THE NEUTRAL PION RADIATIVE WIDTH: THE FINAL RESULT FROM PRIMEX

I. Larin,

ITEP Moscow / University of Massachusetts Amherst,

On behalf of the PrimEx collaboration

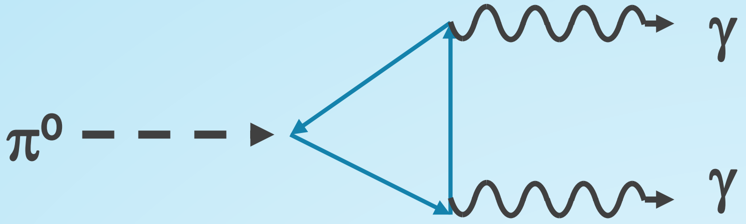
OUTLINE

- Physics motivation
- Experimental methods
- The PrimEx experiment
- PrimEx results

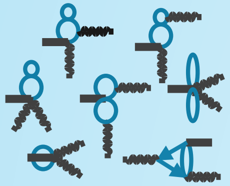
QCD PREDICTIONS FOR $\Gamma(\pi^0\rightarrow\gamma\gamma)$

- $\pi^0 \rightarrow \gamma\gamma$ proceeds primarily via chiral anomaly
- Chiral anomaly predicts exact value for decay width at the leading order and massless quarks:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 N_C^2 m_{\pi^0}^3}{576\pi^3 F_{\pi^0}^2} = 7.725 \pm 0.044\ eV$$

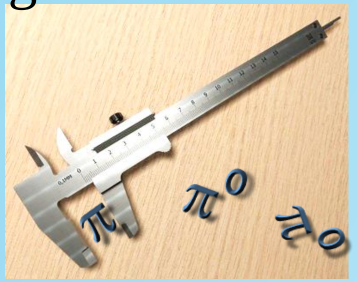


- Next to the leading order corrections have been calculated taking into account different quark masses and mixing effects with percent level precision:
  - J.Goity et al.: 8.1eV±1.0%
  - K.Kampf, B.Moussalam: 8.09±1.4%
  - B.Ananthanarayan et al.: 8.06±1.0%
  - B.Ioffe, A.Oganesian (QCD sum rules): 7.93±1.5%

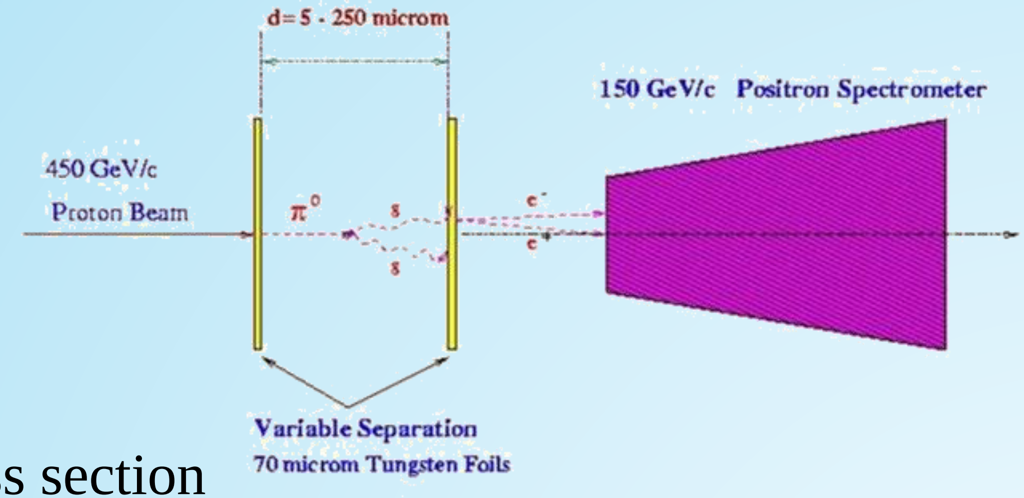


$\Gamma(\pi^0 \to \gamma\gamma)$: EXPERIMENTAL METHODS AND MEASUREMENTS: DIRECT MEASUREMENT

- Direct decay length measurement

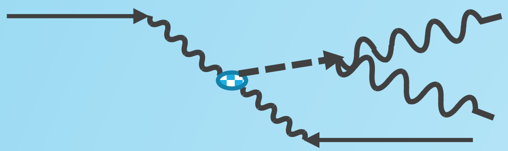


- Decay length is only ~20μm at 100GeV
- Limited by unknown π^0 momentum spectrum
- No need to know production mechanism and cross section
- Measurements:
  - CERN (1984) $\Gamma(\pi^0 \to \gamma\gamma) = 7.34\text{eV} \pm 3.1\%$

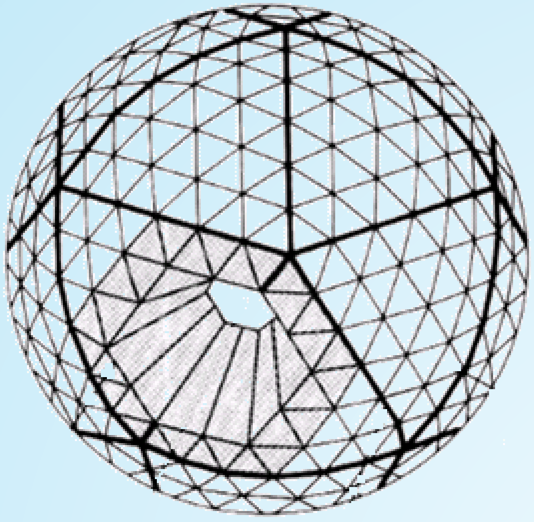


$\Gamma(\pi^0\to\gamma\gamma)$: EXPERIMENTAL METHODS AND MEASUREMENTS: PRODUCTION IN E^+E^- COLLISIONS

- "Photoproduction" on virtual $\gamma^*\gamma^*$ in e^+e^- collisions



- No need to separate coulomb and strong production
- Photoproduction cross section needs to be extracted
- Limited by the luminosity of crossing beams accuracy
- Measurements:
  - CBAL (1988) $\Gamma(\pi^0\to\gamma\gamma) = 7.75\text{eV}\pm6.4\%$

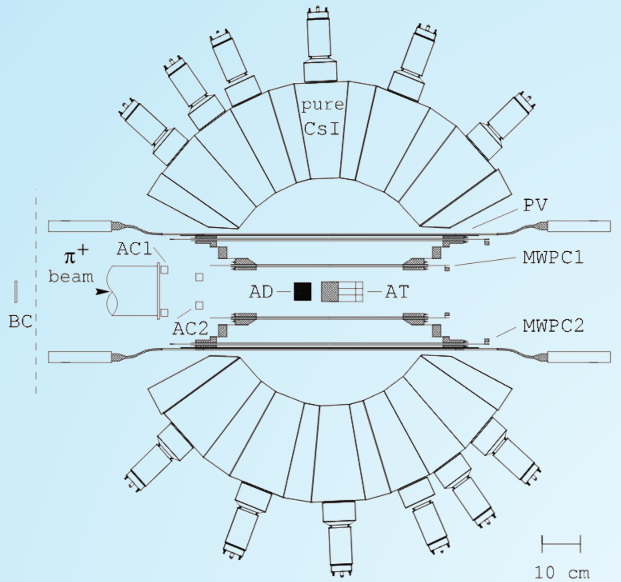


$\Gamma(\pi^0\to\gamma\gamma)$: EXPERIMENTAL METHODS AND MEASUREMENTS: π^+ RADIATIVE DECAY MEASUREMENT

- $\Gamma(\pi^0\to\gamma\gamma)$ can be calculated from $\pi^+\to e\nu\gamma$ radiative decay parameters
- $\pi^+\to e\nu\gamma$ decay in rest analysis
- $\Gamma(\pi^0\to\gamma\gamma)$ extracted from vector form factor $F_V(0)$:

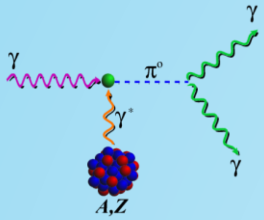
$$\Gamma(\pi^0\to\gamma\gamma^*)=\frac{\alpha^2\pi m_{\pi^0}}{2}|F_V(0)|^2$$

- Measurements:
  - PIBETA (2009) $\Gamma(\pi^0\to\gamma\gamma) = 7.65\text{eV}\pm13\%$

