The π^0 Lifetime Experiment and Future Plans at JLab

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(for the PrimEx Collaboration at JLab)

Outline

- **The PrimEx Experiment at JLab:**
  - □ **Physics Motivation**
  - □ **Previous Experiments**
  - □ **Why do we need a New Primakoff Experiment?**
  - □ **Summary**

- **The $\Gamma(\eta \to \gamma\gamma)$ Experiment at JLab:**
  - □ **Existing World Data**
  - □ **How to make an Improved Primakoff Experiment?**
  - □ **Summary**

Physics Motivation

- $\pi^0 \rightarrow \gamma\gamma$ decay proceeds primarily via chiral anomaly in QCD.

- The prediction of chiral anomaly is exact for massless quarks:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 m_\pi^3}{64\pi^3 F_\pi^2} = 7.725 \text{ eV}$$

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

- Explicit breaking of chiral symmetry, induced by non-zero $u-$ and $d-$quark masses, generates corrections to the chiral limit prediction.

- Corrections due to isospin breaking (π^0, η, η' mixing) are proportional to quark mass differences.

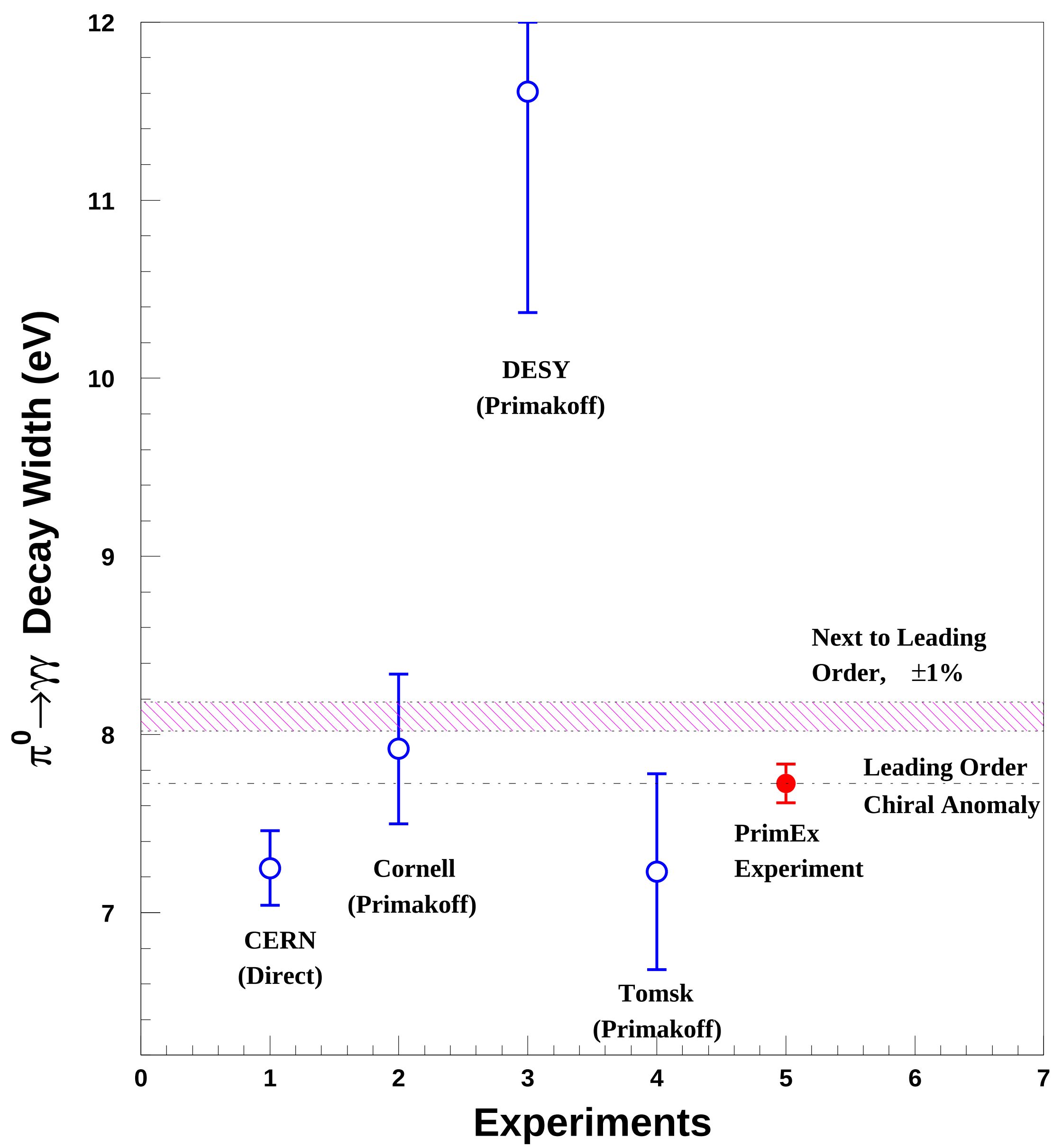
- Recent theoretical calculations of NLO corrections in χPT predict:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10 \text{ eV}$$

  $\sim$4% higher than the LO prediction, with an uncertainty of less than 1%.

- High precision measurements of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at $\sim$1% level will provide ultimate test of fundamental prediction of chiral anomaly in QCD.

