Status of π^0 and η Radiative Decay Width Measurements at JLab

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Outline

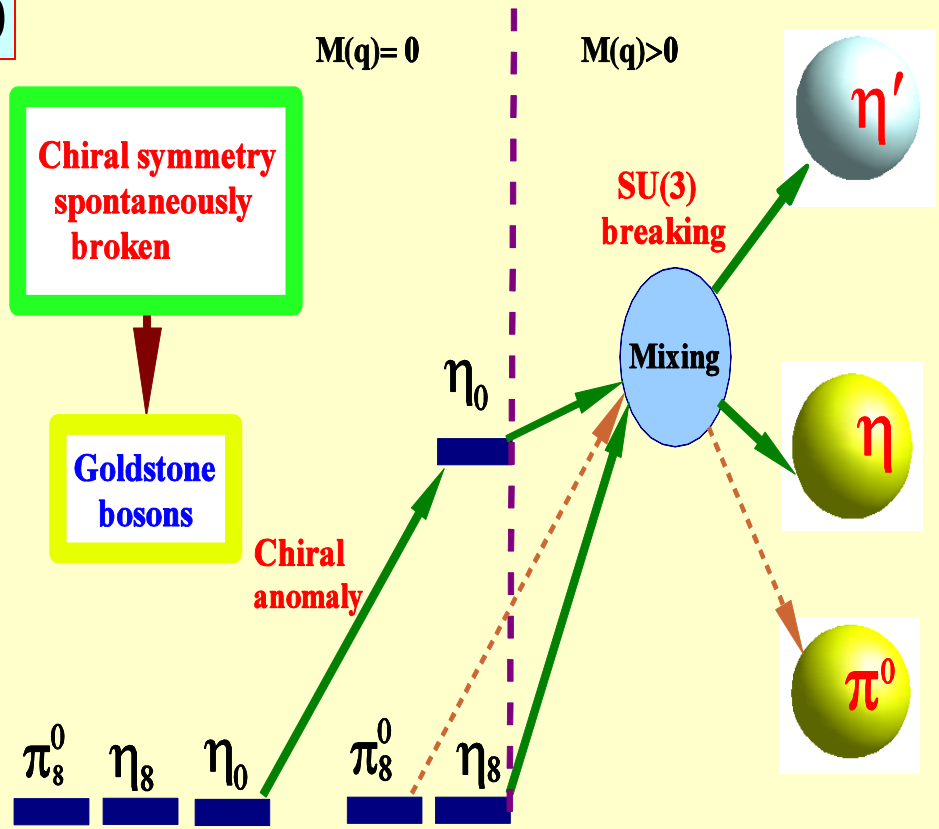
1. **Physics Motivation**
   - QCD Symmetries and Properties of π^0, η and η'
2. **Primakoff Progarm at Jlab**
   - Measurement π^0 lifetime at 6 GeV
   - Experiment of $\Gamma(\eta \to 2\gamma)$ at 12 GeV

QCD Symmetries and light mesons

- QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under:

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

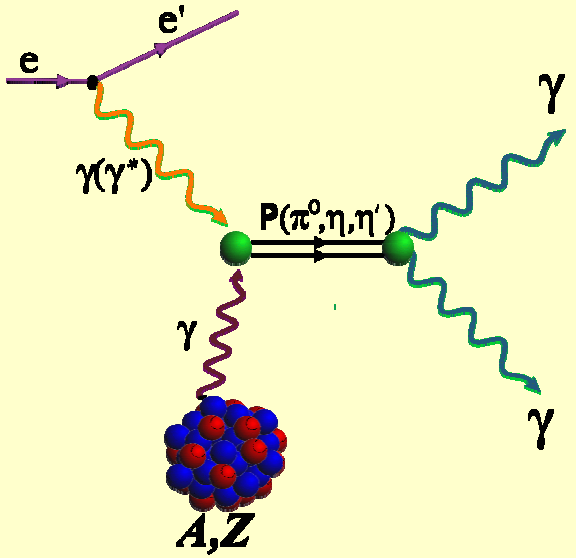
- Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously broken:
  - 8 Goldstone Bosons (π,K,η)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- Massive quarks, SU(3) broken:
  - GB are massive
  - Mixing of π^0 η η'



The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

Primakoff Program at Jlab 6 & 12 GeV

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect.



a) Two-Photon Decay Widths:

1) **$\Gamma(\pi^0\to\gamma\gamma)$ @ 6 GeV**
2) $\Gamma(\eta\to\gamma\gamma)$
3) $\Gamma(\eta'\to\gamma\gamma)$

Input to Physics:

- precision tests of Chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle

b) Transition Form Factors at low Q^2 (0.001-0.5 GeV^2/c^2):

$F(\gamma\gamma^*\to\pi^0)$, $F(\gamma\gamma^*\to\eta)$, $F(\gamma\gamma^*\to\eta')$

Input to Physics:

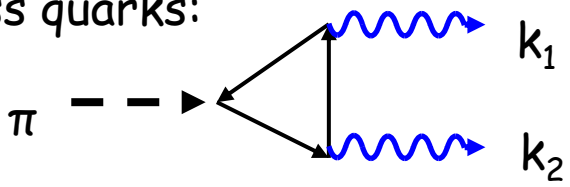
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Experiments @ 6 GeV

$\Gamma(\pi^0 \to \gamma\gamma)$ Experiments @ 6 GeV

- $\pi^0 \to \gamma\gamma$ decay proceeds primarily via the chiral anomaly in QCD.
- The chiral anomaly prediction is exact for massless quarks:

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



- $\Gamma(\pi^0 \to \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely to higher orders!

➢ Corrections to the chiral anomaly prediction:

Calculations in NLO ChPT:

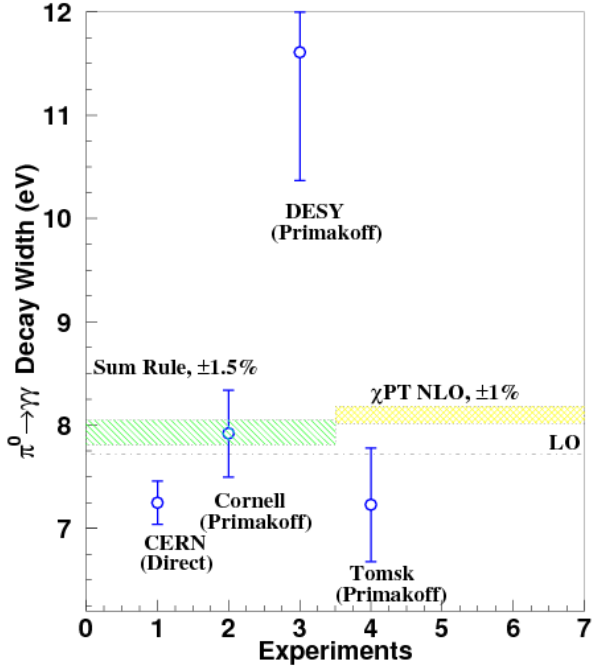
- $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.10eV ± 1.0%
  (J. Goity, et al. Phys. Rev. D66:076014, 2002)
- $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.06eV ± 1.0%
  (B. Ananthanarayan et al. JHEP 05:052, 2002)

Calculations in NNLO SU(2) ChPT:

- $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.09eV ± 1.3%
  (K. Kampf et al. Phys. Rev. D79:076005, 2009)

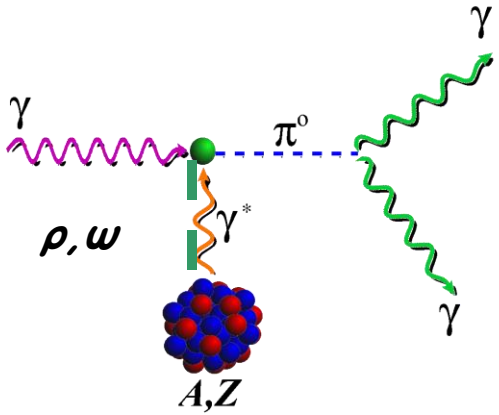
➢ Calculations in QCD sum rule:

- $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.93eV ± 1.5%
  (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)

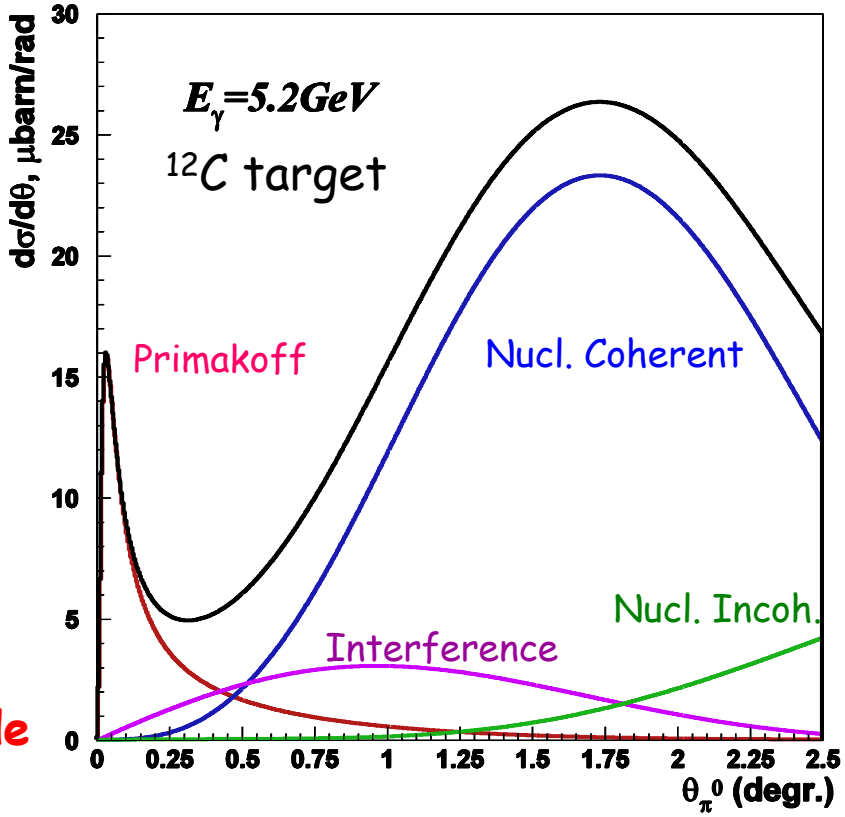


- Precision measurements of $\Gamma(\pi^0 \to \gamma\gamma)$ at the percent level will provide a stringent test of a fundamental prediction of QCD.