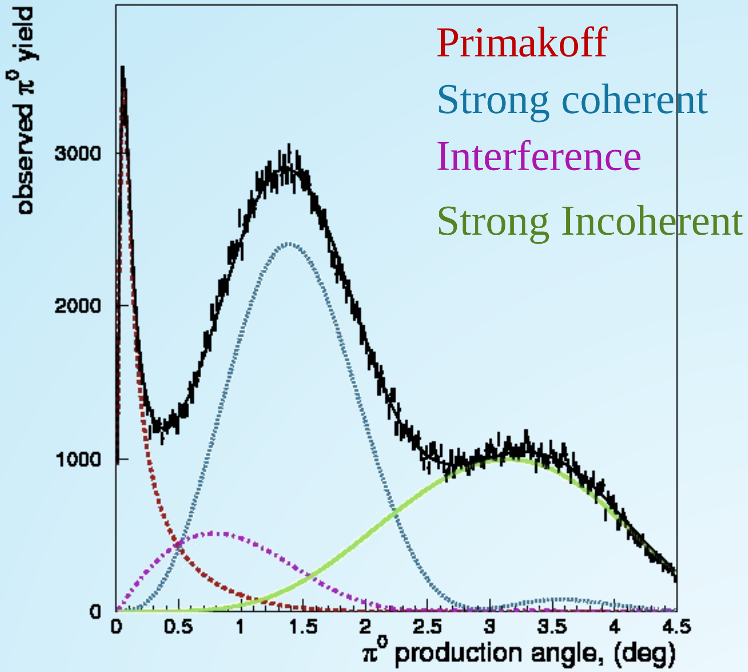


$\Gamma(\pi^0 \to \gamma\gamma)$: PRIMAKOFF METHOD

- π^0 photoproduction in nucleus coulomb field

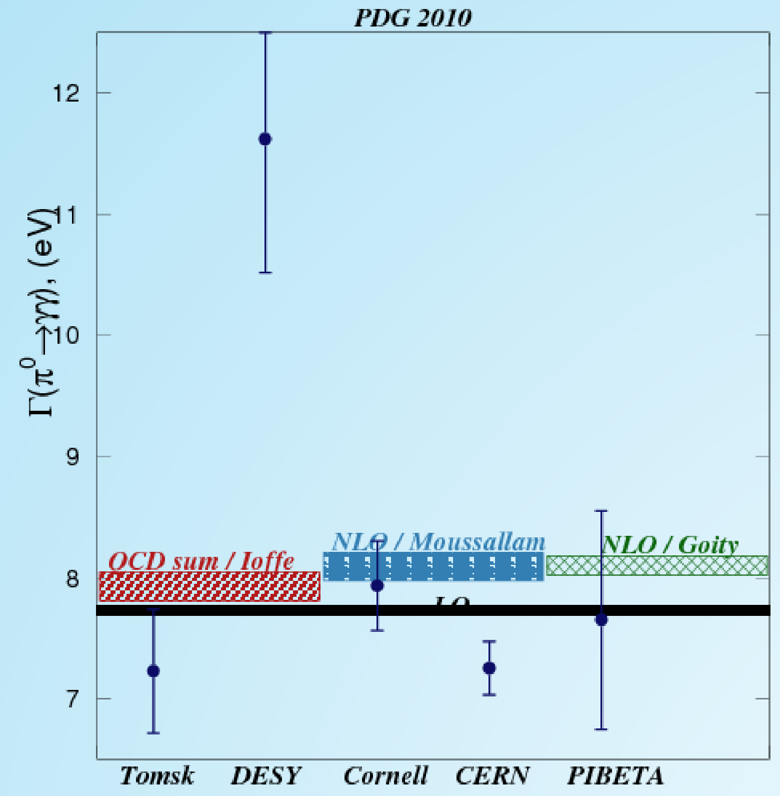


- Coulomb part of photoproduction cross section needs to be extracted: $\left(\frac{d\sigma}{d\Omega}\right)_{Pr} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{em}(Q)|^2 \sin^2\theta_\pi$
- Challenge: separate Coulomb and Strong photoproduction
- Most recent measurement preceding PrimEx:
  - Cornell (1974) $\Gamma(\pi^0 \to \gamma\gamma) = 7.92\text{eV} \pm 5.3\%$



$\Gamma(\pi^0 \to \gamma\gamma)$ STATUS: THEORY CALCULATIONS AND PREVIOUS MEASUREMENTS

Measurement	Method	Result [eV]
PIBETA, 2009	π^+ decay	7.65 ± 1.0
CERN, 1984	Direct	7.25 ± 0.22
CBAL, 1988	Collider	7.75 ± 0.6
Cornell, 1974	Primakoff	7.92 ± 0.42
PDG average	**SF=2.6**	7.74 ± 0.43

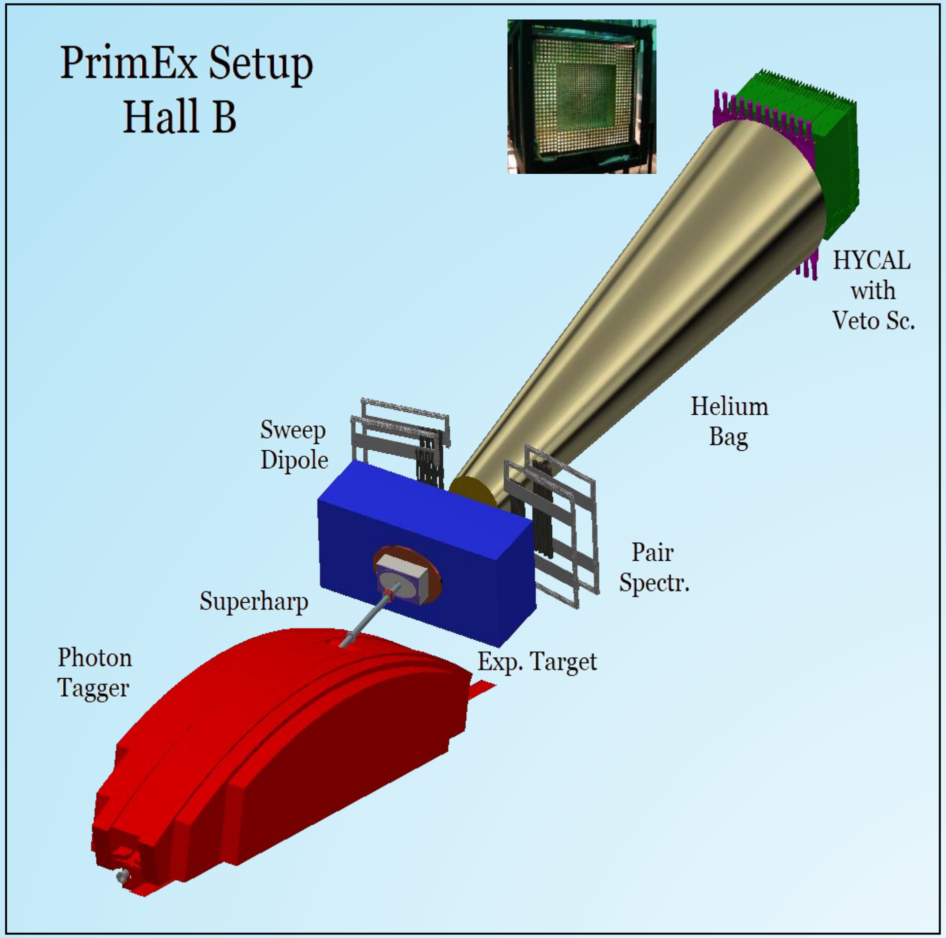


PRIMEX MILESTONES

- 1999: Proposal approved by PAC15
- 2000: NSF awarded MRI $1M grant to develop experimental setup
- 2002: Reapproved by PAC22 (E02-103) with A rating
- 2004: PrimEx-I Installation, Commissioning and Data taking (22 days)
- 2007: PrimEx-I Preliminary result released at APS meeting
- 2007: PrimEx-II proposal approved by PAC33
- 2009: PrimEx-I Final result reported
- 2010: PrimEx-II Detector upgrade and Data taking (28 days)
- 2011: PrimEx-I result published (PRL 2011, Vol 106, P. 162303)
- 2018: PrimEx-II Final result approved by the PrimEx Collaboration

PRIMEX SETUP

- Tagging facility:
  - Precise photon beam flux control
  - High resolution beam energy and time
- Hybrid EM calorimeter:
  - Excellent energy, spatial and time resolution
  - Large geometrical acceptance
- Pair spectrometer for additional flux monitoring
- Ability to control apparatus systematics by QED processes

