A Precision Measurement of the Neutral Pion Lifetime: the PRIMEX Experiment

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and the
PRIMEX Collaboration

- A short review of $\pi^0 \rightarrow \gamma\gamma$
- The PRIMEX experiment at JLab
- Electromagnetic calibration reactions
- Results for the π^0 lifetime
- PRIMEX at 12 GeV

Sixth International Conference on Perspectives in Hadronic Physics
Trieste – Italy, May 12-16, 2008

A short review of $\pi^0 \to \gamma\gamma$: "discovery"

- 1938: Yukawa postulates a neutral meson based on observations of charge independence of the NN force

- 1940: Sakata estimates $\tau \approx 10^{-16}$ s for the π^0 from $p\bar{p}$ loop diagram

- 1948: Oppenheimer suggests that π^0 decays are responsible for gamma backgrounds in high altitude cosmic rays

- 1950: π^0 discovered at Berkeley Cyclotron

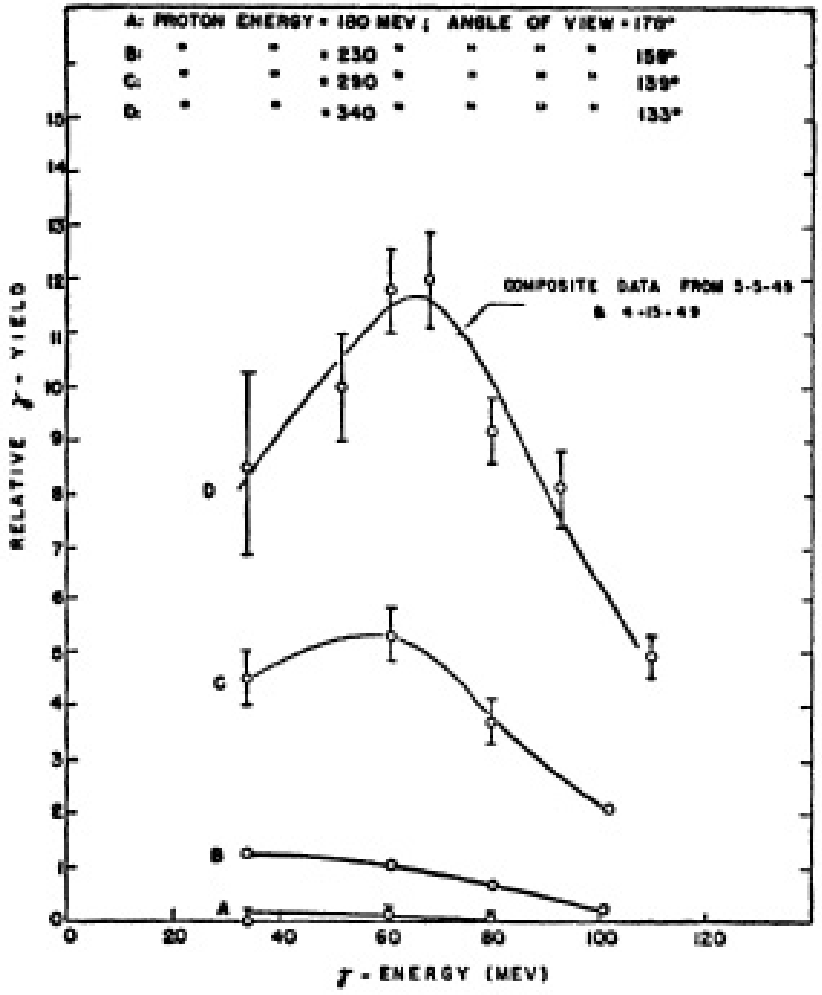
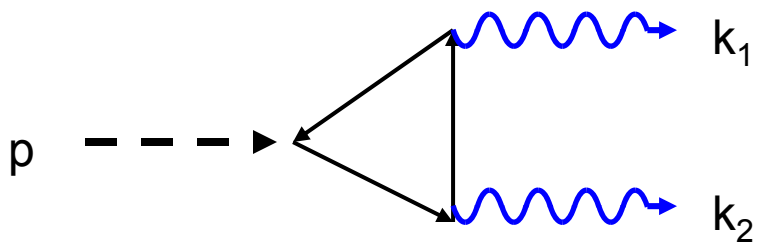


FIG. 4a. Relative gamma-yield from ½-in. carbon target at various proton energies.

A short review of $\pi^0 \to \gamma\gamma$: era of "current algebra"

- The soft-pion limit of PCAC predicts $A(\pi \to \gamma\gamma) = 0$
- *Adler, Bell, Jackiw and Bardeen* discover triangle diagrams that alter PCAC predictions for π^o decay



A short review of $\pi^0 \to \gamma\gamma$: era of QCD and effective interactions

- *Wess, Zumino and Witten* construct anomalous $O(p^4)$ lagrangian that permits transitions between even and odd numbers of pseudo-scalar mesons

- The chiral anomaly has special status in QCD: there are no low energy constants in lagrangian

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.725 \text{ eV}$$

A short review of $\pi^0 \to \gamma\gamma$: era of "chiral dynamics"

- Corrections due to

(i) u- d- quark masses

(ii) isospin breaking (π, η, and η' mixing) proportional to quark mass differences

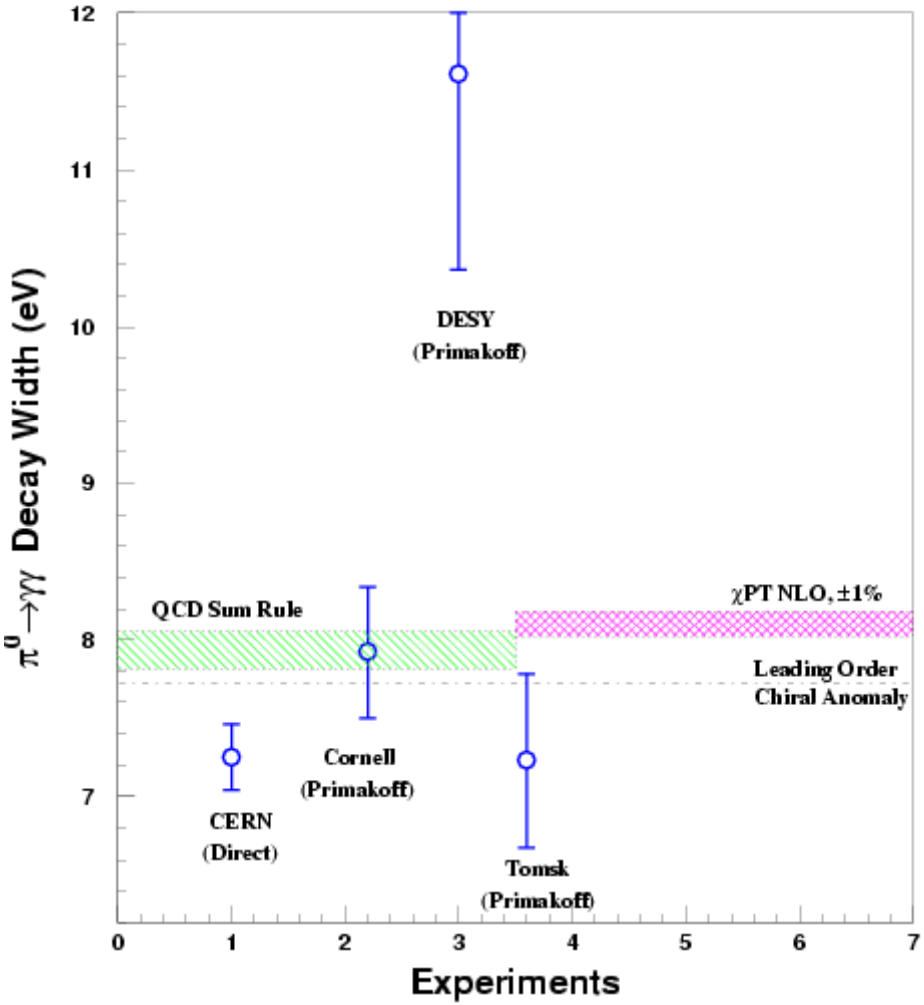
- Recent calculations in NLO ChPT gives†

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = 8.10 \text{ eV}$$

≈ 5% higher than LO, with uncertainty of less than 1%

† J. Goity, A. Bernstein, and B. Holstein, Phys. Rev. D66:076014, 2002, and B. Ananthanarayan and B. Moussallam, JHEP05 (2002) 052.

Experimental results used in PDG average



No collider results $e^+e^- \to \gamma\gamma X$ are in this average

† QCD sum rule calculation: B. Ioffe, A. Oganesian, Phys. Lett. B647, 389 (2007).

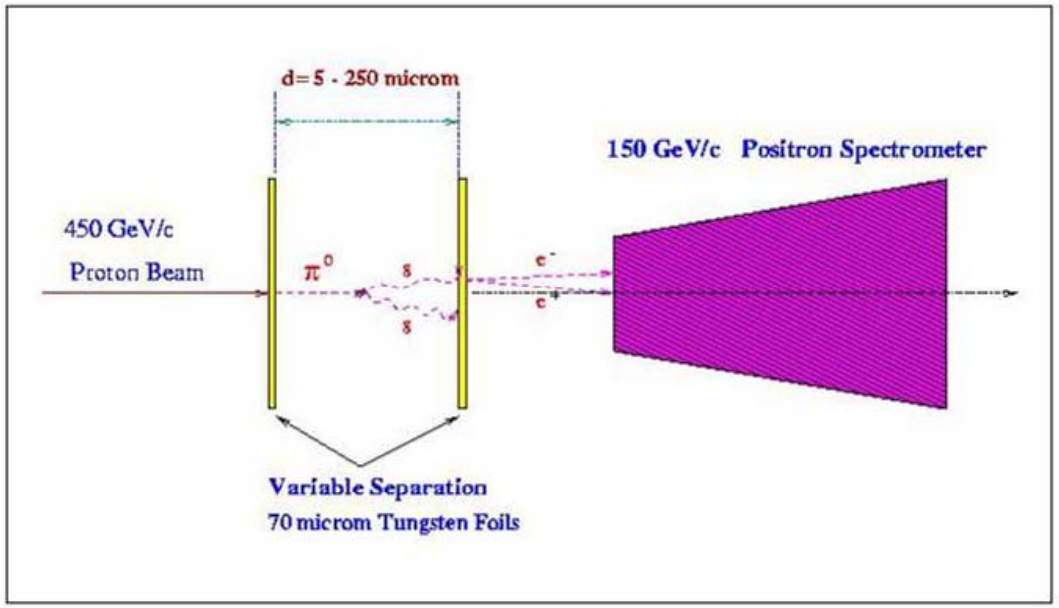
Direct Measurement of Lifetime (CERN 1984)

