Measurement of the π^0 Lifetime
Frascati Spring School
May 16, 2006

A.M. Bernstein
MIT

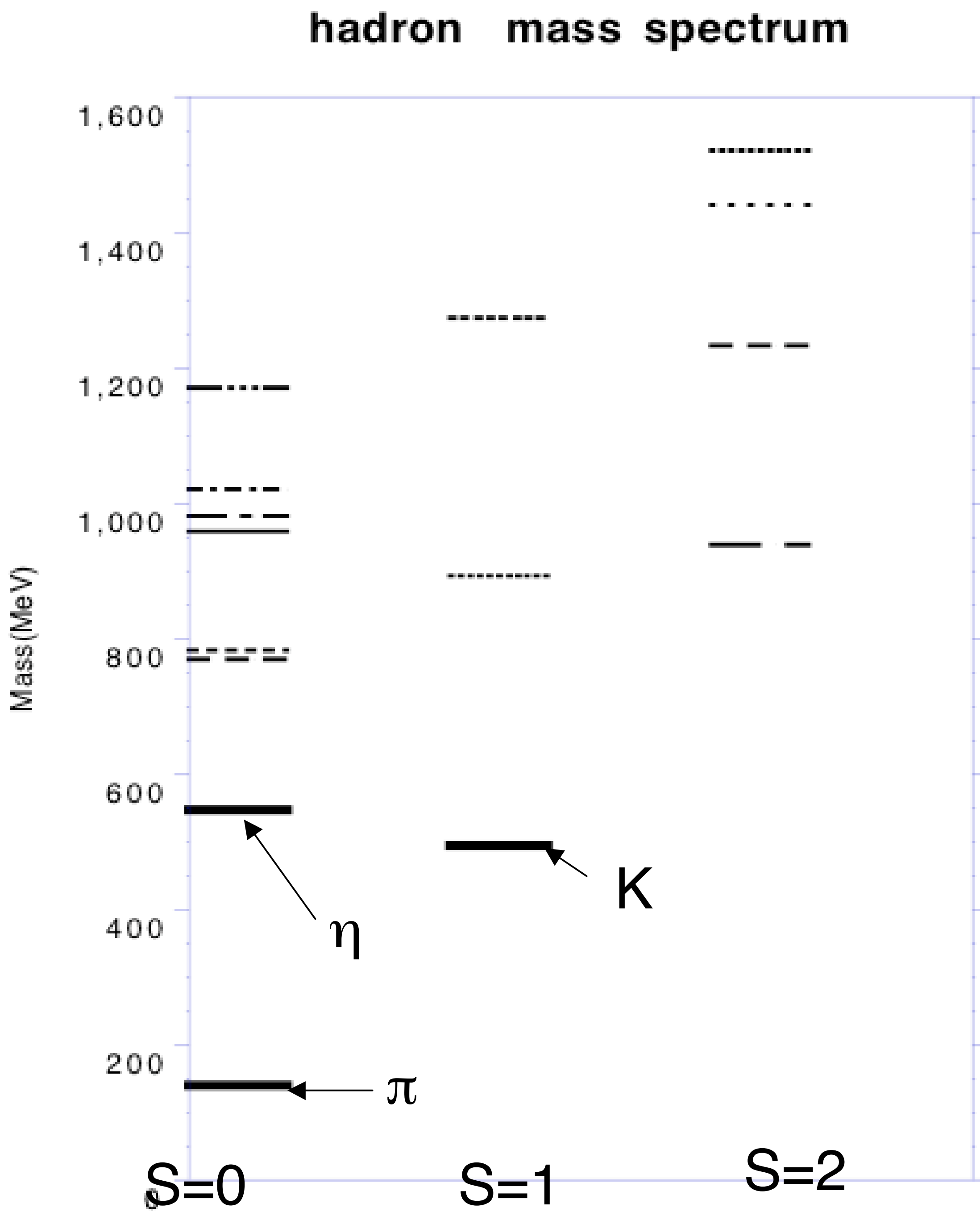
- Spontaneous Chiral symmetry breaking $\Rightarrow$ pions
- $\pi^0 \rightarrow \gamma\,\gamma$: Axial anomaly
- NLO chiral corrections: isospin breaking ~m_d-m_u
- Previous experiments
- Primex Experiment at Jefferson Lab

Spontaneous Breaking(Hiding) of Chiral Symmetry in QCD

- For massless particles h= σ • **p** = ±1 is conserved
- For massless quarks $L_{QC\ D}$ conserves chiral symmetry
- Therefore each state has 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
- lp> $1/2^+$,lp> lπ> $1/2^-$ are degenerate

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)



hadron mass spectrum
Mass(MeV)
1,600
1,400
1,200
1,000
800
600
400
200
0
η
K
π
S=0
S=1
S=2

- π not a pure Goldstone Boson

$m_u, m_d, m_s \neq 0$ chiral symmetry broken

$m_u \approx 5$ MeV, $m_d \approx 9$ MeV, $m_s \approx 140$ MeV

$m_\pi^2 = B(m_u + m_d) \approx 140$ MeV $\rightarrow 0$ as $m_q \rightarrow 0$

$B \propto \langle 0 | \bar{q}q | 0 \rangle$ "vacuum condensate"

- π–hadron interaction small as $p_\pi \rightarrow 0$, how small?

$\sigma(\theta) \rightarrow a(\pi h)^2$ $a(\pi h)$ = s wave πh scattering length
pure Goldstone Boson: $a(\pi h) = 0$
strong interactions: $a(\pi h) \approx 1/m_\pi \approx 1$ fm