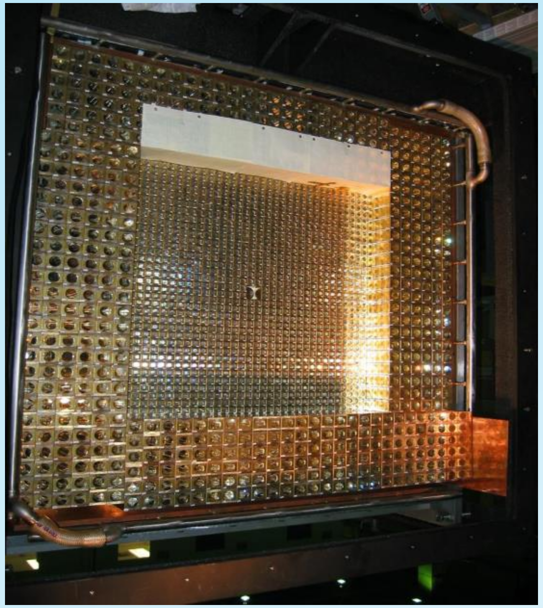


PRIMEX EM CALORIMETER (HYCAL)

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

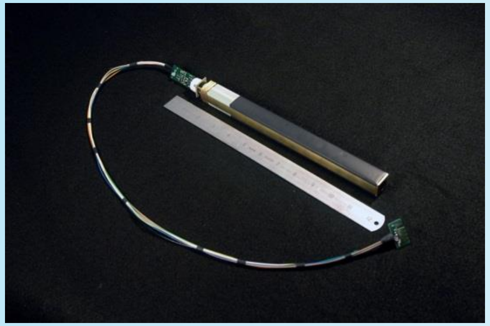
$PbWO_4$ crystals → resolution
Pb-glass → budget

- ✓ 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
- ✓ 7.0…7.3 m from target


front view, before Light Monitoring System assembly

- Good energy and position resolutions:

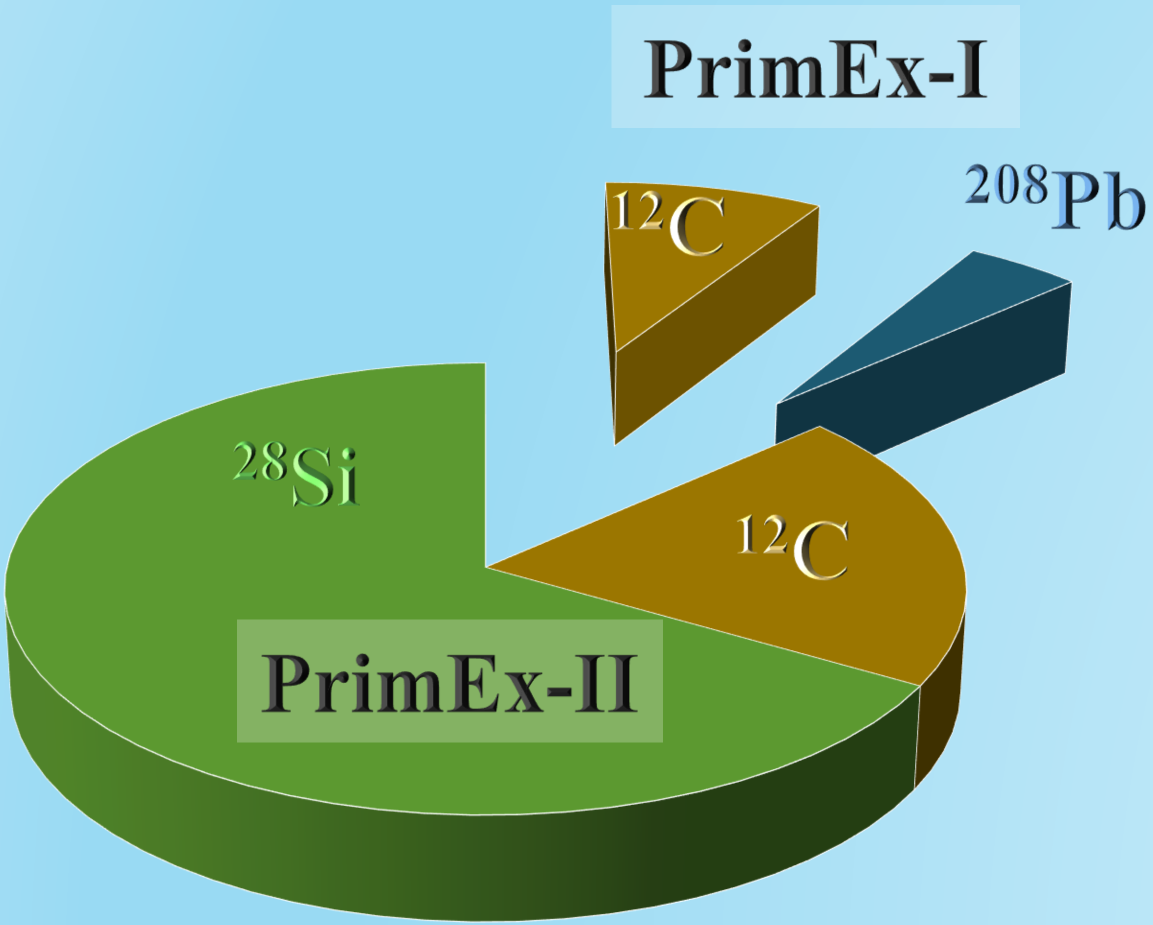
- ✓ $\sigma_E / E = 2.6\% / \sqrt{E}$
- ✓ $\sigma_{xy} / E = 2.7\ mm / \sqrt{E}$


Single $PbWO_4$ detector

PRIMEX UPGRADE FOR THE 2^{ND} RUN

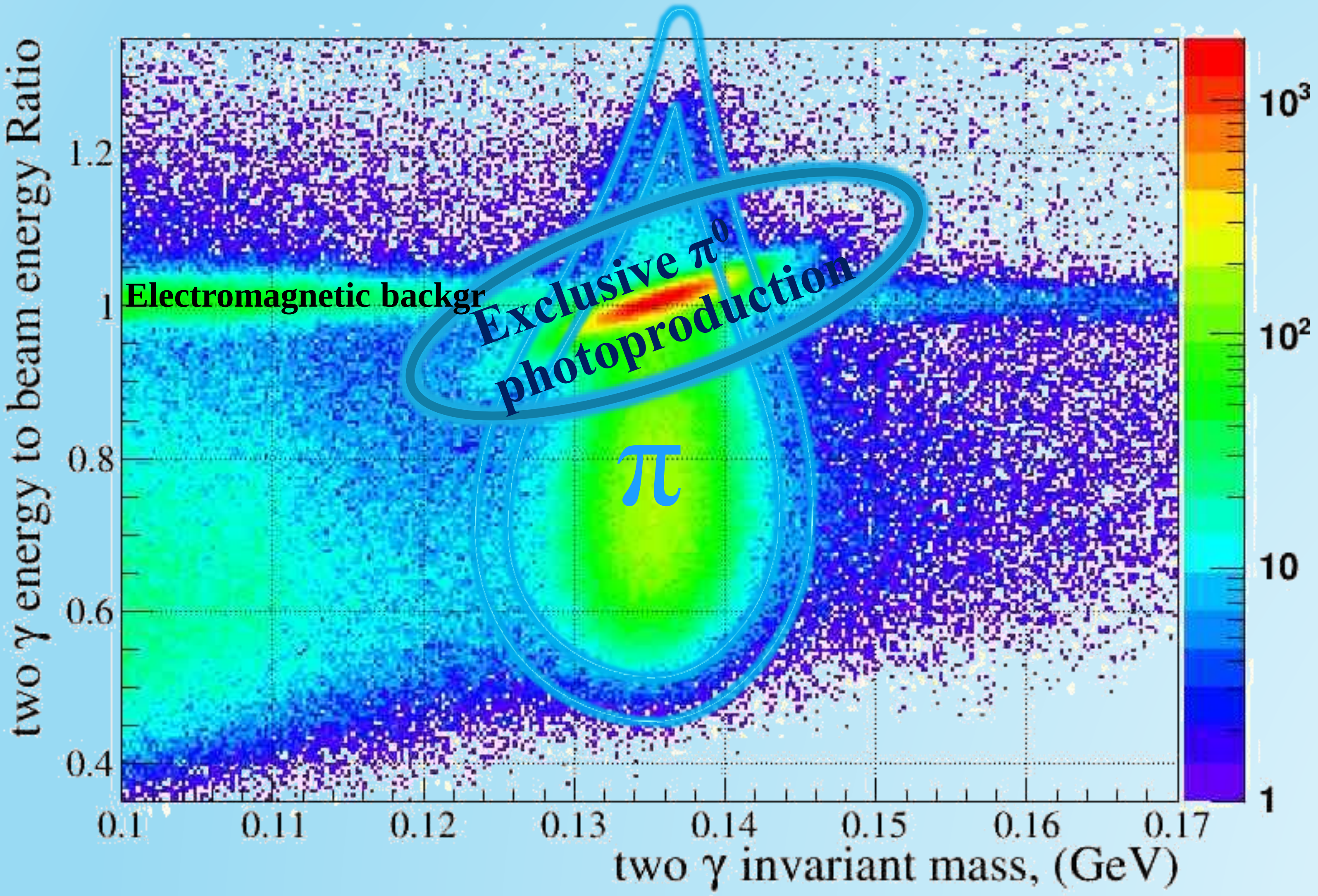
- PrimEx-II used 8% r.l. Carbon and new 10% r.l. Silicon targets:
  - PrimEx-II successfully collected twice more statistics on Carbon compare to PrimEx-I and about 5 times more statistics on Silicon compare to PrimEx-II Carbon
- Tagger energy range in the trigger have been increased by factor of ~1.5
- Central part of HyCal was upgraded with individual TDC modules:
  - out of time clusters were rejected
- Upgraded DAQ electronics were used since the middle of PrimEx-II
  - This main data subset was used in the analysis
- New island calorimeter reconstruction algorithm has been implemented, replacing old 5x5 algorithm
- HyCal closer to the target: 7.0m vs 7.3m (larger acceptance)