$\Gamma(\pi^0 \to \gamma\gamma)$ World Data

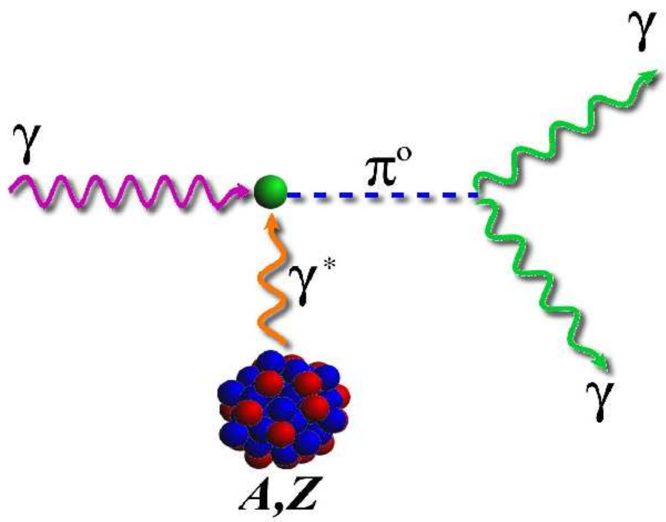


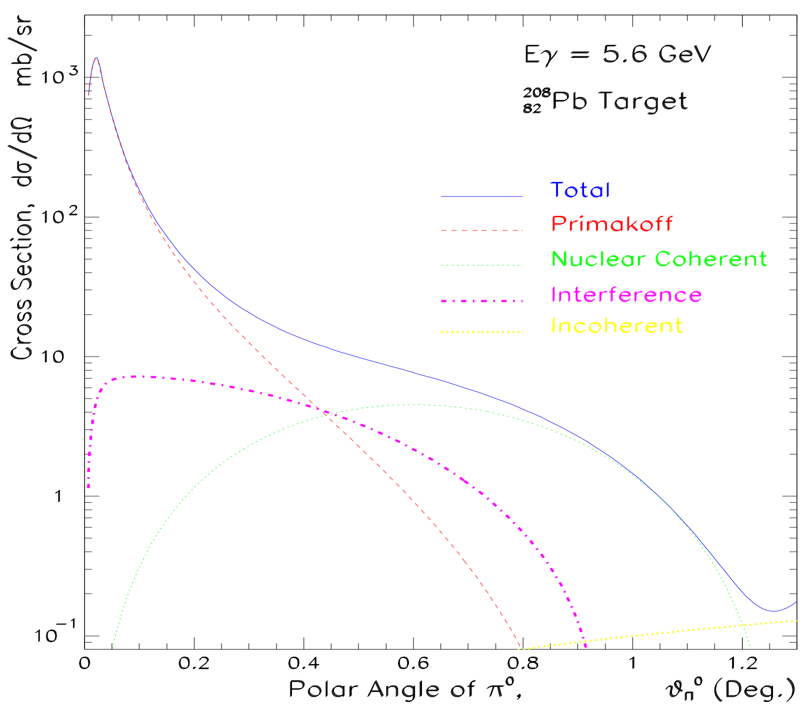
Previous Experiments

- **The Direct Method:**
  Mean decay length measurement
  - ☐ **Experiment at CERN SPS (1985)**
    ($P_{proton} = 450$ GeV$/c \Rightarrow L_{mean} \sim 50\ \mu$m)
  - ☐ **Results:** $\Gamma_{\pi^0 \to \gamma\gamma} = (7.34 \pm 0.18 \pm 0.11)$ eV $(\pm 3.0\%)$
  - ☐ **Dominant systematic error:**
    - **- uncertainty in** P_{π^0} $(\pm 1.5\%)$
      (average from $\pi^\pm$ **spectra.)**

- e^+e^- **Collider Experiments:**
  - ☐ **Experiment: DORIS II @ DESY**
  - ☐ **Results:** $\Gamma_{\pi^0 \to \gamma\gamma} = (7.7 \pm 0.5 \pm 0.5)$ eV $(\pm 10.0\%)$
  - ☐ **Dominant systematic errors:**
    - **- luminosity (**$\sim$ **6%), and**
    - **- beam-residual gas interaction**
  - ☐ **Not included in PDG average**

Primakoff Effect





$$\frac{d^3\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha Z^2}{m^3}\frac{\beta^3 E^4}{Q^4}|F_{e.m.}(Q)|^2 \sin^2\theta_\pi$$

$$<\theta_{Pr}>_{peak} \sim \frac{m^2}{2E^2}, \qquad \int d\sigma_{pr} \sim Z^2 E^2, \qquad \left(\frac{d\sigma_{pr}}{d\Omega}\right)_{peak} \sim E^4$$

□ **Task: extract the Primakoff amplitude.**

Primakoff Experiments

• DESY (1970)

- ☐ bremsstrahlung γ beam: $E_\gamma = 1.5, 2.5$ GeV
- ☐ targets: C, Zn, Al, Pb
- ☐ Results: $\Gamma_{\pi^0 \to \gamma\gamma} = (11.7 \pm 1.2)$ eV $(\pm 10.0\%)$
- ☐ Dominant systematic errors:
  - geometrical acceptance: $\pm 7\%$
  - statistical: $\pm 6\%$
  - quantameter: $\pm 3\%$

• Cornell (1974)

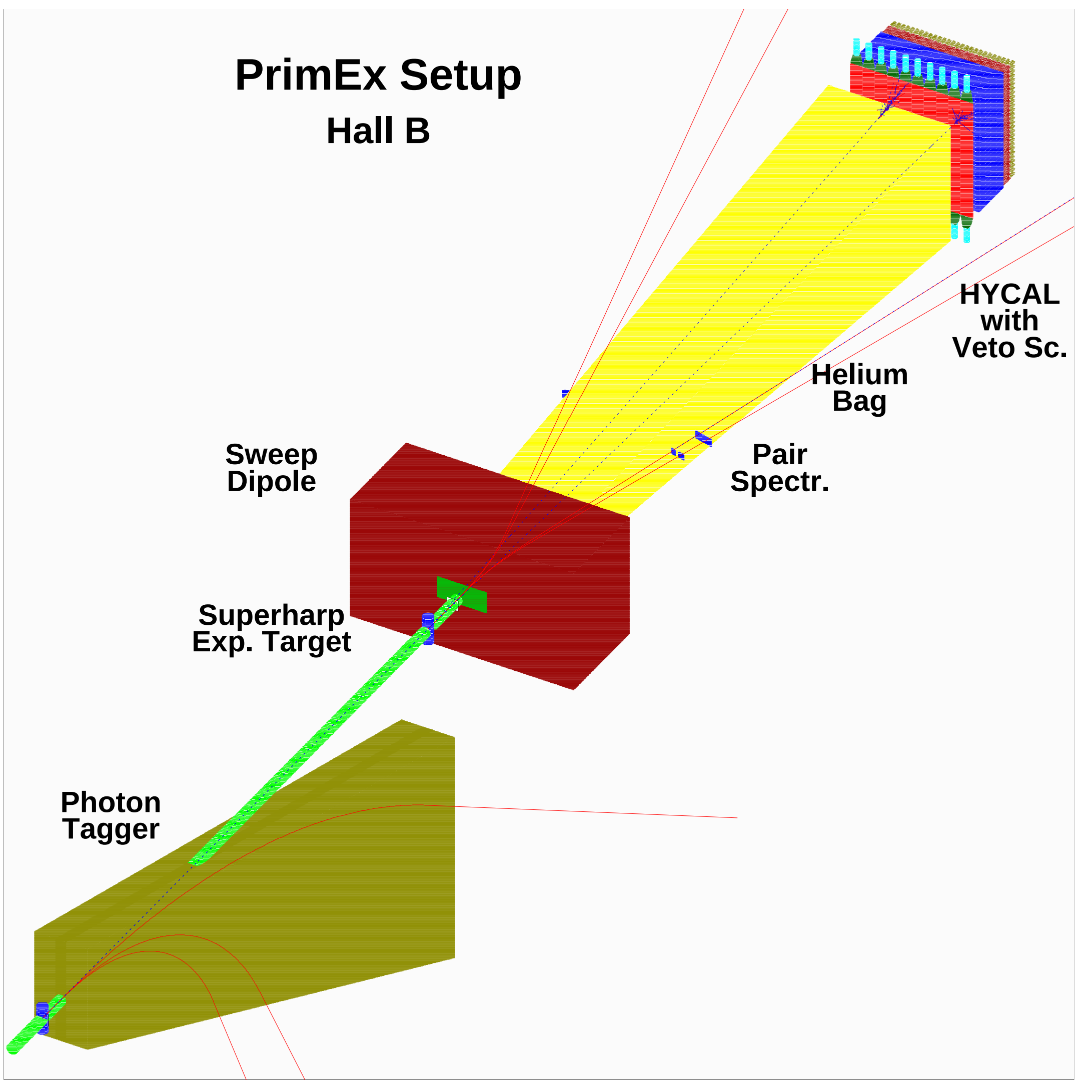
- ☐ bremsstrahlung γ beam: $E_\gamma = 4, 6$ GeV
- ☐ targets: Be, Al, Cu, Ag, U
- ☐ Results: $\Gamma_{\pi^0 \to \gamma\gamma} = (7.92 \pm 0.42)$ eV $(\pm 6\%)$
- ☐ Dominant systematic errors:
  - photon number: $\pm 4\%$
  - quantameter: $\pm 2\%$

