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

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Outline

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

PrimEx Collaboration

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Physics Motivation: 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” (NP) = 1 for S, V, ... particles. NP = -1 for PS, PV, ...

$\rightarrow$ An anomalous reaction changes the NP:

$\rightarrow \gamma\pi$(NP = -1)$\longrightarrow \gamma\pi$(NP = -1) not anomalous

$\rightarrow \pi^0$(NP = -1)$\longrightarrow \gamma\gamma$(NP = 1) anomalous

$\rightarrow \gamma\pi$(NP = -1)$\longrightarrow \pi\pi$(NP = 1) anomalous

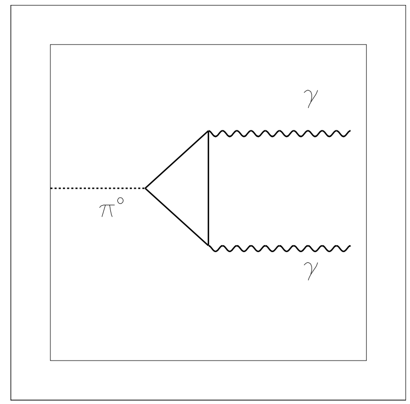
- All anomalous reactions are governed by the Wess-Zumino Lagrangian in ChPT
- In the Chiral limit, the absolute rate of these rections are predicted by QCD

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:

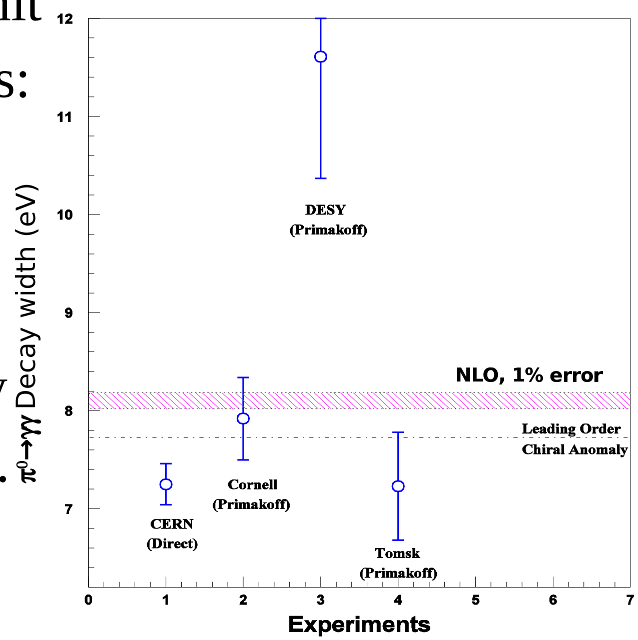
$$\Gamma_{\pi^0 \to \gamma\gamma} = \frac{\alpha^2 m_\pi^3}{64\pi^3 F_\pi^2} = 7.725 \pm 0.044 \text{ eV} \qquad (1)$$

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 $\eta\prime$ 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 $\Rightarrow$ too small to measure

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

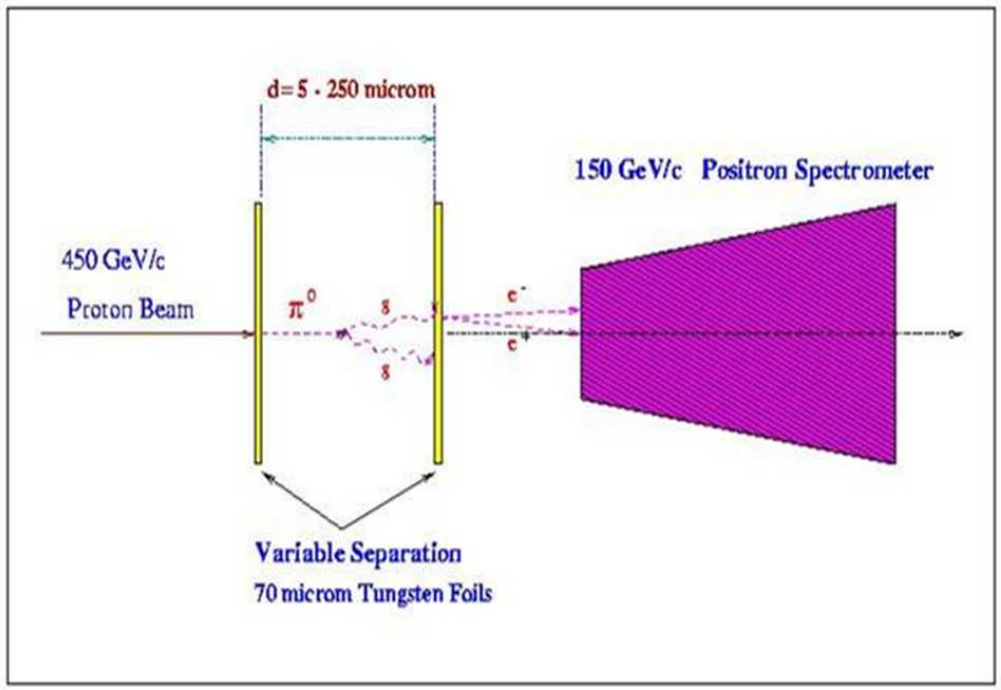
$$L = v\tau_{\pi^0} E/m \quad (2)$$

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

→ Performed in 1984:
Used 450GeV protons

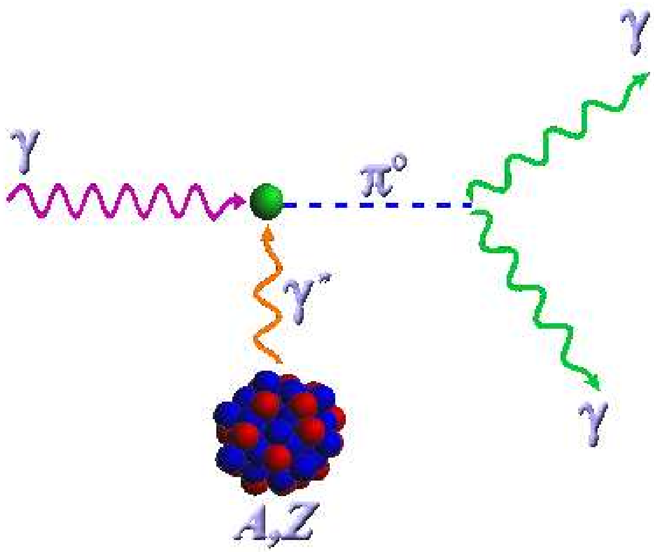
→ Result:
$\Gamma_{(\pi^0 \to \gamma\gamma)}$ = 7.34eV±3.1%

→ 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.

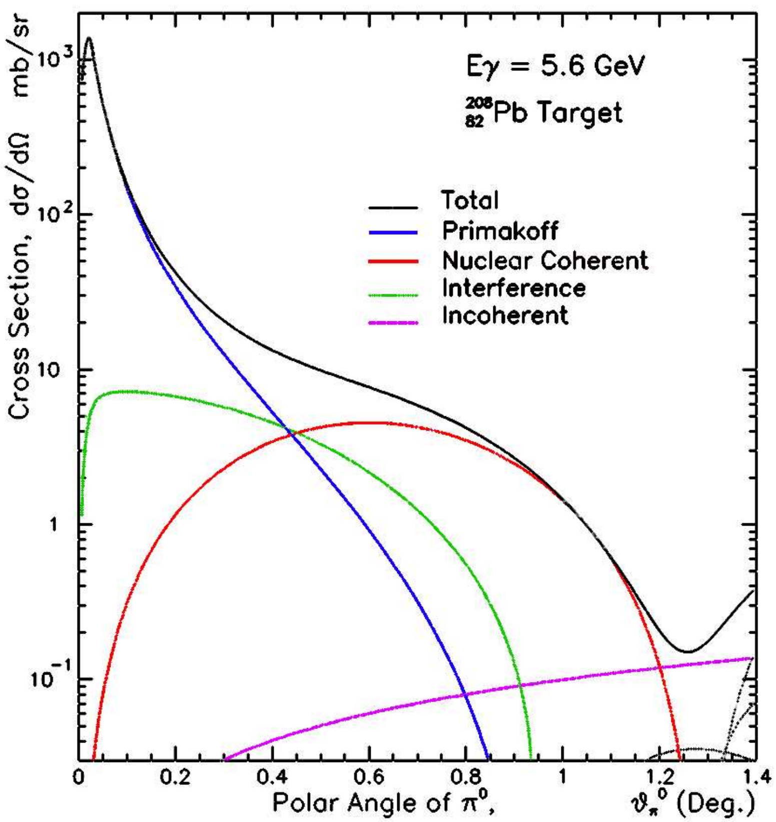


$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\rightarrow\gamma\gamma)} \frac{8\alpha_{em}Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |\tilde{F}_{em}(Q)|^2 sin^2\theta_\pi \qquad (3)$$

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:

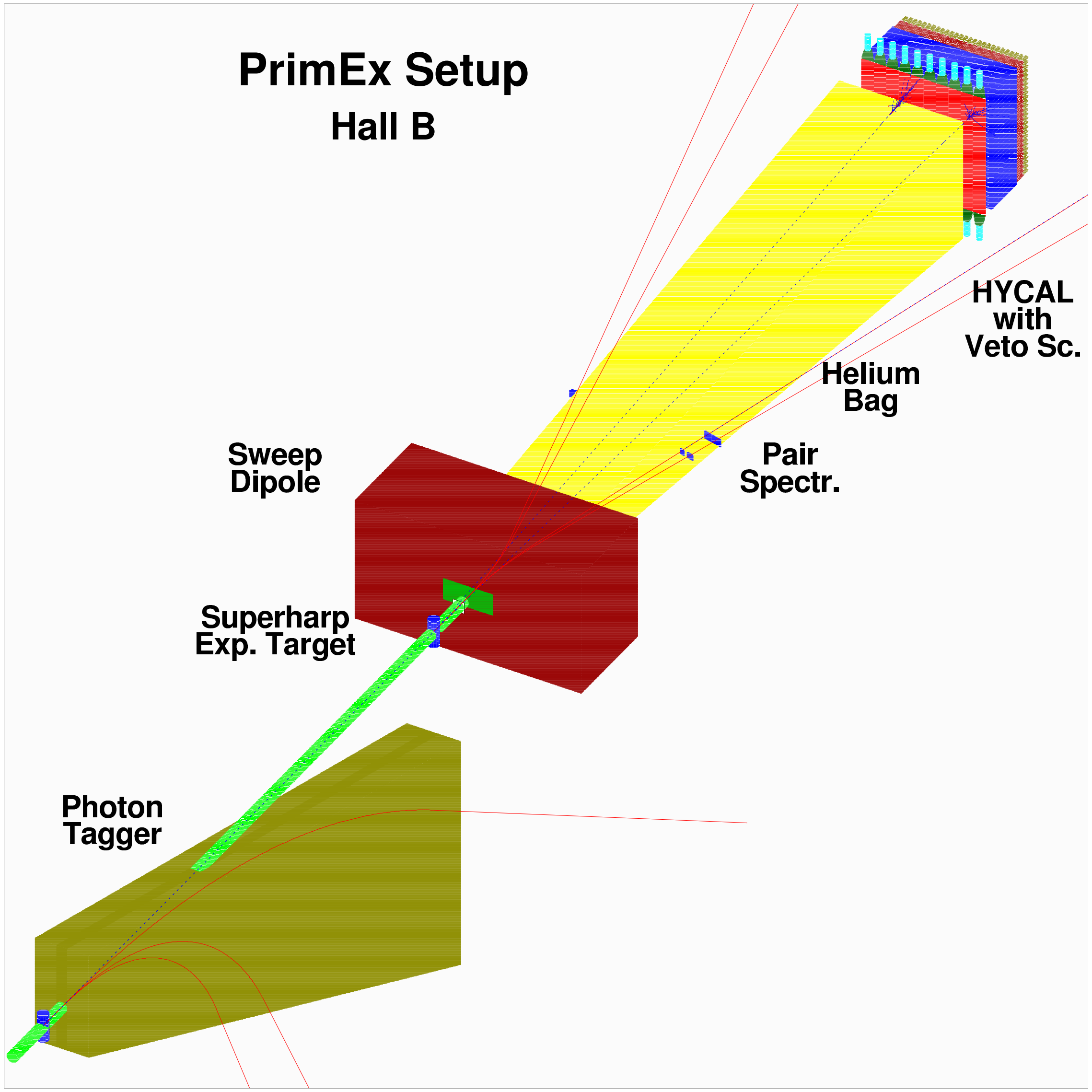
$$\frac{d\sigma_I}{d\Omega} = \xi A(1-G(Q))\frac{d\sigma_H}{d\Omega} \quad (6)$$

