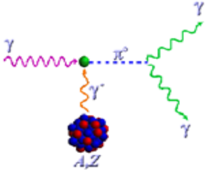
Status of the *PrimEx* Experiment: *A Precision Measurement of the Neutral Pion Lifetime*

7th European Conference on
"Electromagnetic Interactions with Nucleons and Nuclei"

Milos Island, Greece
September 12-15, 2007

Dan Dale
Idaho State University



Participating Institutions

North Carolina A&T State University
University of Kentucky
Jefferson Lab
MIT
Catholic University of America
University of Virginia
IHEP, Russia
University of Illinois
Chinese Institute of Atomic Energy
George Washington University
Southern University at New Orleans
University of Sao Paulo

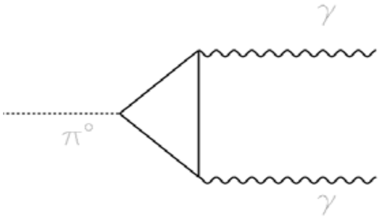
University of Massachusetts
Idaho State University
Hampton University
University of North Carolina at Wilmington
Arizona State University
ITEP, Russia
Norfolk State University
Kharkov Inst. of Physics and Technology
IHEP, Chinese Academy of Sciences
Yerevan Physics Institute, Armenia
Tomsk Polytechnical University, Russia

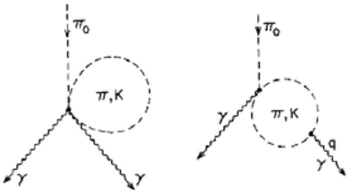
23 institutions, 6 countries

A High Precision Measurement of $\pi^o \rightarrow \gamma\ \gamma$

- Physics motivation
- The Primakoff effect
- Experimental setup
- Towards high precision
- Current analysis
  - -event selection
  - -radiative width extraction
- Summary

The axial anomaly





$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{\alpha_{\rm em}^2 N_c^2 M_\pi^3}{576\pi^3 F_\pi^2}$$

Leading order corrections (Donoghue, 1989)

$F_\pi \simeq 93$ **MeV, pion decay constant**

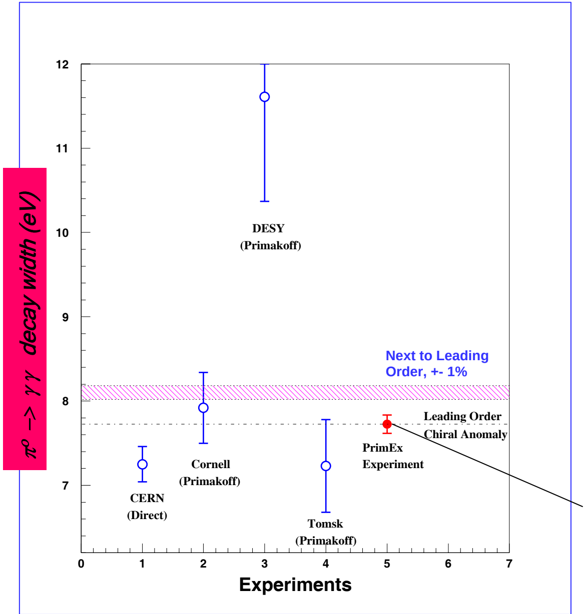
Calculated in chiral limit $m_u, m_d \to 0$

Real world

$m_q \sim$ **5 MeV**

Corrections O(p⁴)

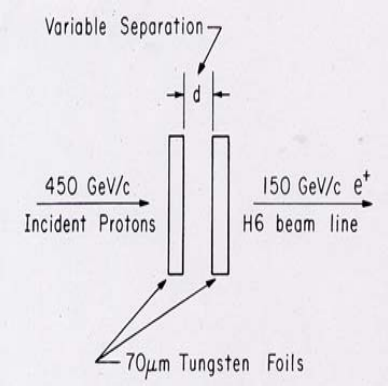
Current experimental and theoretical status



Expected PrimEx error bar, arbitrarily projected to the leading order chiral anomaly

Previous Experiment: The Direct Method

(Phys. Lett., vol 158B, no. 1, 81, 1985)



➡ ***π^o`s produced by 450 GeV protons in tungsten foils.***

➡ ***π^o decays observed by detection of 150 GeV/c positrons produced by decay γ rays converting in foils.***

$$Y(d) = N[A + B(1-e^{-d/\lambda})]$$

Dalitz decay, γ conversion in first foil

Recent Theoretical Advances

(B.L. Ioffe and A.G. Oganesian, Phys. Lett. B647, p. 389, 2007)

- Sum rule approach to axial-vector-vector (AVV) form factor.
- $f_{\pi^o} - f_{\pi^+}$ caused by strong interaction shown to be small.
- Eta width only input parameter.
- $\pi^o - \eta$ mixing included.

$$\Gamma(\pi^o \rightarrow \gamma\gamma) = 7.93 \text{ eV} \pm 1.5\%$$

Recent theoretical advances:

(Goity, Bernstein, Holstein, Phys. Rev. D66:076014, 2002.)

- χ**PT and** $\frac{1}{N_c}$ **expansion up to** $O(p^6)$ **and** $O(p^4 \times \frac{1}{N_c})$.
- $SU_L(2) \times SU_R(2)$ **broken by** m_u, m_d.
- η' **degree of freedom explicitly included.**

Two types of correction:

1 isospin breaking α $\frac{m_u - m_d}{m_s}$ or $\frac{N_c(m_u - m_d)}{\Lambda_\chi}$

$\rightarrow O(p^4)$ (same as leading term)

2 α $\frac{m_{u,d}}{\Lambda_\chi}$

$\rightarrow O(p^6)$

Width increased by 4.5%

$$\Gamma^{NLO}_{\pi^0 \rightarrow \gamma\gamma} = 8.10 \pm 0.08 eV$$

Recent theoretical advances (continued):

(Ananthanarayan and Moussallam, JHEP 0205:052, 2002.)

