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

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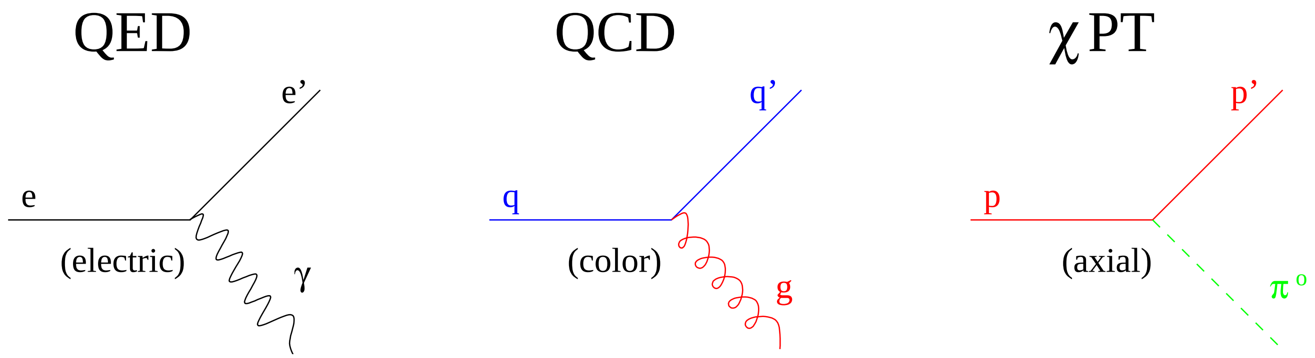
Outline

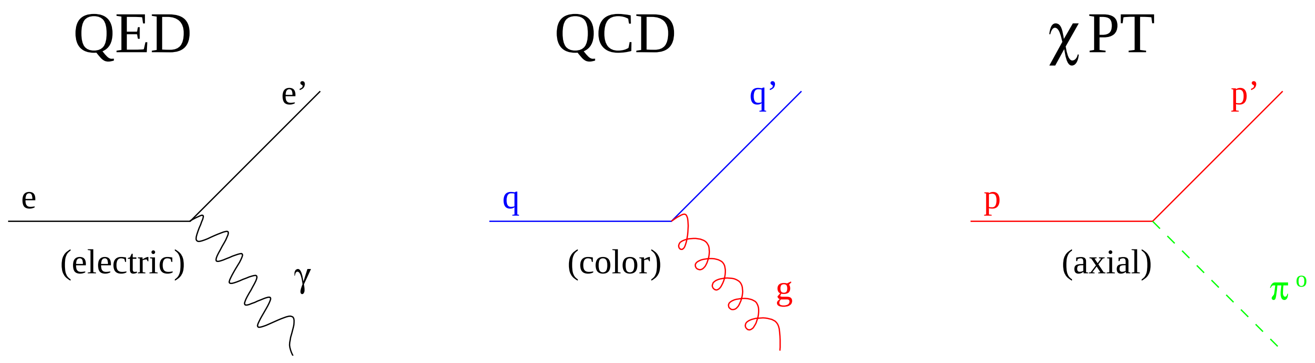
- Introduction and Physics Motivation
- Experimental Overview
- Calibration Reactions
    - Pair Production
    - Compton Scattering
- π^0 Analysis Details
- Final $\Gamma_{\pi^0\rightarrow\gamma\gamma}$ Result
- Summary and Outlook

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: $J^{PC} \equiv 0^{-+}$

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

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

→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

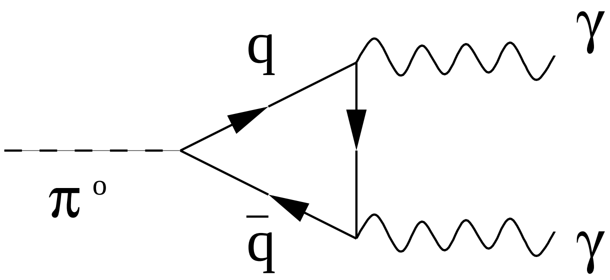
- Decay width $\Gamma = \hbar/\tau$ follows from the energy-time uncertainty principle $\Delta E \Delta t \geqq \hbar/2$
- The idea is this: If you observe a narrow mass peak (small energy uncertainty, ΔE), then its lifetime (Δt) can be relatively long, and vice versa
- So very short lifetimes can be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



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

→ $\Gamma_{\pi^0\rightarrow\gamma\gamma} = (m_\pi^3/64\pi)A^2_{\pi\gamma\gamma} = 7.725\mathrm{eV} \pm 0.5\%$

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

→ $c\tau_{\pi^0} \sim 25$ 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?

→ Define a multiplicative quantum number “natural parity” (P) = 1 for S, V, ... particles. P = -1 for PS, PV, ...

→ 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

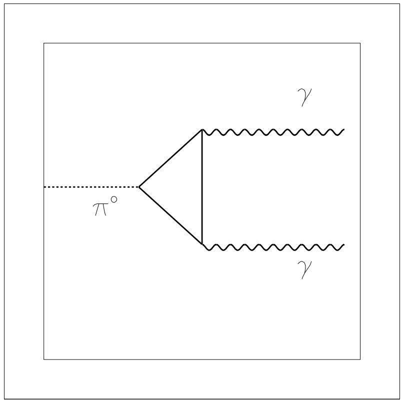
- All anomalous reactions are governed by the Wess-Zumino Lagrangian in χPT which permits transitions that violate certain symmetries.
- In the Chiral limit, the absolute rate of these reactions are predicted by QCD

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:

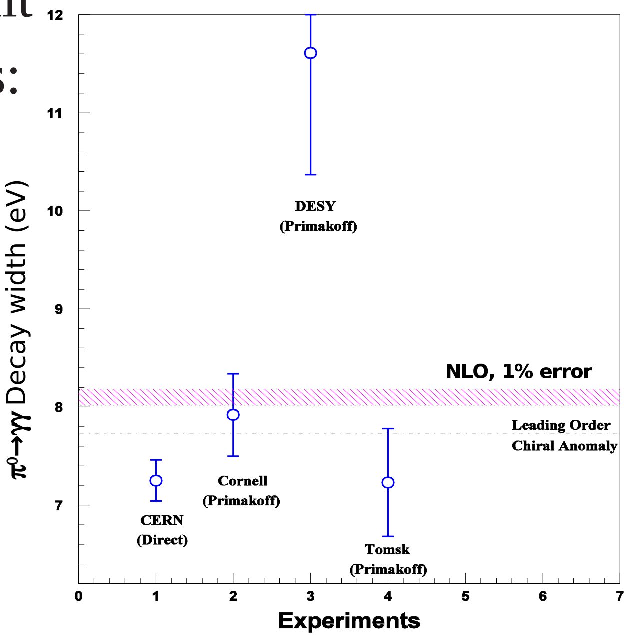
$$\Gamma_{\pi^0\to\gamma\gamma} = \frac{\alpha^2 m_\pi^3}{64\pi^3 F_\pi^2} = 7.725 \pm 0.044\ \text{eV} \tag{1}$$

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:
  - $\rightarrow$ 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 $8.10\ \mathrm{eV} \pm 1\%$
  - $\rightarrow$ 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!

○ 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:

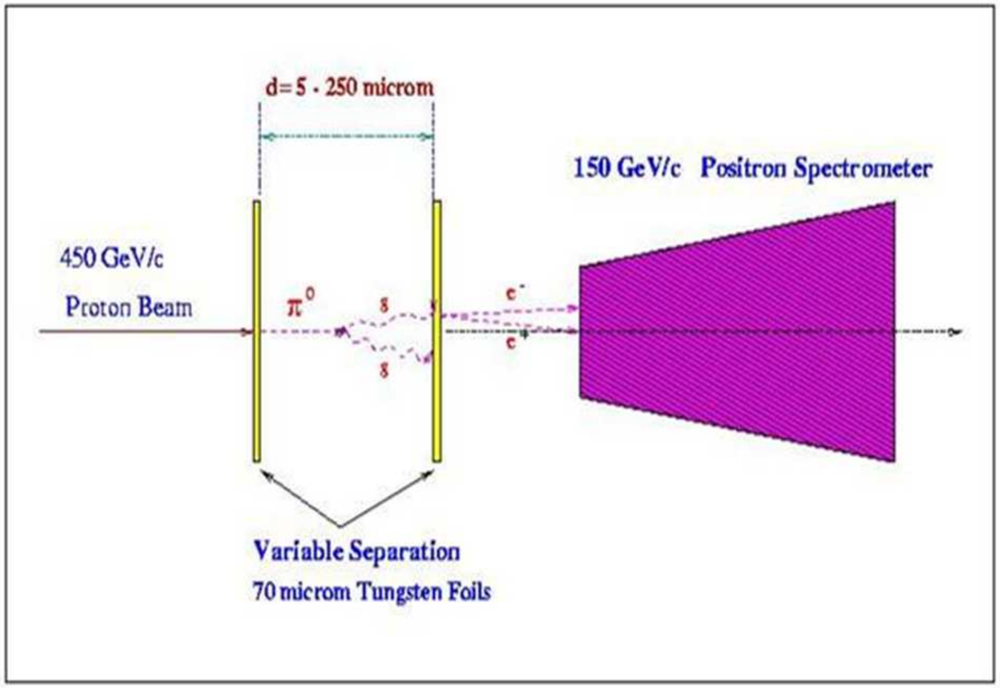
Used 450GeV protons

→ Result:

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

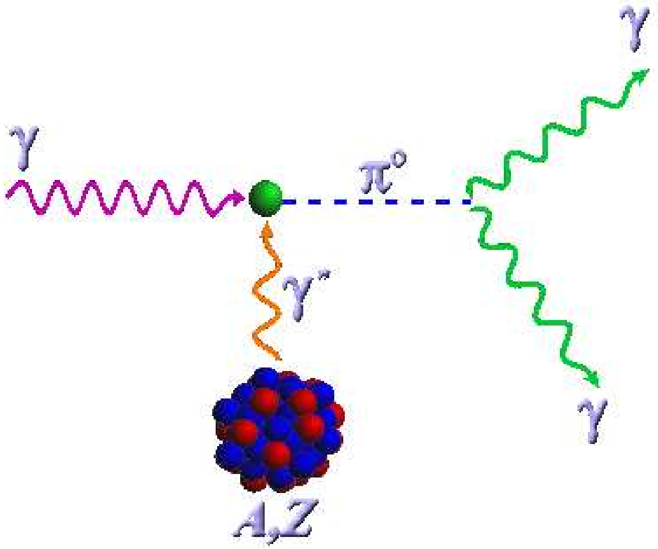
→ Dominant syst. error:

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.

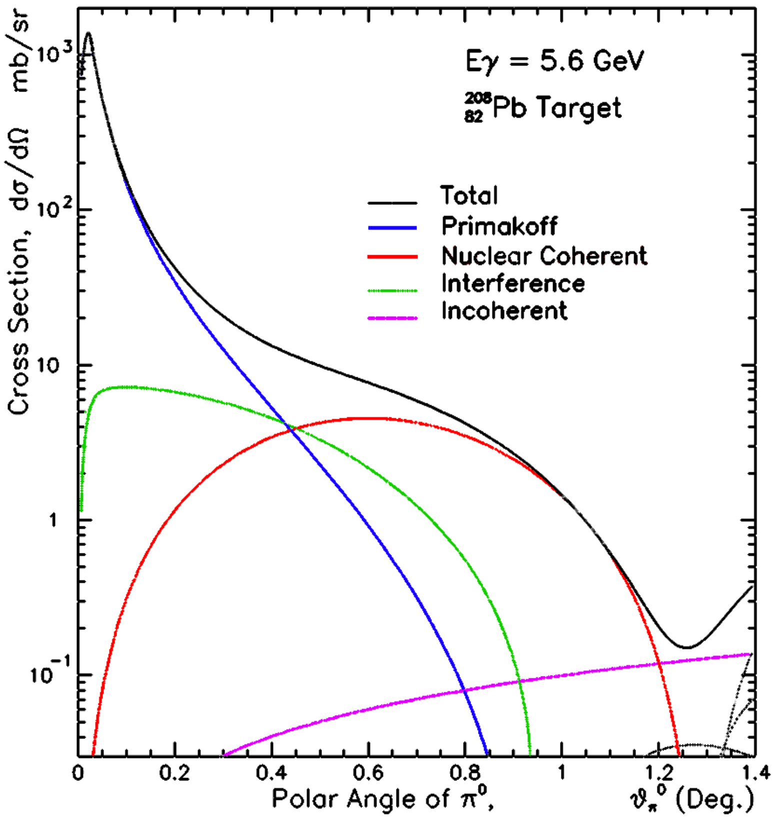


$$\frac{d\sigma_P}{d\Omega} = \Gamma_{(\pi^0\rightarrow\gamma\gamma)} \frac{8\alpha_{em}Z^2}{m^3}\frac{\beta^3E^4}{Q^4}|\tilde{F}_{em}(Q)|^2 sin^2\theta_\pi \qquad (3)$$

Full Cross Section Components

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

Primakoff Nucl.Coherent Incoherent Interference



Primakoff:

