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

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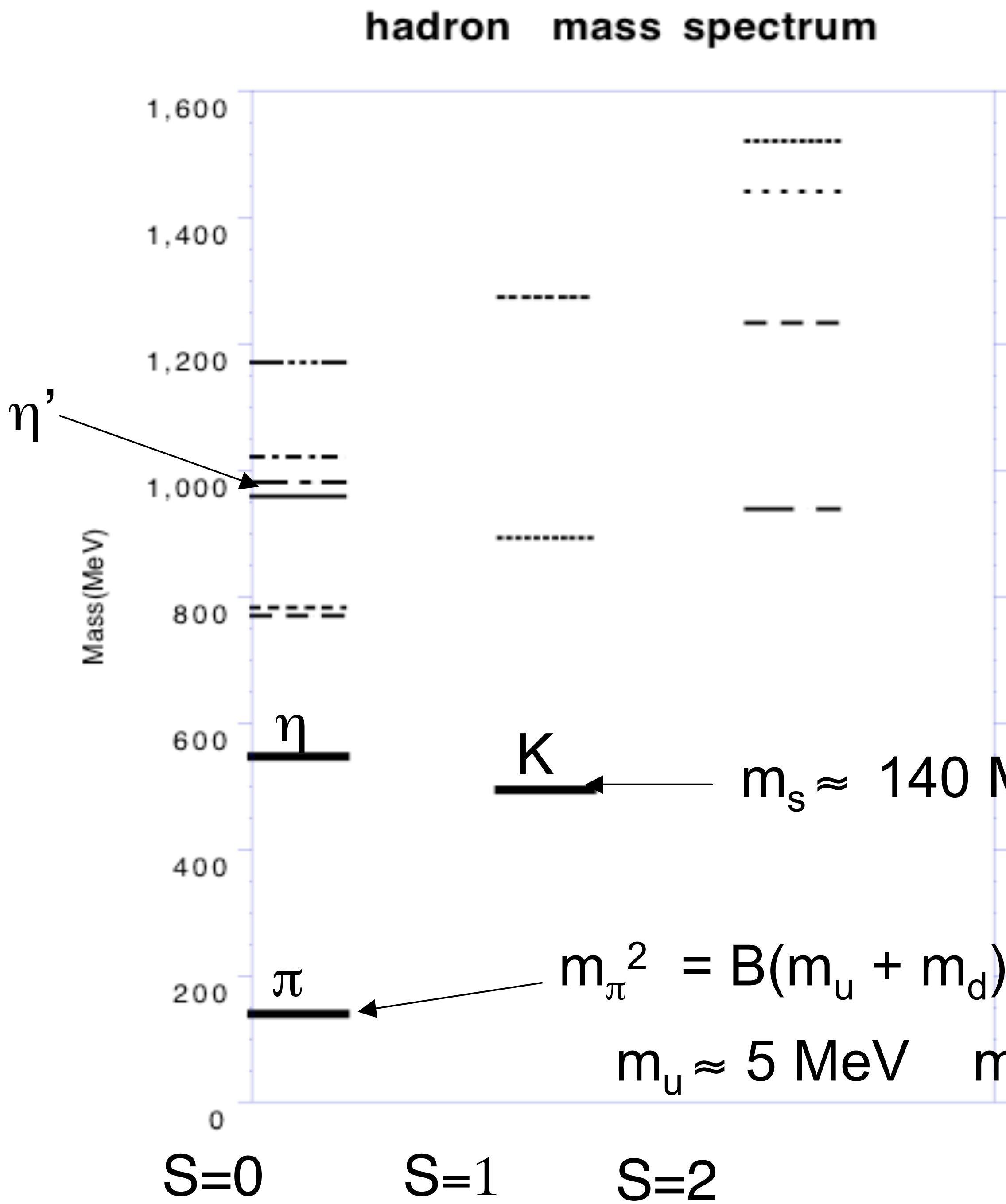
- Symmetries of QCD and their fate
- Spontaneous Chiral symmetry breaking $\Rightarrow$ pions
  $\Rightarrow$ low energy theorems
- threshold electromagnetic pion production
- $\pi^0 \rightarrow \gamma\, \gamma$: Axial anomaly, chiral corrections ~m_d-m_u
- Previous experiments
- Primex Experiment at Jefferson Lab
- Conclusions



$m_s \approx$ 140 MeV

$m_\pi^2 = B(m_u + m_d) \approx (140 \text{ MeV})^2 \rightarrow 0$

$m_u \approx 5$ MeV $\quad m_d \approx 9$ MeV

Chiral Dynamics

- Properties, Interactions, decays of Nambu-Goldstone Bosons (G) at Low Energies
- G-G, G-h scattering (h is any hadron)
- Form factors at low Q^2 (RMS radii)
  $\gamma^* N \rightarrow \Delta$
- Electric and magnetic polarizeabilites
- semi-leptonic decay rates
- special role of the π meson
  long range part of N-N interaction
  nuclear physics, astrophysics
  pion cloud of hadrons

A large range of physical phenomena
The experiments require a wide range of techniques

Spontaneous Breaking(Hiding) of Chiral Symmetry in QCD

- For massless particles h= σ • **p** = ±1 is conserved
- For massless quarks L_{QCD} conserves chiral symmetry
- Therefore each state should have an opposite parity partner: Wigner - Weyl manisfestation of the symmetry
- Since this is not observed in nature chiral symmetry has been spontaneously hidden
- The symmetry is exhibited by the appearance of massless, pseudoscalar (Nambu- Goldstone) Bosons
- $|p\rangle$ $1/2^+$,$|p\rangle|\pi\rangle$ $1/2^-$ are degenerate

$$L_{QCD} = L_0 + L_m$$

chiral symmetry is explicity broken by quark mass effects

Nambu-Goldstone Boson acquire mass

$$L_m = A(m_u+m_d)+B(m_u-m_d)$$

$$m_d/\ m_u \cong 1.8$$

isospin broken by strong and EM interaction

strong int. effect $\approx (m_d - m_u)/\Lambda_{(QCD)} \approx 2\%$

Symmetry becomes Dynamics

- πh system has to have gradient coupling
  due to the pseudoscalar nature of the pion
- weak in the s wave, generally strong in the p wave
- At low energies the interaction vanishes
- this can be systematically exploited
  $\Rightarrow$ effective field theory of QCD (ChPT)

- **low energy π -hadron scattering**

  pure Nambu-Goldstone Boson: $a(\pi h) = 0$

  strong interactions: $a(\pi h) \approx 1/m_\pi \approx 1$ fm

  PCAC calculation by Weinberg (1966)

  lowest order ChPT calculation

$$a^{I}(\pi h) = - I_\pi \bullet I_h \; m_\pi / (\Lambda F_\pi) \approx 1/\Lambda \approx 0.1\text{fm}$$
$$\rightarrow 0 \quad \text{as} \quad m_\pi \rightarrow 0$$
$$I = I_\pi + I_h$$

Λ =chiral sym. breaking scale $\approx 4 \pi F_\pi \approx 1$ GeV

Expect chiral corrections of order $(m_\pi/\Lambda)^2 \approx 0.02$

threshold $\gamma^* N \rightarrow \pi N$

s and p wave production amplitudes

there are ChPT formulas [Bernard, Meissner, Kaiser]

the chiral limit for s wave amplitudes

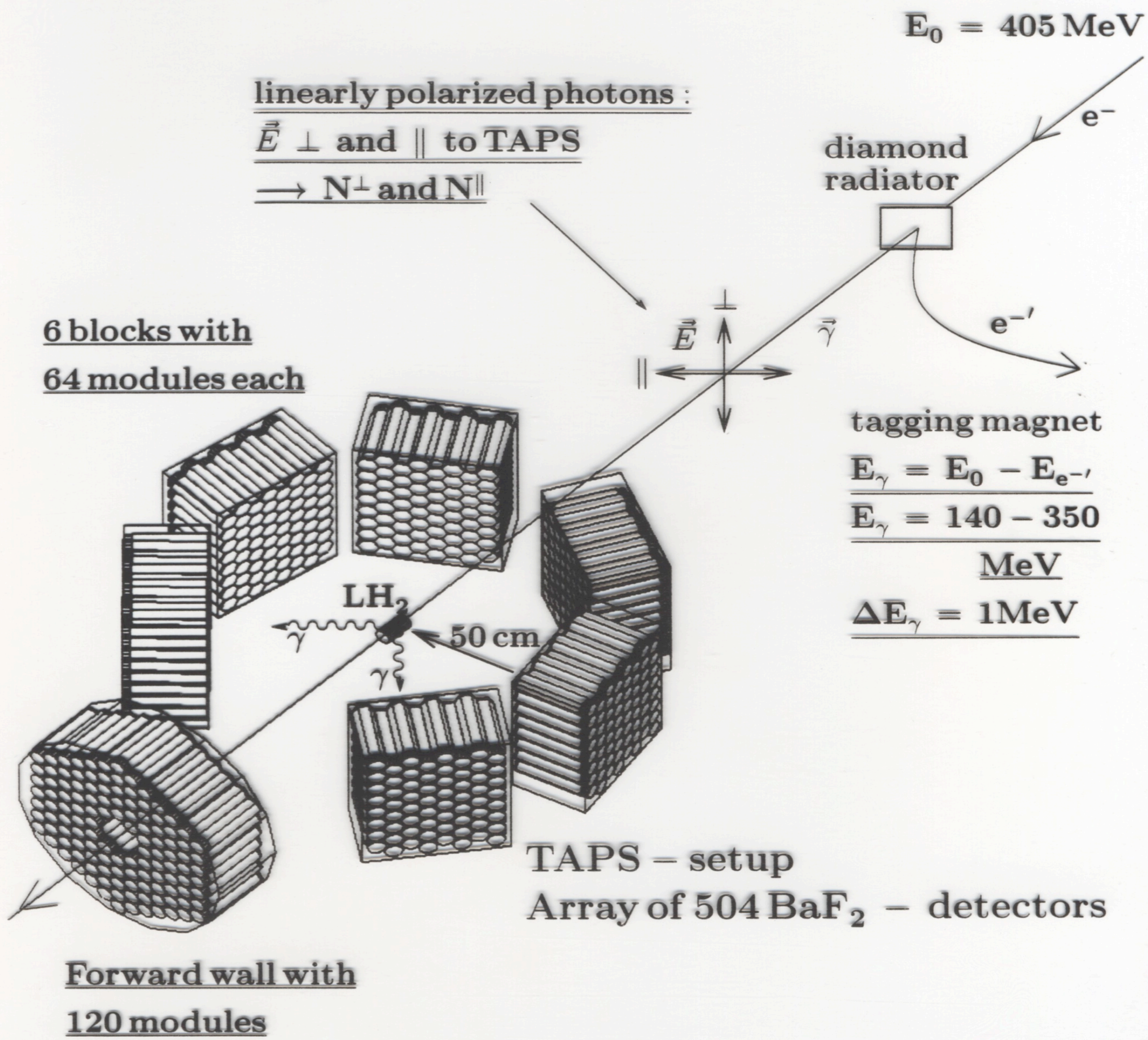
$A(\gamma^* N \rightarrow \pi^0 N) \rightarrow 0$

