The Neutral Pion Lifetime: Final Result from the PrimEx Experiments

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for the PrimEx-II Collaboration

Outline

- A short review of $\pi^0 \rightarrow \gamma\gamma$
- Impact of the PrimEx-I experiment
- PrimEx-II experiment
- Final results
- Summary

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

- π^0 is the lightest strongly interacting particle (hadron) in Nature:

- 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:
    - ➢ explicit braking of axial symmetry, $U_A(1)$ ⟶ axial or chiral anomaly

  - ✓ spontaneous breaking of chiral symmetry, (q-q condensation):

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

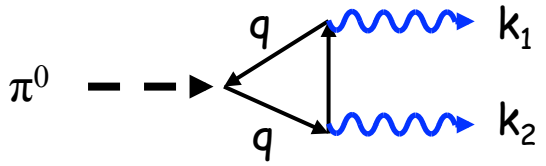
8 massless Goldstone bosons: $\pi^0, \pi^+, \pi^-, K^0, \bar{K}^0, K^+, K^-, \eta_8$

- Lifetime and radiative decay width:

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

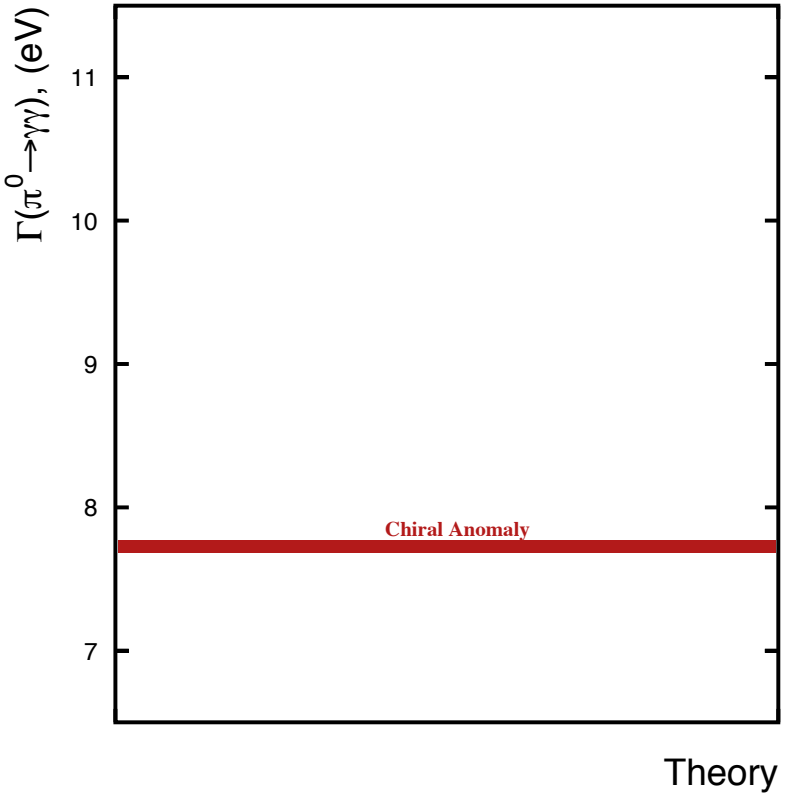
$\pi^0 \to \gamma\gamma$ Decay and Chiral Anomaly

- 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:



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

  - ✓ 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
$\Gamma(\pi^0 \to \gamma\gamma) = 8.10\text{eV} \pm 1.0\%$

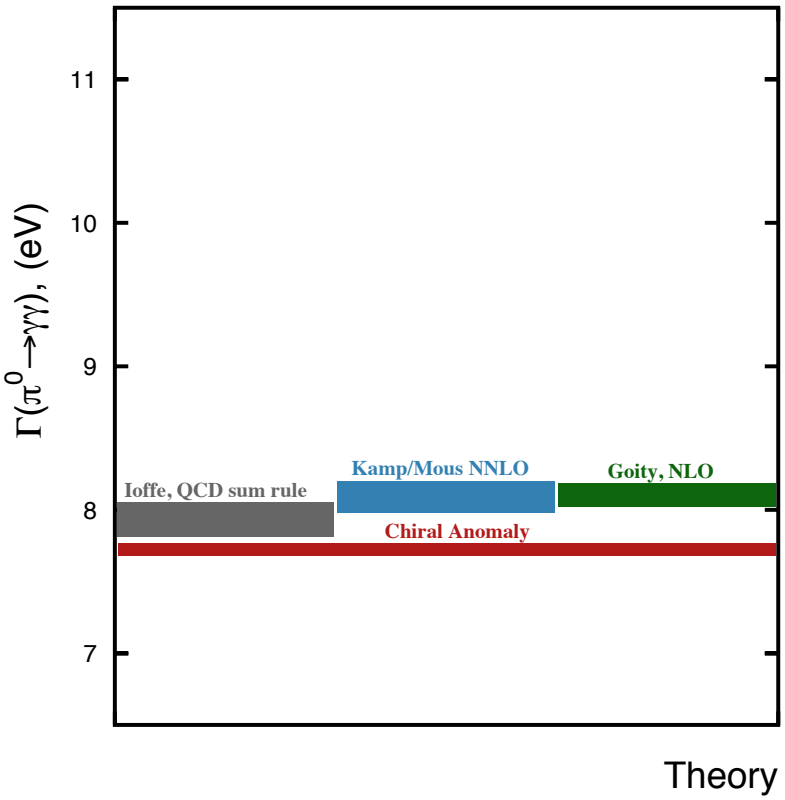
2) B. Ananthanarayan et al. JHEP 05:052, 2002)
ChPT, NLO, η , η' mixing
$\Gamma(\pi^0 \to \gamma\gamma) = 8.06\text{eV} \pm 1.0\%$