Primakoff Method



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



Challenge: Extract the Primakoff amplitude

Requirement:

- **Photon flux**
- **Beam energy**
- **π^0 production Angular resolution**

Features of Primakoff cross section:

- Peaked at very small forward angle:

$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2}$$

- Beam energy sensitive:

$$\left\langle\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right\rangle_{peak} \propto E^4,\ \int d\sigma_{\mathrm{Pr}} \propto Z^2\log(E)$$

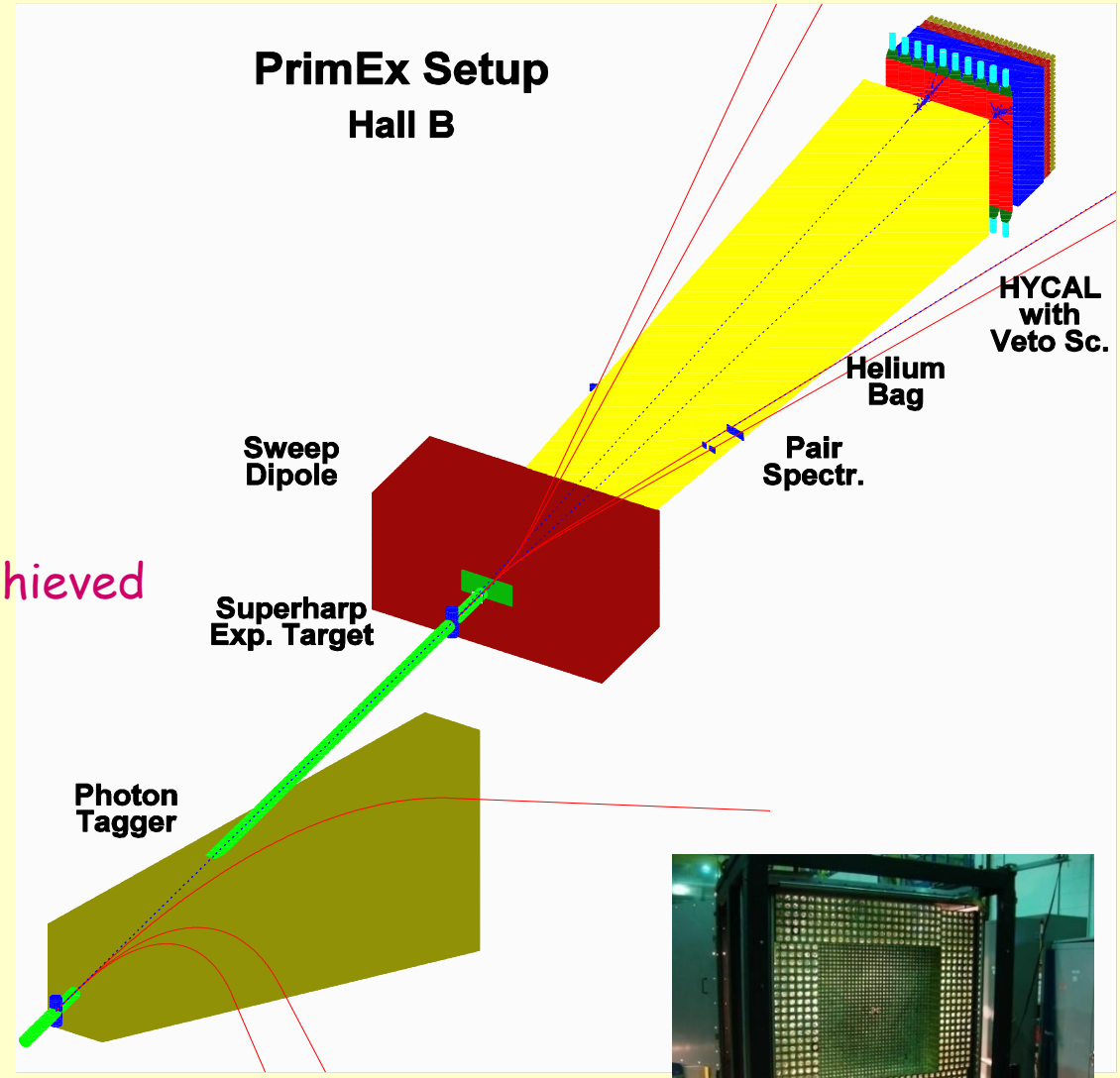
- Coherent process

PrimEx-I (2004)

- JLab Hall B high resolution, high intensity photon tagging facility

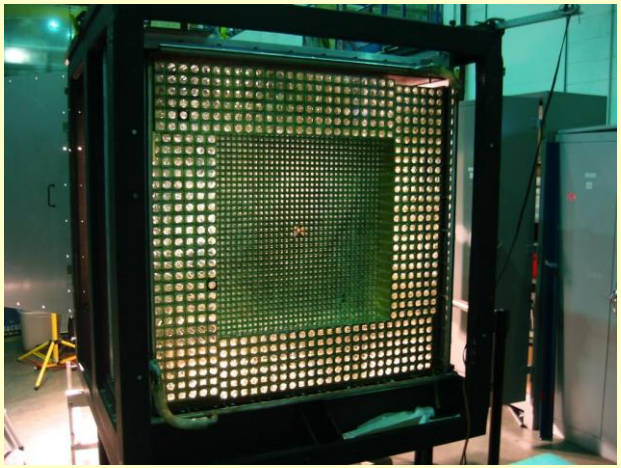
- New pair spectrometer for photon flux control at high beam intensities
  → 1% accuracy has been achieved

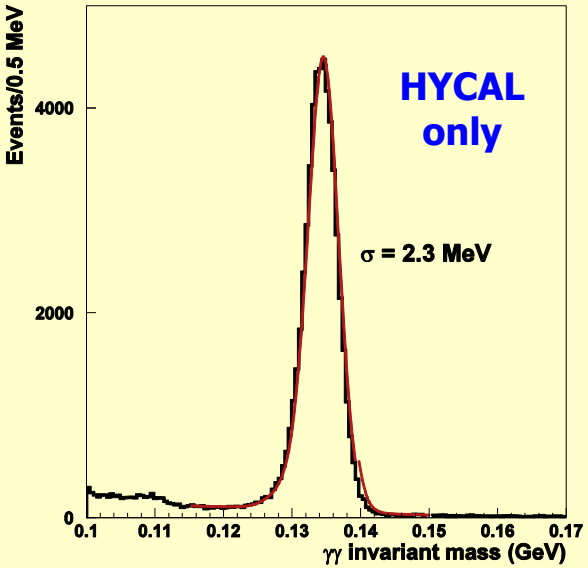
- New high resolution hybrid multi-channel calorimeter (HyCal)