Interference:

Experiment Overview

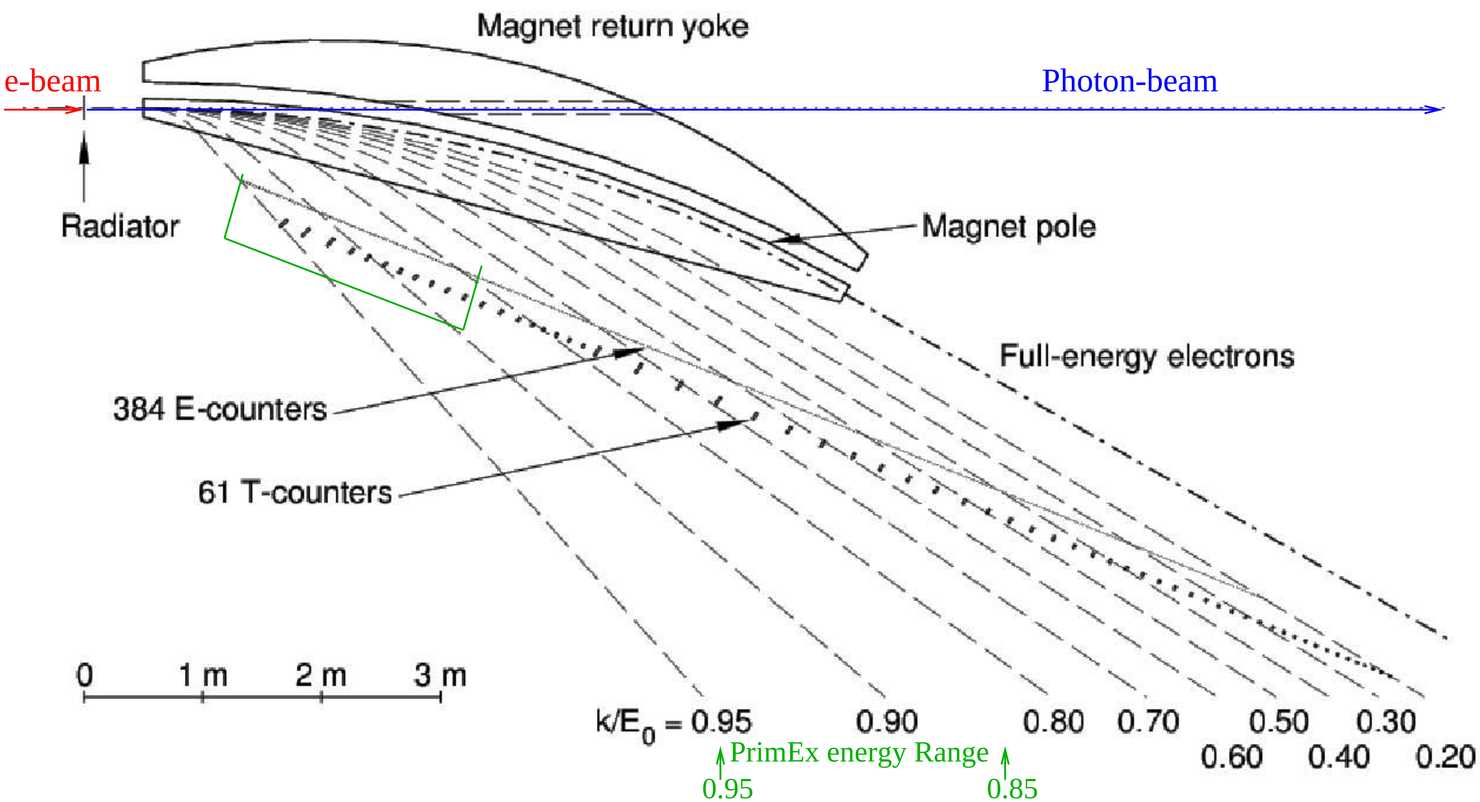
- Conducted at Jefferson Lab, Fall 2004
- Used 5.75 GeV continuous e^- beam and Hall B γ-tagging facility
- Tagged photons incident on $5\% X_0$ targets: ^{12}C and ^{208}Pb
- New PrimEx/Hall B calorimeter (HyCal), upstream of CLAS, designed to detect π^0 decay γ's
- Measured 3 physical processes (absolute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



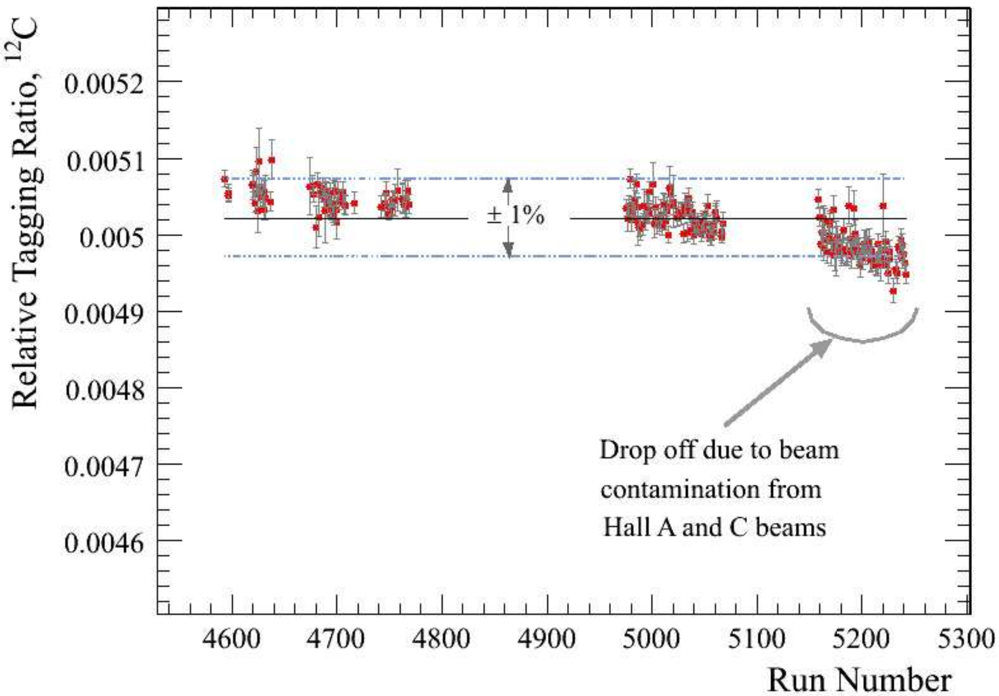
Hall B Photon Tagger

- 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.

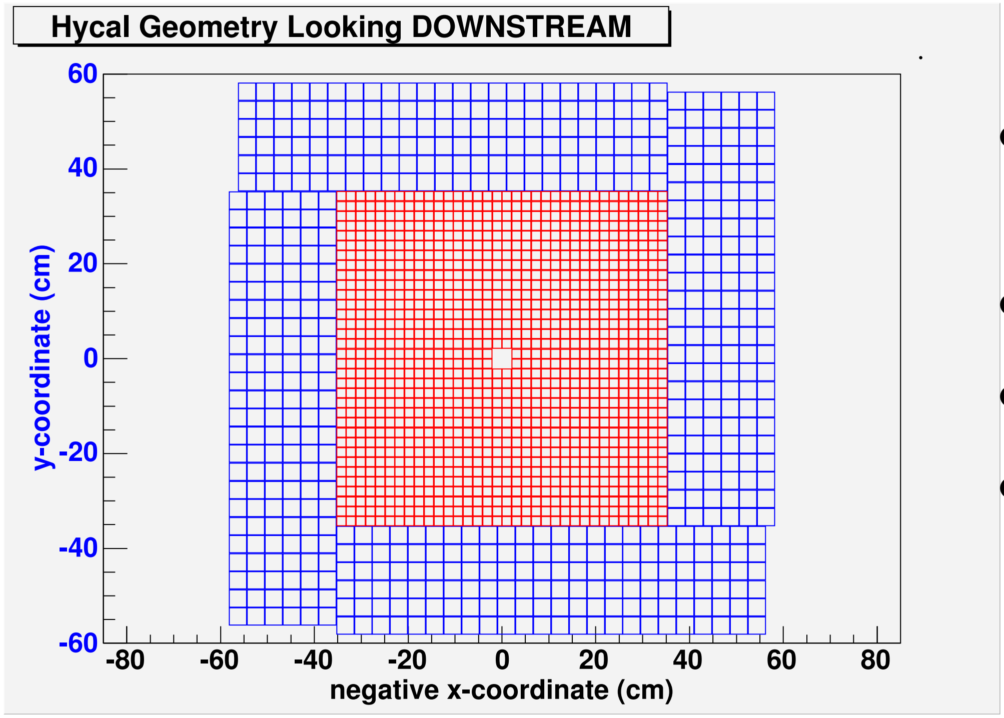


Photon Flux Control

- 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.



