PrimEx Final Result: Neutral Pion Lifetime

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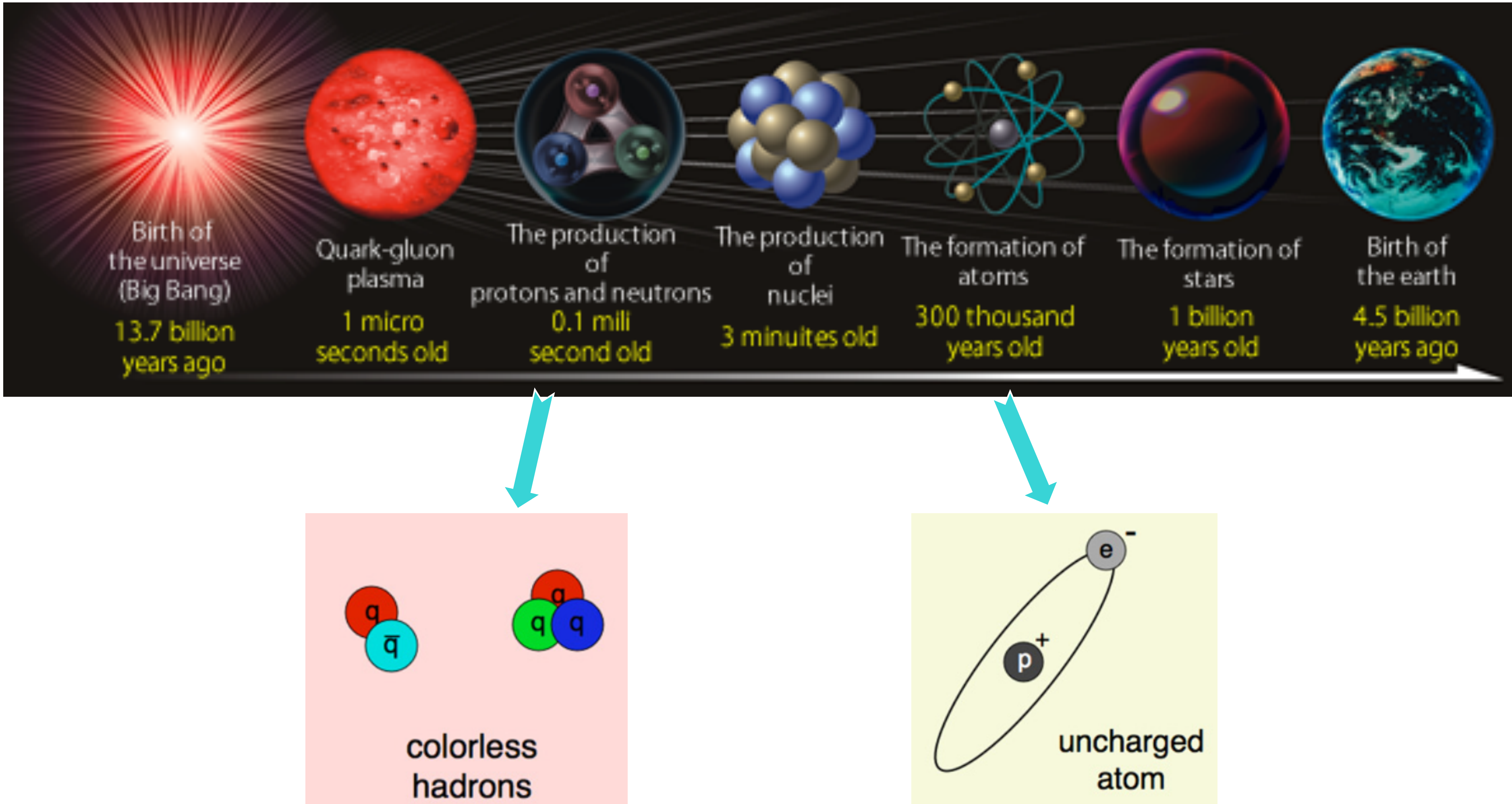
(On behalf of the PrimEx Collaboration)

Outline

- Introduction
- Low-energy QCD symmetries and the π^0 lifetime
- Different experimental approaches
- The PrimEx experiments and final result
- Summary

Thanks for support of MRI PHY-0079840 and PHY-1506303 awards by USA NSF

History of Matter



- QCD confinement is the last frontier in the standard model
- $\pi^0 \rightarrow \gamma\gamma$ offers a sensitive probe for confinement QCD

The π^0 Meson

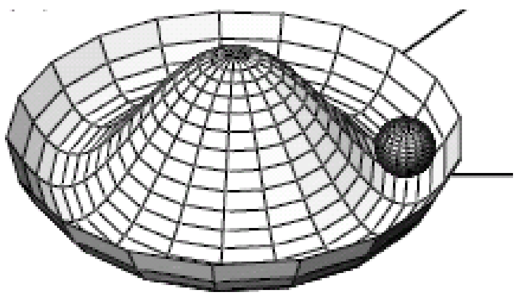
- π^0 is the lightest hadron:
  m_π = 134.9770±0.0005 MeV, $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$

- π^0 is unstable:
  $\pi^0 \rightarrow \gamma\gamma$, BR($\pi^0 \rightarrow \gamma\gamma$)=(98.823±0.034)%

- Lifetime and radiative decay width $\Gamma(\pi^0 \rightarrow \gamma\gamma)$:
  τ = B.R.$(\pi^0 \rightarrow \gamma\gamma)/\Gamma(\pi^0 \rightarrow \gamma\gamma)$
  ~ (8.52±0.18) x 10^{-17} s

- $\pi^0 \rightarrow \gamma\gamma$ is associated to two fundamental symmetry properties of QCD: chiral symmetry and anomaly.

Spontaneous Chiral Symmetry Breaking Gives Rise to π^0



In the massless quark limit

$$SU_L(3) \times SU_R(3) \rightarrow SU(3)$$

Massless Goldstone Bosons:

$$\pi^0, \pi^+, \pi^-, K^+, K^-, K^0, \bar{K}^0, \eta_8$$

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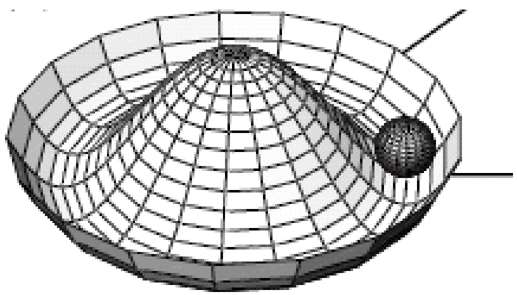

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Corrections to theory:

$SU_L(3) \times SU_R(3)$ and ***$SU(3)$*** are explicitly breaking due to non-zero quark masses and quark mass differences:

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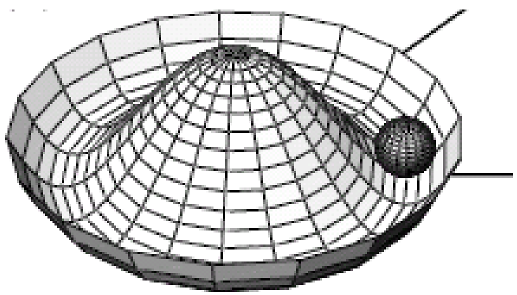

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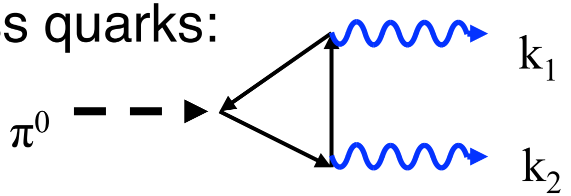
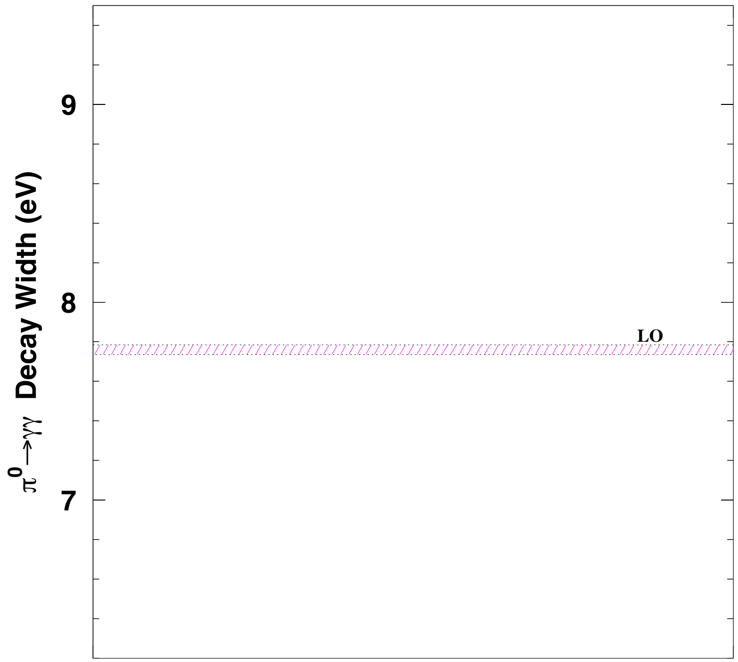
As the lightest quark-antiquark system in nature, these corrections to π^0 are expected to be small.

Axial Anomaly Determines π^0 Lifetime

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

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.760\ eV$$





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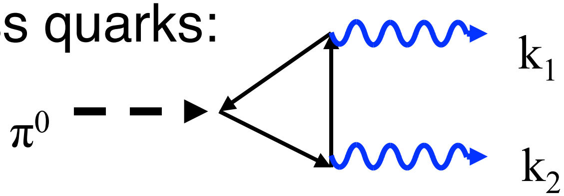

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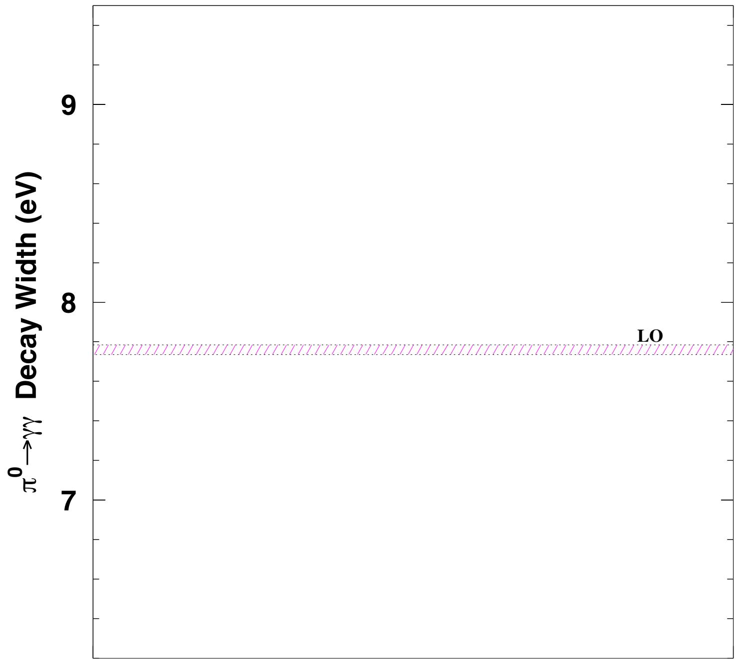

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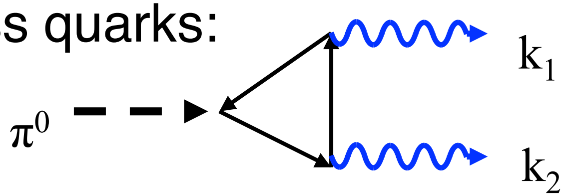

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Calculations in NLO ChPT:

❑ $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10\text{eV} \pm 1.0\%$
GBH (Phys. Rev. D66, 076014, 2002)

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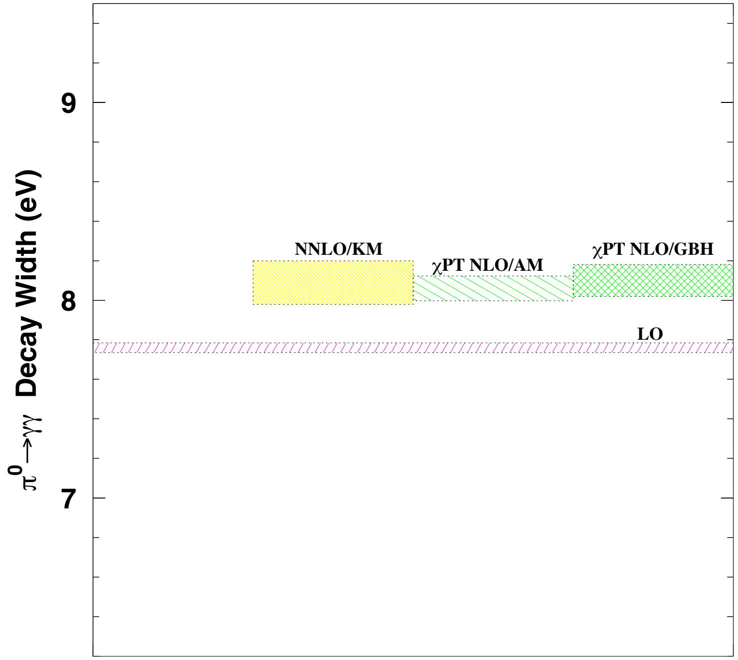

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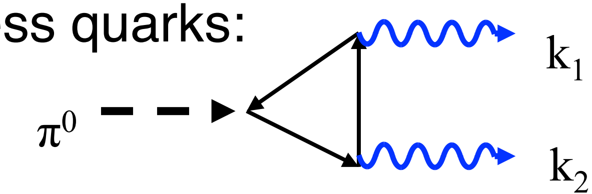

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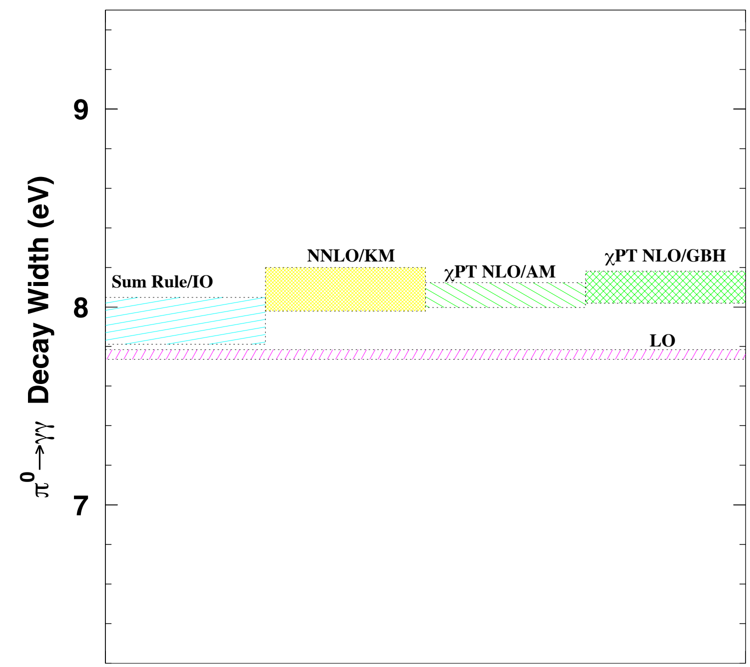

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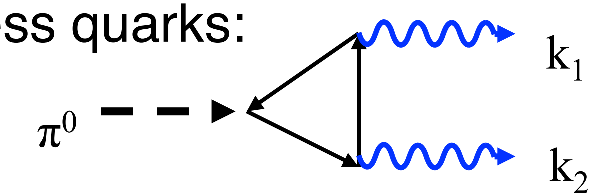

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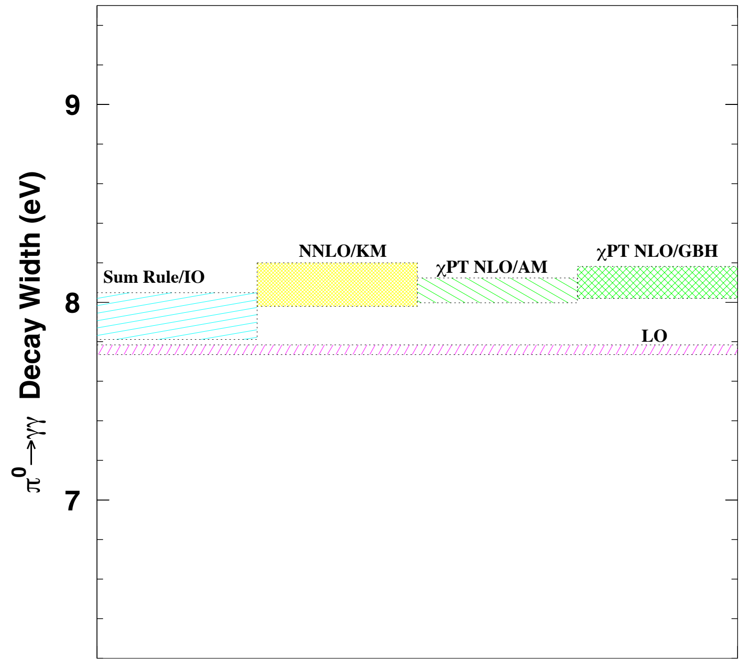

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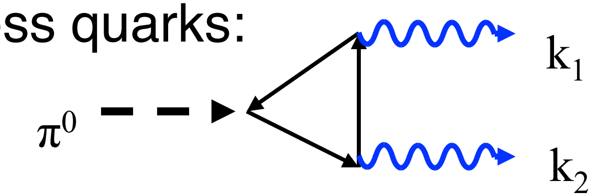

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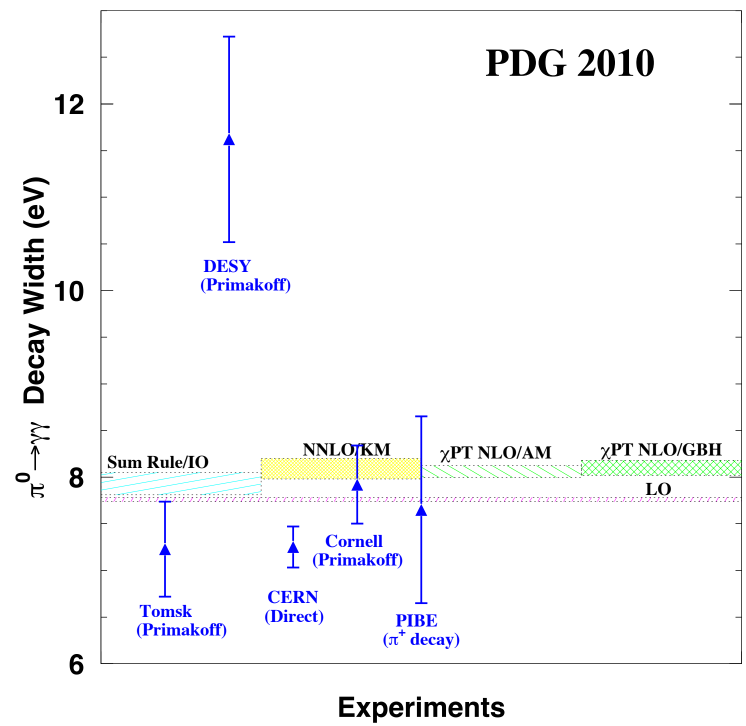

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Decay Length Measurements (Direct Method)

Measure π^0 decay length

$\tau_\pi \sim 8.5\times10^{-17}$ s $\Rightarrow c\tau_\pi \sim 25$ nm

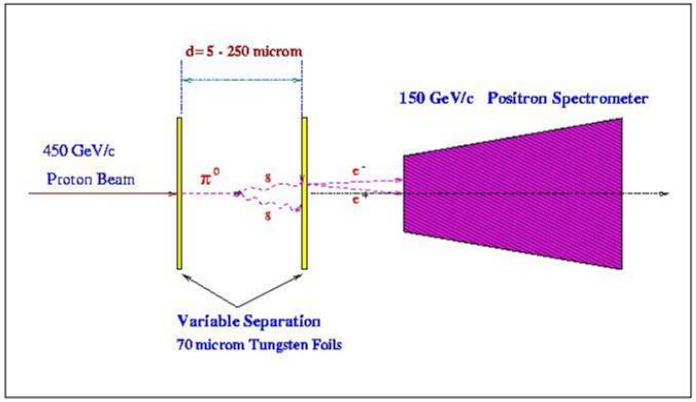
too short to measure!