- $\tau_\pi \sim 1 \times 10^{-16}$ sec $\Rightarrow$ too small to measure
- Solution: Create energetic π^0 's,

$$L = v\tau_\pi E/m$$

- Measure π^0 decay length

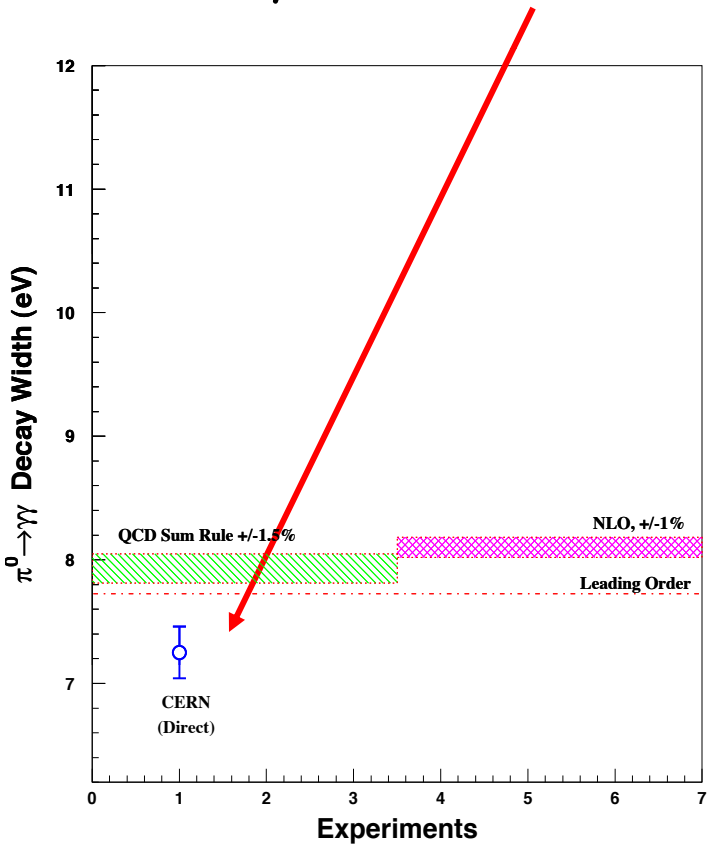
For E= 1000 GeV, $L_{mean} \sim 100$ μm



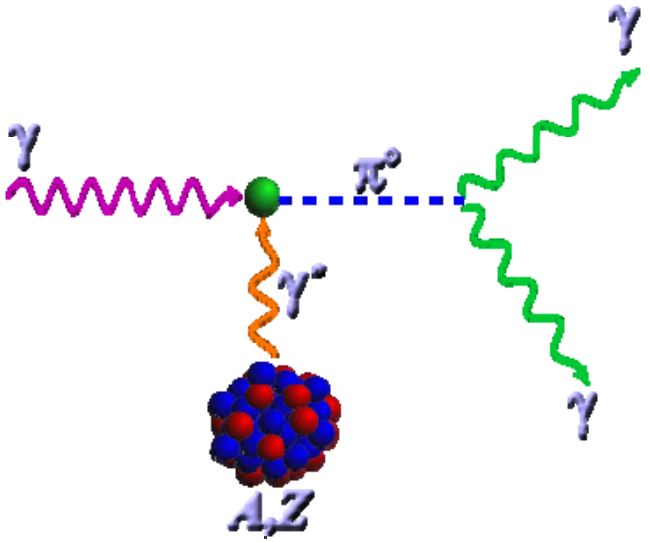
$\Gamma(\pi^0 \to \gamma\gamma) = 7.34\text{eV} \pm 3.1\%(\text{total})$

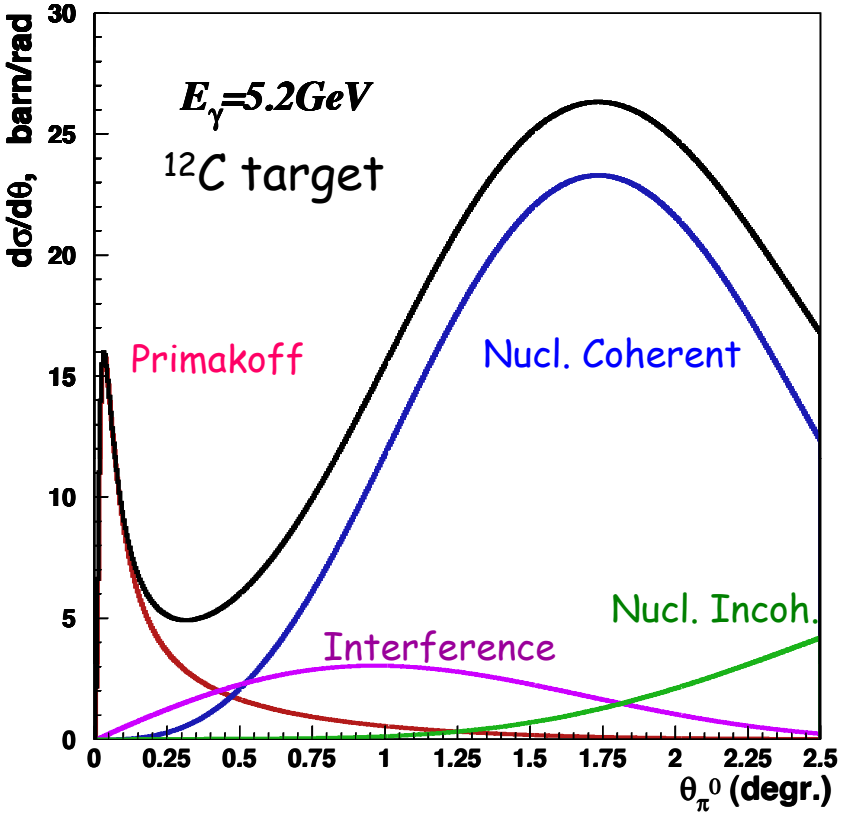
Dominant systematic error:

Uncertainty in P_π ($\pm 1.5\%$)



Primakoff Reaction





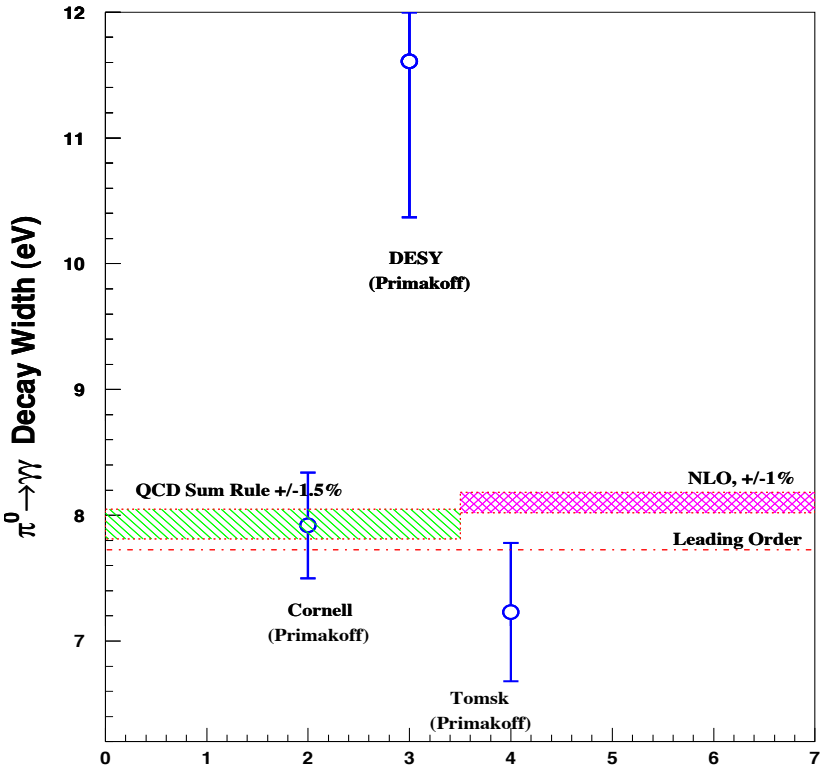
$$\frac{d^3\sigma_{\mathrm{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma}\,\frac{8\alpha Z^2}{m_\pi^3}\,\frac{\beta^3 E^4}{Q^4}\left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$

Challenge: Extract the Primakoff amplitude

Previous Primakoff Experiments

All previous experiments used:

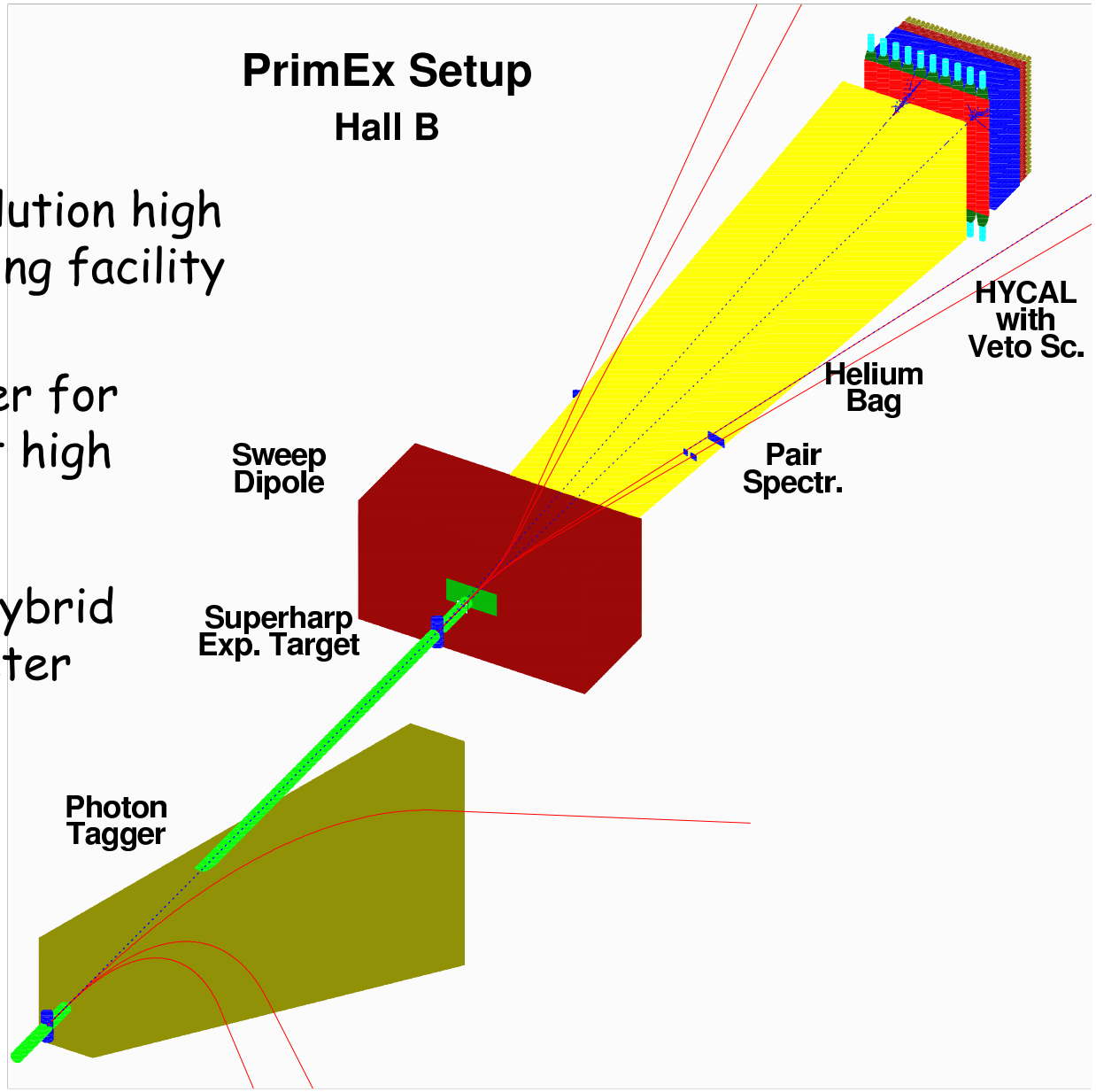
- Untagged bremsstrahlung γ beam
- Conventional Pb-glass calorimetry