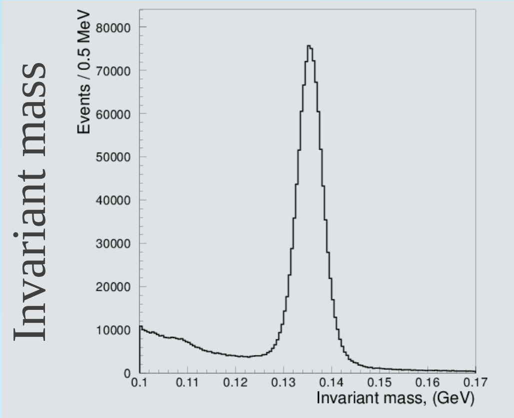
PRIMEX I AND II DATA CHART

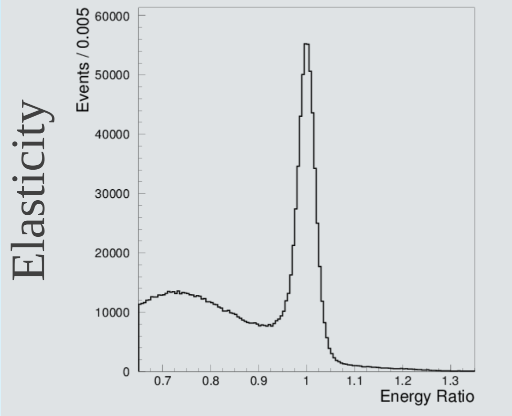


PrimEx run	Target	Thickness [% r.l.]	Beam flux [$\times 10^{12}$]	Beam energy [GeV]
I	^{12}C	5	1.4	4.9…5.5
I	^{208}Pb	5	0.72	4.9…5.5
II	^{12}C	8	2.0	4.4…5.3
II	^{28}Si	10	5.3	4.4…5.3

$\pi^0 \to \gamma\gamma$ event selection



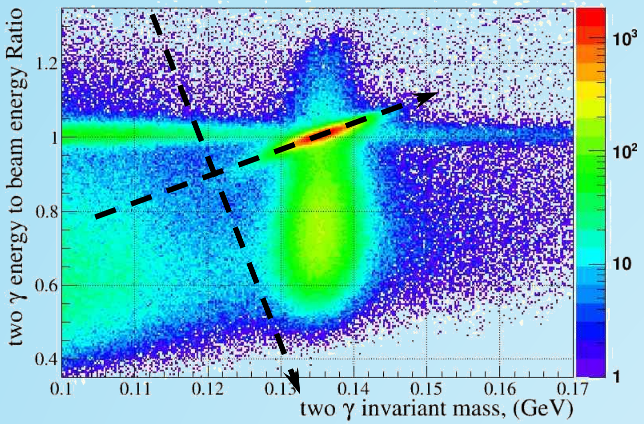


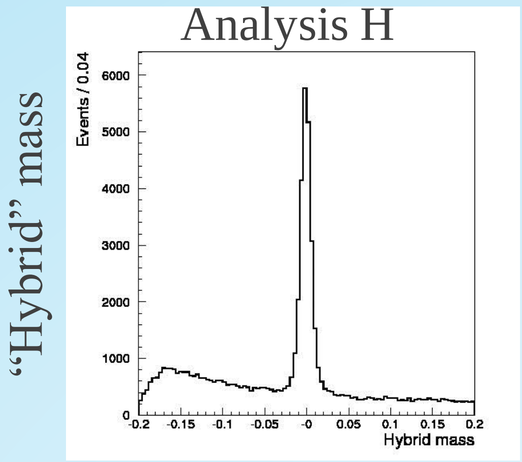


ELASTIC π^0 YIELD EXTRACTION

- **Hybrid mass analysis (H):**

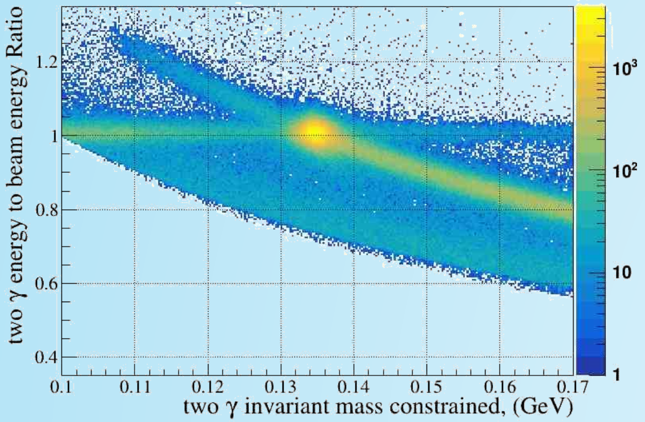
analyze rotated axes projection

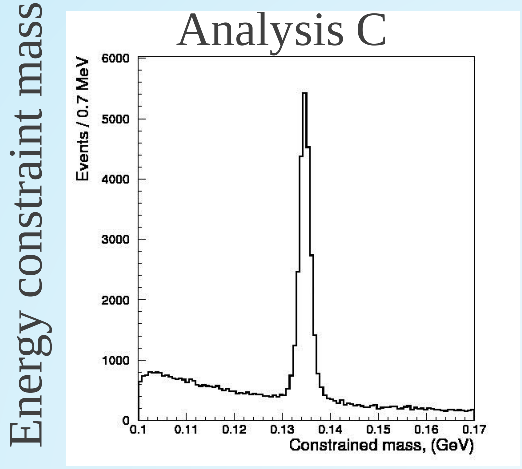




- **Constraint mass analysis (C):**

correct calorimeter energies so they give the sum exactly equal to beam energy



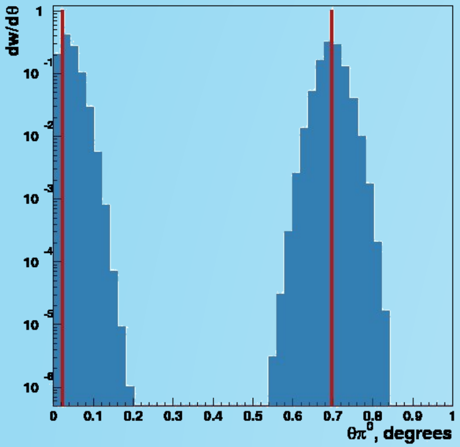


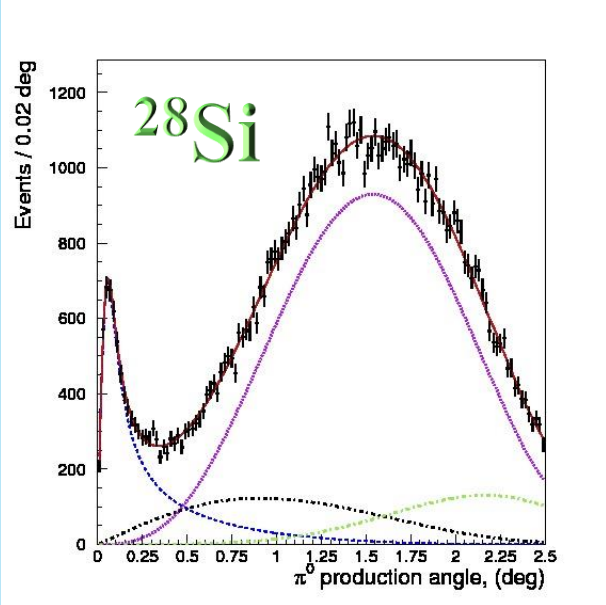
FIT TO EXTRACT $\Gamma(\pi^0\rightarrow\gamma\gamma)$

