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

Dustin E. McNulty
MIT/UMass
mcnulty@jlab.org

October 21, 2009

Physics Career History

- James Madison University (1991-1994): Undergraduate
  - →Research with Kevin Giovanetti (1993 - 1995)
  - →Design, Construct, Install Prototype Cal. Sys. for CLAS EC
- University of Virginia (1995-2002): Graduate
  - →Joined Jim McCarthy's group 1997
  - →Worked on Sol. Pol. Targts for Spin SF Meas at Jlab and SLAC
  - →Dissertation on SLAC E155x – Measured $g_2^{p,d}$ from DIS
- Massachusetts Institute of Technology (2003-2007): Postdoc
  - →Work with Aron Bernstein and Mark Ito
  - →Support PrimEx in Hall B: Hardware and Software
  - →Performed ∼Independent XS and $\Gamma_{\gamma\gamma}$ Analysis
- University of Massachusetts (2007-present): PostdocII
  - →Work with Krishna Kumar and Hall A Parity Group
  - →Support Hall A Parity program: HAPPExIII, PVDIS, and PREx
  - →Development of Hall A 12GeV MOLLER proposal: MC gens

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

Outline

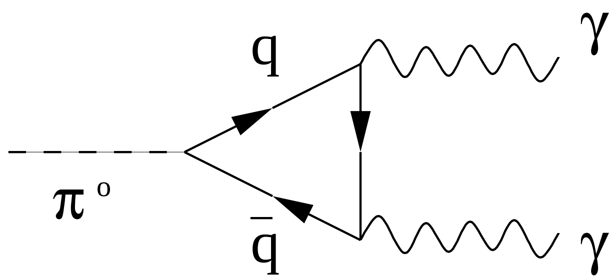
- Introduction and Physics Motivation
- Experimental Overview
- Calibration Reactions
  - Pair Production
  - Compton Scattering
- π^0 Analysis Details
- Final $\Gamma_{\pi^0 \to \gamma\gamma}$ Result
- Summary and Outlook

Intro: 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 Berkley 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)



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

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

$\rightarrow \tau_{\pi^0} \sim 0.8 \times 10^{-16}$ 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?

$\longrightarrow$ Define a multiplicative quantum number “natural parity” (NP) = 1 for S, V, ... particles. NP = -1 for PS, PV, ...

$\longrightarrow$ An anomalous reaction changes the NP:

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

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

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

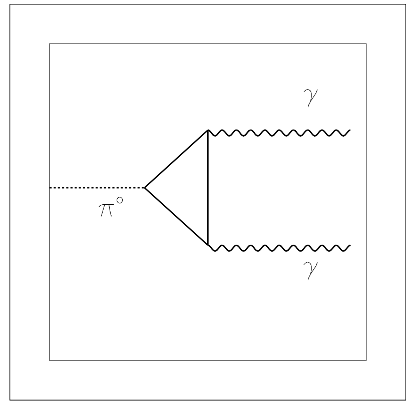
- All anomalous reactions are governed by the Wess-Zumino Lagrangian in χPT which permits transitions that violate certain symmetries.
- In the Chiral limit, the absolute rate of these reactions are predicted by QCD

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.



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

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

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

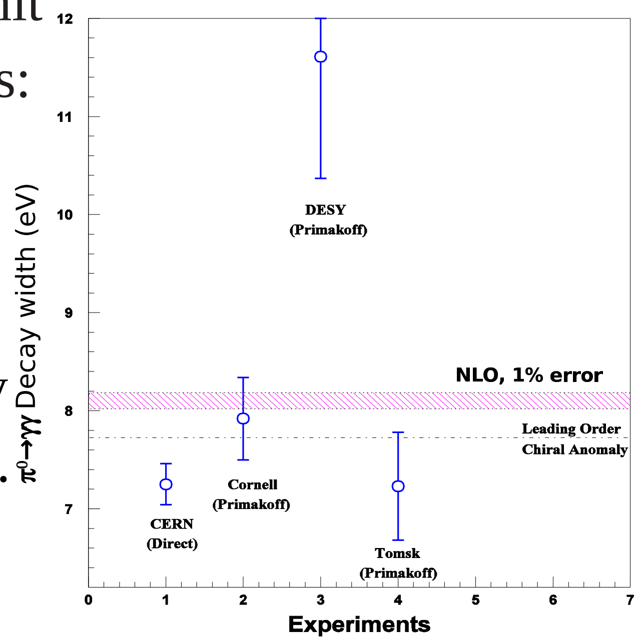
$\rightarrow$ Current Particle Data Book value is 7.84 ± 0.56 eV

Physics Motivation

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

  $\longrightarrow$ 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 4.6% higher than LO prediction

○ 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:

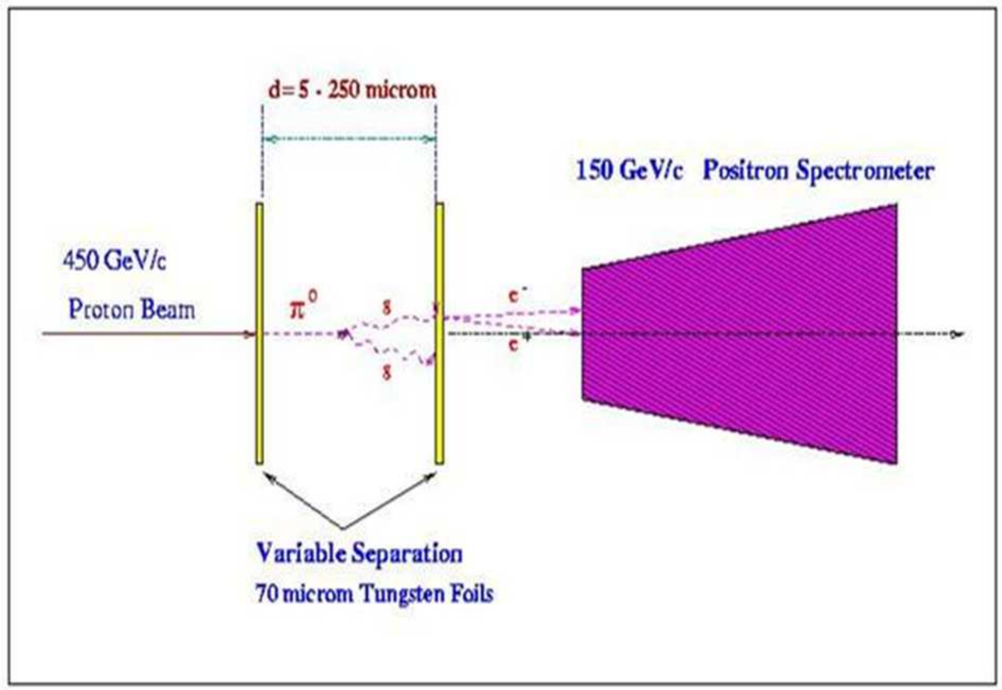
$$L = v\tau_{\pi^0} E/m \qquad (2)$$

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

→ Performed in 1984:
Used 450GeV protons

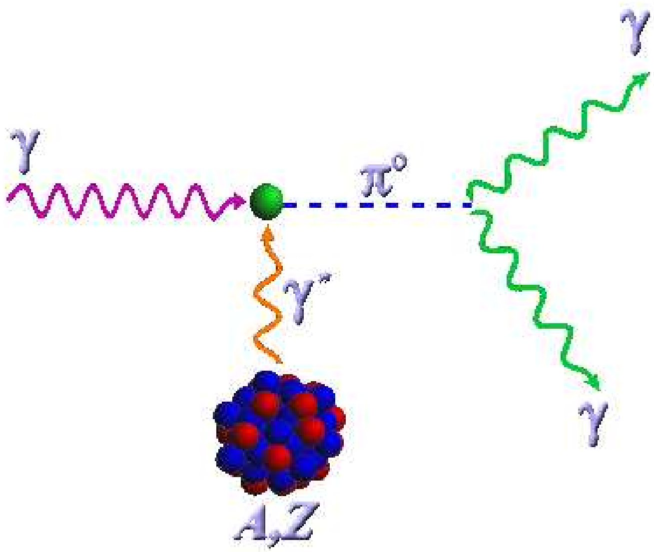
→ Result:
$\Gamma_{(\pi^0 \rightarrow \gamma\gamma)}$ = 7.34eV±3.1%

→ Dominant syst. error:
Uncertainty in P_{π^0} (±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.

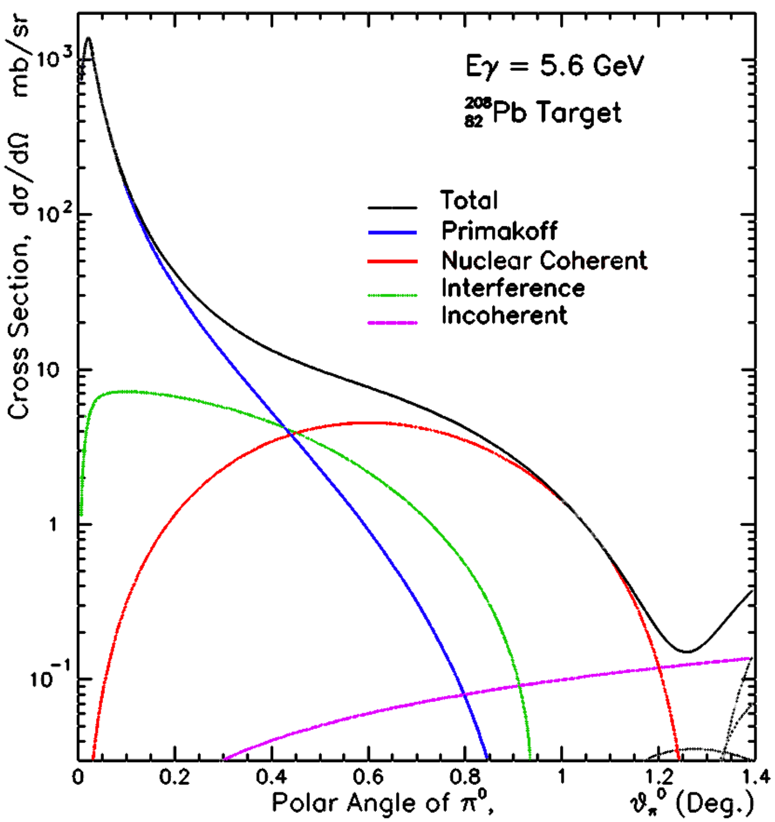


$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\to\gamma\gamma)} \frac{8\alpha_{em}Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |\tilde{F}_{em}(Q)|^2 sin^2\theta_\pi \quad (3)$$

Full Cross Section Components

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

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:

PrimEx Collaboration

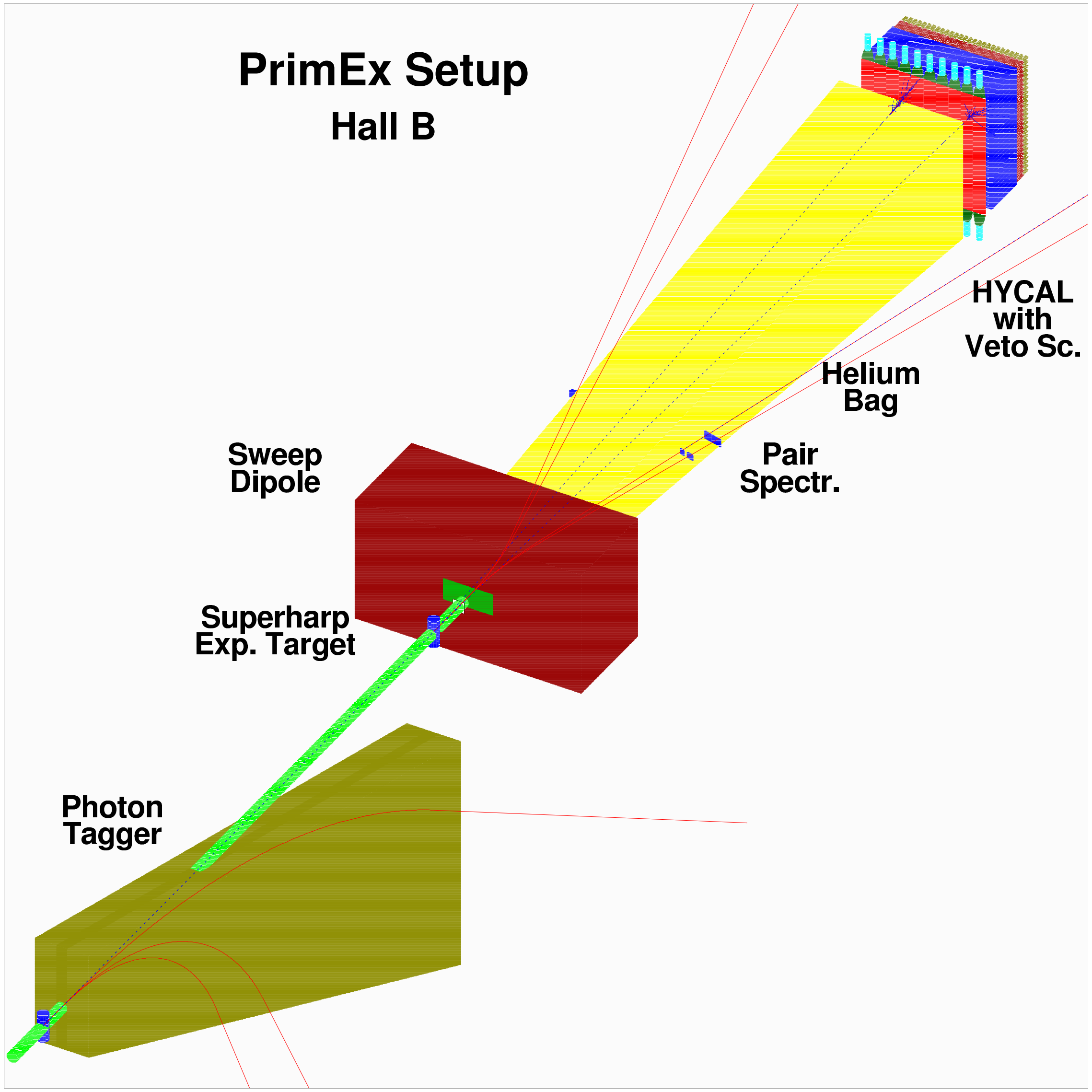
D. Abrahamyan[s], A. Afanasev[d], A. Ahmidouch[l], P. Ambrozewicz[l], K. Baker[d], L. Benton[l], A. Bernstein[j], E. Clinton[i], P. Cole[e], P. Collins[b], D. Dale[g], S. Danagoulian[l], R. Demirchyan[l], A. Deur[f], J. Feng[m], M. Gabrielyan[g], L. Gan[m], A. Gasparian[l], O. Glamazdin[h], J. Goity[d], V. Gyurjyan[f], R. Hakobyan[c], K. Hardy[l], M. Ito[f], M. Khandaker[k], P. Kingsberry[k], M. Konchatnyi[h], O. Korchin[h], S. Kowalski[j], M. Kubantsev[n], V. Kubarovsky[o], I. Larin[a], D. Lawrence[i], D. McNulty[j], R. Minehart[q], R. Miskimen[i], V. Mochalov[o], S. Mtingwa[l], I. Nakagawa[g], S. Overby[l], E. Pasyuk[b], M. Payen[l], R. Pedroni[l], Y. Prok[j], B. Ritchie[b], T. Rodrigues[p], C. Salgado[k], J. Santoro[r], A. Sitnikov[a], D. Sober[c], A. Teymurazyan[g], J. Underwood[l], A. Vasiliev[o], V. Vishnyakov[a], M. Wood[i]

