Measurement of the π^0 Lifetime: QCD Axial Anomaly and Chiral Corrections

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- spontaneous chiral symmetry breaking $\Rightarrow$ pions
- π^0 discovery, early experiments
- $\pi^0 \rightarrow \gamma\,\gamma$: axial anomaly, chiral corrections $\sim m_d - m_u$
- previous lifetime experiments
- PrimEx experiment at Jefferson Lab
- possibilities at Frascati
- conclusions

Reviews of Modern Physics Jan. 2013

Chiral Symmetry

L_{QCD} invariant under global chiral phase transformation

$\psi_L \rightarrow \exp(-\alpha_L)\, \psi_L$

spontaneously broken (hidden)

PCAC: partially conserved axial current

Axial UA(1) Symmetry $\psi \rightarrow \exp(-i\theta\gamma_5)\, \psi$

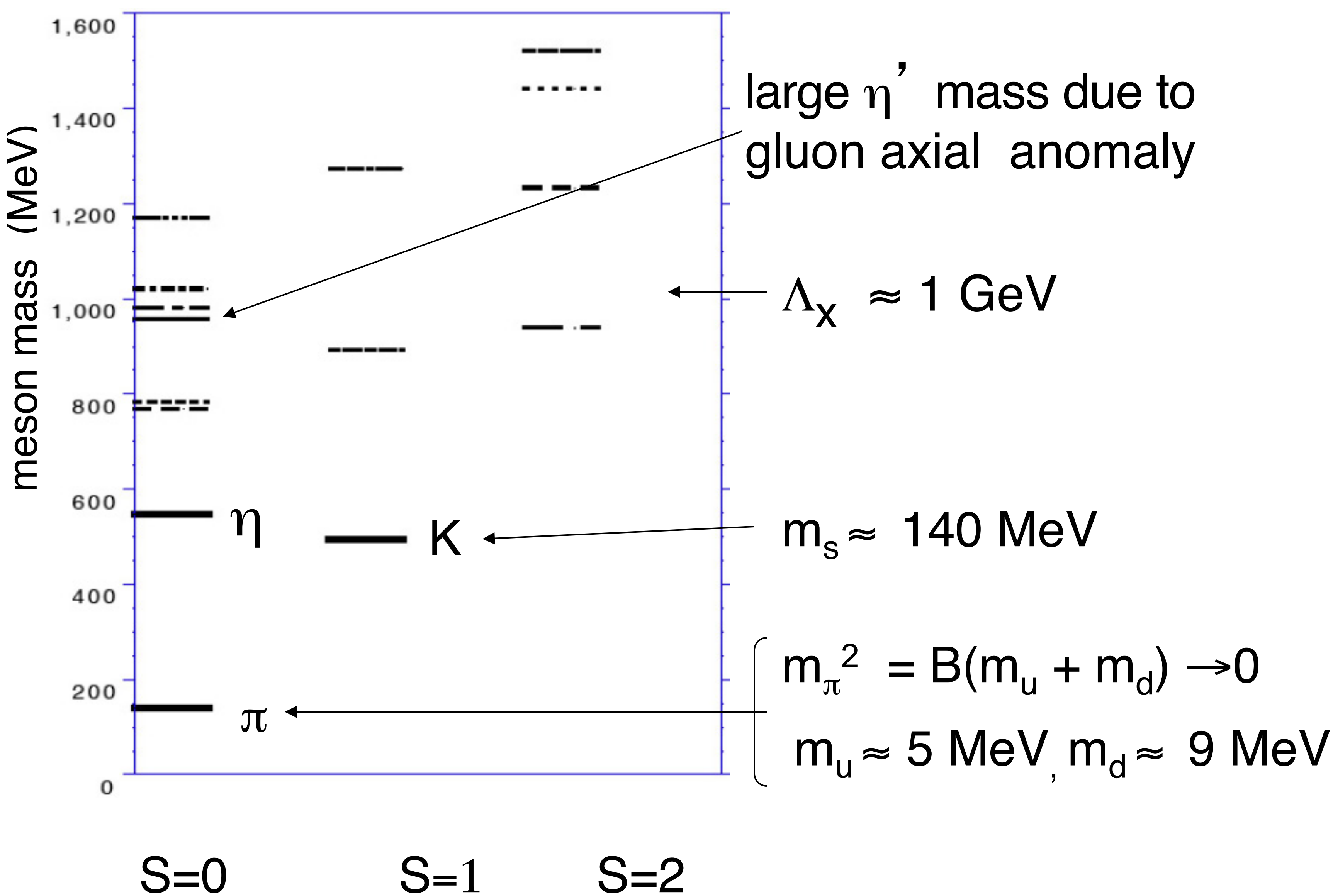
completely broken by quantum effects

divergence of the axial current $\neq 0$

$M\eta' \neq 0$ in chiral limit

$\Gamma(\pi^0 \rightarrow \gamma\,\gamma)$ dominated by axial anomaly

meson mass gap: QCD chiral symmetry breaking



Opportunity to perform a precision π^0 lifetime measurement

- π^0 is the lightest hadron
  spontaneous chiral symmetry hiding:
  $m(\pi) \approx 140$ MeV

- EM: $m(\pi^{\pm}) - m(\pi^0) = 4.6$ MeV

- EM decay $\pi^0 \rightarrow \gamma\ \gamma$ (BR $= 98.8 \pm 0.032\%$)
  axial anomaly dominant

Pion Discovery and Early History

- 1947: π^+ discovered with photographic emulsions in cosmic rays. $\pi^+ \to \mu^+ + \nu_\mu$ observed [Lattes]

- 1950: π^0 discovered at Berkeley (pA, γA, stopped π^-p) and cosmic rays, and the following observations were made:

- The value of $m(\pi^+) - m(\pi^0) = 5.42 \pm 1.02 MeV$ [present value =4.59 MeV]

- $\sigma(\gamma p \to \pi^0 p) \simeq \sigma(\gamma p \to \pi^+ n)$, indicating that the π^0 and π^+ mesons are "of the same type" and therefore the π^0 meson is a pseudoscalar.

- The soft component of the cosmic rays is due to the production and decay of π^0 mesons.

- A lower limit for the lifetime $\tau(\pi^0) < 5 \cdot 10^{-14}$ sec was established by a measurement of the geometric size of the decay region.

Techniques: π^0 Lifetime Experiments

- direct measurement of π^0 decay distance

early measurements used Dalitz decay $\pi^0 \rightarrow \gamma e^+ e^-$

- Primakoff effect $\gamma \gamma \rightarrow \pi^0$
- colliding beams $e^+e^- \rightarrow \gamma \gamma \rightarrow \pi^0$
- None of the early experimental papers refer to theoretical calculations!

stopped $K^+ \rightarrow \pi^+ \pi^0$ $\pi^0 \rightarrow \gamma e^+ e^-$

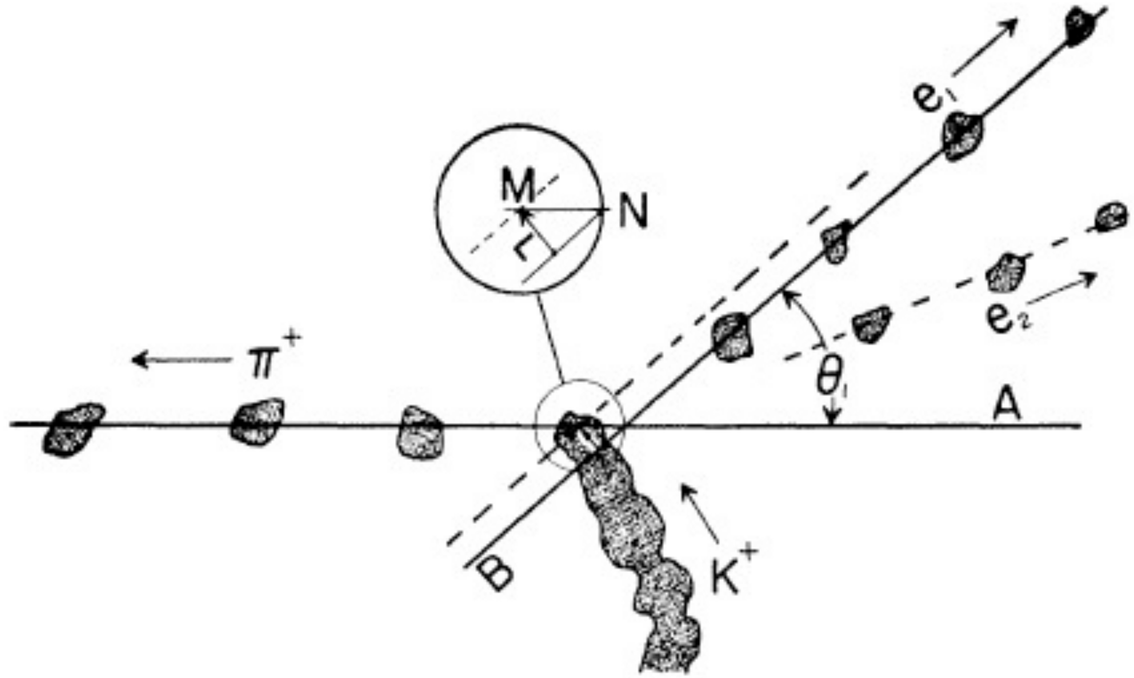
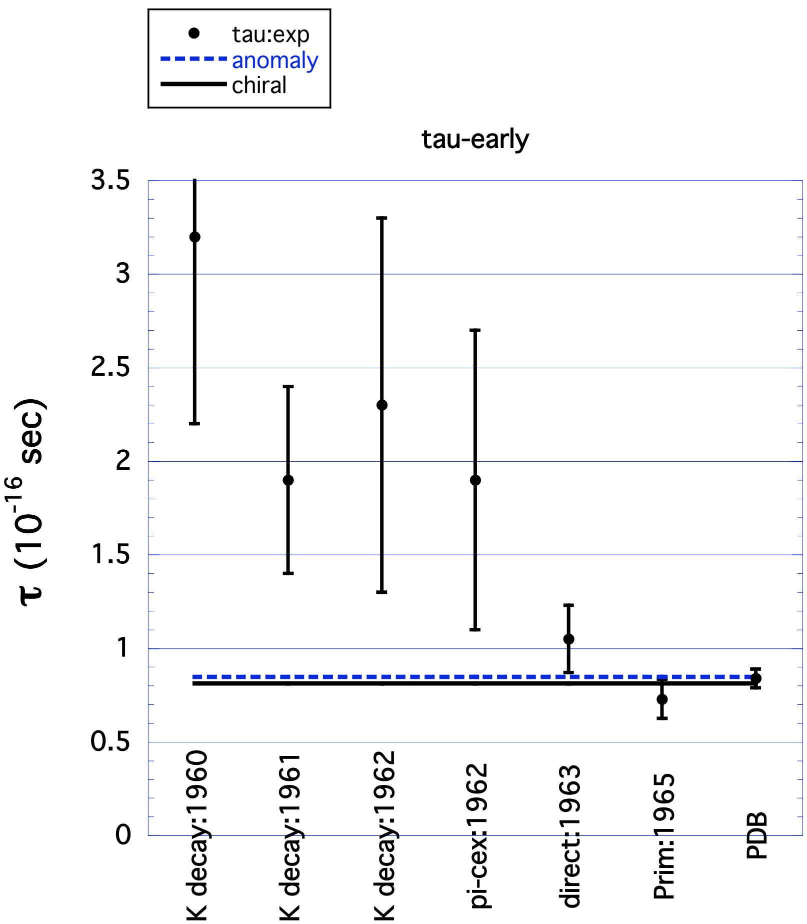


FIG. 2. Drawing to illustrate the measurement technique. A detailed explanation is given in the text. MN is the π^0 flight distance projected onto the emulsion plane. Its value is obtained from the measurement of L and θ.