SU(2):

$$A_{p^4} = \frac{\alpha}{\pi F}$$

with F in limit of $m_{u,d} \rightarrow 0$.

SU(3), $\pi^o - \eta$ mixing:

$$A_{p^4} = \frac{\alpha}{\pi F_o}[1 + \frac{m_d - m_u}{4(m_s - m)}]$$

with

$$m = \frac{1}{2}(m_u + m_d)$$

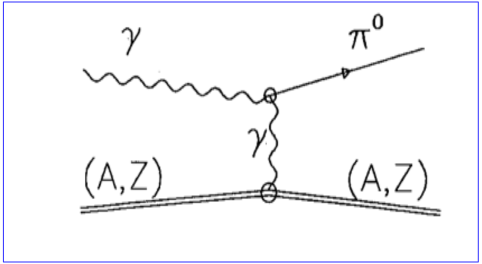
F in limit of $m_{u,d,s} \rightarrow 0$.

To $O(p^6)$, they obtain:

$$A_{\pi^o \rightarrow \gamma\gamma} = A_{CA}[1 + \frac{m_d - m_u}{(m_s - m)}(0.93 \pm 0.12) - 0.34 \times 10^{-2} \pm 0.14 \times 10^{-2}]$$

$$\boxed{\Gamma^{NLO}_{\pi^o \rightarrow \gamma\gamma} = 8.06 \pm 0.02 \pm 0.06 eV}$$

The Primakoff Effect



$$\left(\frac{d\sigma}{d\Omega}\right)_{Pr} = \Gamma_{\gamma\gamma}\frac{8\alpha Z^2}{m^3}\frac{\beta^3 E^4}{Q^4}\left|F_{em}(Q^2)\right|^2 \sin^2\theta$$

Radiative width

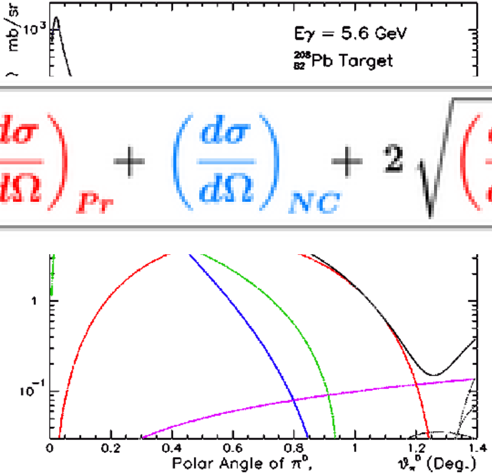
Known, measured quantities

$$\frac{d^3\sigma}{d\Omega_\pi} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_C}{d\Omega} + \frac{d\sigma_I}{d\Omega} + 2\cdot\sqrt{\frac{d\sigma_P}{d\Omega}\cdot\frac{d\sigma_C}{d\Omega}}cos(\phi_1+\phi_2)$$

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

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

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Pr} + \left(\frac{d\sigma}{d\Omega}\right)_{NC} + 2\sqrt{\left(\frac{d\sigma}{d\Omega}\right)_{Pr}\cdot\left(\frac{d\sigma}{d\Omega}\right)_{NC}}\cdot\cos\phi + \left(\frac{d\sigma}{d\Omega}\right)_{I}$$



➡ ***Angular distribution***
enables separation of amplitudes

For high precision:

- Measure angular distribution well to separate various amplitudes

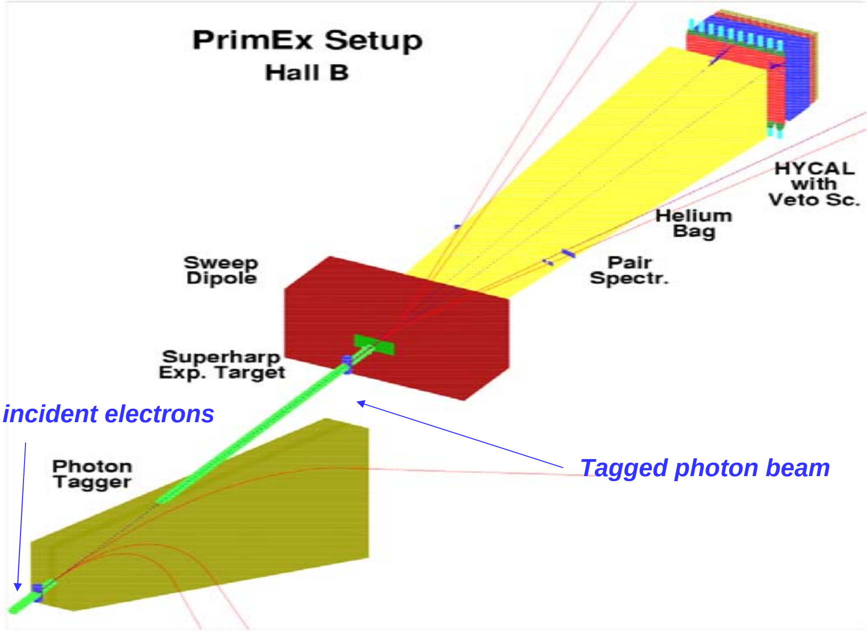
  → new state of the art π^o detector

- Measure on a variety of targets to test validity of background extraction ($\sigma_{Primakoff} \propto Z^2$).