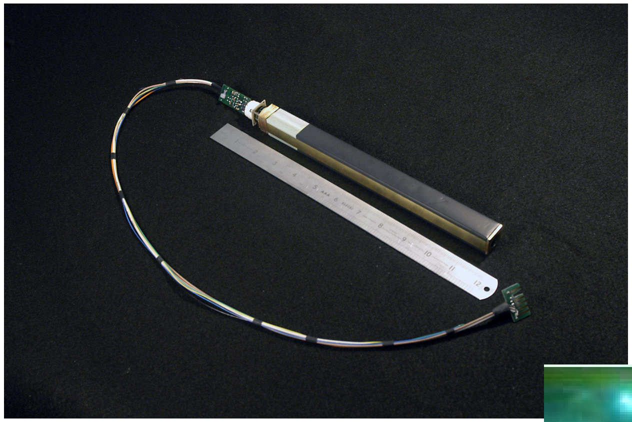
PrimEx Hybrid Calorimeter – "HyCal"

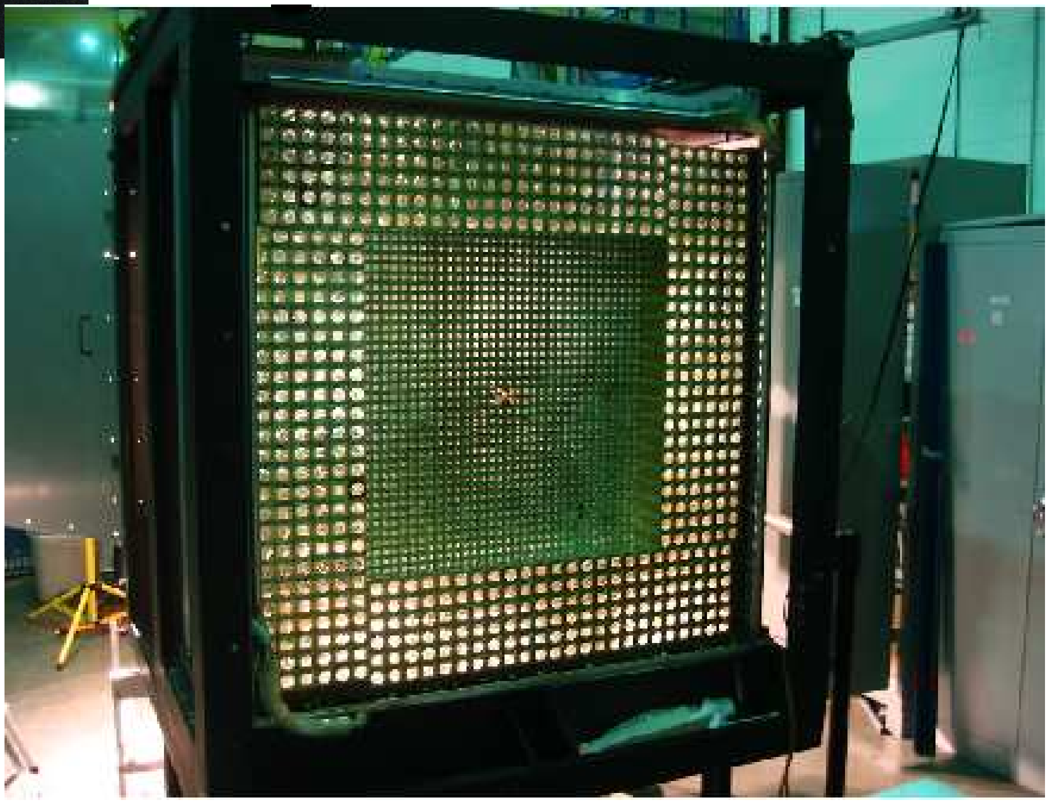


- Optimal performance/cost design
- 1.2 m $\times$1.2 m, 1728 channels
- 576 Lead-glass (outer layers)
- 1152 Lead-Tungstenate crystal (inner layers)

	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

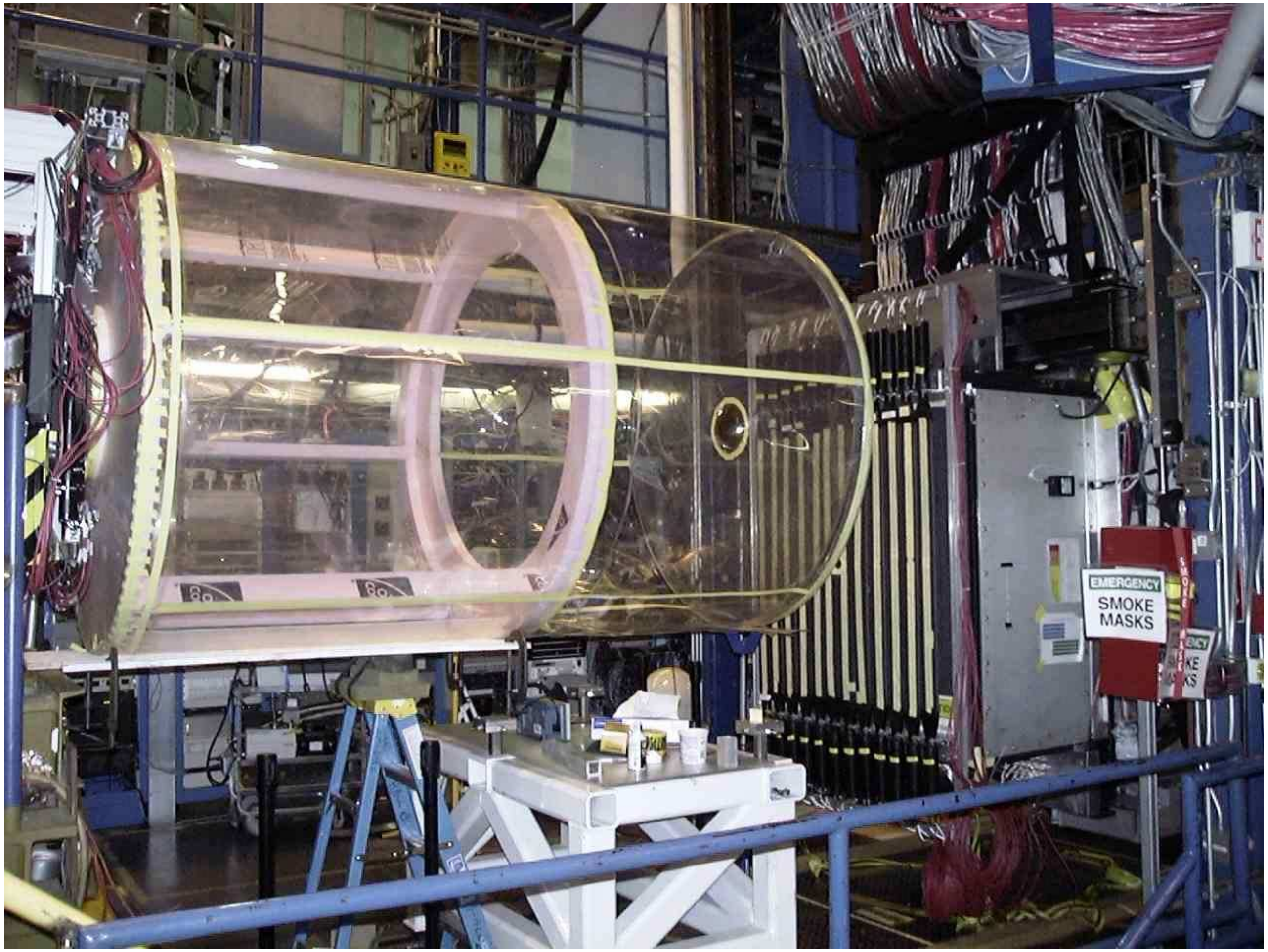
PrimEx Hybrid Calorimeter – "HyCal"



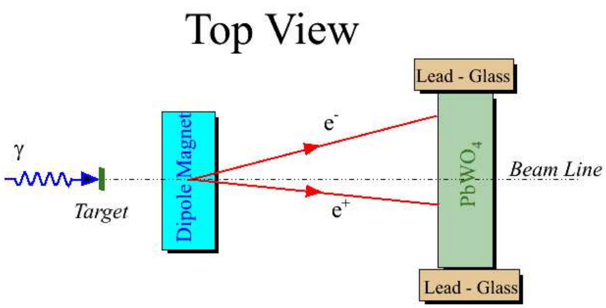


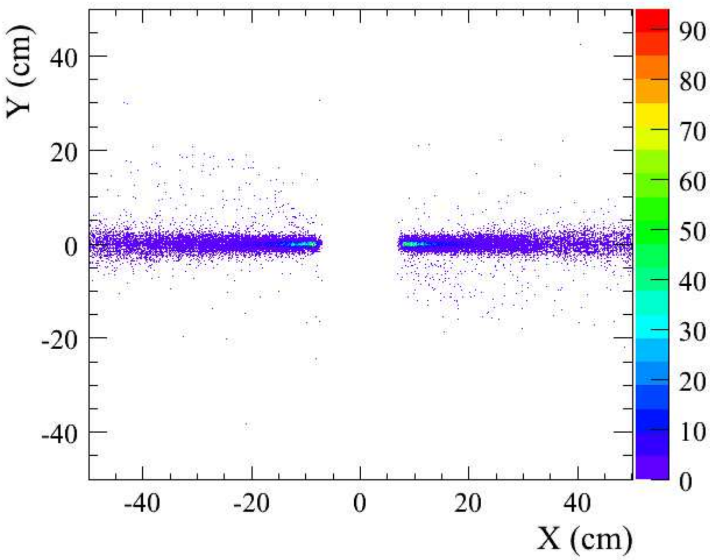
HyCal Calibration

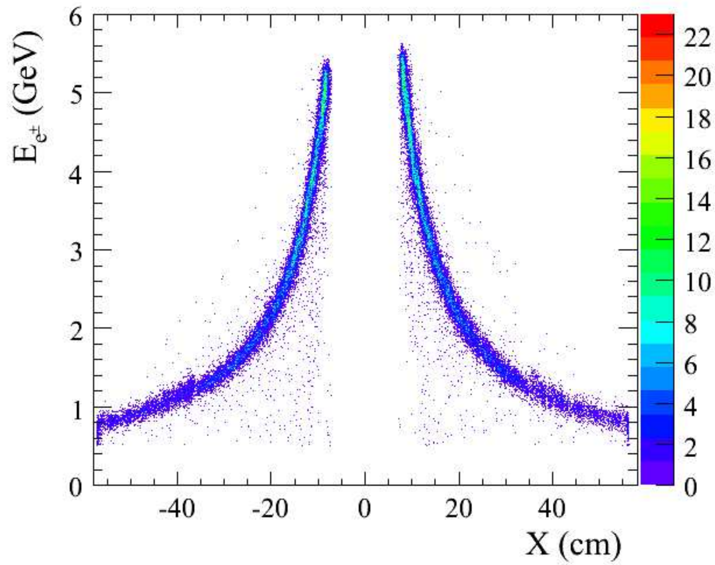
- Full x,y motion allowed each ch. to be scanned through tagged γ beam.
- Performed at both the beginning and end of the experiment.