(a) Alikhanov Institute for Theoretical and Experimental Physics, (b) Arizona State University, (c) Catholic University, (d) Hampton University, (e) Idaho State University, (f) Jefferson Lab, (g) University of Kentucky, (h) Kharkov Institute of Physics and Technology, (i) University of Massachusetts, (j) Massachusetts Institute of Technology, (k) Norfolk State University, (l) North Carolina A&T, (m) University of North Carolina, Wilmington, (n) Northwestern University, (o) Institute for High Energy Physics, Protvino, (p) University of Sao Paulo, (q) University of Virginia, (r) Virginia Tech, (s) Yerevan Physics Institute

Experiment Overview

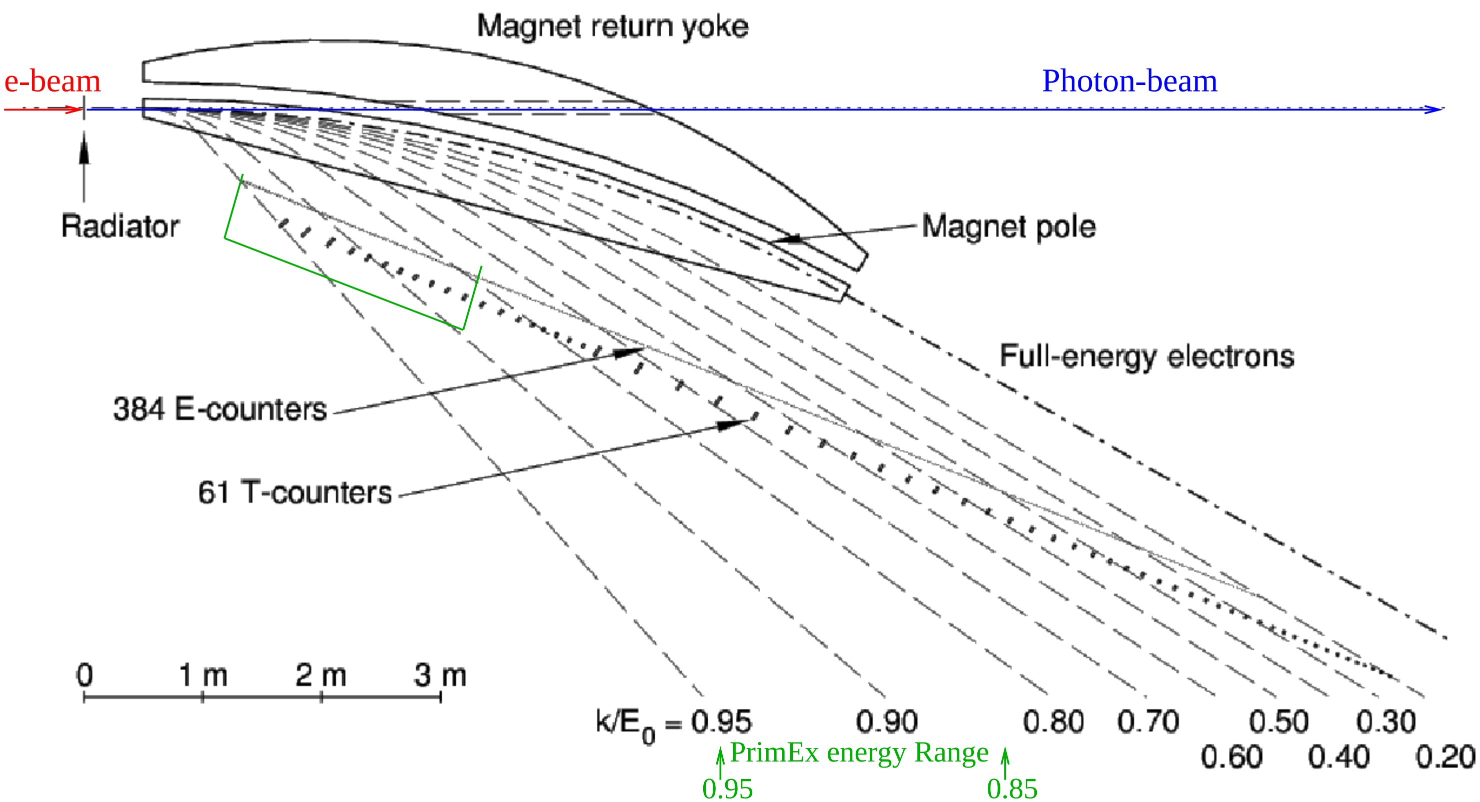
- Conducted at Jefferson Lab, Fall 2004
- Used 5.75 GeV continuous e^- beam and Hall B γ-tagging facility
- Tagged photons incident on 5%X_0 targets: ^{12}C and ^{208}Pb
- New PrimEx/Hall B calorimeter (HyCal), upstream of CLAS, designed to detect π^0 decay γ's
- Measured 3 physical processes (absolute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



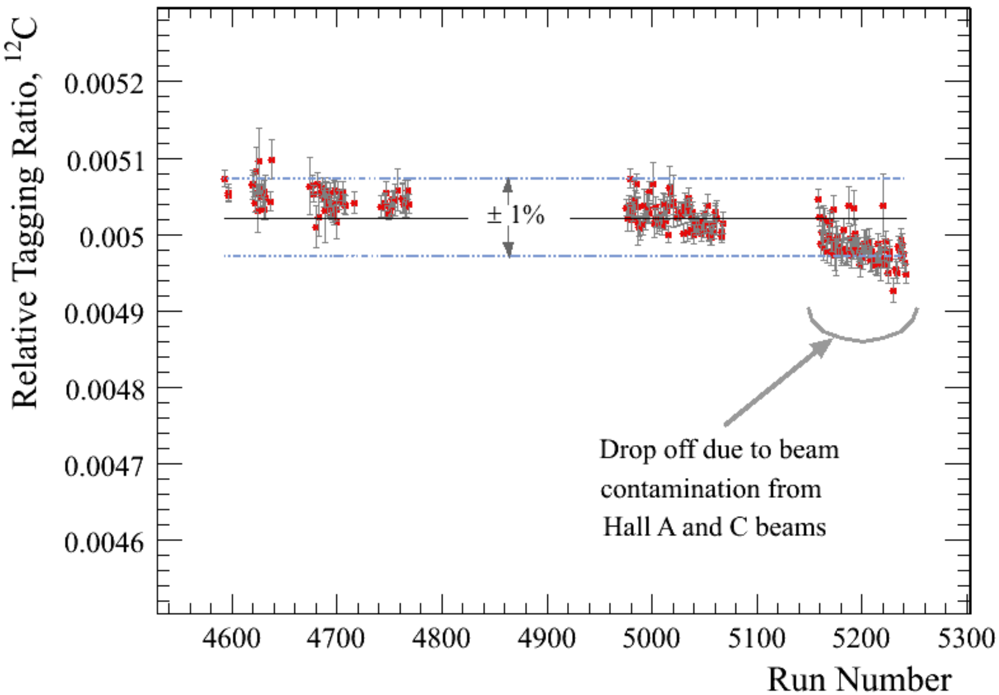
Hall B Photon Tagger

- 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.



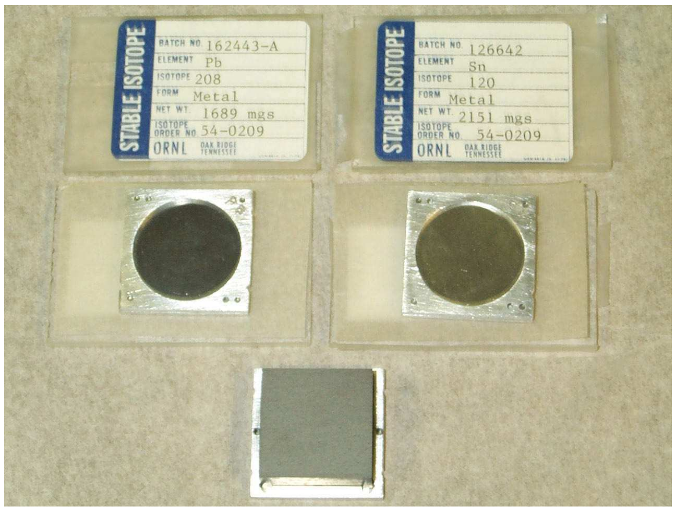
Photon Flux Control

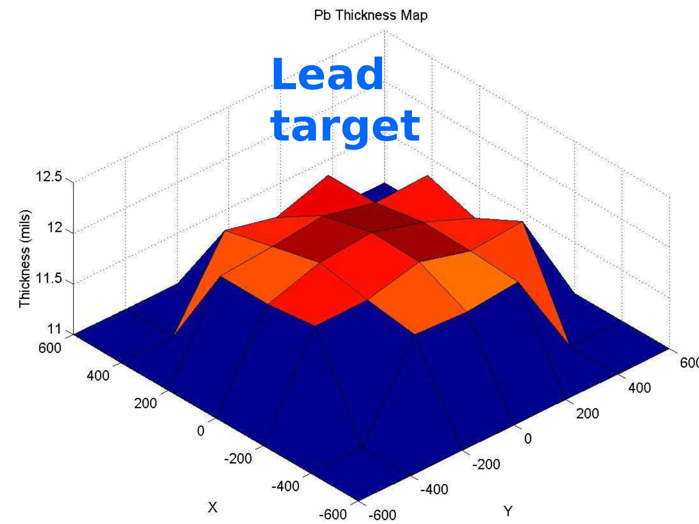
- PrimEx achievement: Total uncertainty in photon flux = 0.98%.
- Number of tagged photons on target (N_γ) calibrated periodically using a Total Absorption Counter (TAC).
- Any drifts in the tagging ratio, occurring between calibration points, are monitored online with the e^+e^- pair spectrometer.

