Recent High Precision Measurement of the Neutral Pion Lifetime and the PrimEx Experimental Program at Jefferson Lab

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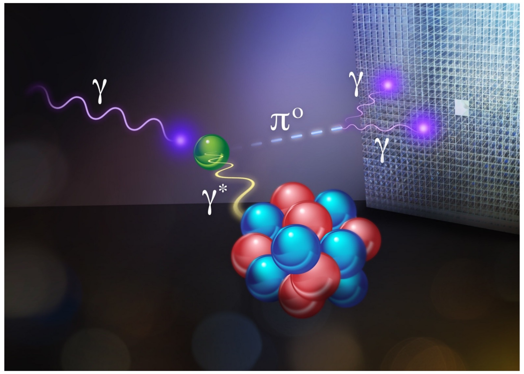
for the PrimEx Collaboration



Outline

- the PrimEx experimental program at JLab, very short
- QCD symmetries and the $\pi^0 \to \gamma\gamma$ decay, a short review
- previous experiments
- the PrimEx way: control of systematic uncertainties
- impact of the PrimEx-I experiment
- PrimEx-II experiment, final results
- PrimEx with JLab 22+ GeV energy upgrade, very short
- summary and outlook

The PrimEx Experimental Program at Jefferson Lab

- **Experimental program:**

1) Precision measurements of two-photon decay widths (real photon exchange):

   a) $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

   b) $\Gamma(\eta \rightarrow \gamma\gamma)$

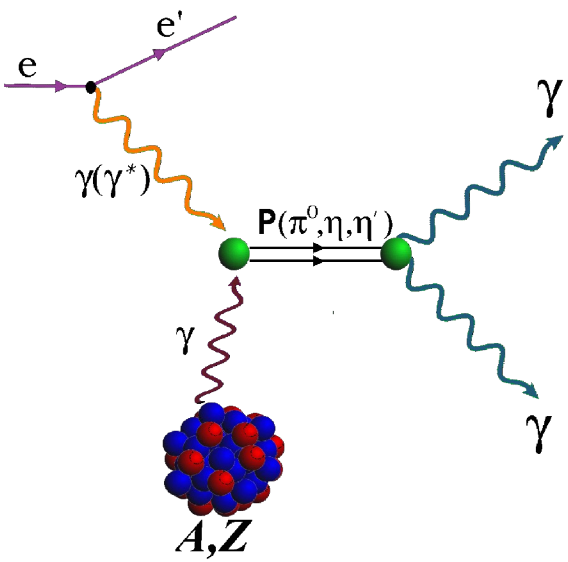
   c) $\Gamma(\eta' \rightarrow \gamma\gamma)$

2) Transition Form Factors at very low Q^2 range, 0.001-0.5 GeV^2/c^2 (virtual photon exchange):

   a) $F(\gamma\gamma^* \rightarrow \pi^0)$

   b) $F(\gamma\gamma^* \rightarrow \eta)$

   c) $F(\gamma\gamma^* \rightarrow \eta')$



- **Physics reach:**

a) precision tests of chiral symmetry and anomalies
b) determination of light quark mass ratio
c) mixing angles
d) π^0, η and η' interaction electromagnetic radii
e) Is η' an approximate Goldstone boson?

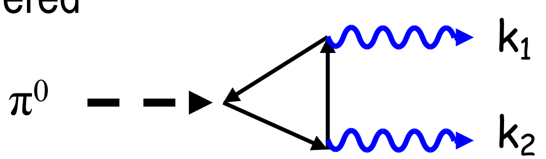
$\pi^0 \to \gamma\gamma$ Decay, Theory Status before QCD

- π^0 discovered at Berkeley Cyclotron in 1950 with the $\pi^0 \to \gamma\gamma$ decay channel
- π^0 is the lightest hadron in Nature: $m_\pi = 134.9770 \pm 0.0005$ MeV
- π^0 is unstable: B.R.$(\pi^0 \to \gamma\gamma) = (98.823 \pm 0.034)\%$
- Lifetime and radiative decay width:

$$\tau_{\pi 0} = \text{B.R.}(\pi^0 \to \gamma\gamma)\, \hbar / \Gamma(\pi^0 \to \gamma\gamma) = (8.52 \pm 0.18) \times 10^{-17}\ \text{s}$$

- Theory of Current Algebra (in 1960s, Sutherland and Veltman):
  - ✓ in soft-pion limit of PCAC the amplitude $A(\pi^0 \to \gamma\gamma) = 0$
  - ✓ $\pi^0 \to \gamma\gamma$ decay is not allowed,
    or it is suppressed by: $(m_\pi^2 / 1\ \text{GeV}^2)^2 \approx 3 \times 10^{-4}$

- Bell, Jackiw (1967) and Adler, Bardeen (1969) discovered anomalous triangle diagrams, that changed the PCAC predictions for $\pi^0 \to \gamma\gamma$



$\pi^0 \to \gamma\gamma$ Decay and QCD

- Properties of π^0 most directly affected from Symmetries and their Breaking effects in QCD:
  - In the limit of vanishing u- d- and s- quark masses (chiral limit) QCD has:

    $SU_L(3) \times SU_R(3) \times U_A(1) \times U_{(barion)}(1)$ (classical) symmetry

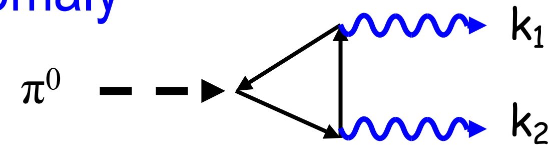
  - Quantum fluctuations reducing this symmetry into:
    - ✓ spontaneous breaking of chiral symmetry, (q - anti q condensation):

      $SU_L(3) \times SU_R(3) \longrightarrow SU_{L+R}(3)$

      $\longrightarrow$ 8 massless Goldstone bosons: $\pi^0, \pi^+, \pi^-, K^0, K^0, K^+, K^-, \eta_8$

    - ✓ explicit braking of axial symmetry, $U_A(1)$ $\longrightarrow$ axial or chiral anomaly

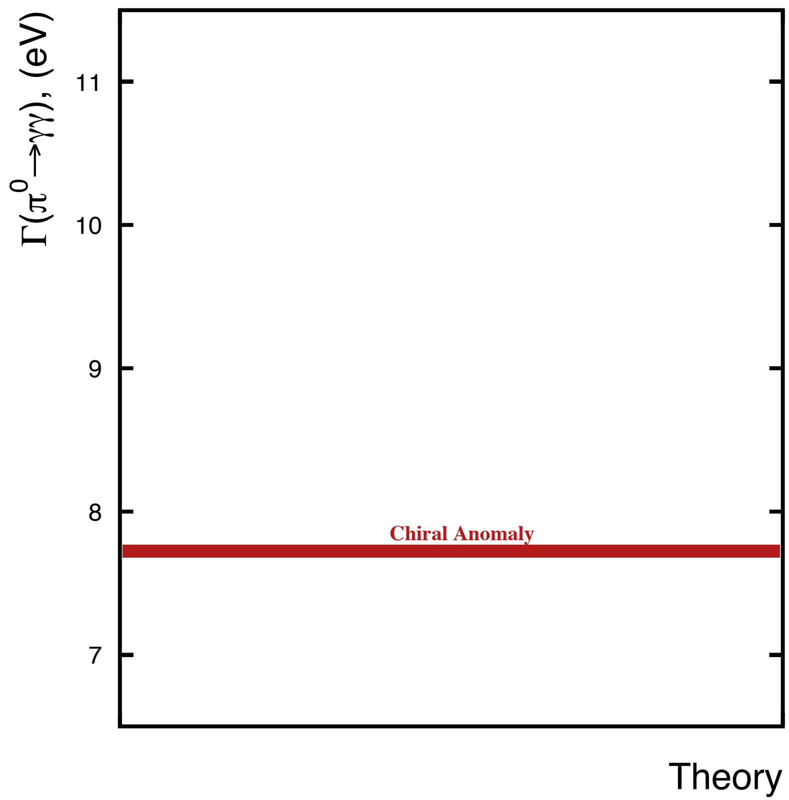
$\pi^0 \to \gamma\gamma$ Decay and Chiral Anomaly



- Chiral anomaly defines the $\pi^0 \to \gamma\gamma$ decay width:
  O(P^4) order Lagrangian (Wess, Zumino (1971) and Witten (1981))
  with anomalous term.
  - ✓ anomaly prediction is exact in massless quark limit (chiral limit):

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

  - ✓ parameter free, no low-energy constants!



- Corrections to Chiral anomaly:
  - ✓ quarks have mass (light):
    - ➢ Goldstone bosons are massive
  - ✓ quarks have different mass: explicit breaking of $SU_{L+R}(3)$ (isospin breaking effects):
    - ➢ mixing of π^0, η and η' (decay widths and decay constants)
- Recent theory calculations give ≈ 4.5% increase with ≈1% uncertainty

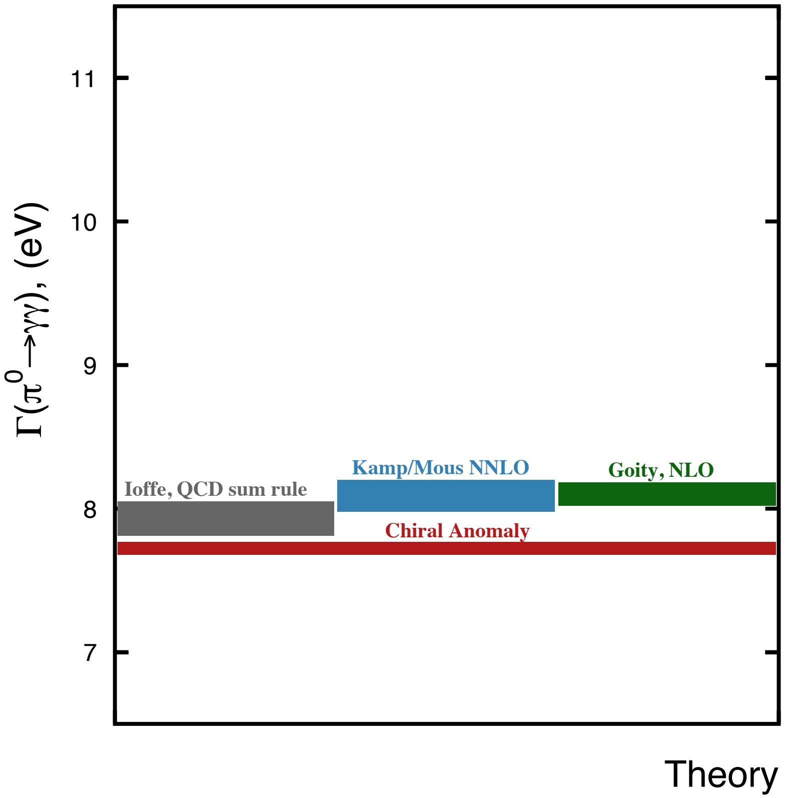
$\pi^0 \to \gamma\gamma$ Decay, Corrections to Chiral Anomaly

- ChPT based calculations:

1) J. Goity, et al. Phys. Rev. D66:076014, 2002)
   ChPT + $1/N_c$ expansion, $O(p^6)$ and $O(P^4 x 1/N_c)$
   η , η' mixing
   $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.10eV ± 1.0%
2) B. Ananthanarayan et al. JHEP 05:052, 2002)
   ChPT, NLO, η , η' mixing
   $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.06eV ± 1.0%
3) K. Kampf et al. Phys. Rev. D79:076005, 2009)
   ChPT,one and two-loops NNLO, SU(2)
   $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.09eV ± 1.3%

- QCD sum rules and dispersion relations

4) B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007
   η' is not included
   $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.93eV ± 1.5%

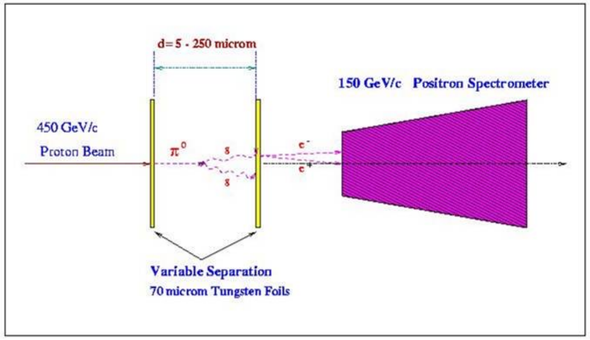


✓ Precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ at the percent level is a stringent test of low-energy QCD