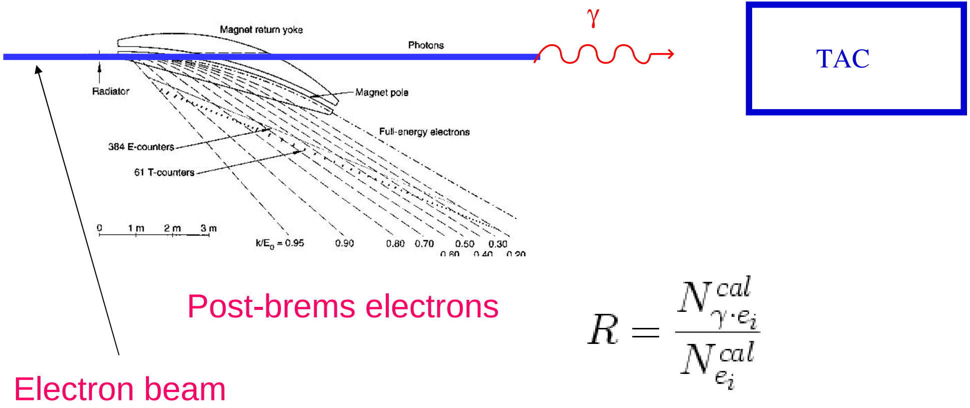
- Tight photon energy ($\sigma_{peak} \propto E^4$) and flux control

  → photon tagging

- Measure QED processes (Compton and pair production) to validate setup and analysis techniques.


PrimEx Setup
Hall B
HYCAL
with
Veto Sc.
Helium
Bag
Pair
Spectr.
Sweep
Dipole
Superharp
Exp. Target
incident electrons
Photon
Tagger
Tagged photon beam

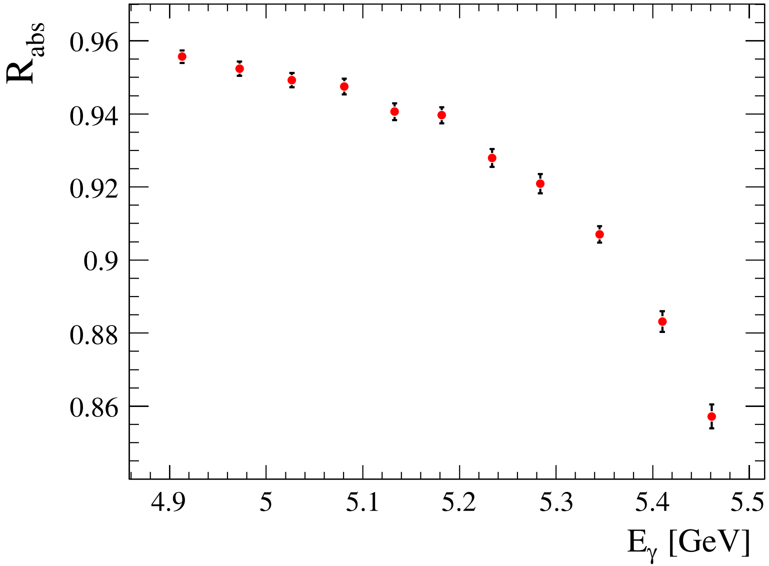
Bremsstrahlung photon tagging



$$R = \frac{N^{cal}_{\gamma \cdot e_i}}{N^{cal}_{e_i}}$$

$$N^{tagged}_{\gamma} = R \times N^{prod}_{e_i}$$

Tagging Ratios



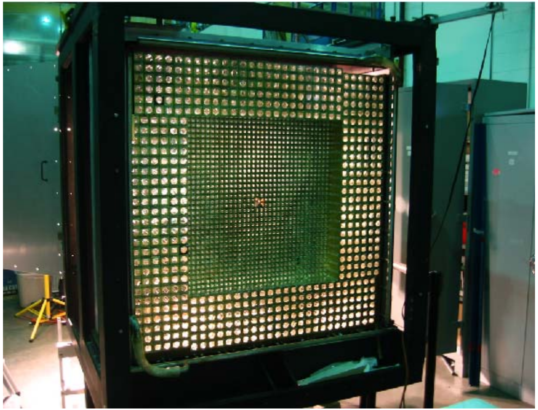
$$R = \frac{N_{\gamma \cdot e^-}}{N_{e^-}}$$

Photon Calorimetry – the HYCAL calorimeter

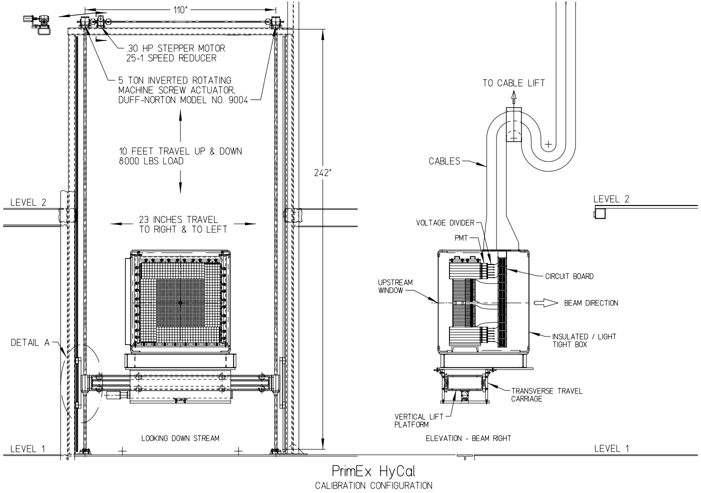
1152 $PbWO_4$ and
576 lead glass modules