Proportional to Z^2,

peaked at $\theta_{\pi^0} = m_{\pi^0}^2/2E_\gamma^2$

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

PrimEx Collaboration

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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),
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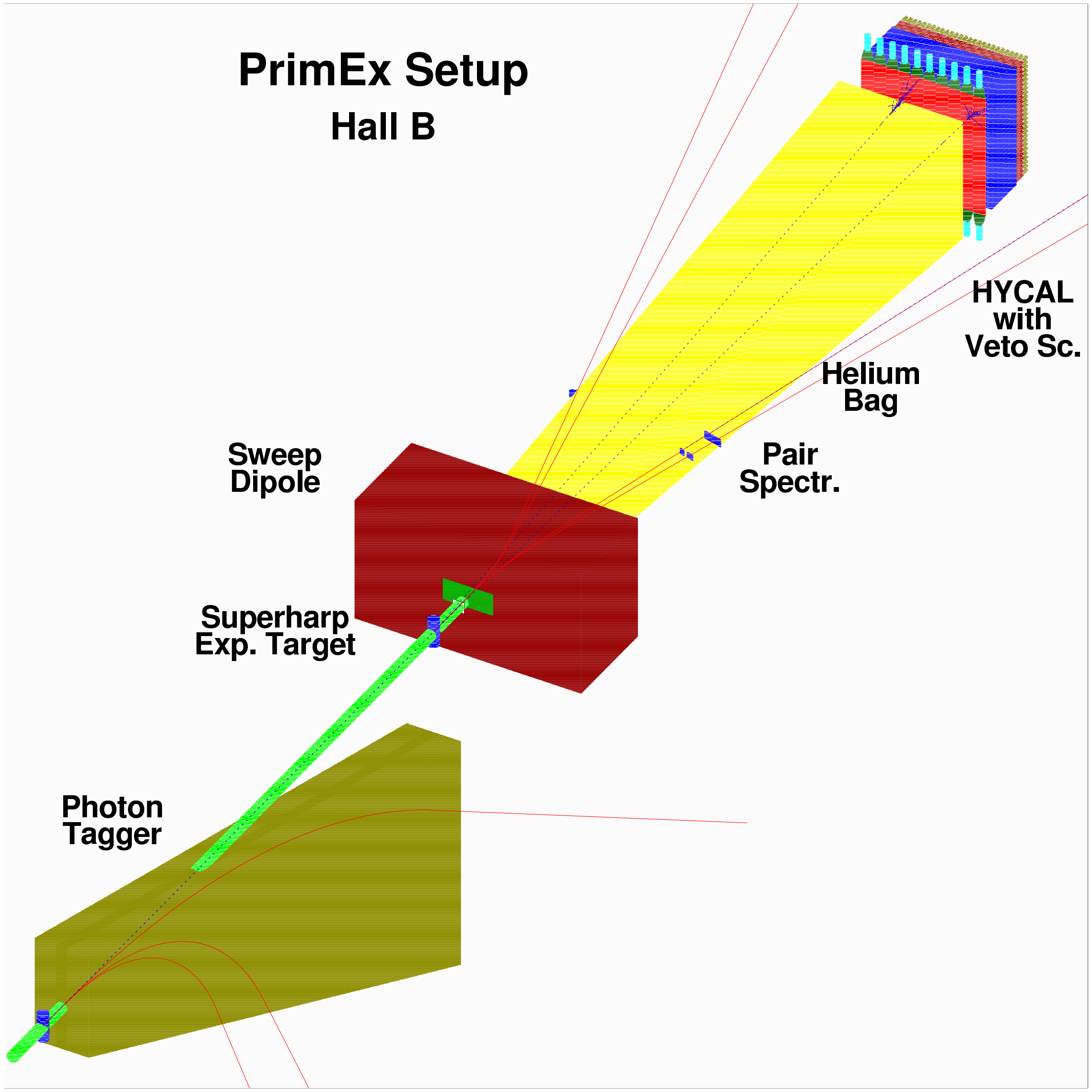
(a) Alikhanov Institute for Theoretical and Experimental Physics, (b) Arizona State University,
(c) Catholic University, (d) Hampton University, (e) Idaho State University, (f) Jefferson Lab,
(g) University of Kentucky, (h) Kharkov Institute of Physics and Technology,
(i) University of Massachusetts, (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

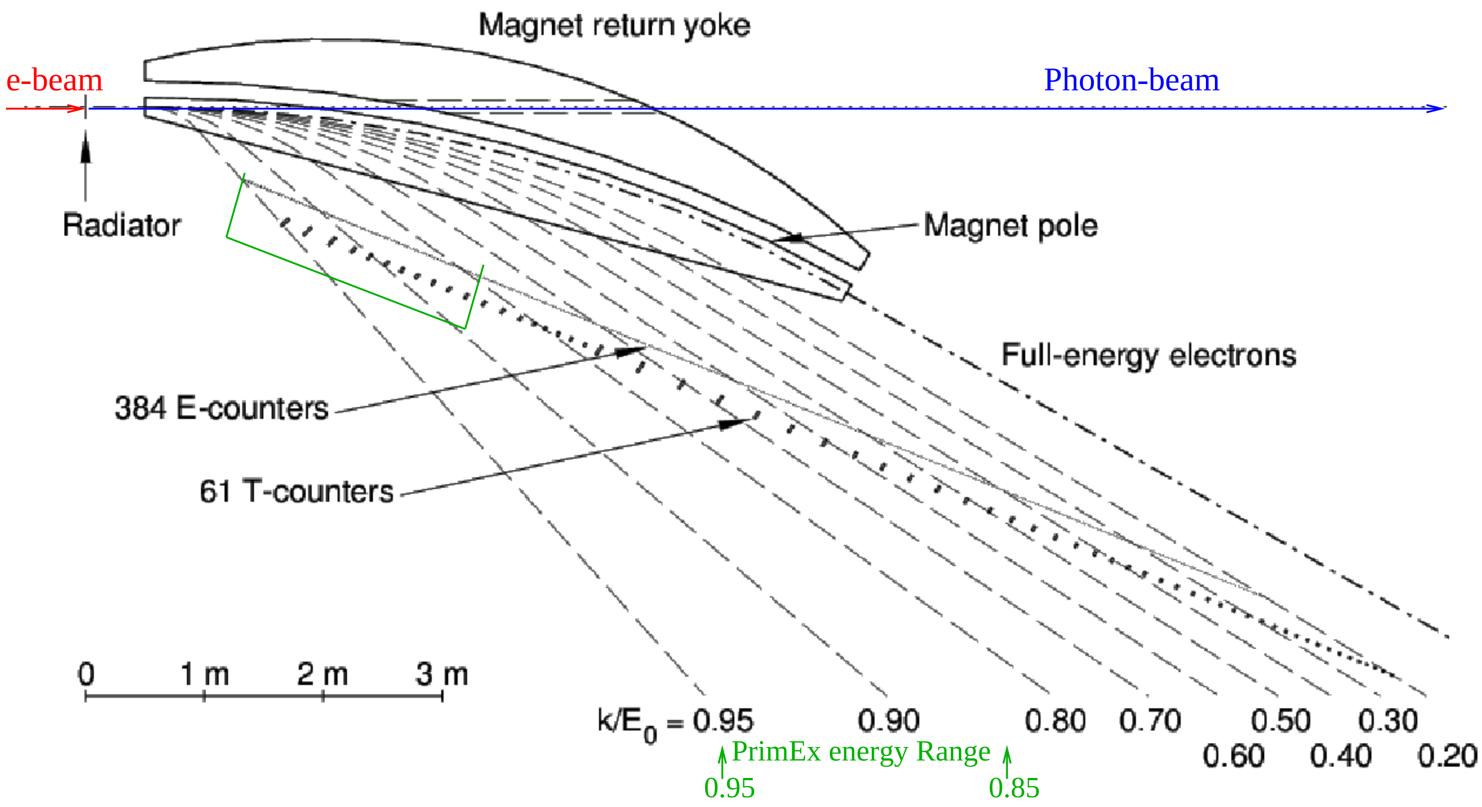
- Conducted at Jefferson Lab, Fall 2004
- Used 5.75 GeV continuous e^- beam and Hall B γ-tagging facility
- Tagged photons incident on 5%X_0 targets: ^{12}C and ^{208}Pb
- New PrimEx/Hall B calorimeter (HyCal), upstream of CLAS, designed to detect π^0 decay γ's
- Measured 3 physical processes (absolute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



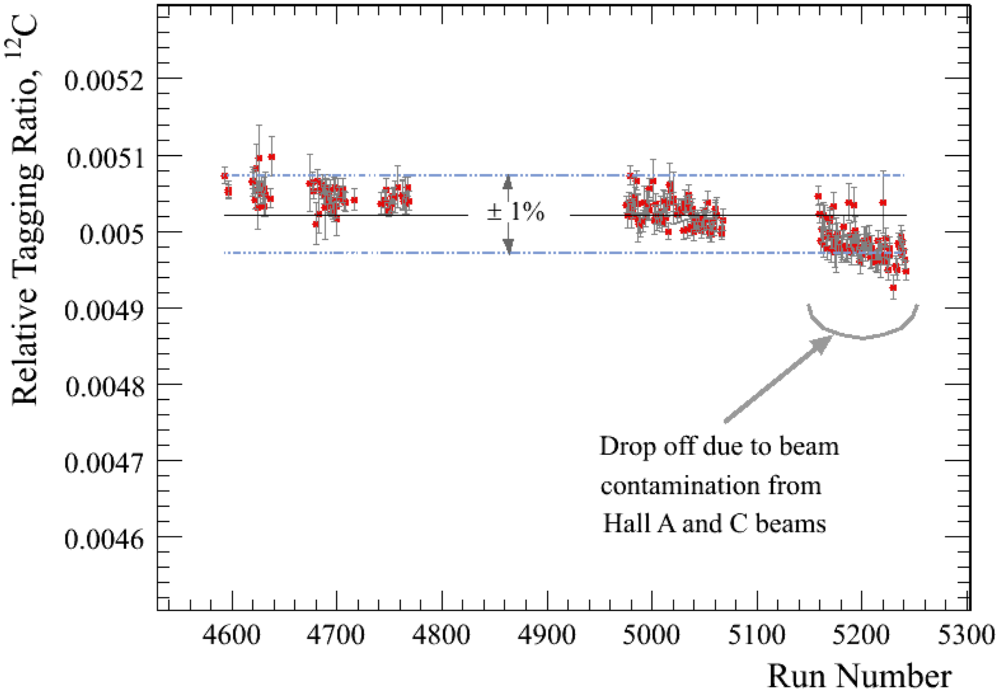
Hall B Photon Tagger

- 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.



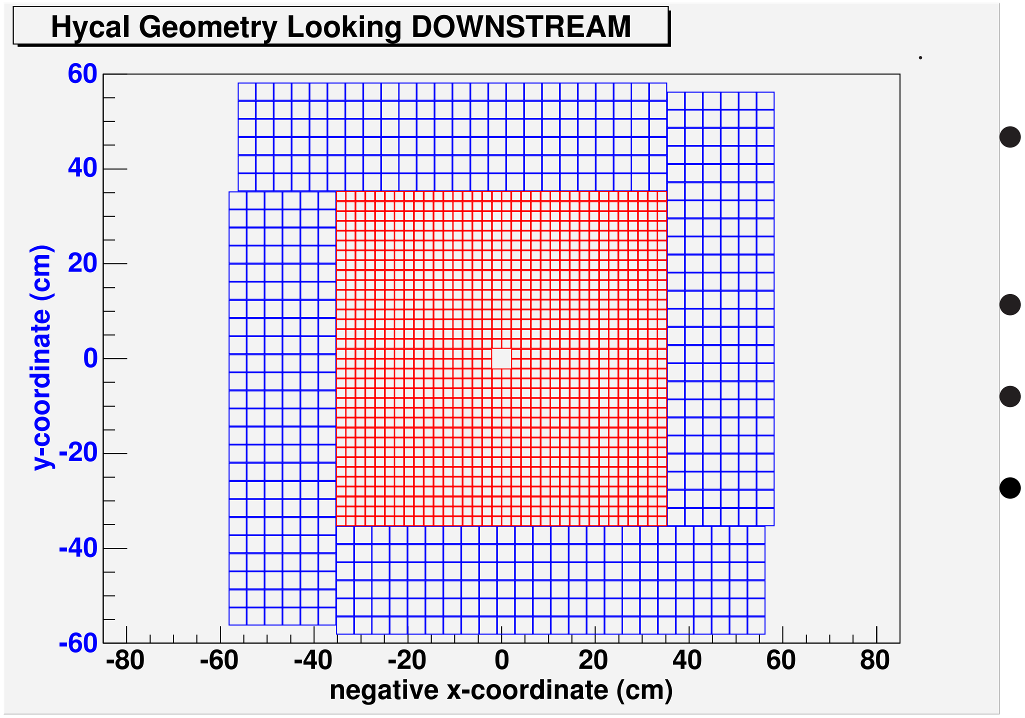
Photon Flux Control

- 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.



Drop off due to beam contamination from Hall A and C beams

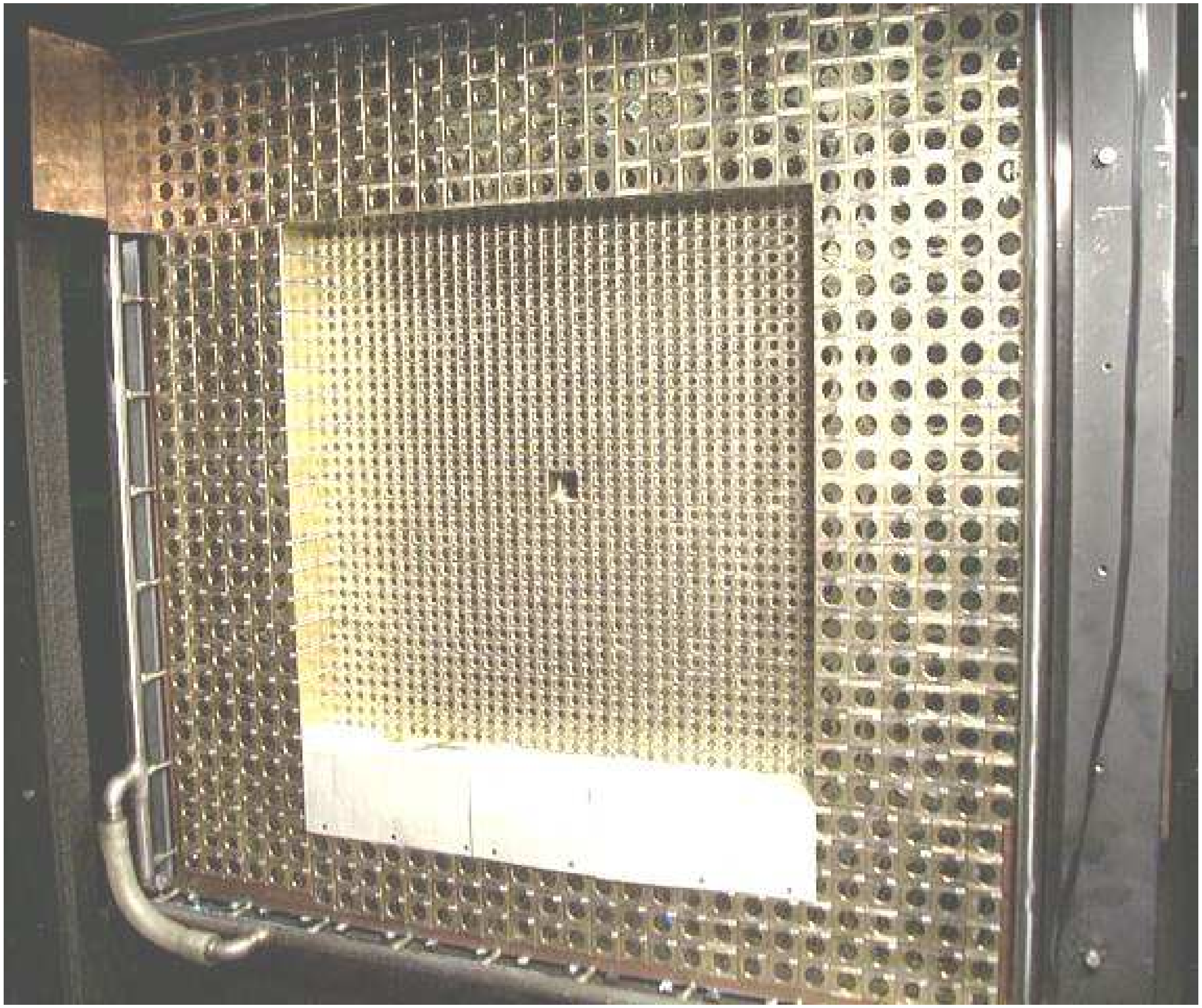
PrimEx Hybrid Calorimeter – “HyCal”