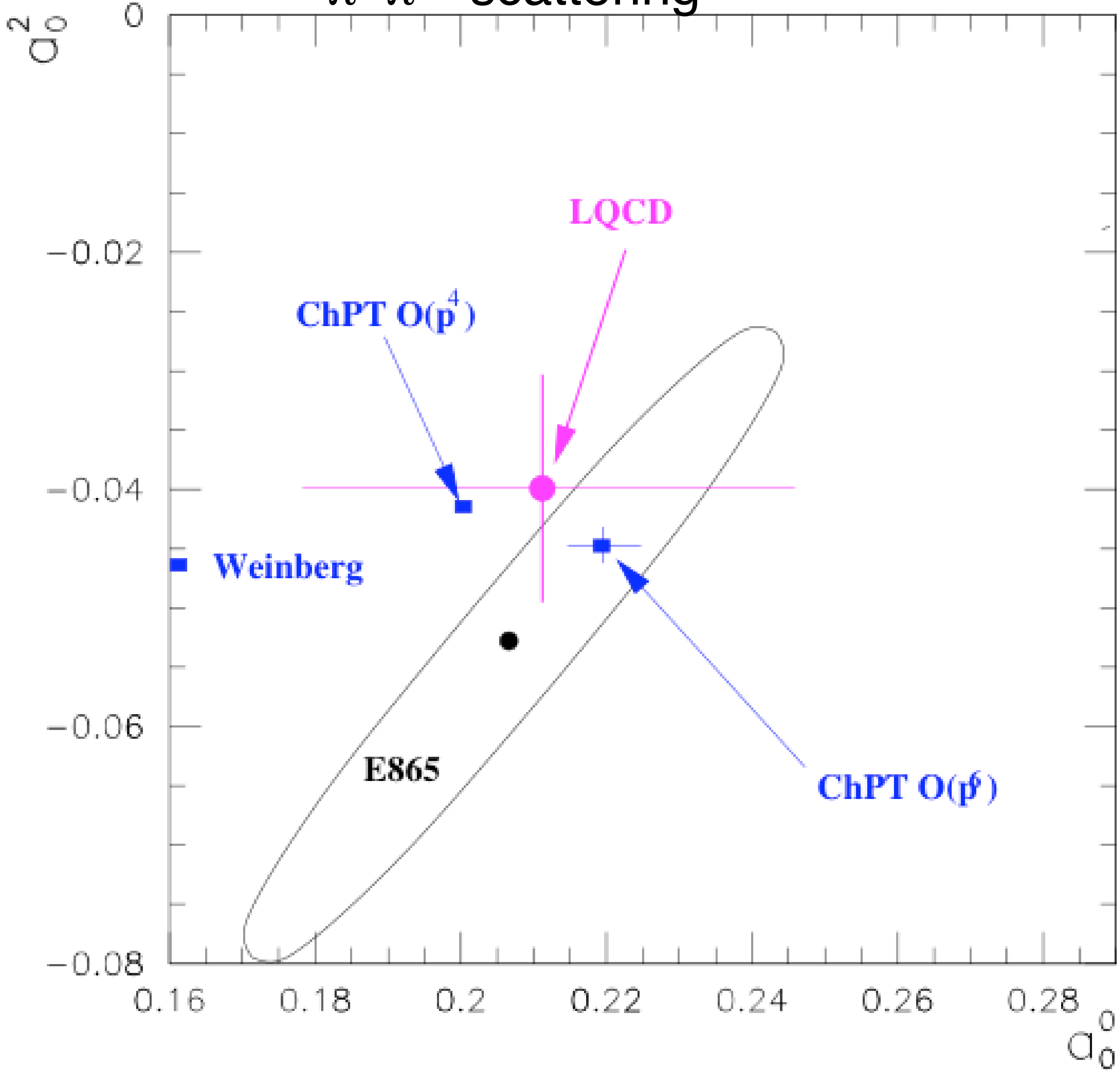
intuitively for a "Goldstone Boson" $a(\pi h) \approx 1/\Lambda \approx 0.1$fm
Λ =chiral sym. breaking scale $\approx 4\pi F_\pi \approx 1$ GeV
pion decay constant $F_\pi = 92$ MeV

PCAC calculation by Weinberg (1966)

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

This is the lowest order ChPT calculation
Expect chiral corrections of order $(m_\pi/\Lambda) \approx 0.02$

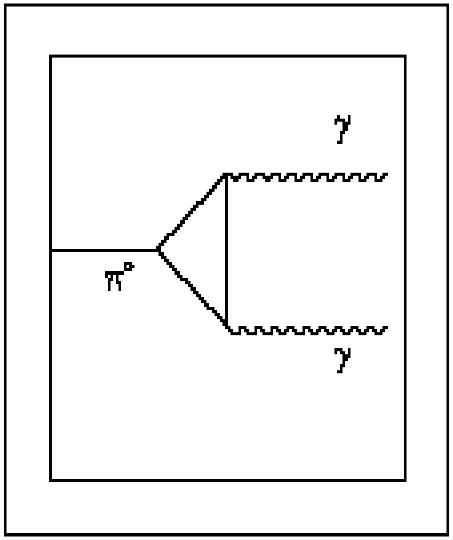
$\pi - \pi$ scattering



- π^0 decay rate is a fundamental prediction of confinement scale 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 amplitude:

$$A_{\pi^0\to\gamma\gamma} = \frac{\alpha_{em}}{4\pi F_\pi}\varepsilon_{\mu\nu\rho\sigma}k^{\mu}k^{\prime\nu}\varepsilon^{*\rho}\varepsilon^{*\sigma}, \quad (1)$$

or the reduced amplitude,

$$A_{\gamma\gamma} = \frac{\alpha_{em}}{4\pi F_\pi} = 0.02513\ \mathrm{GeV}^{-1} \quad (2)$$

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

•axial anomaly predicts $\Gamma(\pi 0 \rightarrow \gamma\gamma) \sim |A\gamma\gamma|^2$ m_π^3 =7.725 eV

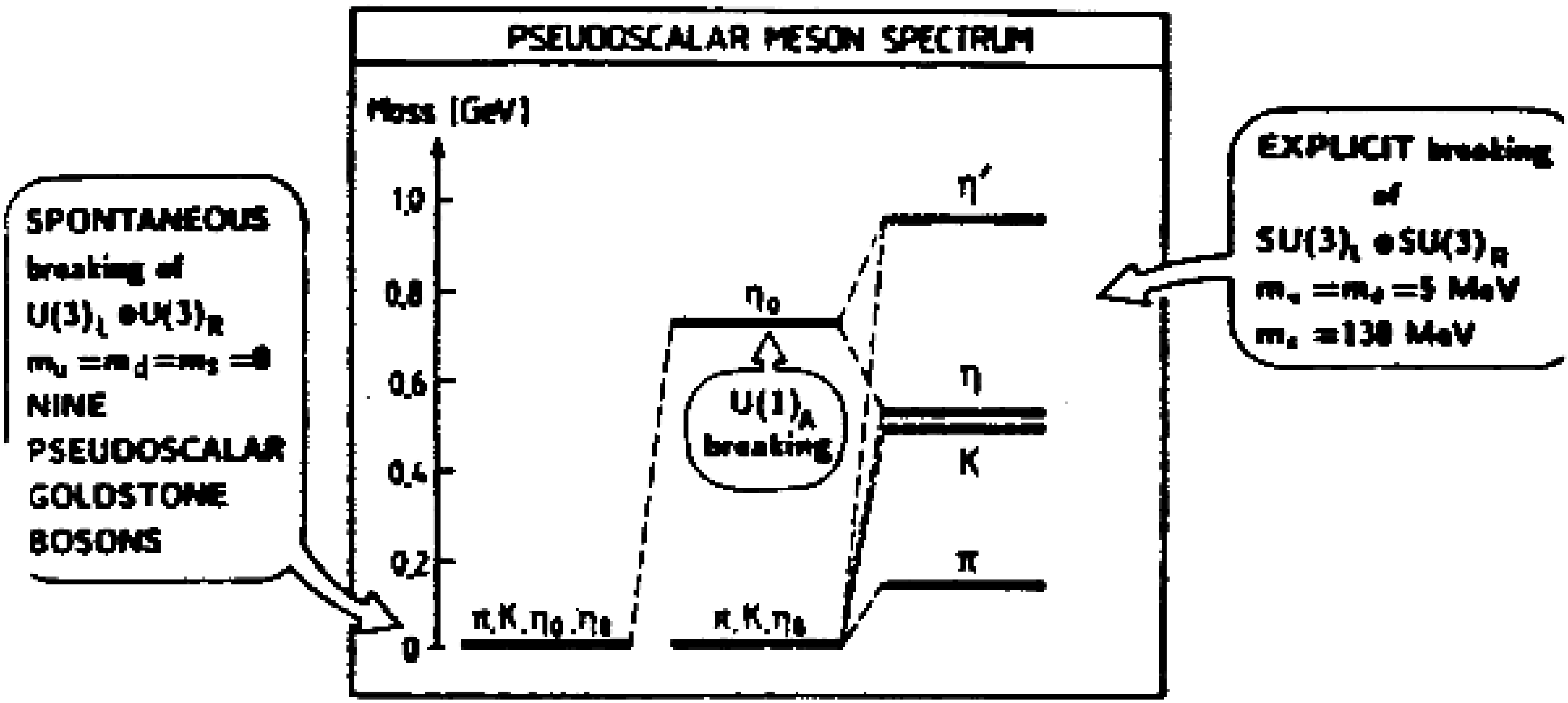
• chiral corrections due to finite quark masses
Calculated by J.Goity, AB, B. Holstein, PRD 2002
in NLO: ChPT in large Nc limit