☐ All experiments used:

- Bremsstrahlung Photon Beams;
- Conventional Lead Glass Calorimeter

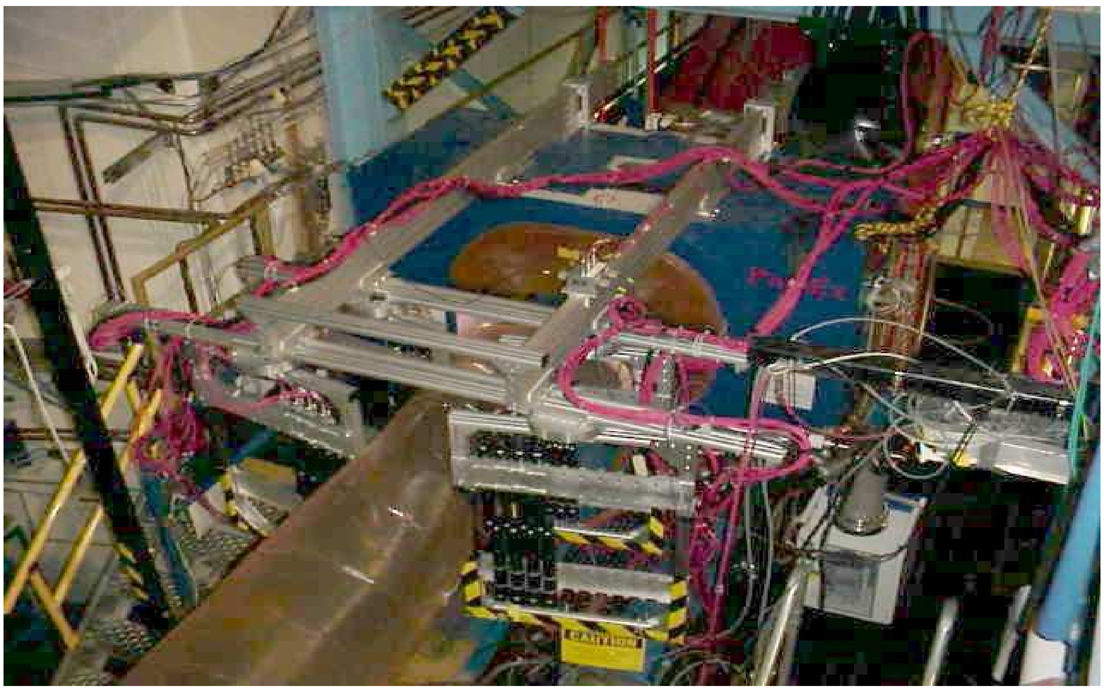
PrimEx Setup

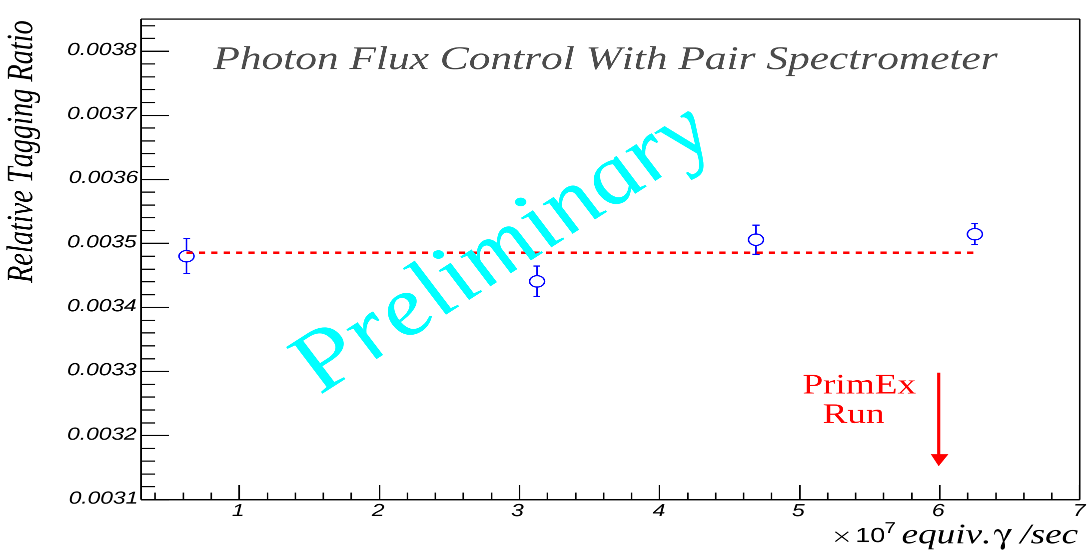
- ☐ High resolution, high intensity CW JLab Photon Tagging Facility
- ☐ Pair Spectrometer (PS) to correct Tagger at high intensities
- ☐ High resolution $PbWO_4$ novel Hybrid Electromagnetic Calorimeter (HYCAL)