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



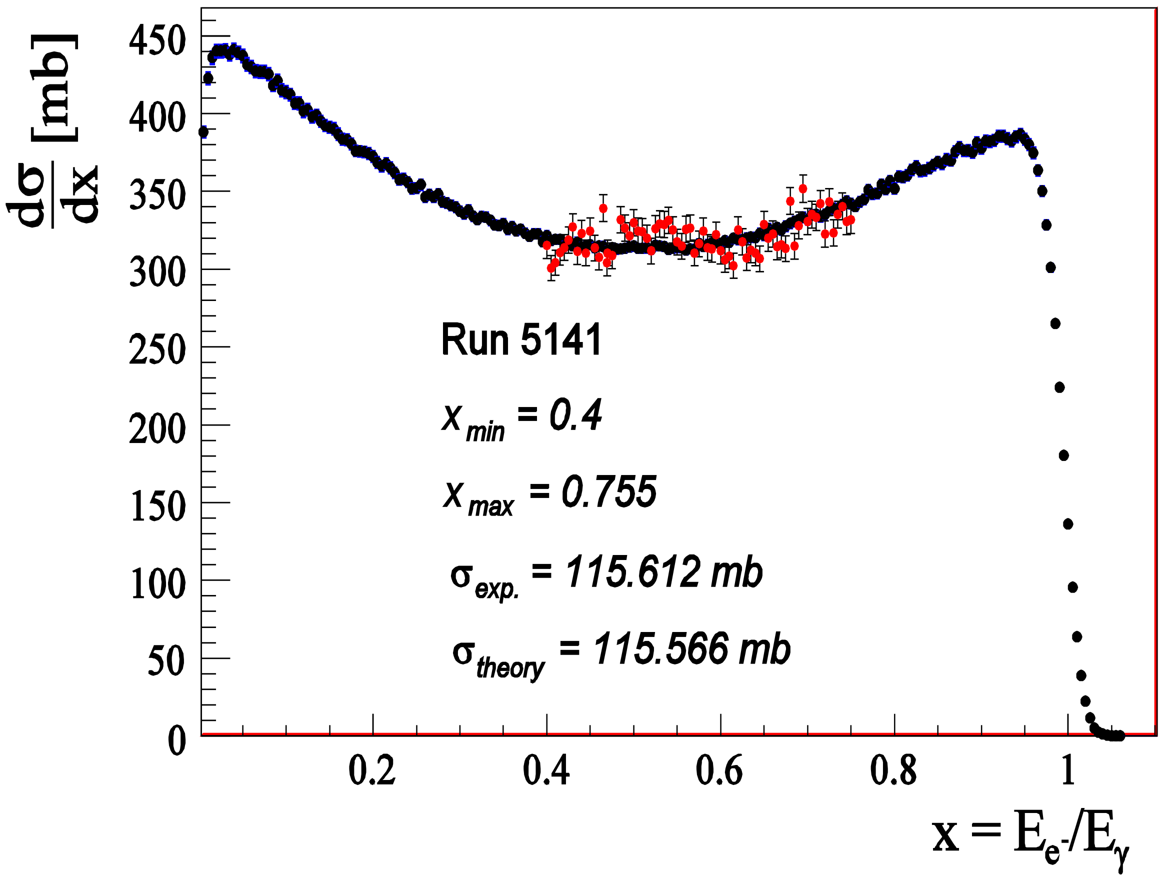




Calculation of Pair Production Cross Section at PrimEx Kinematics

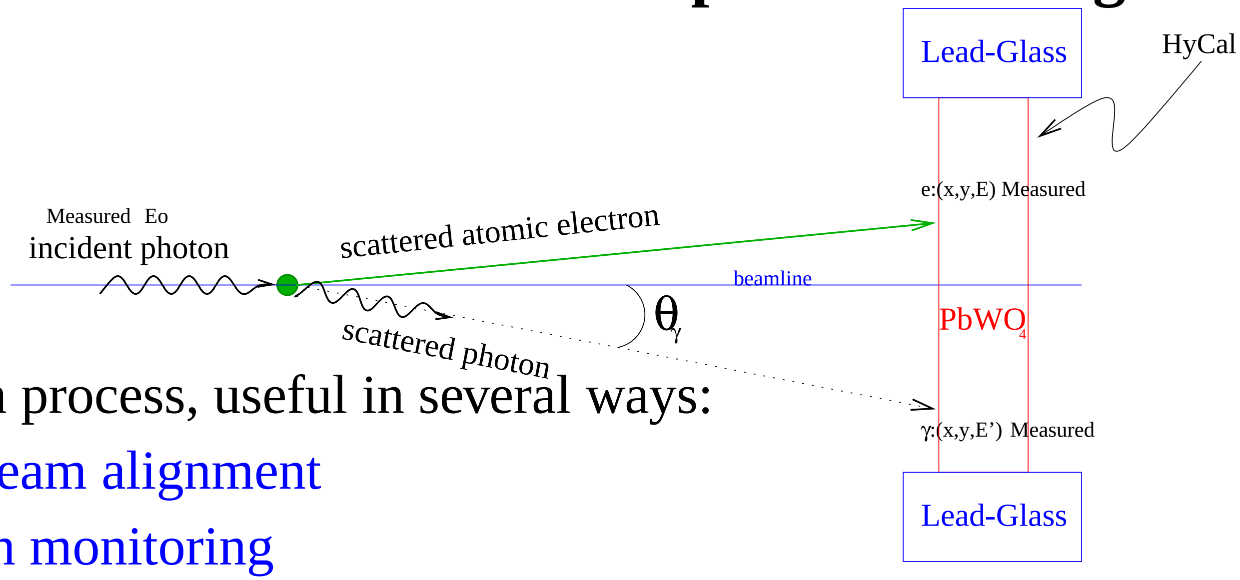
- Bethe-Heitler mechanism of pair production on the nucleus with screening effects due to atomic electrons and Coulomb distortion
- Pair production off atomic electrons, considering excitation of all atomic states and correlation effects due to the presence of other electrons and the nucleus
- Radiative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



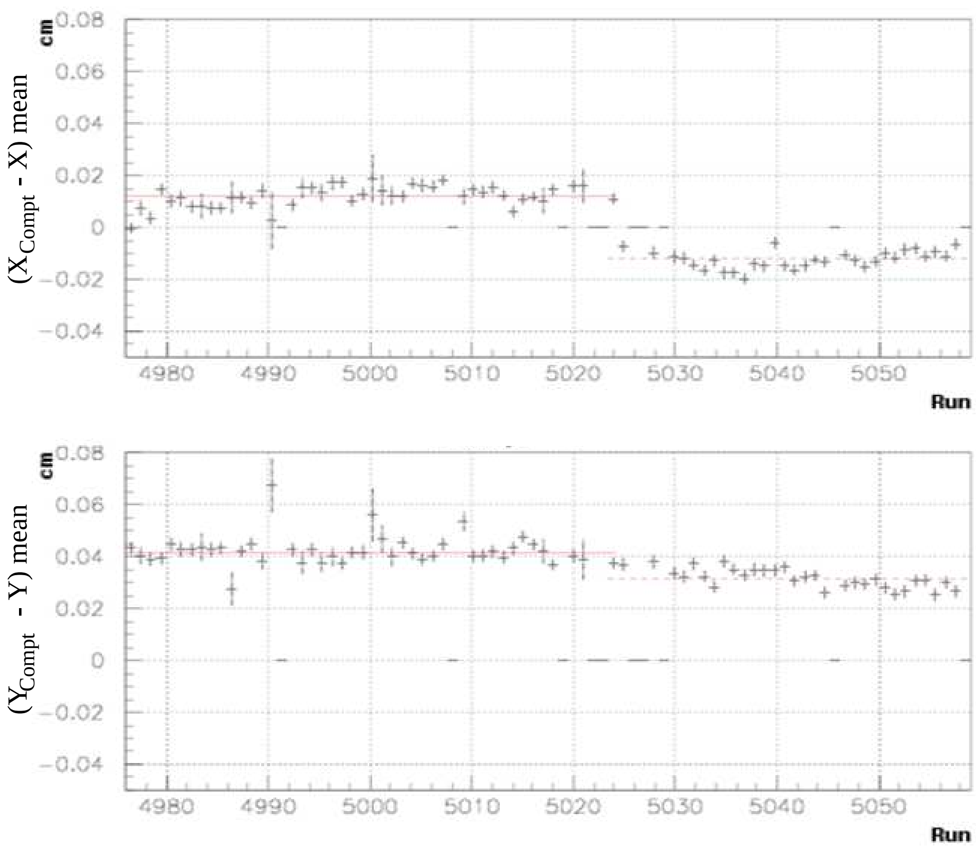
- Agreement with theory at $\sim$ 1.0% level

Calibration Reactions: Compton Scattering



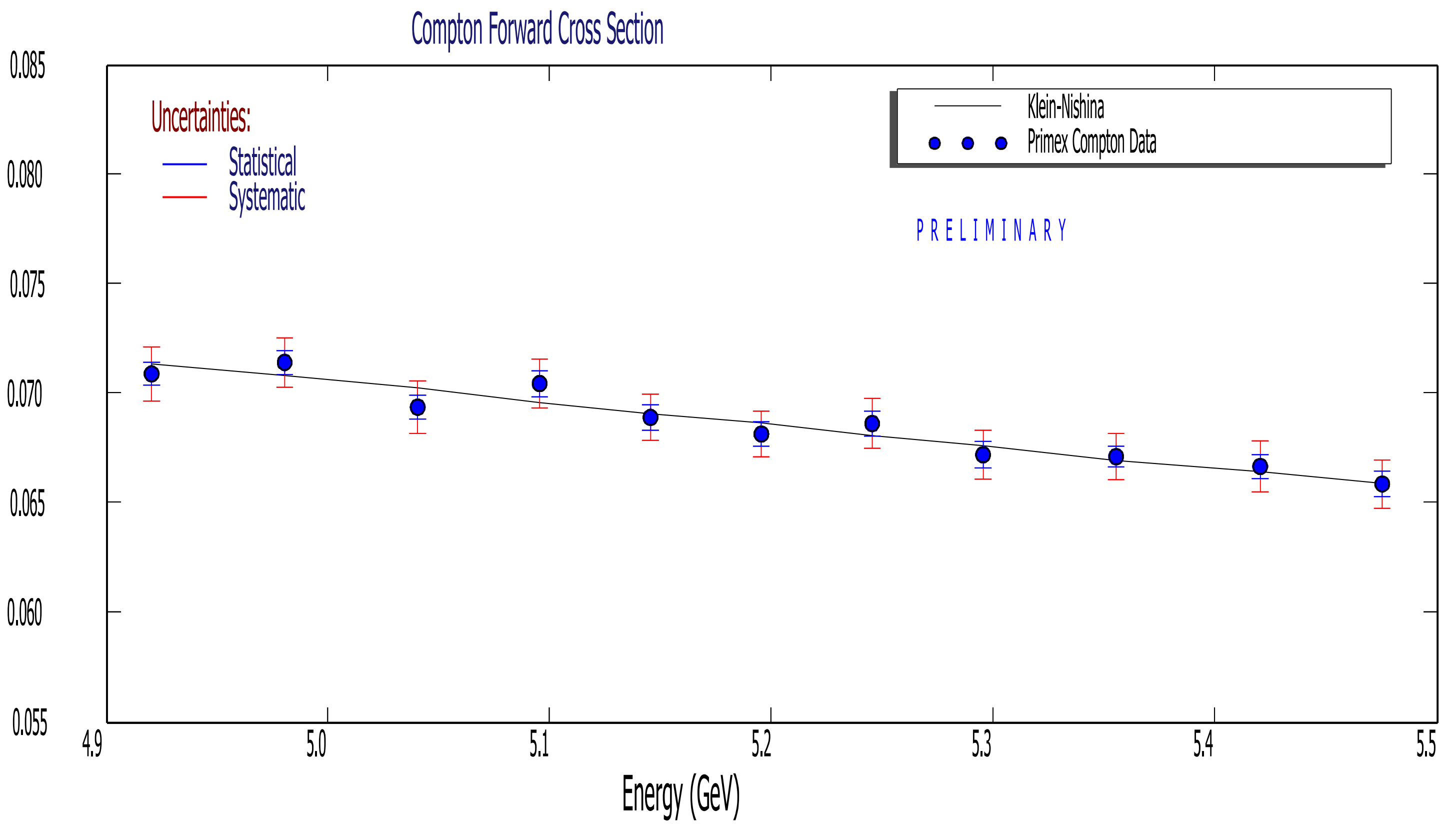
- A well known process, useful in several ways:
  - → Detector/beam alignment
  - → HyCal gain monitoring
  - → Overall check of PrimEx setup to measure absolute cross sections
    - ○ Dedicated "Double-Arm" Compton Runs:
      - → Performed on a weekly basis, $B_{PS} = 0$, $I_{beam} \sim 5 - 10$ nA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