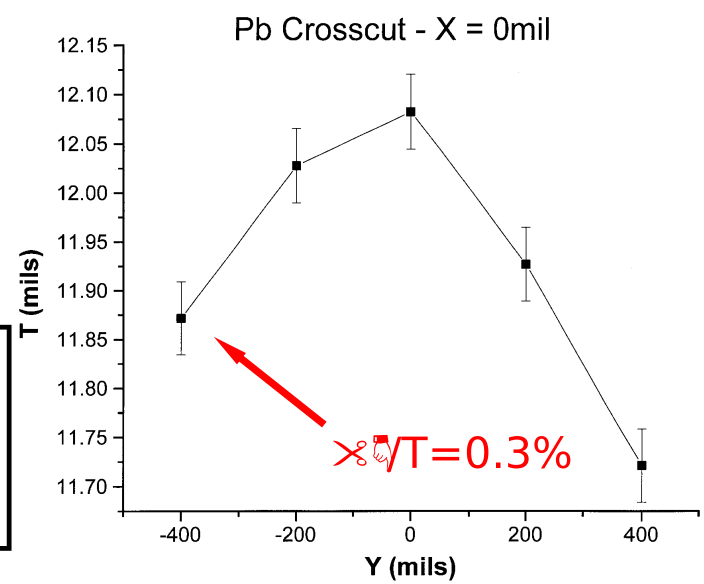


Isotopically pure ^{12}C and ^{208}Pb

PRIMEX Targets



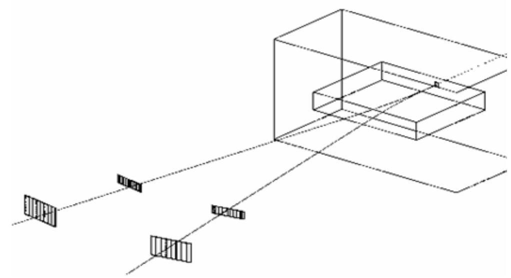


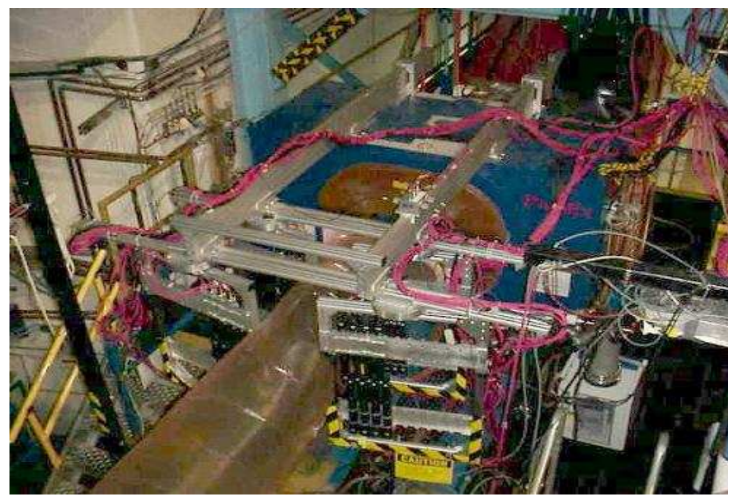


The effective number of carbon atoms/cm² in the carbon target is known to precision of ±0.05%

Pair Spectrometer

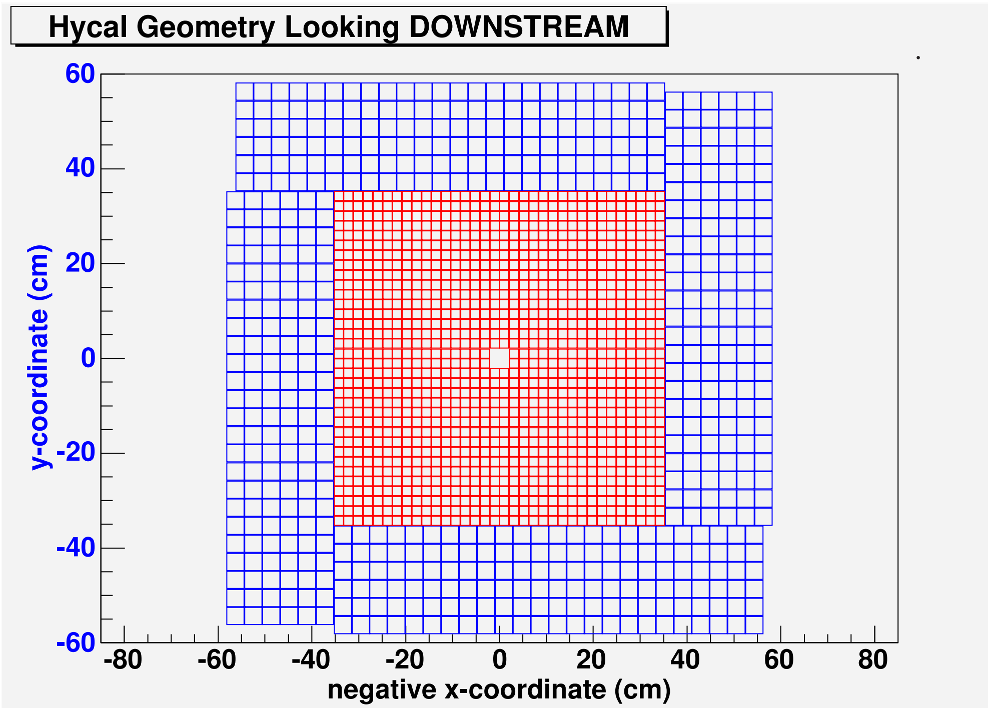
- relative photon flux monitor:
  by detecting e^+e^- pairs from beam during the experiment





- Combination of:
  - 16 KGxM dipole magnet
  - 2 telescopes of 2x8 scintillating detectors

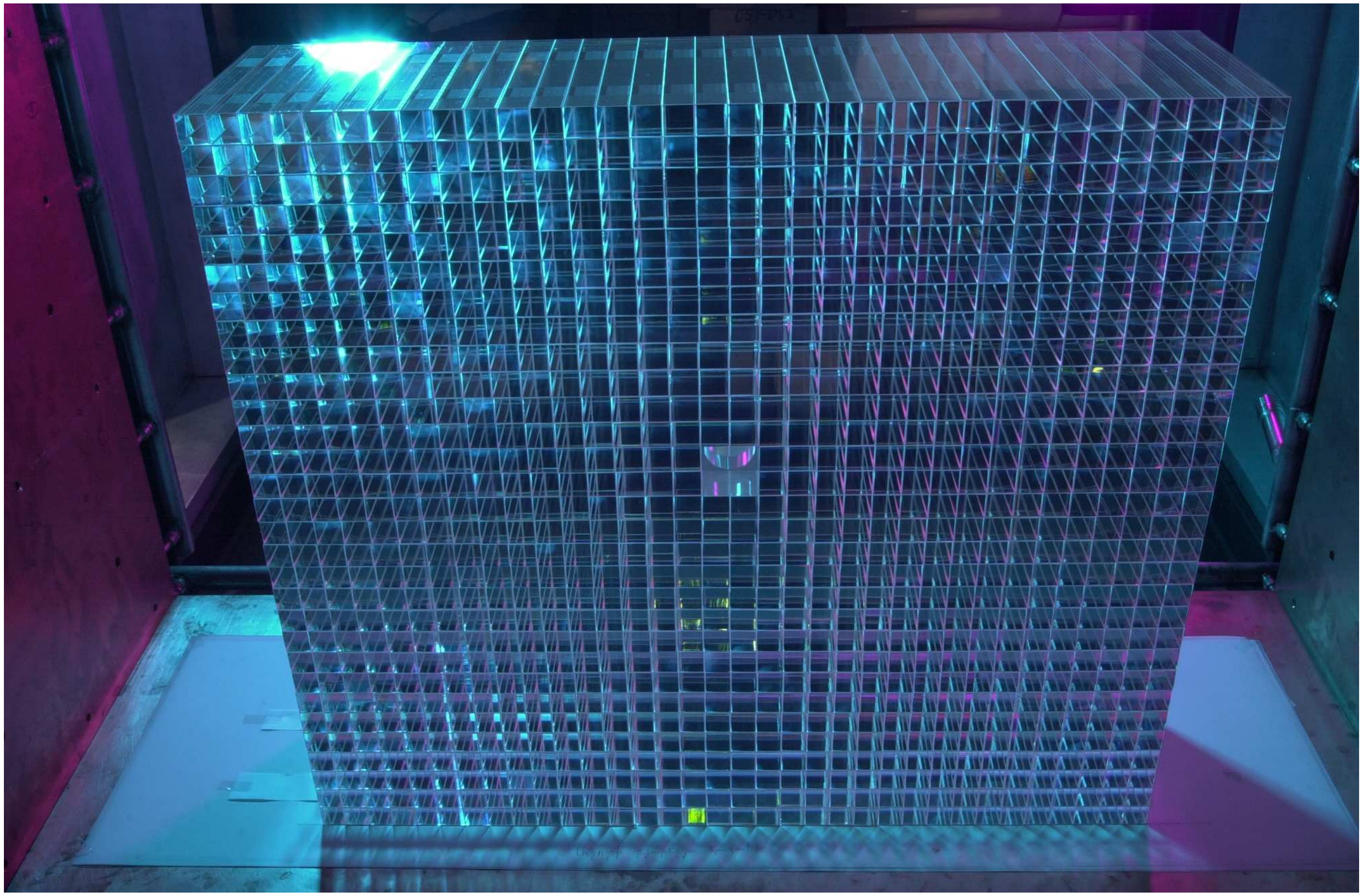
PrimEx Hybrid Calorimeter – "HyCal"



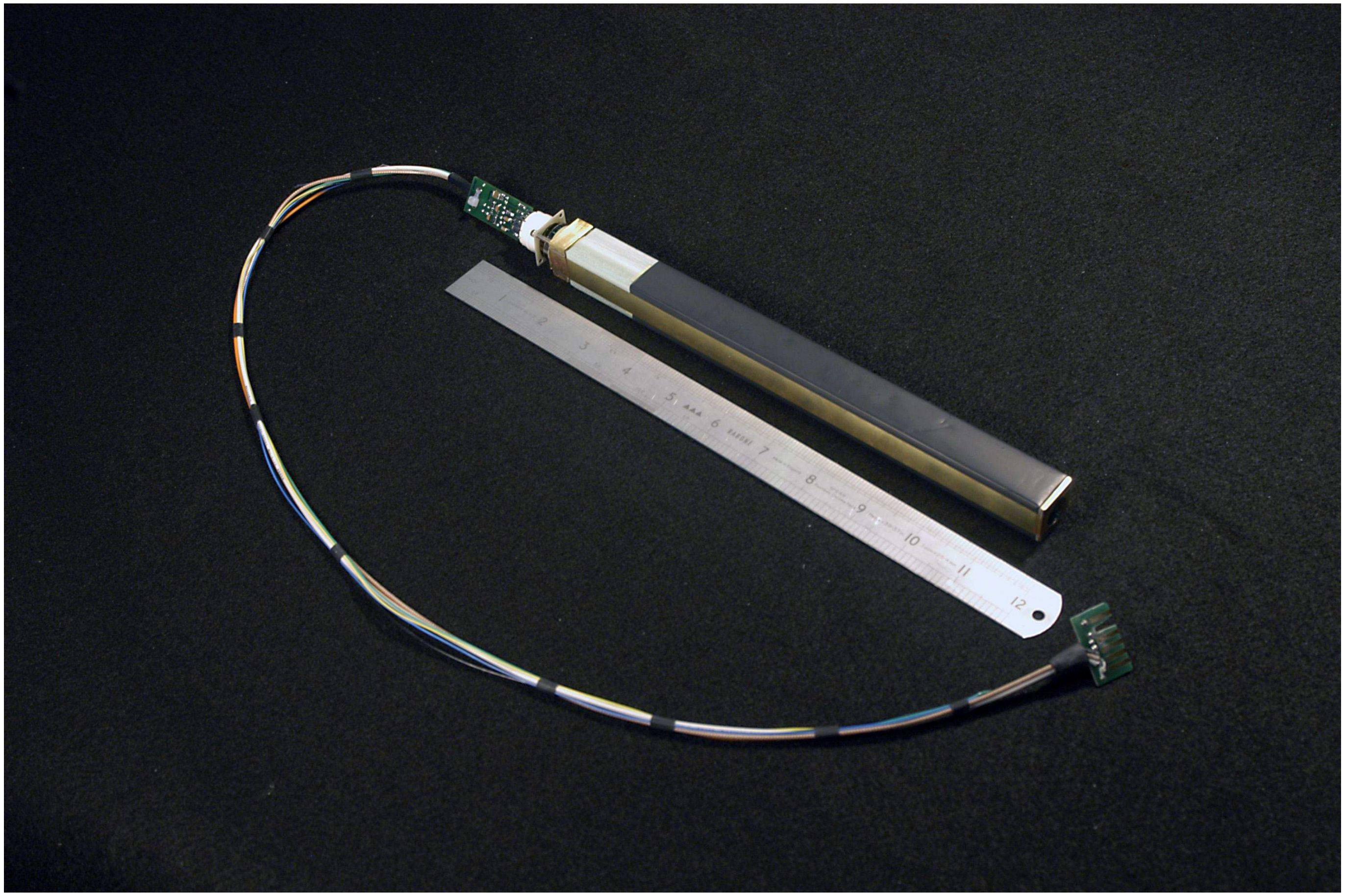
- Optimal performance/cost design
- 1.2 m ×1.2 m, 1728 channels
- 576 Lead-glass (outer layers)
- 1152 Lead-Tungstenate crystal (inner layers)