3) K. Kampf et al. Phys. Rev. D79:076005, 2009)
ChPT,one and two-loops NNLO, SU(2)
$\Gamma(\pi^0 \to \gamma\gamma) = 8.09\text{eV} \pm 1.3\%$

- QCD sum rules and dispersion relations

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

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

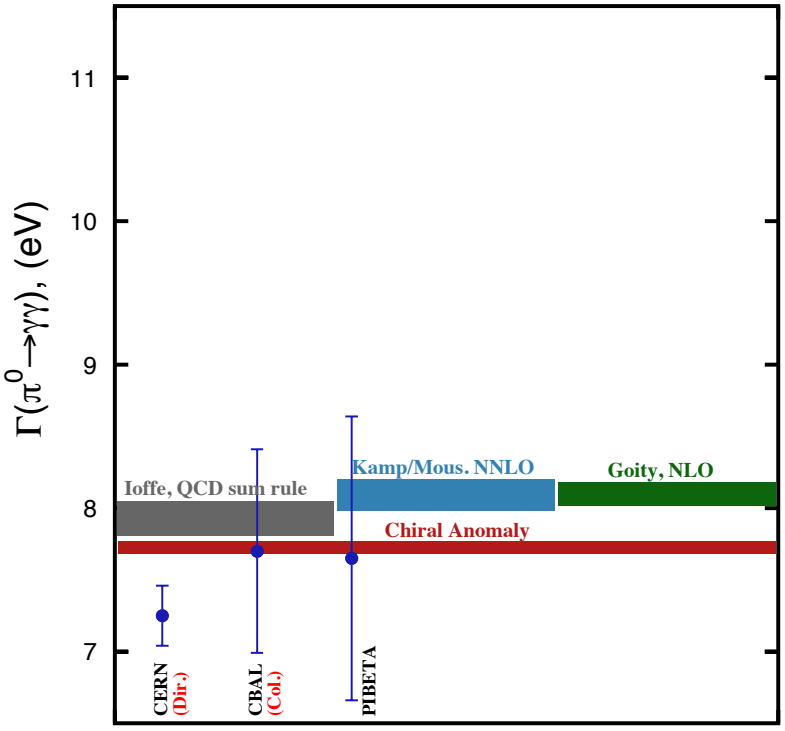


Previous Experiments (included in PDG, except Primakoff exp.'s)

- CERN in 1985 (direct method, π^0 decay length)
  H.W. Atherton, et al. Phys. Lett. B158:81 (1985)
  Resut:
  $\Gamma(\pi^0 \to \gamma\gamma) = 7.25 \pm 0.18 \pm 0.14$ eV (2.9% total)

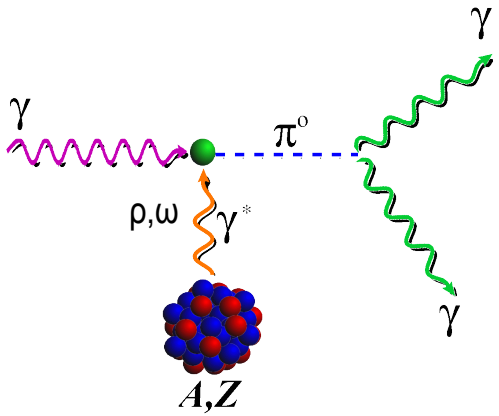
- DESY (DORIS II) in 1988
- $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0 \to e^+e^-\gamma\gamma$
  D.A. Williams, et al. Phys. Rev. D38:1365 (1988)
  Result:
  $\Gamma(\pi^0 \to \gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV (10.9%)
  Not included in PDG until 2012

- PIBETA experiment at PSI in 2009
  $\pi^+ \to e^+ + \nu_e + \gamma$
  M. Bychkov, et al. Phys. Rev. Lett. 103:05 1802 (2009)
  Result:
  $\Gamma(\pi^0 \to \gamma\gamma) = 7.65 \pm 0.99$ eV (13%)

