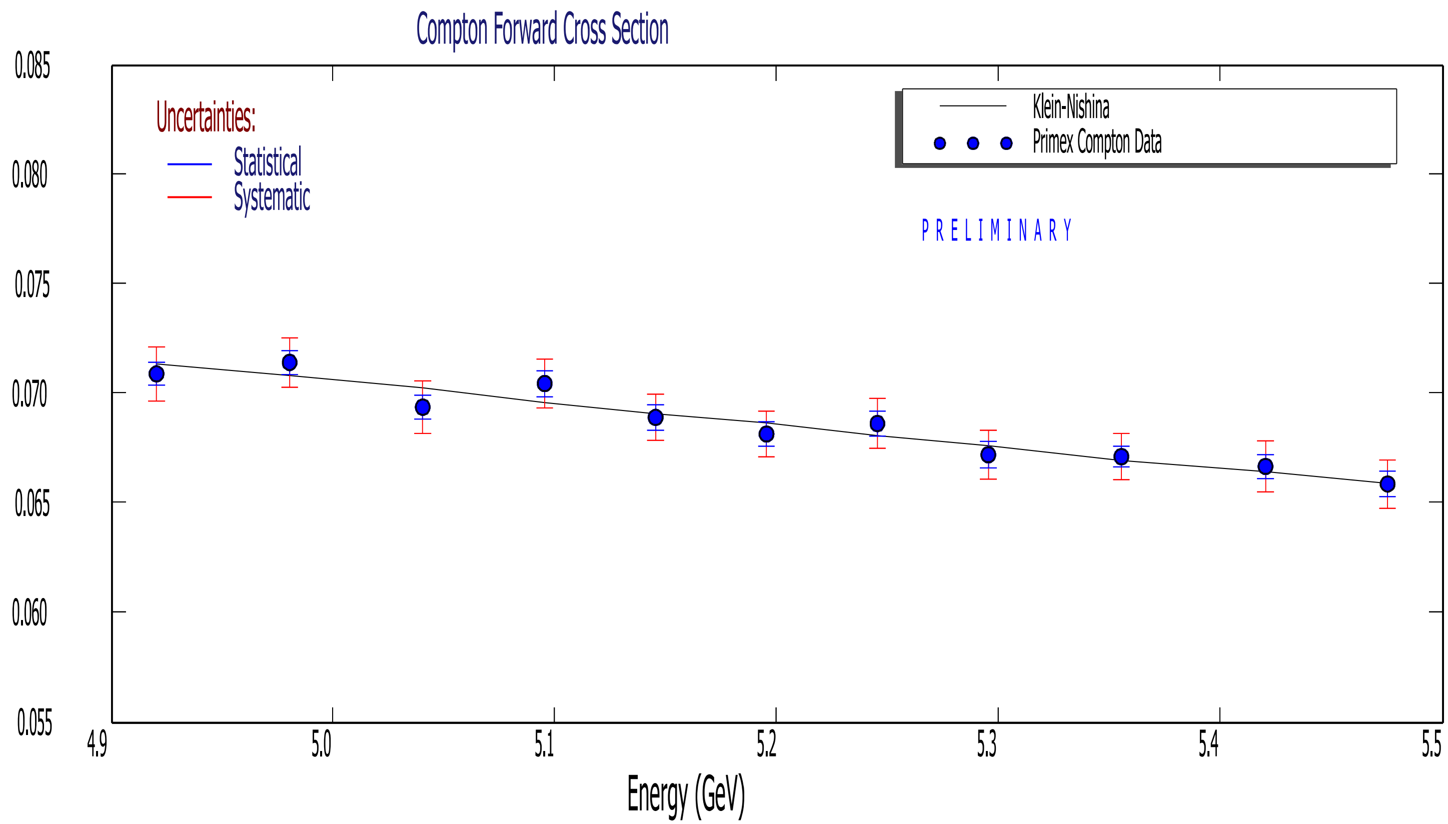
- Agreement with theory at $\sim$ 1.0% level

Calibration Reactions: Compton Scattering



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

Compton Cross Section Preliminary Result



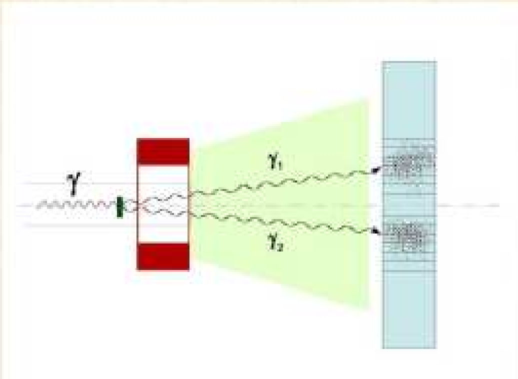
- Average statistical error: 0.6%
- Total error: 1.3% (dominated by photon flux: 1.0%)

Analysis Details: π^0 Event Selection

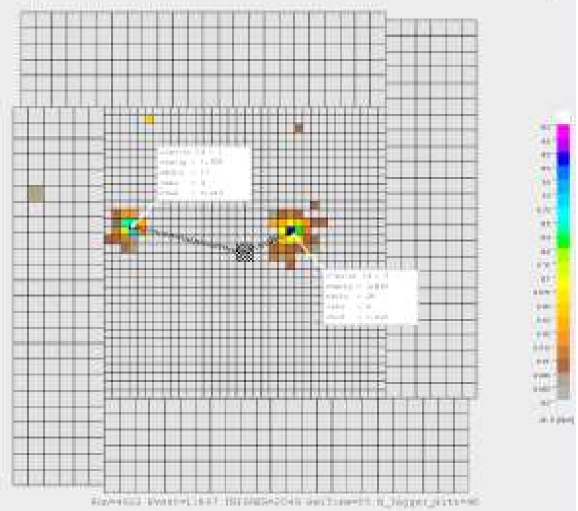
π^0 analysis

We measure:

incident photon: energy and time
π^0 decay photons:
energies, coordinates and time



Schematic view of π^0 event

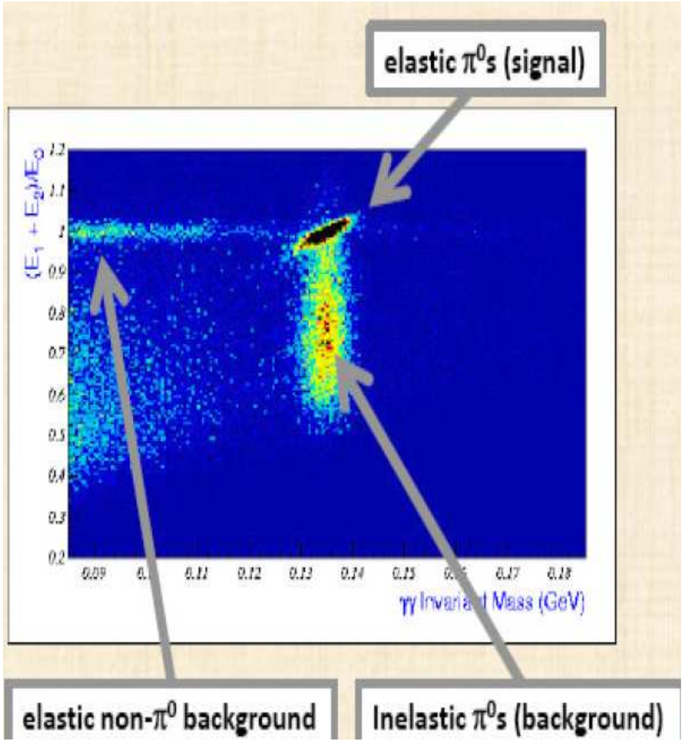


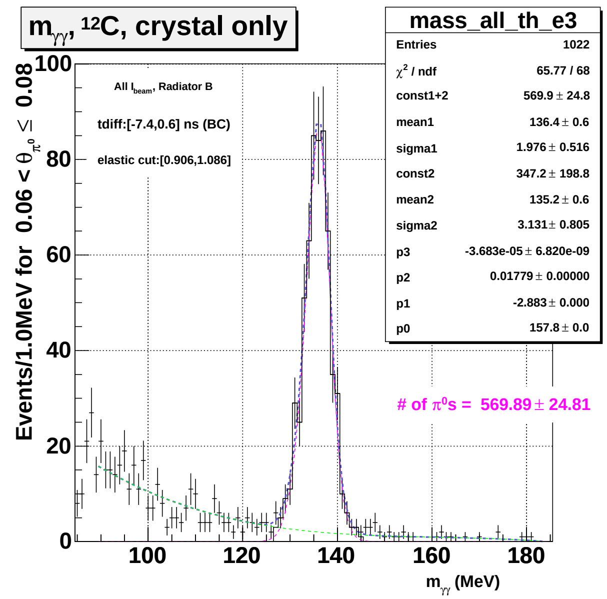
Kinematical constraints:

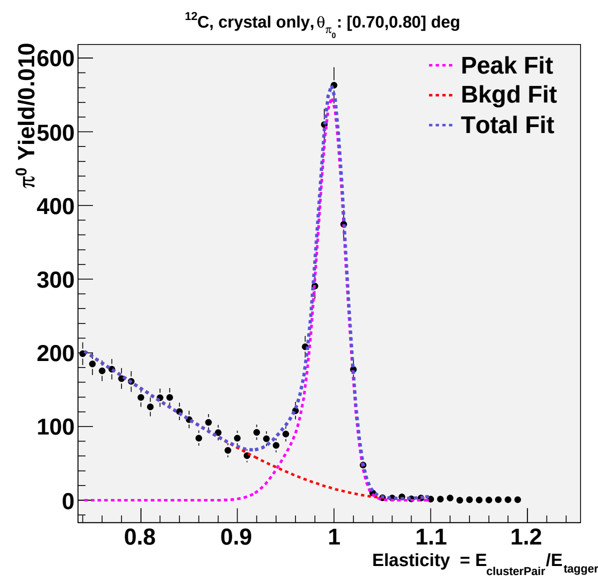
Conservation of energy;
$m_{\gamma\gamma}$ invariant mass

Three groups analyzed the data independently

PrimEx Collaboration

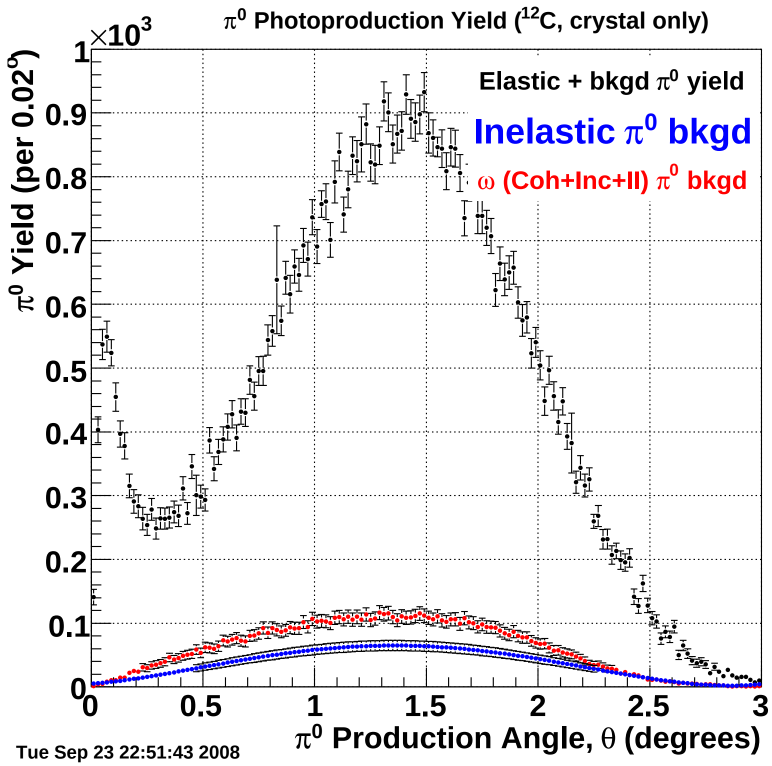


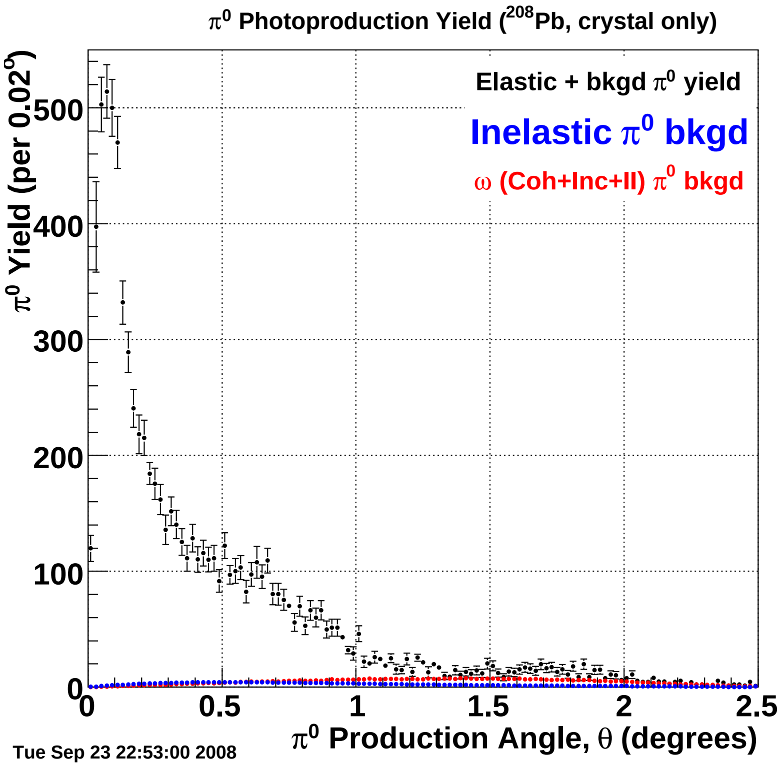




- For each θ_{π^0} bin, apply elastic cut and form $m_{\gamma\gamma}$ distributions; perform fit and extract peak counts = uncorrected yield.
- Correct for inelastic bkgd by eval π^0 elast. dist. explicitly for each θ_{π^0}; eval. inel. bkgd under the elastic pk using fit and sub. from yield.

Analysis Details: Yield with backgrounds (^{12}C and ^{208}Pb)





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

- Convert Yield to Cross Section.

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

$\rightarrow$ where $N_\gamma \equiv$ # of γ's on target (uncertainty $\sim 1.0\%$).

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

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

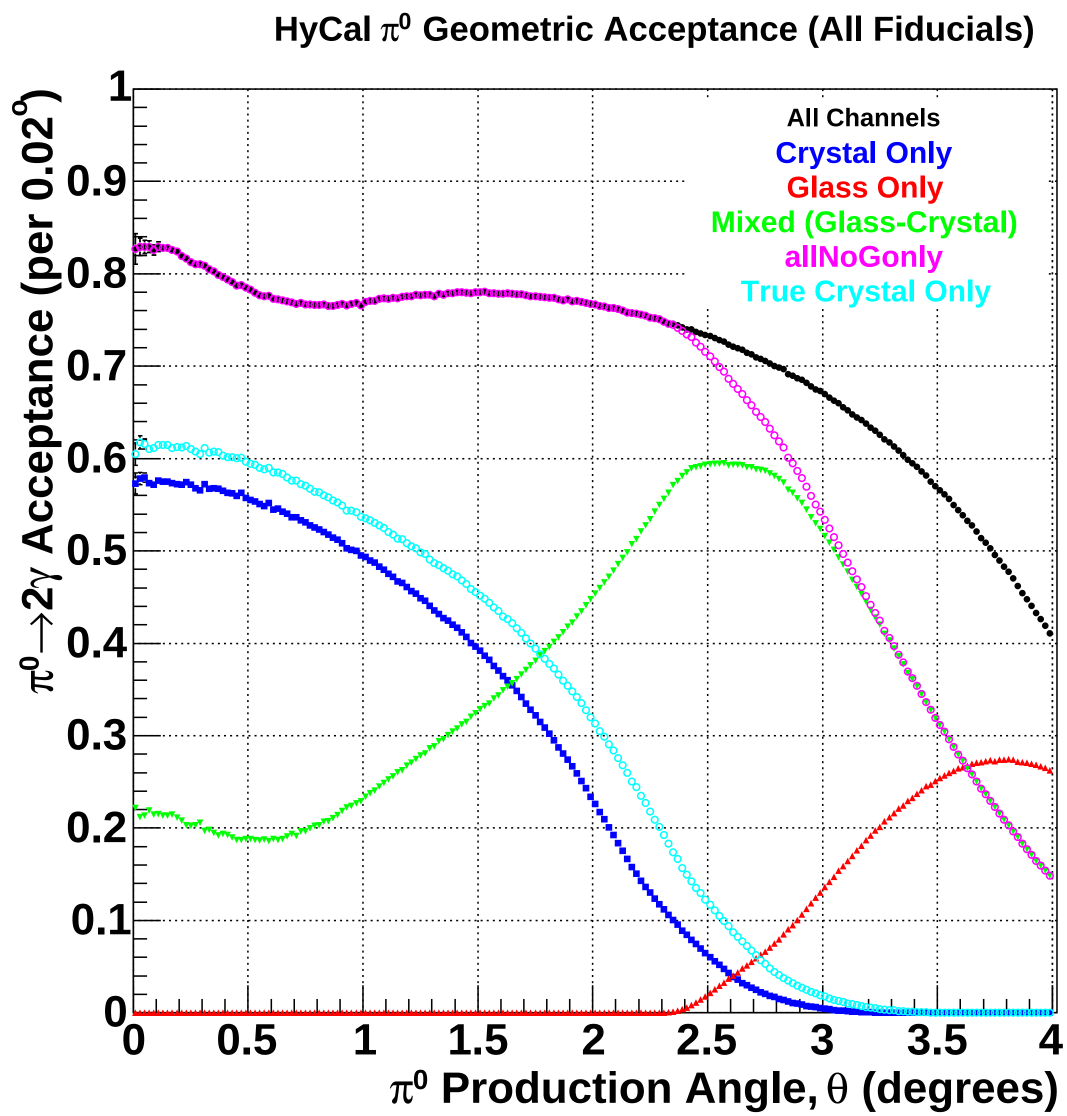
- Fit experimental data with parametrization:

$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = \mathrm{b_p}\frac{d\sigma_P}{d\theta} + \mathrm{b_{nc}}\frac{d\sigma_N}{d\theta} + \mathrm{b_b}\frac{d\sigma_I}{d\theta} + 2cos\phi\sqrt{\mathrm{b_p}\mathrm{b_{nc}}\frac{d\sigma_P}{d\theta}\frac{d\sigma_C}{d\theta}} \tag{8}$$

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

∘ Vary the four parameters ($\mathrm{b_p}$, $\mathrm{b_{nc}}$, $\mathrm{b_b}$, and ϕ) and minimize χ^2.