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

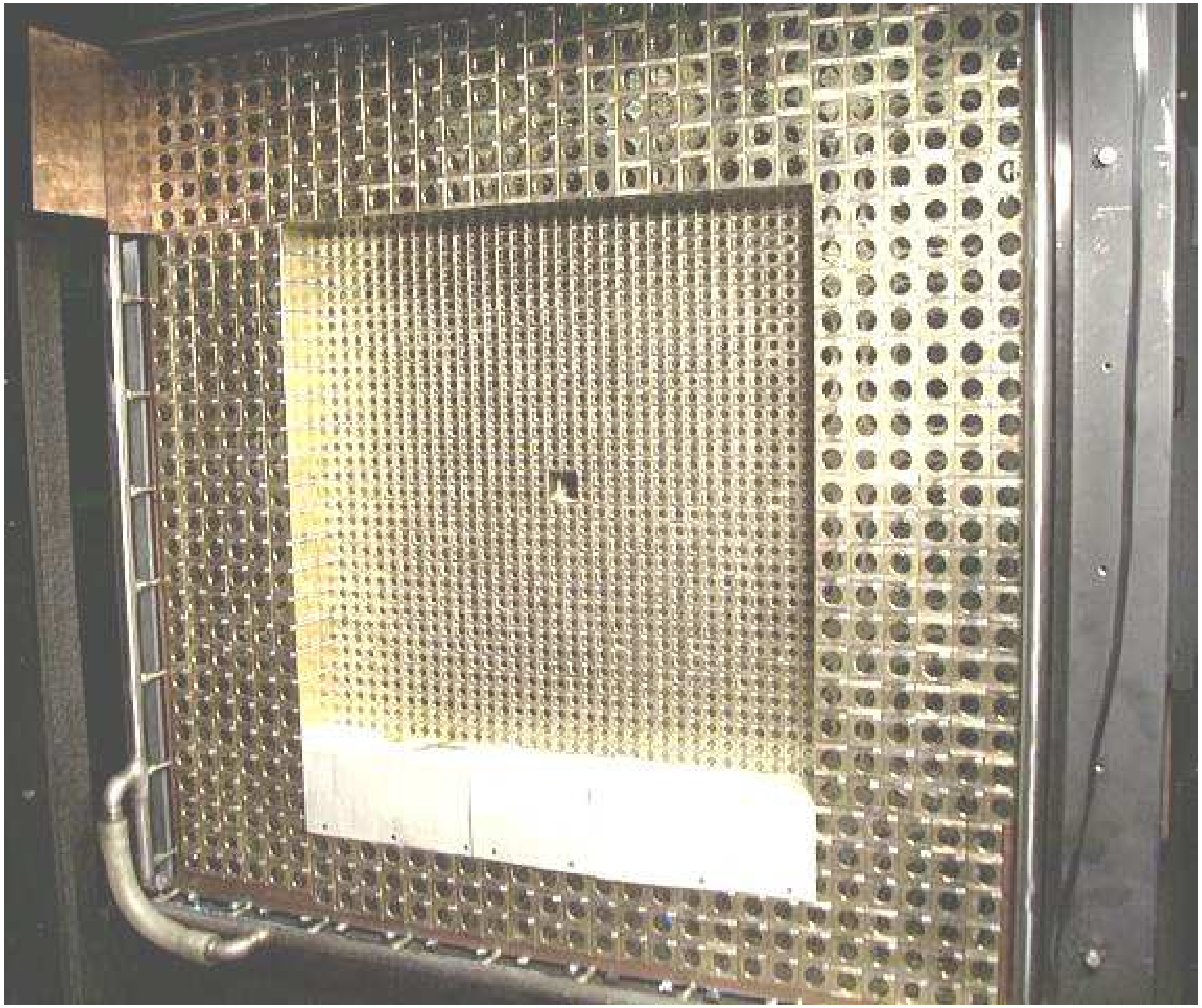
HyCal – Bare (unwrapped) $PbWO_4$ Crystals



HyCal Assembly – Crystal Wrapping

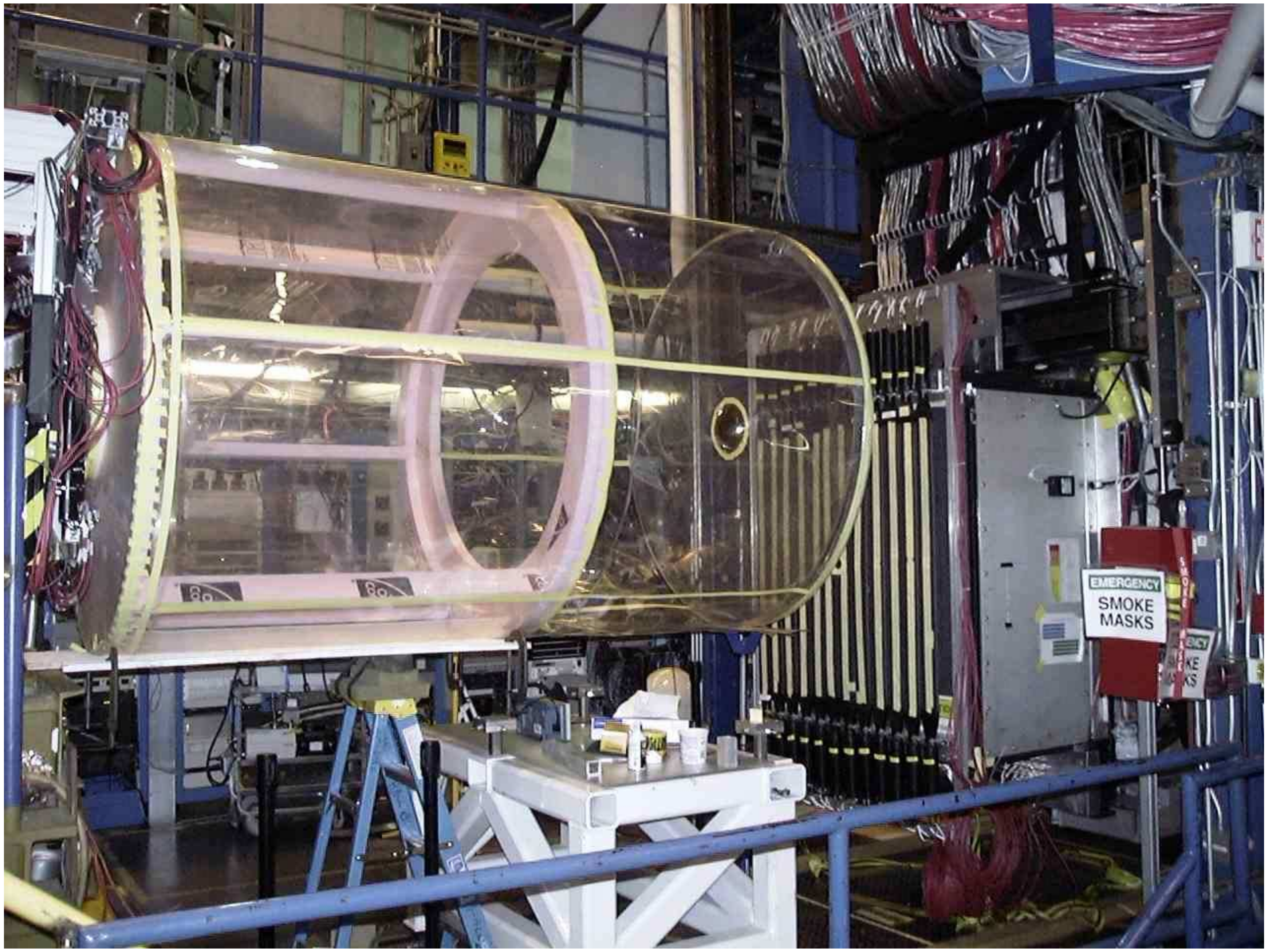


HyCal Assembly – Support Frame and Cooling System



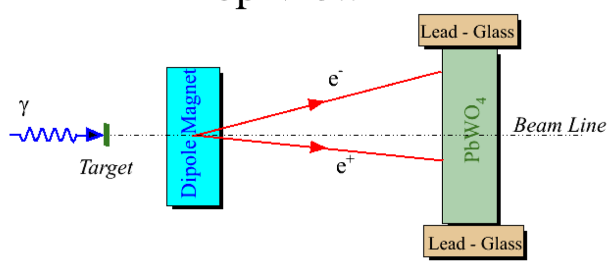
HyCal Calibration –"Snake Scans"

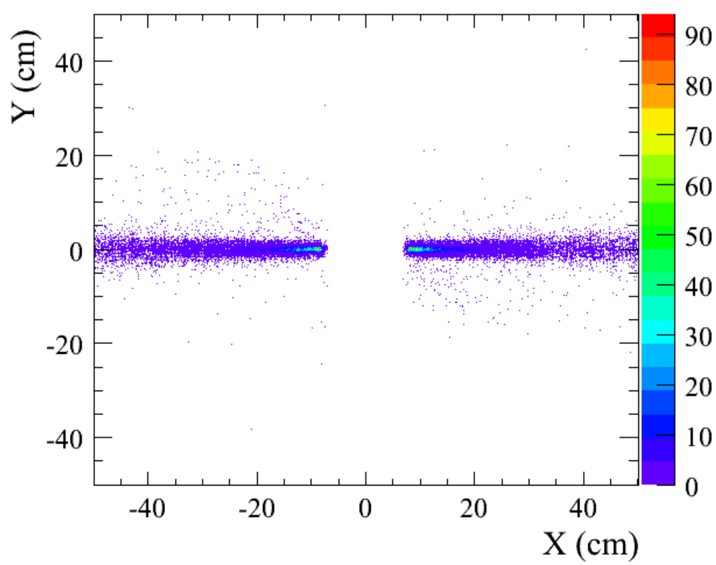
- Full x,y motion allowed each ch. to be scanned through tagged γ beam.
- Performed at both the beginning and end of the experiment.

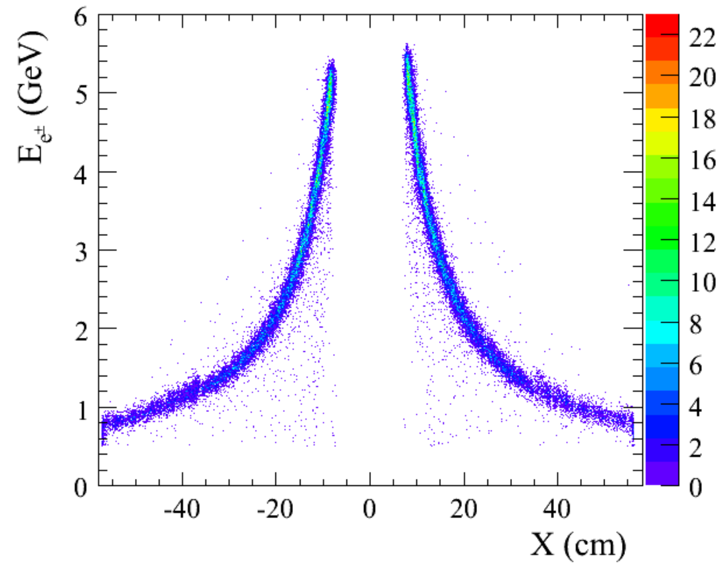


Calibration Reactions: $e^{+}\, e^{-}$ Pair Production

Top View



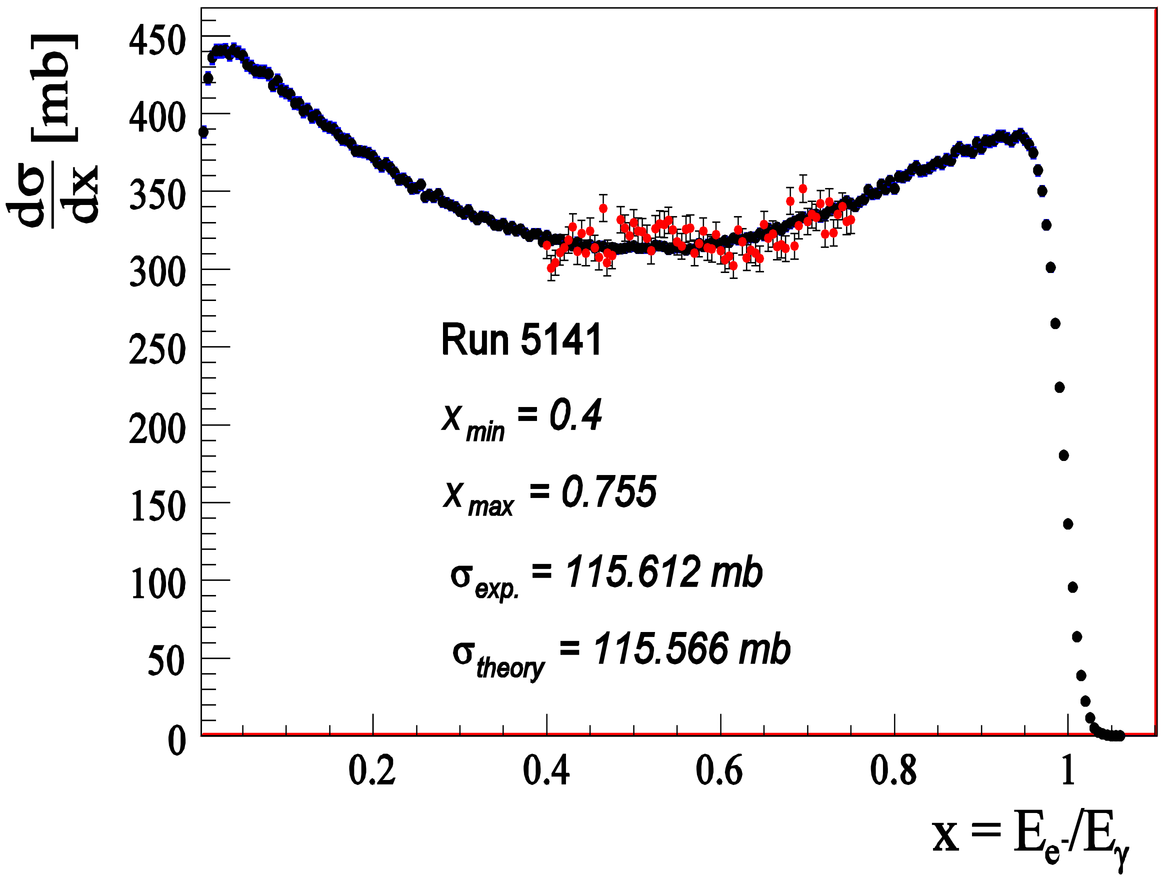




Calculation of Pair Production Cross Section at PrimEx Kinematics

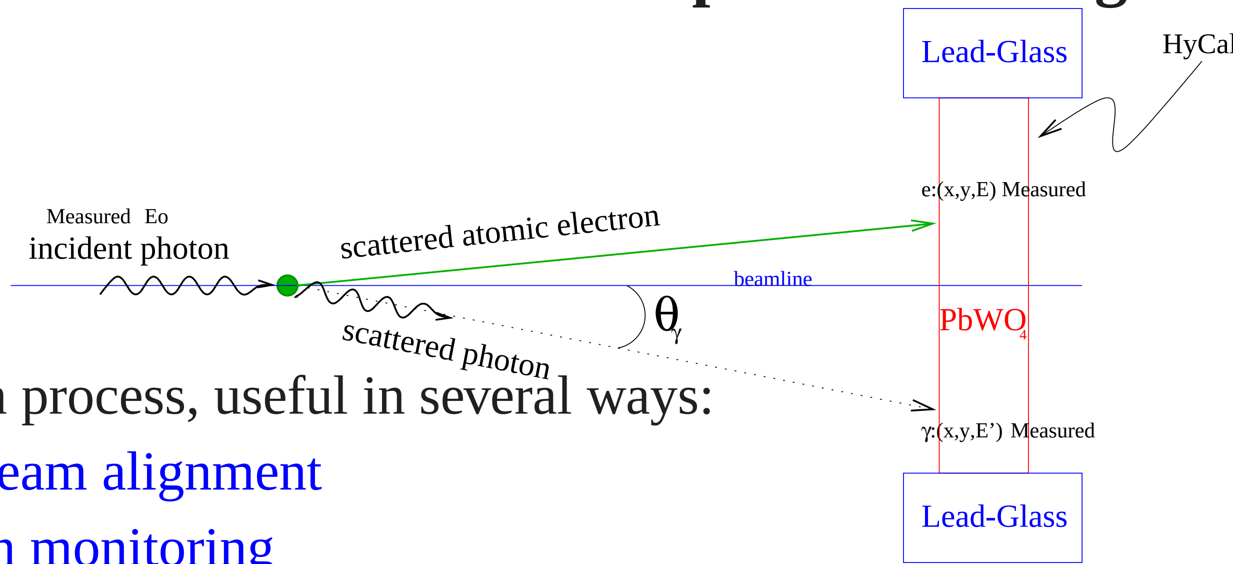
- Bethe-Heitler mechanism of pair production on the nucleus with screening effects due to atomic electrons and Coulomb distortion
- Pair production off atomic electrons, considering excitation of all atomic states and correlation effects due to the presence of other electrons and the nucleus
- Radiative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