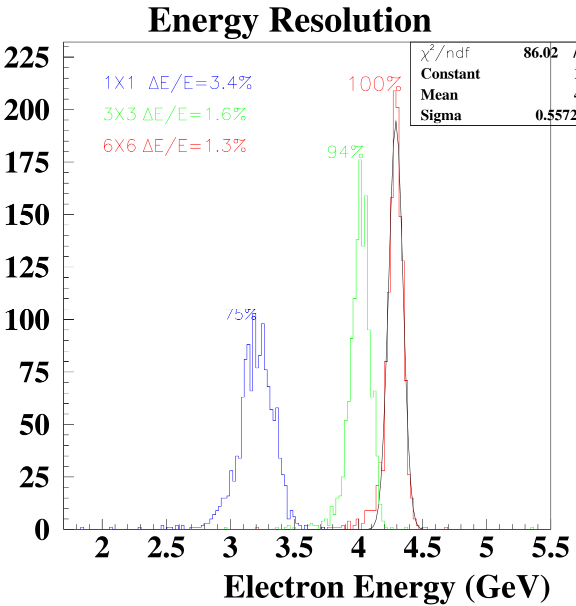
1.6% energy resolution

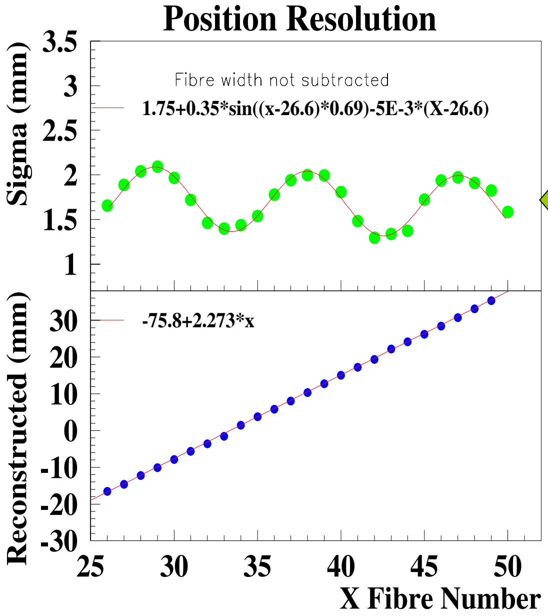
1-2 mm position resolution



In-beam calibration

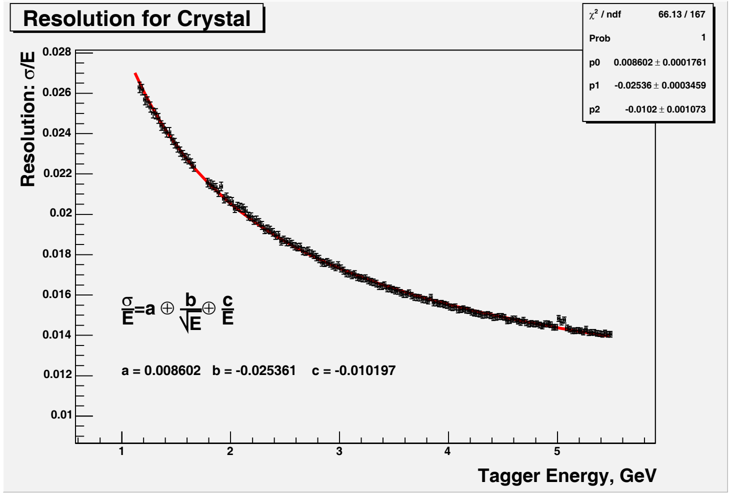


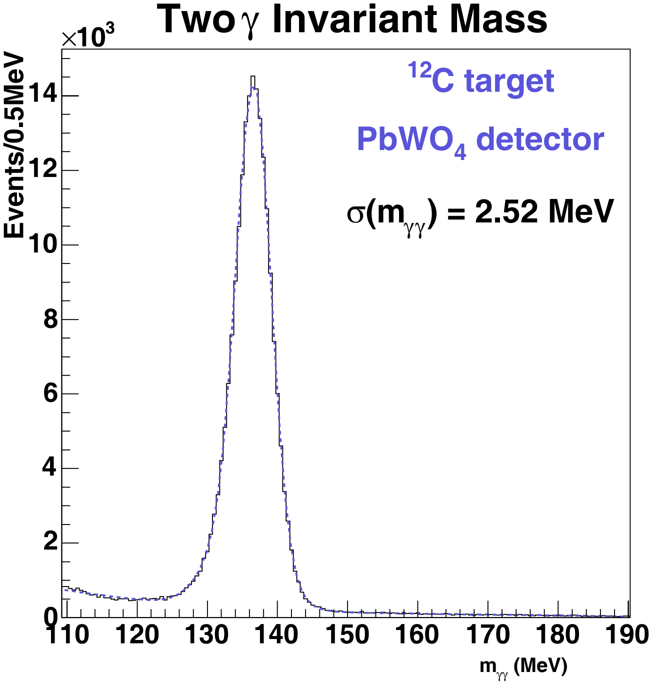

Energy Resolution
χ²/ndf 86.02 / 31
Constant 194.4
Mean 4.290
Sigma 0.5572E-01
1X1 ΔE/E=3.4%
3X3 ΔE/E=1.6%
6X6 ΔE/E=1.3%
100%
94%
75%
225
200
175
150
125
100
75
50
25
0
2
2.5
3
3.5
4
4.5
5
5.5
Electron Energy (GeV)



Effect of periodicity of detector modules.

Energy resolution – lead tungstate



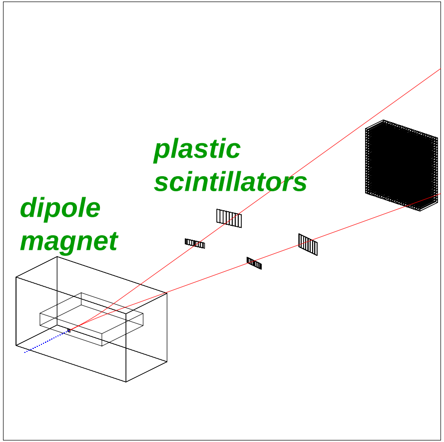


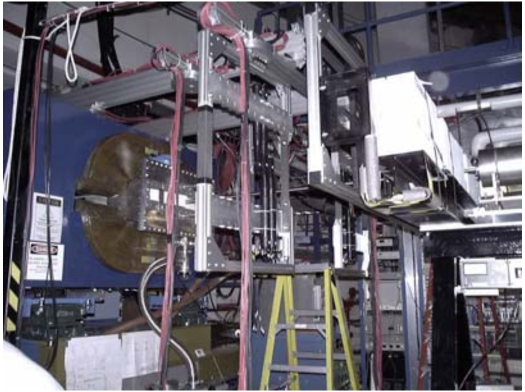
Two γ Invariant Mass
×10³
Events/0.5MeV
0
2
4
6
8
10
12
14
¹²C target
PbWO₄ detector
σ(m_γγ) = 2.52 MeV
110
120
130
140
150
160
170
180
190
m_γγ (MeV)