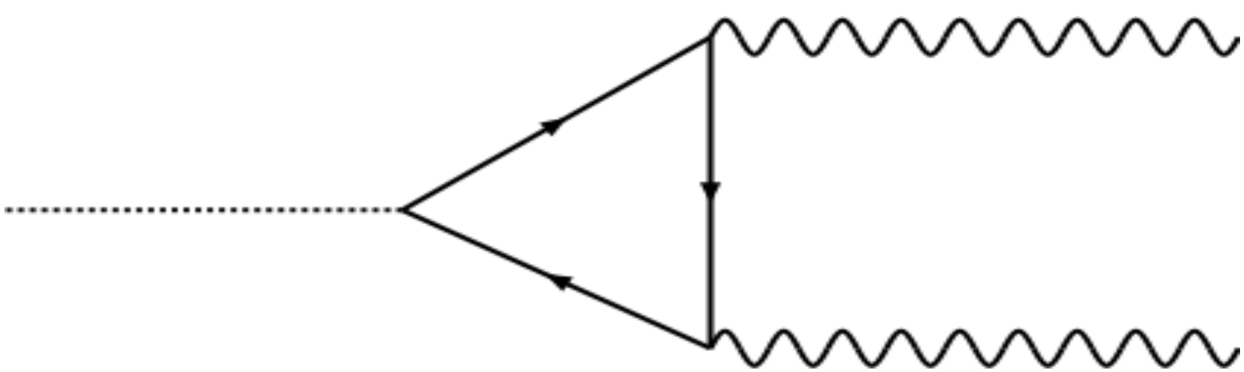
tau:exp
anomaly
chiral
tau-early
τ (10^-16 sec)
3.5
3
2.5
2
1.5
1
0.5
0
K decay:1960
K decay:1961
K decay:1962
pi-cex:1962
direct:1963
Prim:1965
PDB

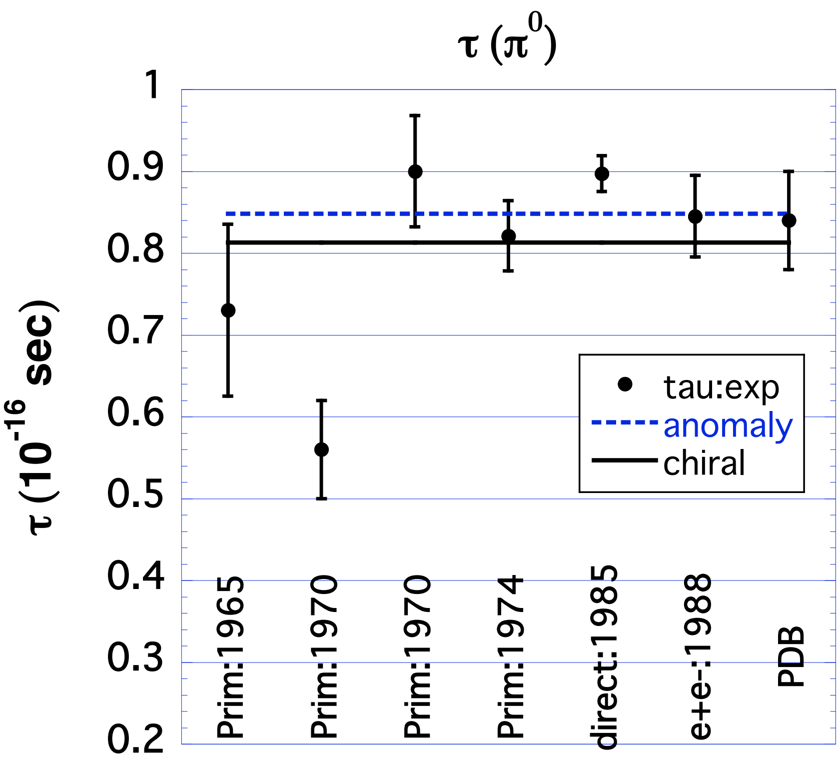
Axial Anomaly

Bell and Jackiw, Adler 1969

Chiral Symmetry is exact in the Lagrangian (for massless up and down quarks) but is lost in quantization

- $\Gamma(\pi^0 \rightarrow \gamma\,\gamma) = (m_\pi/4\pi)^3\,(\alpha\,/F_\pi)^2 = 7.76$ eV
- exact in the chiral limit m_u, m_d, $m_\pi \rightarrow 0$
- no adjustable constants
- chiral corrections ~ $(m_\pi\,/\,4\pi\,F_\pi\,)^2$ ~ 2 %




τ (π0)
τ (10-16 sec)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Prim:1965
Prim:1970
Prim:1970
Prim:1974
direct:1985
e+e-:1988
PDB
tau:exp
anomaly
chiral

Feb. 1999
PrimEx
Collab.
Meeting

π, η Mixing.

Mass eigenstates $\pi_3 \quad \eta_8 \quad \eta_0$

observed particles $\pi \quad \eta \quad \eta'$

$$|\pi^0\rangle \cong |\pi_3\rangle + \theta_8 |\eta_8\rangle + \theta_0 |\eta_0\rangle$$

$$\langle\gamma\gamma|A|\pi^0\rangle = \langle\gamma\gamma|A|\pi_3\rangle + \theta_8 \langle\gamma\gamma|A|\eta_8\rangle + \theta_0 \langle\gamma\gamma|A|\eta_0\rangle$$

relative $\gamma\gamma$ amplitudes

$$\langle 0| Q_u^2 + Q_d^2 + Q_s^2 | N^0\rangle$$

$$\pi^0 : \eta^8 : \eta^0 = 1 : \frac{1}{\sqrt{3}} : 2\sqrt{\frac{2}{3}}$$

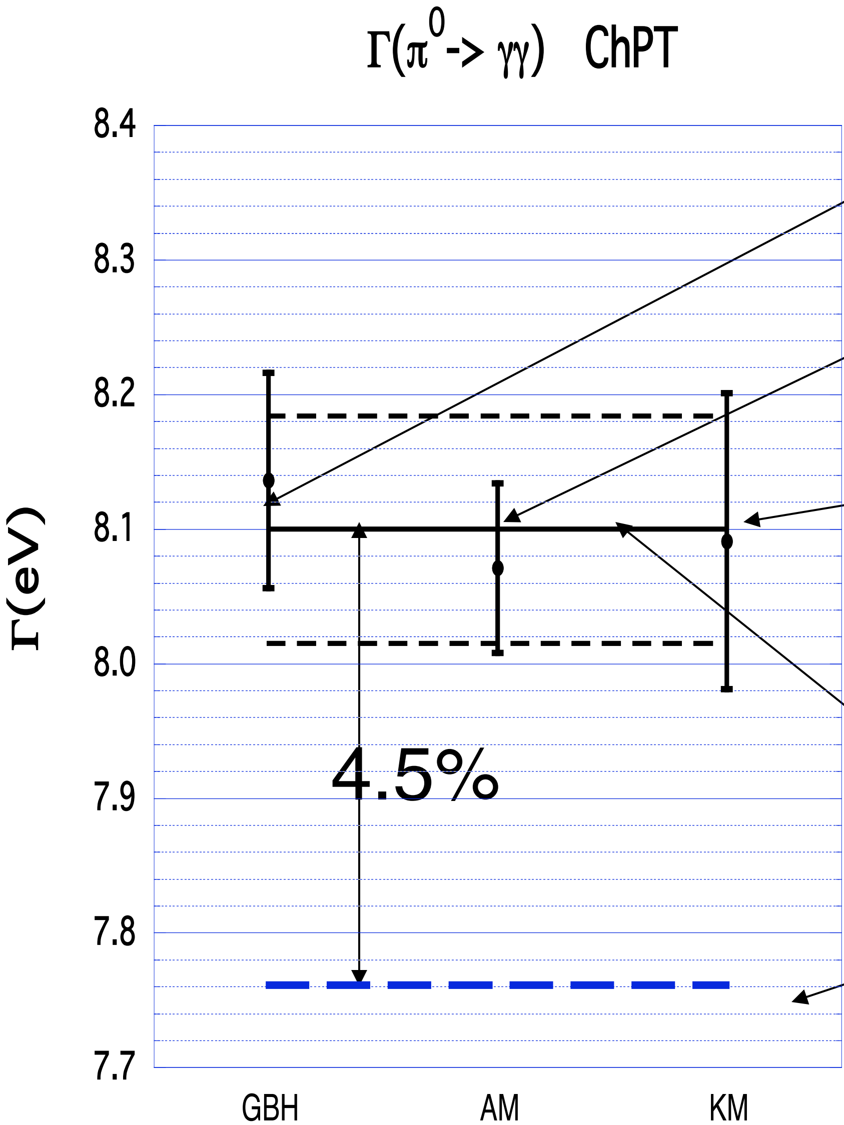
$$\theta_8 = \frac{\sqrt{3}}{4} \frac{(m_u - m_d)}{(m_s - \hat{m})} \cong 0.010 \ (0.016)$$

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

$$\theta_0 / \theta_8 \cong \sqrt{2} \left[\frac{m(\eta)}{m(\eta')}\right]^2 \cong 0.44$$

$$\delta A / A \cong +1.3\% \ (2.1\%)$$

Chiral calculations $\Gamma(\pi^0 \rightarrow \gamma\gamma)$: π,η,η'