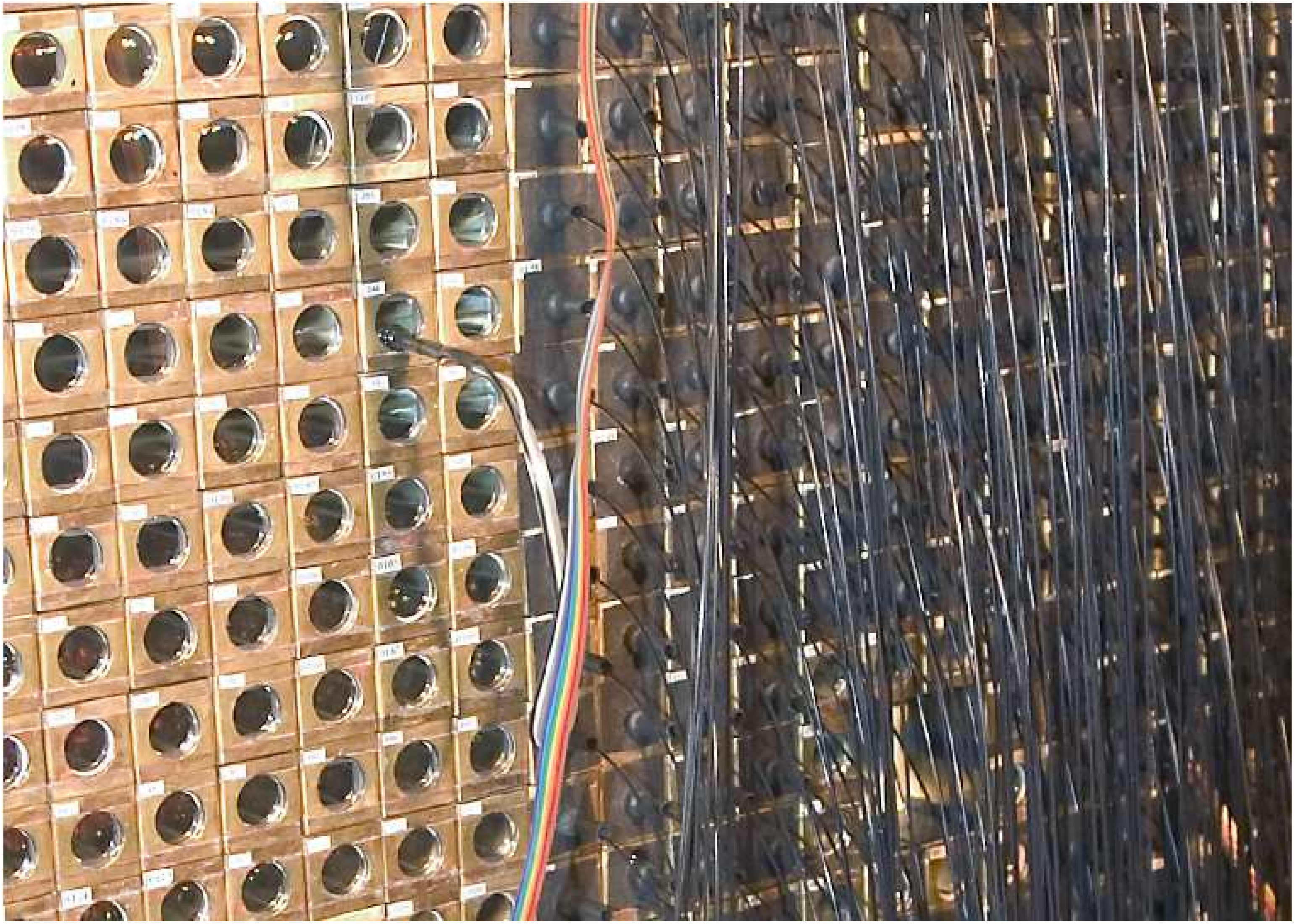
- Optimal performance/cost design
- 1.2 m ×1.2 m, 1728 channels
- 576 Lead-glass (outer layers)
- 1152 Lead-Tungstenate crystal (inner layers)

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

HyCal Assembly – Support Frame and Cooling System

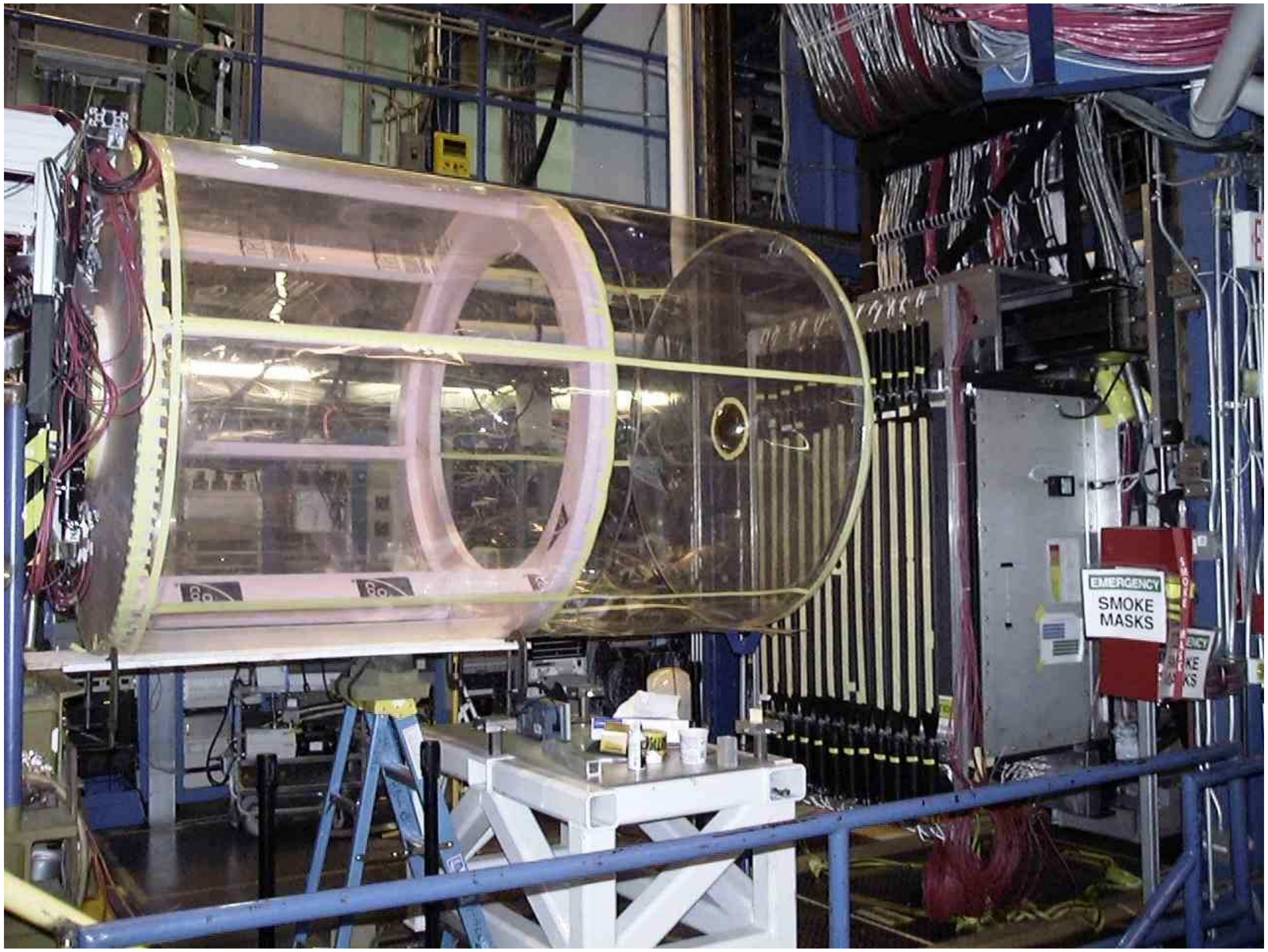


HyCal Assembly – Light Monitoring System

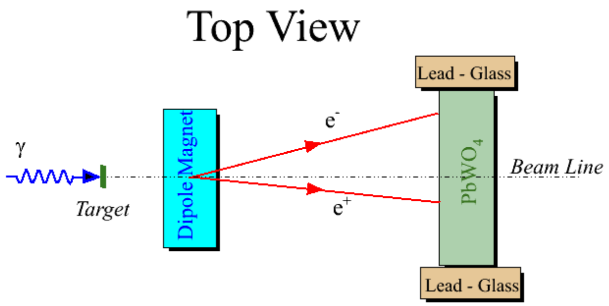


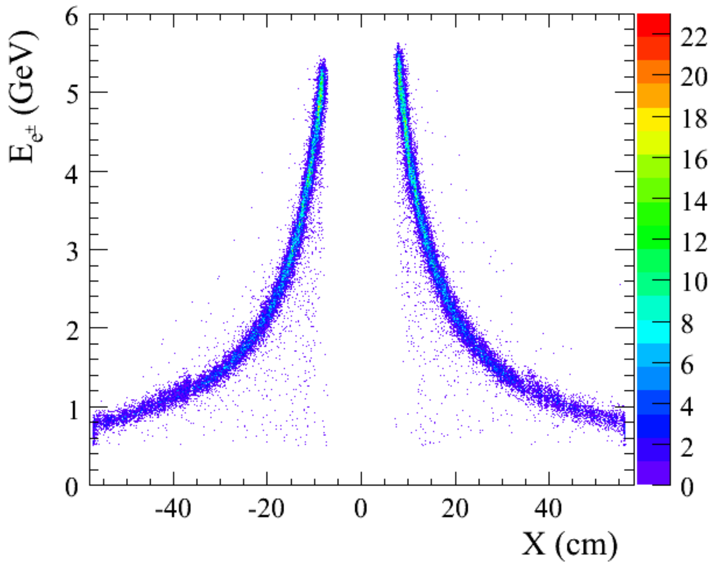
HyCal Calibration –”Snake Scans”

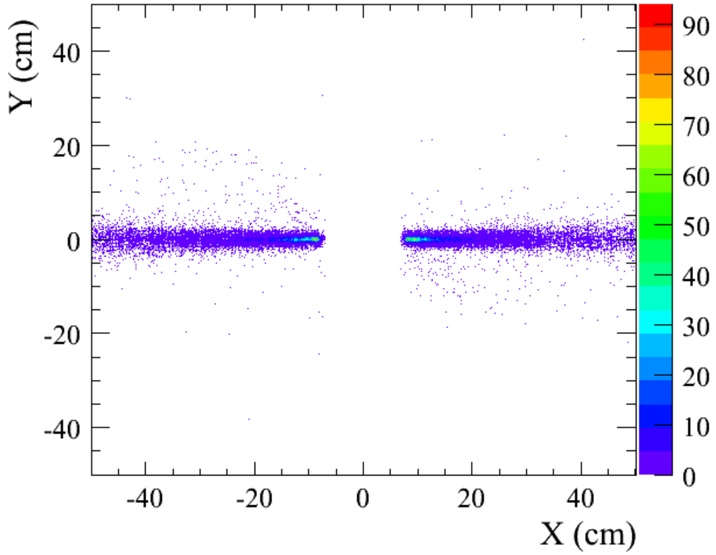
- Full x,y motion allowed each ch. to be scanned through tagged γ beam.
- Performed at both the beginning and end of the experiment.