Beam Alignment Monitoring using Single-Arm Compton



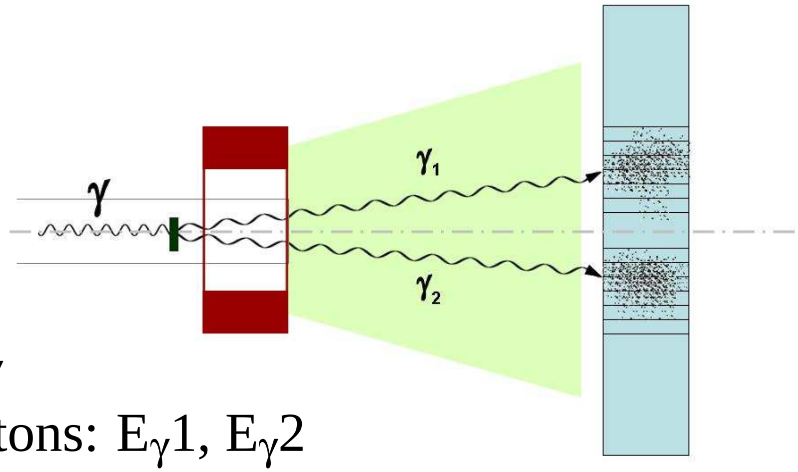
- Only scattered γ measured
- $X \equiv$ reported HyCal coord
- $X_{Compt} \equiv$ calc. (x,y) from Hycal E and Compton kin.
- If beam alignment perfect: $(X_{Compt}-X) = 0$
- Technique tracks alignment at 0.1 mm level
- Jump in X correlated with beamline BPM

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



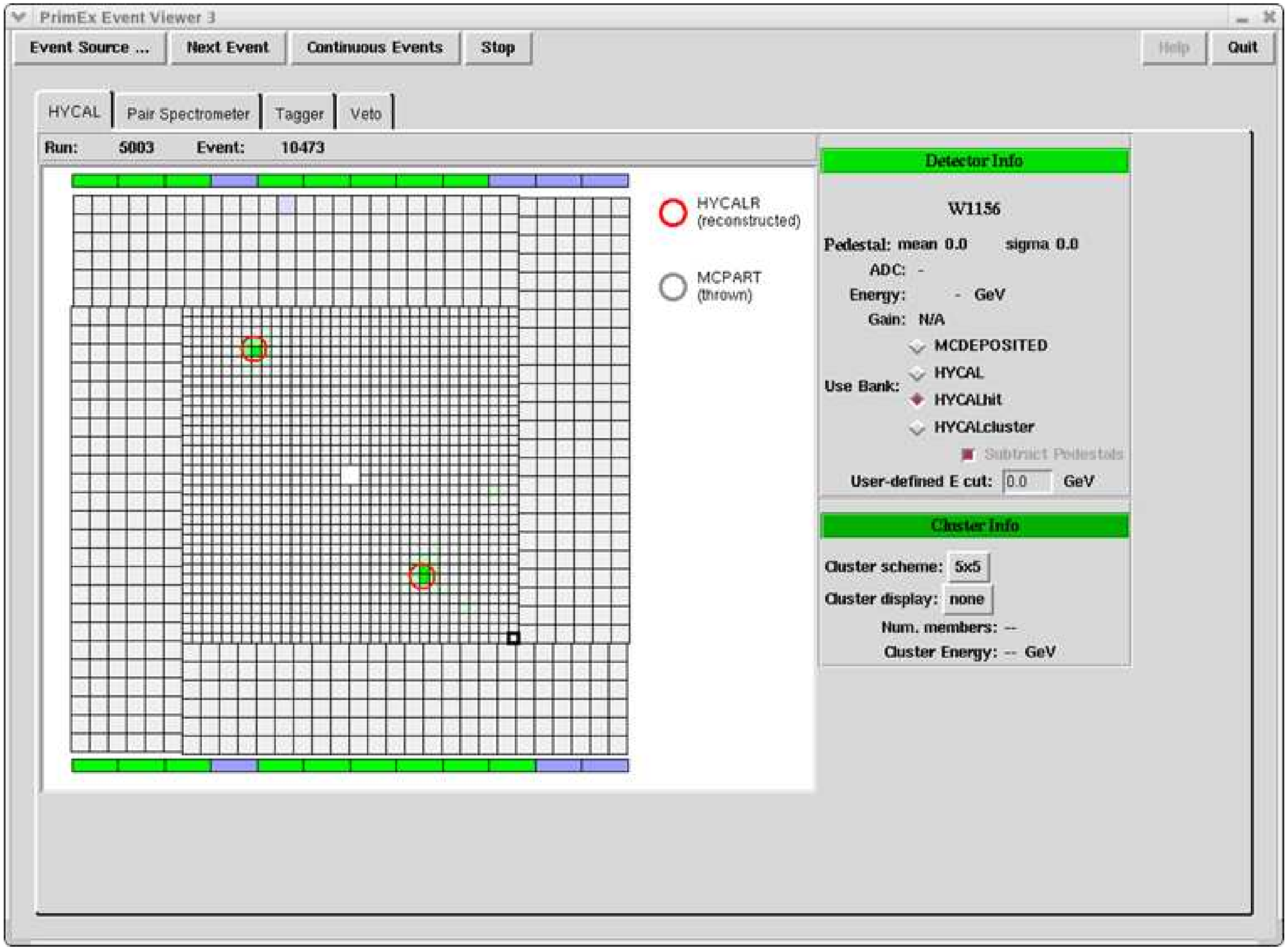
We measure:

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

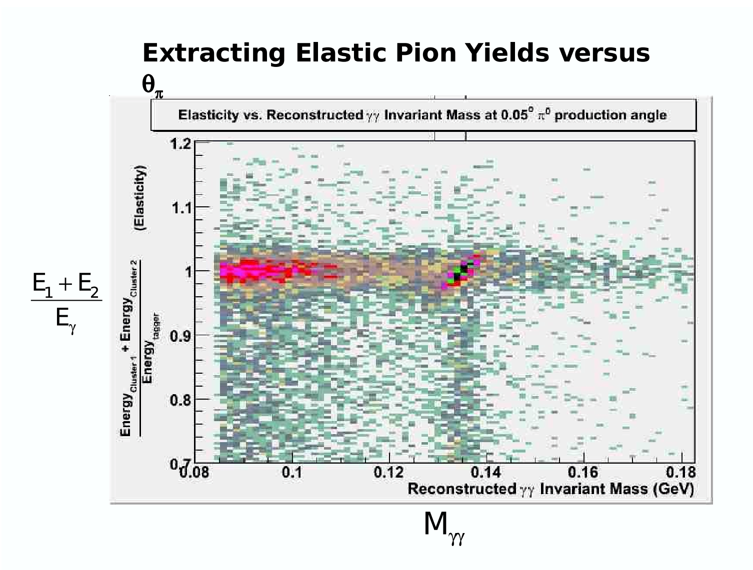
Kinematical constrains:

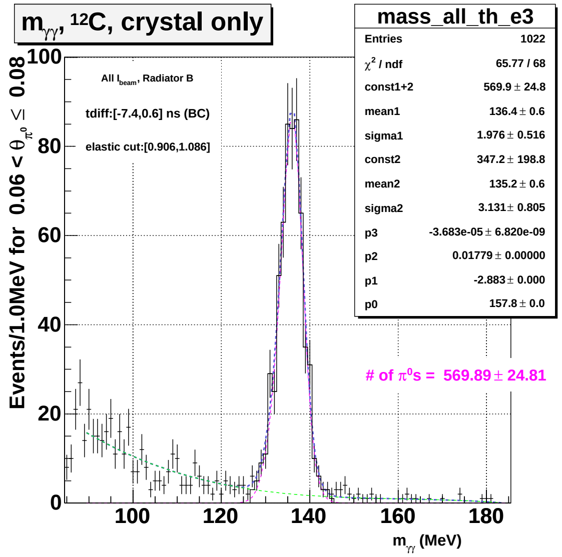
- → Conservation of energy
- → Conservation of momentum
- → $m_{\gamma\gamma}$ invariant mass