Solution: create energetic π^0

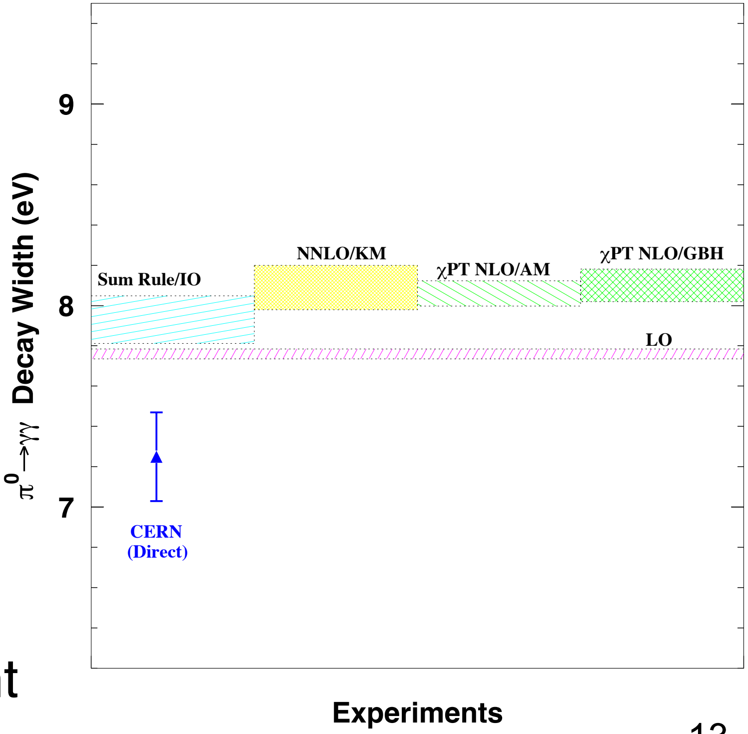
$$L = v_\pi \gamma \tau_\pi \qquad \gamma = 1/\sqrt{1 - v_\pi^2/c^2}$$

for $E_\pi = 450$ GeV, $L_{mean} \sim 50$ μm

1984 CERN experiment (Phys.Lett.,158B,81):
P=450 GeV proton beam
Two variable separation (5-250μm) foils



Result:
$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.25 \pm 0.18 \pm 0.11$ eV (3%)



Major limitations of method:

1. unknown P_{π^0} spectrum
2. needs higher energies for improvement

The e^+e^- Collision Method

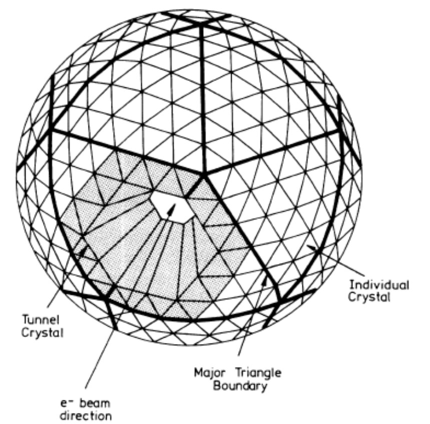
CBAL @ DESY (1988)

Phy.Rev.,D38,1365

$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0 \to e^+e^-\gamma\gamma$

e^+, e^- scattered at small angles (not detected)

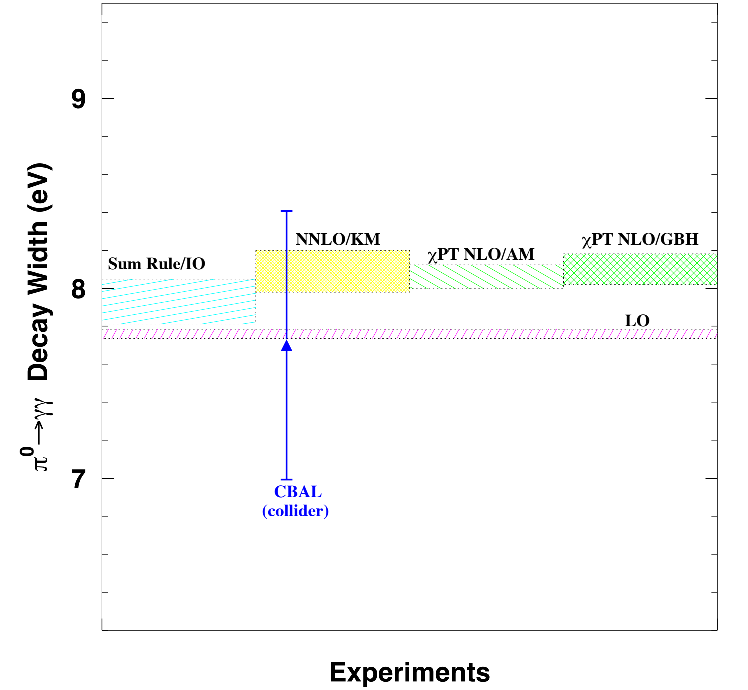
only $\gamma\gamma$ detected



Results:

$\Gamma(\pi^0 \to \gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV (9.2%)

Not included in PDG until 2012



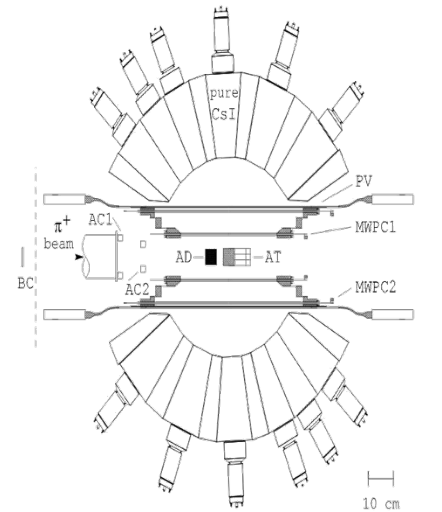
Major limitations of method

1. knowledge of luminosity
2. unknown q^2 for $\gamma^*\gamma^*$

Pion Beta Decay Method

PIBETA @ PSI, 2009

Phys.Rev.Lett.,103,051802

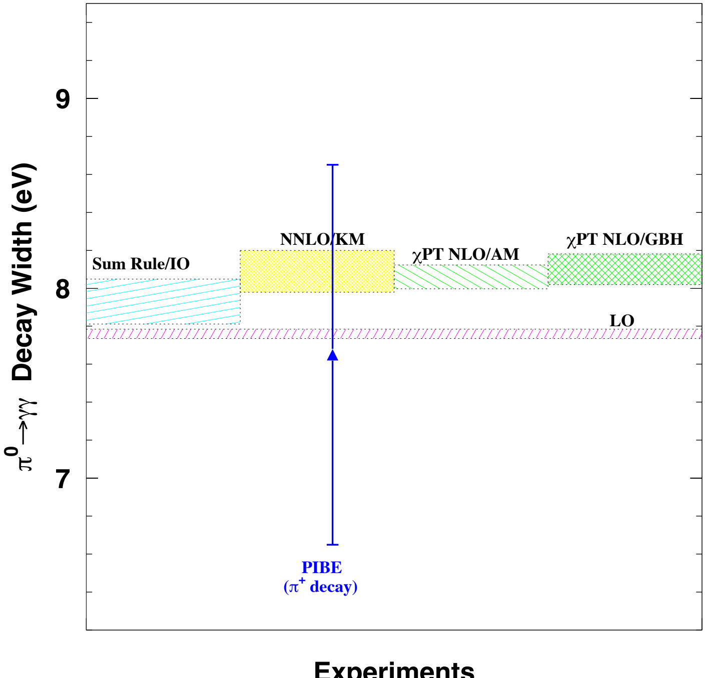


- Measure $\pi^+ \rightarrow e^+\nu_e\gamma$ at rest to extract weak form factors F_V and F_A

- Assume conserved vector current and isospin invariance, then

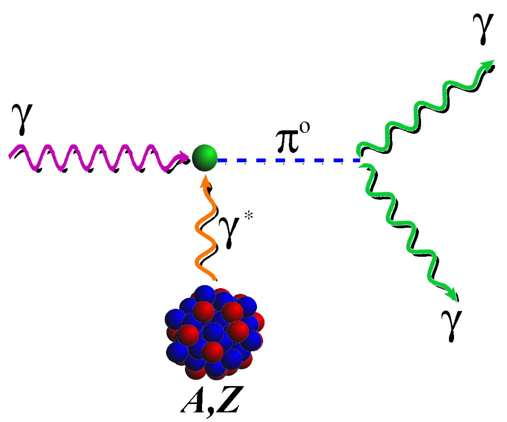
$$\Gamma(\pi \rightarrow \gamma\gamma) = \pi m_\pi \alpha^2 \left|F_V(0)\right|^2 / 2$$

Results:
$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.7 \pm 1.0$ eV (13%)

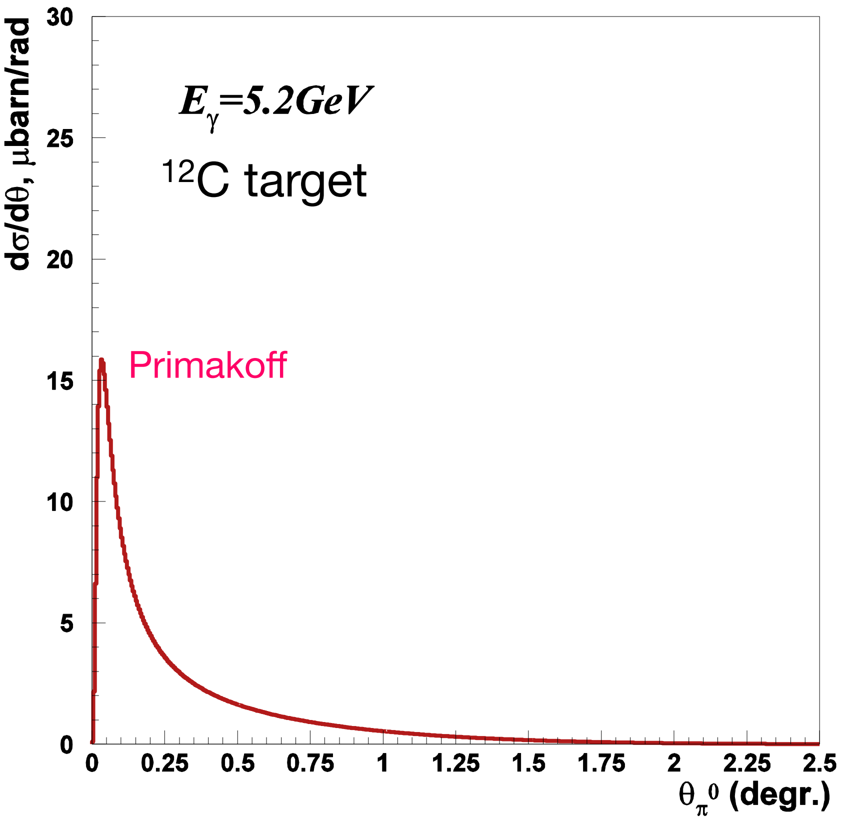


Major limitations of method
1. Isospin violation effect
2. Rare decay

Primakoff Method



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



Features of Primakoff cross section:

- Peaked at very small forward angle:

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

- Beam energy sensitive:

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

- Coherent process

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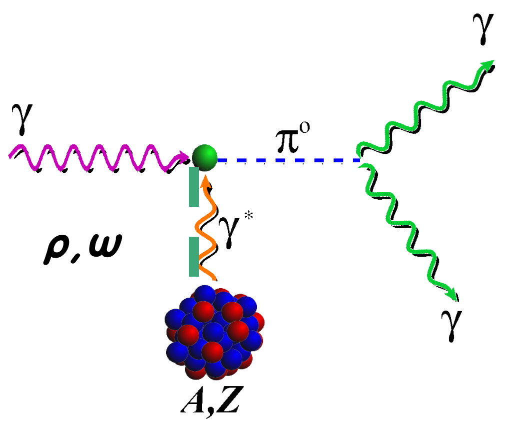

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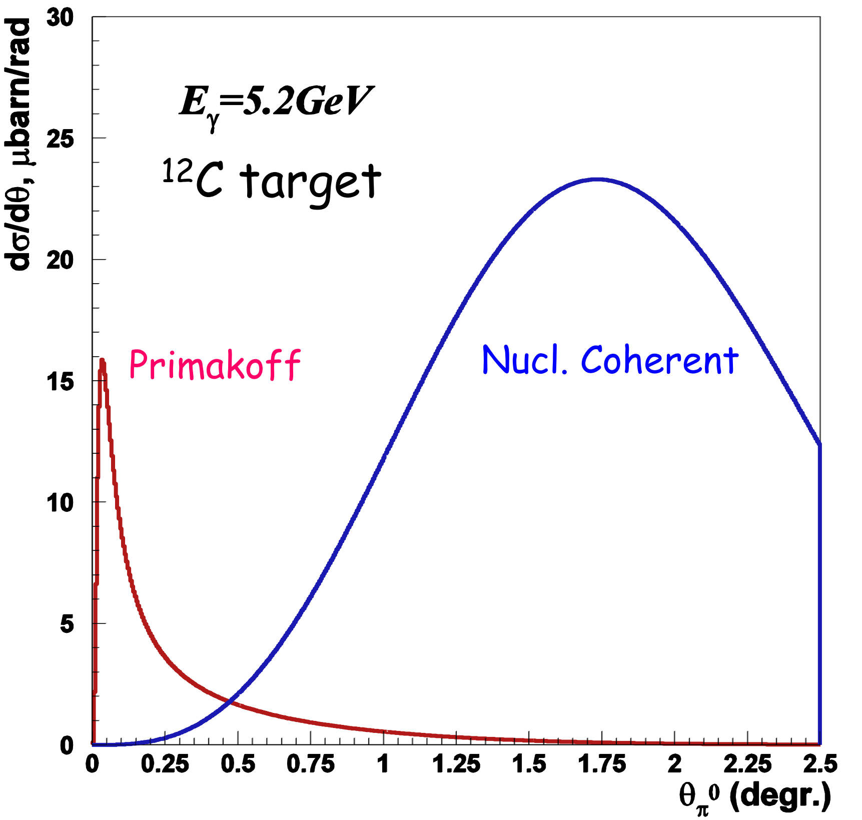

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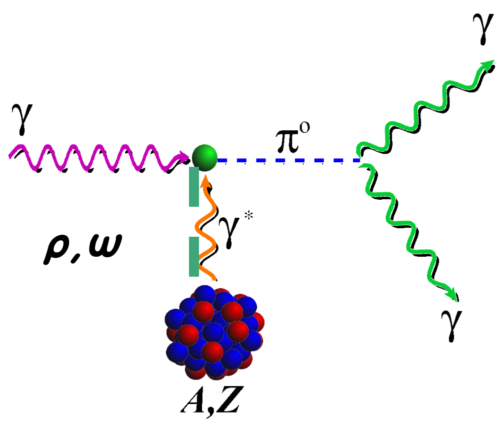

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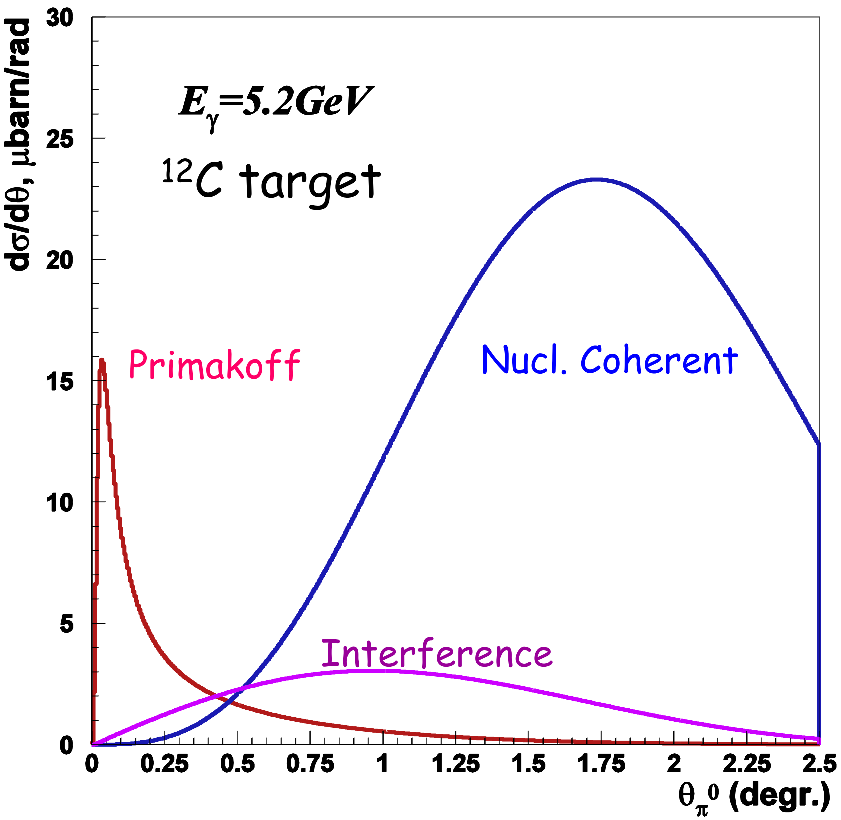

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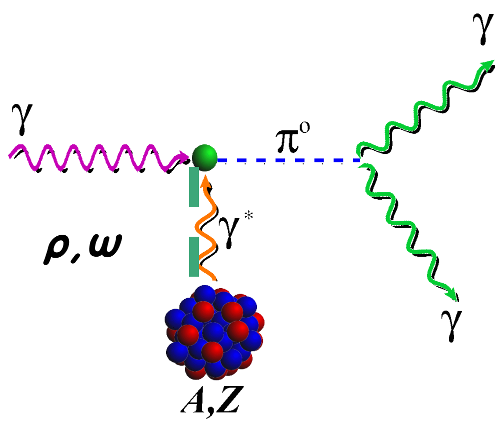

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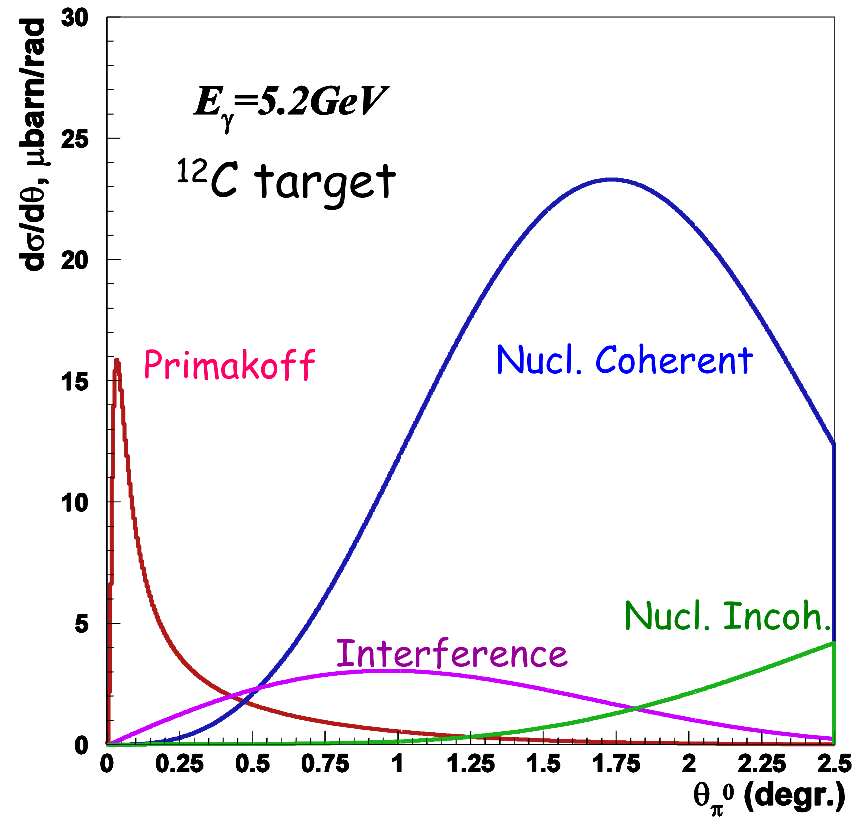

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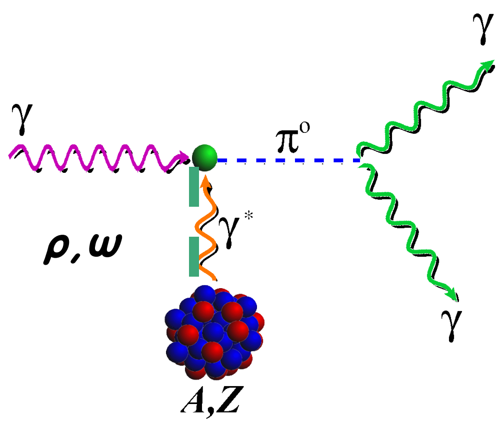

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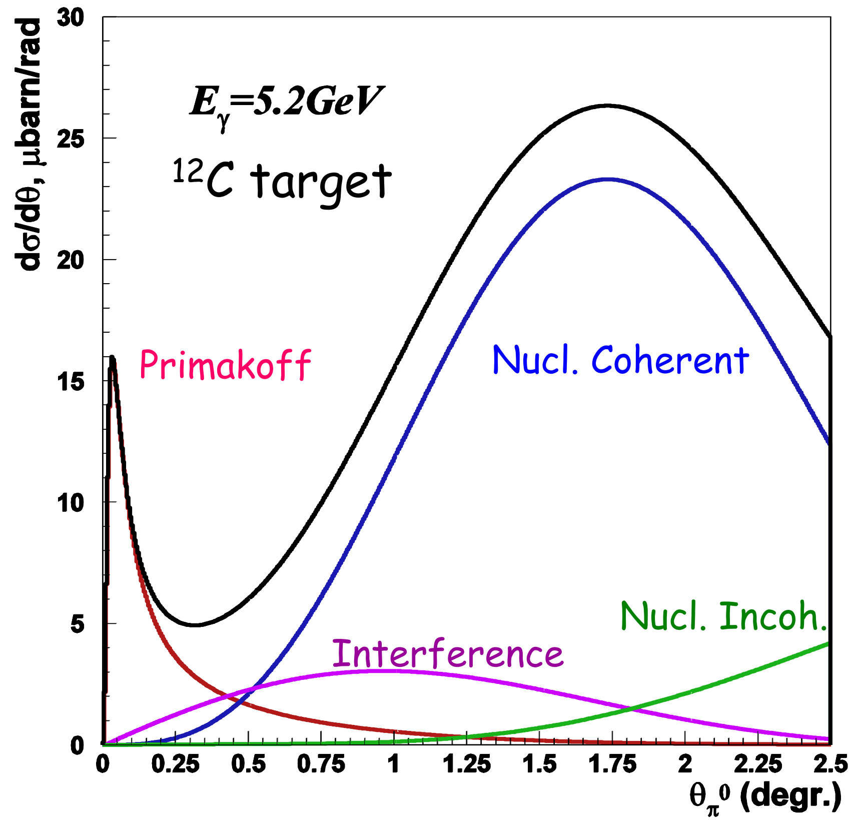