Previous Experiments: Direct Method

- Measure π^0 decay length :
  - ✓ $\tau_\pi \sim 8.5 \times 10^{-17}$ s $\Rightarrow$ $c\tau_\pi \approx 25$ nm, too short to measure
  - ✓ create energetic π^0 : $L \approx c\tau_\pi(E_\pi/m_\pi)$
    for E= 1000 GeV, $L_{mean} \sim 100$ μm

    very challenging experiment



✓ Experiment done at CERN in 1985

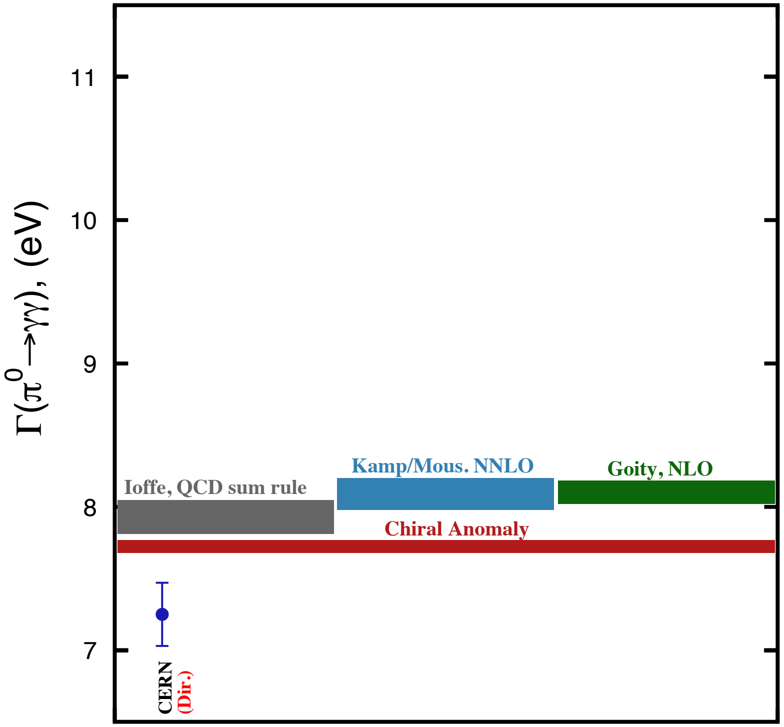
H.W. Atherton, et al. Phys. Lett. B158:81 (1985)

P_P = 450 GeV/c proton beam

two variable separation (5-250μm) tungsten foils

Result:

$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.25 \pm 0.18 \pm 0.14$ eV (2.9% total)

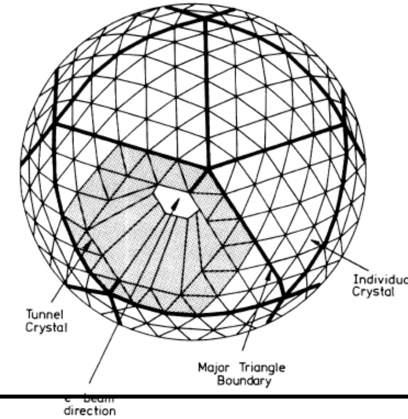


Theory and Experiments

- Major limitations of method:
  - ✓ unknown P_{π^0} spectrum
  - ✓ needs higher energies for improvement

Previous Experiments: Collider Method

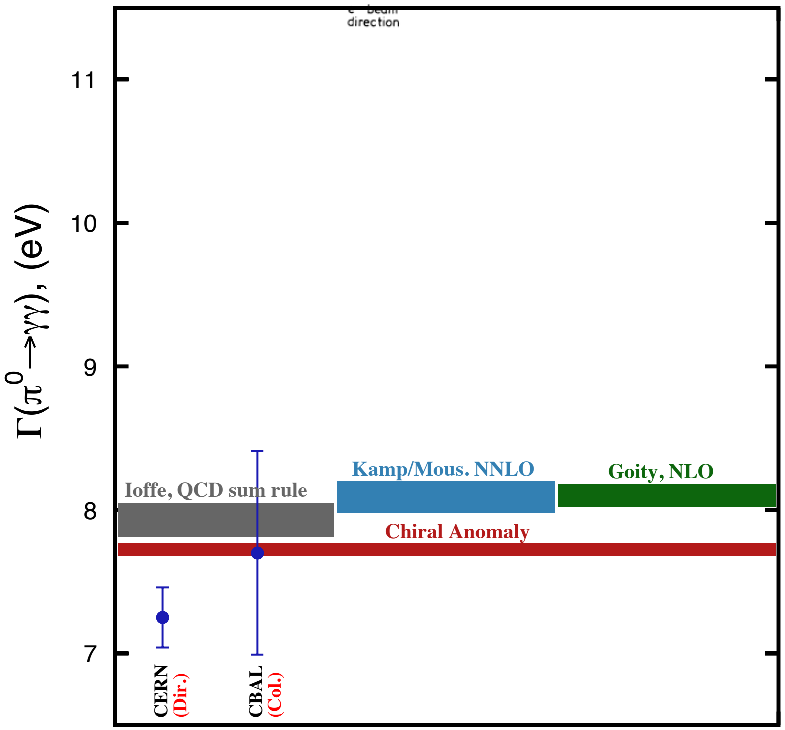
- $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0 \to e^+e^-\gamma\gamma$
  - ✓ e^+, e^- scattered at small angles (not detected)
  - ✓ only $\gamma\gamma$ detected



✓ Experiment done at DESY (DORIS II) in 1988
D.A. Williams, et al. Phys. Rev. D38:1365 (1988)

Result:
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.7 ± 0.5 ± 0.5 eV (10.9%)

Not included in PDG until 2012



Theory and Experiments

- Major limitations of method:
  - ✓ knowledge of luminosity
  - ✓ unknown q^2 for $\gamma^*\gamma^*$

Previous Experiments: Pion Beta Decay Method

- $\pi^+ \rightarrow e^+ + \nu_e + \gamma$ decay rate at rest to measure:
  - ✓ weak form factors F_V and F_A
  - ✓ under assumption of “conserved vector current” hypothesis:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \pi\, m_\pi\, \alpha\, |F_V|^2 / 2$$

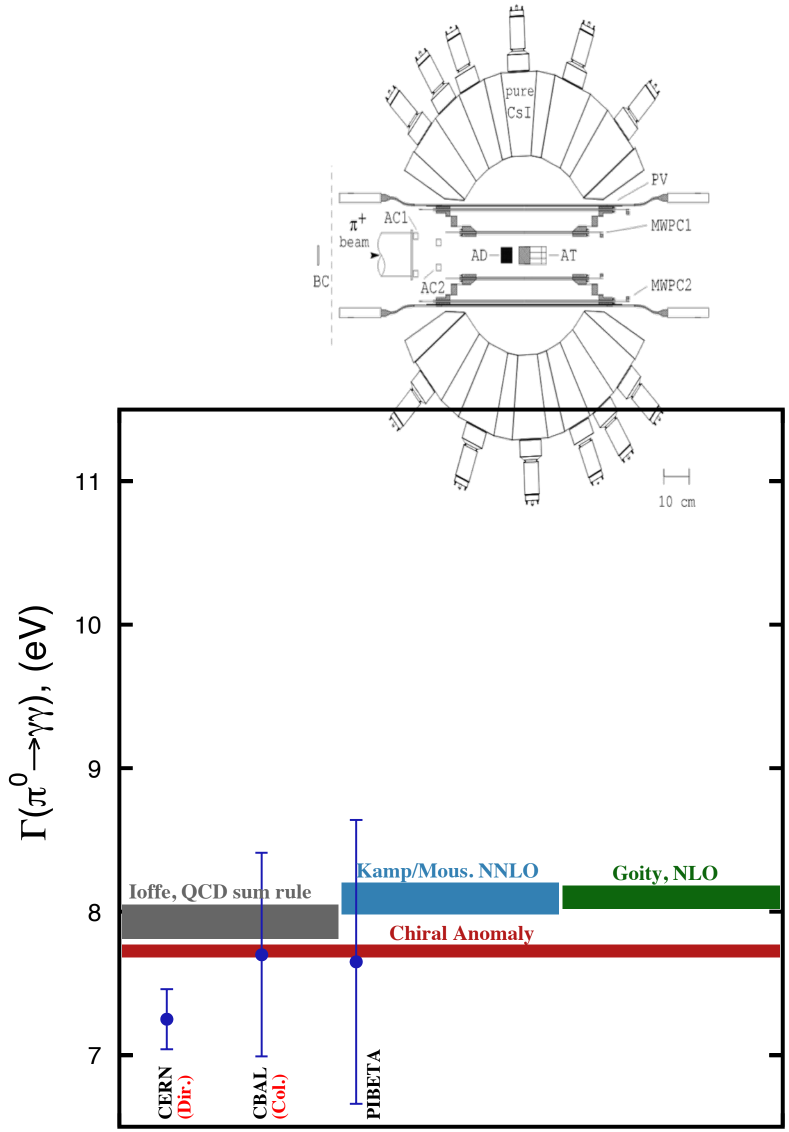
✓ PiBeta experiment at PSI in 2009

M. Bychkov, et al. Phys. Rev. Lett. 103:05 1802 (2009)

Result:

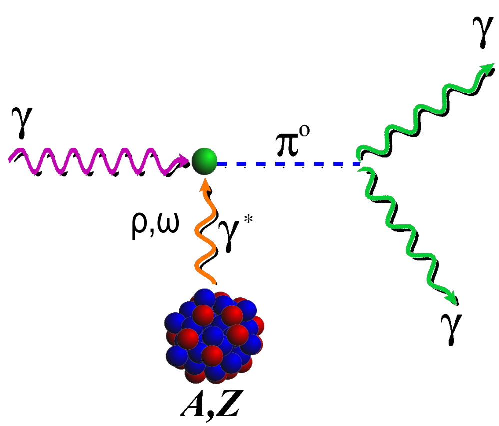
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.65 ± 0.99 eV (13%)

- Major limitations of method:
  - ✓ isospin violation effect
  - ✓ rare decay process

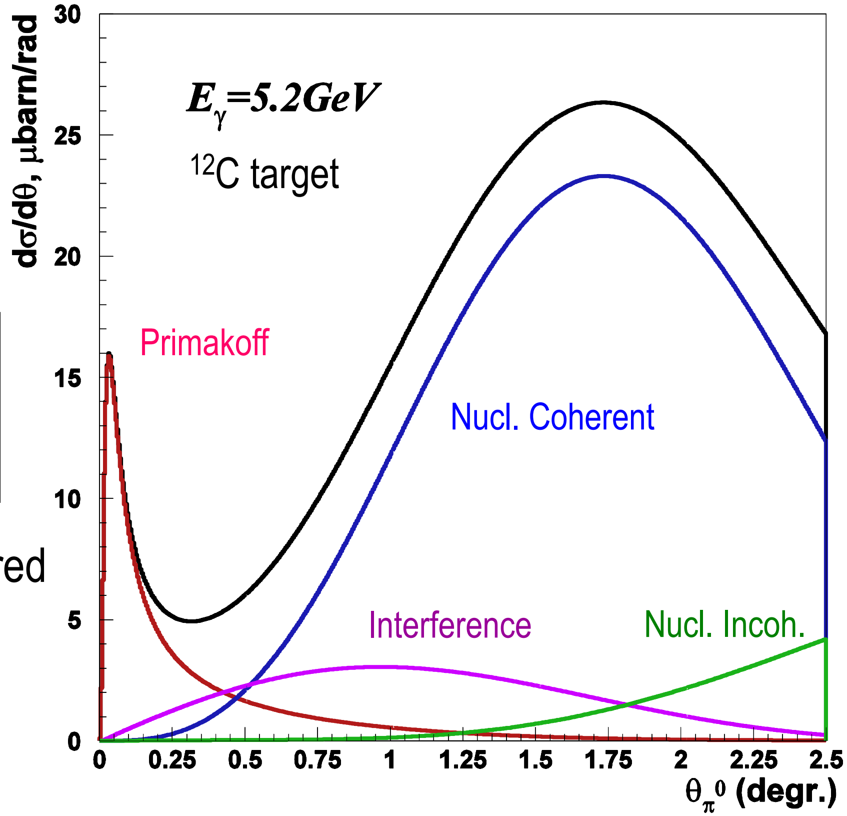


Theory and Experiments

Primakoff Method



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



- Primakoff coherent cross section measurement required

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

- Challenge of the method:
  - measure the cross section at forward angles with high precision
  - extract the Primakoff amplitude from diff. cross sections vs. angle

Previous Primakoff Experiments

✓ **DESY, 1970**

G. Bellettini, et al. Nuovo Cim. A66:243 (1970)

untagged bremsstrahlung beam, $E_{\gamma max}$: ≈1.5 and 2.5 GeV

targets: C, Zn, Al, Pb

Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = (11.7±1.2) eV (10%)

✓ **Tomsk, 1970**

V. Kryshkin, et al. Exp. Theor. Phys. 30:1037 (1970)

untagged bremsstrahlung beam, $E_{\gamma max}$ ≈ 1.1 GeV

target: Pb

Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = (7.23±0.55) eV (7.6%)