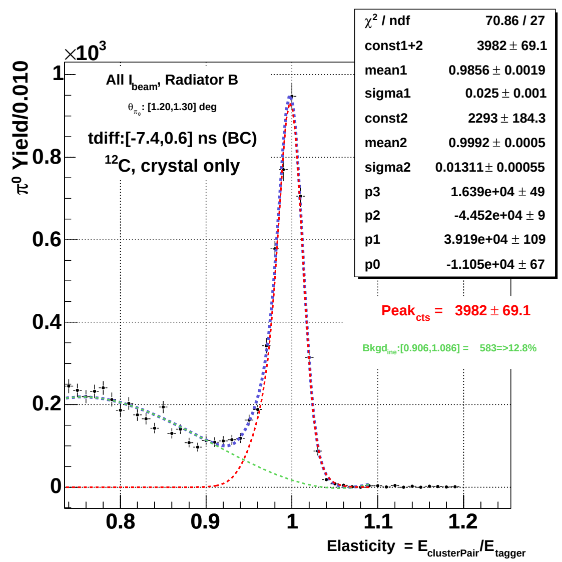
Analysis Details: π^0 Event Selection



Analysis Details: π^0 Yield Extraction

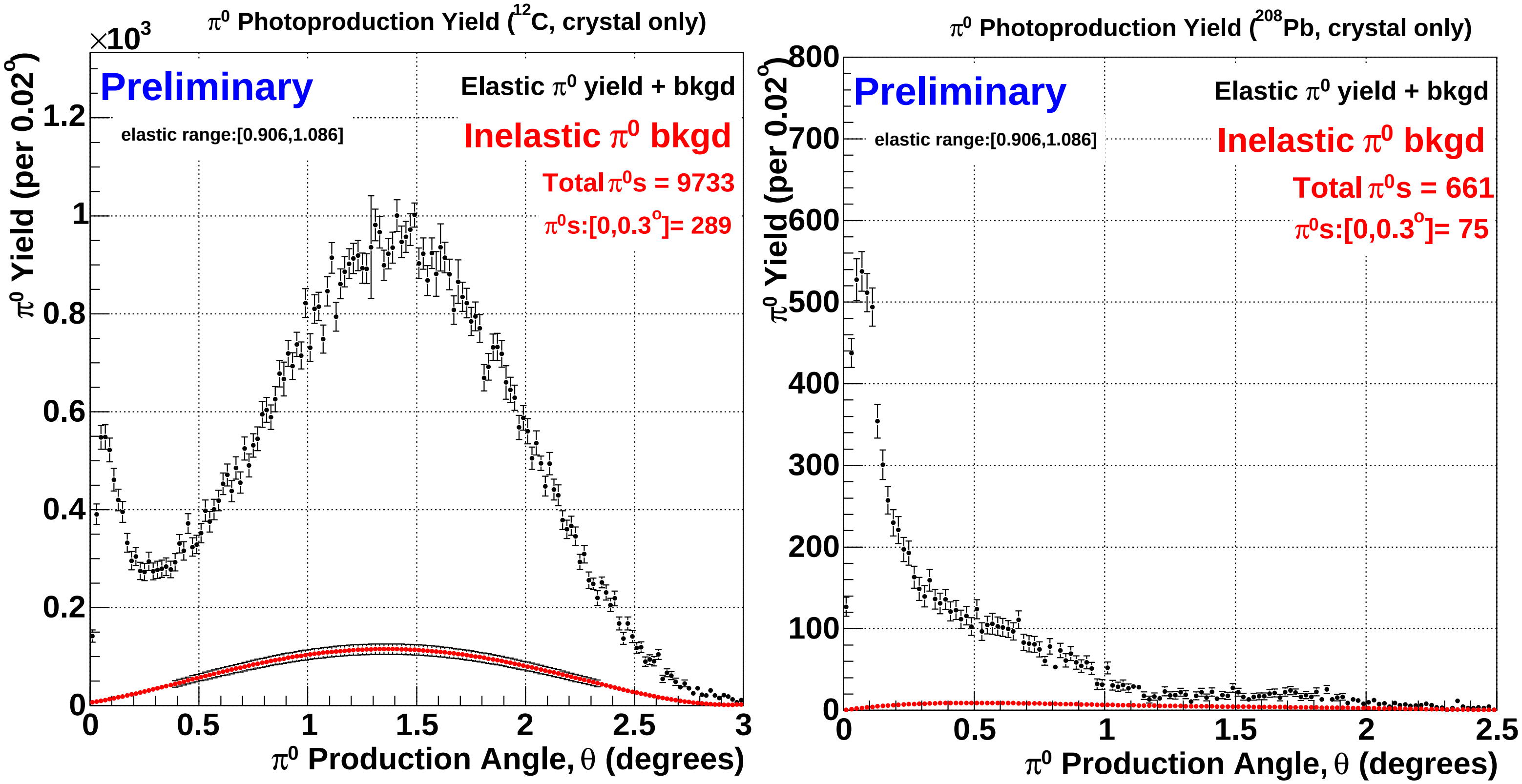




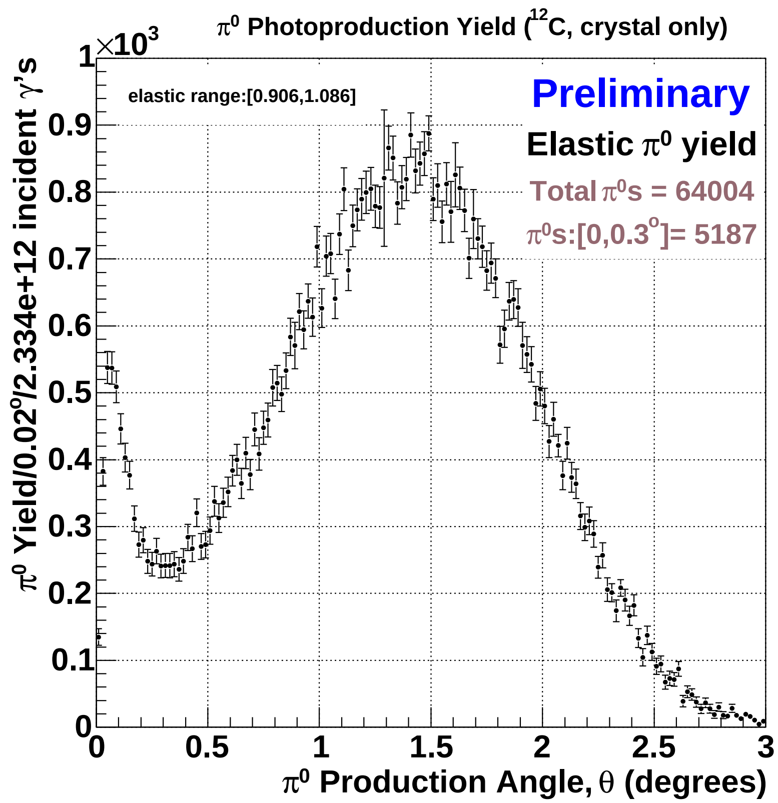


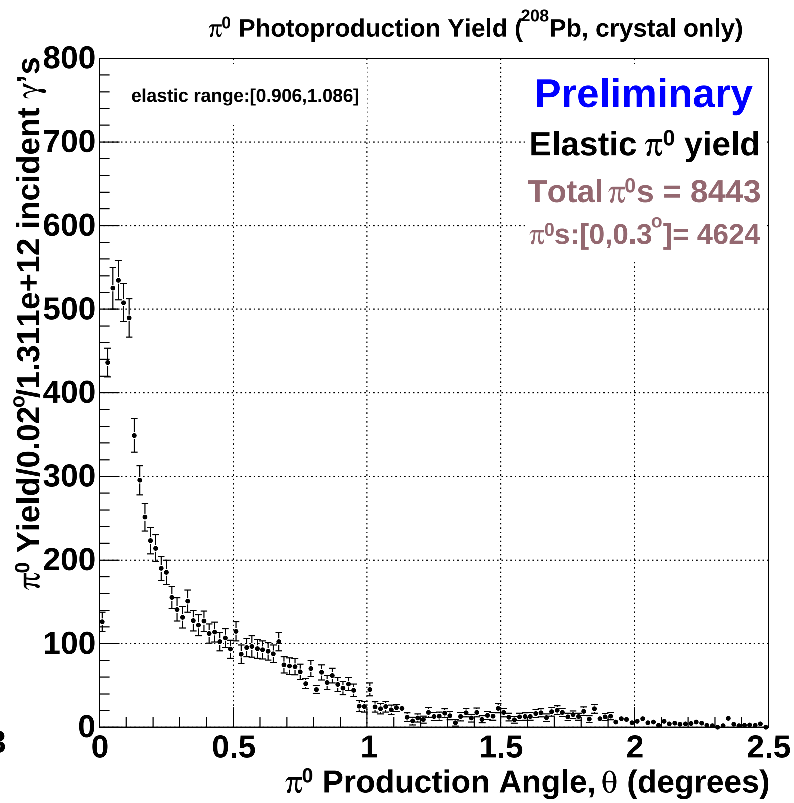
- For each θ_{π^0} bin, apply elastic cut and form $m_{\gamma\gamma}$ distributions; perform fit and extract peak counts = uncorrected yield.
- Correct for inelastic bkgd by evaluating π^0 elasticity distribution explicitly for each θ_{π^0}; evaluate inelastic bkgd under the elastic peak using fit and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

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

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

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

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

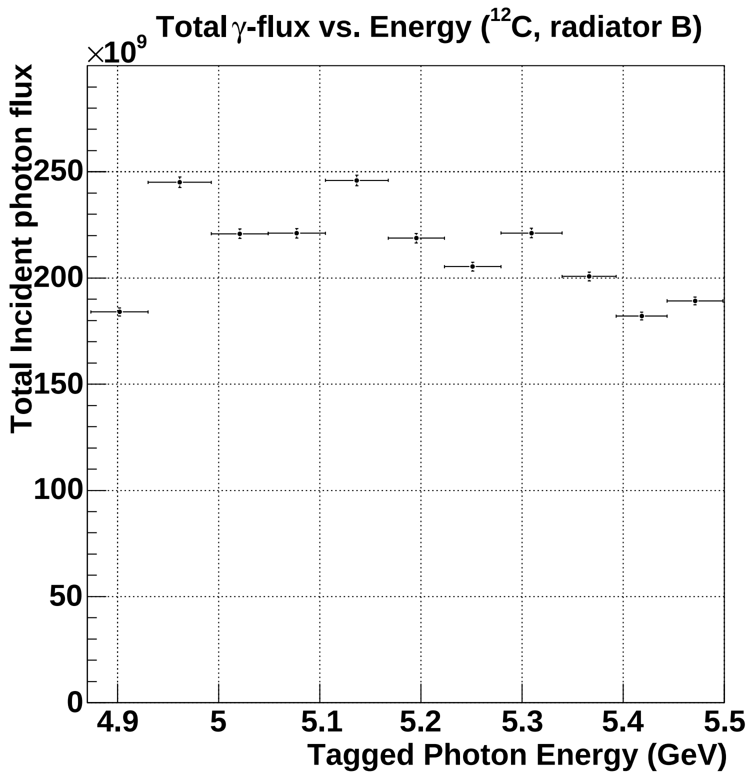
- Fit experimental data with parameterization:

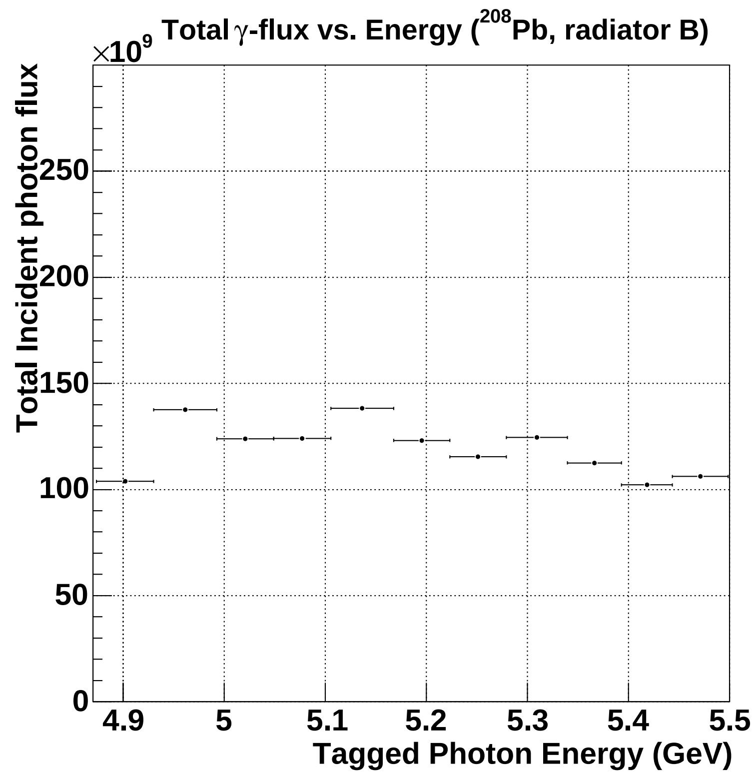
$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = b_p\frac{d\sigma_P}{d\Omega} + b_c\frac{d\sigma_N}{d\Omega} + b_i\frac{d\sigma_I}{d\Omega} + 2cos\phi\sqrt{b_p b_c\frac{d\sigma_P}{d\Omega}\frac{d\sigma_C}{d\Omega}} \quad (8)$$