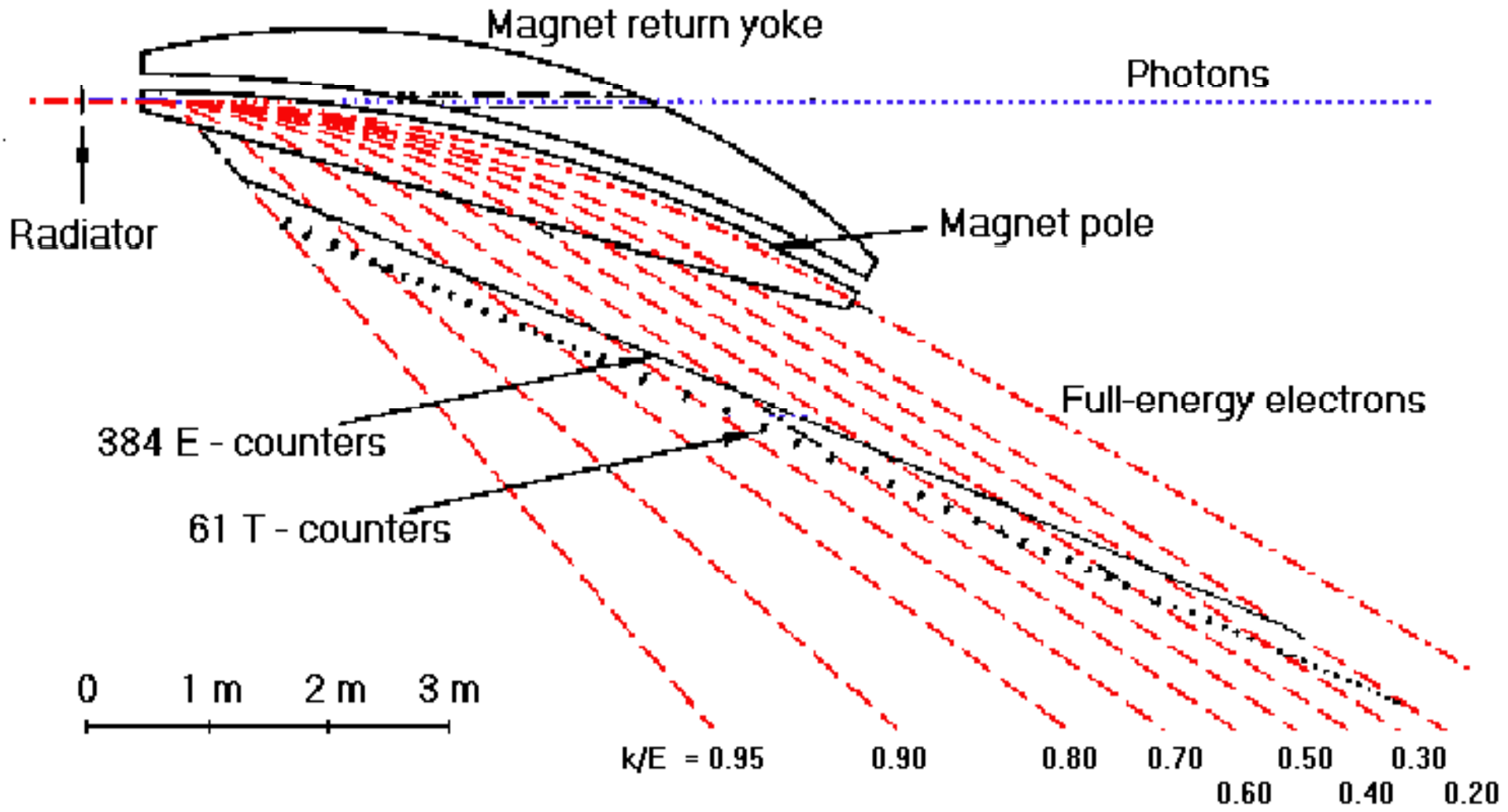
PRIMEX Collaboration

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

- JLab Hall B high resolution high intensity photon tagging facility
- New pair spectrometer for photon flux control at high intensities
- New high resolution hybrid multi-channel calorimeter (HYCAL)

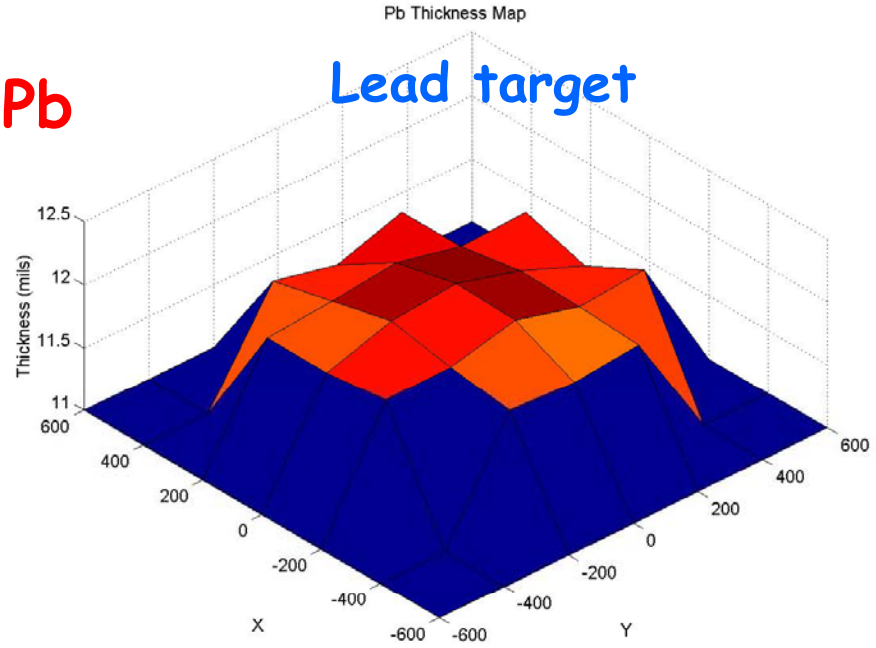


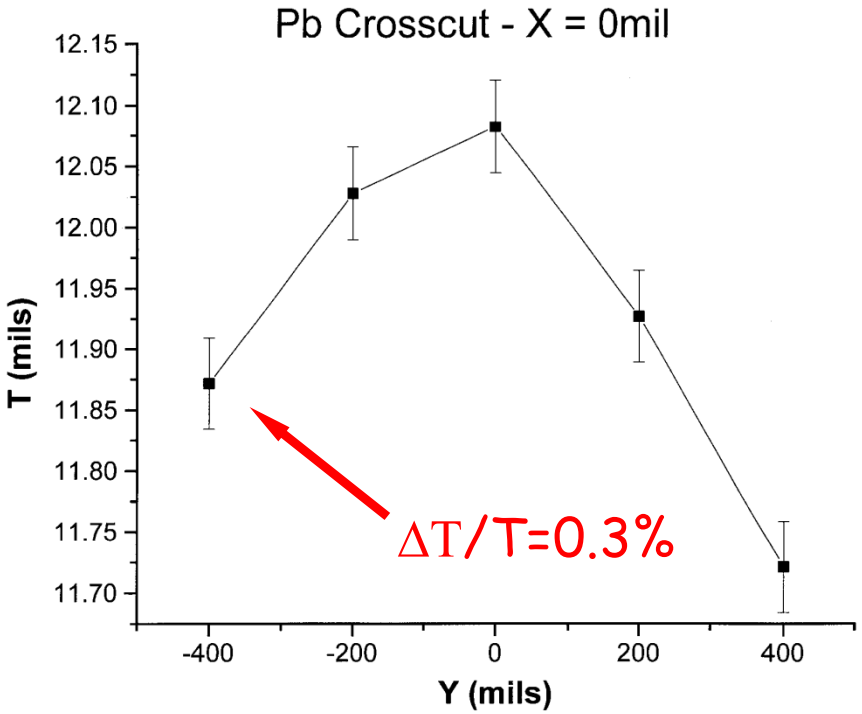
Jefferson Lab Photon Tagger



PRIMEX Targets: ^{12}C and ^{208}Pb

Lead target





Effective number of atoms/cm^2 in the targets:

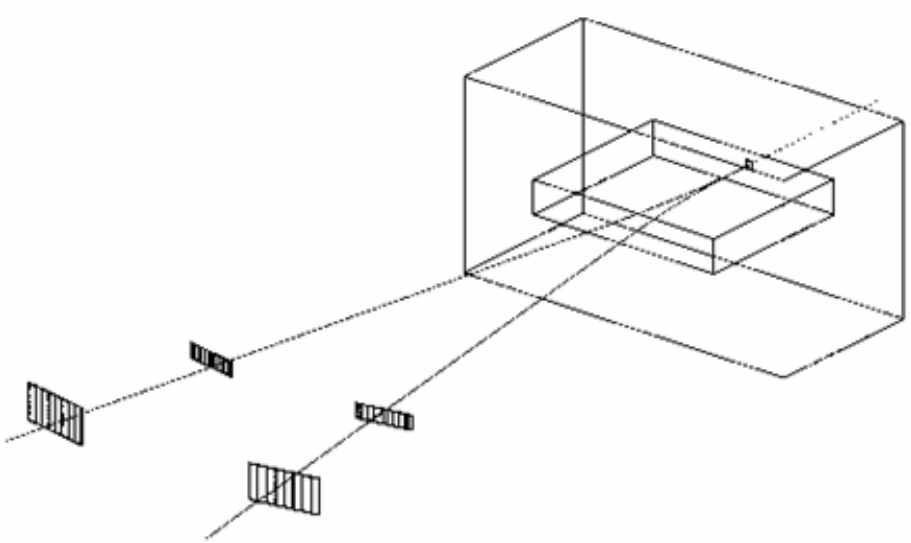
Carbon known to ± 0.04%

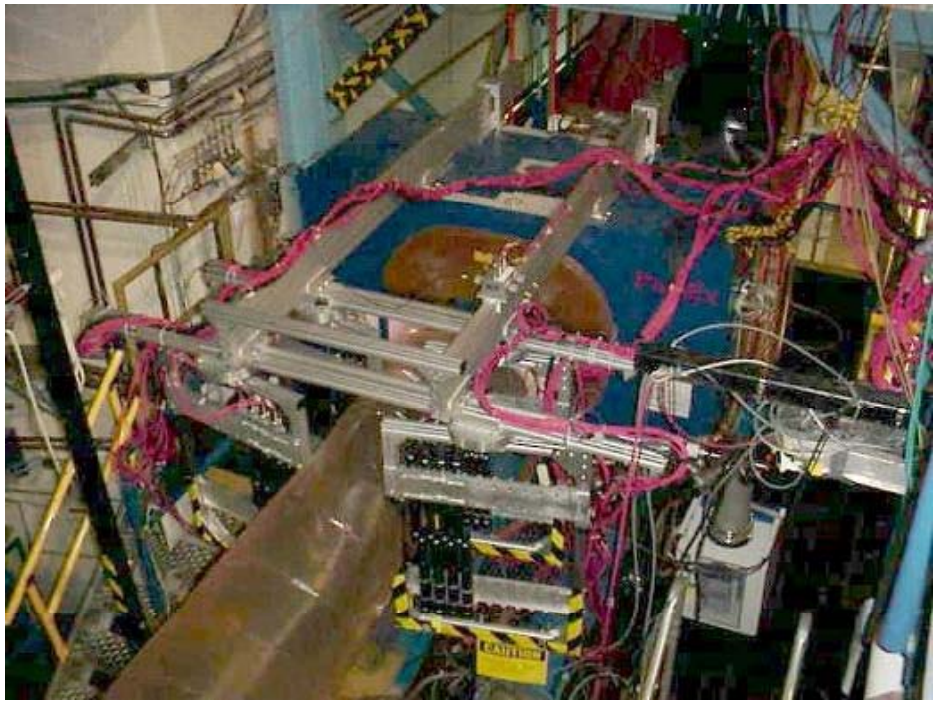
Lead known to ± 0.4%

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





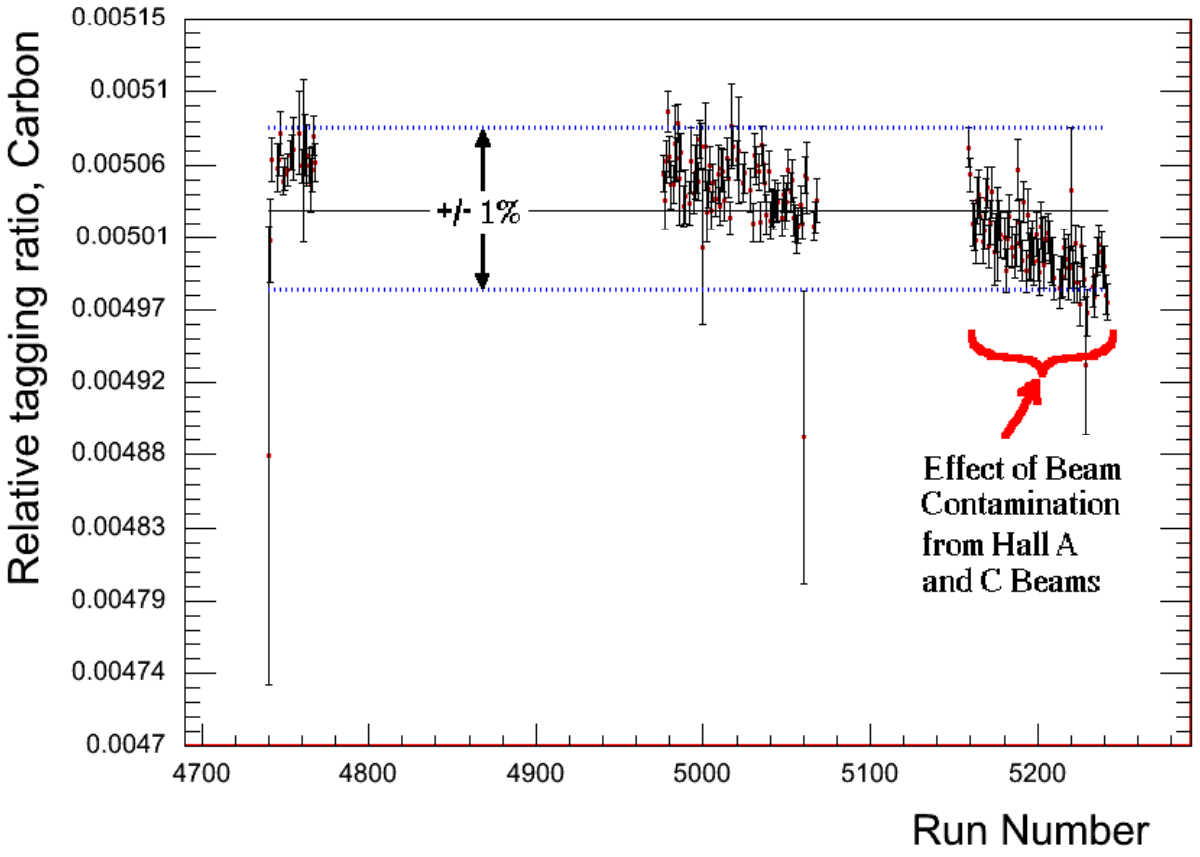
Stability of relative tagging ratios

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

PS+tagger

Tagger

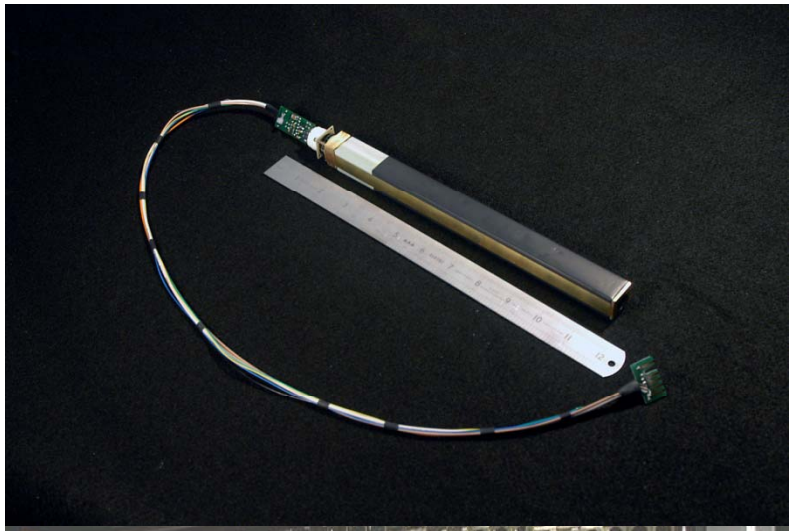
- Monitored by PS during production data taking.

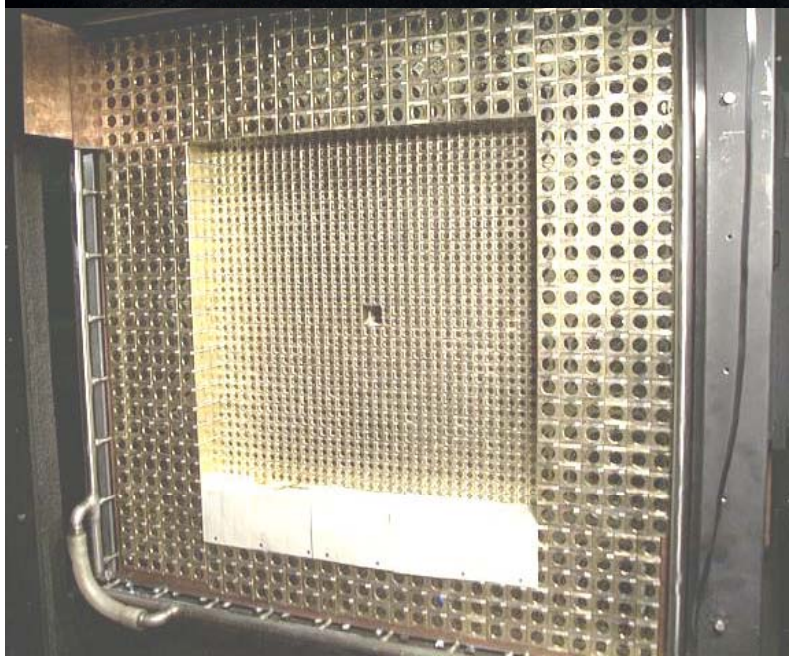


PrimEx Hybrid Calorimeter - HyCal

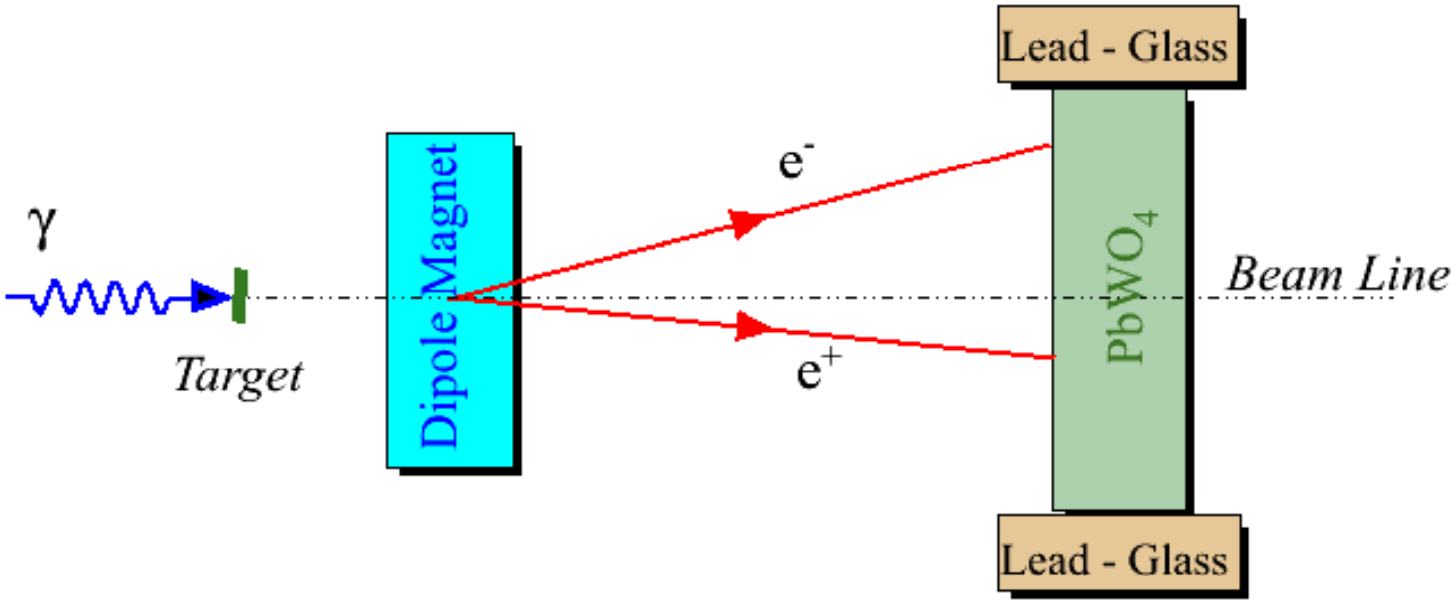
A highly segmented hybrid calorimeter

- 576 lead-glass detectors ($4.00 \times 4.00 \times 40$ cm^3)
- 1152 lead-tungstate detectors ($2.125 \times 2.125 \times 21.5$ cm^3)
- energy resolution 1.3%
- position resolution 1.3 mm