• largest effect is π, η, η' mixing

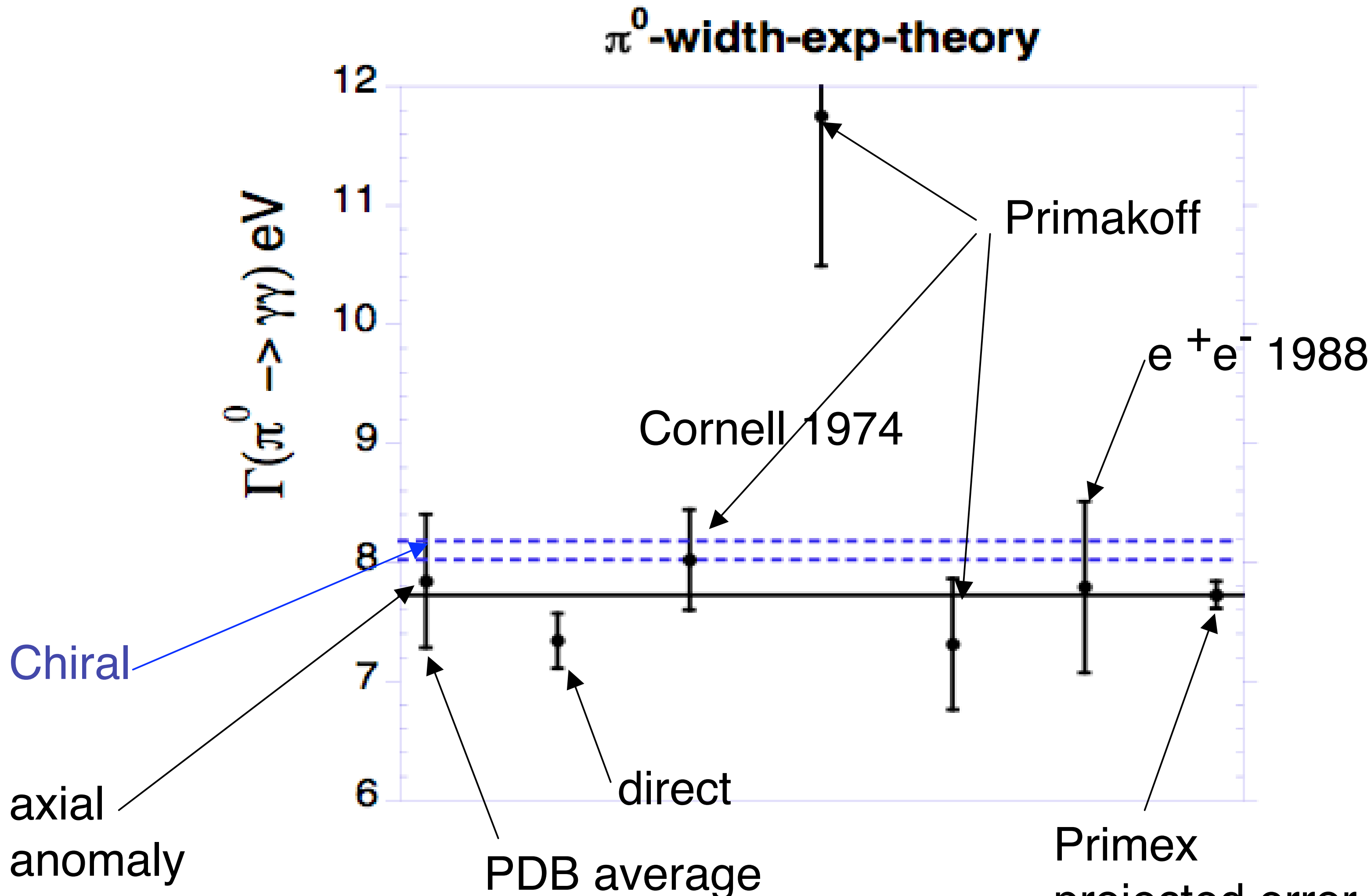
•Isospin mixing ~ m_d-m_u

•4.5±1 % increasein width

• $\Gamma(\pi 0 \rightarrow \gamma\gamma)$ =8.04 ±0.08 eV

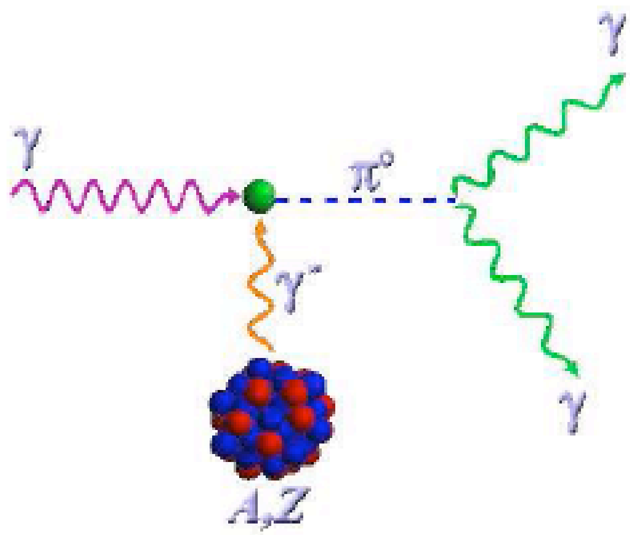


PSEUDOSCALAR MESON SPECTRUM
Mass [GeV]
1.0
0.8
0.6
0.4
0.2
0
π, K, η_0, η_8
η_0
$U(1)_A$ breaking
π, K, η_8
η'
η
K
π
SPONTANEOUS breaking of
$U(3)_L \otimes U(3)_R$
$m_u = m_d = m_s = 0$
NINE PSEUDOSCALAR GOLDSTONE BOSONS
EXPLICIT breaking of
$SU(3)_L \otimes SU(3)_R$
$m_u = m_d = 5$ MeV
$m_s = 130$ MeV