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

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

Photon Flux

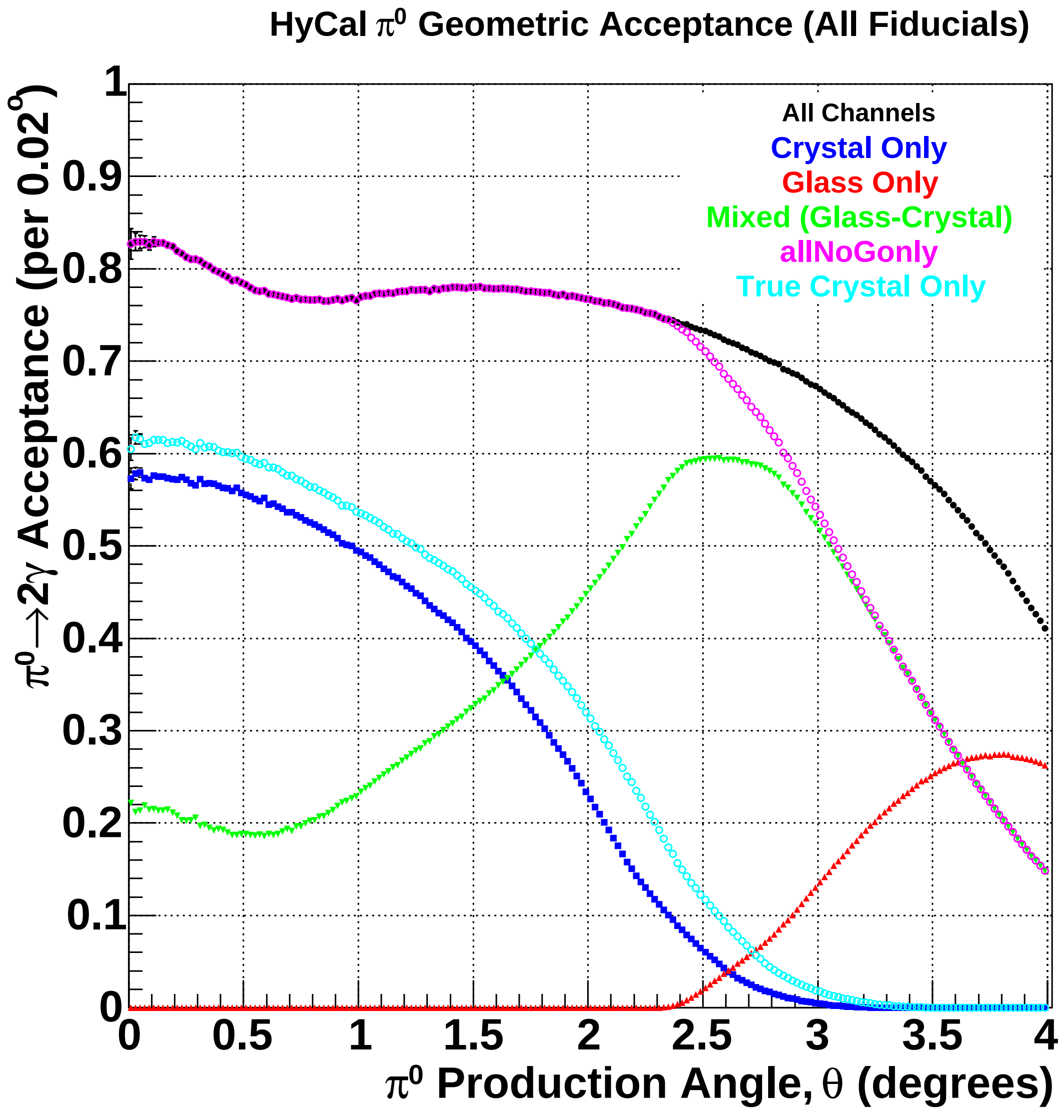




Flux for ^{12}C: 2.33×10^{12} γ's

Flux for ^{208}Pb: 1.31×10^{12} γ's

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

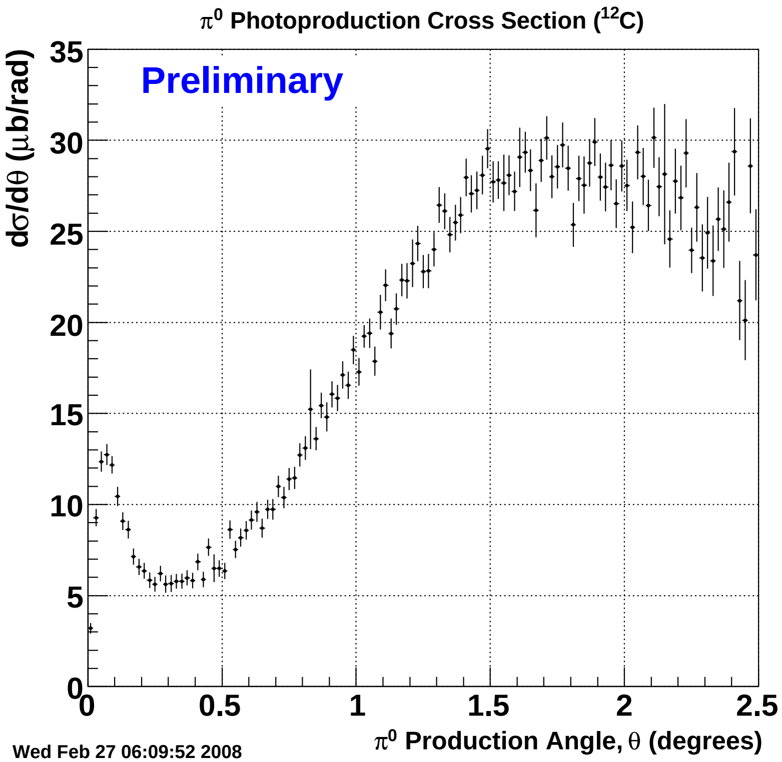


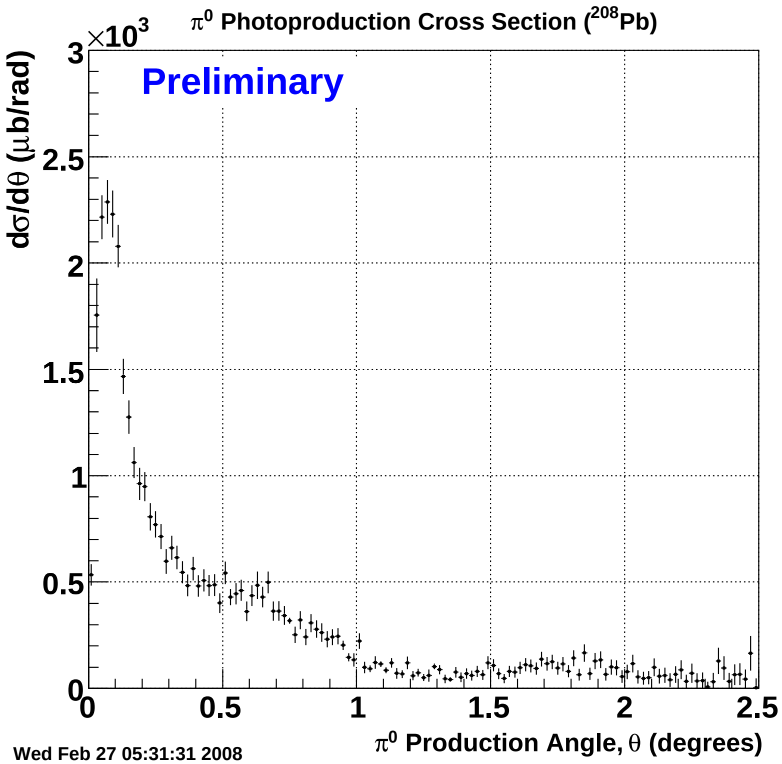
Experimental Efficiencies: ^{12}C

	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.

Cross Sections





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

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

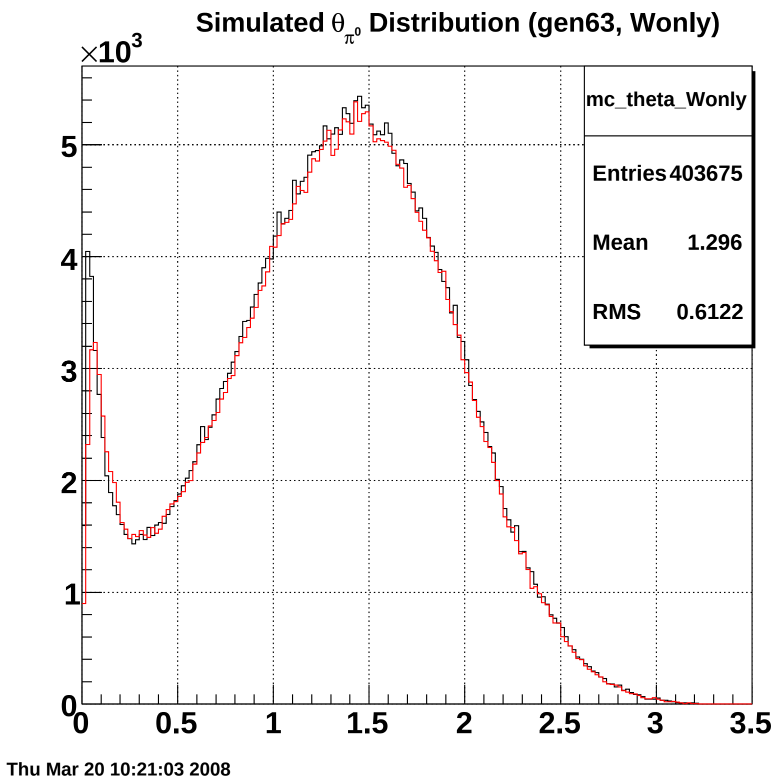
$\longrightarrow$ Calculate theory input shapes (cross sections) energy-weighted according to experimental flux.

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

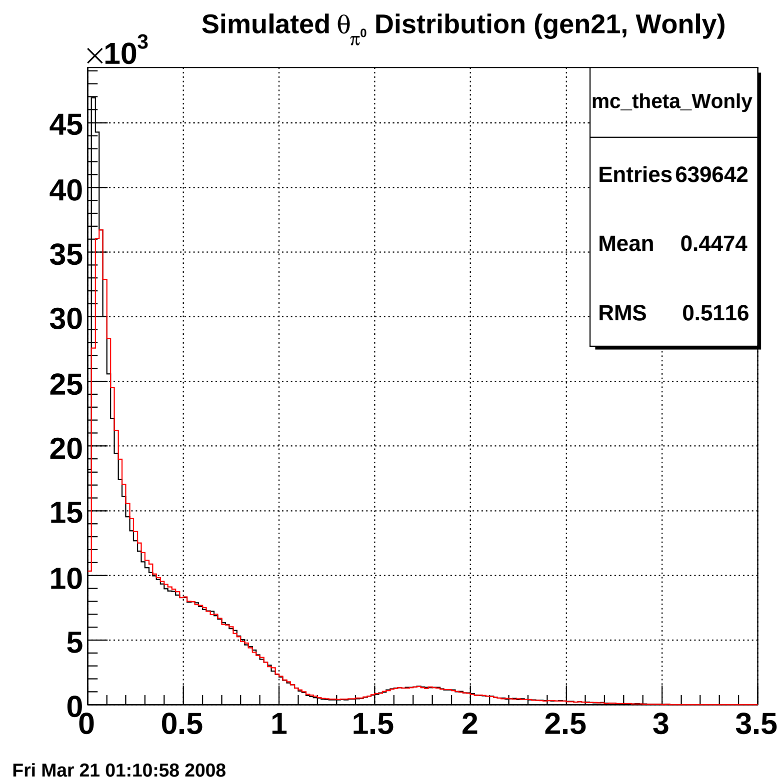
$\longrightarrow$ Digitize simulated data and reconstruct events using same algorithms as for real data. Produce simulated yield distributions with built-in experimental resolutions.