✓ **Cornell (1974)**

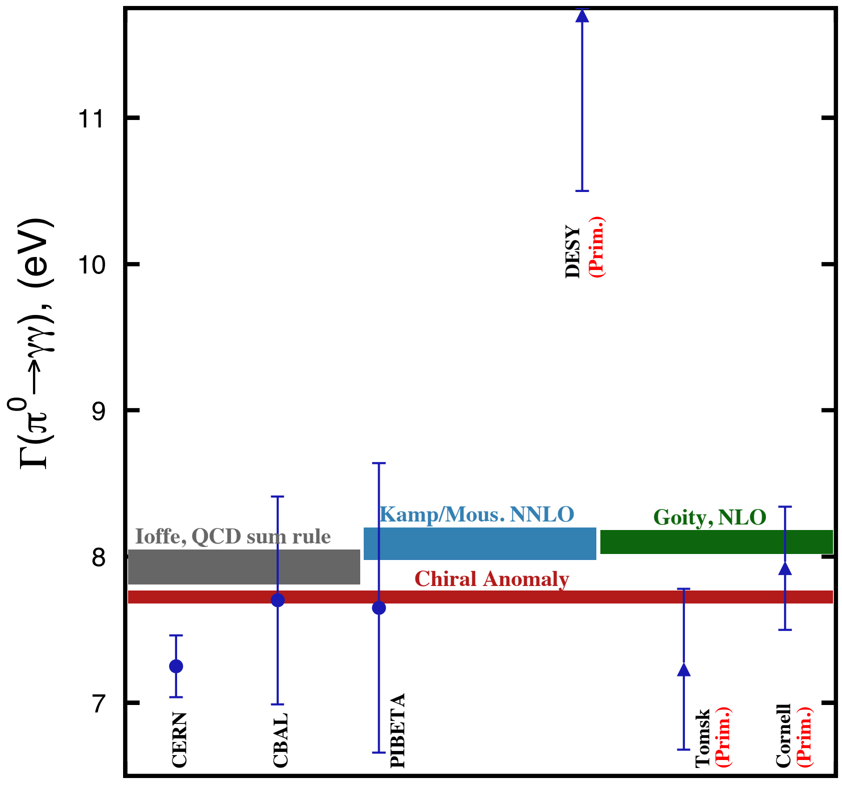
A. Browman, et al. Phys. Rev. Lett. 33:1400 (1974)

untagged bremsstrahlung γ beam

$E\gamma max$: ≈ 6.6 GeV

targets: Be, Al, Cu, Ag, U

Result: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = (7.92±0.42) eV (5.3%)



Theory and Experiments

PDG Status before the PrimEx-I Experiment

- 4 experiments were included in PDG before 2008:
  $\Gamma(\pi^0 \to \gamma\gamma)$ = **7.74 ± 0.55 (7.1%)**

✓ CERN (direct) in 1985

H.W. Atherton, et al. Phys. Lett. B158:81 (1985)

$\Gamma(\pi^0 \to \gamma\gamma) = 7.25 \pm 0.18 \pm 0.14$ eV (2.9%)

✓ DESY, (Primakoff) in 1970

G. Bellettini, et al. Nuovo Cim. A66:243 (1970)

$\Gamma(\pi^0 \to \gamma\gamma) = (11.7 \pm 1.2)$ eV (10%)

✓ Tomsk, (Primakoff) in 1970

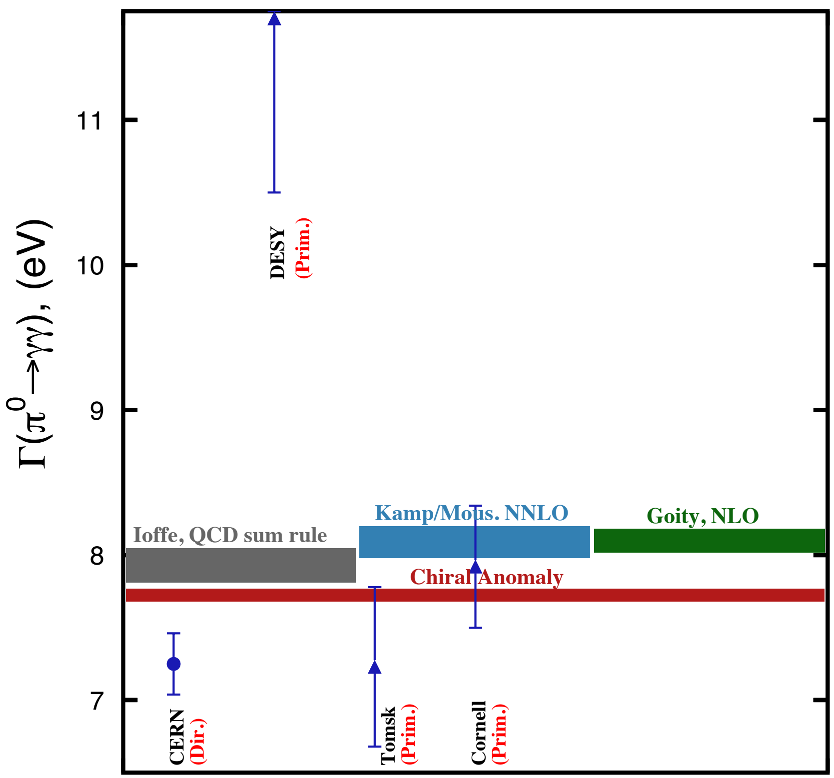
V. Kryshkin, et al. Exp. Theor. Phys. 30:1037 (1970)

$\Gamma(\pi^0 \to \gamma\gamma) = (7.23 \pm 0.55)$ eV (7.6%)

✓ Cornell (Primakoff) in 1974

A. Browman, et al. Phys. Rev. Lett. 33:1400 (1974)

$\Gamma(\pi^0 \to \gamma\gamma) = (7.92 \pm 0.42)$ eV (5.3%)



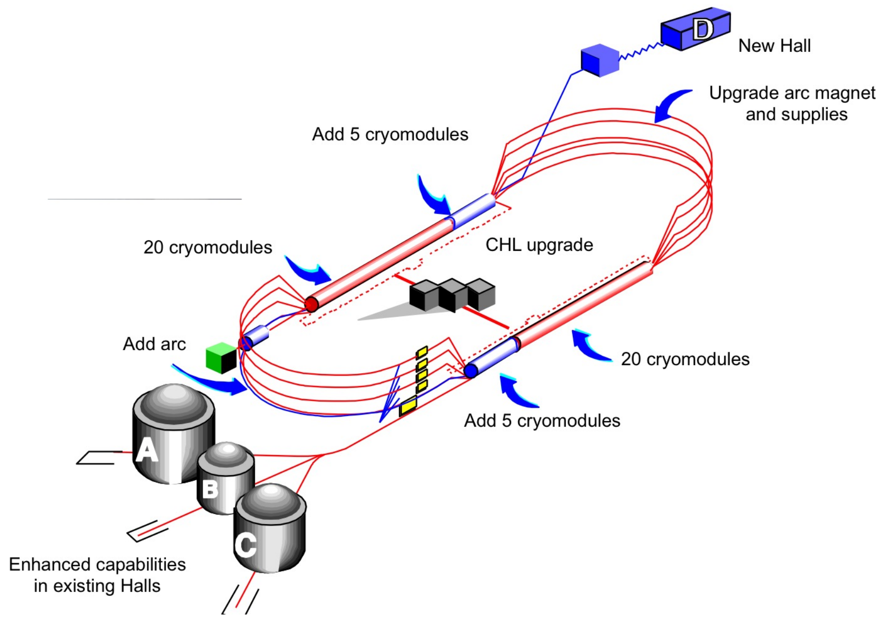
Theory and Experiments

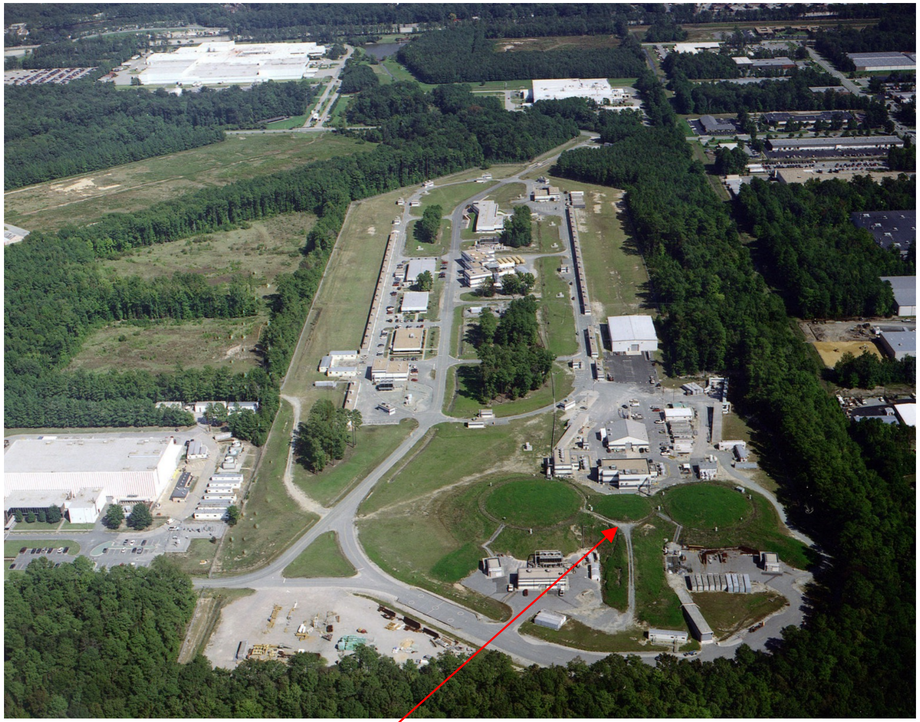
- New experiment was needed !!!

PrimEx Approach for New Generation Primakoff Experiment(s)

- Use tagged photon beam:
  - ✓ better knowledge of photon flux
  - ✓ energy and timing of incident photons
- Use high resolution electromagnetic calorimeter:
  - ✓ better π^0 invariant mass resolution
  - ✓ better π^0 production angle resolution
  - ✓ less background in "event selection"
- Use particle ID detectors for charged background separation:
  - ✓ reduction of the background at event selection stage
- Monitor photon flux at high intensities (with the Pair Spectrometer):
  - ✓ photon flux measurement on 1% level
- Parallel measurement of purely QED processes to control/verify the cross section on 1% level:
  - ✓ Compton scattering from target electrons $(\gamma + e^- \to \gamma + e^-)$
  - ✓ e^+e^- Pair production from target $(\gamma + {}^{12}C \to e^+ + e^- + {}^{12}C)$

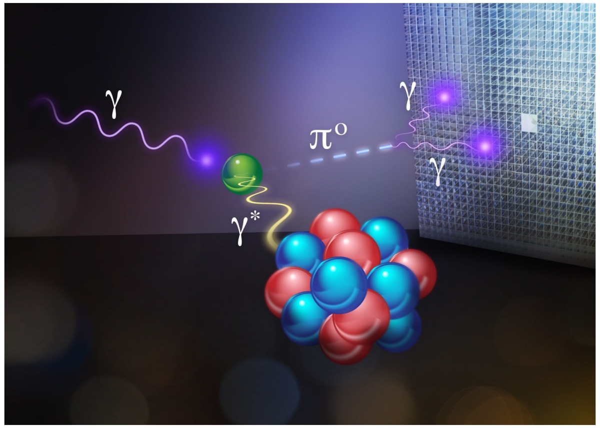
PrimEx Experiments Performed in Hall B at Jefferson Lab