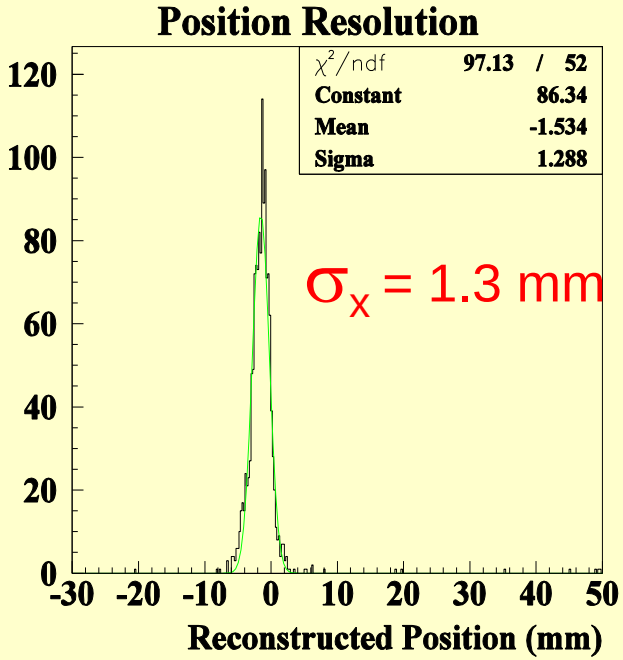


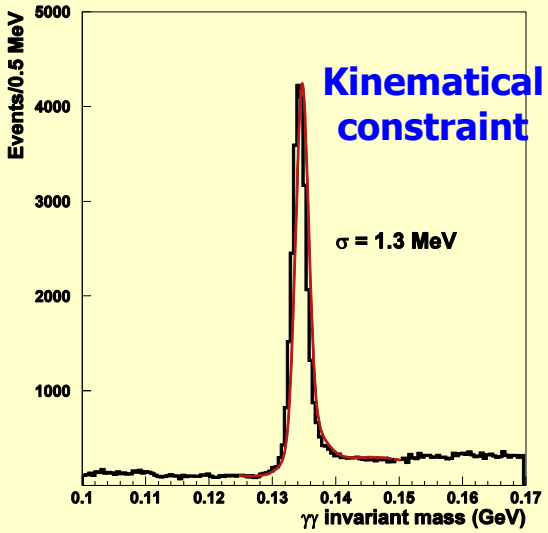
PrimEx Hybrid Calorimeter - HyCal

- 1152 $PbWO_4$ crystal detectors
- 576 Pb-glass Cherenkov detectors



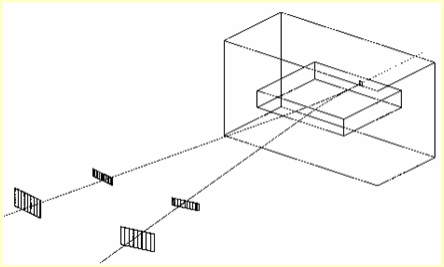


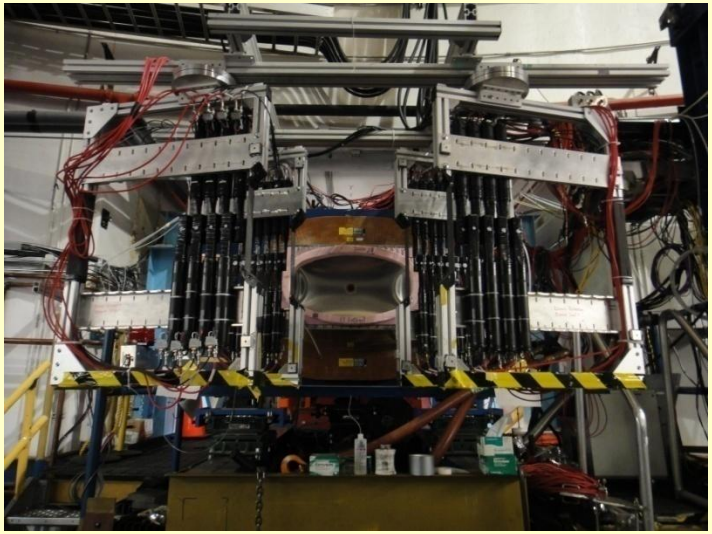




Luminosity Control: Pair Spectrometer

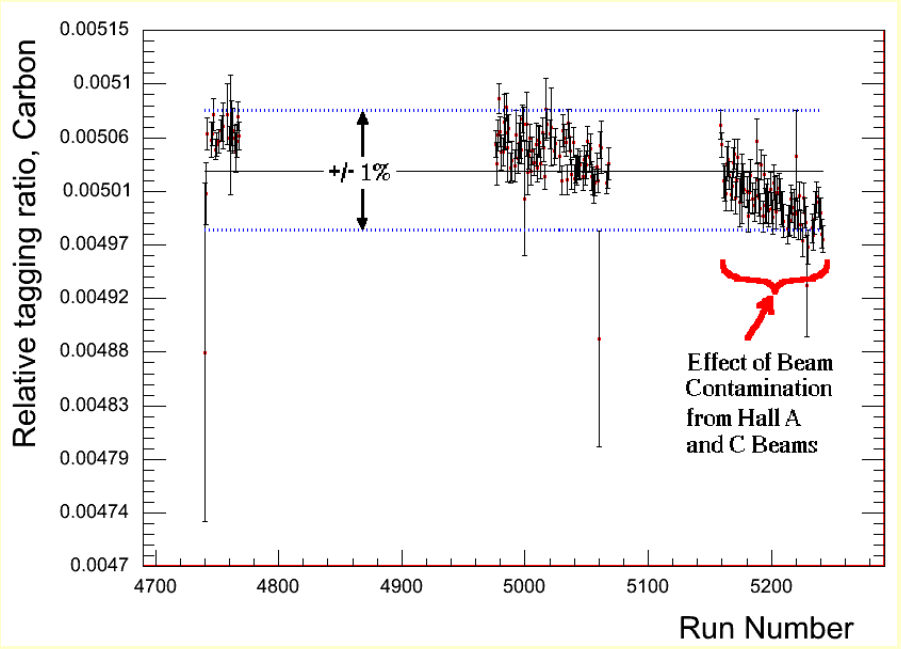
- Combination of:
  - 16 KGxM dipole magnet
  - 2 telescopes of 2x8 scintillating detectors





Measured in experiment:

- absolute tagging ratios
  TAC at low intensities
- relative tagging ratios
  pair spectrometer at low and high intensities



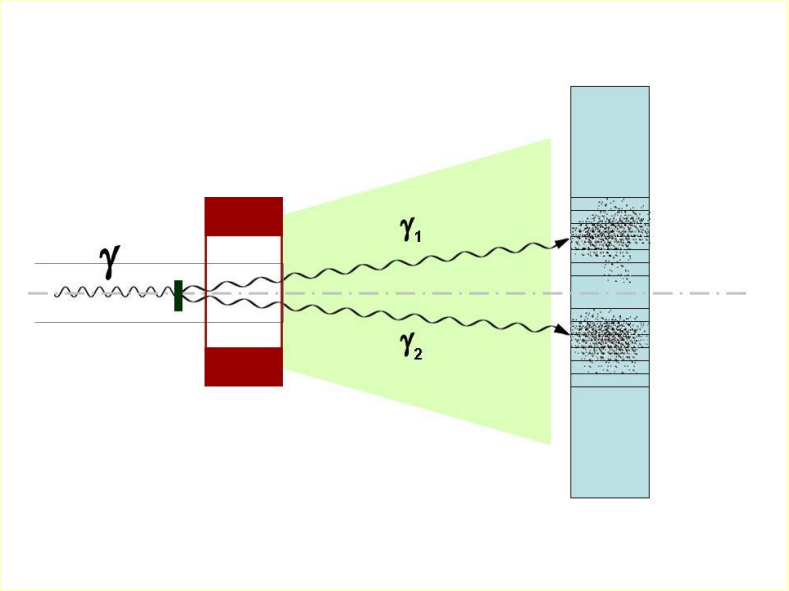
- Uncertainty in photon flux at the level of 1% has been reached

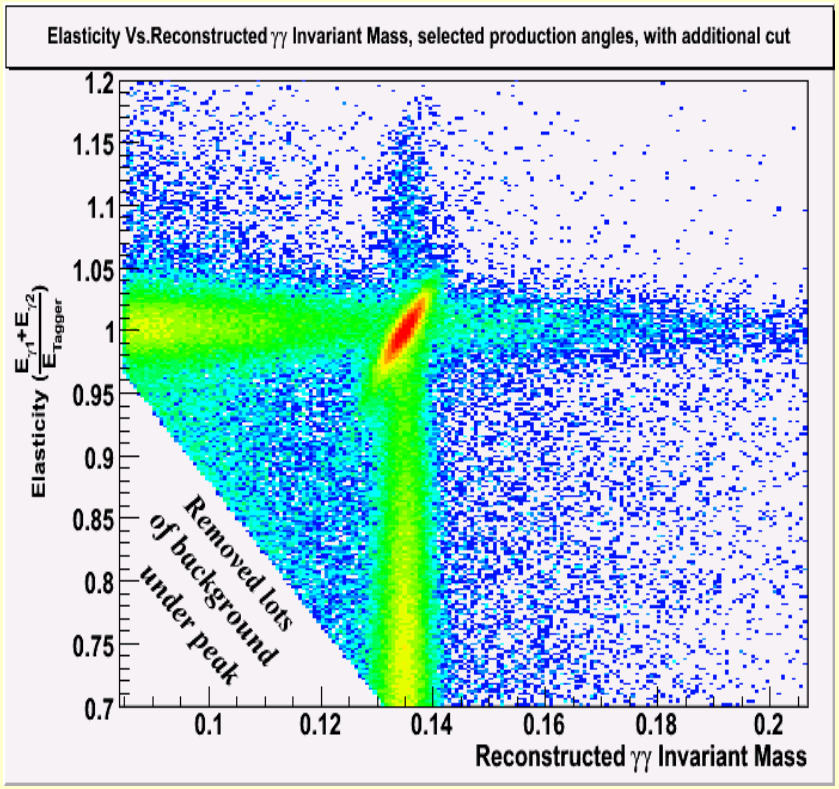
- Verified by known cross sections of QED processes
  - Compton scattering
  - e^+e^- pair production

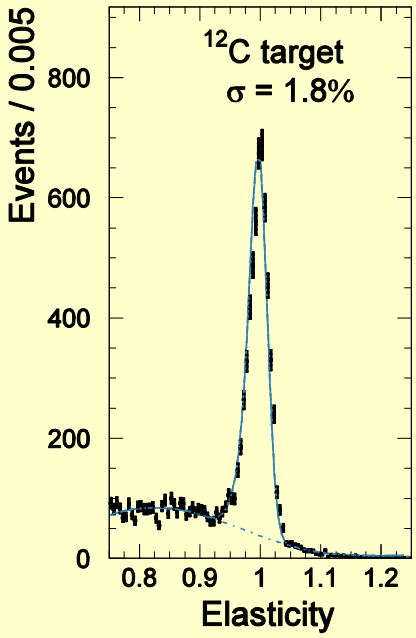
π^0 Event selection

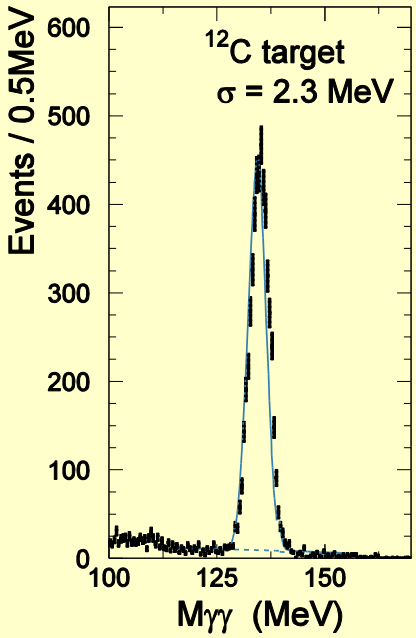
We measure:

- incident photon energy: $E\gamma$ and time
- energies of decay photons: $E\gamma_1$, $E\gamma_2$ and time
- X,Y positions of decay photons