Hycal Geometric acceptance of both π^0 decay γ's



Yield Fit, $\Gamma_{\gamma\gamma}$ Extraction: Procedure

- Parametrize yield using sum of 4 theoretical shapes–smeared according to experimental resolutions.

$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = \mathrm{b_p}\frac{d\sigma_P}{d\theta} + \mathrm{b_{nc}}\frac{d\sigma_N}{d\theta} + \mathrm{b_b}\frac{d\sigma_I}{d\theta} + 2cos\phi\sqrt{\mathrm{b_p b_{nc}}\frac{d\sigma_P}{d\theta}\frac{d\sigma_C}{d\theta}} \qquad (9)$$

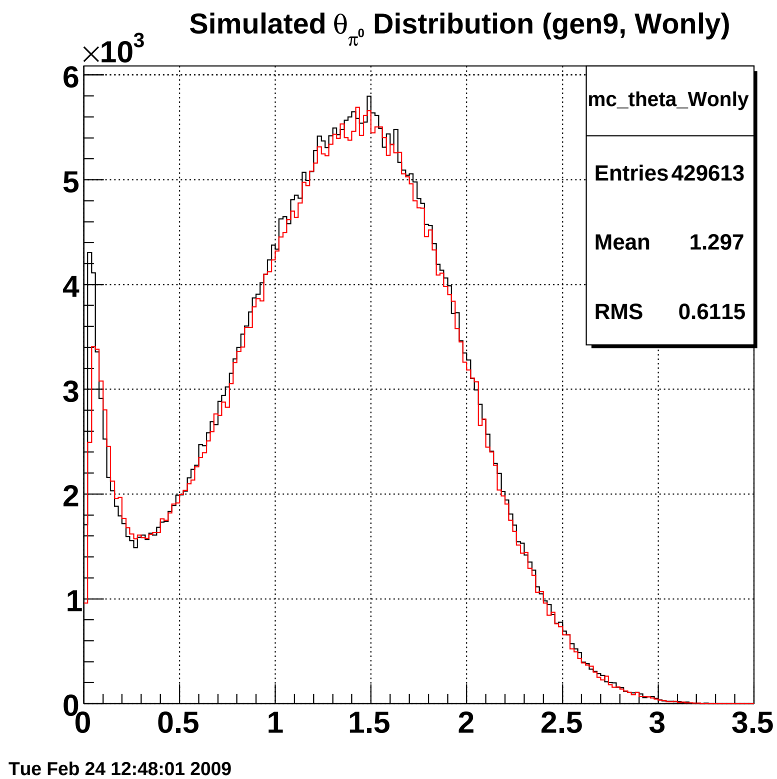
$\longrightarrow$ Calculate theory input shapes (cross sections) energy-weighted according to experimental flux.

$\longrightarrow$ Create π^0 event generator based on above cross sections and run through Primsim Monte Carlo.

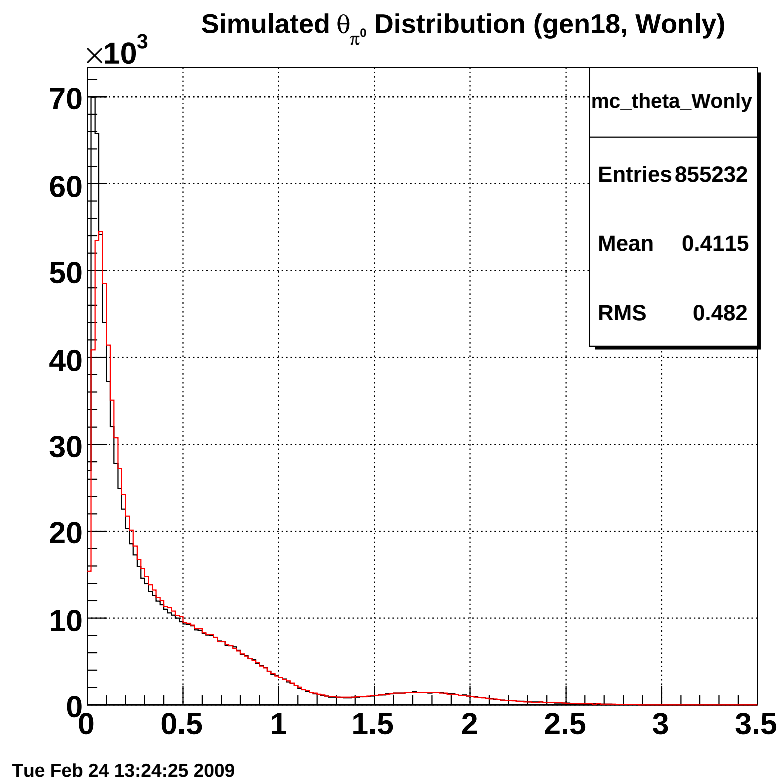
$\longrightarrow$ Digitize simulated data and reconstruct events using same algorithms as for real data. Produce simulated yield distributions with built-in experimental resolutions.

- Freely vary amplitudes of 4 shapes and minimize χ^2.

MC Shape Generation: Exmpl. Thrown & Det. Spectra

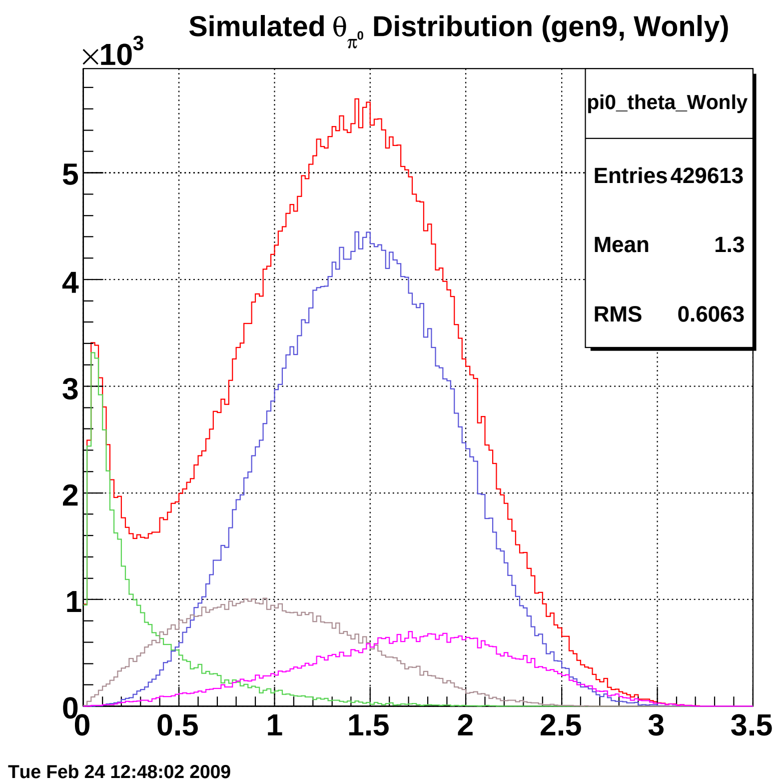


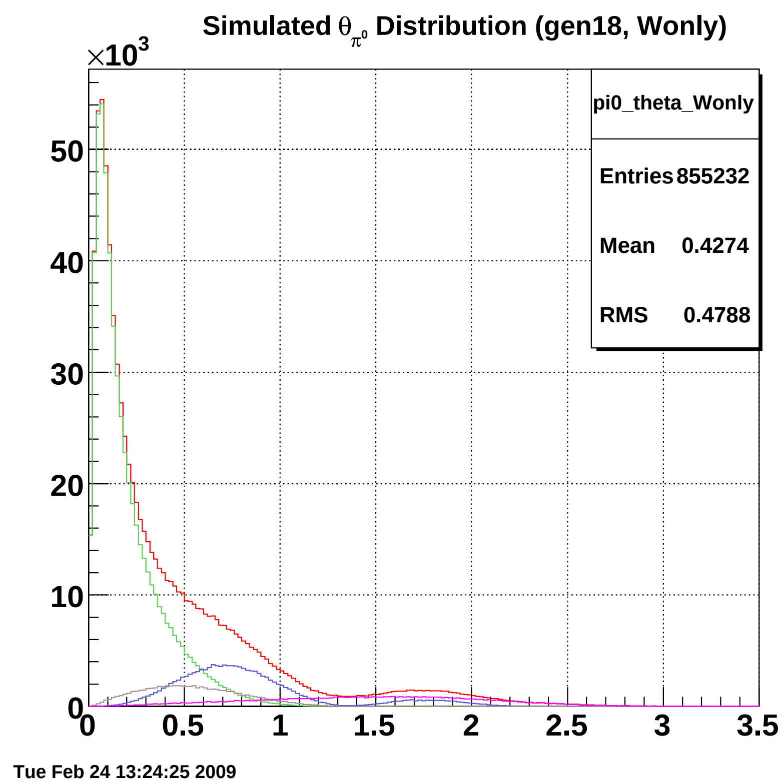
^{12}C: —θ_{π^0} Thrown —θ_{π^0} Detected