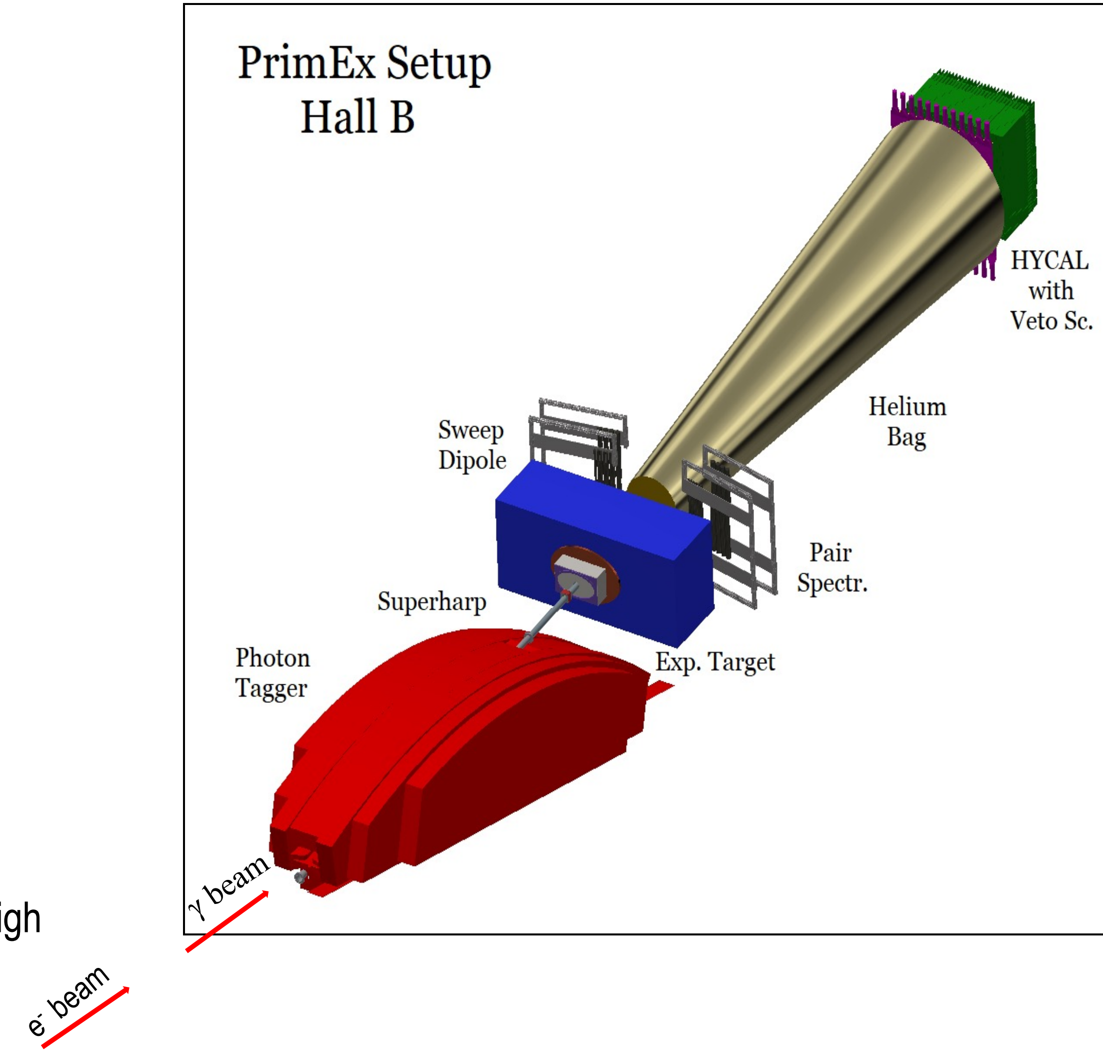




PrimEx experiments performed in Hall B at JLab

PrimEx Experiments in Hall B





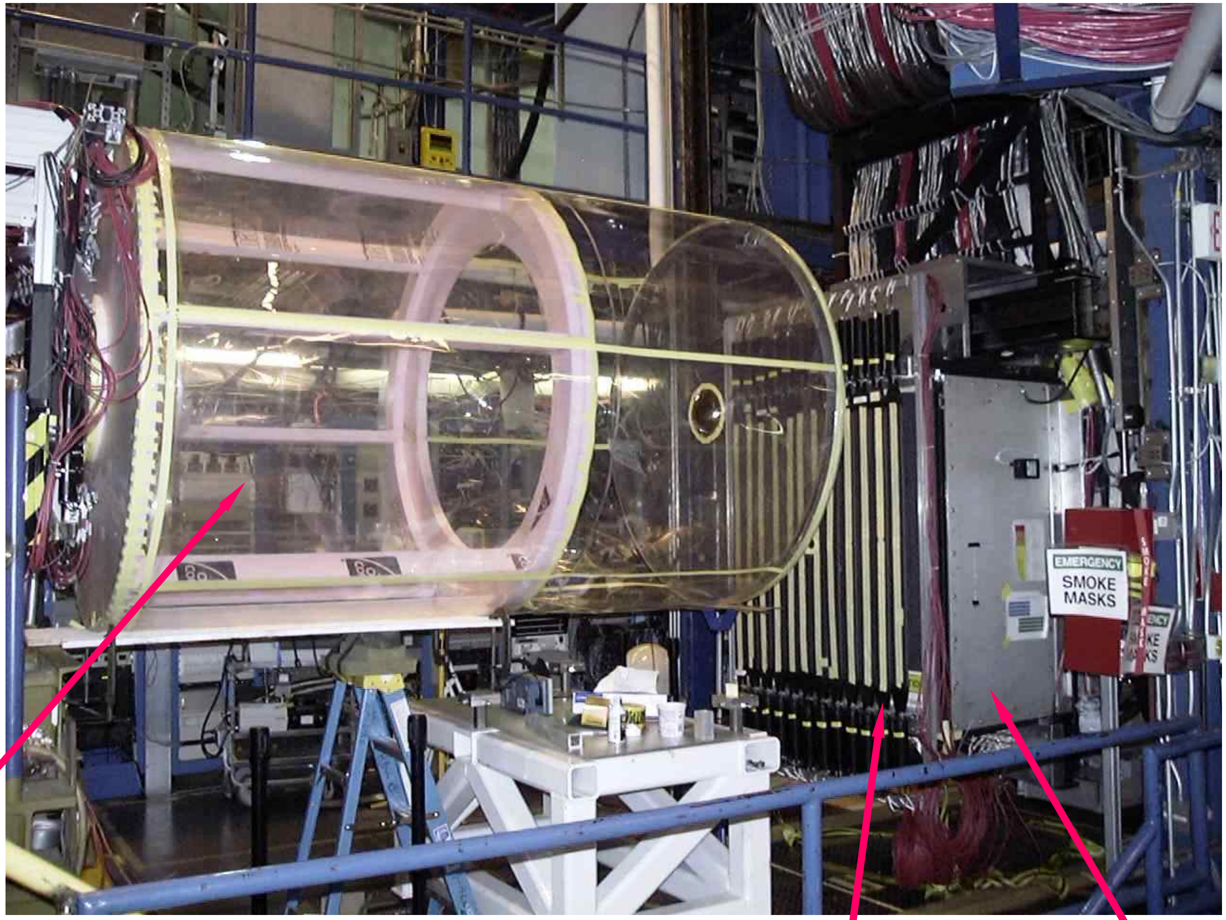
Performed in Hall B in 2004 (PrimEx-I) and in 2010 (PrimEx-II)

- ✓ high resolution, high intensity Hall B photon tagging facility.
- ✓ new high resolution hybrid multi-channel EM calorimeter (HyCal).
- ✓ set of 12 scintillator veto counters.
- ✓ new pair spectrometer for photon flux at high intensities.

HyCal and Veto Counters in Hall B Beam Line

- Installed in 2004
  for PrimEx-I experiment

✓ about 7.5 m from targets



He-bag
at 1atm

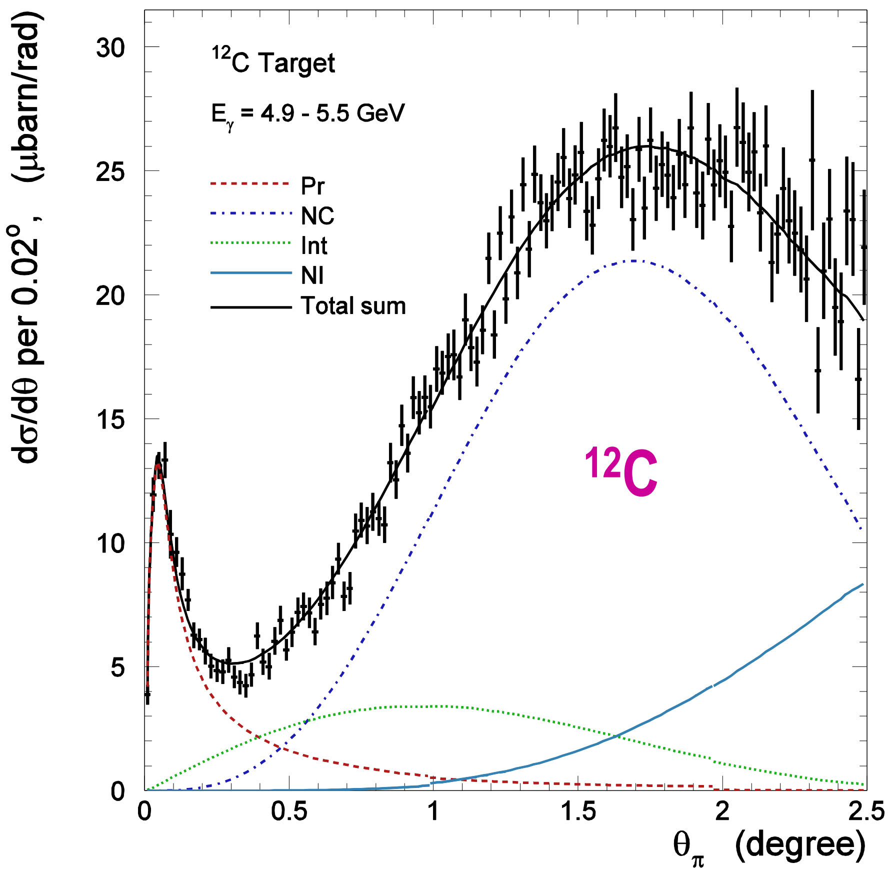
Beam side view

Veto counters

HyCal

PrimEx-I: Extracted Diff. Cross Sections on ^{12}C

- Performed in Hall B in fall of 2004
  - ✓ nuclear targets: 5% R.L. ^{12}C and ^{208}Pb
  - ✓ photon beam energy range: $E_\gamma = (4.9 \div 5.5)$ GeV
  - ✓ Accumulated statistics (number of π^0):
    - on ^{12}C target: 39K
    - on ^{208}Pb target: 5K

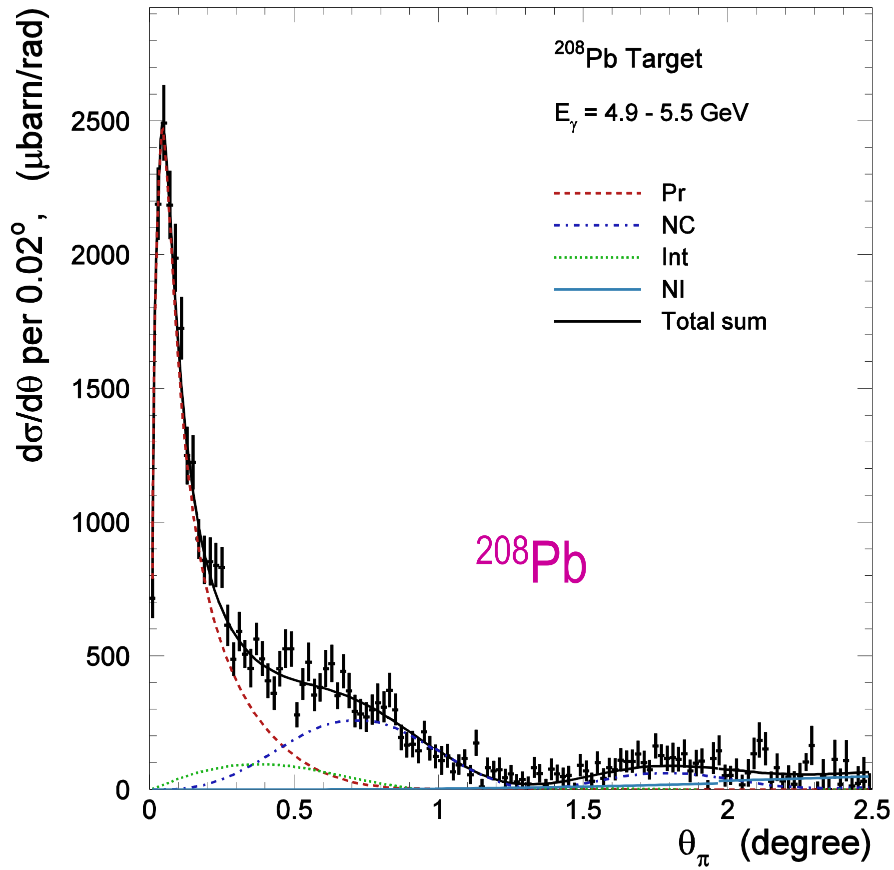


PrimEx-I: Extracted Diff. Cross Sections on ^{208}Pb

- Performed in Hall B in fall of 2004

  ✓ nuclear targets: 5% R.L. ^{12}C and ^{208}Pb
  ✓ photon beam energy range:
  $E_\gamma = (4.9 \div 5.5)$ GeV

  ✓ Accumulated statistics (number of π^0):
  - on ^{12}C target: 39K
  - on ^{208}Pb target: 5K



- To extract the $\Gamma(\pi^0 \to \gamma\gamma)$:
  ✓ angular and energy resolutions smeared the theoretical distributions to fit the experimental cross sections.