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



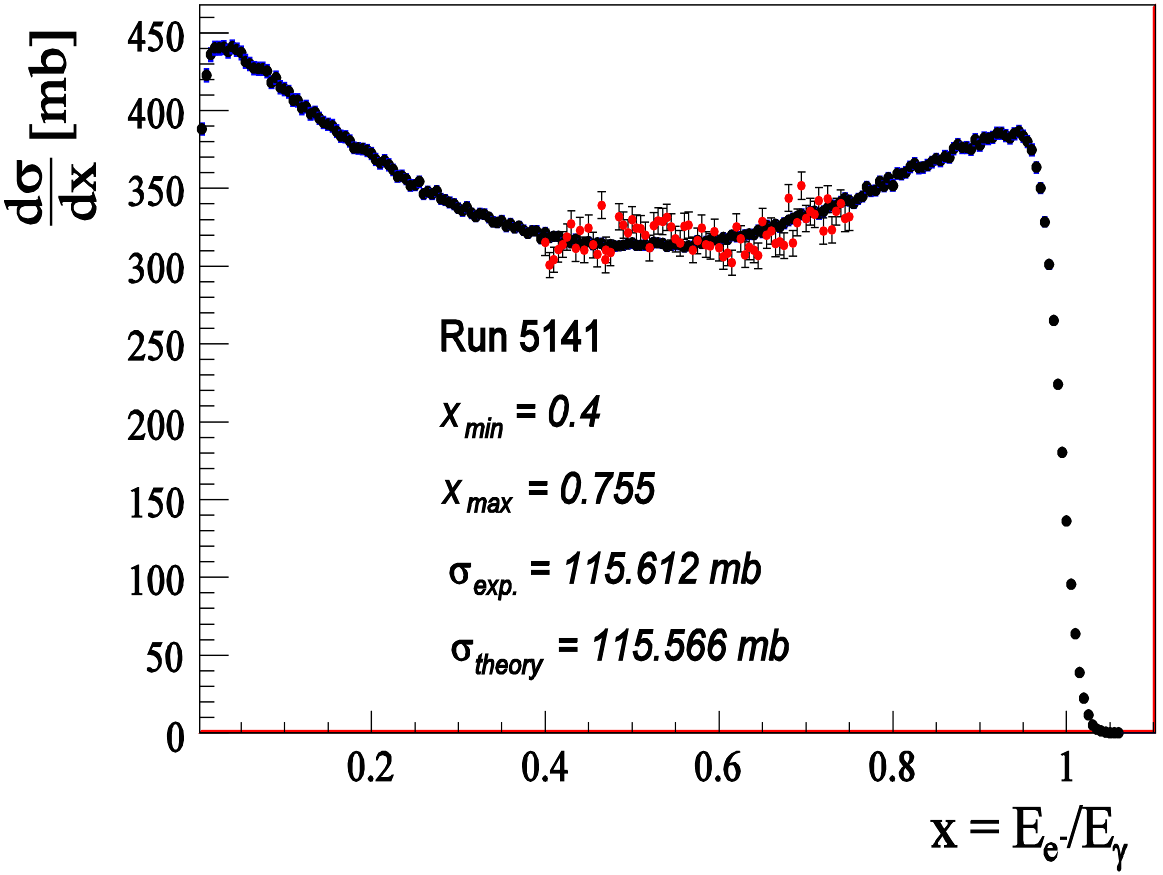




Calculation of Pair Production Cross Section at PrimEx Kinematics

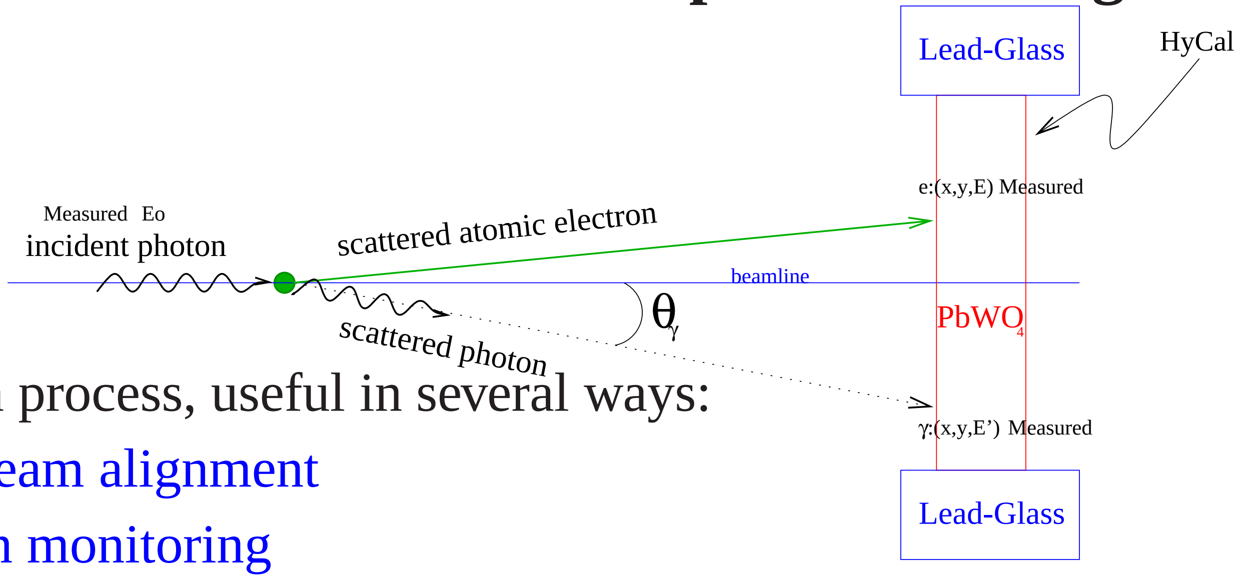
- Bethe-Heitler mechanism of pair production on the nucleus with screening effects due to atomic electrons and Coulomb distortion
- Pair production off atomic electrons, considering excitation of all atomic states and correlation effects due to the presence of other electrons and the nucleus
- Radiative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



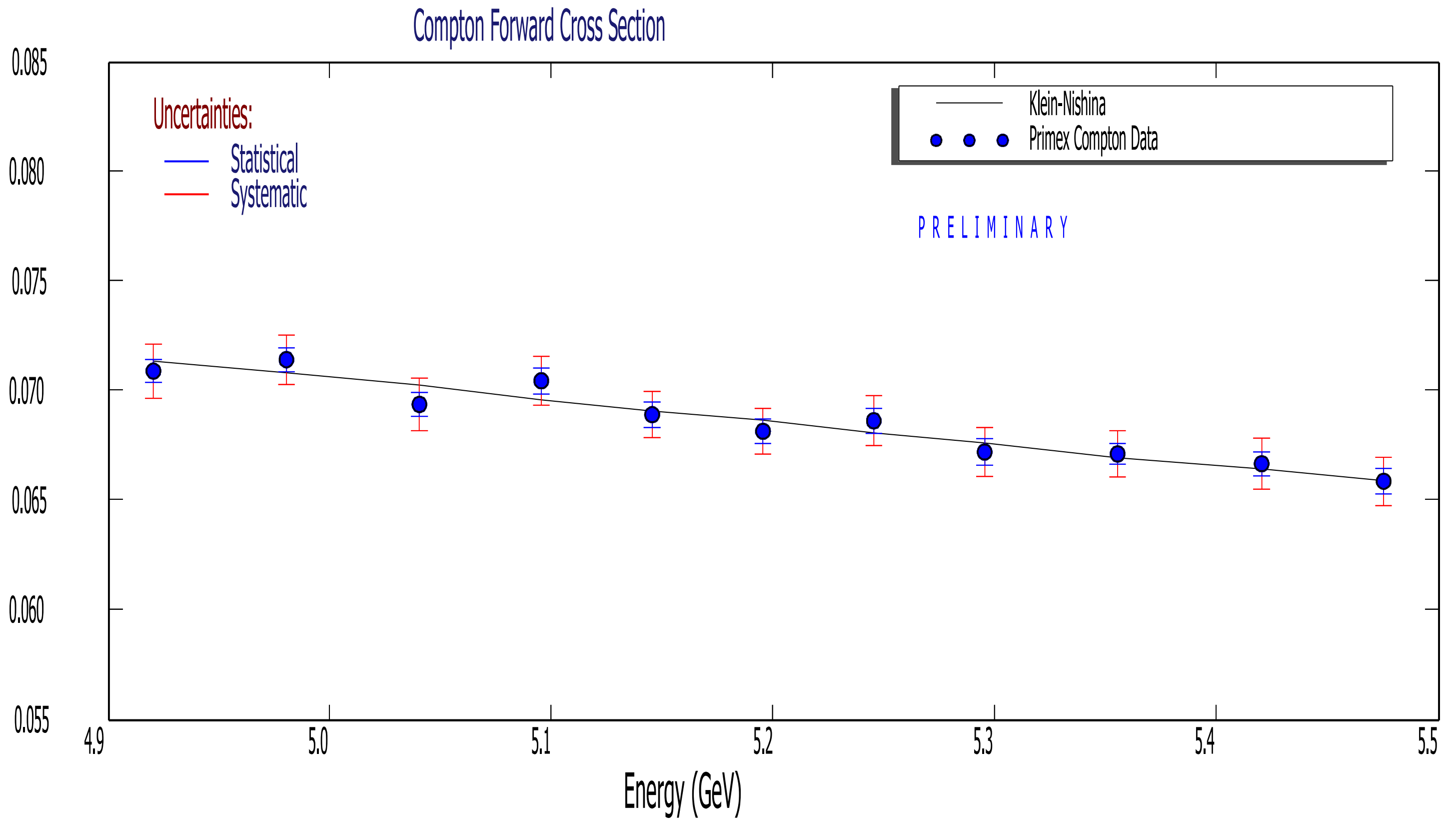
- Agreement with theory at ∼ 1.0% level

Calibration Reactions: Compton Scattering



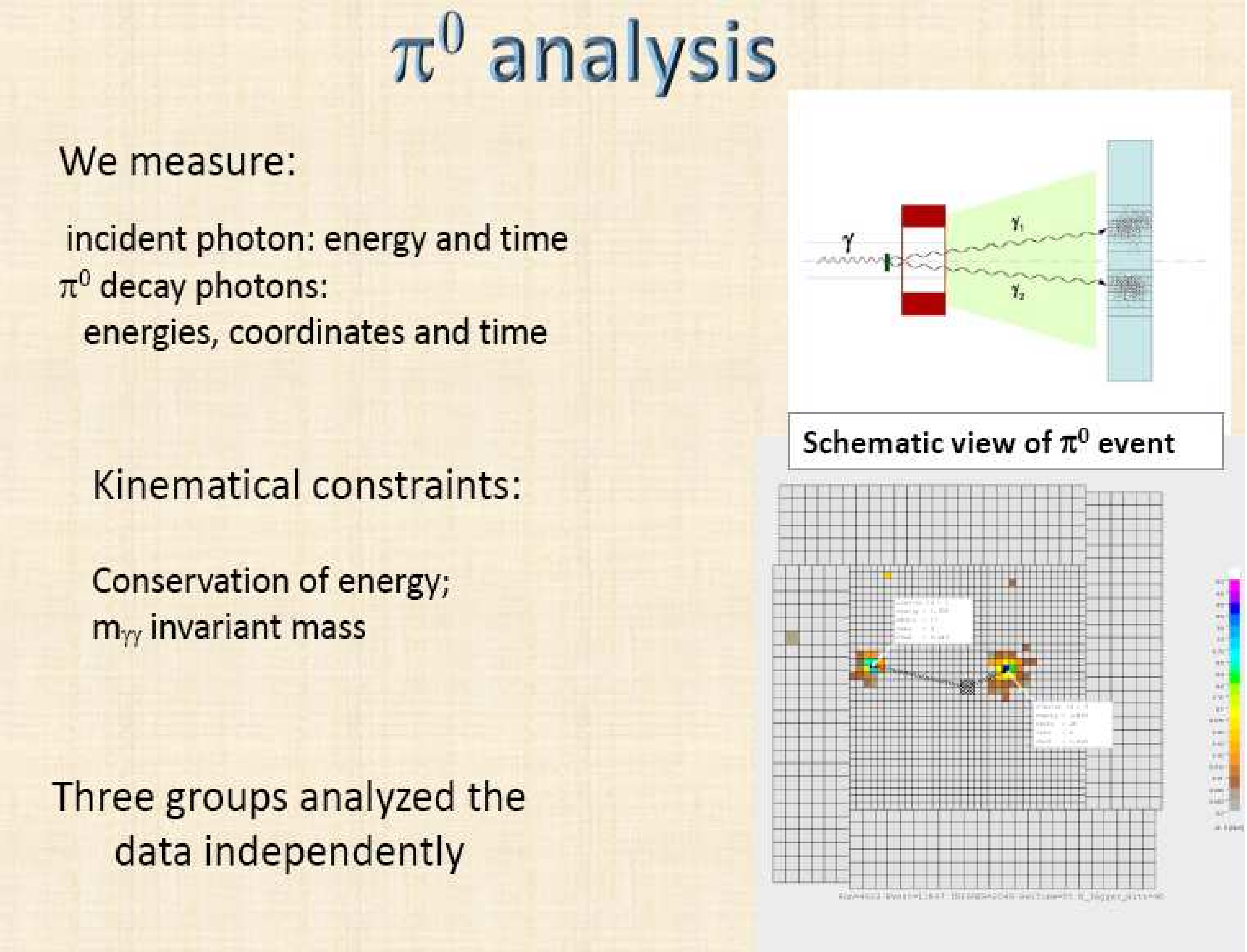
- A well known process, useful in several ways:
  - → Detector/beam alignment
  - → HyCal gain monitoring
  - → Overall check of PrimEx setup to measure absolute cross sections
    - ○ Dedicated ”Double-Arm” Compton Runs:
      - → Performed on a weekly basis, $B_{PS} = 0$, $I_{beam} \sim 5 - 10$ nA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

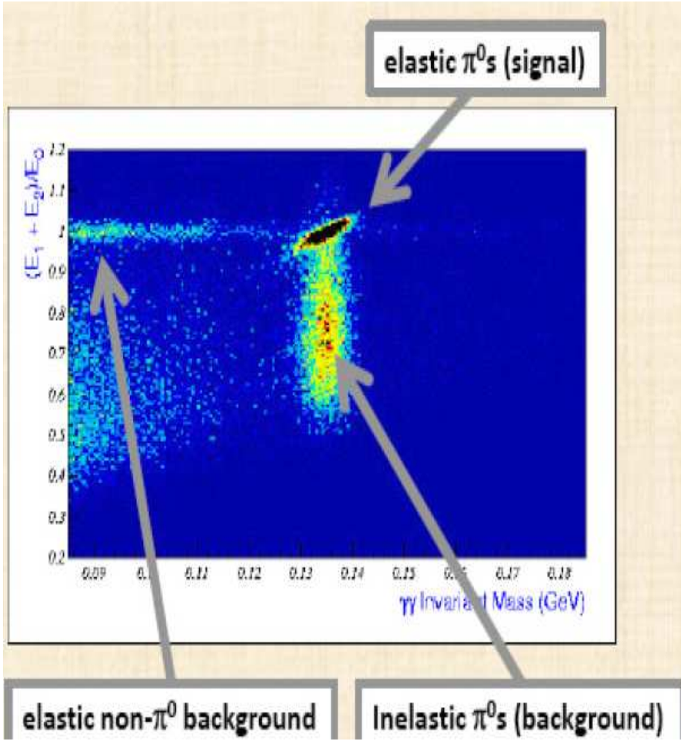
incident photon: energy and time
π^0 decay photons:
energies, coordinates and time

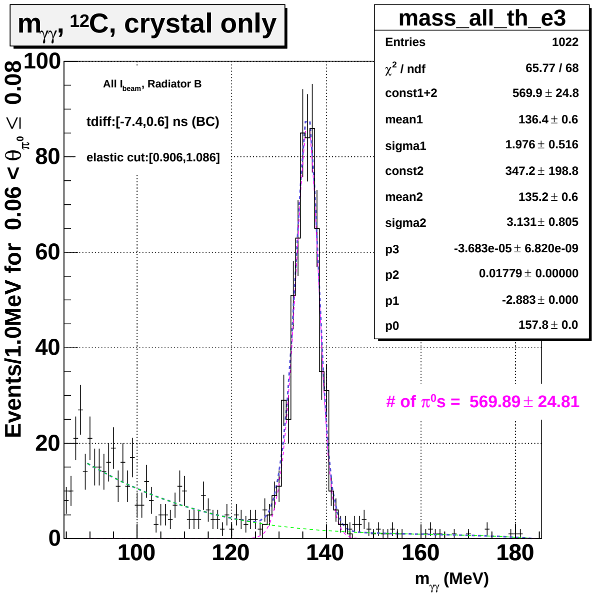
Kinematical constraints:

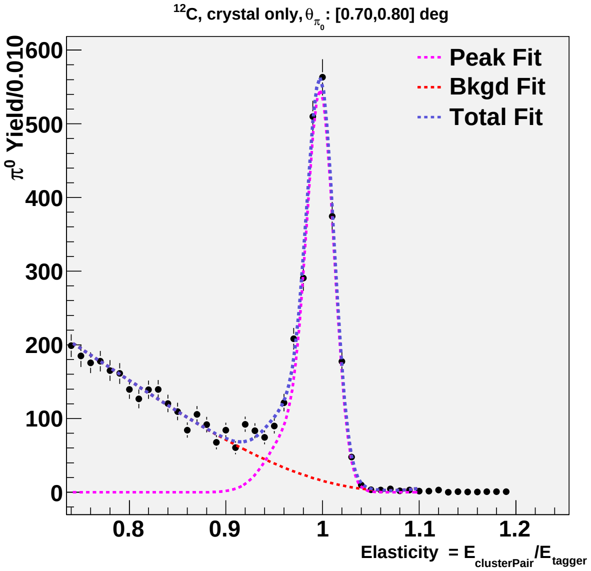
Conservation of energy;
$m_{\gamma\gamma}$ invariant mass

Three groups analyzed the data independently

Schematic view of π^0 event



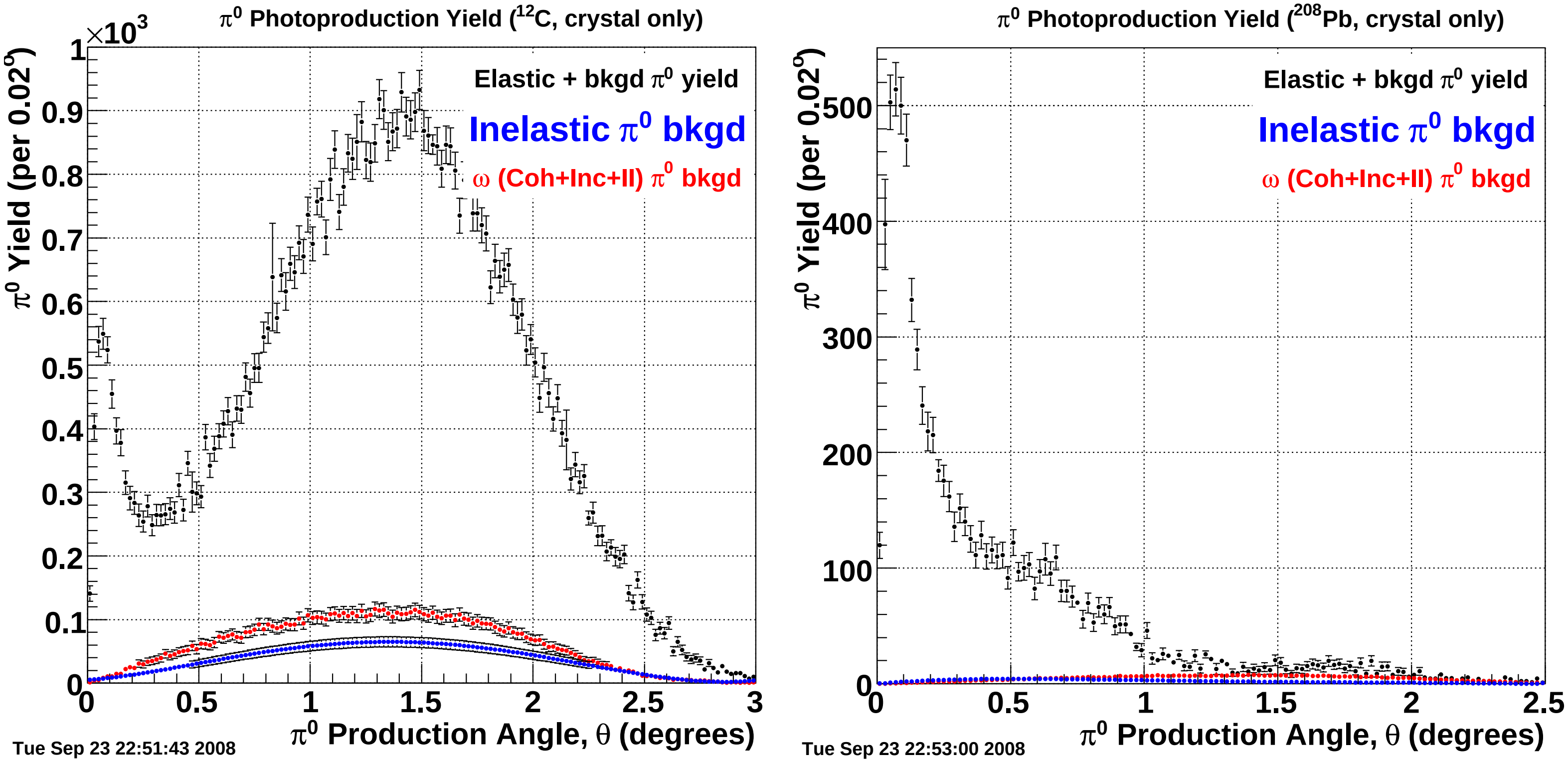




- For each θ_{π^0} bin, apply elastic cut and form $m_{\gamma\gamma}$ distributions; perform fit and extract peak counts = uncorrected yield.

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

- Convert Yield to Cross Section.

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

→ 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 $\sim 0.6\%$).

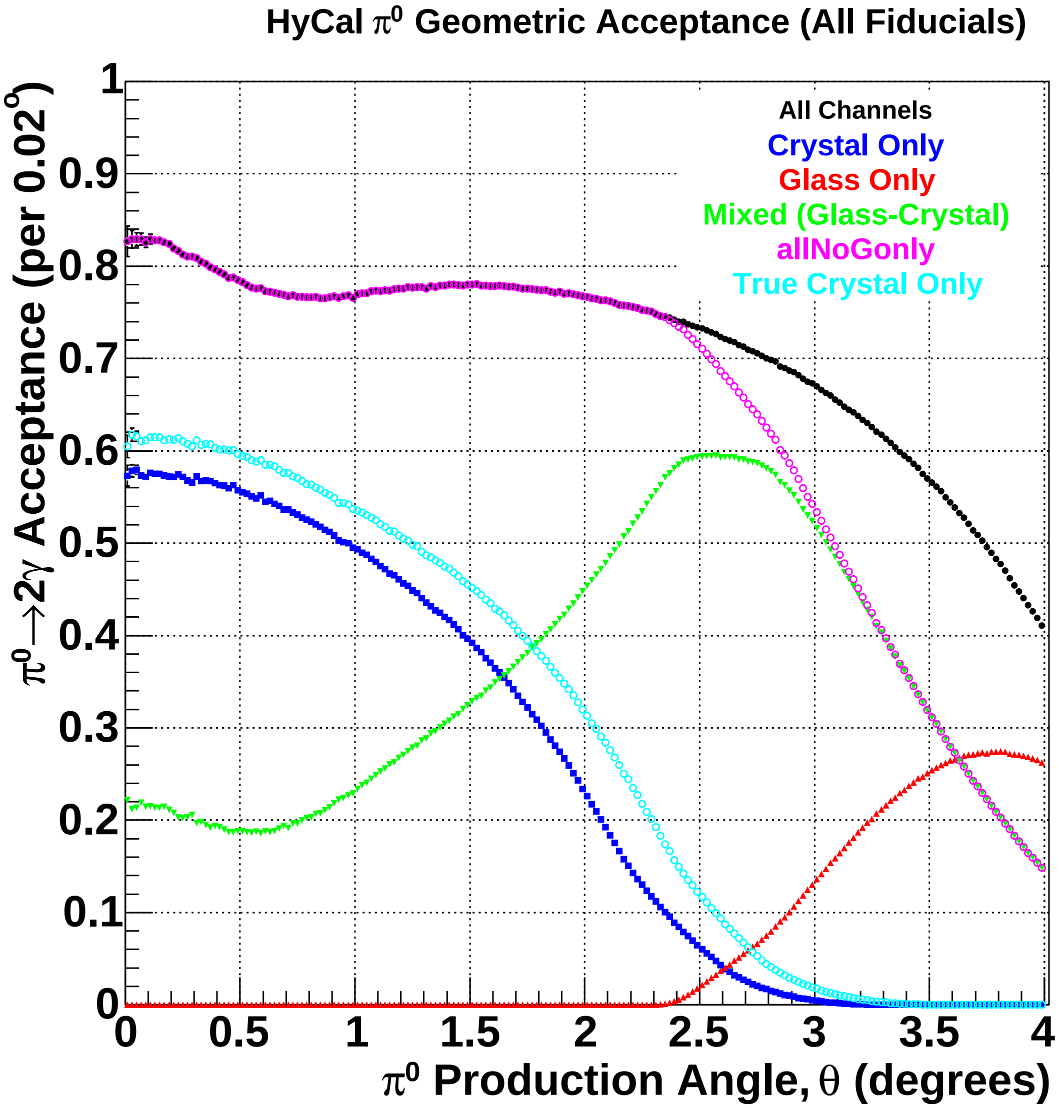
- Fit experimental data with parametrization:

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

→ 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.

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

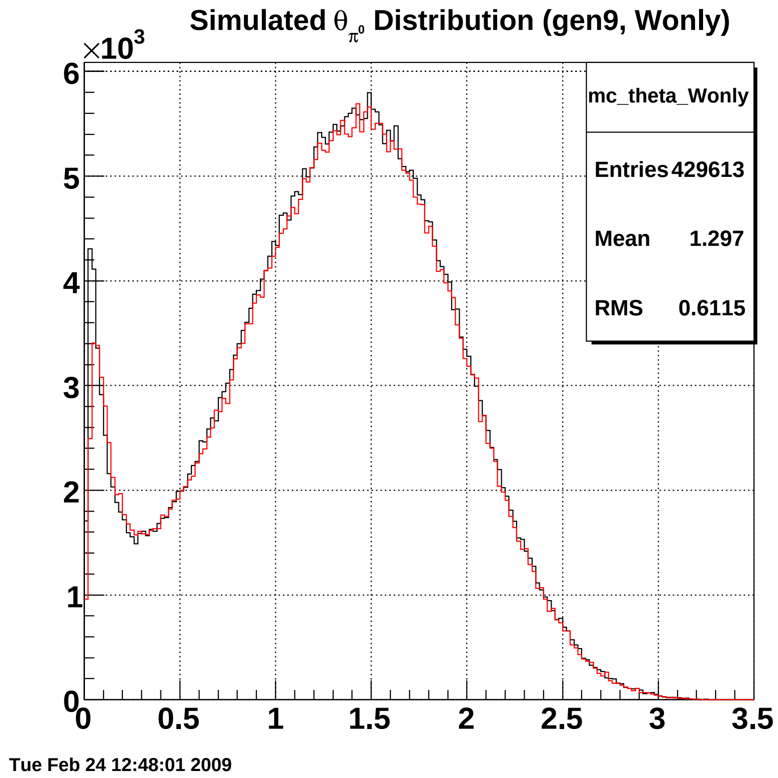
→ Calculate theory input shapes (cross sections) energy-weighted according to experimental flux.

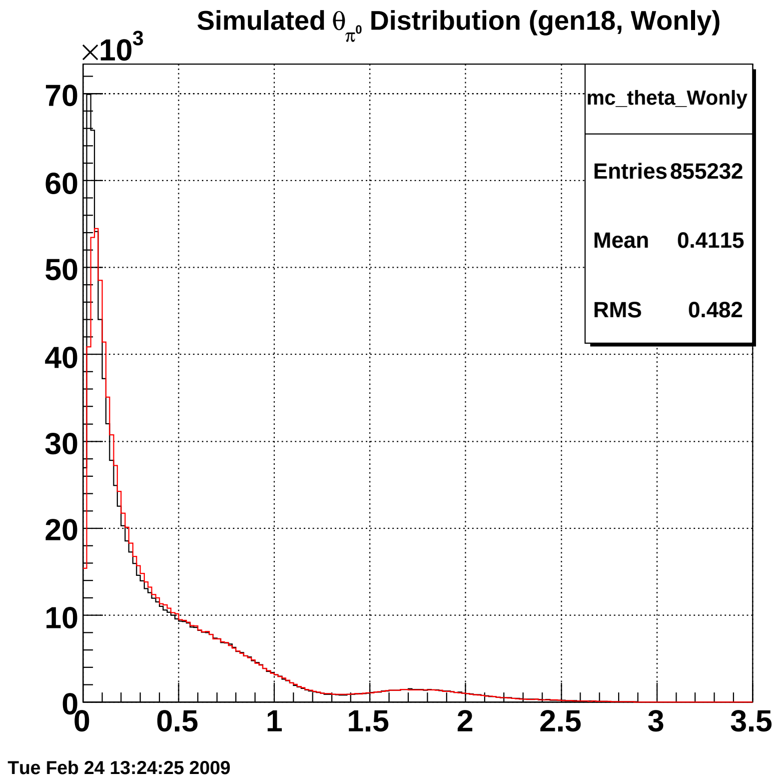
→ Create π^0 event generator based on above cross sections and run through Primsim Monte Carlo.