Photon Flux Control

- **Goal: 1.0%** in N_γ: $\Longleftarrow$ from Tagger
- **Problem:** will run at high intensities $\sim 6 \times 10^7$ equiv. γ/sec
- **Solution:** Pair Spectrometer as on-line Photon Flux Monitor

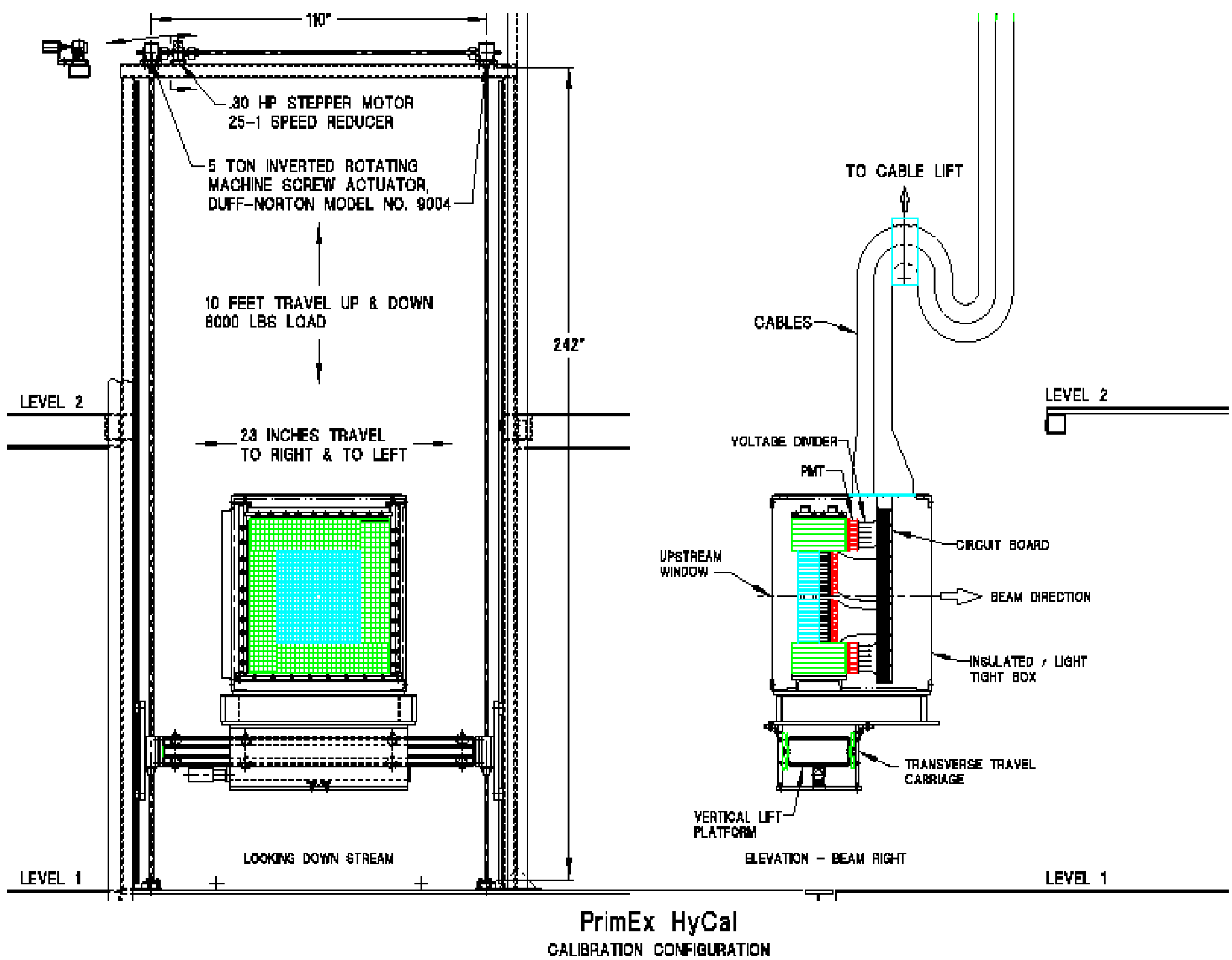




The HYCAL Calorimeter

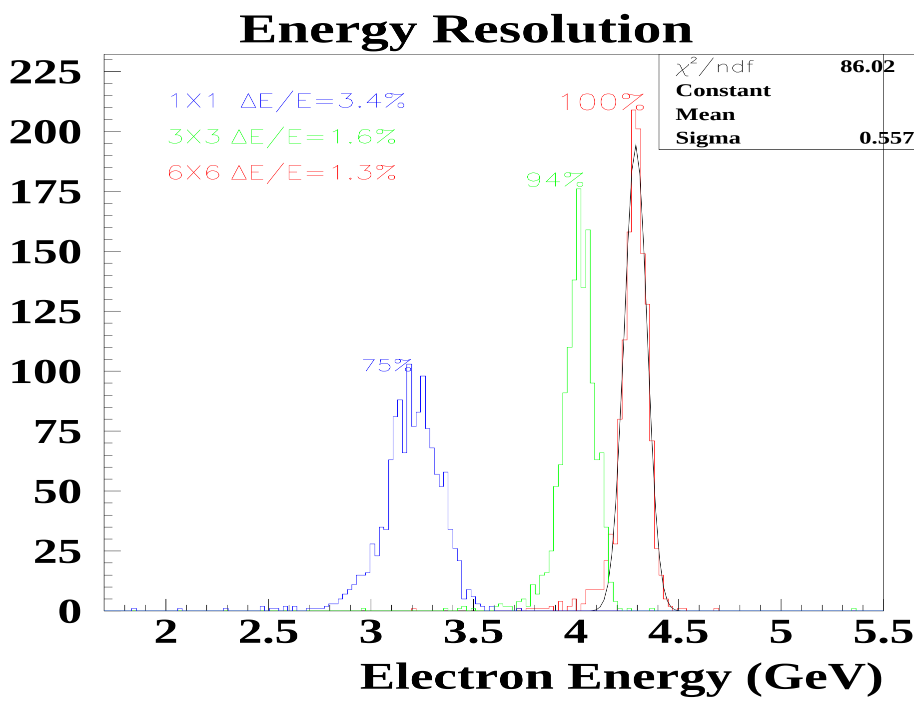
Calorimeter Concept: Optimize Performance and Cost