ChPT: Goity, AB, Holstein: $O(p^6)$, $O(p^4 \bullet 1/N_c)$

sum rules: Ananathanarayan, Moussallam

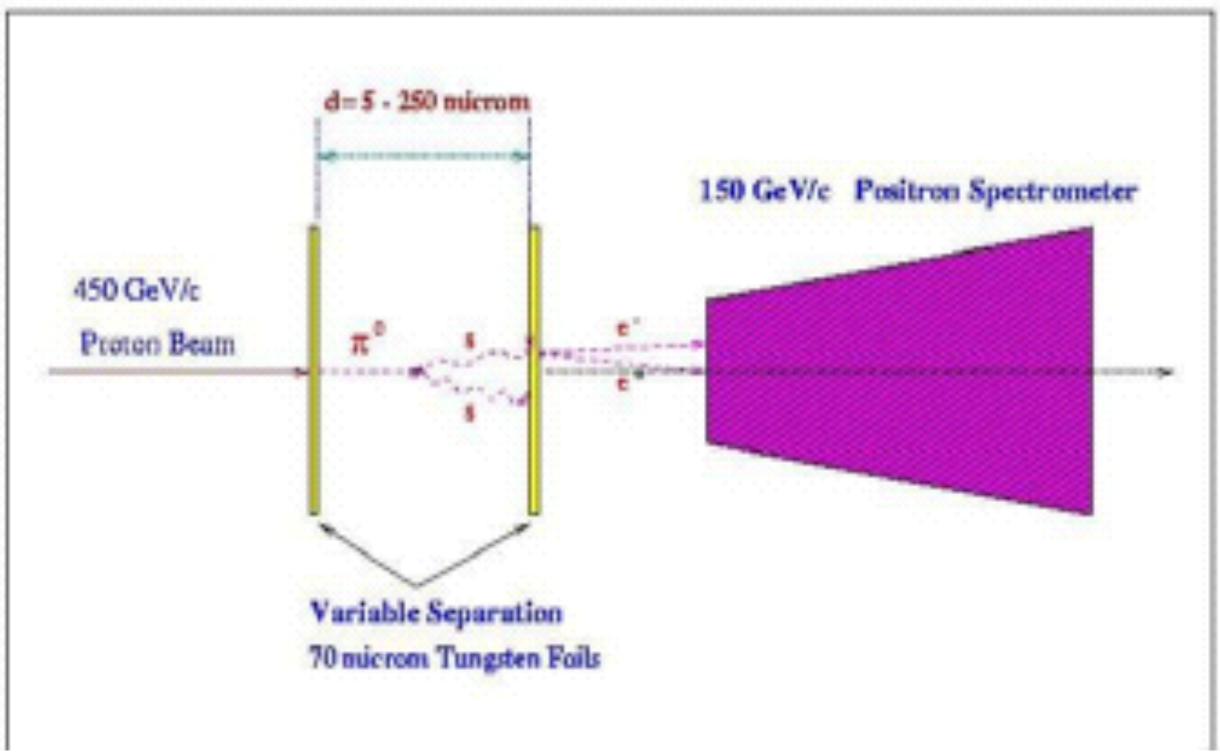
ChPT(2 flavor): Kampf, Moussallam

ChPT average(LEC errors)

Anomaly, $O(p^4)$

CERN: Direct lifetime measurement: PL 1985

$E = 450$ GeV $\langle p\_\pi^0 \rangle \approx 240$ GeV $\langle \gamma \rangle \approx 1700$ $\langle d \rangle \approx 45u$



$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.34\text{eV} \pm 3.1\%(\text{total})$,

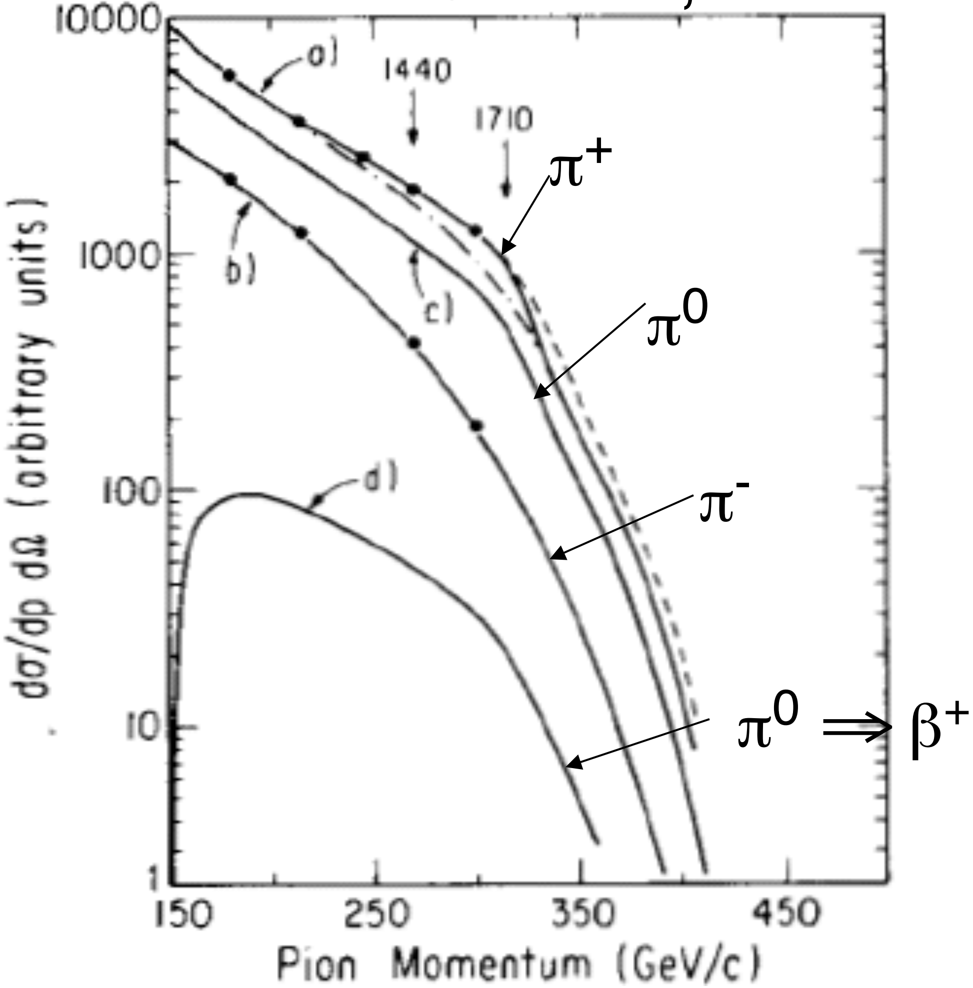
Dominant systematic error:

Uncertainty in P_π ($\pm 1.5\%$)

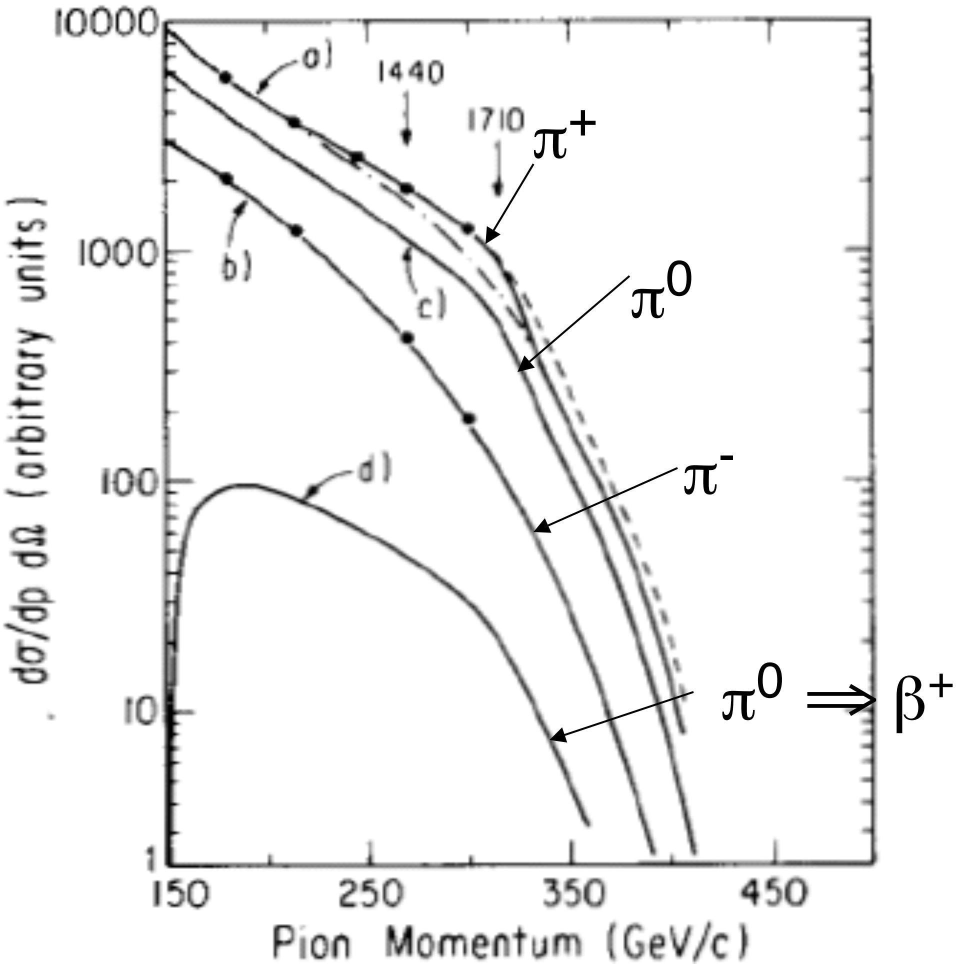
statistical $\pm$ 2.45%

systematic $\pm$ 1.9%

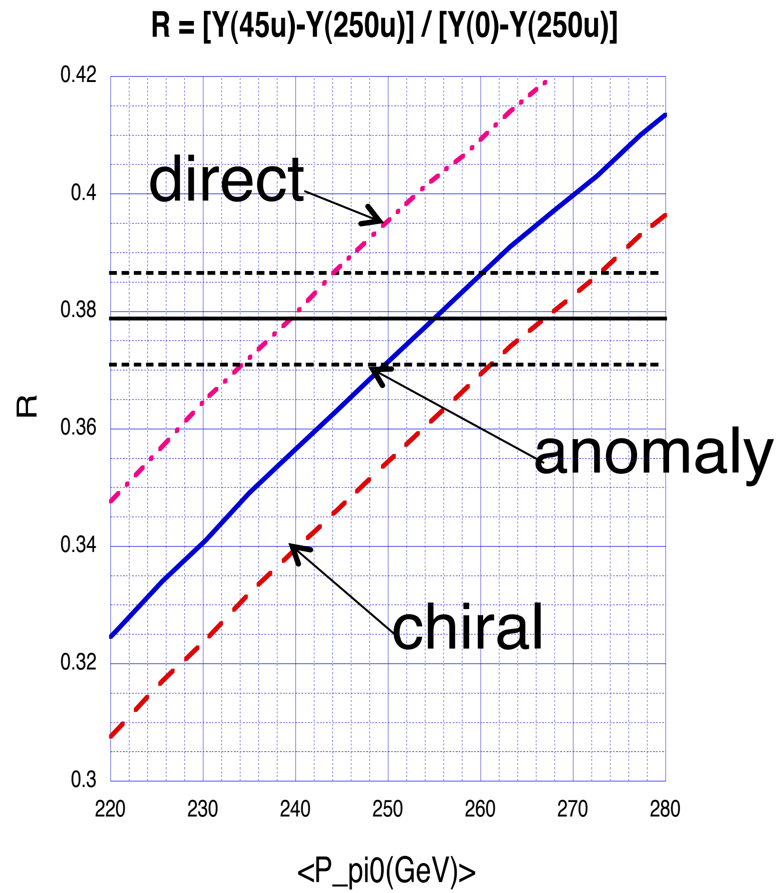
π^0 spectrum derived from measured π^+, π^-