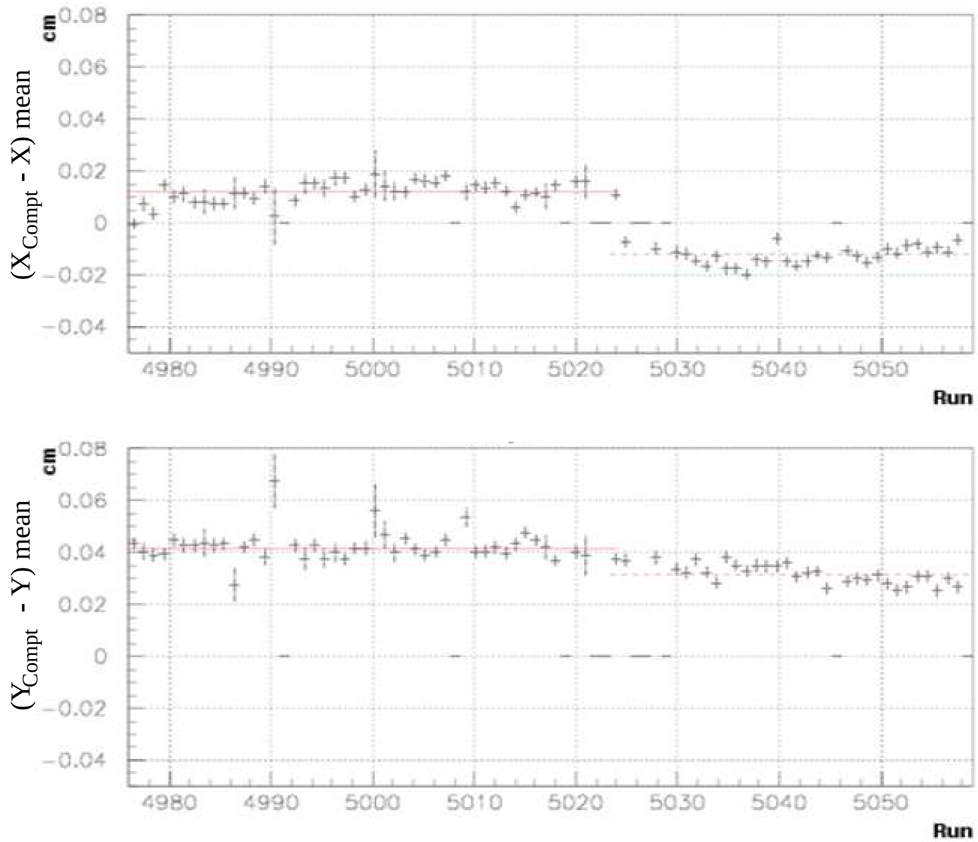
- Agreement with theory at $\sim$ 1.0% level

Calibration Reactions: Compton Scattering



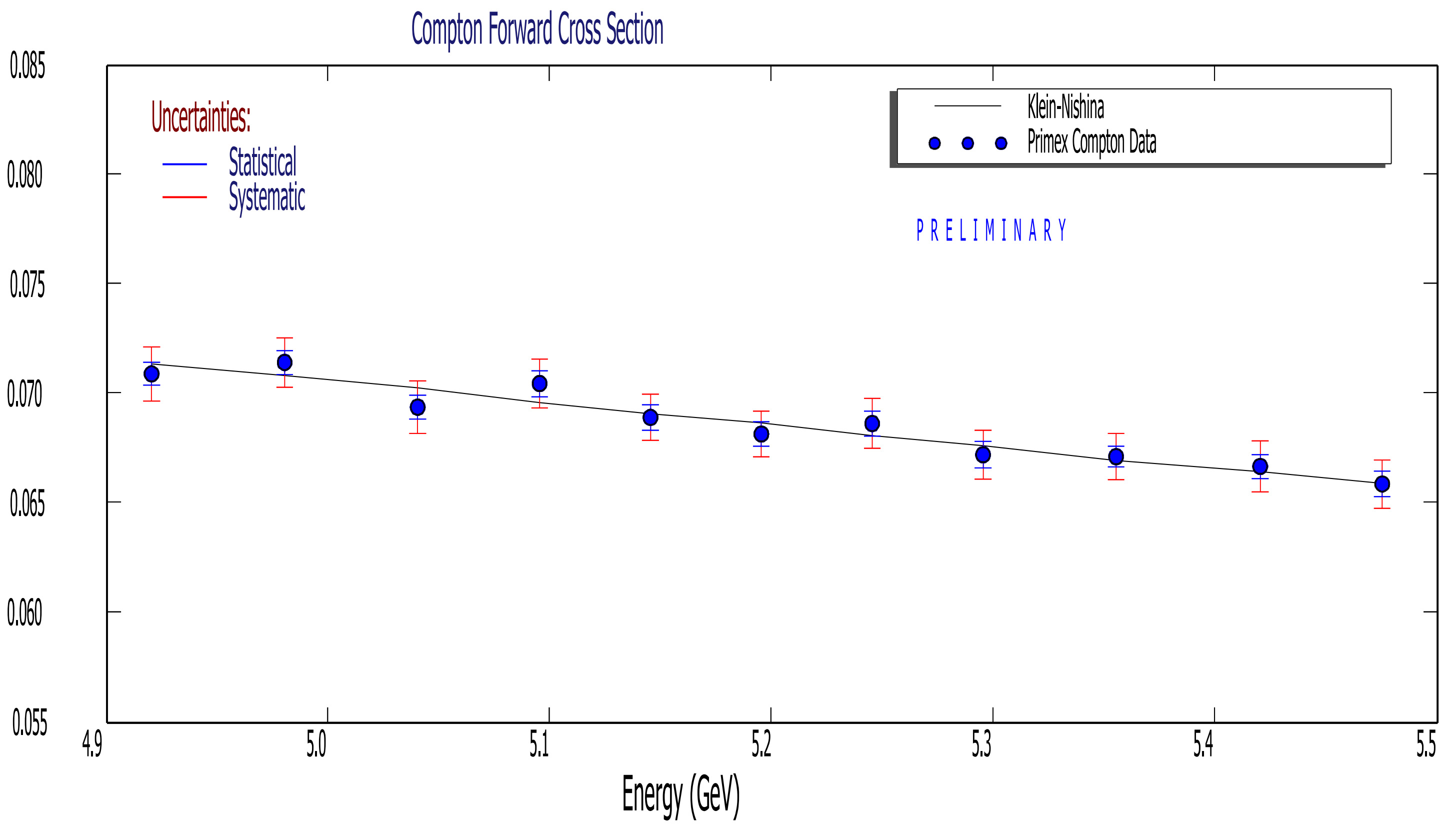
- A well known process, useful in several ways:
  - → Detector/beam alignment
  - → HyCal gain monitoring
  - → Overall check of PrimEx setup to measure absolute cross sections
    - ○ Dedicated "Double-Arm" Compton Runs:
      - → Performed on a weekly basis, $B_{PS} = 0$, $I_{beam} \sim 5 - 10$ nA
      - → 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 data-runs
      - → $B_{PS} \sim 2$ T, $I_{beam} \sim 100$ nA, only scattered photon detected

Beam Alignment Monitoring using Single-Arm Compton



- Only scattered γ measured
- X ≡ reported HyCal coord
- X_{Compt} ≡ 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 Result



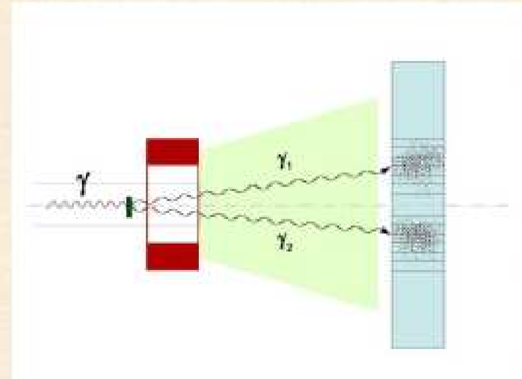
- Average statistical error: 0.6%
- Total error: 1.3% (dominated by photon flux: 1.0%)

Analysis Details: π^0 Event Selection

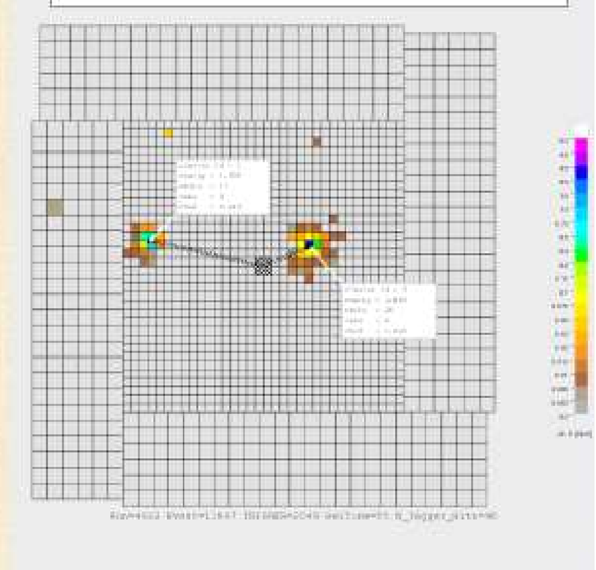
π^0 analysis

We measure:

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



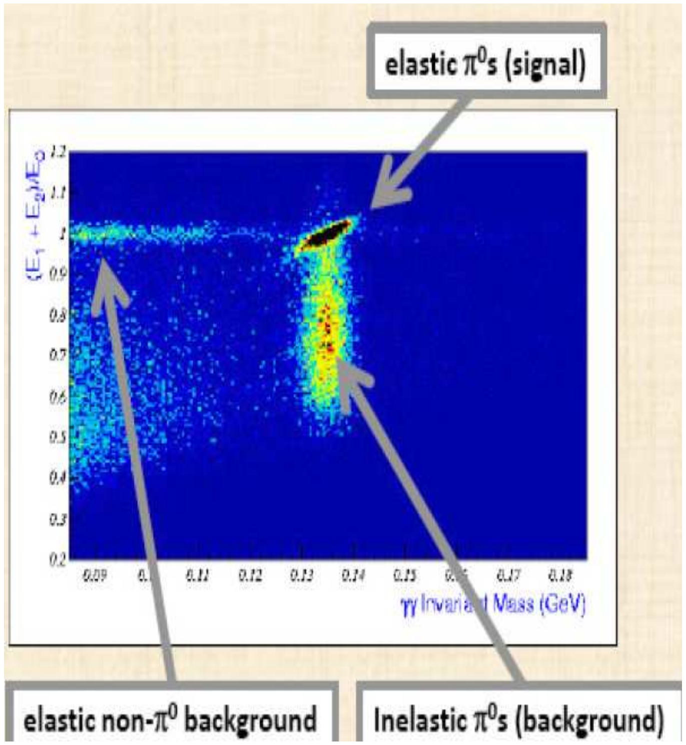
Schematic view of π^0 event

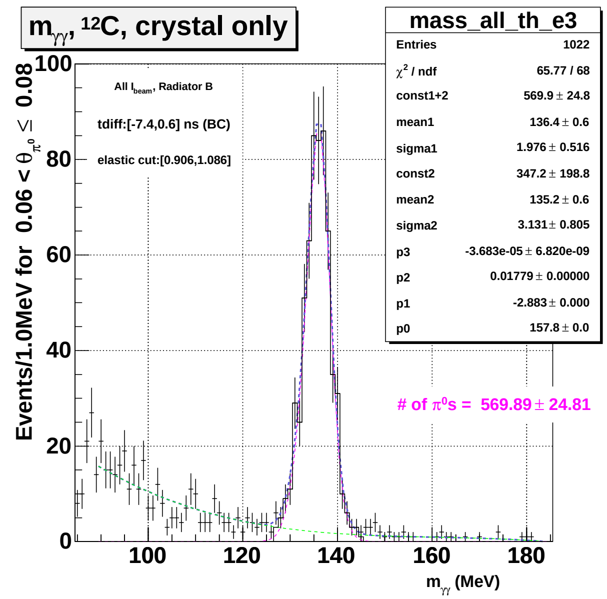


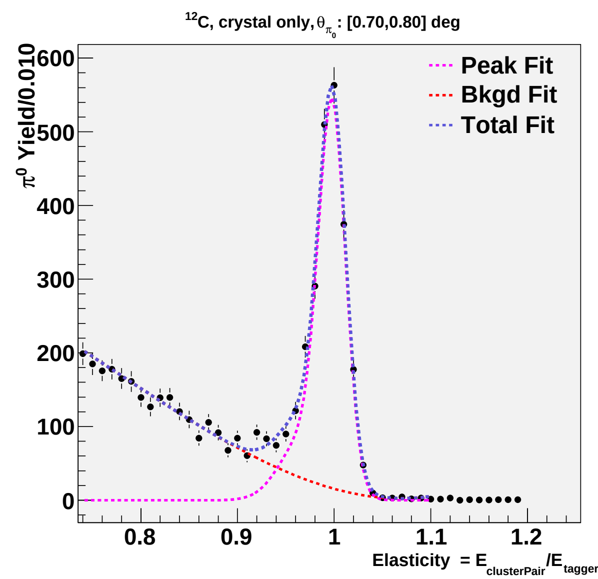
Kinematical constraints:

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

Three groups analyzed the data independently





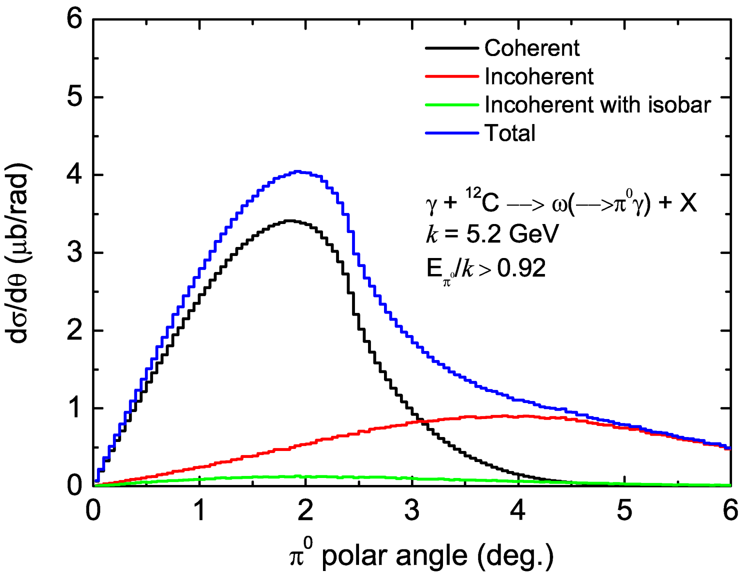


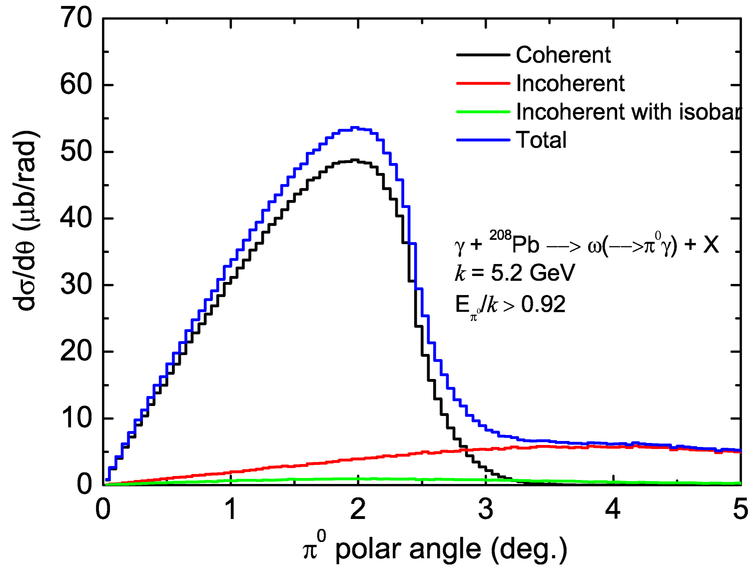
- For each θ_{π^0} bin, apply elastic cut and form $m_{\gamma\gamma}$ distributions; perform fit and extract peak counts = uncorrected yield.

- 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.

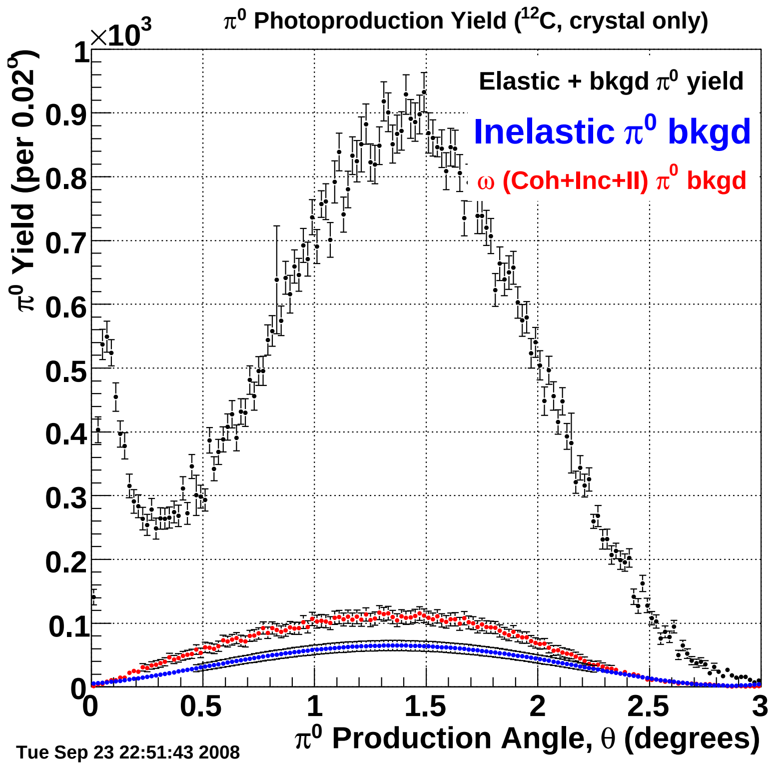
The $\omega \rightarrow \pi^0\gamma$ Background Correction

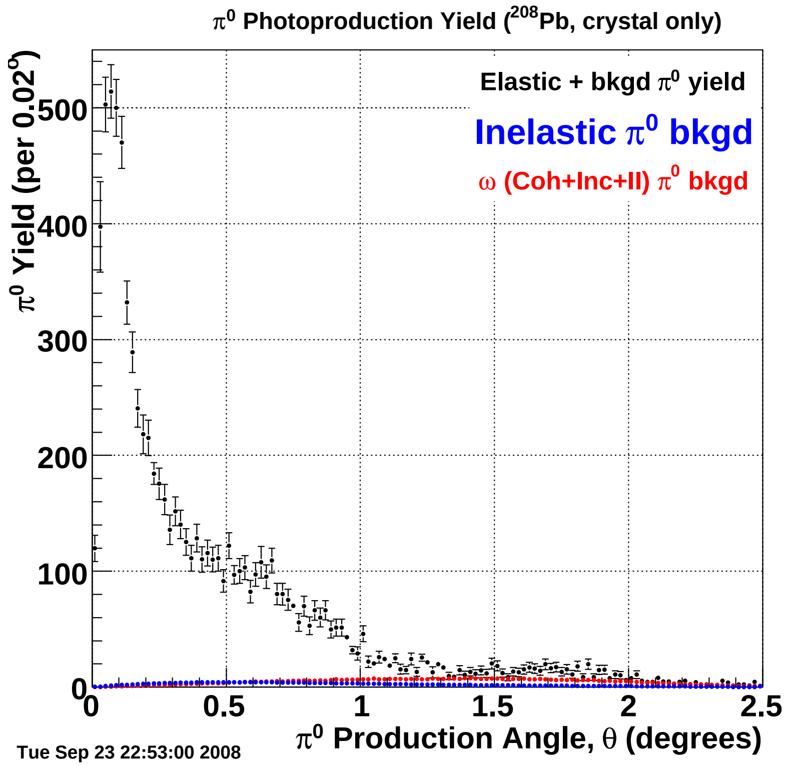
- $d\sigma/d\theta_{\pi^0}$ for $\omega \rightarrow \pi^0\gamma$ taken from T. Rodrigues and implemented
- Convert ω cross section into absolute yield while imposing experimental resolutions using Monte Carlo
- Explicitely subtract contribution from experimental yield



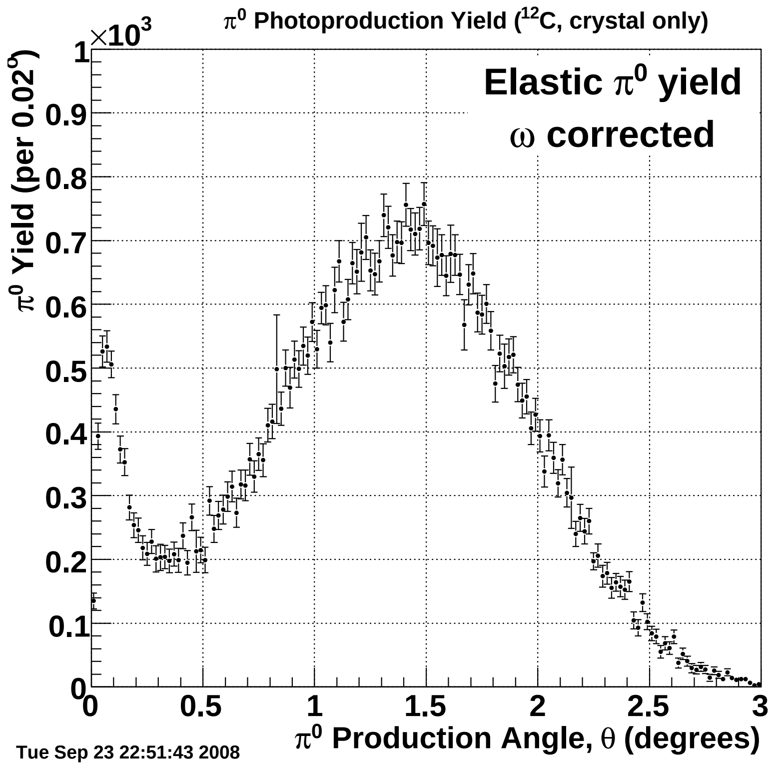


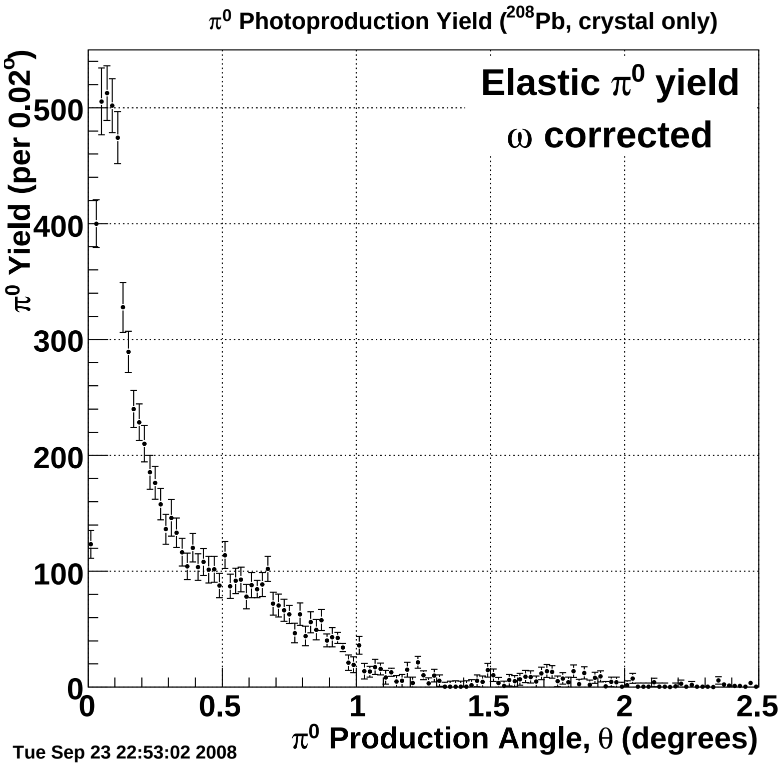
Analysis Details: Yield with backgrounds (^{12}C and ^{208}Pb)





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





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

- Convert Yield to Cross Section.

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

$\rightarrow$ 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%).