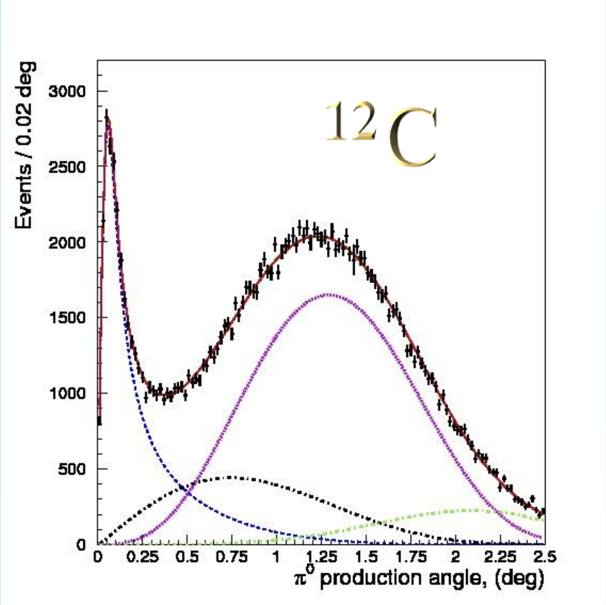
$$\left(\frac{d\sigma}{d\Omega}\right)_{Pr} = \boxed{\Gamma_{\gamma\gamma}}\,\frac{8\alpha Z^2}{m_\pi^3}\frac{\beta^3 E^4}{Q^4}|F_{em}(Q)|^2\sin^2\theta_\pi$$

$\otimes$

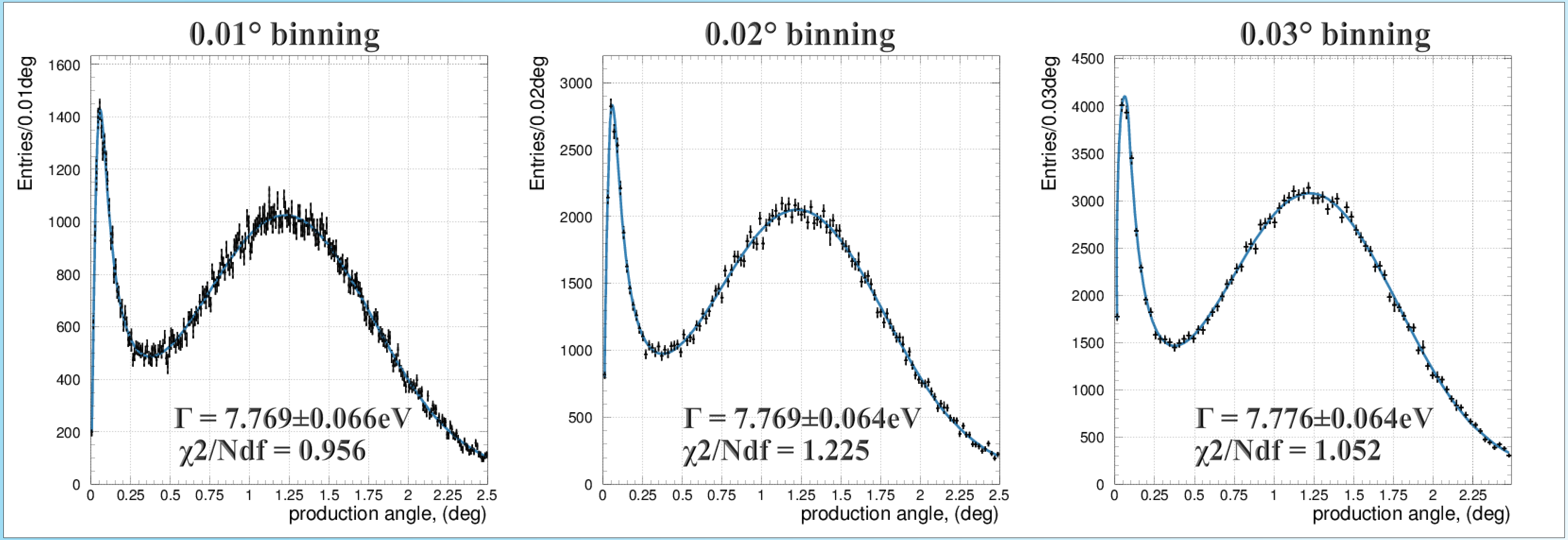
Theory functions have been folded with experimental resolution and setup acceptance to fit the data