π^0 spectrum derived from measured π^+, π^-

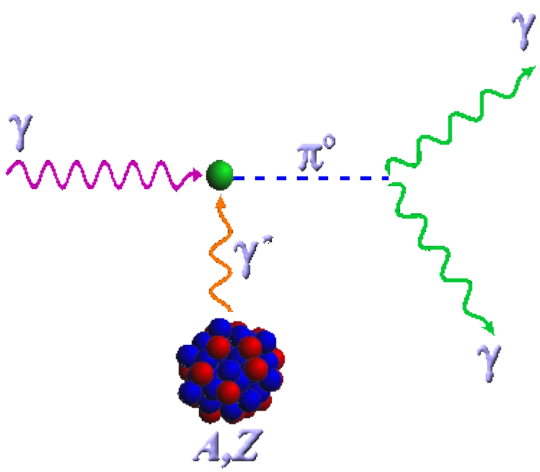


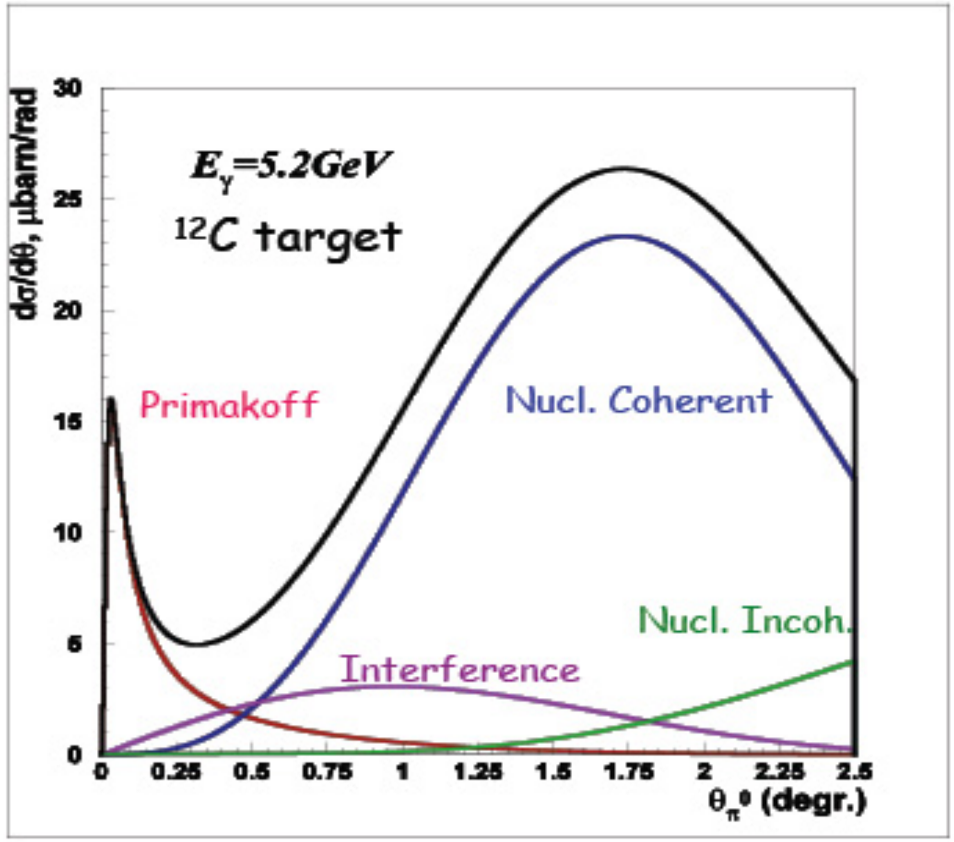
$<p\_\pi^0> \approx$ 240 GeV ?



$\sigma(\gamma A \rightarrow \pi^0 X)$

Primakoff + nuclear





$\sigma_{prim}(\theta_\pi) \propto \Gamma_{\gamma\gamma} Z^2 \ E_\gamma{}^4 \sin^2(\theta_\pi)/Q^4$ Q= mom.trans.

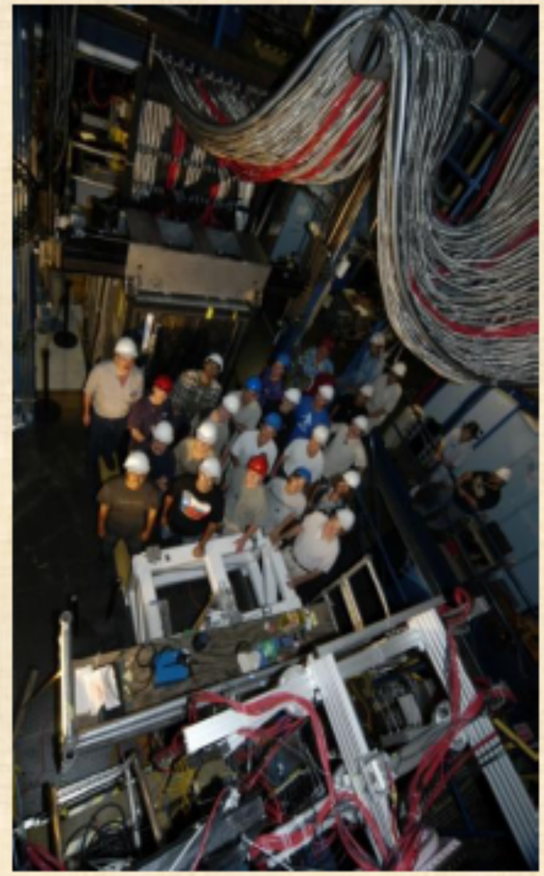
$\sigma\ (\theta_\pi) = |\ A_{prim} + e^{i\phi} A_{nc}|^2 \ + \sigma_{incoherent}$

fit data with 4 parameters; $\Gamma_{\gamma\gamma}$, ϕ,

scale factors for nuclear coherent and incoherent

PrimEx Collaboration

Arizona State University, Tempe, AZ, Catholic University of America, Washington, DC, Chinese Institute of Atomic Energy, Beijing, China, Eastern Kentucky University, Richmond, KY, George Washington University, Washington, DC, Hampton University, Hampton, VA, Institute for High Energy Physics, Chinese Academy of Sciences, Beijing, China, Institute for High Energy Physics, Protvino, Moscow region, Russia, Institute for Theoretical and Experimental Physics, Moscow, Russia, Kharkov Institute of Physics and Technology, Kharkov, Ukraine, Massachusetts Institute of Technology, Cambridge, MA, Moscow Engineering Physics Institute, Moscow, Russia, Norfolk State University, Norfolk, VA, North Carolina A&T State University, Greensboro, NC, North Carolina Central University, Durham, NC, Thomas Jefferson National Accelerator Facility, Newport News, VA, Tomsk Polytechnic University, Tomsk, Russia, Idaho State University, Pocatello, ID, University of Illinois, Urbana, IL, University of Kentucky, Lexington, KY, University of Massachusetts, Amherst, MA, University of North Carolina at Wilmington, Wilmington, NC, University of Virginia, Charlottesville, VA, Yerevan Physics Institute, Yerevan, Armenia



Ph.D. students, postdocs

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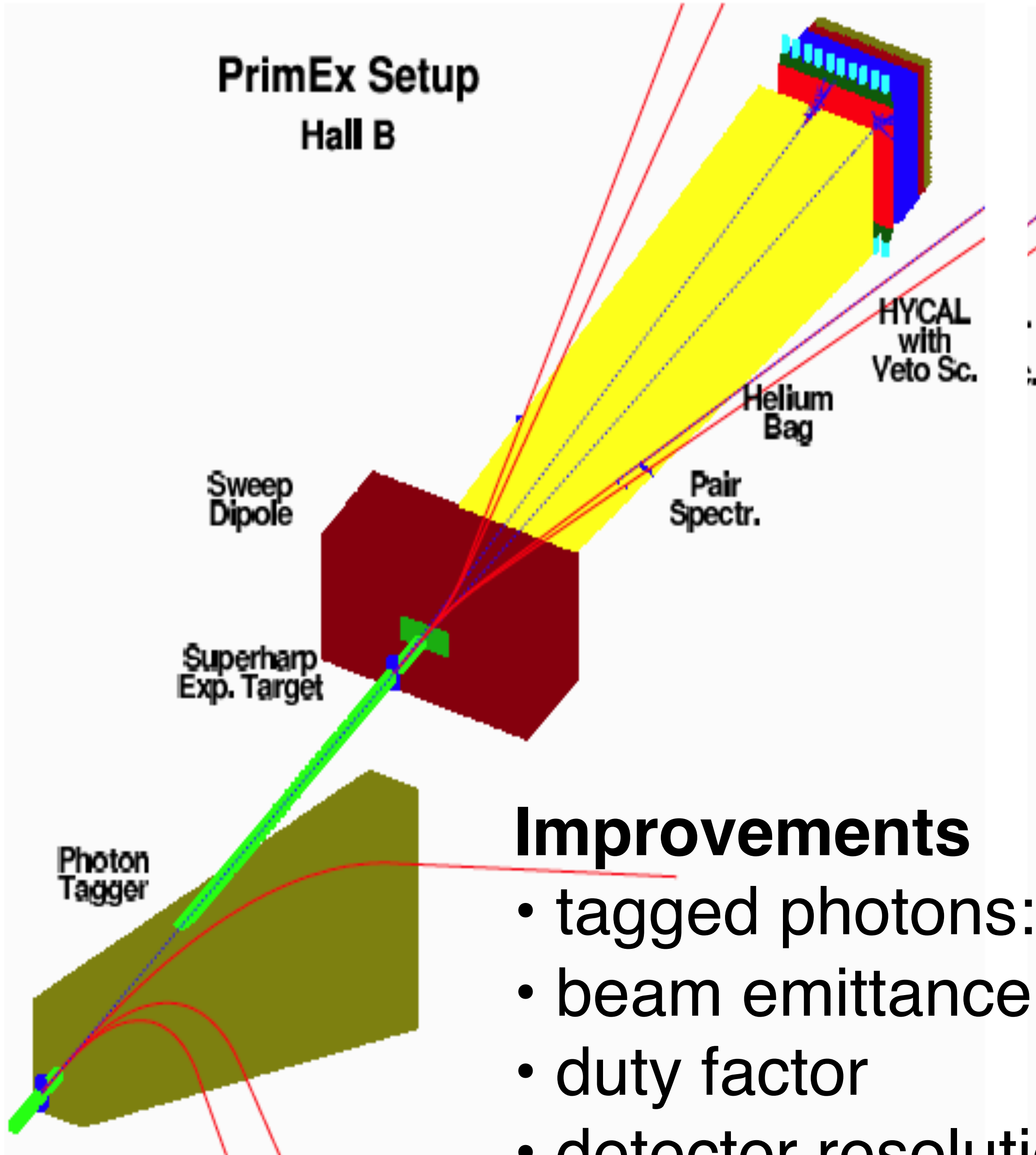
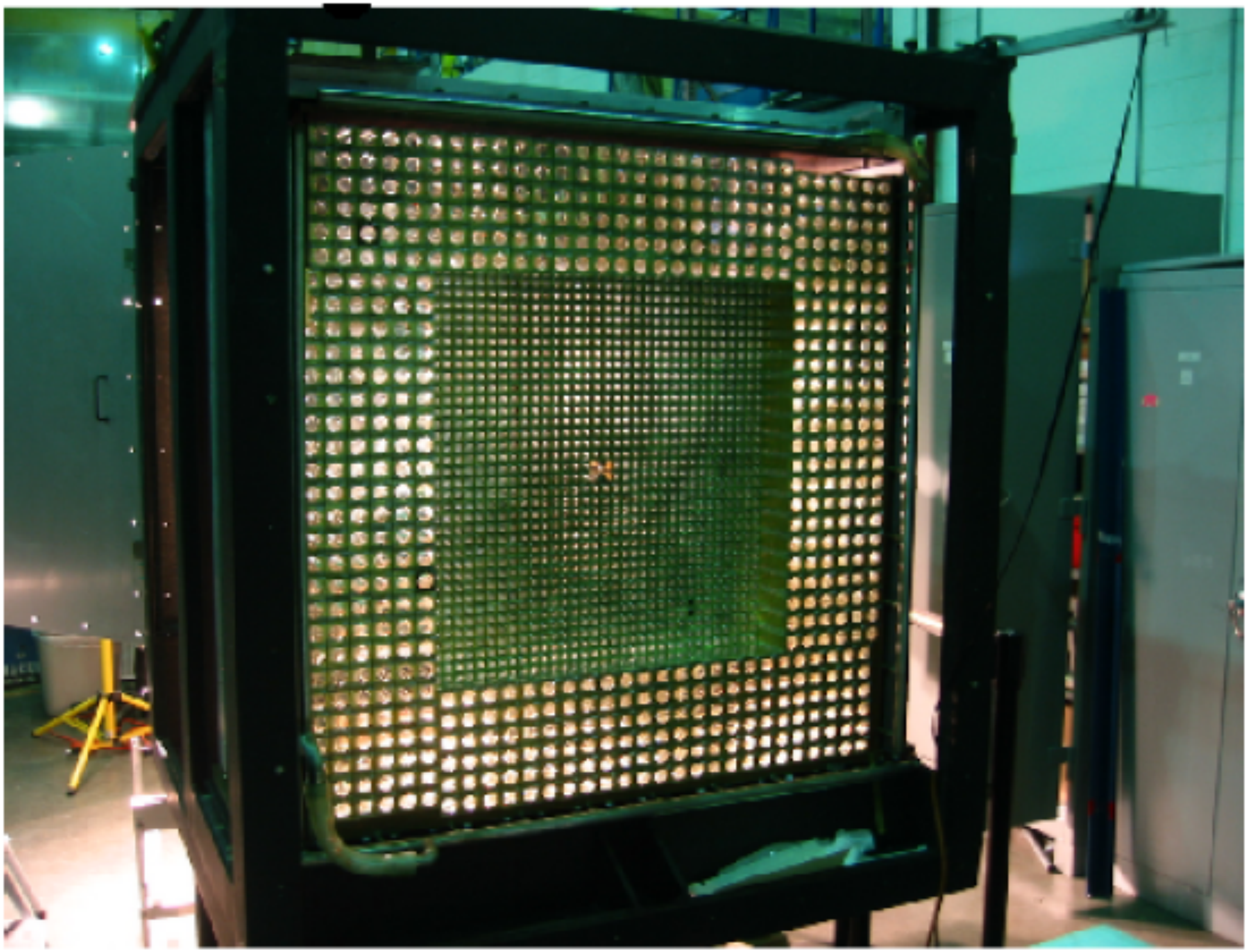
EXPERIMENTAL SETUP