$A(\gamma^* N \rightarrow \pi^\pm N') \neq 0$ and large (Kroll-Ruderman theorem)

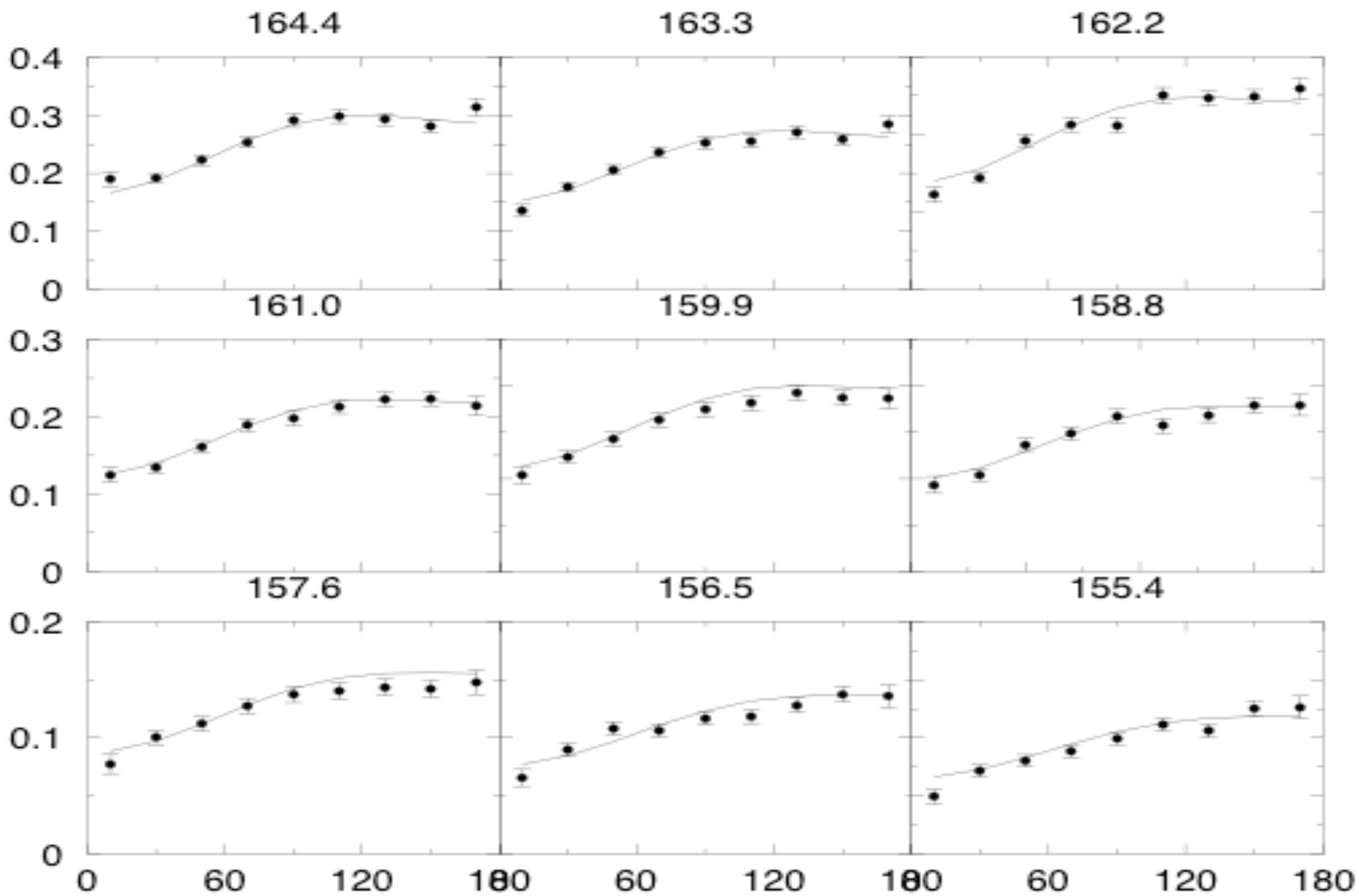
Some Experimental Tests of Spontaneious Chiral Symmetry Hiding

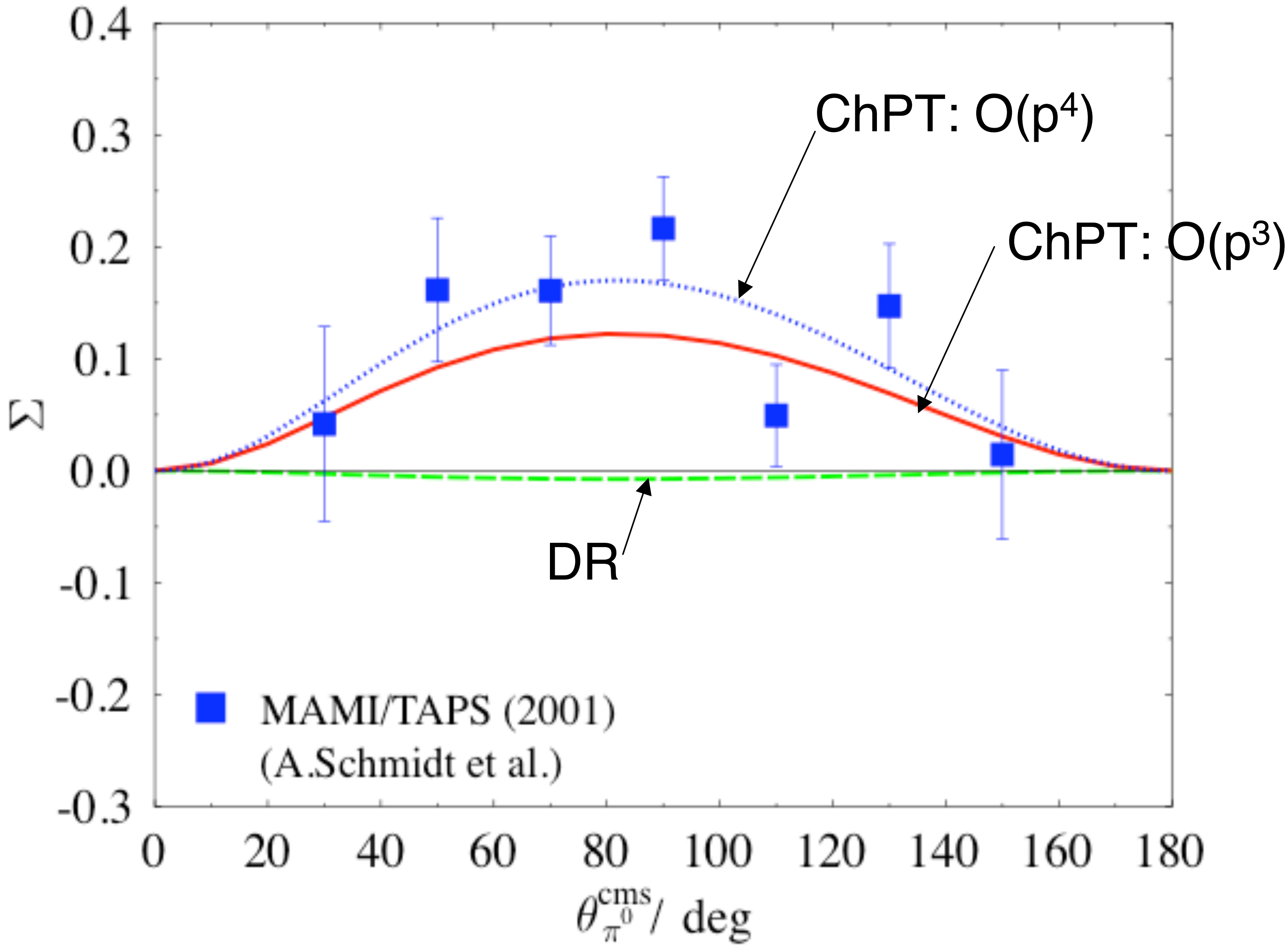
- $\pi\ \pi$ scattering
- atomic π^- p energies,widths
- π N scattering
- $\gamma^*p \rightarrow \pi^0$ p

