Neutral Pion Lifetime: Final Results from the PrimEx-I Experiment

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for the PrimEx Collaboration

Outline

- Importance of $\Gamma(\pi^0 \to \gamma\gamma)$ precision measurement
- The PrimEx experiment
- Control of systematic errors
- Results from PrimEx-I
- Summary and outlook

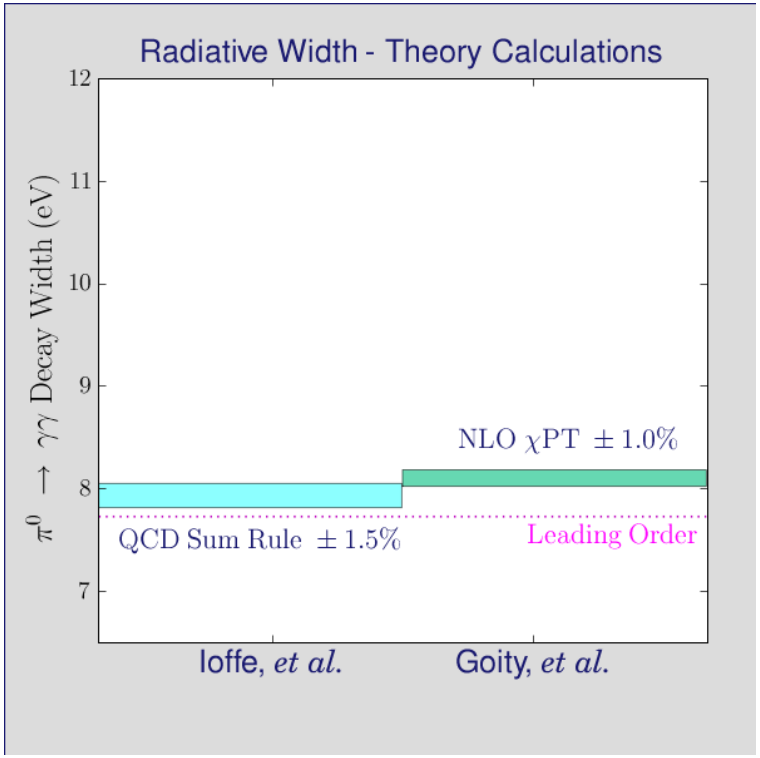
$\pi^0 \to \gamma\gamma$ Decay Width: Theory

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

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

- Corrections to the chiral anomaly prediction:
  (u-d quark masses and mass differences)
  Calculations in NLO ChPT:
  (J. Goity, at al. Phys. Rev. D66:076014, 2002)
  $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.10eV ± 1.0%

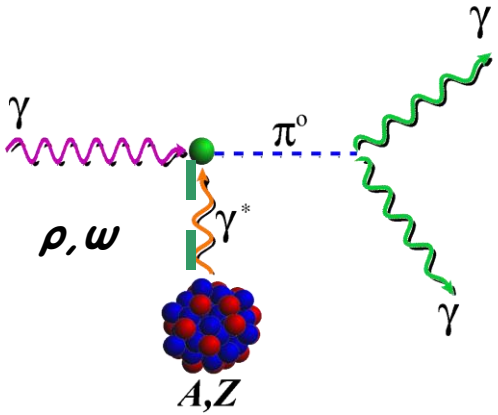
~4% higher than LO, uncertainty: less than 1%



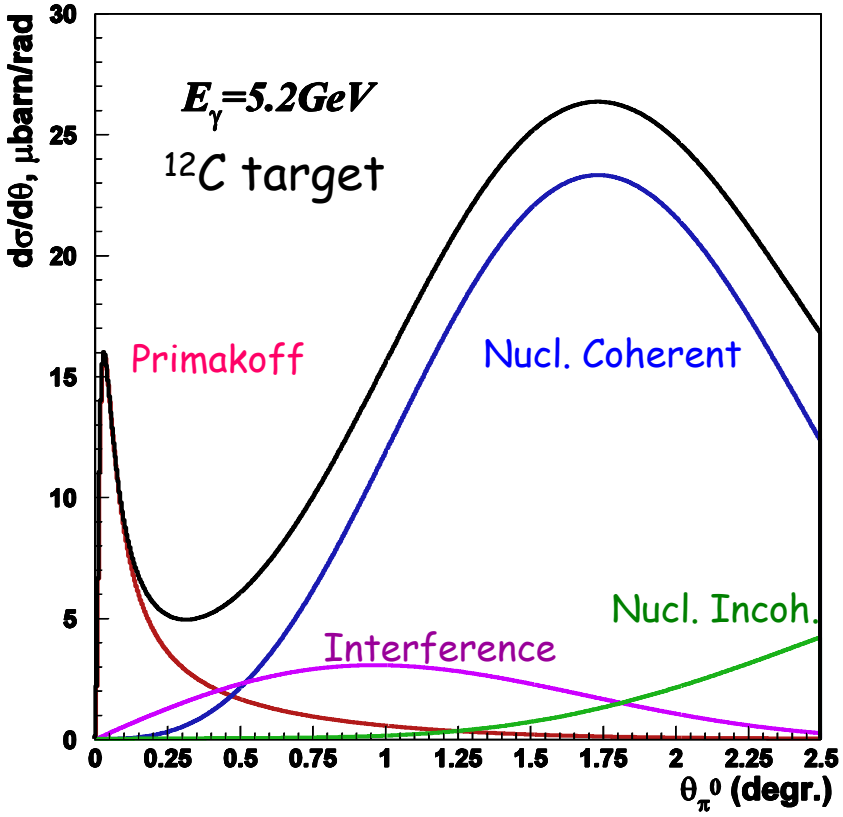
- QCD sum rule calculations:
  (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)
  - $\Gamma(\eta \to \gamma\gamma)$ is only input parameter
  - π^0-η mixing included
  $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.93eV ± 1.5%