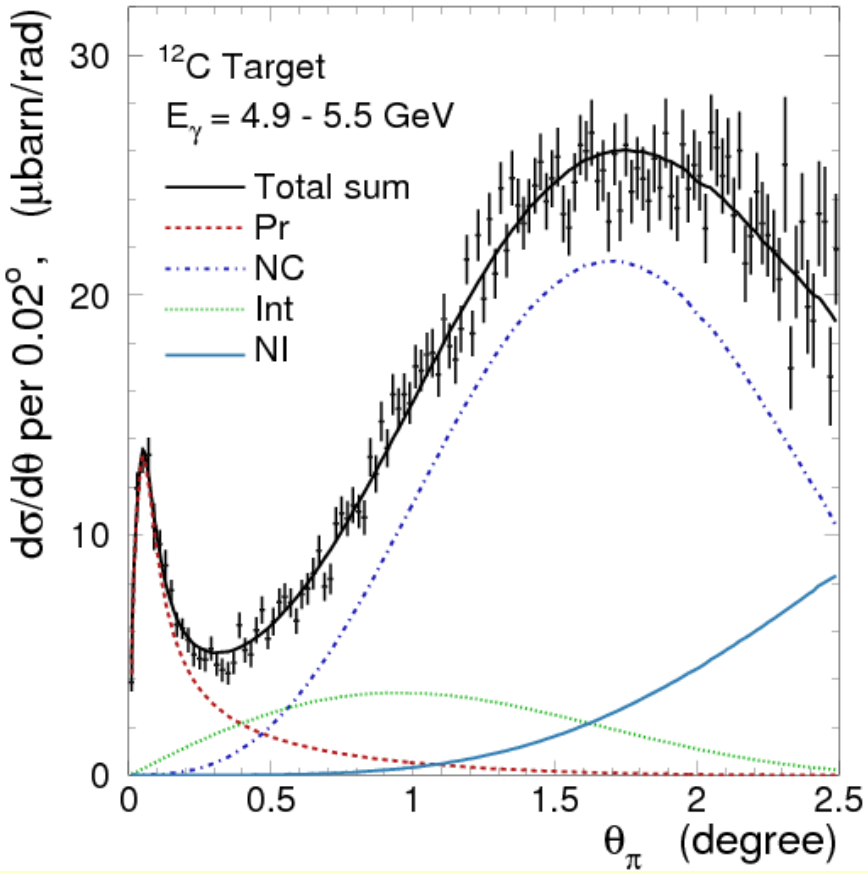


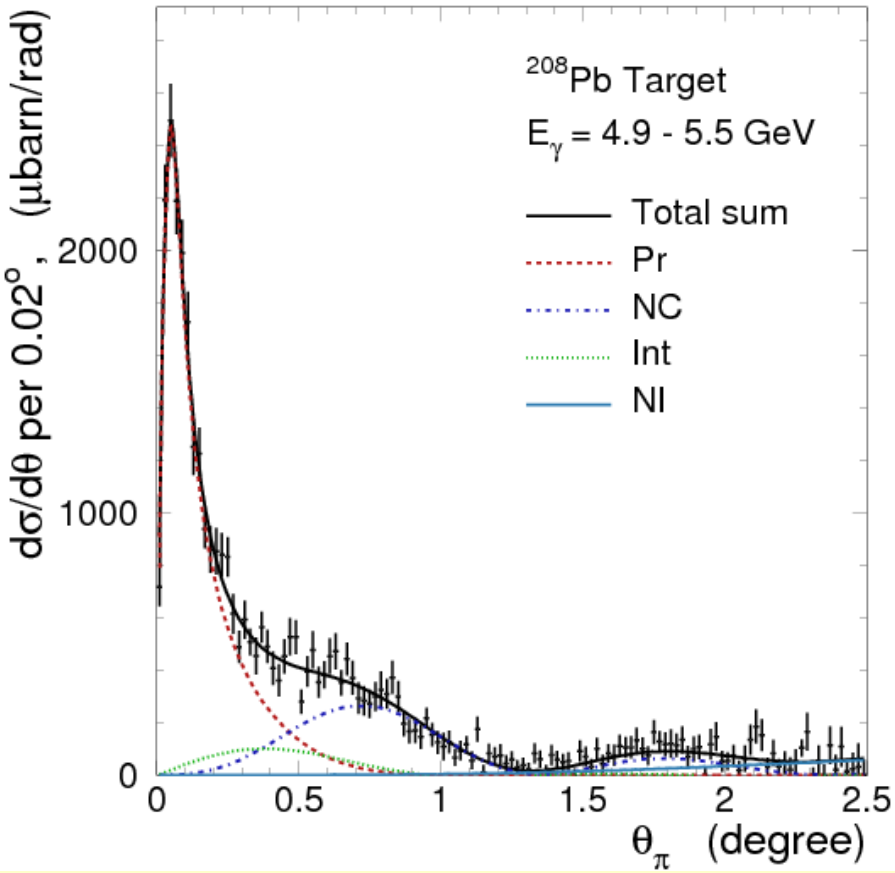


Fit Differential Cross Sections to Extract $\Gamma(\pi^0 \to \gamma\gamma)$

PrimEx-I (2004)

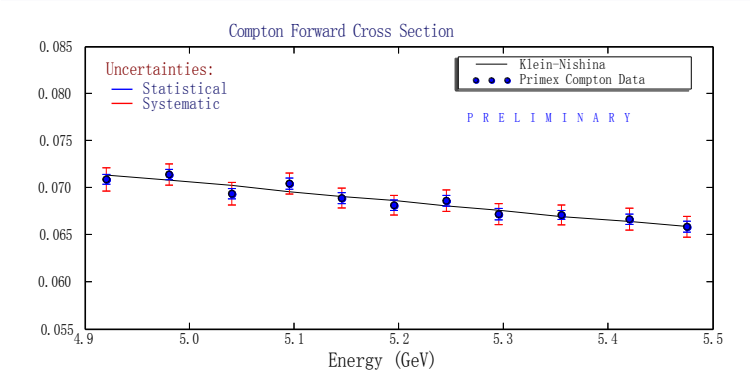
Theoretical angular distributions smeared with experimental resolutions are fit to the data on two nuclear targets:

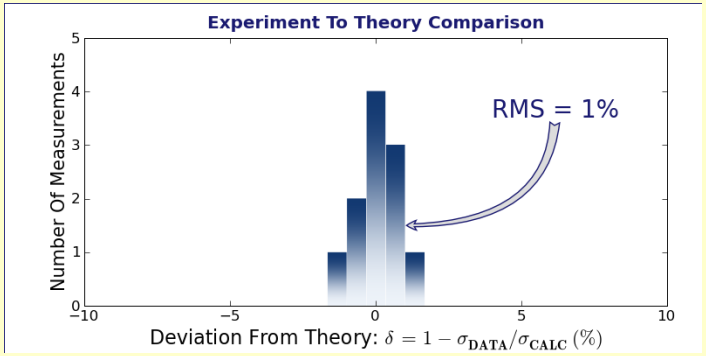




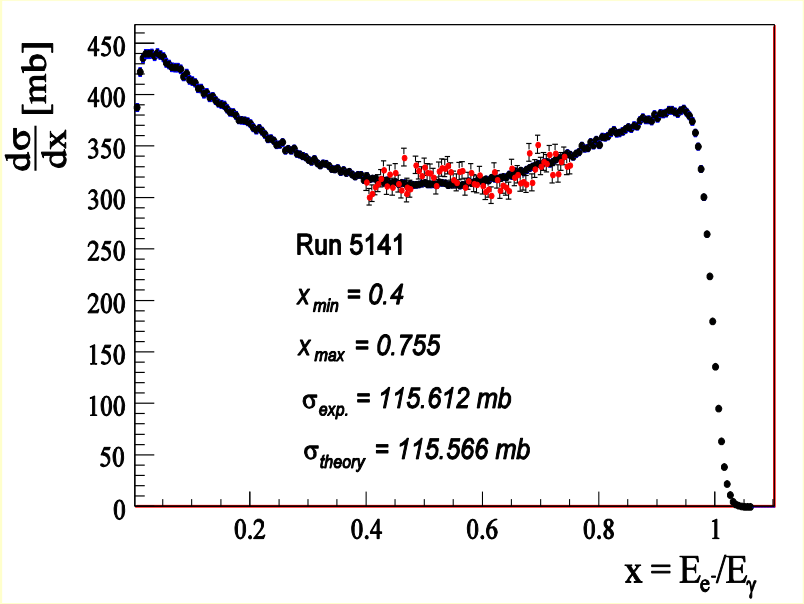
Verification of Overall Systematical Uncertainties

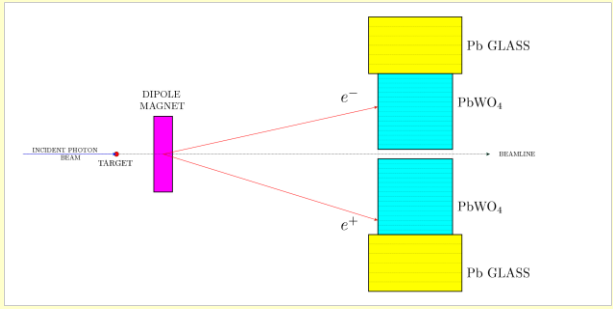
- $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