Luminosity analysis efforts

- Electron counting (absolute flux)
- Pair spectrometer (relative tagging ratios)
- TAC (absolute tagging ratios)
- Target thickness
- Known cross sections (pair production, Compton)

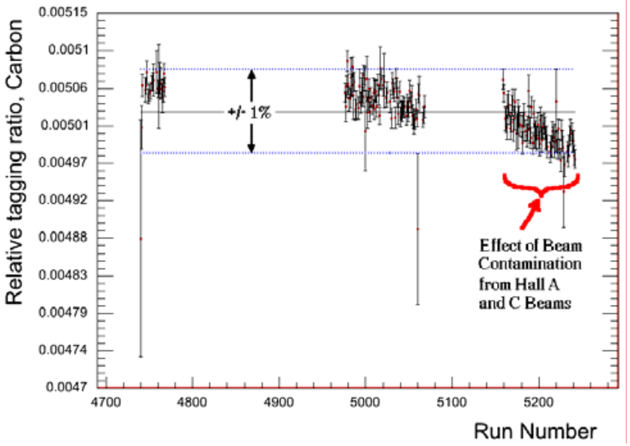
Online Flux Monitoring





e^+ - e^- pair spectrometer

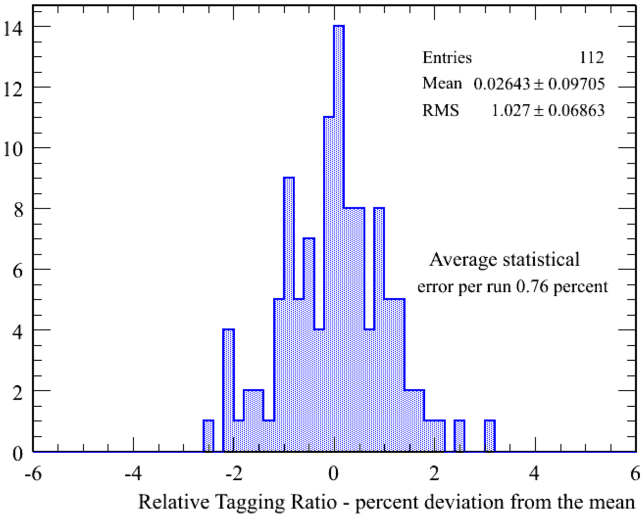
Stability of relative tagging ratios



$$R_{rel} = \frac{N_{e^+ \cdot e^- \cdot e_i}}{N_{e_i}}$$

➡ **Monitored *during* production data taking.**

Stability of relative tagging ratios



$$R_{rel} = \frac{N_{e^+ \cdot e^- \cdot e_i}}{N_{e_i}}$$

Stable to 1%.

Pair production cross section

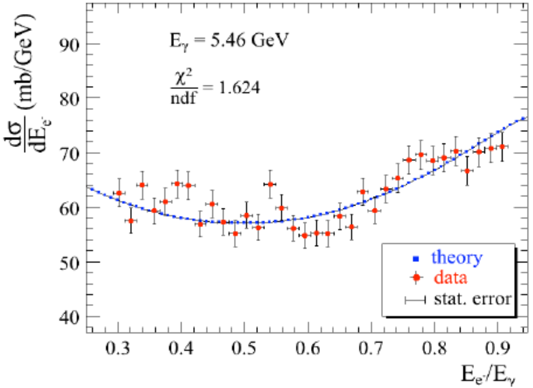
(1)Bethe-Heitler (modified by nuclear form factor).

(2)Virtual Compton scattering.

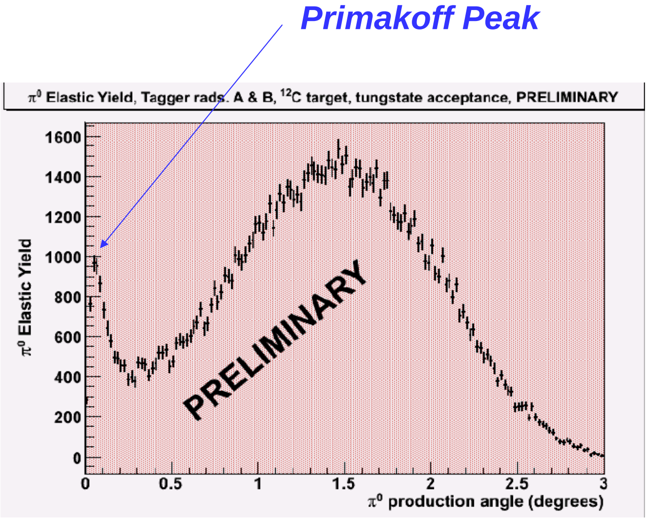
(3)Radiative effects.

(4)Atomic screening.

(5)Electron field pair production.