→ 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

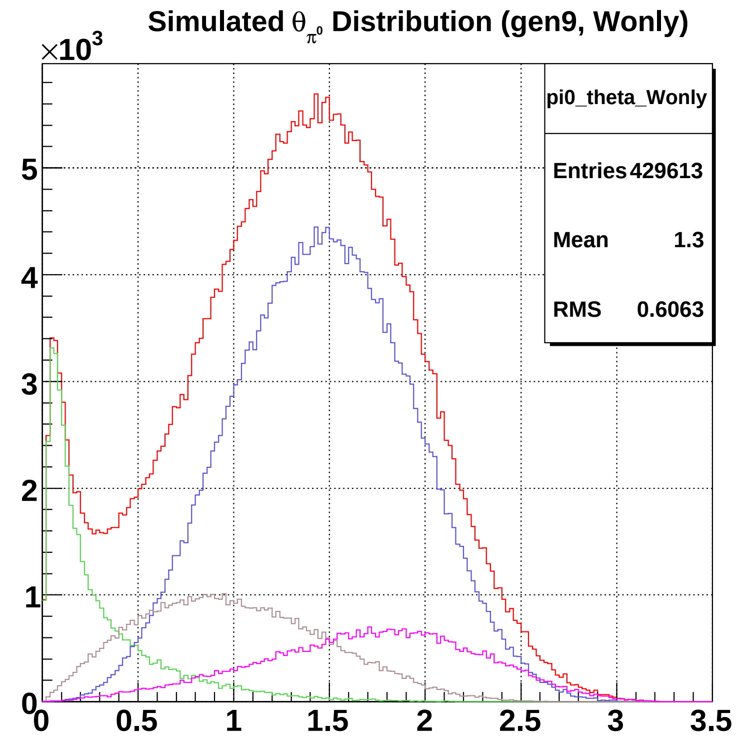




^{12}C: —θ_{π^0} Thrown —θ_{π^0} Detected

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

MC Shape Generation: Exmpl Fit Input Shapes (smeared)



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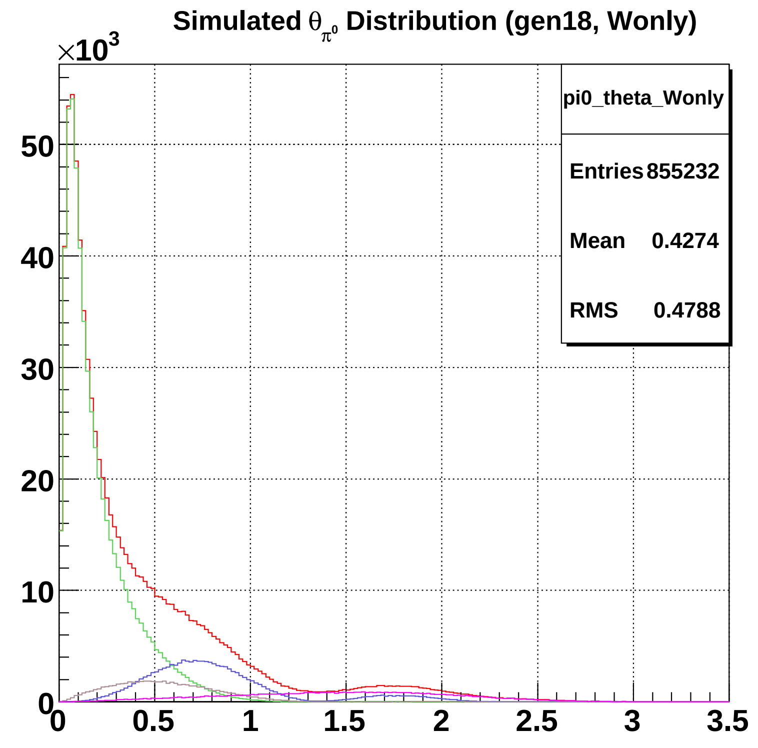

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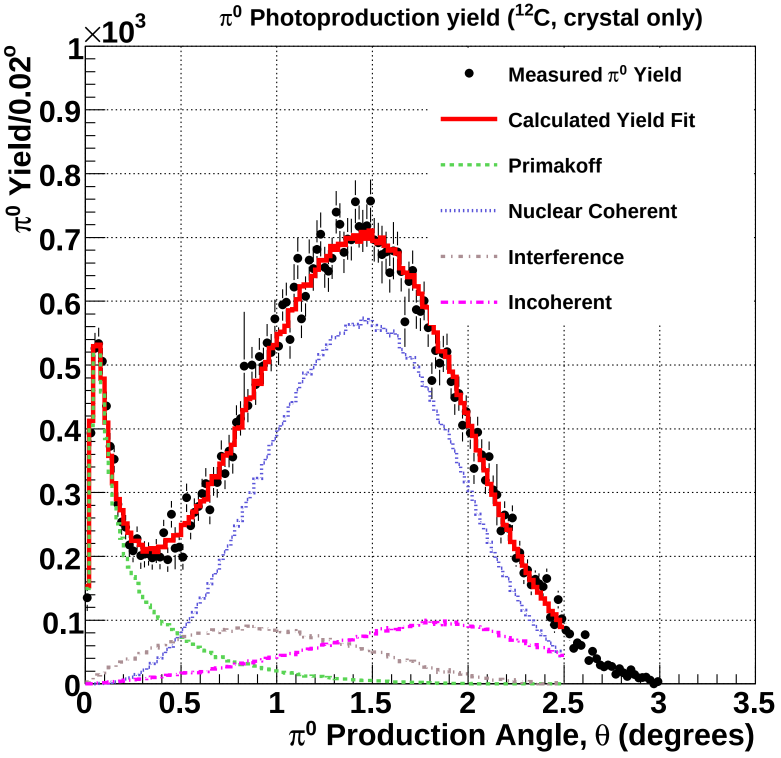
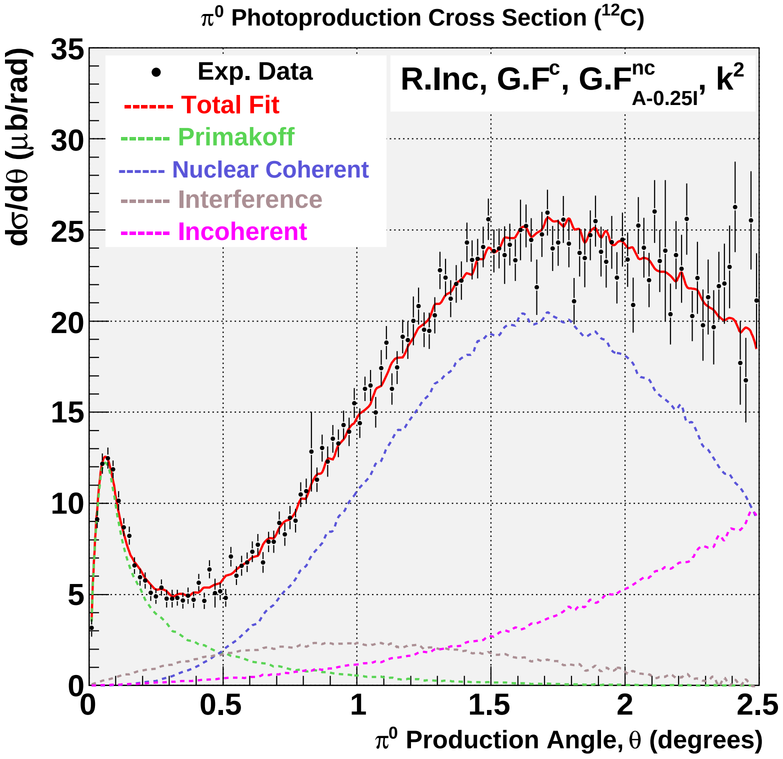
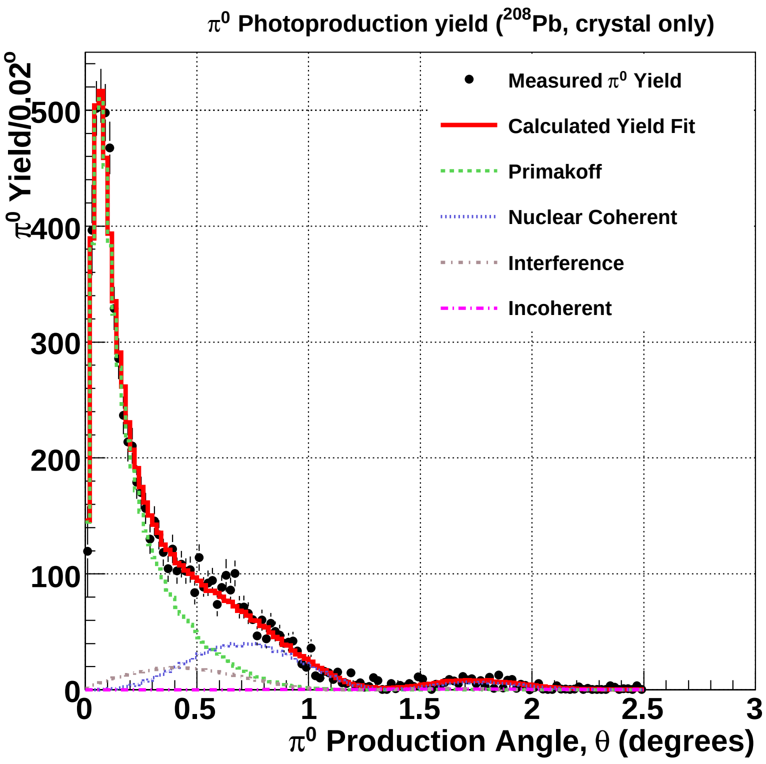
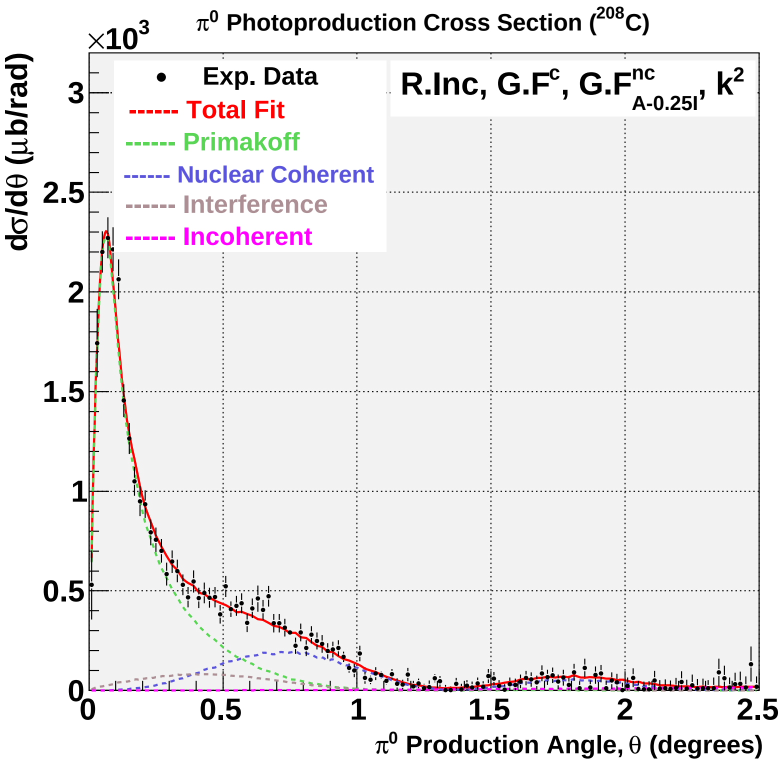
Yield Fit and Cross Section for ^{12}C





Yield Fit and Cross Section for ^{208}Pb



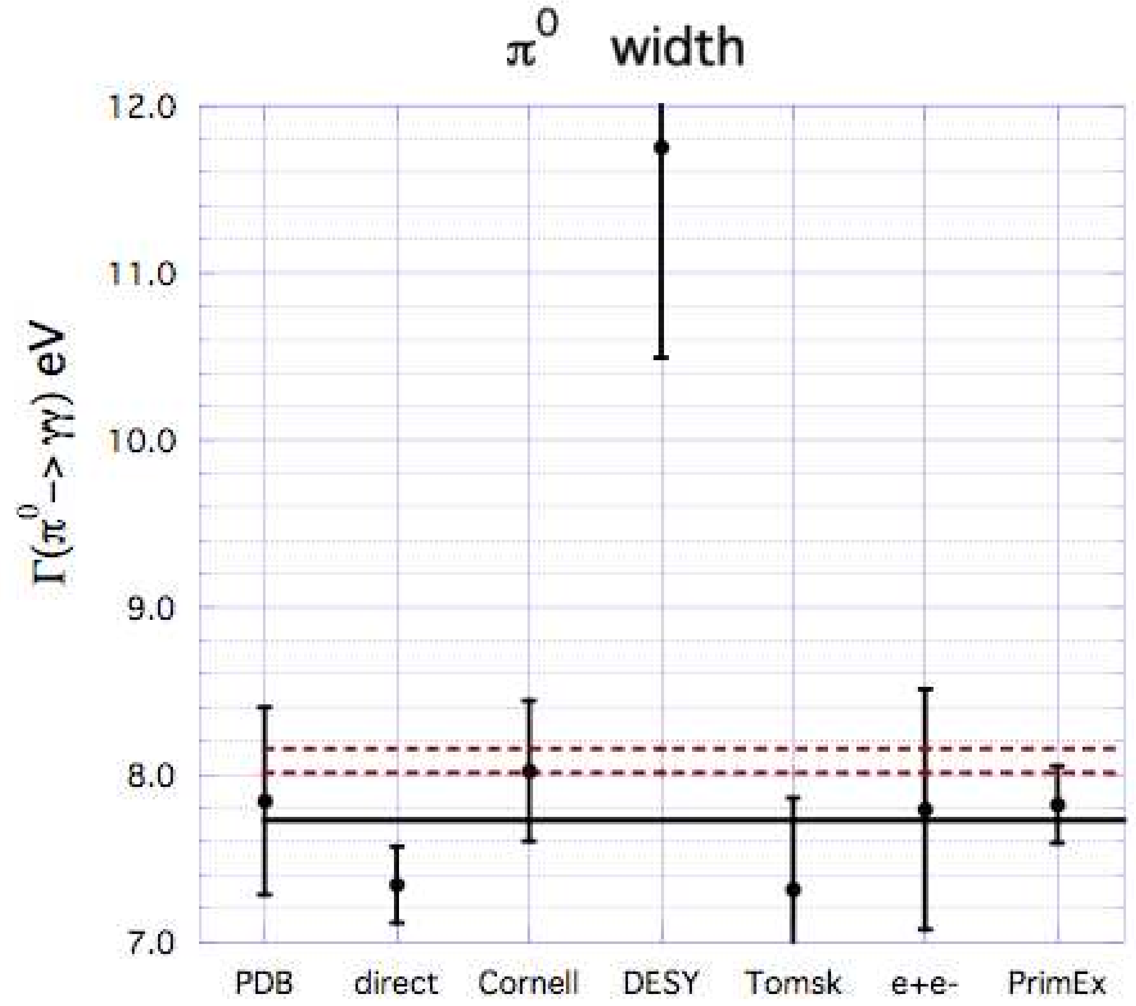


$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Systematic Errors

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	±2.1%	±1.3%

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

.