- 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



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



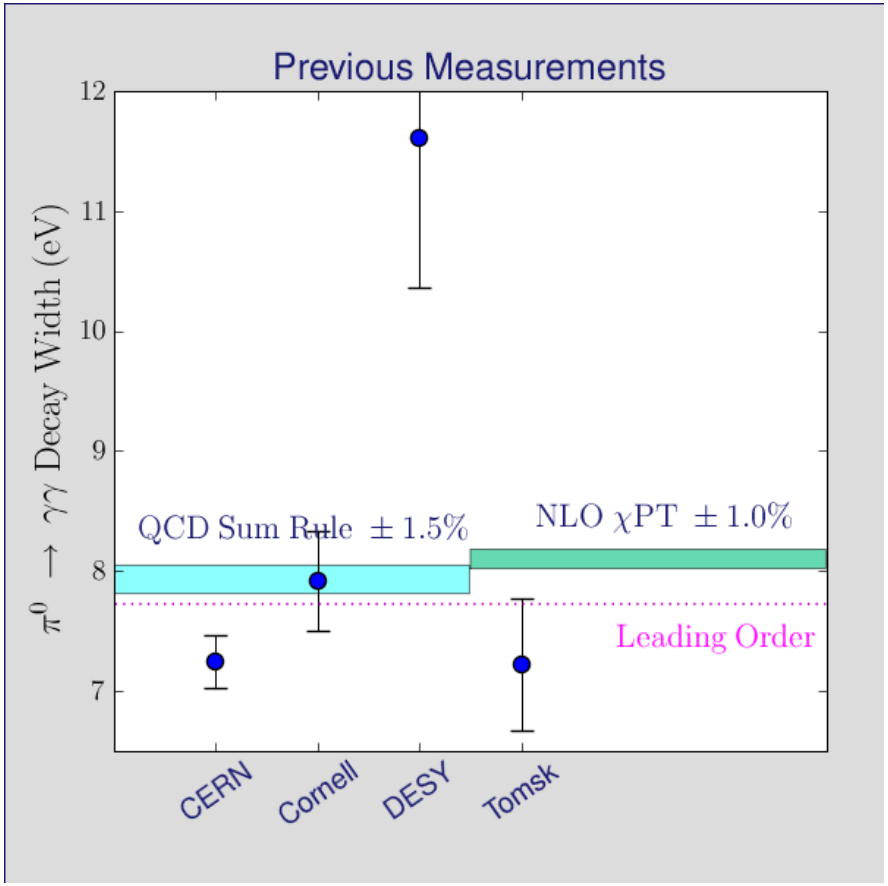
Challenge: Extract the Primakoff amplitude

Previous Experiments (included in PDG)

- CERN experiment (1984):
  P=450 GeV proton beam
  $\Gamma(\pi^0\to\gamma\gamma)$ = 7.34eV±3.1% (total)

- DESY (1970)
  - bremsstrahlung γ beam,
    $E\gamma$=1.5 and 2.5 GeV
  - Targets C, Zn, Al, Pb
  - Result: $\Gamma(\pi^0\to\gamma\gamma)$=(11.7±1.2) eV
    ±10.%

- Cornell (1974)
  - bremsstrahlung γ beam
    $E\gamma$=4 and 6 GeV
  - targets: Be, Al, Cu, Ag, U
  - Result: $\Gamma(\pi^0\to\gamma\gamma)$=(7.92±0.42) eV
    ±5.3%



- All previous Primakoffexperiments used:
  - Untagged bremsstrahlung γ beam
  - Conventional Pb-glass calorimetry

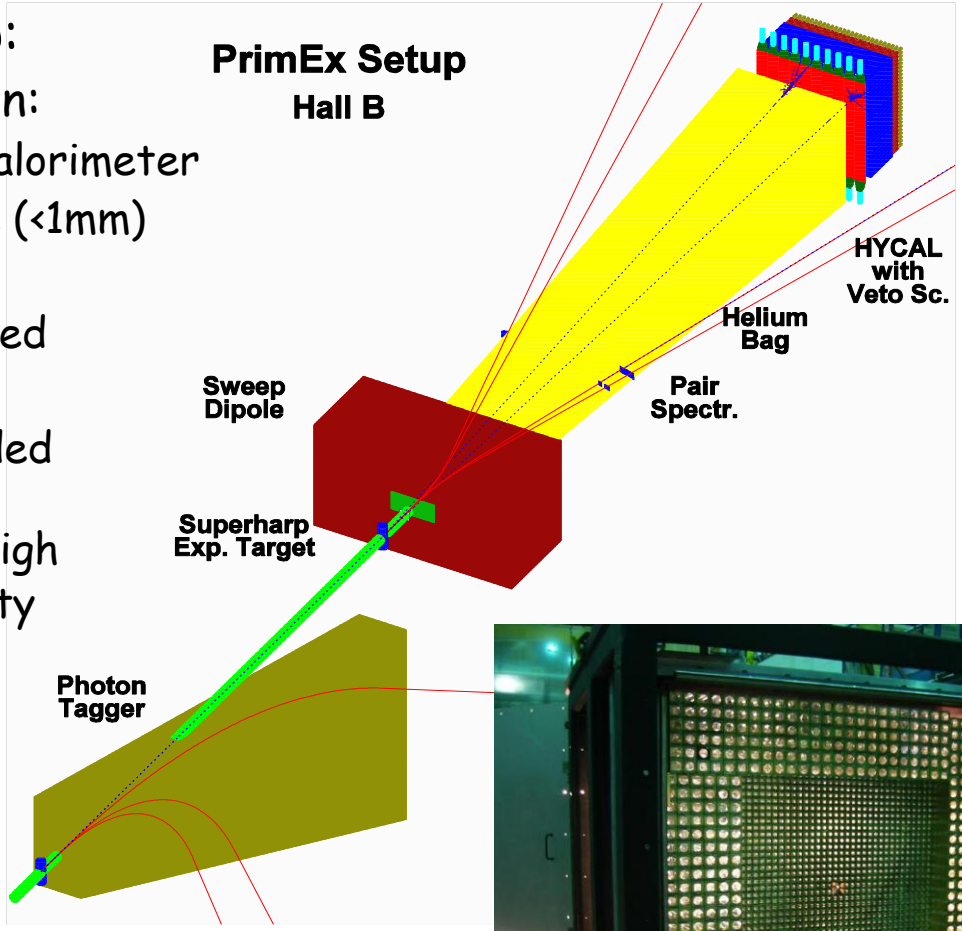
The PrimEx Experiment at JLab

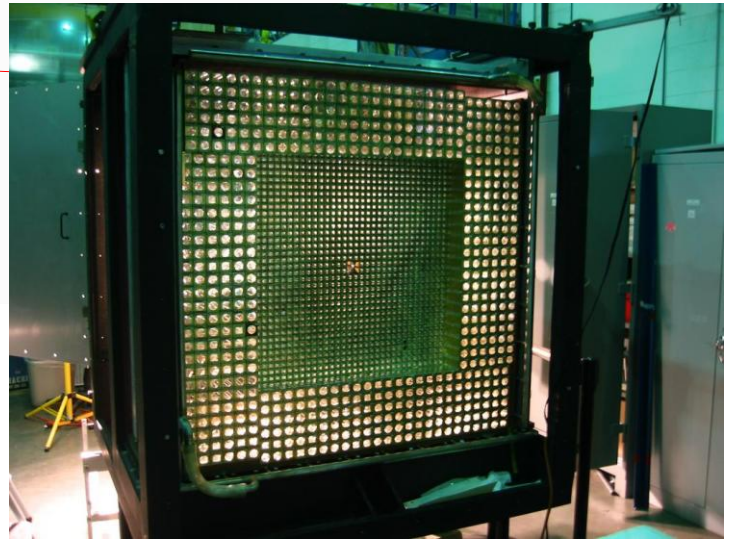
- Requirements of Setup:
  - high angular resolution:
    - high resolutions in calorimeter
    - small beam spot size (<1mm)
  - Background:
    - tagging system needed
  - Particle ID
    - veto detectors needed