Angular distribution for Carbon

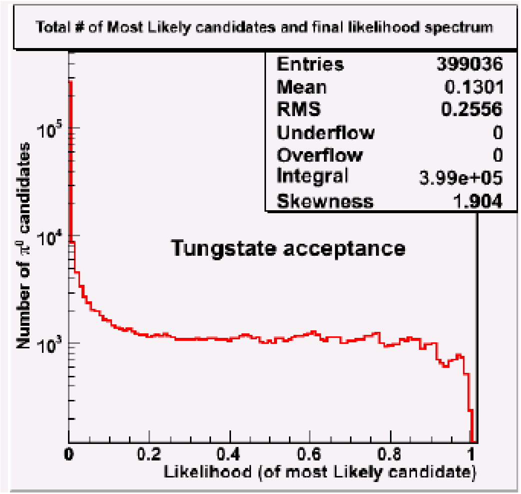


UMass Analysis

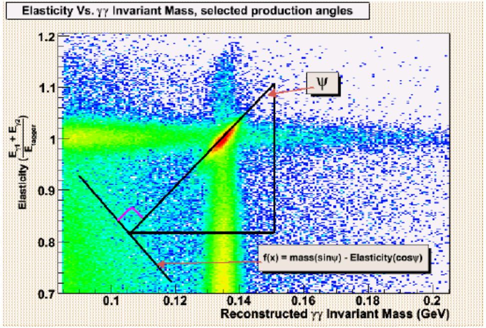
Event selection:

Normalized probability distributions for

- HYCAL – Tagger timing
- Invariant Mass
- Elasticity

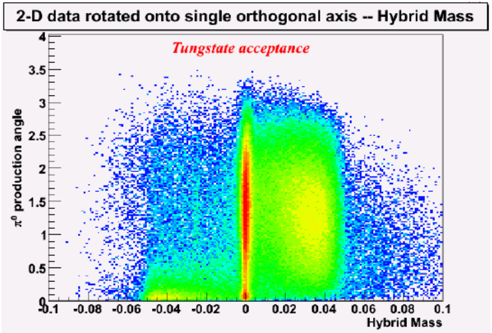


Total Probability = Timing x Mass x Elasticity

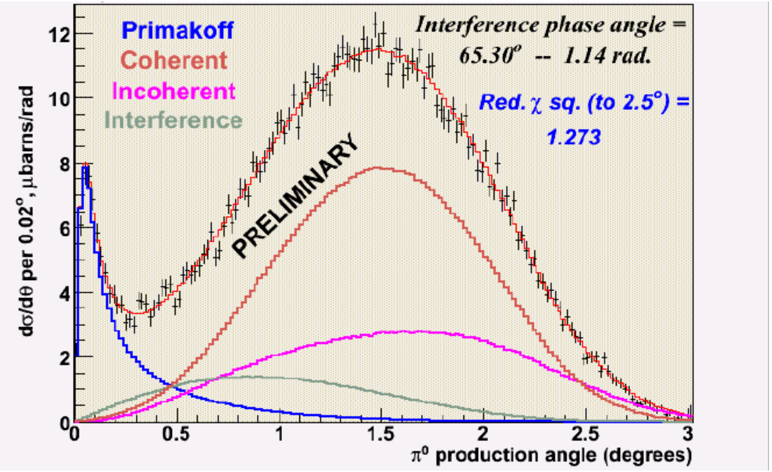


Elasticity versus invariant mass

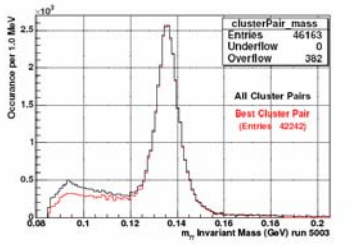
Hybrid mass



UMass Analysis: Radiative Width for Carbon

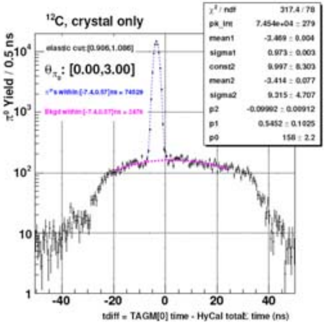


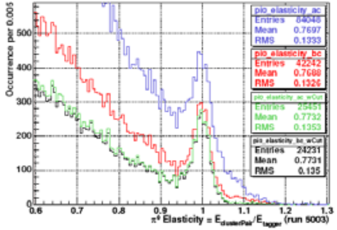
MIT/JLab Analysis: Event Selection



Invariant mass

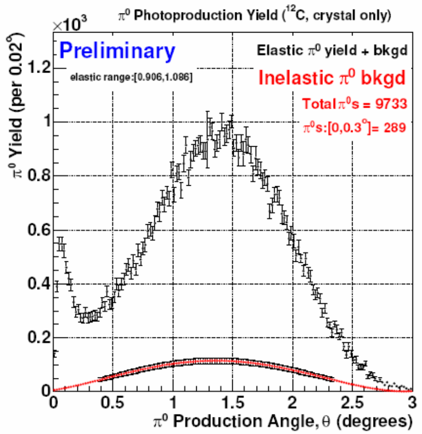
HYCAL – Tagger timing



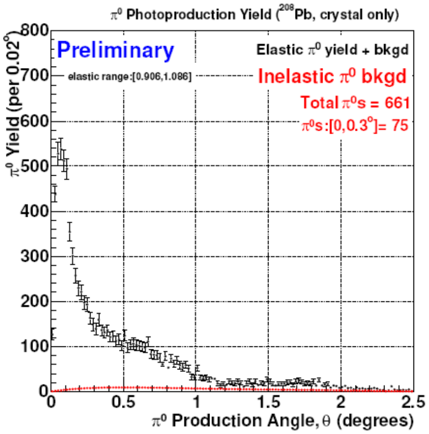


Elasticity

Angular distributions and background

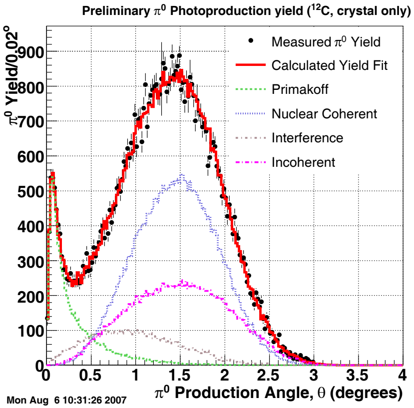


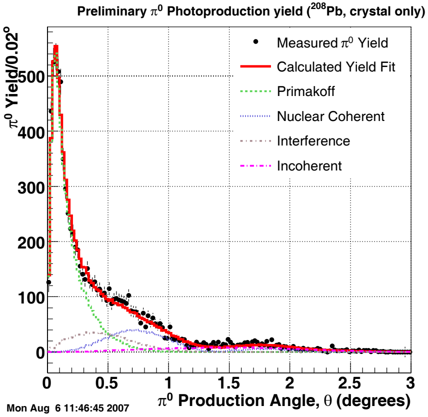
Carbon



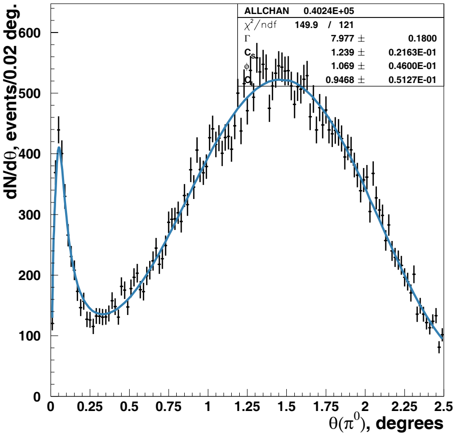
Lead

MIT/JLab Analysis: Radiative Widths for Carbon and Lead



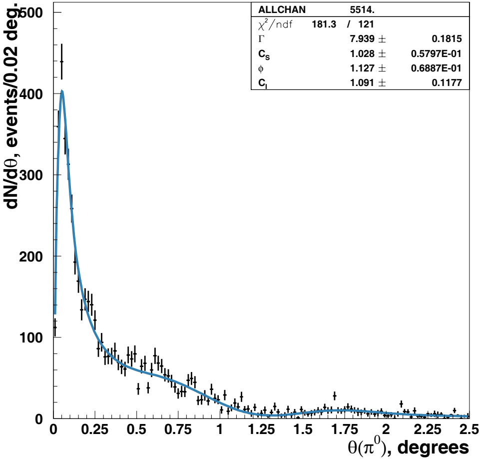


ITEP/NCA&T Analysis: Radiative Width for Carbon



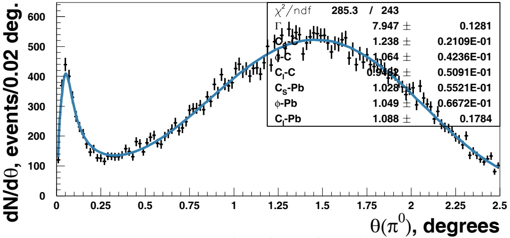
- *All possible cluster combinations.*
- *Elasticity imposed.*
- *HYCAL – tagger timing < 4 nsec.*

ITEP/NCA&T Analysis: Radiative Width for Lead

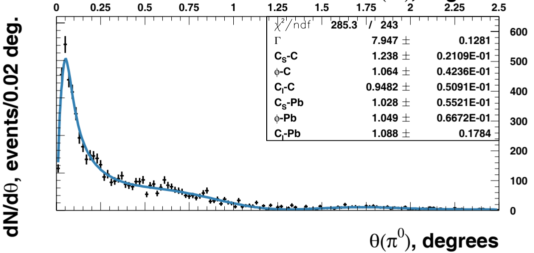


ITEP/NCA&T Analysis: Radiative Width Combined Fit for Carbon and Lead

Carbon



Lead



Sample Error Budget

Target thickness and density	0.05
Target material (impurity)	0.05
Admixture of ^{13}C	0.1
Photon flux	1.0
Beam energy uncertainty	0.13
Beam position uncertainty	negligible
Beam angle uncertainty	0.1
Beam divergence uncertainty	0.3
Branching ratio	0.03
Pion production angle resolution	0.25
HYCAL response function	0.5
HYCAL z uncertainty	0.4
Trigger efficiency	0.1
MC efficiency (limited statistics)	0.3
MC efficiency (target absorption)	0.27
Event loss – best in time cut	0.3
Energy cut for single photon	0.2
Energy cut for pion	negligilble
Timing cut	1.0
Pion mass fit	1.0
Coherent cross section energy dependence	0.1
Form Factor uncertainty	0.2
Incoherent production uncertainty	<1.0
Omega and rho subtraction	0.24
Total	**2.2**

Summary

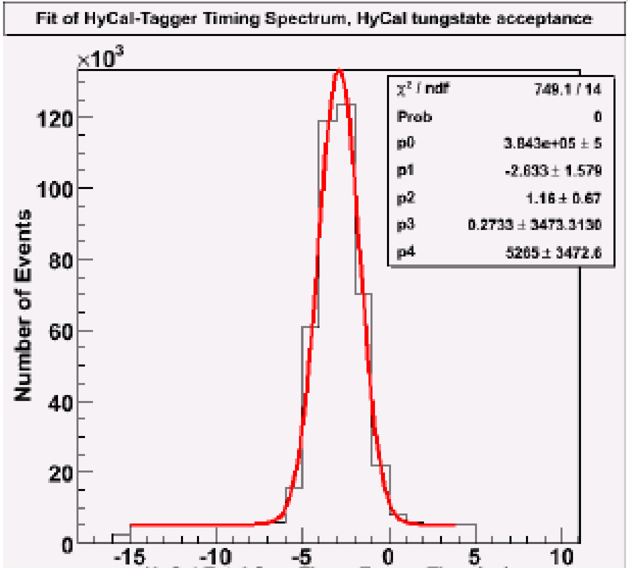
- The neutral pion lifetime is a stringent test of confinement scale QCD.
- High precision of the experiment has pushed the limits of photon calorimetery, luminosity monitoring, and QED calculations.
- Experimental systematic errors controlled by pair production and Compton scattering.
- High quality data taken in late 2004. Three quasi-independent analyses.
- Our preliminary result is:

Γ = **7.93 eV ± 2.1% (stat) ± 2.2% (sys)**

- In good agreement with QCD sum rule and ChPT predictions.
- Further studies of backgrounds underway.