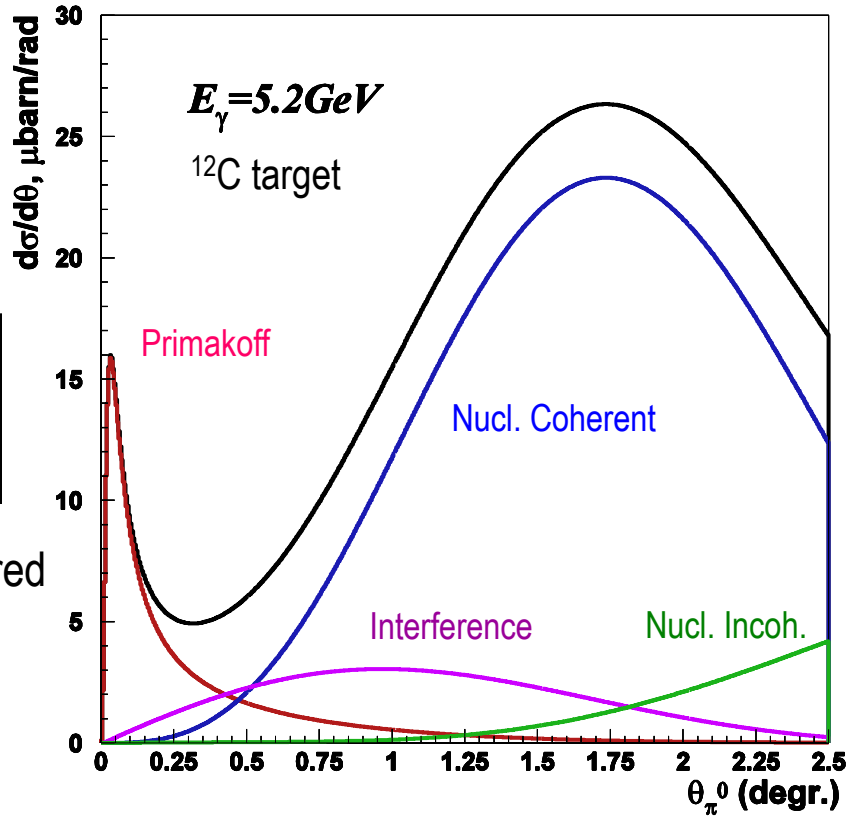


Theory and Experiments

Primakoff Method



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



- Primakoff coherent cross section measurement required

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

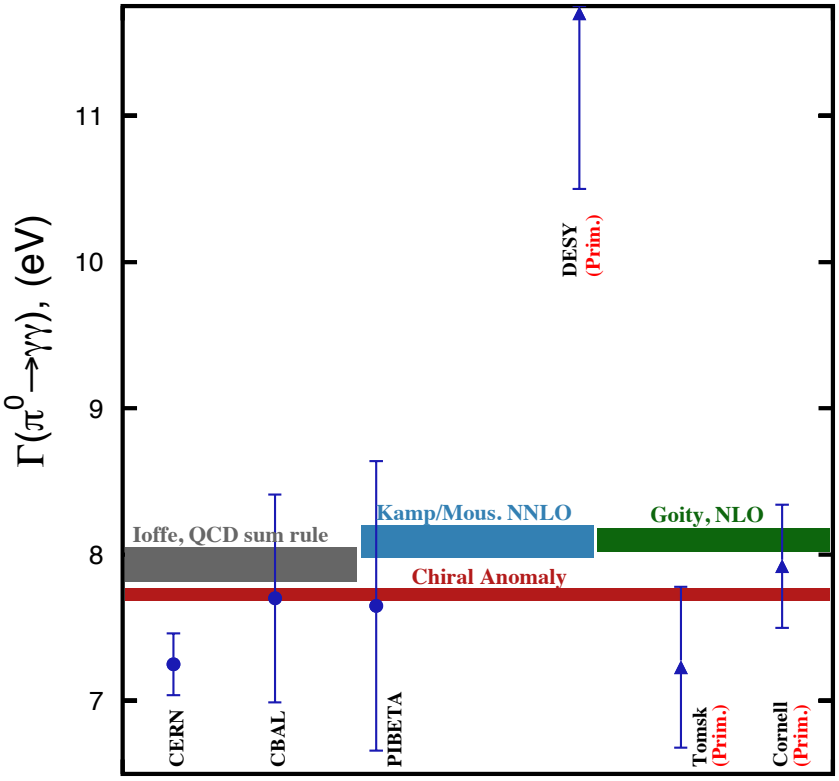
- Challenge of the method:
  - measure the cross section at forward angles with high precision
  - extract the Primakoff amplitude from diff. cross sections vs. angle

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

- Tomsk, 1970
  V. Kryshkin, et al. Exp. Theor. Phys. 30:1037 (1970)
  untagged bremsstrahlung beam, $E_{\gamma max} \approx 1.1$ GeV
  target: Pb
  Result: $\Gamma(\pi^0 \to \gamma\gamma) = (7.23 \pm 0.55)$ eV (7.6%)

- Cornell (1974)
  A. Browman, et al. Phys. Rev. Lett. 33:1400 (1974)
  untagged bremsstrahlung γ beam
  Eγmax: ≈ 6.6 GeV
  targets: Be, Al, Cu, Ag, U
  Result: $\Gamma(\pi^0 \to \gamma\gamma) = (7.92 \pm 0.42)$ eV (5.3%)



Theory and Experiments

PDG Status before PrimEx

- 4 experiments included in PDG before 2008
  PDG average: $\Gamma(\pi^0 \to \gamma\gamma) = 7.74 \pm 0.55$ (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, 1970

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

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

✓ Tomsk, 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%)