PrimEx-I Result and the PDG status Before 2012

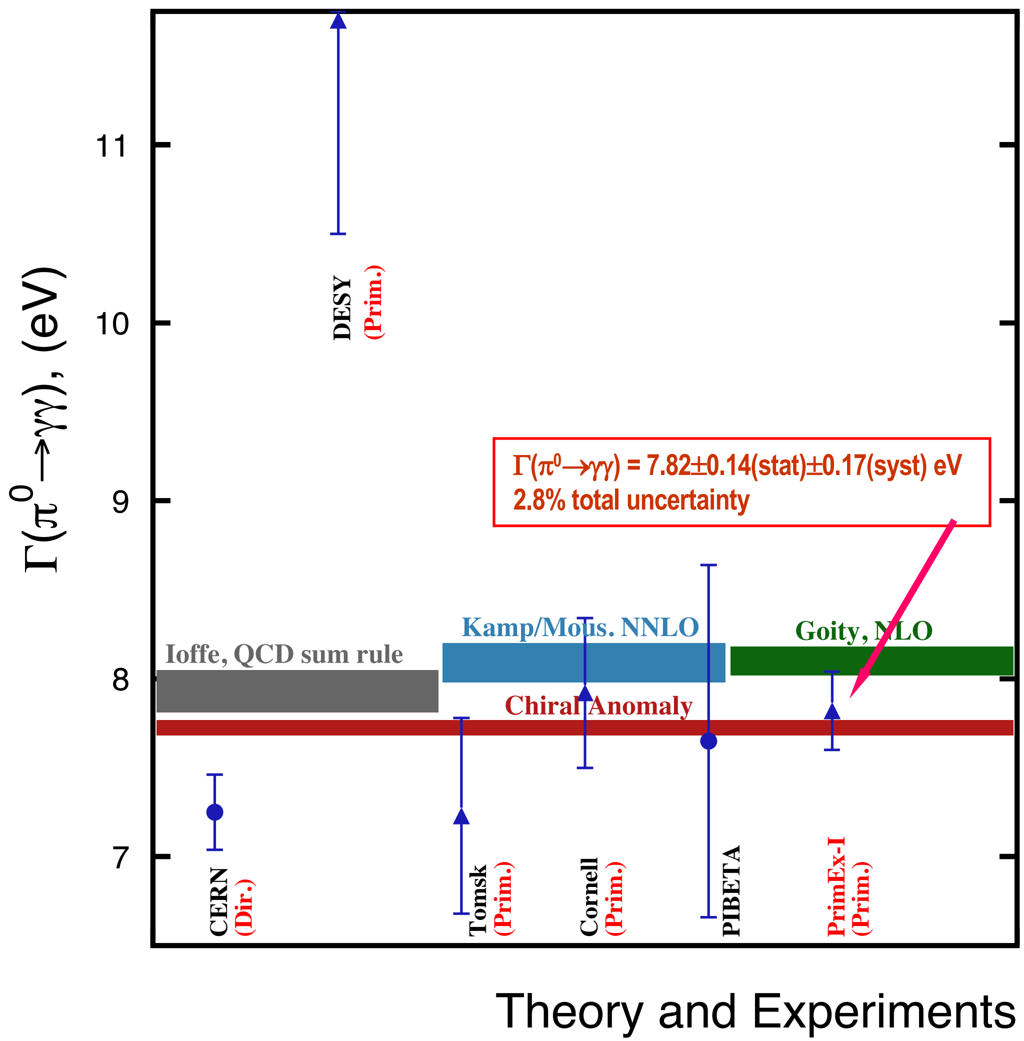
- ✓ **PrimEx-I achieved 2.8% precision (total):**

  $\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82 eV ±1.8% (stat) ±2.1% (syst.)

- ✓ Published in PRL in 2011:
  I. Larin, et al. PRL 106, 162303, 2011

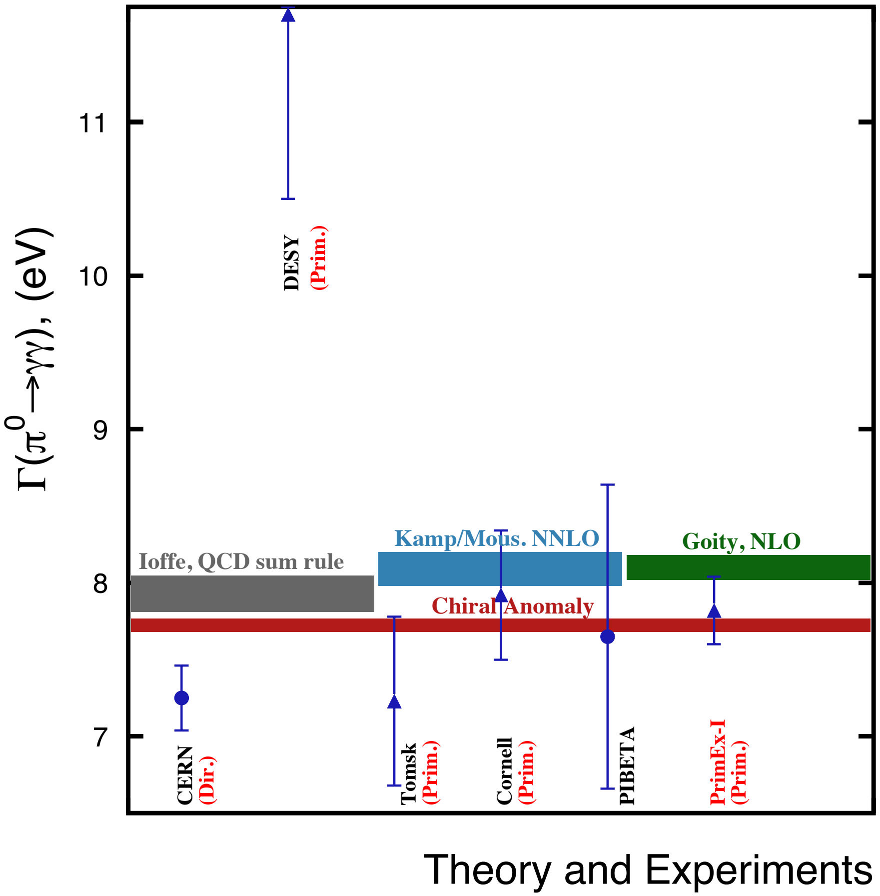
- Task for PrimEx-II:
  to reach to 1.4% precision:

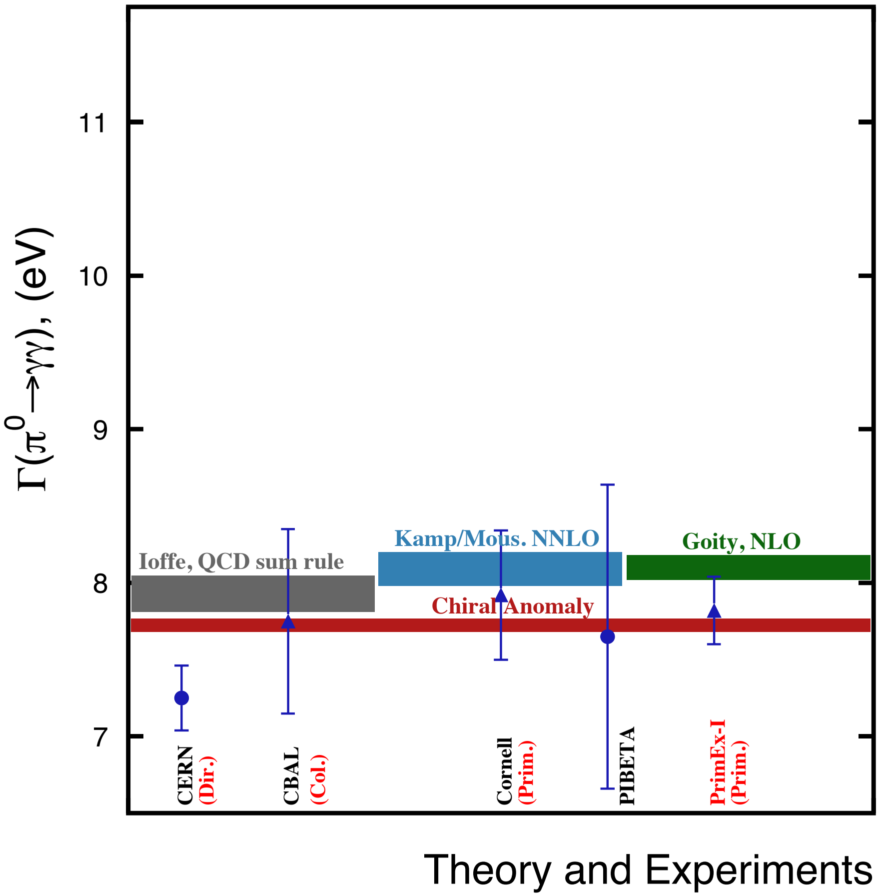
  with the projected uncertainties:
  ±0.5% (stat.) ±1.3% (syst.)



PDG status After the PrimEx-I Publication

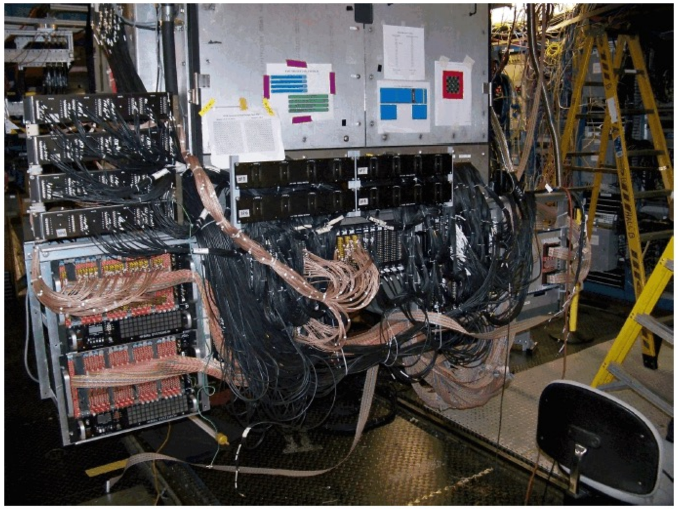
- ✓ PrimEx-I result changed the PDG-2012 "landscape" for the $\pi^0 \rightarrow \gamma\gamma$ sector.
  $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.63 \pm 0.16$ (2.1%)
- ✓ It improved the decay width uncertainty by a factor of 3





PrimEx-II Experiment

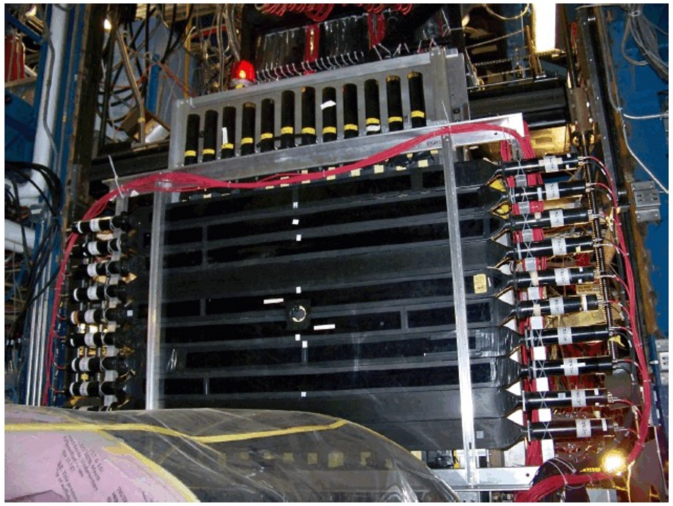
- Experiment was performed in Hall B in 2010



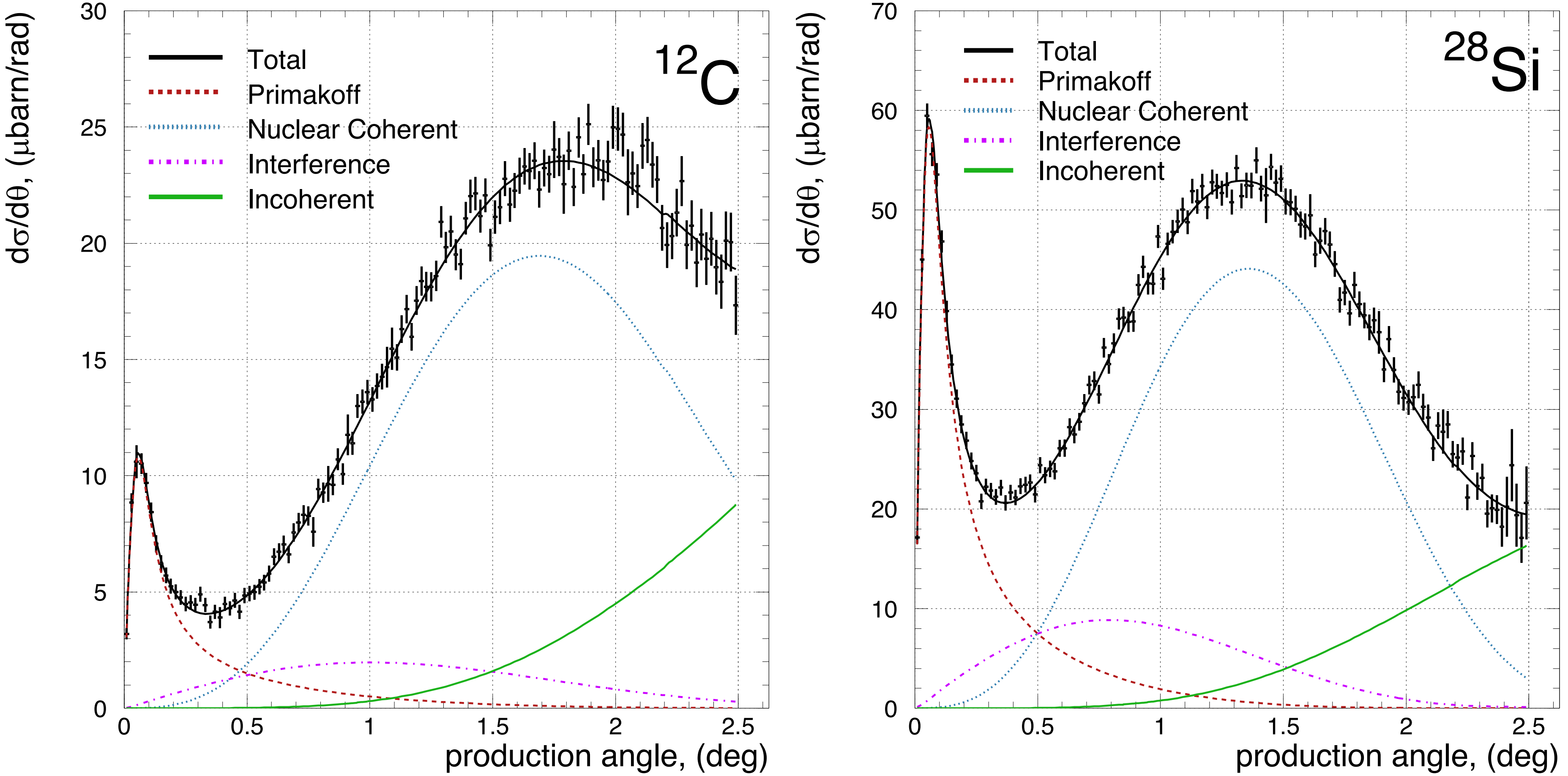
Improvements over PrimEx-I

- Statistics (factor of ≈10 more stat. needed):
  - ✓ double the target thickness (10% R.L.)
  - ✓ Increase DAQ speed to 5 kHz (factor of 5 gain)
  - ✓ increase twice the tagged photon energy interval

- Systematics (factor of ≈2):
  - ✓ add more timing information in HyCal (~500 TDC channels)
  - ✓ improve PID (add horizontal veto counters)
  - ✓ improve photon beam line
  - ✓ take more "empty target" data
  - ✓ measure HyCal detection efficiency
  - ✓ get data for new ^{28}Si target.