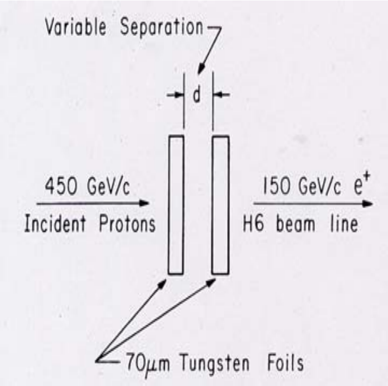
Extra Slides

PDF1: HYCAL – Tagger timing



Previous Experiment: The Direct Method

(Phys. Lett., vol 158B, no. 1, 81, 1985)

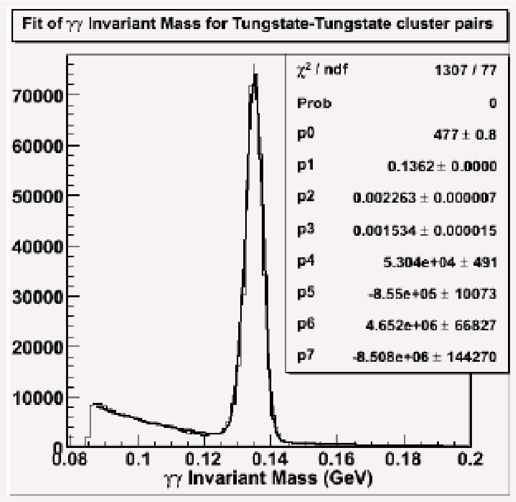


- ***π^o`s produced by 450 GeV protons in tungsten foils.***
- ***π^o decays observed by detection of 150 GeV/c positrons produced by decay γ rays converting in foils.***

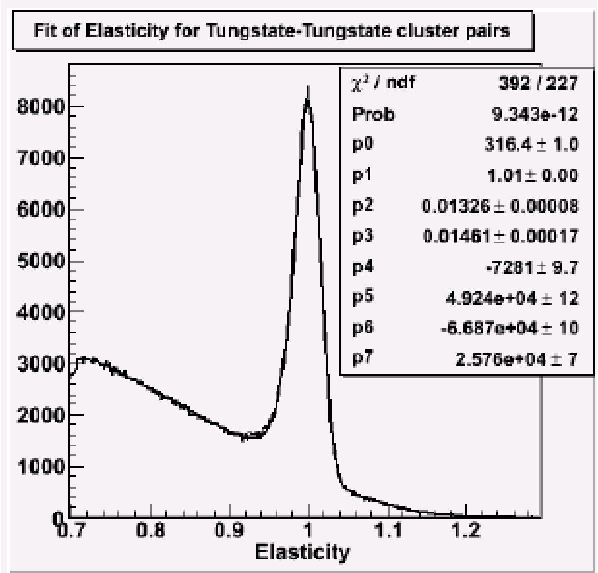
$$Y(d) = N[A + B(1-e^{-d/\lambda})]$$

A: Dalitz decay, γ conversion in first foil

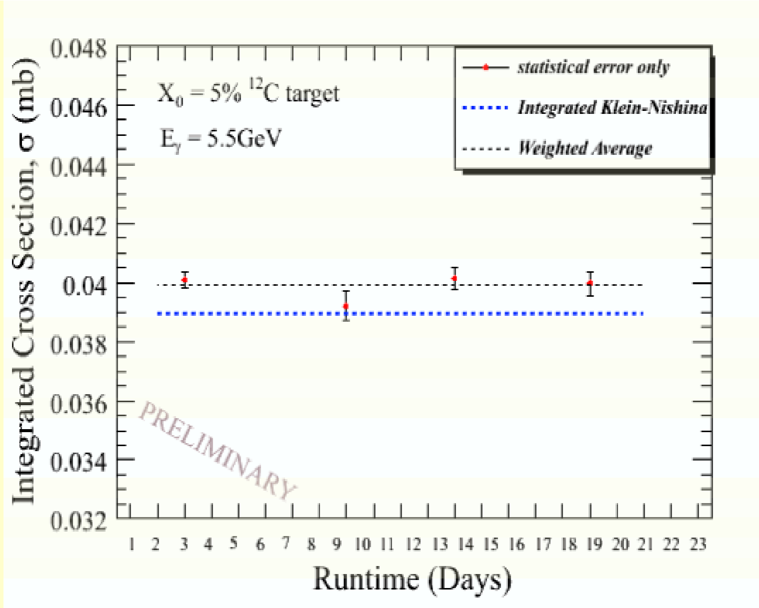
PDF 3: Invariant mass



PDF 2: Elasticity



Compton Scattering--Stability of Setup



Error budget entry	Contribution [%]
Target thickness and density	0.05
Target material (impurity)	0.05
Admixture of ^{13}C	0.1
Electron flux	1.0
Beam energy uncertainty within T_counters	0.13
Beam position uncertainty	negligible
Beam slope uncertainty	0.1
Beam divergence (width) uncertainty	0.3
π^0 branching ratio	0.03
π^0 prod. angle resolution	0.25
Hycal response function	0.5
Hycal z uncertainty	0.4
Trigger efficiency	0.1
MC efficiency simulations (limited statisctics)	0.3
MC efficiency simulations (absorption in target)	0.27
ADC channels status during the run	negligible
Misidentified beam particles	
Lost beam particles by taking only "the best in time beam candidate"	0.3
Energy cut for single γ	0.2
Energy cut for π^0	negligible
Timing cut	1.0
π^0 mass fit (exctraction of number of π^0s)	1.
Coherent cross section dependence on energy	0.1
Formfactors uncertainty	0.2
Incoherent production uncertainty	
π^0s from ω and ρ decays subtraction	0.24
Total	2.0