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

- New high resolution hybrid calorimeter (HYCAL)

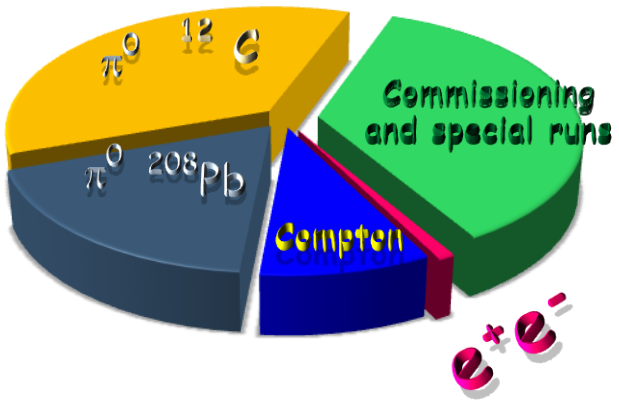
- New pair spectrometer for photon flux control at high intensities





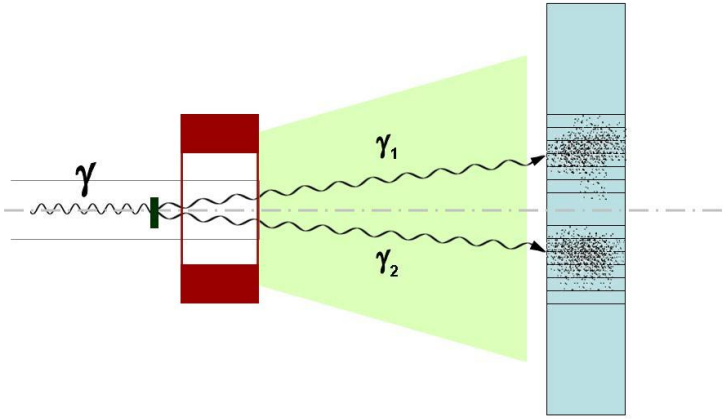
PrimEx Milestones

- Approved in 1999, Re-approved in 2002 (E02-103).
- Installation of setup in August, 2004.
- Commissioning: September, 2004
- Data taking: September-November
  - data on two targets: ^{12}C and ^{208}Pb,
  - Total number of π^0 : ~3.2 M
  - Total elastic π^0 : ~300 K
  - Total Primakoff π^0 : ~3-5 K
- First preliminary results released at the April, 2007 APS meeting with AIP press conference.
- The final result reported at Chyral Dynamics, CD-2009, July 2, 2009
- Preparing for publication.



π^0 Event selection

We measure:

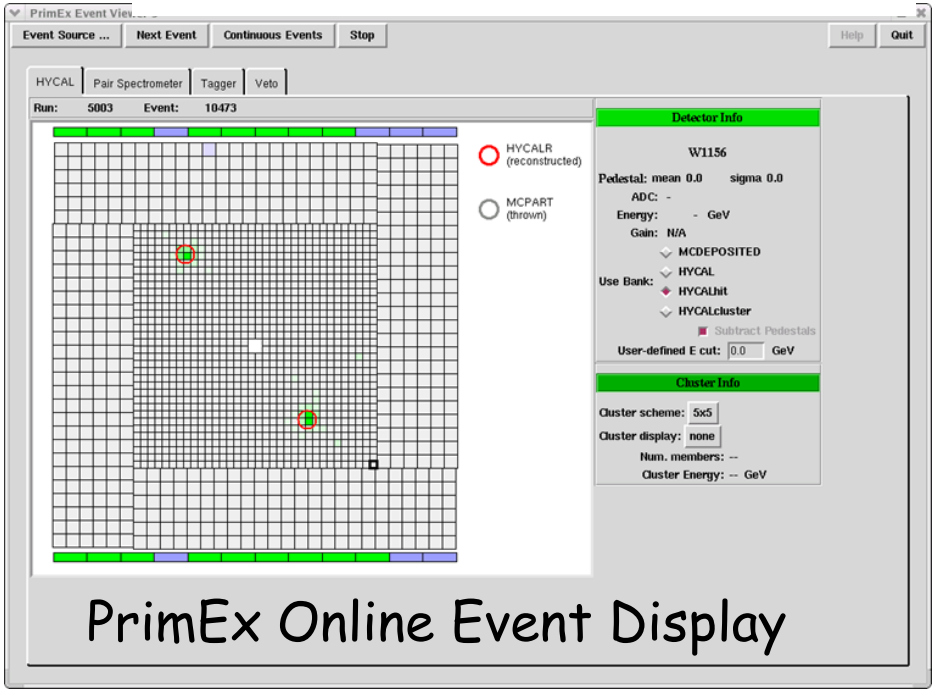


- incident photon energy: $E\gamma$ and time
- energies of decay photons:
  $E\gamma_1$, $E\gamma_2$ and time
- X,Y positions of decay photons

Kinematical constraints:

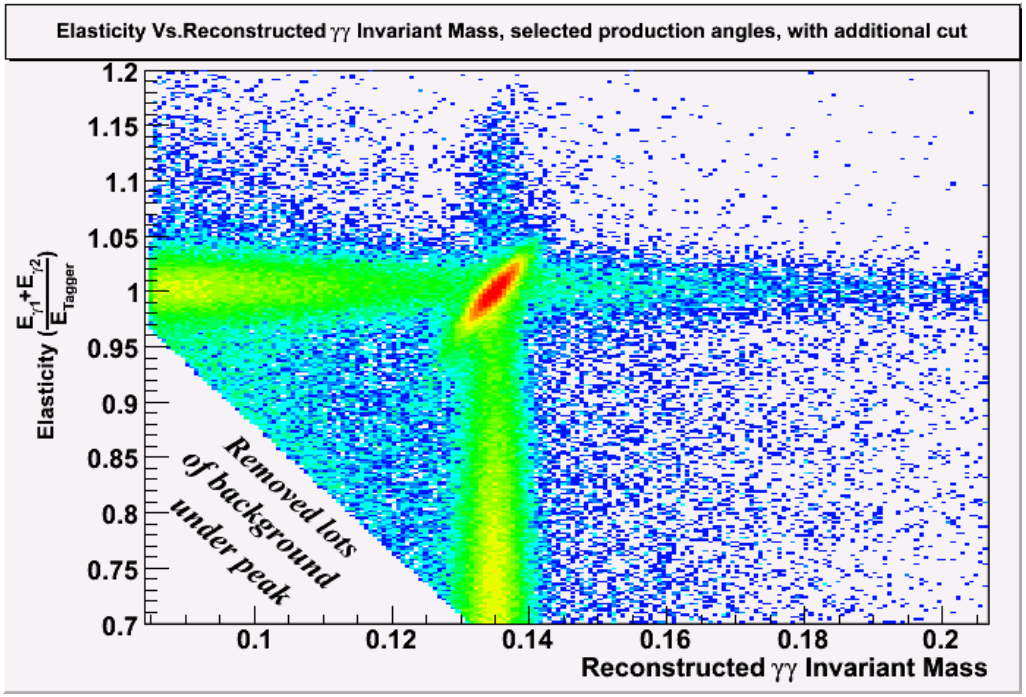
- Conservation of energy;
- Conservation of momentum;
- $m_{\gamma\gamma}$ invariant mass