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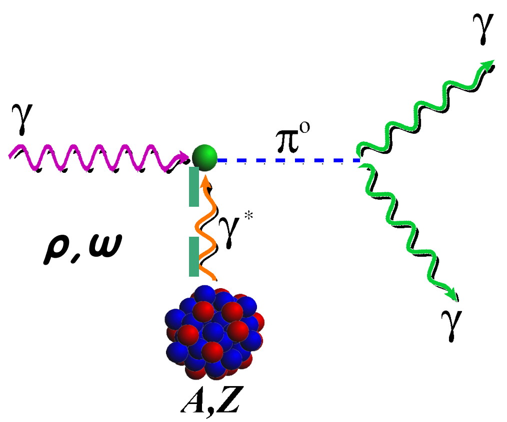

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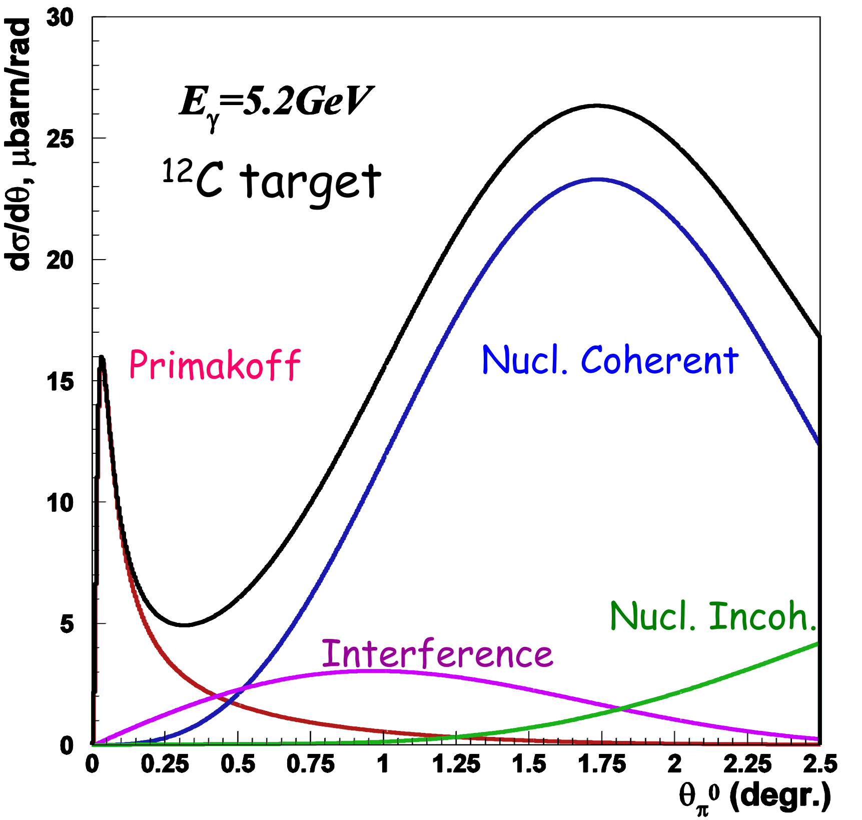
Challenge: Extract the Primakoff amplitude



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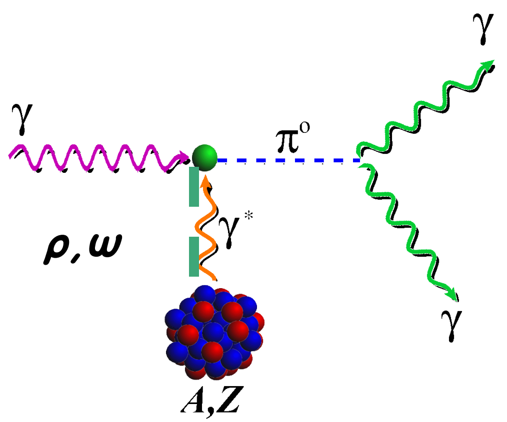

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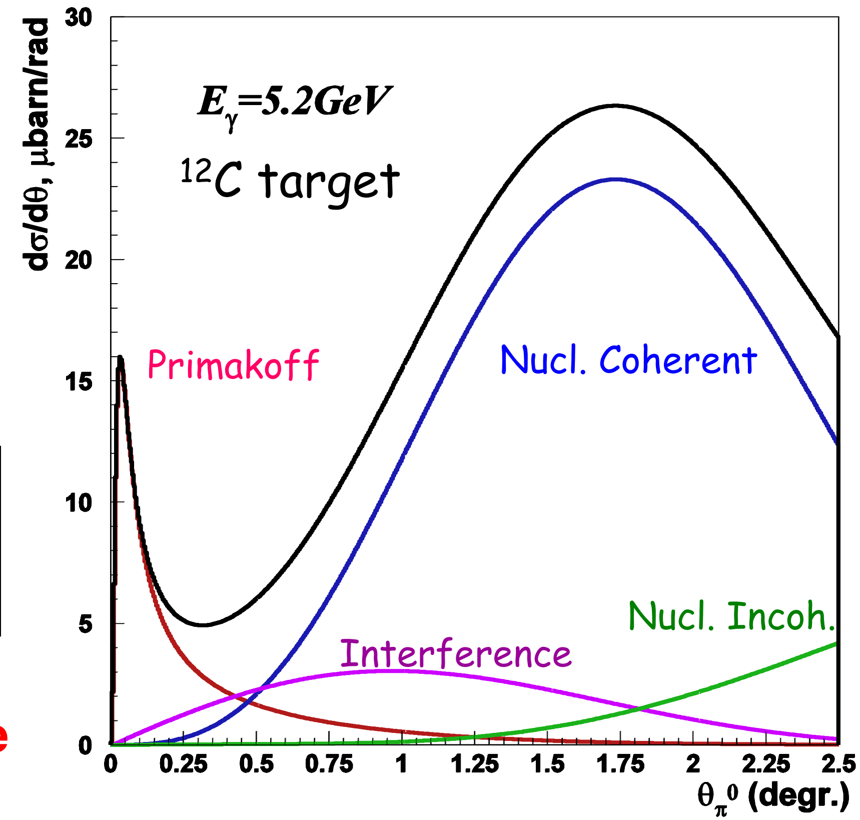

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Requirement:

- **Photon flux**
- **Beam energy**
- **π^0 production angle resolution**
- **Compact nuclear target**

Features of Primakoff cross section:

- Peaked at very small forward angle:

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

- Beam energy sensitive:

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

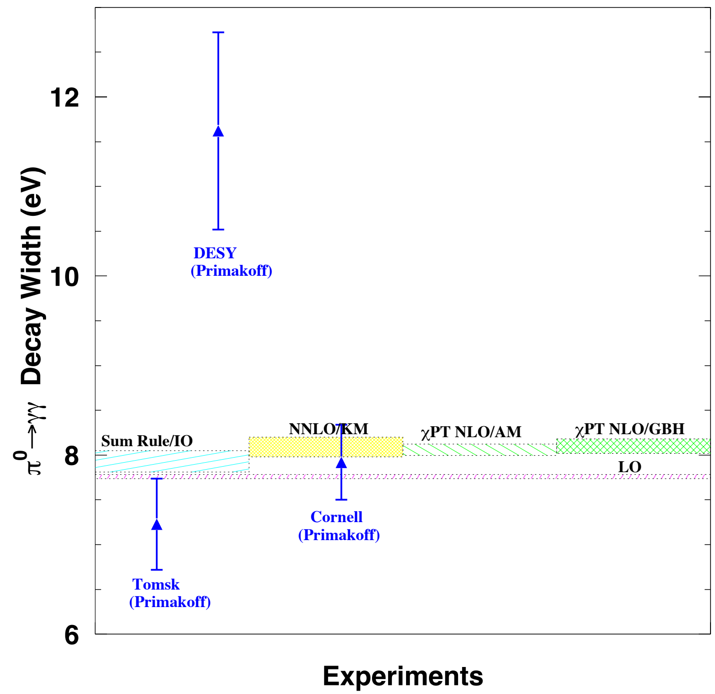
- Coherent process

Previous Primakoff Experiments

- DESY (1970) (N.C.,66A,243)
  Untagged bremsstrahlung beam,
  $E\gamma$: about 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) (Sov.Phys.JETP,30, 1037)
  Untagged bremsstrahlung beam
  $E\gamma \sim 1.1$ GeV
  target: Pb
  Result: $\Gamma(\pi^0 \to \gamma\gamma) = (7.23 \pm 0.51)$ eV
  (7.1%)

- Cornell (1974) (PRL,33,1400)
  Untagged bremsstrahlung γ beam
  $E\gamma$: about 4 and 6 GeV
  targets: Be, Al, Cu, Ag, U
  Result: $\Gamma(\pi^0 \to \gamma\gamma) = (7.92 \pm 0.42)$ eV
  (5.3%)

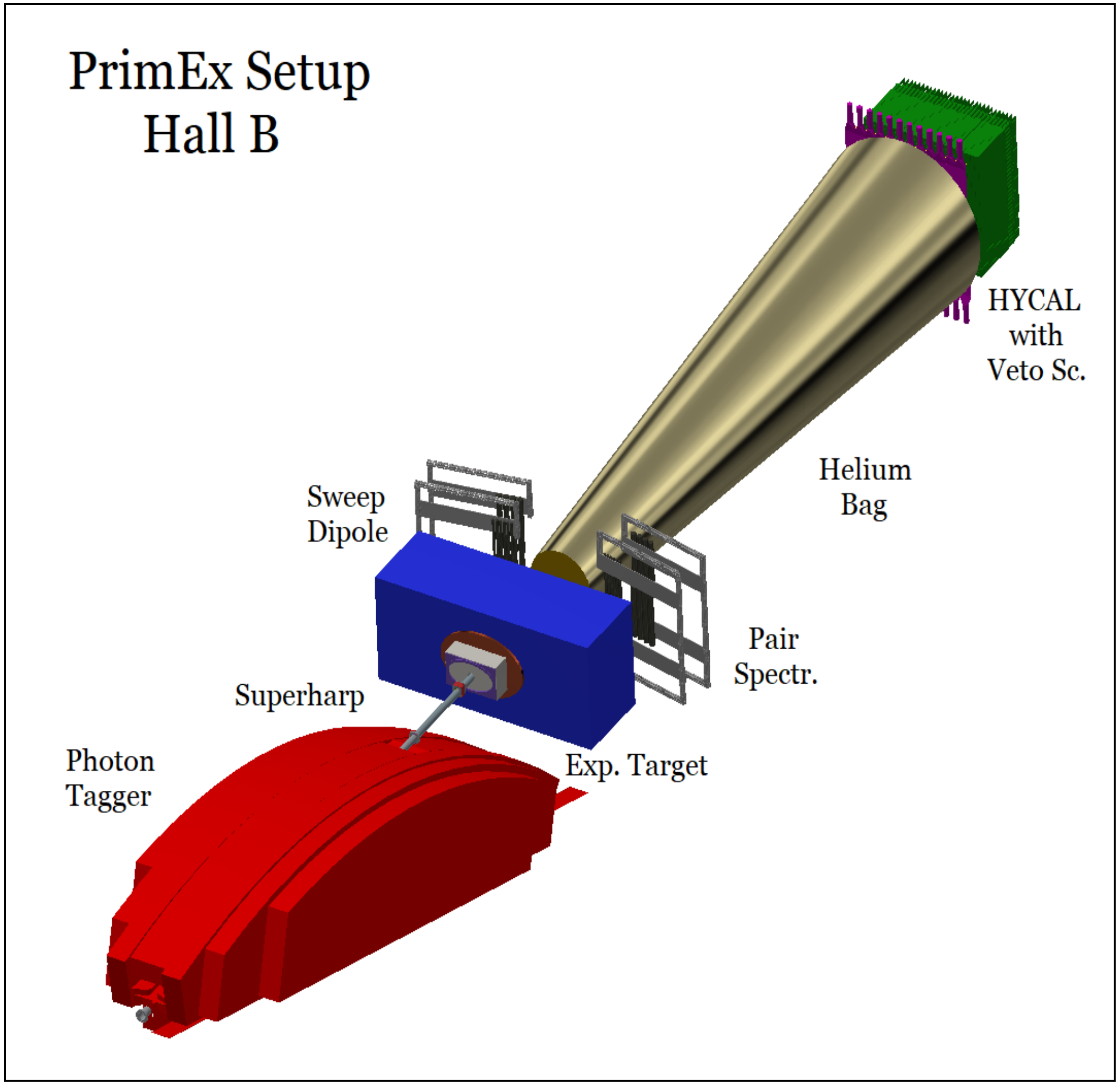


All these experiments used

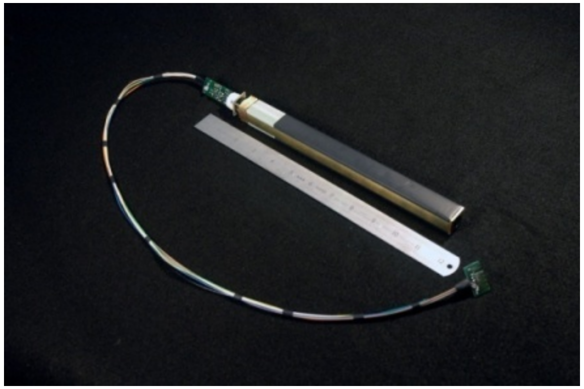
1. Untagged bremsstrahlung photon beam
2. Conventional Pb-glass calorimeter
3. Earlier theoretical calculations

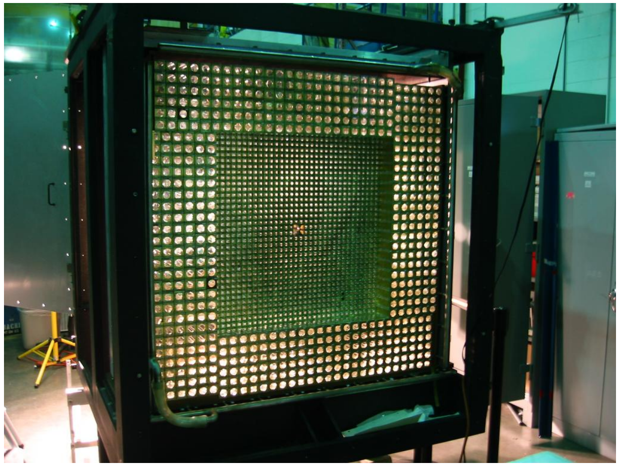
PrimEx Experimental Setup

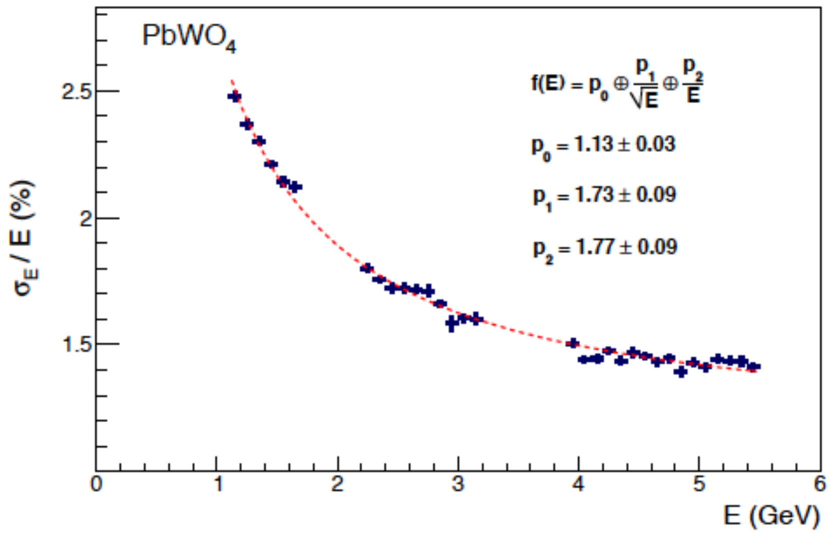
- Hall B high resolution, high intensity photon tagging facility
- A pair spectrometer for photon flux control at high beam intensities
- New high resolution hybrid multi-channel calorimeter (HyCal)

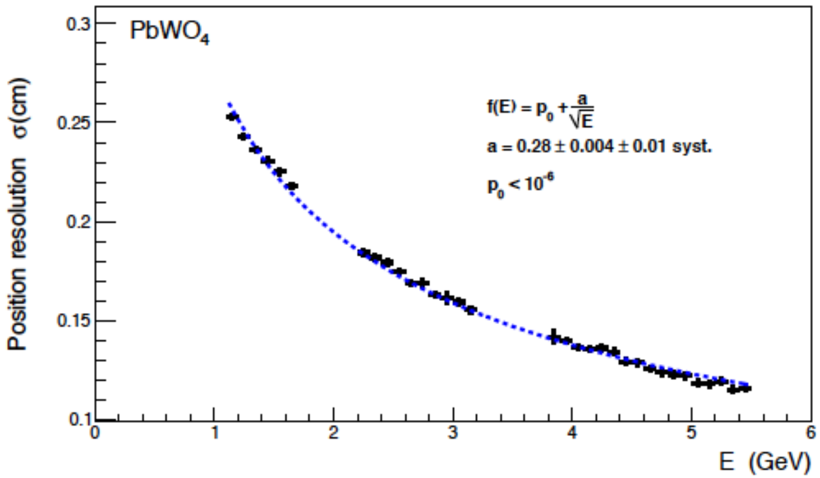


PrimEx Hybrid Calorimeter - HyCal







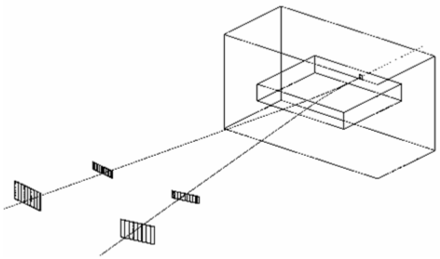


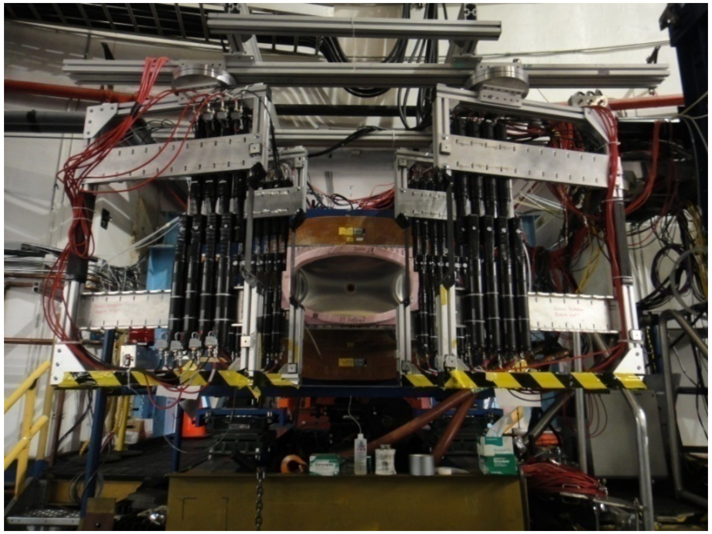
1152 $PbWO_4$ crystal detectors
576 Pb-glass Cherenkov detectors

Photon Flux Control

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

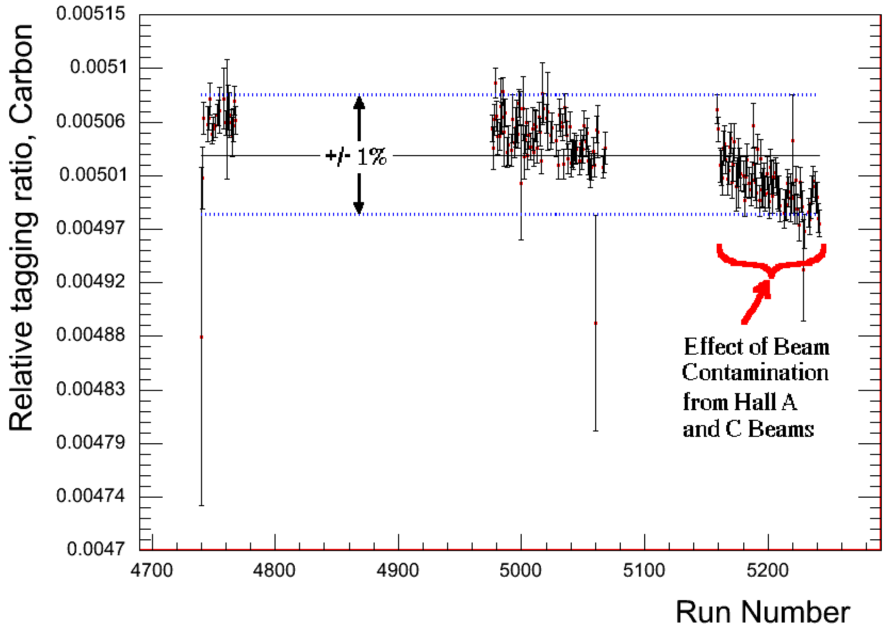
Pair Spectrometer





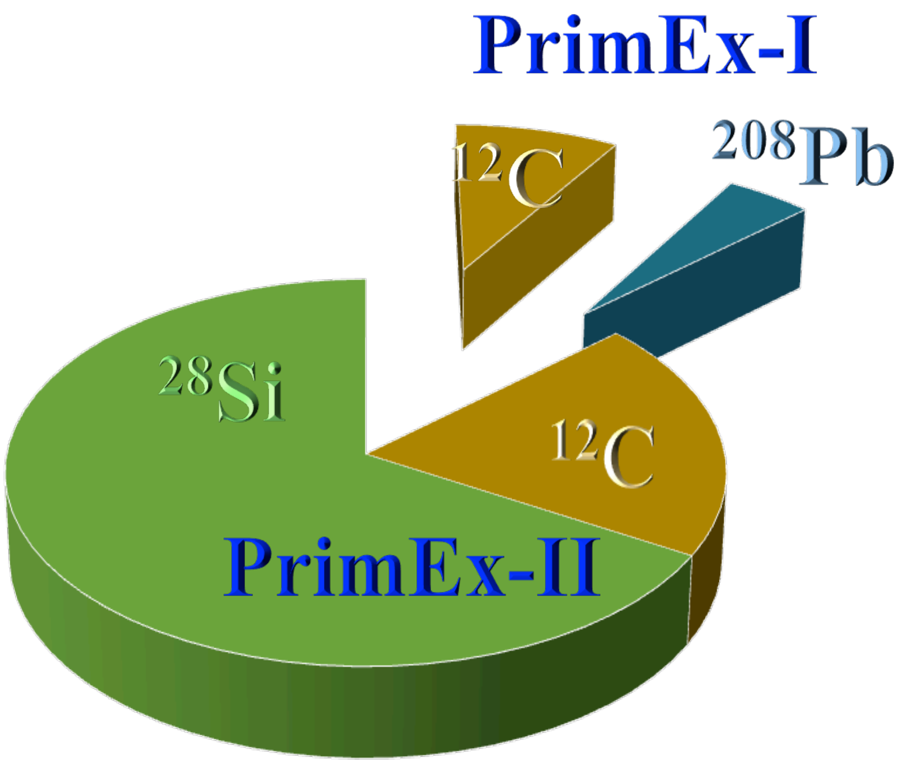
Measured in experiment:

- absolute tagging ratios
  - TAC measurements at low intensities
- relative tagging ratios:
  - pair production measured by pair spectrometer at low and high intensities



- Uncertainty of photon flux has been controlled at 1%
- Verified by measuring two well-known QED processes:
  - Compton scattering
  - e^+e^- pair production

Two Experiments: PrimEx I and II



- PrimEx I was performed on ^{12}C and ^{208}Pb targets with Eγ=4.9-5.5 GeV, and the result was published in 2011.