PrimEx-II: the Extracted Differential Cross Sections



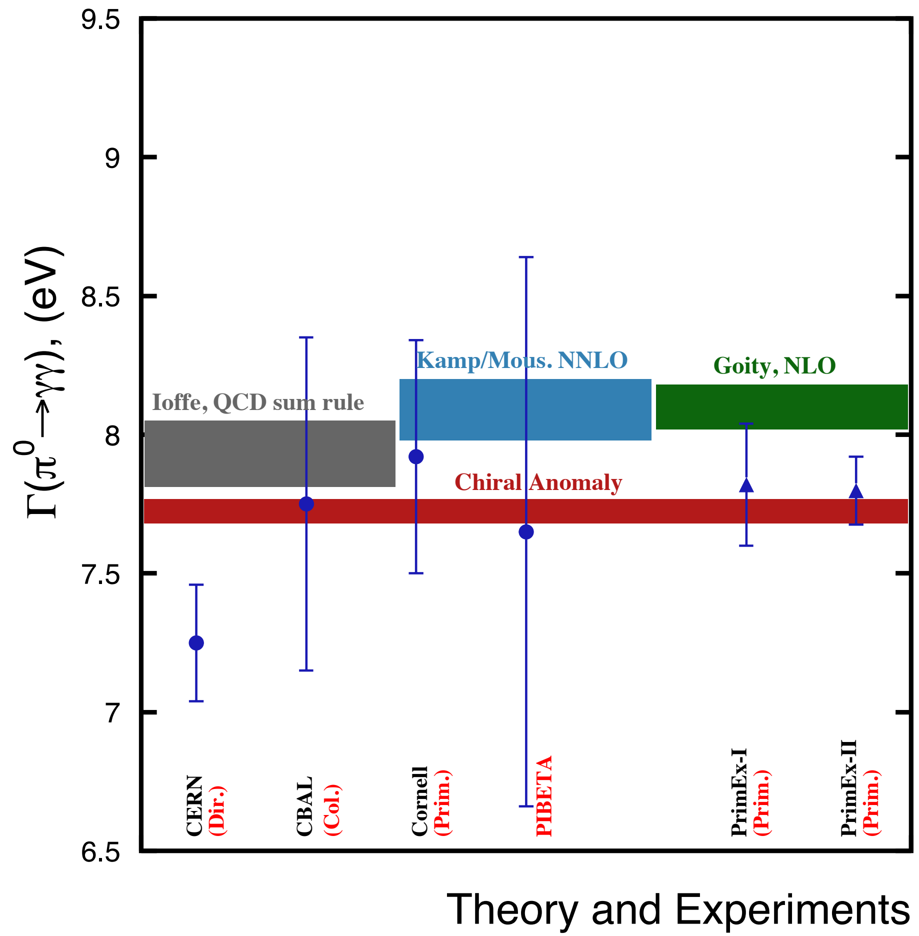
- To extract the $\Gamma(\pi^0 \rightarrow \gamma\gamma)$:
  - ✓ angular and energy resolutions smeared the theoretical distributions to fit the experimental cross sections.

$\Gamma(\pi^0\to\gamma\gamma)$: Final Result from the PrimEx-II Experiment

- Weighted average from two analysis groups, and from two targets:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.798 ±0.056(stat) ± 0.109(syst.) eV

with the total uncertainty of:
± 1.6%



$\Gamma(\pi^0\to\gamma\gamma)$: Final Result from the PrimEx Experiments

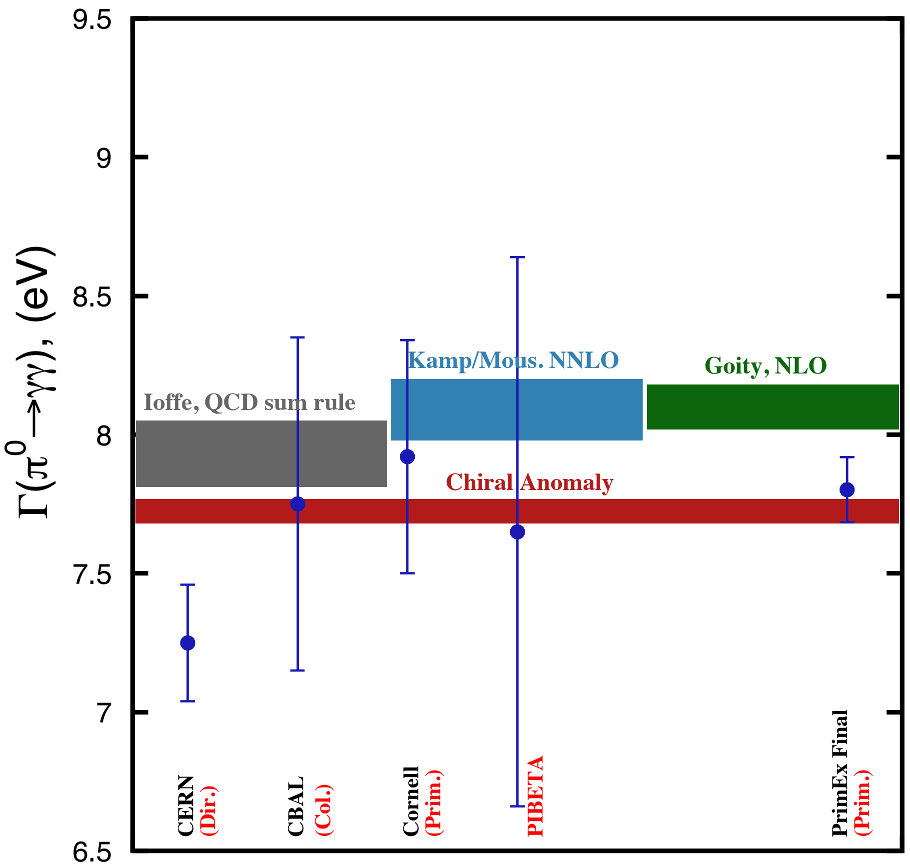
- Weighted average from two experiments:
  (PrimEx-I and PrimEx-II)

  $\Gamma(\pi^0\to\gamma\gamma) = 7.802 \pm 0.052(\text{stat}) \pm 0.105(\text{syst.})$ eV

  with the total uncertainty of:
  $\pm$ 1.5%

- and for the lifetime:

  $\tau_{\pi 0} = (0.834 \pm 0.125) \times 10^{-16}$ s



Science

Precision measurement of the neutral pion lifetime

I. Larin, Y. Zhang, A. Gasparian, L. Gan, R. Miskimen, M. Khandaker, D. Dale, S. Danagoulian, E. Pasyuk, H. Gao, A. Ahmidouch, P. Ambrozewicz, V. Baturin, V. Burkert, E. Clinton, A. Deur, A. Dolgolenko, D. Dutta, G. Fedotov, J. Feng, S. Gevorkyan, A. Glamazdin, L. Guo, E. Isupov, M. M. Ito, F. Klein, S. Kowalski, A. Kubarovsky, V. Kubarovsky, D. Lawrence, H. Lu, L. Ma, V. Matveev, B. Morrison, A. Micherdzinska, I. Nakagawa, K. Park, R. Pedroni, W. Phelps, D. Protopopescu, D. Rimal, D. Romanov, C. Salgado, A. Shahinyan, D. Sober, S. Stepanyan, V. V. Tarasov, S. Taylor, A. Vasiliev, M. Wood, L. Ye, B. Zihlmann and PrimEx-II Collaboration

Science **368** (6490), 506-509.
DOI: 10.1126/science.aay6641

Next PrimEx Experiments at Jefferson Lab

- $\Gamma(\eta\rightarrow\gamma\gamma)$ decay width measurement in Hall D at JLab
  - ✓ model independent extraction of the light quark mass ratio
  - ✓ experiment completed in December, 2022, preliminary results in 2024

- $F(\gamma\gamma*\rightarrow\pi^0)$ measurement at very low Q^2 range
  - ✓ approved by JLab PAC50
  - ✓ regular Primakoff method on atomic nucleus (^{28}Si)
  - ✓ In Hall B at JLab with PRad experimental setup

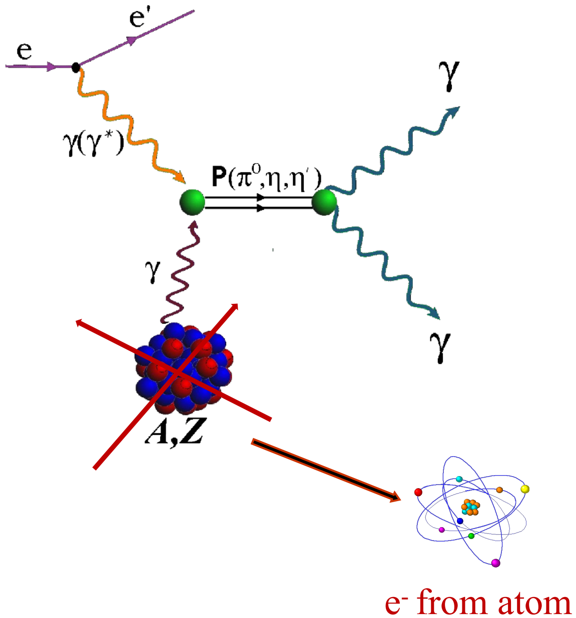
- Next Generation Primakoff experiments on atomic electrons.
  - ➢ sub-percent measurement of $\Gamma(\pi^0\rightarrow\gamma\gamma)$ decay width

    $\gamma + e^- \rightarrow e^- + \boldsymbol{\pi^0}$

    $\pi^0\rightarrow\gamma\gamma$
  - ➢ sub-percent measurement of $F(\gamma\gamma*\rightarrow\pi^0)$ TFF

    $e^- + e^- \rightarrow e' + e^- + \boldsymbol{\pi^0}$

    $\pi^0\rightarrow\gamma\gamma$



- Requires threshold energy for γ^* (or γ)

  $E_\gamma \approx 18$ GeV

✓ Will be done with the JLab 22+ energy upgrade

Conclusions

- The $\pi^0 \to \gamma\gamma$ decay was and still is one of the best tests of QCD in low-energy domain.
- PrimEx collaboration developed and performed two new generation of Primakoff experiments.
  - ✓ PrimEx-I in 2004 with 2.8% total uncertainty:
    - ➢ significantly changed the "landscape" of PDG for π^0 decay width;
    - ➢ improved the uncertainty of the decay width average by a factor of 3.
  - ✓ PrimEx-II in 2010 with a 1.6% total uncertainty:
  - ✓ and the combined, Final PrimEx result:

$\Gamma(\pi^0 \to \gamma\gamma) = 7.802 \pm 0.052\ (\text{stat}) \pm 0.105\ (\text{syst.})\ \text{eV}$ with 1.5% total uncertainty

- ➢ firmly confirms the prediction of the chiral anomaly at the percent level;
- ➢ 2σ deviation from the QCD higher order theory corrections to the anomaly;
- ➢ significant input to the (g-2) theoretical calculations.

my research work is supported in part by NSF award: PHY-2111233

Thank You

PrimEx-II: Statistical and Systematic Uncertainties

Item	PrimEx-II
Photon flux	0.80%
Yield extraction	0.80%
MC simulations	0.55%
Theory simulations	0.40%
Beam parameters	0.30%
Target	0.30%
Event selection	0.20%
DAQ	0.10%
Total Systematics	**1.40%**
Statistical	0.70%
Total	**1.60%**