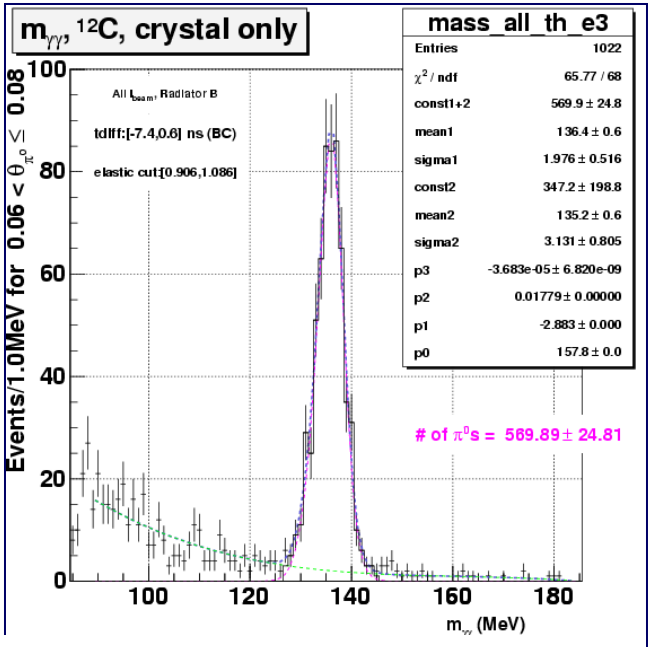
Three groups analyzed the data independently