PRL 106, 162303 (2011)

- PrimEx II was performed on ^{12}C and ^{28}Si targets with Eγ=4.4-5.3 GeV. The result is recently finalized

Improvements for PrimEx-II

Systematics

- Better control of Background:
  - ✓ Add timing information in HyCal (~500 chan.)
  - ✓ Improve photon beam line
  - ✓ Improve PID in HyCal (add horizontal veto counters to have both x and y detectors)
  - ✓ More empty target data
- Measure HyCal detection efficiency
- New ^{28}Si target

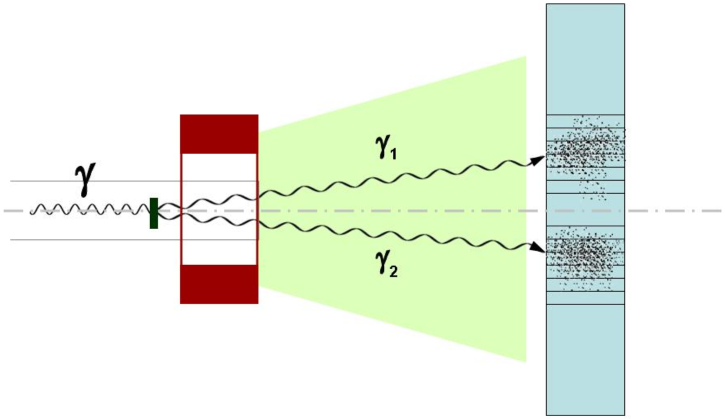
Statistics

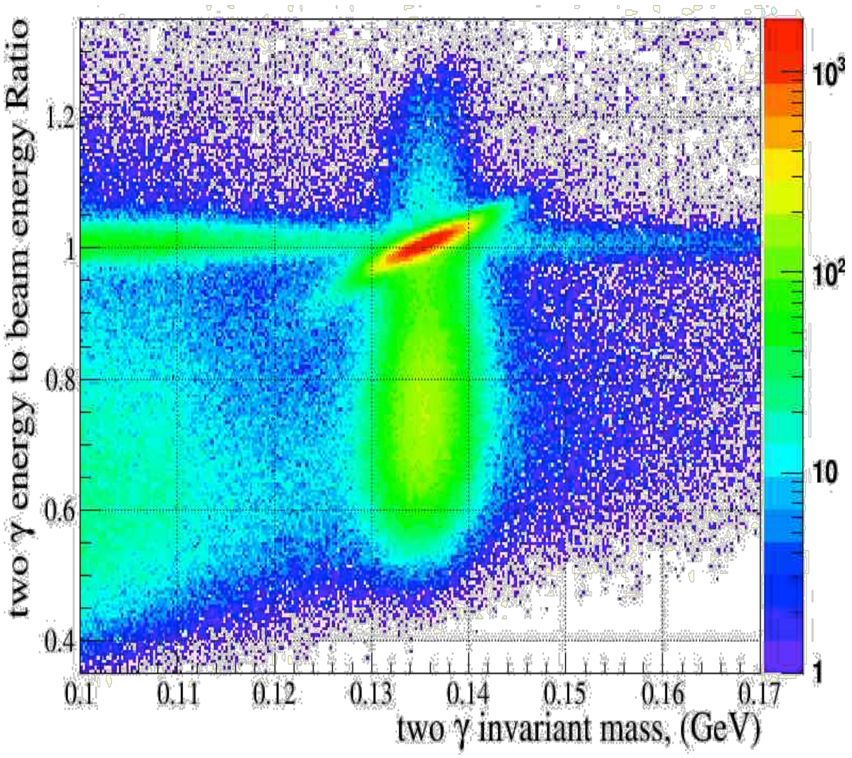
- ✓ Double target thickness (factor of 2 gain)
- ✓ Hall B DAQ with 5 kHz rate, (factor of 5 gain)
- ✓ increase photon beam energy interval by 50% in the trigger

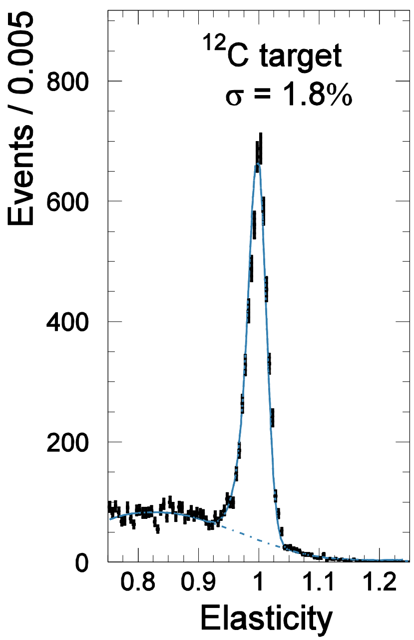
π^0 Event selection

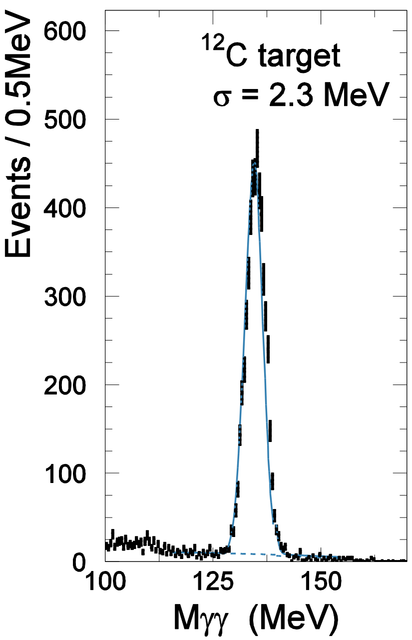
We measure:

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





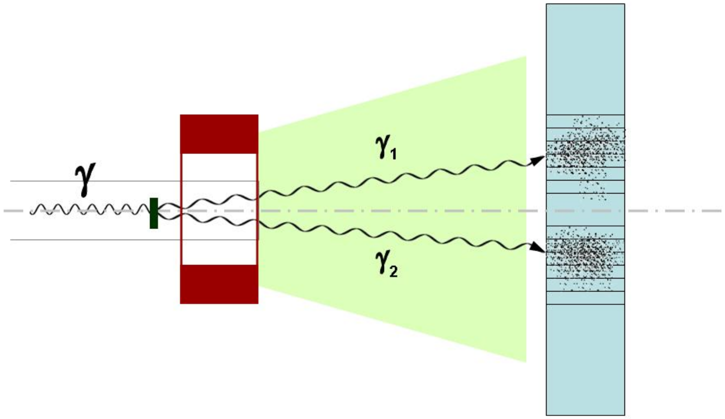


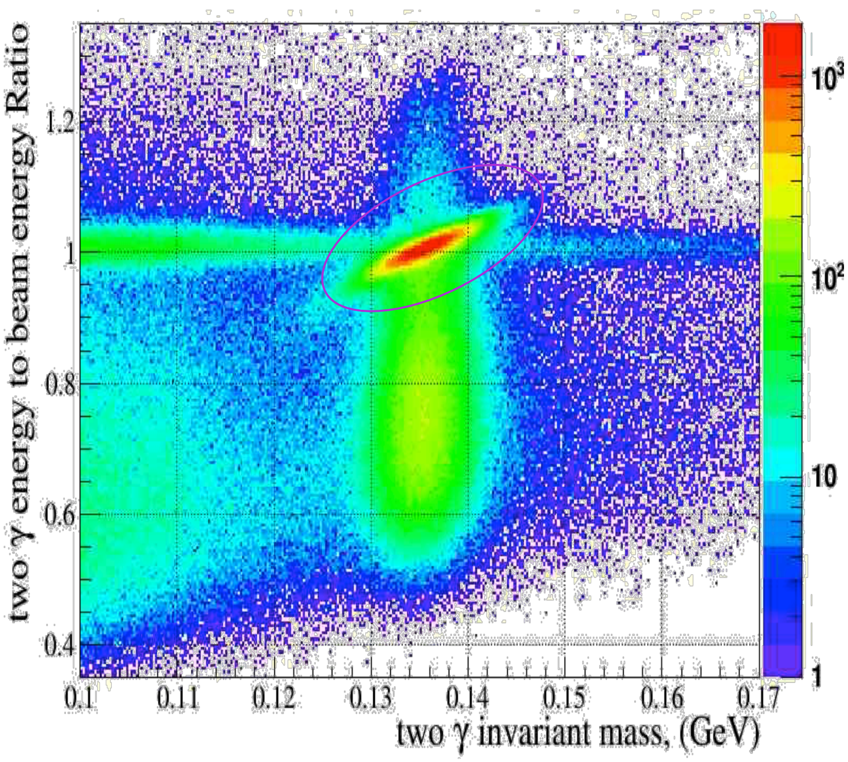


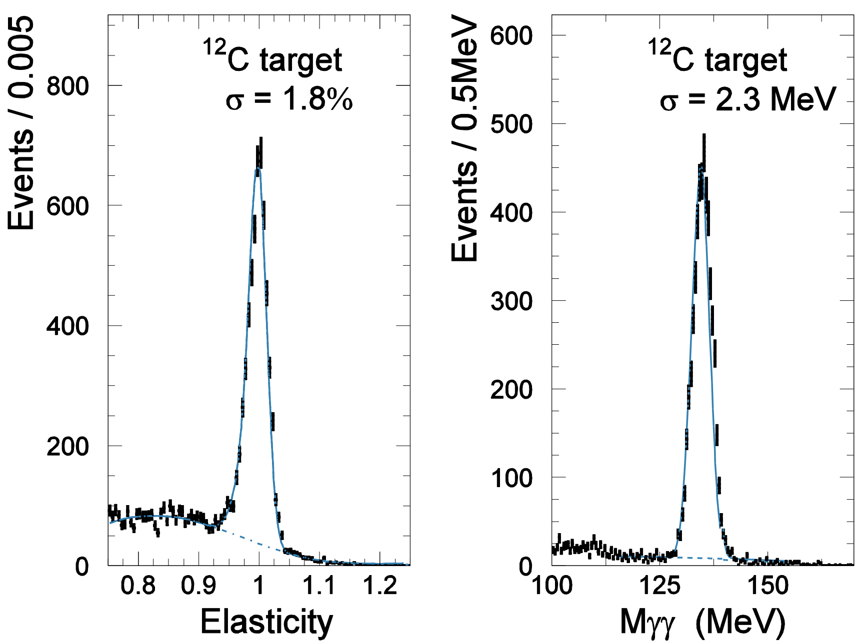
π^0 Event selection

We measure:

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



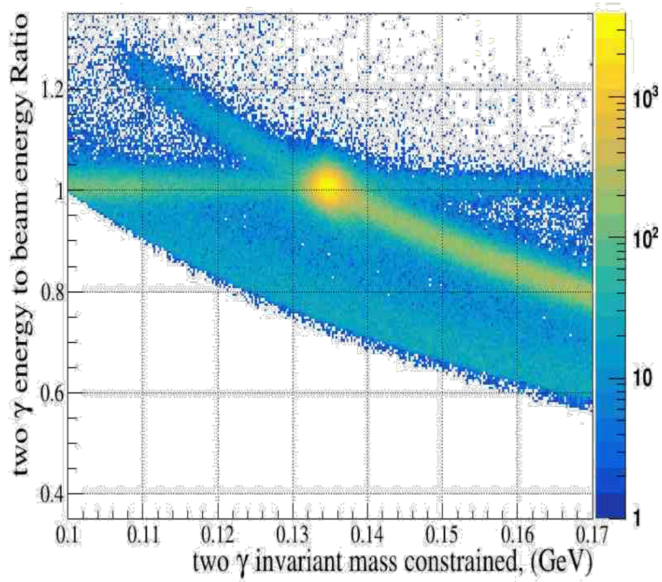




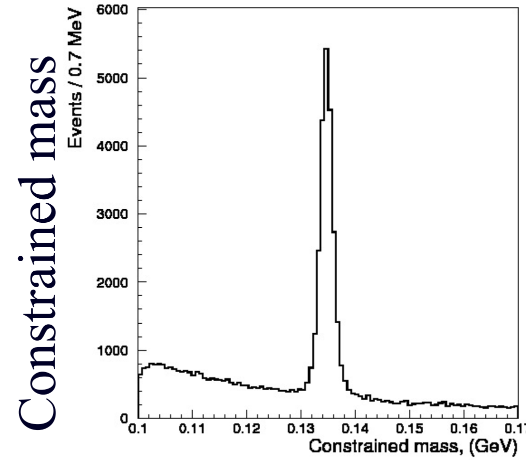
Two Methods for π^0 yield extraction

- **Energy Constrained mass analysis (C)**

  by I. Larin, Umass

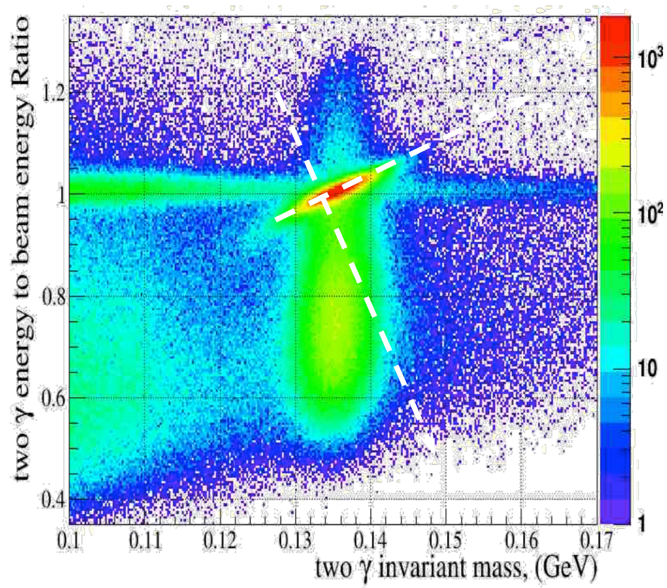


C-analysis

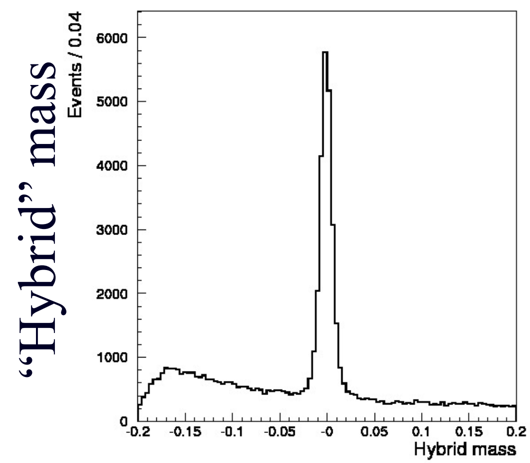


- **Hybrid mass analysis (H)**

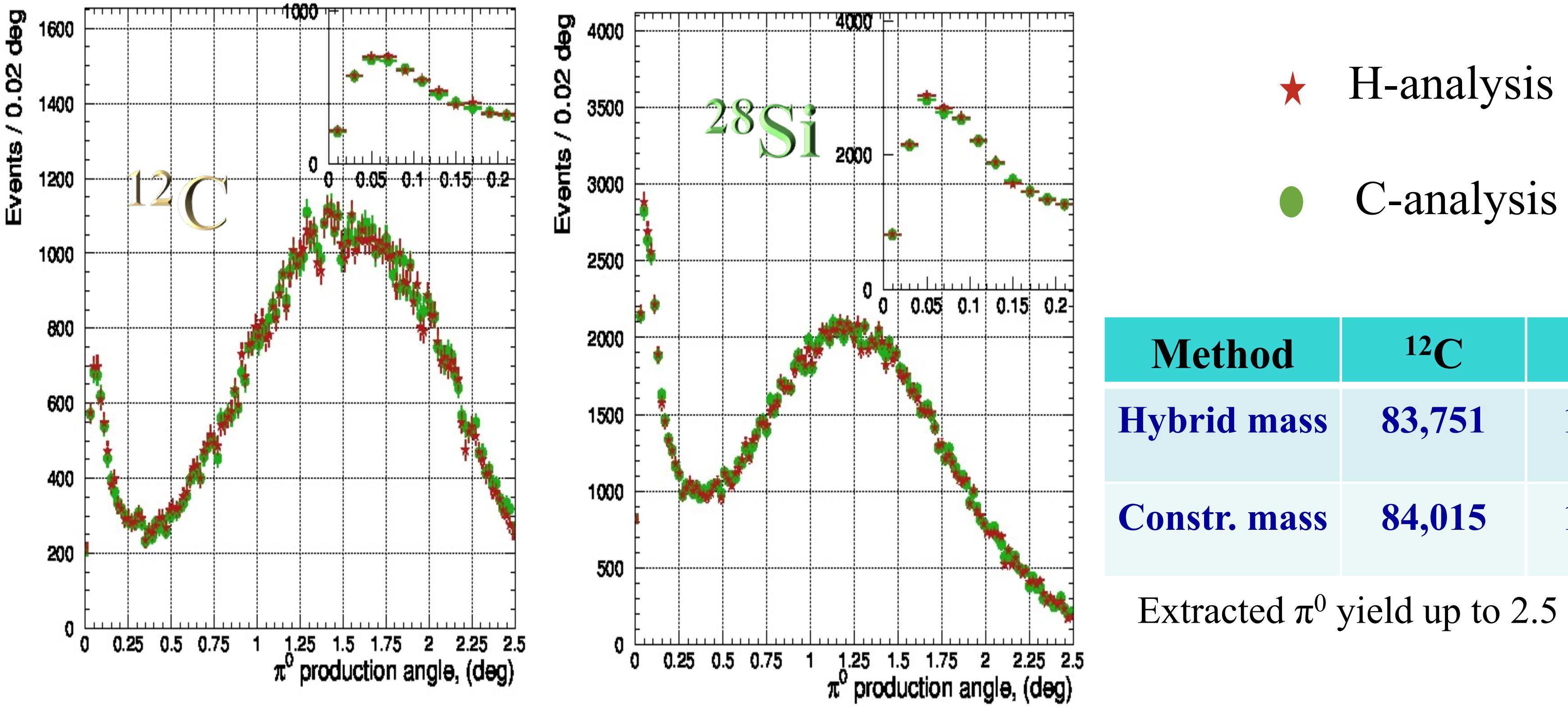
  by Y. Zhang, Duke Univ.