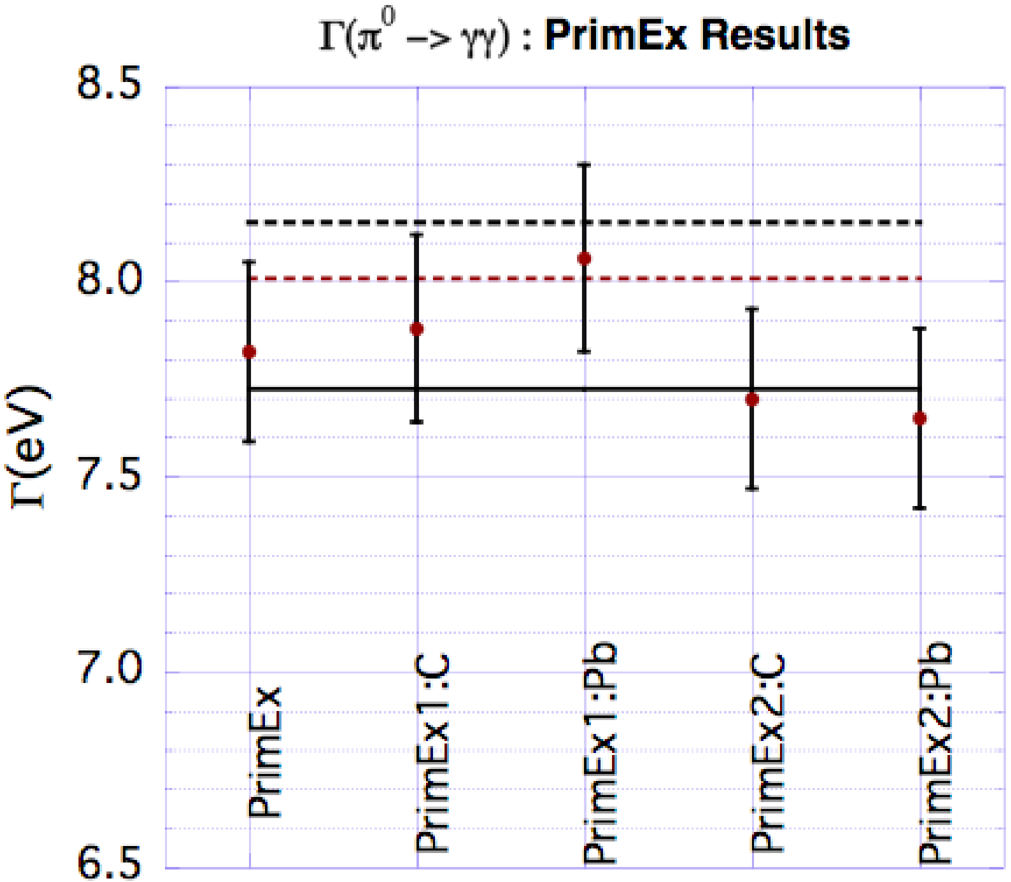


Summary and Outlook

- 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: $\Gamma_{\pi^0 \rightarrow \gamma\gamma} = 7.82\text{eV} \pm 2.2\%(\text{stat}) \pm 2.1\%(\text{syst})$; Overall ±3.0% error.
- The mean lifetime: $(8.32 \pm 0.25) \times 10^{-17}$ s
- $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$ 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...