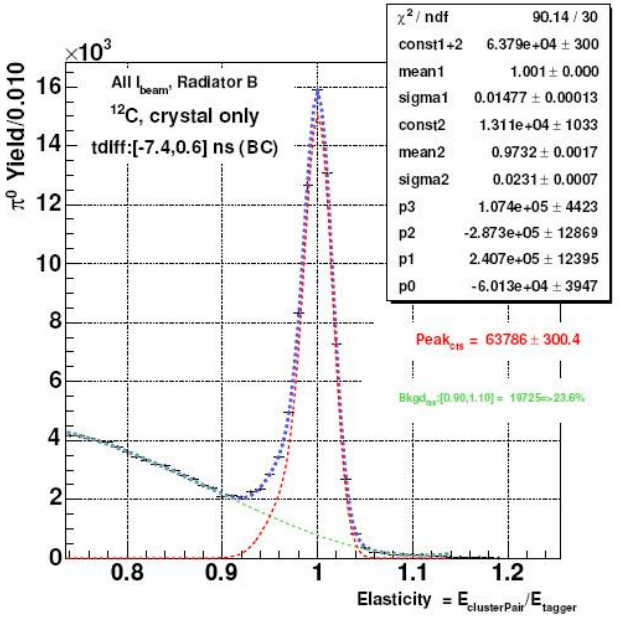


PrimEx Online Event Display

π^0 Event selection



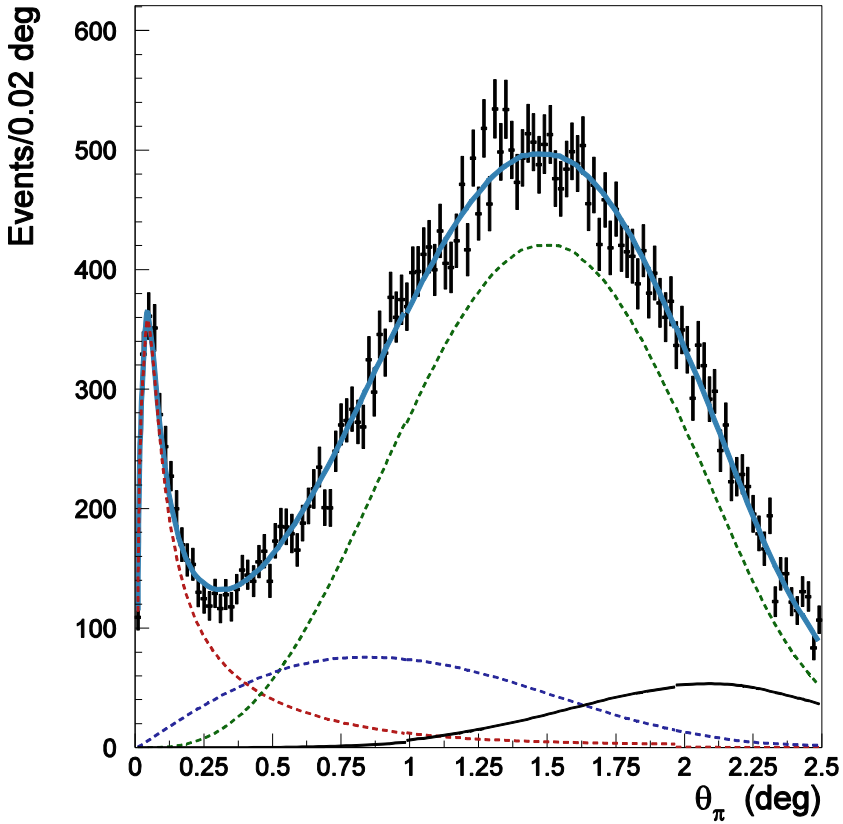


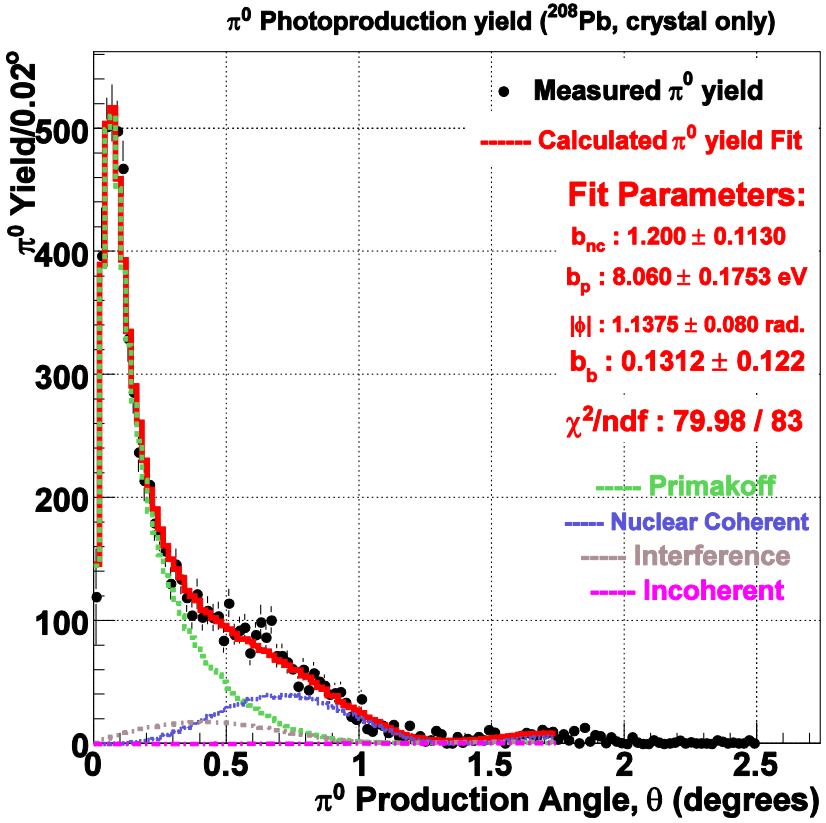


- Tagger-HyCal timing (Δt);
- Invariant mass ($M_{\gamma\gamma}$);
- Energy conservation:
  Elasticity $((E_{\gamma 1}+E_{\gamma 2})/E_{tagger})$

Fit to Extract $\pi^0 \to \gamma\gamma$ Decay Width

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



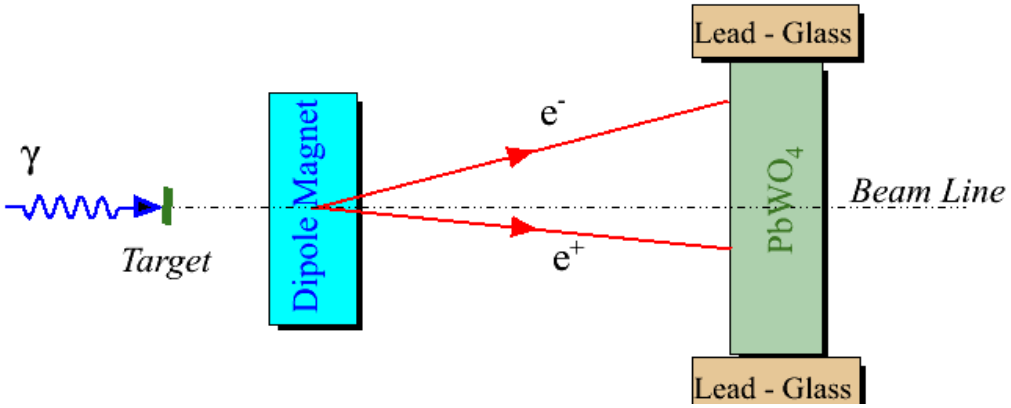


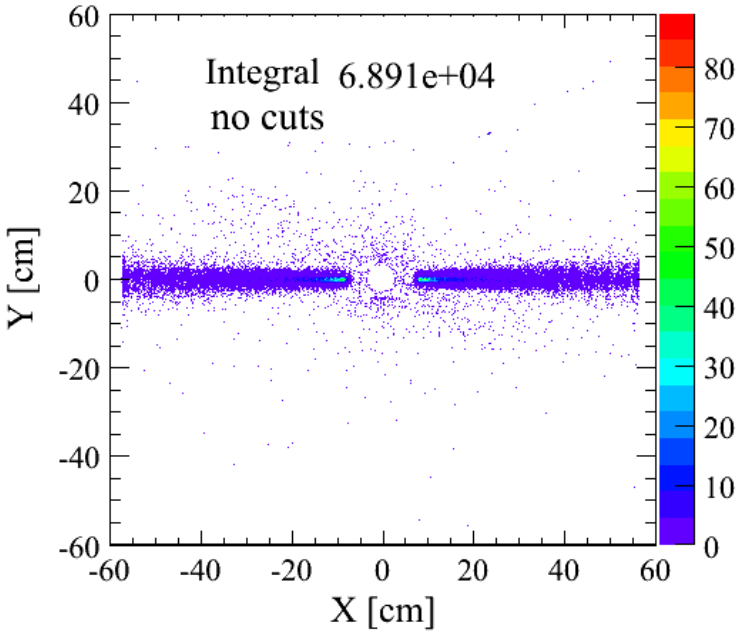
$\Gamma(\pi^0 \to \gamma\gamma) = 7.82$ eV ± 2.2% (stat. error, including fit error)

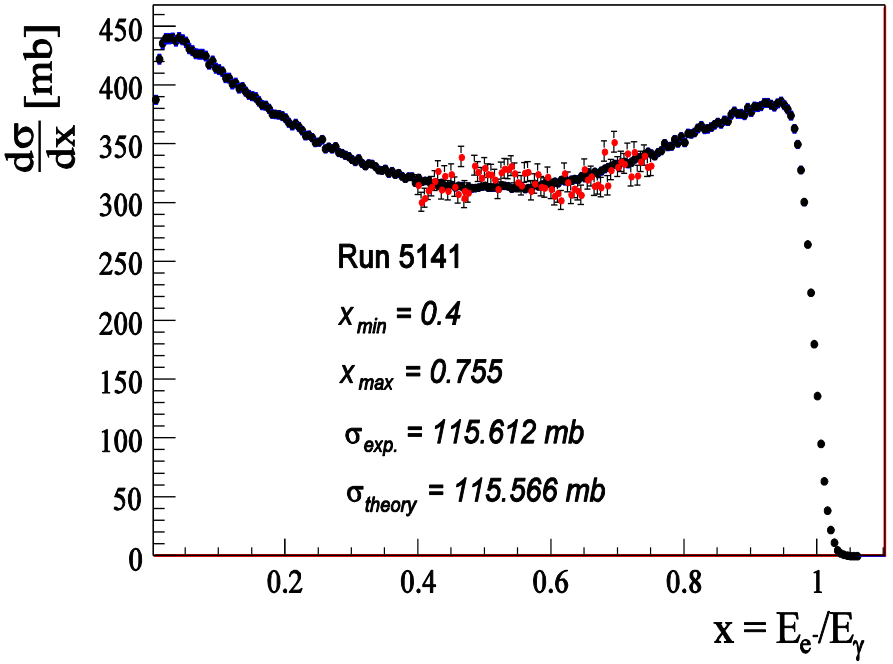
The systematic errors ?