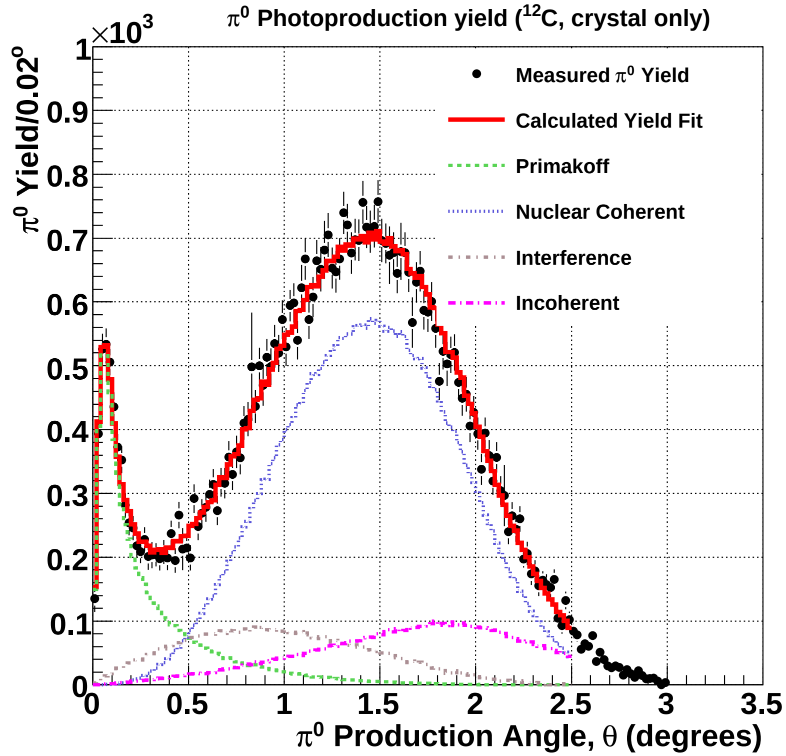
^{208}Pb: —θ_{π^0} Thrown —θ_{π^0} Detected

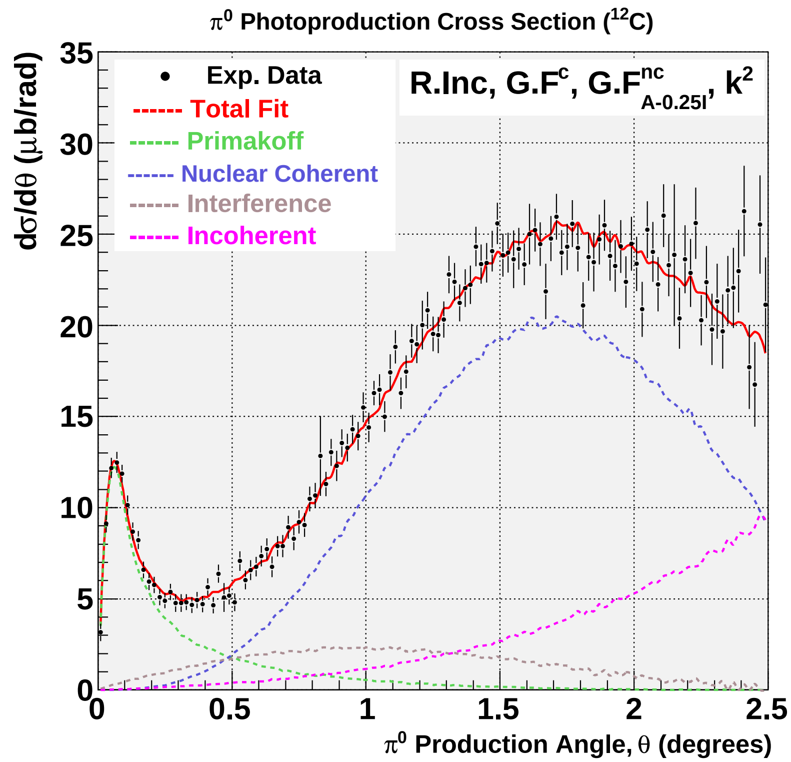
MC Shape Generation: Exmpl Fit Input Shapes (smeared)