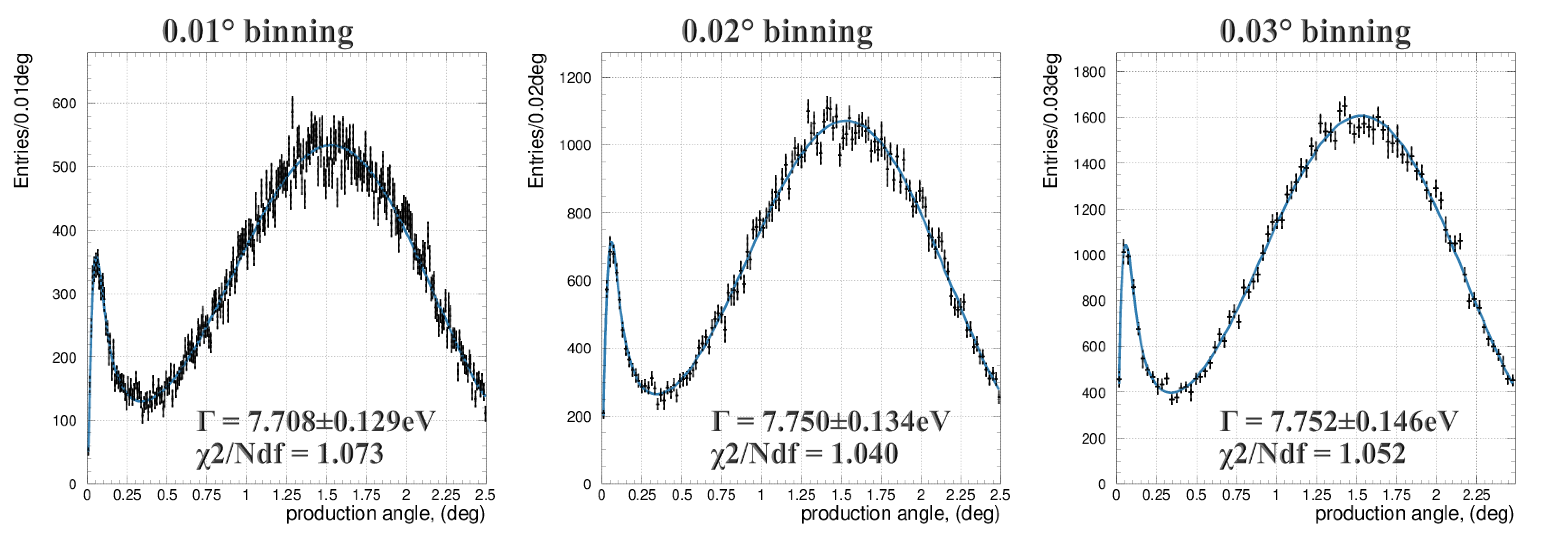




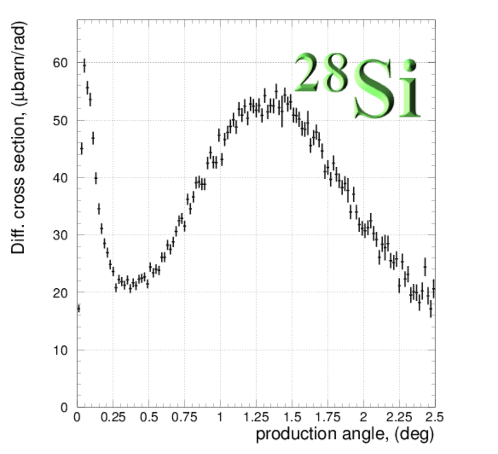
PRIMEX-II π^0 YIELD FIT, SILICON TARGET

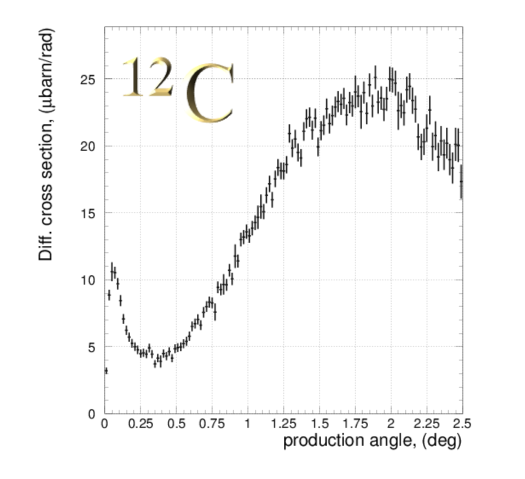


PRIMEX-II π^0 YIELD FIT, CARBON TARGET

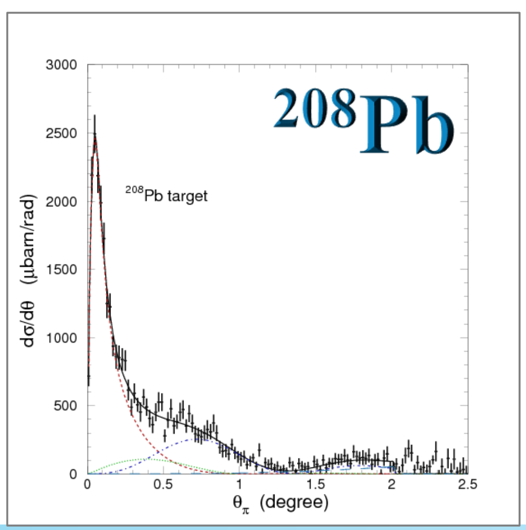


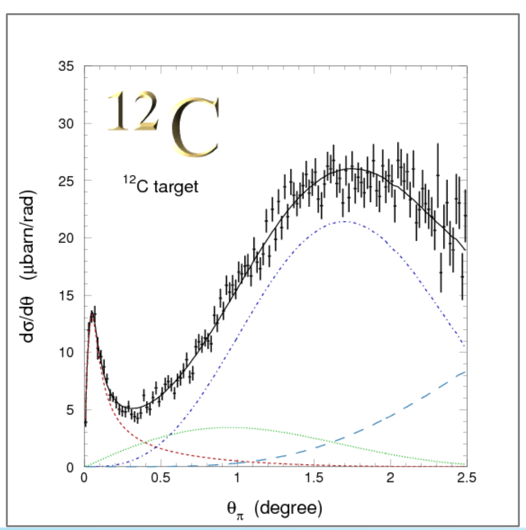
DIFFERENTIAL CROSS SECTION VS PRODUCTION ANGLE





PrimEx-II: 4.45GeV…5.3GeV photon beam energy

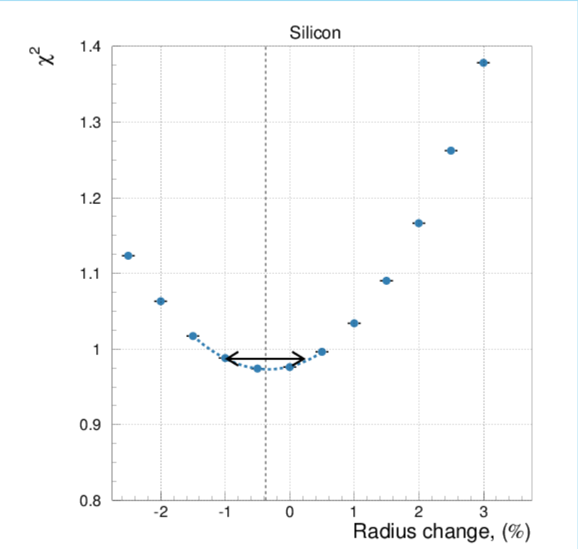


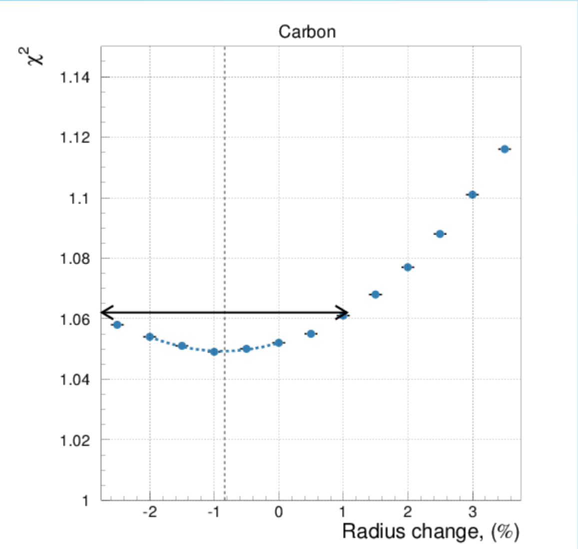


PrimEx-I: 4.9GeV…5.5GeV photon beam energy

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ systematic uncertainty item: Strong nucleus radius vs Electromagnetic radius

Fit χ^2/Ndof dependence vs strong radius change, [%]





Radius increase, minimizing χ^2:

- Si: ΔR = -0.3% ± 0.6% (stat.)
- C: ΔR = -1.4% ± 1.8% (stat.)

has been used in the final result, statistical uncertainty of this procedure is going directly to the theory systematics:

- Si: $\delta\Gamma(\Delta R$ syst.) = 0.24%
- C: $\delta\Gamma(\Delta R$ syst.) = 0.52%

"SECOND STEP" CONTRIBUTION ("SHADOWING" EFFECT)

Real photons at high energies are shadowed in nuclei. In case of pion photo-production it's resulting from two step process: initial photon produces vector (mostly ρ) meson, which produces pseudoscalar meson on another nucleon (ω contribution is additionally suppressed by opposite sign of amplitudes on protons and neutrons). This gives an additional term for strong amplitude mostly coming from intermediate ρ channel

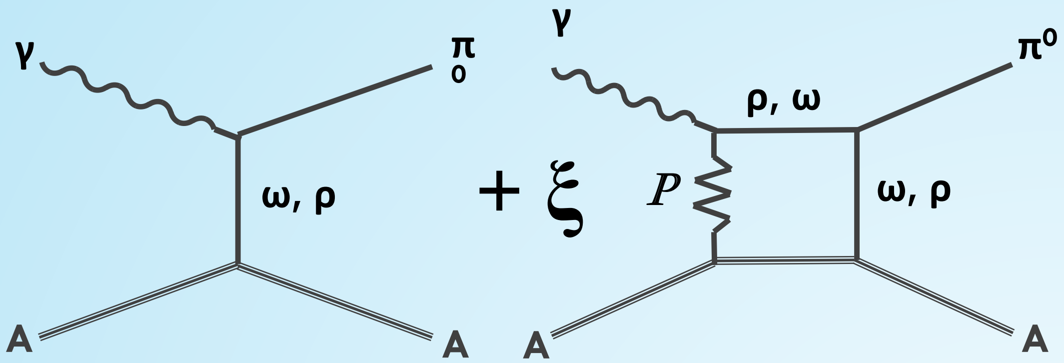
$$T_{st}(q) = (\vec{h} \cdot \vec{q})\, \varphi(0)\, (F_{st} - \xi F_I) \qquad \vec{h} = [\vec{k} \times \vec{\epsilon}]/k$$

parameter ξ can be expressed via elastic amplitude ratio:

$$\xi = \frac{f(\gamma N \to \rho N) f(\rho N \to \pi N)}{f(\rho N \to \rho N) f(\gamma N \to \pi N)}$$

and is within range between 0 (no shadowing) and 1 (VDM)

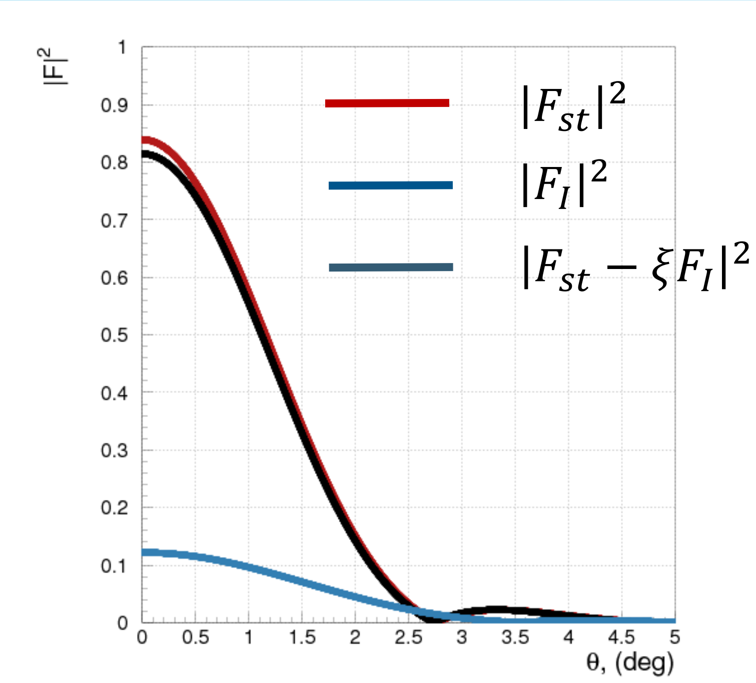
$\xi = 0.25$ value has been used in analysis*