- DATA TAKING FALL 2004
- C, Pb TARGETS
- JLAB HALL B PHOTON TAGGING FACILITY - HIGH INTENSITY, HIGH RESOLUTION DEVICE
- STATE-OF-THE-ART CALORIMETRY - HyCal
- PAIR SPECTROMETER

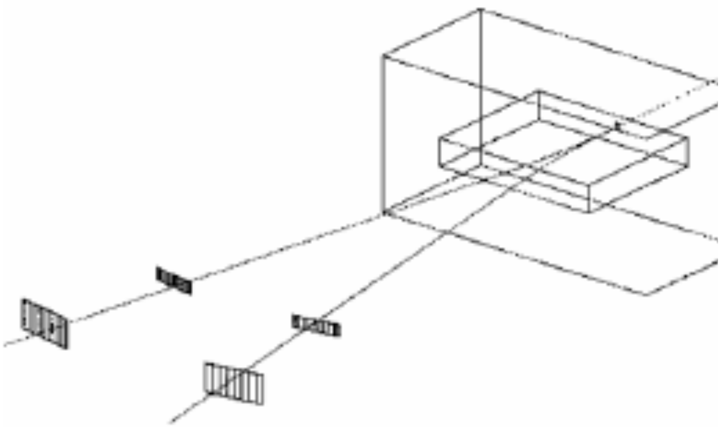


Improvements

- tagged photons:0.1%
- beam emittance
- duty factor
- detector resolution

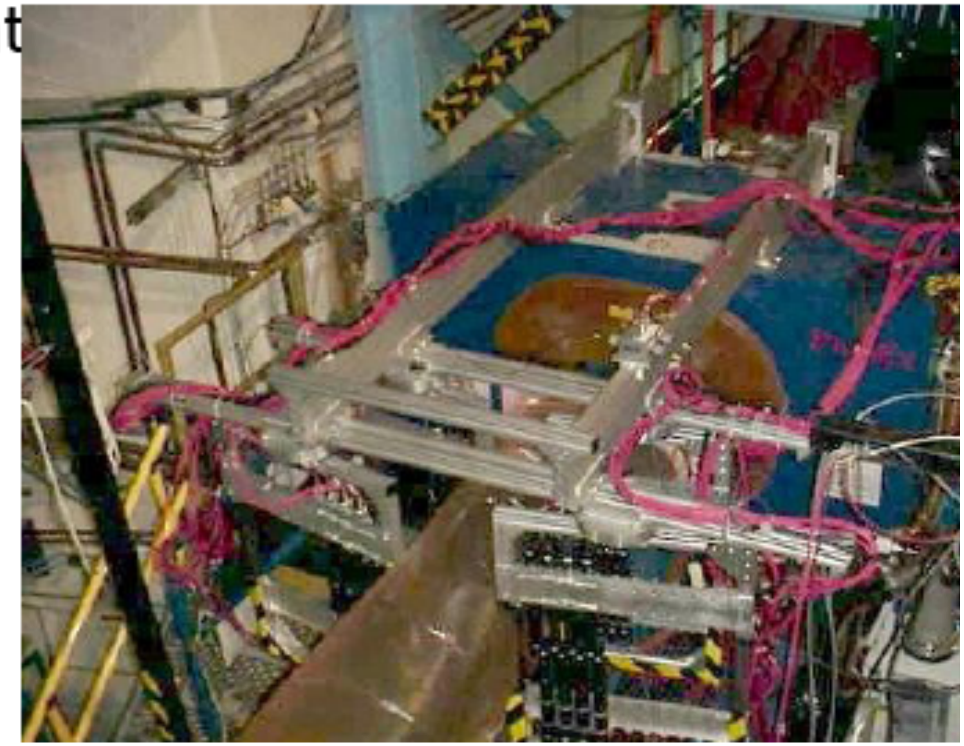


Pair Spectrometer



- 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

π^0 analysis

We measure:

incident photon: energy and time

π^0 decay photons:

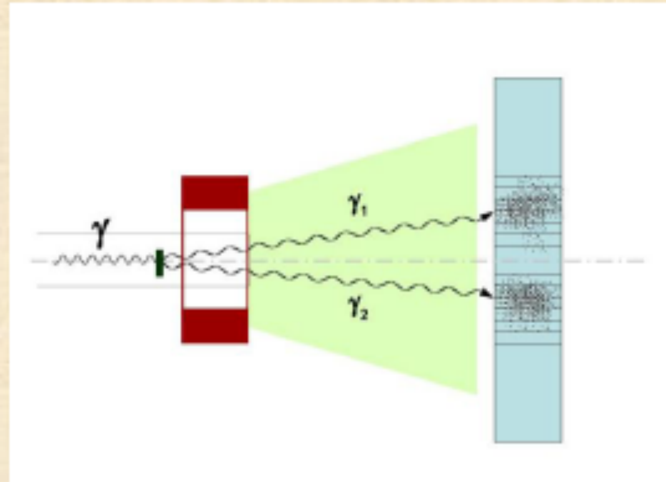
energies, coordinates and time

Kinematical constraints:

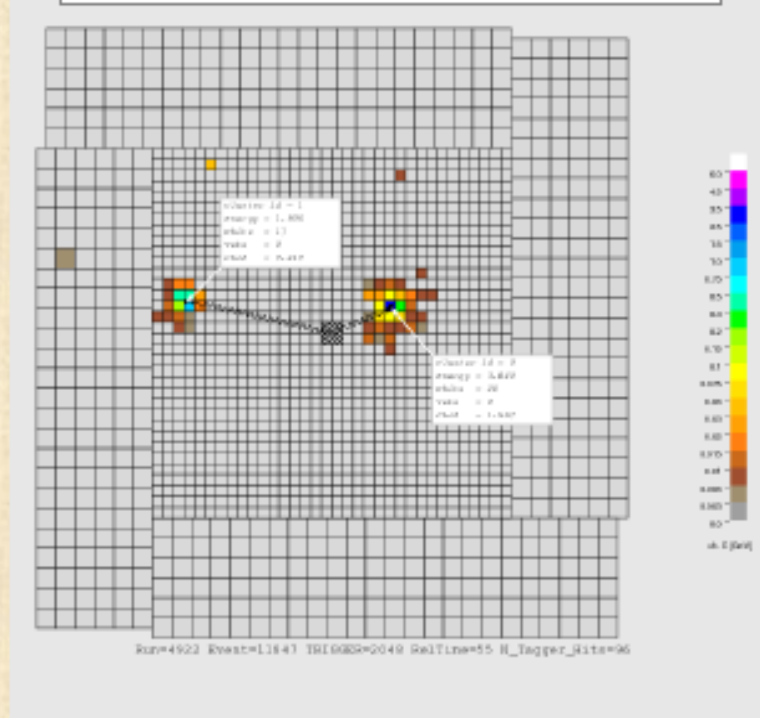
Conservation of energy;

$m_{\gamma\gamma}$ invariant mass

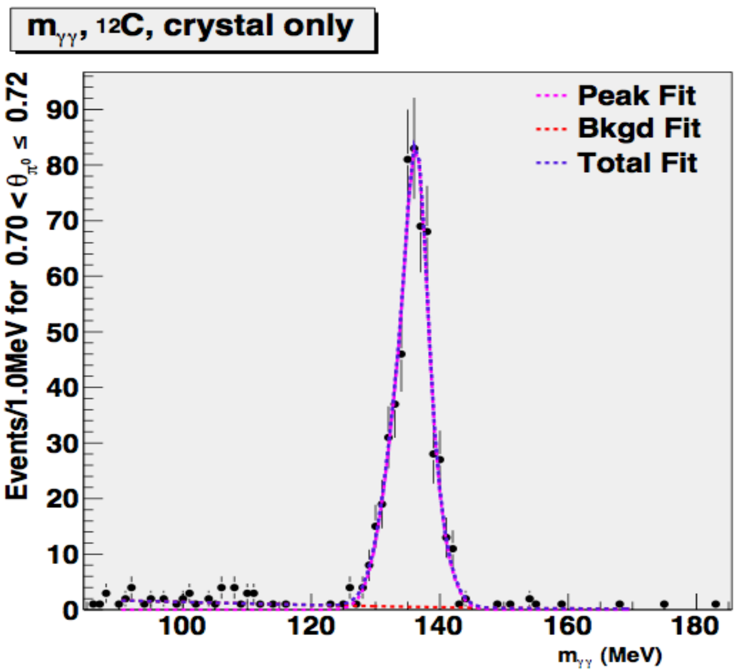
Three groups analyzed the data independently