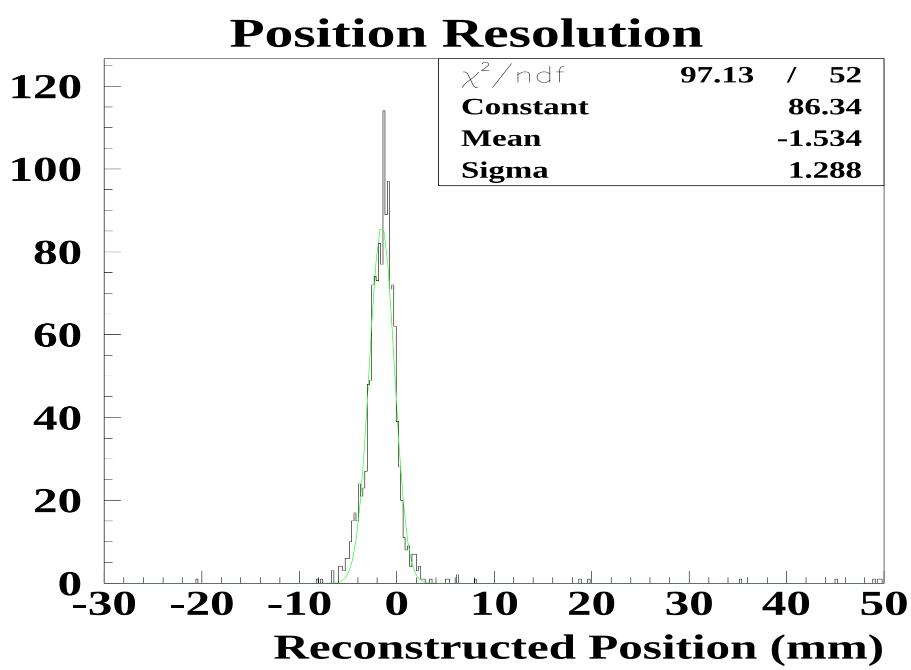
- ~1200 $PbWO_4$ crystal detectors:
  (to enhance position and energy resolutions)
- ~600 Pb-glass detectors: (to optimize the costs)
- Detector area ~120×120 cm^2



HYCAL Resolution

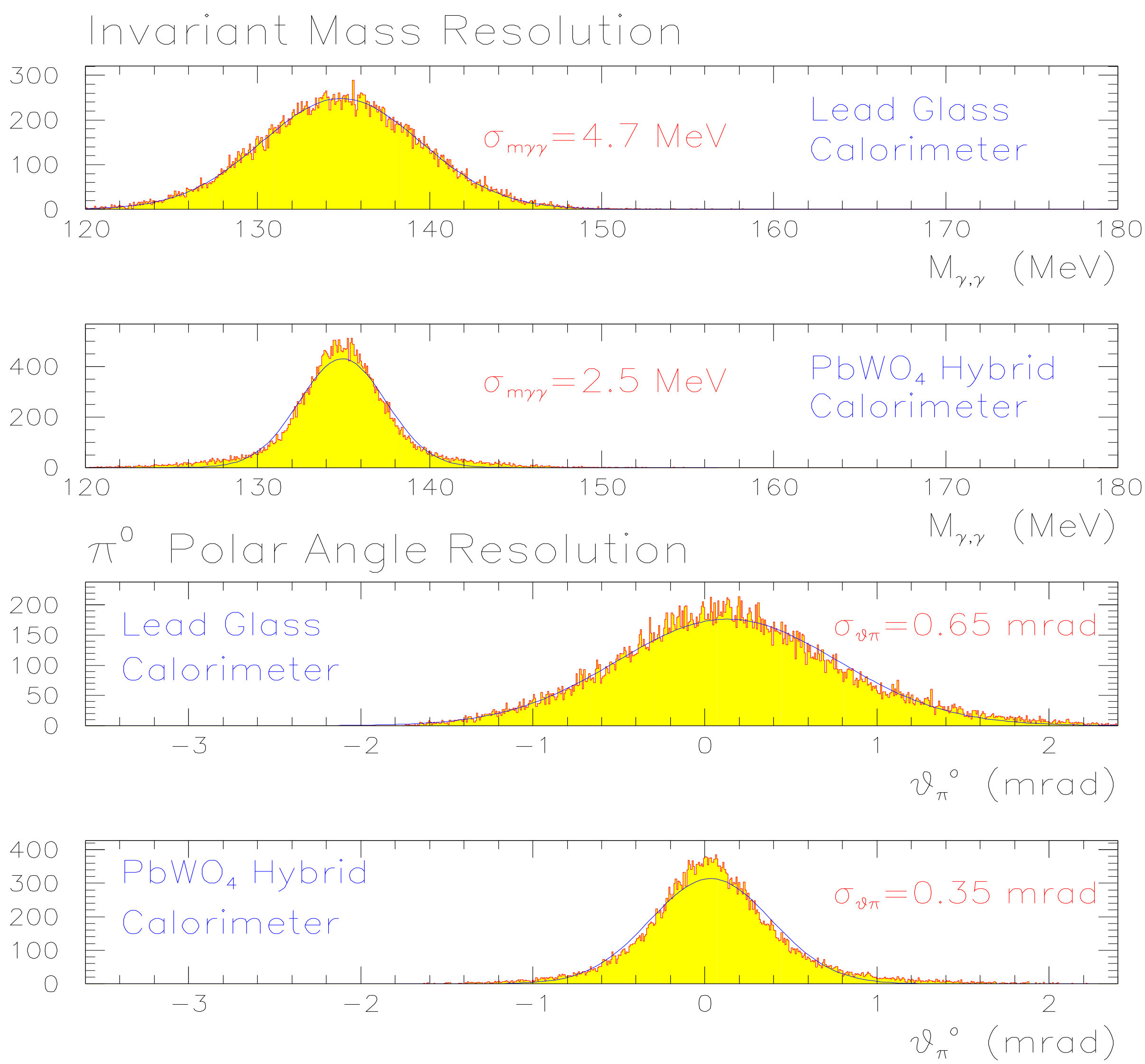
- ☐ Lead glass detectors are well known.
- ☐ Beam tests for $PbWO_4$ crystal detectors at JLab:





Improvements Over Previous Experiments

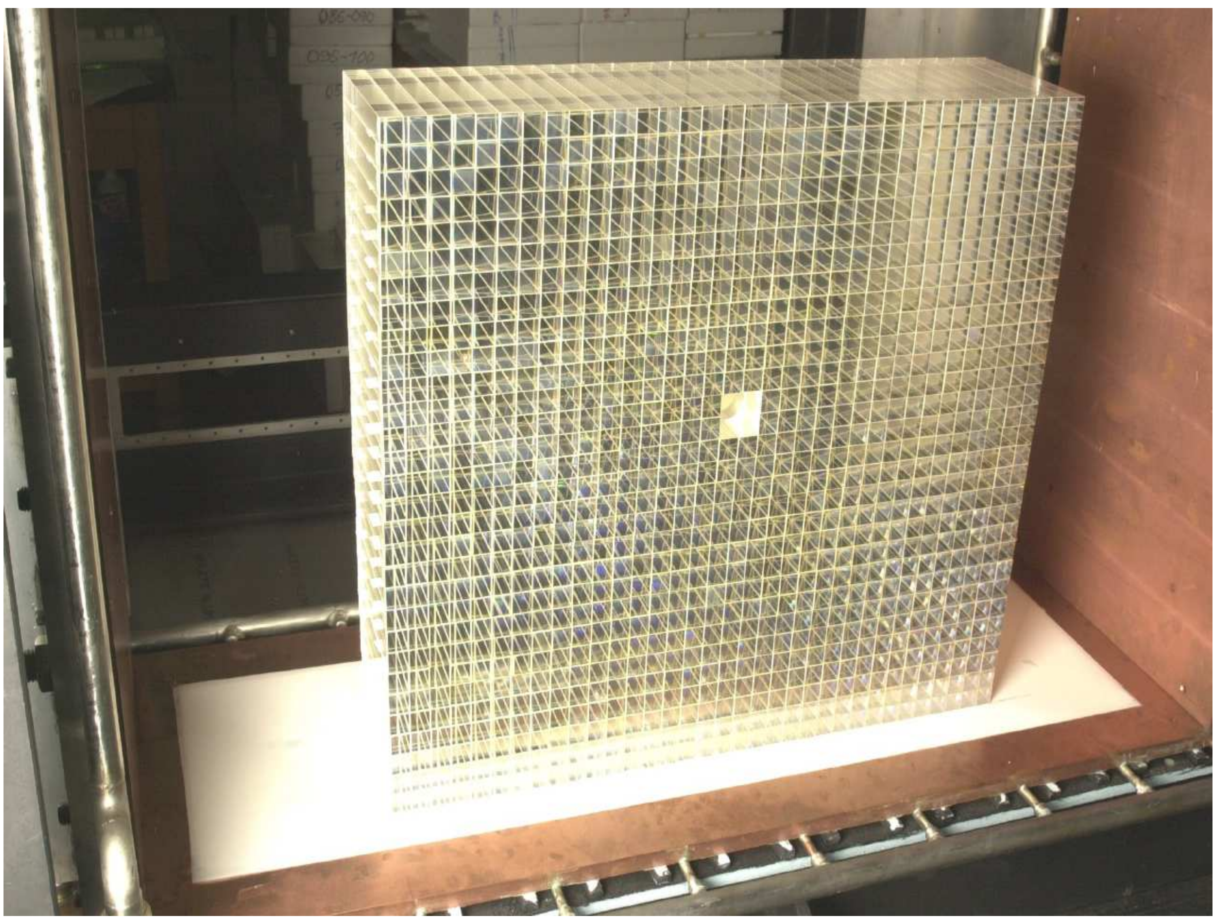
- **Photon Flux:** N_γ $\Longleftarrow$ **from (Tagger + Pair Spectrometer)**
- **Invariant Mass:** $M_{\gamma\gamma}$ $\Longleftarrow$ **from HYCAL**
- **Pion Production Angle:** θ_π $\Longleftarrow$ **from (HYCAL + Tagger)**
- **Background Subtraction:** $\Longleftarrow$ **from (HYCAL + Tagger)**



PrimEx Error Budget

Experimental Uncertainties

statistical	0.4%
target thickness (atoms/cm^2)	0.7%
photon flux	1.0%
π^o detector acceptance and misalignment	0.4%
background subtraction	0.2%
beam energy	0.2%
distorted form factor calculation errors	0.4%
total	1.4%



PrimEx Summary

- Perform 1.4% precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$.

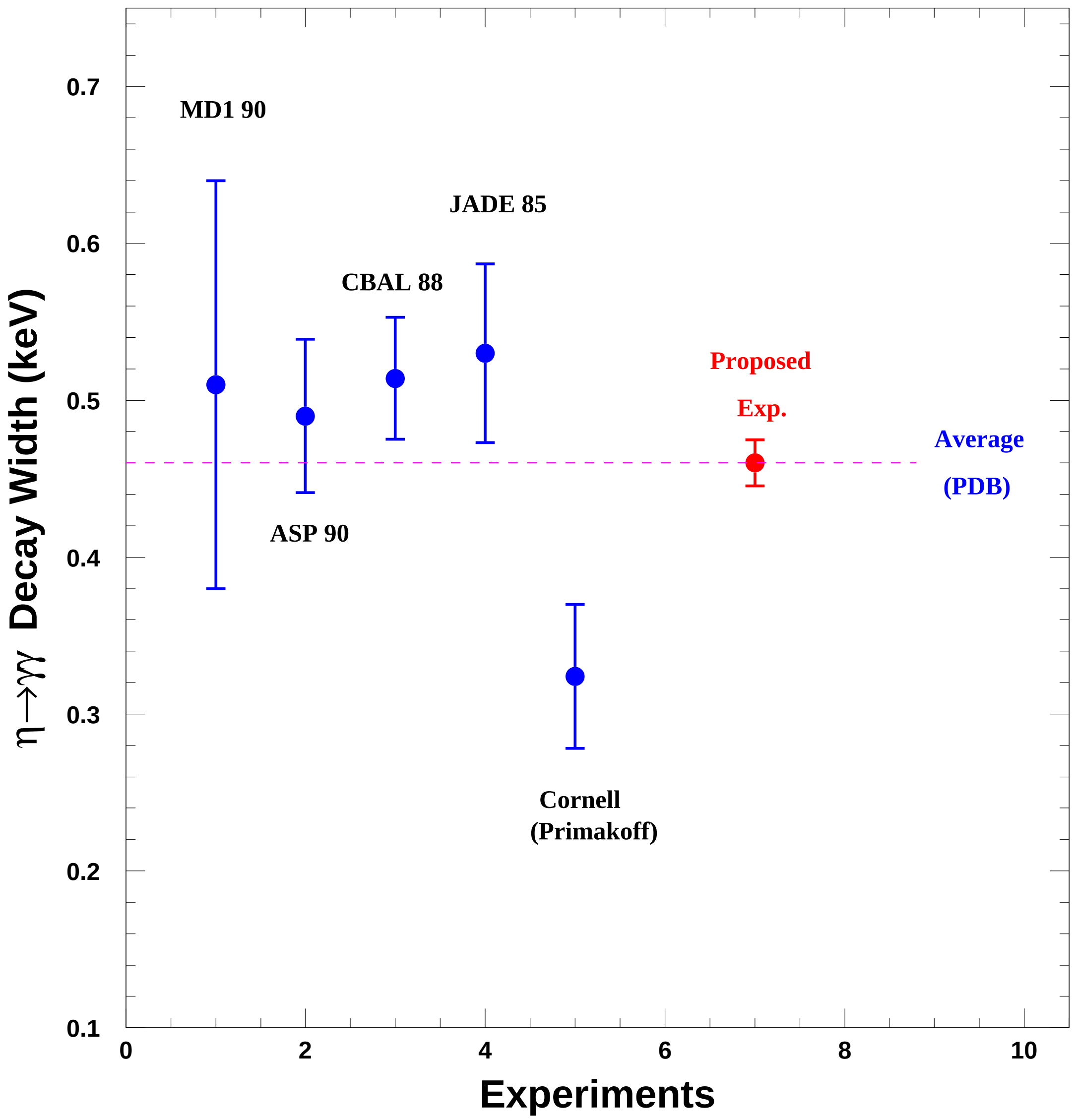
- Test fundamental prediction of QCD – the axial anomaly.