H-analysis



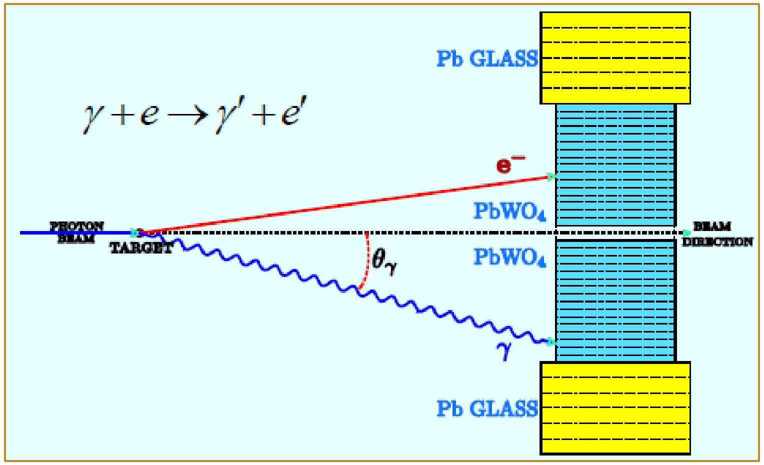
Comparison of yield extraction methods
(PrimEx-II)

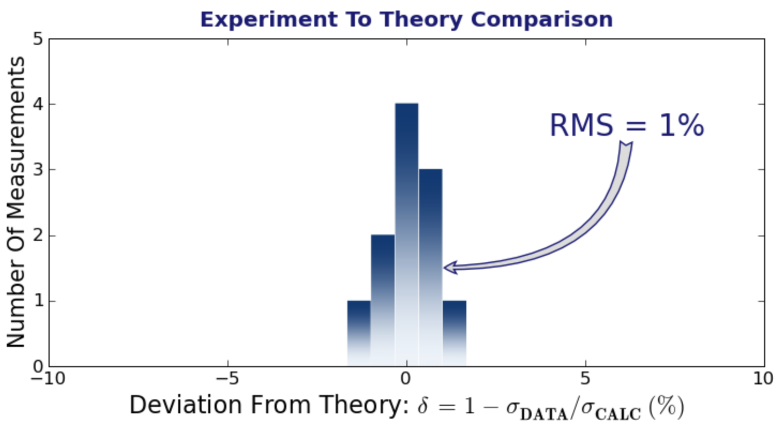


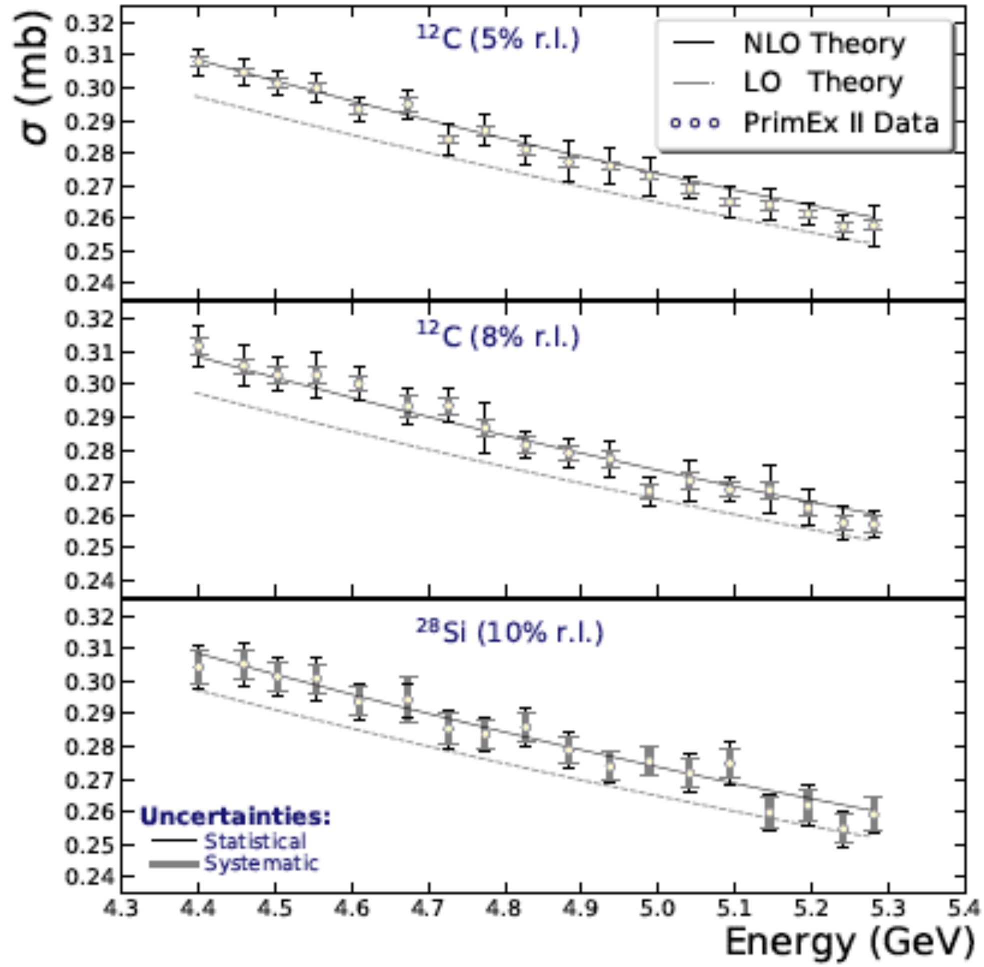
Method	^{12}C	^{28}Si
Hybrid mass	**83,751**	**165,329**
Constr. mass	**84,015**	**165,736**

Extracted π^0 yield up to 2.5 deg.

Verification of Overall Experimental Systematics with Compton Scattering



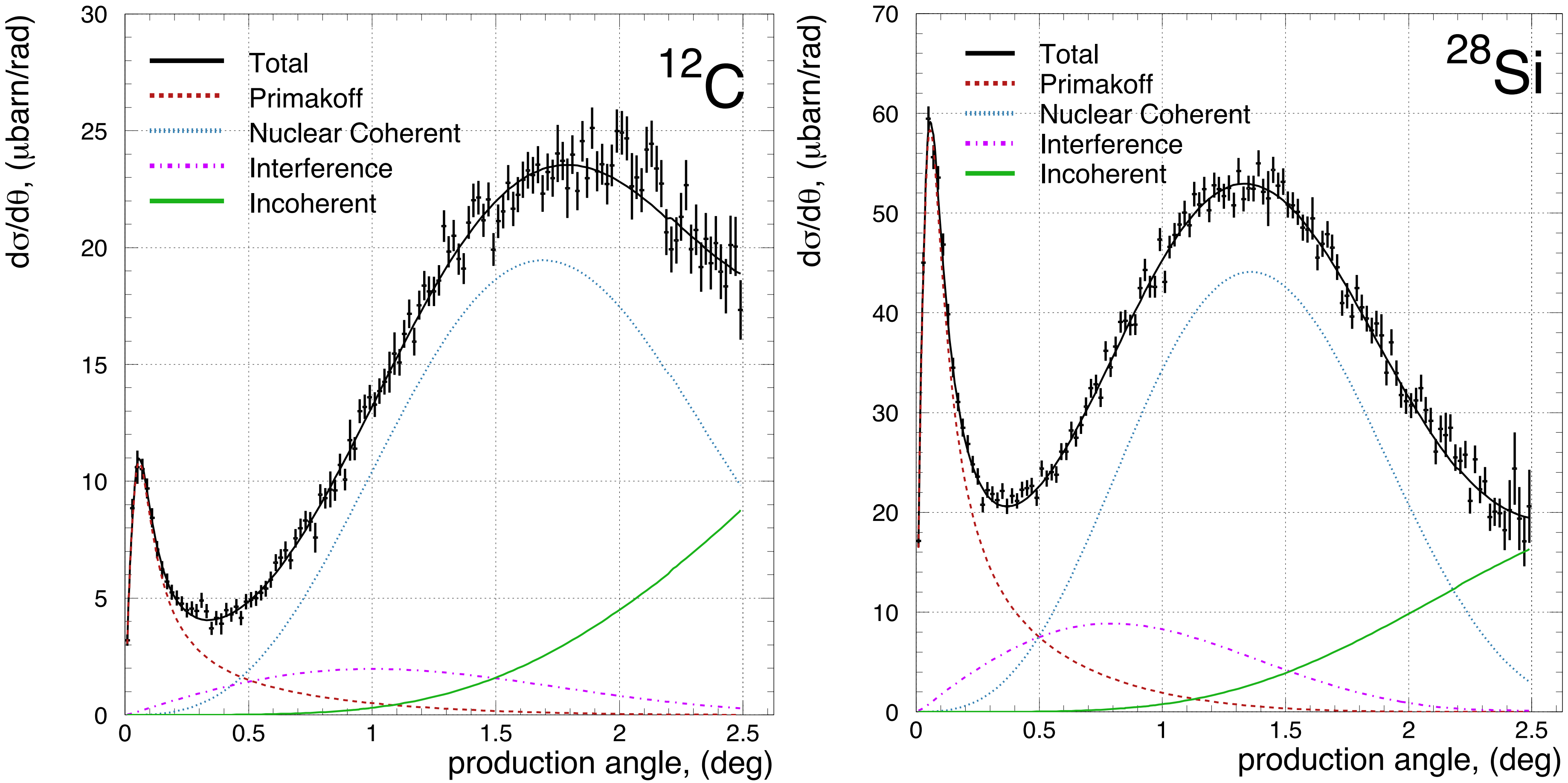




Systematic uncertainties of measured cross section are controlled at 1.5%

Measured Differential Cross Sections

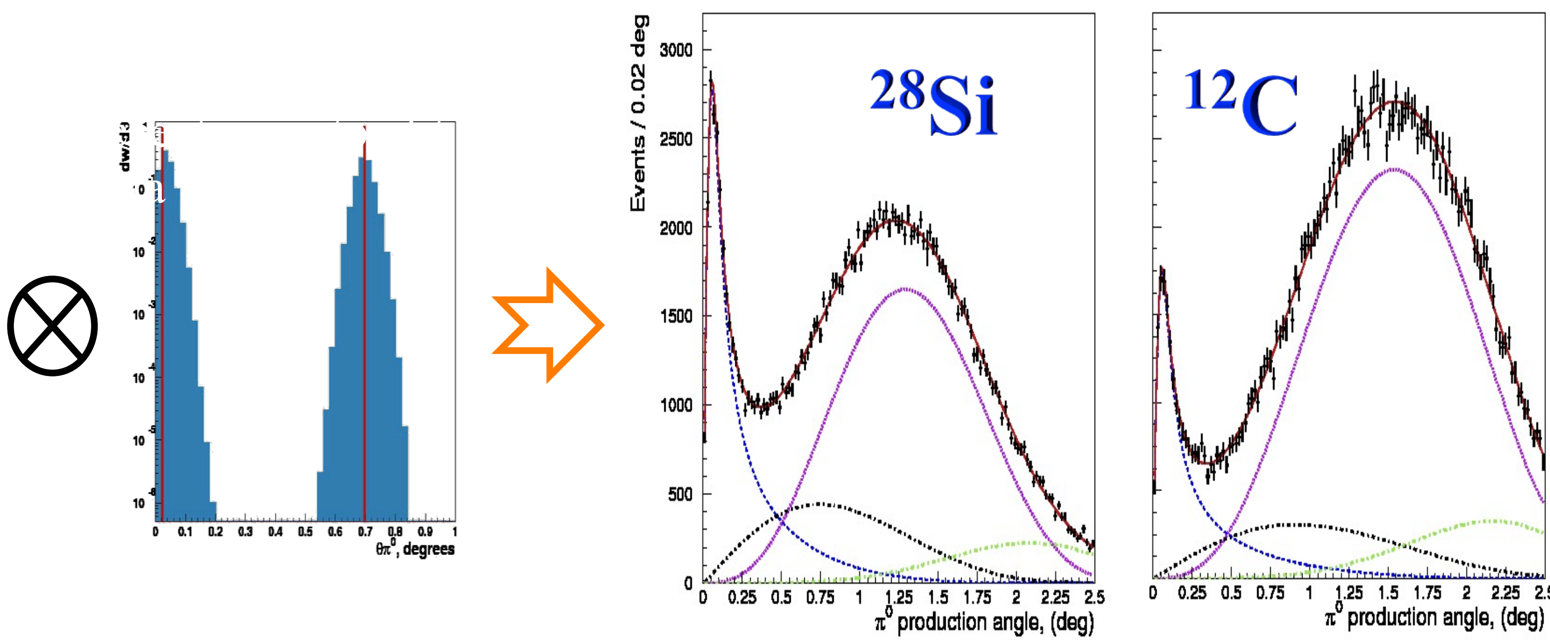
$\gamma + A \rightarrow \pi^0 + A$



Extraction of $\Gamma(\pi^0 \to \gamma\gamma)$

- **Theoretical angular distributions smeared with experimental resolutions**
- **Fit the experimental yield (normalized with the luminosity and the detection efficiency) to extract $\Gamma(\pi^0 \to \gamma\gamma)$**

$$\left(\frac{d\sigma}{d\Omega}\right)_{P_r} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{em}(Q)|^2 \sin^2\theta_\pi$$

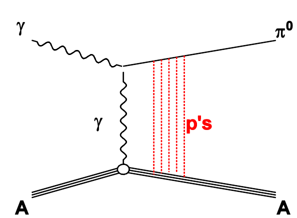


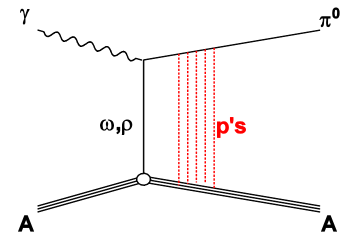
Theoretical Calculations

Coherent Production $\gamma+A\rightarrow\pi^0+A$

- ❑ 1964, G. Morpurgo, Neuovo Cimento, 31, 569
  - ✓ Strong absorption for outgoing pion in uniform nuclear density

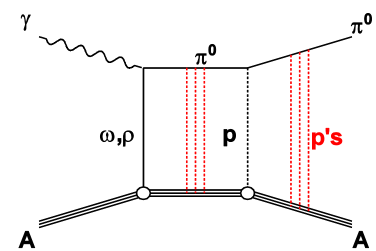
    Used for Tomsk and DESY Primakoff Exp.





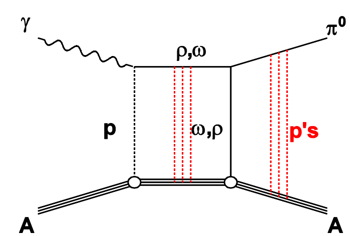
- ❑ 1972, G. Faldt, Nucl. Phys. B43, 591
  - ✓ Strong absorption in a nucleus for both incident and produced particles
  - ✓ final state pion re-scattering in nucleus
  - ✓ corrections for light nuclei

    Used for Cornell exp.

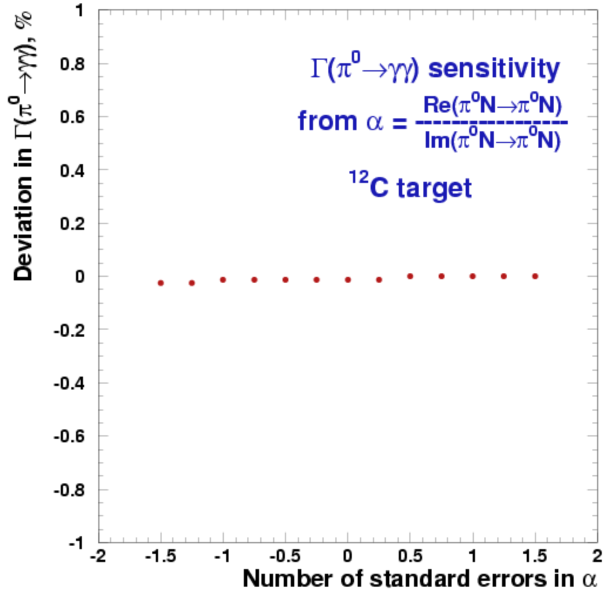


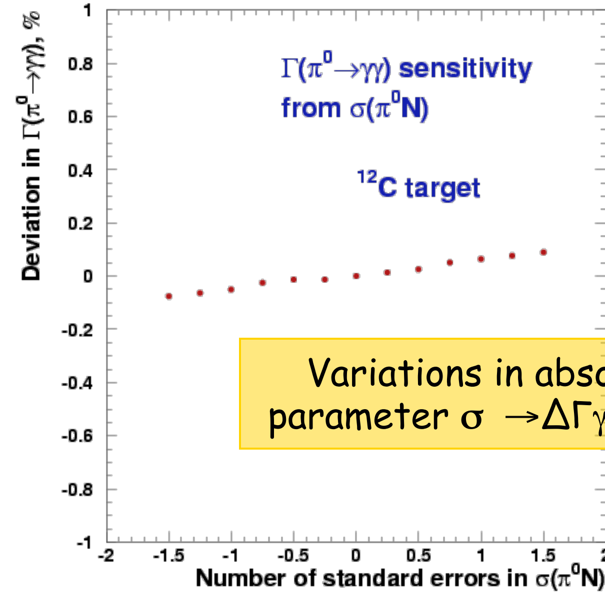
- ❑ 2009, S. Gevorkyan *et. al.*, Phys.Rev. C80, 055201, PrimEx note #85
  - ✓ Strong absorption in a nucleus for initial and final states
  - ✓ the final state pion re-scattering in nucleus
  - ✓ corrections for light nuclei
  - ✓ photon shadowing effect
  - ✓ Pion form factor

    Used for PrmEx

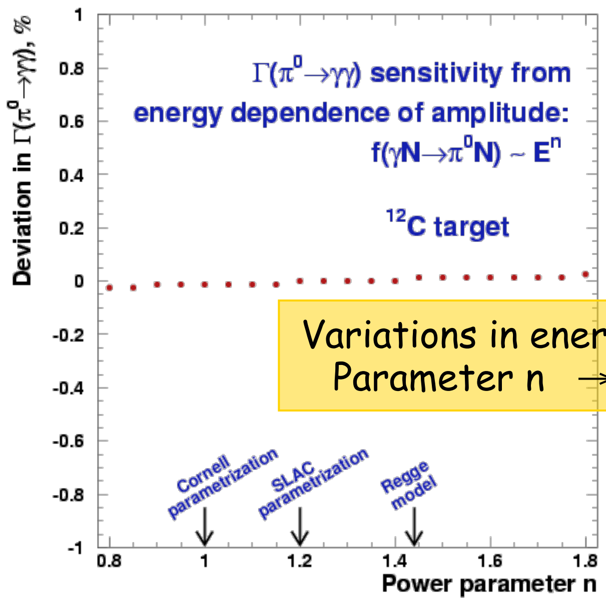


$\Gamma(\pi^0 \to \gamma\gamma)$ dependence on model parameters

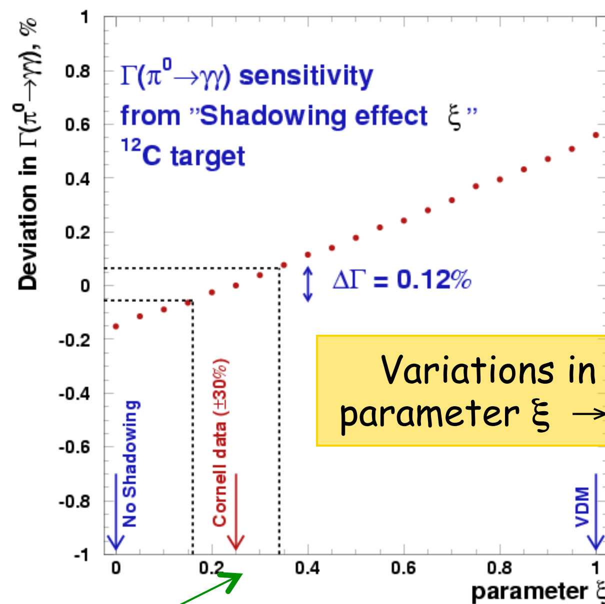




Variations in absorption parameter σ $\to \Delta\Gamma_{\gamma\gamma}$ <0.06%



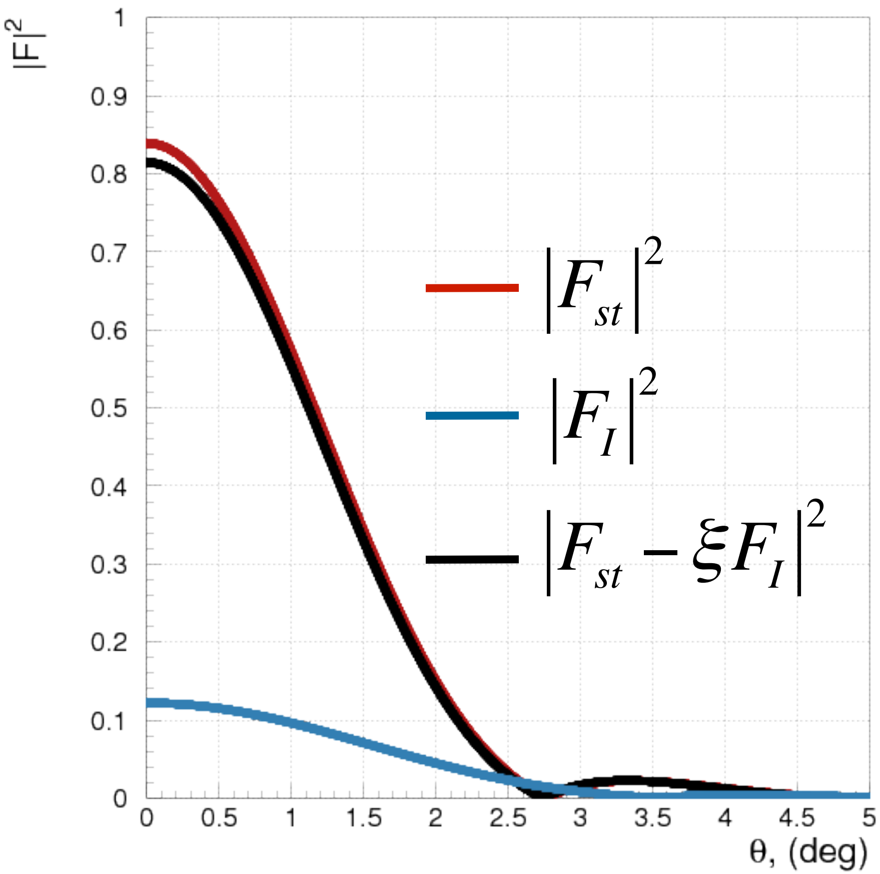
Variations in energy dependence Parameter n $\to \Delta\Gamma_{\gamma\gamma}$ <0.04%