Mainz Experimental setup $\vec{\gamma} + p \rightarrow p + \pi^{\circ}$



$\gamma\, p \rightarrow \pi^0\, p$ Mainz data, ChPT



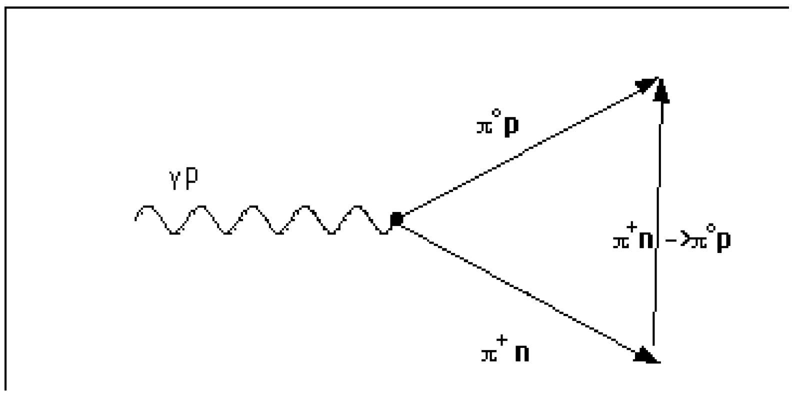


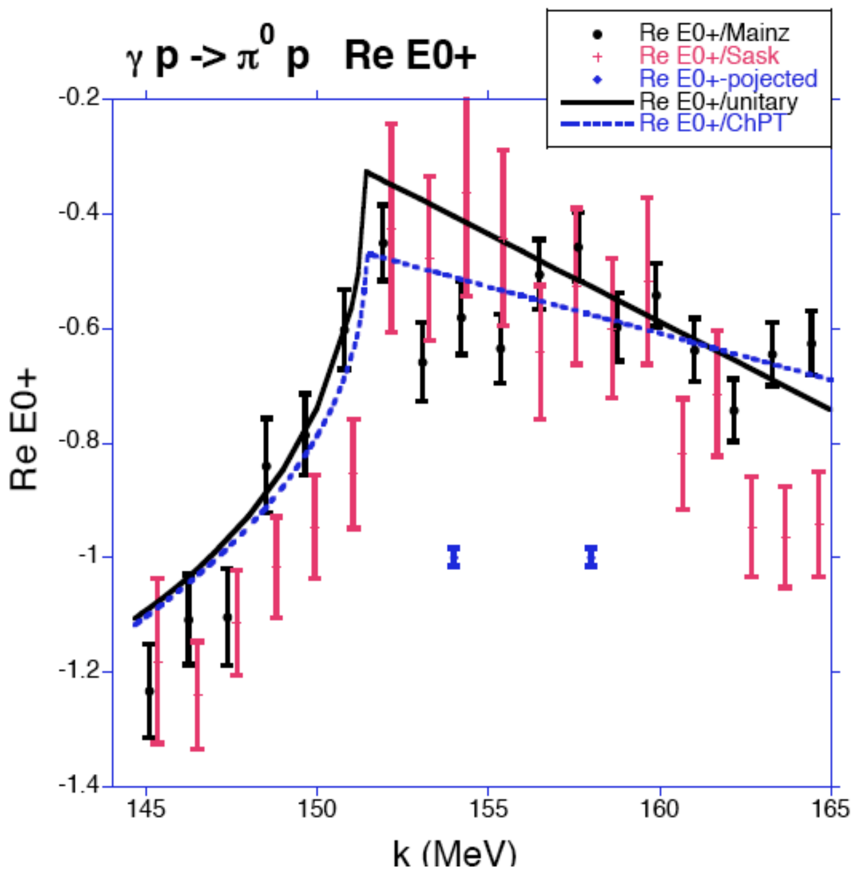
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Σ
0
20
40
60
80
100
120
140
160
180
θ^cms_π0 / deg
ChPT: O(p4)
ChPT: O(p3)
DR
MAMI/TAPS (2001)
(A.Schmidt et al.)

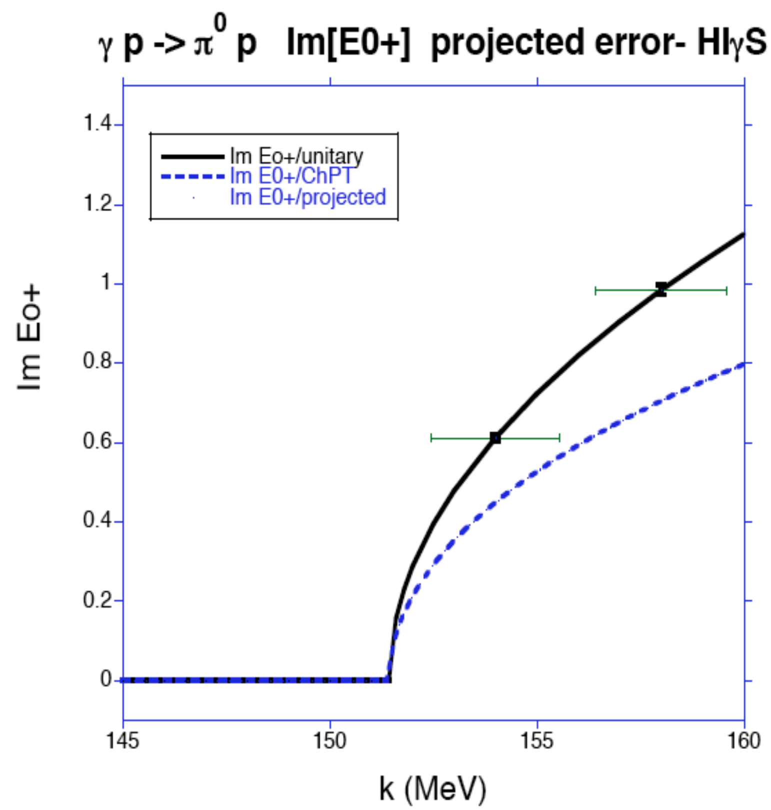
Unitary Cusp $\gamma p \to \pi^0 p$

$$\beta = E_{0+}(\gamma p \to \pi^+ n)\, a_{cex}(\pi^0 p \leftrightarrow \pi^+ n)$$