Control of Systematic Errors: Luminosity: e^+e^- Cross Section

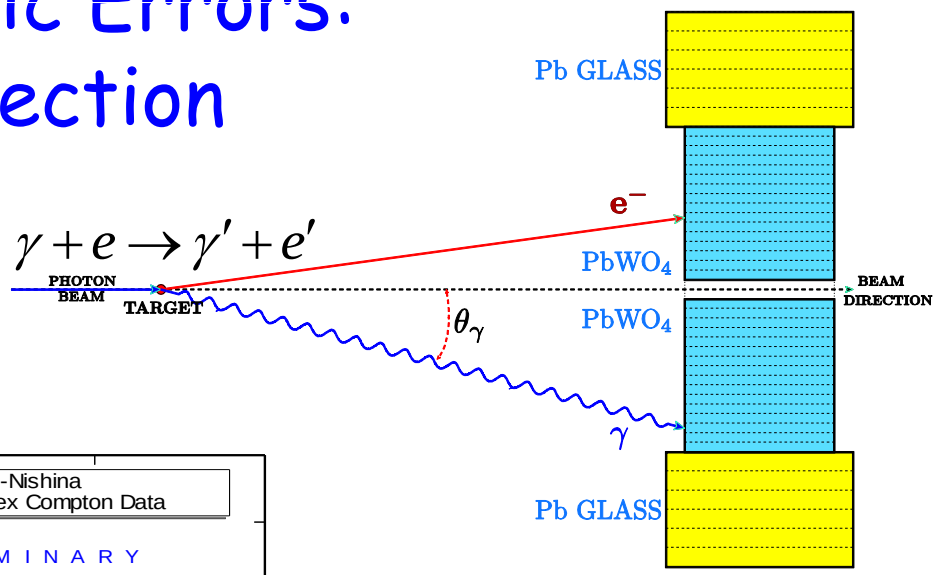
- Measured Quantities
  - Energy of the incident photon
  - Energies of each lepton
  - Positions of each lepton

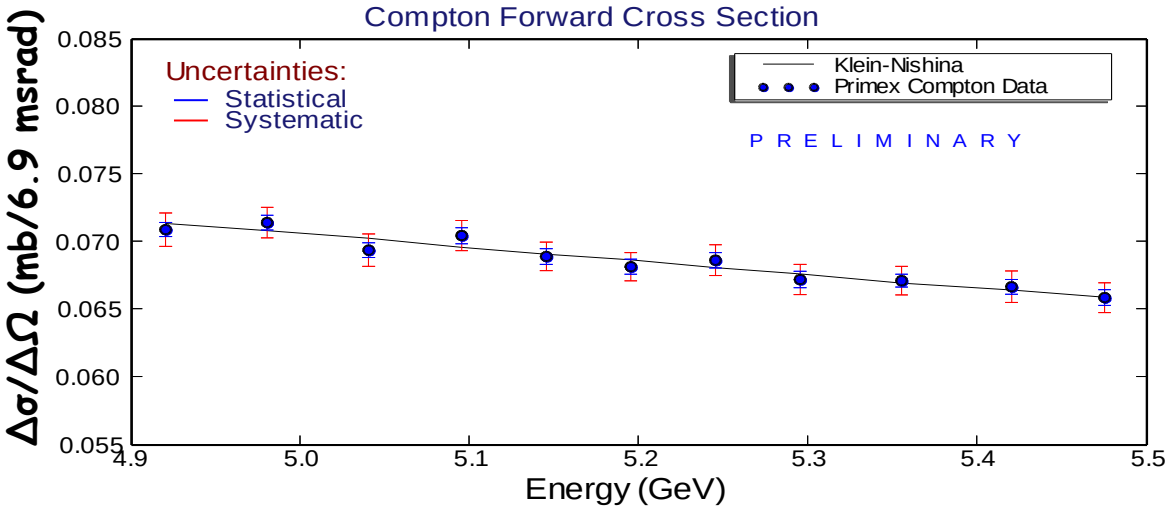


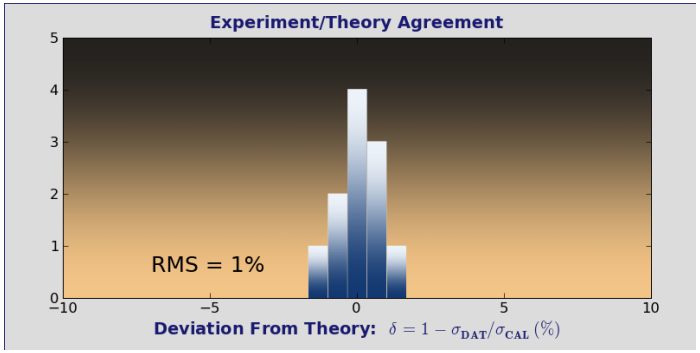




Control of Systematic Errors: Compton Cross Section



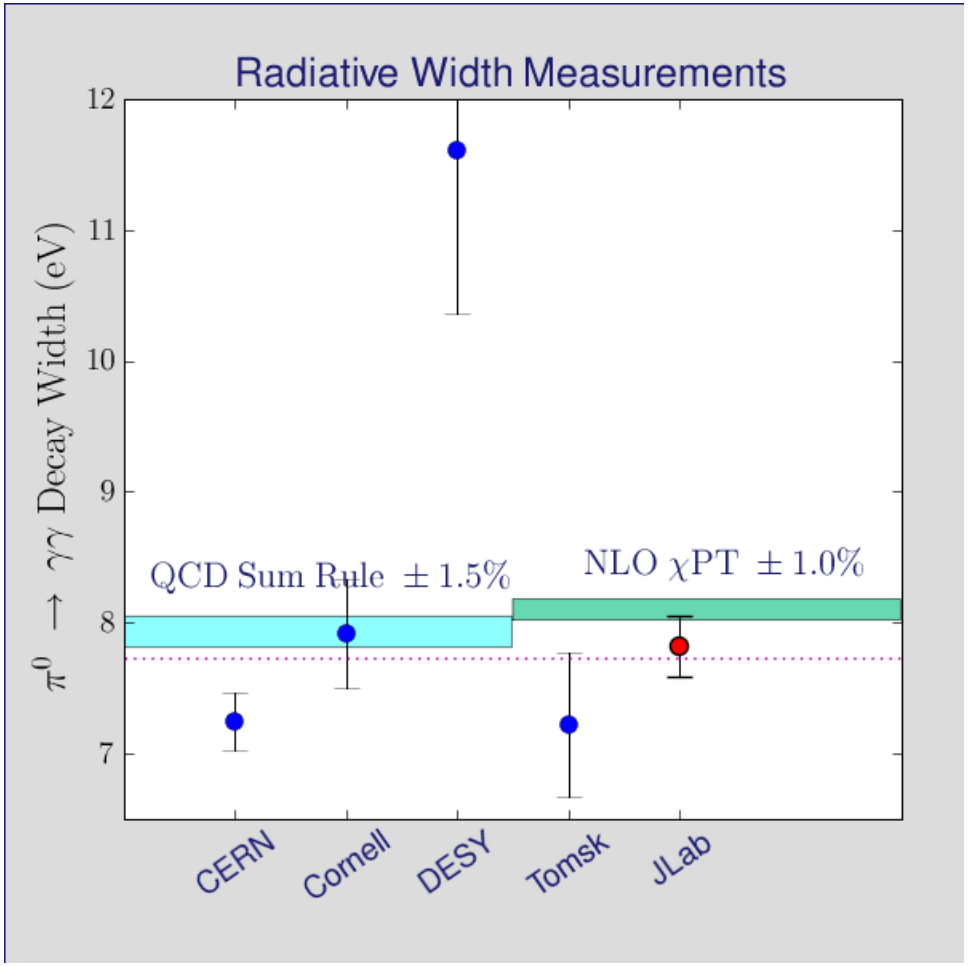




- **Average stat. error: 0.6%**
- **Average syst. error: 1.5%**
- **Total error: 1.6%**