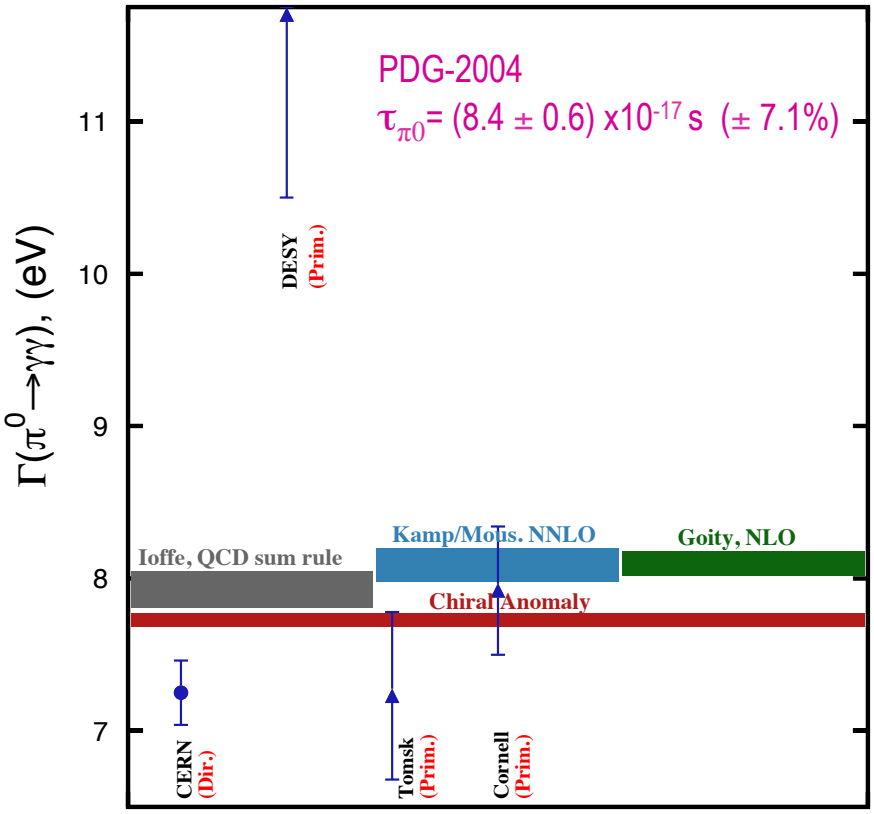
✓ Cornell (1974)

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

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

PDG average before PrimEx-I

$\tau_{\pi^0} = (8.4 \pm 0.6) \times 10^{-17}$ s (± 7.1%)

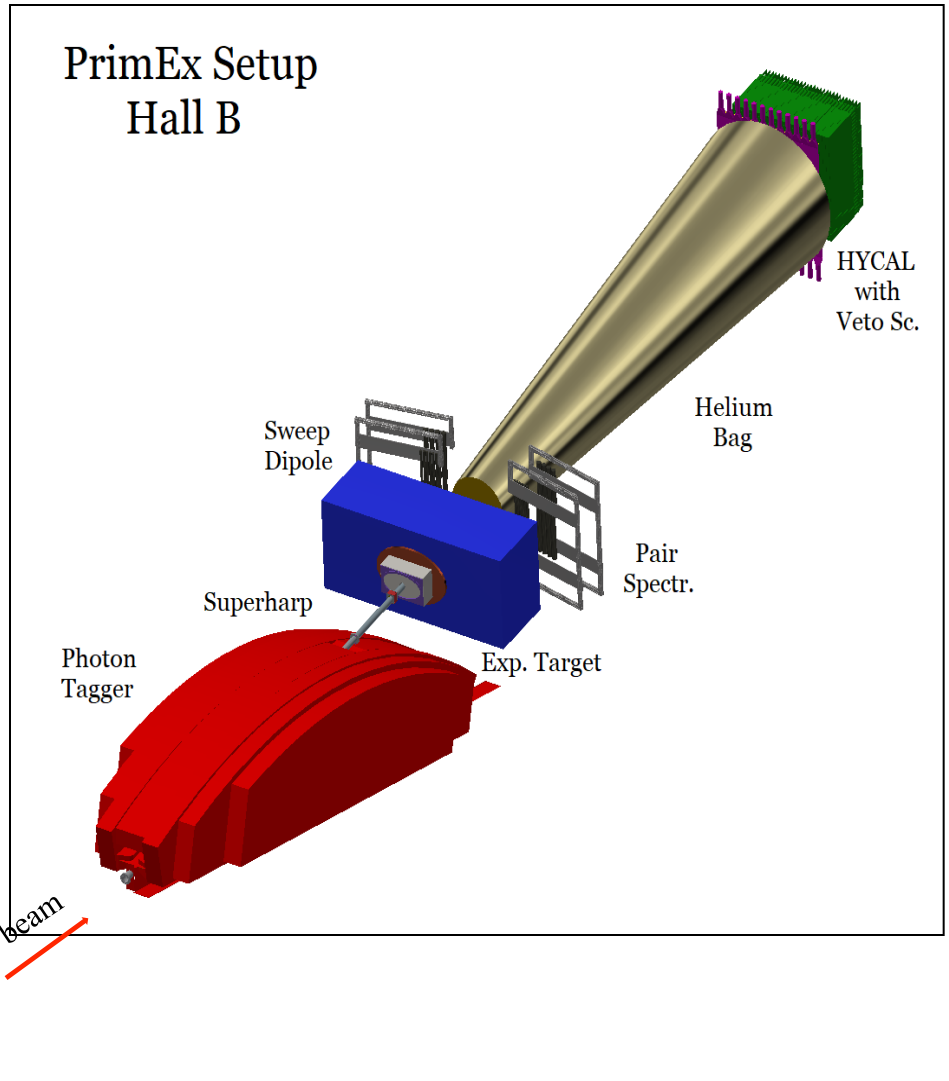


Theory and Experiments

- New experiment was needed !!!