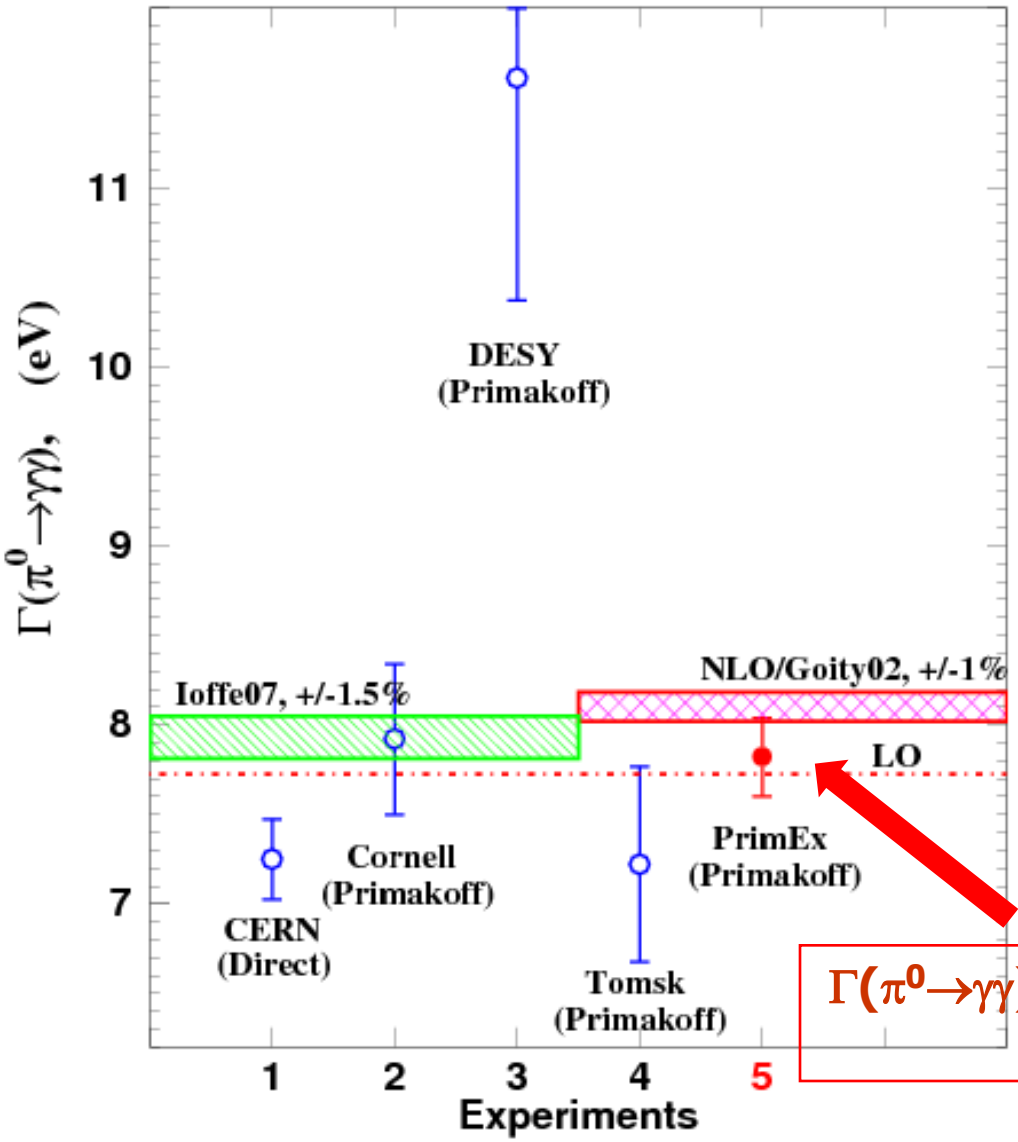
- e^+e^- pair-production cross section measurement:





Systematic uncertainties on cross sections are controlled at 1.3% level.

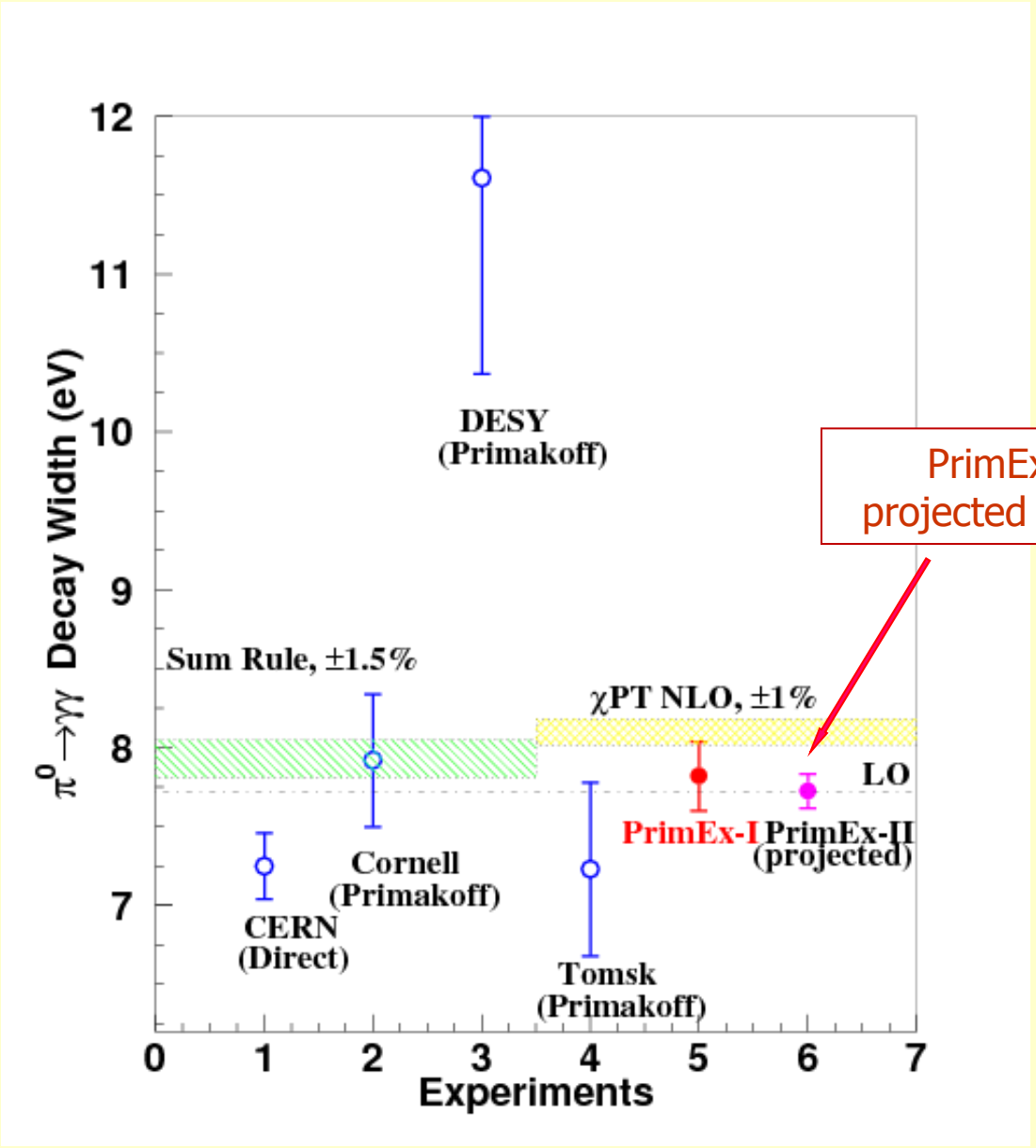
PrimEx-I Result



PRL 106, 162303 (2011)

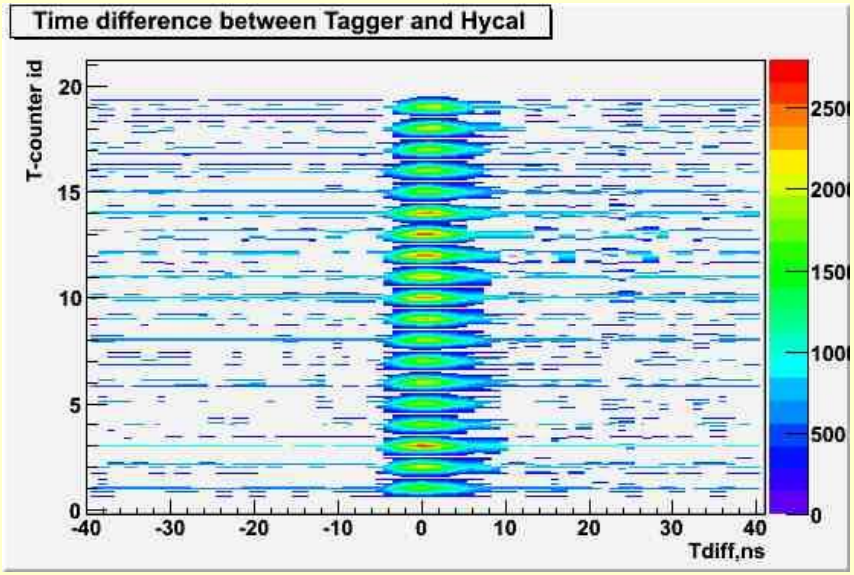
$\Gamma(\pi^0\to\gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

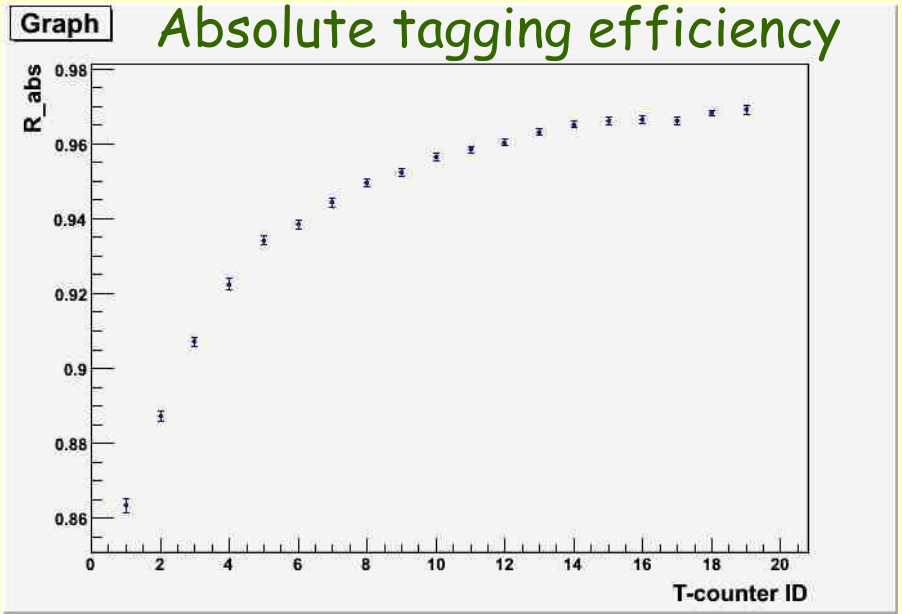
Goal for PrimEx-II (2010)