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

MC Shape Generation: Exmpl. Thrown & Det. Spectra

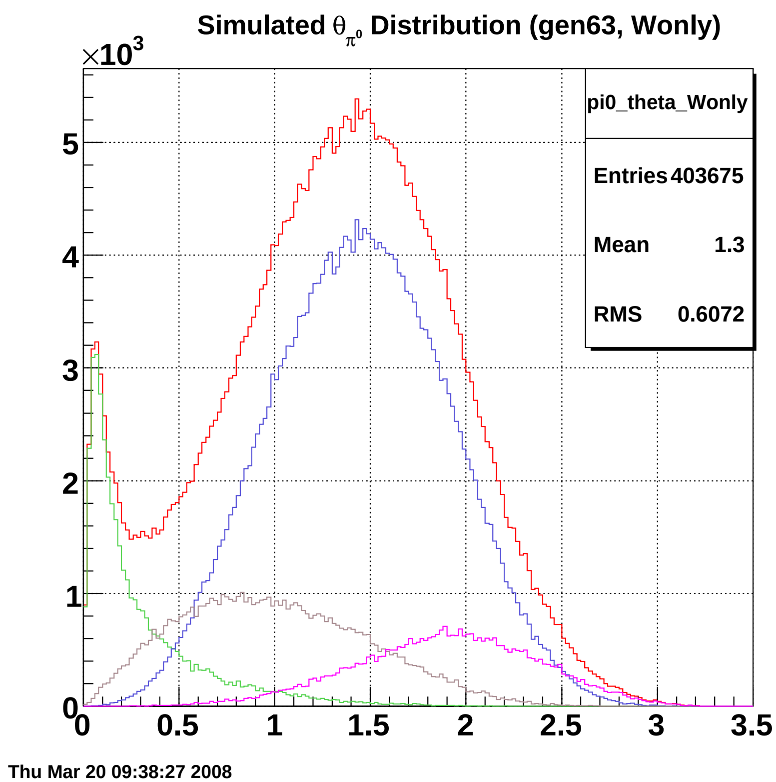


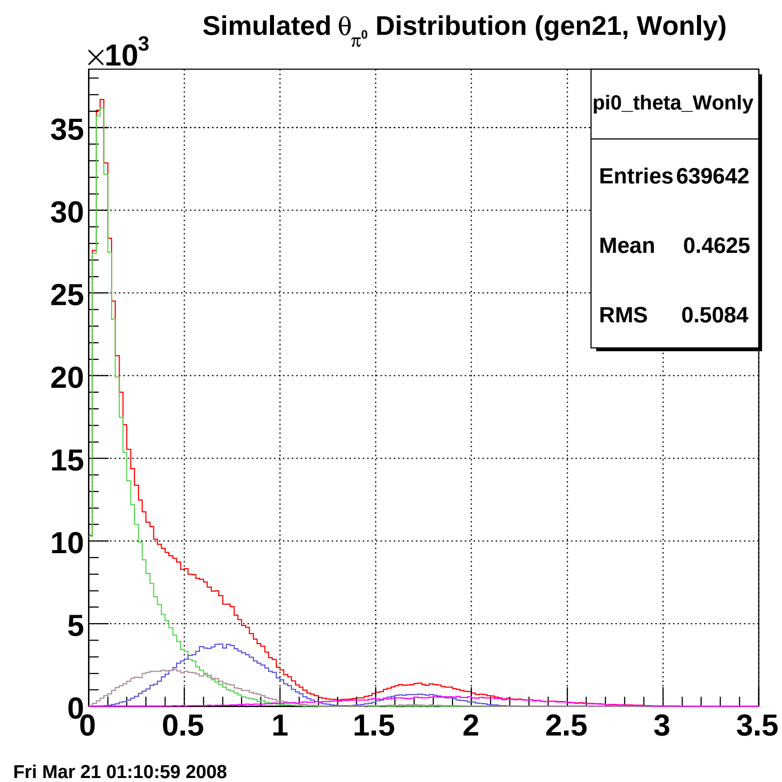
^{12}C: —θ_{π^0} Thrown —θ_{π^0} Detected



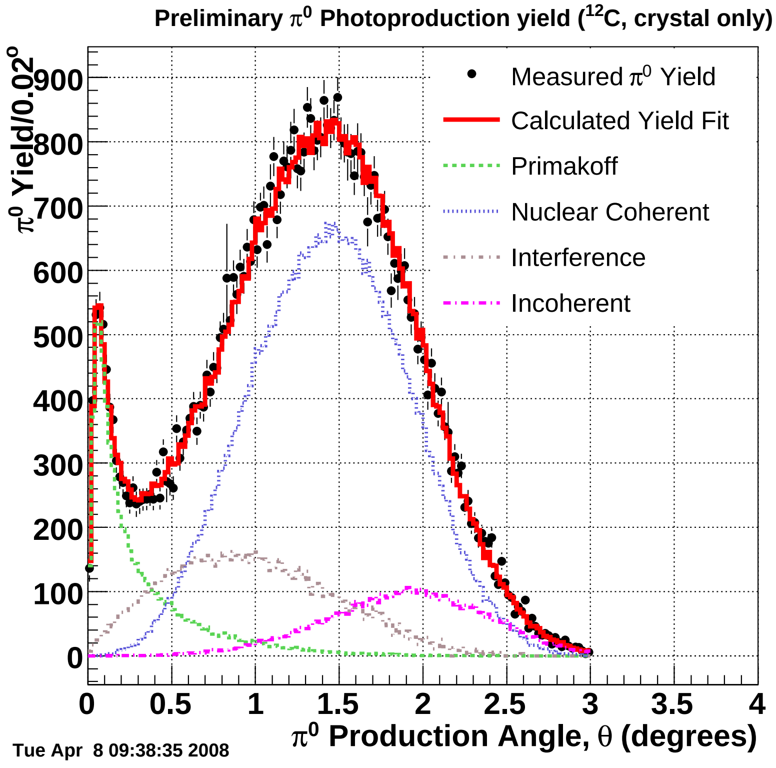
^{208}Pb: —θ_{π^0} Thrown —θ_{π^0} Detected

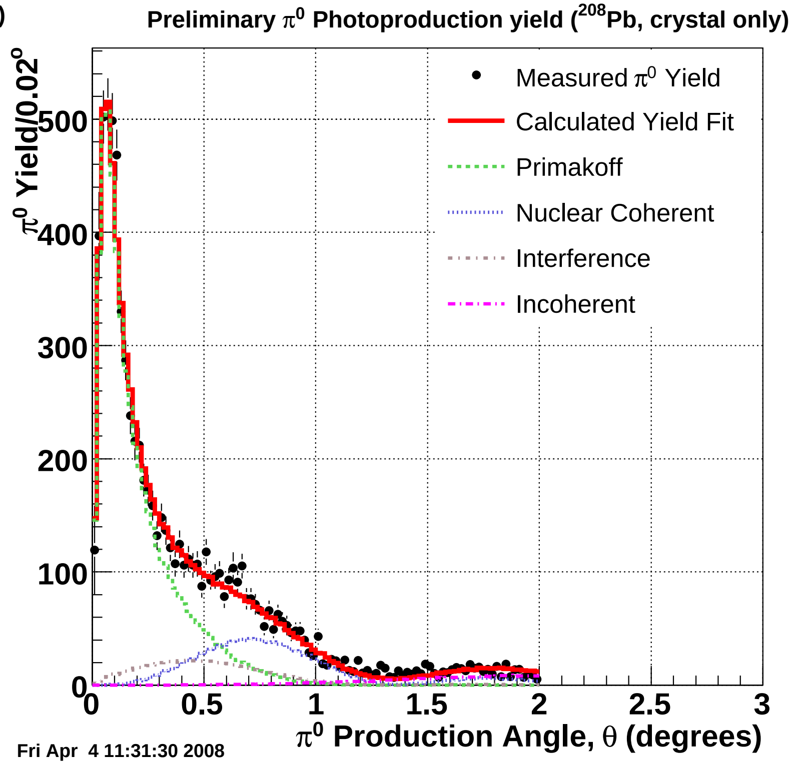
MC Shape Generation: Exmpl Fit Input Shapes (smeared)





^{12}C and ^{208}Pb Target Yield Fits



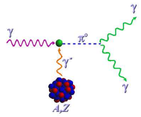


Preliminary Systematic Error Table

Description	$\Gamma_{\gamma\gamma}$ dev (%)
$m_{\gamma\gamma}$ fits + inelast bkgd corr.	±1.1
Inelastic bkgd shape uncert.	±0.75
Photon flux	±0.98
Experimental efficiencies	±0.5
Fiducial Acceptance	±0.3
Event Selection	±0.9
π^0 bkgd from ω and ρ decay	±1.0
Target thickness	±0.1
branch ratio	±0.03
Tagged Photon Energy	±0.1
Total Systematic Error	±2.3%

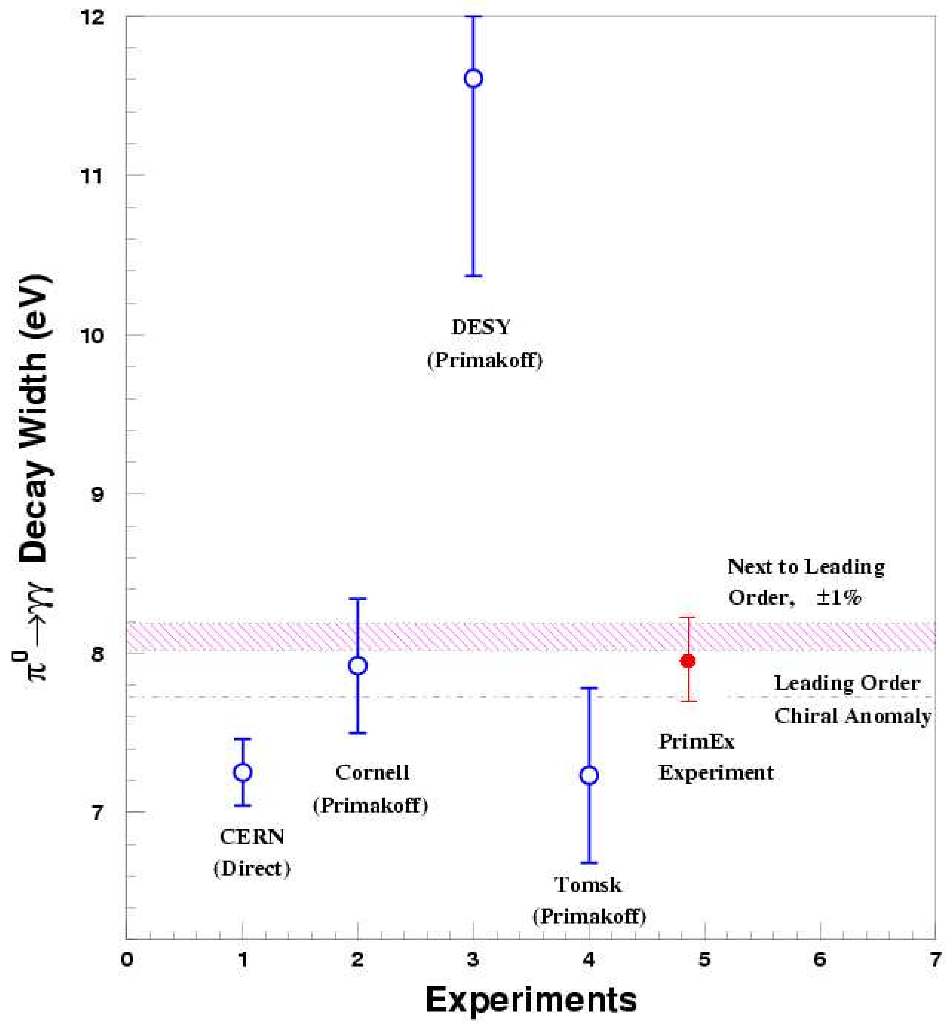
Preliminary Theoretical Input (Model) Error Table

Description	$\Gamma_{\gamma\gamma}$ dev (%)	
	^{12}C	^{208}Pb
Incoherent XS shape uncert.	± 1.35	± 0.11
Nuclear coh. XS energy dep.	± 0.16	± 0.06
F_{NC} intermediate state	± 0.02	± 0.73
π-N cross section uncertainty		
Total Model Error	± 1.38	± 0.74



PrimEx Collaboration

$\Gamma_{\pi^0 \to \gamma\gamma}$ 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: $\Gamma_{\pi^0\to\gamma\gamma} = 7.93\text{eV} \pm 1.8\%(\text{stat}) \pm 2.3\%(\text{syst}) \pm 1.1\%(\text{model})$.
- 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.