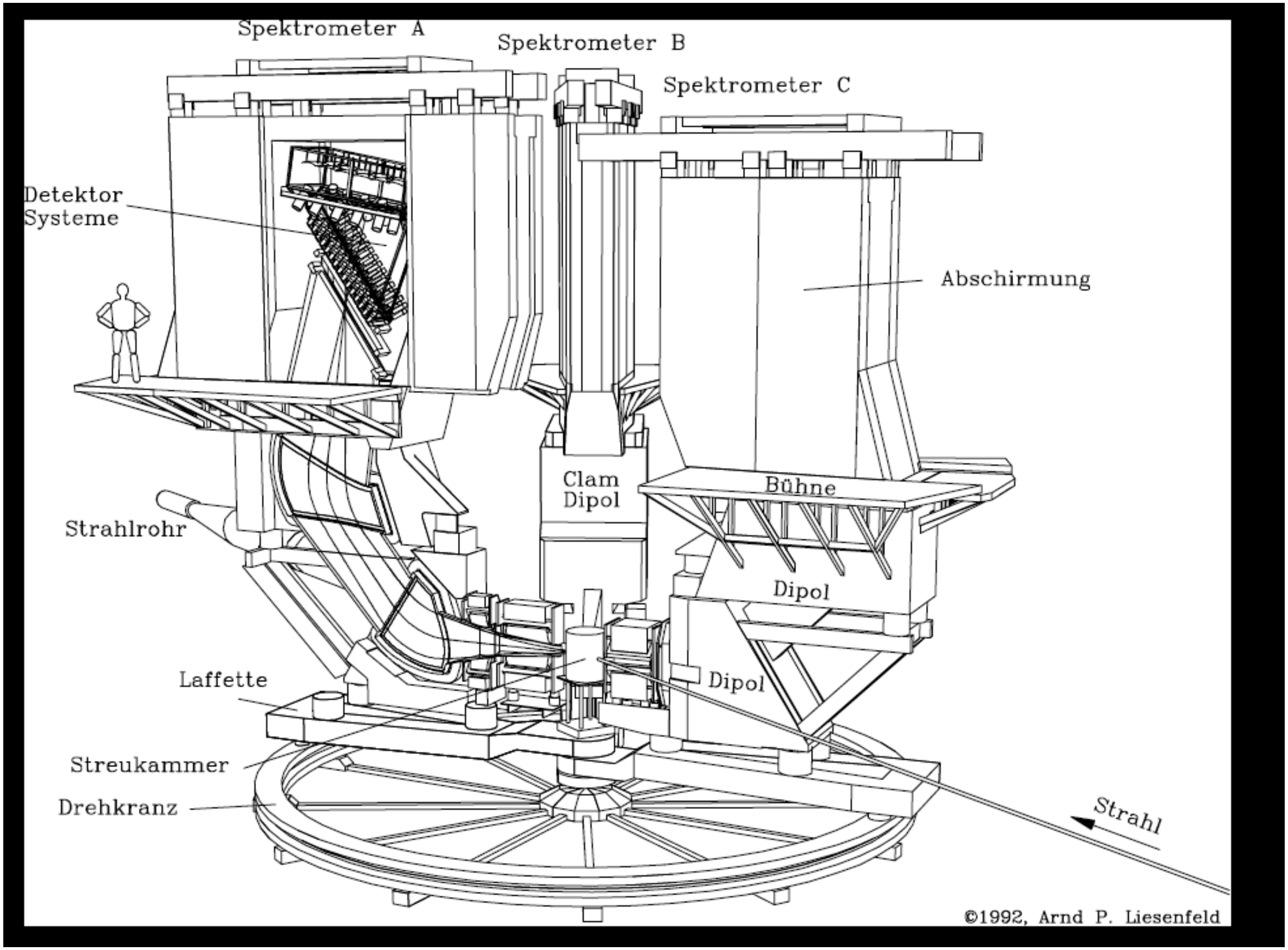
cusp sign and magnitude







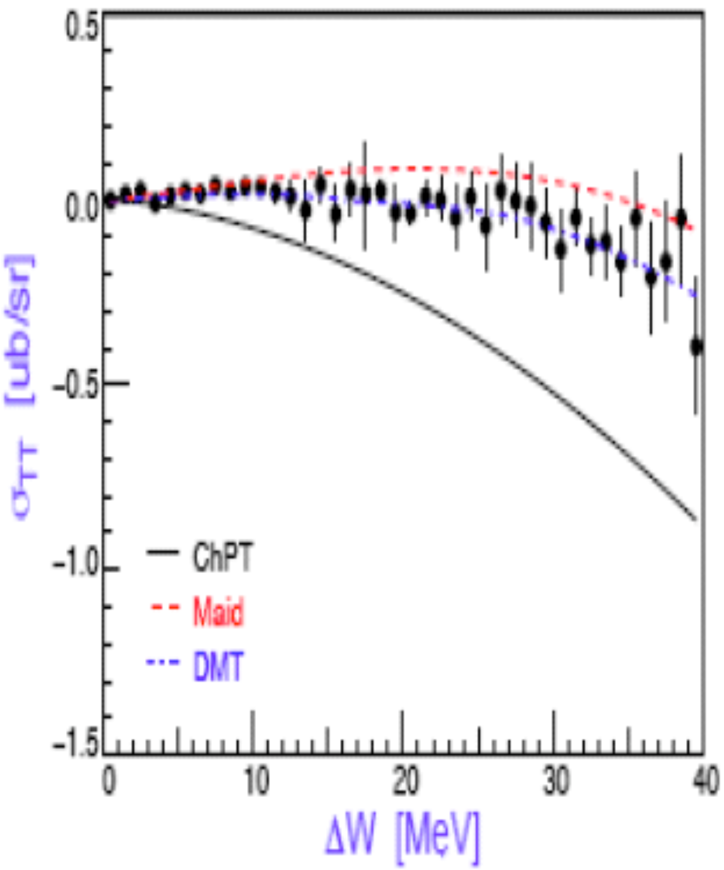
Mainz A1

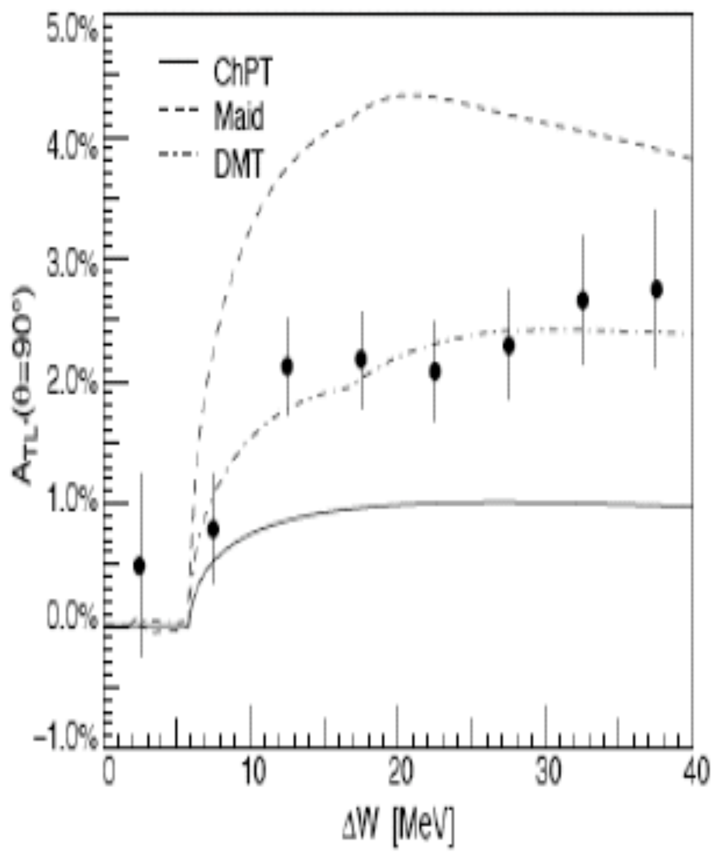


Spektrometer A
Spektrometer B
Spektrometer C
Detektor
Systeme
Abschirmung
Clam
Dipol
Bühne
Strahlrohr
Dipol
Dipol
Laffette
Streukammer
Drehkranz
Strahl
©1992, Arnd P. Liesenfeld

Mainz A1 ep $\rightarrow$ e'p π^0 Weis, Merkel,.. Q^2=0.05 GeV^2

$A_{TL'}$ $\Rightarrow$ Im L_{0+}





Anomaly

When a symmetry of the classical theory is not present in the quantized version

In QCD the anomaly is not anamalous
It is an essential part of the theory

It is responsible for the large η' mass
so that it is not the 9th Goldstone Boson

It is primarily responsible for the $\pi^0 \to \gamma\,\gamma$ decay mode

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 ± 0.032%)

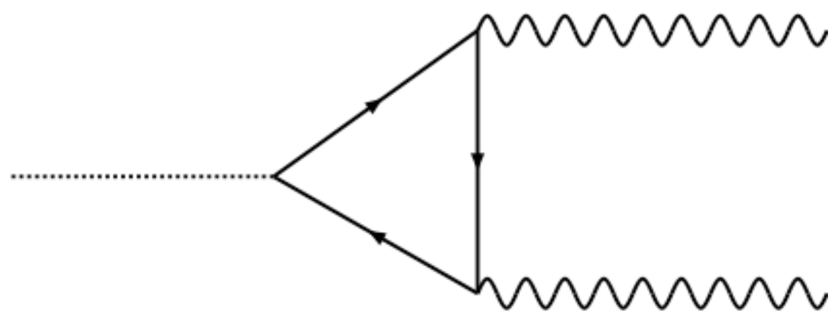
  Axial anomaly dominant

History: π^0 Lifetime Experiments

- 1947 π^+ discovered in cosmic rays
- 1950 π^0 discovered, cosmic rays, Berkeley cyclotron
  $\pi^0 \rightarrow \gamma\,\gamma$ decay mode observed
  lifetime too short for electronic measurement
- $\tau < 10^{-15}$ sec established by 1957
  $K^+ \rightarrow \pi^+ \pi^0$ emulsion experiment ($d < 0.5\mu$)
- 1951: Primakoff effect $\gamma\,\gamma \rightarrow \pi^0$: experiments 1970-5
- PDB data base established by 1988

History: π^0 Lifetime Theory

- PCAC predicts $A_{\pi\gamma\gamma} = 0$ in the chiral limit
- 1968 Adler, Bell, Jackiw discover the axial anomaly