Schematic view of π^0 event



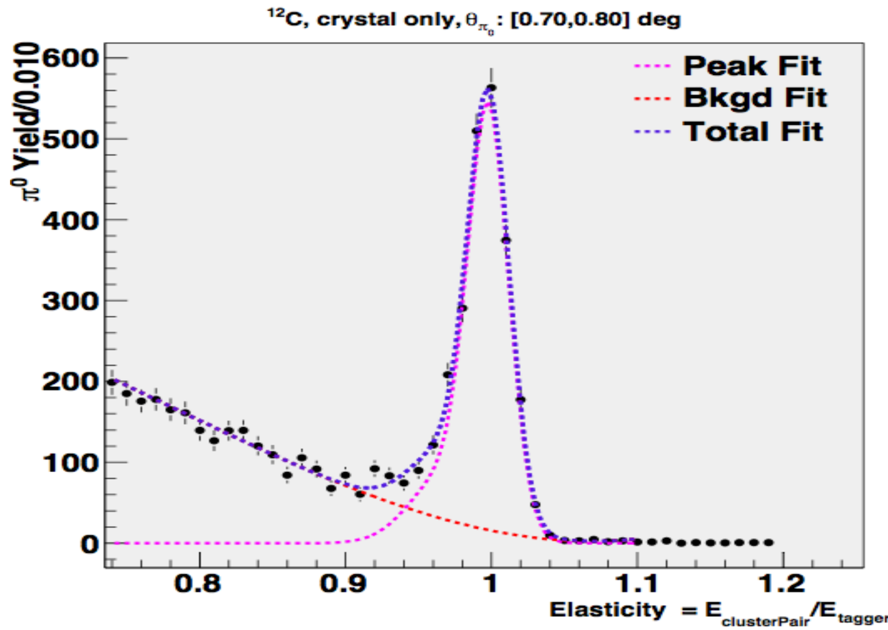
π^0 yield from data



$m_{\gamma\gamma}$

$m_{\gamma\gamma}^2 = (k_1+k_2)^2$

Elasticity distribution

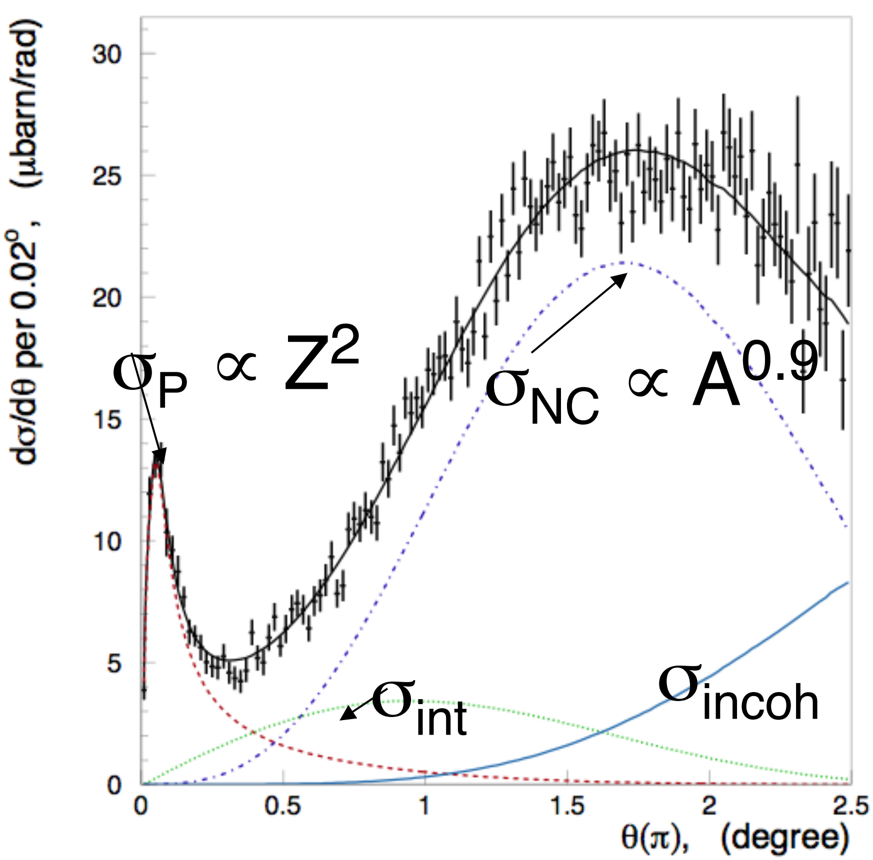


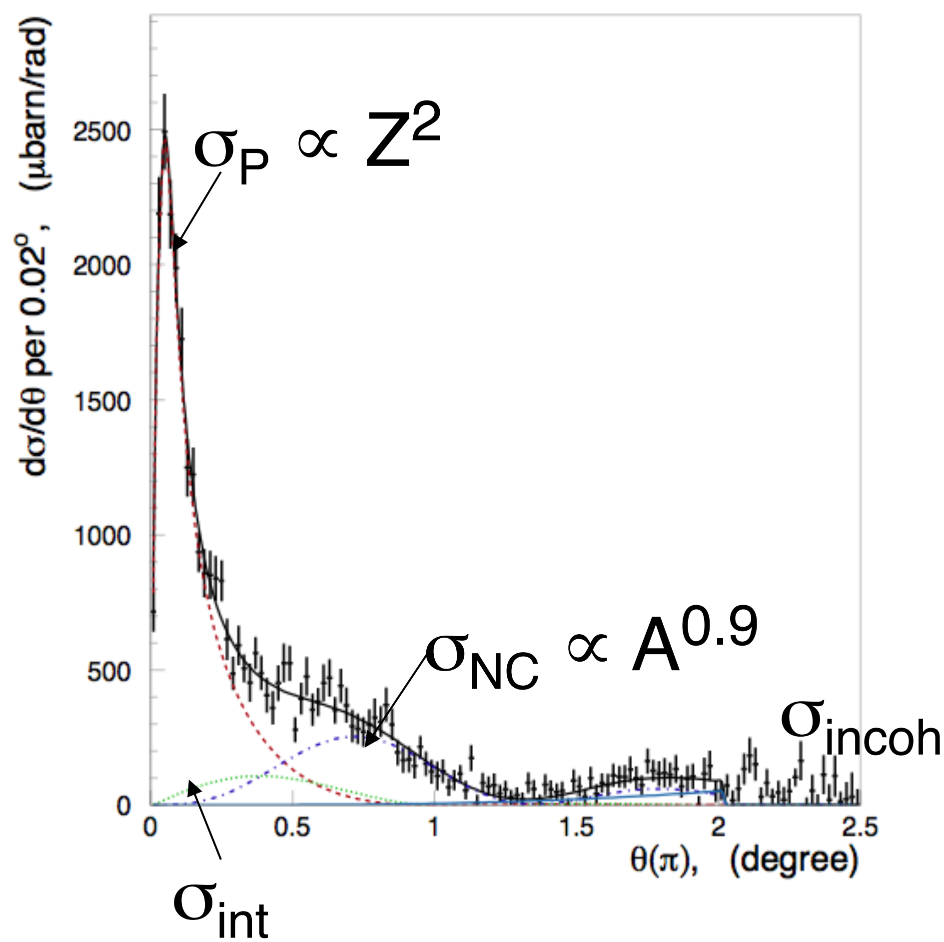
elasticity=E_π/k

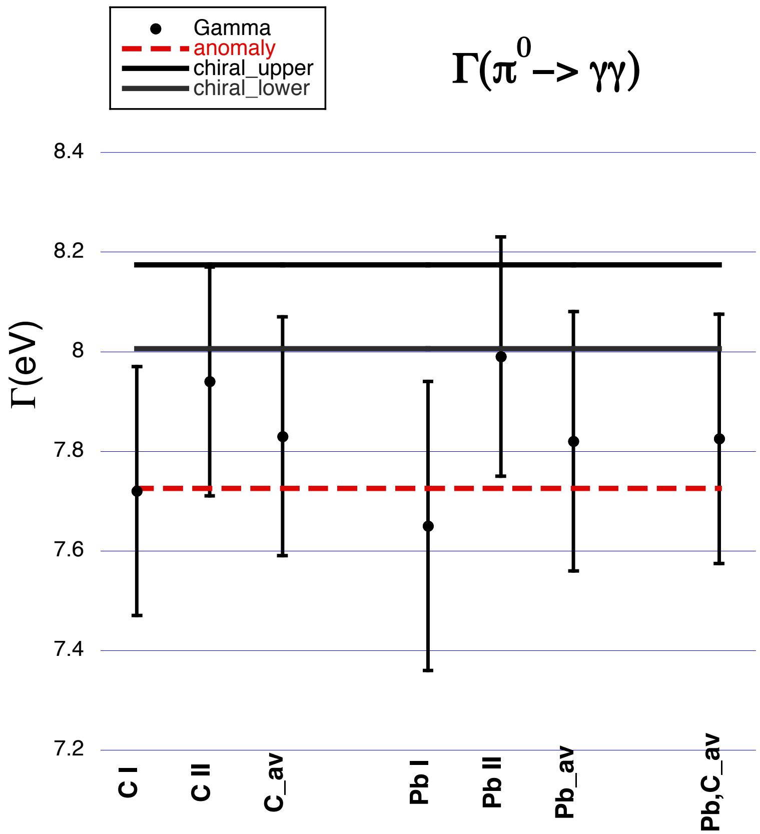
remove inelastic background

find N(π^0) from $m_{\gamma\gamma}$ peak

C and Pb cross sections
relative values of Prim and NC differ greatly
obtain equal values of Γ from both!







Gamma
anomaly
chiral_upper
chiral_lower
Γ(π0 -> γγ)
Γ(eV)
8.4
8.2
8
7.8
7.6
7.4
7.2
C I
C II
C_av
Pb I
Pb II
Pb_av
Pb,C_av

Systematic Errors

yield extraction: 1.6%

photon Flux: 1.0 %

……..

total in quadrature: 2.1%

checks: measure Compton scattering and pair production to < 2% accuracy

PrimEx result

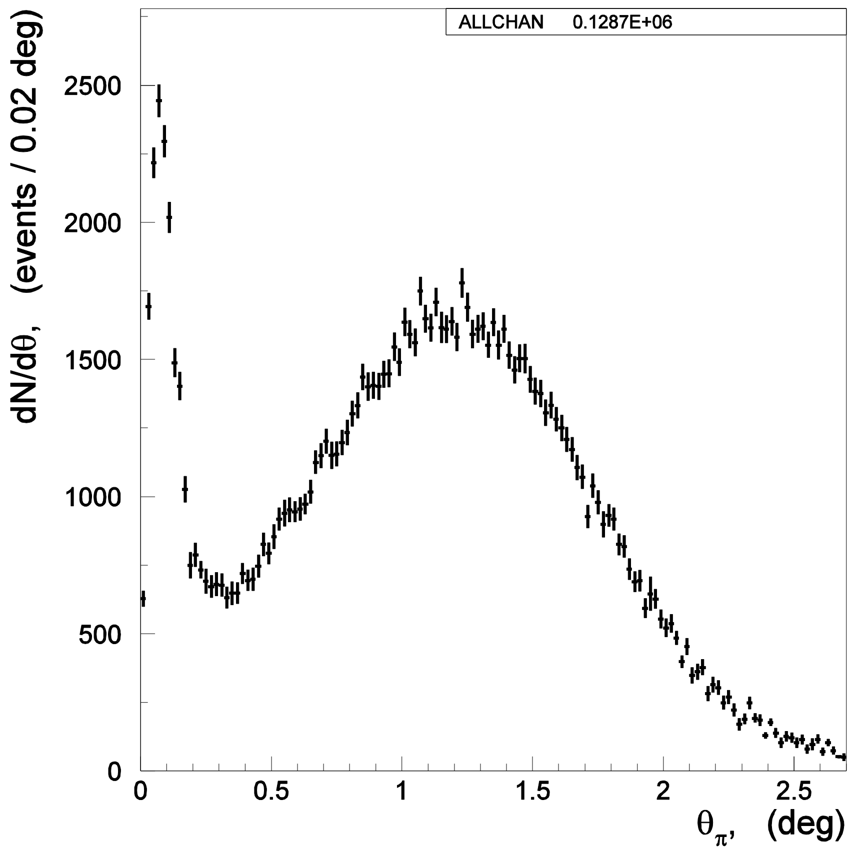
$\Gamma(\pi^0 \rightarrow \gamma\,\gamma)$=7.82eV± 1.8%(stat) ± 2.1%(sys)