❑ **Cross sections are in agreement with theory at few percent level**

Final Result from PrimEx-I

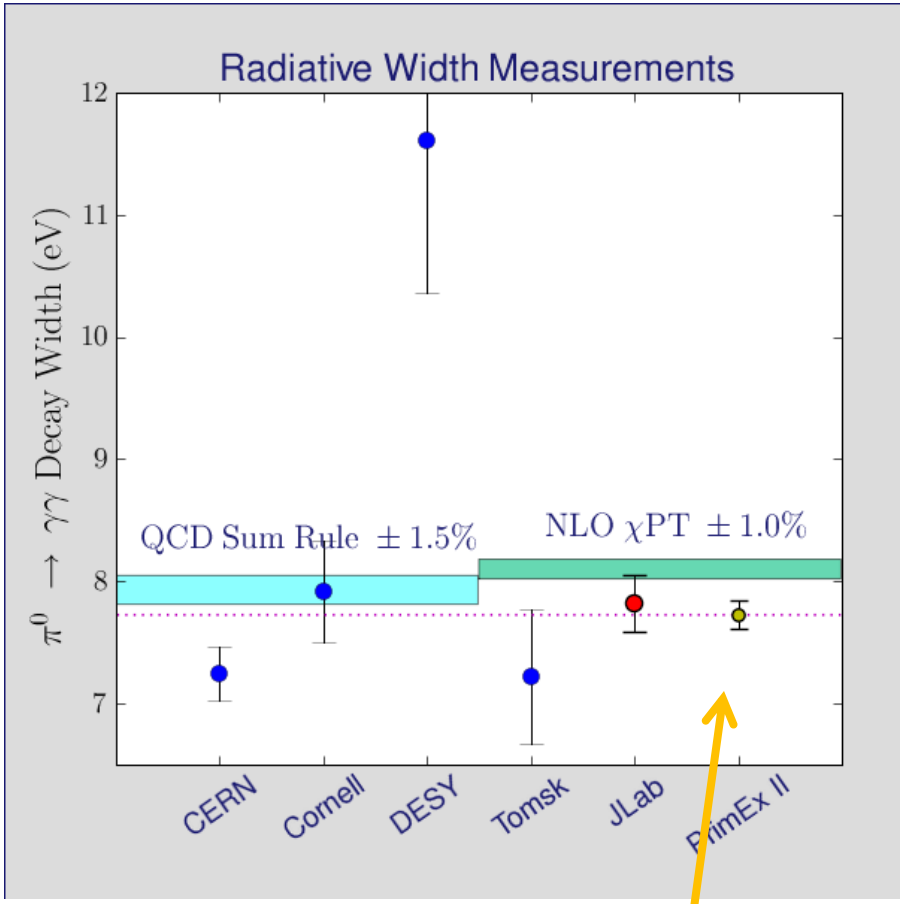


$\Gamma(\pi^0 \to \gamma\gamma) = 7.82\text{eV} \pm 2.2\%\ (\text{stat.}) \pm 2.1\%\ (\text{syst.})$
$(\pm\ 3.0\%\ \text{total})$

Next PrimEx-II Experiment

➢ **Statistical error: 0.44%**

Contributions	Error, [%]
Photon flux	1.0
Target	0.1
Yield extraction	0.5
HYCAL eff.	0.2
Beam parameters	0.4
Trigger eff.	0.1
VETO eff.	0.3
Acceptance	0.3
Model errors (theory)	0.3
Physics background	0.25
Branching ratio	0.03
Total (syst.)	1.3



Projected PrimEx-II

Summary and Outlook

- The π^0 lifetime is one of the few high precision QCD parameter-free predictions. Percent level measurement is a stringent test of QCD.

- Availability of modern tagged-photon beams and novel calorimetry made the Primakoff method a feasible tool to reach the required few percent accuracy in $\pi^0 \to \gamma\gamma$ decay width.

- Compton and pair production cross section measurements demonstrate that the systematical errors can be controlled on one percent level. 1.5%

- The model error in π^0 decay width extraction is currently controlled on 0.3% level.

- The result from PrimEx-I is: $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82eV $\pm$ 2.2% stat. $\pm$ 2.1% syst. (3.0% total).

  It is 2.4 times more precise than current PDG value

- With the PrimEx-II run we will reach the planned precision of 1.4%

- The $\Gamma(\eta \to \gamma\gamma)$ $\Gamma(\eta/ \to \gamma\gamma)$ precision experiments will be done with 12 GeV upgrade.