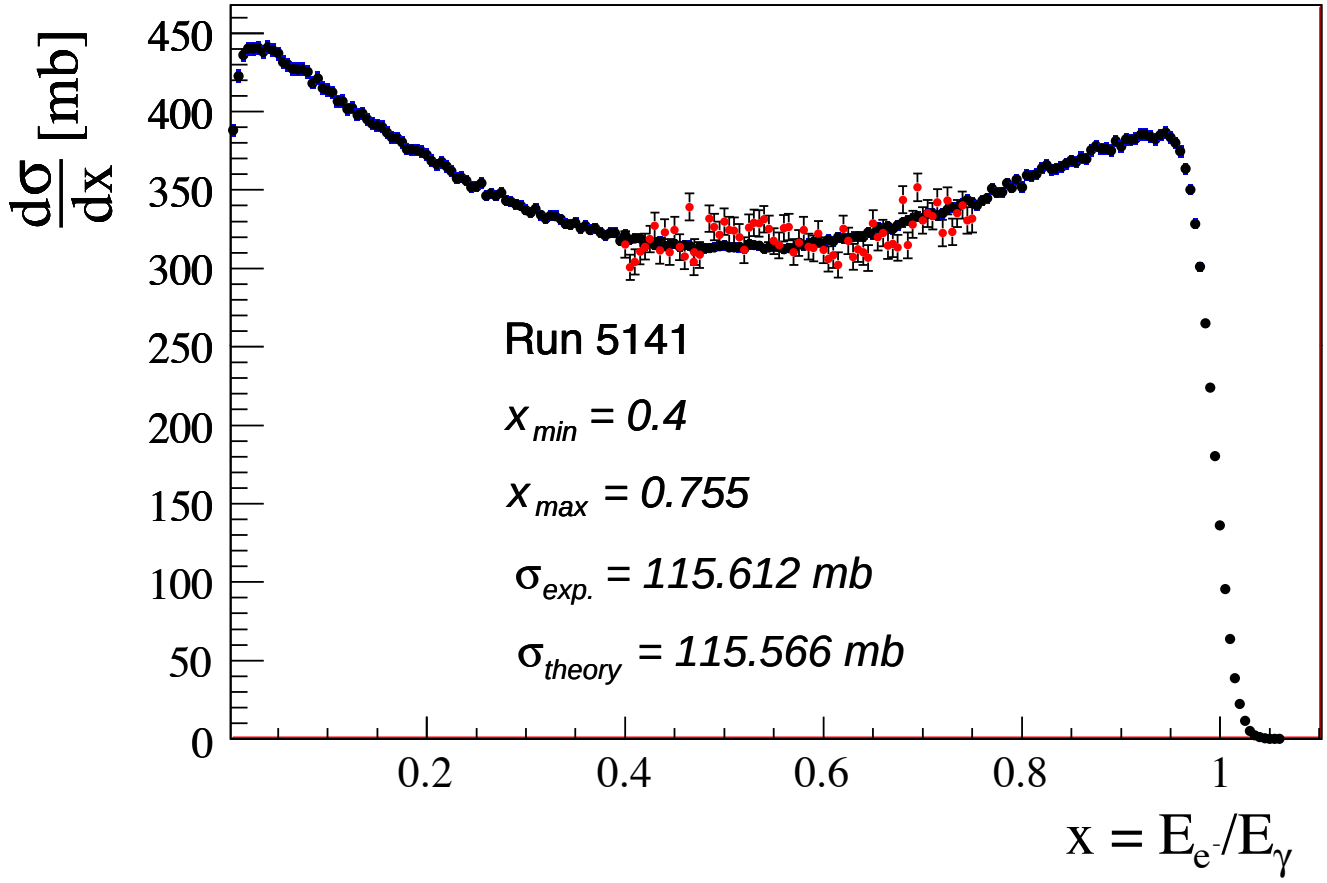




QED calibration reaction I: pair production



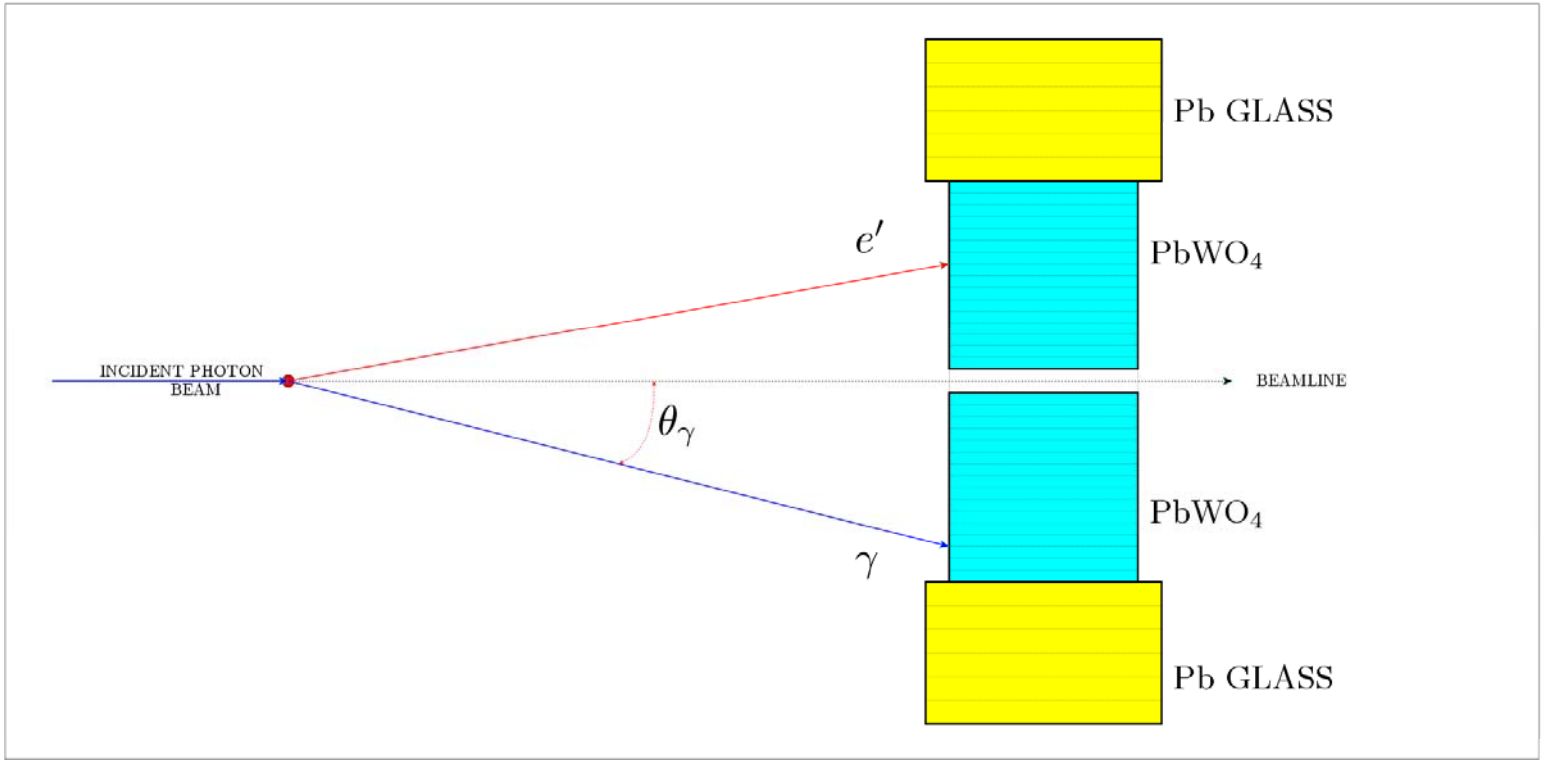
Differential cross sections for pair production