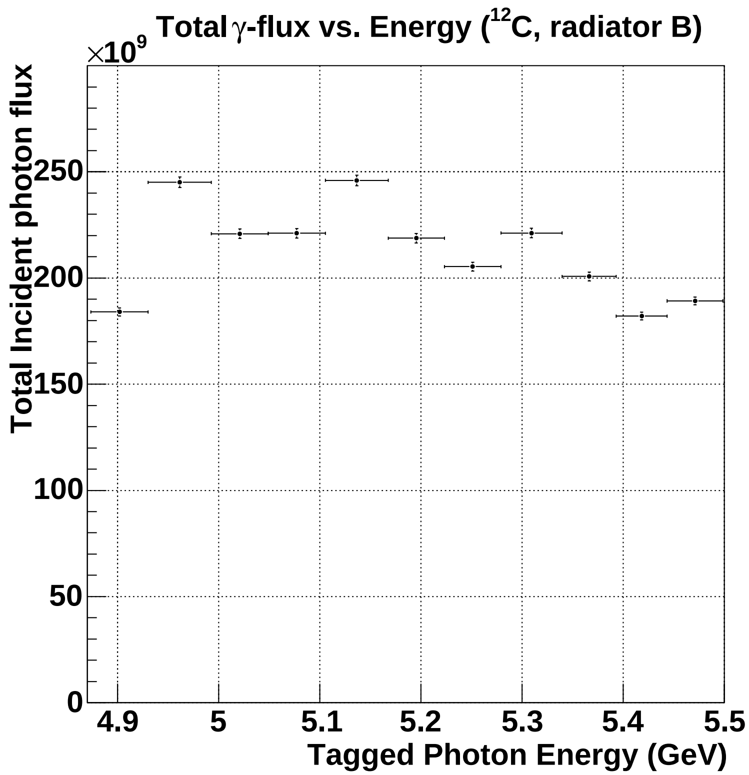
- Fit experimental data with parametrization:

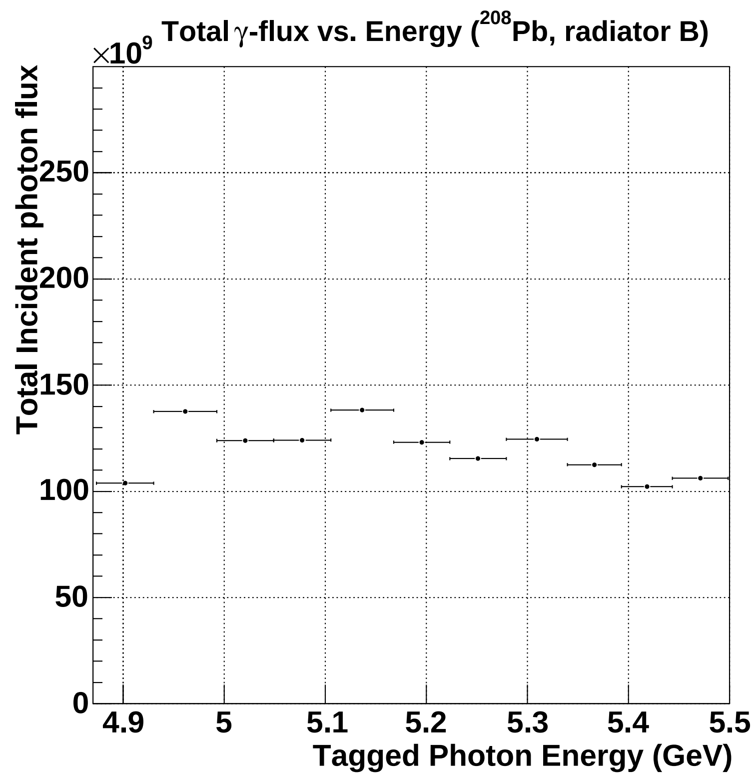
$$\frac{d\sigma_{exp}}{d\theta_{\pi^0}} = \mathrm{b_p}\frac{d\sigma_P}{d\theta} + \mathrm{b_{nc}}\frac{d\sigma_N}{d\theta} + \mathrm{b_b}\frac{d\sigma_I}{d\theta} + 2cos\phi\sqrt{\mathrm{b_p b_{nc}}\frac{d\sigma_P}{d\theta}\frac{d\sigma_C}{d\theta}} \qquad (8)$$

$\rightarrow$ 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.

Photon Flux

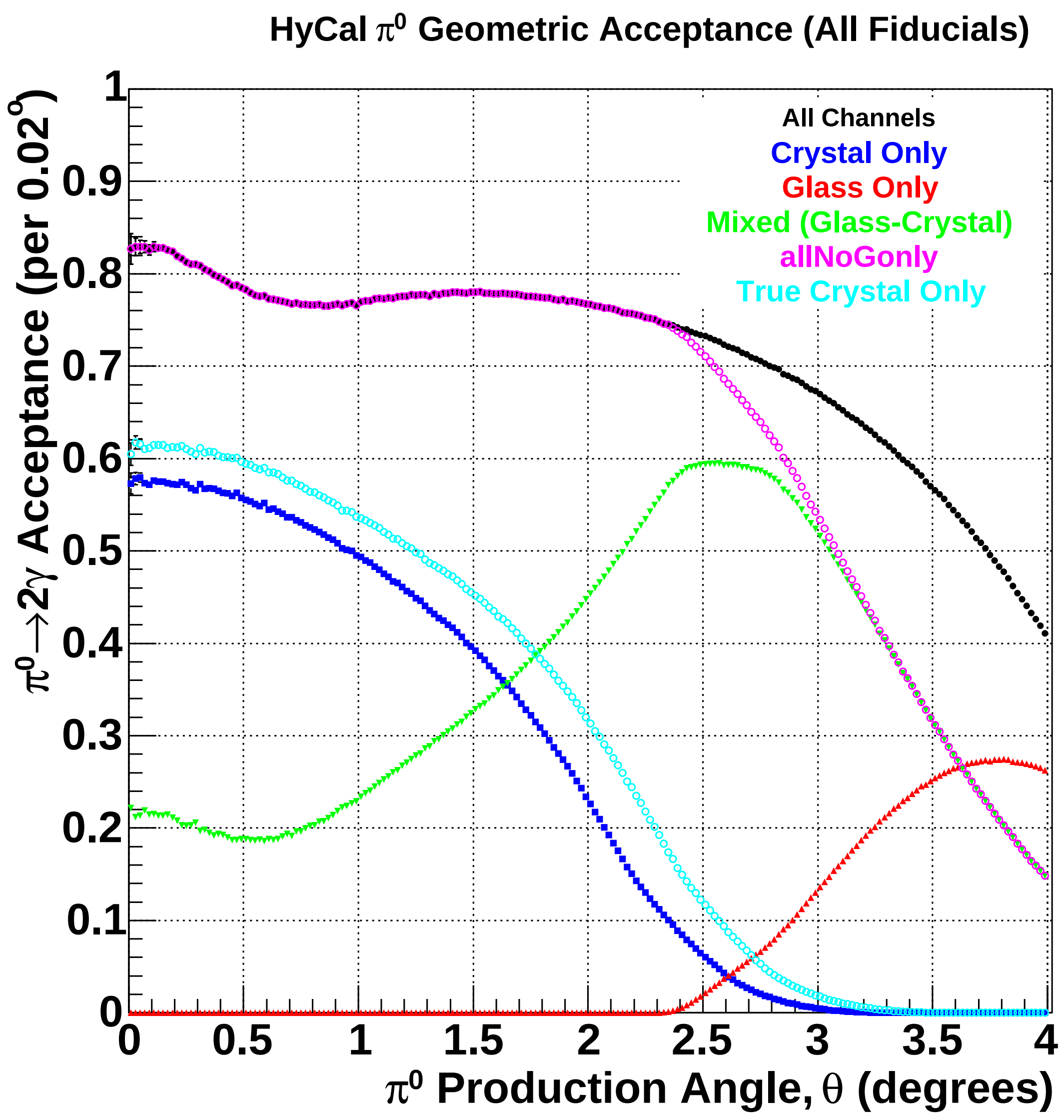




Flux for ^{12}C: 2.33×10^{12} γ's

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.

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

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

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

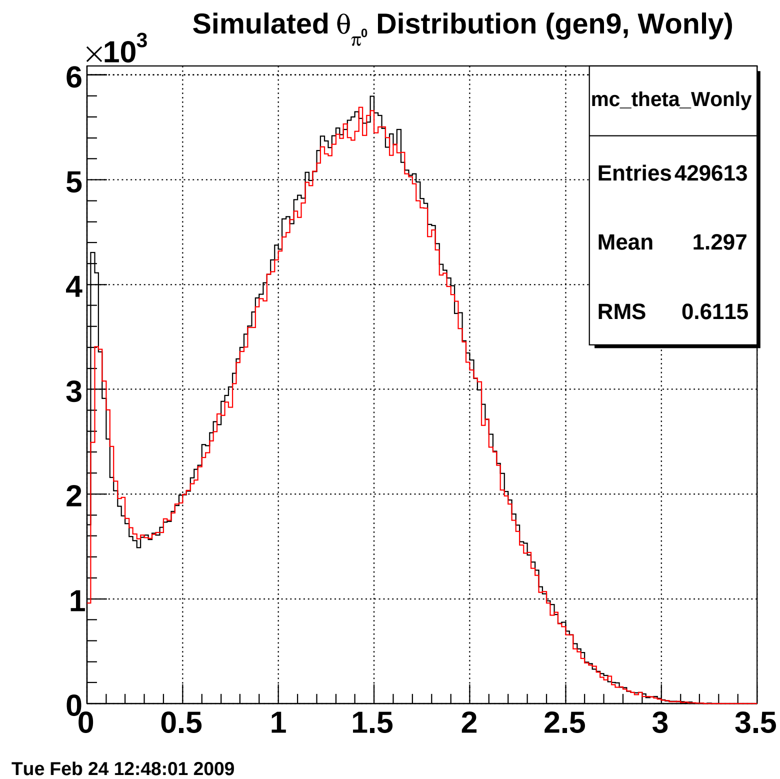
$\rightarrow$ Calculate theory input shapes (cross sections) energy-weighted according to experimental flux.

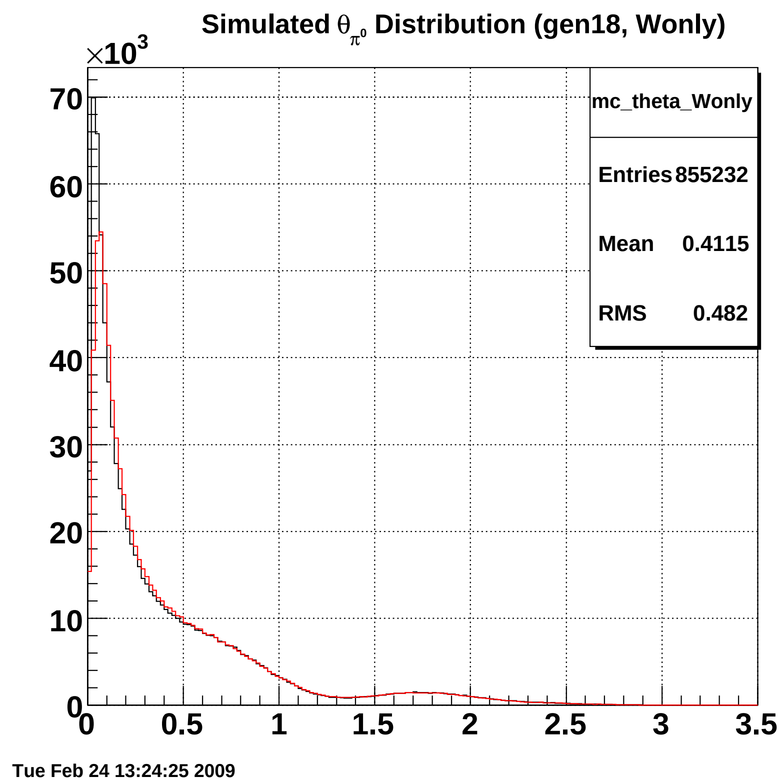
$\rightarrow$ Create π^0 event generator based on above cross sections and run through Primsim Monte Carlo.