- Check NLO corrections (~4%) induced by isospin breaking as predicted by χPT.

- Will significantly improve all systematic uncertainties over previous experiments:
  - □ high precision CW photon tagging facility in Hall B.
  - □ pair spectrometer for on-line photon flux control.
  - □ high resolution electromagnetic calorimeter (HYCAL).

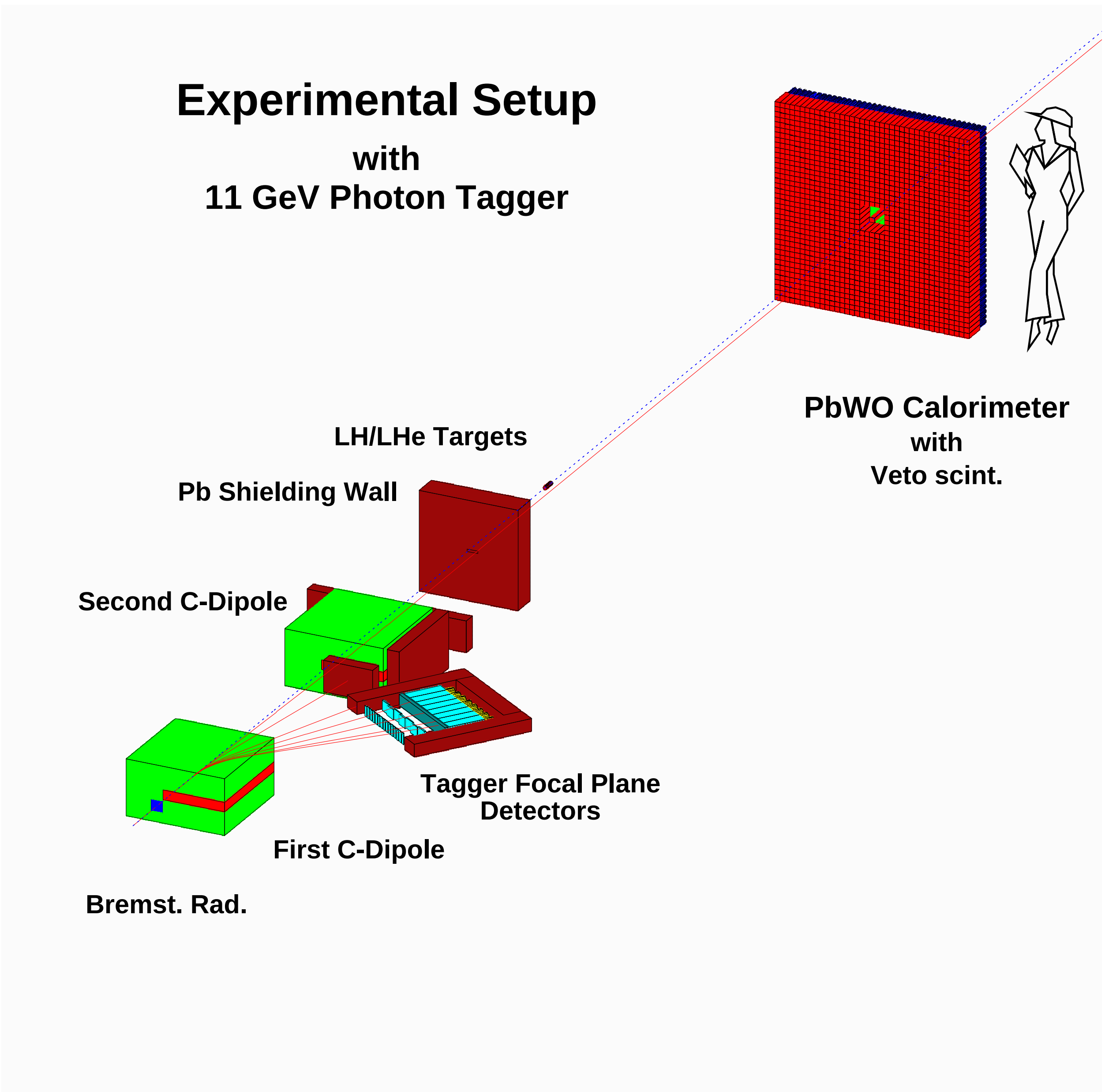
- PrimEx will start January, 2004 at JLab.