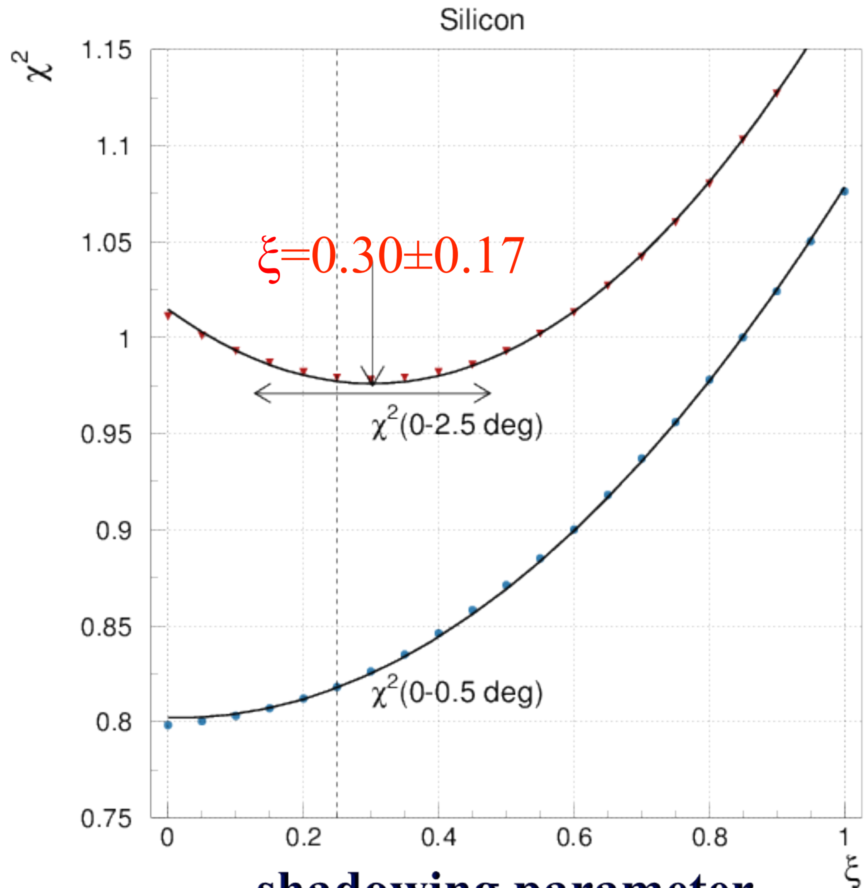


Variations in shadowing parameter ξ $\to \Delta\Gamma_{\gamma\gamma}$ <0.06%

Phys. Rev. Lett. 28, 1344 (1972)

Shadowing parameter from PrimEx-II Data

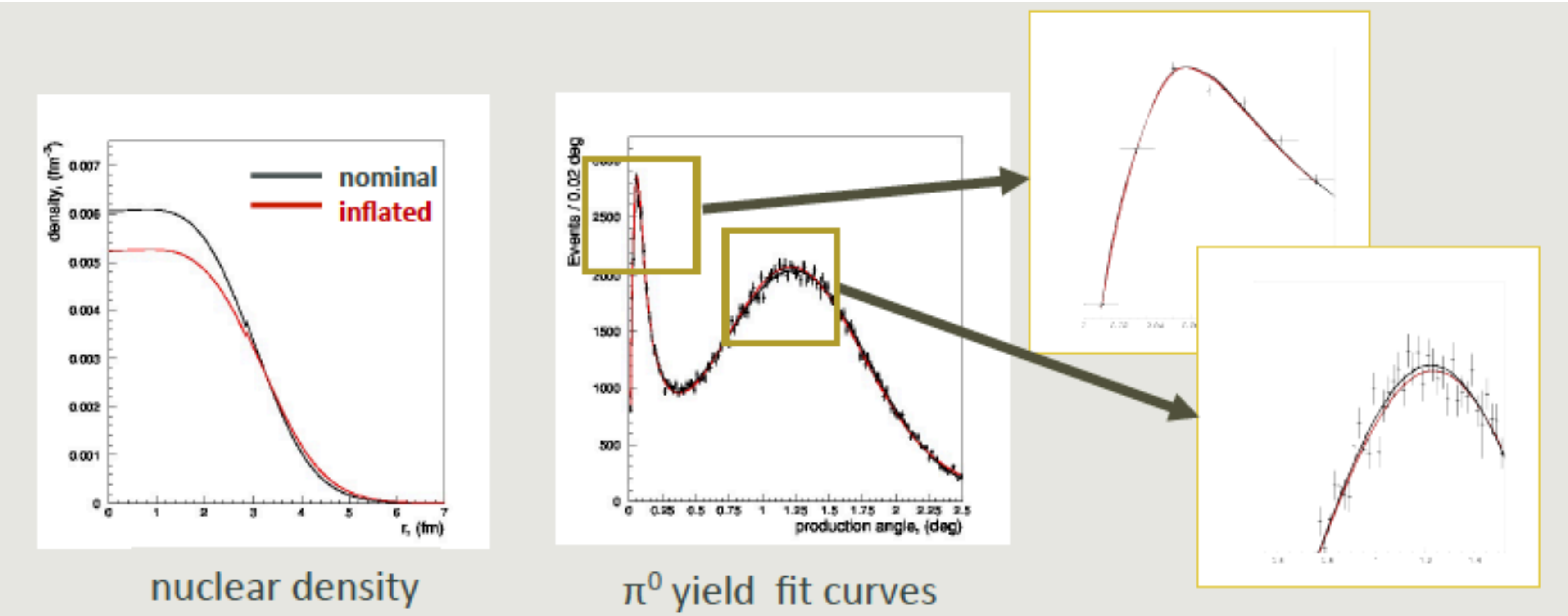




The measured value of ξ=0.25* from the previous experiment is used in PrimEx analysis

* *W. Meyer et al., Phys. Rev. Lett. 28, 1344 (1972); A. M. Boyarski et al., Phys. Rev. Lett. 23, 1343 (1969)*

Effects of nuclear density models



Three nuclear density models are compared

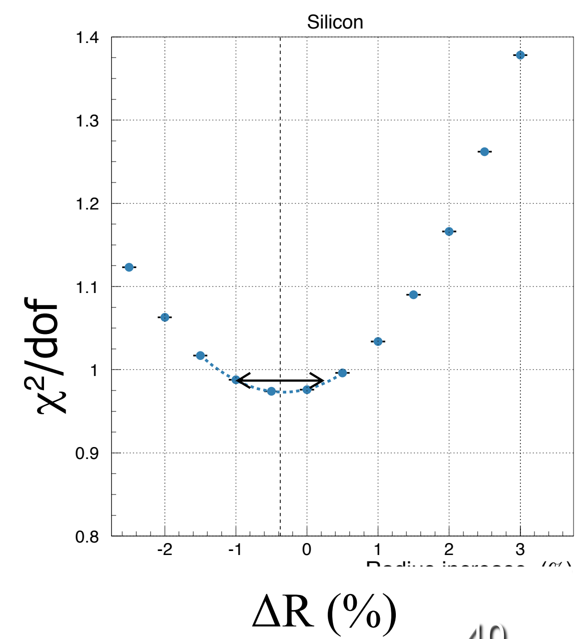
- Harmonic Oscillator,
- 3 parameter Fermi,
- Fourier-Bessel, ← Best for describing PrimEx data

Extracted $\Gamma(\pi^0\to\gamma\gamma)$ vs. Nuclear Matter Radius

Slope a_p (fm^2)	Target	Radius ΔR**	$\Gamma(\pi^0\to\gamma\gamma)$ (eV)
0.4*	^{28}Si	-0.33%±0.6% (stat)	7.78 (±0.17% sys)
	^{12}C	-1.4%±1.8% (stat)	7.74 (±0.52% sys)
0.24	^{28}Si	2.2%±0.4% (stat)	7.77 (±0.14% sys)
	^{12}C	2.5%±1.4% (stat)	7.75 (±0.39% sys)

$$\frac{d\sigma(\gamma N\to\pi^0 N)}{dt} = \left|f_N(0)\right|^2 e^{-a_p q^2}$$

Extracted $\Gamma(\pi^0\to\gamma\gamma)$ is not sensitive to parameters of nuclear radius and slope of $\sigma(\gamma N\to\pi^0 N)$



*ArXiv:1806.08414; J.Eur.Phys.,A41,71

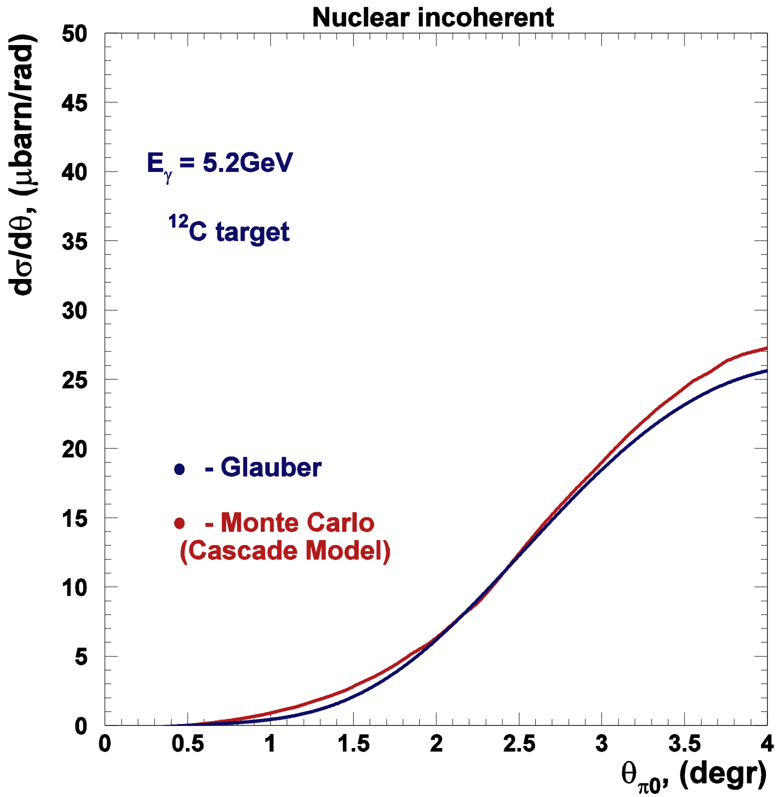
**Changes of matter radius relative to the nuclear charge radius listed in Atom.Nucl.Tab.(1987) from the electron scattering exp.

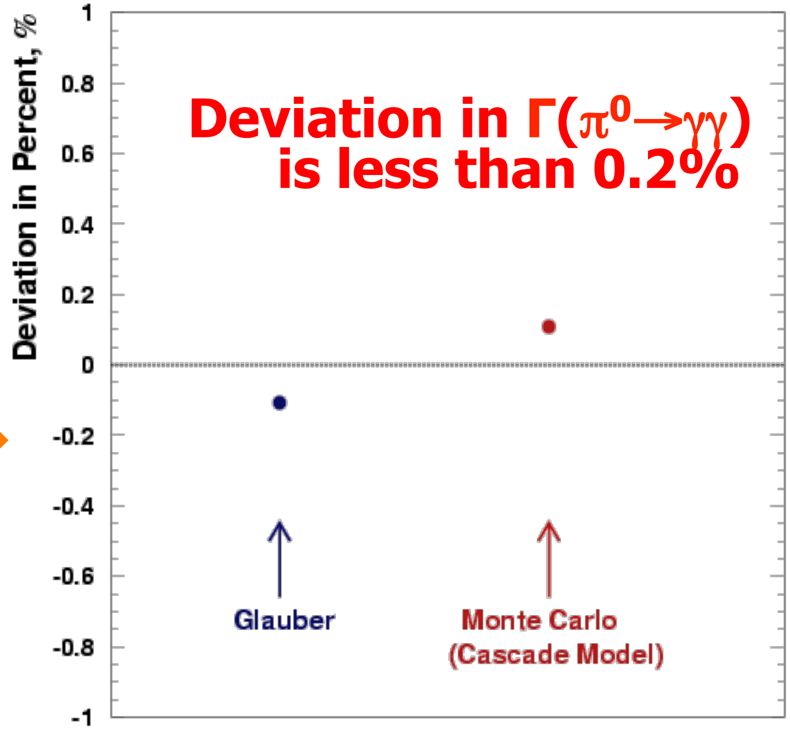
Theoretical Calculation (cont.)

Incoherent Production $\gamma + A \rightarrow \pi^0 + A'$

Two independent approaches:

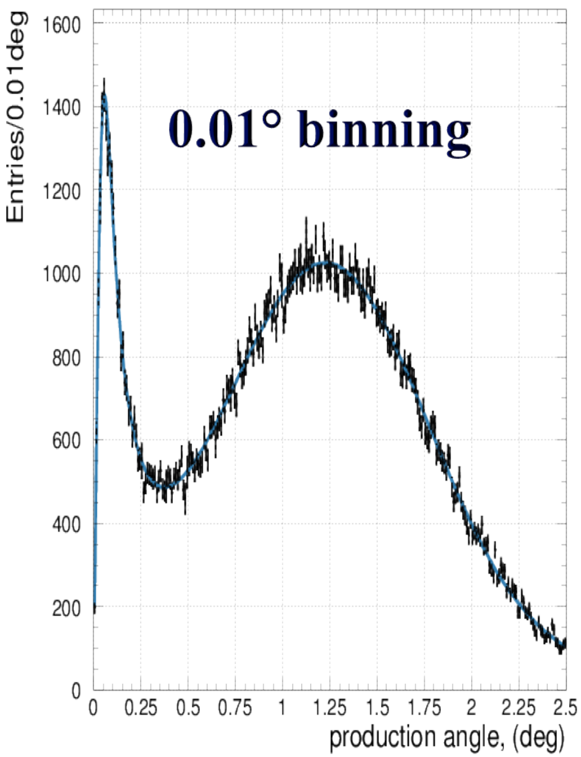
- Glauber theory, Phys.Part.Nucl.Lett.,9,3 (2012)
- Cascade Model, Phys.Rev.Lett.,101, 012301 (2008)



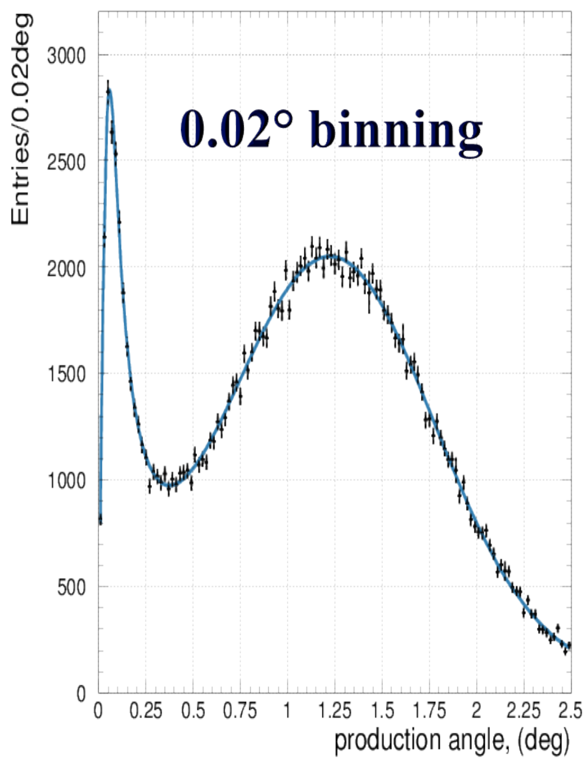


Uncertainty due to angular binning

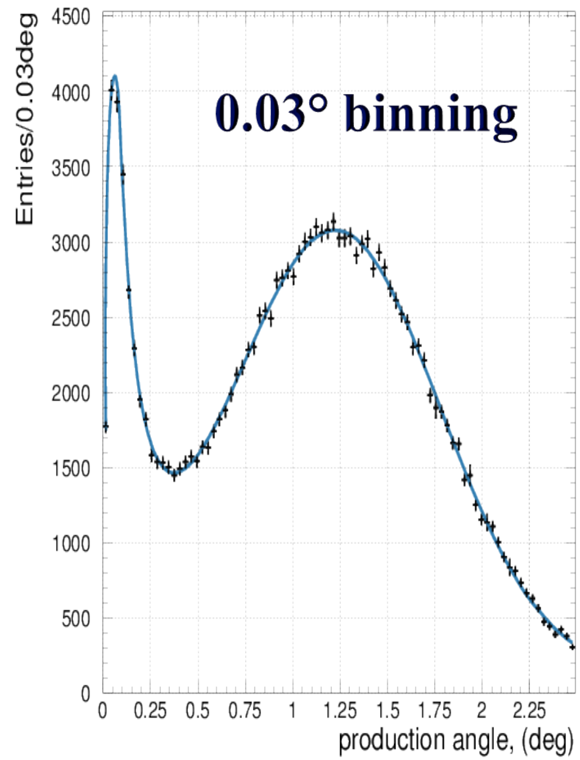
^{28}Si target



$\Gamma = 7.769 \pm 0.066 eV$
$\chi^2/Ndf = 0.956$



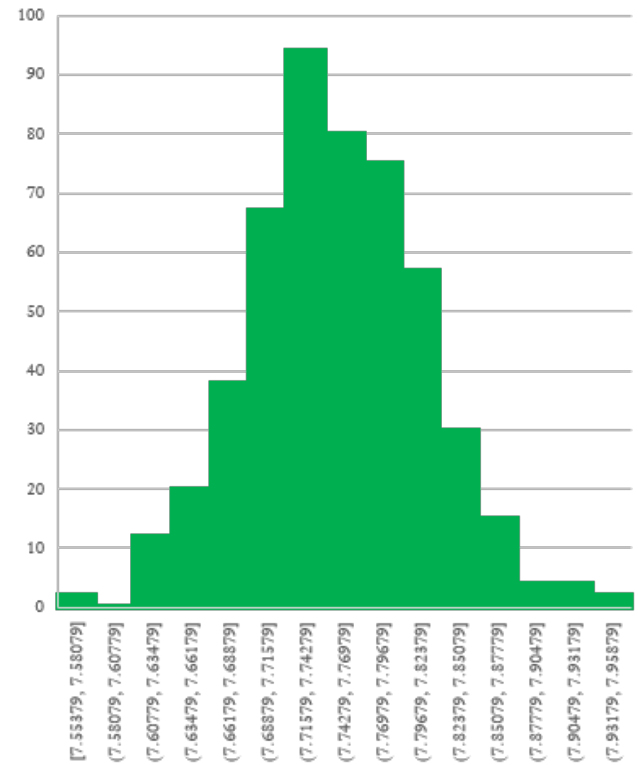
$\Gamma = 7.769 \pm 0.064 eV$
$\chi^2/Ndf = 1.225$



$\Gamma = 7.776 \pm 0.064 eV$
$\chi^2/Ndf = 1.052$

Uncertainty due to fitting procedure

- 500 sets of Monte-Carlo data sample with predefined parameters (Γ, nuclear coherent, interference, and incoherent amplitudes)
- Each MC data set has the same statistics as the experimental data
- Add the background from experimental data
- $\Gamma(\pi^0 \to \gamma\gamma)$ is extracted by fitting these MC samples



Uncertainty due to fitting procedure:

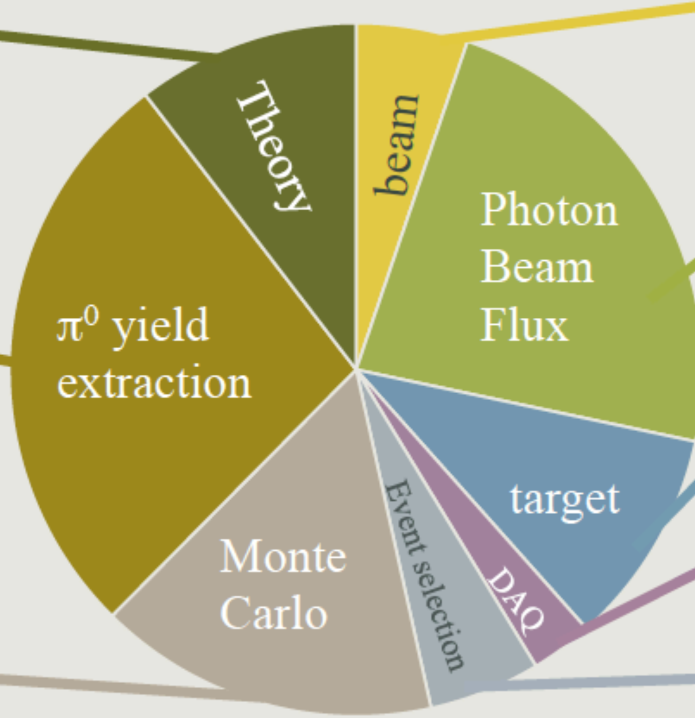
Analysis	C-analysis	H-analysis
Uncertainty	0.2%	0.65%

PrimEx-II $\Gamma(\pi^0 \to \gamma\gamma)$ systematic breakdown for ^{28}Si

πN cross section	0.1%
Shadowing effect amplitude	0.31%
Nuclear coherent parameterization	0.08%
Incoherent model	0.08%
Non-zero spin admixture	$\leq$0.1%
Nuclear strong vs EM radius	0.20%
Total	0.40%

Background shape	0.4%
Fitting range	0.4%
Empty target subtraction	0.2%
Fit parameter uncertainty	0.5%
Signal accounting	0.55%
Omega/rho background subtraction	0.09%
Bin migration at zero angle	0.2%
dN/dθ binning 0.01°, 0.02°, 0.03°	0.12%
Extraction from MC test	0.2%
Total	0.93%

Target absorption	0.24%
Pi0 angular resolution	0.17%
Pi0 two gamma decay branching	0.034%
Calorimeter geometry	0.05%
Calorimeter energy response	0.45%
Limited statistics	0.02%
Total	0.54%



Energy	0.14%
Position	0.05%
Slope	0.09%
Width	0.12%
Total	0.24%

Absolute tagging ratio	0.37%
Electron counting	0.55%
Beam collimation	0.18%
Relative tagging ratio	0.4%
Total	0.80%