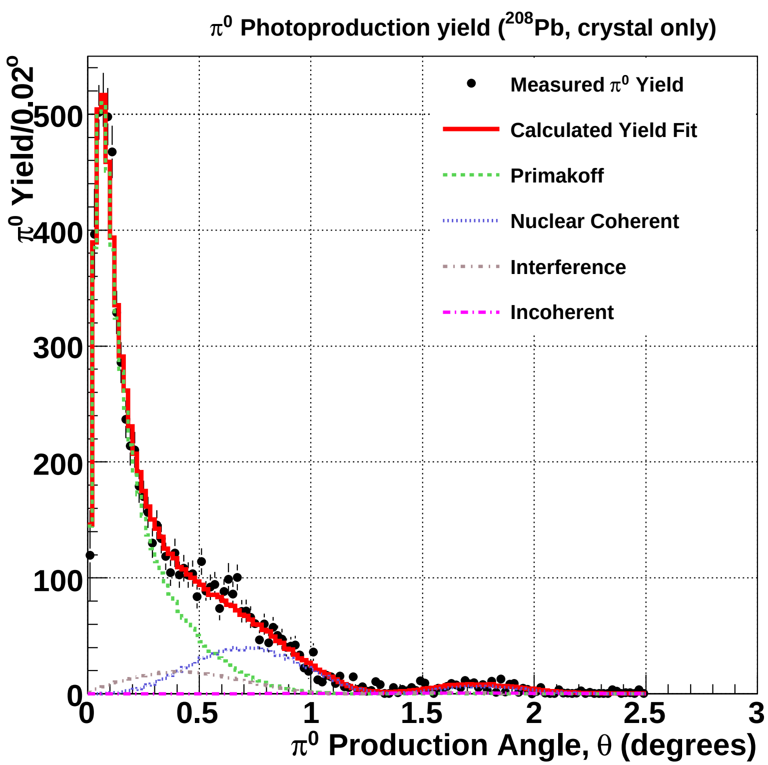


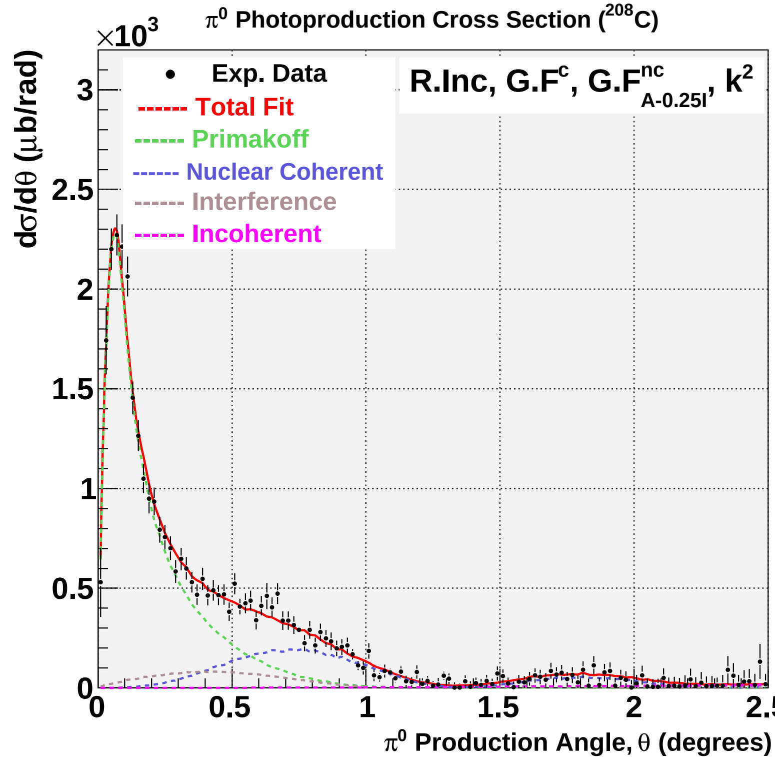
Yield Fit and Cross Section for ^{12}C





Yield Fit and Cross Section for ^{208}Pb

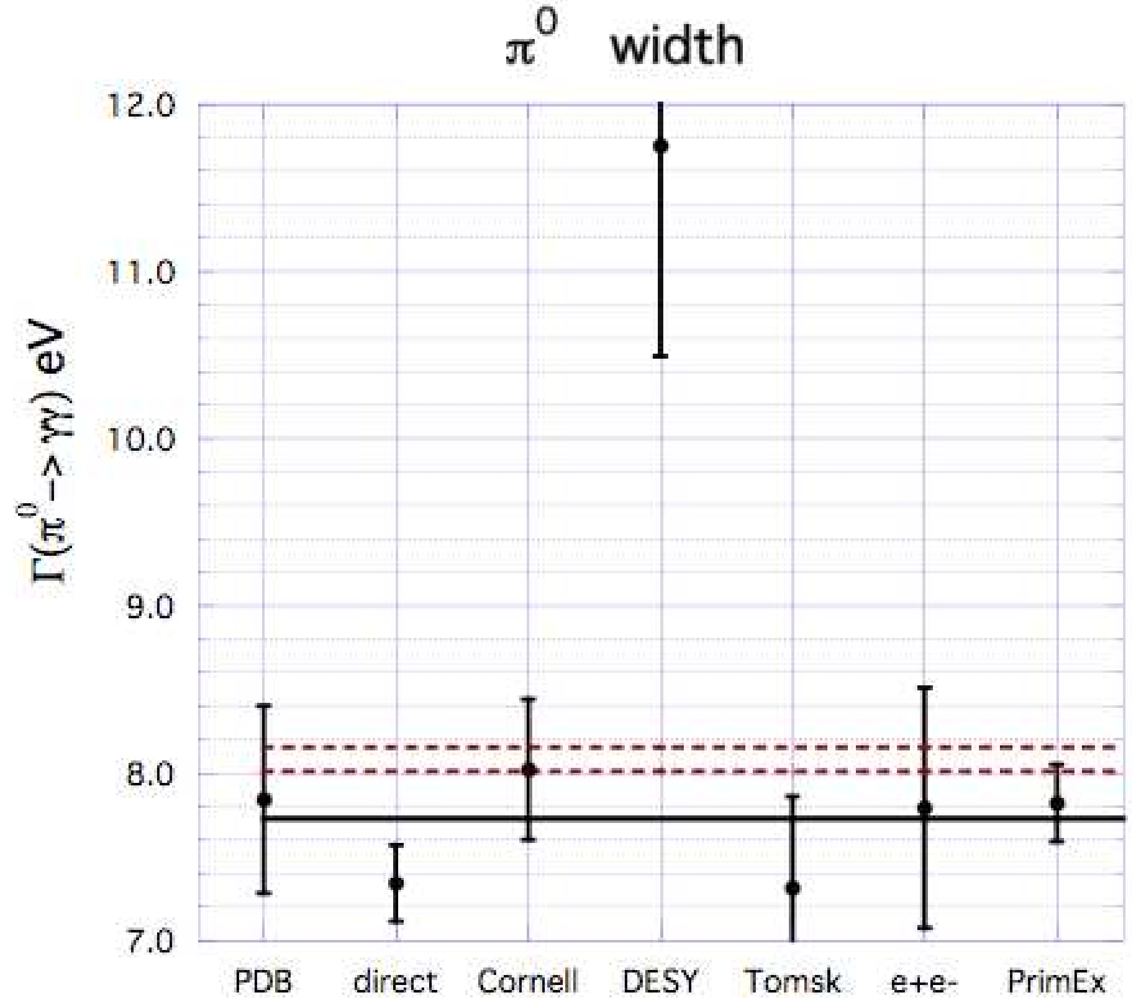




$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Systematic Errors

Contributions	$\Gamma_{\gamma\gamma}$ dev (%)	PrimEx II
Photon flux	± 1.0	
Target Thickness	± 0.1	
Yield Extraction	± 1.6	± 0.5
HyCal Efficiency	± 0.5	± 0.2
Beam Parameters	± 0.4	
Trigger Efficiency	± 0.1	
Veto Efficiency	± 0.4	
Fiducial Acceptance	± 0.3	
ModelErrors (Theory)	± 0.3	
Physics Background	± 0.25	
Branching Ratio $\pi^0 \nrightarrow \gamma\gamma$	± 0.03	
Total	$\pm 2.1\%$	$\pm 1.3\%$

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



Summary and Outlook

- High Quality precision π^0 photoproduction data on ^{12}C and ^{208}Pb targets using $4.9 \leq E_\gamma^{\text{tagged}} \leq 5.5$ GeV has been collected and analyzed by the PrimEx Collaboration
- Cross section results from studied calibration reactions e^+e^- production and Compton scattering are both in excellent agreement with theory (at the 2% level)
- All three $\sim$independent π^0 analysis groups have achieved very consistent results for both targets
- The final π^0 partial width result:
  $\Gamma_{\pi^0\to\gamma\gamma} = 7.82\text{eV} \pm 2.2\%(\text{stat}) \pm 2.1\%(\text{syst})$; Overall $\pm$3.0% error.
- The mean lifetime: $(8.32 \pm 0.25) \times 10^{-17}$ s
- $\Gamma_{\pi^0\to\gamma\gamma}$ result consistent with both LO and NLO predictions
- Continuation of this measurement in Hall B late this year; approved 12GeV Hall D measurement of η, η' lifetime...

Extra Slides

Independent Group Results

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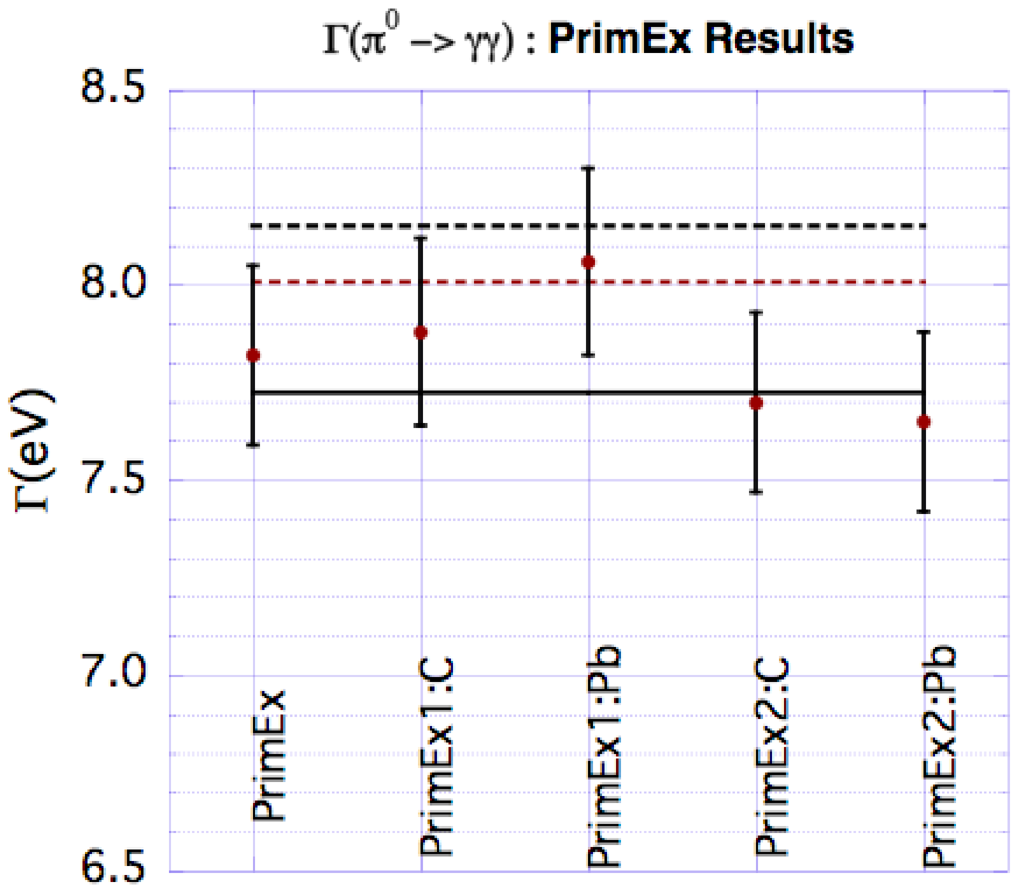
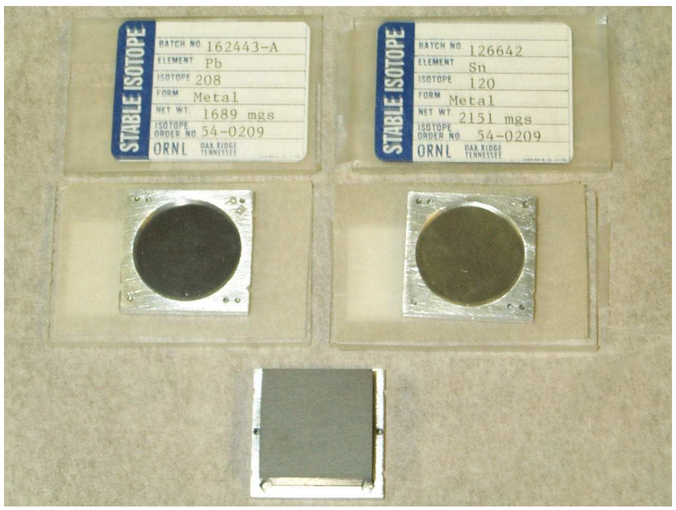
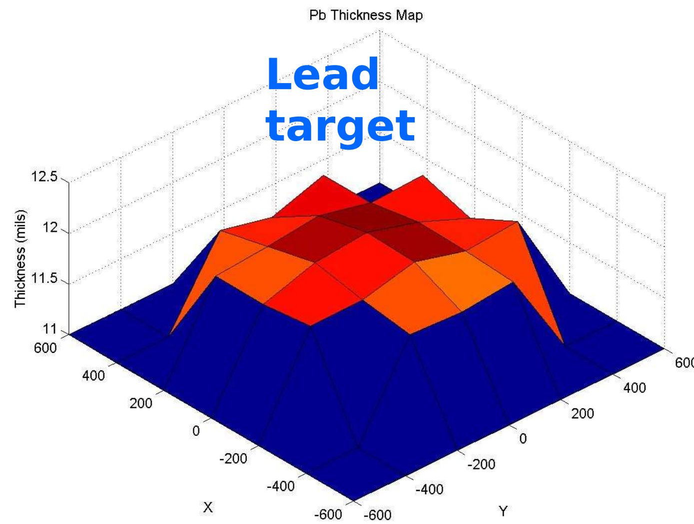
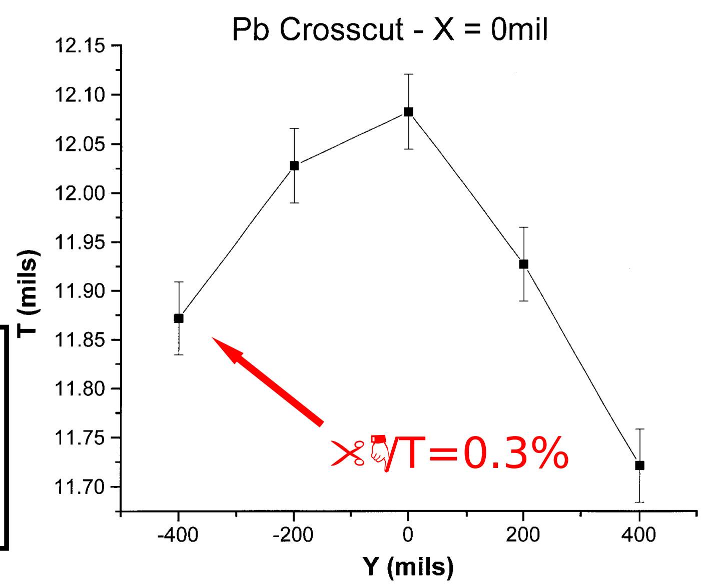