[2.8% total]

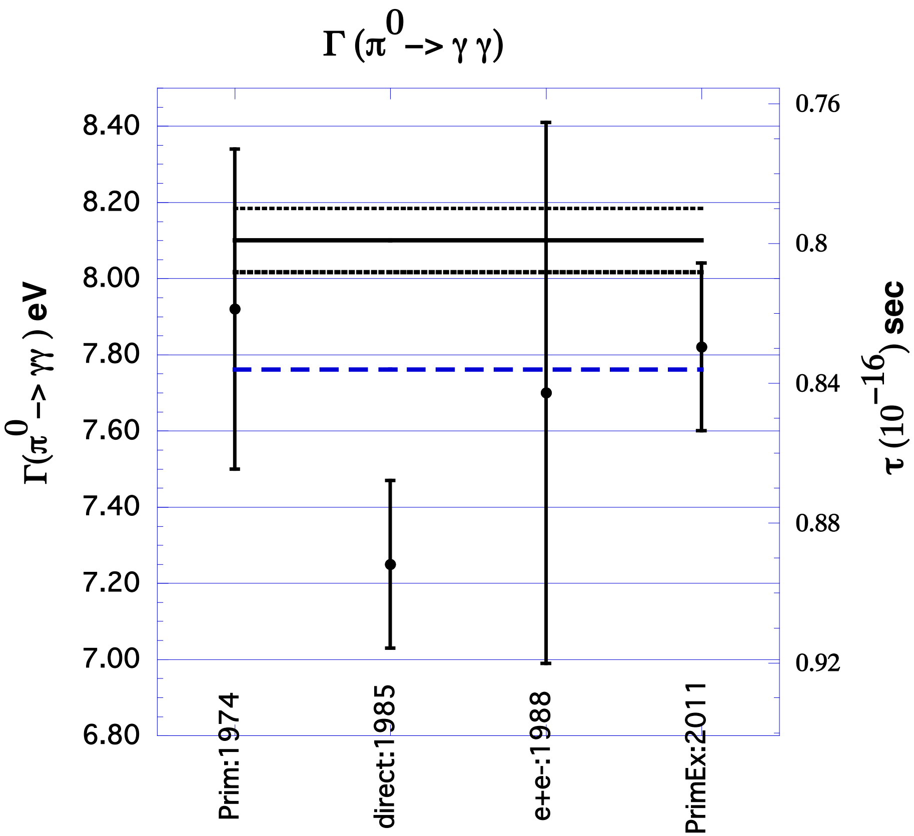
$\tau(\pi^0)$ =(0.832 ± 0.023)10^{-16} sec

PrimEx-II: experimental yield

^{28}Si

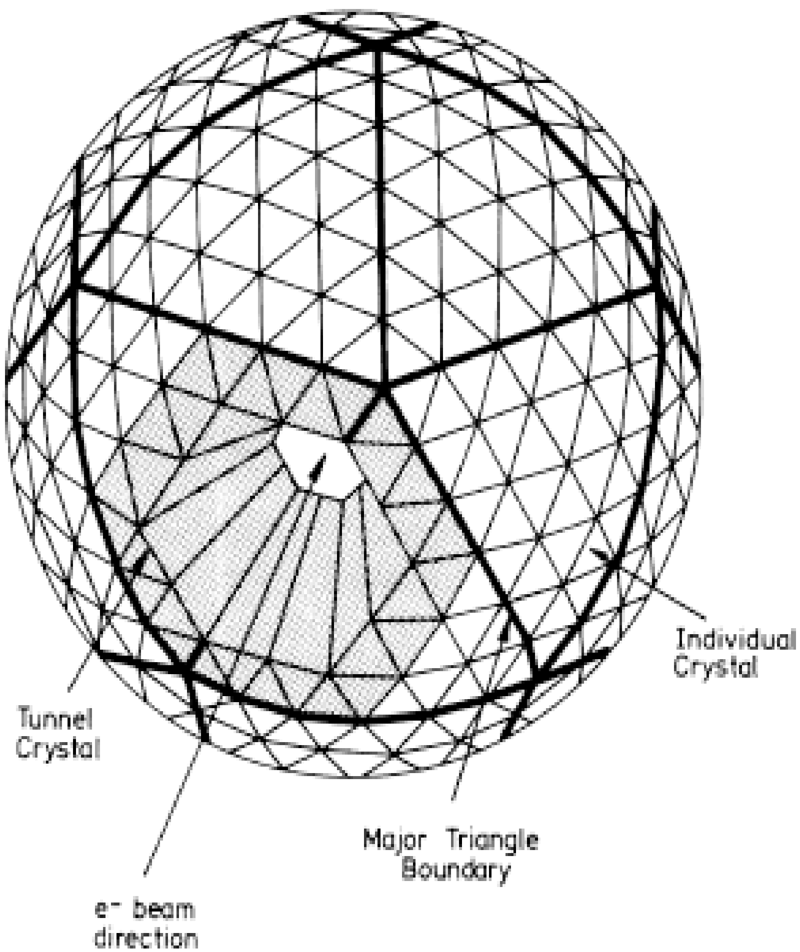


~20K Primakoff events



Γ (π0 −> γ γ)
Γ(π0 −> γγ) eV
τ (10−16) sec
8.40
8.20
8.00
7.80
7.60
7.40
7.20
7.00
6.80
0.76
0.8
0.84
0.88
0.92
Prim:1974
direct:1985
e+e-:1988
PrimEx:2011

DESY e+ e- 1988



Individual Crystal
Tunnel Crystal
Major Triangle Boundary
e⁻ beam direction

Conclusions

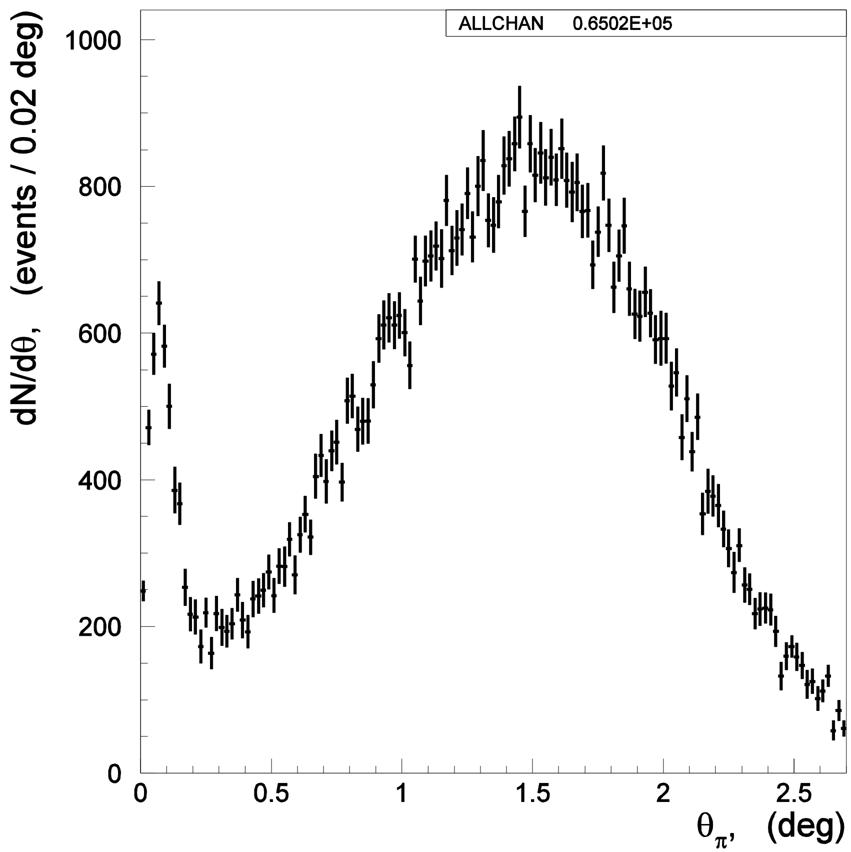
- QCD predictions of the lifetime are accurate to 1%
- the chiral corrections to the axial anomaly are 4.5%
- the best measurements are at the 3% level and should be checked.
- the next stage should be at the ~1% level
- Primex 2 at JLab to reduce error to ~2 %
- new direct and e^+e^- experiments are being planned
- evaluation of nuclear effects in Primakoff effect in progress with C. Fernandez-Ramirez,T.W. Donnelly
- predictions for $\eta, \eta' \rightarrow \gamma\,\gamma$ lattice calculations?

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ systematic errors

Contributions	Error, [%]
Photon flux	1.0
Target	0.1
Yield extraction	1.6
HYCAL eff.	0.5
Beam parameters	0.4
Trigger eff.	0.1
VETO eff.	0.4
Acceptance	0.3
Model errors (theory)	0.3
Physics background	0.25
Branching ratio	0.03
Total	2.1