Experimental Data for $\Gamma(\eta \rightarrow \gamma\gamma)$

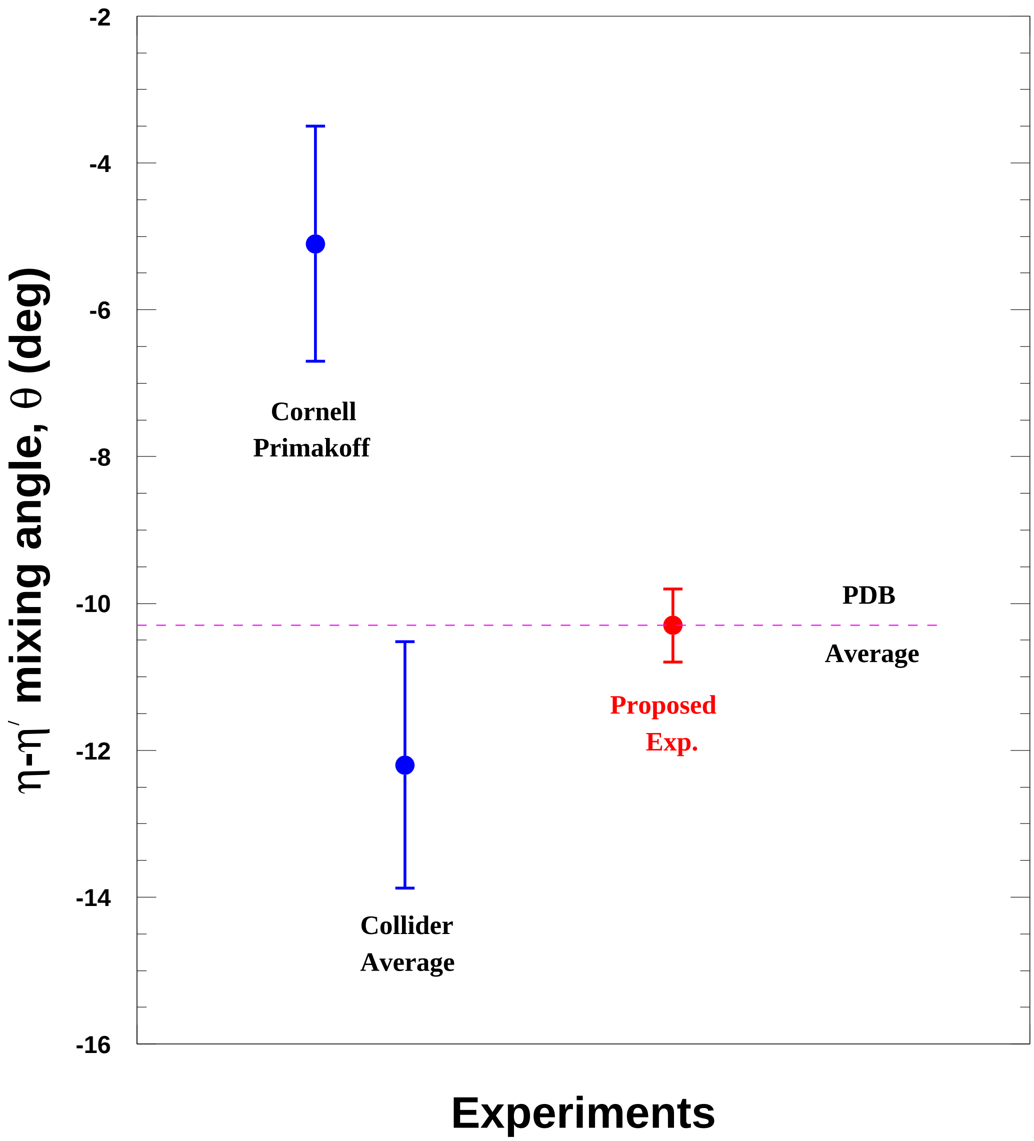


Experimental Setup

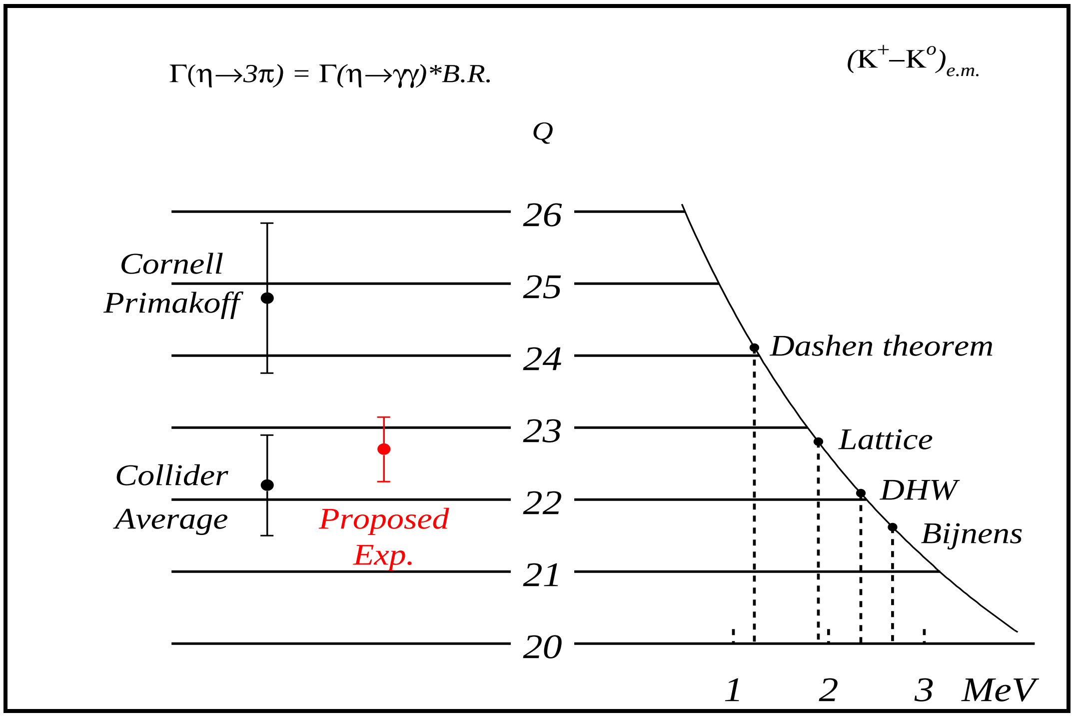
- Choose the Right Target $\Longrightarrow$ ^{4}He and ^{1}H
- New High Energy Photon Tagger (12 GeV JLab upgrade)
- Improved Calorimetry $\Longrightarrow$ HYCAL with all $PbWO_4$



Improvement on η–η' mixing angle



Determination of Quark Mass Ratio



$$Q^2 = \frac{M_K^2}{M_\pi^2} \cdot \frac{M_K^2 - M_\pi^2}{M_{K^0}^2 - M_{K^+}^2}(1 + \mathcal{O}(m^2))$$

From observed values of meson masses

⇒ **tight constraint on particular ratio of quark masses :**

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

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

Summary

- **High precision ($\sim$ 2-5%) measurements of two-photon decay widths at 12 GeV:**
  - ☐ $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$

- **Crucial input for fundamental physics:**
  - ☐ $(\eta - \eta')$ **mixing**
  - ☐ **Determination of light quark mass ratio**
  - ☐ **Critical tests of QCD-based models**

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URL: www.jlab.org/primex/