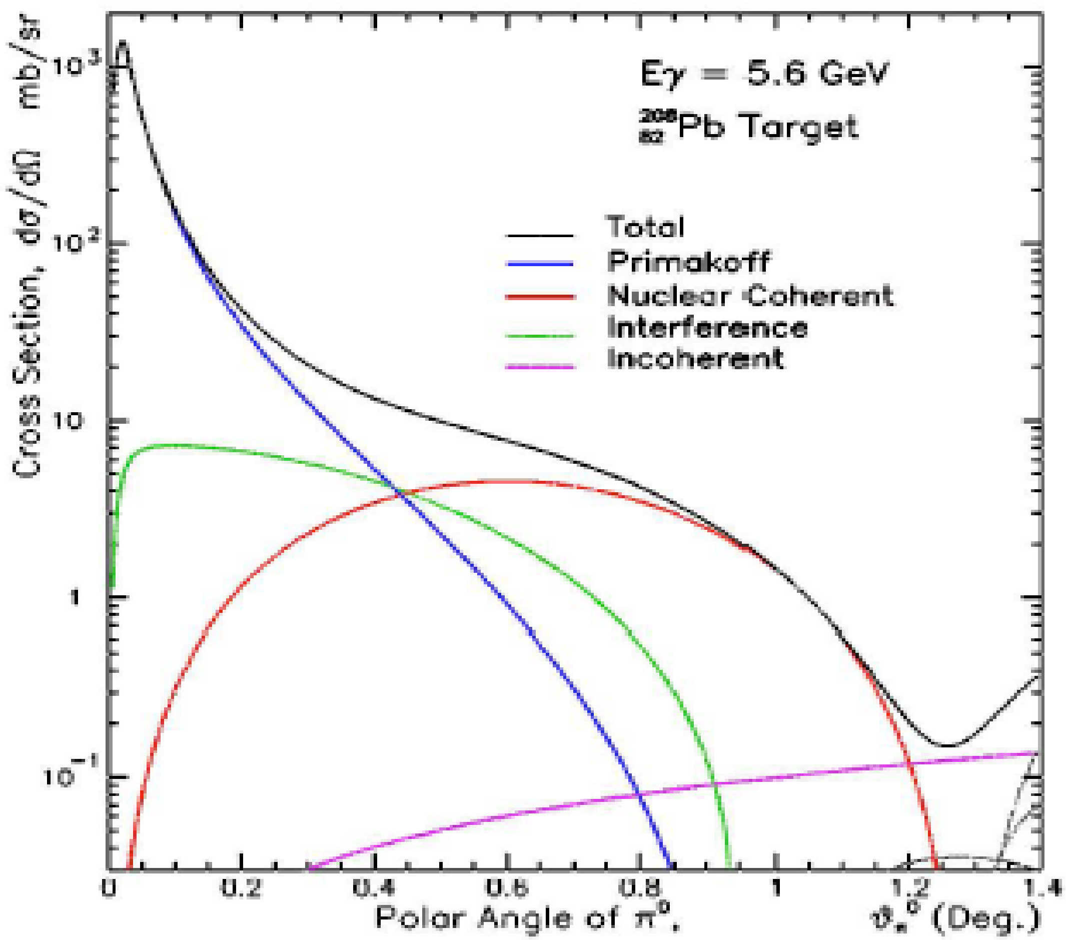


π^0-width-exp-theory
$\Gamma(\pi^0 \to \gamma\gamma)$ eV
12
11
10
9
8
7
6
Primakoff
e^+e^- 1988
Cornell 1974
Chiral
axial
anomaly
PDB average
direct
Primex
projected error