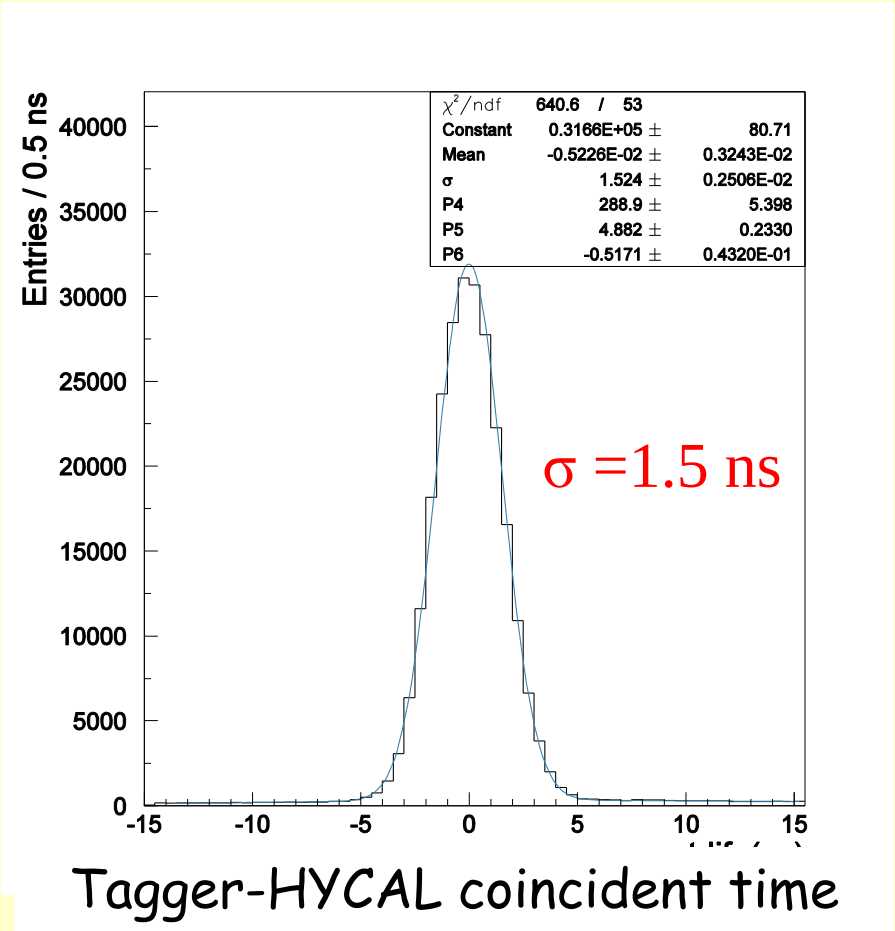


PrimEx-II Data Analysis in Progress

Tagger timing calibration

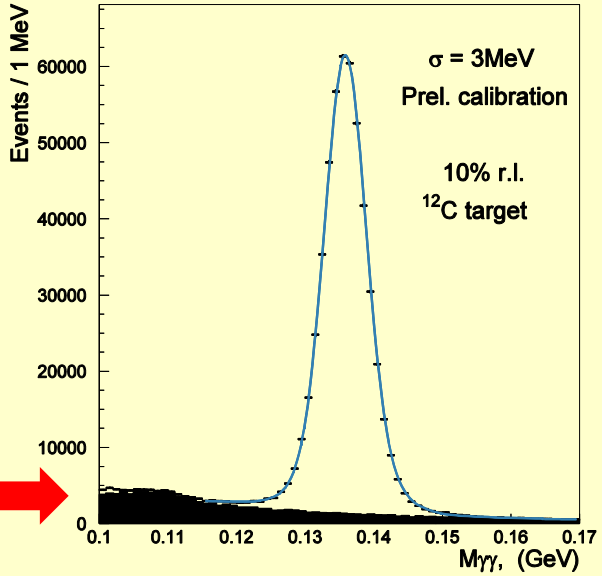


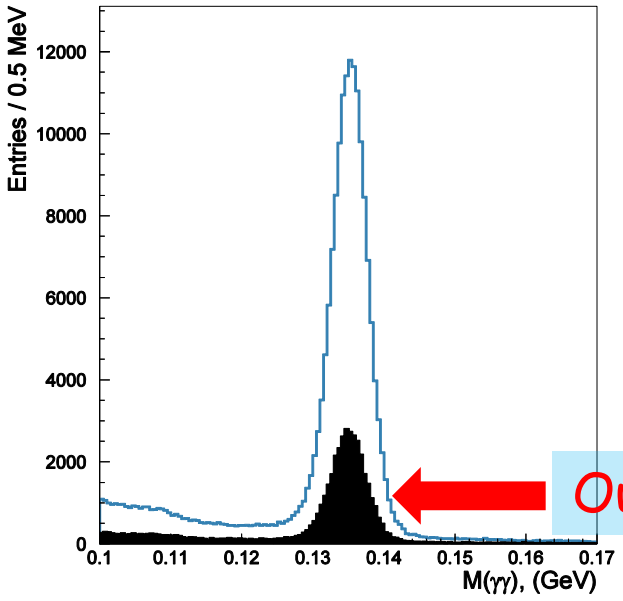




Background study in π^0 reconstruction

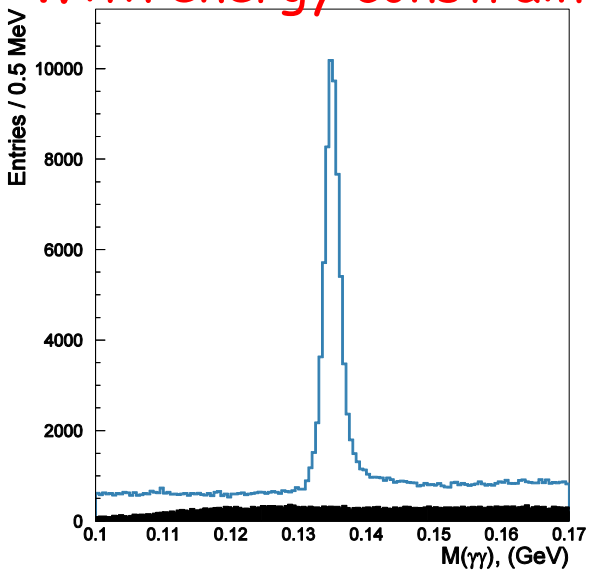
Empty target





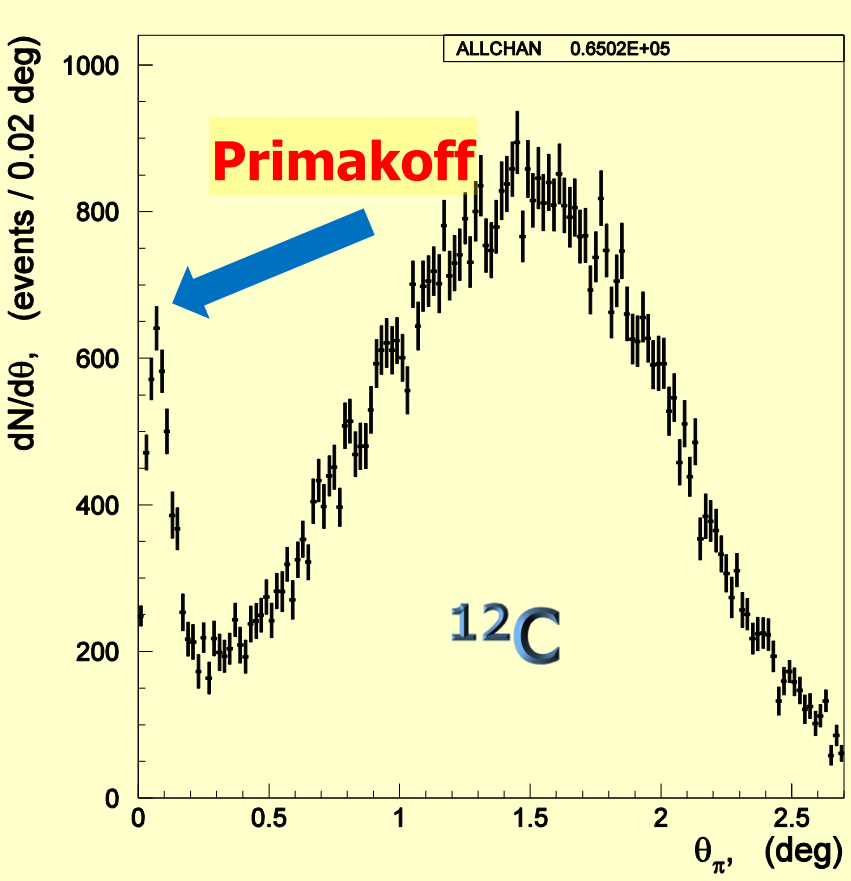
Out of time events

With energy constrain

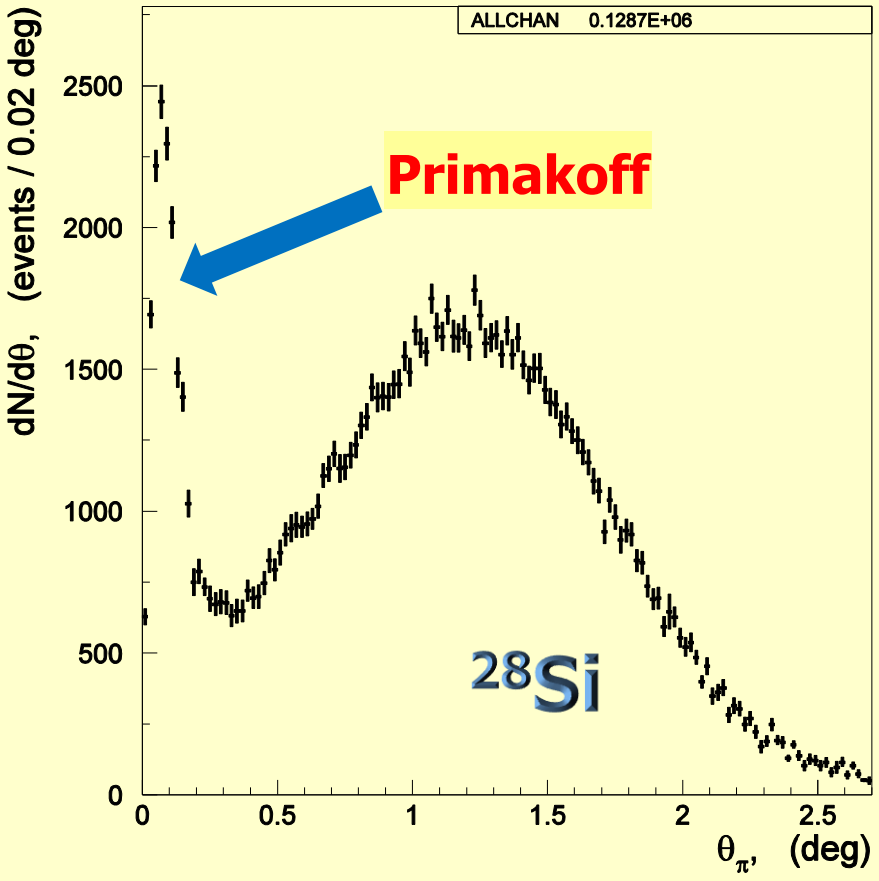


PrimEx-II Experimental Yield (preliminary)

(Eγ = 4.4-5.3 GeV)



~8K Primakoff events

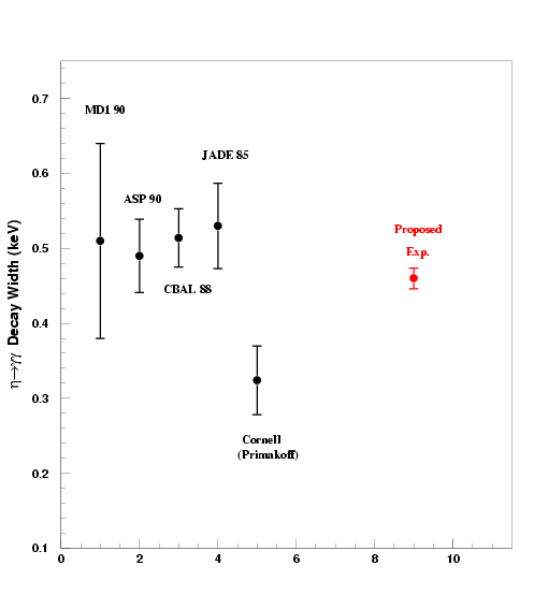


~20K Primakoff events

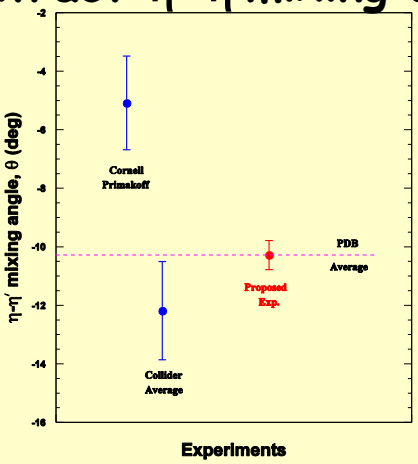
$\Gamma(\eta \to \gamma\gamma)$ Experiment @ 12 GeV

Physics Outcome from New $\eta \to \gamma\gamma$ Experiment