Symmetries and their Partial Violations in QCD

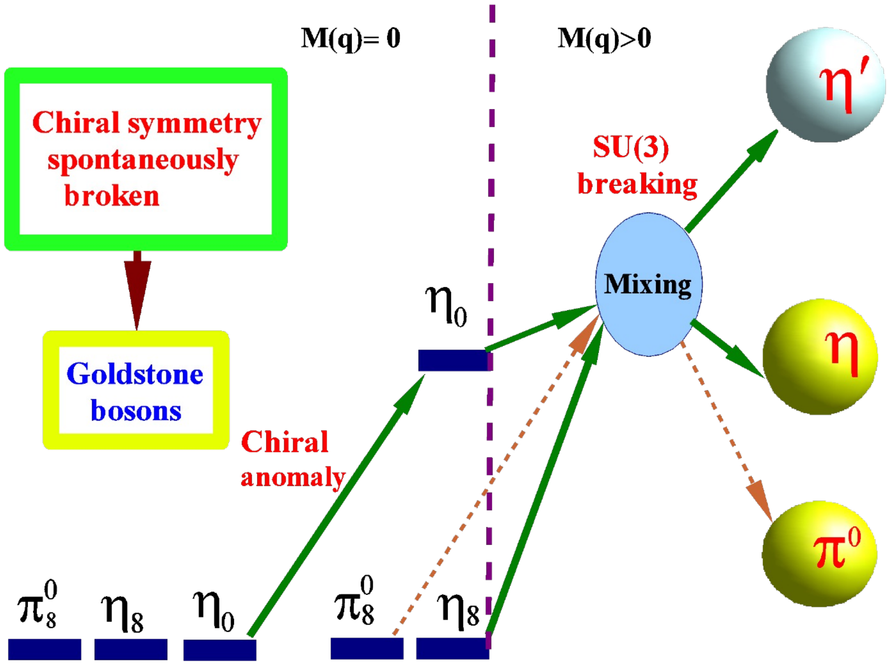
- Classical QCD Lagrangian in Chiral limit is invariant under:

$$\boxed{SU_L(3)\times SU_R(3)\times U_A(1)\times U_B(1)}$$

- Chiral $SU_L(3)xSU_R(3)$ spontaneously broken:
  - 8 Goldstone bosons (π,K,η)
- $U_A(1)$ is explicitly broken:

(axial or chiral anomaly)

  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - mass of η_0
- quarks are massive and different, SU(3) is broken:
  - Goldstone bosons are massive
  - mixing of π^0 η η'

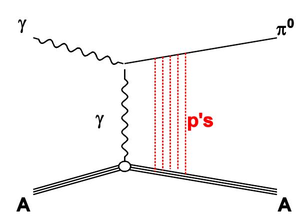


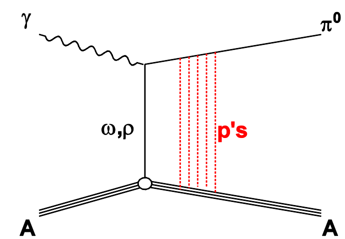
The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

π^0 Photoproduction Theory on Nuclei

- 1964, G. Morpurgo, Neuovo Cimento, 31, 569, (1964)
  - ✓ strong absorption of outgoing pions in uniform nuclear density.

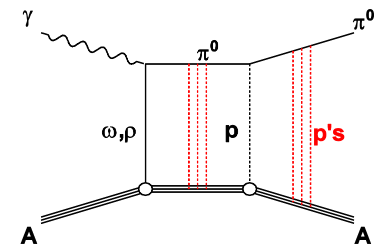
    used in the Tomsk and DESY experiments





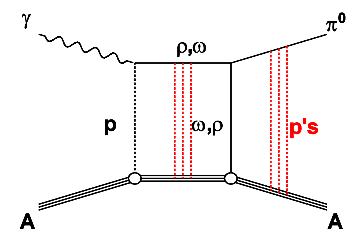
- 1972, G. Faldt, Nucl. Phys. B43, 591, (1972)
  - ✓ strong absorption in nuclei for both incident and produced particles;
  - ✓ outgoing pion re-scattering in nucleus;
  - ✓ corrections for light nuclei;

    used in the Cornell experiment



- 2009, S. Gevorkyan *et. al.*, Phys. Rev. C80, 055201, (2009), also PrimEx note #85
  - ✓ strong absorption in a nucleus for initial and final states
  - ✓ the final state pion re-scattering in nucleus
  - ✓ corrections for light nuclei
  - ✓ photon shadowing effect
  - ✓ Pion form factor

    used in the PrimEx experiments



PrimEx Hybrid EM Calorimeter (HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2)

  $PbWO_4$ crystals ⟶ resolution
  Pb-glass ⟶ budget

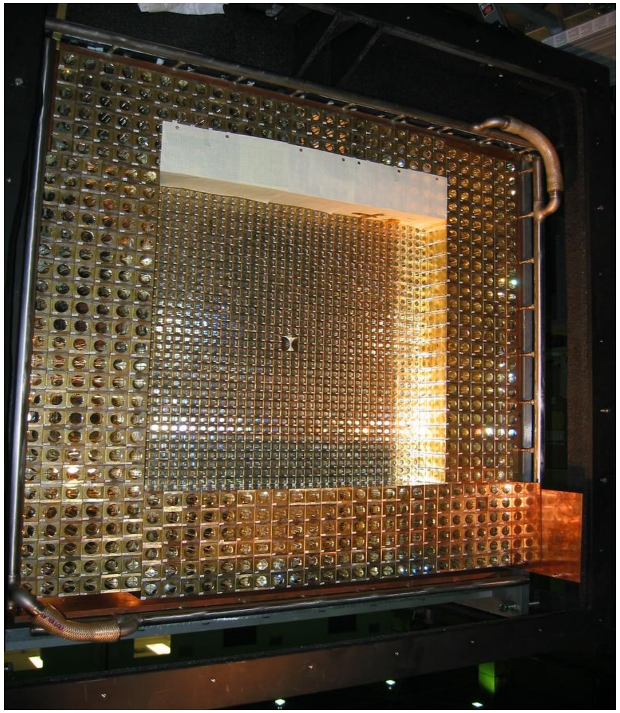
  - ✓ 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors (1152 $PbWO_4$ detectors)
  - ✓ 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
  - ✓ 2 x 2 $PbWO_4$ modules removed in middle for beam passage
  - ✓ ≈7.5 m from target

- Good energy and position resolutions:

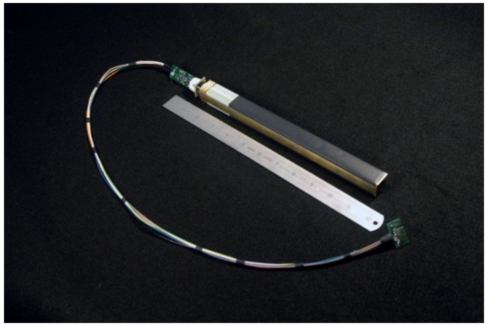
  - ✓ $\sigma_E / E = 2.6\% / \sqrt{E}$
  - ✓ $\sigma_{xy} / E = 2.7\ \mathrm{mm} / \sqrt{E}$

- Good photon detection efficiency (≈100%)

- Served in 3 precision experiments!



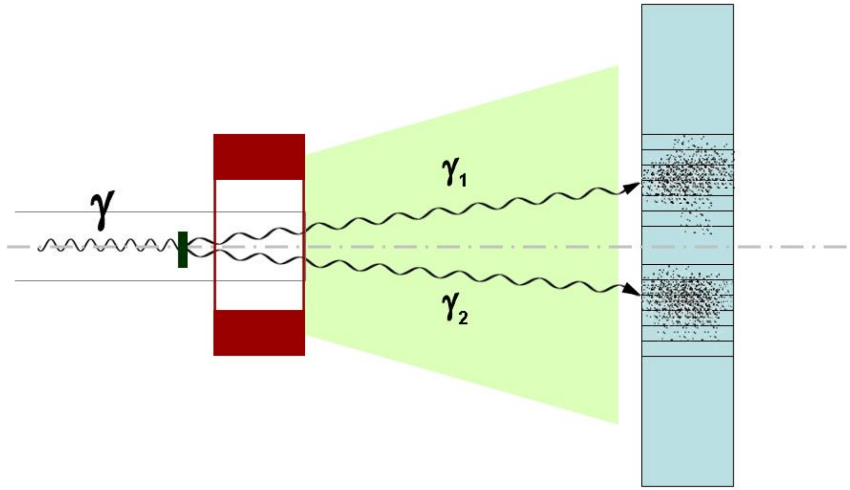
front view, before Light Monitoring System assembly



Single $PbWO_4$ detector

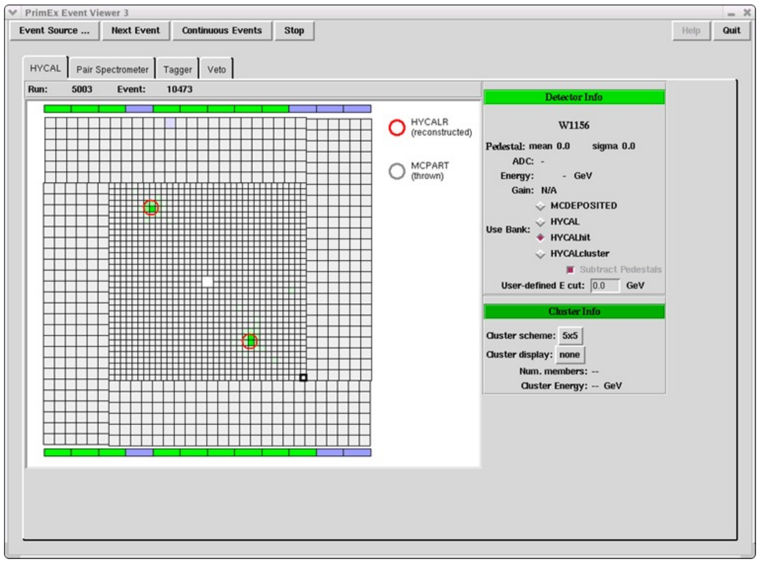
PrimEx Data Analysis Methods

- Two experiments have been performed:
  - ✓ PrimEx-I in fall of 2004
  - ✓ PrimEx-II in fall of 2010



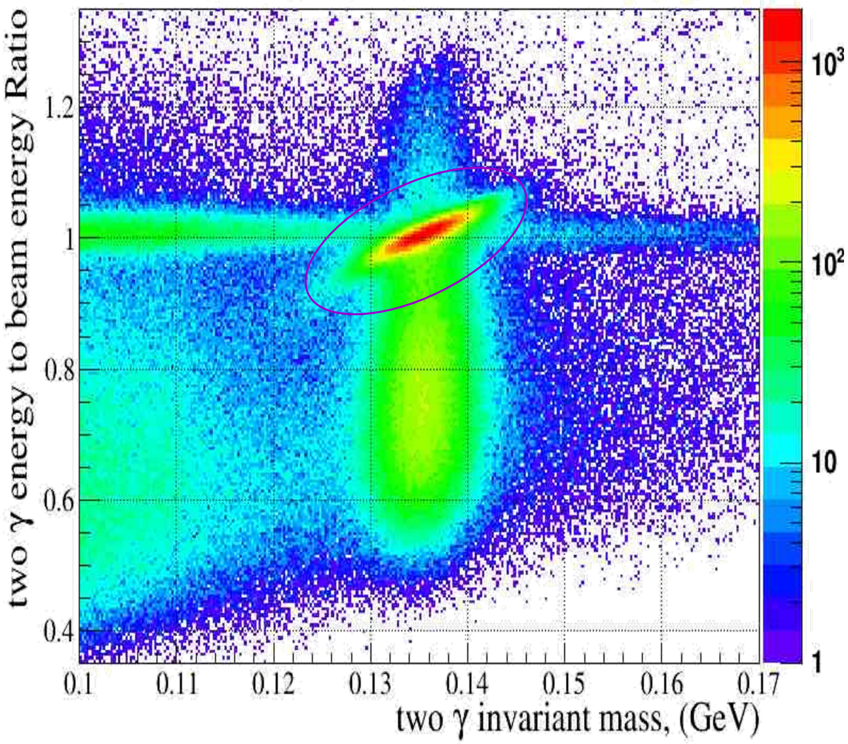
- Experimental information recorded:
  - ✓ initial photon energy and time, E_γ t_γ
  - ✓ energies of decayed photons, $E_{\gamma1}$, $E_{\gamma2}$
  - ✓ Positions of decayed photons, $XY_{\gamma1}$ $XY_{\gamma1}$
  - ✓ time in HyCal, $t_{\gamma1}$ $t_{\gamma2}$

- Kinematical constraints:
  - ✓ conservation of energy;
  - ✓ conservation of 3d-momenta
  - ✓ $m_{\gamma\gamma}$ invariant mass (to fit)