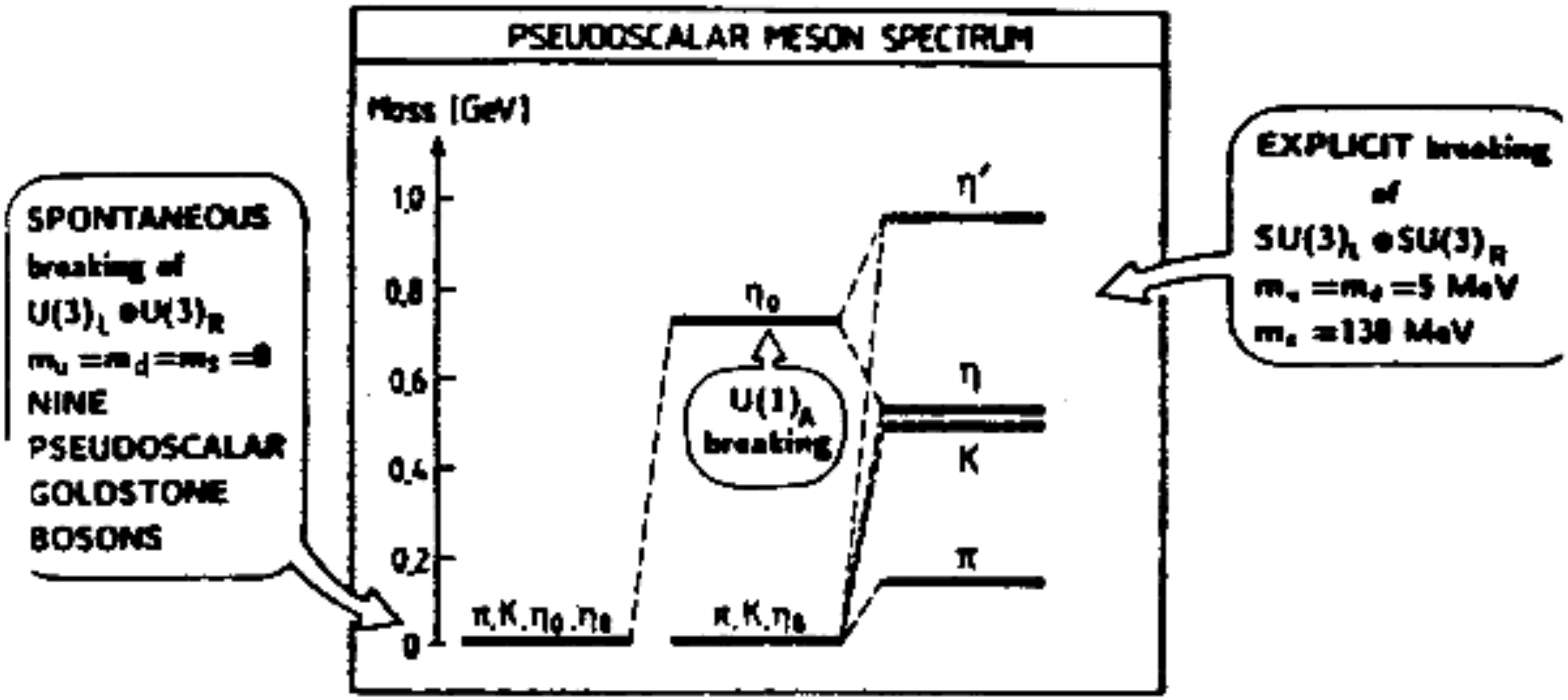


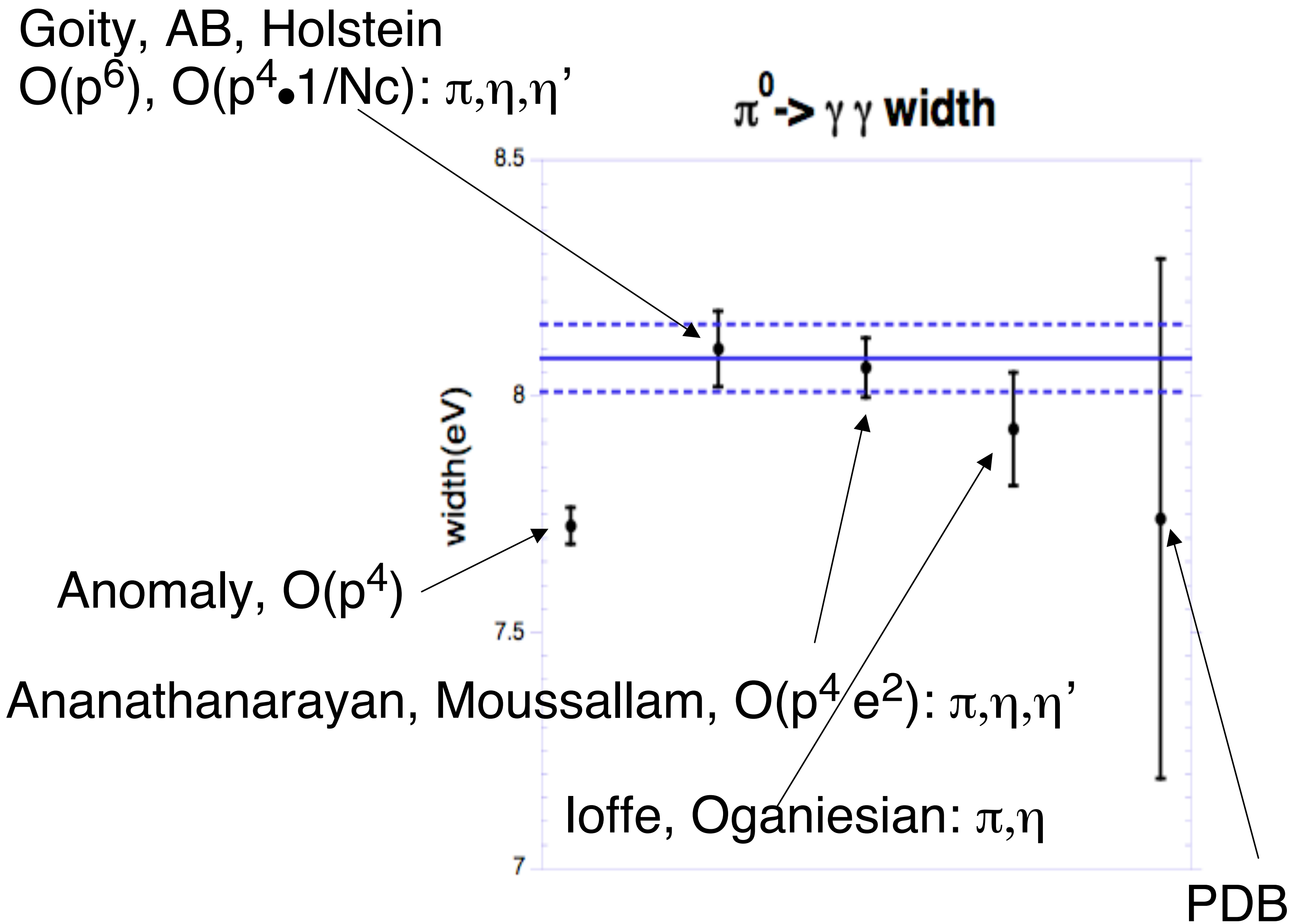
- $A_{\pi\gamma\gamma} = \alpha / \pi \, F_\pi$

$\Gamma(\pi^0 \to \gamma\,\gamma) = (m_\pi{}^3/64\pi) A_{\pi\gamma\gamma}{}^2 = 7.725$ eV ± 0.5%

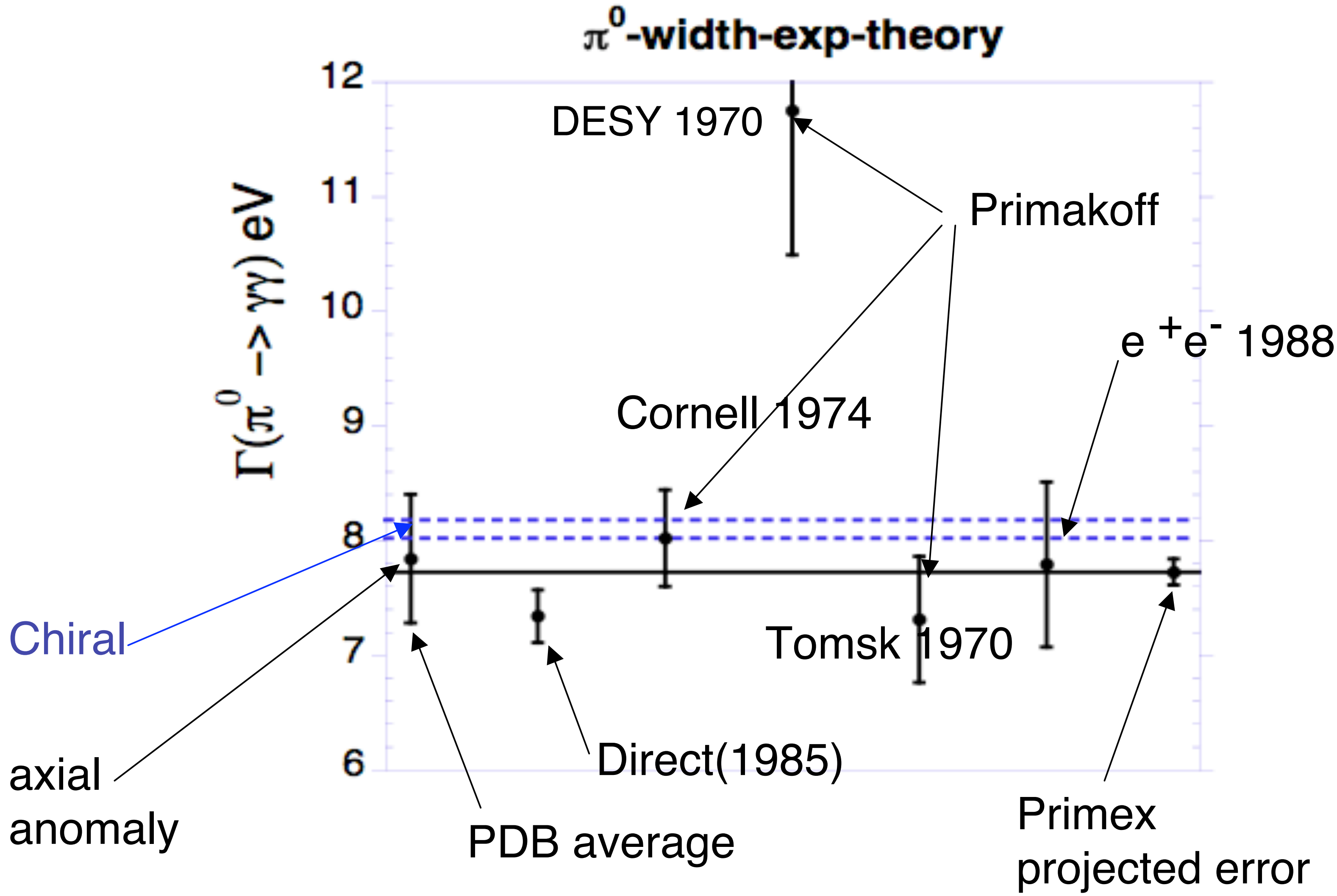
$\tau(\pi^0) = 0.807 \cdot 10^{-16}$ sec

$c\,\tau(\pi^0) = 0.0253\ \mu$


PSEUDOSCALAR MESON SPECTRUM
Mass (GeV)
1,0
0,8
0,6
0,4
0,2
0
π, K, η0, η8
η0
U(1)A breaking
π, K, η8
η′
η
K
π
SPONTANEOUS breaking of U(3)L ⊗ U(3)R
mu = md = ms = 0
NINE PSEUDOSCALAR GOLDSTONE BOSONS
EXPLICIT breaking of SU(3)L ⊗ SU(3)R
mu = md = 5 MeV
ms = 130 MeV

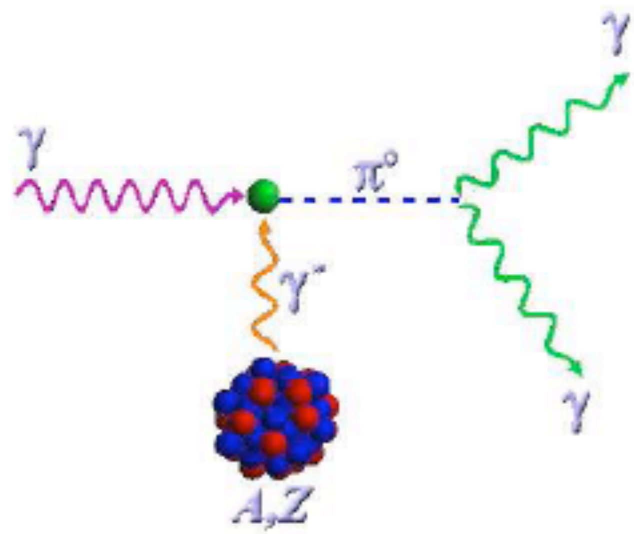


Goity, AB, Holstein
O(p6), O(p4•1/Nc): π,η,η'
π0-> γ γ width
8.5
8
7.5
7
width(eV)
Anomaly, O(p4)
Ananathanarayan, Moussallam, O(p4 e2): π,η,η'
Ioffe, Oganiesian: π,η
PDB



π^0-width-exp-theory
$\Gamma(\pi^0 \to \gamma\gamma)$ eV
12
11
10
9
8
7
6
DESY 1970
Primakoff
e^+e^- 1988
Cornell 1974
Chiral
Tomsk 1970
axial
anomaly
Direct(1985)
PDB average
Primex
projected error