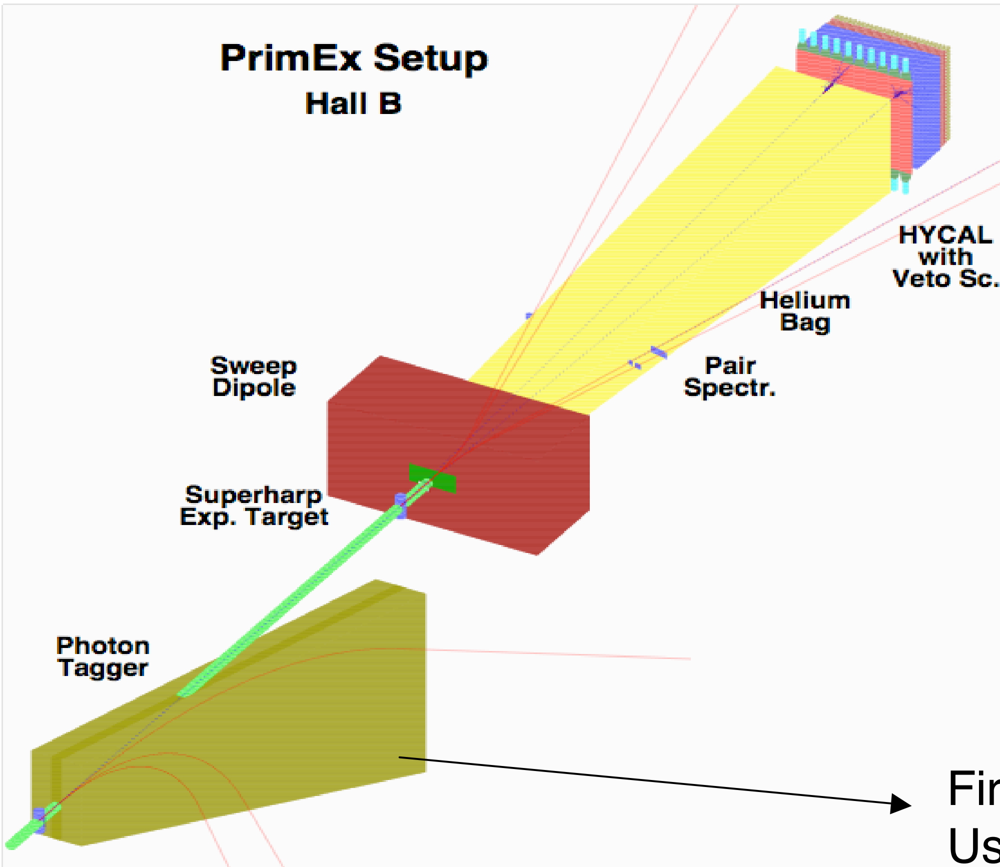
Primakoff Effect



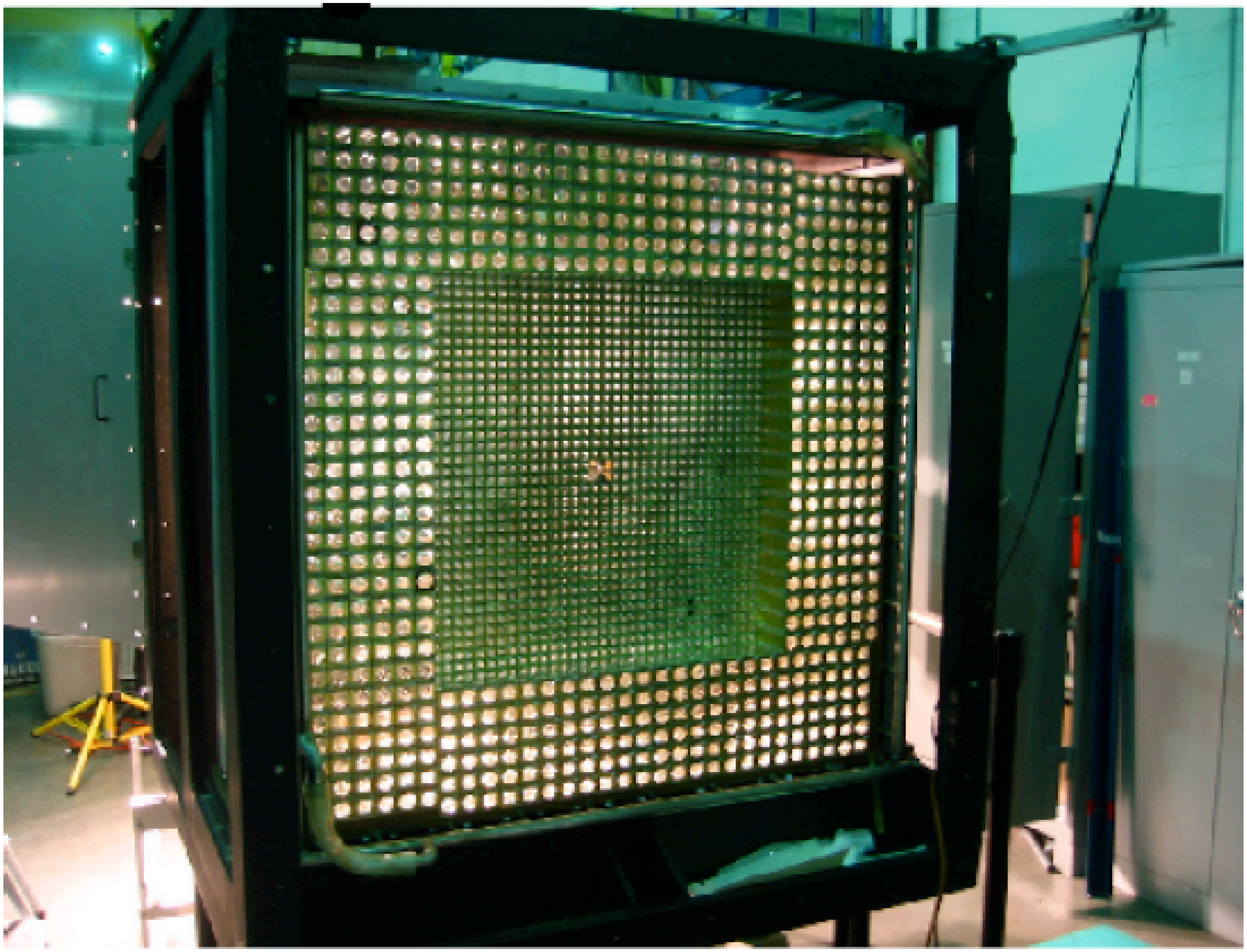
- π^0 photoproduction from Coulomb field of nucleus.
- Equivalent production ($\gamma\gamma^* \rightarrow \pi^0$) and decay ($\pi^0 \rightarrow \gamma\gamma$) mechanism implies Primakoff cross section proportional to π^0 lifetime.
- Primakoff π^0 produced at very forward angles.



Eγ = 5.6 GeV
208 82 Pb Target
Total
Primakoff
Nuclear Coherent
Interference
Incoherent
Cross Section, dσ/dΩ mb/sr
Polar Angle of π⁰, ϑπ⁰ (Deg.)
10³
10²
10
1
10⁻¹
0
0.2
0.4
0.6
0.8
1
1.2
1.4



First Primakoff exp to
Use tagged photons



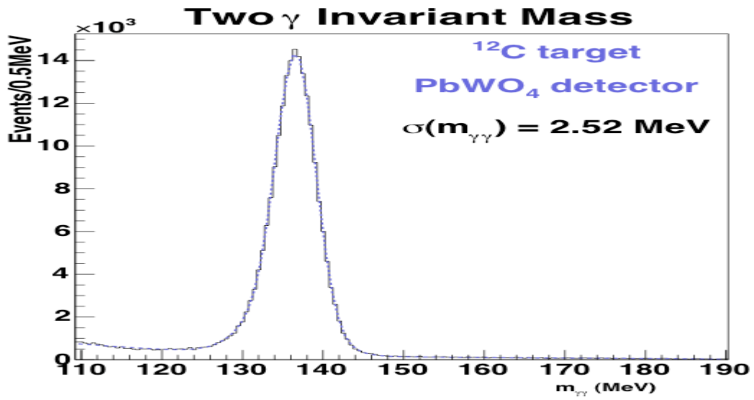
Experiment Overview

- 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.

Data Collection

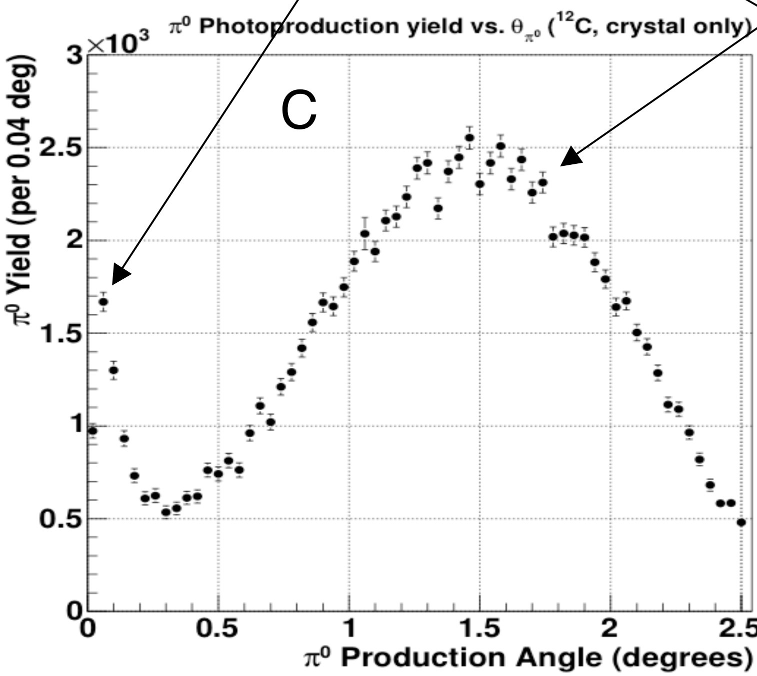
- HyCal Calibration: "snake" scan before and after experiment (for gain alignment and energy calibration)
- Periodic TAC/luminosity runs–measure absolute tagging efficiency for photon flux determination
- Periodic Compton runs (to measure absolute Compton coss section)–used f systematic studies of experimental setup (detector alignment, π^0 yield normalization, and monitor Hycal gain drifts).
- π^0 photoproduction from 5% χ_0 ^{12}C and ^{208}Pb targets using $\sim$ 100nA e-beam current wich generated $\sim$ 5MHz tagged photon rate.
- DAQ event readout triggered by HyCal total ADC sum in coincidence with tagger hodoscope hit (produced a rate of $\sim$ 1.5kHz)