Isotopically pure ^{12}C and ^{208}Pb

PRIMEX Targets

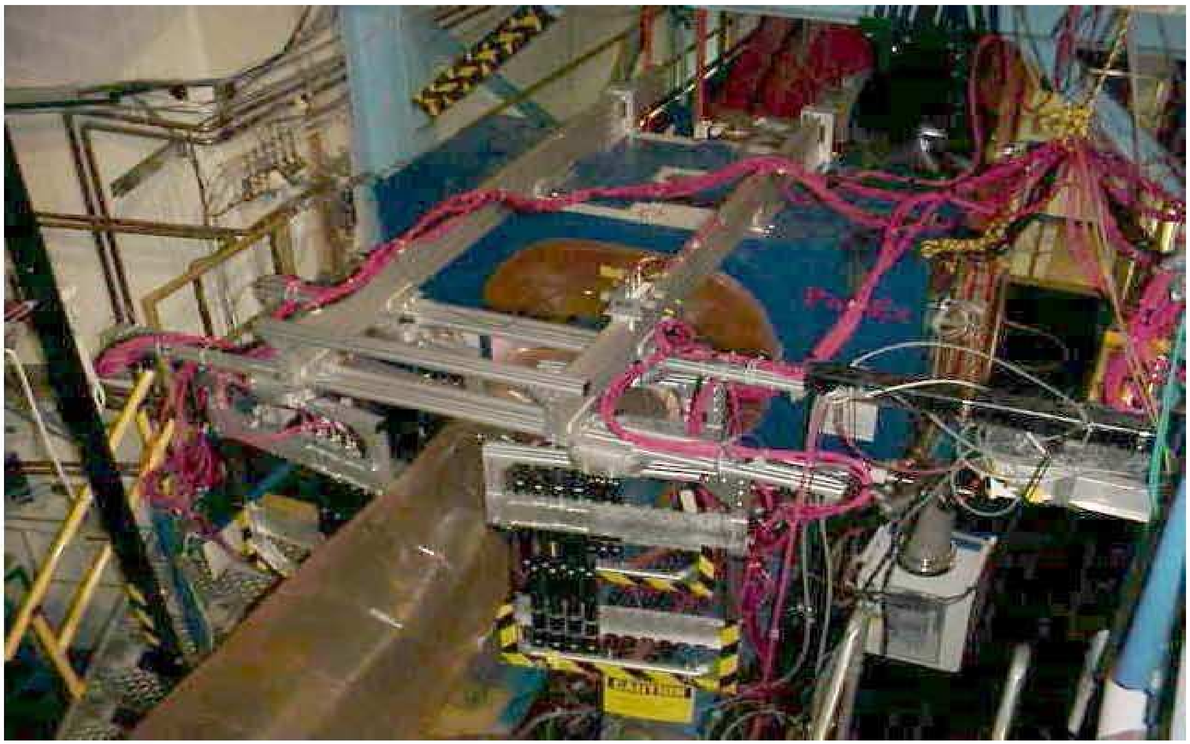






The effective number of carbon atoms/cm² in the carbon target is known to precision of ±0.05%