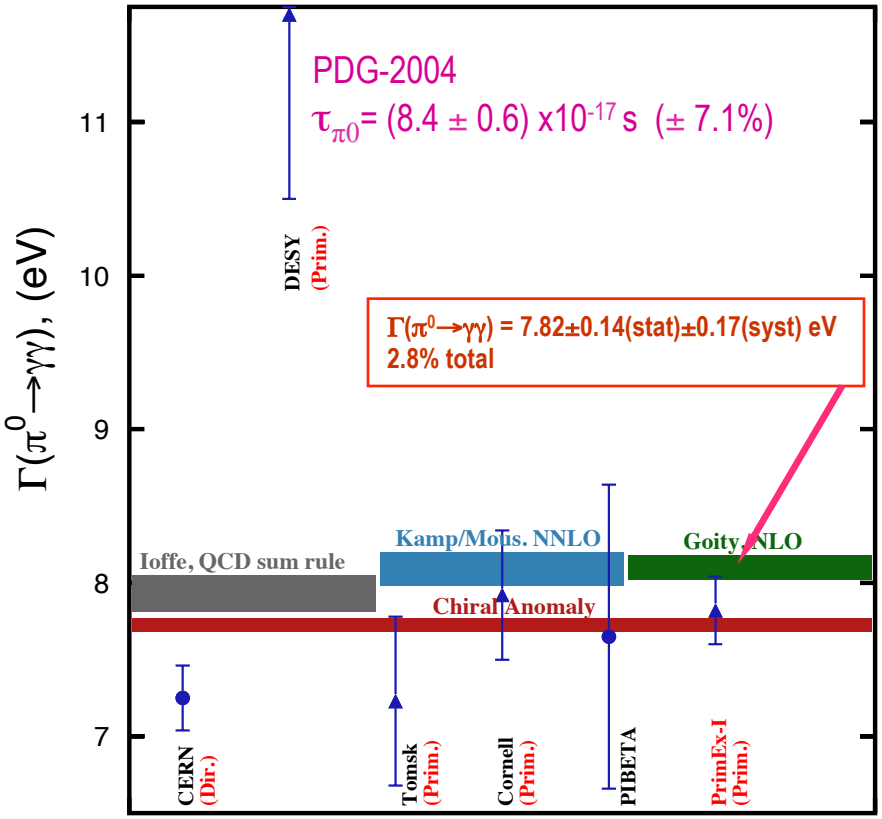
PrimEx Approach for a New Generation Primakoff Experiment

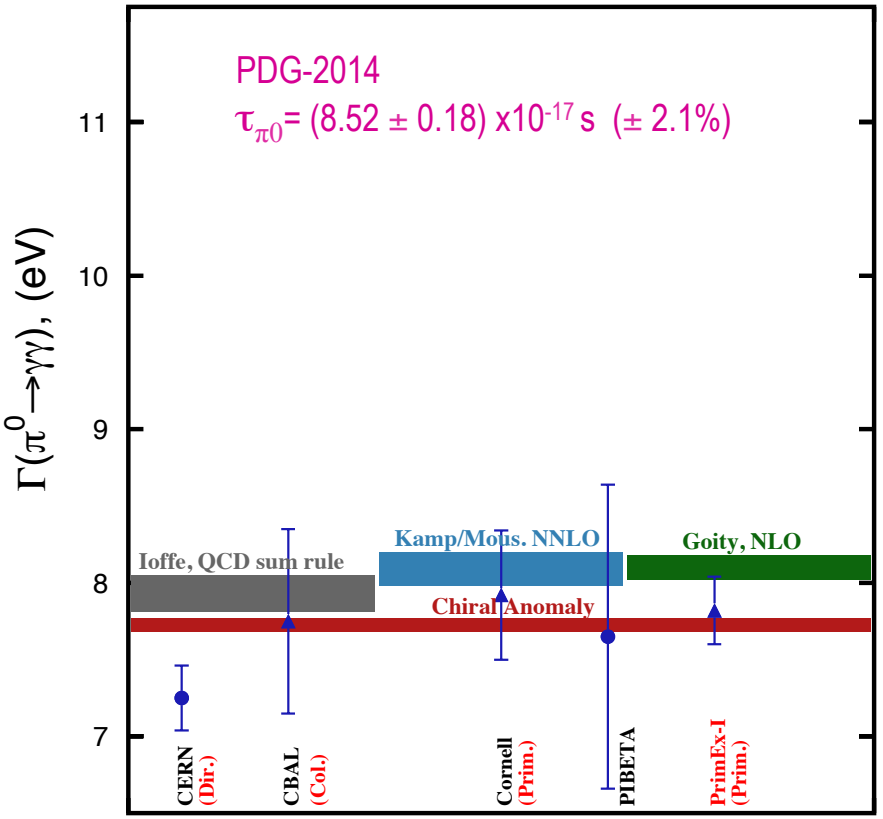
- Use tagged photon beam:
  - ✓ better knowledge of photon flux
  - ✓ energy and timing of incident photons
- Use high resolution EM calorimeter:
  - ✓ better $M\gamma\gamma$ resolution
  - ✓ better θ_{π^0} resolution
  - ✓ less background
- Monitor photon flux at high intensities:
  - ✓ photon flux measurement on 1% level
- Parallel measurement of purely QED processes to control/verify the cross section on 1% level:
  - ✓ Compton scattering $(\gamma + e^- \rightarrow \gamma + e^-)$
  - ✓ e^+e^- Pair production $(\gamma + {}^{12}C \rightarrow e^+ + e^- + {}^{12}C)$