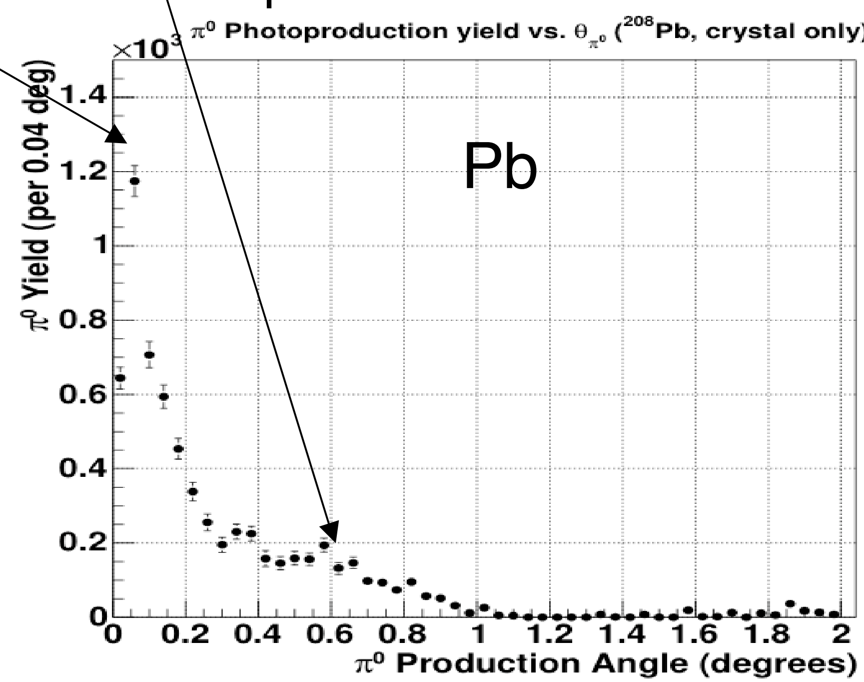
Primex:
Preliminary



Primakoff peak

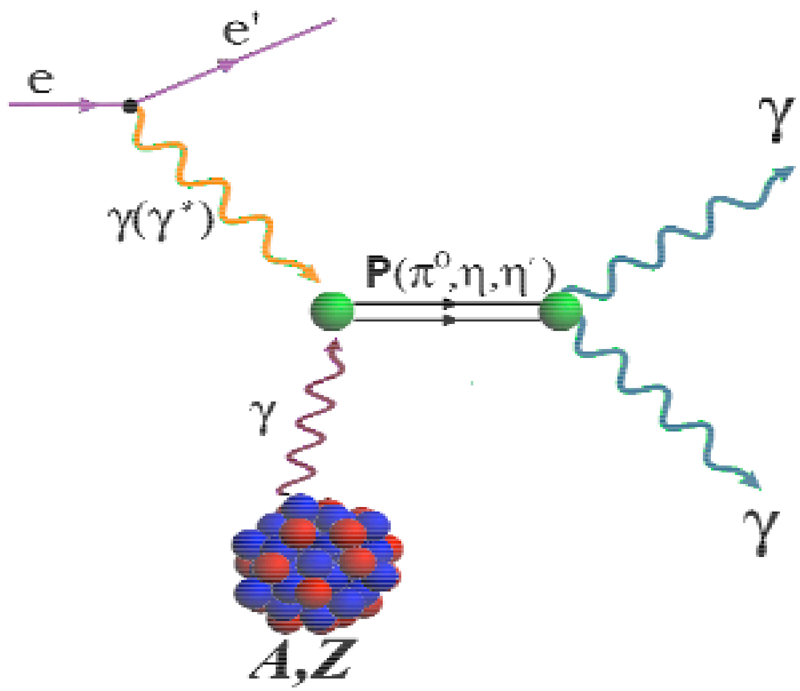
Nuclear coherent
Suppressed in Pb
compared to C





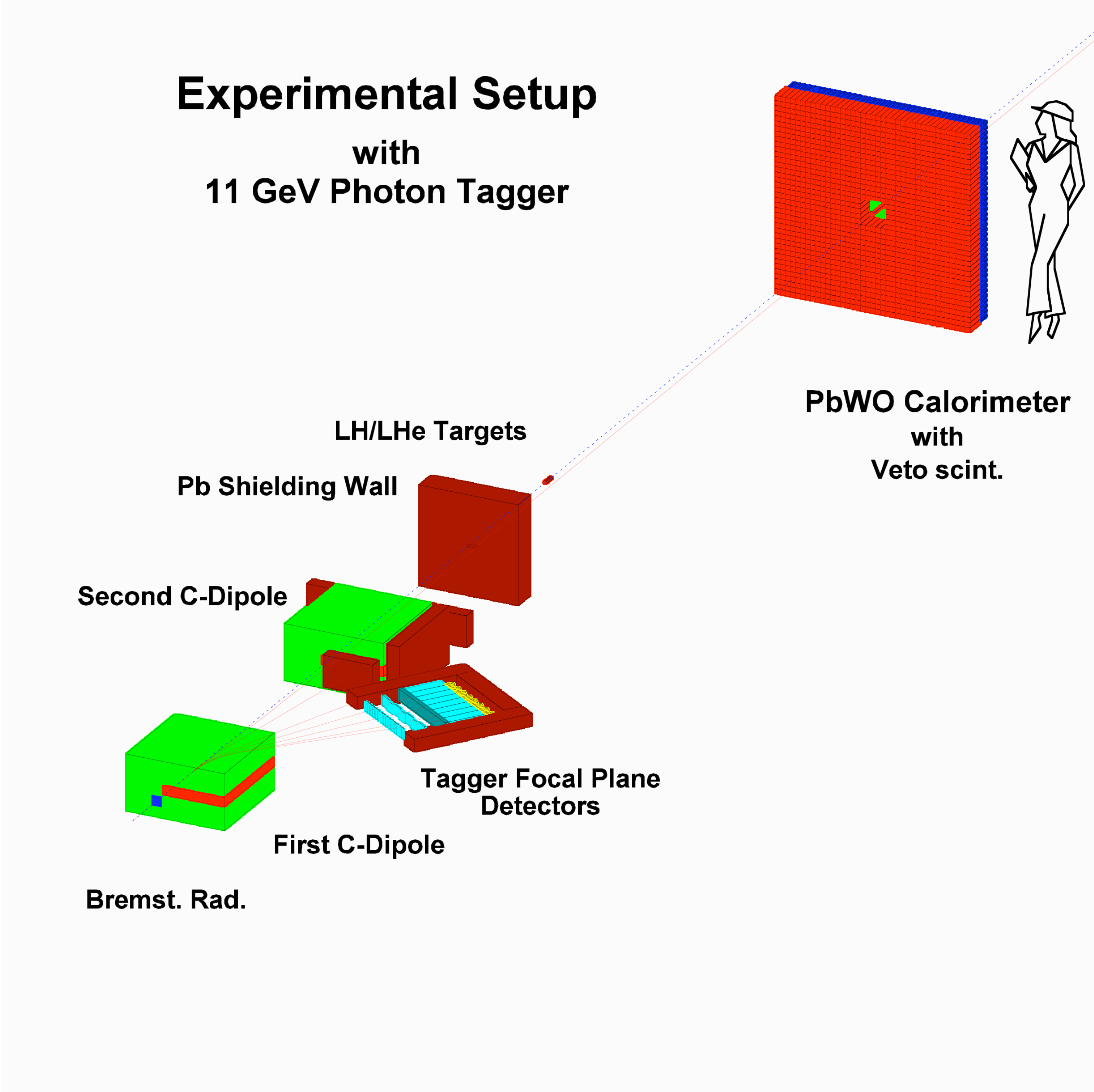
12 GeV JLab Program: The PrimEx Collaboration