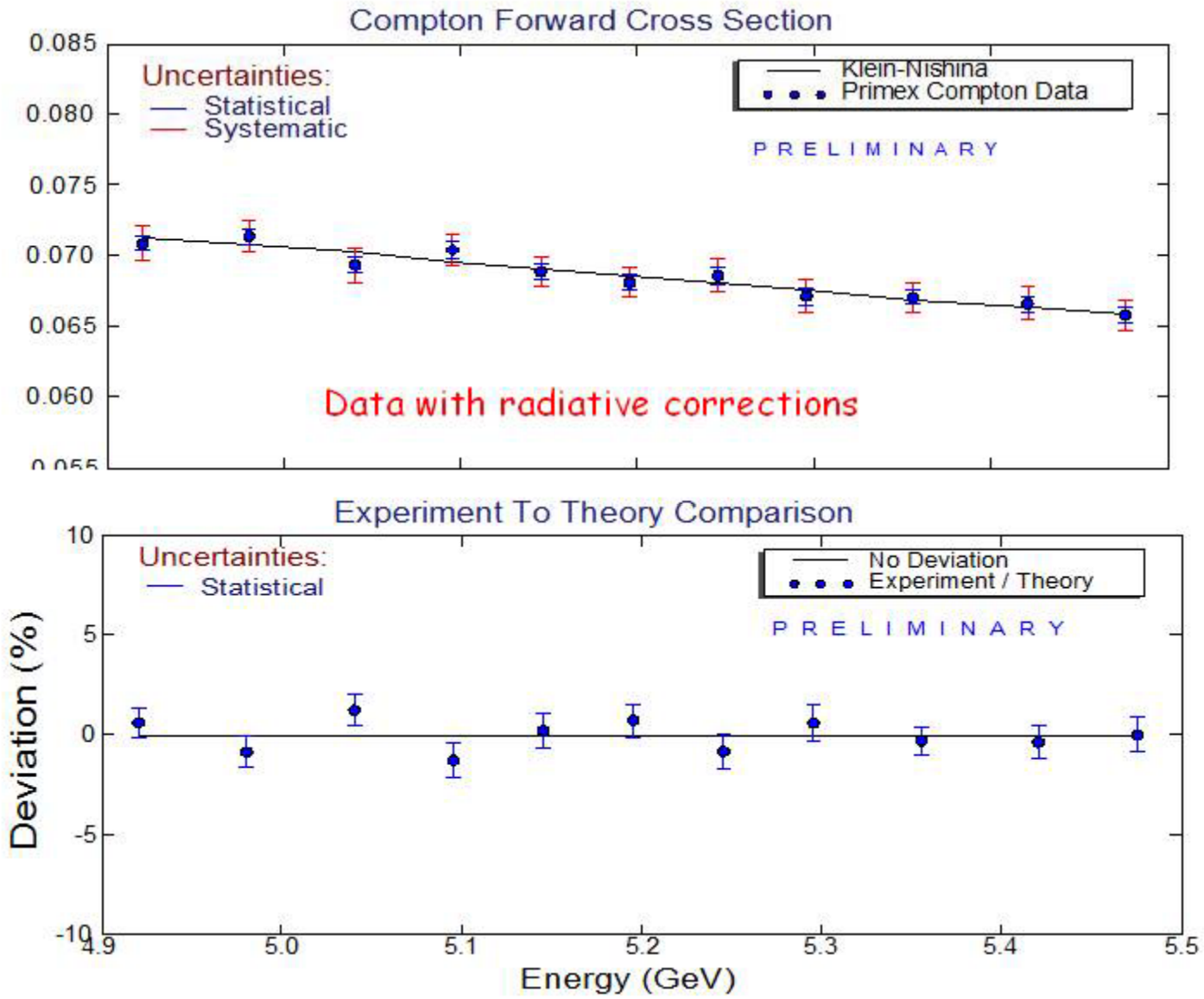


- Integrated cross sections in agreement with theory at the sub-percent level

QED calibration reaction II: Compton scattering

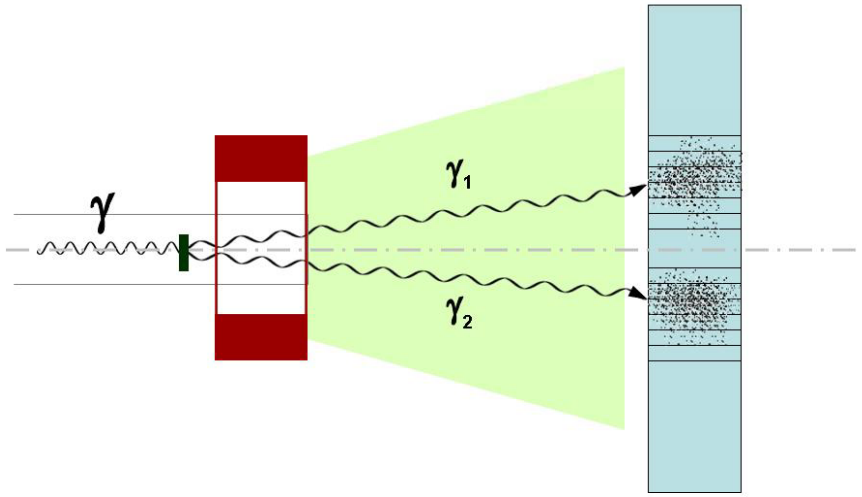
$$\gamma + e \rightarrow \gamma' + e'$$

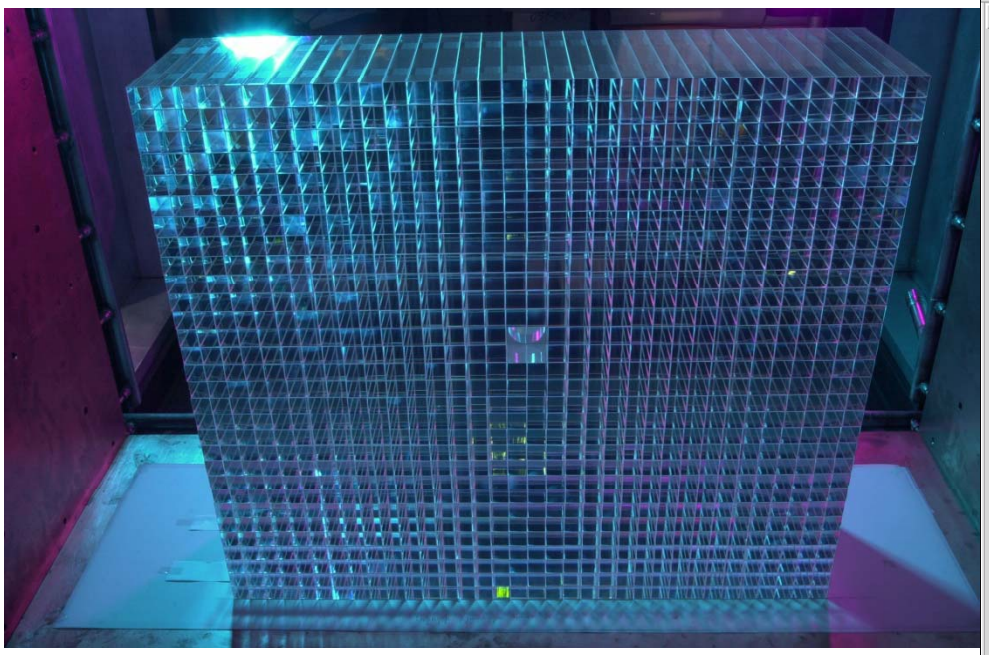


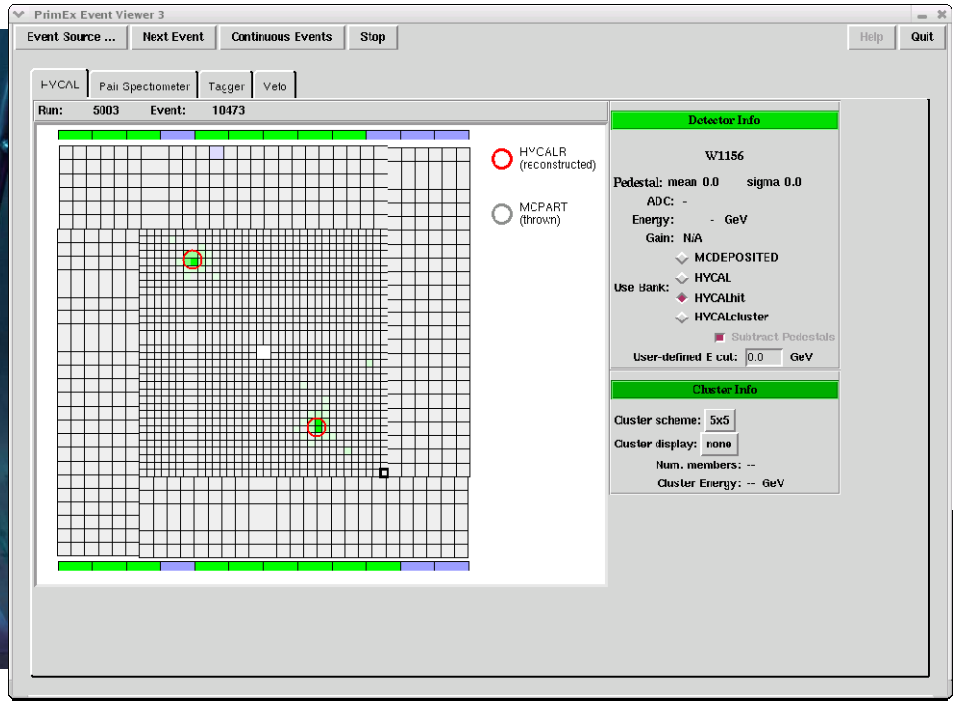


- Cross sections in agreement with theory at the percent level

Latest results for the π^0 lifetime

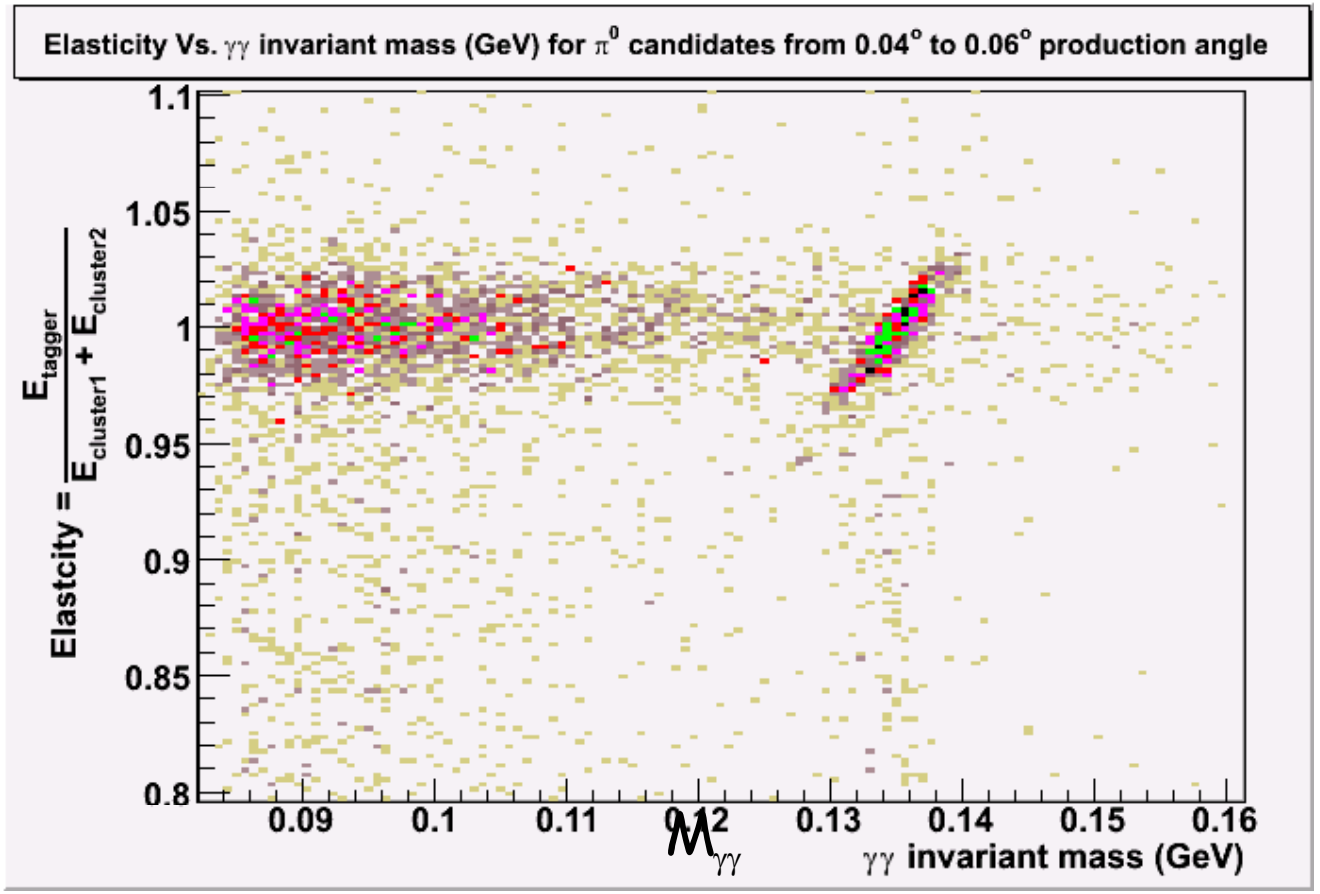






Extracting Elastic Pion Yields versus θ_π

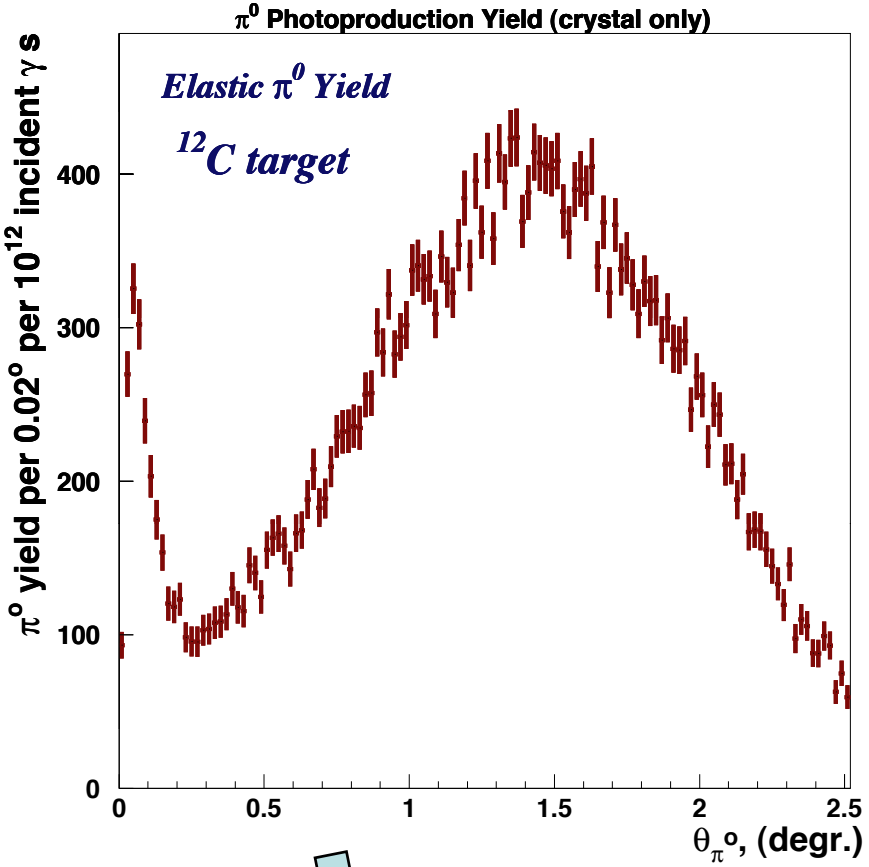
$$\frac{E_1 + E_2}{E_{\text{tagged}-\gamma}}$$

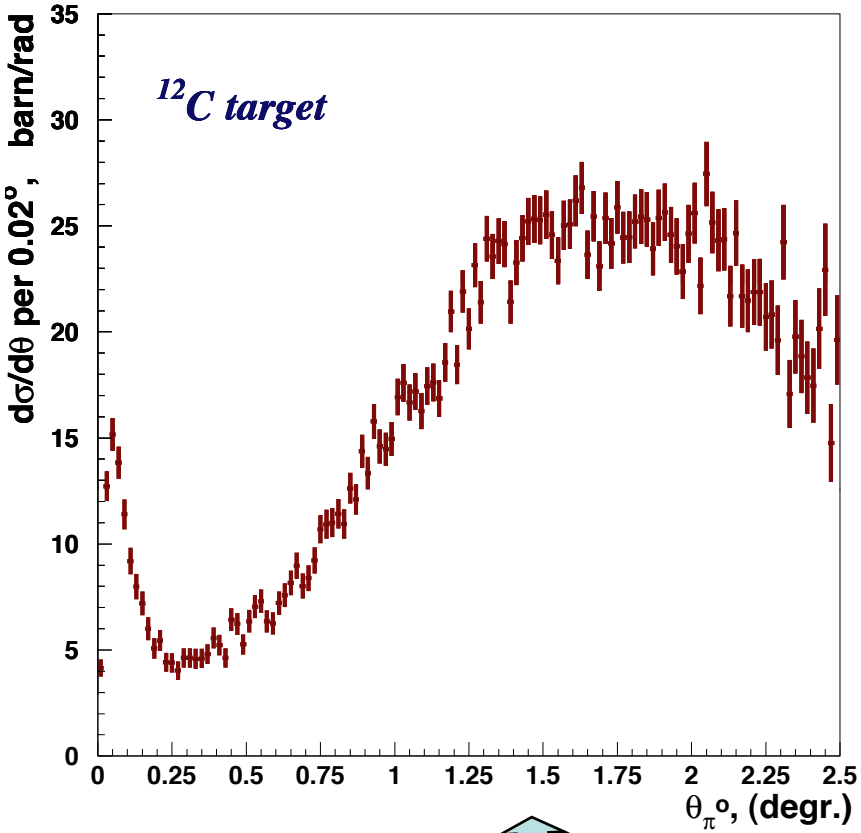


Three groups analyzed the data independently:

E.Clinton (UMass), D. McNulty (MIT/JLab) and I. Larin (ITEP)

Differential Cross section





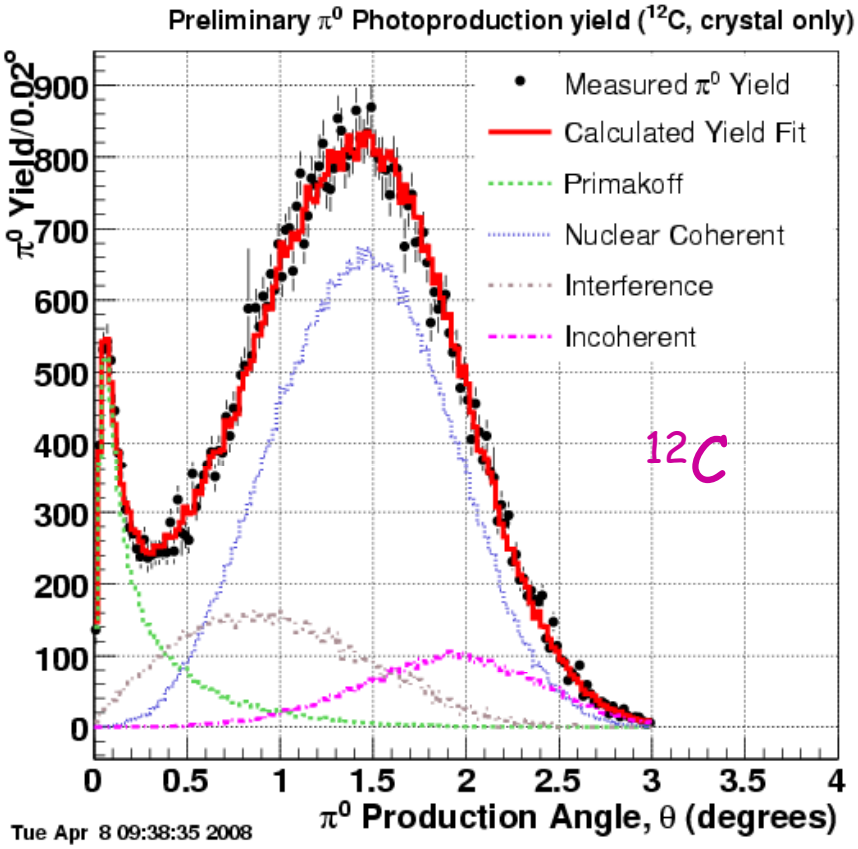
Experimental Yield per $\Delta\vartheta_\pi$