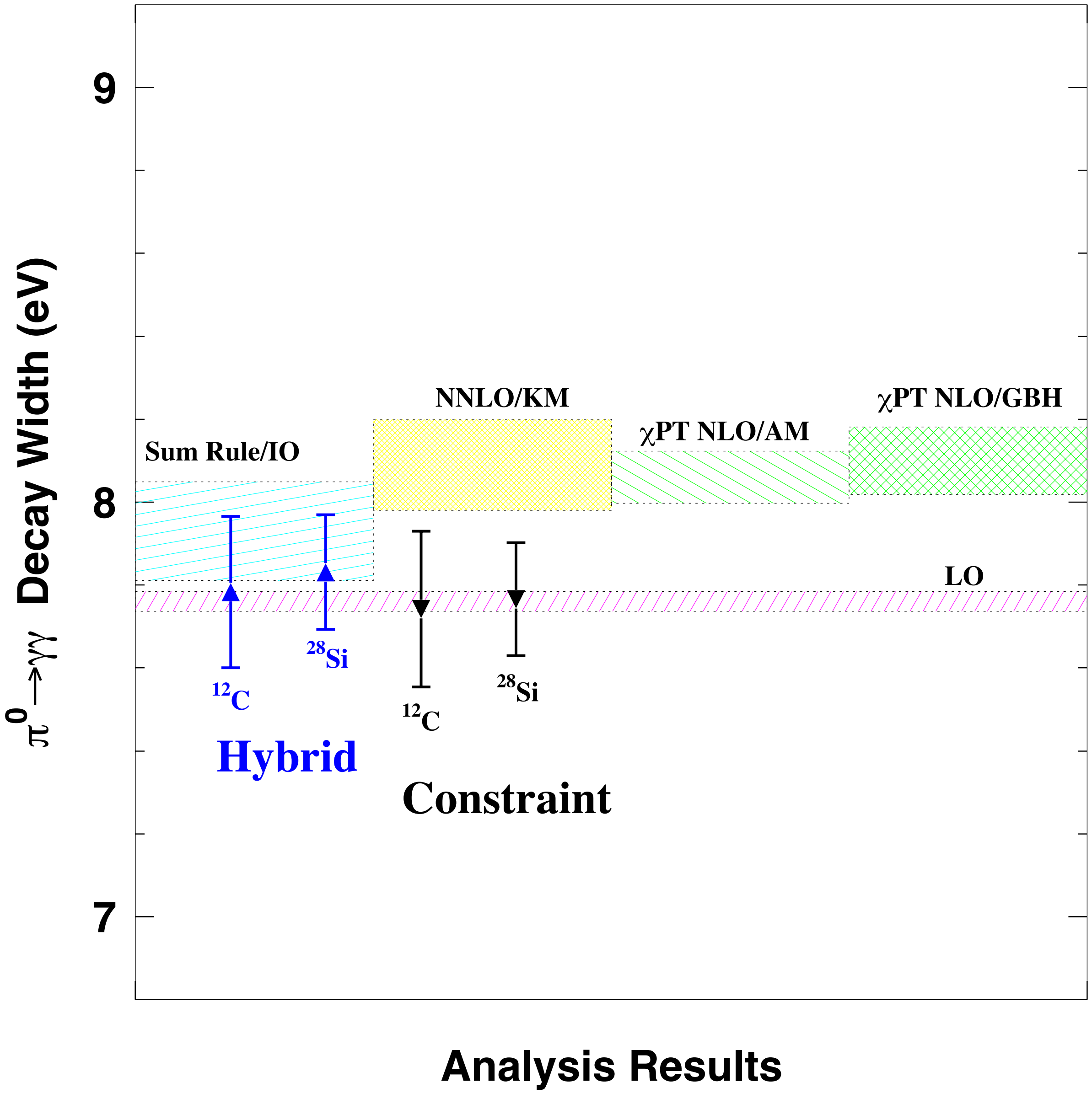
Density	0.35%
Thickness	0.03%
Purity	<0.01%
Total	0.35%

Trigger efficiency	<0.1%
ADC errors	<0.1%
Dead channels	<0.1%
Total	0.1%

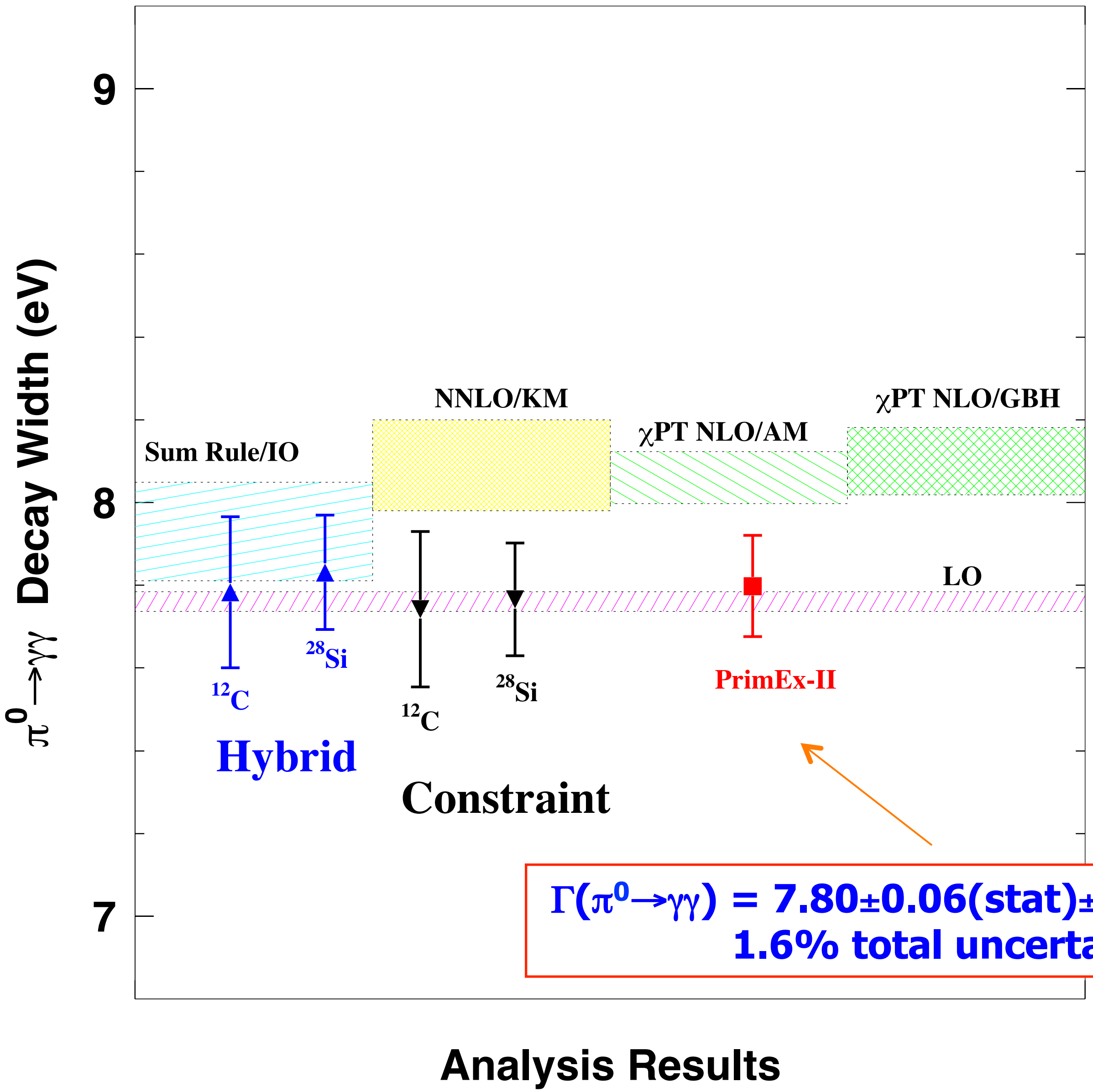
Gamma energy cut	0.1%
Pion energy cut	<0.1%
Time window	0.05%
Wrong beam candidate	0.10%
Total	0.18%

from I. Larin

PrimEx-II Analyses



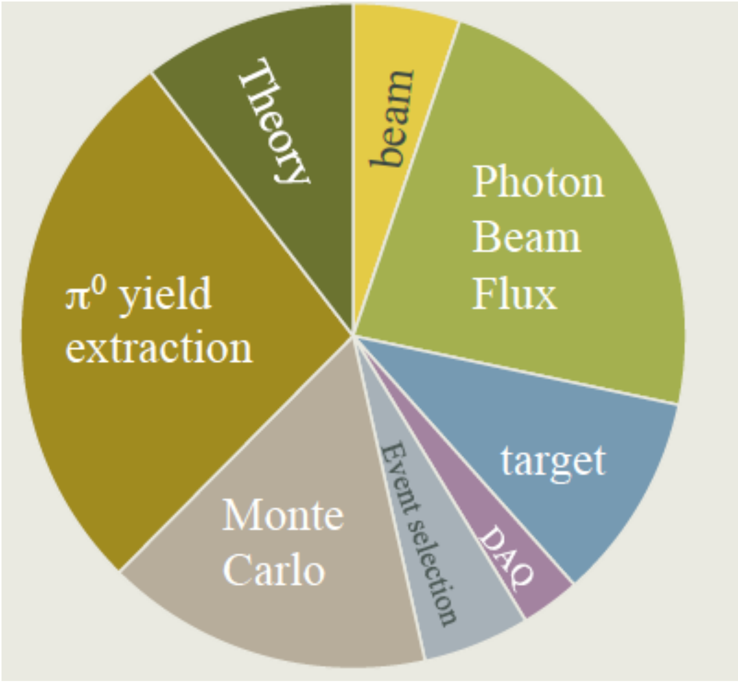
PrimEx-II Result



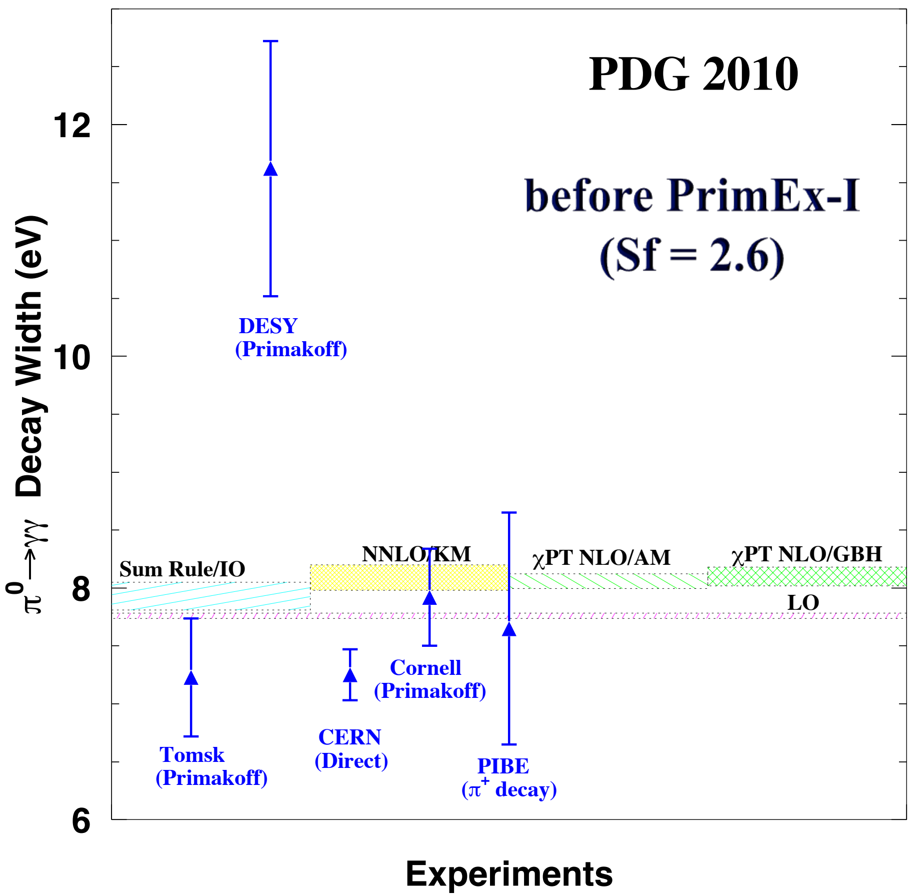
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.80±0.06(stat)±0.11(syst) eV
1.6% total uncertainty

Uncertainties of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

Item	PrimEx-II
Beam parameters	0.2%
Photon flux	0.8%
Target	0.3%
DAQ	0.1%
Event selection	0.2%
Monte-Carlo simulation	0.6%
Yield extraction	1.0%
Photoproduction theory parameters	0.4%
Systematics	**1.5%**
Statistical	0.7%
Total	**1.6%**



Impact of PrimEx result



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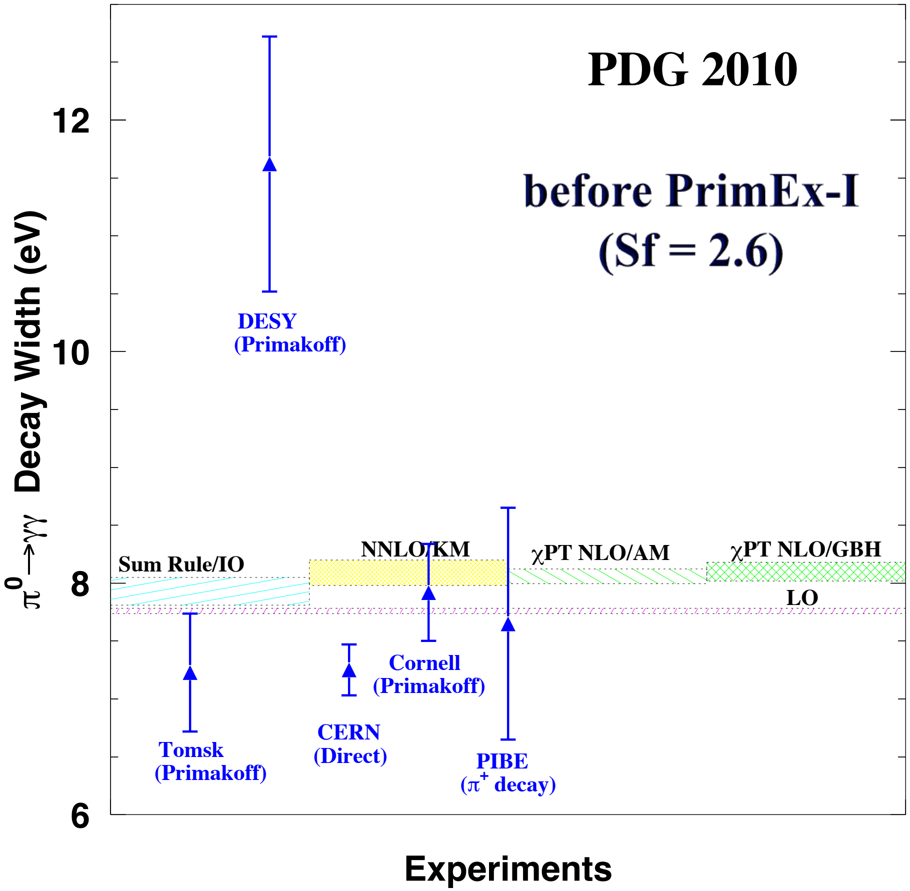
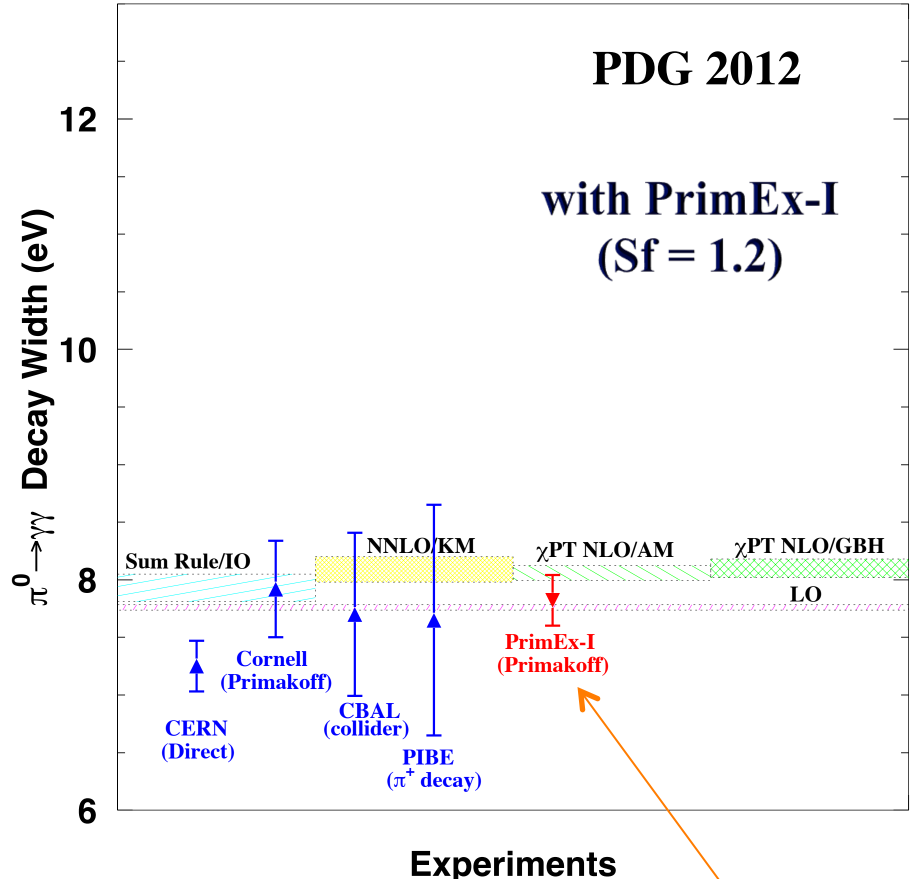
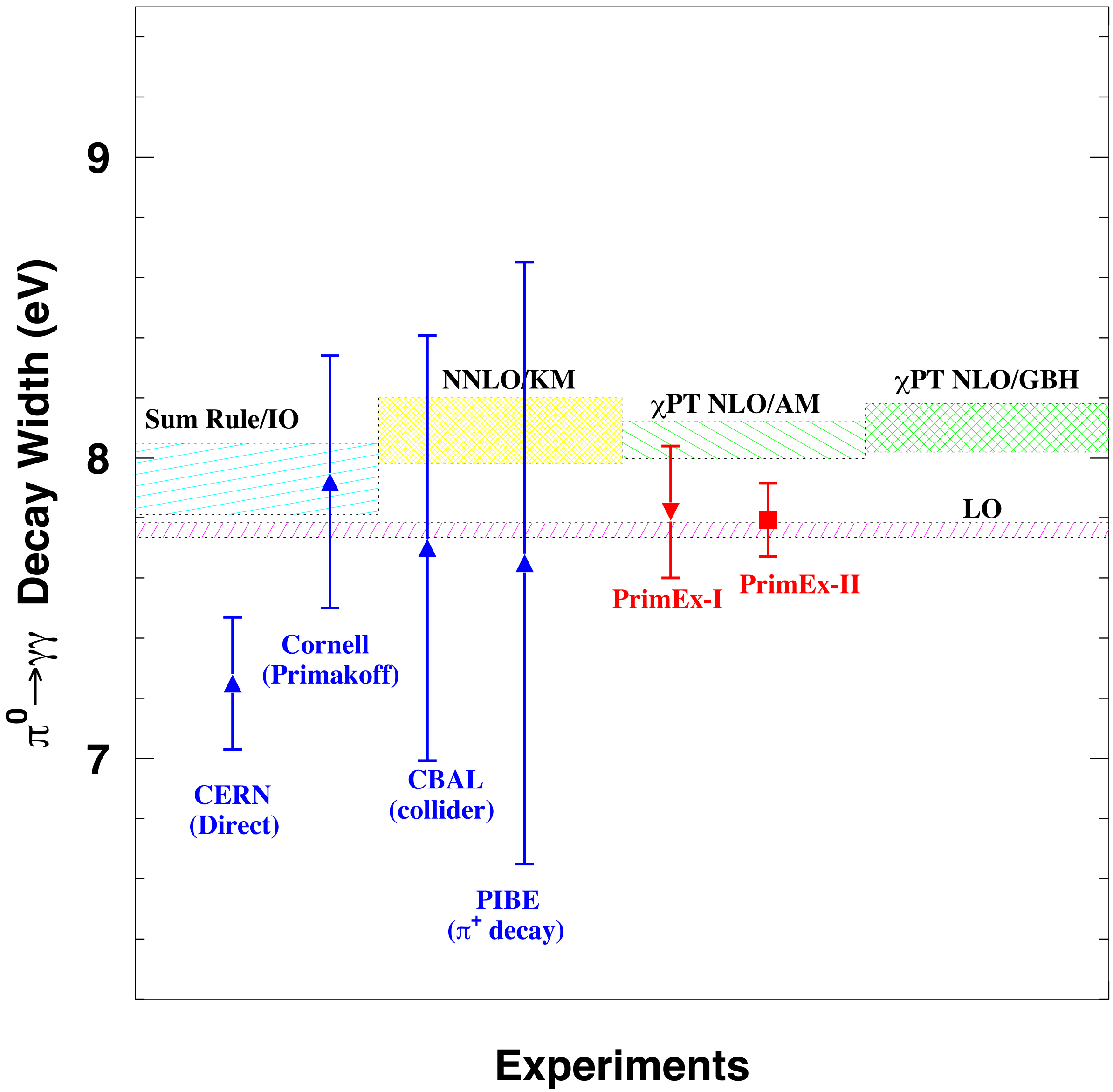




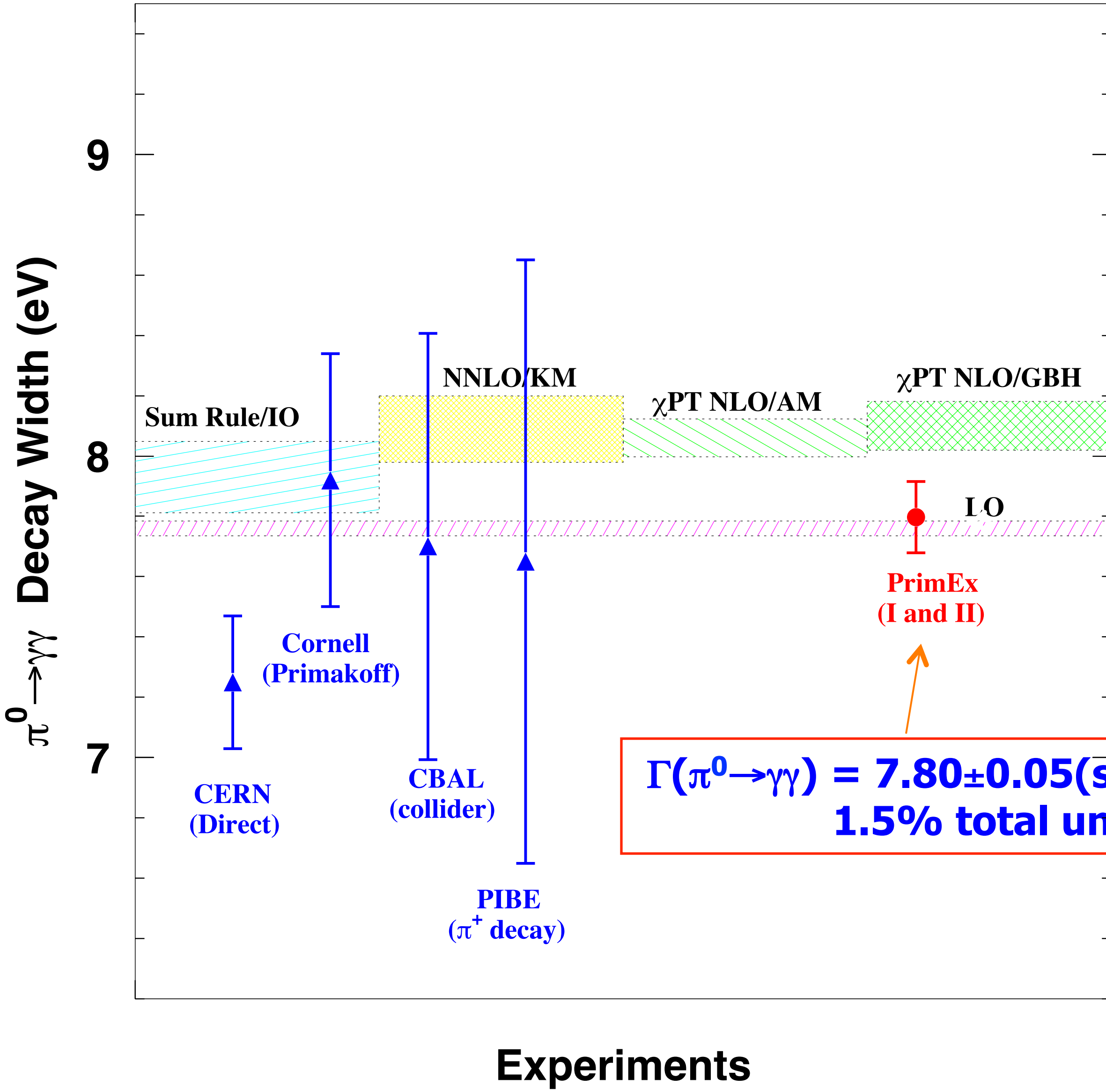
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

PRL 106, 162303 (2011)

Impact of PrimEx Result Cont.