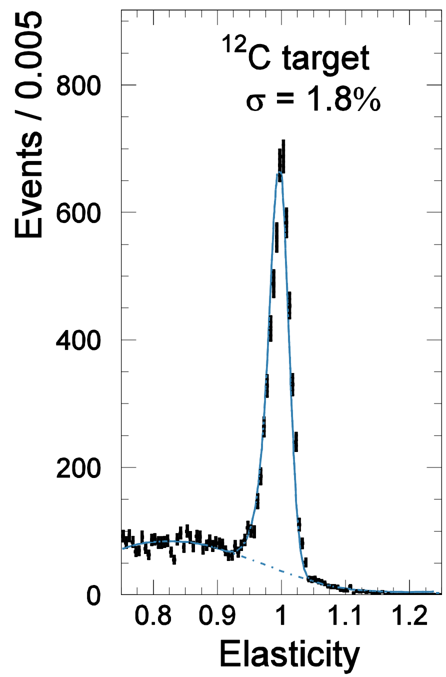


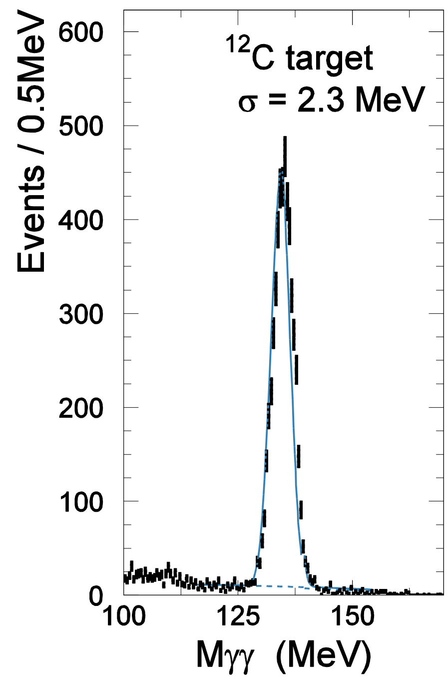
PrimEx online event viewer

π^0 Event Selection



Elasticity vs. invariant mass





- elasticity: $(E_{\gamma 1}, + E_{\gamma 2})/E_{\gamma}$

- The task: select number of elastic π^0 events for each $\theta_{\pi 0}$ and E_γ bins to define the "experimental yields"

$\Gamma(\pi^0\to\gamma\gamma)$ from PrimEx-II

- The extracted $\Gamma(\pi^0\to\gamma\gamma)$
  (with different analysis methods)

^{12}C target:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.783 ±0.120 (stat) ± 0.137(syst.) eV (Hib.)

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.742 ±0.134 (stat) ± 0.130(syst.) eV (Con.)

^{28}Si target:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.831±0.060 (stat) ± 0.124(syst.) eV (Hib.)

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.781±0.064 (stat) ± 0.120(syst.) eV (Con.)

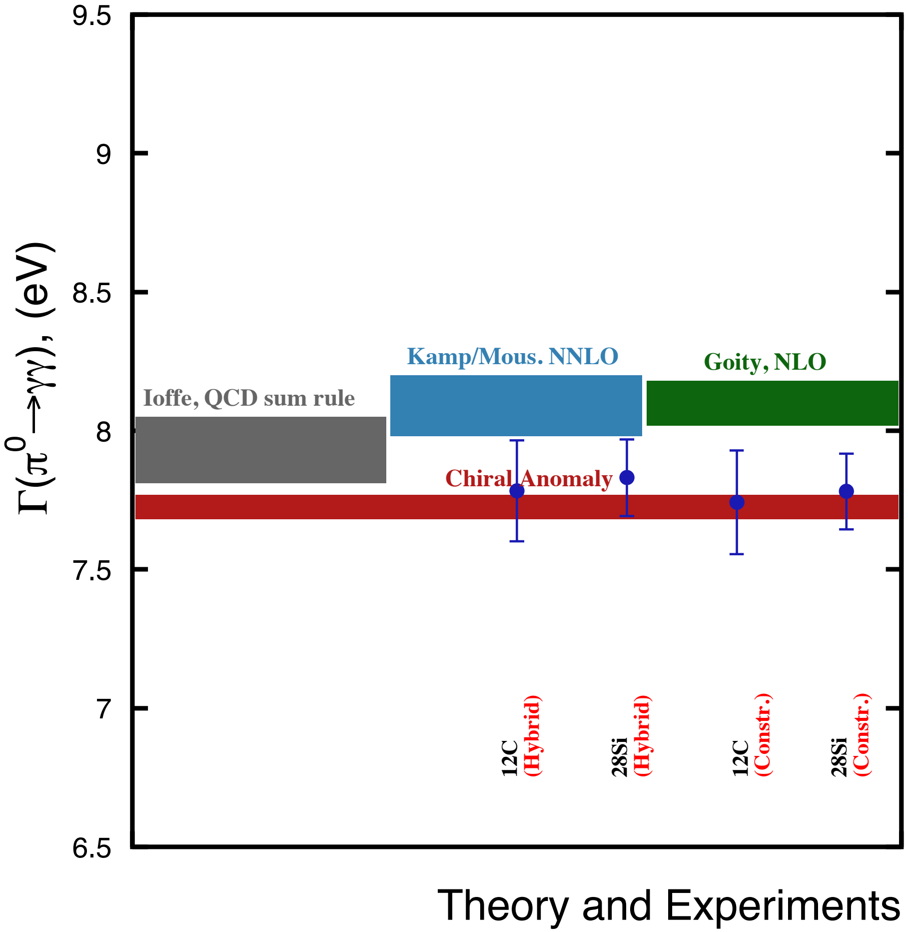
Combined weighted average per target:

^{12}C target:

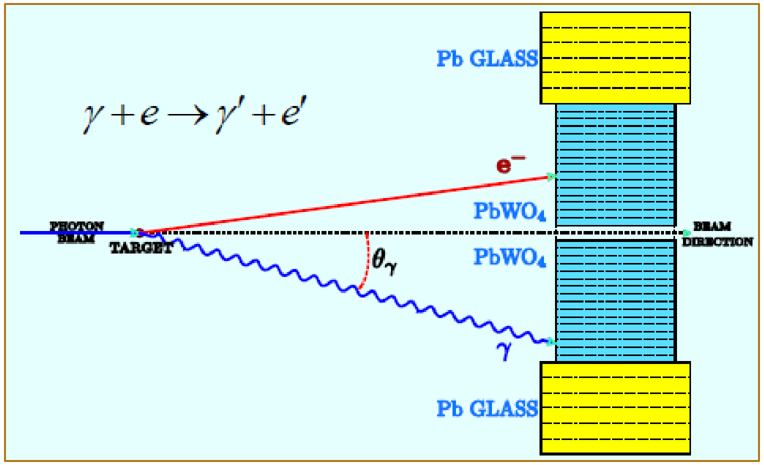
$\Gamma(\pi^0\to\gamma\gamma)$ = 7.763 ±0.127 (stat) ± 0.117(syst.) eV

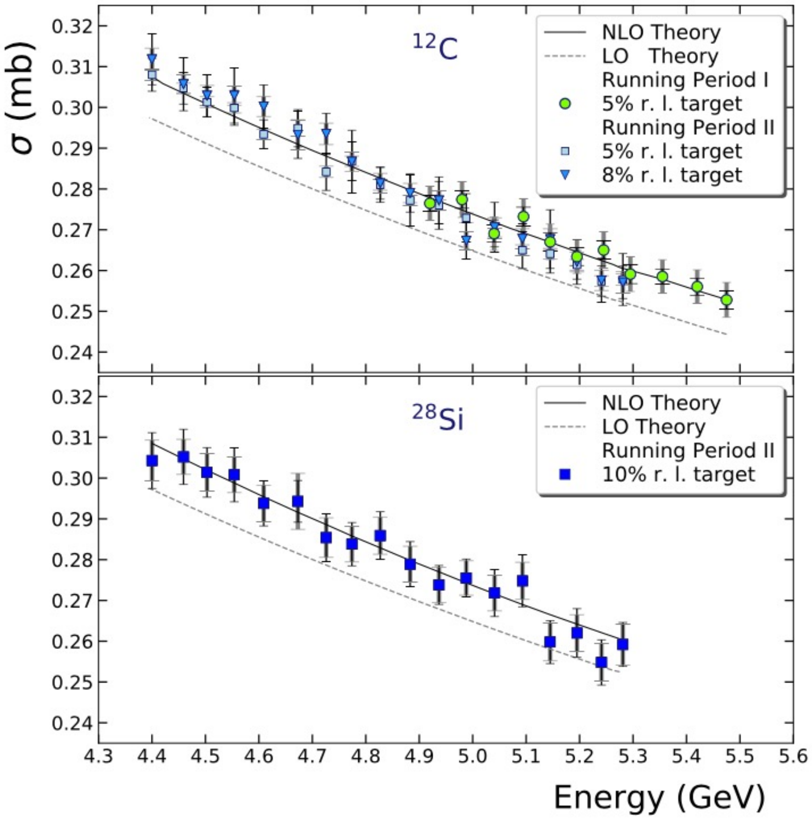
^{28}Si target:

$\Gamma(\pi^0\to\gamma\gamma)$ = 7.806 ±0.062 (stat) ± 0.109(syst.) eV

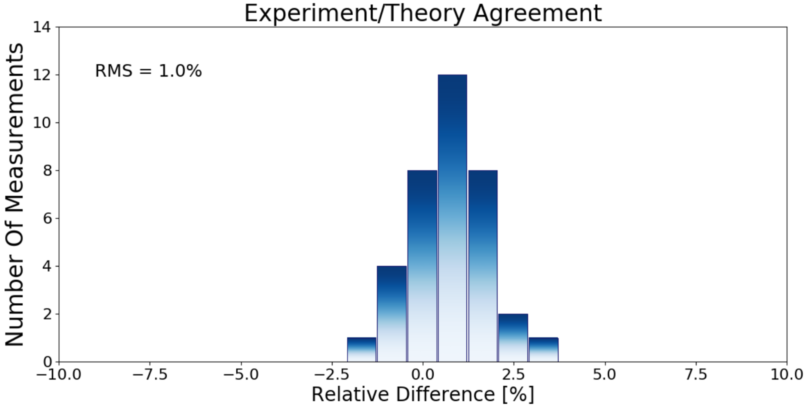


Verification of Experimental Uncertainties with Compton





- Measurement of Compton scattering from atomic electrons performed periodically during both experiments.



- Validates PrimEx experimental uncertainties on percent level!

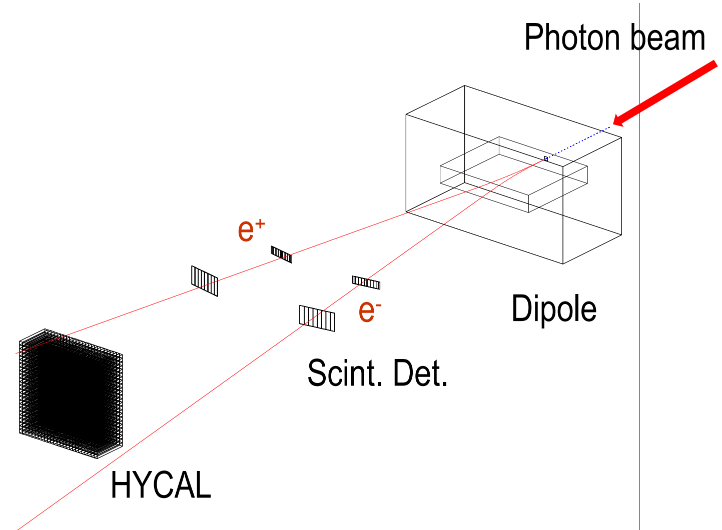
Pair Spectrometer for the Photon Flux Measurement

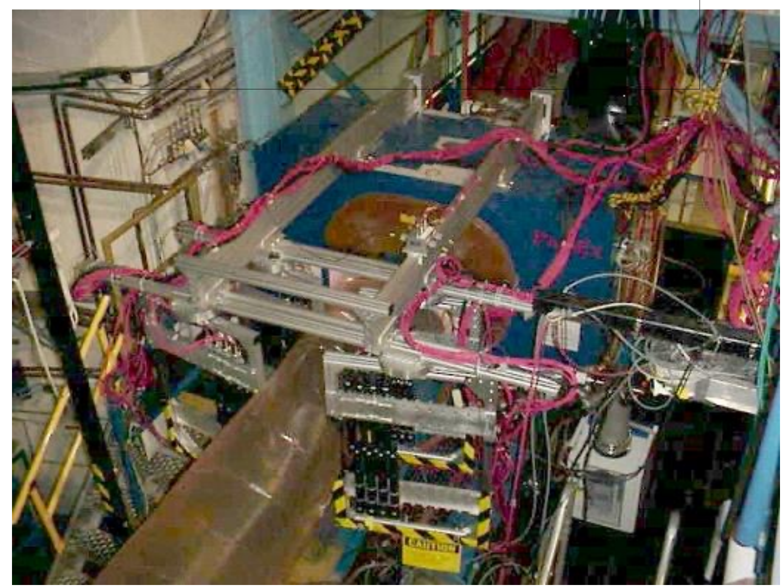
- Precision cross section measurements need control of photon flux at 1% level

- PS consist of:
  - ✓ 1.7 Txm dipole magnet;
  - ✓ 2 telescopes of 2x8 scintillators.

- Photon flux measurement with Tagger:
  - ✓ absolute tagging ratio with TAC at very low intensities;
  - ✓ relative tagging ratios with PS at low and high intensities.

- 1% level uncertainty in photon flux has been reached (verified by the Compton and pair production processes).





downstream view