Primakoff Effect

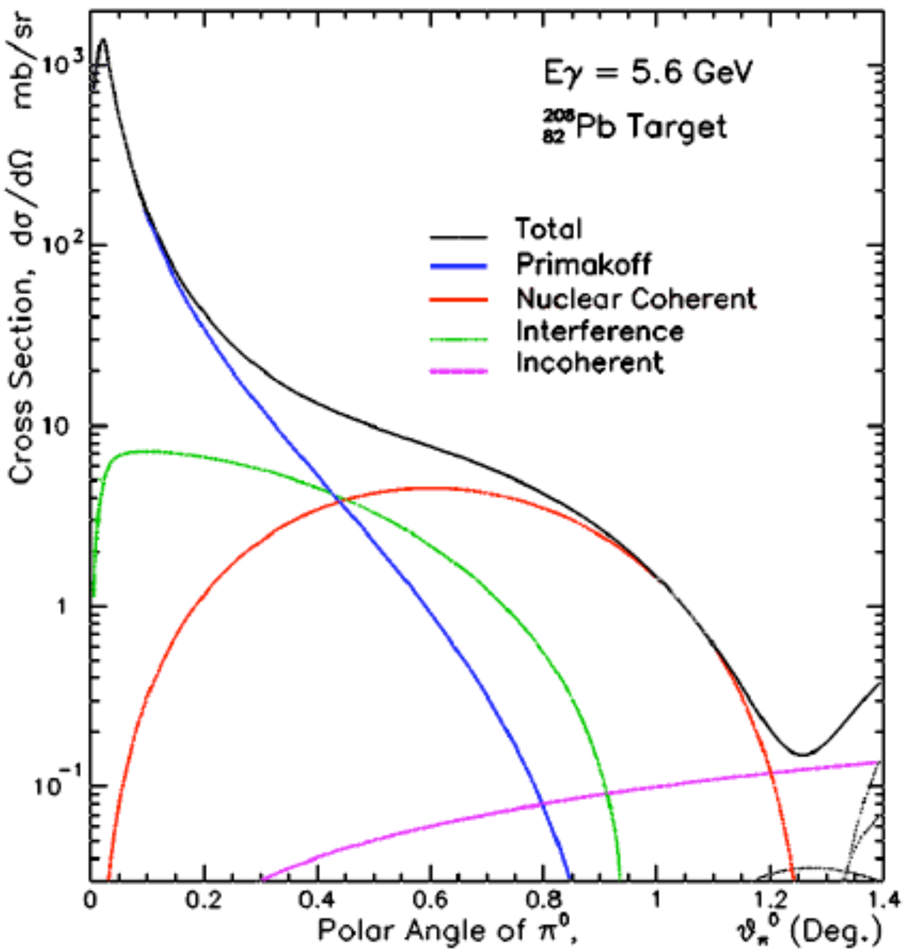


- π^0 photoproduction from Coulomb field of nucleus.
- Equivalent production ($\gamma\gamma^* \to \pi^0$) and decay ($\pi^0 \to \gamma\gamma$) mechanism implies Primakoff cross section proportional to π^0 lifetime.
- Primakoff π^0 produced at very forward angles.

Full Cross Section Components

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

Primakoff Nucl.Coherent Incoherent Interference



Primakoff:

Proportional to Z^2,

peaked at $\theta_{\pi^0} = m^2_{\pi^0}/2E^2_\gamma$

Nuclear Coherent:

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

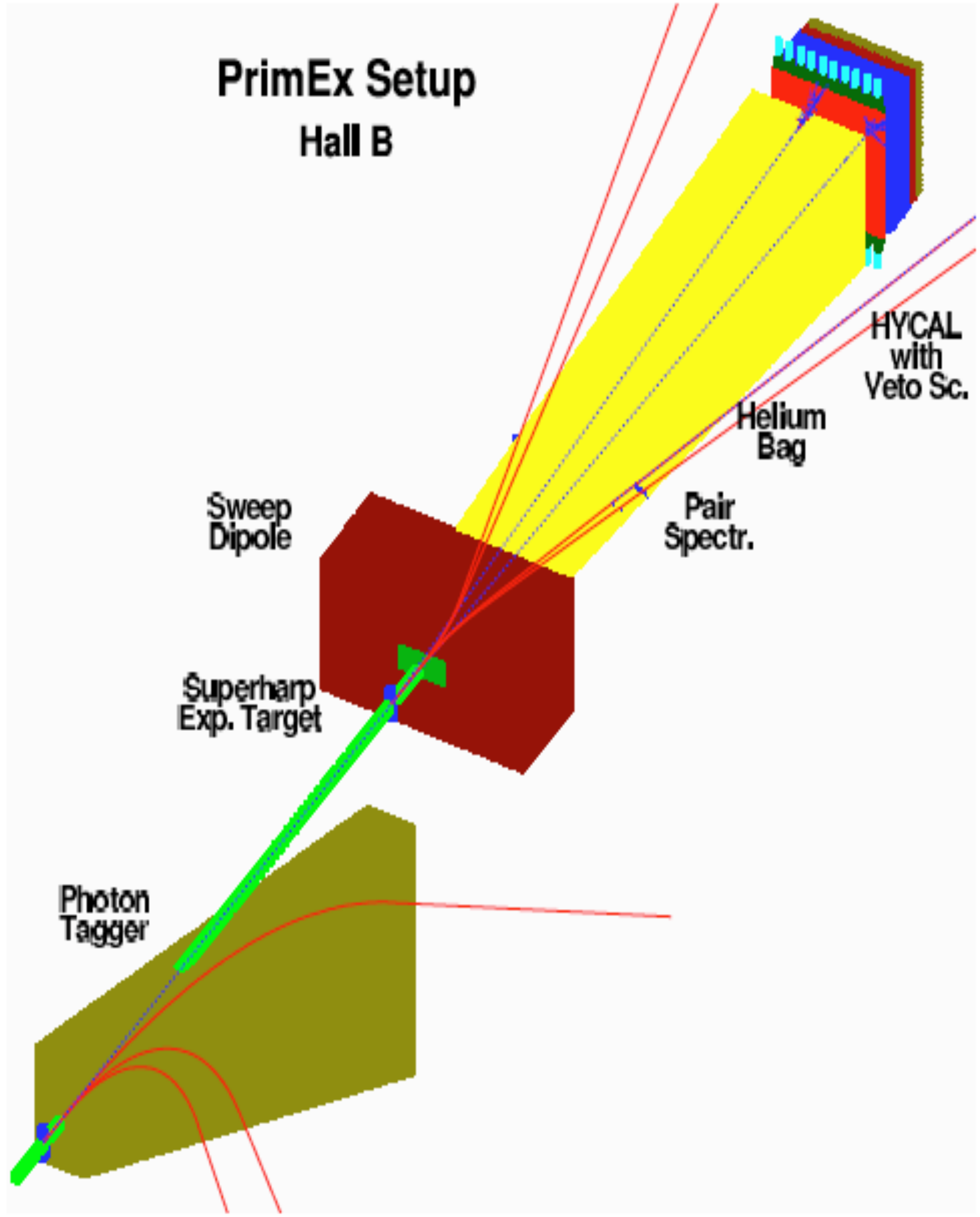
Nuclear Incoherent:

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

Interference:

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

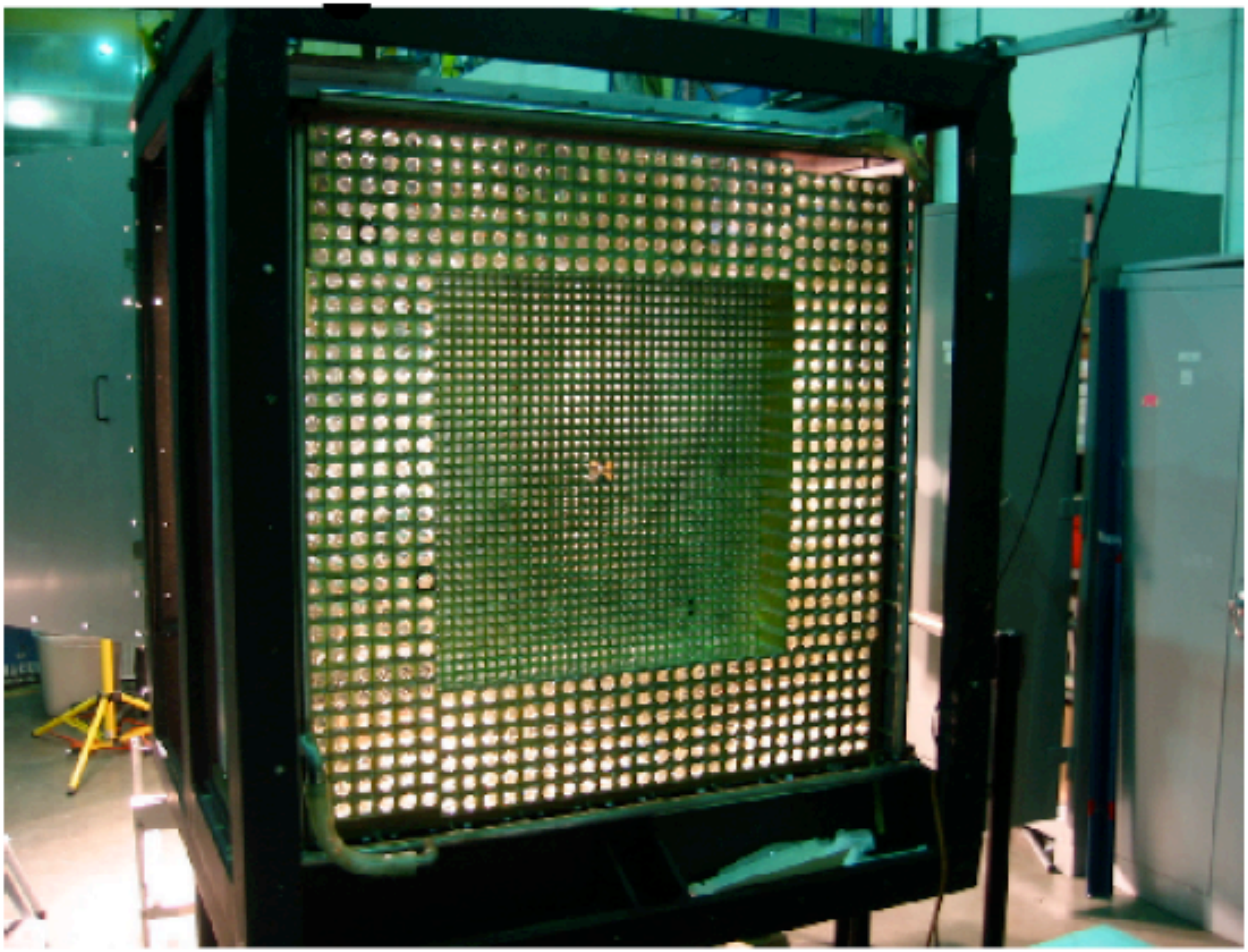


Experiment Overview

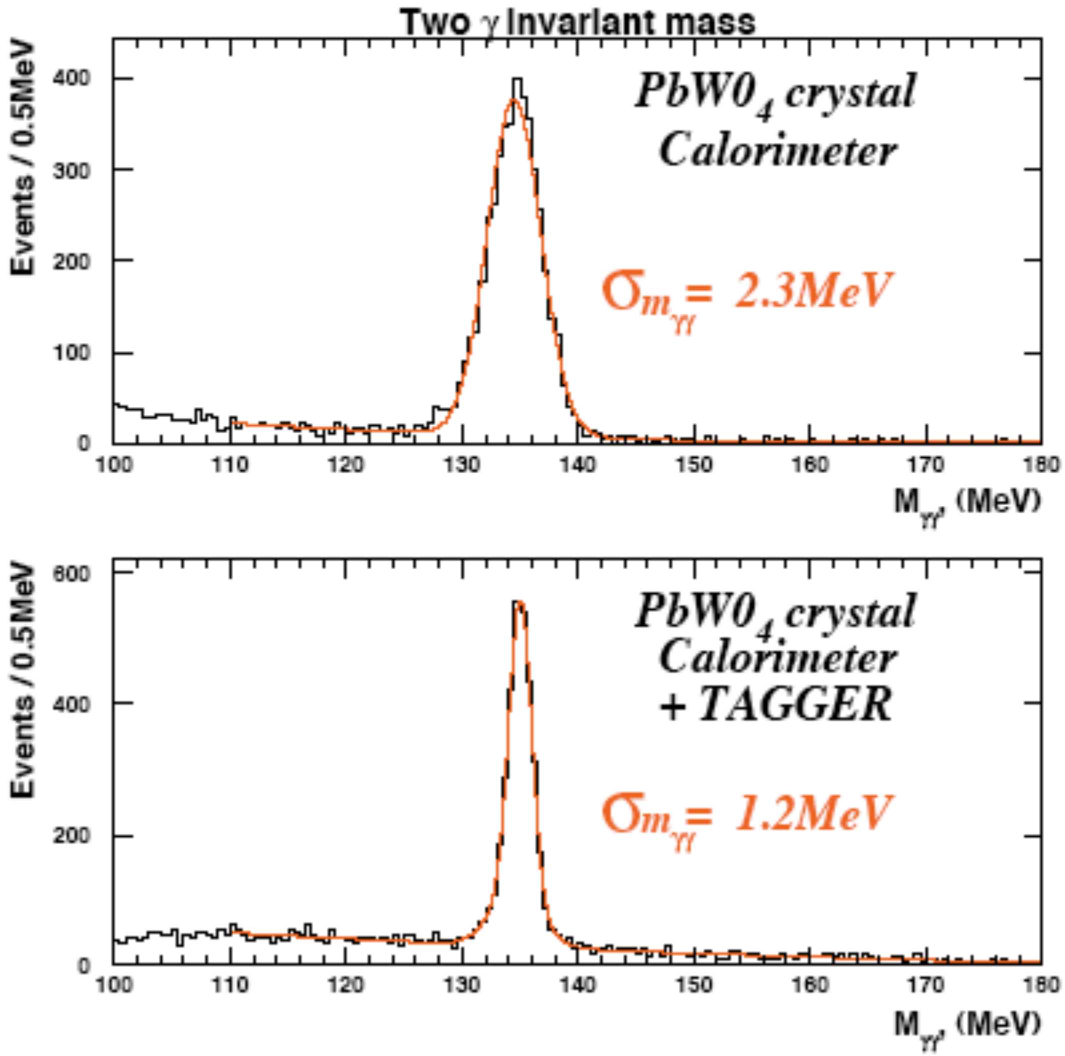
- Tagged photons of energy 4.9 - 5.5 GeV were used to measure the absolute cross section of small angle π^0 photoproduction from the coulomb field of two nuclei (^{12}C and ^{208}Pb).

- The invariant mass and production angle of the pion were reconstructed by detecting the two π^0 decay photons in a highly segmented calorimeter centered on the beamline.

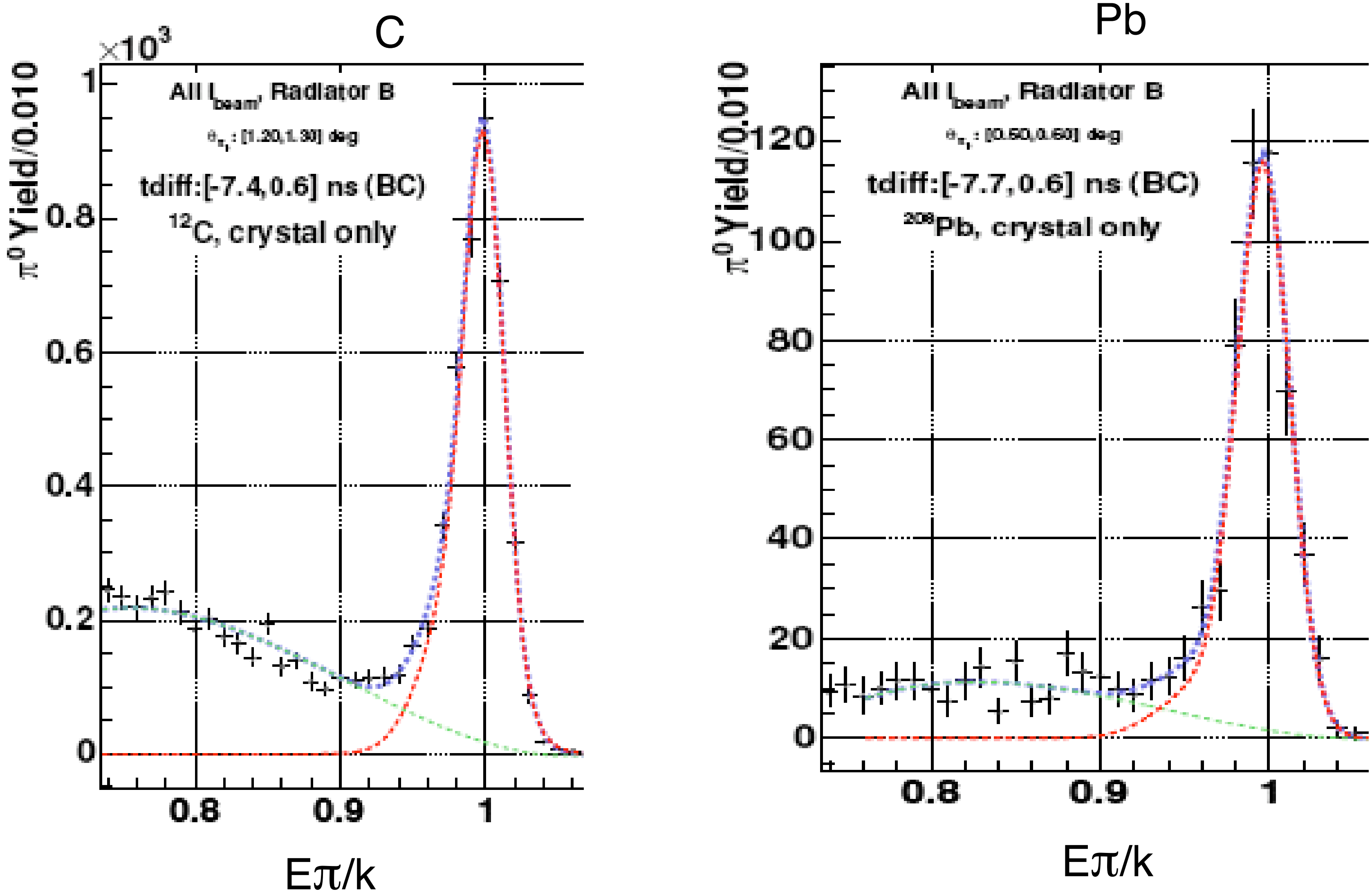
- The number of tagged photons reaching the target was calibrated using a Total Absorption Counter (TAC) and monitored with an e^+e^- pair spectrometer.