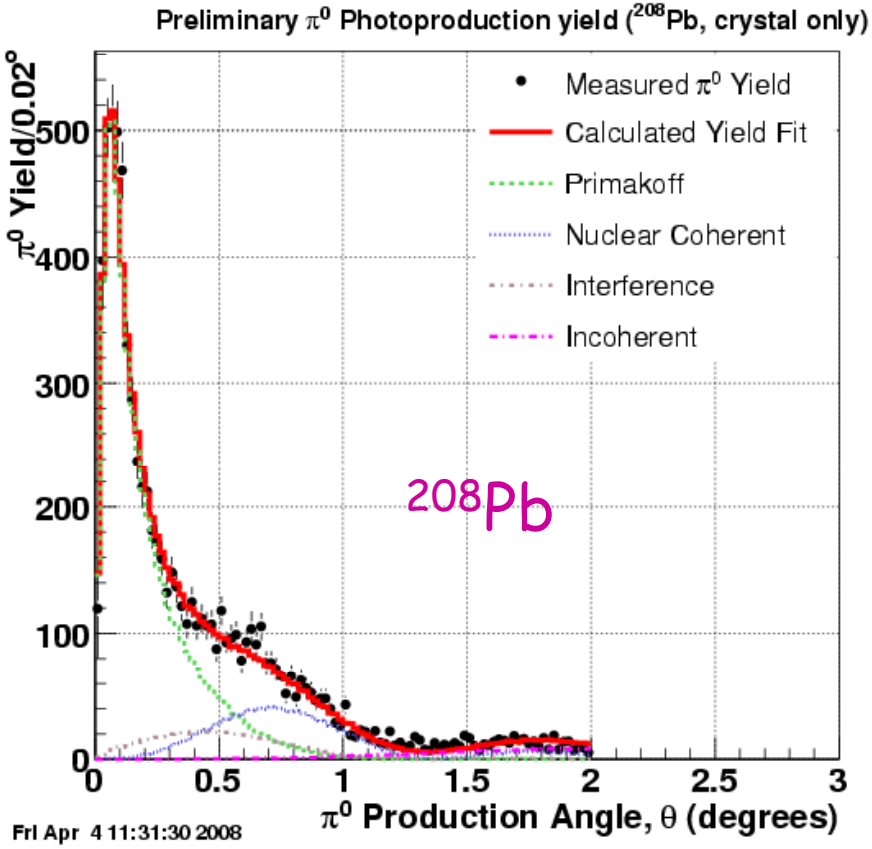
GEANT:
- acceptances;
- efficiencies;
- resolutions;

Diff. cross section

Fit to Extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Decay Width

- **Theoretical angular distributions smeared with experimental resolutions are fit to the data**

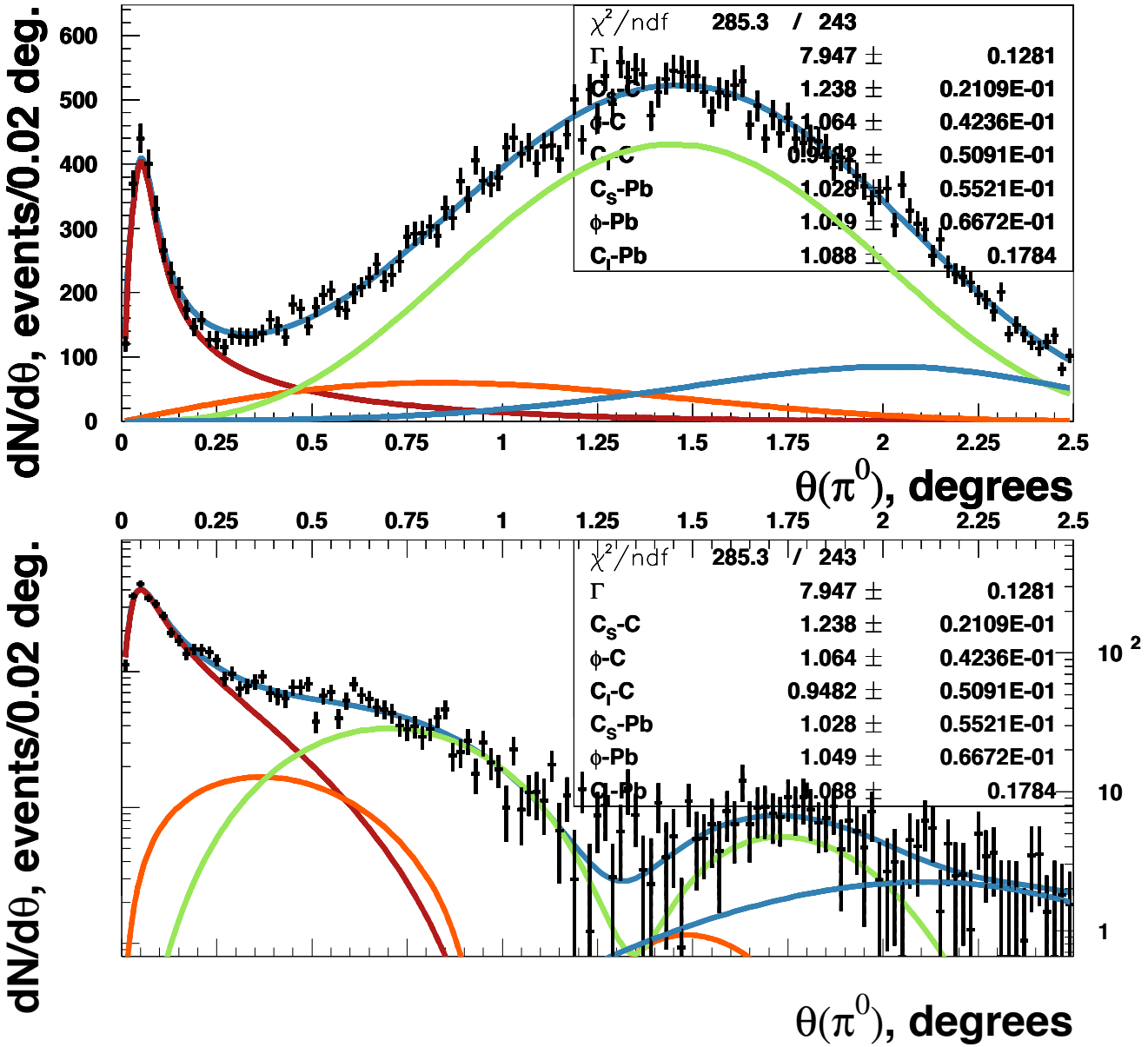




Combined Sumultaneous Fit to Both Targets

^{12}C

^{208}Pb



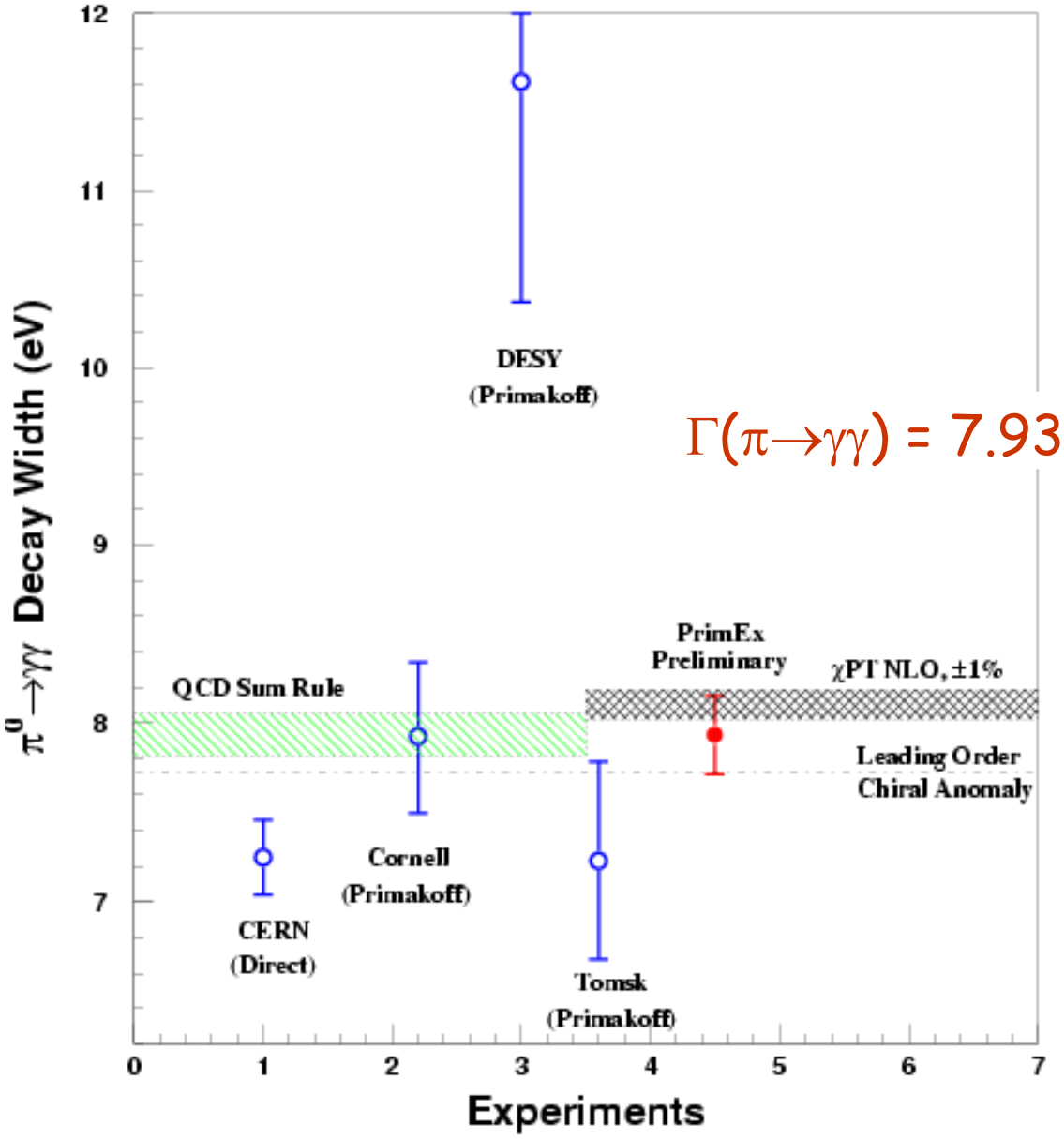
Analysis Averages for $\Gamma(\pi^0 \to \gamma\gamma)$

Target	$\Gamma(\pi^0 \to \gamma\gamma)$
^{12}C	7.86 ± 0.21 eV
^{208}Pb	7.99 ± 0.18 eV
Combined carbon+lead	7.93 ± 0.18 eV

Estimated Systematic Errors

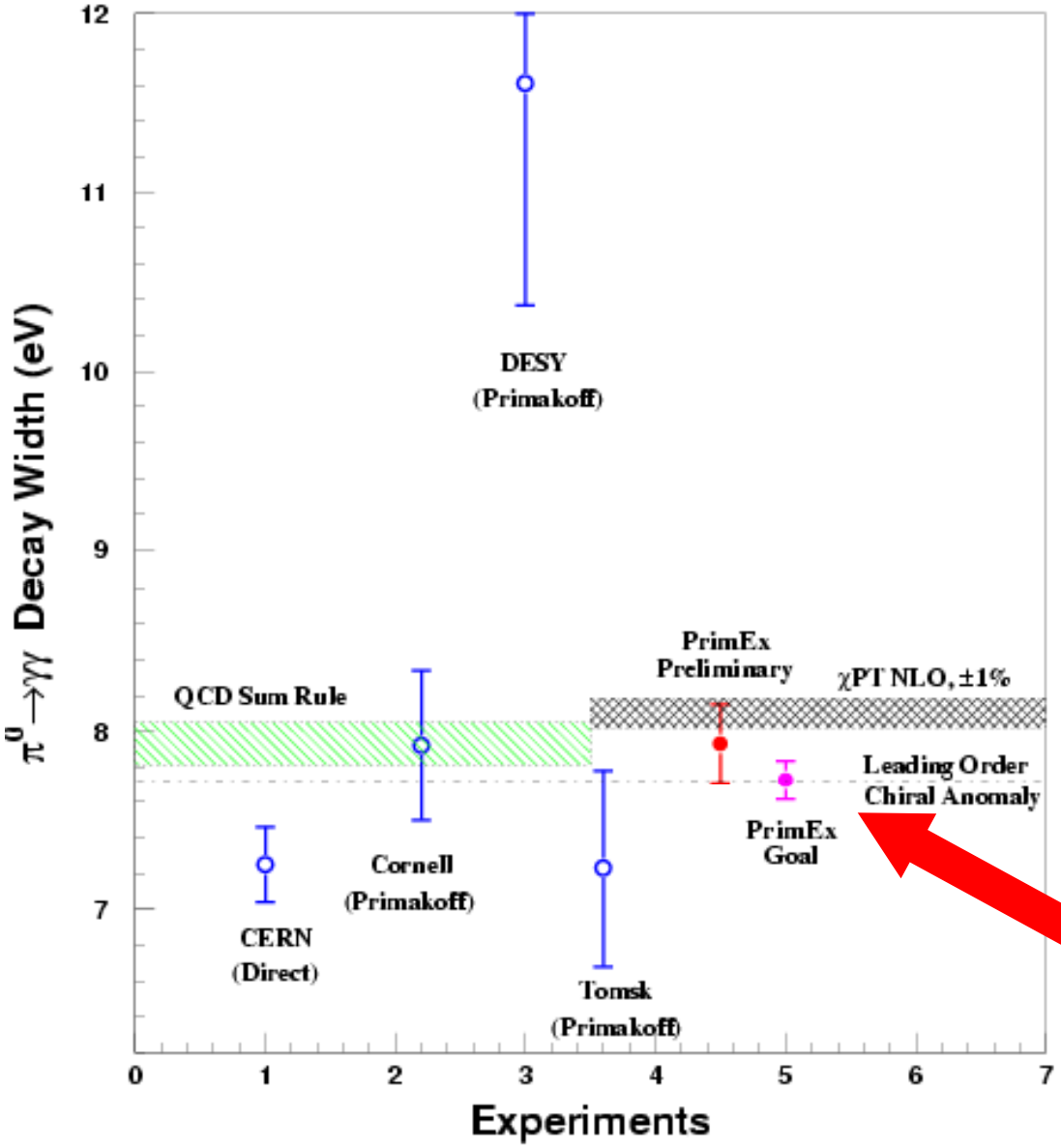
Contributions	Errors
Photon flux	1.0%
Target number	0.1%
Background subtraction	0.9%
Event selection	0.5%
HYCAL response function	0.5%
Beam parameters	0.4%
Acceptance	0.3%
Model errors (theory)	0.25%
Physics background	0.24%
Branching ratio (PDG)	0.03%
Total	**1.6%**