PrimEx-I Result: PDG status Before and After PrimEx-I

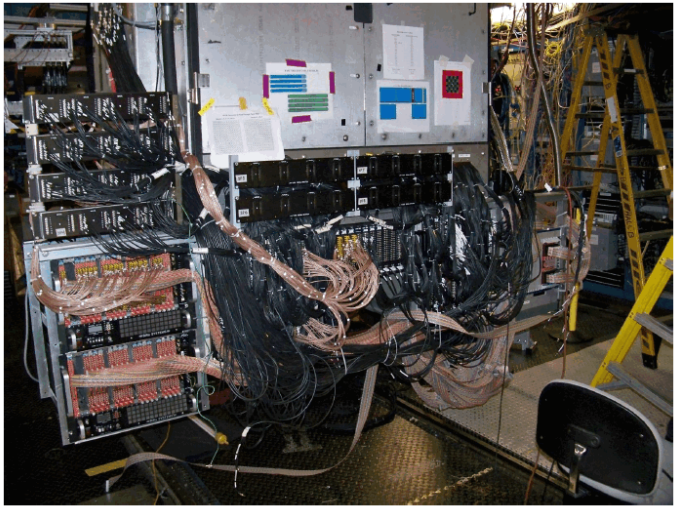
- PrimEx-I result: $\Gamma(\pi^0\to\gamma\gamma) = 7.82$ eV $\pm 1.8\%$ (stat) $\pm 2.1\%$ (syst.), I. Larin, et al. PRL 106, 162303, 2011
  - ✓ PrimEx-I result changed the PDG "landscape" for the $\pi^0\to\gamma\gamma$ sector.
  - ✓ Improved the decay width by factor of ≈ 2.5