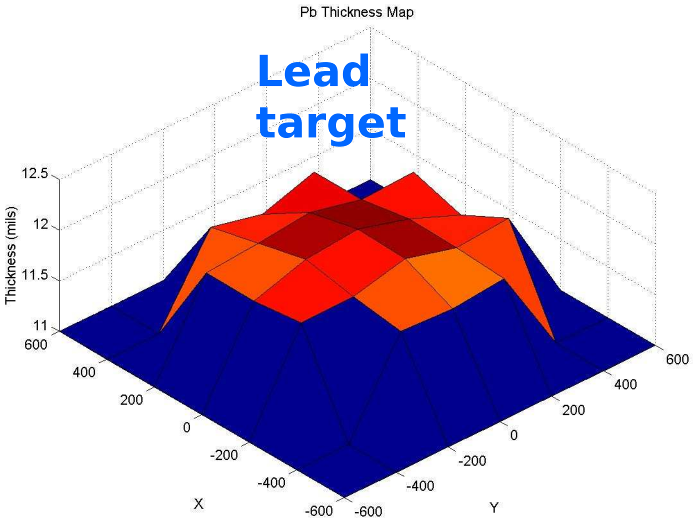
Extra Slides

Independent Group Results

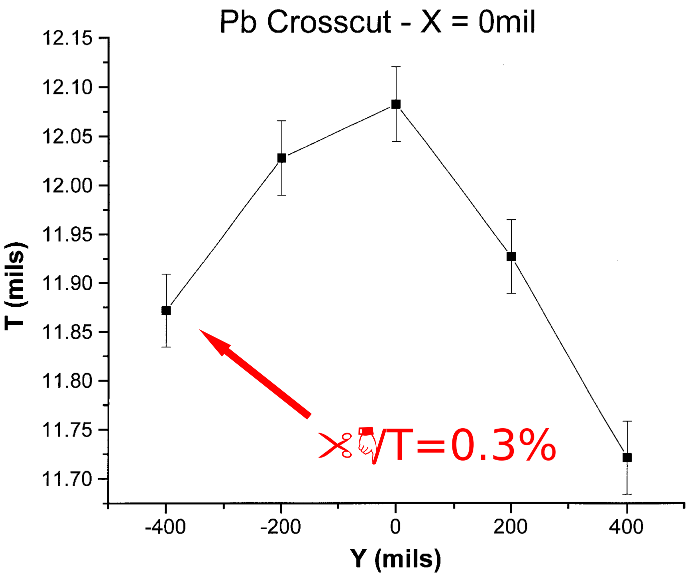


Isotopically pure ^{12}C and ^{208}Pb

PRIMEX Targets



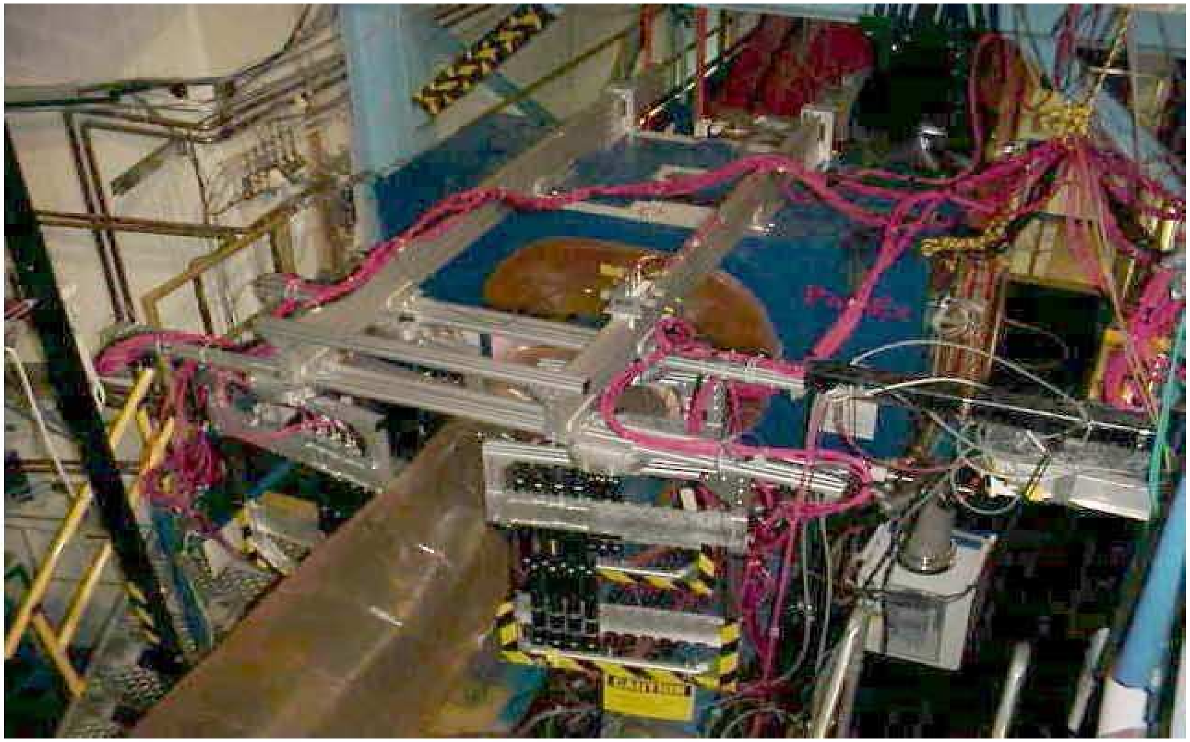
Lead target



✂☟/T=0.3%

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

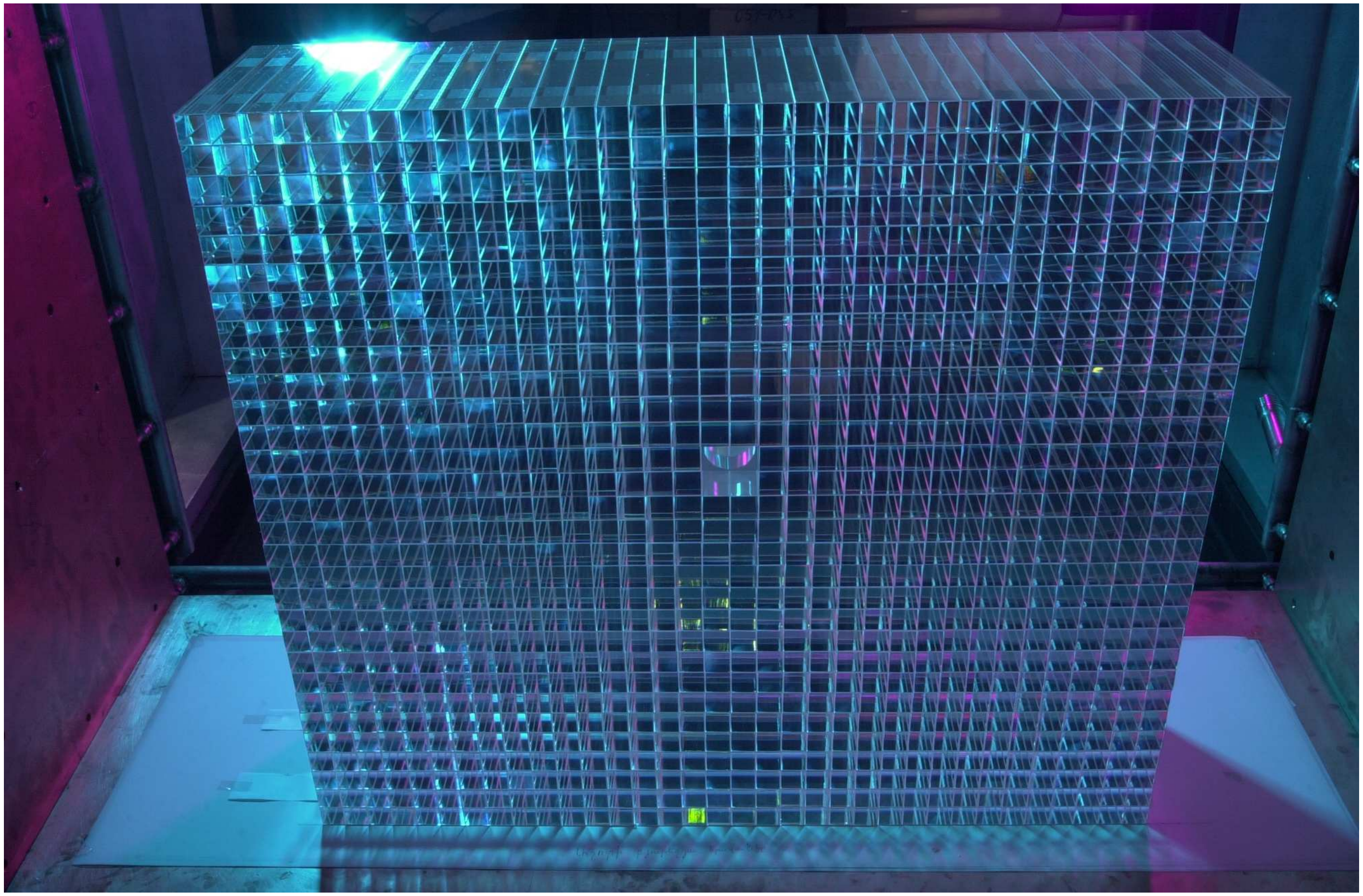
Pair Spectrometer



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

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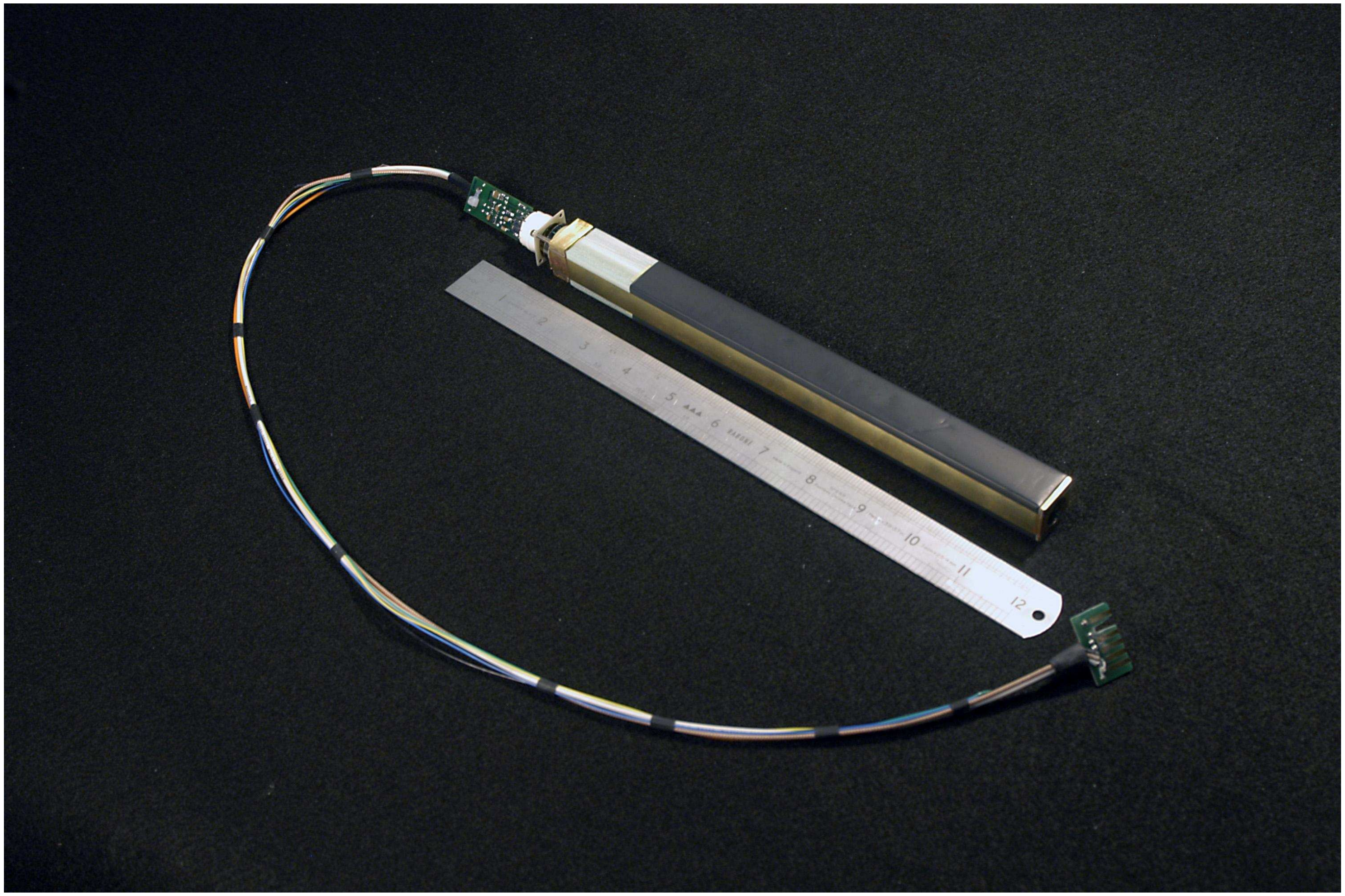
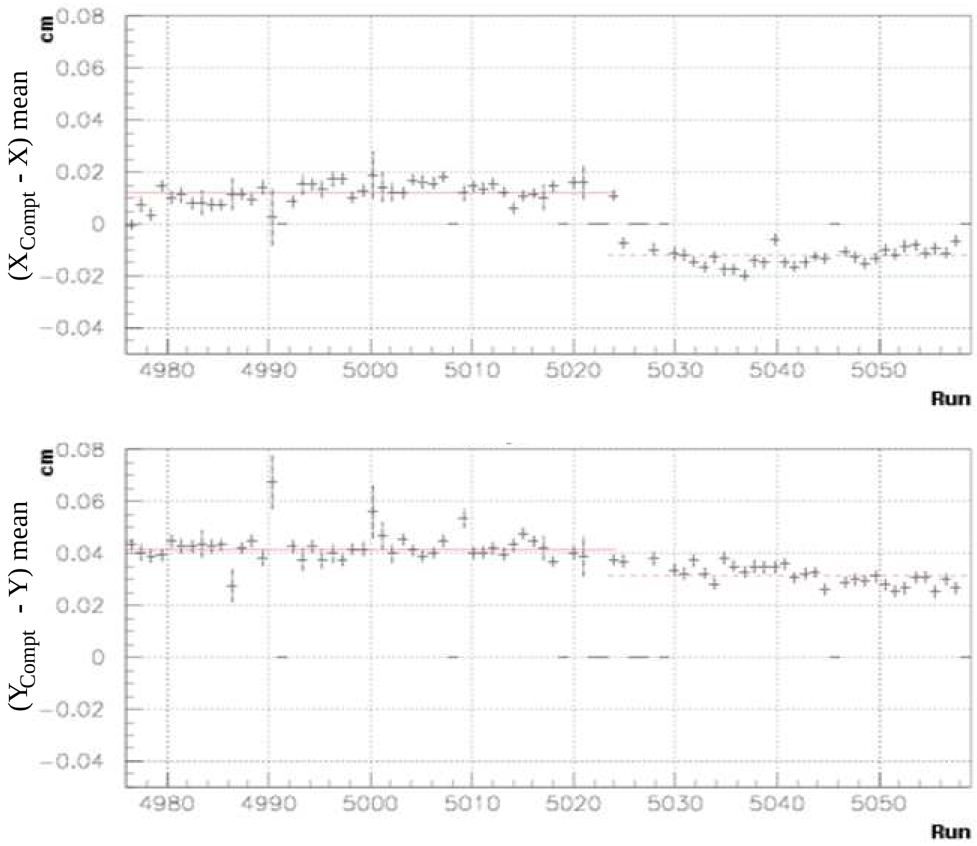


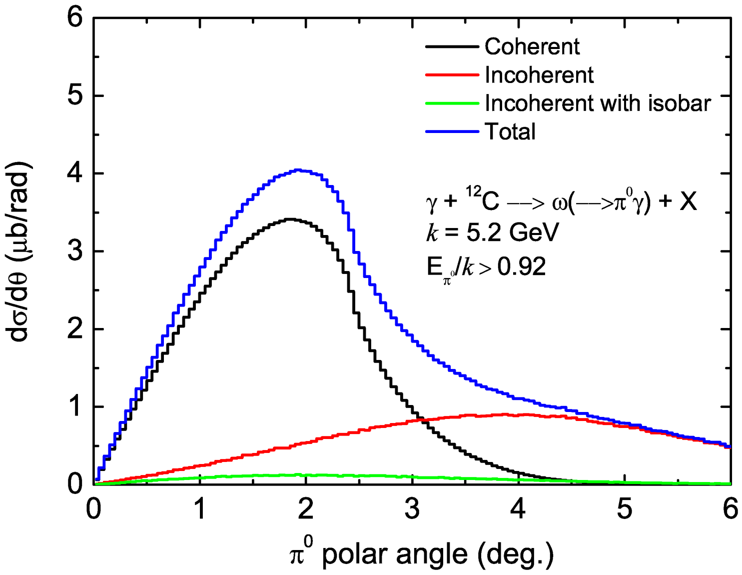
Beam Alignment Monitoring using Single-Arm Compton

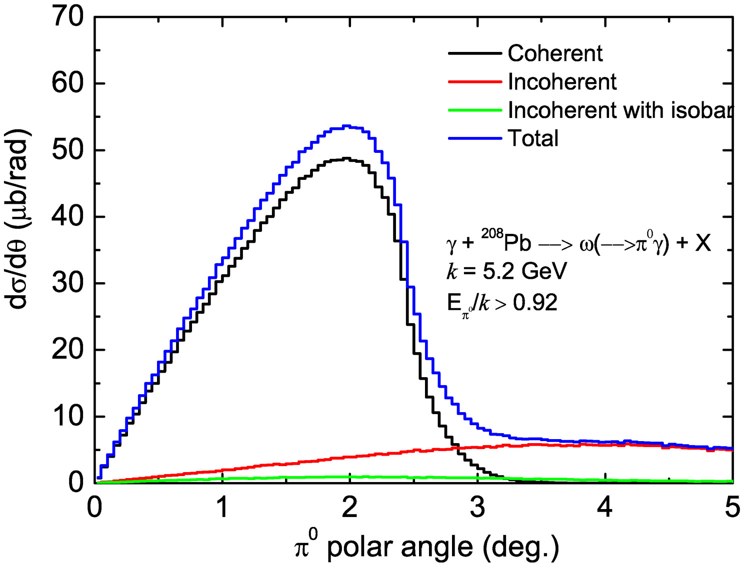


- Only scattered γ measured
- X ≡ reported HyCal coord
- X_{Compt} ≡ calc. (x,y) from Hycal E and Compton kin.
- If beam alignment perfect: $(X_{Compt}-X) = 0$
- Technique tracks alignment at 0.1 mm level
- Jump in X correlated with beamline BPM

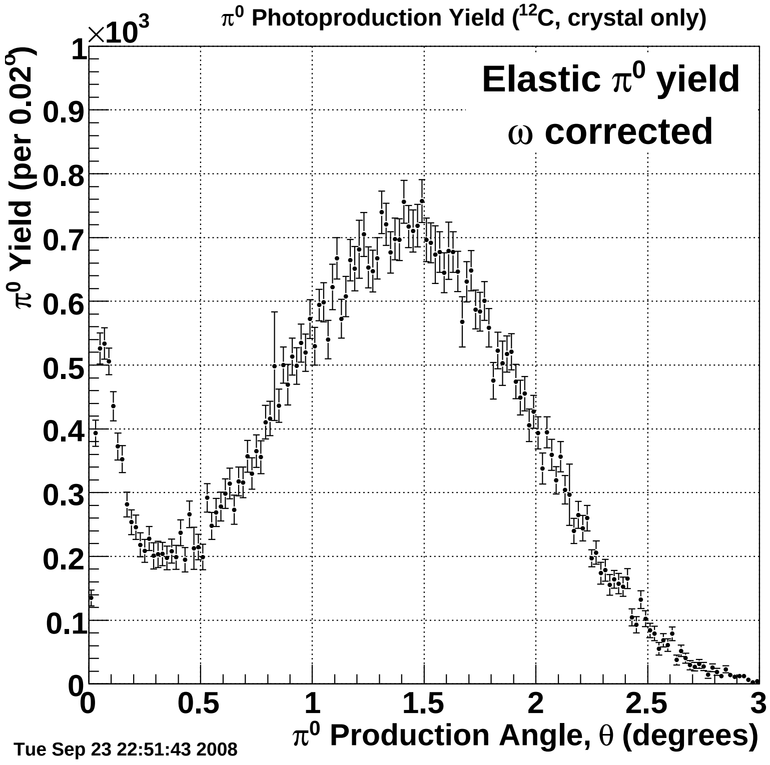
The $\omega \rightarrow \pi^0\gamma$ Background Correction

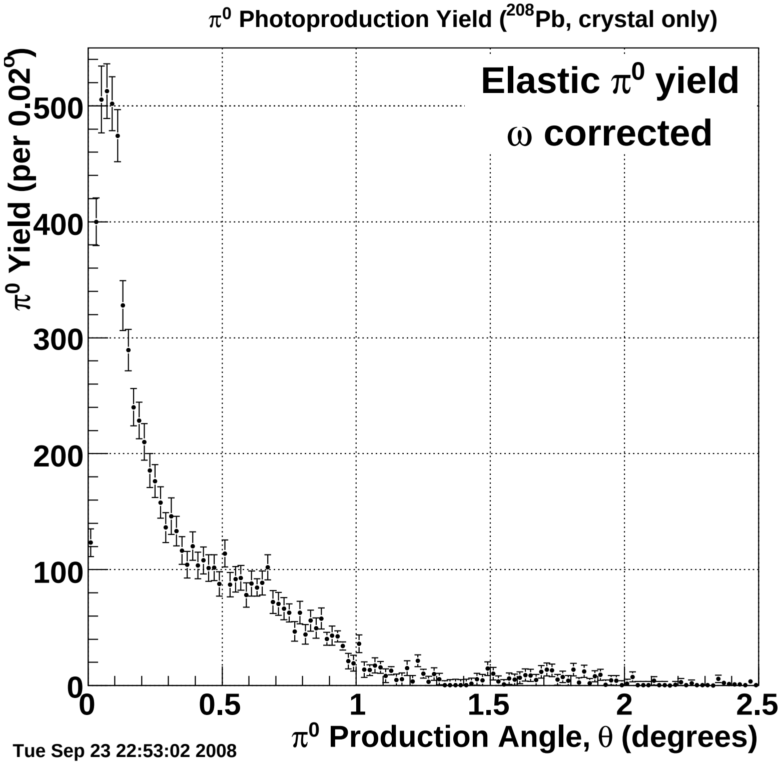
- $d\sigma/d\theta_{\pi^0}$ for $\omega \rightarrow \pi^0\gamma$ taken from T. Rodrigues and implemented
- Convert ω cross section into absolute yield while imposing experimental resolutions using Monte Carlo
- Explicitly subtract contribution from experimental yield





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





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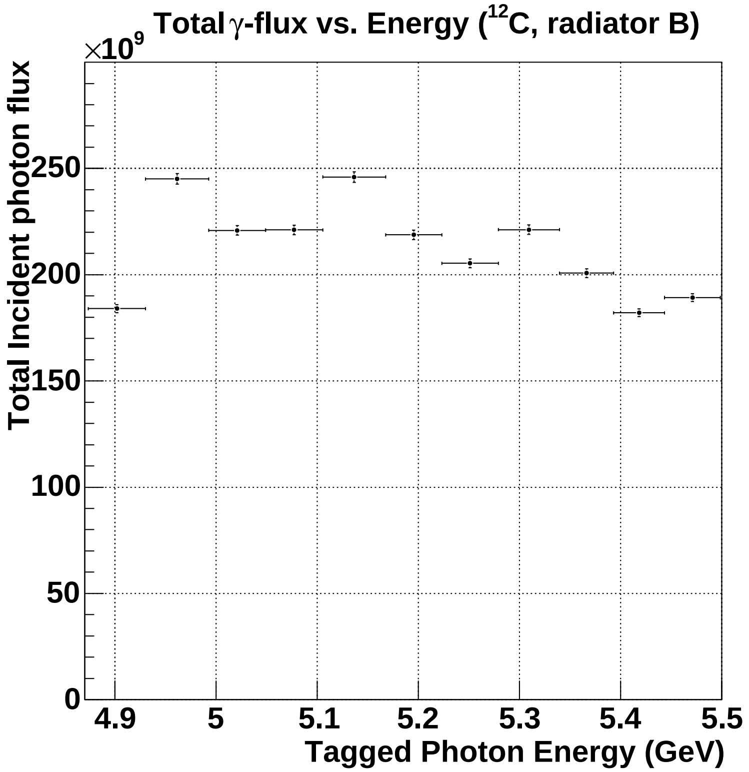
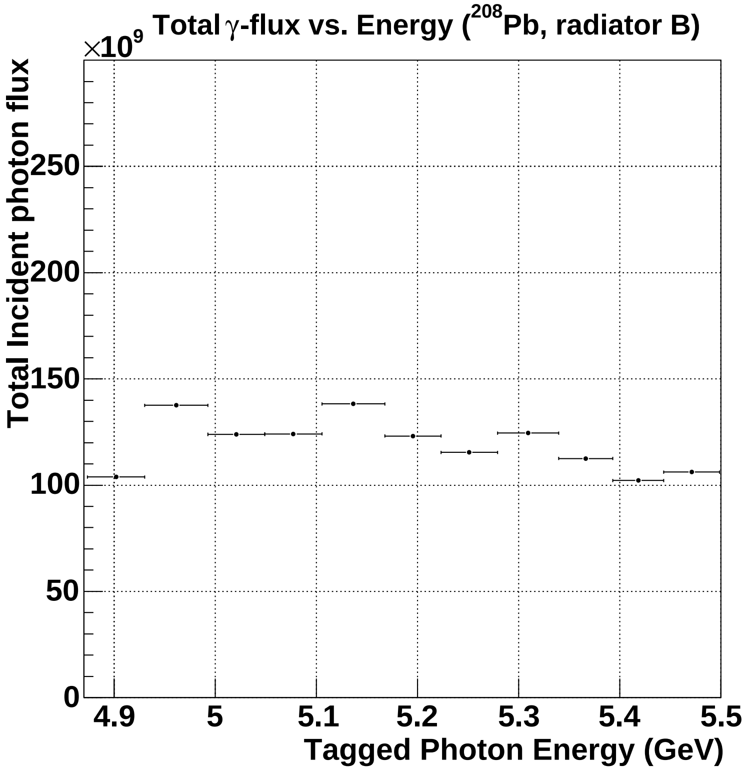
Photon Flux





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.