- Two-Photon Decay Widths: $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
- Transition Form Factor $F_{\gamma\gamma^* P}$ of π^0, η, η' at low Q^2 (0.001–0.5 GeV^2)

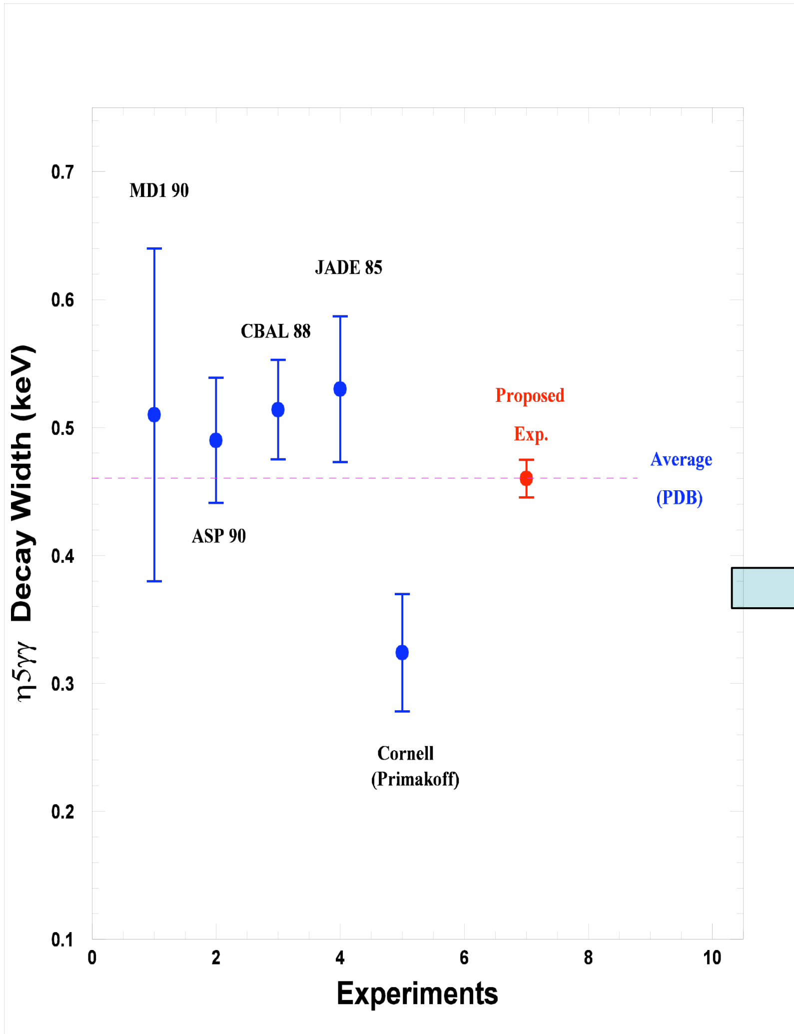


12 GeV Experimental Setup

- Use Light targets: ¹H and ⁴He
- New High Energy Photon Tagger
- Upgrade HYCAL Calorimeter with all $PbWO_4$