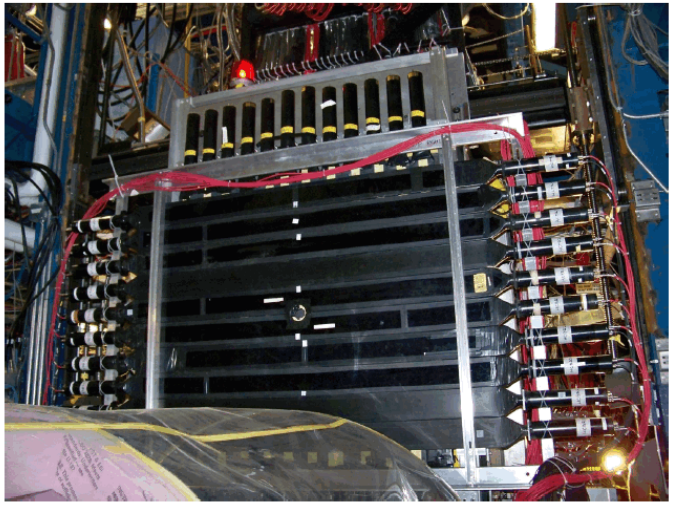
PrimEx-II Experiment

- Experiment was performed in Hall B in 2010

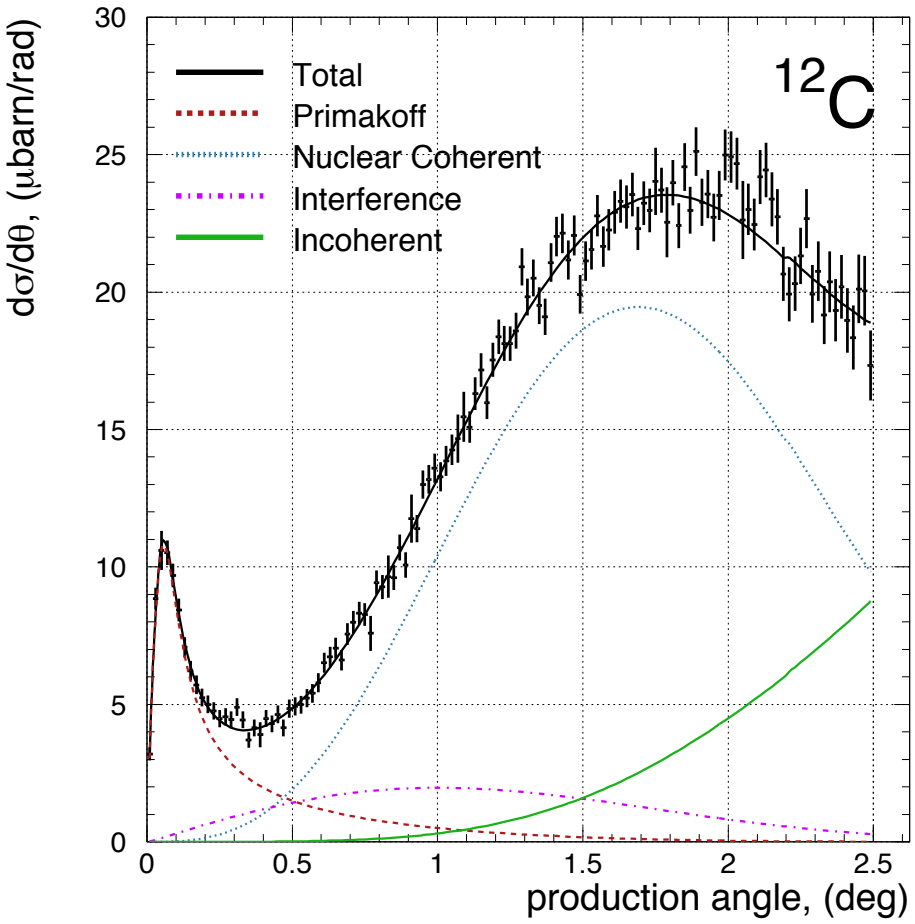


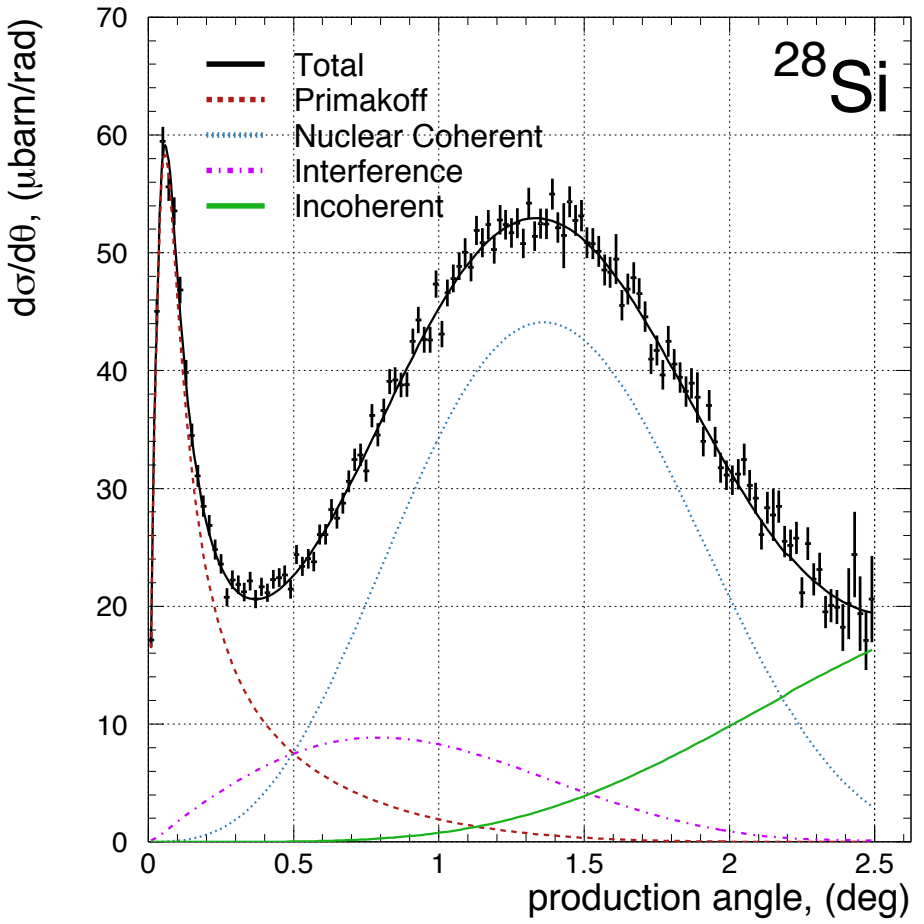
Improvements over PrimEx-I

- 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.



Extracted Differential Cross Sections





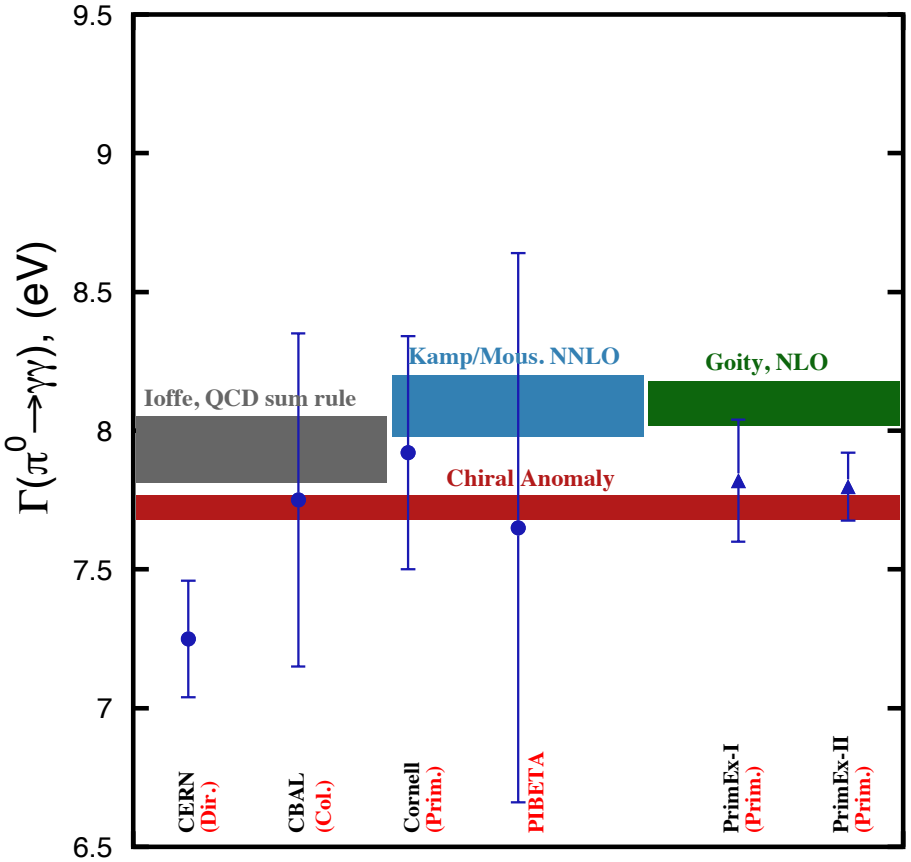
- To extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$:
  - ✓ angular and energy resolutions smeared the theoretical distributions to fit the experimental cross sections.