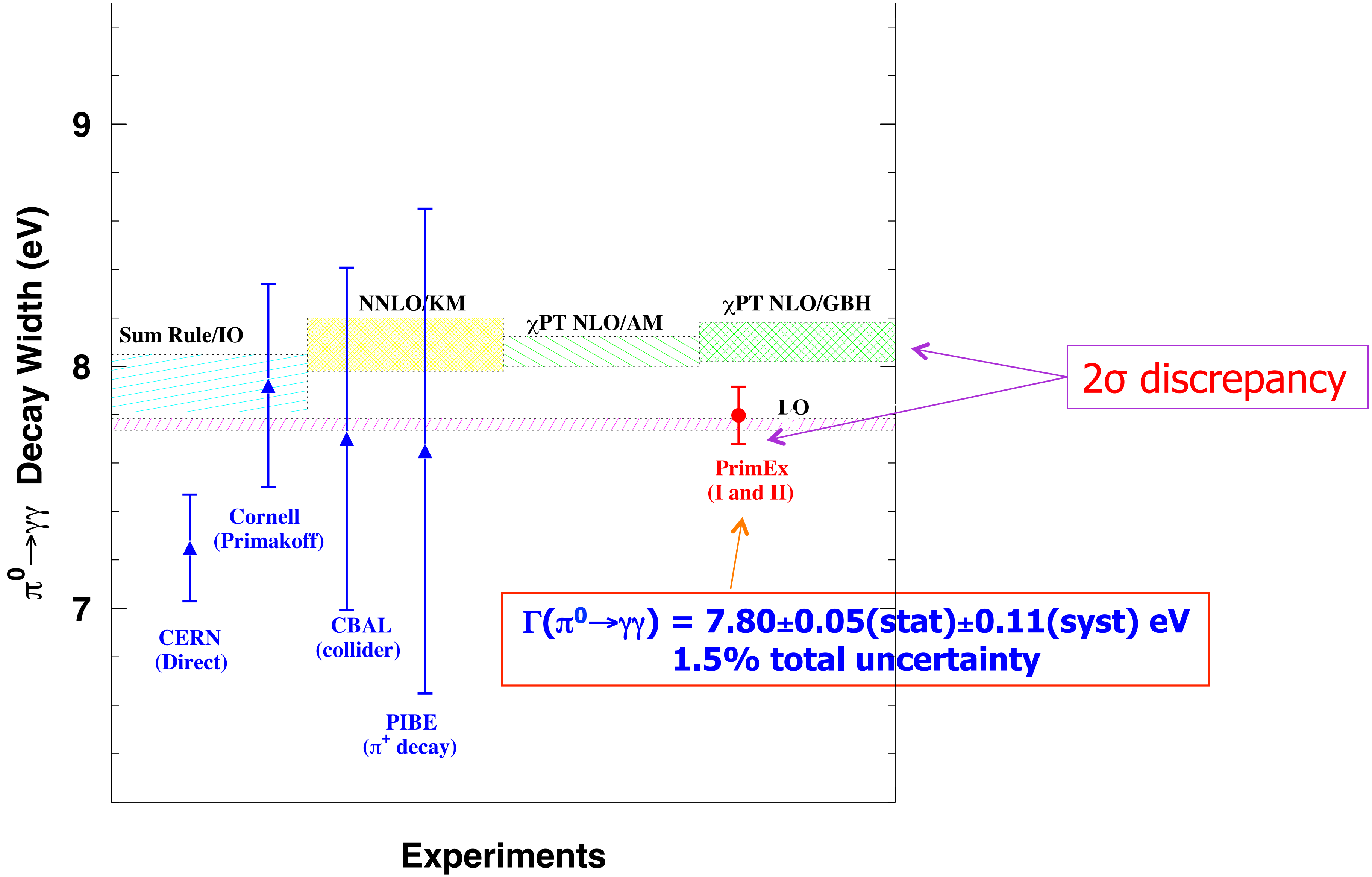
PrimEx Final Result



$\Gamma(\pi^0 \to \gamma\gamma) = 7.80 \pm 0.05(stat) \pm 0.11(syst)$ eV

1.5% total uncertainty

PrimEx Final Result



Challenges to theory colleagues

1. Calculation from Light-Front Holography

2. Lattice calculation

3. Exam the input parameters in ChPT calculations

   - F_π
   - m_u-m_d
   - Meson mixing
   - LEC's

4. Other possibilities?

Challenges to theory colleagues

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3. Exam the input parameters in ChPT calculations

   - F_π ← Possible non-standard electroweak coupling contribution in $\pi^+ \to \nu_\mu \mu^+$? JHEP 01 (2008) 015
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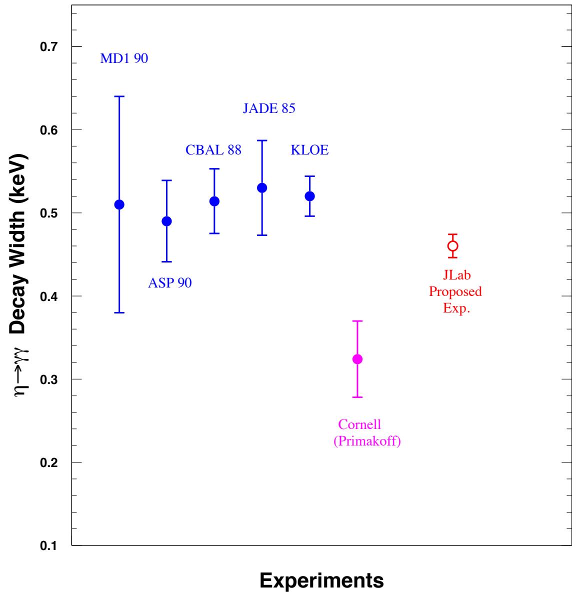


Summary

- The PrimEx collaboration developed a state-of-the-art experimental setup to perform a high precision measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ via the Primakoff effect.

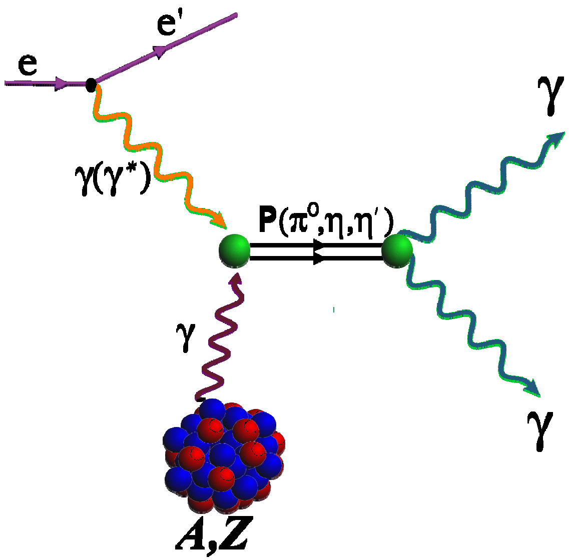
- The final PrimEx result is:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.80 \pm 0.05\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{eV} \quad (1.5\%\ \text{total})$$

- Our result is consistent with the leading order chiral anomaly calculation and ~2σ below the high order QCD predictions.

Primakoff Program at Jlab

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):

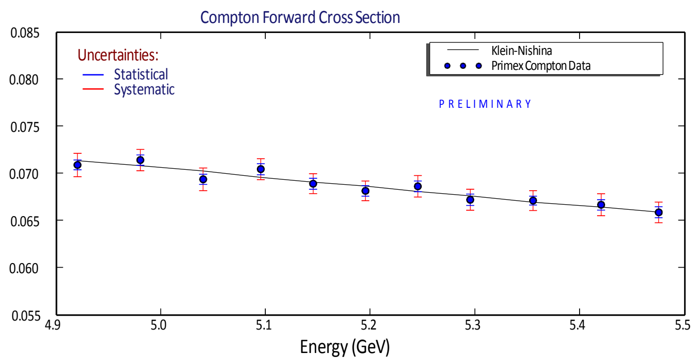
$F(\gamma\gamma^* \to \pi^0)$, $F(\gamma\gamma^* \to \eta)$, $F(\gamma\gamma^* \to \eta')$

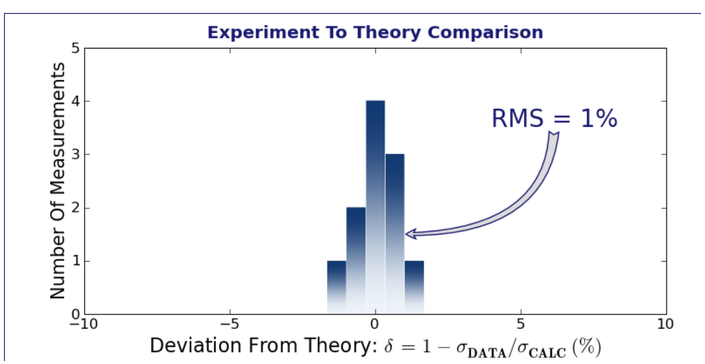
Input to Physics:

- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- inputs to a_μ(HLbL) calculations

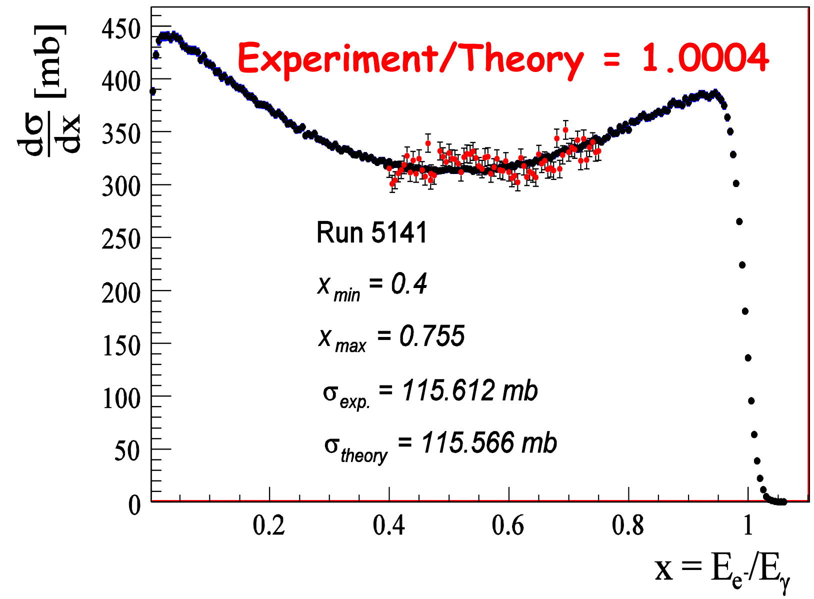
Verification of Overall Systematical Uncertainties

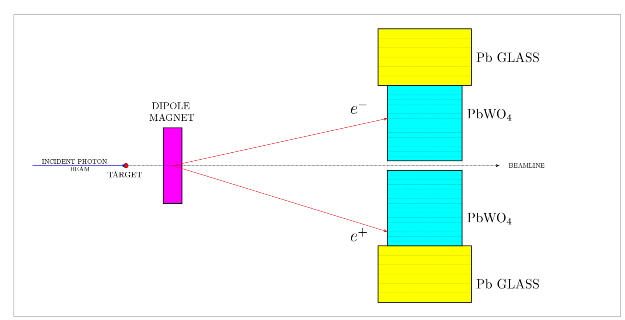
- ❑ $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





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





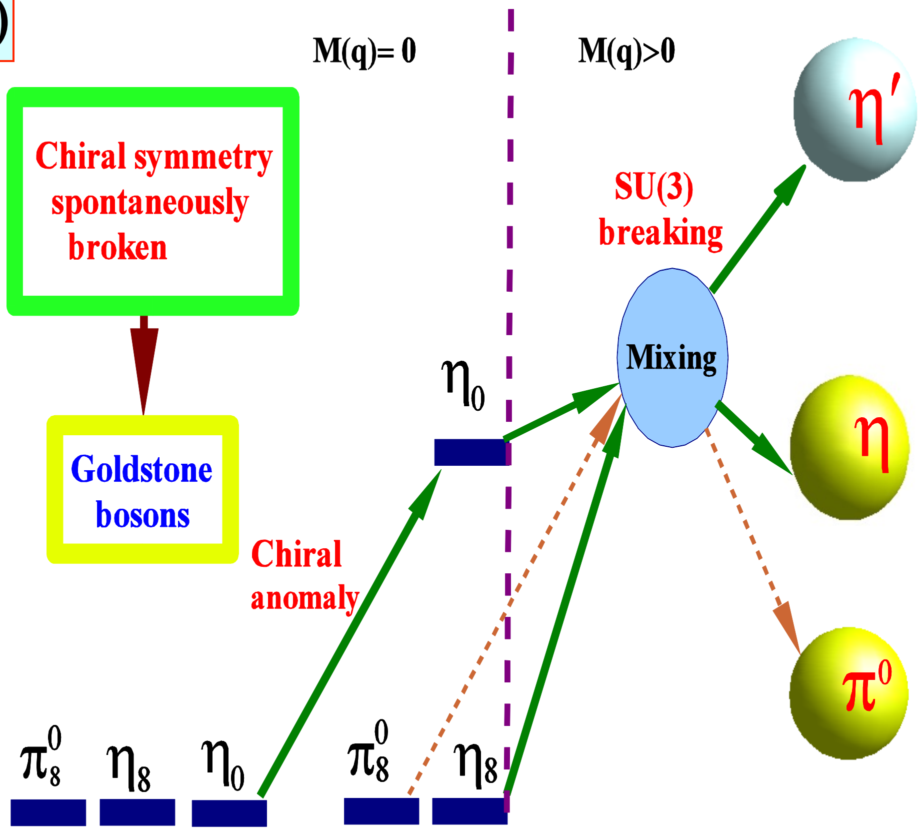
Systematic uncertainties on cross section are controlled better than 1.5%

Low-Energy QCD Symmetries and Light Mesons

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

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

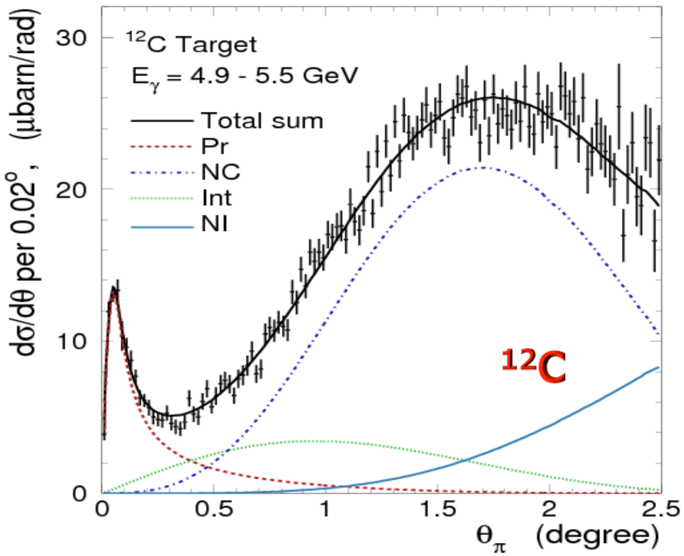
- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to SU(3)
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - Mass of η_0
- $SU_L(3)xSU_R(3)$ and SU(3) are explicitly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

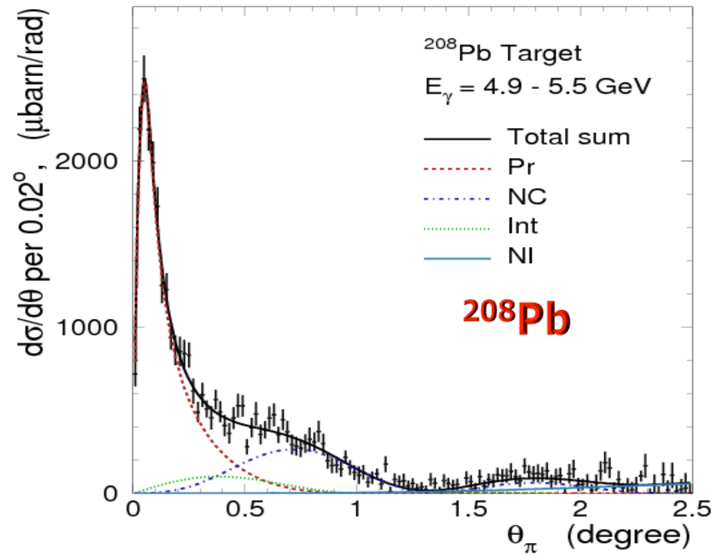


The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

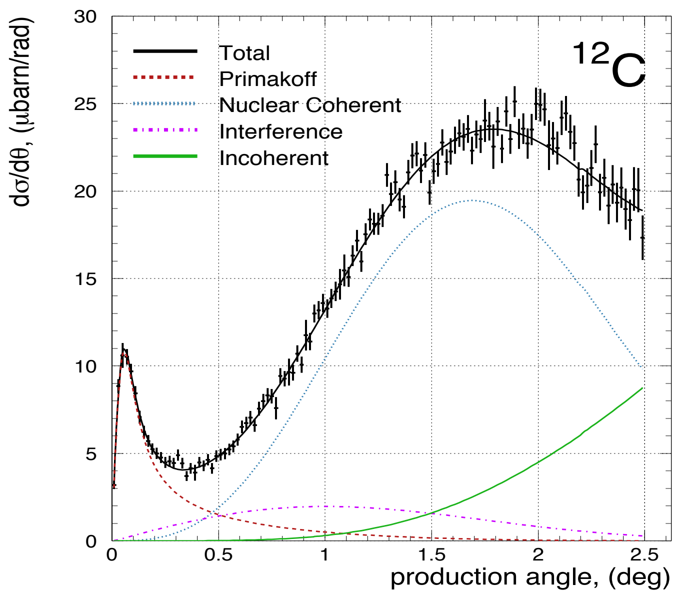
Differential Cross Sections

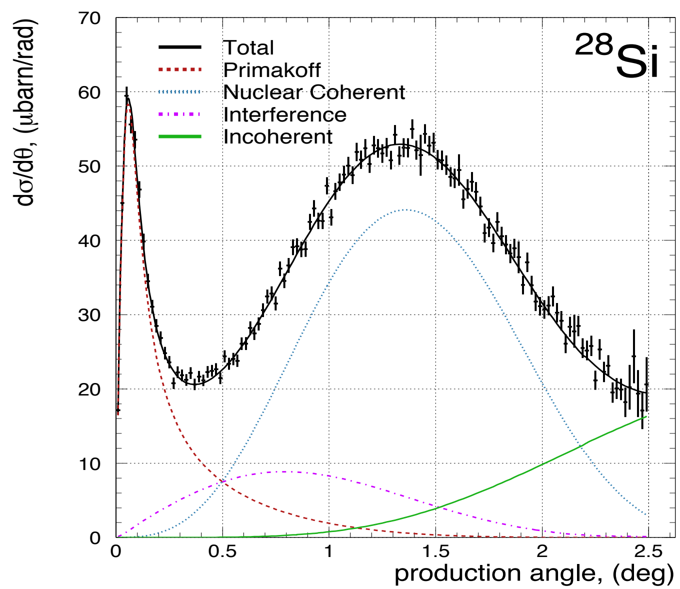
PrimEx I:





PrimEx II:





Time and Run Condition Dependence