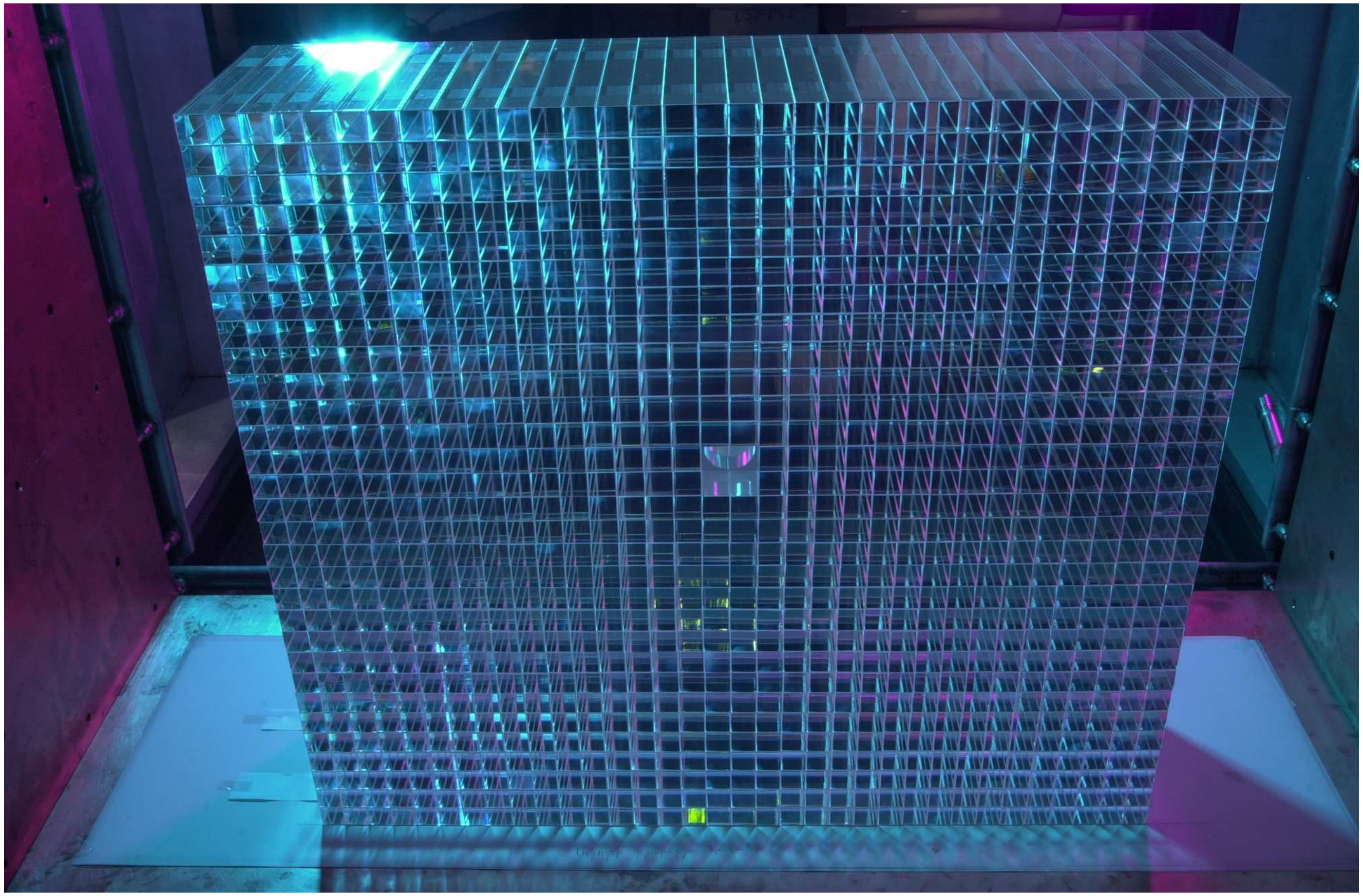
Pair Spectrometer



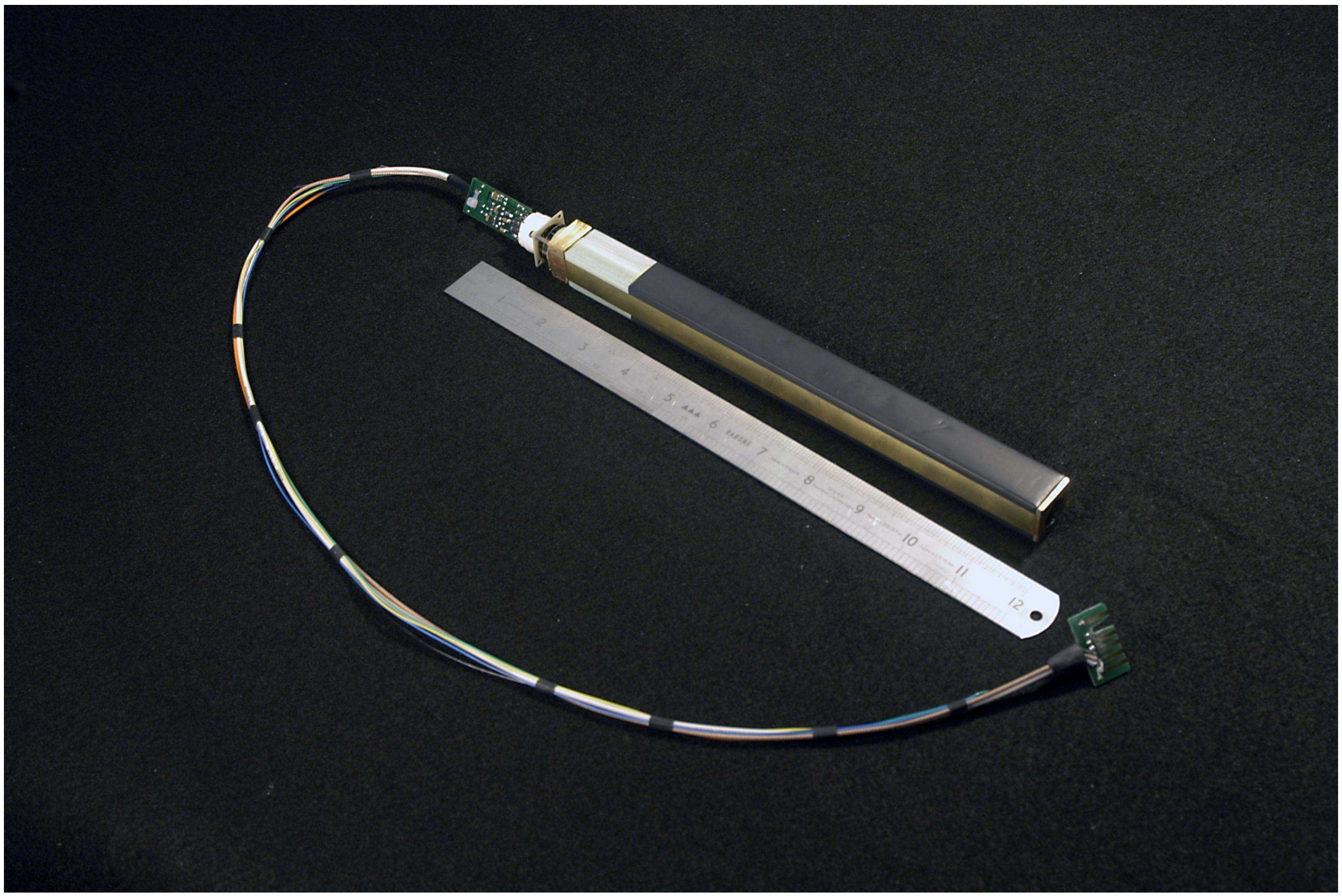
HyCal Specifications

	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

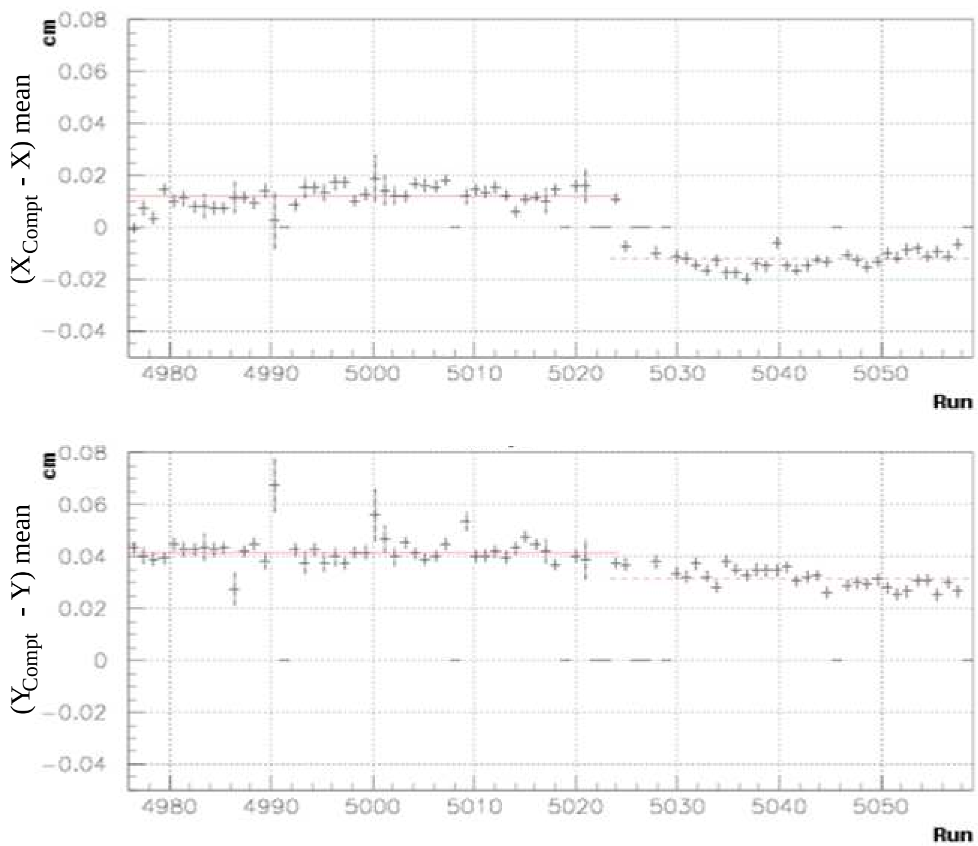
HyCal – Bare (unwrapped) $PbWO_4$ Crystals



HyCal Assembly – Crystal Wrapping



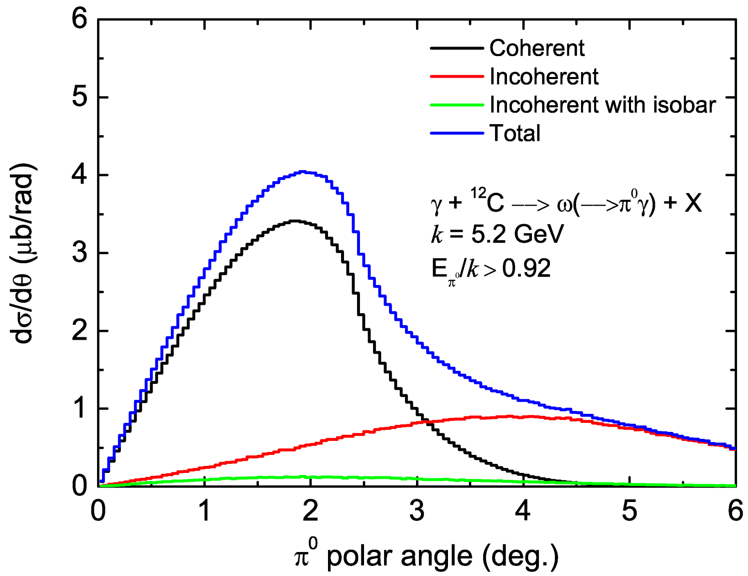
Beam Alignment Monitoring using Single-Arm Compton

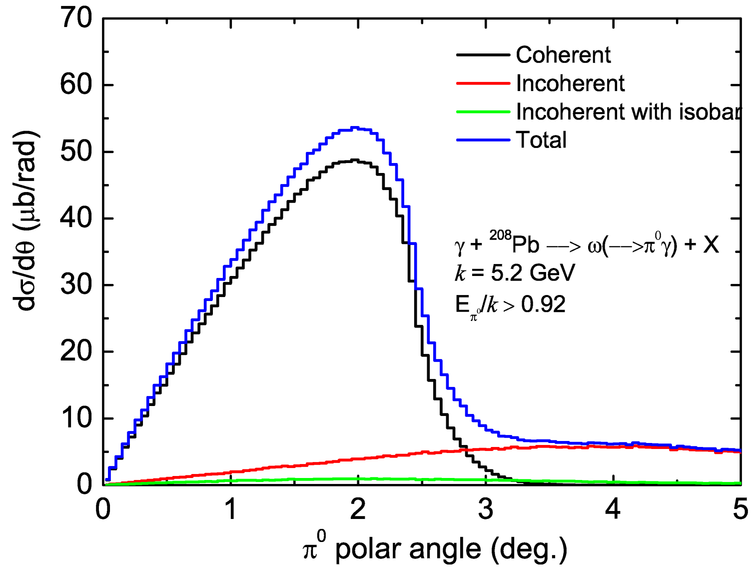


- Only scattered γ measured
- $X \equiv$ reported HyCal coord
- $X_{Compt} \equiv$ calc. (x,y) from Hycal E and Compton kin.
- If beam alignment perfect: $(X_{Compt}-X) = 0$
- Technique tracks alignment at 0.1 mm level
- Jump in X correlated with beamline BPM