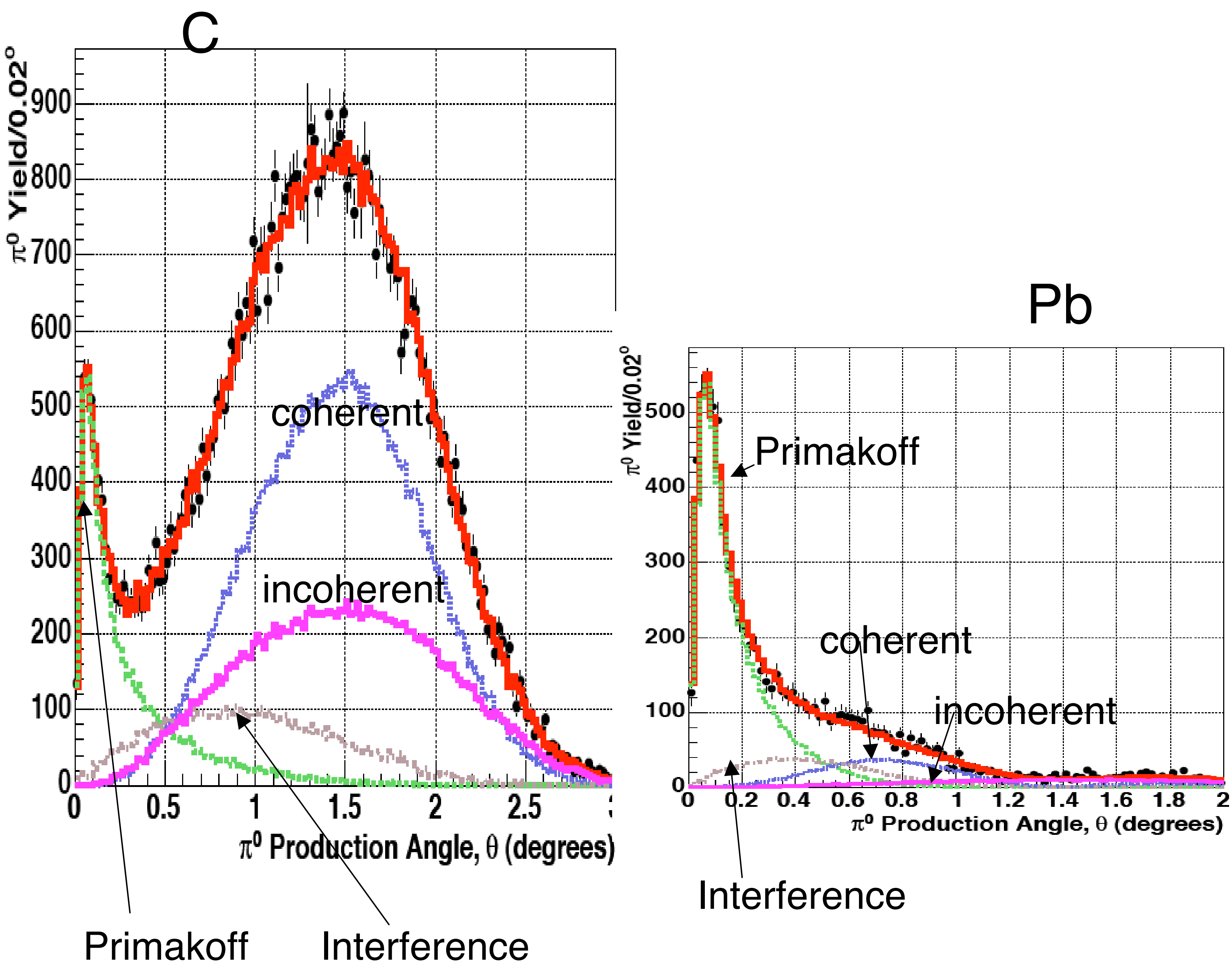


Analysis Status: ^{208}Pb: $\gamma\gamma$ Invariant Mass



π^0 Elasticity



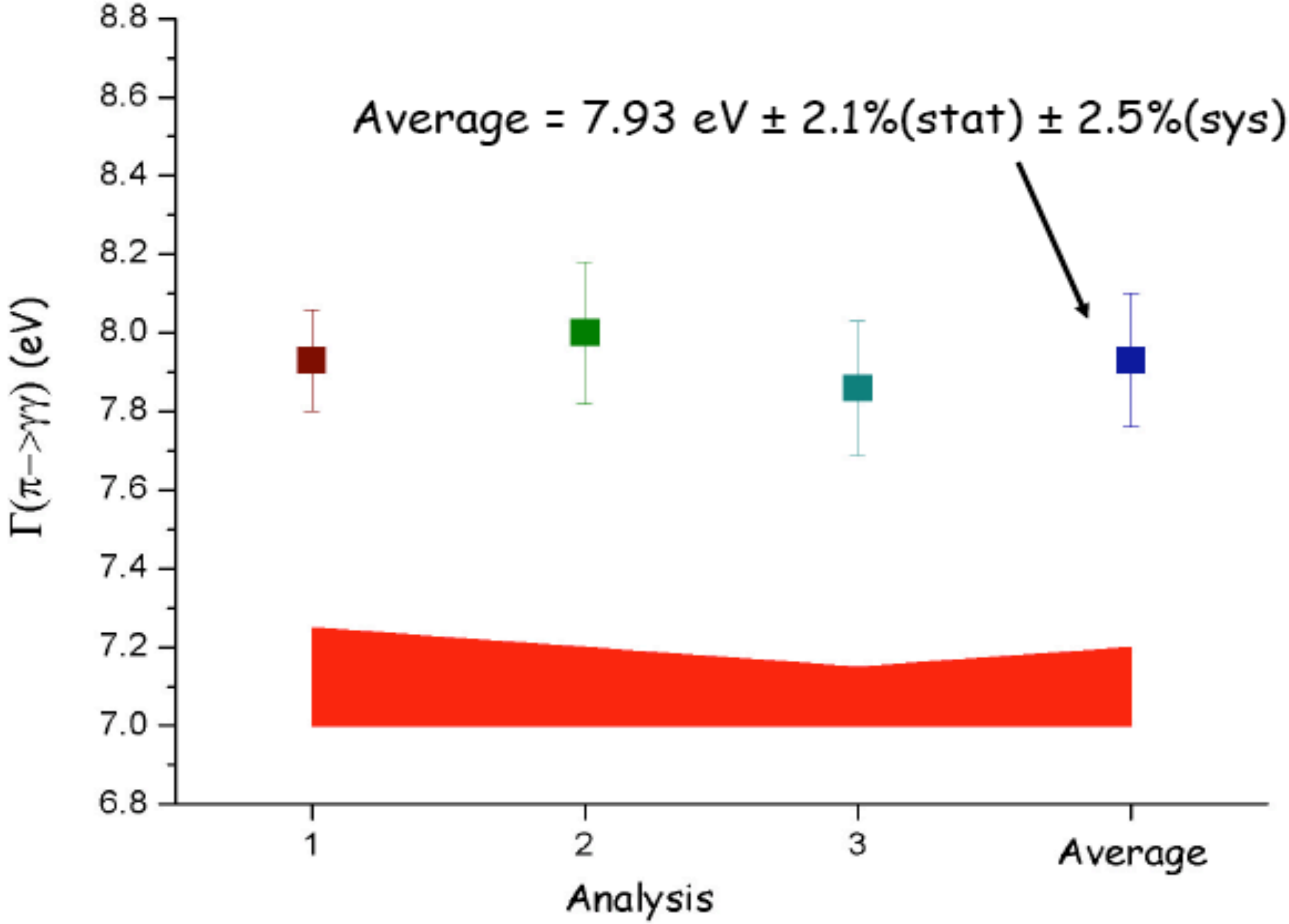

C
π⁰ Yield/0.02°
900
800
700
600
500
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
π⁰ Production Angle, θ (degrees)
coherent
incoherent
Primakoff
Interference
Pb
π⁰ Yield/0.02°
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
π⁰ Production Angle, θ (degrees)
Primakoff
coherent
incoherent
Interference

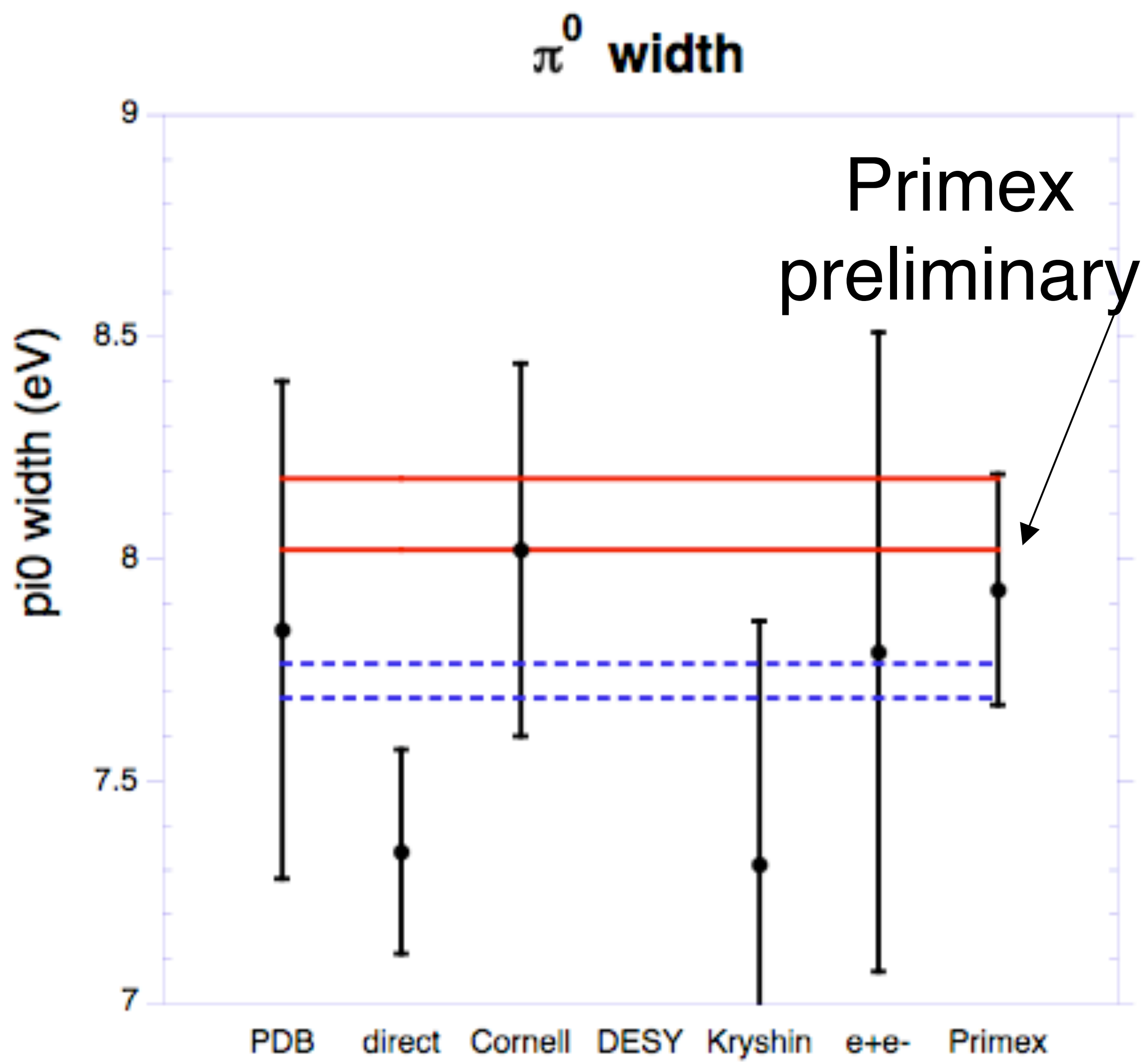
Systematic Error Table

$m_{\gamma\gamma}$ fits + inelast bkgd corr.	± 1.0
Inelastic bkgd shape uncert.	± 0.75
Photon flux	± 1.1
Incoherent XS shape uncert.	± 1.3
Nuclear coh. XS energy dep.	± 0.04
Detection/Recon efficiency	± 0.5
Fiducial Acceptance	± 0.3
Event Selection	± 1.0
Target thick. + branch ratio	± 0.06
Tagged Photon Energy	± 0.1
Total Systematic	$\pm 2.4\%$

Preliminary

** analysis results from E. Clinton, I. Larin, and D. McNulty*





π^0 width
9
8.5
8
7.5
7
pi0 width (eV)
Primex preliminary
PDB
direct
Cornell
DESY
Kryshin
e+e-
Primex

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, 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 Polytechnical 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

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Outlook for Experimental Tests of Spontaneous Chiral Symmetry Breaking Nambu ⇒Goldstone Boson

√ most low energy reactions involving pions:
there are a few problems (electroproduction,…)
quark mass difference effects are still unverified
extension to eta, kaon still in beginning stages

Axial Anamoly + chiral corrections(~m_d-m_u)

√ for $\pi^0 \rightarrow \gamma\,\gamma$ at ~ 3%
needs work for $\eta \rightarrow \gamma\,\gamma$, $\eta' \rightarrow \gamma\,\gamma$