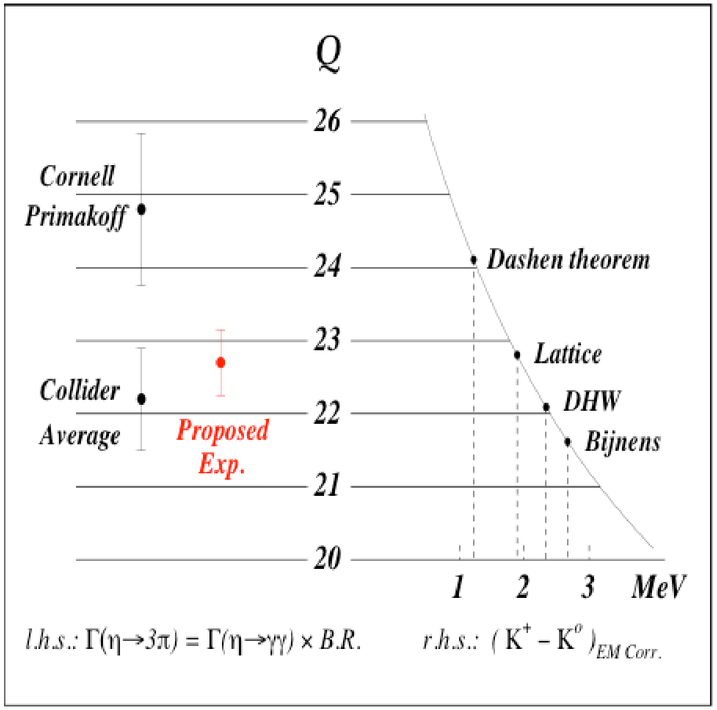


Decay Width $\Gamma(\eta \to \gamma\gamma)$

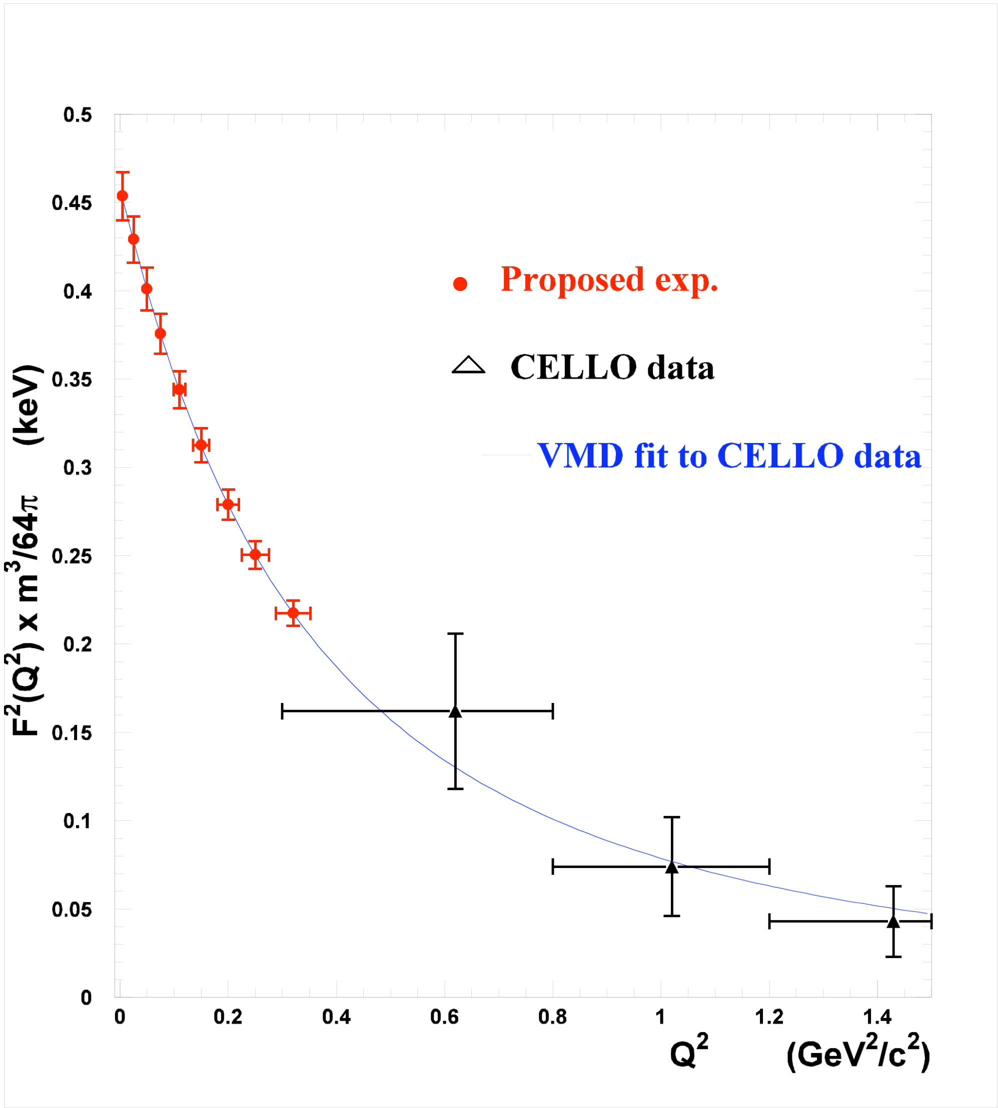


Quark Mass Determination

$$Q^2 = \frac{m_s^2 - \bar{m}^2}{m_d^2 - m_u^2} \quad , \quad \bar{m} = \frac{m_u + m_d}{2}$$



Transition form factor $F(\gamma \gamma^* \to \eta)$



Outlook: measurement of the π^0 lifetime: testing a prediction axial anomaly and NLO chiral correction $\sim m_d - m_u$
⇒spontaneous chiral symmetryhiding, quark mass effects

•Spontaneous Chiral symmetry hiding ⇒ Goldstone Bosons
has been verified in $\pi-\pi$, $\pi-N$, $\gamma N \rightarrow \pi N$

- quark mass effects: $(m_d + m_u)$
- pion cloud effects: non-spherical effects in N, Δ

Opportunities : IS breaking (m_d - m_u)

- $\pi-N$ scattering, $\gamma N \rightarrow \pi N$

Spokesperson

Spokesperson and contact person

A. Afanasev [p], A. Ahmidouch [m], M. Alexanian [u], A. Asratyan [i], I. Aznauryan [x], K. Baker [f], J. Ball [a], A.M. Bernstein [k], T. Black [u], W. Briscoe [e], J.P. Chen [p], O. Chernyshov [i], M. Christy [f], E. Chudakoff [p], E. Clinton [t], P.L. Cole [v], H. Crannell [b], D. Dale [s], S. Danagoulian [m], G. Davidenko [i], A. Dolgolenko [i], M. Dugger [a], G. Dzyubenko [i], H. Egiyan [p], K. Egiyan [x], M. Elaasar [o], R. Ent [p], A. Evdokimov [i], A.I. Fix [q], M. Gabrielyan [s], L. Gan [u], **A. Gasparian [m]**, S. Gevorgyan [x], A. Glamazdin [j], J. Goity [f], Yu. Goncharenko [h], V. Goryachev [i], P. Gueye [f], V. Gyurjyan [p], R. Hakobyan [b], D. Hasell [k], J. He [g], R. Hicks [t], M. Hollister [u], B. Hu [s], M. Ito [p], C. Jackson [m], A. Kamenskii [i], C. Keppel [f], A. Ketikyan [x], M. Khandaker [l], W. Korsch [s], S. Kowalski [k], M. Kubantsev [i], V. Kubarovsky [h], I. Larin [i], D. Lawrence [t], C. Li [c], Z. Liu [c], S. Lu [c], A. Margaryan [x], V. Matveev [i], A. Meschanin [h], B. Milbrath [d], R. Minehart [w], R. Miskimen [t], S. Mtingwa [m], A. Nathan [r], A. Omelaenko [j], E. Pasyuk [a], A. Petrosyan [x], V. Punjabi [l], B.G. Ritchie [a], C. Salgado [l], V. Semyachkin [i], A. Shahinyan [x], Y. Sharabian [p], A. Sitnikov [i], E. Smith [p], D. Sober [b], L. Soloviev [h], B. Stevens [w], R. Suleiman [k], L. Tang [f], A. Teymurazyan [s], V.A. Tryasuchev [q], J. Underwood [m], A. Vasiliev [h], V. Verebryusov [i], V. Vishnyakov [i], H. Voskanyan [x], J. Yuan [c], L. Yuan [f], J. Zhou [c], S. Zhou [c], X. Zhu [c], P. Zolnierczuk [s]

[a] Arizona State University, Tempe, AZ
[b] Catholic University of America, Washington, DC
[c] Chinese Institute of Atomic Energy, Beijing, China
[d] Eastern Kentucky University, Richmond, KY
[e] George Washington University, Washington, DC
[f] Hampton University, Hampton, VA
[g] Institute for High Energy Physics, Chinese Academy of Sciences, Beijing, China
[h] Institute for High Energy Physics, Protvino, Moscow region, Russia
[i] Institute for Theoretical and Experimental Physics, Moscow, Russia
[j] Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[k] Massachusetts Institute of Technology, Cambridge, MA
[l] Norfolk State University, Norfolk, VA
[m] North Carolina A&T State University, Greensboro, NC
[n] North Carolina Central University, Durham, NC
[o] Southern University at New Orleans, New Orleans, LA
[p] Thomas Jefferson National Accelerator Facility, Newport News, VA
[q] Tomsk Polytechnical University, Tomsk, Russia
[r] University of Illinois, Urbana, IL
[s] University of Kentucky, Lexington, KY
[t] University of Massachusetts, Amherst, MA
[u] University of North Carolina at Wilmington, Wilmington, NC
[v] University of Texas at El Paso, El Paso, TX
[w] University of Virginia, Charlottesville, VA
[x] Yerevan Physics Institute, Yerevan, Armenia