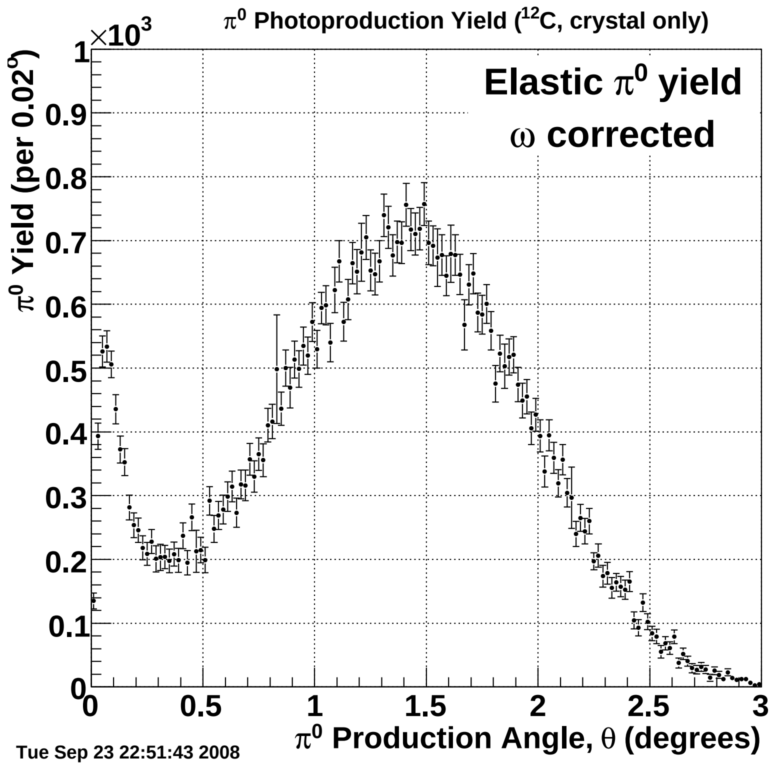
The $\omega \rightarrow \pi^0\gamma$ Background Correction

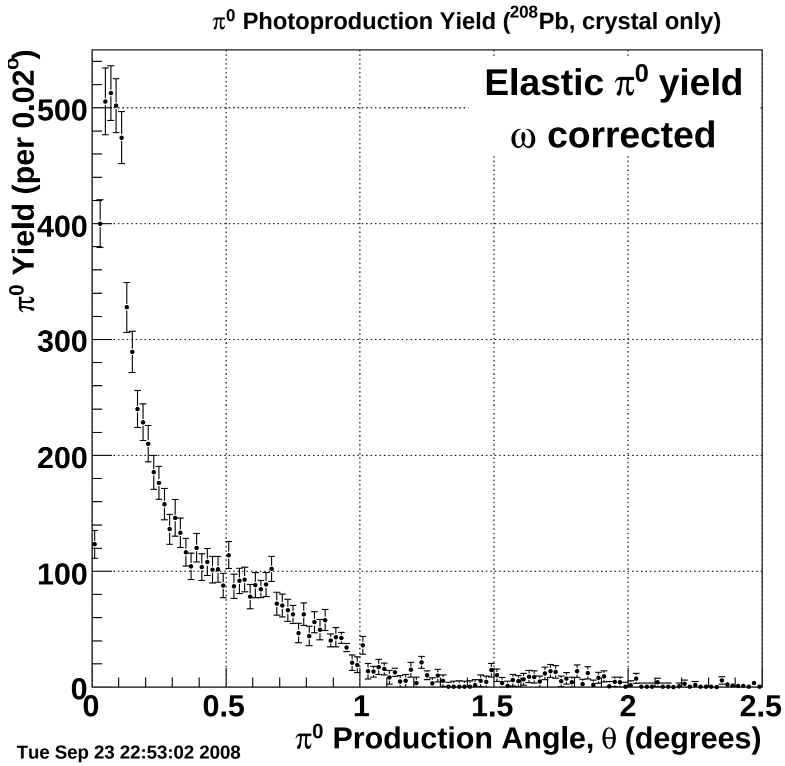
- $d\sigma/d\theta_{\pi^0}$ for $\omega \rightarrow \pi^0\gamma$ taken from T. Rodrigues and implemented
- Convert ω cross section into absolute yield while imposing experimental resolutions using Monte Carlo
- Explicitly subtract contribution from experimental yield



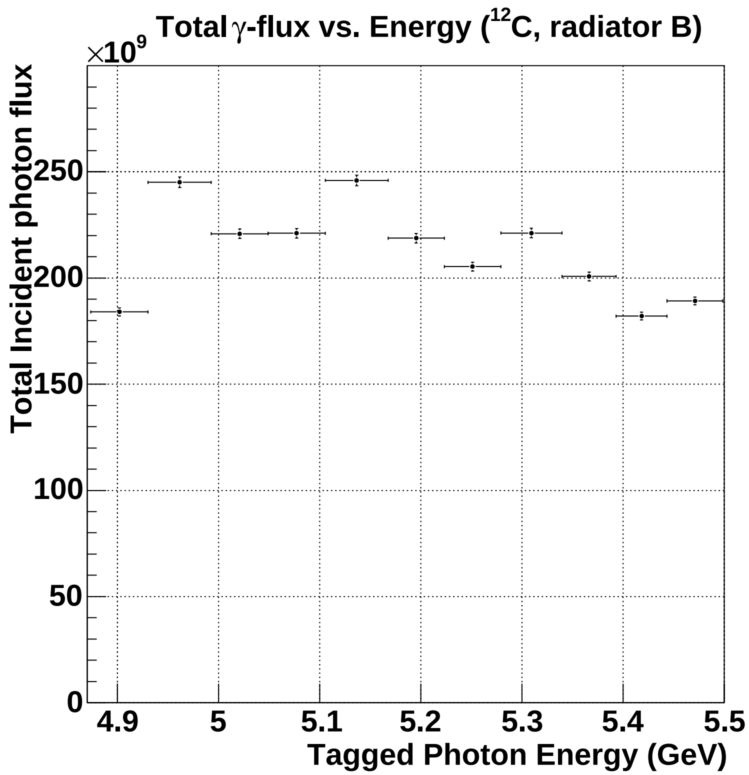


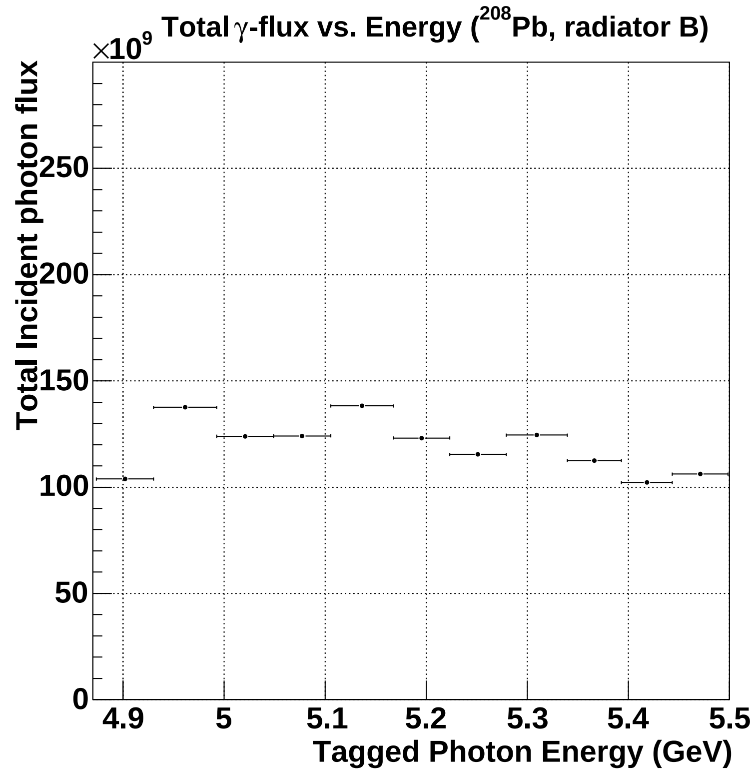
Final Yields for ^{12}C and ^{208}Pb





Photon Flux





Flux for ^{12}C: 2.33×10^{12} γ's

Flux for ^{208}Pb: 1.31×10^{12} γ's

Experimental Efficiencies

	Losses (%)	
Description	^{12}C	^{208}Pb
Photon Absorption in Target	5.41 ± 0.02	5.92 ± 0.01
Best (tdiff) Candidate selection	2.5 ± 0.3	1.1 ± 0.3
Elasticity Cut: $[0.906, 1.086]$	1.7 ± 0.3	1.7 ± 0.3
Veto Cut: all flags $(0, 1, 2, 3)$	1.97 ± 0.12	1.97 ± 0.12
Branching Ratio $\pi^0 \nrightarrow \gamma\gamma$	1.2 ± 0.03	1.2 ± 0.03
Total	12.8 ± 0.5	11.9 ± 0.4

Table 1: Summary of non-geometric losses.