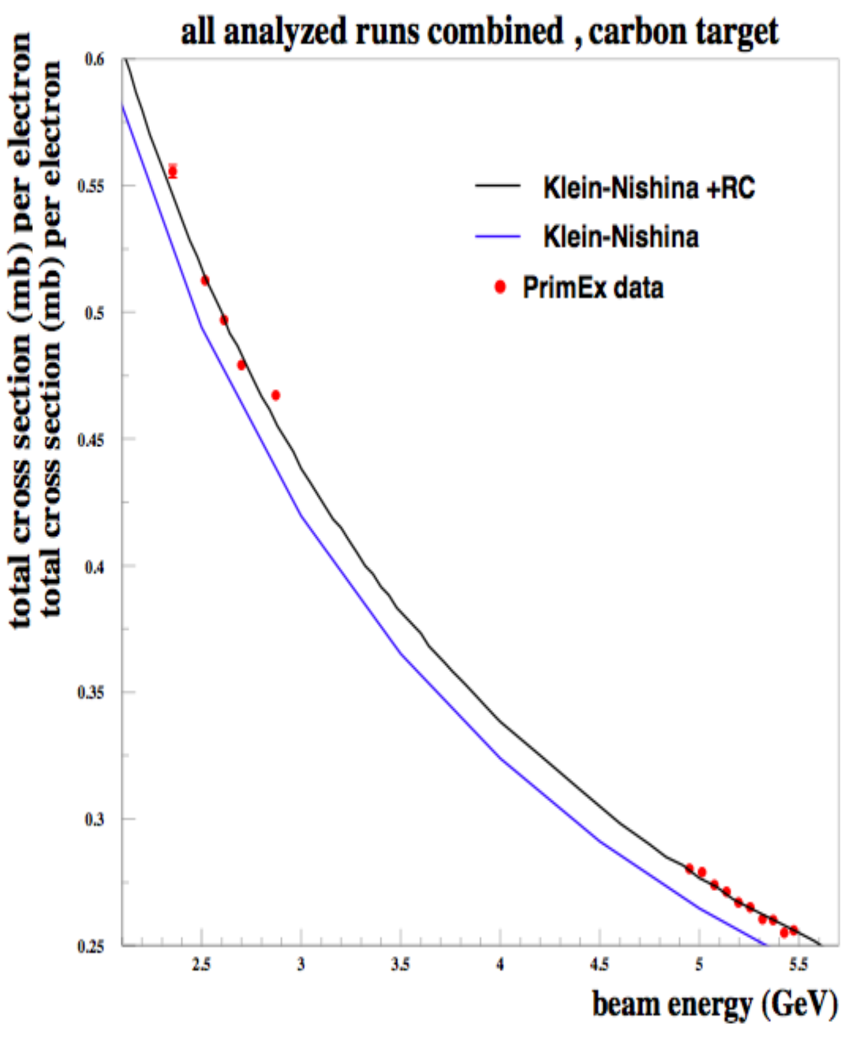
PrimEx-II: experimental yield

^{12}C



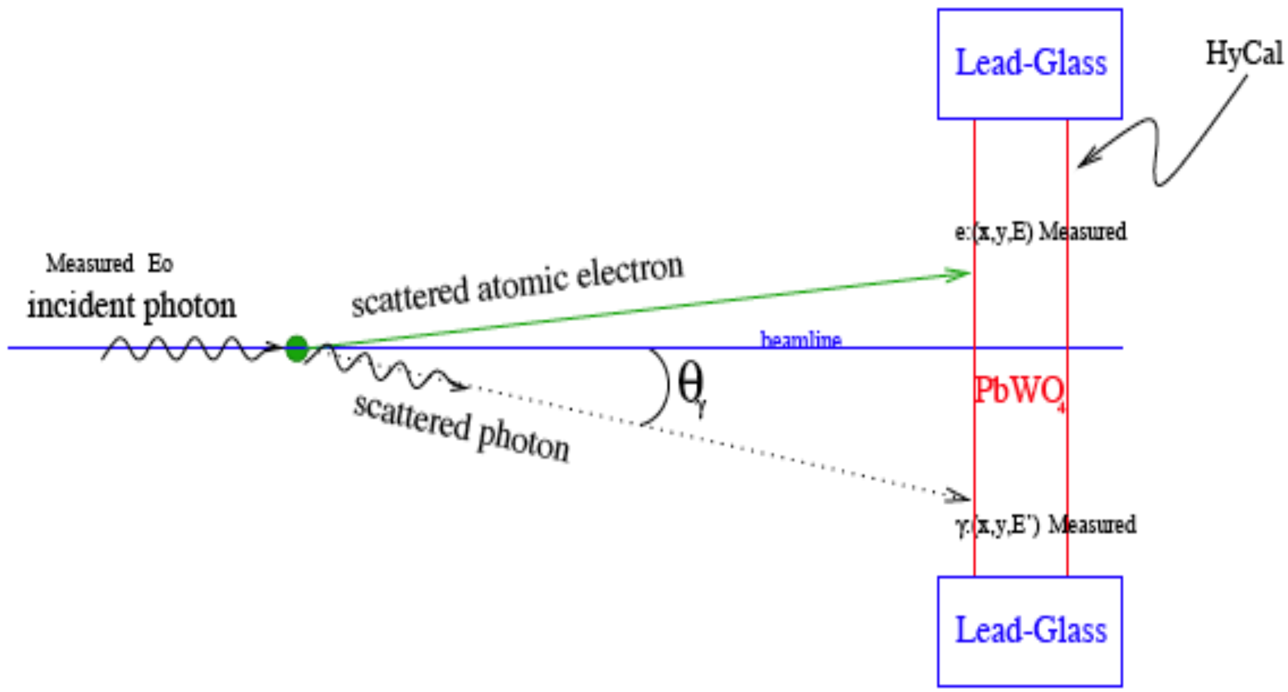
~8K Primakoff events

Compton Cross Section

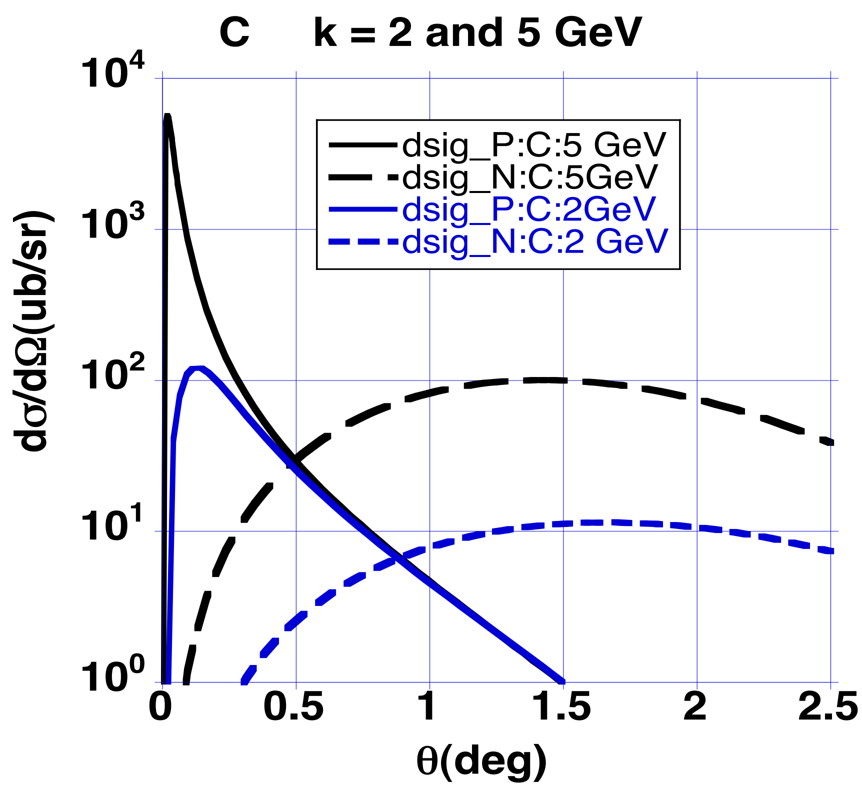


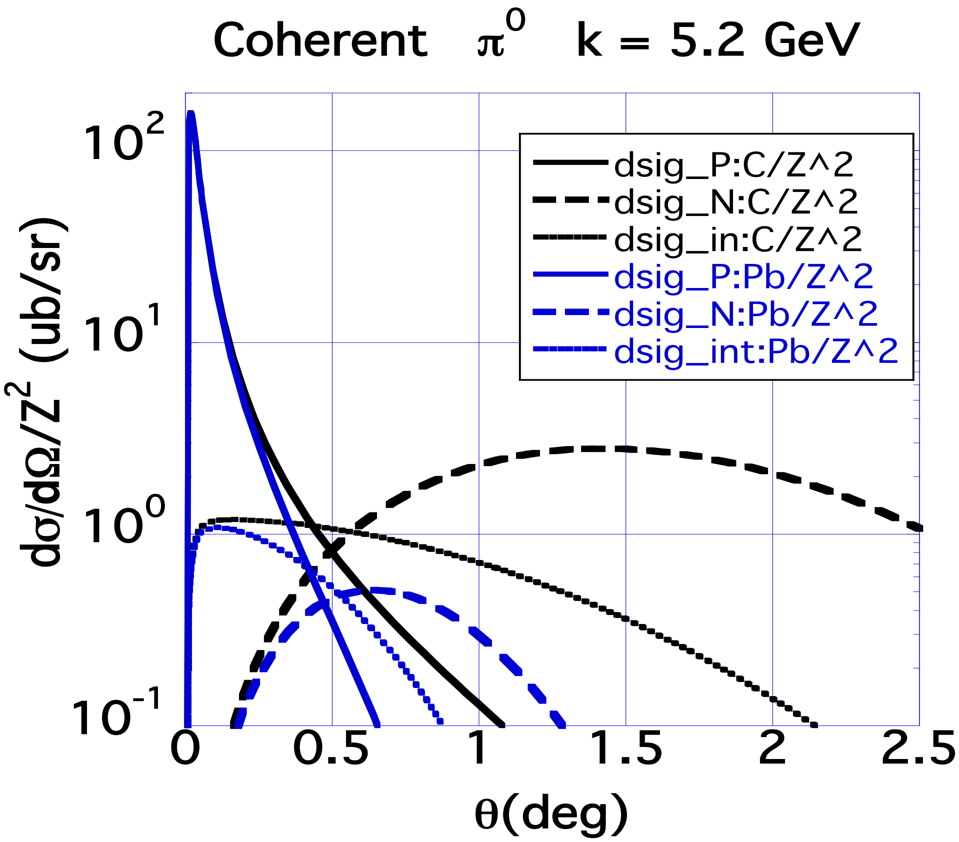
Experiment and theory agree within the 0.6% statistical and ≈1.8% systematic errors

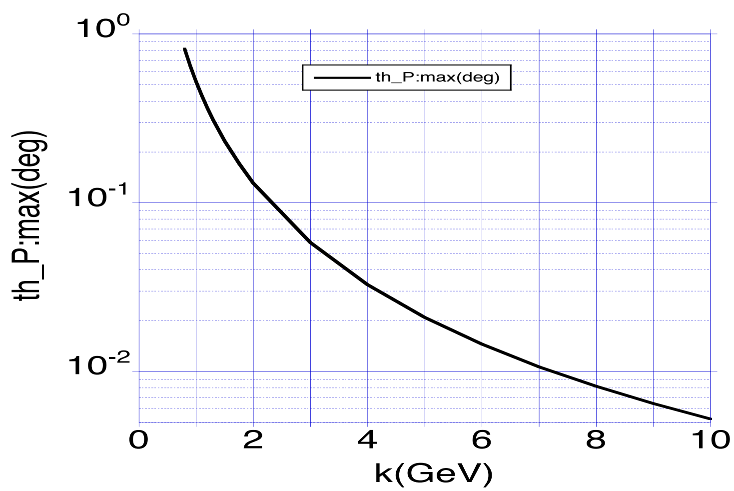
COMPTON SCATTERING IN PRIMEX*



** analysis results from by P. Ambrozewicz, L. Gan, Y. Prok*


C k = 2 and 5 GeV
dsig_P:C:5 GeV
dsig_N:C:5GeV
dsig_P:C:2GeV
dsig_N:C:2 GeV
dσ/dΩ(ub/sr)
θ(deg)


Coherent π0 k = 5.2 GeV
dsig_P:C/Z^2
dsig_N:C/Z^2
dsig_in:C/Z^2
dsig_P:Pb/Z^2
dsig_N:Pb/Z^2
dsig_int:Pb/Z^2
dσ/dΩ/Z2 (ub/sr)
θ(deg)


th_P:max(deg)
th_P:max(deg)
k(GeV)