1. **Resolve long standing discrepancy between collider and Primakoff measurements:**

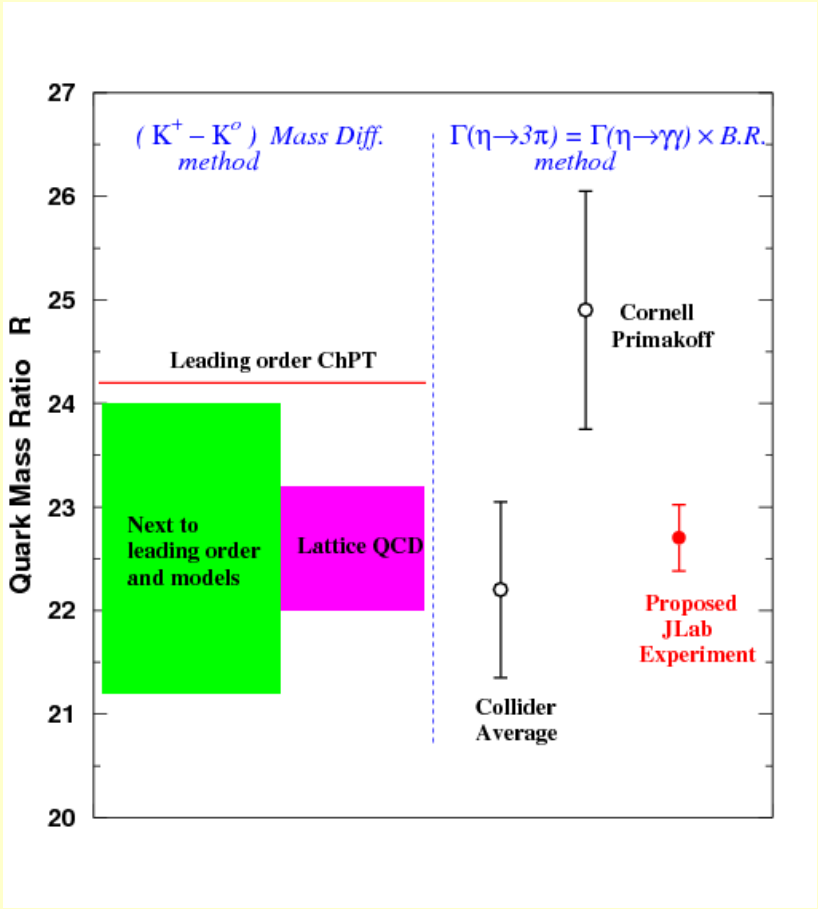


2. **Extract η-η'mixing angle:**



3. **Determine Light quark mass ratio:**

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



H. Leutwyler Phys. Lett., B378, 313 (1996)

Challenges in the $\eta \to \gamma\gamma$ Primakoff experiment

Compared to π^0:

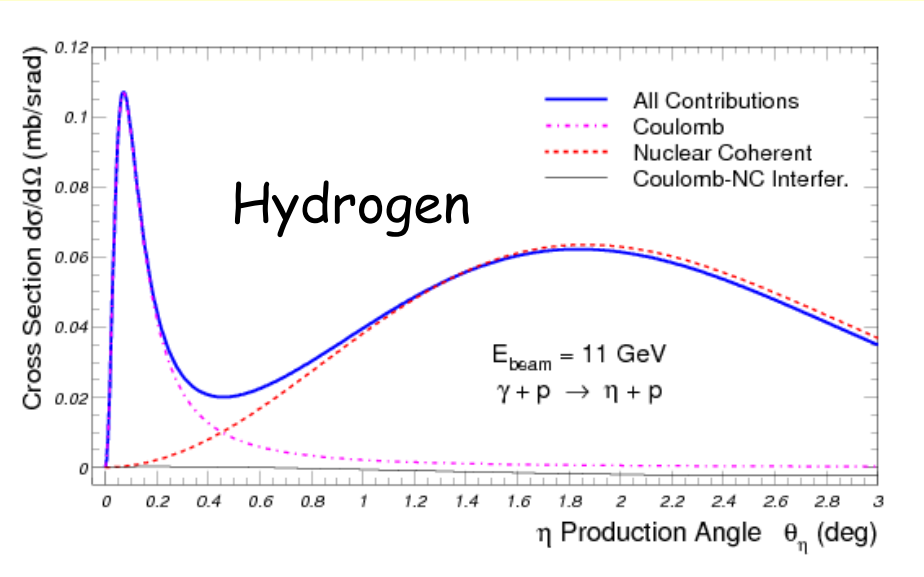
- η mass is a factor of 4 larger than π^0 and has a smaller cross section

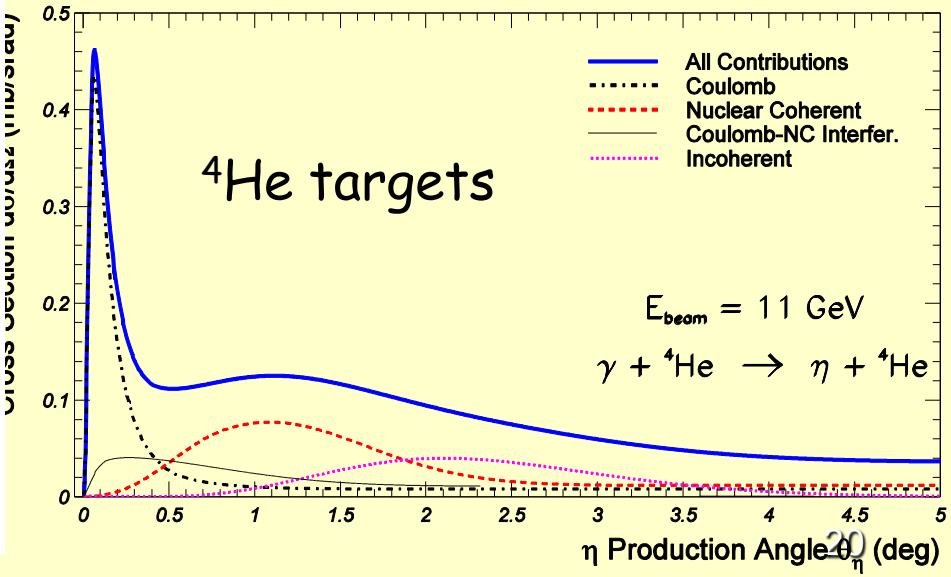
$$\left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{\mathrm{peak}} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