The End

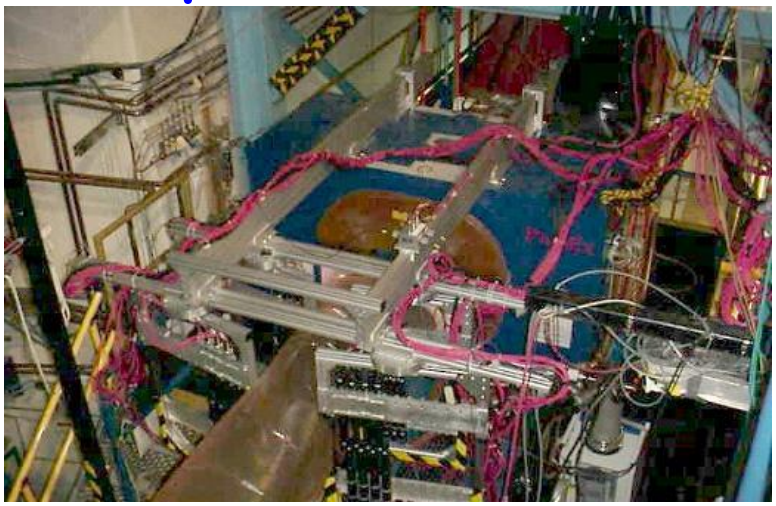
Estimated Systematic Errors

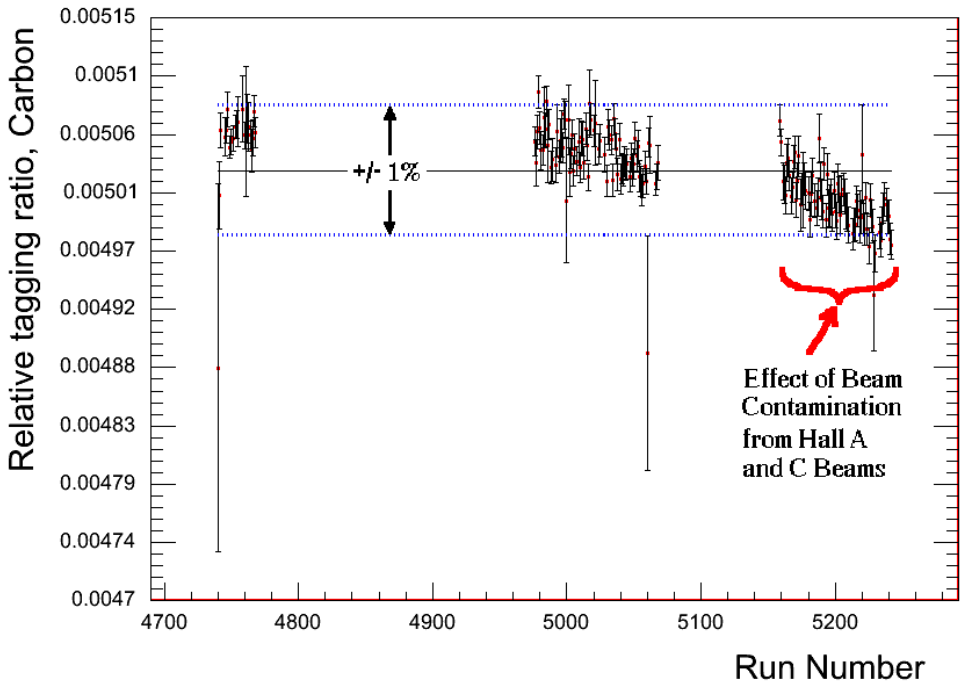
Contributions	Error, [%]
Photon flux	1.0
Target	0.1
Yield extraction	1.6
HYCAL eff.	0.5
Beam parameters	0.4
Trigger eff.	0.1
VETO eff.	0.4
Acceptance	0.3
Model errors (theory)	0.3
Physics background	0.25
Branching ratio	0.03
Total	2.1

Luminosity Control: Pair Spectrometer

Measured in experiment:

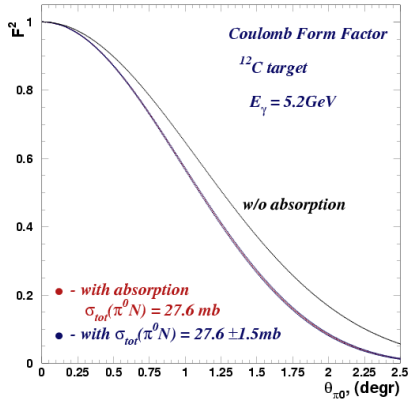
- absolute tagging ratios:
  - TAC measurements at low intensities
- relative tagging ratios:
  - pair spectrometer at low and high intensities
- Uncertainty in photon flux at the level of 1% has been reached
- Verified by known cross sections of EM processes:
  - e^+e^- pair production
  - Compton scattering

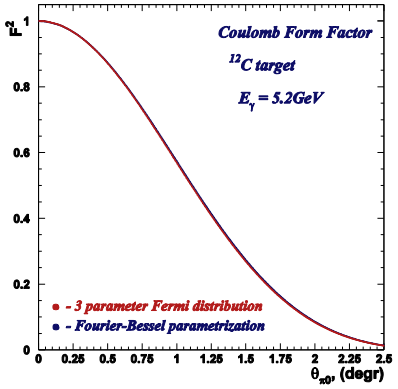


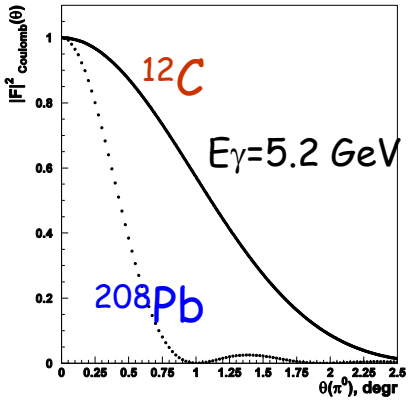


Some results on Coherent Production $\gamma+A\rightarrow\pi^0+A$

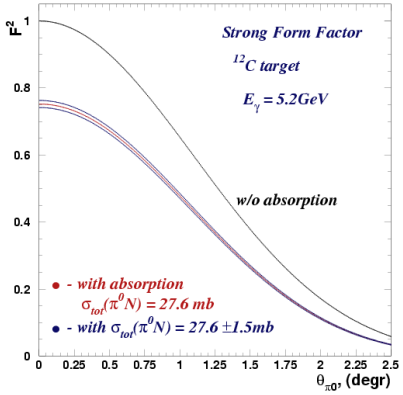
- Electromagnetic form factors

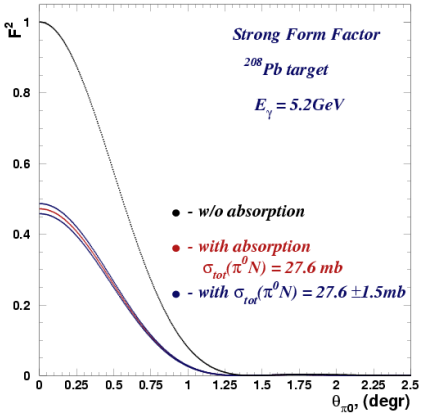


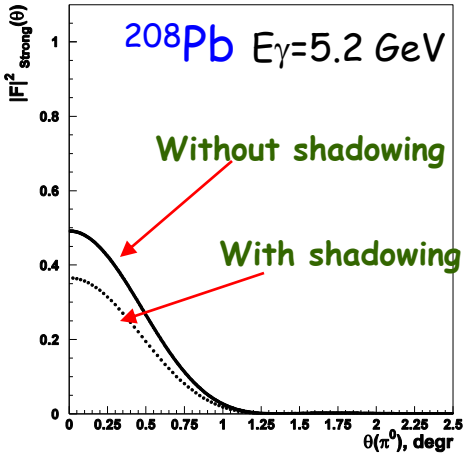




- Strong form factors







Estimated Systematic Errors for PrimEx-II

Type of Errors	Errors in current data	Errors in this proposal
Photon flux	1.0%	1.0%
Target number	0.1%	0.1%
Background subtraction	1.0%	0.4%
Event selection	0.5%	0.35%
HYCAL response function	0.5%	0.2%
Beam parameters	0.4%	0.4%
Acceptance	0.3%	0.3%
Model errors (theory)	1.0%	0.25%
Physics background	0.25%	0.25%
Branching ratio	0.03%	0.03%
Total	**2.0%**	**1.3%**