Current PrimEx Result



$\Gamma(\pi \to \gamma\gamma) = 7.93\text{eV} \pm 2.3\% \pm 1.6\%$

Future JLab Run



±1.4%

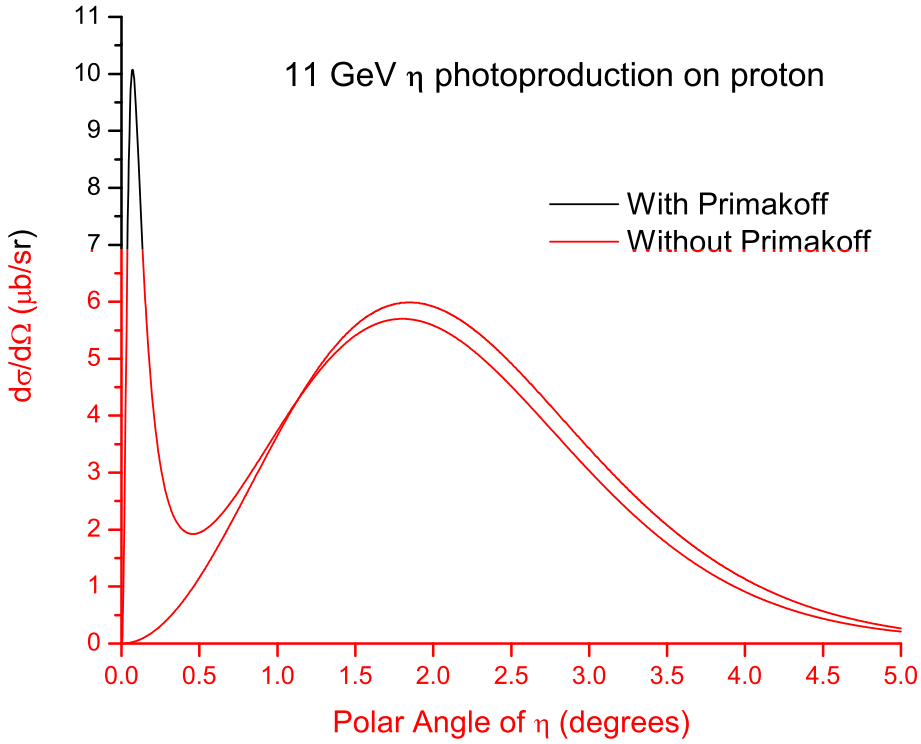
PrimEx Program at 12 GeV JLAB

We propose to measure:

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

via the Primakoff effect.

11 GeV η photoproduction on proton

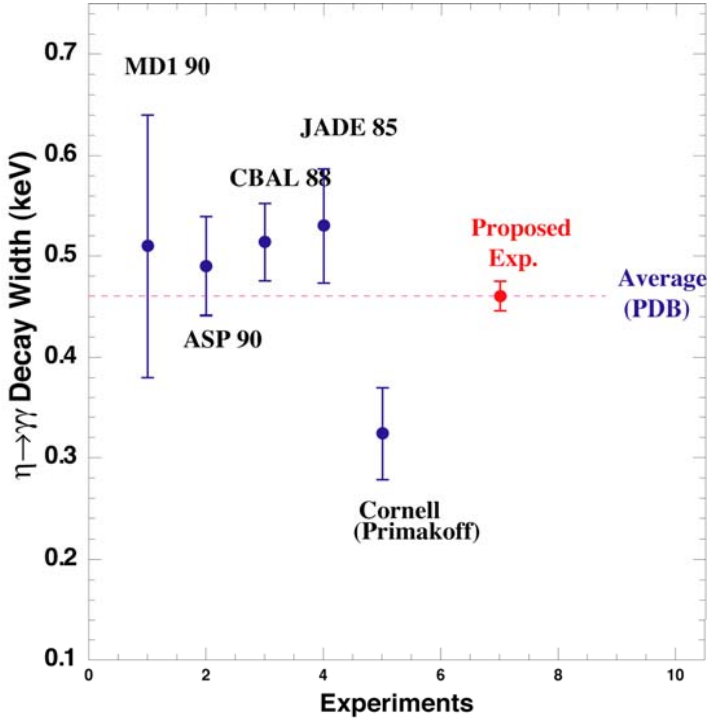


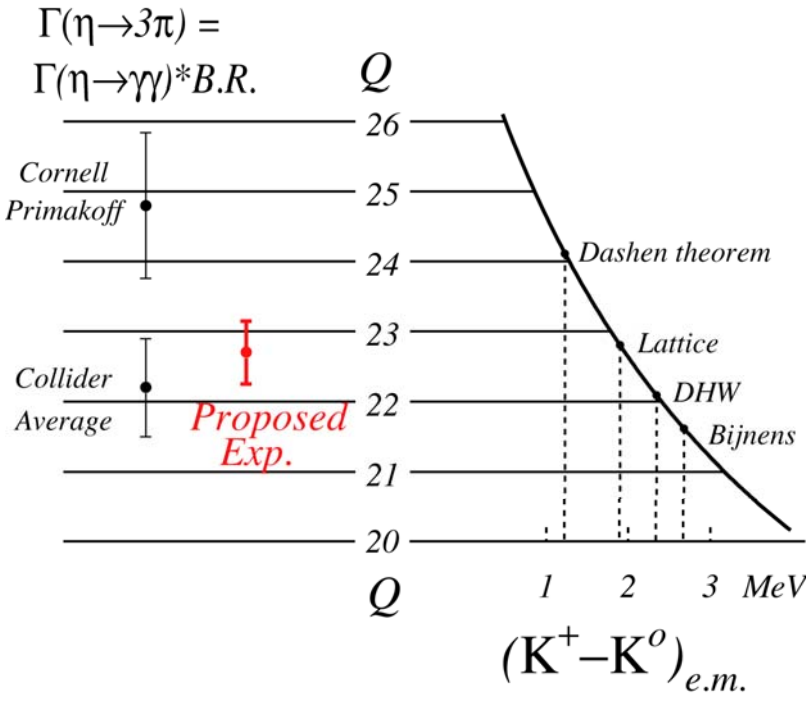
Fundamental input to physics:

- Determination of quark mass ratio

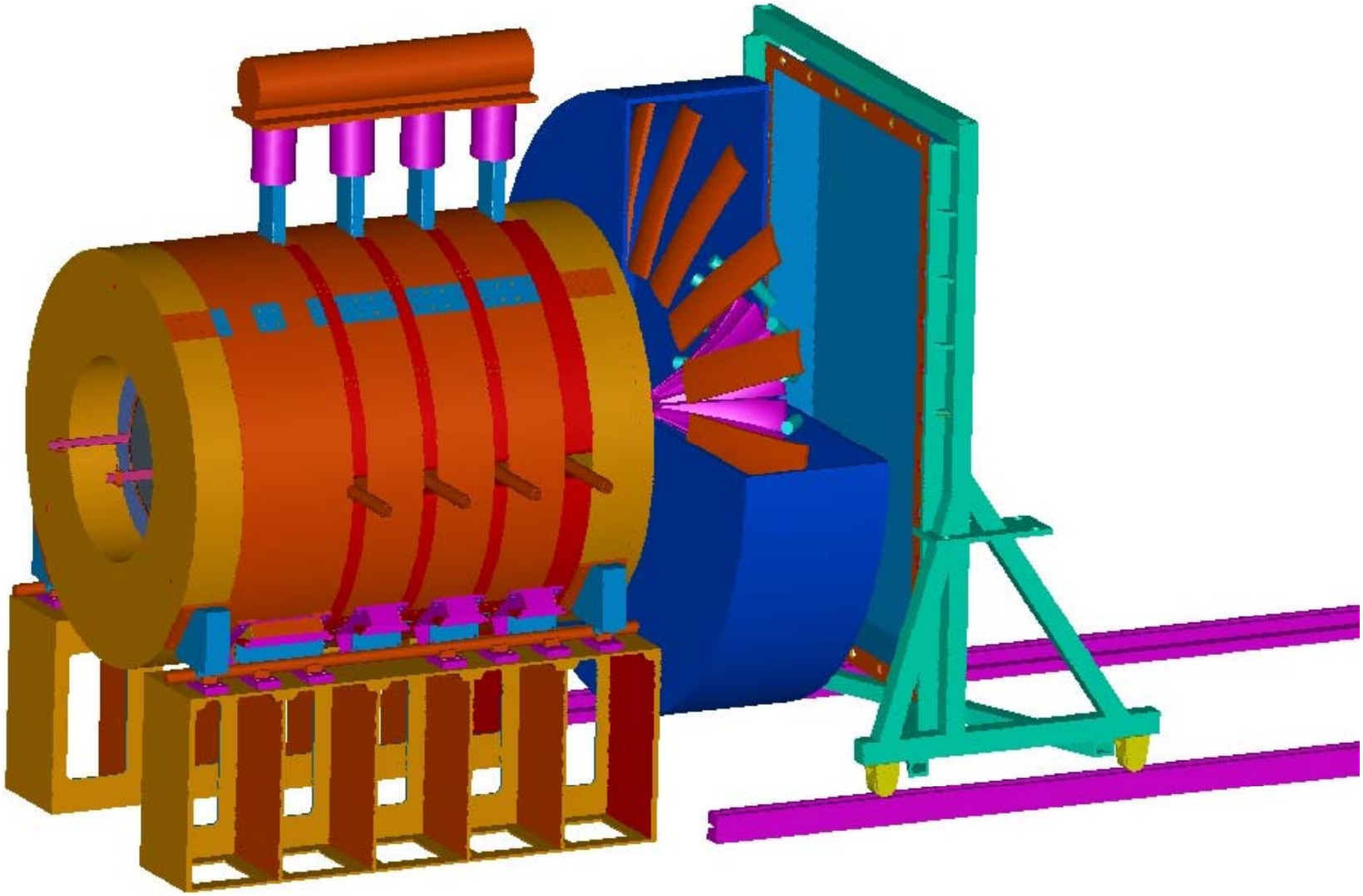
$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$

- η-η´ mixing
- Interaction radius of π^0, η and η´
- Is the η´ an approximate Goldstone boson?





PRIMEX at 12 GeV: GlueX detector in JLab Hall D



Summary and Conclusions

- We are in the process of finalizing the π^0 lifetime analysis. Our result is:

$$\Gamma_{\pi^0 \to \gamma\gamma} = 7.93 \pm 0.18 \pm 0.13 \text{eV}$$

- Our result is in agreement with LO and NLO ChPT, and the QCD sum rule calculation.
- Additional running can reduce our combined statistical and systematic errors by about $\frac{1}{2}$. We are approved for another run at Jefferson Lab.
- A Primakoff program at 12 GeV holds great promise for studies of the pseudo-scalar mesons