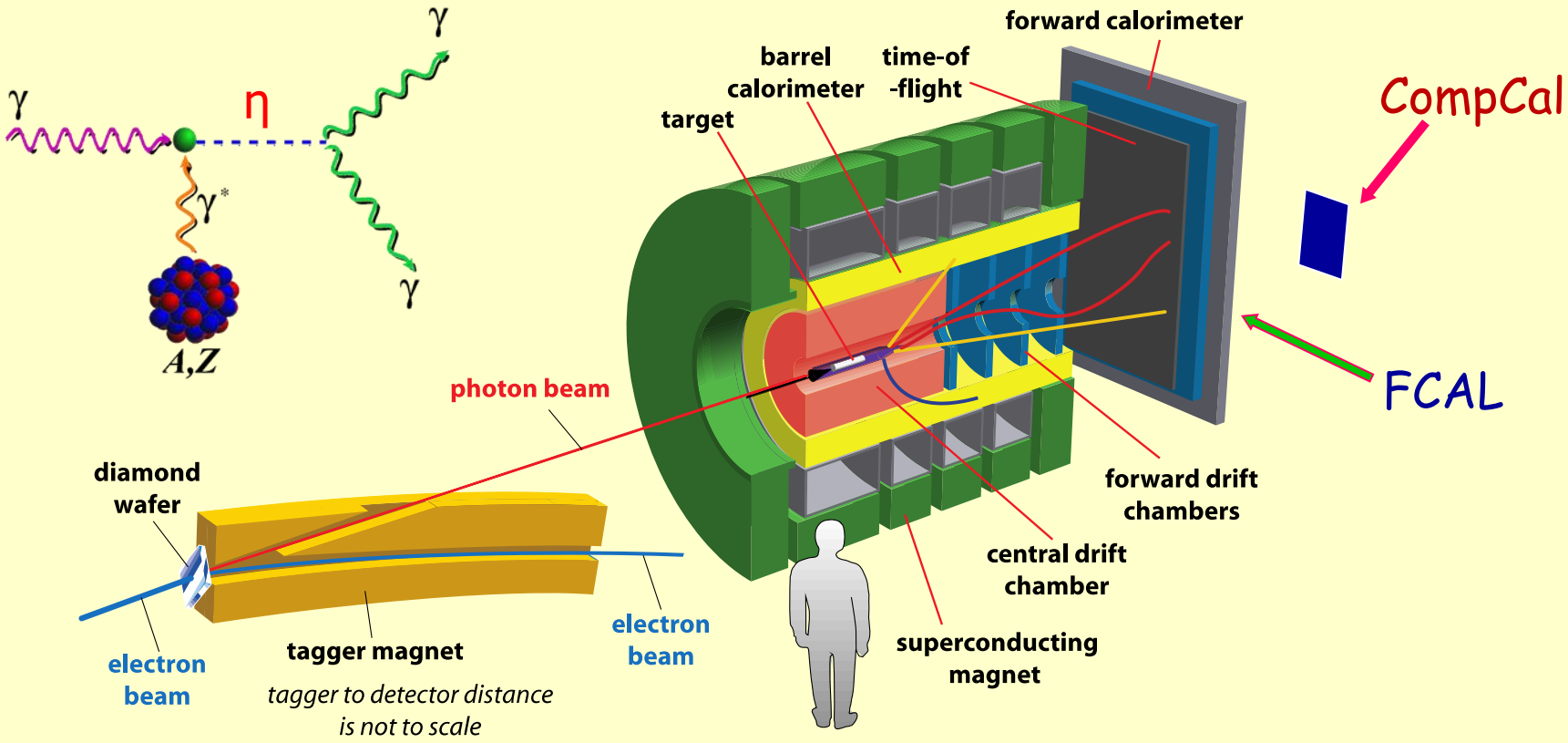
$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \theta_{NC} \propto \frac{2}{E \bullet A^{1/3}}$$

- larger momentum transfer (coherency, form factors, FSI,…)





Measurement of Γ(η→γγ) in Hall D at 12 GeV



- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for η→γγ decay photons
- CompCal and FCAL to measure well-known Compton scattering for control of overall systematic uncertainties.
- Solenoid detectors and forward tracking detectors (for background rejection)

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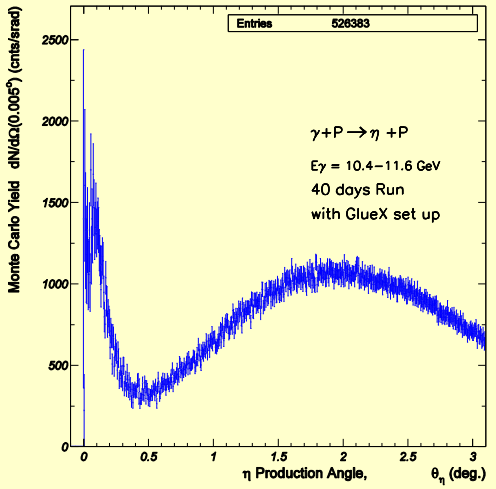
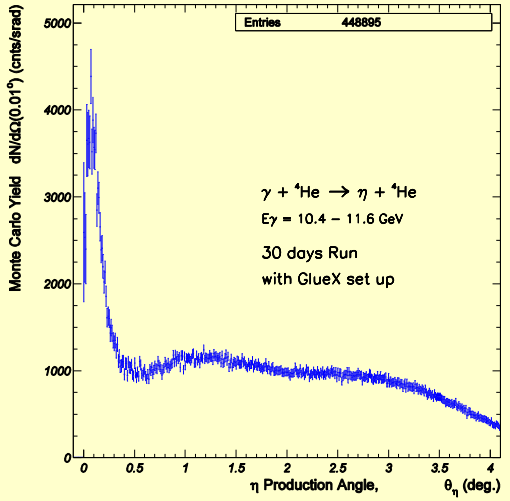
Approved Beam Time

	Days
Setup calibration, checkout	2
Tagger efficiency, TAC runs	1
^4He target run	30
LH_2 target run	40
Empty target run	6
Total	**79**





Estimated Error Budget

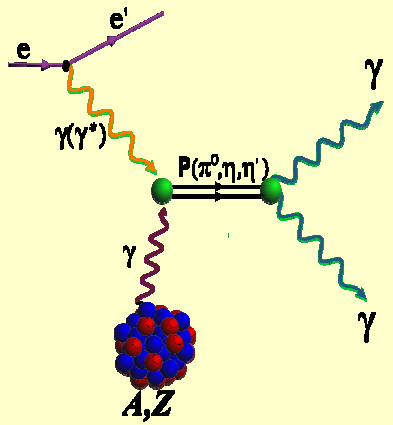
- **Systematical uncertainties** (added quadratically):

Contributions	Estimated Error
Photon flux	1.0%
Target thickness	0.5%
Background subtraction	2.0%
Event selection	1.7%
Acceptance, misalignment	0.5%
Beam energy	0.2%
Detection efficiency	0.5%
Branching ratio (PDG)	0.66%
Total Systematic	**3.02%**

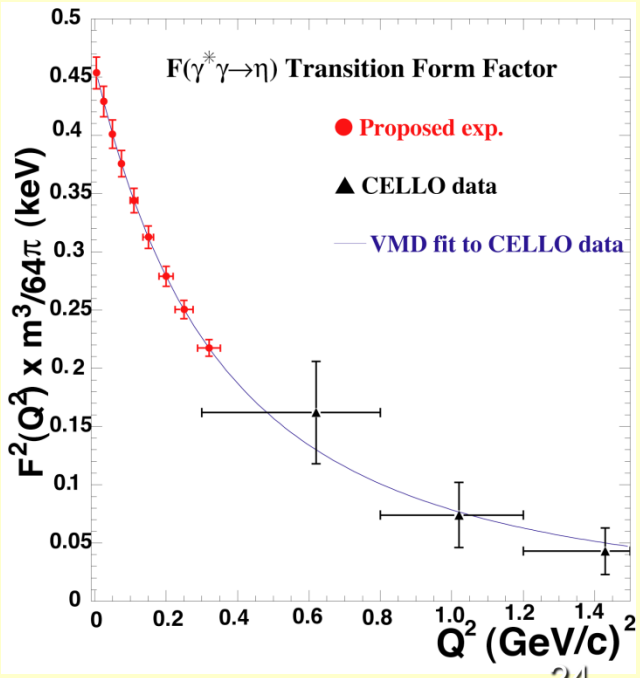
- **Total uncertainty** (added quadratically):

Statistical	1.0%
Systematic	3.02%
Total	**3.2%**

Transition Form Factors F(γγ*→p)
(at Low Q^2)



- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian
- Input for light-by-light scattering for muon (g-2) calculation
- Test of future lattice calculations



Summary

- **Precision measurements of the π^0, η and η' system will provide rich data sets to test the fundamental symmetries of QCD.**
  - precision tests of chiral symmetry and anomalies
  - determination of light quark mass ratio
  - η-η' mixing angle
  - π^0,η and η' electromagnetic interaction radii

- **A comprehensive Primakoff program has been developed at Jlab to measure $\Gamma(p \to \gamma\gamma)$ and $F(\gamma\gamma^* \to p)$ of π^0, η and η'.**
  - Two experiments on $\Gamma(\pi^0 \to \gamma\gamma)$ were performed in Hall B.

    PrimEx-I: $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14(\text{stat.}) \pm 0.17(\text{syst.})$ eV (2.8% tot)

    Phys. Rev. Lett., 106, 162302 (2011)

    PrimEx-II was performed and analysis is in progress. The π^0 lifetime at level of 1.4% precision is expected.
  - A new precision experiment on $\Gamma(\eta \to \gamma\gamma)$ has been planned to run in Hall D at 12 GeV.