$\rightarrow$ 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

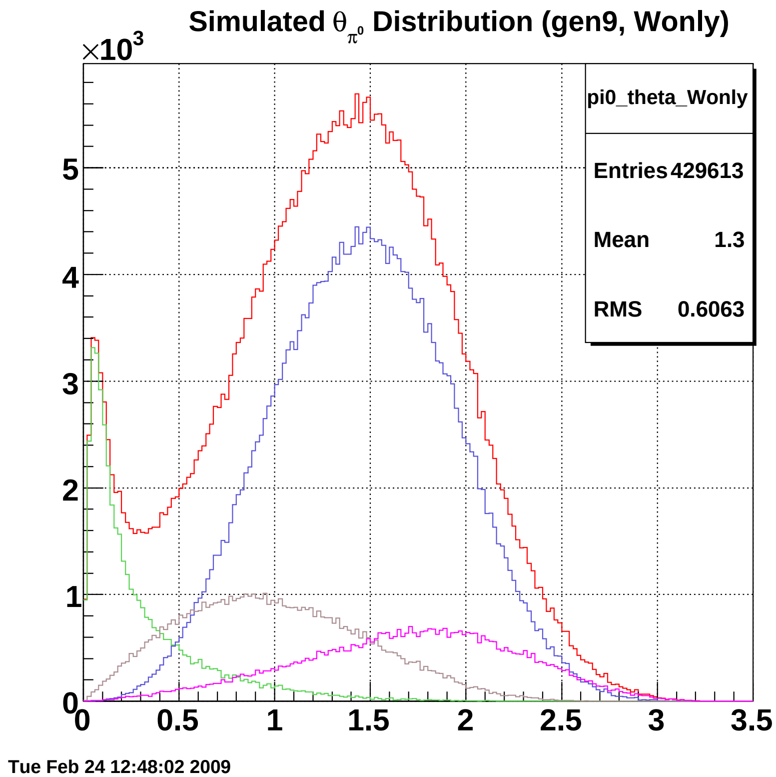


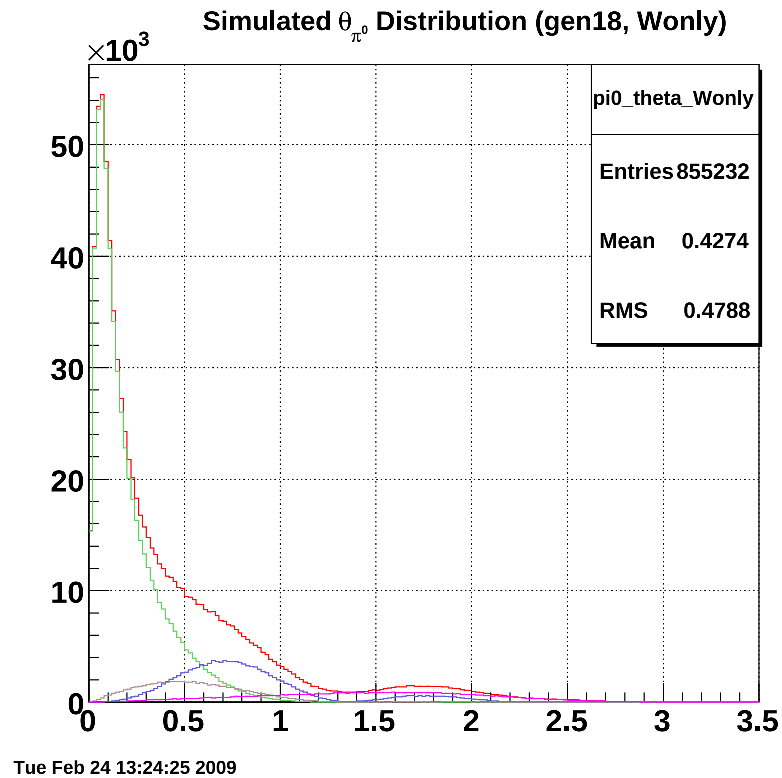


^{12}C: —θ_{π^0} Thrown —θ_{π^0} Detected

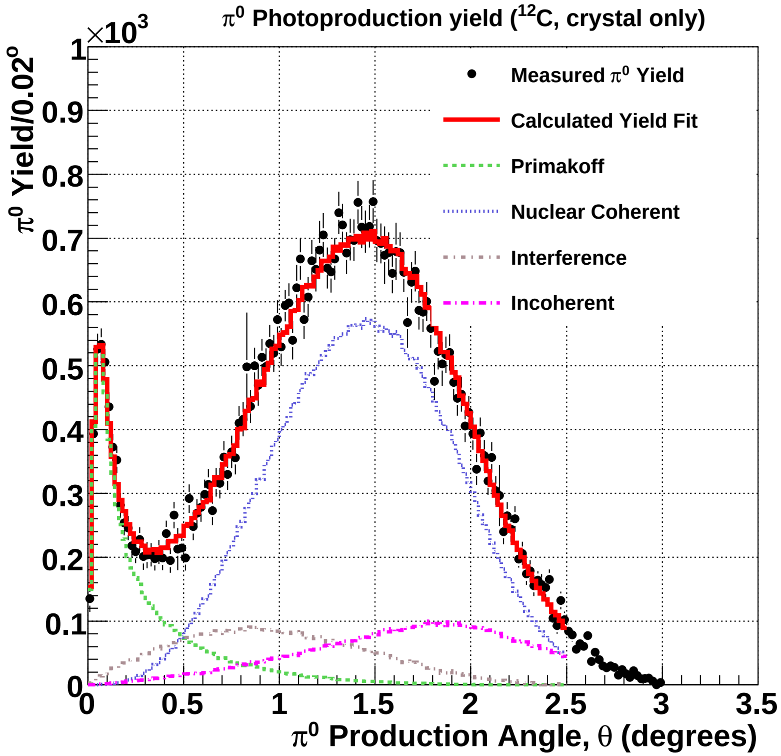
^{208}Pb: —θ_{π^0} Thrown —θ_{π^0} Detected

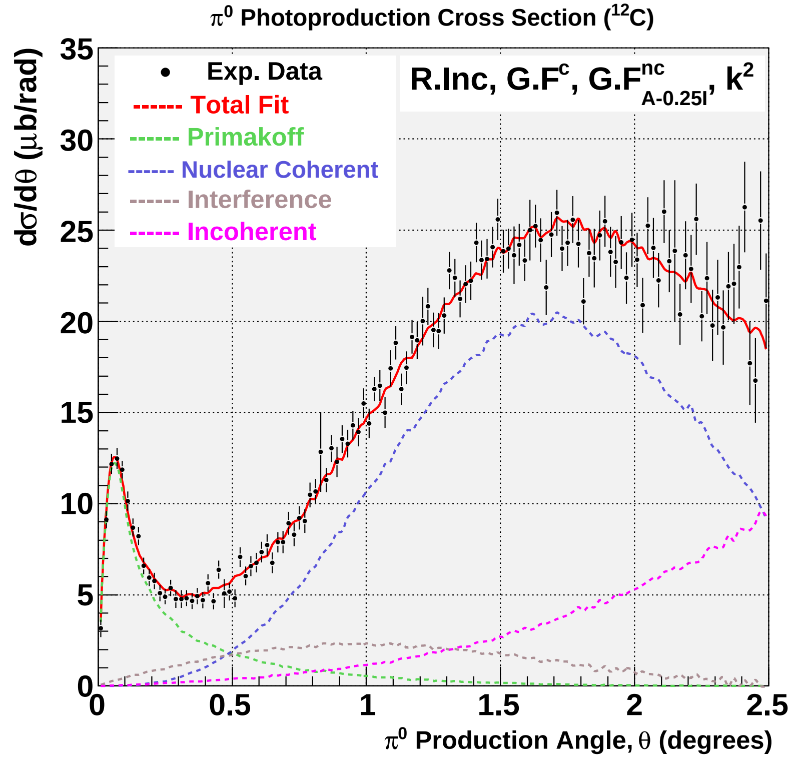
MC Shape Generation: Example Fit Input Shapes (smeared)



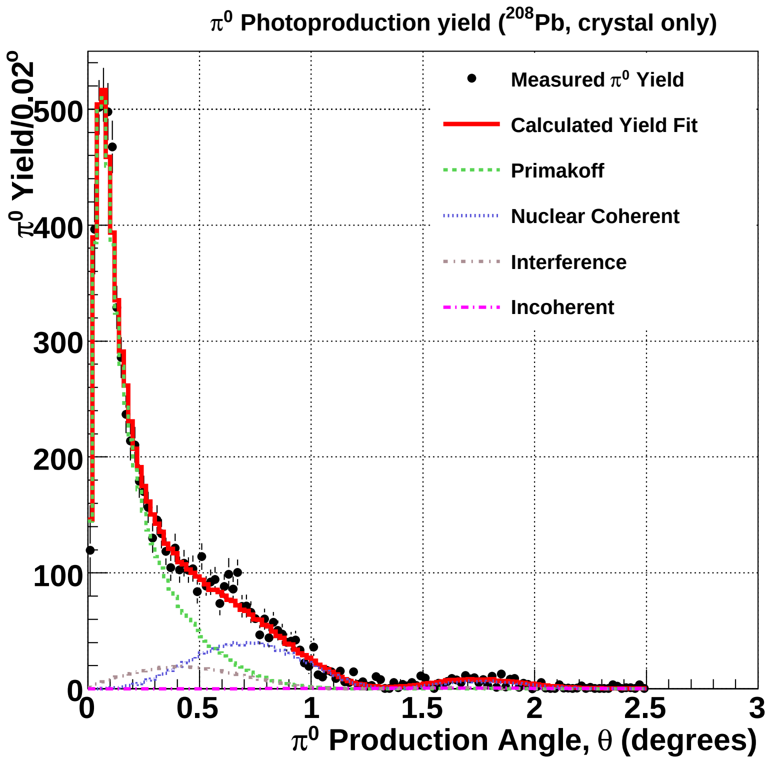


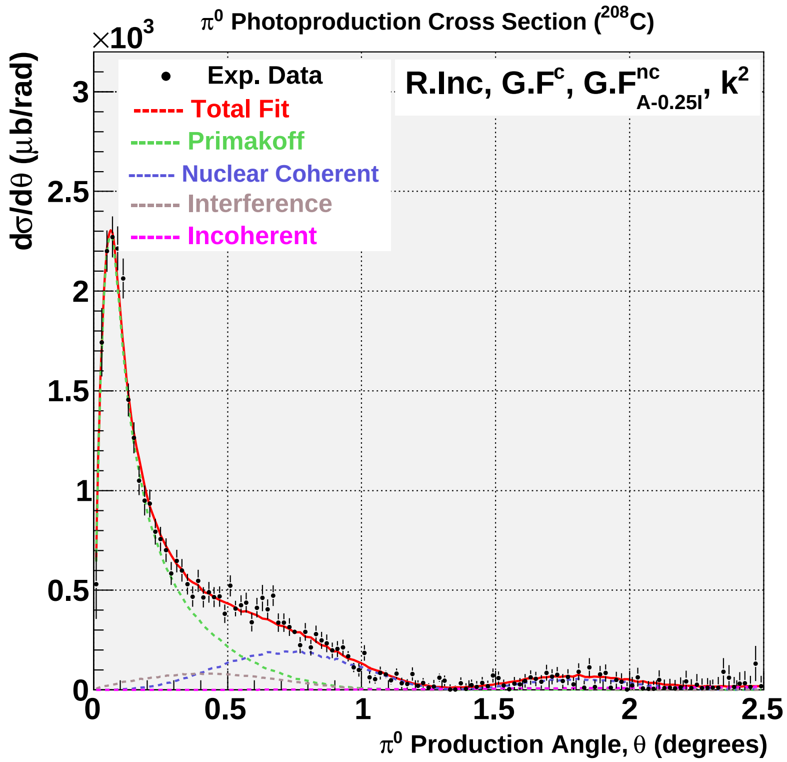
Yield Fit and Cross Section for ^{12}C





Yield Fit and Cross Section for ^{208}Pb

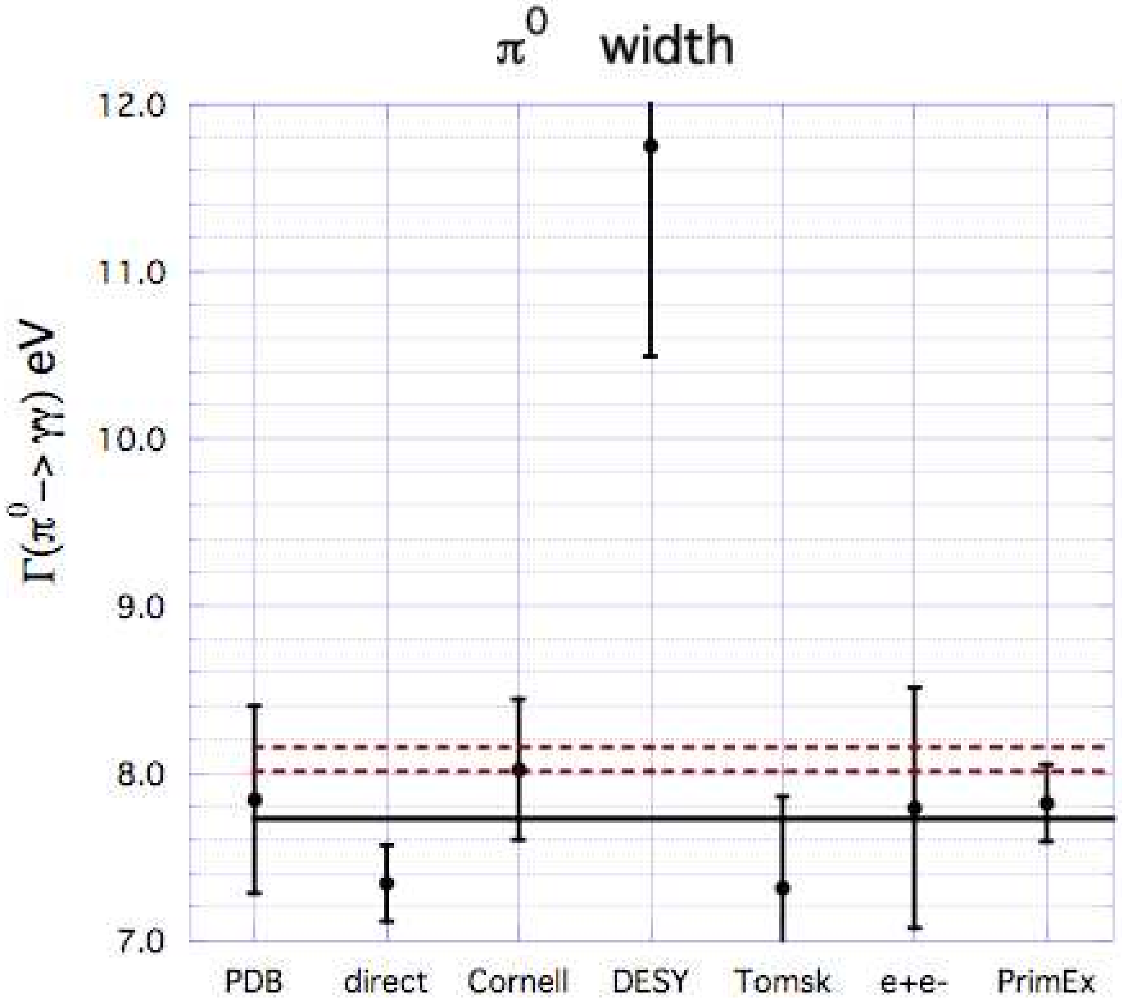




$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Systematic Errors

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 $4.9 \leq E_\gamma^{tagged} \leq 5.5$ 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 ∼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 ±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.
- Continued work on cross-checking independent group results for final publication.

Independent Group Results