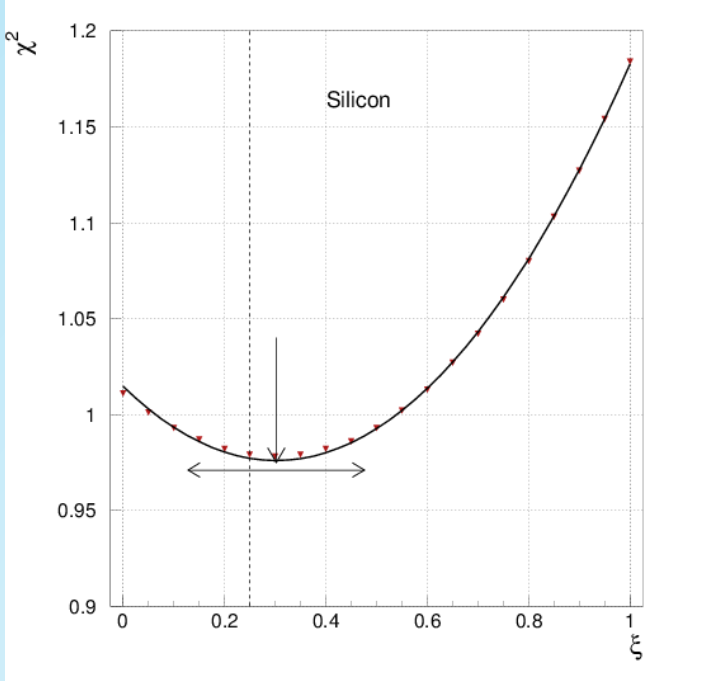
** W. Meyer et al., Phys. Rev. Lett. 28, 1344 (1972);*
A. M. Boyarski et al., Phys. Rev. Lett. 23, 1343 (1969)

$\Gamma(\pi^0\to\gamma\gamma)$ systematic uncertainty item: Shadowing parameter ξ

Strong FF and shadowing



Data fit χ2 vs shadowing parameter



The value ξ=0.25* used in the analysis is in agreement with the value giving the best fit χ^2: ξ=0.30±0.17

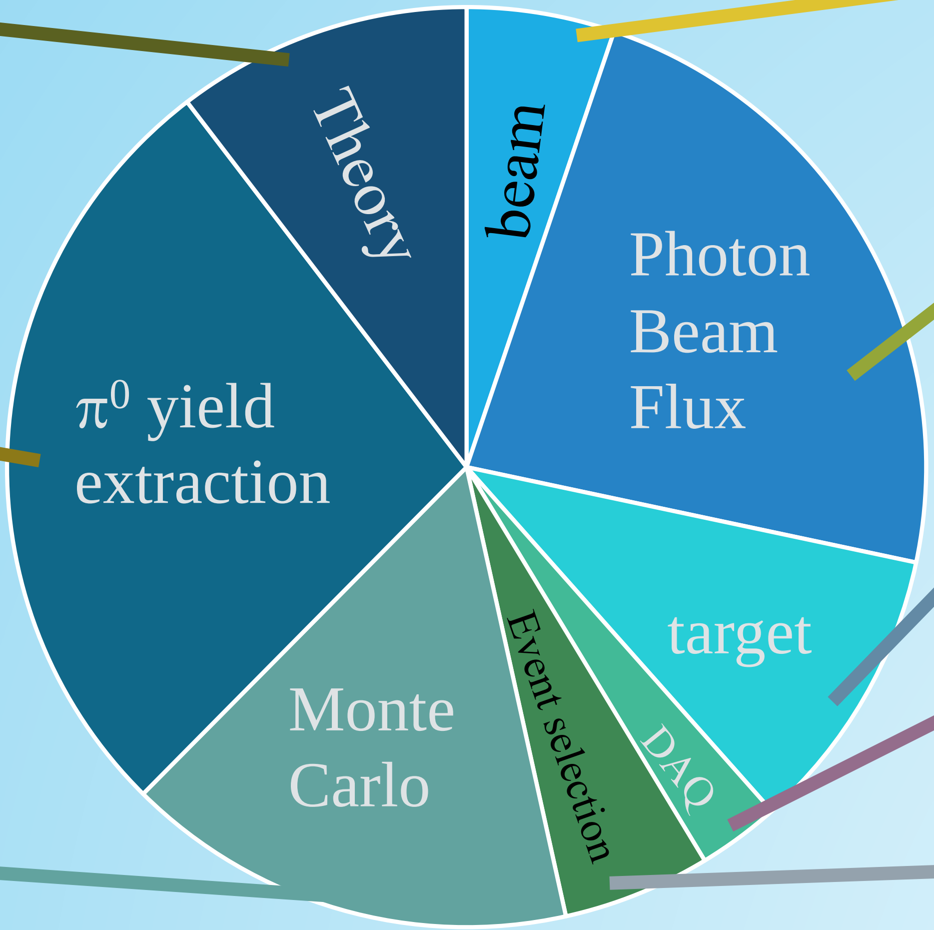
* *W. Meyer et al., Phys. Rev. Lett. 28, 1344 (1972);*
A. M. Boyarski et al., Phys. Rev. Lett. 23, 1343 (1969)

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	≤0.1%
Nuclear strong vs EM radius	0.24%
Total	0.42%

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%
$dN/d\theta$ 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%

PRIMEX I VS PRIMEX-II $\Gamma(\pi^0 \to \gamma\gamma)$ UNCERTAINTY

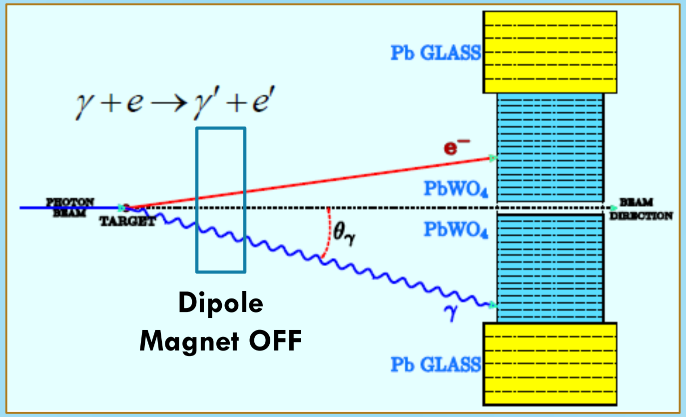
Item	PrimEx-I	PrimEx-II
Beam parameters	0.4%	0.3%
Photon flux	1.0%	0.8%
Target	0.3%	0.3%
DAQ	0.1%	0.1%
Event selection	0.5%	0.2%
Monte-Carlo simulation	0.6%	0.6%
Yield extraction	1.6%	0.8%
Photoproduction theory parameters	0.6%	0.4%
Systematics	**2.1%**	**1.4%**
Statistical	1.8%	0.7%
Total	**2.8%**	**1.6%**

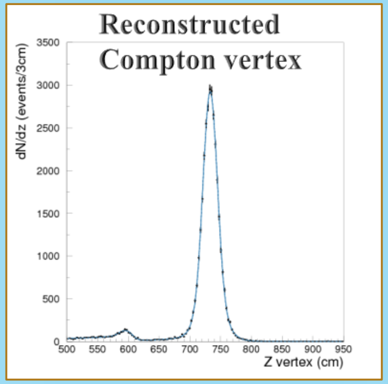
Better beam quality

Statistically driven systematics (improved statistics)