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

- Weighted average from two groups and for two targets is:

$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.798 \pm 0.056(\text{stat}) \pm 0.109(\text{syst.})$ eV

with the total uncertainty of:
± 1.6%



Theory and Experiments

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

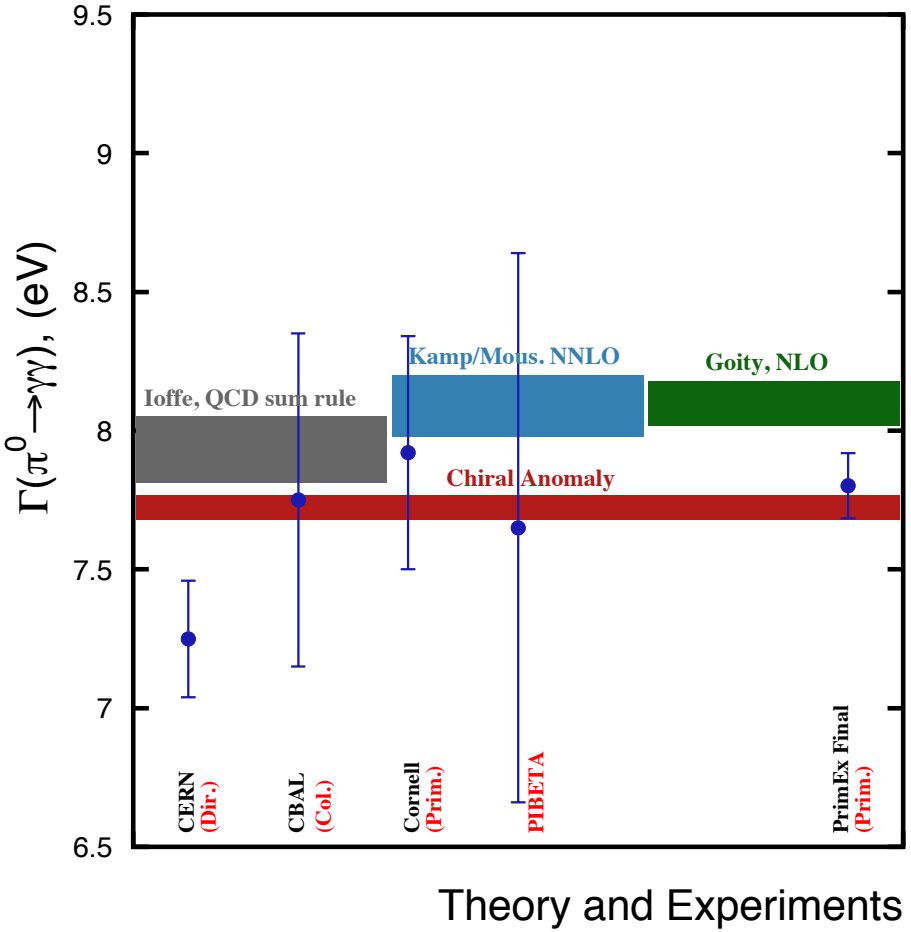
- PrimEx-I:
- Weighted average from two experiments, PrimEx-I and PrimEx-II is:

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

with the total uncertainty of:
± 1.5%

- and for the lifetime:

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



Theory and Experiments

PrimEx Collaboration

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ITEP, 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,
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University of Massachusetts, Amherst, MA,
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Summary

- The $\pi^0 \rightarrow \gamma\gamma$ decay was and still is (one of) the best test(s) of QCD at low-energy domain.

- PrimEx collaboration developed and performed two new generation of Primakoff experiments.

  - ✓ PrimEx-I in 2014 with 2.8% total uncertainty:

    - significantly changed the "landscape" of PDG for π^0 decay width;
    - improved the decay width average by factor of 2.

  - ✓ PrimEx-II in 2010 with a 1.6% total uncertainty:

  - ✓ The combined, Final PrimEx result:

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

    - confirms firmly the validity of the chiral anomaly;
    - few σ lower than the next order theory calculations.