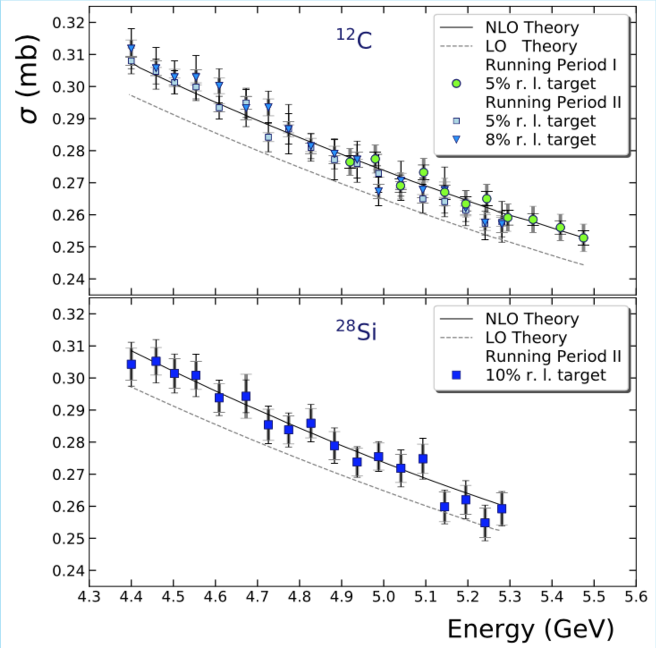
VERIFICATION WITH COMPTON CROSS SECTION

Compton event

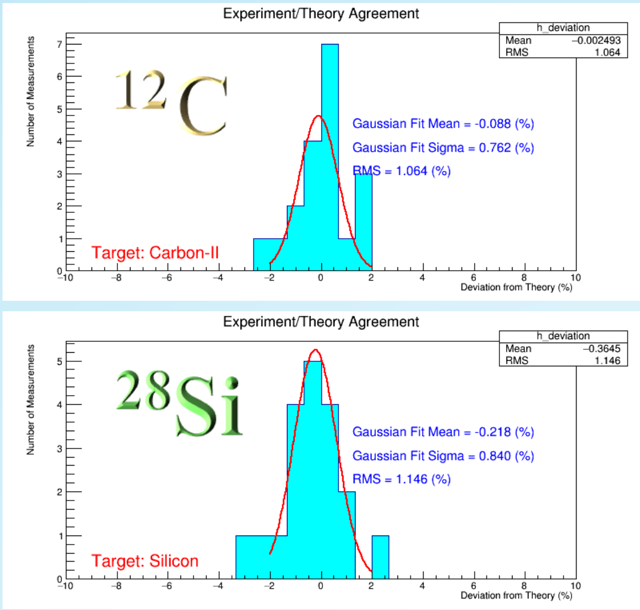




Compton cross section deviation from theory prediction vs photon beam energy

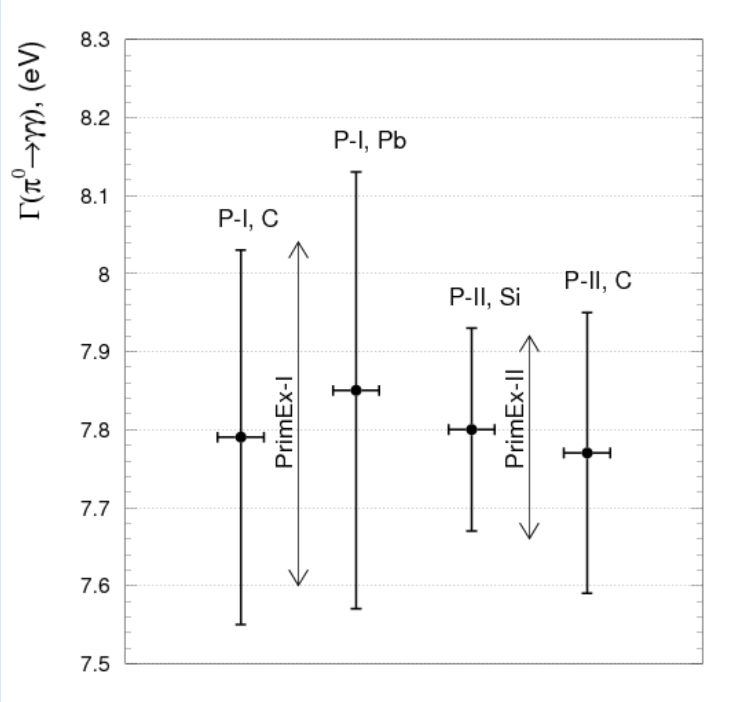


Projected points



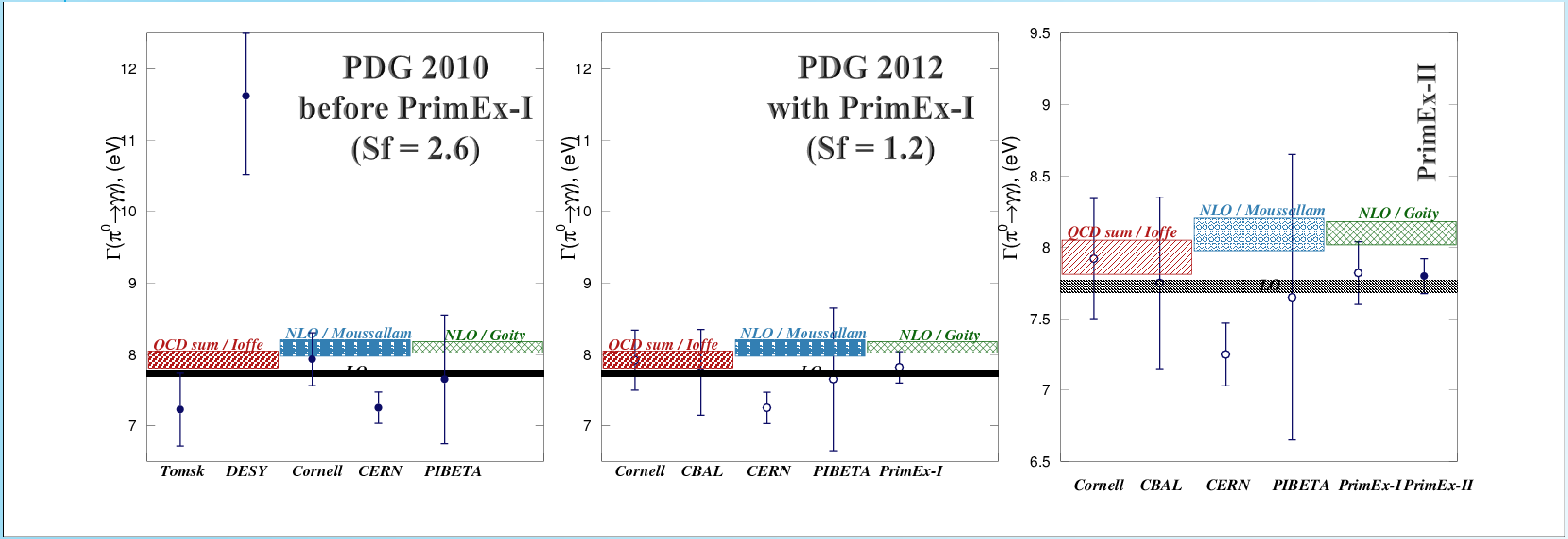
extracted cross sections are in agreement with theory prediction at the level of systematic uncertainty of 1.5%

PRIMEX I VS PRIMEX II RESULT



Run	Target	$\Gamma(\pi^0\to\gamma\gamma)$, eV
PrimEx-I	^{12}C	7.79±0.24
PrimEx-I	^{208}Pb	7.85±0.28
PrimEx-II	^{28}Si	7.81±0.13
PrimEx-II	^{12}C	7.76±0.17

PRIMEX RESULT CHANGED PDG LANDSCAPE ON $\Gamma(\pi^0 \to \gamma\gamma)$ PART



SUMMARY

- The neutral pion radiative decay is one of the best tests of QCD at low energy domain
- The PrimEx collaboration performed two new generation Primakoff experiments
- PrimEx-II reduced measurement error down to 1.6%, which is the most precise measurement to the date
- Compton cross section measurement verifies PrimEx systematical uncertainty for the cross section on the 1.5% level

PrimEx-I physics result:

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.82\text{eV} \pm 0.14\text{eV stat.} \pm 0.17\text{eV syst.}; \pm 0.22\text{eV}(2.8\%) \text{ total}$$

PrimEx-II physics result:

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.798\text{eV} \pm 0.056\text{eV stat.} \pm 0.109\text{eV syst.}; \pm 0.122\text{eV}(1.6\%) \text{ total}$$

PrimEx final result:

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.802\text{eV} \pm 0.052\text{eV stat.} \pm 0.105\text{eV syst.}; \pm 0.117\text{eV}(1.5\%) \text{ total}$$